Quantifying milldam legacy sediment storage in valley bottoms of two New England watersheds

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QUANTIFYING MILLDAM LEGACY SEDIMENT STORAGE IN VALLEY BOTTOMS OF TWO NEW ENGLAND WATERSHEDS

Kaitlin M. Johnson

A thesis

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QUANTIFYING MILLDAM LEGACY SEDIMENT STORAGE IN VALLEY BOTTOMS OF TWO NEW ENGLAND WATERSHEDS

Kaitlin M. Johnson

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Large-scale human modification of the northeastern U.S. landscape began in the 17^{th} century with forest clearing and milldam construction. In the mid-Atlantic Piedmont region of the U.S., Walter and Merritts (2008) found that millpond deposits persist for centuries after dam breaching, resulting in fill terraces composed of legacy sediment. Stratigraphic observations in the mid-Atlantic indicate that these laminated to massive fine-grained layers typically overly a prominent Holocene hydric soil that overlies a Pleistocene basal gravel. I test whether this set of processes applies to glaciated New England. This study focuses on two New England watersheds: the South River in Massachusetts and the Sheepscot River in Maine. I use stratigraphic analysis and radiocarbon dating to identify legacy deposits, and then use lidar digital elevation models to map planar terrace extents in each watershed. Finally, I use lidar digital elevation models to estimate thickness of legacy sediment found behind breached or removed milldams and estimate volumes of legacy sediment storage in valley bottoms over entire watersheds. The South River watershed has 32 historic dam sites; 18 have been field checked and 14 show evidence for legacy sediment storage. The Sheepscot River watershed has 33 historic dam sites; 13 have been field checked and six show evidence of legacy sediment storage. Stratigraphic analyses of bank exposures in both watersheds show a brown fine sand and silt layer (up to 2.19 m thick in the South River watershed and up to 2.30 m thick in the Sheepscot River watershed) which sometimes is underlain by gravel and/or clay; no buried Holocene hydric soil has been found. Further evidence

for legacy milldam sedimentation comes from radiocarbon dating. Three radiocarbon dates from the South River watershed and six from the Sheepscot River watershed are less than 300 years old; no underlying Holocene material has been dated. The maximum volume of legacy sediment estimated using lidar methods for the South River watershed is 2.5 x 10^6 m^3 and for the Sheepscot River watershed the volume is 3.7 x 10^6 m^3. These volumes of legacy sediment can be translated to maximum mean thickness of sediment eroded from each landscape: 37 mm for the South River watershed and 7 mm for the Sheepscot River watershed. The Sheepscot River watershed has most of its legacy sediment terraces in the lower section of the watershed with many lakes and wetlands disturbing sediment transport in the upper section of the watershed. Compared to the Sheepscot River watershed, the South River watershed has more widespread glacial deposits contributing to legacy sediment with few lakes and wetlands.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Research Motivation

Humans are a primary geomorphic force shaping the Earth's surface (Zalasiewicz et al, 2008). Past and present human alteration of landscapes is so ubiquitous and intensive that it dominates erosional, depositional, and geochemical processes in river corridors (Wohl, 2015). Even though human-induced soil erosion has increased sediment transport in many rivers, the global sediment flux to the world's oceans has decreased due to storage in reservoirs (Syvitski et al., 2005; Wohl, 2015) and post-settlement aggradation along valleys (Wilkinson and McElroy, 2007). These changes to the Earth's surface have led geologists to propose adding the Anthropocene Epoch to the geological timescale (Crutzen 2002; Zalasiewicz et al., 2008; Waters et al., 2016).

To look at the changes humans are making in northeastern United States (NEUS; including Maryland and states to the north and east), I seek to quantify the amount of legacy sediment (material deposited in associated with human activities during the past 300-400 years) stored in valley bottoms of two watersheds in Maine and Massachusetts. This project extends the work done by Walter and Merritts (2008) and Merritts et al. (2011; 2013) in the mid-Atlantic piedmont region of the NEUS to New England. Walter, Merritts and colleagues conclude that milldam-influenced streams store sediment for centuries after breaching, resulting in fill terraces composed of legacy sediment.

New England is a glaciated environment, which contrasts with the nonglaciated mid-Atlantic region (Figure 1.1). Due to this, the New England landscape has thinner soils than the mid-Atlantic, localized sediment deposits of glacial material, and terrestrial accommodation space in natural lakes and wetlands (Snyder et al., 2013).

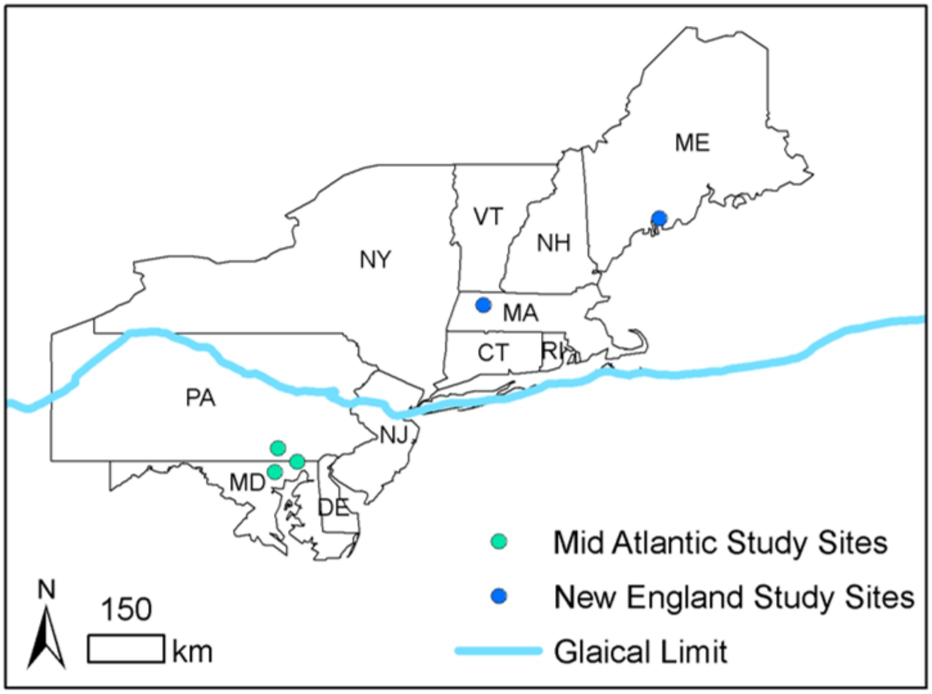

Figure 1.1. Map of the eastern United States showing the southern extent of the Laurentide Ice Sheet at the last glacial maximum ~21 ka. New England study sites for this study are shown in blue, north of the glacial extent line, compared with green study sites of previous work done by Walter and Merritts (2008) and Merritts et al. (2010; 2011; 2013) south of the glacial extent line in Pennsylvania and Maryland.

Europeans began to change the landscape of NEUS during the 17th century by forest clearing and milldam construction. Studies have identified deposits associated with elevated sediment yield because of colonial land clearing in both the mid-Atlantic (Costa, 1975; Jacobson and Coleman, 1986; Evans et al., 2000; Walter and Merritts, 2008) and New England (Brakenridge et al., 1988; Bierman et al., 1997; Wessels, 1997, Thorson et al, 1998) regions. Milldams created slackwater conditions that raised local base levels upstream. At the same time, deforestation for agriculture, charcoaling, and mining increased upland erosion and the supply of fine sediment that was trapped by the millponds. In the mid-Atlantic, Walter and Merritts (2008) determined that the typical millpond profile consists of 1-5 m of laminated to massive fine-grained sediment overlying a <0.5-1 m Holocene hydric soil and a <0.5 m basal Pleistocene gravel, all overlying bedrock. Recently, dam failures and removals have lowered base level, causing incision of stream channels into millpond deposits. These channels have a different form than pre-settlement channels and the resulting valley morphology now includes milldam deposits that function as fill terraces (Walter and Merritts, 2008; Merritts et al, 2011 and 2013) or active floodplains (Pizzuto et al., 2016).

Terms such as Anthropocene, legacy, post-settlement alluvium, and historic have all been used in the literature to describe recent deposits (Wilkinson and McElroy, 2007; Walter and Merritts, 2008; Merritts et al., 2011; James, 2013; Merritts et al, 2013; Waters et al., 2016). The term "Anthropocene" has not been officially incorporated into the geological time scale but it has been used widely to explain anthropogenic global environmental changes (Crutzen, 2002; Zalasiewicz et al., 2008). Waters et al. (2016) suggests that the Anthropocene is stratigraphically distinct from the Holocene and proposes that the start of the Anthropocene is in the mid-20th century (~1950), and therefore Anthropocene sediment would only apply to sediment dated after this time. Legacy sediment and post-settlement alluvium are terms that have generally applied to sediment resulting from human landscape changes, but the implications of this may vary between disciplines (James, 2013). James (2013) calls for a definition of legacy sediment that applies to "anthropogenic sediment that was produced episodically over a period of decades or centuries, regardless of position on the landscape, geomorphic process of deposition, or sedimentary characteristics." The term "historic sediment" also implies recent deposition of sediment but has no formal definition. For the purposes of this thesis, I use “legacy sediment” to define material deposited in association with human activities during the past 300-400 years in the NEUS.

Understanding how the Earth’s surface responds to Anthropocene global change is essential for making informed land-management and conservation decisions. Stream restoration is a multibillion-dollar industry (Bernhardt et al., 2005; Hartranft et al., 2011; Walter et al., 2014b) that relies on knowledge of the geomorphic rates and processes active in a particular landscape. Quantifying valley-bottom sedimentation in two New England watersheds will further understanding for flood risk, dam removal, and the downstream delivery of sediment to developed estuaries and deltas.

1.2 Objectives

Applying the methods of Walter and Merritts (2008) and Merritts et al. (2011; 2013) to New England will further the understanding of milldam effects in this glaciated region. I look to test the hypothesis presented by Water and Merritts (2008) that the same stratigraphic relations observed in the Mid-Atlantic should apply to other areas with a high density of milldams. To test this hypothesis the primary objective of this study is to determine the presence or absence, extent, thickness, age and volume of Anthropocene sediment stored in valley bottoms of two New England watersheds. This objective will be met by the following steps in each watershed: (1) locate historic and current dams; (2) map planar legacy terrace extents using Geographic Information Systems (GIS) methods; (3) use field stratigraphic analysis and radiocarbon dating to identify legacy deposits; (4) compare legacy sediment field bank exposure measurements with lidar digital elevation models (DEMs) measurements and; (5) estimate thickness and volumes of legacy sediment found behind breached or removed milldams in each watershed, and determine errors and limitations of legacy sediment volume calculation.

1.3 Previous Work

1.3.1 Previous Work on Legacy Sediment

Post-settlement aggradation in valley bottoms has widely been studied in the mid-Atlantic Piedmont and the Midwest regions of the United States (e.g., Costa, 1975; Knox, 1977; Magilligan, 1985; Jacobson and Coleman, 1986; Knox, 2006; Water and Merritts, 2008; Fitzpatrick et al., 2009, Pizzuto and O'Neal, 2009; Merritts et al., 2011; Pizzuto et al, 2016). In the Midwest, Knox (1977) looked at a watershed in Wisconsin with a history of land use change from prairie and forest to agricultural in the 1830s. By comparing a land survey done in the early 1830s to the early 1970s, they found that channels are wider and shallower than prior to European settlement due to increased flooding, erosion, and sedimentation. Another study comparing stream channels and valley cross-sections surveyed showed that post-settlement land-use changes in southern Wisconsin and northern Illinois have accelerated floodplain sedimentation (Magilligan, 1985).

Looking at the Upper Mississippi River Valley in southern Wisconsin and northern Illinois, Knox (2006) concluded that land use changes from prairie and forest cover to cropland and pasture produced an increase in magnitudes of high and moderate frequency floods that accelerated floodplain sedimentation by at least one order of magnitude. Also located in the upper Mississippi River valley, Fitzpatrick et al. (2009) estimated rates of overbank sedimentation of a marsh in Wisconsin. They determined that from 1919-1936 overbank sedimentation exceeded early settlement rates by ~30 times and after improvements in land-use conservation practices, it still exceed early settlement rates by ~4 times from 1994-2006.

In the mid-Atlantic Piedmont region of Maryland and Virginia, Costa (1975) estimated 15.2 cm of soil erosion for a 155 km^2 study watershed. Costa (1975) concluded that ~2/3 of sediment eroded since the introduction of tobacco farming in these regions (~1700s) remained in the watersheds as alluvium in flood plains and colluvial-sheetwash deposits on hillslopes. Jacobson and Coleman (1986) looked at streams in the Piedmont region of Maryland where they found distinct stratigraphic units from different sets of fluvial conditions. Prior to European settlement, floodplains formed with thin, fine, over bank deposits. Fluvial conditions changed as settlement and agricultural use in the Piedmont uplands became prevalent. The sediment supply increased greatly from 1730 to ~1930, resulting in thick, fine overbank sediment deposits (Jacobson and Coleman, 1986).

Walters and Merritts (2008) were the first to propose that sediment accumulation in valley bottoms resulted not only from land clearing and agricultural practices that increased sediment supply but also due to construction of milldams that lowered water surface slopes and enhanced sedimentation. The damming caused sediment to be trapped in millponds that would later become terraces after dam breaching and removal. Pizzuto and O'Neal (2009) supported the hypothesis presented by Walter and Merritts (2008) by testing the association of milldams with bank erosion rates along the South River in Virginia. Bank erosion rates along this stream increased by more than a factor of two after 1957, around the time the last dam along their study reach was breached. The study found that erosion rates increased around the same time that several dams were breached, concluding that milldams have an important impact on fluvial processes in the mid-Atlantic region. Pizzuto et al. (2016) quantified floodplain sedimentation rates for the South River in Virginia and found that it was an active process throughout the 20th century, storing 8-12% of its total suspended sediment load. They suggest that, while sedimentation rates have decreased following European settlement, floodplains continue to store total suspended sediment load and these floodplains are fully connected to rivers. Therefore these terraces should not be considered removed from fluvial processes.

1.3.2 Previous Work in New England

Relatively few studies have documented valley-bottom sedimentation in the post-glacial New England landscape. Brakenridge et al. (1988) analyzed trenched cross-sections in northern Vermont and found a unit deposited immediately after conversion of forests to agriculture fields, in the mid-19th century. Also in Vermont, Bierman et al. (1997) looked at alluvial fans and ponds as recorders of Holocene geomorphic processes. They determined that the highest rates of erosion were in the late Holocene, attributing elevated erosion rates to clear cutting and agricultural practices, causing aggradation on valley-bottom alluvial fans. Thorson et al. (1998) studied a small watershed in Connecticut, looking at wetlands to document changes in land use history. They found that pre-settlement wetlands were strongly impacted by land use practices from the colonial period and the extensive deposition that occurred is still impacting the sediment budget, flood regime, and riparian habitat of these watersheds.

Previous work on legacy sediment in the Sheepscot River watershed of mid-coastal Maine has been done by Strouse (2013), Hopkins (2014), and Hopkins and

Snyder (2016). Strouse (2013) identified reservoir sediment terraces upstream of two breached dams using analysis of sediment characteristics and limited radiocarbon dating. She also used hydraulic modeling to estimate the upstream extent of the millponds. Hopkins (2014) and Hopkins and Snyder (2016) compared several methods to identify and map terraces from lidar digital elevation models (DEMs) upstream of dam sites. Once terraces were mapped, thicknesses and volumes of terraces were quantified (Hopkins, 2014). In this study, observations and measurements of legacy cut banks from these studies are used alongside new data taken in the Sheepscot River watershed to help constrain and refine the Hopkins (2014) volume measurements.

1.4 Study Areas

Two NEUS watersheds are used in this study: the 68 km^2 South River in western Massachusetts and the 558 km^2 Sheepscot River in mid-coastal Maine (Figure 1.2). These watersheds were chosen based on the high densities of 18th and 19th century milldams and previous research about legacy sediment (Field, 2013; Strouse, 2013; Hopkins, 2014).

1.4.1 Western Massachusetts Geologic and Geomorphic Background

The South River watershed drains into the Deerfield River in western Massachusetts with an average gradient of 0.013 m/m (Field, 2013). The watershed is underlain by metamorphosed Paleozoic sedimentary rocks known as the lower Devonian Conway Formation (Segerstrom, 1956). This unit is composed of dark garnetiferous quartz-mica schist with many beds of dark limestone and sandy quartzite (Segerstrom, 1956). Glacial material overlays much of the bedrock.

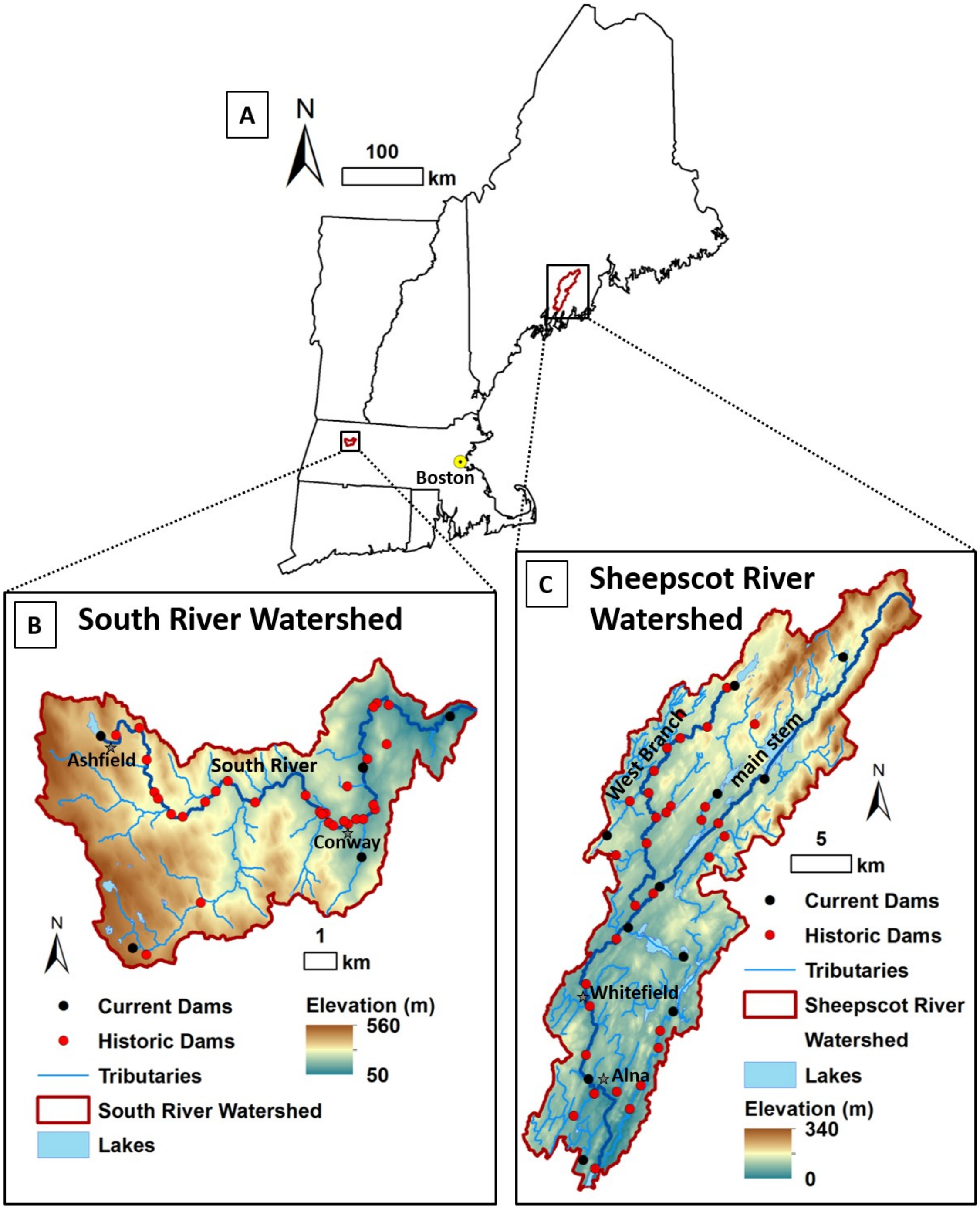

Figure 1.2. Location of the South River watershed and Sheepscot River watershed in New England (A) with 2 m DEMs of the South River watershed (B) and Sheepscot River watershed (C), showing current and historic dam sites.

New England was covered by the Laurentide Ice Sheet at the last glacial maximum, ~21 ka. Western Massachusetts was fully covered by the ice sheet, which extended to present-day Long Island. As the glacier retreated, surficial deposits of glacial outwash, till, and moraines were left on the New England landscape.

The South River watershed has many glacial terraces and these are a main source of sediment (Field, 2013). Glacial Lake Hitchcock existed in the Connecticut River basin during deglaciation, extending from mid-Connecticut to northern Vermont and New Hampshire with a small portion extending into the South River watershed (Figure 1.3; Stone et al., 2005; McGann et al., 2016). It is proposed that two smaller glacial lakes were present in the South River watershed as well: Conway Lake and Ashfield Lake (Emerson, 1898). Conway Lake is thought to have been created when an ice barrier was formed at the junction of the South River and the Deerfield River, blocking the water from escaping and allowing for water to fill the entire valley up to the present day town of Conway (Figure 1.3; Emerson, 1898). Eventually the ice barrier melted, allowing the lake to drain to the Deerfield River. Coarse glacial stratified deposits of gravel and sand are mapped throughout the valley bottom of the South River; these were deposited by flowing meltwater in glacial streams and lakes (Stone et al., 2010). Further evidence for glacial lakes in the area are delta-foreset beds of sand found south of Ashfield, suggesting a glaciodeltaic depositional environment (Figure 1.4).

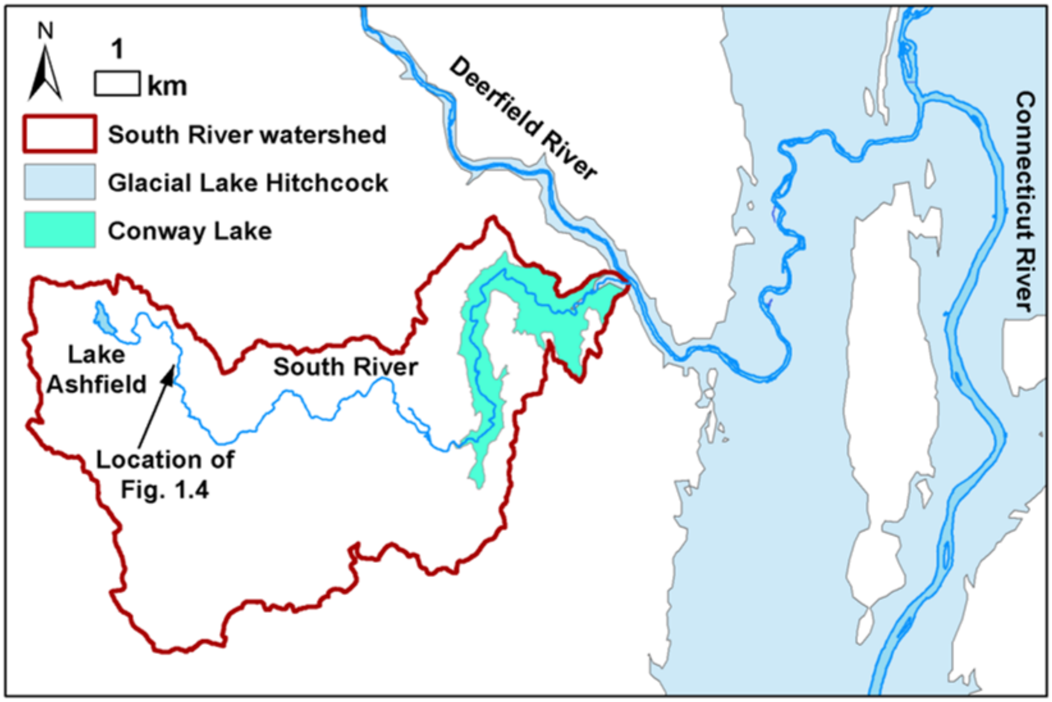

Figure 1.3. Illustration of the proposed glacial-age Conway Lake within the South River watershed as described by Emerson (1898). The Conway Lake was created when an ice barrier formed at the junction of the South River and the Deerfield River as the Laurentide Ice Sheet retreated. Also shown is the former extent of Glacial Lake Hitchcock (McGann et al., 2016), as well as current Lake Ashfield, and the South, Deerfield, and Connecticut rivers.

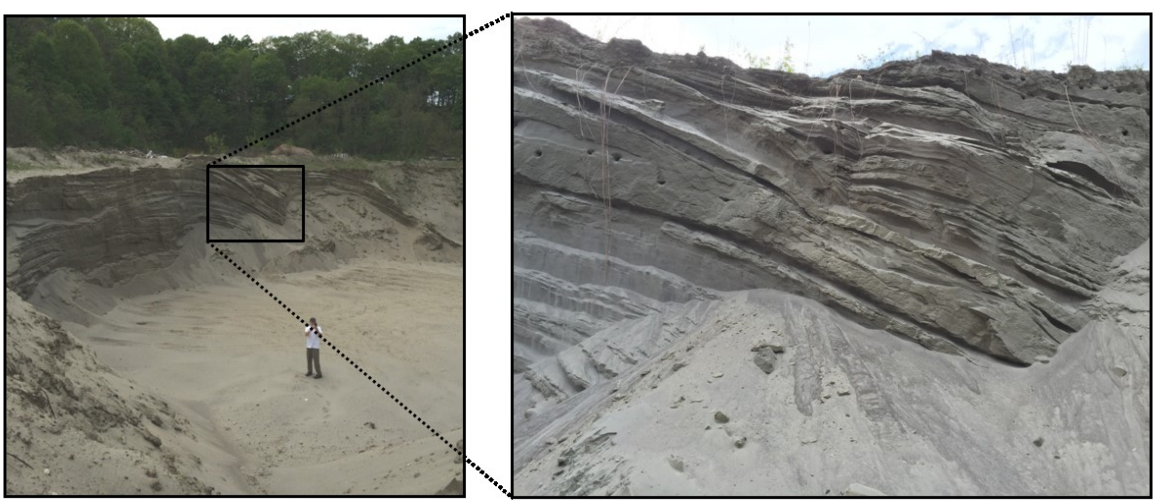

Figure 1.4. Photographs of fine sand delta-foreset beds found south of Ashfield, MA, evidence of a glaciodeltaic environment.

1.4.2 Mid-Coastal Maine Geologic and Geomorphic Background

The Sheepscot River watershed flows south-westerly to the Atlantic Ocean near Wiscasset with an average gradient of 0.0016 m/m. The direction is strongly influenced by the metasedimentary rocks in the northeast-southwest trending Norumbega fault zone (Osberg et al., 1985). The watershed is also influenced by the past glaciation, similar to the South River watershed. The Laurentide Ice Sheet flowed across Maine and terminated on Georges Bank in the Gulf of Maine (Stones and Borns, 1986). As deglaciation occurred the present-day coastal region was inundated with seawater due to isostatic depression caused by the weight of the ice sheet. At this time the Presumpscot Formation, a massive gray glaciomarine mud with sand-lenses was deposited in low-lying areas (Bloom, 1960; Smith, 1985; Thompson and Borns, 1985; Figure 1.5). This formation can

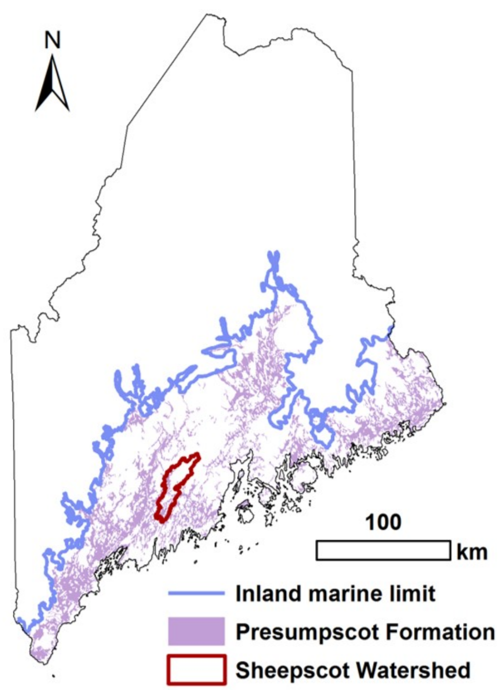

Figure 1.5. Location of the Sheepscot River watershed seaward of the late Pleistocene shoreline with mapping of the glaciomarine Presumpscot Formation by Thompson and Borns (1985).

be seen in stratigraphic sections throughout the river valley as nearly the entire Sheepscot River watershed is seaward of the late Pleistocene shoreline (Smith, 1985). Deglaciation also left localized glacial deposits of outwash, till, and moraines across the landscapes.

1.4.3 South River Watershed Milldam and Land-Use History

Watershed land use has changed considerably over the past two centuries. In 1830, the South River watershed was 7.7% forest, 0.8% wetland, and 92.4% cleared land (Foster and Motzkin, 2009; Table 1.1; Figure 1.6 A). As of 2005, the land use consists of 79.9% forest, 2.5% wetland, 6.0% cropland, 4.5% pasture, and 3.9% residential (Office of Geographic Information, MassGIS; Table 1.1; Figure 1.6 B).

Table 1.1. South River watershed land use through time. 1830 data from Foster and Motzkin (2009) and 1971-2005 data from Office of Geographic Information (MassGIS).

	1830	**1971**	**1985**	**1999**	**2005**
Land Use	% area	% area	% area	% area	% area
Cropland		9.4	9.0	8.0	6.0
Pasture		6.3	5.5	4.6	4.5
Forest	7.7	77.9	77.3	77.1	79.5
Wetland	0.8	0.8	0.8	1.0	2.5
Open Land		1.3	2.1	2.2	1.5
Total residential		3.5	4.5	6.1	3.9
Water	0.2	0.3	0.3	0.3	0.8
land cleared	92.4				
other		0.6	0.7	0.8	1.3

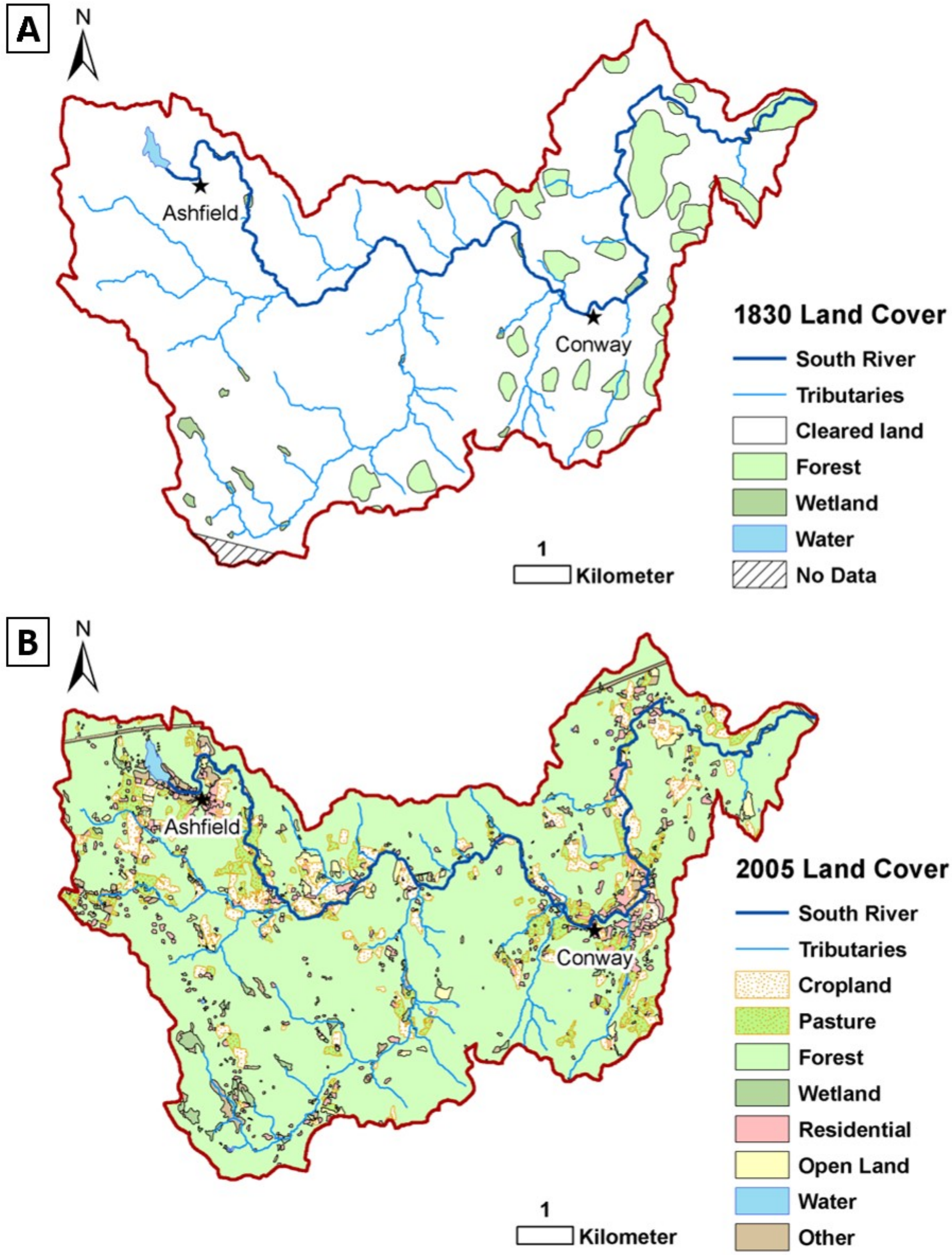

Figure 1.6. South River watershed land use in 1830 (A; Foster and Motzkin, 2009) and 2005 (B; Office of Geographic Information, MassGIS).

The South River watershed was cleared for agriculture and sheep pasture in the 18th century (Pease, 1917). The upland regions around Ashfield were best suited for livestock grazing (Massachusetts Historical Commission Reconnaissance Survey Town Report Ashfield, MHC Ashfield, 1982), and the town of Conway soon followed with dairy and sheep production (Pease, 1917; Massachusetts Historical Commission Reconnaissance Survey Town Report Conway, MHC Conway, 1982). Ashfield was the leading wool producing town in Franklin County in the mid-19th century as the demand for Merino wool was high across the region (MHC Ashfield, 1982). In the late-19th century, dairy farming became the major industry, but by the early-20th century Ashfields's creamery closed and population decreased. The soil and topography of the area made good grazing land for sheep and cattle; where flat land was present, commercial crops produced corn, rye, wheat, oats, and tobacco (Pease, 1917; MHC Ashfield, 1982; MHC Conway, 1982).

In 1744, the first dam was built along the South River to power a corn grist mill in the town of Ashfield (MHC Ashfield, 1982; Field, 2013). Later, in 1762, the first dam in Conway was built to power a saw mill (MHC Ashfield, 1982; Field, 2013). Grist and saw mills continued to be built as well as fulling, cider, and oil mills along the South River. Conway's first woolen and cotton mills were built in 1837 (Pease, 1917; MHC Conway, 1982). Several more cotton mills were built within the next 20 years (MHC Conway, 1982). In response to the large flocks of sheep in the area, an expansion of the woolen mill occurred in 1856 allowing the mill to produce nearly 86% of the county's woolen cloth that year (MHC Conway, 1982). Although the population of Ashfield was on a steady decline through the 19th century (Howes, 1910; MHC Ashfield, 1982), the population of Conway fluctuated in the mid-19th century as these new mills were built (Figure 1.7; Pease, 1917; MHC Conway, 1982; 1920 Census of Population, 1920; 1950 Census of Population; 1980 Census of Population, 1981; 2010 Census of Population and Housing, 2010). To power the numerous mills built, dams were constructed throughout the watershed. Thirty-seven dams were active in the watershed, with five still present today (Figure 1.2B).

As mills and dams were built in the area, the South River was straightened in many locations (Field, 2013). Human manipulation of the South River also stemmed from fear of flooding, as large floods breached dams and caused considerable damage in the towns of Ashfield in 1878 (MHC Ashfield, 1982) and Conway in 1869 and 1878 (Pease, 1917; Field, 2013). This led to the public backing the decision to straighten and widen the South River to 12 m wide for 6.4 km through the town of Conway (Field, 2013; Epstein, 2016). By 1886-1887 it is estimated that 67% of the South River was straightened (Field, 2013).

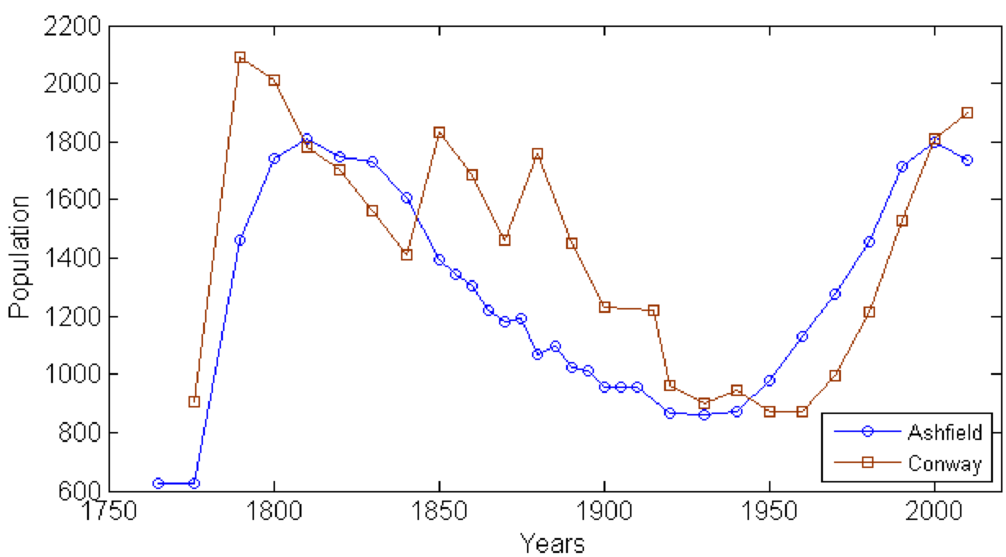

Figure 1.7. Population of the South River watershed towns of Ashfield and Conway.

1.4.4 Sheepscot River Watershed Milldam and Land-Use History

As early Colonial settlers came to the Sheepscot watershed in the late 1600s, forests were clear cut for agriculture, timber companies, and to make room for port towns (Laser et al., 2009; Sheepscot Valley Conservation Association, SVCA, 2011). Timber harvesting was prevalent until the mid-20th century, and logging companies used rivers as a way to move large volumes of timber to mills (Halsted, 2002). Sawmills were commonly built at run-of-the-river dams. Dams also powered the mining, textile, and grain industries in the area. During the 19th century, farming declined as crops were difficult to grow with thin, rocky soil and long winters. Second growth forests are dense in the watershed and now it is mostly forested (89%) with a small amount of agriculture (2.5%) and residential (1.5%; Brady, 2007). The Sheepscot River watershed had 45 dams, including 20 on the main stem or West Branch, of which 4 are still intact (Figure 1.2C; SVCA, 2011).

2 METHODOLOGY

To test if the Walter and Merritts (2008) and Merritts et al. (2011; 2013) mid-Atlantic stratigraphic observations extend to New England, historic maps and documents were used to map milldams to identify likely locations for legacy sediment storage in valley bottoms. I then used a semi-automated method to map terraces throughout each study watershed (Hopkins, 2014; Stout and Belmont, 2014; Hopkins and Snyder, 2016). Field work was done to measure bank exposure thicknesses of mapped terraces, determine characteristics of legacy sediment, and radiocarbon date organic material in bank exposures to determine ages of sedimentary layers. Thicknesses of bank exposures were compared to equivalent measurements from lidar DEMs to ground truth GIS-based measurements. Finally, volumes of legacy sediment were estimated for each watershed.

2.1 Location of Historic and Current Dams

In the eastern United States, dams were built for water power beginning in the late 1600s (Walter and Merritts, 2008). These dams formed upstream millponds that with time filled with sediment in many locations (Merritts et al., 2011). Walter and Merritts (2008) showed that when these historic dams breach, streams incise through the deposits, leaving paired terraces composed of legacy sediment. Therefore, determining where milldams were in each watershed provides insight to where legacy sediment may be stored in these valley bottoms.

Historic maps show locations of milldams, millponds, mill buildings, and canal races. In the South River watershed, Field (2013) mapped milldams along the main stem. I used historic maps and documents to find milldams along tributaries elsewhere in the watershed and to find more information about the milldams along the South River, such as purpose of the dam, year built or years active, and height (Table 2.1). All historic maps used in the South River watershed were georeferenced to 1990 U.S. Geological Survey topographic maps from the Massachusetts Office of Geographic Information (MassGIS) by using road intersections to provide control points. The historic maps rarely had milldams labeled directly on the maps and therefore millponds, races, (Figure 2.1 A, C) and mill buildings (Figure 2.1 B) were used to infer where milldams were located.

Table 2.1. Historic maps used to determine milldams in the South River watershed.

Map Name	Year	Original Scale	Publisher
Map of Franklin County Massachusetts	1858	1:47,520	Smith and Ingrapham, Boston
Atlas of Franklin County Massachusetts: Burkville and Conway	1871	1:5,940	Beers and Company, New York
Atlas of Franklin County Massachusetts: Conway	1871	1:39,600	Beers and Company, New York
Atlas of Franklin County Massachusetts: Ashfield Plains	1871	1:7,920	Beers and Company, New York
Atlas of Franklin County Massachusetts: Ashfield	1871	1:39,600	Beers and Company, New York
Greenfield, Massachusetts	1887	1:62,500	U.S. Geological Survey
Shelburne Falls Quadrangle Massachusetts, Franklin County	1937	1:31,680	U.S. Geological Survey
Ashfield Quadrangle Massachusetts	1940	1:31,680	U.S. Geological Survey

The Sheepscot Valley Conservation Association (SVCA, 2011) compiled a table of current and historic dams in the Sheepscot River watershed that were used for this study. I also used the Maine Stream Habitat Viewer (MSHV, 2008) to find 4 dams not listed in the previously mentioned table. Historic topographic maps circa 1910 and 1945 were found, but there was no information to indicate milldams on them.

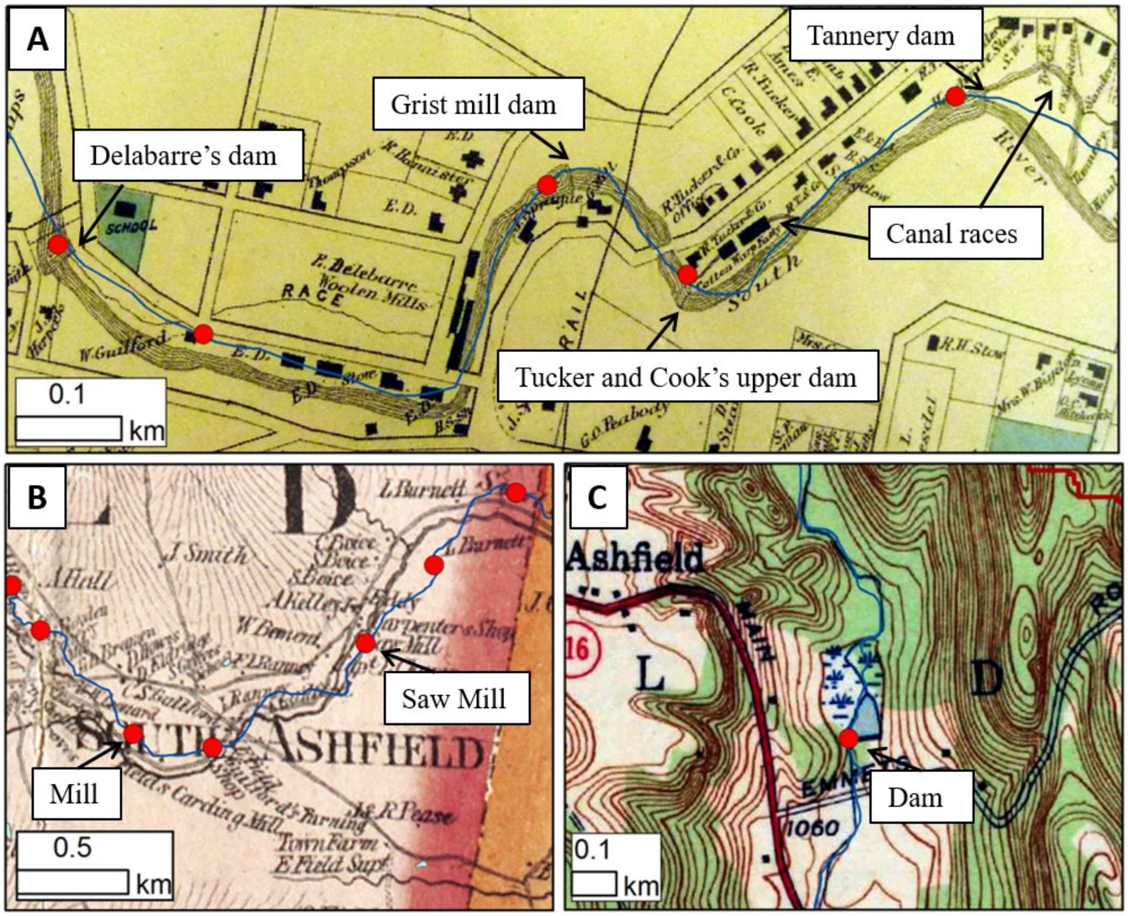

Figure 2.1. Portions of historic maps along the South River (blue lines) showing evidence for milldams. The 1871 historic map of Conway, MA shows five millponds and three canal races (A) and 1858 historic map of South Ashfield, MA has two mill buildings (B). The 1940 historic topographic map (C) shows a millpond.

2.2 Terrace Mapping and Longitudinal Profiles

Terrace area can be estimated from high-resolution DEMs. This can be done for an entire watershed through manual delineation or through fully or semi-automated algorithms (Wood, 1996; Demoulin, et al., 2007; Walter et al., 2007; Finnegan and Balco, 2013; Hopkins, 2014; Stout and Belmont, 2014; Hopkins and Snyder, 2016). This study used a combination of manual delineation and a semi-automated method. Hopkins and Snyder (2016) compared DEM-based methods for fluvial terrace mapping in the Sheepscot River watershed. They determined that the semi-automated TerEx mapping toolbox (Stout and Belmont, 2014) was effective for mapping terraces at the watershed scale. Positive aspects of the method include efficiency, a limited number of input parameters, a continuous mapped output that fully encompasses the terrace perimeter, limited manual editing, and an accurate terrace output (Hopkins and Snyder, 2016). TerEx can be incorporated into ArcGIS; this allows for adjustable input parameters and user edits mid-way. User edits include the edit or removal of polygons and can increase accuracy.

Two meter pixel high-resolution lidar DEMs are available for both study watersheds, as well as a 1-m-pixel dataset for a portion of the Sheepscot River watershed along the main stem and West Branch. Terraces were manually delineated along the South River by analysis of lidar DEMs, topographic maps, and Google Earth before field work was done; this analysis consisted of looking for flat surfaces adjacent to the river that were of appropriate height, < 3 m, given the known heights of historic dams. Manual delineation and TerEx toolbox with user edits (Stout and Belmont, 2014) for this area indicate that the TerEx toolbox underestimates the manual delineation technique by ~20%. Similar results from Hopkins (2014) found deviation values of < 20%, upstream of 4 dam sites, validating the use of this semi-automated method. TerEx with user edits was then used for rivers and tributaries throughout both study watersheds; final parameters used for each stream are summarized in Table 2.2. Only lower terraces (< 3 m), thought to be historic in age, were mapped; higher, likely glacial-age, terraces also occur in both watersheds. Glacial-age terraces were identified by their higher elevation relative to the modern stream channel, and these were removed with user edits mid-way through the TerEx analysis. Field work was later conducted to examine the accuracy of TerEx mapping.

Table 2.2. Final parameters used for terrace mapping with TerEx toolbox (Stout and Belmont, 2014) for each stream.

Stream Name	Δ Elevation (m)	Focal Window (m^2)	Min. Area (m^2)	Max. Valley Width (m)	DEM pixel resolution (m)
South River watershed					
South River main stem 1	0.3	3	10	300	2
South River main stem 2	0.3	3	10	300	2
South River main stem 3	0.3	3	10	300	2
South River main stem 4	0.3	3	10	250	2
Chadwick	0.5	3	1	250	2
Pumpkin Hallow	0.5	5	1	300	2
Johnny Bean	0.5	5	1	250	2
Nye Brook	0.5	3	1	200	2
Poland Brook	0.5	5	1	300	2
Chapel	0.5	3	1	300	2
Creamery	0.5	5	1	250	2
Unnamed 1	0.5	3	1	250	2
Unnamed 2	0.3	3	1	200	2
Unnamed 3	0.5	3	1	150	2
Unnamed 4	0.3	3	1	100	2
Unnamed 5	0.5	3	1	100	2
Unnamed 6	0.3	3	1	250	2
Unnamed 7	0.5	3	1	250	2
Unnamed 8	0.3	3	1	100	2
Unnamed 9	0.5	3	1	200	2
Unnamed 10	0.5	3	1	200	2
Unnamed 11	0.5	3	1	200	2
Unnamed 12	0.5	3	1	200	2
Unnamed 13	0.3	3	1	100	2
Unnamed 14	0.3	3	1	100	2
Unnamed 15	0.3	3	1	100	2
Unnamed 16	0.5	5	1	200	2
Unnamed 17	0.5	5	1	200	2
Unnamed 18	0.5	5	1	200	2
Unnamed 19	0.5	5	1	200	2
Unnamed 20	0.5	5	1	300	2
Unnamed 21	0.5	5	1	100	2

Table 2.2. Final parameters used for terrace mapping with TerEx toolbox (Stout and Belmont, 2014) for each stream - Continued

Stream Name	Δ Elevation (m)	Focal Window (m^2)	Min. Area (m^2)	Max. Valley Width (m)	DEM pixel resolution (m)
Sheepscot River watershed					
Sheepscot main stem 1	0.5	5	1	300	1
Sheepscot main stem 2	0.3	3	1	150	1
Sheepscot main stem 3	0.3	3	1	300	1
Sheepscot main stem 4	0.3	3	1	250	1
West Branch 1	0.5	5	1	250	1
West Branch 2	0.5	3	1	100	1
West Branch 3	0.5	3	1	100	1
Dyer River	0.3	3	1	150	2
Ben Brook	0.3	5	1	150	2
Trout Brook	0.3	5	1	75	2
Crummett Brook	0.3	5	1	200	2
Gully Brook	0.3	5	1	200	1
Lovejoy Stream	0.3	5	1	100	1
Choate Brook	0.3	5	1	250	1
Dearborn Brook	0.3	3	1	150	1
Meadow Brook	0.3	3	1	150	1
Carlton Brook	0.3	3	1	200	2
Finn Brook	0.3	5	1	100	2
Travel Brook	0.3	3	1	100	1
Brann Brook	0.3	3	1	250	2
Black Brook	0.3	3	1	250	2
Colby Brook	0.5	5	1	150	2
Bull Brook	0.3	5	1	75	1
Hewitt Brook	0.3	5	1	100	1
Linscott Brook	0.3	3	1	100	2
Turner Brook	0.3	3	1	100	1
Trib 10.8 rkm	0.3	5	1	75	2
Unnamed 1	0.5	5	1	150	2
Unnamed 2	0.3	3	1	150	2
Unnamed 3	0.5	5	1	75	1
Unnamed 4	0.3	5	1	100	2
Unnamed 5	0.3	5	1	100	2

Projecting terrace edges onto stream longitudinal profiles provides a cross-sectional view to look at heights of terraces compared to river elevation, adjacent terraces, and heights of dams. Using lidar DEMs longitudinal profiles were constructed along the South River, main stem Sheepscot River, and West Branch Sheepscot River. In ArcGIS points were constructed 1 point per pixel (1 m apart in the Sheepscot River watershed and 2 m apart in the South River watershed) on terrace surfaces adjacent to these rivers; right bank, left bank, and island terraces were each identified. These mapped points were then projected onto longitudinal profiles.

2.3 Field Stratigraphy and Radiocarbon Dating

2.3.1 Bank Sediment Measurements

Field observations of bank exposures were used to determine whether the material was Pleistocene, Holocene, legacy, or active floodplain deposits. These measurements were also used to calibrate DEM-based methods for estimating legacy sediment volumes. In each watershed locations of former millponds were selected to detail the stream bank stratigraphy: 15 sites in the South River watershed and nine sites in the Sheepscot River watershed. Previous stratigraphy in cut banks and soil pits was analyzed in the Sheepscot River watershed: nine locations by Strouse (2013) and 17 locations by Hopkins (2014). These were also used to quantify legacy sediment volumes in this study.

Bank exposures were chosen based on location with respect to current and historic dam locations, terrace mapping, and geomorphic setting. To interpret these sites, the banks were cleared of vegetation and slumped sediment, exposing fresh faces. Each bank exposure was measured downward relative to the top (terrace or floodplain) surface. The stratigraphy was observed noting the grain-size composition, color, presence of organic material, and evidence for anthropogenic activities. Samples of organic material were taken wherever present for radiocarbon dating, while also recording the depth of each sample in the stratigraphic column.

The preliminary ages of layers in a stratigraphic column were estimated by examining sediment size and color, amount of organic matter, boundary change between layers, and structures found in layers such as cross bedding. Observations consistent with Walter and Merritts (2008), Strouse (2013), and Hopkins (2014) are used to determine preliminary ages. In the field, thickness measurements of interpreted legacy sediment deposits were made for each bank exposure using a tape measure. Sediment was interpreted as legacy sediment if it was found stratigraphically at or near the top of an exposure, brown in color, and uniform in sand size particles. Layers of pebbles/cobbles near the base were interpreted as former channel bars or pre-dam river bed deposits.

Real time kinematic (RTK) GPS using a Leica Viva GNSS GS14 Rover was used to record the location and elevation of each site and other key features in the stratigraphic column, including prominent change in grain size, color, or organic material, radiocarbon sample depths, and the water surface. A high level of accuracy was needed for registering the stratigraphic columns with lidar data horizontally and vertically so the field-measured thicknesses could be compared to terrace thickness estimates used for volume calculations.

During normal to favorable conditions this RTK GPS has a horizontal and vertical accuracy of ±8 mm and ±15 mm, respectively (Leica Geosystems, 2016). During the field data collection, I observed a minimum horizontal and vertical accuracy of ±5 mm and

±14 mm, respectively, but also observed a maximum horizontal and vertical accuracy of ±3.1 m and ±6.2 m, respectively (Table 2.3). Centimeter accuracy is not always available in the field when trees obscure the view of the receiver and/or differential corrections via

Table 2.3. Real time kinematic (RTK) GPS horizontal and vertical accuracy for South River stratigraphic column points. * denotes points that were corrected using Online Positioning User Service (OPUS) provided by the National Oceanic and Atmospheric Administration (NOAA). UTM locations area based on NAD1983 zone 18 North.

Point Id	Northing (m)	Easting (m)	Std. deviation N	Std. deviation E	Std. deviation H
1	4710009	689084	0.007	0.006	0.014
2	4710009	689085	0.008	0.007	0.017
3	4710009	689086	0.009	0.008	0.020
4	4710274	689027	0.011	0.009	0.022
5	4710266	689023	0.012	0.010	0.025
6*	4709047	682683	0.010	0.008	0.048
7*	4709072	682689	0.009	0.004	0.044
8	4709708	687169	0.011	0.009	0.025
9	4709709	687171	0.010	0.008	0.022
10	4709708	687168	0.011	0.009	0.025
11	4709651	687199	0.011	0.009	0.027
12*	4711149	681900	0.040	0.009	0.088
13	4711163	681964	2.600	2.852	6.175
14*	4710244	682314	0.010	0.006	0.027
15	4708910	687793	0.011	0.008	0.022
16	4708908	687792	0.021	0.010	0.028
17	4709051	689308	0.141	0.161	0.343
18	4709247	689407	0.009	0.009	0.024
19	4712479	689624	0.298	0.309	0.881
20	4712300	689114	3.262	2.588	4.972
21	4709829	687147	0.006	0.004	0.020
22	4709830	687148	0.007	0.006	0.025
23*	4711507	688896	0.008	0.004	0.031
24*	4711860	689036	0.012	0.006	0.025
		Average	0.272	0.252	0.540
		Minimum	0.0055	0.004	0.0144
		Maximum	3.2624	2.8523	6.1751

a cellular internet data connection are not available. When this happened, 15 minutes of position data were recorded at a single spot and the data uploaded to the Online Positioning User Service (OPUS) provided by the National Oceanic and Atmospheric Administration (NOAA) to calculate differentially corrected position data. Nine of 24 data points did not have centimeter accuracy, and of these six were corrected using OPUS, and three were unable to be corrected. The corrected OPUS data points have an average horizontal and vertical accuracy of ±26 cm and ±54 cm, respectively (Table 2.3).

2.3.2 Bank Sediment Age

Radiocarbon dating was used to determine whether bank exposures were composed of active floodplain, legacy, Holocene (i.e., post-glacial but not legacy), or Pleistocene (glacial-age) deposits. I used ^{14}C to date organic macrofossils (bark chips, twigs, and charcoal) found from varying depths in the stratigraphic column at several sites in each study watershed. ^{14}C samples were chosen in layers based on the location of the bank (distance from upstream milldam and on a terrace), presence of enough organic material, lack of modern roots found in the layer, and to test preliminary age interpretations.

In the field, the organic material was removed using metal trowels, taking care to avoid contamination with human hands and modern organic material, and then placed in plastic bags (Figure 2.2). At Boston College, all samples were cleaned using distilled water to remove excess sediment, dried in a low temperature oven (55°C), weighed, and placed in labeled individual plastic vials. Time was taken to search for seeds to be identified or dated from the organic material, but none were found. I selected three samples of wood from two cut banks at river kilometer (rkm; increasing upstream and originating in Wiscasset, ME at the bridge crossing the estuary) 10.8 and 11.1 in the Sheepscot River watershed; this was in addition to the seven previous radiocarbon dates from Strouse (2013) in this watershed. From the South River watershed, four samples of wood and charcoal were selected from cut banks at rkm 5.94, 12.46, 19.41, and 21.06 (originating at the confluence with the Deerfield River). The samples were sent for analysis at Woods Hole Oceanographic Institution (WHOI) in fall 2015, using accelerator mass spectrometry.

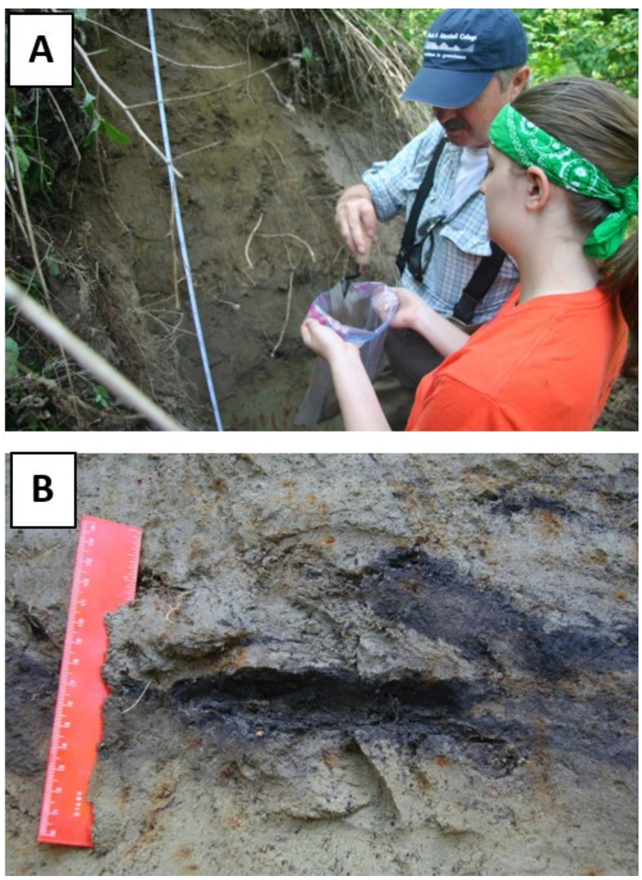

Figure 2.2. Sediment samples (A) and charcoal samples (B) taken at a bank exposure at Sheepscot River kilometer 10.8 in summer 2015.

2.3.2.1 Radiocarbon Methods and Accuracy

The radioisotope ^{14}C is produced when atmospheric ^{14}N is bombarded by a neutron (Bradley, 2015). ^{14}C is then incorporated into the living biosphere, and when an organic carbon-containing sample dies, the ^{14}C in its tissue is no longer replenished through the exchange with atmospheric CO_2, and begins the process of radioactive decay back to ^{14}N. The half-life of ^{14}C is 5,730 years (Trumbore, 2000). The concentration of ^{14}C in the organism at the time of death is equivalent to the concentration of ^{14}C in the atmosphere. The age of the organism at time of death can be determined by comparing the present concentration to the logarithmic decay of ^{14}C (Trumbore, 2000). ^{14}C dating is appropriate for samples that are less than 50,000-60,000 years old (Trumbore, 2000), making it suitable for this study because we can compare legacy, Holocene, and Pleistocene ages.

The accuracy in determining radiocarbon ages can be compromised by contamination, variations in the ^{14}C amount in the atmosphere, and the old wood problem. Contamination with any addition of carbon to a sample of a different age will cause the measured date to be inaccurate (Bradley, 2015). Contamination with modern or old carbon could occur when a terrace is altered from its original deposition. This could happen with a land use change or if the presence of modern roots comes in contact with samples taken. Measures were taken to avoid these contaminations, such as only using clean trowels when extracting samples and selecting samples where no or few were roots present in the stratigraphic column. Another difficulty with determining the accuracy of the radiocarbon dates are variations in ^{14}C abundance in the atmosphere. Recently humans have altered the $^{14}C/^{12}C$ ratio through the burning of fossil fuels, which adds ^{12}C

to the atmosphere, diluting the ^{14}C concentration (Trumbore, 2000). This variation in ^{14}C in the atmosphere makes the sample appear older. On the other hand, the ^{14}C concentration in the atmosphere was approximately doubled by detonation of nuclear weapons before the Nuclear Test Ban Treaty in 1964 (Trumbore, 2000). This presents a large issue in determining an accurate age for samples that are very young and therefore any radiocarbon age younger than AD 1950 is considered modern and not given an age determination. A radiocarbon date is not equal to a calendar date because of past variations in the amount of ^{14}C, resulting in the necessity of a calibration curve. In the last 450 years, the "wiggles" of the calibration curve are magnified and therefore the true age of a sample has several discrete sets of ages (Bradley, 2015). Finally, the age of the sample could be compromised due to the old wood problem. In radiocarbon dating, the determined age of the organism is assumed to be roughly equivalent to the time of deposition, but if a tree is very old at the time of deposition the dating technique may be off by several hundred years (Schiffer, 1986). More importantly, old trees could have fallen and rested on a floodplain or been buried in a floodplain for a period of time, and only later transported and buried or re-buried in a historic millpond.

2.4 Lidar DEM Measurements of Legacy Sediment Thickness

To check volume calculations, field-measured legacy sediment thicknesses made at bank sites throughout each study watershed were compared with the equivalent measurements from lidar DEMs. The most relevant pixel closest to where the RTK GPS survey point was taken in the field represents the terrace or floodplain surface elevation. This method assumes that the river elevation is at approximately the base of the legacy sediment. The lidar DEM thickness calculation was done by subtracting the river elevation from the DEM terrace or floodplain surface elevation. The lidar DEM thickness calculation was also compared to the total field-measured height from water surface to bank top, which is directly equivalent to the lidar DEM thickness measurement.

2.5 Legacy Sediment Volume Calculations

2.5.1 Water Surface and Valley Bottom Surface Method

Volumes of legacy sediment behind milldams can be estimated using DEM-based methods, by multiplying terrace area by thickness of reservoir sediment (Hopkins, 2014). Terrace area mapping methods are well established (section 2.2), but the depth of the contact with pre-legacy sediment is more difficult to estimate from topographic data. Therefore a datum for the base of reservoir sedimentation needs to be identified. I followed the methods developed by Hopkins (2014) in the Sheepscot River watershed. Hopkins (2014) used the elevation of the water surface within the river channel as the datum for the elevation of the base of reservoir sedimentation. This assumption is reasonable because we observe that streams typically erode to the original base level after a dam is breached or removed, and this level is generally the water surface. The water surface datum (WSD) surface is flat orthogonal from the river channel, extending to the edge of the terrace or valley wall (Figure 2.3).

A second datum surface tested has a non-horizontal surface orthogonal to the river channel. This datum plane begins at the river channel and extends to elevation points along the surface of the perimeter of the delineated terrace; this is referred to as the valley bottom surface datum and circumscribes a trapezoidal reservoir geometry (VBSD; Figure

2.3). These datum surfaces bracket the range of possible volume estimates; the WSD method provides a maximum and the VBSD a minimum estimate.

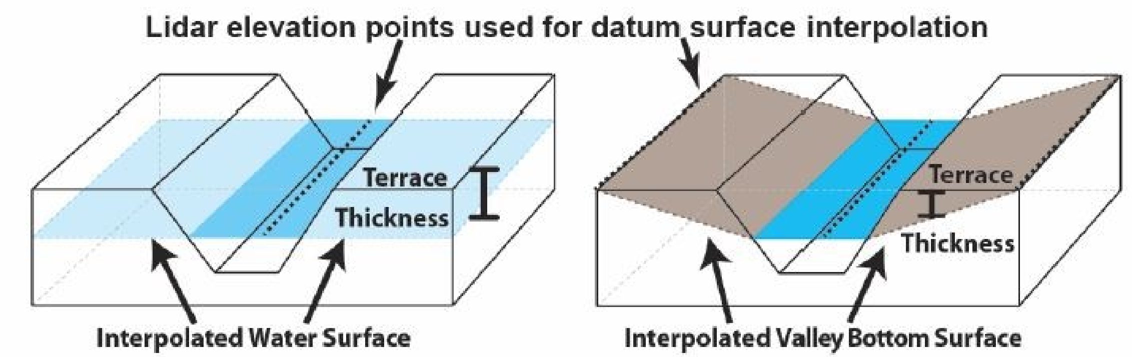

Figure 2.3. Illustration comparing the water surface datum (WSD) method (left) and valley bottom surface datum (VBSD) method (right) for estimating legacy sediment volumes. The water surface method datum uses only river surface elevation points and the valley bottom surface method uses a combination of the river surface elevation points and elevation points on the perimeter of the delineated terrace (Hopkins, 2014).

To create these datum surfaces in ArcGIS, points were placed along the center line of each stream in both study watersheds. Center lines were created by looking at recent topographic maps and high resolution DEMs. For the VBSD method, points were also placed along the outside perimeter of each terrace extent. Elevation values were assigned to each point from the high-resolution DEMs. These elevation values are used to estimate, or interpolate, each datum surface in ArcGIS by inverse distance weighting (IDW). This method interpolates unknown cell values by averaging the values of the points previously placed; this method works best for closely packed, consistently spaced sample point sets (Kennedy, 2004). Interpolating only the points placed along each stream using IDW created the WSD. Alternatively, interpolating the points placed along each stream and along the outside perimeter of each terrace created the VBSD. A detailed methods description of the WSD and VBSD, including toolboxes used in ArcGIS, is provided in Appendix 1.

For both of these datum surface estimates, the thickness of the terrace at each pixel of the mapped terrace could be computed by subtracting the datum elevation from the coincident terrace surface elevation. The thickness values are then multiplied by their pixel area and summed to provide an estimate of volume (Hopkins, 2014).

2.5.2 TerEx Toolbox Method

The volume of sediment stored along a valley can be calculated using the outputs from TerEx (Stout and Belmont, 2014). Although TerEx was created primarily to map terraces and floodplains, not to calculate volumes, it can be used to provide thickness estimates. This method makes the assumption that the stream water surface is at an elevation less than or equal to the terrace sediment boundary with the underlying lithology (similar to Hopkins, 2014). As part of TerEx toolbox, the stream is split into reach lengths defined by the user and each reach is joined to the nearest terrace (Stout and Belmont, 2014). The average elevation for each stream reach and the average elevation of the terrace polygon associated with each stream reach are calculated (Stout and Belmont, 2014). The average thickness of sediment for each terrace polygon is calculated by differencing these values. Volumes of sediment can be estimated by multiplying each given terrace area by the average thickness for each terrace polygon.

3 RESULTS AND INTERPRETATIONS

3.1 Location of Historic and Current Dams

3.1.1 South River Watershed

Thirty-two historic dams and five intact dams were found in the South River watershed (Table 3.1; Figure 3.1). Of the 32 historic dams, 28 were found along the South River main stem, as were three intact dams (Field, 2013). The three present dams include the Conway Electric Dam at 0.99 river kilometer (rkm; defined upstream from the confluence with the Deerfield River), the C.C. Flagg Dam at 7.26 rkm, and the Ashfield Pond Dam at the outlet of Ashfield Lake, 24.51 rkm (Figures 1.2B & 3.1). Elsewhere in the watershed I identified five dams on historic maps, with two still intact on tributaries, Chapel Brook and Pumpkin Hollow Brook (Table 3.1). I field checked 18 dams in the watershed and 14 of those show evidence for legacy sediment (Table 3.1).

A series of U.S. Geological Survey topographic maps were used to examine the changes to the historic Conway Reservoir, which I use as an example because its history is well documented (Figure 3.2). The dam creating this reservoir was built in 1837. As shown in Figure 3.2 B, the reservoir was still present 100 years later in 1937, but was dismantled soon after. From historic documents this dam was breached at least twice after flooding in 1869 and 1878 (Pease, 1917). The reservoir appears to have partially filled in between 1886 and 1937 (Figure 3.2 A-B).

A milldam density of the watershed can be calculated if the number of milldams and watershed area are known (Walter and Merritts, 2008). The South River watershed has a milldam density of 0.49 milldams/km^2. Water and Merritts (2008) calculated the milldam density of counties for the entire eastern United States based on 1840 census records where they identified a milldam density of 0.1-0.2 milldams/km^2 for Franklin County, where the South River watershed is located.

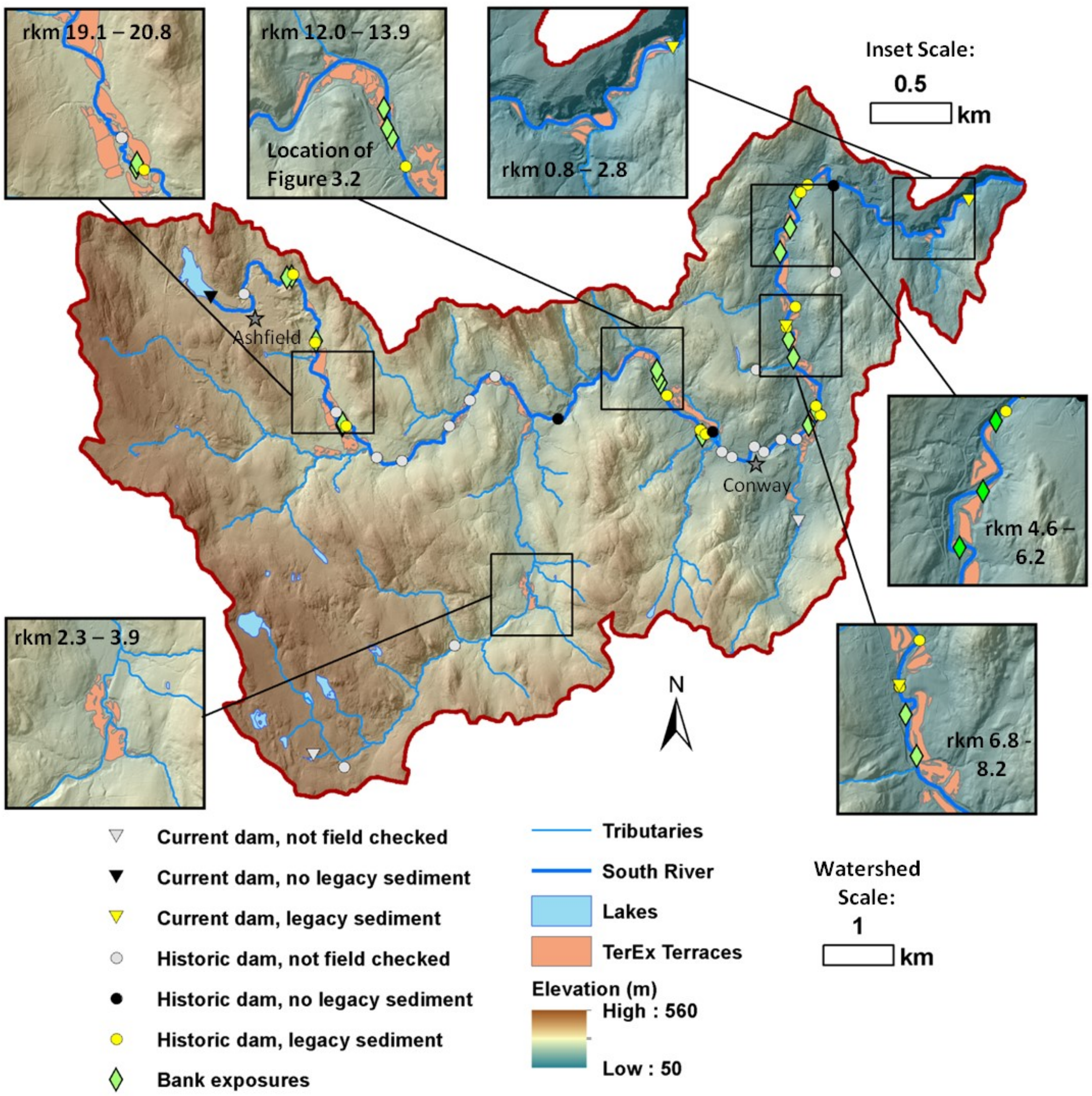

Figure 3.1. Watershed map showing locations of field measured bank exposures, current and historic dams, and TerEx terraces (Stout and Belmont, 2014) with insets of some locations for the South River watershed. Current and historic dams are colored based on if the dams were field checked and do or do not have legacy sediment. Base image is a transparent hillshade raster is overlaying a 2 m lidar digital elevation model.

Table 3.1. Current and historical dams in the South River watershed.

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Unnamed	South River		<1943		no	no	?	U.S. Geological Survey, 1940; Field, 2013	4710913	681283
Unnamed	South River	grist mill	1743		no	yes	little	Howes, 1910; Field, 2013	4711185	681983
Tucker and Cook's upper dam	South River	cotton mill	1846		no	no	?	Beers, 1871; Field, 2013	4708666	688657
Unnamed	South River	cider mill	<1871		no	no	?	Beers, 1871; Field, 2013	4708539	683524
Unnamed	South River	saw mill	<1858		no	no	?	Walling, 1858; Field, 2013; field evidence	4709035	684193
Unnamed	South River				no	yes	no	Field, 2013	4708955	687931
Delabarre's Dam	South River		<1871		no	no	?	Beers, 1871; Field, 2013	4708669	688062
Tucker and Cooks lower dam	South River		<1871		no	yes	yes	Beers, 1871; Field, 2013	4709187	689465
Unnamed	South River		1837		no	yes	yes	Beers, 1871; Field, 2013	4709316	689398
Unnamed	South River				no	no	?	Field, 2013; field evidence	4709398	684488
Unnamed	South River				no	no	?	Field, 2013	4709740	684842
Unnamed	South River	grist mill	<1858		no	yes	yes	Walling, 1858; Field, 2013	4712464	689282
Unnamed	South River				no	yes	no	Field, 2013 field evidence	4709137	685738

Table 3.1. Current and historical dams in the South River watershed - Continued

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Conway Reservoir/Tucker and Cook reservoir dam	South River		1837	6	no	yes	yes	U.S. Geological Survey, 1887; U.S. Geological Survey, 1937; Field, 2013	4709468	687281
Unnamed	South River				no	yes	little	Field, 2013; field evidence	4708982	687757
Unnamed	South River				no	yes	yes	Field, 2013	4708922	687830
Unnamed	South River				no	no	?	Field, 2013	4708591	688203
John Sprague's grist mill dam	South River	grist mill	<1871		no	no	?	Beers, 1871; Field, 2013; field evidence	4708744	688521
Tannery Dam	South River		1871		no	no	no	Beers, 1871; Field, 2013; field evidence	4708844	688902
Unnamed	South River	shingle mill		0.6	no	yes	yes	Walling, 1858; Field, 2013	4710434	688979
Ashfield Pond Dam	South River		~1844	~6.5	yes	yes	?little	Field, 2013; current dam	4710853	680815
Eldridge road dam	South River			~3	no	yes	yes	Field, 2013; field evidence	4710220	682291
Unnamed	South River		<1830		no	no	?	Beers, 1871; Field, 2013	4709229	682591
Unnamed	South River		1855		no	no	?	Field, 2013	4708585	683166
Unnamed	South River	saw mill	1762		no	no	?	Field, 2013	4708853	689119

Table 3.1. Current and historical dams in the South River watershed - Continued

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
C.C. Flagg dam	South River		<1871	~2.2	yes	yes	yes	Beers, 1871; Field, 2013	4710442	688977
Unnamed	South River				no	yes	yes	Field, 2013; field evidence	4709033	682729
Unnamed	South River	saw mill			no	yes	yes	Walling, 1858; Field, 2013	4712351	689180
Unnamed	South River				no	yes	no	Field, 2013	4712446	689650
Conway Electric Dam	South River	trolly car	1899	17	yes	yes	yes	Field, 2013; current dam	4712229	691568
Unnamed	South River				no	yes	yes	Field, 2013; field evidence	4710726	689103
Unnamed	Chapel Brook	saw mill	<1858		no	no	?	Walling, 1858	4705919	684269
Twining Brook Pond Dam	Chapel Brook				yes	no	?	Current dam	4704361	682271
Conway Recreation Dam	Pumpkin Hollow Brook				yes	no	?	Current dam	4707677	689153
Unnamed	Unnamed	cider mill	<1858		no	no	?	Walling, 1858	4711225	689673
Unnamed	Chapel Brook	saw mill	<1858		no	no	?	Walling, 1858; Beers, 1871	4704189	682706
Unnamed	Unnamed	cider mill	<1858		no	no	?	Walling, 1858	4709836	688551

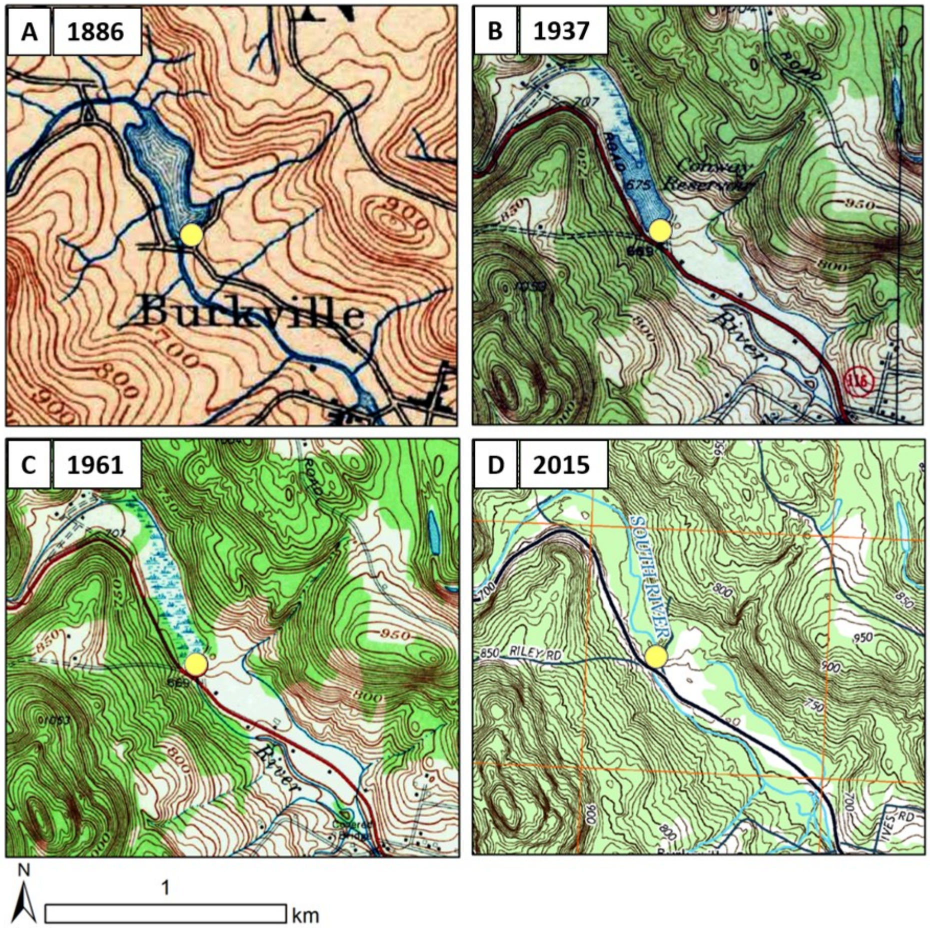

Figure 3.2. Series of U.S. Geological Survey topographic maps showing the changes of the historic Conway Reservoir in 1886 (A), 1930 (B), 1961 (C), and 2015 (D). The historic dam location is shown as the yellow circle in the series of maps. Figure 3.1 shows the location of these maps.

3.1.2 Sheepscot River Watershed

Forty-five dams were found in the Sheepscot River watershed, with 12 dams still intact (Table 3.2; Figures 1.2 C & 3.3). Twenty of these dams were found on the Sheepscot River main stem or West Branch, with four intact (SVCA, 2011). Thirteen dams were field checked in the watershed. Six of those dams show evidence for legacy sediment and seven dams show little to no evidence for legacy sediment (Table 3.2). Walter and Merritts (2008) calculated a milldam density of 0.05-0.10 milldams/km^2 for the counties included in the Sheepscot River watershed. My milldam density calculation of 0.08 milldams/km^2 is in this range.

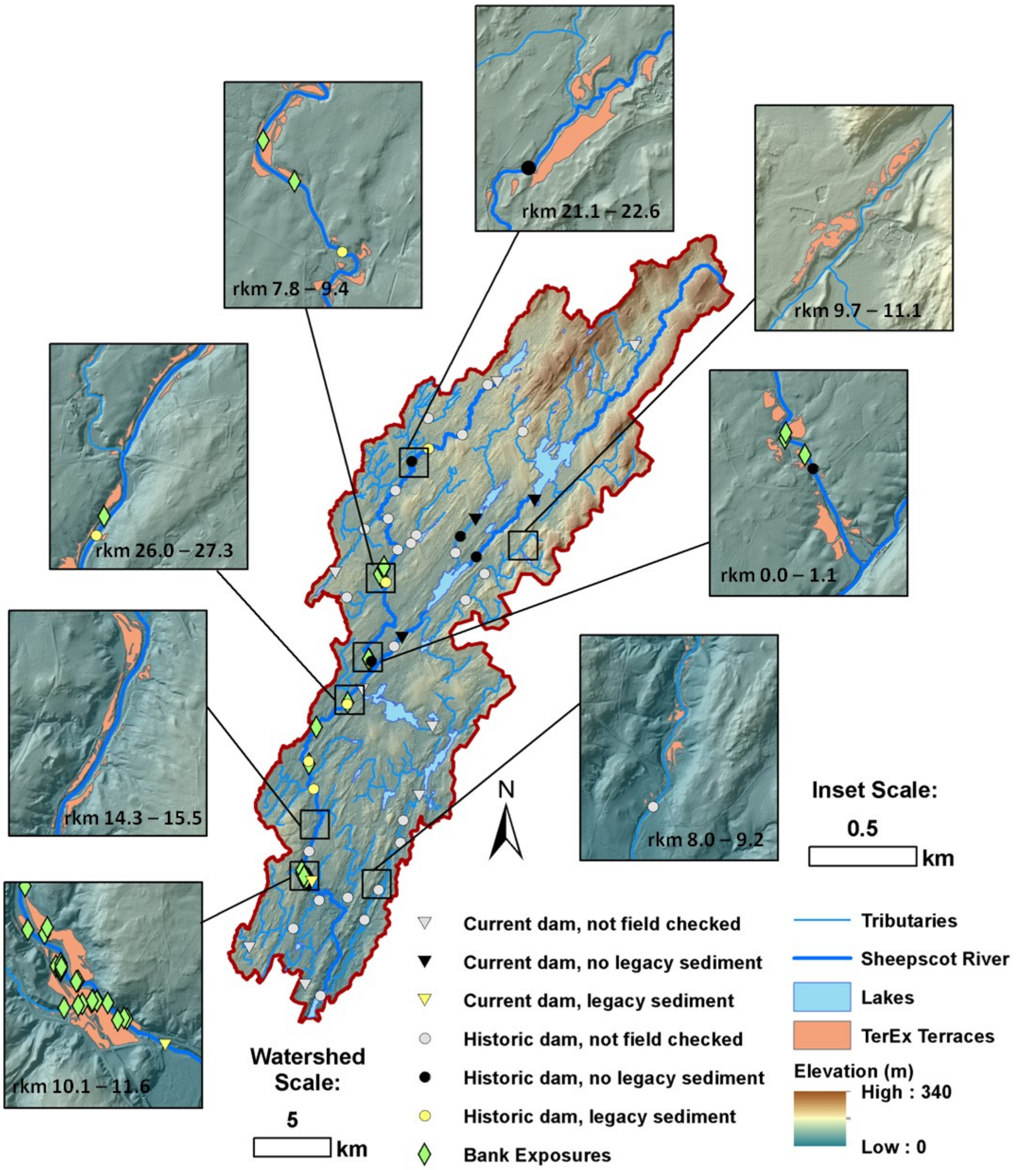

Figure 3.3. Watershed map showing locations of field measured bank exposures from Strouse (2013), Hopkins (2014), and this study, current and historic dams, and TerEx terraces (Stout and Belmont, 2014) with insets of some locations for the Sheepscot River watershed. Current and historic dams are colored based on if the dams were field checked and do or do not have legacy sediment. Base image is a transparent hillshade raster is overlaying a 2 m lidar digital elevation model.

Table 3.2. Current and historical dams in the Sheepscot River watershed.

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Sheepscot Falls	Main Stem	SP, SM, GM	~1760	4.3	no	no	?	SVCA, 2011	4877400	450692
Head Tide Dam	Main Stem	SM,FM, GM	1762-1768	4	yes	yes	yes	SVCA, 2011	4884821	450156
Joshua Little	Main Stem	SM	<1800 ?	?	no	somewhat	little to none	SVCA, 2011	4886827	449959
King's Mills	Main Stem	SM, SH, GM	~1774	?	no	yes	probably	SVCA, 2011	4890869	450265
Turner Prebble	Main Stem	SM	~1775	?	no	yes	probably	SVCA, 2011	4892673	449933
Youngs	Main Stem	SH, SM, FM	~1807	?	no	yes	yes	SVCA, 2011	4896421	452459
Un-named	Main Stem	SH, GM	?	?	no	no	?	SVCA, 2011	4900180	455508
Cooper's Mills	Main Stem	SM, SH, GM	1804	5.5	yes	yes	no	MSHV, 2008; SVCA, 2011	4900737	456049
Un-named	Main Stem	SM	<1869	3.7	no	yes	little to none	SVCA, 2011	4906010	460872
Sheepscot Pond Dam	Main Stem	SH, SM, GM, ST	1790	2.4	yes	yes	little to none	MSHV, 2008; SVCA, 2011	4909676	464701
Pinhook	West Branch	SM	1804	?	no	yes	little to none	SVCA, 2011	4899185	454009
Maxcys Mills	West Branch	SM,GM	1809	?	no	yes	yes	SVCA, 2011	4904359	454958
Haskell Pope	West Branch	FM, SM	<1815	?	no	no	?	SVCA, 2011	4906487	455741
Chadwick Pratt	West Branch	GM	<1829	?	no	no	?	SVCA, 2011	4908502	455123
Prescott	West Branch	GM, SH	~1829	?	no	no	?	SVCA, 2011	4910332	455584

Table 3.2. Current and historical dams in the Sheepscot River watershed - Continued

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Weeks Mills	West Branch	SM, GM	<1807	?	no	yes	no	SVCA, 2011	4912239	456658
Un-named	West Branch	T	<1856	?	no	yes	yes	SVCA, 2011	4913062	457747
Pullen	West Branch	SM	<1856	?	no	no	?	SVCA, 2011	4913979	459962
Hammond	West Branch	T, SM, SH	<1856	?	no	somewhat	little to none	SVCA, 2011	4917233	461613
Branch Mills	West Branch	SM, GM	<1800	4.3	yes	no	?	MSHV, 2008; SVCA, 2011	4917396	462256
Unnamed	Dyer River	SM, SH	<1869	3.7	no	no	?	SVCA, 2011	4882342	453578
unnamed	Dyer River	?	?	?	no	no	?	SVCA, 2011	4884282	454492
Match	Dyer River	M,	?	?	no	no	?	SVCA, 2011	4887390	455929
Fulling	Dyer River	GM, FM, SH, ST	<1869	3	no	no	?	SVCA, 2011	4888839	456091
Boynton Trask	Dyer River	SM	1850	2.4	yes	no	?	MSHV, 2008; SVCA, 2011	4890420	457172
Chases Mill	Clary Lake	SM, SH	~1791	2.4	yes	no	?	MSHV, 2008; SVCA, 2011	4897352	453451
Streans	Clary Lake	SM, SH	1790s	3	yes	no	?	MSHV, 2008; SVCA, 2011	4894944	458021
David Bryant	Gully Brook	SH, ST	1850	1.8	no	no	?	SVCA, 2011	4903373	452429
Tolman Colburn	Dearborn Brook	SM, SH	1832	?	no	no	?	SVCA, 2011	4907829	453588

Table 3.2. Current and historical dams in the Sheepscot River watershed - Continued

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Dearborn Brook Dam	Dearborn Brook	?	?	1.3	yes	no	?	MSHV, 2008	4904985	451667
Solomon Bruce	Choate Brook	FM, ST	<1832	2	no	no	?	SVCA, 2011	4907431	456967
Choate Brook	Choate Brook	?	?	2.1	no	no	?	MSHV, 2008	4906891	456602
Un-named	Meadow Brook	SM	<1856	?	no	no	?	SVCA, 2011	4915056	457724
Turner	Colby Stream	SM	<1819	?	no	no	?	SVCA, 2011	4903206	460159
Berry	Colby Stream	SM	<1886	?	no	no	?	SVCA, 2011	4904930	461400
Dodges	Lovejoy Stream	SH	<1869	?	no	no	?	SVCA, 2011	4906288	459496
French's	Lovejoy Stream	SM	<1869	?	no	yes	little to none	SVCA, 2011	4907345	459821
Colby	Lovejoy Stream	SM	1825	4.3	yes	yes	little to none	MSHV, 2008; SVCA, 2011	4908430	460825
Greeley	Beech Pond	GM	1807	?	no	no	?	SVCA, 2011	4914197	463897
Head Mill	Trout Brook	SM	~1750	?	no	no	?	SVCA, 2011	4883604	450622
Trout Brook Dam1	Trout Brook	SM	1940	4.9	no	no	?	SVCA, 2011	4881784	448923
Trout Brook Dam2	Trout Brook	?	?	6.1	yes	no	?	MSHV, 2008	4880541	446088
Hodge	Ben Brook	SM	?	?	no	no	?	SVCA, 2011	4883787	452476
Mill Dam	Chisolm Pond	FM, SM	1820	6.1	yes	no	?	MSHV, 2008; SVCA, 2011	4919754	471216

Table 3.2. Current and historical dams in the Sheepscot River watershed - Continued

Dam Name	River	Purpose	Year Built	Height (m)	Intact Dam	Field Checked	Legacy Sediment	Source	Northing (m)	Easting (m)
Verney-Leighton Marsh Dam	unnamed	?	?	?	yes	no	?	MSHV, 2008	4878107	449723

*SP=Ship Passage, SM=Sawmill, GM=Gristmill, WS=Water Supply, FM=Fullingmill, PM=Potters Mill, M=Match factory, SH=Shingle Mill, ST=Stave Mill, T=Tannery

3.2 GIS Terrace Mapping and Longitudinal Profiles

3.2.1 South River Watershed

Terraces were mapped for the South River and all tributaries using TerEx toolbox (Stout and Belmont, 2014; Figure 3.1). TerEx (Stout and Belmont, 2014) identifies and maps flat features near streams in a landscape, which results in terraces as well as floodplains delineated. To increase accuracy, TerEx allows for user edits to revise and remove polygons generated during the first step of this method; examples include the removal of polygons mapped on roads, water surfaces, and upland areas. The resulting delineated polygons were considered likely legacy sediment terraces. After user edits, TerEx delineated a terrace area of 8.3×10^5 m^2 for the South River main stem and 2.0×10^5 m^2 for the tributaries. The total area of terraces is 1.5% of the watershed. Eighty percent of the terraces in the South River watershed were mapped along the South River as opposed to tributaries. Field work and longitudinal profiles were used to investigate whether the results of TerEx are terraces or active floodplains.

A longitudinal profile was created for the South River, including the projections of the mapped legacy sediment terraces (Figure 3.4). There are higher (~30 m), potentially glacial-age terraces in the watershed that were not mapped or projected on the longitudinal profiles. The longitudinal profiles show that in some areas the terraces appear to be steeper than the current channel.

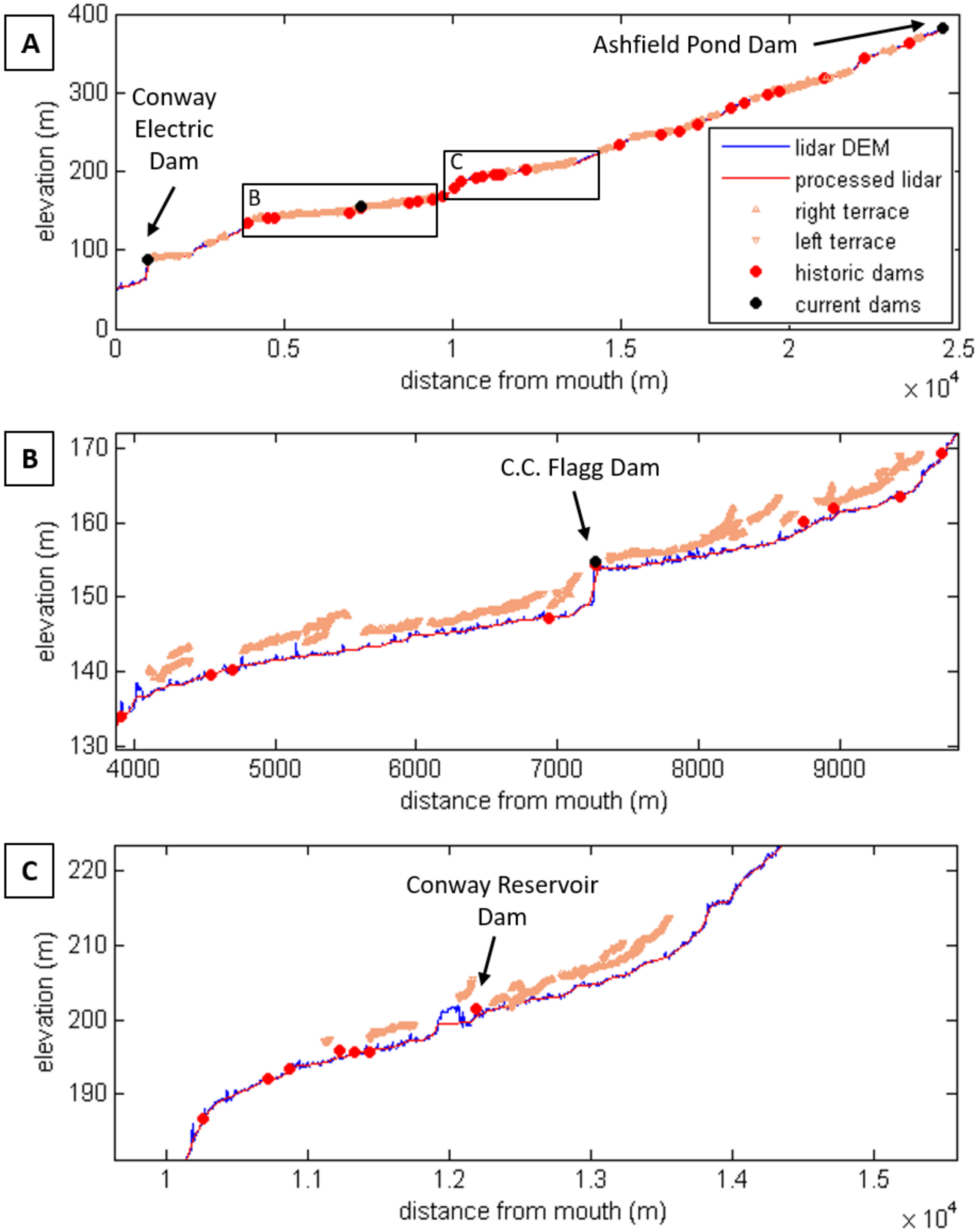

Figure 3.4. Longitudinal profile of the South River from a 2 m DEM (A), with detailed views of two segments (B & C).

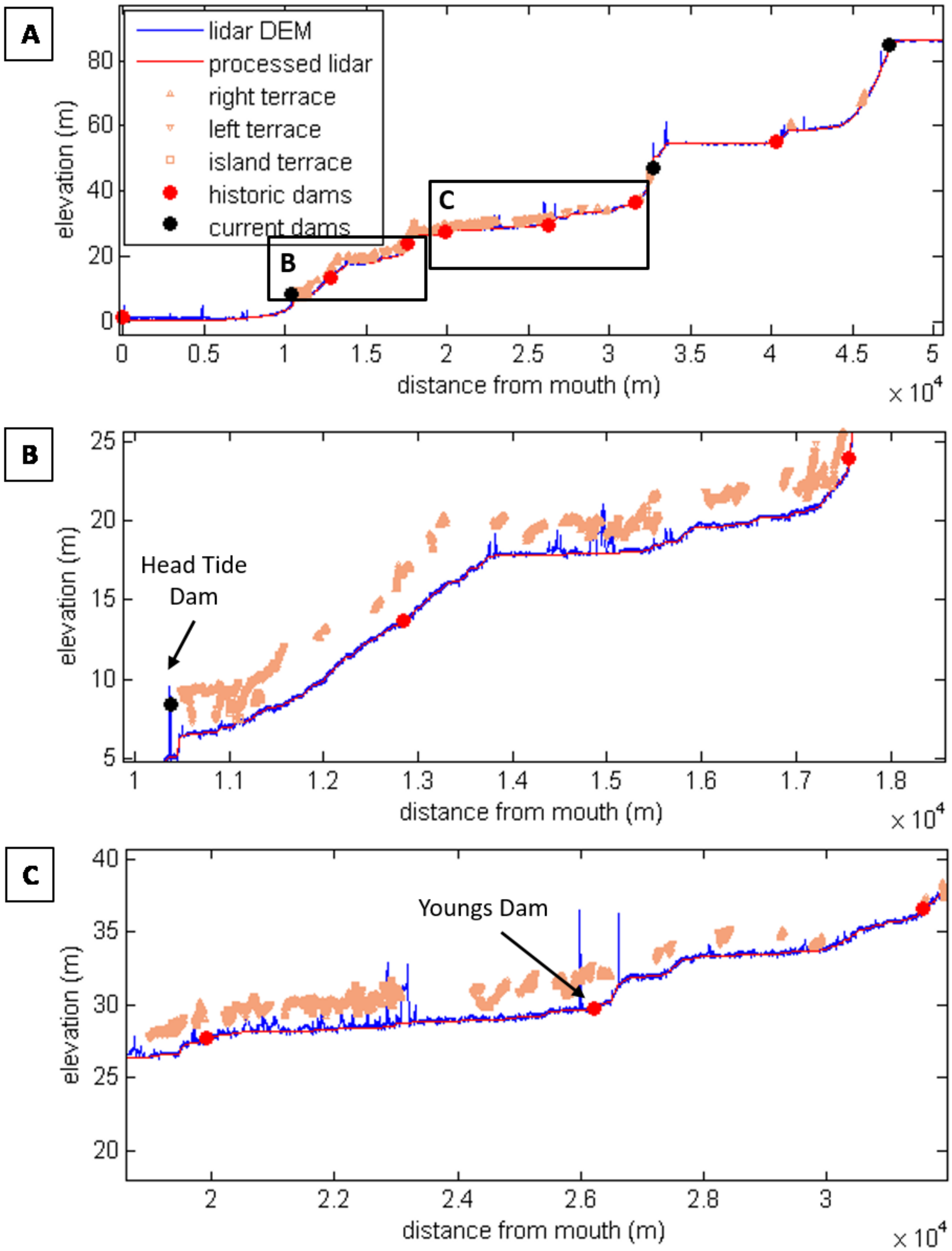

Figure 3.5. Longitudinal profile for the main stem Sheepscot River from a 1 m DEM (A), with detailed views of two segments (B & C). The blue line is the raw lidar; the spikes in the data are from bridges or errors in the original data. The red line is the processed lidar showing a smoothed profile.

3.2.2 Sheepscot River Watershed

Terraces were mapped for the main stem Sheepscot River, the West Branch Sheepscot River, and all tributaries using TerEx toolbox (Stout and Belmont, 2014; Figure 3.3). After user edits, TerEx delineated a terrace area of 9.6 x 10^5 m^2 along the main stem and West Branch and 5.3 x 10^5 m^2 on the tributaries. The total area of terraces is 0.3% of the watershed.

Longitudinal profiles with terraces mapped were created for the main stem Sheepscot River (Figure 3.5). As Strouse (2013) observed, the terraces mapped along the profile do not appear to be consistently flat but rather have many variations in elevation. This could be associated with low relief surface topography or dense vegetation cover, which may not be removed by bare-earth filtering algorithms.

3.3 Field Stratigraphy and Radiocarbon Dating

3.3.1 South River Watershed

Field work was conducted to explore the terraces and dams mapped in the South River watershed in summer 2015. Sixteen bank exposures were found and stratigraphically described (Appendix 2). These exposures were found to have massive, fine grained sand and silt layers ranging from 40-219 cm thick. Four of these bank exposures had wood samples radiocarbon dated, at rkm 5.94, 12.46, 19.41, and 21.06 (Table 3.3; Figure 3.1). The sample from 19.41 rkm yielded a modern age. The other radiocarbon dates were calibrated using the INTCAL13 curve on the CALIB Radiocarbon Calibration program online (Stuiver and Reimer, 1993; Table 3.4; Appendix 3).

Table 3.3. Radiocarbon results from Woods Hole Oceanographic Institute (WHOI).

Location	Depth (cm)	^{14}C age yr BP	Age Error (years)	d13C	F Modern	Fm Err
South River: rkm 12.46	106	210	20	-25.79	0.9739	2.1 x 10-03
South River: rkm 5.94	120	155	20	-25.72	0.9810	2.3 x10-03
South River: rkm 19.41	68	>Modern		-27.08	1.6397	3.6 x10-03
South River: rkm 21.06	123	190	20	-24.7	0.9766	2.2 x10-03
Sheepscot River: rkm 11.1 island	144	175	20	-25.04	0.9783	2.1 x10-03
Sheepscot River: rkm 11.1 island	161	175	15	-25.92	0.9785	2.1 x10-03
Sheepscot River: rkm 10.8 tributary	130	115	15	-27.11	0.9855	2.1 x10-03

Table 3.4. South River radiocarbon calibration results from CALIB Radiocarbon Calibration (Reimer et al., 2013).

rkm 12.46 rb (106 cm)		rkm 5.94 rb (120 cm)		rkm 21.06 rb (123 cm)	
One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution
1657-1670 CE	0.32	1675-1689 CE	0.14	1665-1680 CE	0.26
1779-1798 CE	0.56	1730-1769 CE	0.48	1739-1742 CE	0.03
1943-1949* CE	0.12	1771-1777 CE	0.07	1763-1785 CE	0.37
		1799-1809 CE	0.12	1793-1802 CE	0.14
		1926-1941 CE	0.18	1938-1949* CE	0.20
Two sigma ranges		Two sigma ranges		Two sigma ranges	
1649-1681 CE	0.35	1668-1696 CE	0.17	1661-1683 CE	0.22
1739-1745 CE	0.02	1725-1782 CE	0.43	1735-1806 CE	0.61
1762-1802 CE	0.52	1797-1814 CE	0.11	1930-1949* CE	0.17
1937-1949* CE	0.12	1835-1877 CE	0.09		
		1917-1949* CE	0.20		
Median Probability 1781 CE		Median Probability 1765 CE		Median Probability 1772 CE	

* Ranges suspect due to impingement on the end of the calibration data set (Reimer et al., 2013)

The bank exposure at 5.94 km is 1.2 km upstream of a historic dam (Figure 3.6). It is 157 cm thick, with 50 cm more of slump material to the water surface. The top 69 cm is light brown fine grained sand that grades to medium sand. The bottom 88 cm of sediment is fine brown sand. This layer has two lenses of wood and charcoal at 81 and 121 cm from the top of the bank and two gravel lenses at 144 and 155 cm. A radiocarbon sample taken at 120 cm has a calibrated median probability age of 1765 CE (Table 3.4). This exposure of 157 cm exposure is interpreted to be legacy sediment, which is a minimum thickness due to the slump block that obscures the underlying strata.

The bank exposure at 12.46 rkm is just upstream of the historic Conway Reservoir dam (Figure 3.7). The longitudinal profile shows roughly two terrace levels, where the RTK GPS point for the bank exposure found at 12.46 rkm underlies the higher terrace, and two other bank exposures found close by (rkm 12.40 and 12.59) underlie the lower terrace level (Figures 3.4 and 3.7B). The exposure at 12.46 rkm is 244 cm thick (Figure 3.7). The top 48 cm consists of light brown sand and silt. The middle 72 cm has alternating layers of dark gray silt and clay with brown fine sand and silt. This layer also includes millimeter-thick white fine sand lens. The next 99 cm includes more brown fine sand. The bottom 25 cm layer of this bank exposure consists of laminated 2 cm thick layers of red gravel that coarsens down. Some cobbles were found throughout the bottom layer (Figure 3.7C). A radiocarbon sample was taken 106 cm from the top and has a calibrated age with a median probability age of 1781 CE (Table 3.4); therefore, this layer is interpreted to be legacy sediment. Similar sediment size and color characteristics found in the next 99 cm, below the radiocarbon sample, are also interpreted to be legacy sediment. The bottom red gravel layer is interpreted to be a historic river bed or channel bar deposit (Figure 3.7C).

The bank exposure at 21.06 rkm measured 131 cm thick in the field (Figure 3.8), and is just upstream of an unnamed historic dam ~3 m tall. The outcrop has a wide range of sediment sizes. The top 56 cm consists of fine brown sand and silt with cross-beds. Sediment sizes vary the most in the middle 72 cm with layers of coarse sand, red-stained laminations of medium sand, and dark gray clay and silt. A thin wood layer was observed in the dark gray clay and silt layer. The bottom 3 cm coarsen to a dark gray sand and silt layer. A radiocarbon sample was taken at 123 cm from the top of the bank and calibrated with a median probability age of 1772 CE (Figure 3.8C; Table 3.4). This whole bank exposure is interpreted to be minimum of 131 cm of legacy sediment.

Most exposures observed in the South River watershed are fine to medium brown sand, which I interpret to be legacy sediment. These extend from the terrace to the water surface with no basal layer present (Appendix 2). Six exposures have a basal layer of pebbles and cobbles and two exposures have a clay layer at their base. These two bank exposures with clay were found along the main stem at rkm 19.41 and 19.42 (Figure 3.1). Both exposures have a top layer of ~45 cm of fine to medium brown sand interpreted to be legacy sediment with a middle layer of large rounded cobbles interpreted to be a pre-dam river bed or channel bar deposit. Gray clay was found as a bottom layer, interpreted to be a glacial lake deposit.

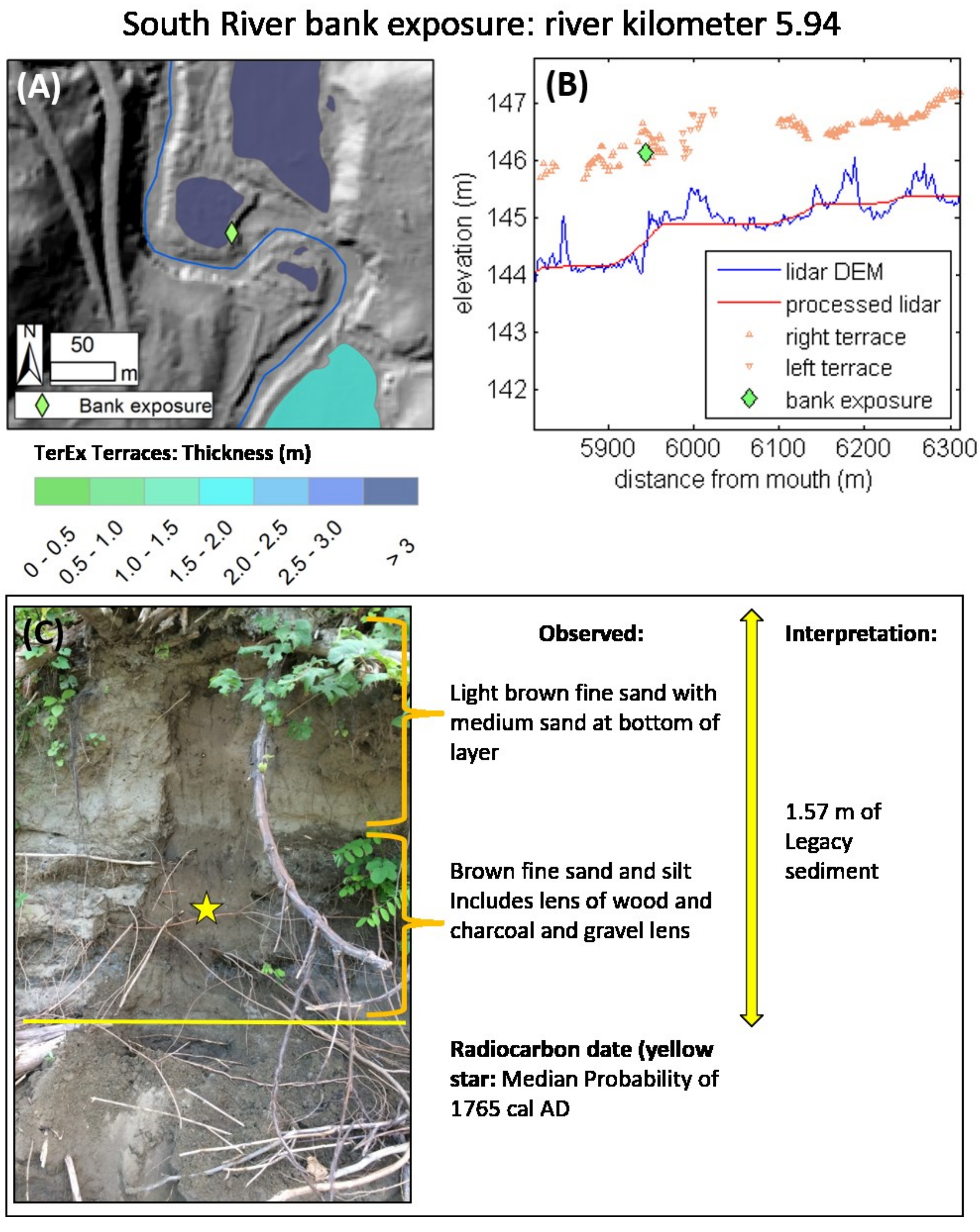

Figure 3.6. TerEx (Stout and Belmont, 2014) mapping of an area on the South River at river kilometer 5.94, with associated average thickness of each polygon (A). Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure (B). Field photograph of the bank exposure annotated with sediment characteristics and interpretations (1.57 m of legacy sediment), as well as radiocarbon sample location (yellow star; 1.20 m from top of bank) and median calibrated age (C).

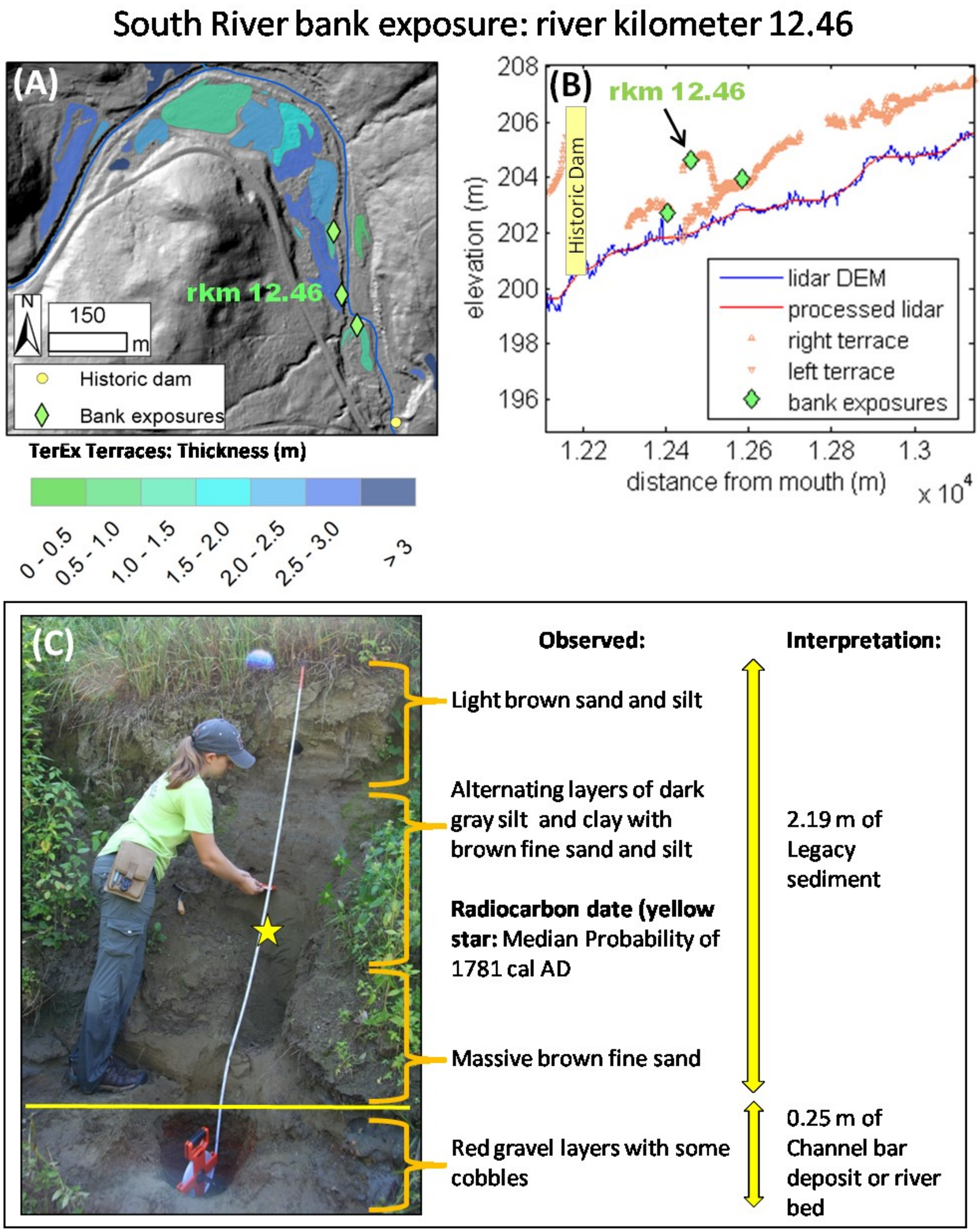

Figure 3.7. TerEx (Stout and Belmont, 2014) mapping an area on the South River at river kilometer 12.46, with associated average thickness of each polygon (A). Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure (B). Field photograph of bank exposure annotated with sediment characteristics and interpretations (2.19 m of legacy sediment), as well as radiocarbon sample location (yellow star; 1.06 m from top of bank) and median calibrated age (C).

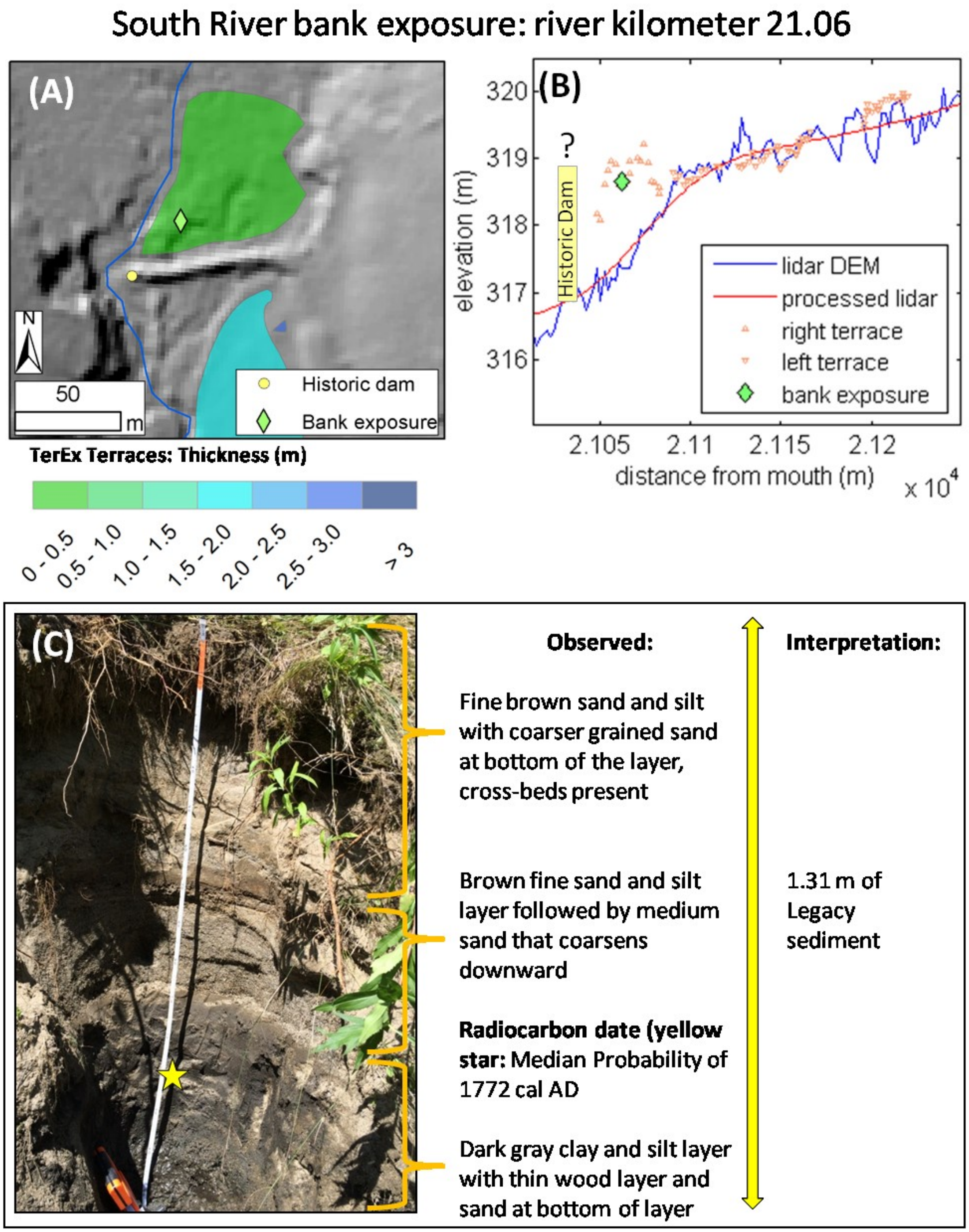

Figure 3.8. TerEx (Stout and Belmont, 2014) mapping an area on the South River at river kilometer 21.06, with associated average thickness of polygon (A). Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure (B). Field photograph of bank exposure annotated with sediment characteristics and interpretations (1.31 m of legacy sediment), as well as radiocarbon sample location (yellow star; 1.23 m from top of bank) and median calibrated age (C).

3.3.2 Sheepscot River Watershed

In the Sheepscot River watershed Strouse (2013) examined nine bank exposures, Hopkins (2014) examined 17, and this study examined nine (Figure 3.3). At Head Tide Dam, I observed six bank exposures upstream of the dam found from 10.75-11.1 rkm; two of these exposures are described in detail below. The three other bank exposures are also along the main stem downstream of the confluence with the West Branch Sheepscot River, all on the right bank, at rkm 19.2, 23.0, and 26.3. The sediments at these locations are topped with mostly brown-gray silt and fine sand deposits with some medium to coarse sand lenses (1-3 cm thick). When an underlying layer is visible it consists of either pebble/cobbles, clay material, or cut planks. The average thickness of the massive brown silt layer measured at these seven bank exposures is 1.33 m.

For this study, three radiocarbon samples from the Sheepscot River watershed were analyzed (Table 3.3), and calibrated using the INTCAL13 curve on the CALIB Radiocarbon Calibration program online (Stuiver and Reimer, 1993; Table 3.5). For these samples the median calibrated ages span 1765-1838 CE and therefore are interpreted to be legacy. Strouse (2013) radiocarbon dated seven samples from two bank exposures found behind the Head Tide Dam and Maxcy Mills historic dam (Table 3.6), but these were never calibrated. Here I report the calibrated ages in Table 3.7 and Appendix 3. At both sites, a radiocarbon sample was determined to be Holocene in age but stratigraphically lower radiocarbon dates constrain the age of the entire deposit to be legacy. The Holocene-aged samples are attributed to the old wood problem (Schiffer, 1986; Strouse, 2013).

Table 3.5. Sheepscot River radiocarbon calibration results from CALIB Radiocarbon Calibration (Reimer et al., 2013).

rkm 11.1 island r (144 cm)		rkm 11.1 island r (161 cm)		rkm 10.8 (130 cm)	
One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution
1669-1682 CE	0.20	1669-1681 CE	0.21	1692-1707 CE	0.16
1737-1757 CE	0.26	1738-1753 CE	0.23	1719-1728 CE	0.10
1761-1781 CE	0.31	1762-1781 CE	0.33	1811-1820 CE	0.09
1798-1803 CE	0.09	1798-1803 CE	0.08	1823-1825 CE	0.02
1936-1946*CE	0.15	1937-1945* CE	0.14	1832-1883 CE	0.58
				1914-1920 CE	0.06
Two sigma ranges		Two sigma ranges		Two sigma ranges	
1665-1689 CE	0.19	1667-1684 CE	0.19	1686-1731 CE	0.28
1729-1787 CE	0.51	1733-1783 CE	0.54	1808-1892 CE	0.61
1792-1810 CE	0.11	1796-1807 CE	0.09	1907-1927 CE	0.11
1925-1949*CE	0.18	1929-1949* CE	0.18		
Median Probability 1766 CE		Median Probability 1765 CE		Median Probability 1838 CE	

* Ranges suspect due to impingement on the end of the calibration data set (Reimer et al., 2013)

Table 3.6. Strouse (2013) radiocarbon results for the Sheepscot River watershed.

Location	Depth (cm)	^{14}C age yr BP	Age Error (years)	d13C	F Modern	Fm Err
Sheepscot River: Maxcy's Mills	58	1750	30	-25	0.81	3 x10-3
Sheepscot River: Maxcy's Mills	62	220	25	-26	0.97	3 x10-3
Sheepscot River: Maxcy's Mills	76	175	40	-24	0.98	5 x10-3
Sheepscot River: Head Tide Dam	137	105	30	-23.7	0.9900	4 x10-3
Sheepscot River: Head Tide Dam	152	350	25	-22.8	0.9600	3 x10-3
Sheepscot River: Head Tide Dam	164	265	50	-27.2	0.9700	6 x10-3
Sheepscot River: Head Tide Dam	187	180	25	-27	0.9800	3 x10-3

Table 3.7. Radiocarbon calibration for Strouse (2013) Sheepscot River watershed from CALIB Radiocarbon Calibration (Reimer et al., 2013).

Head Tide Dam (137 cm)		Head Tide Dam (152 cm)		Head Tide Dam (164 cm)		Head Tide Dam (187 cm)	
One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution
1694-1727 CE	0.29	1482-1522 CE	0.43	1521-1578 CE	0.42	1667-1682 CE	0.20
1813-1854 CE	0.34	1573-1628 CE	0.57	1582-1591 CE	0.05	1737-1757 CE	0.24
1857-1863 CE	0.04			1620-1668 CE	0.11	1761-1783 CE	0.30
1907-1918 CE	0.10			1949*-1949* CE	0.00	1796-1804 CE	0.09
						1936-1949* CE	0.17
Two sigma ranges		Two sigma ranges		Two sigma ranges		Two sigma ranges	
1681-1738 CE	0.29	1460-1529 CE	0.44	1477-1682 CE	0.82	1658-1693 CE	0.21
1765-1761 CE	0.01	1541-1635 CE	0.56	1737-1758 CE	0.02	1727-1812 CE	0.61
1803-1937 CE	0.71			1761-1804 CE	0.13	1919-1949* CE	0.19
				1936-1949* CE	0.03		
Median Probability 1837 CE		Median Probability 1557 CE		Median Probability 1626 CE		Median Probability 1768 CE	

* Ranges suspect due to impingement on the end of the calibration data set (Reimer et al., 2013)

Table 3.7. Radiocarbon calibration for Strouse (2013) Sheepscot River watershed from CALIB Radiocarbon Calibration (Reimer et al., 2013) - Continued

Maxcy's Mills (58 cm)		**Maxcy's Mills (62 cm)**		**Maxcy's Mills (76 cm)**	
One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution	One sigma ranges	relative area under distribution
245-265 CE	0.23	1650-1669 CE	0.46	1665-1690 CE	0.20
271-331 CE	0.77	1781-1798 CE	0.47	1729-1787 CE	0.48
		1945-1949* CE	0.07	1792-1810 CE	0.13
				1925-1949* CE	0.19
Two sigma ranges		Two sigma ranges		Two sigma ranges	
224-384 CE	1.00	1644-1681 CE	0.43	1652-1707 CE	0.21
		1738-1752 CE	0.03	1719-1826 CE	0.51
		1762-1803 CE	0.45	1832-1885 CE	0.12
		1937-1949* CE	0.09	1913-1949* CE	0.17
Median Probability		Median Probability		Median Probability	
292 CE		1771 CE		Cal AD 1775 CE	

* Ranges suspect due to impingement on the end of the calibration data set (Reimer et al., 2013)

My primary stratigraphic observations on the Sheepscot River were upstream of Head Tide Dam. This was originally built as a run-of-the-river dam, 4 m high, in the 1760s (Halsted, 2002). In 1952 and 1956 the dam was partially breached when two 1.5 m holes were made at mid-height to assist the passage of migrating Atlantic salmon (Halsted, 2002). Today, Head Tide Dam continues to cause some flow impoundment, particularly at high discharge.

The 10.8 rkm right bank exposure is in a small tributary valley, and is 200 cm thick (Figure 3.9). The top 80 cm is brown silt and fine sand (Figure 3.9C). The middle 50 cm is a gray silt layer with a 6 cm layer of black organic rich material. The bottom layer is 60 cm of tan white silt and fine sand. There is a pebble and cobble layer at the base of the exposure. The wood radiocarbon dated from the black organic rich layer at 130 cm from the top of the bank has a median calibrated age of 1838 CE (Table 3.5; Appendix 3). A minimum of 130 cm from the top of this bank exposure is interpreted to be legacy sediment. Because similar silt and fine sand is found below the radiocarbon date, an additional 60 cm is also interpreted to be legacy sediment. The basal pebble and cobble layer at this site is interpreted to be a pre-dam tributary channel deposit.

Farther upstream of Head Tide dam is a mid-channel island bank exposure at 11.1 rkm (Figure 3.10). The top 150 cm is light brown silt and fine sand with several small 1 cm lenses of medium to coarse sand, similar to the outcrop at rkm 10.8. This layer also contained a thin 2 mm layer of reddish black organic bark material, which was one of two samples radiocarbon dated at this bank (Figure 3.10C). The bottom layer is 50 cm of gray clay with several 1-2 cm lens of sand until the water table is reached (Figure 3.10C). This clay layer also contained a few twigs that were radiocarbon dated. The stratigraphically higher radiocarbon sample at 144 cm was found to have a median calibrated date of 1766 CE; as this sample was found in a brown fine sand layer, this 150 cm layer is interpreted as legacy sediment. The lower radiocarbon sample taken at 161 cm from the top of the bank and found in gray clay has a median calibrated radiocarbon date of 1765 CE. Although the age for this wood sample is young enough to be considered legacy sediment this gray clay layer is interpreted to be the older Presumpscot Formation. In the modern river bed, exposures of the Presumpscot Formation clay are common and wood can become embedded in this cohesive, sticky layer. The young date of this sample suggests that it was sitting on the Presumpscot Formation exposed in the river bed close to the time that the dam was built and later buried by legacy sediment.

The exposures at rkm 10.8 and 11.1 have basal layers of pebbles/cobbles and clay, respectively. Some exposures found upstream of Head Tide Dam and Pinhook Dam (Hopkins, 2014) have no basal layer, but rather fine to medium sand extends to the water surface. These exposures are interpreted to be legacy sediment. Alternatively, legacy sediment has been interpreted to overlay a basal layer of cut planks. Cut planks have been seen at 10.6 rkm, just upstream of Head Tide Dam, and 26.3 rkm, upstream of historic Turner Prebble Dam (Figure 3.11). Cut planks are likely from historic sawmills as they are thin, long sections of wood with some flat cut ends.

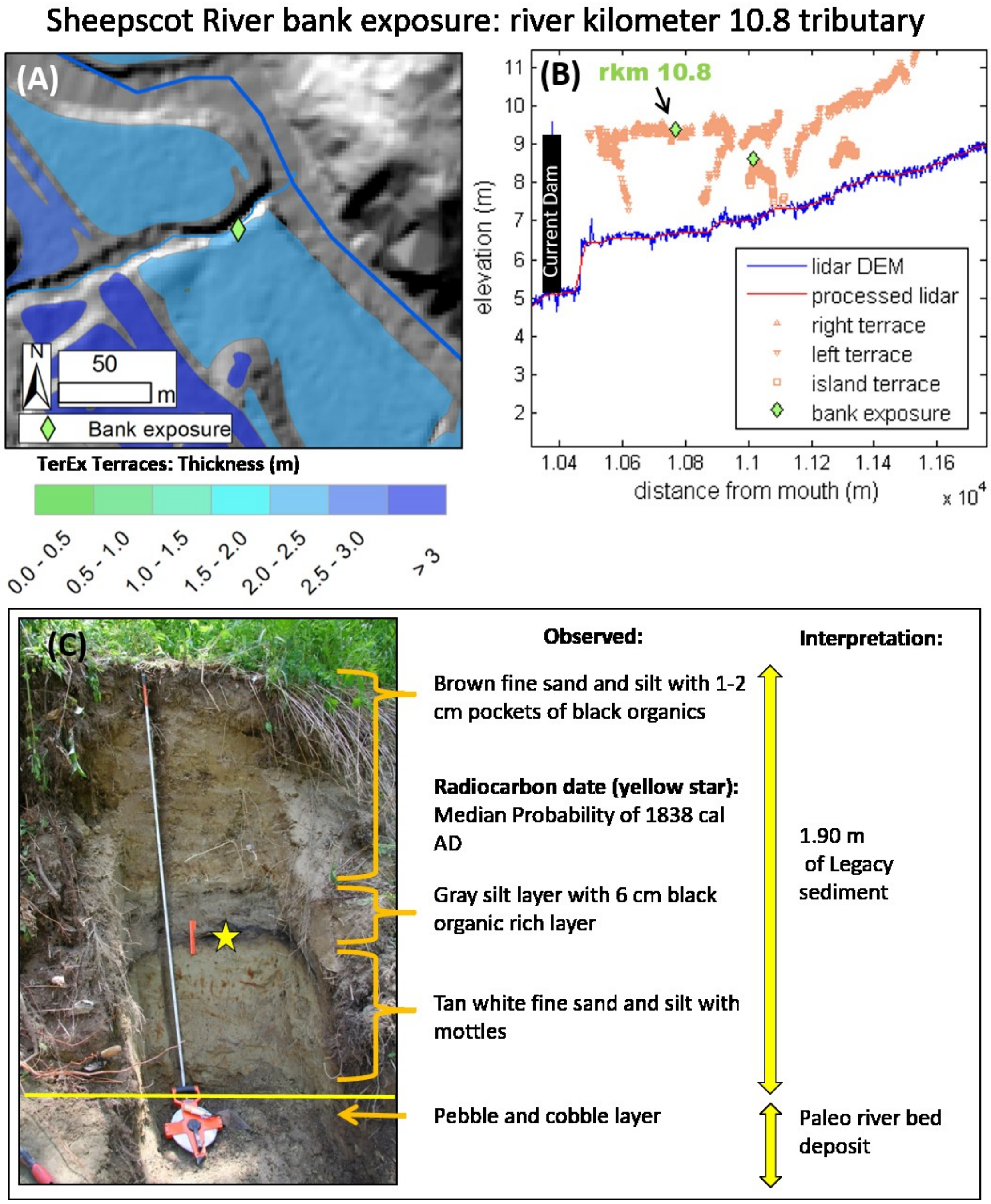

Figure 3.9. TerEx (Stout and Belmont, 2014) mapping an area on a small tributary of the main stem Sheepscot River at river kilometer 10.8, with associated average thickness of each polygon (A). Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure (B). Field photograph of bank exposure annotated with sediment characteristics and interpretations (1.90 m of legacy sediment), as well as radiocarbon sample location (yellow star; 1.30 m from top of bank) and median calibrated age (C).

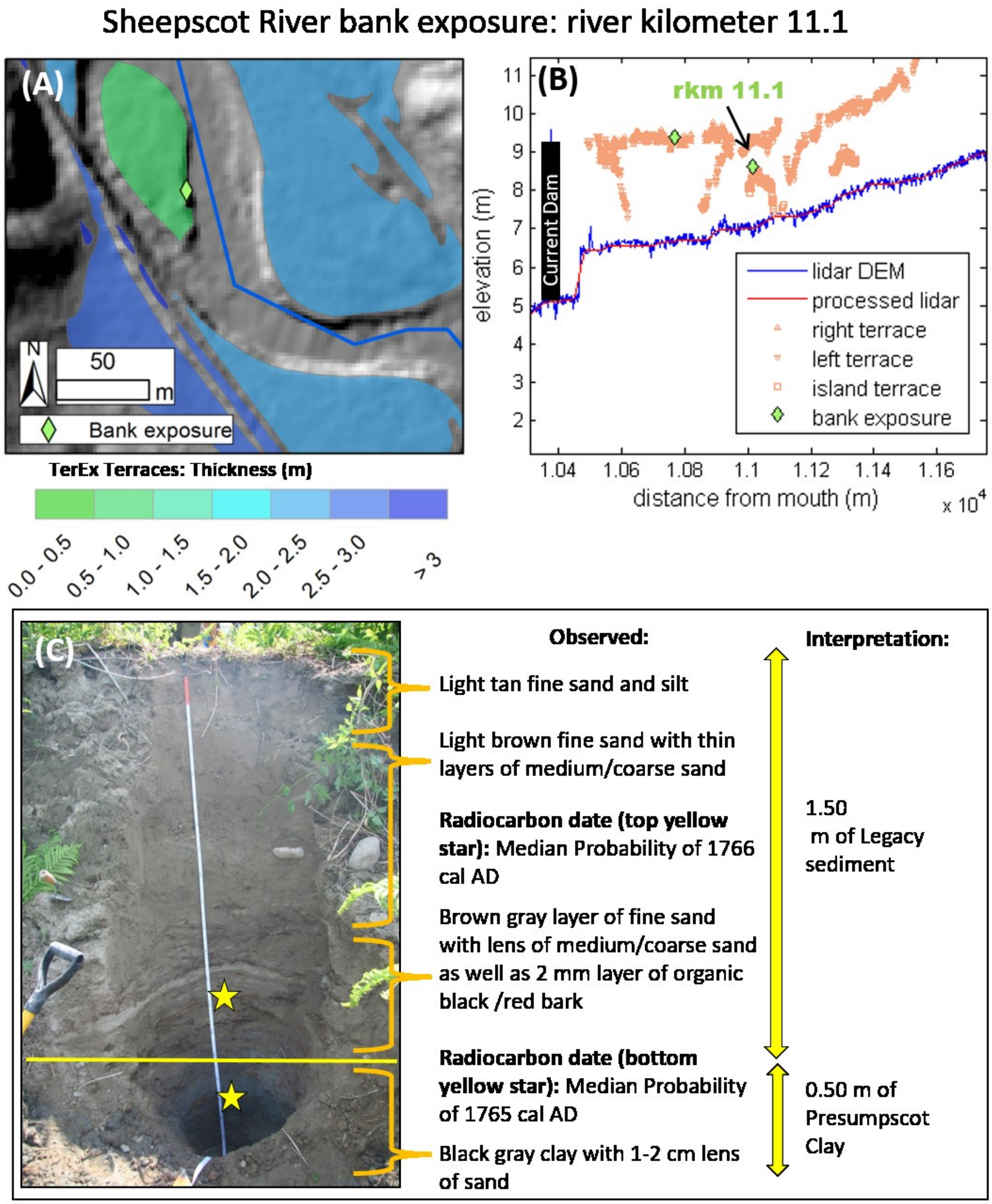

Figure 3.10. TerEx (Stout and Belmont, 2014) mapping an area on the main stem Sheepscot River at river kilometer 11.1, with associated average thickness of each polygon (A). Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure (B). Field photograph of bank exposure annotated with sediment characteristics and interpretations (1.50 m of legacy sediment), as well as radiocarbon sample locations and median calibrated ages (C).

Figure 3.11. Photographs of cut planks found sticking out of exposed banks at river kilometer 10.6 (A) and 26.3 (B) along the Sheepscot River.

3.4 Comparison between Field and Lidar DEM Measurements

3.4.1 South River Watershed

Field-measured sediment thicknesses in the South River watershed are compared with the equivalent measurements from lidar DEMs (Figure 3.12A & E; Table 3.8). These lidar DEM measurements are made by subtracting the river elevation from the DEM elevation at the top of the bank exposure (where the field GPS survey point was taken), resulting in estimated legacy sediment thicknesses. This method assumes the water surface elevation is at the base of the legacy sediment. The lidar DEM measurements are compared to both field-measured legacy sediment thickness and total field-measured height from water surface to bank top. This was done to assess the accuracy of lidar DEM volume calculations. Lidar DEM measurements average 61 cm greater (57%) than field estimates of legacy sediment thickness and average 0% from total field-measured thicknesses from water surface to bank top (Figure 3.12A & E; Table 3.8). The lidar DEM measurements agree with field measurements well, with 88% within ±50% of legacy sediment thickness (Figure 3.12A), and 100% within ± 50% of bank to water surface thickness (Figure 3.12E).

Once volume calculations were complete, local thicknesses from each method were also compared to field-measured thicknesses (Figure 3.12B-D & F-H). The thicknesses from the coincident pixel of each bank exposure are recorded from the water surface datum (WSD) and valley bottom surface datum (VBSD) methods (Table 3.9). TerEx (Stout and Belmont, 2014) produces one thickness for each polygon delineated and these are recorded for each bank exposure as well (Table 3.9).

TerEx (Stout and Belmont, 2014) measurements average 165 cm greater (148%) than field-measured legacy sediment thickness (Figure 3.12B; Table 3.9). When compared with field-measured total sediment thickness, TerEx (Stout and Belmont, 2014) averages 102 cm greater (58%) (Figure 3.12F; Table 3.9). TerEx produced the poorest comparison with field-measured legacy sediment measurements, where 64% of points agree within ±50% (Figure 3.12B); 79% agree within ±50% of bank to water surface thickness (Figure 3.12F).

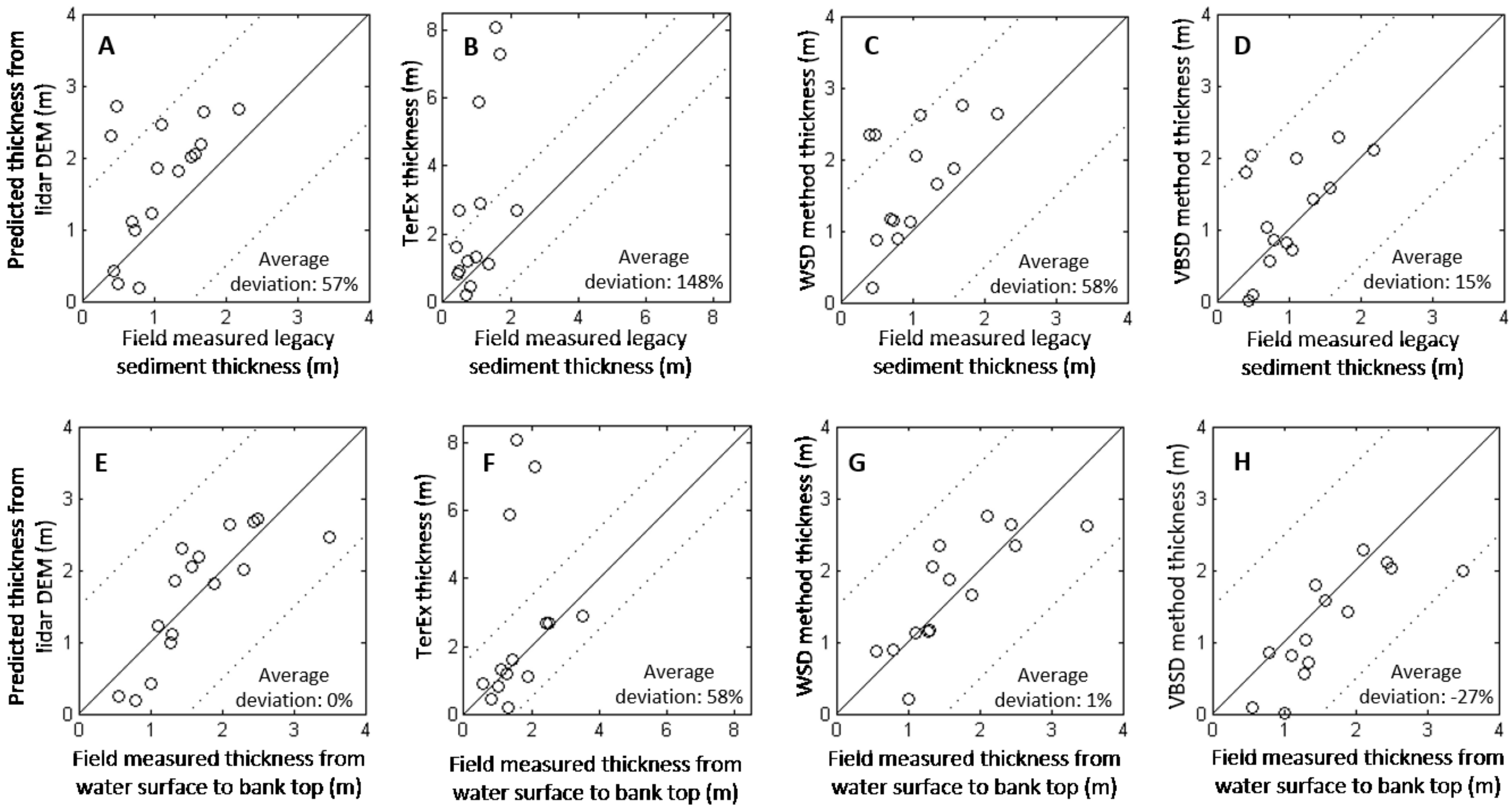

Figure 3.12. Comparisons between field measurements and coincident thicknesses estimated from lidar DEMs at bank exposures along the South River (Figure 3.1). A-D compare field legacy sediment thickness estimates and lidar DEM terrace thickness measurements. E-H compare field-measured height from water surface to bank top with lidar DEM terrace thickness measurements. The black solid lines represent a 1:1 ratio and dashed lines represent a 1:1.5 and 1.5:1 ratio.

Table 3.8. South River bank exposure data with corresponding DEM thickness estimates.

Location	Northing gps	Easting gps	Elevation gps (m)	Field legacy thickness (m)	Field total thickness (m)	DEM northing	DEM easting	DEM point elevation (m)	DEM river elevation (m)	DEM thickness (m)	Difference (DEM-field legacy)	Difference (DEM-total thickness)
rk_4.78_rb	4712300	689114	141.92	**1.05**	**1.35**	4712292	689121	142.72	140.86	**1.86**	0.81	0.51
rk_5.35_rb	4711860	689036	143.39	**1.7**	**2.1**	4711857	689039	145.14	142.51	**2.63**	0.93	0.53
rk_5.94_rb	4711507	688896	146.13	**1.57**	**1.57**	4711507	688896	146.53	144.49	**2.04**	0.47	0.47
rk_7.53_lb	4710266	689023	154.10	**1.65**	**1.67**	4710266	689020	156.27	154.08	**2.19**	0.54	0.52
rk_7.81_rb	4710009	689086	156.70	**1.35**	**1.9**	4710009	689087	156.49	154.68	**1.81**	0.46	-0.09
rk_8.9_rb	4709247	689407	163.04	**1.1**	**3.5**	4709248	689409	163.01	160.54	**2.47**	1.37	-1.03
rk_9.15_lb	4709051	689308	162.35	**0.4**	**1.44**	4709057	689301	164.24	161.94	**2.30**	1.90	0.86
rk_11.36_lb	4708908	687792	195.33	**1.51**	**2.3**	4708908	687792	197.66	195.65	**2.01**	0.50	-0.29
rk_12.40_rb	4709651	687199	201.70	**0.97**	**1.1**	4709651	687199	202.82	201.60	**1.22**	0.25	0.12
rk_12.46_rb	4709708	687168	204.63	**2.19**	**2.44**	4709708	687167	204.56	201.87	**2.68**	0.49	0.24
rk_12.59_rb	4709829	687147	203.95	**0.73**	**1.28**	4709829	687147	204.03	203.04	**0.99**	0.26	-0.29
rk_19.41_rb	4709047	682683	298.12	**0.45**	**1.01**	4709046	682682	298.24	297.82	**0.42**	-0.03	-0.59
rk_19.42_lb	4709072	682689	299.22	**0.48**	**2.5**	4709075	682689	300.36	297.64	**2.71**	2.23	0.21
rk_21.06_rb	4710244	682314	318.66	**0.7**	**1.31**	4710247	682313	318.66	317.55	**1.11**	0.41	-0.20
rk_22.32_rb	4711163	681964	353.69	**0.5**	**0.55**	4711163	681964	343.99	343.74	**0.25**	-0.25	-0.30
rk_22.45_lb	4711149	681900	345.55	**0.8**	**0.8**	4711150	681899	345.48	345.30	**0.18**	-0.62	-0.62
Minimum				**0.4**	**0.55**					**0.18**	-0.62	-1.03
Maximum				**2.19**	**3.5**					**2.71**	2.23	0.86
Average				**1.07**	**1.68**					**1.68**	0.61	0.00
Average deviation											57%	0%

Table 3.9. South River bank exposure locations with corresponding DEM thickness estimates from TerEx Toolbox, water surface datum and valley bottom datum methods. NA- not available data occurs where there was no data to compare field measured and DEM derived value.

Location	TerEx thickness (m)	Difference (TerEx-Historic thickness)	Difference (TerEx-total thickness)	Water surface datum (WSD) method thickness (m)	Difference (WSD-Historic thickness)	Difference (WSD-total thickness)	Valley bottom surface datum(VBSD) method thickness (m)	Difference (VBSD-Historic thickness)	Difference (VBSD-total thickness)
rk_4.78_rb	**5.90**	4.85	4.55	**2.05**	1.00	0.70	**0.72**	-0.33	-0.63
rk_5.35_rb	**7.30**	5.60	5.20	**2.76**	1.06	0.66	**2.28**	0.58	0.18
rk_5.94_rb	**8.10**	6.53	6.53	**1.87**	0.30	0.30	**1.57**	0.00	0.00
rk_7.53_lb	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
rk_7.81_rb	**1.10**	-0.25	-0.80	**1.65**	0.30	-0.25	**1.43**	0.08	-0.47
rk_8.9_rb	**2.90**	1.80	-0.60	**2.61**	1.51	-0.89	**2.00**	0.90	-1.50
rk_9.15_lb	**1.60**	1.20	0.16	**2.34**	1.94	0.90	**1.79**	1.39	0.35
rk_11.36_lb	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
rk_12.40_rb	**1.30**	0.33	0.20	**1.13**	0.16	0.03	**0.81**	-0.16	-0.29
rk_12.46_rb	**2.70**	0.51	0.26	**2.63**	0.44	0.19	**2.10**	-0.09	-0.34
rk_12.59_rb	**1.20**	0.47	-0.08	**1.15**	0.42	-0.13	**0.56**	-0.17	-0.72
rk_19.41_rb	**0.80**	0.35	-0.21	**0.20**	-0.25	-0.81	**0.01**	-0.44	-1.00
rk_19.42_lb	**2.70**	2.22	0.20	**2.34**	1.86	-0.16	**2.02**	1.54	-0.48
rk_21.06_rb	**0.20**	-0.50	-1.11	**1.17**	0.47	-0.14	**1.02**	0.32	-0.29
rk_22.32_rb	**0.90**	0.40	0.35	**0.88**	0.38	0.33	**0.09**	-0.41	-0.46
rk_22.45_lb	**0.42**	-0.38	-0.38	**0.90**	0.10	0.10	**0.86**	0.06	0.06
Minimum	**0.20**	-0.50	-1.11	**0.20**	-0.25	-0.89	**0.01**	-0.44	-1.50
Maximum	**8.10**	6.53	6.53	**2.76**	1.94	0.90	**2.28**	1.54	0.32
Average	**2.65**	1.65	1.02	**1.69**	0.69	0.06	**1.23**	0.23	-0.40
Average deviation		148%	58%		58%	1%		15%	-27%

The WSD method measurements average 69 cm greater (58%) than field estimates of legacy sediment thickness and 6 cm greater (1%) than total field-measured thicknesses from water surface to bank top (Figures 3.12C & G; Table 3.9). 79% of WSD method measurements agree within ±50% of field legacy sediment thickness measurements (Figure 3.12C) and 100% within ±50% of bank to water surface thickness measurements (Figure 3.12G).

The VBSD method measurements average 23 cm greater (15%) than field estimates of legacy sediment thickness. (Figure 3.12D; Table 3.9). The VBSD method measurements average 40 cm less (-27%) than the total field-measured sediment thickness, this is the only deviation that underestimated the field measurements (Figure 3.12H; Table 3.9). This method had the best results, with 93% of VBSD method measurements agree within ±50% of field legacy sediment thickness measurements (Figure 3.12D) and 100% within ±50% of bank to water surface thickness measurements (Figure 3.12H).

3.4.2 Sheepscot River Watershed

Field-measured legacy sediment thicknesses made in the Sheepscot River watershed from Strouse (2013), Hopkins (2014), and this study were compared with the equivalent measurements from lidar DEMs. The lidar DEM measurements average 42 cm greater (44%) than field-measured legacy sediment thickness (Figure 3.13A; Table 3.10). The lidar DEM thickness calculation are also compared to the total field-measured height from water surface to bank top, averaging 2 cm greater (7%) (Figure 3.13E; Table 3.10). The lidar DEM measurements estimate field-measured thickness accurately, with 94%

within ±50% of field legacy sediment thickness measurements (Figure 3.13A) and 100% within ±50% of bank to water surface thickness measurements (Figure 3.13E).

Thicknesses estimated at each field bank exposure were also compared to thicknesses derived from each legacy sediment volume method (Figure 3.13B-D & F-H). TerEx (Stout and Belmont, 2014) measurements average 65 cm greater (72%) than field-measured legacy sediment thickness and average 23 cm greater (28%) than total field-measured sediment thickness (Figure 3.13B & F; Table 3.11). 83% of TerEx measurements agree within ±50% of field legacy sediment thickness measurements (Figure 3.13B) and 92% within ±50% of bank to water surface thickness measurements (Figure 3.13F).

The WSD method measurements average 86 cm greater (103%) than field-measured legacy sediment thickness and average 41 cm greater (51%) than total field-measured sediment thickness. (Figure 3.13C & G; Table 3.11). This method was the most variable for the Sheepscot River watershed but 72% of WSD methods measurements agree within ±50% of field legacy sediment thickness measurements (Figure 3.13C) and 92% agree within ±50% of bank to water surface thickness measurements (Figure 3.13G).

The VBSD method measurements average 36 cm less (-15%) than field-measured legacy sediment thickness and average 83 cm less (-36%) than total field-measured sediment thickness (Figure 3.13D & H; Table 3.11). 90% of VBSD method measurements agree within ±50% of field legacy sediment thickness measurements (Figure 3.13D) and 85% within ±50% of bank to water surface thickness measurements (Figure 3.13H).

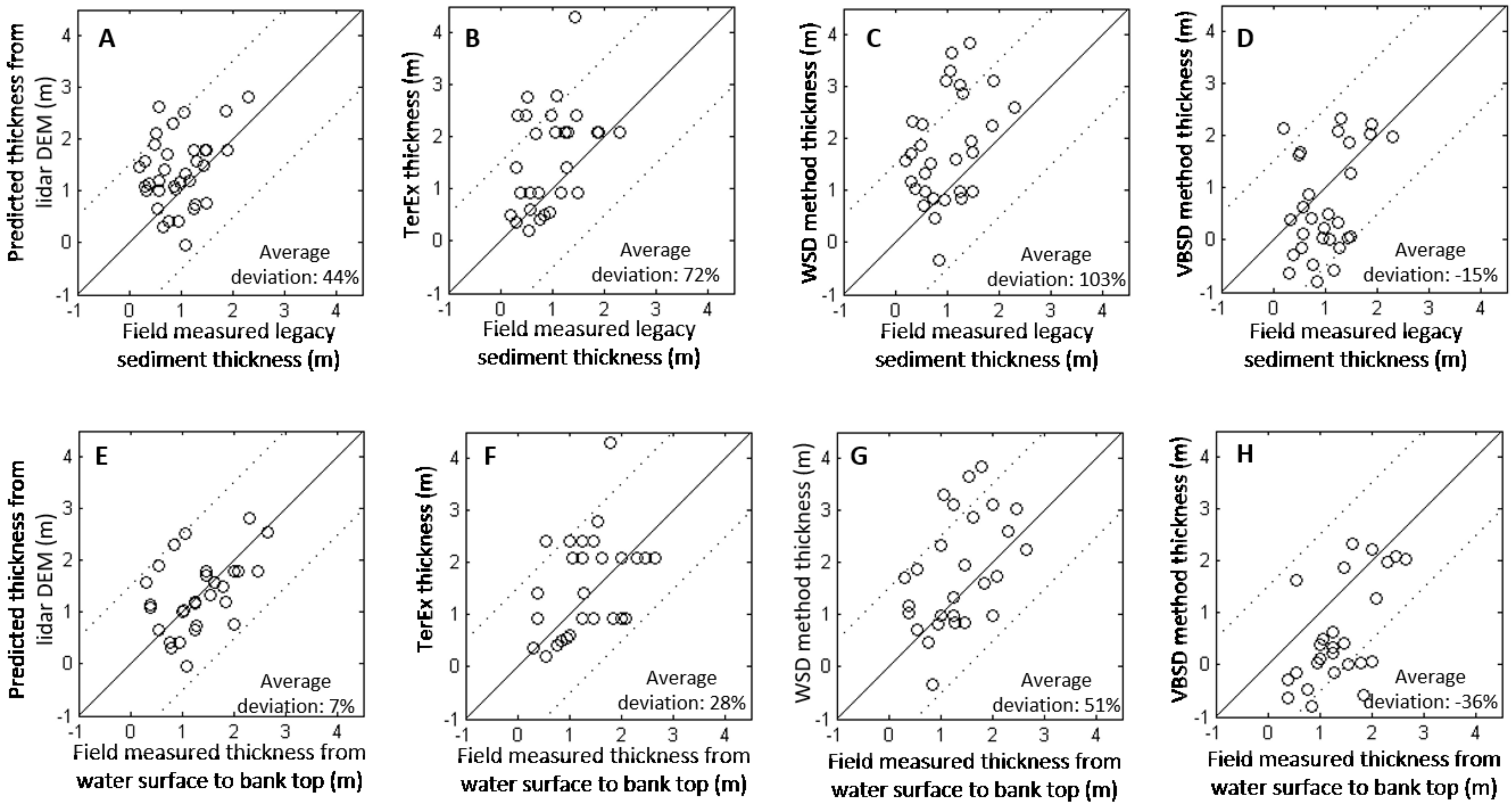

Figure 3.13. Comparisons between field measurements and coincident thicknesses estimated from lidar DEMs at bank exposures along the main stem and West Branch Sheepscot River (Figure 3.3). A-D compare field legacy sediment thickness and lidar DEM terrace thickness measurements. E-H compare field measured height from water surface to bank top and lidar DEM terrace thickness measurements. The black lines represent a 1:1 ratio and dashed lines represent a 1:1.5 and 1.5:1 ratio.

Table 3.10. Sheepscot River watershed bank exposure data with corresponding DEM thickness estimates. NA- not available data occurs where there was no data about water surface.

Location	Northing gps	Easting gps	GPS Elevation (m)	Field historic thick-ness (m)	Field total thick-ness (m)	DEM easting	DEM northing	DEM point elevation (m)	DEM river elevation (m)	DEM thickness (m)	Difference (DEM-Historic thickness)	Difference (DEM-total thickness)
Head tide dam (Hopkins)												
rk_10.61_lbank	4884943	449968	5.8	**1.29**	**1.29**	449966	4884945	7.4	6.6	**0.74**	-0.55	-0.55
rk_10.62_rbank	4884935	449938	6.1	**1.26**	**1.26**	449938	4884935	7.3	6.7	**0.66**	-0.60	-0.60
rk_10.8_rtrib	4885028	449822	7.9	**1.3**	**1.64**	449824	4885026	9.6	8.0	**1.57**	0.27	-0.07
rk_10.8_rtrib2	4885021	449814	8.4	**1.25**	**2.46**	449814	4885020	9.7	7.9	**1.79**	0.54	-0.67
rk_10.8_rtrib3	4885010	449772	9.0	**1.06**	**1.06**	449772	4885010	10.1	7.6	**2.52**	1.46	1.46
rk_10.8_rtrib4	4885002	449752	10.0	**1.43**	**1.8**	449752	4885001	10.3	8.8	**1.50**	0.07	-0.30
rk_10.8_rtrib5	4884990	449688	9.4	**1.09**	**1.54**	449687	4884990	10.4	9.1	**1.34**	0.25	-0.20
rk_10.9_lbank	4885113	449745	6.9	**1.47**	**1.47**	449745	4885115	9.0	7.2	**1.78**	0.31	0.31
rk_11_island1	4885198	449672	7.7	**0.58**	**1.26**	449672	4885198	8.4	7.2	**1.20**	0.62	-0.06
rk_11_island2	4885185	449674	7.8	**0.73**	**1.46**	449674	4885185	8.5	6.8	**1.71**	0.98	0.25
rk_11.2_ltrib	4885365	449608	9.5	**0.98**	**1.25**	449610	4885365	10.6	9.4	**1.16**	0.18	-0.09
rk_11.2_ltrib2	4885336	449596	9.5	**0.34**	**1**	449596	4885336	9.8	8.8	**1.01**	0.67	0.01
rk_11.2_island	4885355	449517	8.5	**0.58**	**1**	449518	4885355	8.5	7.5	**1.01**	0.43	0.01
rk_11.48_soilpit	4885559	449506	10.9	**0.58**	**NA**	449506	4885559	10.9	8.3	**2.63**	2.05	NA
Head tide dam (Johnson)												
rk_10.75_lb	4885009	449885	6.6	**0.9**	**1.04**	449891	4885016	7.7	6.6	**1.05**	0.15	0.01
rk_10.8_rtrib	4885016	449819	9.3	**1.9**	**2**	449815	4885020	9.7	7.9	**1.78**	-0.12	-0.22
rk_10.8_rtrib2	4885026	449819	7.9	**2.3**	**2.3**	449819	4885026	9.4	6.6	**2.81**	0.51	0.51
rk_11.0_islandL	4885183	449675	4.3	**1.5**	**2.1**	449674	4885183	8.6	6.8	**1.79**	0.29	-0.31
rk_11.1_islandL	4885171	449673	8.6	**1.5**	**2**	449673	4885171	7.9	7.1	**0.77**	-0.73	-1.23
rk_11.1_islandR	4885181	449641	8.1	**1.16**	**1.85**	449648	4885186	8.5	7.3	**1.20**	0.04	-0.65

Table 3.10. Sheepscot River watershed bank exposure data with corresponding DEM thickness estimates - Continued

Location	Northing gps	Easting gps	GPS Elevation (m)	Field historic thick-ness (m)	Field total thick-ness (m)	DEM easting	DEM northing	DEM point elevation (m)	DEM river elevation (m)	DEM thickness (m)	Differenc e (DEM-Historic thickness)	Difference (DEM-total thickness)
Head tide dam (Strouse)												
rk_10.6_soilpit	4884940	449979	7.8	**0.3**	**0.4**	449979	4884940	7.8	6.7	**1.10**	0.80	0.70
rk_10.75_rb	4885022	449840	9.1	**1.87**	**2.65**	449842	4885025	9.2	6.7	**2.54**	0.67	-0.11
rk_10.9_soilpit	4885117	449754	8.8	**0.5**	**0.56**	449754	4885117	8.8	6.9	**1.91**	1.41	1.35
rk_11.0_soilpit	4885164	449671	8.2	**0.4**	**0.4**	449671	4885164	8.2	7.0	**1.14**	0.74	0.74
Other main stem (Johnson)												
rk_19.7_rb	4892491	449980	25.4	**0.95**	**0.95**	449978	482492	27.9	27.5	**0.41**	-0.54	-0.54
rk_23.0_rb	4894896	450467	28.7	**1.1**	**1.1**	450467	4894896	28.8	28.9	**-0.05**	-1.15	-1.15
Youngs dam (Johnson)												
rk_26.3_rb	4896508	452498	30.2	**0.65**	**0.8**	452498	4896508	30.0	29.7	**0.30**	-0.35	-0.50
Pinhook dam (Hopkins)												
rk_0.58_Rsoilpit	453976	4899250	41.7	**0.68**	**NA**	453973	4899249	42.4	41.0	**1.43**	0.75	NA
rk_0.71_Lsoilpit	453880	4899324	42.9	**0.885**	**NA**	453880	4899326	43.2	42.1	**1.09**	0.20	NA
rk_0.75_Lsoilpit	453885	4899351	44.8	**0.51**	**NA**	453885	4899353	44.8	42.7	**2.11**	1.60	NA
Maxcy's Mills (Strouse)												
rk_8.6_soilpit	4904689	454737	49.5	**0.76**	**0.76**	454737	4904689	49.5	49.1	**0.43**	-0.33	-0.33
rk_8.9_soilpit	4904880	454587	50.3	**0.3**	**0.3**	454591	4904879	50.6	49.1	**1.58**	1.28	1.28
rk_9.5_soilpit	4905257	454850	51.3	**0.2**	**NA**	454845	4905233	50.7	49.3	**1.47**	1.27	NA
rk_9.5_	4905233	454843	50.6	**0.86**	**0.86**	454852	4905257	51.6	49.2	**2.32**	1.46	1.46
rk_9.7_soilpit	4905362	454892	50.3	**0.54**	**0.54**	454890	4905366	50.3	49.6	**0.66**	0.12	0.12
Minimum				**0.2**	**0.3**					**-0.05**	-1.15	-1.23
Maximum				**2.3**	**2.65**					**2.81**	2.05	1.46
Average				**0.96**	**1.29**					**1.38**	0.42	0.02
Average deviation											44%	7%

Table 3.11. Sheepscot River watershed bank exposure locations with corresponding DEM thickness estimates from TerEx Toolbox, water surface datum and valley bottom datum methods. NA- not available data occurs where there was no data to compare field measured and DEM derived value and when there was no data about water surface.

Location	TerEx thickness (m)	Difference (TerEx-Historic thickness)	Difference (TerEx-total thickness)	Water Surface Datum (WSD) Method thickness (m)	Difference (WSD-Historic thickness)	Difference (WSD-total thickness)	Valley Bottom Surface Datum (VBSD) method thickness (m)	Difference (VBSD-Historic thickness)	Difference (VBSD-total thickness)
Head tide dam (Hopkins)									
rk_10.61_lbank	**1.40**	0.11	0.11	**0.86**	-0.43	-0.43	**-0.14**	-1.43	1.43
rk_10.62_rbank	**2.10**	0.84	0.84	**0.99**	-0.27	-0.27	**0.34**	-0.92	0.92
rk_10.8_rtrib	**2.10**	0.80	0.46	**2.86**	1.56	1.22	**2.32**	1.02	-0.68
rk_10.8_rtrib2	**2.10**	0.85	-0.36	**3.02**	1.77	0.56	**2.1**	0.85	0.36
rk_10.8_rtrib3	**2.10**	1.04	1.04	**3.29**	2.23	2.23	**0.49**	-0.57	0.57
rk_10.8_rtrib4	**4.30**	2.87	2.50	**3.84**	2.41	2.04	**0.05**	-1.38	1.75
rk_10.8_rtrib5	**2.80**	1.71	1.26	**3.64**	2.55	2.10	**0.01**	-1.08	1.53
rk_10.9_lbank	**2.40**	0.93	0.93	**1.96**	0.49	0.49	**1.87**	0.40	-0.40
rk_11_island1	**0.94**	0.36	-0.32	**1.33**	0.75	0.07	**0.62**	0.04	0.64
rk_11_island2	**0.94**	0.21	-0.52	**0.84**	0.11	-0.62	**0.41**	-0.32	1.05
rk_11.2_ltrib	**2.40**	1.42	1.15	**3.10**	2.12	1.85	**0.22**	-0.76	1.03
rk_11.2_ltrib2	**2.40**	2.06	1.40	**2.32**	1.98	1.32	**0.38**	0.04	0.62
rk_11.2_island	**0.61**	0.03	-0.39	**0.98**	0.40	-0.02	**0.13**	-0.45	0.87
rk_11.48_soilpit	**3.20**	2.62	NA	**2.74**	2.16	NA	**0.41**	-0.17	NA
Head tide dam (Johnson)									
rk_10.75_lb	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
rk_10.8_rtrib	**2.10**	0.20	0.10	**3.1**	1.20	1.10	**2.22**	-0.32	0.22
rk_10.8_rtrib2	**2.10**	-0.20	-0.20	**2.61**	0.31	0.31	**1.99**	0.31	-0.31
rk_11.0_islandL	**0.94**	-0.56	-1.16	**1.74**	0.24	-0.36	**1.28**	0.22	-0.82
rk_11.1_islandL	**0.94**	-0.56	-1.06	**0.97**	-0.53	-1.03	**0.06**	1.44	-1.94
rk_11.1_islandR	**0.94**	-0.22	-0.91	**1.59**	0.43	-0.26	**-0.58**	1.74	-2.43

Table 3.11. Sheepscot River watershed bank exposure locations with corresponding DEM thickness estimates from TerEx Toolbox, water surface datum and valley bottom datum methods - Continued

Location	TerEx thickness (m)	Difference (TerEx-Historic thickness)	Difference (TerEx-total thickness)	Water surface datum (WSD) method thickness (m)	Difference (WSD-Historic thickness)	Difference (WSD-total thickness)	Valley bottom surface datum (VBSD) method thickness (m)	Difference (VBSD-Historic thickness)	Difference (VBSD-total thickness)
Head tide dam (Strouse)									
rk_10.6_soilpit	**1.40**	1.10	1.00	**1.17**	0.87	0.77	**-0.63**	-0.93	-1.03
rk_10.75_rb	**2.10**	0.23	-0.55	**2.26**	0.39	-0.39	**2.03**	0.16	-0.62
rk_10.9_soilpit	**2.40**	1.90	1.84	**1.87**	1.37	1.31	**1.64**	1.14	1.08
rk_11.0_soilpit	**0.94**	0.54	0.54	**1.03**	0.63	0.63	**-0.28**	-0.68	-0.68
Other main stem (Johnson)									
rk_19.7_rb	**0.56**	-0.39	-0.39	**0.81**	-0.14	-0.14	**0.03**	-0.92	-0.92
rk_23.0_rb	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
Youngs dam (Johnson)									
rk_26.3_rb	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
Pinhook dam (Hopkins)									
rk_0.58_Rsoilpit	**2.06**	1.38	NA	**1.51**	0.83	NA	**0.87**	0.19	NA
rk_0.71_Lsoilpit	**NA**	NA	NA	**NA**	NA	NA	**NA**	NA	NA
rk_0.75_Lsoilpit	**2.77**	2.26	NA	**2.27**	1.76	NA	**1.69**	1.18	NA
Maxcy's Mills (Strouse)									
rk_8.6_soilpit	**0.42**	-0.34	-0.34	**0.48**	-0.28	-0.28	**-0.48**	-1.24	-1.24
rk_8.9_soilpit	**0.36**	0.06	0.06	**1.71**	1.41	1.41	**-1.25**	-1.55	-1.55
rk_9.5_soilpit	**0.49**	0.29	NA	**1.51**	1.31	NA	**2.15**	1.95	NA
rk_9.5_	**0.49**	-0.37	-0.37	**-0.34**	-1.20	-1.20	**-0.80**	-1.66	-1.66
rk_9.7_soilpit	**0.20**	-0.34	-0.34	**0.70**	0.16	0.16	**-0.15**	-0.69	-0.69
Minimum	**0.20**	-0.56	-1.16	**0.51**	-1.20	-1.20	**-0.63**	-1.74	-2.43
Maximum	**4.30**	2.87	2.50	**3.84**	2.55	2.23	**2.32**	1.95	1.08
Average	**1.65**	0.65	0.23	**1.95**	0.86	0.47	**0.82**	-0.36	-0.83
Average deviation		72%	28%		103%	51%		-15%	-36%

3.4.3 Interpretations of Sediment Thickness Measurements

All lidar-derived thickness measurements have lower average deviations when compared to field-measured sediment thicknesses from bank top to water surface than compared to field-measured legacy sediment (expect for the Sheepscot River watershed VBSD method comparison; Figure 3.12 & 3.13; Table 3.8-3.11). In the South River watershed, 100% of the points agree within 50% for three of the comparisons between lidar-derived and total field-measured sediment thicknesses, validating the use of these methods (the lidar DEM measurements, WSD method, and VBSD method; Table 3.8 & 3.9). Lidar-derived thickness measurements overestimate the field-measured legacy sediment for the TerEx and WSD methods in both watersheds; this is not surprising because at many of the exposures the base of the legacy sediment observed in the field is above the water surface. The remaining field measurements that are made are minima because the unit underlying the legacy sediment was not exposed. In the South River watershed the TerEx (Stout and Belmont, 2014) method produced the highest average deviation (148%) when compared to field-measured legacy sediment and 64% of these points agree within 50% (Figure 3.12C; Table 3.9). In the Sheepscot River watershed the WSD method produced the highest average deviation (103%) when compared to field-measured legacy sediment; 72% of these points agree within 50% (Figure 3.13C; Table 3.11). The VBSD method has the lowest average deviations when compared to field-measured legacy sediment (15% in the South River watershed and -15% in Sheepscot River watershed) and therefore is the best datum surface for thickness calculations (Figure 3.12D & Figure 3.13D; Table 3.9 & Table 3.11). The WSD method and TerEx method produce maximum volume estimates for each watershed.

3.5 Legacy Sediment Volume Calculations

3.5.1 South River Watershed

Legacy sediment volumes throughout each watershed were estimated using three different methods: the water surface datum (WSD), valley bottom surface datum (VBSD), and TerEx Toolbox (Figures 2.3, 3.14 & 3.15). The terraces mapped with the TerEx Toolbox were used for thickness and volumes calculations for the WSD and VBSD methods. The WSD method is a maximum volume estimate and the VBSD method provides a minimum volume estimate of legacy sediment in each watershed (Table 3.12 & 3.13). The VBSD method produced some negative thickness values along the edges of terraces and these values were changed to zero. These negative cells resulted from the sloping datum that interpolates over localized low points in topography and produce a negative thickness value when subtracted (Hopkins, 2014).

Along the main stem of the South River the volume of sediment estimated by the WSD method is 2.3 x 10^6 m^3 and by the VBSD method is 7.6 x 10^5 m^3 (Table 3.12). Using the WSD and VBSD methods along the tributaries of the South River as well, legacy sediment volumes are estimated to be 1.7 x 10^5 m^3 and 5.8 x 10^4 m^3, respectively (Table 3.12). This results in a total of 2.5 x 10^6 m^3 of legacy sediment estimated using the WSD method and 8.2 x 10^5 m^3 estimated using the VBSD method for the South River watershed.

Table 3.12. Comparison of volume estimates for the South River watershed.

	TerEx Toolbox method volume (m^3)	Water surface datum method volume (m^3)	Valley bottom surface datum method volume (m^3)
Main stem	2.2×10^6	2.3×10^6	7.6×10^5
Tributaries	2.9×10^5	1.7×10^5	5.8×10^4
Total	2.5×10^6	2.5×10^6	8.2×10^5
Mean volume 1.9×10^6			
Standard deviation 7.9×10^5			

TerEx (Stout and Belmont, 2014) was created primarily to map terraces and floodplains but it can be used to provide thickness estimates. As part of TerEx, the stream channel is split into reach lengths defined by the user and all mapped terraces are assigned to the closest channel reach. The average thickness of each river segment is subtracted from the average thickness of each mapped terrace and a volume of sediment can be estimated by multiplying each given terrace area by the average thickness for each terrace polygon. Examples of thickness assigned to terrace polygons along the South River are shown in Figure 3.14 A, D, & G. The TerEx estimated volume of sediment along the South River is 2.2×10^6 m^3 and 2.9×10^5 m^3 for the tributaries; for a total of 2.5×10^6 m^3 (Table 3.12).

The total volume of legacy sediment stored in terraces can be divided by watershed area to estimate an average thickness of sediment eroded from the landscape, assuming that densities are equal. For the South River watershed, I estimate an average thickness of ~37 mm of sediment eroded from the landscape that is stored in valley bottom deposits using the TerEx and WSD method, as compared to 12 mm using the VBSD method.

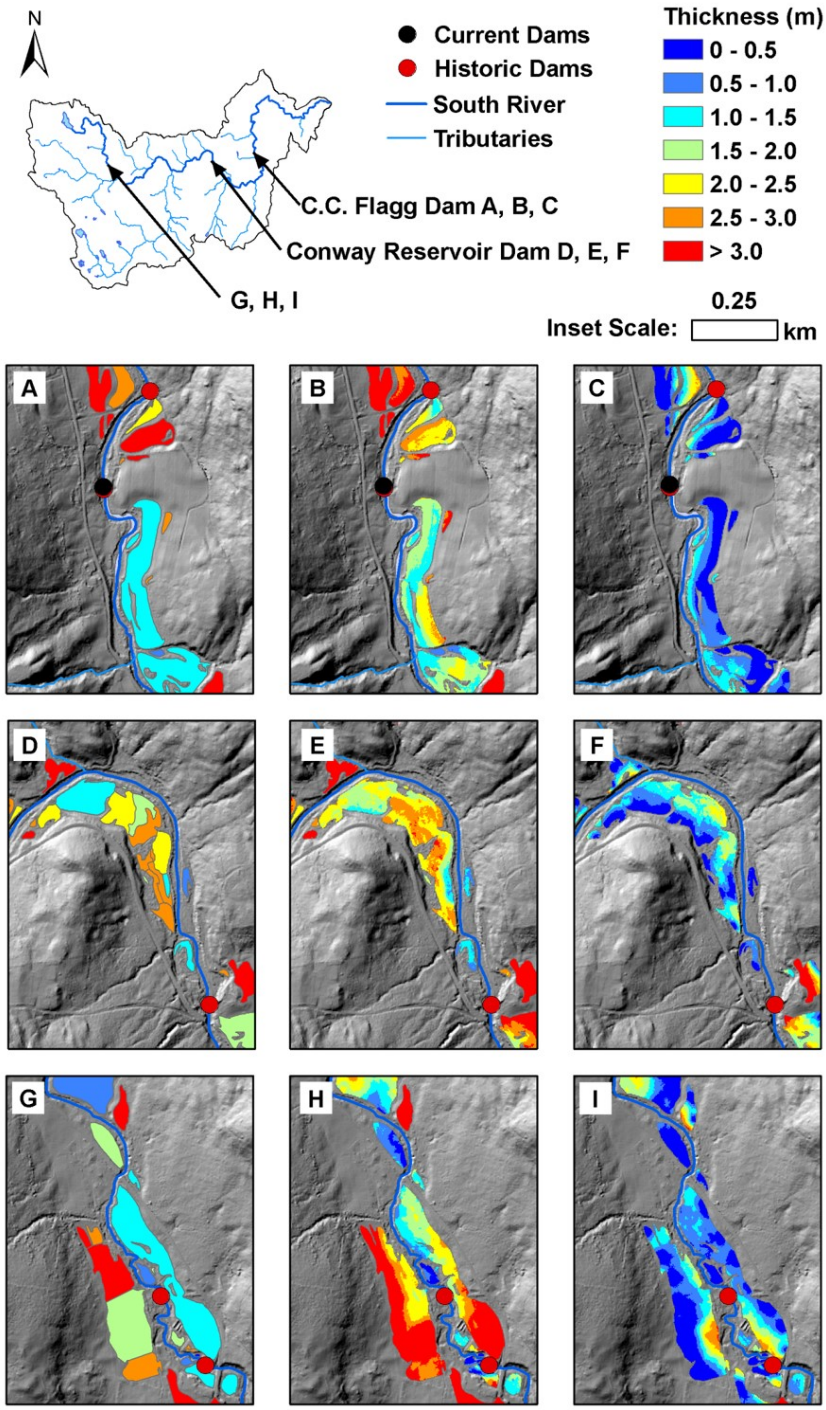

Figure 3.14. Legacy sediment thickness maps for the C.C. Flag Dam (A, B, C) area, Conway Reservoir (D, E, F) area, and the area near two unnamed historic dams north of South Ashfield (G, H, I) in the South River watershed. Calculations were done by the Terex Toolbox method (A, D, G), water surface datum (WSD) method (B, E, H), and valley bottom surface datum (VBSD) method (C, F, I). Base map is hillshade image from the lidar DEM.

3.5.2 Sheepscot River Watershed

Along the Sheepscot main stem and West Branch legacy sediment estimated by WSD method is 2.7 x 10^6 m^3 and by the VBSD method is 8.7 x 10^5 m^3 (Table 3.13). Along the tributaries legacy sediment volumes estimated using the WSD and VBSD methods are estimated to be 1.0 x 10^6 m^3 and 2.8 x 10^5 m^3, respectively; resulting in a total of 3.7 x 10^6 m^3 of legacy sediment estimated using the WSD method and 1.2 x 10^6 m^3 estimated using the VBSD method (Table 3.13).

TerEx (Stout and Belmont, 2014) was used to estimate volumes of legacy sediment stored in the Sheepscot River as well (Figure 3.15A, D, & G). This resulted in an estimated volume of 2.56 x 10^6 m^3 for the main stem and West Branch and 1.11 x 10^6 m^3 for the tributaries; for a total estimate of 3.67 x 10^6 m^3 (Table 3.13).

The average sediment thickness eroded from the watershed were then estimated using the total legacy sediment volume for each method of volume estimated. The average thickness estimate 7 mm of sediment eroded from the landscape that is still stored in valley bottom deposits today using the TerEx Toolbox and WSD methods, and 2 mm using the VBSD method.

Table 3.13. Comparison of volume estimates for the Sheepscot River watershed.

	TerEx Toolbox method volume (m^3)	**Water surface datum method volume (m^3)**	**Valley bottom surface datum method volume (m^3)**
Main stem and West Branch	2.6 x 10^6	2.7 x 10^6	8.7 x 10^5
Tributaries	1.1 x 10^6	1.0 x 10^6	2.8 x 10^5
Total	3.7 x 10^6	3.7 x 10^6	1.2 x 10^6
Mean volume 2.9 x 10^6			
Standard deviation 1.2 x 10^6			

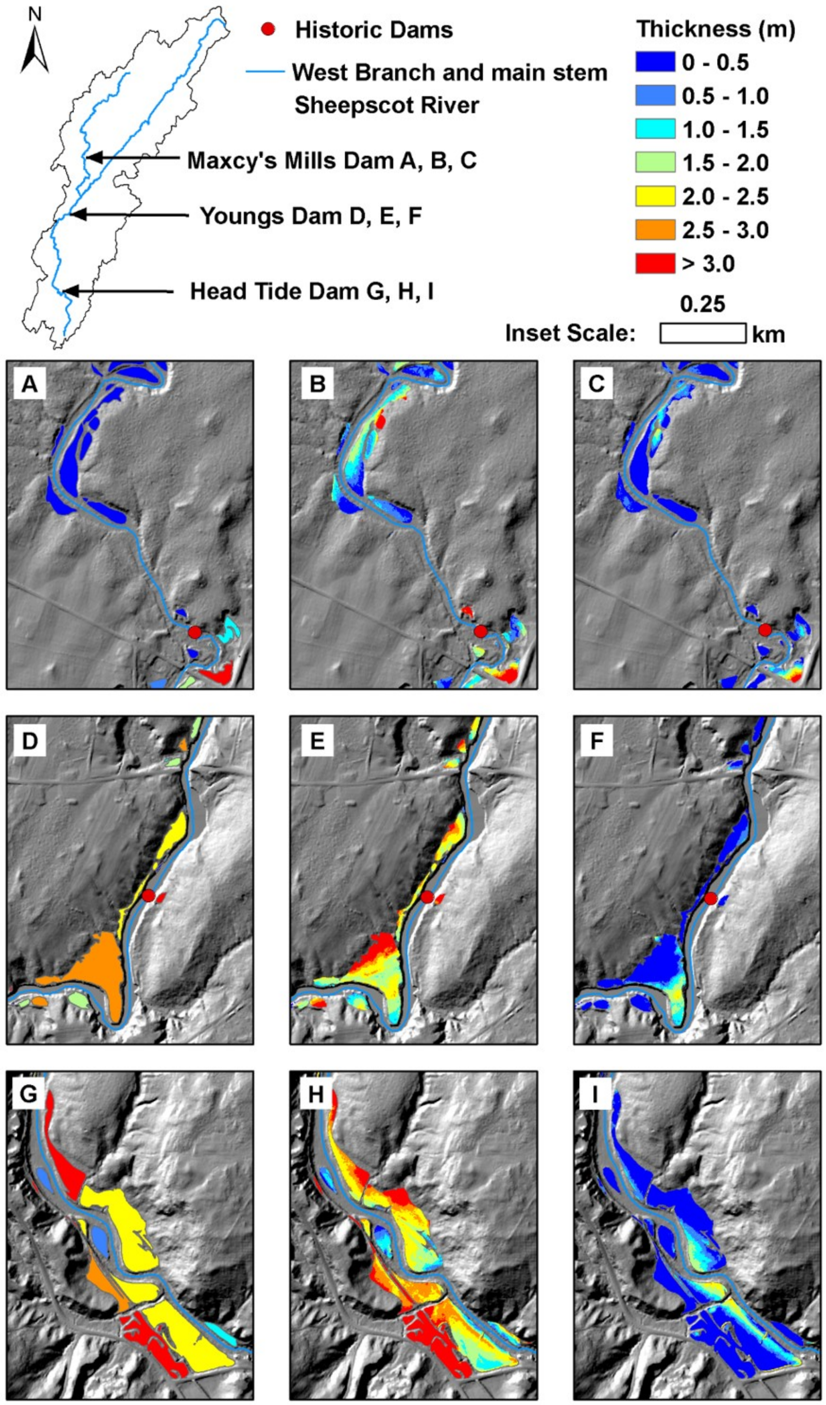

Figure 3.15. Legacy sediment thickness maps for the Maxcy's Mills Dam (A, B, C), Youngs Dam (D, E, F), and Head Tide Dam (G, H, I) areas of the Sheepscot River watershed. Calculations were done by the Terex Toolbox method (A, D, G), water surface datum (WSD) method (B, E, H), and valley bottom surface datum (VBSD) method (C, F, I). Base map is hillshade image from the lidar DEM.

3.5.3 Interpretations of Sediment Volume Calculations

All methods were effective in producing volume estimates. The TerEx method and WSD method produced similar volume estimates and the VBSD produced a minimum volume estimate for each watershed (Figure 3.14 & 3.15; Table 3.9 & 3.11). The mean volume for the South River Watershed is 1.9 x 10^6 m^3, and 2.9 x 10^6 m^3 for the Sheepscot River watershed (Tables 3.12 & 3.13). The standard deviation of the total volumes of legacy sediment is 7.9 x 10^5 m^3 for the South River watershed and 1.2 x 10^6 m^3 for Sheepscot River watershed (Tables 3.12 & 3.13).

Hopkins (2014) mapped terraces and quantified thicknesses and volumes of legacy sediment in the Sheepscot River watershed. For the main stem and West Branch, Hopkins (2014) used the feature classification method developed by Wood (1996) to map a total terrace area of 3.1 x 10^6 m^2 compared to the 1.0 x 10^6 m^2 I delineated (Figure 3.3). To illustrate the original output from this method Hopkins (2014) did not make edits to the terrace polygons. The larger area could be related to the generally flatter landscape of the West Branch Sheepscot River, as discussed by Hopkins (2014). The TerEx (Stout and Belmont, 2014) method used in this study has a user input that defines the width of the valley and this likely constrained the area defined by TerEx method accounting for some of the differences between the two values.

This study uses two of the same methods to determine volume estimates of legacy sediment. Hopkins (2014) estimated 1.9 x10^6 m^3 of legacy sediment stored behind 11 dams using the water surface datum (WSD) method and 1.2 x 10^6 m^3 using the valley bottom surface datum (VBSD) method along the main stem and West Branch of the Sheepscot River. I estimated legacy sediment behind the entire length of the main stem and West Branch resulting in a higher volume estimate of 2.7×10^6 m^3 using the WSD method but a slightly smaller volume estimate of 8.7×10^5 m^3 using the VBSD method (Table 3.13).

4 DISCUSSION

4.1 Comparison of Legacy Sedimentation in the South River and Sheepscot River Watersheds

The 68 km^2 South River watershed had a milldam density of 0.49 milldams/km^2 in the mid-19th century (Figure 1.2B; Table 3.1). Fourteen of 18 historic dams visited show evidence for legacy sediment with an observed range of 0.4-2.19 m of legacy sediment and an average thickness of 1.07 m (Table 3.1 & 3.8). The larger 558 km^2 Sheepscot River watershed had a milldam density of 0.08 milldams/km^2 (Figure 1.2C; Table 3.2). Of the 13 historic dam sites visited, there is likely legacy sediment at six. Legacy sediment ranges from 0.2-2.3 m thick with an average thickness of 0.96 m (Tables 3.2 & 3.10). Total volumes of legacy sediment estimated using DEM methods can be translated to a thickness range of sediment eroded from each landscape: 12-37 mm for the South River watershed and 2-7 mm for the Sheepscot River watershed. The South River watershed has more evidence of legacy sediment, which could be due to differing land use history, geomorphology and glacial geology.

Both watersheds have undergone extensive changes in land use over the past two centuries. By 1830, 92.4% of the South River watershed was cleared for dairy, sheep, and crop production, but as of 2005, 79.9% of the watershed was forested, and only 6.0% is cropland and 4.5% is pasture (Pease, 1917; MHC Ashfield, 1982; MHC Conway, 1982; Foster and Motzkin, 2009; MssGIS; Table 1.1; Figure 1.6). Similarly, the Sheepscot River watershed had many forests cleared for agriculture beginning in the late 18th century (Laser et al., 2009), and timber was an important industry in this region, using the rivers to transport logs to sawmills. Today the watershed is 89% covered by second growth forests (Halsted, 2002; Brady, 2007; Laser et al., 2009; SVCA, 20011). The overall similarity in land-use history suggests that this is not a major factor in causing the difference in legacy sediment storage in the two study watersheds.

Both watersheds have glacial deposits that are a likely source of legacy sediment. Surficial geology mapped at a scale of 1:24,000 for each watershed was used to determine glacial deposits (>5 m thick) that could contribute to legacy sediment, as opposed to thinner till deposits and exposed bedrock that are the surficial materials elsewhere in the watersheds. Glacial deposits are mapped in 14.2% of the South River watershed (13.9% coarse glacial stratified deposits and 0.3% thick till; MassGIS; Figure 4.1A). Most of the watershed is mapped as thin till with some deposits of early postglacial stream terrace deposits, postglacial alluvium, and swamp and marsh deposits found along the South River and its tributaries (MassGIS). The upper portion of the Sheepscot River watershed has not been mapped for surficial geology at this scale, but the portion of the watershed that has been mapped contains 5.1% glacial deposits (Maine Geological Survey; Figure 4.1B). These deposits include glaciomarine fans, glaciomarine deltas, ice-contact deposits, eskers, marine nearshore deposits, and end moraines. Other surficial deposits mapped in the watershed include till, the Presumpscot Formation, stream terrace and alluvium deposits, and wetland deposits. The Presumpscot Formation is 34.4% of the mapped area and is predominately a clay deposit. This formation would contribute clay-sized particles to the stream when eroded and therefore it would not be deposited in millponds but act as wash load in the river. Legacy deposits consist typically of silt and fine sand (Strouse 2013; Appendix 2).

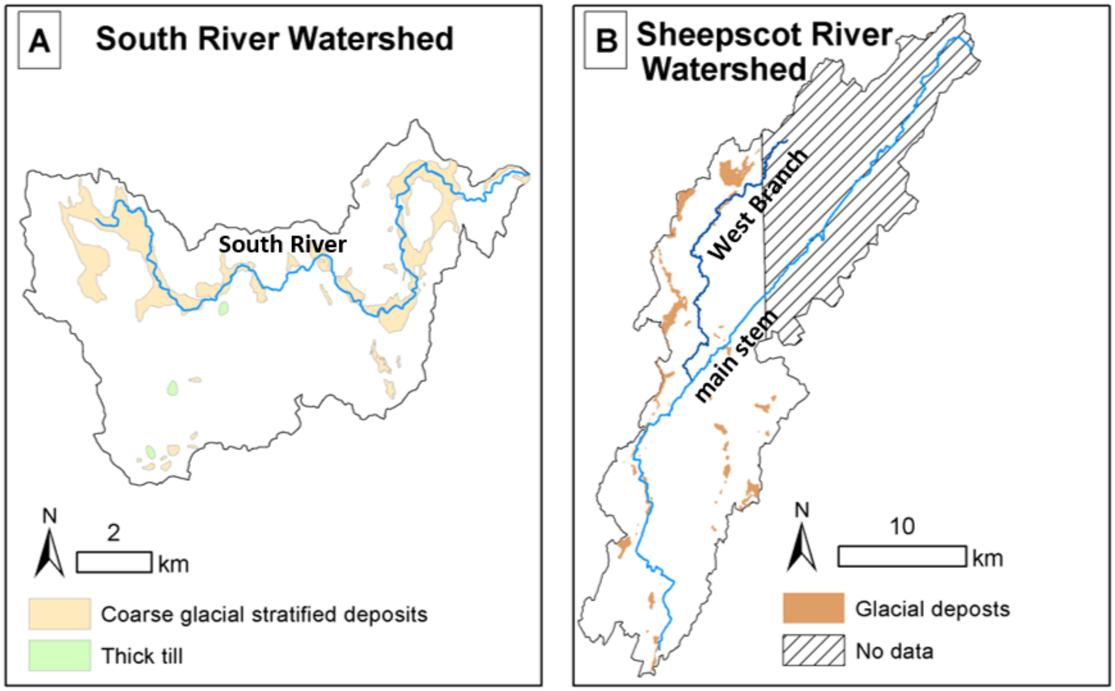

Figure 4.1. Mapped surficial glacial geology from MassGIS for the South River watershed (A) and Maine Geological Survey for part of the Sheepscot River watershed (B).

The average gradient of the South River is 0.013 m/m (Figure 3.4; Field, 2013). This river has a few confined areas where steep valley walls are composed of glacial material, and at the confluence with the Deerfield River the valley is 40 m deep and confined by bedrock walls (Field, 2013). Other sections of the river are still recovering from a straightened and dammed history and are beginning to meander across floodplains when space is available. The South River longitudinal profiles show that in some areas the terraces appear to be steeper than the current channel (Figure 3.4B & C). This could be interpreted as higher sediment load at the time of deposition. As forests were clear cut, upland soil erosion accelerated, increasing sediment loads in rivers (Merritts et al., 2011), but as forests have regrown the sediment supply decreased. The average gradient of the

Sheepscot River is 0.0016 m/m and the longitudinal profile shows a series of steps where there are long low-gradient sections broken up by short high gradient steps (Figure 3.5). The low-gradient reaches include lakes, wetlands, and areas where the water is slow-flowing; these sections are sediment sinks (Snyder et al., 2013). The high gradient segments are controlled by bedrock outcrops and/or glacial deposits.

In the Sheepscot River watershed most legacy sediment terraces are in the lower section, downstream of eroding glacial deposits (Figures 3.3 & 3.5). Upstream, lakes and wetlands act as sinks for bedload transport and few legacy sediment terraces are found. The South River watershed has few lakes and wetlands, and these are found in the uppermost areas of the watershed (Figure 3.1). With more widespread supply of coarse, thick glacial deposits and fewer natural sediment traps, the South River watershed has more legacy sediment stored in the valley bottom than the Sheepscot River watershed.

4.2 Comparison with Observations of Legacy Sediment in the Mid-Atlantic Region

In the Mid-Atlantic region, Walter and Merritts (2008) describe a typical valley-bottom stratigraphic profile: a thick, 1-5 m, brown fine sand and silt layer on top (interpreted to be legacy sediment), a middle 0.5-1 m dark organic-rich silt loam and a bottom <0.5 m angular to subangular gravel above bedrock. The dark organic-rich silt loam is interpreted to be a buried hydric (wetland) soil. It includes wood, seeds, nuts, roots, and tree stumps, and this material has been radiocarbon dated to ages ranging from 11,240 to 300 years before the present, suggesting the soils accumulated in the Holocene epoch (Walter and Merritts, 2008).

In New England, I have observed 0.2-2.3 m of brown fine sand and silt legacy sediment deposits underlain by several different units, including rounded gravel and cobbles, which I interpret to be the pre-dam river bed (Table 3.8 & 3.10; Figure 3.7 & 3.9; Appendix 2). I have also observed legacy sediment overlying clay (the Presumpscot Formation in the Sheepscot River and glacial lake deposits in the South River watershed; Figure 3.10; Appendix 2). Legacy sediment has also been observed to overlay cut wood planks in at least two places in the Sheepscot River watershed (Figure 3.11). No radiocarbon date has been observed with a Holocene age in the South River watershed. Previous work by Strouse (2013) observed two radiocarbon dates with a Holocene age in the Sheepscot River watershed (Table 3.6 & 3.7). At both locations a stratigraphically lower sample recorded a younger date, constraining the date of the entire deposit.

No buried Holocene wetland or floodplain soil has been observed in either New England watershed. This could mean that the rivers have not eroded to these surfaces yet at locations where the likely older cobble or clay layer has not been observed. Alternatively, in the relatively short time since glaciation, the buried floodplain soil may have been thin and/or not well developed, making it hard to observe in bank exposures. Some study sites have legacy sediment overlying rounded gravel and cobbles, which is likely the pre-dam river bed.

This study has demonstrated a quantitative comparison between two New England watersheds and could serve as a method to compare watersheds in the Mid-Atlantic and New England regions. Further understanding of the sedimentation of valley-bottoms in the northeastern United States would result from quantitatively comparing milldam density, legacy sediment thicknesses measurements from field and DEM lidar analysis, radiocarbon dating, and legacy-sediment terrace mapping and volume calculations between these two regions.

5 SUMMARY AND CONCLUSIONS

Both study watersheds have been heavily influenced by human activity, particularly through land-use changes, dam building and breaching (Figures 1.2, 1.6, & 2.1). Detailed field analyses have been done to identify the effects of dam building at several locations along the Sheepscot River, ME (Strouse, 2013; Hopkins 2014; Hopkins and Snyder, 2016) and preliminary analyses along the South River, MA have identified historic dams and legacy sediment (Field, 2013). This study expanded on these observations to quantify extent and volume of legacy sediment throughout each watershed through a combination of field and DEM-based analysis.

TerEx Toolbox (Stout and Belmont, 2014) was successful at mapping legacy sediment terraces for each study watershed (Figure 3.1 & 3.3) after comparing visually with lidar-derived terrace longitudinal profiles (Figure 3.4 & 3.5). The ability to edit terraces mid-way through was crucial in making sure glacial terraces and nearby roads were not mapped. After user edits, I mapped 1.5% of the South River watershed as legacy sediment terraces (total terrace area of 1.03×10^6 m^2), and 0.3% of the Sheepscot River watershed (total terrace area of 1.5×10^6 m^2).

Field based analysis was completed in each watershed to determine composition, thicknesses and age of legacy sediment. Legacy sediment in each watershed consists of brown fine sand and silt. The maximum thickness measured is 2.19 m in the South River watershed, and 2.30 m in the Sheepscot River watershed. Radiocarbon dating of six wood samples (three in the South River watershed and three in the Sheepscot River watershed) determined their age to be less than 300 years old and in the time period of historic dam building. This is consistent with five radiocarbon dates by Strouse (2013) at two dam sites in the Sheepscot River watershed.

Using TerEx-delineated terraces and lidar DEMs, I estimated legacy sediment thickness and volumes. I used the methods outlined by Hopkins (2014) to extend these estimates for the entire Sheepscot River and South River watersheds. The water surface datum (WSD), valley bottom surface datum (VBSD), and TerEx toolbox (Stout and Belmont, 2014) methods were all effective in producing volume estimates, where the TerEx method was similar to the maximum estimate from the WSD and the VBSD produced a minimum volume estimate for each watershed (Figure 3.14 & 3.15; Table 3.9 & 3.11). The mean volume for the South River watershed is 1.9 x 10^6 m^3, and 2.9 x 10^6 m^3 for the Sheepscot River watershed (Table 3.12 & 3.13). TerEx volume estimate method has a much lower resolution due to single thickness values assigned to whole delineated terrace polygons. Overall, each datum surface overestimated thicknesses when compared to field-measured legacy sediment bank exposures (except the VBSD method in the Sheepscot River watershed; Tables 3.9 & 3.11). No datum surface was ideal when compared to field data but the VBSD method produced the closest results. Average deviations between the VBSD method and field-measured legacy sediment is 15% in both South River watershed and the Sheepscot River watershed, with 93% and 90% agreeing within ±50% of measured points for each respective watershed (Figures 3.12D & 3.13D; Table 3.9 & 3.11), validating the use of the VBSD method for volume calculations.

The South River watershed is underlain by metamorphosed Paleozoic sedimentary rocks (Segerstrom, 1956) and the Sheepscot River watershed is underlain by metasedimentary rocks within the northeast-southwest trending Norumbega fault zone (Osberg et al., 1985). Both watersheds are influenced by past glaciation when the Laurentide Ice Sheet flowed over New England. As the glacier retreated, surficial deposits of moraines, till, and outwash were left in the landscape (Figure 4.1). These deposits are likely sources of legacy sediment. Total volumes of legacy sediment estimated using DEM methods were divided by watershed area to estimate a thickness range of sediment eroded from each landscape: 12-37 mm for the South River watershed and 2-7 mm for the Sheepscot River watershed. This is a small amount of sediment compared to the Piedmont region where estimates of soil erosion range from 7.6-30.5 cm since initial land clearing (Bennett and Chapline, 1928; Hartman and Wooten, 1935; Happ, 1945; Overstreet et al., 1968; Costa, 1975).

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APPENDIX 1: Volume Calculation Methods

WATER SURFACE DATUM (WSD) METHOD

- Need stream centerline, DEM, and terrace shapefile to start
    - Create a smaller subset DEM around the portion of stream being used. Make sure this extends to the valley walls.

1) To start, you'll want to work with a small portion of your watershed. You need a stream centerline shapefile. In Arc, you can break this into evenly spaced segments using the editor on the top toolbar.
    a) First, create a blank point shapefile from tool "create feature class"
        i) Geometry type -> point
    b) Start editing the point shapefile just created
    c) Highlight the stream that is to be broken up
    d) Select "construct points" in the editor toolbar
        i) Make sure the template is the point shapefile just created
        ii) Select distance and enter the distance that points will be evenly spaced apart
    e) Once points are created stop editing

2) Add elevation to points
    a) Use the tool "extract values to points"
        i) Select your DEM to have data extracted from and the stream points just created for data to go to. Once this is done, your stream points should have the elevation directly beneath them saved to each corresponding point.

3) Use the interpolation tool to create the water surface datum
    a) Use the tool "IDW"
        i) input point feature -> point shapefile with elevation just created
        ii) **Output cell size -> enter the cell size of DEM *very important***
        iii) Select environments – select processing extent -> select same layer as smaller DEM subset created. This limits the interpolation to only cover the extent of your DEM subset.
    Once this is done, you now have a surface representing the water table.

4) Subtract the terrace surface elevation from the water table surface and that should be your thickness
    a) Use the tool "minus"
        i) the two input rasters will be the raster created from the IDW tool and the smaller DEM subset created

5) Clip thickness raster to terrace areas
    a) Use the tool "extract by mask"
        i) input raster -> raster just created using minus tool

ii) input raster or feature mask data -> previously defined terrace shapefile

Once this is done, the output raster should only have data where terraces are defined

6) Calculating volumes

a) Display layer properties of thickness raster just created

b) Under symbology -> classified -> select "classify"

i) Here are classification statistics listed in the top right box. By taking the sum value and multiplying by the area of an individual cell for your DEM you have the total volume of sediment for this section of stream. This is also the screen were you can exclude negative values through the exclusion button.

VALLEY BOTTOM SURFACE DATUM (VBSD) METHOD

1) Adding points to terrace perimeters

a) Create a new point shapefile from tool "create feature class"

i) Geometry type -> point

b) Place points around the terrace perimeter where they butt up to the valley walls. This assumes that your terraces are pinching out where the valley is sloping up.

c) Add elevation values to these points using "extract values to points"

d) Use the tool "merge" to combine these points with points created in step 2 of WSD method (points evenly spaced on stream centerline with elevation)

2) Use the interpolation tool "IDW" to create the valley bottom surface datum (same as step 3 of WSD but input point feature will be point shapefile just created with merged points)

Follow steps 4-6 above with new interpolated water surface.

- The interpolated surface might have a steeper slope than that true valley bottom. This means when you subtract the valley bottom surface from the terrace elevation surface you may get some negative values along the perimeter.

APPENDIX 2: Stratigraphic Data Collected from Bank Exposures

South River: river kilometer 4.78 right bank		
Depth (cm)	Description	Interpretation
0-84	Brown find sand and silt with some layering of medium to coarse sand that is redder, particularly at depths of 37-42 and 81-84. Has mottles throughout.	Legacy sediment
84-105	Brown find sand and silt with no layering and with some clay	Legacy sediment
105	Cobble and pebble layer with red color	Paleo river channel
135	water	

South River: river kilometer 5.35 right bank		
Depth (cm)	Description	Interpretation
0-170	Massive brown fine sand and silt layer with some lens of lighter sand throughout and a redder brown color to the sand at 104 cm	Legacy sediment
170-210	slump to water	

South River: river kilometer 5.94 right bank		
Depth (cm)	Description	Interpretation
0-69	Light brown fine grained sand with medium grained sand at bottom of layer	Legacy sediment
69-157	Brown fine sand and silt with pockets of wood/charcoal at 81 and 121 cm as well as a gravel lens at 144 and 155 cm. Some mottleing around the 121 cm black wood/charcoal area.	Legacy sediment
157-207	Slump material to water edge	

South River: river kilometer 7.53 left bank		
Depth (cm)	Description	Interpretation
0-130	Massive brown fine sand and silt layer	Legacy sediment
130-165	Brown gray medium sand and silt layer with little clay. Mottles present.	Legacy sediment
165-167	Gravel layer at water boundary	Paleo river channel

South River: river kilometer 7.81 right bank		
Depth (cm)	Description	Interpretation
0-50.5	Massive brown fine sand and silt layer that diffuses to second layer	Legacy sediment
50.5-135	Dark brown sandy layer with less silt present	Legacy sediment
135-137	Course sand and gravel layer defined by abrupt and smooth boundary	Floodplain deposit?
137-190	Dark brown medium and fine grained sand that diffuses to gravel and cobble at water boundary	Legacy sediment

South River: river kilometer 8.90 right bank		
Depth (cm)	Description	Interpretation
0-110	Massive light brown sand and silt with coarser sand near bottom of layer	Legacy sediment
110-154	Abrupt smooth coarse sand and gravel layer with some red color	Floodplain deposit
154	Rounded cobble and sand layer with slump to water	Paleo river channel or point bar deposit
350	large cobble layer?	Paleo river channel or point bar deposit

South River: river kilometer 9.15 left bank		
Depth (cm)	Description	Interpretation
0-40	Brown fine sand and silt layer	Legacy sediment
40-105	Massive root layer with brown sand. Hard to see clear bank exposure	Potential legacy sediment
105-140	Dark brown silt with little clay. Pebbles and cobbles present.	Legacy sediment or floodplain deposit
144	water surface	

South River: river kilometer 11.36 left bank		
Depth (cm)	Description	Interpretation
0-65	Massive brown sand layer with mottles and a red color at bottom	Legacy sediment
65-151	Alternating 1-2 cm layer of red coarse sand, tan layers of sand and silt and red/gray layer of sand, silt, and minor amounts of clay	Legacy sediment
151-162	Dark brown red layers of fine sand and silt	Floodplain deposit
162-193	Alternating 1-2 cm layers of dark brown and brown sand and silt. Mottled throughout.	Legacy sediment
193-230	Gravel at bottom, very coarse sand layers 3 cm with red bands at water table	Paleo river channel or point bar deposit

South River: river kilometer 12.40 right bank		
Depth (cm)	Description	Interpretation
0-4	Brown fine sand and silt	Legacy sediment
4-51	Rounded gravel and cobble layer with sand matrix	Point bar deposit
51-97	Brown medium sand layer with some large roots throughout. Has some medium cobbles in middle of layer	Legacy sediment
97-110	Brown sand and gravel layer	Floodplain deposit

South River: river kilometer 12.46 right bank		
Depth (cm)	Description	Interpretation
0-48	Plow layer with light brown sand and silt. Large bird hole present.	Legacy sediment
48-120	Alternating ~5m layers of dark gray silt with little clay and brown very fine sand and silt. Mm thick white fine sand lens and cm diameter mottles throughout	Legacy sediment
120-219	Massive brown fine sand layer	Legacy sediment
219-244	Red gravel layers with few cobbles. Laminated 2 cm thick layers with the coarser layers with deeper red color	channel bar deposit or river bed

South River: river kilometer 12.59 right bank		
Depth (cm)	Description	Interpretation
0-73	Brown fine sand layer, little silt present	Legacy sediment
73-84	Rounded cobble and pebble layer with medium sand in matrix	Paleo river bed or point bar deposit
84-128	Brown sand layer that fines downward with red layer near bottom in coarser sand	Legacy sediment or floodplain deposit

South River: river kilometer 19.41 right bank		
Depth (cm)	Description	Interpretation
0-45	Top soil rich in roots and vegetation. Diffuses into brown fine sand and silt with mottles (30% 1/2 cm in diameter) and some small pebbles and cobbles leading into next layer.	Legacy sediment
45-73	Large dense rounded cobble layer with sand matrix	channel bar deposit
73-101	medium rounded cobble layer with red oxidized color and sand matrix	channel bar deposit
101	Gray clay layer with minor amounts of silt present	Glacial lake deposit

South River: river kilometer 19.42 left bank		
Depth (cm)	Description	Interpretation
0-46	Fine brown sand and silt layer with a potientially 1.2 cm plow layer	Legacy sediment
46-48	Brown medium sand layer	Legacy sediment
48-67	Gray pebble and cobble layer with medium and fine sand matrix	Channel bar deposit or paleo river bed
67	Heavy oxidized pebble and cobble layer with redder color in the first cm	Channel bar deposit or paleo river bed
~250	Down slope at water edge is gray clay and silt	Glacial lake deposit

South River: river kilometer 21.06 right bank		
Depth (cm)	Description	Interpretation
0-56	Fine brown sand and silt with coarser grained sand present and cross-beds	Legacy sediment
56-63	Coarse sand layers	Legacy sediment
63-70	Brown fine sand and silt layer with mottles present	Legacy sediment
70-100	Medium sand that coarsens downward. Laminations present at top with red staining	Legacy sediment
100-128	Dark gray clay and silt layer with a thin wood layer at 123 cm	Organic rich legacy sediment
128-131	Dark gray sand and silt layer	Legacy sediment

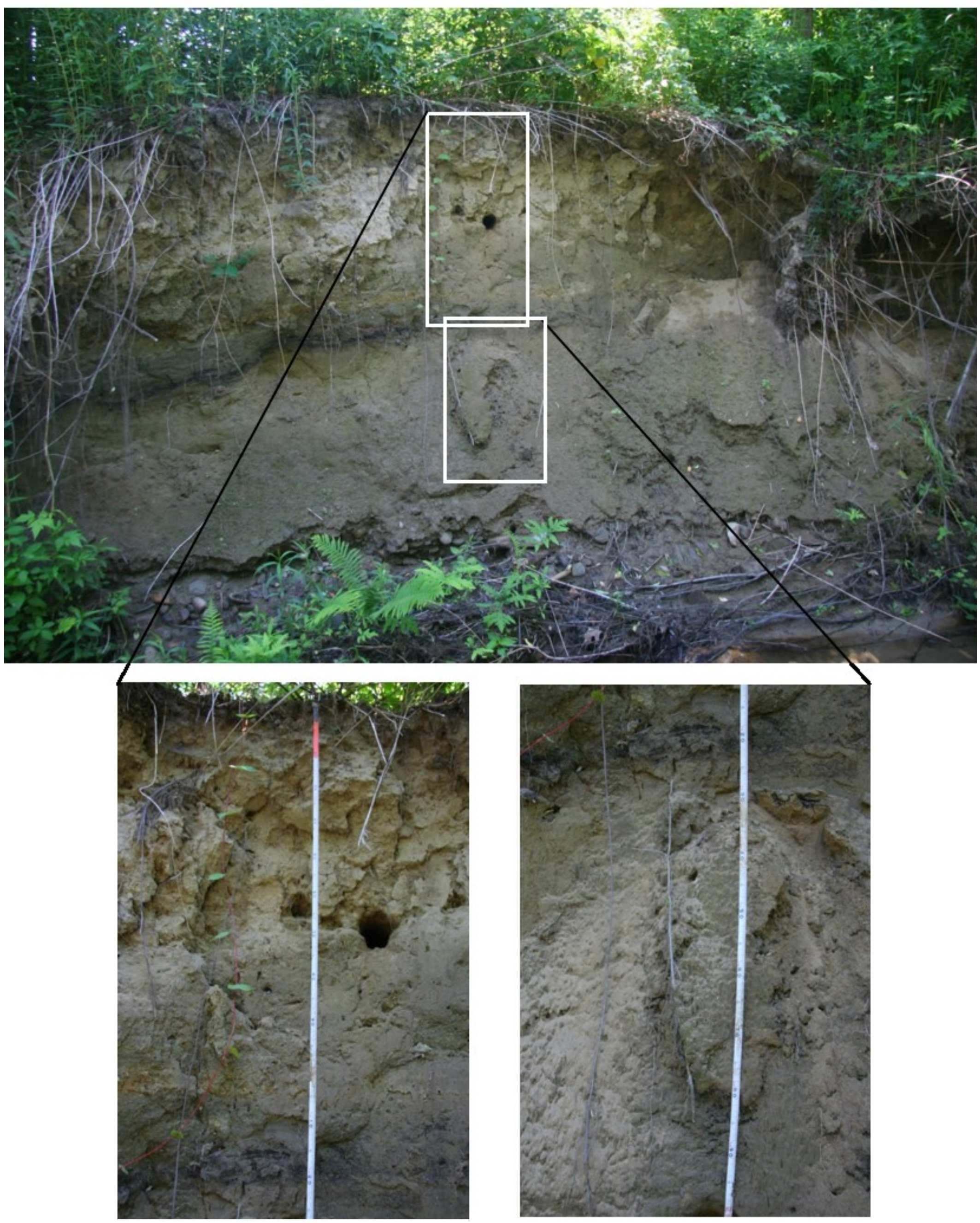
South River: river kilometer 22.32 right bank		
Depth (cm)	Description	Interpretation
0-55	Massive brown fine sand and silt. Lots of roots present.	Legacy sediment
55	At water level gray sand with silt and clay present.	Legacy sediment

South River: river kilometer 22.45 left bank		
Depth (cm)	Description	Interpretation
0-80	Massive brown fine sand	Legacy sediment

Sheepscot River: river kilometer 10.75 left bank		
Depth (cm)	Description	Interpretation
0-111	Slump material	
111-163	Brown massive fine sand layer containing roots that grades into next layer	Legacy sediment
163-201	Dark gray fine sand with 20% orange mottles	Legacy sediment
201-215	Brown fine sand layer containing mostly gravel and cobbles	Legacy sediment or paleo river channel

Sheepscot River: river kilometer 10.8 right tributary		
Depth (cm)	Description	Interpretation
0-10	Dark brown very fine sand/silt in a dense root layer	Legacy sediment
10-60	Tan/Brown very fine sand/silt with some pockets (1-2 cm) of black organics. Some roots present. Grades into next layer.	Legacy sediment
60-80	Brown/gray silt with start of mottles.	Legacy sediment
80-105	Gray layer with 1 cm white/tan silt layers with mottles. Grades into next layer.	Legacy sediment
105-130	Gray massive layer with some pockets of black organics.	Potential buried wetland material
130-136	Black organic rich layer. Top of layer is undulating from soft sediment deformation	Potential buried wetland material
136-190	Tan/white fine sand/silt with mottles	Legacy sediment
190-200	190-200 cm. Pebble/cobble layer.	Paleo riverbed deposit

Sheepscot River: river kilometer 10.8 right tributary 2		
Depth (cm)	Description	Interpretation
0-120	Tan-gray fine sand and silt	Legacy sediment
120-124	Organic rich thin layer	Potential buried wetland material
124-230	Tan fine sand and silt	Legacy sediment
230	Gravel and pebbles	Paleo riverbed deposit



Sheepscot River: river kilometer 11.0 island left		
Depth (cm)	Description	Interpretation
0-150	Fine sand	Legacy sediment
150-180	Wood pieces	Organic rich floodplain deposit
180-210	Clay	Presumpcot Clay
210	Gravel river bed	

Sheepscot River: river kilometer 11.1 island left		
Depth (cm)	Description	Interpretation
0-30	Light tan fine sand/silt, granular layer with roots present that grades into the next layer.	Legacy sediment
30-120	Light brown/tan fine sand with thin layers of medium/coarse sand including pockets of mottles.	Legacy sediment
120-150	Brown gray layer of fine sand. At 126 cm depth a 1 cm layer of medium/coarse sand and mottles present. At 140 cm depth a 2mm layer of organic black/red bark.	Legacy sediment
150-200	Black/gray clay with 1-2 cm lens of sand, mottles and some organics (twigs).	Presumpcot clay
200	Water Table. Pebbles/cobbles.	Paleo river bed deposit

Sheepscot River: river kilometer 11.1 island right		
Depth (cm)	Description	Interpretation
0-116	Brown sand and silt with some lens of coarse sand	Legacy sediment
116-155	Gray clay layer with mottles. Water contact at base	Presumpcot Clay
155-185	Brown organic layer on a shelf below water	Organic rich floodplain deposit

Sheepscot River: river kilometer 19.7 right bank		
Depth (cm)	Description	Interpretation
0-50	Brown fine sand and silt with roots	Legacy sediment
50-60	Brown silt and clay	Legacy sediment
60-75	Sand	Legacy sediment or floodplain deposit
75-90	Gray-brown silt and clay with	Presumpcot Clay
90-95	Wood and brown silt with iron silt. Water surface	Organic rich floodplain deposit

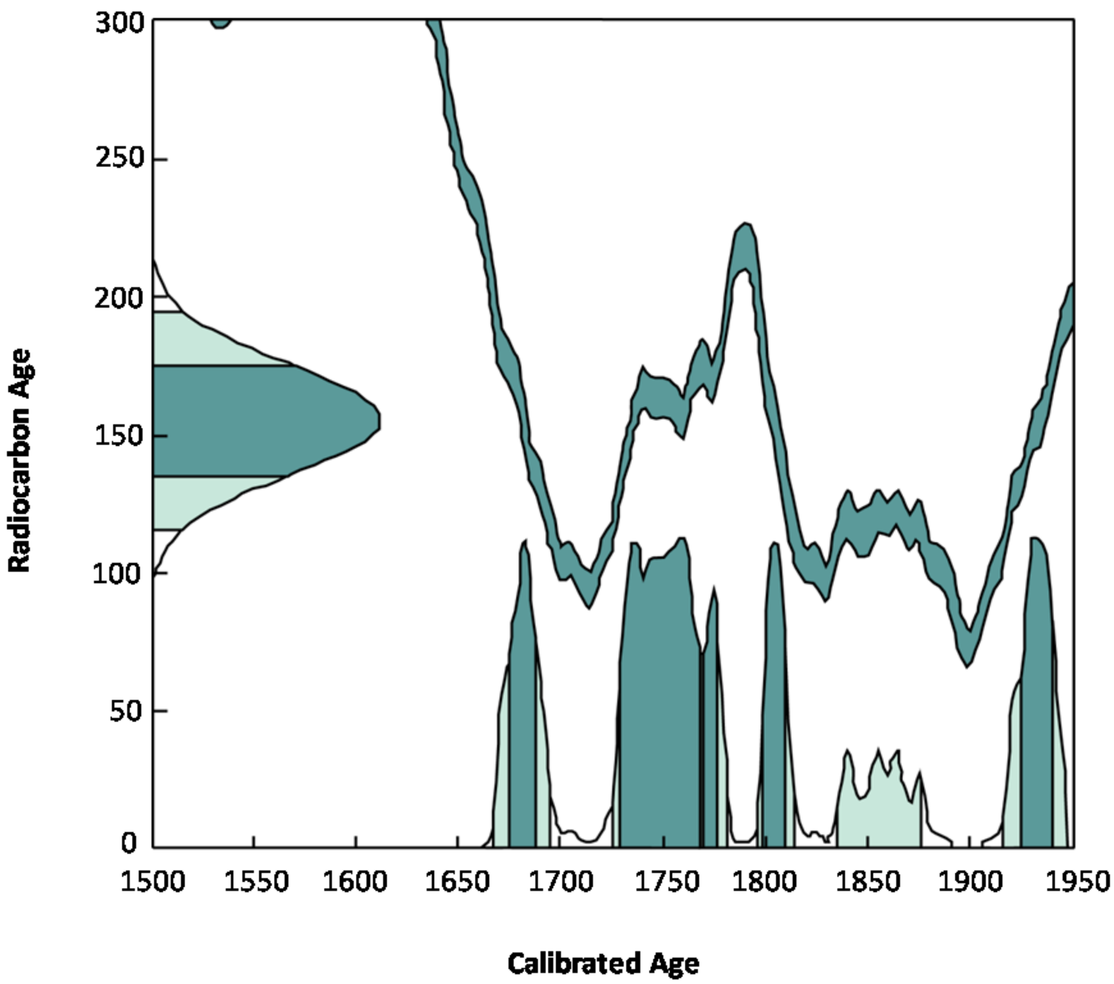
Sheepscot River: river kilometer 23.0 right bank		
Depth (cm)	Description	Interpretation
0-25	Sand with roots	Legacy sediment
25-80	Fine sand with wood layer	Legacy sediment
80-90	Water line with lots of wood and charcoal	Organic rich floodplain deposit
90-110	Some charcoal	Organic rich floodplain deposit

Sheepscot River: river kilometer 26.3 right bank		
Depth (cm)	Description	Interpretation
0-25	Dark brown silty soil with roots	Legacy sediment
25-45	Brown silt and clay with red mottles. At 45 cm there is a layer of mussel shells	Legacy sediment
45-57	Gray clay an silt, red mottles	Legacy sediment
57-65	Gray clay and silt. No mottles. Water surface at 65 cm.	Legacy sediment
65-80	Cut blanks with gray clay and silt	Legacy sediment

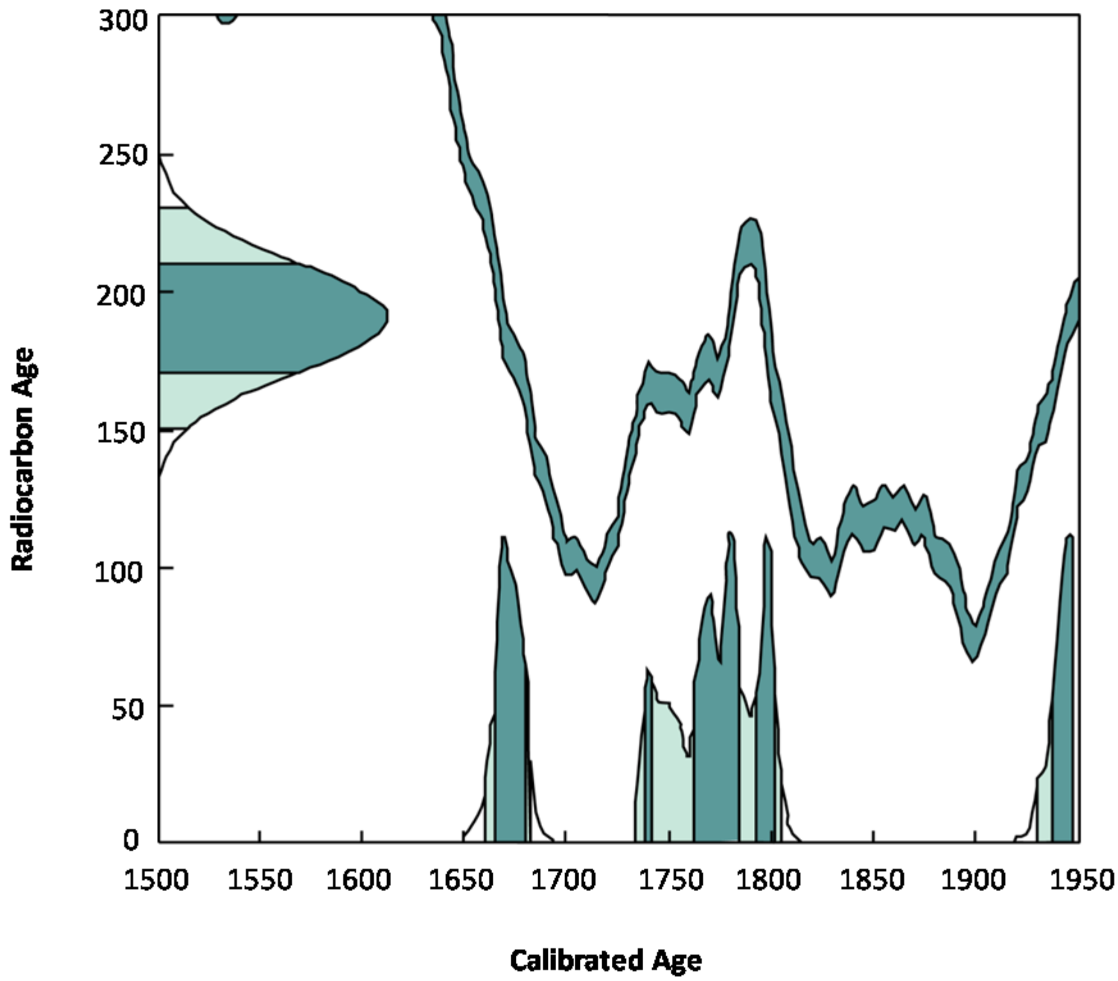
APPENDIX 3: Radiocarbon Calibration Figures

After radiocarbon samples were dated at Woods Hole Oceanographic Institution National Ocean Sciences Accelerator Mass Spectrometry (WHOI NOSAMS) they were calibrated using the CALIB Radiocarbon Calibration program (Stuiver and Reimer, 1993 (version 5.0); http://calib.org/calib/). This program converts the given radiocarbon age from WHOI NOSAMS to calibrated calendar years by calculating the probability distribution of the sample's age. The IntCal13 curve was used for calibration dataset.

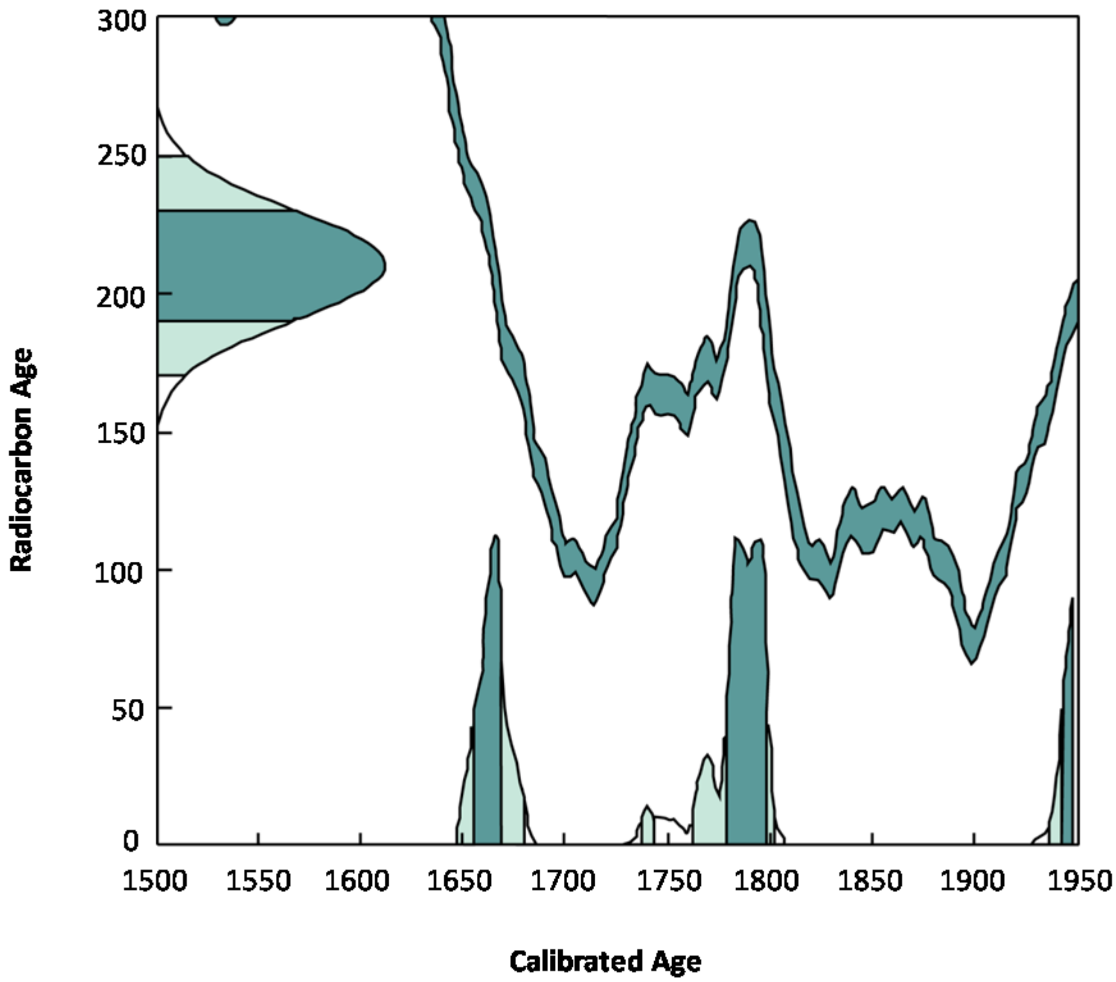
Reported here is a graph of each radiocarbon sample and the reported median probability (Reimer et al., 2013).
The calibrated ages reported are in years AD.
Sigma 1 distributions are colored dark blue/green and sigma 2 distributions are colored light teal.



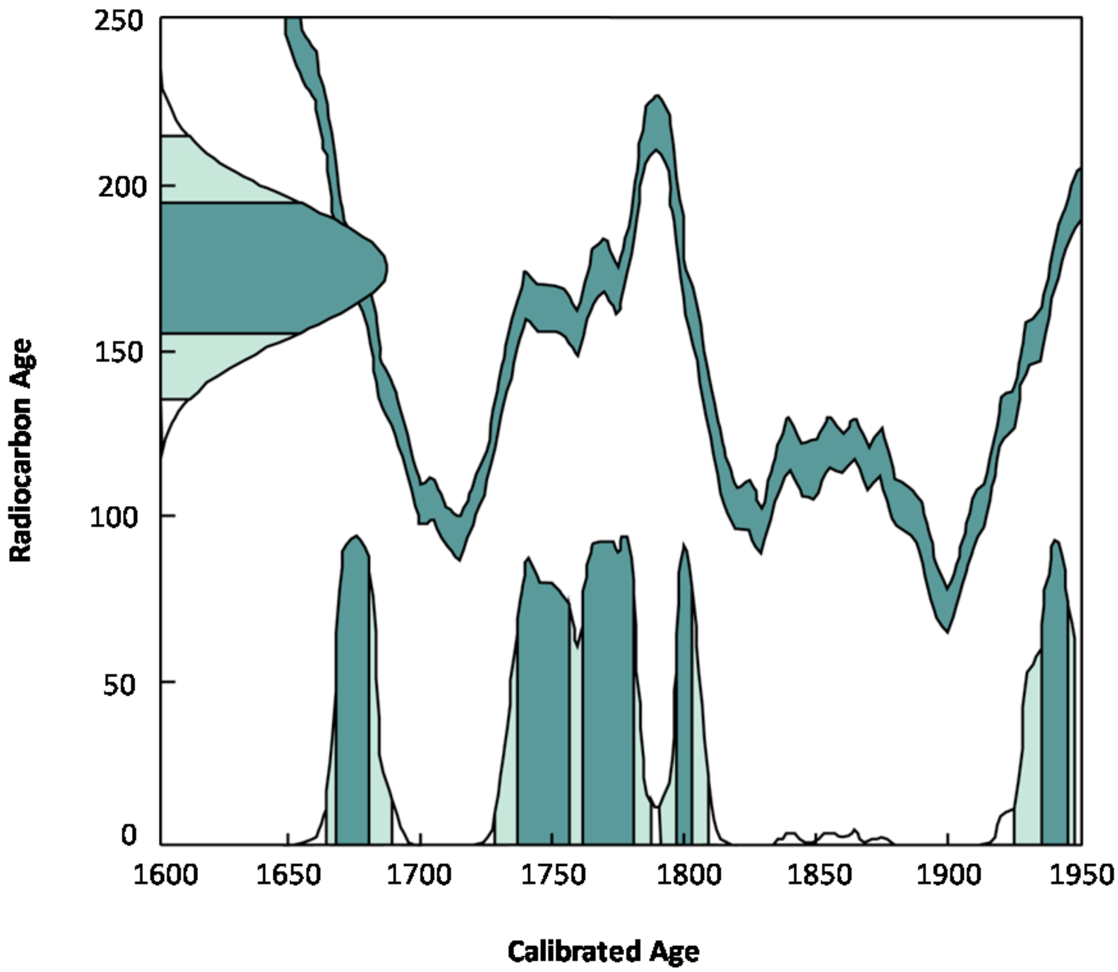
South River: river kilometer 5.94 right bank; median probability: 1765; sample from a depth of 120 cm.



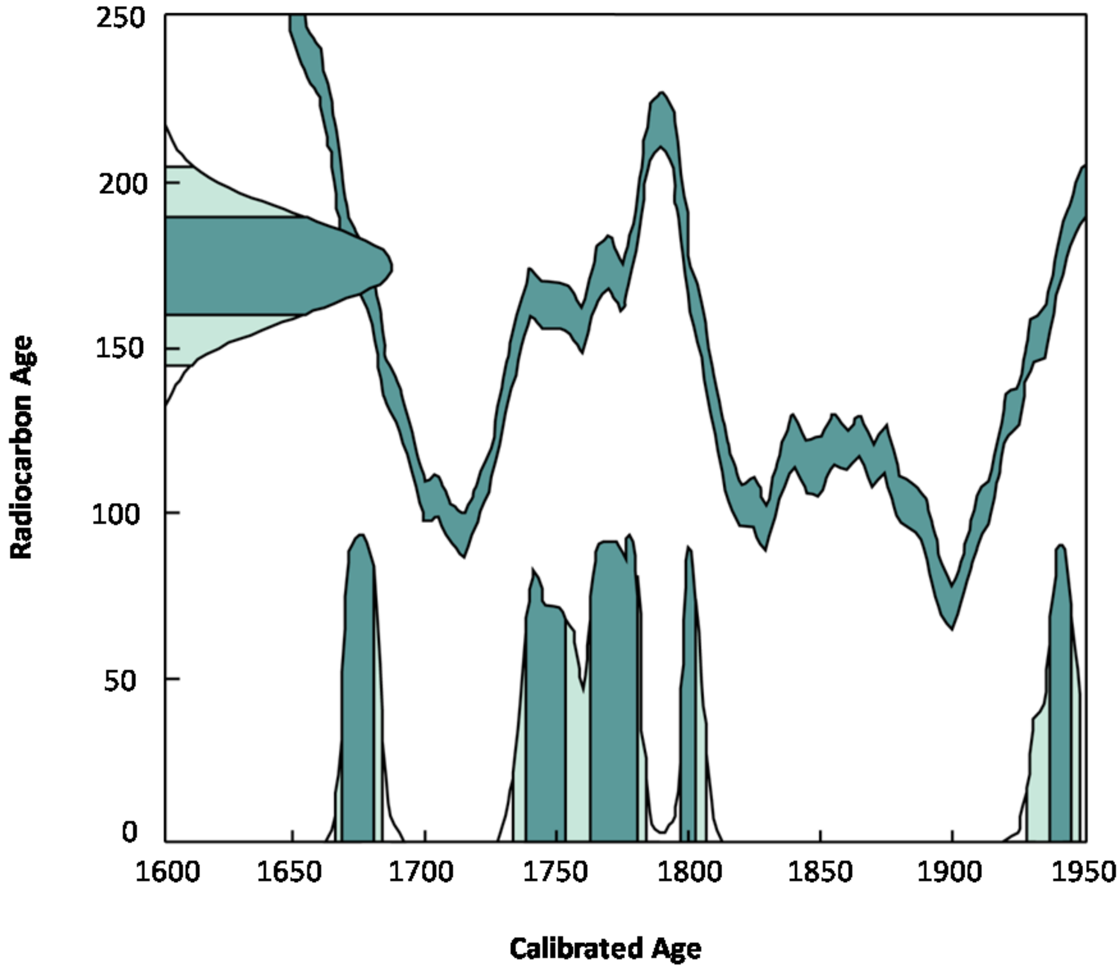
South River: river kilometer 21.06 right bank; median probability: 1772; sample from a depth of 123 cm.



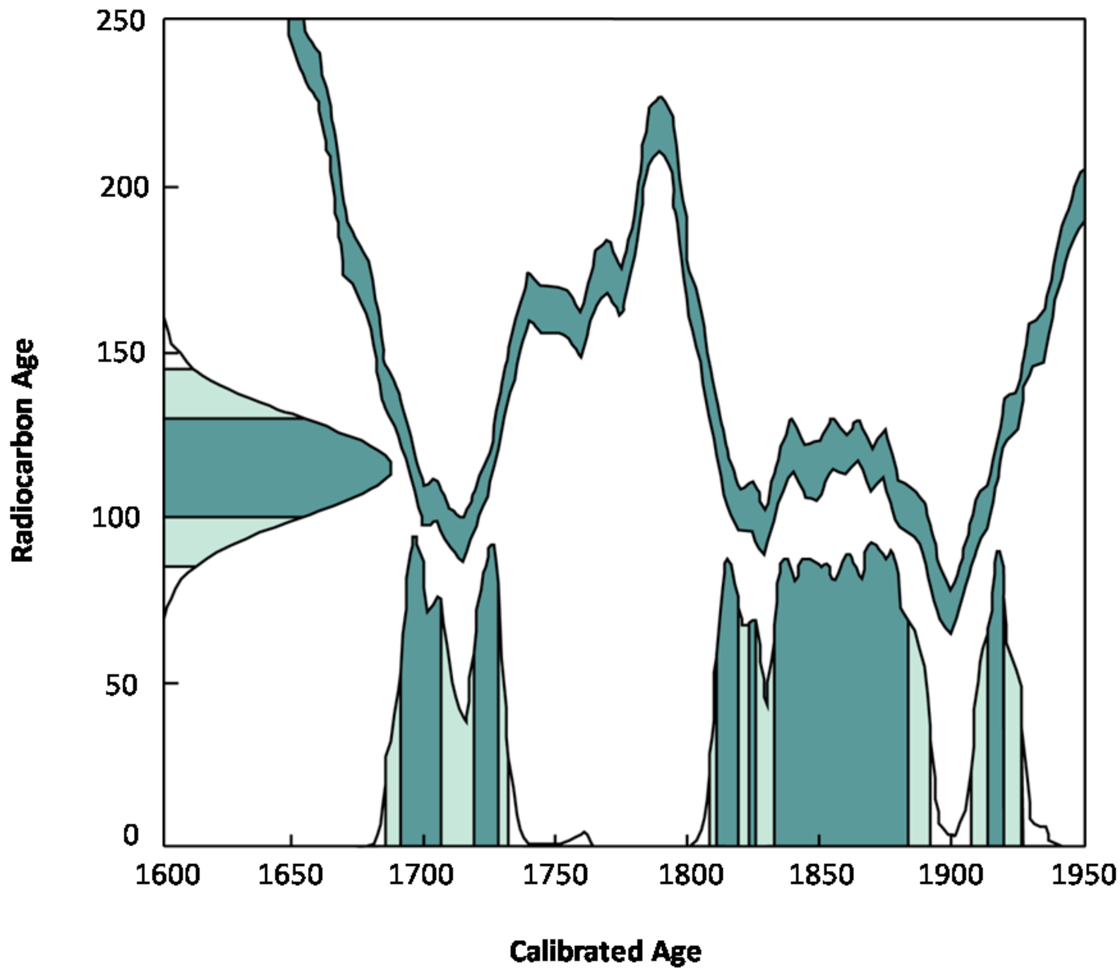
South River: river kilometer 12.46 right bank; median probability: 1781; sample from a depth of 106 cm.



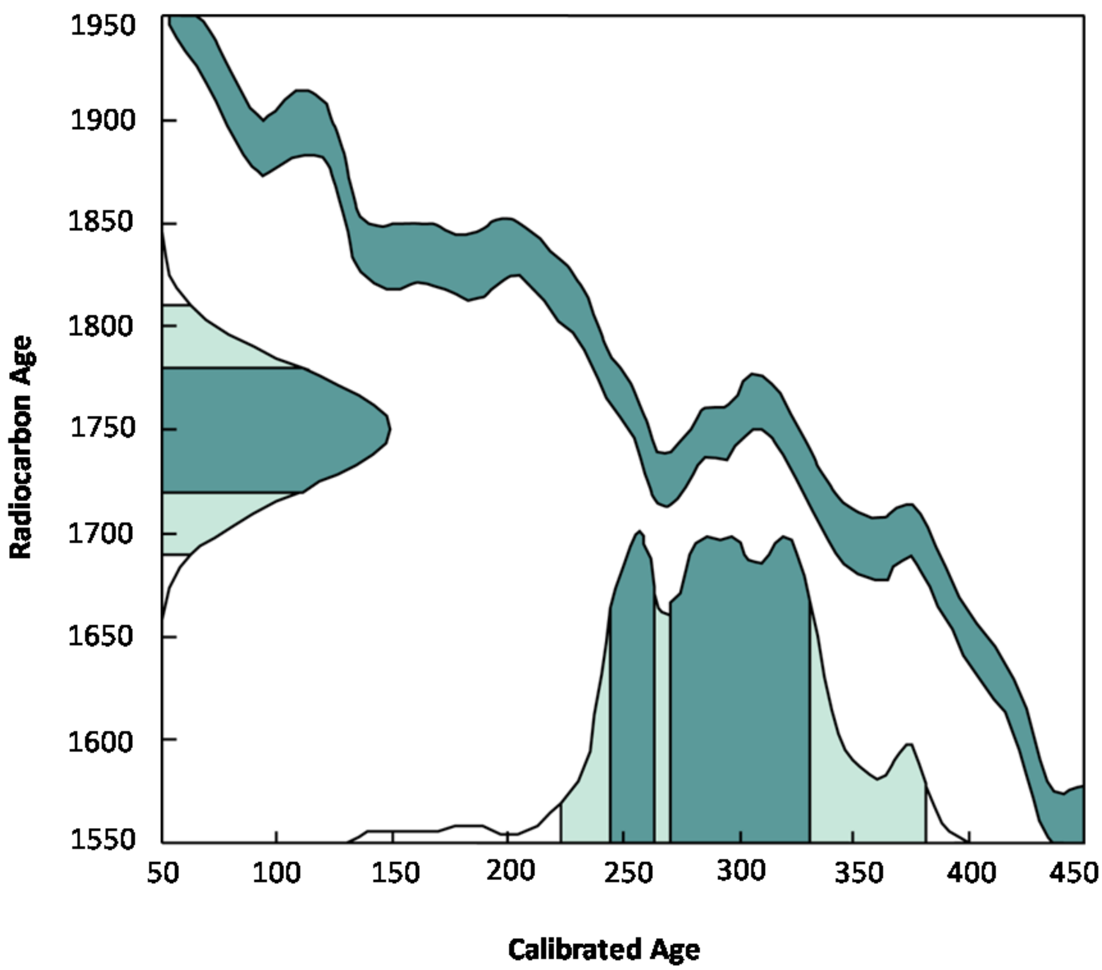
Sheepscot River main stem: river kilometer 11.1 island right; median probability: 1766; sample from a depth of 144 cm.



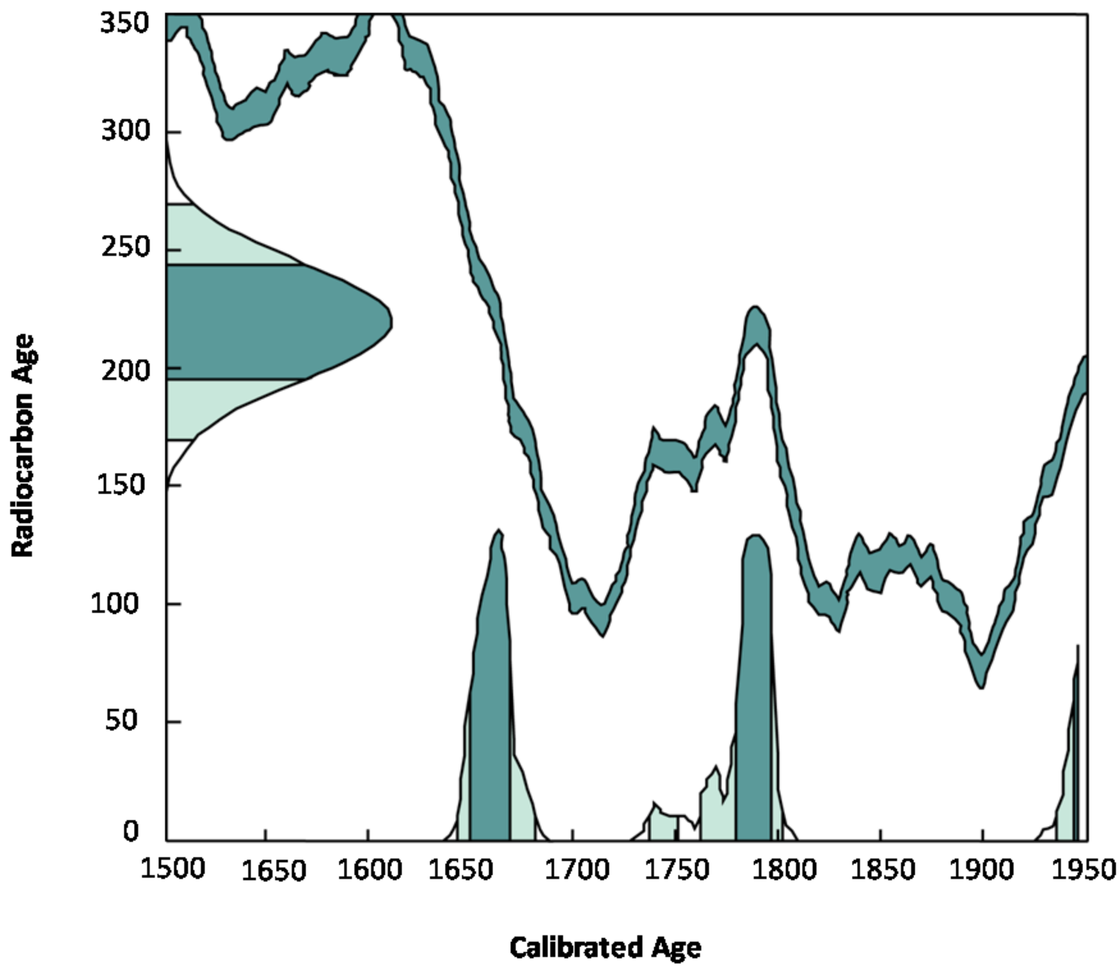
Sheepscot river main stem: river kilometer 11.1 island right; median probability: 1765; sample from a depth of 161 cm.



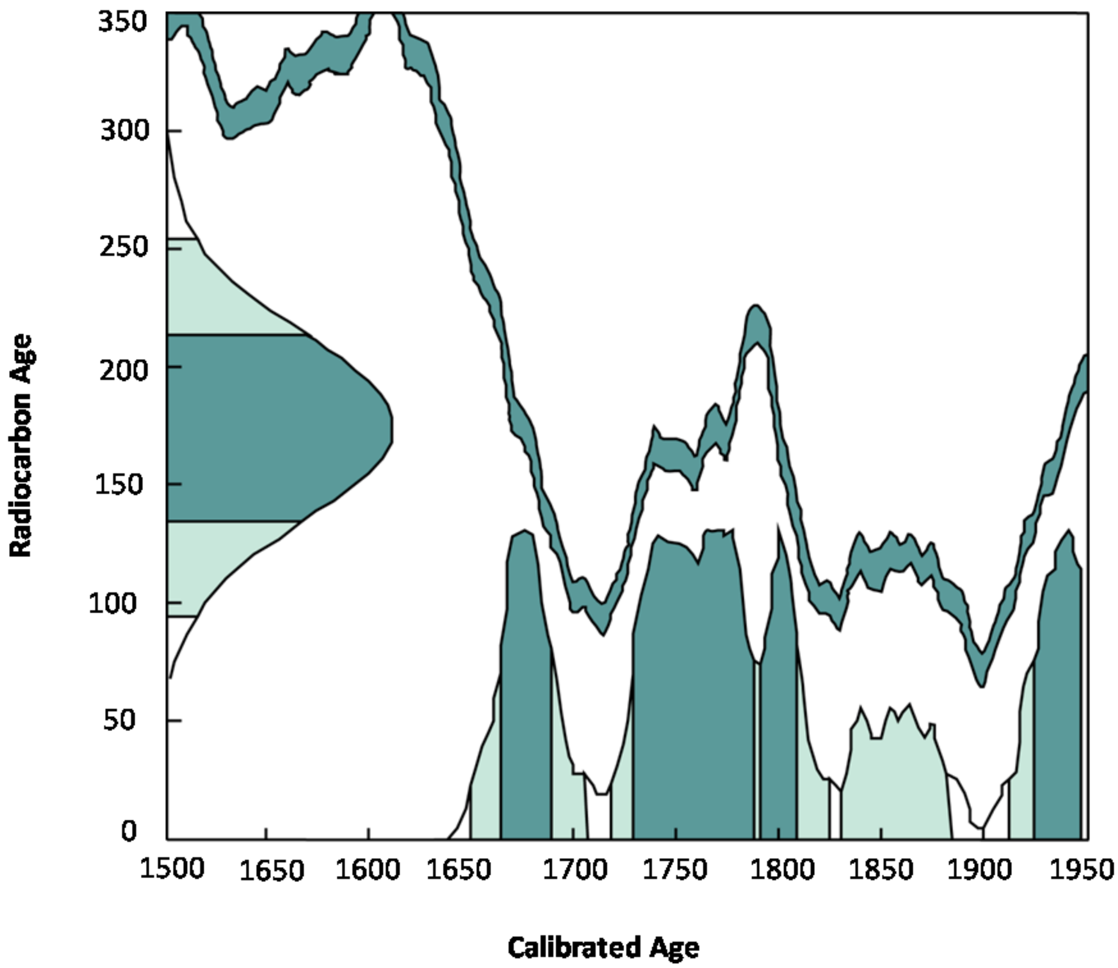
Sheepscot river main stem: river kilometer 10.8 tributary; median probability: 1838; sample from a depth of 130 cm.



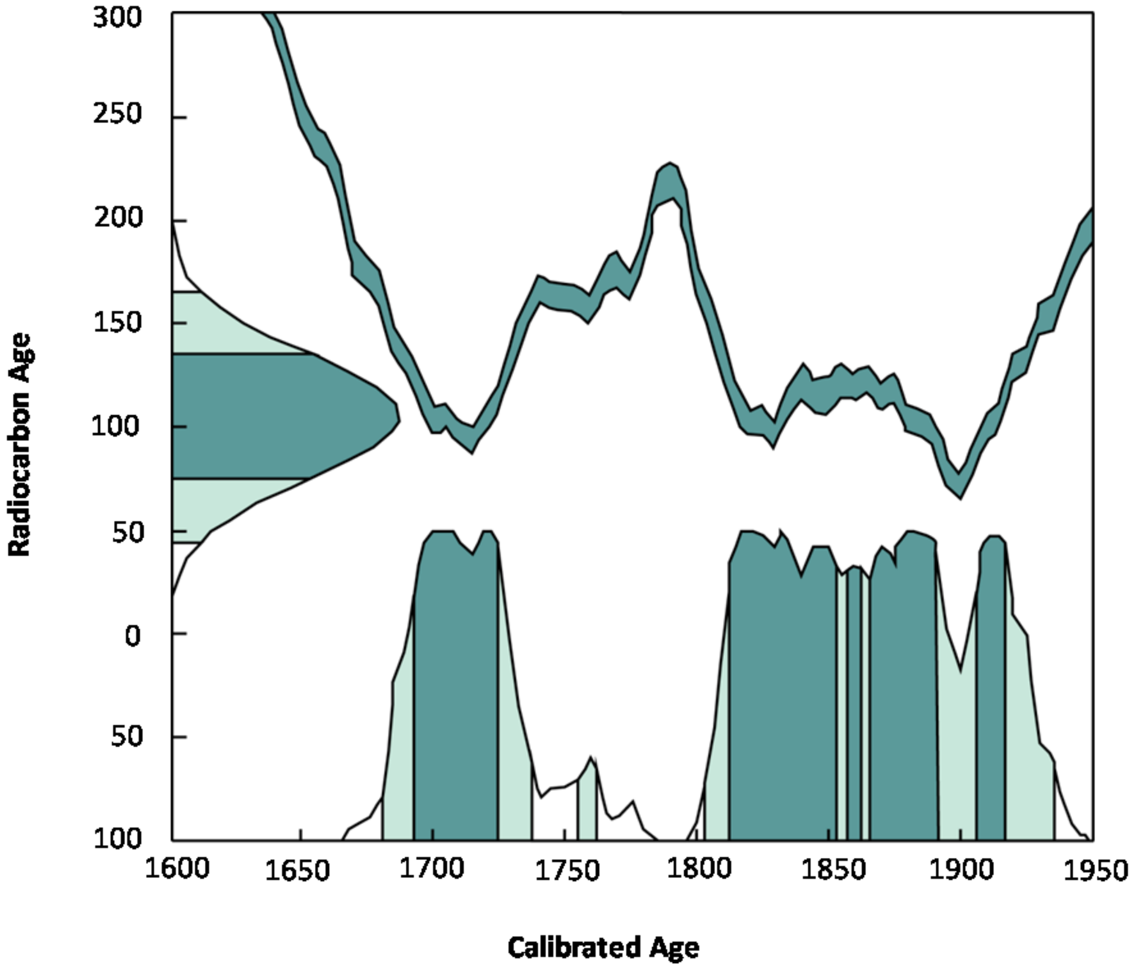
Sheepscot river west branch: river kilometer 9.5; median probability: 292; sample from a depth of 58 cm.



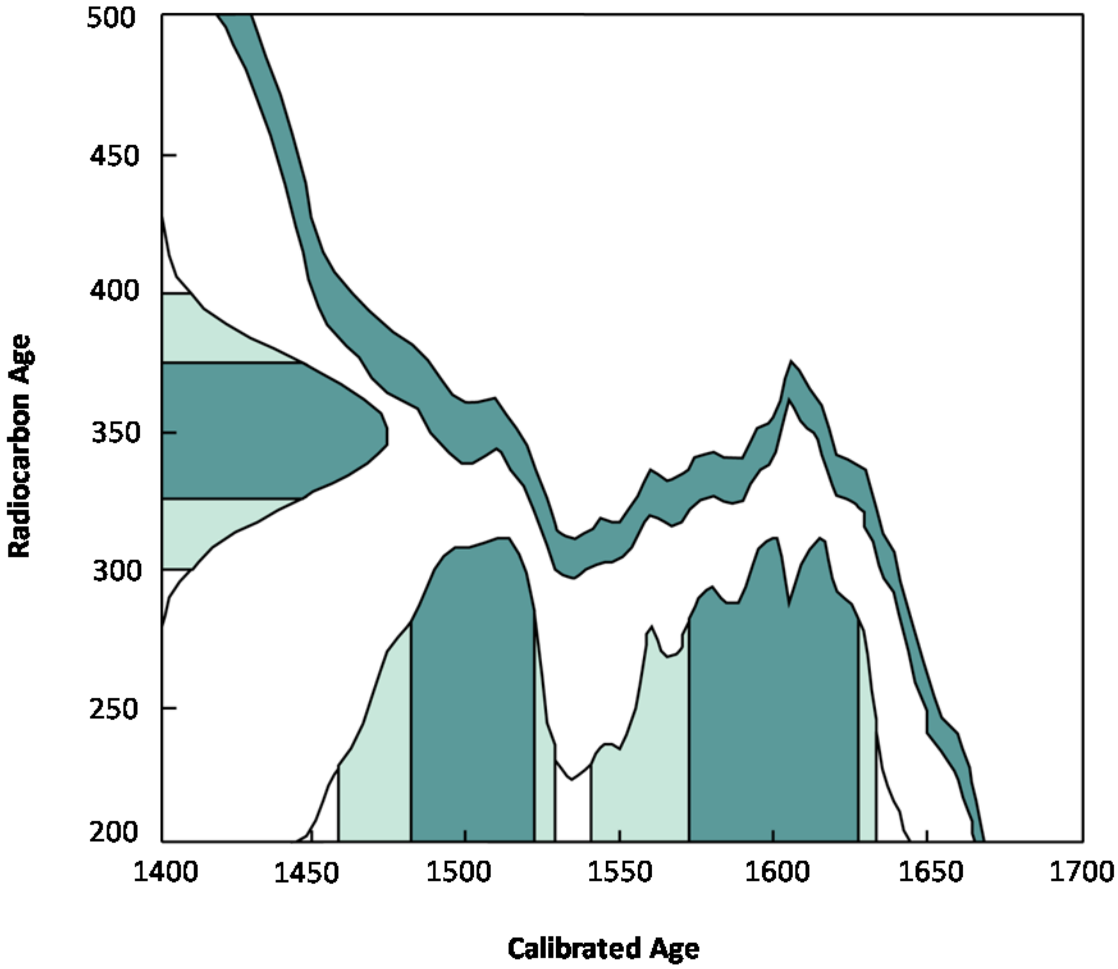
Sheepscot river west branch: river kilometer 9.5; median probability: 1771; sample from a depth of 62 cm.



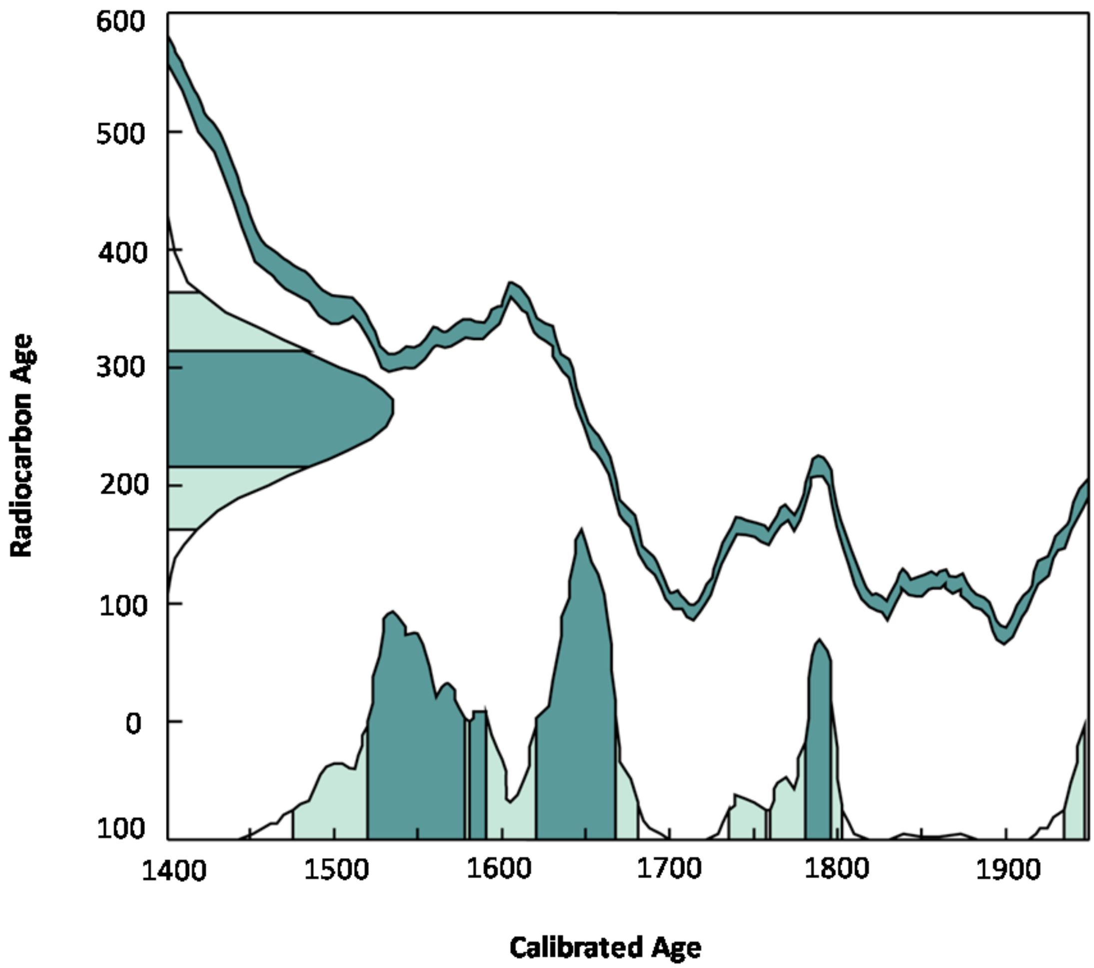
Sheepscot river west branch: river kilometer 9.5; median probability: 1775; sample from a depth of 76 cm.



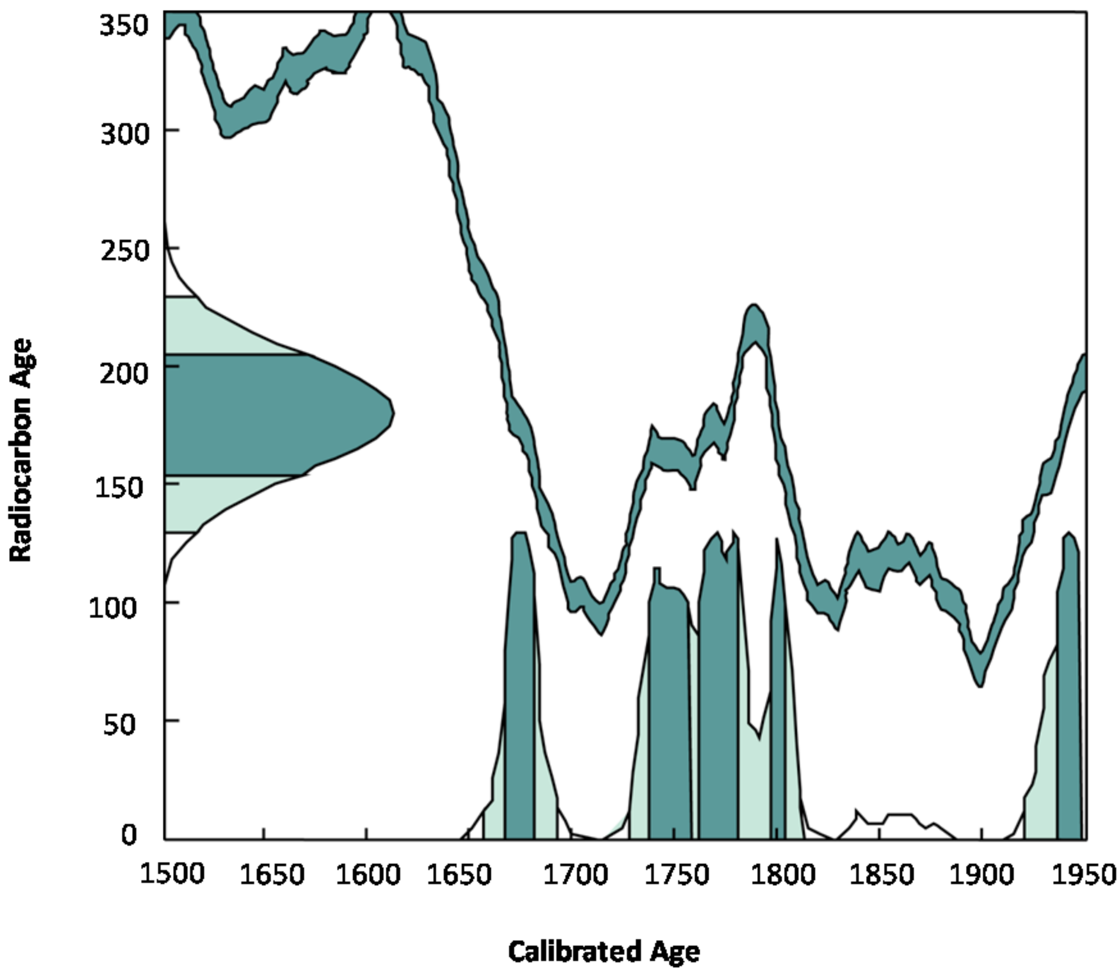
Sheepscot river main stem: river kilometer 10.75; median probability: 1837; sample from a depth of 137 cm.



Sheepscot River main stem: river kilometer 10.75; median probability: 1557; sample from a depth of 152 cm.



Sheepscot River main stem: river kilometer 10.75; median probability: 1626; sample from a depth of 164.



Sheepscot River main stem: river kilometer 10.75; median probability: 1768; sample from a depth of 187 cm.