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Invited Research Article

Legacy sediment storage in New England river valleys: Anthropogenic processes in a postglacial landscape

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ABSTRACT

Legacy sediment associated with erosion from land clearing is a common feature in river valleys of the unglaciated Mid-Atlantic Piedmont region. Here, we quantify the volume of legacy sediment storage in three watersheds in New England, a formerly glaciated region with similar history and intensity of forest clearing and milldam construction during the seventeenth to nineteenth centuries. We combine field observations of bank stratigraphy, radiocarbon dating, and mapping of terraces and floodplains using lidar digital elevation models and other GIS datasets. The 68 km^2 South River watershed in western Massachusetts exhibits the most extensive evidence for legacy sediment storage. We visited 18 historic dam sites in the watershed and found field evidence for up to 2.2 m of fine sand and silt legacy sediment storage at 14 of the sites. In the 555 km^2 Sheepscot River watershed in coastal Maine, we visited 13 historic dam sites and found likely legacy sediment up to 2.3 m thick at six of the dams. In the 171 km^2 upper Charles River watershed in eastern Massachusetts, we investigated 14 dam sites, and found legacy sediment up to 1.8 m thick at two of them. Stratigraphically, we identified the base of fine-grained legacy sediment from a change to much coarser grain size (gravel at most sites) or to glacial lacustrine or marine deposits. Along the Sheepscot River, we observed cut timbers underlying historic sediment at several locations, likely associated with sawmill activities. Only at the Charles River were we able to radiocarbon date the underlying gravel layer (1281–1391 calibrated CE). At no site did we find a buried organic-rich Holocene soil, in contrast to the field relations commonly observed in the Mid-Atlantic region. We use lidar elevation data to map planar terrace extents in each watershed, estimate thickness of remaining legacy sediment found stored behind breached or removed milldams, and estimate volumes of remaining legacy sediment storage in valley bottoms for entire watersheds. The maximum volume of stored legacy sediment estimated for the South, Sheepscot, and upper Charles watersheds is 2.5×10^6 m^3, 3.7×10^6 m^3, and 2.6×10^4 m^3, respectively. These volumes of legacy sediment can be translated to an equivalent thickness of soil eroded from each watershed: 37 mm, 7 mm, and 0.2 mm, respectively. We attribute the variation in presence and thickness of legacy sediment at the New England sites to the existence or absence of upstream sediment supply in the form of thick glacial deposits and to sinks such as lakes and wetlands along valley bottoms. Of the three study watersheds, the South River has the most extensive glacial sediments, fewest sinks, and the most legacy sediment in storage along the river corridor.

1. Introduction

Humans are a primary geomorphic force shaping the Earth's surface (e.g., Wilkinson and McElroy, 2007; 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 many 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 modern reservoirs (Syvitski et al., 2005; Wohl, 2015) and aggradation along valleys after land clearing for agriculture and other activities (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).

Terms such as Anthropocene, legacy, post-settlement alluvium, and historic have all been used in the literature to describe recent deposits and landforms (e.g., Wilkinson and McElroy, 2007; Walter and Merritts, 2008; James, 2013; Waters et al., 2016). James (2013) calls for a definition of legacy sediment that applies to “anthropogenic sediment that was produced episodically over a period of decades or

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centuries, regardless of position on the landscape, geomorphic process of deposition, or sedimentary characteristics." Here we use "legacy" and "historic" to define material deposited in association with human activities during the past 300–400 yr in the northeastern U.S., and which record a sudden, dramatic shift in valley bottom depositional style from the pre- to the post-European settlement condition.

The landscape of the eastern U.S. was changed markedly since the seventeenth century by timber harvest, charcoaling, agriculture, and milldam construction (Fig. 1A). Studies have identified deposits associated with elevated sediment yields because of colonial land clearing in the Mid-Atlantic (e.g., Costa, 1975; Jacobson and Coleman, 1986; Evans et al., 2000; Walter and Merritts, 2008; Pizzuto and O'Neal, 2009), Midwestern (e.g., Knox, 1977, 2006; Magilligan, 1985; Fitzpatrick et al., 2009), southeastern (e.g., James, 2011; Wegmann et al., 2012), and New England (Brakenridge et al., 1988; Bierman et al., 1997; Wessels, 1997; Thorson et al., 1998) regions.

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

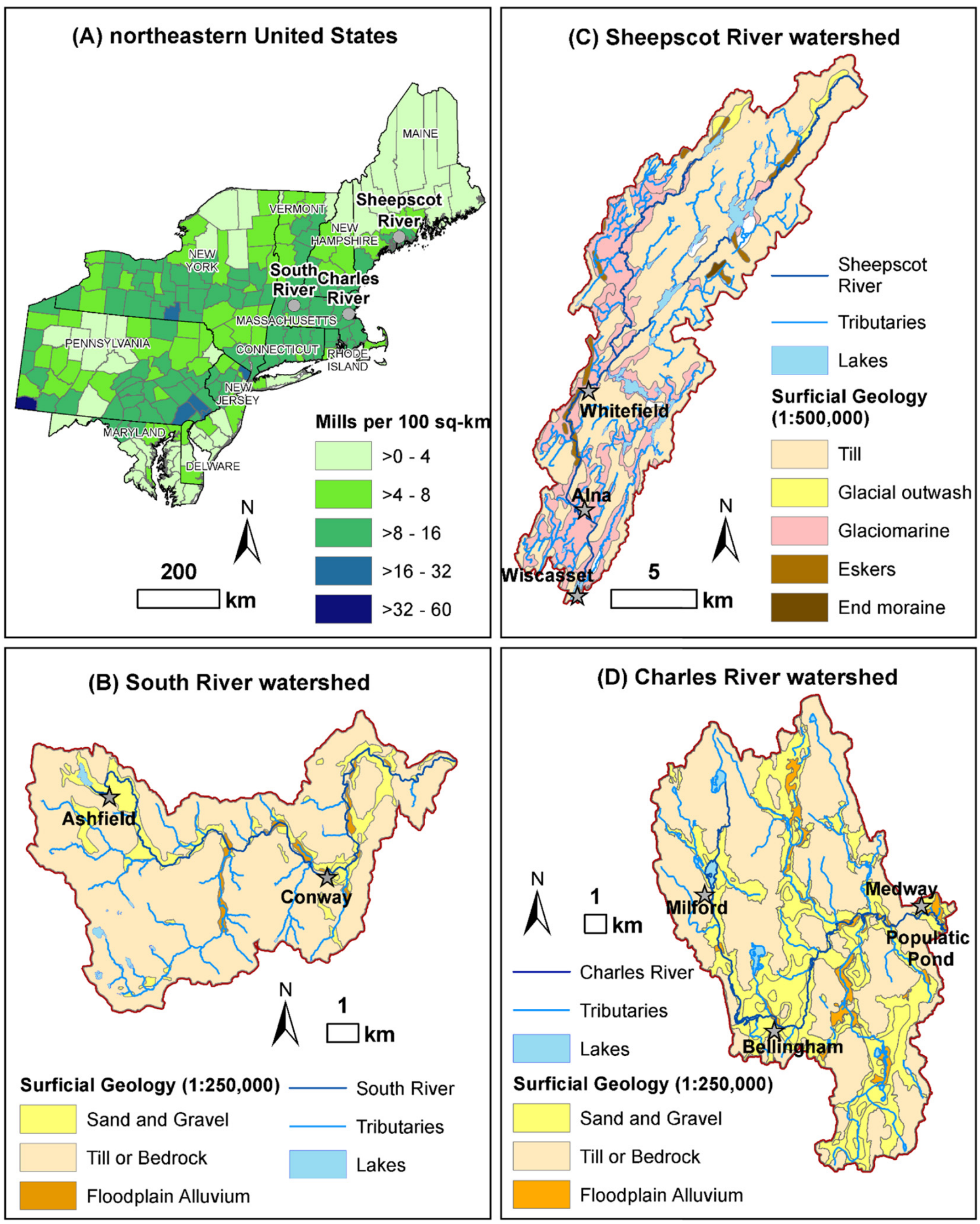

Fig. 1. (A) Map of the northeastern U.S., showing the density of mills according to 1840 census data (Walter and Merritts, 2008), and our three study watersheds. (B–D) Simplified surficial geologic maps of the South River, Sheepscot River, and upper Charles River watersheds, respectively. Surficial geologic map layers are from the Massachusetts Office of GIS (B and D) and the Maine Office of GIS (B).

Walter and Merritts (2008) emphasized that construction of milldams raised base level, lowered water surface slopes, made accommodation space in millpond reservoirs, and enhanced valley-bottom sedimentation. 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 southeastern Pennsylvania and adjacent Maryland, 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 organic-rich, 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, 2013).

Recently, other workers in the Mid-Atlantic Piedmont have evaluated both the ubiquity of milldam deposits and the interpretation that such landforms become fill terraces. Working in Virginia and Maryland, respectively, Hupp et al. (2013) and Donovan et al. (2016), found nearly continuous deposits of legacy sediment along channels, in locations both upstream of known breached historic milldams and outside of the backwater influence of these structures. Further, Pizzuto et al. (2016) quantified floodplain sedimentation rates for the South River in Virginia and found that overbank sedimentation remained an active process throughout the twentieth century, storing 8–12% of the total suspended sediment load.

Relatively few studies have documented historic valley-bottom sedimentation in the post-glacial New England landscape. Brakenridge et al. (1988) analyzed trenched cross sections in northern Vermont and found a dark brown well-bedded sand and silt floodplain unit deposited after conversion of forests to agriculture fields, during the mid-nineteenth century. Also in Vermont, Bierman et al. (1997) identified alluvial fans and pond sediments as recorders of Holocene geomorphic processes. They determined that the highest rates of upland soil erosion occurred during the late Holocene, attributing elevated erosion rates to clear cutting and agricultural practices that led to aggradation on valley-bottom alluvial fans. Thorson et al. (1998) studied a 14 km^2 watershed in Connecticut, looking at 61 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 of floodplain alluvium that occurred is still impacting the sediment budget, flood regime, and riparian habitat.

In this study, we determine the presence or absence, extent, thickness, age and volume of legacy sediment stored in valley bottoms of three New England rivers. We have two goals. First, we seek to evaluate whether the valley-bottom stratigraphic relationships observed in the unglaciated Mid-Atlantic region are common in glaciated New England. In particular, we seek to test whether watersheds that have a similar timing and intensity of milldam construction to the area studied by Walter and Merritts (2008; Fig. 1) have a similar ubiquity of legacy sediment overlying a buried Holocene wetland soil. We expect differences because, in contrast with southeastern Pennsylvania and Maryland, New England was covered repeatedly by continental ice sheets during the Pleistocene, and therefore has localized thin soils overlying bedrock and thick deposits of glacial material, as well as terrestrial accommodation space in natural lakes and wetlands. This leads to variations in sediment supply and trapping along channels (Snyder et al., 2013). Our second goal is to develop and test methods that use high-resolution lidar digital elevation models (DEMs) to quantify the volume of legacy sediment stored in our study watersheds.

1.1. Study area

We studied three watersheds: the South River in western Massachusetts, the Sheepscot River in mid-coastal Maine, and the upper Charles River in eastern Massachusetts (Fig. 1). All were covered by the Laurentide ice sheet, and thin till and bedrock dominate the surficial geology. These watersheds were chosen based on the high densities of eighteenth and nineteenth century milldams and previous research on legacy sediment in the South River (Field, 2013) and in the Sheepscot River (Strouse, 2013; Hopkins, 2014; Hopkins and Snyder, 2016). Strouse (2013) identified reservoir sediment terraces upstream of two breached dams using analysis of sediment characteristics and limited radiocarbon dating. Also, she used hydraulic modeling to estimate the upstream extent of the former millponds. Hopkins (2014) and Hopkins and Snyder (2016) compared several methods to identify and map terraces from lidar DEMs upstream of dam sites. Once terraces were mapped, thicknesses and volumes of sediment in the terraces were quantified (Hopkins, 2014). In this study, observations and measurements of legacy cut banks from the Sheepscot River studies (Strouse, 2013; Hopkins, 2014; Hopkins and Snyder, 2016) are used alongside new data from all three watersheds.

The South River drains into the Deerfield River in western Massachusetts. The 68 km^2 watershed has an average slope of 16% (Fig. 1B). It is underlain by metamorphosed Paleozoic sedimentary rocks of the lower Devonian Conway Formation (Segerstrom, 1956). The watershed includes glacial-age terraces associated with deltas graded to one or more glacial lakes once present in the watershed, and these deposits are now a main source of sediment to the river (Field, 2013). 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 and DiGiacomo-Cohen, 2010).

The coastal 555 km^2 Sheepscot River watershed in Maine has an average slope of 7% (Fig. 1C). The river flows southwesterly to the Atlantic Ocean. The direction is strongly influenced by the metasedimentary rocks in the northeast-southwest trending Norumbega fault zone (Osberg et al., 1985). As deglaciation occurred the coastal region was inundated with seawater due to isostatic depression and 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). This formation can 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 outwash deposits, eskers and moraines across the landscape.

The Charles River is a low gradient river in eastern Massachusetts that winds through suburban towns and into the city of Boston (Fig. 1D). This study investigates the watershed upstream of Populatic Pond in Medway, Massachusetts. This watershed is 171 km^2, with an average slope of 5%. The bedrock is made up of Proterozoic plutonic, metaplutonic, metavolcanic, and metasedimentary rocks (Goldsmith, 1991). The surficial geology is dominated by stratified glacial-age deposits interspersed with pockets of till <10 m thick.

1.1.1. Land-use history

Population and land use have changed considerably in the South River watershed over the past two centuries. The towns of Ashfield and Conway each had ~2000 residents in the early nineteenth century, slowly declining by about 50% over the next 150 yr. Since 1950, the populations of both towns have increased to nearly nineteenth century levels. In 1830, the watershed was 8% forest, 1% wetland, and 92% cleared land (Foster and Motzkin, 2009; Johnson, 2017). Current land use is 79% forest and 6% developed, with 2.5% composed of wetlands and surface water bodies (USGS StreamStats, 2018). The landscape was cleared for agriculture and sheep pasture in the eighteenth century (Pease, 1917). During the late-nineteenth century, dairy farming became the major industry, but by the early-twentieth century Ashfield'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 grist mill in the town of Ashfield (MHC Ashfield, 1982; Field, 2013). Later, in 1762, the first known dam in Conway was built to power a saw mill (MHC Ashfield, 1982; Field, 2013). Grist, saw, fulling, cider, oil, woolen and cotton mills continued to be built through the nineteenth century. Field (2013) mapped 28 historic milldams along the main stem of the South River. 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 events 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 of its length 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).

As early Colonial settlers came to the Sheepscot watershed in the late 1600s, forests were clear cut for agriculture and timber, and to make room for port towns (Laser et al., 2009; Sheepscot Valley Conservation Association, SVCA, 2011). Timber harvesting was prevalent until the mid-twentieth century, and logging companies used rivers to move large volumes of timber to mills (Halsted, 2002). Sawmills commonly were built at run-of-the-river dams. Dams also powered the mining, textile, and grain industries in the area. During the nineteenth century, farming declined because crops were difficult to grow with thin, rocky soil and long winters. The watershed is now mostly forested (89%) with a small amount of agriculture (2.5%) and residential land (1.5%; Brady, 2007). Water bodies and wetlands occupy 16% of the watershed (USGS StreamStats, 2018). The SVCA (2011) mapped 41 historic dams in the watershed.

The upper Charles River watershed was only 25% forested by 1850. Numerous dams for water-powered milling existed in town centers throughout the watershed by the mid-nineteenth century. Since then, it has reforested to 52%, and suburban sprawl has established the area as a suburb of Boston (44% developed land; USGS StreamStats, 2018). Water bodies and wetlands cover 13% of the watershed.

2. Methods

To accomplish our goals, we completed the following steps for each watershed: (1) located historic and current dams; (2) mapped legacy sediment terrace extents using Geographic Information Systems (GIS) methods and lidar DEMs (e.g., Stout and Belmont, 2014; Hopkins and Snyder, 2016); (3) used field-based stratigraphic analysis and radiocarbon dating to identify legacy deposits; (4) estimated thickness and volumes of legacy sediment along channels using lidar DEMs; and (5) evaluated our volume estimates by comparing field and DEM measurements of legacy sediment thickness.

2.1. Locations of historic and current dams

We identified the locations of historic dams for two reasons: (1) to use milldam density as a rough measure of historic land use, and (2) to guide fieldwork toward places with likely legacy sediment storage. In the South and upper Charles watersheds, we used nineteenth-twentieth century historic maps available from the Boston Public Library and other documents to locate milldams, along with statewide mapping of existing dams from the Massachusetts Bureau of Geographic Information Systems. All historic maps were georeferenced in ArcGIS to modern U.S. Geological Survey (USGS) topographic maps

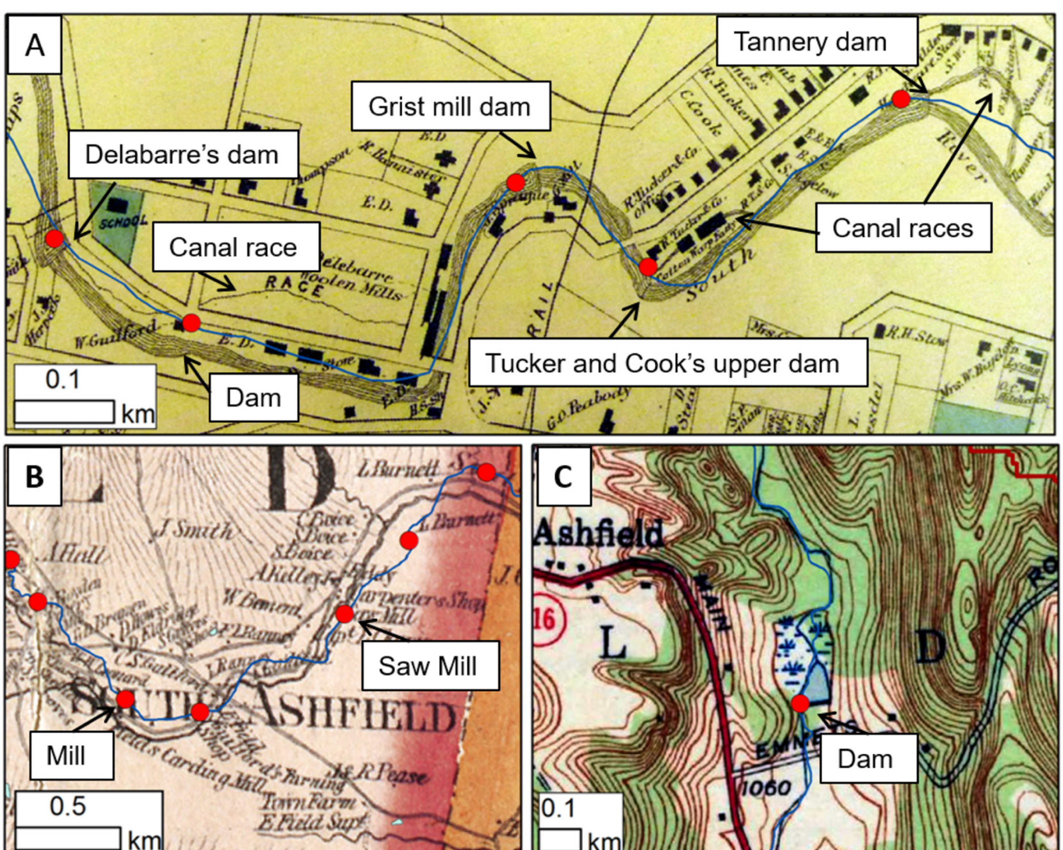

Fig. 2. Portions of historic maps along the South River showing evidence for milldams (red dots). The 1871 historic map of Conway, MA shows five millponds and three canal races (A) and 1858 historic map of South Ashfield, MA has two mill buildings (B). Locations of historic dams, based on these and other sources (e.g., Field, 2013), are placed on the modern South River channel (blue lines, A and B). The 1940 historic topographic map (C) shows a millpond.

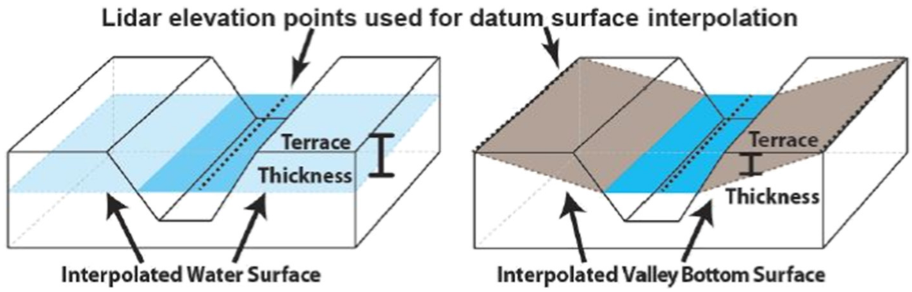

Fig. 3. Illustration comparing the water surface datum (WSD) method (left) and valley bottom surface datum (VBSD) method (right) for estimating legacy sediment volumes. The WSD interpolation method uses only channel centerline surface elevation points and the VBSD method uses a combination of the centerline elevation points and elevation points on the perimeter of the delineated terrace.

using road intersections to provide control points. Unlike the historic maps used by Walter and Merritts (2008) in the Mid-Atlantic region, historic maps in New England rarely had milldams labeled directly, and therefore millponds, races, and mill buildings were used to infer where milldams were located (Fig. 2). Limitations in georeferencing of historic maps, often without available projection information, meant that the locations of historic dams could only be identified to within ± 100 m. Along the main stem rivers and major tributaries, we identified dam locations (and other features) based on distance upstream from the mouth or confluence (river km or rkm).

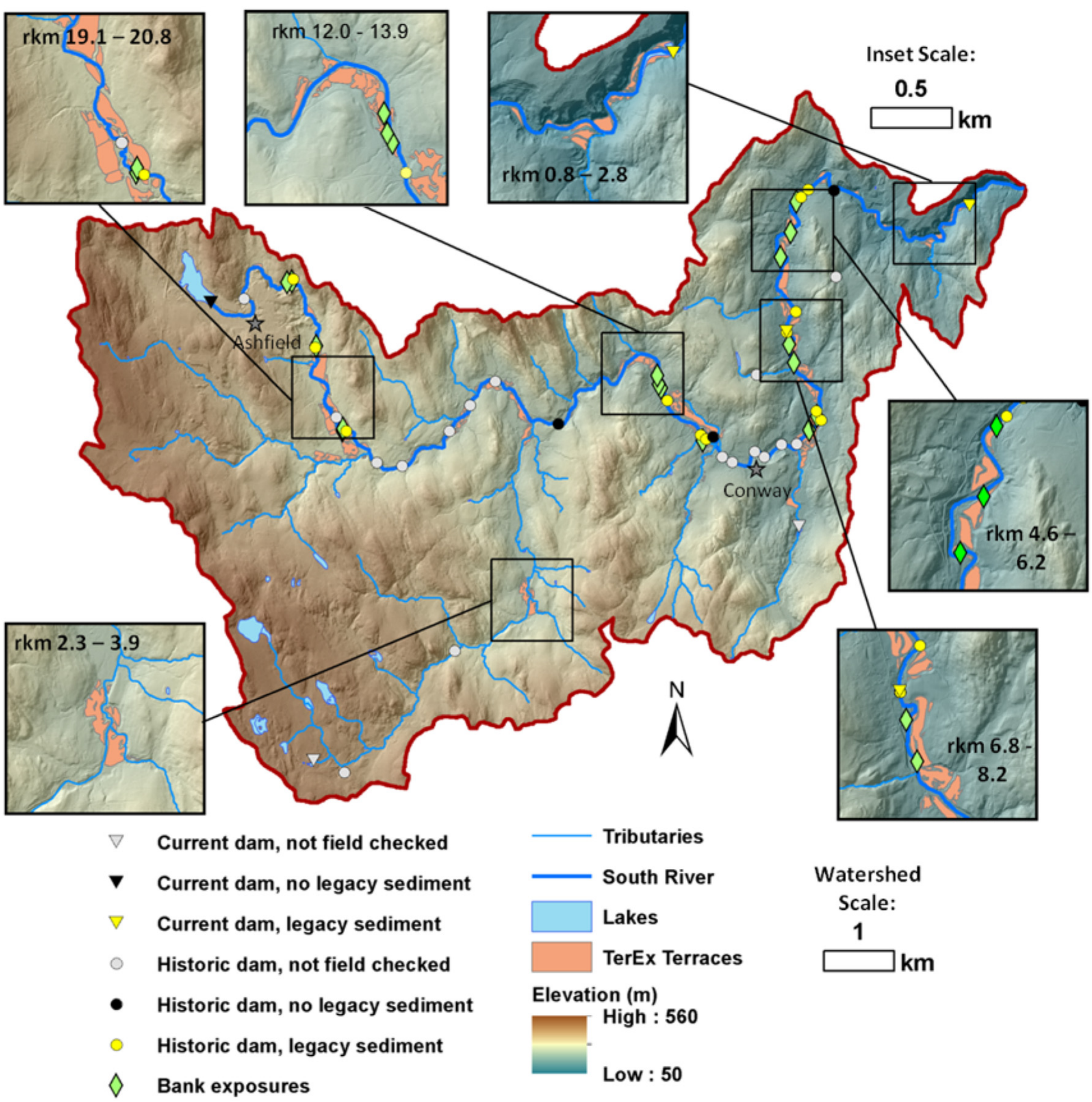

Fig. 4. Watershed map showing locations of field measured bank exposures, current and historic dams, and mapped terraces with insets of some locations for the South River watershed. Current and historic dams are colored based on if the dams were field checked and do or do not have legacy sediment. Of the 37 mapped dams, 18 were visited, and 14 have legacy sediment. Base image is 2 m lidar DEM with hillshading.

The Sheepscot Valley Conservation Association (SVCA, 2011) compiled a table of current and historic dams in the Sheepscot River watershed, which we used for this study. We also used online mapping available in the Maine Stream Habitat Viewer (MSHV, 2008) to find four dams not identified by the SVCA (2011). We also used historic topographic maps from circa 1910 and 1945 to aid in identifying dam locations.

2.2. Terrace mapping and longitudinal profiles

We mapped potential legacy sediment deposits using existing GIS-based methods that map planar surfaces on high-resolution DEMs. Here we use the term "terrace" to refer to these surfaces, whether or not they are active floodplains. Measurements of terrace area 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). We 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 need for manual editing, and an accurate terrace output (Hopkins and Snyder, 2016). TerEx can be incorporated into ArcGIS, which allows for adjustable input parameters and user edits mid-way. To increase accuracy, TerEx allows for user edits to remove polygons mapped on roads, water surfaces, and upland areas.

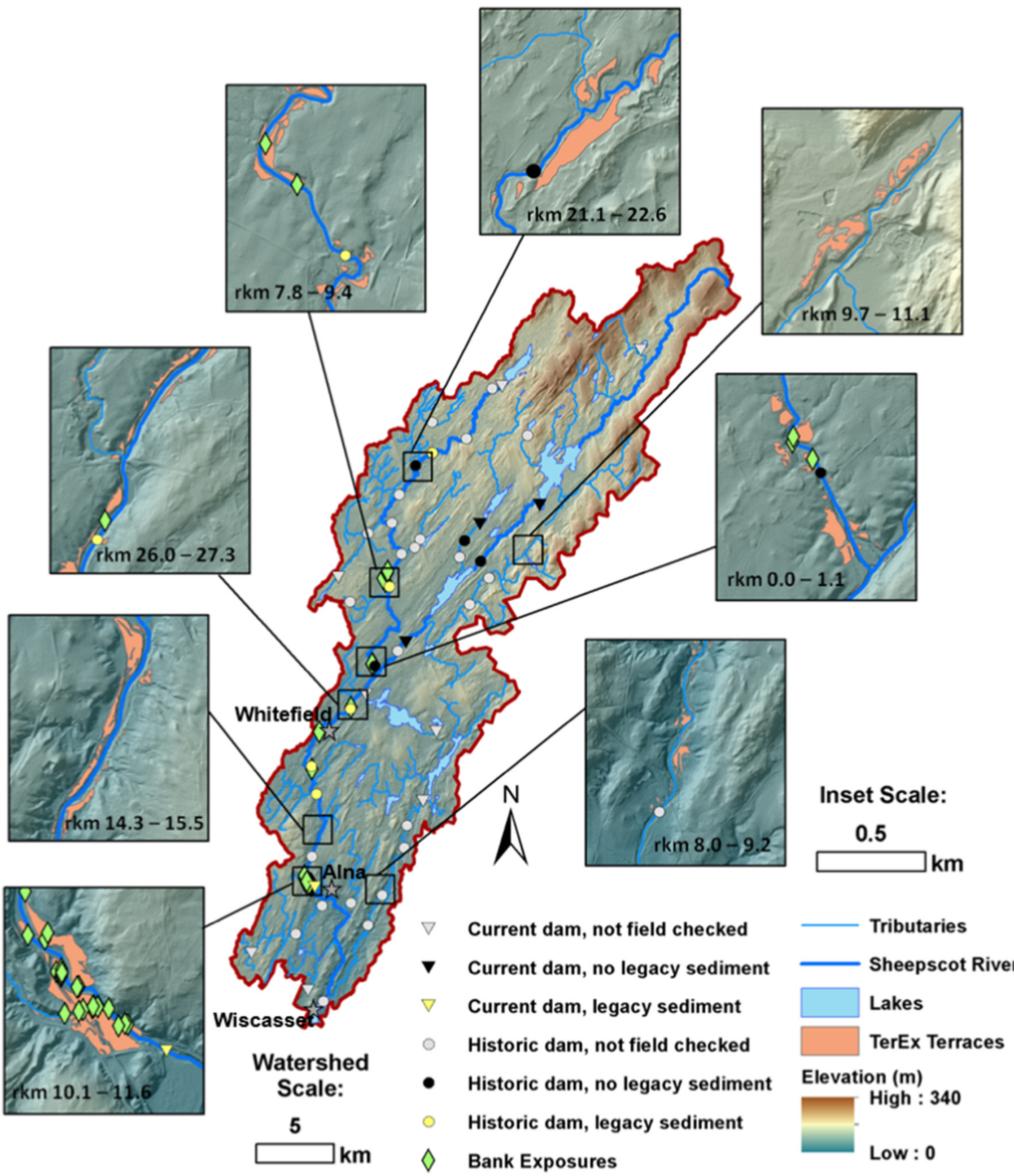

Fig. 5. Sheepscot River watershed map showing locations of field measured bank exposures, current and historic dams, and mapped terraces with insets of some locations. Current and historic dams are colored based on if the dams were field checked and do or do not have legacy sediment. Of the 45 mapped dams, 13 were visited, and 6 have legacy sediment. Base image is 2 m lidar DEM with hillshading.

High-resolution lidar DEMs (with 1–2 m horizontal resolution and 5–20 cm vertical accuracy) are available for all three study watersheds. 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 comparable heights to historic dams (<3 m). Manual delineation and delineation using the TerEx toolbox with user edits indicate that, along the South River, estimates of terrace area generated by TerEx are ~20% less than those produced by the manual delineation technique. Hopkins (2014) found a similar difference between manual and TerEx delineation of terraces upstream of four dam sites on the Sheepscot River. TerEx with user edits was then used for all of the rivers and tributaries in each watershed. The TerEx method did not work well in most parts of the low-gradient upper Charles River watershed, so we focused on manual terrace mapping there, as discussed in Section 3.2. TerEx input parameter values ranged as follows: change in terrace

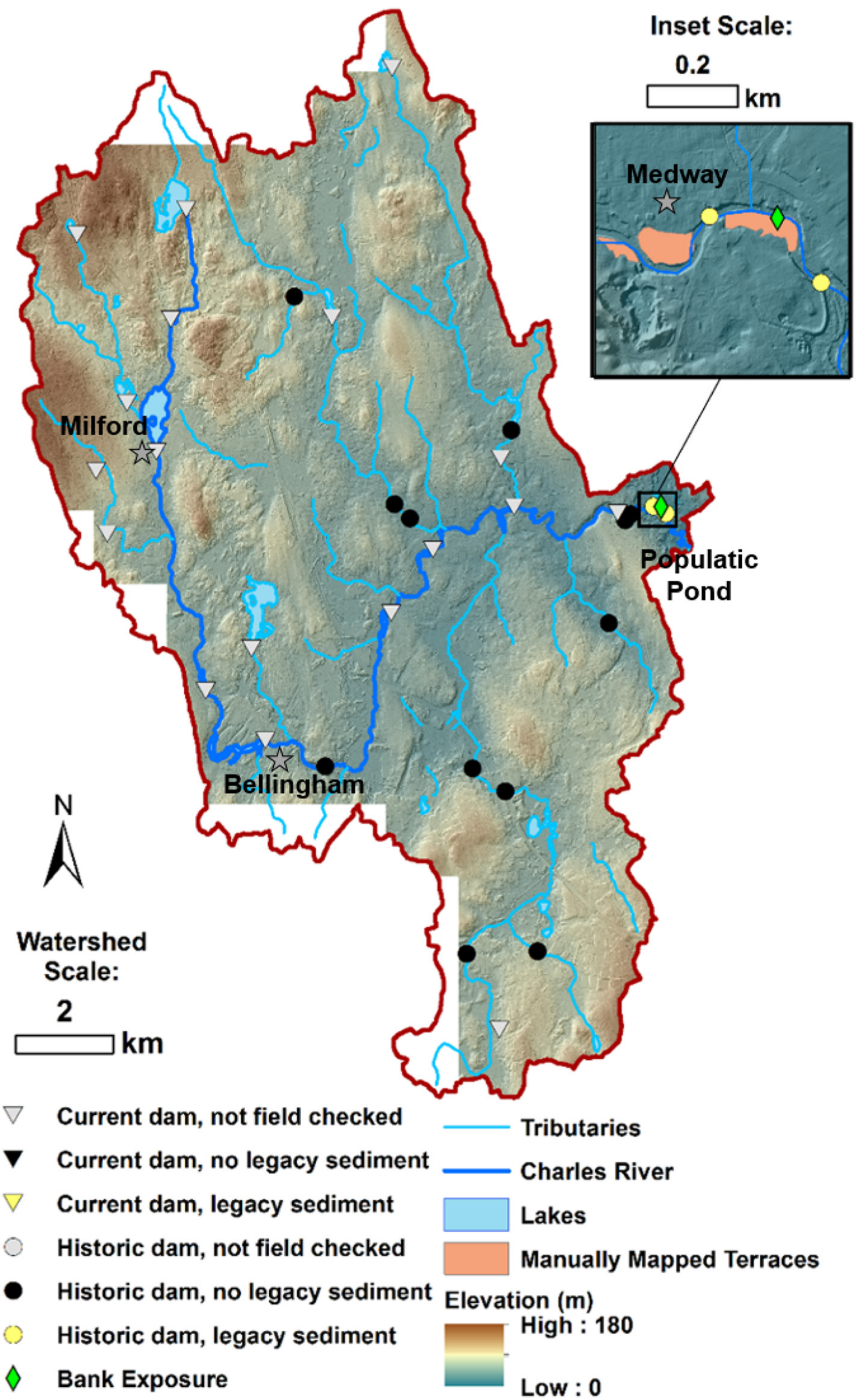

Fig. 6. Lidar DEM of the upper Charles River watershed with hillshade overlay. The watershed was delineated upstream of Populatic Pond. Of the 23 mapped dams, 14 were visited, and two have legacy sediment Inset shows mapped legacy sediment terraces near the town of Medway, and the bank exposure sample site 1.64 river km upstream from Populatic Pond (Fig. 13). Base image is 1 m lidar DEM with hillshading.

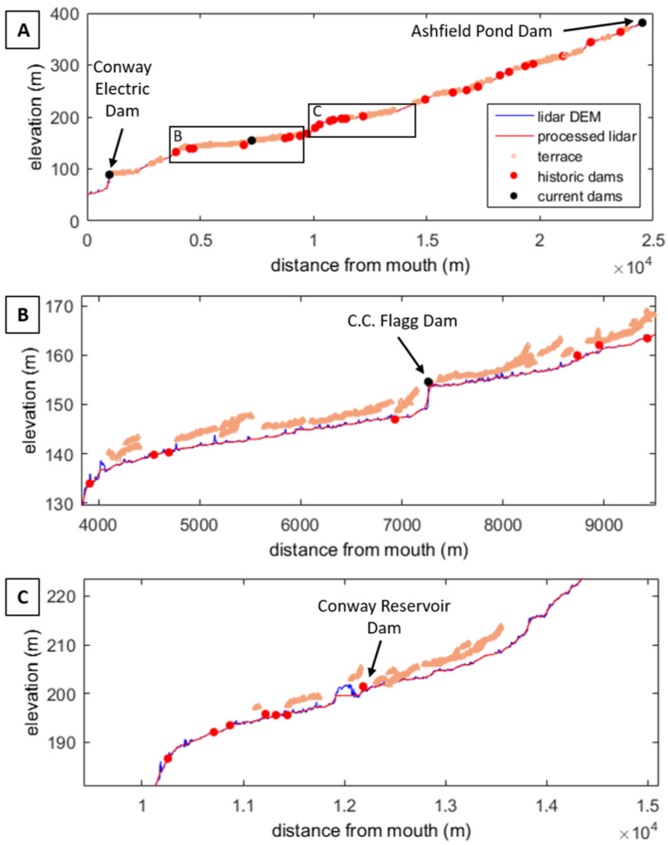

Fig. 7. Longitudinal profile of the South River from a 2 m DEM (A), with detailed views of two segments (B and C). The blue lines are an estimate of the water surface extracted from lidar DEM data; spikes in the data are from bridges or unfiltered errors. The red lines are the processed lidar showing a smoothed profile.

elevation (local relief), 0.3–0.5 m; focal window (size of moving window), 3–5 m^2; minimum terrace area 1–10 m^2, maximum valley width, 75–300 m (see Johnson, 2017 for details on TerEx parameters used in each watershed).

For this analysis, we mapped only lower terraces (< 3 m above the channel) thought to be historic in age, based on previous work in the study areas (Field, 2013; Strouse, 2013; Hopkins, 2014; Hopkins and Snyder, 2016). Much higher, likely glacial-age, terraces also occur in the study areas, 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. Longitudinal profiles of mainstem rivers were constructed using the lidar DEMs and the methods of Snyder (2009). Adjacent points on mapped terraces were manually projected onto the longitudinal profiles.

2.3. Field stratigraphic observations and radiocarbon dating

2.3.1. Bank sediment measurements

Field observations of bank exposures, combined with ^{14}C dating, were used to determine whether the material was Pleistocene, Holocene, legacy, or active floodplain deposits. Measurements of estimated legacy sediment thickness and terrace height were also used to calibrate DEM-based methods for estimating legacy sediment volumes (Section 2.5). In each watershed, we visited as many historic milldam locations as we could access within time and permission constraints, to determine the presence or absence of legacy sediment upstream. In places with good bank exposures, we conducted detailed stratigraphic analysis (described below), including at 16 sites in the South River watershed, nine sites in the Sheepscot River watershed, and one site in the upper Charles River watershed. We also used previous analyses of cut banks and soil pits in the Sheepscot River watershed, including nine locations by Strouse (2013) and 17 locations by Hopkins (2014). We conducted wading or canoe surveys to make qualitative observations of bank stratigraphy along 1–10 km lengths of channels in each watershed to assess the continuity of legacy sediment deposits.

In our stratigraphic analysis 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 and recent overbank sedimentation (such as fresh deposits after high-flow events). Samples of organic material were taken wherever present for radiocarbon dating.

The preliminary ages of layers in a stratigraphic column were estimated by examining stratigraphic position, sediment size and color, amount of organic matter, boundary change between layers, and structures found in layers such as cross bedding. Sediment was preliminarily interpreted as legacy sediment if it was found stratigraphically at or near the top of an exposure, brown in color, and composed of sand and silt, which are the typical characteristics observed in these watersheds (Field, 2013; Strouse, 2013; Hopkins, 2014). Layers of pebbles to cobbles near the base were interpreted as likely former channel bars or pre-dam river bed deposits because of their position and grain-size contrast with the overlying material. In the field, thickness measurements of interpreted legacy sediment deposits were made for each bank exposure using a tape measure.

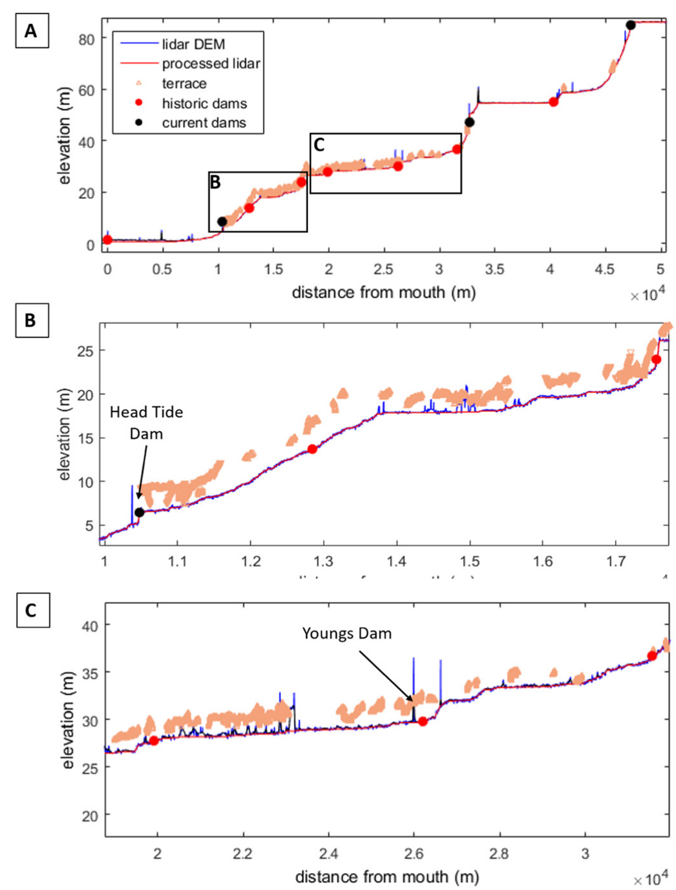

Fig. 8. Longitudinal profile for the main stem Sheepscot River from a 1 m DEM (A), with detailed views of two segments (B and C). The blue lines are an estimate of the water surface extracted from lidar DEM data; spikes in the data are from bridges or unfiltered errors. The red lines are the processed lidar showing a smoothed profile.

Real time kinematic (RTK) GPS measurements with a Leica Viva GNSS GS14 Rover were used to record the location and elevation of each site. 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, we 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 (see Johnson, 2017 for more detail on GPS methods and results). Centimeter accuracy was not always available in the field when trees obscured the view of the GPS satellites by the receiver and/or differential corrections via a cellular internet data connection were not available. In these instances, 15 min 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.

2.3.2. Radiocarbon dating

Radiocarbon dating, along with stratigraphic observations, was used to determine whether bank exposures were composed of recently active floodplain (modern dates), legacy (historic or post-settlement age, approximately 1700–1950 CE), Holocene (i.e., post-glacial but not legacy), or Pleistocene (glacial-age) deposits. We used ^{14}C analyses to date organic macrofossils (pieces of wood, charcoal or leaves) 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 presence of sufficient organic material, lack of modern roots found in the layer, and to test preliminary age interpretations made based on stratigraphy.

In the field, the organic material was removed using metal trowels, taking care to avoid contamination with human hands and modern organic material, then placed in plastic bags. 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. From the South River watershed, four samples of wood and charcoal were selected from four different bank exposures. In the Sheepscot River we selected 14 samples from various exposures. In the Charles River, two samples from one bank exposure in the town of Medway were dated. The samples were sent for analysis at Woods Hole Oceanographic Institution, using accelerator mass spectrometry.

The accuracy in determining ^{14}C ages can be compromised by contamination, variations in the ^{14}C amount in the atmosphere, and the old wood problem, all of which are relevant to our study. 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 modern roots come into contact with the 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 roots were present in the stratigraphic column. A ^{14}C 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. We used the INTCAL13 curve on the CALIB Radiocarbon Calibration program online (Stuiver and Reimer, 1993) to calibrate all ^{14}C dates (Supplementary data). In the last 450 yr, the “wiggles” of the calibration curve are magnified and therefore the true age of a historic 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 and only later transported and buried or re-buried in a historic millpond.

2.4. Legacy sediment volume calculations

2.4.1. Water surface and valley bottom surface methods

Volumes of legacy sediment can be estimated using DEM-based methods by multiplying terrace area by thickness (Hopkins, 2014). Terrace area mapping methods are well established (Section 2.2), but the

Table 1
Results of radiocarbon analyses (from the Woods Hole Oceanographic Institution NOSAMS facility). Full calibration results are in the Supplementary data (Appendix A).

Location	Type of material	Depth (cm)	Calibrated median probability date (CE)	^{14}C age (yr BP)	Age error (years)	δ^{13}C	Fraction modern	Fraction modern error	Accession #
South River									
rkm 5.94	Charcoal	120	1765	155	20	−25.72	0.9810	2.3×10^{-3}	OS-122193
rkm 12.46	Charcoal	106	1781	210	20	−25.79	0.9739	2.1×10^{-3}	OS-122178
rkm 19.41	Plant/Wood	68		>Modern	NA	−27.08	1.6397	3.6×10^{-3}	OS-122195
rkm 21.06	Plant/Wood	123	1772	190	20	−24.70	0.9766	2.2×10^{-3}	OS-122196
Sheepscot River mainstem									
rkm 10.75	Bark	137	1837	105	30	−23.70	0.9867	3.6×10^{-3}	OS-76871
rkm 10.75	Bark	152	1557	350	25	−22.82	0.9574	3.3×10^{-3}	OS-76872
rkm 10.75	Bark	164	1626	265	50	−27.21	0.9676	5.9×10^{-3}	OS-77293
rkm 10.75	Bark	187	1768	180	25	−27.03	0.9777	3.2×10^{-3}	OS-76773
rkm 10.8	Plant/Wood	130	1840	115	15	−27.11	0.9855	2.1×10^{-3}	OS-122181
rkm 11.1 island	Bark	144	1766	175	20	−25.04	0.9783	2.1×10^{-3}	OS-122180
rkm 11.1 island	Plant/Wood	161	1765	175	15	−25.92	0.9785	2.1×10^{-3}	OS-122197
rkm 19.7	Plant/Wood	95	1775	190	15	−25.45	0.9765	2.0×10^{-3}	OS-137107
rkm 23.0	Plant/Wood	80	1870	75	20	−25.55	0.9907	2.5×10^{-3}	OS-137169
rkm 23.0	Charcoal	110	1840	115	15	−25.32	0.9859	1.9×10^{-3}	OS-137105
rkm 26.3	Plant/Wood	65	1656	245	20	−25.26	0.9700	2.3×10^{-3}	OS-137106
West branch Sheepscot River									
rkm 9.5	Bark	58	292	1750	30	−24.93	0.8040	2.9×10^{-3}	OS-76774
rkm 9.5	Bark	62	1771	220	25	−26.06	0.9730	3.0×10^{-3}	OS-76775
rkm 9.5	Bark	76	1775	175	40	−24.40	0.9784	4.7×10^{-3}	OS-76776
Charles River									
rkm 1.64	Plant/Wood	83		>Modern	NA	−28.25	1.1346	2.5×10^{-3}	OS-122231
rkm 1.64	Plant/Wood	178	1352	655	25	−26.91	0.9219	2.7×10^{-3}	OS-122232

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. We used the elevation of the water surface within the river channel to estimate the elevation of the base of legacy sedimentation. This assumption is reasonable because we observe that streams typically erode to near the original base level after a dam is breached or removed (Walter and Merritts, 2008), and this level is generally near the water surface in places with breached milldams. We test and discuss the validity of this assumption below. The water surface datum (WSD) surface is nearly flat in an orthogonal direction from the river centerline elevations, extending to the edge of the terrace or valley wall (Fig. 3). A second datum surface tested has a non-horizontal surface orthogonal to the river channel. This datum plane begins at the river centerline and extends to elevation points along the valley-side edge of the delineated terrace; this is referred to as the valley bottom surface datum (VBSD) and circumscribes a trapezoidal geometry (Fig. 3). The VBSD method produces some negative thickness values along the edges of terraces and these values are 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 (see further discussion in Hopkins (2014)).

To create these datum surfaces in ArcGIS, center lines were estimated manually from recent topographic maps and high resolution DEMs, and converted to points spaced every 1–2 m (depending on the DEM resolution). For the VBSD method, points were also placed along the outside perimeter of each mapped terrace extent. The elevation values at these points 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 from 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 steps used in ArcGIS, is provided by Johnson (2017).

For both 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

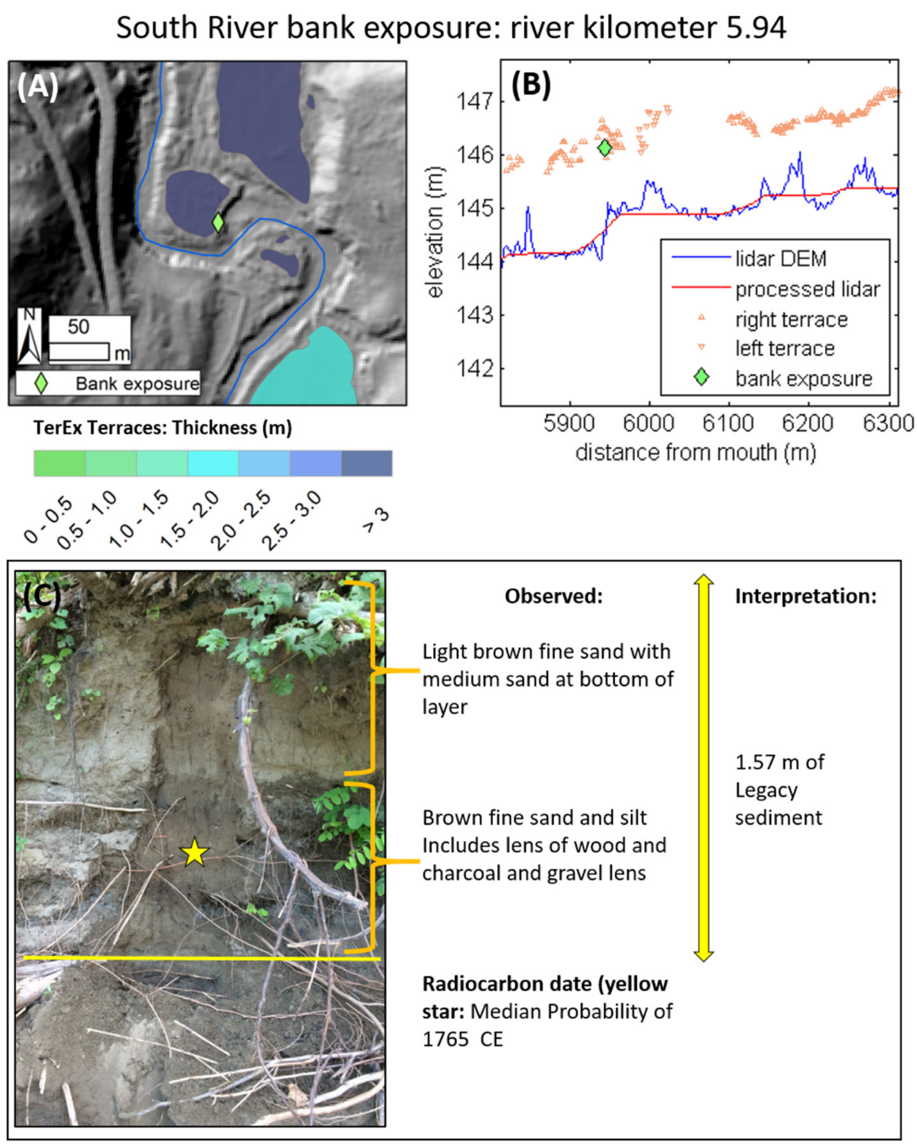

Fig. 9. (A) Terrace mapping of an area on the South River at river kilometer 5.94, with associated average sediment thickness for each mapped polygon (flow to north; Fig. 4). (B) Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure. (C) Field photograph of 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.

thickness values are then multiplied by their pixel area and summed to provide an estimate of volume. The two datum surfaces bracket the range of possible volume estimates; the WSD method provides a maximum and the VBSD a minimum estimate.

2.4.2. TerEx 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 assumes that the stream water surface is at an elevation less than or equal to the terrace sediment boundary with the underlying lithology, similar to our approach. As part of the 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, similar to the WSD method. Volumes of sediment can be estimated by multiplying each given terrace area by the average thickness for each terrace polygon.

2.5. Comparing lidar DEM to field measurements of sediment thickness

To check volume calculations (Section 2.4), field-measured legacy sediment thicknesses made at bank sites throughout each study watershed were compared with the equivalent measurements from lidar DEMs. The DEM pixel closest to where the RTK GPS survey point was taken in the field was chosen to estimate the terrace or floodplain surface elevation. The adjacent river water surface elevation was then subtracted from this to measure the sediment thickness. We refer to this as the “point measurement” of sediment thickness from the lidar DEM. The point measurement was also compared to the field-measured height from water surface to bank top, which should be approximately equivalent quantities if the stage on the lidar DEM is similar to that on the day the field surveys. Once volume calculations were completed (Section 2.4), thicknesses from each method were also compared to field-measured thicknesses. The thicknesses from the coincident pixel of each bank exposure are recorded from the water surface

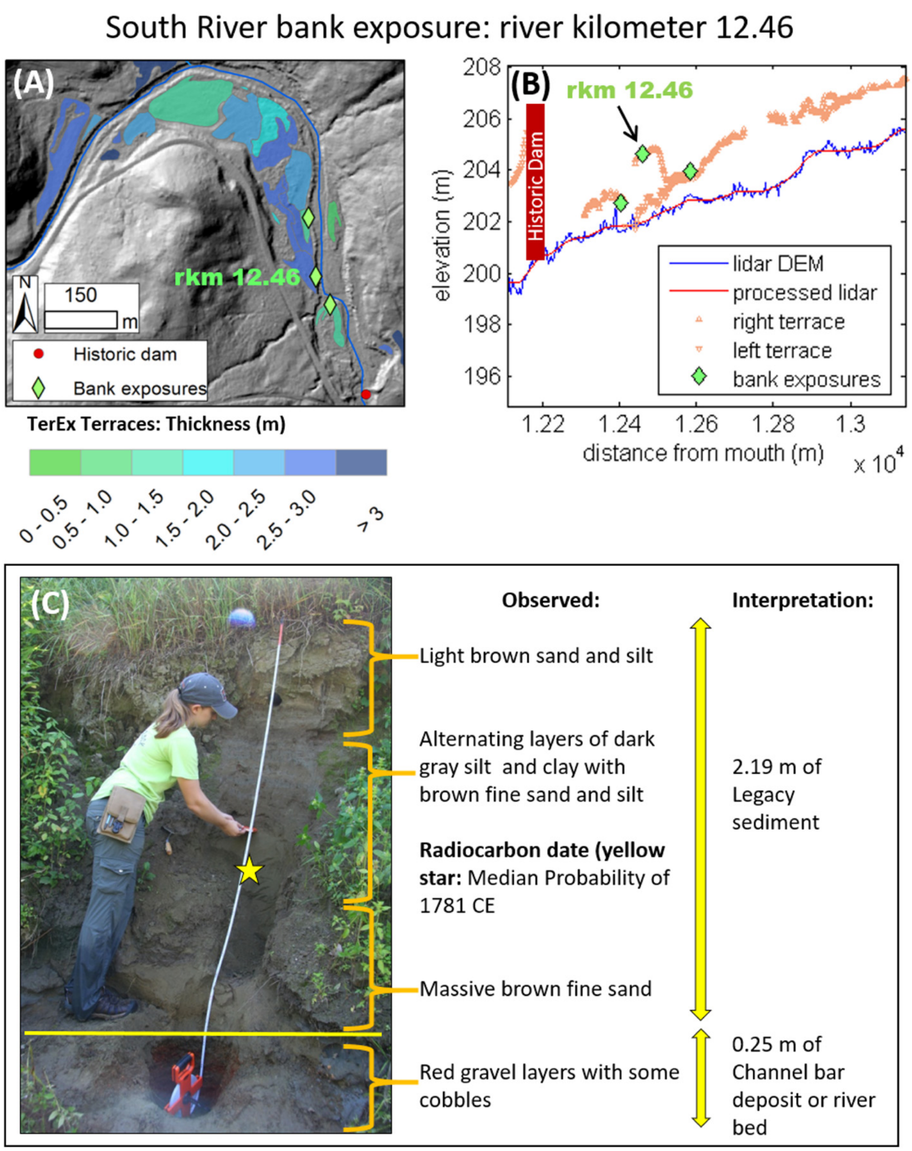

Fig. 10. (A) Terrace mapping of an area on the South River at river kilometer 12.46, with associated average sediment thickness of each mapped polygon (flow to east; Fig. 4). (B) Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure. Historic dam height is a maximum based on remnants; the spillway was likely lower. (C) 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.

datum (WSD) and valley bottom surface datum (VBSD) methods. Although these values are similar to the lidar measured thicknesses described above, they differ somewhat because of variations in the IDW interpolation of the elevation of the centerline to the adjacent terrace edge. TerEx (Stout and Belmont, 2014) produces one thickness for each polygon delineated and these are recorded for each bank exposure as well.

We use two methods to evaluate our comparisons. First, we calculate average deviation between the lidar and field measurements (absolute and percentage). Second, we calculate the percentage of the lidar measurements that agree within ±50% of the field measurements.

3. Results and interpretations

3.1. Location of historic and current dams

Thirty-two breached historic dams and another five intact dams were found in the South River watershed (Fig. 4). We field checked 18 dams in the watershed and 14 of those have evidence of legacy sedimentation. The South River watershed has a density of 0.49 milldams/km^2. Walter and Merritts (2008) calculated the number of mills in counties for the entire eastern United States based on 1840 census records, and they estimated a mill density of 0.12 mills/km^2 for Franklin County, where the South River watershed is located (Fig. 1A). This difference likely reflects (1) the high concentration of dams in the relatively high-relief watershed, as compared with the county as a whole, and (2) that we compiled all of the dams that have existed in the watershed, not just those in 1840.

Forty-five dams were mapped in the Sheepscot River watershed, with 12 dams still intact (Fig. 5). Thirteen dams were field checked, and six show evidence for legacy sediment. Walter and Merritts (2008) calculated a density of 0.07–0.10 mills/km^2 for the counties included in the Sheepscot River watershed (Fig. 1A). Our milldam density calculation of 0.08 milldams/km^2 is in this range.

In the upper Charles River watershed, 23 dams were located on historic maps from the 1850s (Fig. 6). Of these, nine are still intact. We field checked 14 dam sites, and two showed evidence for legacy sedimentation. The dam density for the watershed in the 1850s was 0.18 dams/km^2, which is similar to the 0.10–0.13 mills/km^2 for the three counties included in the watershed found by Walter and Merritts (2008; Fig. 1A).

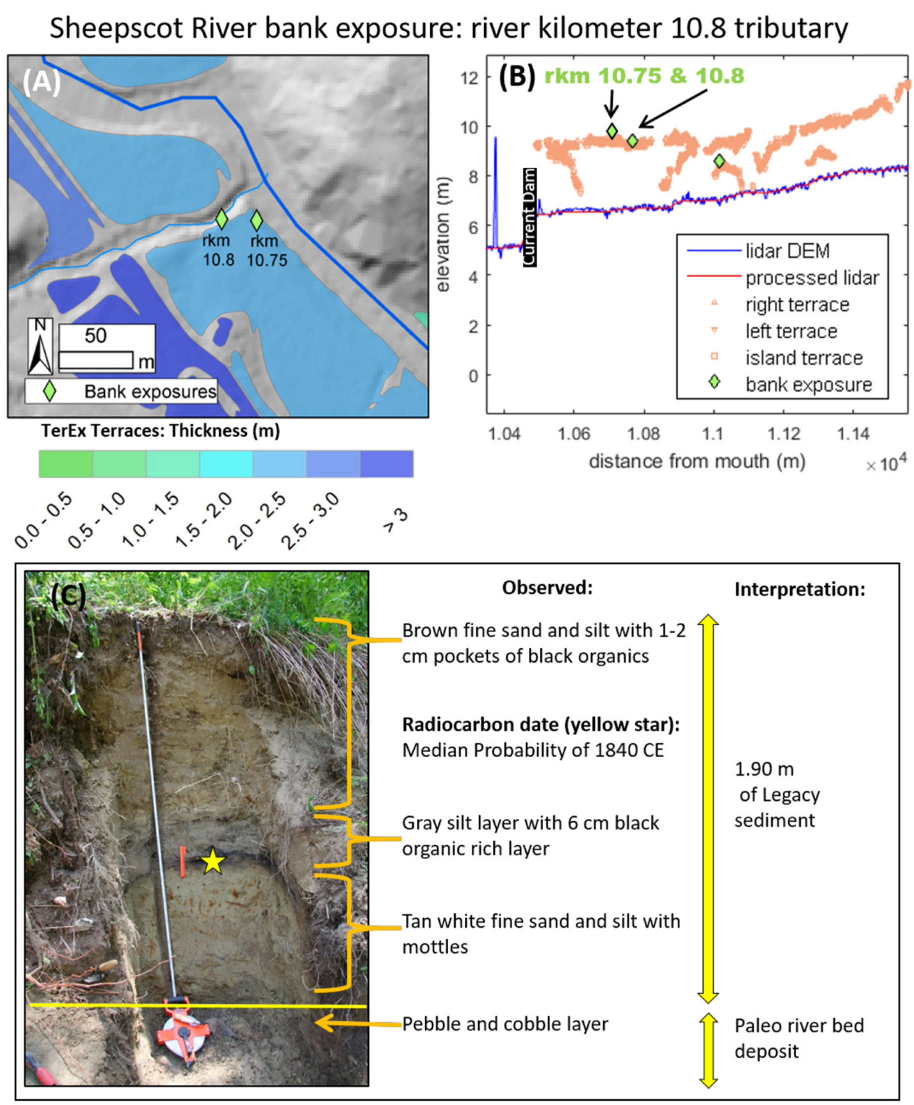

Fig. 11. (A) Terrace mapping of an area on a small tributary of the main stem Sheepscot River at river kilometer 10.8, with associated average sediment thickness of each mapped polygon (flow to the southeast; Fig. 5). (B) Longitudinal profile with TerEx-mapped terraces shown and RTK GPS elevation of the bank exposure. (C) 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.

3.2. GIS terrace mapping and longitudinal profiles

Terraces were mapped for the South River and all tributaries using TerEx toolbox (Stout and Belmont, 2014; Fig. 4). 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, which likely reflects the greater supply of glacial sand and gravel available in the main stem valley, as opposed to the surrounding uplands (Fig. 1B).

After user edits, TerEx delineated a terrace area of 9.6×10^5 m^2 along the Sheepscot River main stem and West Branch, and 5.3×10^5 m^2 on the tributaries (Fig. 5). The total area of terraces is 0.3% of the watershed.

The TerEx (Stout and Belmont, 2014) method was ineffective at locating terraces in upper Charles River watershed. The low relief of the landscape made it difficult for the program to identify terraces, as opposed to floodplains, wetlands and adjacent hillsides. We concluded that manual mapping was more useful and accurate in the relatively small watershed. Clear legacy sediment terraces were observed only upstream of two historic dam sites in Medway (Fig. 6). The area of these terraces is 1.7×10^4 m^2.

Longitudinal profiles were created for the South River, Sheepscot River and the West Branch Sheepscot River, including the TerEx-mapped terraces (i.e., likely legacy sediment terraces) along each channel (Figs. 7 and 8). In general, mapped terraces are approximately parallel with the channel profile.

3.3. Field stratigraphic observations and radiocarbon dating

3.3.1. South River watershed

In the South River watershed, we made detailed observations at 16 bank exposures (Fig. 4). Each had massive, fine grained sand and silt layers ranging from 40 to 219 cm thick. We collected and radiocarbon-dated samples at four sites, with median calibrated dates ranging from 1765 CE to modern (Table 1). Here we describe in detail two sites.

The bank exposure at 5.94 km is 1.2 km upstream of a historic dam (Fig. 9). The exposure was 157 cm thick, with 50 cm more of slump material to the water surface. The top 69 cm was light brown, fine sand grading to medium sand. The bottom 88 cm of sediment was fine brown sand. A charcoal sample taken at 120 cm has a calibrated median age of 1765 CE (Table 1). This exposure of 157 cm 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 (Fig. 10). The longitudinal profile at this location shows two terrace levels, which are likely the result of cutting and filling. The dam failed at least twice, in 1869 and 1878 (Field, 2013). The exposure at 12.46 rkm is 244 cm thick, and the top 48 cm consisted of light brown sand and silt. The middle 72 cm had layers of dark gray silt and clay alternating with brown fine sand and silt. The next 99 cm includes more brown fine sand. A charcoal sample was taken 106 cm from the top and had a calibrated age with a median probability age of 1781 CE (Table 1); therefore, this layer is interpreted to be legacy sediment. The bottom 25 cm layer of this bank exposure consists of 2 cm layers of red rounded gravel that coarsens down. Some cobbles were found throughout the bottom layer. This layer is interpreted to be a pre-historic river bed or channel bar deposit, with the red coloring consistent with long duration (centuries-millennia) groundwater flux.

All of the exposures observed in the South River watershed include brown sand, which we interpret as legacy sediment, consistent with the historical dates from the sites described above (Figs. 9 and 10; Table 1). All of the exposures extend from the terrace to the water surface (or a slump block) with no basal layer present (see detailed stratigraphic descriptions in Johnson, 2017). Six exposures have a basal layer of pebbles and cobbles, which we interpret as the pre-dam river bed, 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 (Fig. 4); we interpret this clay as a likely glacial lake deposit, based on mapping elsewhere in the watershed (Emerson, 1898; Stone and DiGiacomo-Cohen, 2010).

3.3.2. Sheepscot River watershed

We studied bank exposures at 35 sites in the Sheepscot River watershed (Fig. 5), and collected 14 organic samples for ^{14}C dating at seven sites (Table 1). In all cases, the stratigraphically lowest samples yielded historical dates, with calibrated median ages from 1656 to 1840 CE, supporting our interpretation of legacy sediment. At two sites, stratigraphically higher samples yielded older dates (292 CE and 1557 CE), but we interpret these as remobilized old wood.

Here we focus on observations upstream of Head Tide Dam, based on six bank exposures from 10.75–11.1 rkm (Fig. 5). A wooden, run-of-the-river dam was originally built at this site in the 1760s to power a grist mill, and later a saw mill (Halsted, 2002). The dam was breached during a spring flood in 1896, and was replaced by the modern concrete structure in 1916. In 1952 and 1956 the 4-m-high modern concrete 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 raise stage upstream, particularly at high discharge, and we have observed overbank sedimentation of silt and fine sand after recent flood events, indicating that this surface remains an active floodplain.

The 10.8 rkm right bank exposure is in a small tributary valley ~40 m from the confluence with the Sheepscot River, and measured 200 cm

Fig. 12. Photographs of cut planks found sticking out of exposed banks at river kilometer 10.6 (A) and 26.3 (B) along the Sheepscot River. Wood from the rkm 26.3 exposure had a median calibrated radiocarbon date of 1656 CE, with a 2σ range of 1641–1668 CE (77%) and 1782–1797 CE (22%), indicating that it is from the post-settlement period.

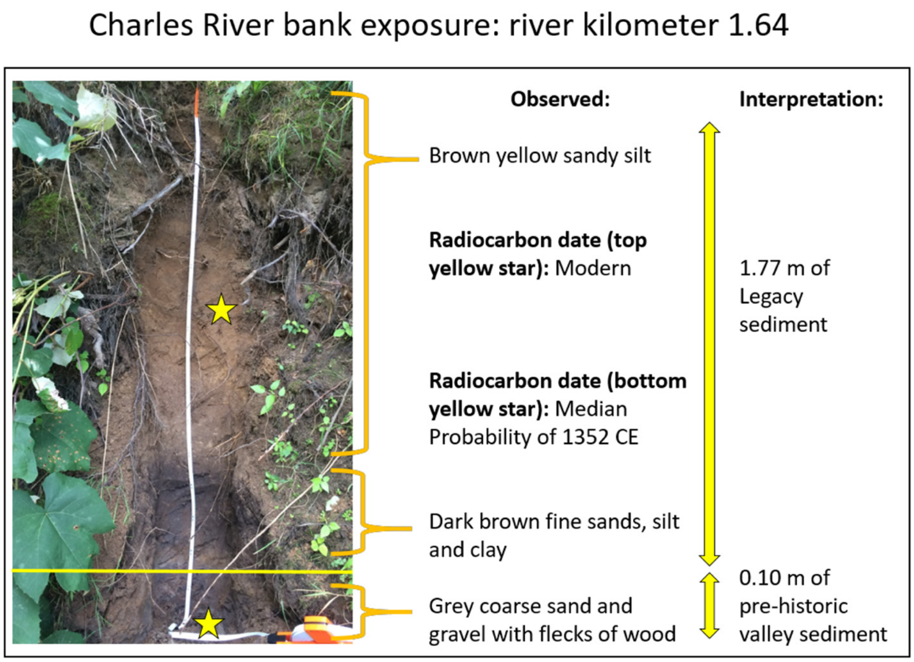

Fig. 13. Photograph of the bank exposure on the Charles River at Medway (river km 1.64; Fig. 6), including stratigraphic section description and two ^{14}C dates.

thick (Fig. 11). The top 80 cm was brown silt and fine sand. The middle 50 cm was a gray silt layer with a 6-cm layer of black organic rich material. The bottom layer was 60 cm of tan white silt and fine sand. There was a pebble and cobble layer at the base of the exposure. The sample from the black organic rich layer at 130 cm from the top of the bank had a median calibrated age of 1840 CE (Table 1). A minimum of 130 cm from the top of this bank exposure is interpreted to be legacy sediment. Because similar silt and fine sand was 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. This interpretation is consistent with the >187 cm of sediment deposited after 1768 CE at a nearby right-bank exposure (Table 1; Fig. 11; Strouse, 2013).

The exposures at rkm 10.8 (Fig. 11) and 11.1 have basal layers of pebbles-cobbles and Presumpscot Formation clay, respectively (Johnson, 2017). Some other exposures found upstream of Head Tide Dam and some at Pinhook Dam on the West Branch (described in Hopkins, 2014) have no visible basal layer, but rather fine to medium sand extends to the water surface. These exposures are interpreted to be legacy sediment. In other sites, 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 (Fig. 12). Cut planks are likely from historic sawmills as they are thin, long sections of wood with some flat cut ends. A piece of wood from the 26.3 rkm site yielded a calibrated median date of 1656 CE, with a 2σ intercepts at 1641–1668 CE (77%) and 1782–1797 CE (22%), suggesting a historic age, particularly when noting that the tree could have been >100 yr old when it was sawed.

3.3.3. Upper Charles River watershed

We studied one bank exposure on the upper Charles River at Medway (Figs. 6 and 13). The section extended 1.87 m down from the top of the bank to the modern river level. The top 1.4 m was light brown sand and silt with a 1 cm-thick organic-rich layer at 0.83 m. Radiocarbon analysis of a wood sample from this layer yielded a modern date (Table 1). The color changed at 1.4 m to dark brown and the sediment was slightly finer. The lowest distinct unit was a basal gray sandy gravel layer at 1.77–1.87 m, which contained more wood material than the other layers. Radiocarbon analysis of a wood sample from this layer gave a median calibrated date of 1352 CE, with a 2σ intercept of 1281–1320 CE (47%) and 1350–1391 CE (53%). This is the only site where we have a pre-historic

Table 2
Comparison of volume estimates for the study watersheds.

	TerEx Toolbox method volume (m^3)	Water surface datum method volume (m^3)	Valley bottom surface datum method volume (m^3)
South River 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
South River mean volume: $1.9 \times 10^6 \pm 7.9 \times 10^5$ m^3			
soil erosion equivalent: 28 ± 12 mm			
Sheepscot River main stem and West Branch	2.6×10^6	2.7×10^6	8.7×10^5
Tributaries	1.1×10^6	1.0×10^6	2.8×10^5
Total	3.7×10^6	3.7×10^6	1.2×10^6
Sheepscot River mean volume: $2.9 \times 10^6 \pm 1.2 \times 10^6$ m^3			
soil erosion equivalent: 5.2 ± 2.2 mm			
Upper Charles River	NA	2.6×10^4	1.3×10^4
Charles River mean volume: $2.0 \times 10^4 \pm 9.2 \times 10^3$ m^3			
soil erosion equivalent: 0.11 ± 0.05 mm			

Note: uncertainties are the standard deviation of the three calculations.

age, suggesting 1.77 m of legacy sediment, overlying a pre-historic valley-bottom deposit that does not have a well-developed soil.

3.4. Legacy sediment volume calculations

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 (Figs. 3–6; Table 2). Along the main stem of the South River, the volume of sediment estimated by the WSD method is 2.3×10^6 m^3 and by the VBSD method is 7.6×10^5 m^3 (Table 2; Fig. 14). Adding mapping of the tributaries results in a relatively small increase, for a total of 2.5×10^6 m^3 of legacy sediment estimated using the WSD method and 8.2×10^5 m^3 estimated using the VBSD method for the South River watershed. The tributaries include few historic dams or mappable terraces (Fig. 4). In the Sheepscot River watershed the total volumes are 3.7×10^6 m^3 using the WSD

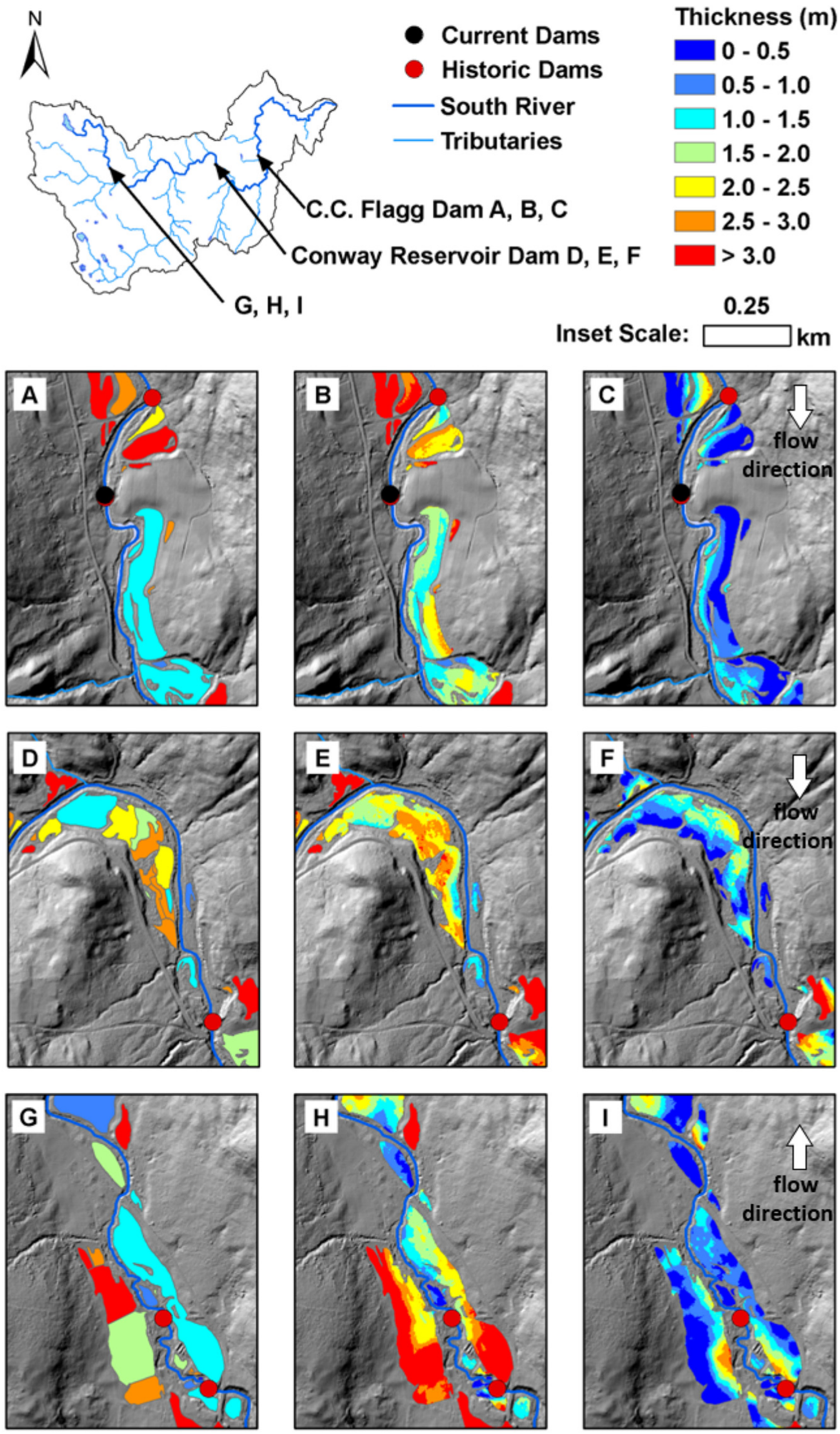

Fig. 14. Legacy sediment thickness maps for the C.C. Flag Dam (A, B, C) area, Conway Reservoir (D, E, F) area, and the area near two unnamed historic dams north of South Ashfield (G, H, I) in the South River watershed. Calculations were done by the Terex Toolbox method (A, D, G), water surface datum (WSD) method (B, E, H), and valley bottom surface datum (VBSD) method (C, F, I). Base map is hillshade image from the lidar DEM. White arrows on the left-hand panels indicate flow direction for each location. Integration of these sediment thickness calculations over whole watersheds yields sediment volumes.

method and 1.2×10^6 m^3 using the VBSD method (Table 2; Fig. 15). The TerEx volume estimates for the South and Sheepscot watersheds are similar to those from the WSD method (Table 2; Figs. 14 and 15). The limited legacy sediment of the upper Charles River has a WSD volume of 2.6×10^4 m^3, and a VBSD volume of 1.3×10^4 m^3 (Table 2).

The total volume of legacy sediment stored in terraces can be divided by watershed area to estimate an equivalent average thickness of soil eroded from the landscape (Table 2). To make this simple calculation, we assume that the densities of soil and legacy sediment are equal. This quantity does not include eroded sediment that might have been deposited elsewhere, such as colluvial, lacustrine and marine deposits. For the South River watershed, we 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 methods, as compared to 12 mm using the VBSD method. For the Sheepscot River, the numbers are 7 mm using the TerEx Toolbox and WSD methods, and 2 mm using the VBSD method. The WSD soil erosion equivalent for the upper Charles River is 0.15 mm, and the VBSD is 0.08 mm.

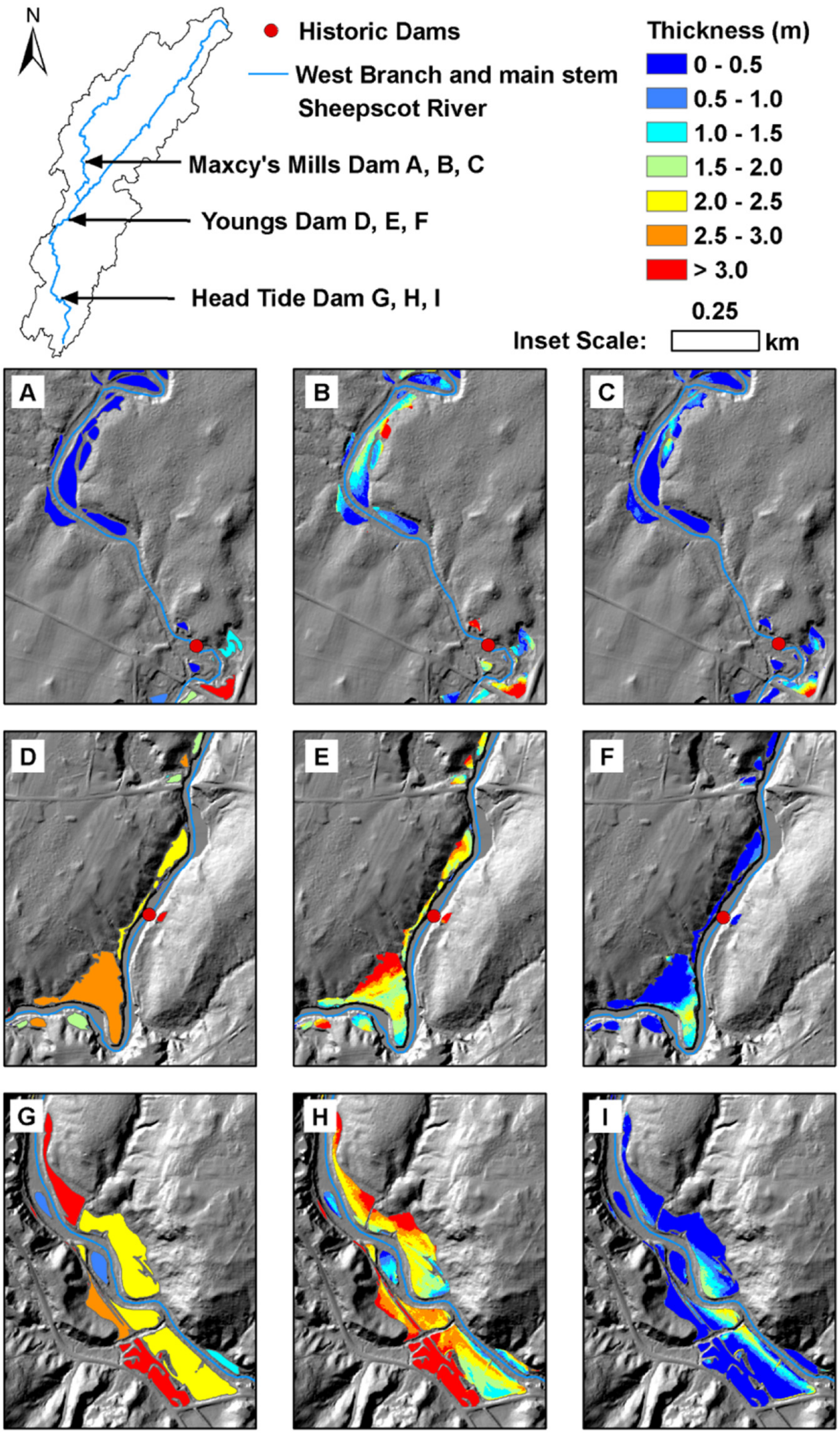

Fig. 15. Legacy sediment thickness maps for the Maxcy's Mills Dam (A, B, C), Youngs Dam (D, E, F), and Head Tide Dam (G, H, I) areas of the Sheepscot River watershed. Calculations were done by the Terex Toolbox method (A, D, G), water surface datum (WSD) method (B, E, H), and valley bottom surface datum (VBSD) method (C, F, I). Base map is a hillshade image from the lidar DEM. Flow is to the south in all panels.

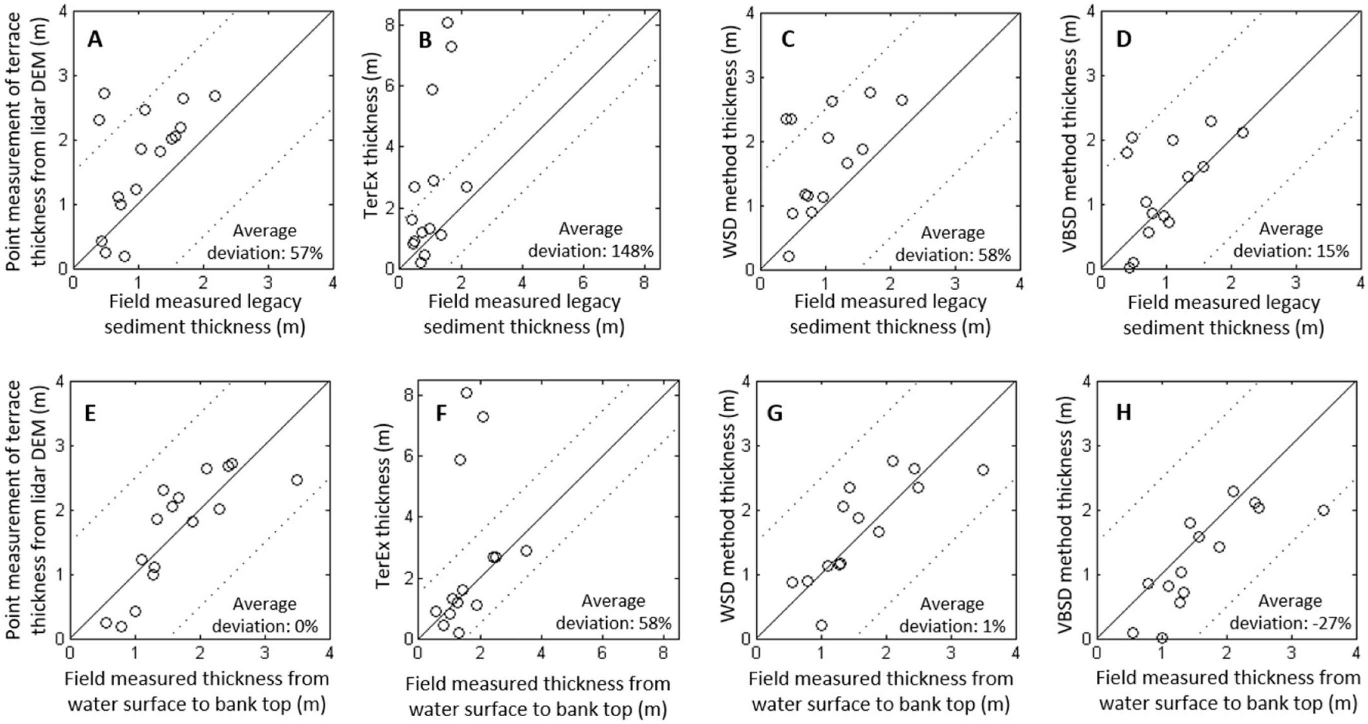

Fig. 16. Comparisons between field measurements and coincident thicknesses estimated from lidar DEMs at bank exposures along the South River (see Fig. 4). A–D compare field legacy sediment thickness estimates and four different lidar DEM terrace thickness measurements. E–H compare field-measured height 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.

3.5. Comparing lidar DEM to field measurements of sediment thickness

Comparisons between field and lidar DEM measurements of legacy sediment thickness were completed for the South River and Sheepscot River watersheds to assess the validity of using DEMs to estimate legacy sediment volumes. The paucity of terraces in the upper Charles River watershed precluded this analysis (Fig. 6). In the South River, point measurements from lidar DEMs have an average deviation 61 cm greater (57%) than field estimates of legacy sediment thickness and have an average deviation of 0% from total field-measured thicknesses

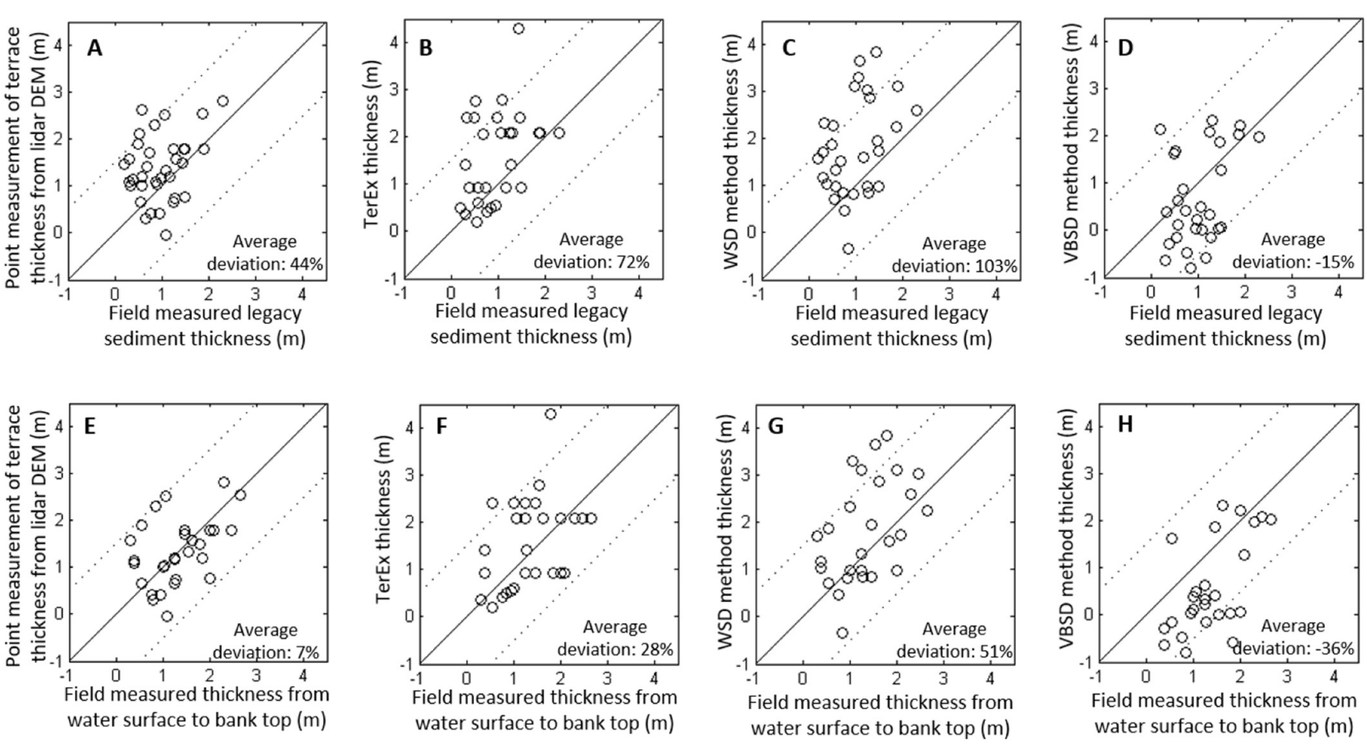

Fig. 17. Comparisons between field measurements and coincident thicknesses estimated from lidar DEMs at bank exposures along the main stem and West Branch Sheepscot River (Fig. 5). A–D compare field legacy sediment thickness and four different lidar DEM terrace thickness measurements. E-H compare field 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.

from water surface to bank top (Fig. 16A, E). In the Sheepscot River, the lidar point measurements average 42 cm greater (44%) than field-measured legacy sediment thickness (Fig. 17A), and 2 cm greater (7%) than the field measured bank top to water surface (Fig. 17E).

In six of our eight comparisons, lidar-derived values of sediment thickness are closer to field measurements of sediment thickness from the water surface to the bank top than to field measurements of legacy sediment thickness (except for the VBSD method comparisons; Figs. 16 and 17). In the South River watershed, 100% of the lidar measurements agree within 50% of the total field-measured sediment thicknesses for three of the comparisons, validating the use of these methods (the point measurements, WSD method, and VBSD method). 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 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% (Fig. 16C). 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% (Fig. 17C). 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 (Figs. 16D and 17D), and probably represents the best volume estimate. The WSD and TerEx methods produce maximum thickness and volume estimates for each watershed.

4. Discussion

4.1. Controls on legacy sedimentation in the three watersheds

Our first goal was to evaluate whether and where legacy sediment is found in formerly glaciated New England watersheds, and to compare it with patterns of legacy sedimentation in the Mid-Atlantic Piedmont. Following Walter and Merritts (2008), our field analysis focused on bank exposures upstream of former milldams because these are likely to be sites where legacy sediment was deposited during the period of land clearing following European settlement. Milldam density is also an approximation for the degree to which the rivers were impacted directly during this period.

Our second goal was to develop and test three methods to estimate the total volume of legacy sediment stored in valley-bottom deposits, thus providing a means to quantify and compare the degree of human alteration of river corridors. In our volume estimates, we used objective methods to map and measure potential legacy sediment terraces along river channels throughout the watersheds. Much of this material appears upstream of dam sites (Figs. 4–6, 16–17), but we did not restrict the analysis to these areas. We have not attempted to differentiate between milldam deposits and other legacy sediment deposits, as did some other researchers (e.g., Donovan et al., 2016). This was not our focus because we did not see obvious differences between millpond and non-millpond locations in either field or lidar analyses.

During wading and canoe surveys along the channels we did not observe differences in sediment texture, color or gain size in bank exposures just upstream of milldams and in locations presumably outside the extent of former millponds. This may be because most of our field analysis took place in locations where rivers are fairly large (>10 km^2 drainage area, third order or greater channels) and dams are relatively small (≤6 m high). In such riverine impoundments, we hypothesize that the process of sedimentation upstream of milldams involves accumulation on former floodplain surfaces that were inundated constantly or frequently after the base-level rise caused by dams. This process is similar to overbank sedimentation that occurs upstream of the backwater effects by dams, particularly during the period of soil erosion after land clearing. This is a difference between our analysis and those of Walter and Merritts (2008) and Merritts et al. (2011), which focus on first- to third-order streams. In our study watersheds, we did not find milldams in many lower-order streams. We also acknowledge that our lidar-based terrace mapping methods may not work well in small, first-order channels that are not well resolved in lidar DEMs with 1–2 m pixel sizes.

In the lidar analysis, mapped legacy sediment terraces were generally parallel with the modern channel (Figs. 7 and 8). We did not observe downstream thickening terraces at most mill dam sites, as seen in some places in the Mid-Atlantic Piedmont (e.g., Merritts et al., 2011; Hupp et al., 2013; Donovan et al., 2016). We interpret this to reflect the processes of sedimentation mentioned; this suggests the possibility that the elevated base-level signal of milldams propagates upstream as accommodation space in the floodplain fills and raises stage during high flow events. In a few locations on the South River terraces thicken upstream of dams (Fig. 7), which could reflect steepening of the channel bed to accommodate a higher sediment load during the period of intense land clearing in the nineteenth century, or more likely, the influence of tributary-mouth alluvial fans on terrace morphology. In the next few paragraphs we consider the observed variations in legacy sediment storage within and between each of the three study watersheds.

The 68 km^2 South River watershed had a milldam density of 0.49 dams/km^2 in the mid-nineteenth century (Fig. 4). 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. The larger 555 km^2 Sheepscot River watershed had a milldam density of 0.08 dams/km^2 (Fig. 5). 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. The 171 km^2 upper Charles River stores much less legacy sediment than the other two (Table 2; Fig. 6), and had a milldam density of 0.18 dams/km^2. The study watersheds have undergone extensive, and broadly similar, changes in land use over the past two centuries. They were deforested for agriculture and timber harvest in the nineteenth century, and then reforested in the twentieth century. The South River and Sheepscot River are both in rural areas (5–6% developed land), while the upper Charles River watershed is suburban (44% developed). The observed variations in legacy sedimentation among the three watersheds likely reflect the interaction of land use, surficial geology and geomorphology.

All three watersheds have glacial deposits that are the likely source of legacy sediment (Fig. 1). Surficial geology mapped at a scale of 1:24,000 for each watershed was used to estimate the area of glacial deposits that might be expected to contribute much of the 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). 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 mostly along the South River main stem. The low supply from glacial deposits in the uplands may be a reason for the relative lack of legacy sediment terraces along the tributaries (Fig. 4; Table 2). 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, 2016). 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 glaciomarine Presumpscot Formation, stream terrace and alluvium deposits, and wetland deposits. The Presumpscot Formation covers 34.4% of the mapped area and is predominately clay. This formation would contribute fine-grained particles to the stream when eroded and therefore it much of the material would travel as wash load in the river. Legacy deposits consist typically of mostly silt and sand, which is consistent with our hypothesized model for legacy sedimentation at milldam sites. The Presumpscot Formation is also extremely cohesive (in places in Maine exposures form near-vertical cliffs >5 m high) and difficult to erode. The upper Charles River watershed contains extensive (37.3%) but relatively thin (less than ~5 m) glacial sand and gravel deposits.

The average gradient watershed average gradient of the South River is 16%, and only 2.5% of the area is water bodies and wetlands. This river has a few confined areas where steep valley walls are composed of glacial material >10 m thick. Other sections of the river are still recovering from a straightened and dammed history and are beginning to meander across floodplains where space is available. In contrast with the South River, the longitudinal profiles of the Sheepscot (Fig. 8) and upper Charles rivers show a series of steps where long low-gradient sections were broken up by short high gradient reaches. The low-gradient sections include lakes, wetlands, and areas where the water is slow-flowing; these sections are sediment sinks (Snyder et al., 2013), and they encompass 16% and 13% of the watershed areas, respectively. These reaches are mostly unincised, with low floodplain wetlands on either side of a single channel. The high-gradient segments of the rivers are controlled by bedrock outcrops and/or glacial deposits. The overall gradient of both watersheds is low (5–7%). We suspect that the more localized nature of legacy sedimentation in these watersheds (compared with the South River) reflects the variations in sediment supply induced by sedimentation in lakes and wetlands.

In the Sheepscot River watershed most legacy sediment terraces are in the lower section, downstream of eroding glacial deposits (Figs. 1C, 5 and 8). Upstream, lakes and wetlands act as sinks for bedload transport; here few legacy sediment terraces are found and many current and historic dams do not show evidence of sediment storage. The situation is similar in the upper Charles River, where the only legacy sediment deposits occur downstream from where the low-gradient river cuts through a thick (>10 m) glacial deposit (Fig. 6). This deposit is not a large sediment source; if all of it was eroded and transported downstream, Populatic Pond, just a few hundred meters downstream of the deposits, has a total volume of 3.71×10^5 m^3, and could easily hold all of this sediment (Table 2; Ingram and Weisberg, 1988). The South River has few lakes and wetlands (2.5%), and these are found in the uppermost areas of the watershed (Fig. 4). With more widespread supply of sand-rich, thick glacial deposits, fewer natural sediment sinks, and a high density of milldams to harness the river's energy and trap sediment eroded from cleared hillsides in the nineteenth century, the South River watershed has more legacy sediment stored in the valley bottom than the lower-gradient coastal Sheepscot and upper Charles watersheds. The importance of sediment supply in dictating where legacy sedimentation occurs contrasts with Mid-Atlantic watersheds, which are generally more sediment transport limited.

4.2. Comparison with observations of legacy stratigraphy in the Mid-Atlantic region

In the Mid-Atlantic region, Jacobson and Coleman (1986) and 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 yr before the present, suggesting the soils accumulated in the Holocene epoch (Walter and Merritts, 2008; Merritts et al., 2011).

In New England, we have observed 0.2–2.3 m of brown sand and silt legacy sediment deposits underlain by several different units, including rounded gravel and cobbles, which we interpret to be the pre-dam river bed (Figs. 10 and 11). We have also observed legacy sediment overlying clay (the glaciomarine Presumpscot Formation in the Sheepscot River and glacial lake deposits in the South River watershed; Johnson, 2017). Legacy sediment has also been observed to overlay cut wood planks in at least two places in the Sheepscot River watershed (Fig. 12). No radiocarbon date has been observed with a pre-settlement age in the South River watershed (Table 1). Two radiocarbon dates with a pre-settlement age were observed in the Sheepscot River watershed (Table 1). At both locations, a stratigraphically lower sample recorded a younger date, constraining the entire deposit to post-settlement age. Only in the upper Charles River do we observe a date that conclusively indicates exposure of the pre-settlement valley bottom (Fig. 13; Table 1). No buried Holocene wetland or floodplain soil has been observed in the South and Sheepscot watersheds. This could mean that the rivers have not yet eroded to these surfaces, or the locations with an older cobble or clay layer have not yet 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 difficult to observe in bank exposures.

5. Summary and conclusions

The three study watersheds in New England have been impacted by human activity, particularly through land-use changes, dam building and breaching (Figs. 4–6). Field based analysis was completed to determine the composition, thickness, and age of legacy sediment. Legacy sediment consists of brown sand and silt. The maximum thicknesses measured are 2.19 m in the South River watershed, 2.30 m in the Sheepscot River watershed, and 1.77 m in the upper Charles River watershed. Radiocarbon dating of organic samples determined that all examined bank exposures contain sediment <300 yr old, which was therefore deposited during the period of historic dam building (Table 1).

Using TerEx-delineated terraces and lidar DEMs, we estimated legacy sediment thickness and volumes. The water surface datum (WSD), valley bottom surface datum (VBSD), and TerEx toolbox (Stout and Belmont, 2014) methods were all effective in measuring volumes. Based on the comparison with field measurements at bank exposures, the VBSD is the most accurate method for measuring sediment thickness (Table 2; Figs. 16 and 17). The WSD and TerEx methods yielded similar results, which represent maximum volume estimates. The three methods provide a range of plausible volume estimates that enable comparison among watersheds.

Past glaciations influenced the study watersheds. As the Laurentide ice sheet retreated, surficial deposits were left in the landscapes, as well as many depressions (lakes and wetlands) that act as sediment sinks throughout the landscapes (Fig. 1). The glacial deposits are likely sources of legacy sediment, because elsewhere thin till and bedrock dominates the landscape. Total volumes of legacy sediment stored in valley bottoms estimated using DEM methods were divided by watershed area to infer an equivalent thickness range of soil eroded from each landscape: 12–37 mm in the South River watershed, 2–7 mm in the Sheepscot River watershed, and 0.08–0.15 mm in the upper Charles River watershed. This variability likely reflects the more extensive, thick glacial deposits available for river erosion and transport in the South River watershed, the higher hillslope gradient and relative lack of natural sediment sinks in the form of lakes, and the high density of nineteenth century milldams in the watershed. Our findings demonstrate the heterogeneity of geomorphic responses to anthropogenic forcings, caused by downstream variations in sediment supply, in the formerly glaciated New England landscape.

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Author contributions

Much of this research was originally presented as a M.S. thesis by K. Johnson. It also includes material from a B.S. thesis by M. Waltner, and M.S. theses by S. Castle (née Strouse) and A. Hopkins. K. Johnson and N. Snyder wrote the text of this manuscript. The other co-authors contributed ideas and edits.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geomorph.2018.11.017.

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