Timber harvest and flood impacts on sediment yield in a postglacial, mixed-forest watershed, Maine, USA

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ARTICLE INFO

Article history:
Received 10 July 2019
Received in revised form 3 December 2019
Accepted 5 December 2019
Available online 16 December 2019

Keywords:
Sediment yield
Land-use change
Extreme hydrologic events
Lake sedimentation

ABSTRACT

The impact of human activities on sediment yield is poorly constrained in the northeastern United States, as in other northern hemisphere forested landscapes previously occupied by Pleistocene ice sheets. This study examines changes in sedimentation in Little Kennebago Lake (LKL), Maine, in relation to extreme hydrologic events and land-use change. Historical records indicate minimal disturbance before the onset of commercial logging after 1891. Sediment cores record >1,200 years of sedimentation and allow comparison of prehistoric and anthropogenic conditions. Variations in sediment yield are evaluated in the context of hydrologic records and reconstructions of road density and timber harvest derived from historical topographic maps and aerial photographs. Cores collected before and after a highly erosive, localized extreme rainfall event in July 2018 provide a template for interpreting clastic layers found earlier in the record. The frequency of these events increased around 1900, with five layers in the previous ~1,100 years and 12 layers from 1900-2018. This timing corresponds to an increase in suspended sediment yield from 2.0 Mg/km²/yr to 6.4 Mg/km²/yr and increased abundance of pollen taxa associated with forest disturbance. A relative lack of discrete erosion events since ~1970, in spite of increasing timber harvest, suggests that modern best management practices may be effective in reducing erosion. The 2018 event is a reminder, however, that ongoing reevaluation of management practices is necessary in light of changing hydrology, in this region and elsewhere.

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1. Introduction

Enhanced erosion and delivery of fine-grained sediment to surface waters in response to changing hydrologic conditions and anthropogenic disturbances poses a threat to water quality and aquatic habitats. The delivery and dispersal of fine-grained sediment affects the distribution of particle-borne contaminants (Axtmann and Luoma, 1991; Coulthard and Macklin, 2003). Excessive fine sediment accumulation in streams degrades habitat (Waters, 1995; Wood and Armitage, 1997) and reduces spawning success (e.g., Greig et al., 2005) and survival of salmonids (Suttle et al., 2004). Instances of land cover alteration and anthropogenic disturbances leading to enhanced sediment delivery are widespread (e.g., Walling, 2004; Montgomery, 2007; Wilkinson and McElroy, 2007; Walter and Merritts, 2008). Much work has examined the impacts of timber harvest and construction of forest roads on the hydrology and sediment yield of mountainous watersheds in the western United States (e.g., Beshta, 1978; Constantine et al., 2005; Jones and Grant, 1996; Montgomery et al., 2000; Wemple et al., 1996) and tropical regions (e.g., Douglas, 1999; Douglas et al., 1999).

The northeastern USA is among the most forested and densely populated parts of North America, and timber harvest is the predominant disturbance impacting regional forests (Brown et al., 2018). Occupied by continental ice sheets during the late Pleistocene, this landscape shares many characteristics with other glaciated regions of northern North America and Eurasia covered by mixed and boreal forest biomes, including soils, vegetation composition, land-use history, and forest management. Areas subjected to recent timber harvest activity, and never affected by agriculture, provide a unique opportunity to investigate the impacts of forestry relative to other land-use activities that...
dominate the history of most temperate broadleaf and mixed forests. Such areas also allow examination of potential impacts of increased forest management in boreal forest landscapes, the second largest global expanse of intact forest ecosystems (Potapov et al., 2008). The predominance of timber harvest as a disturbance to northeastern forests is consistent with the causes of forest-cover change throughout the post-glacial forested landscapes of Eurasia (Achard et al., 2006) and other northern regions (Hansen et al., 2013). In the state of Maine, forests cover 83 % of the land (71,000 km²), and 97 % of the forested area is timberland available for harvest (McCaskill et al., 2016). Regionally, 84 % of forested land is in private ownership (Butler et al., 2016). Changes in ownership away from large corporate timber companies has, in many cases, increased harvesting rates (Hagan et al., 2005; Jin and Sadler, 2006). In addition, increased focus on renewable energy sources will likely further intensify harvesting of forest biomass as a renewable fuel stock (Brown et al., 2018). Greater pressure on forest resources, in combination with ongoing and projected changes in hydrologic conditions (e.g., Collins, 2009; Armstrong et al., 2014; Ning et al., 2015), makes the northeastern USA an excellent analogue for understanding the impacts of land cover alteration on erosion, as well as evaluating the changing sensitivity of post-glacial forested landscapes around the globe to disturbance.

Except for research conducted at the Hubbard Brook Experimental Forest (e.g., Likens et al., 1970; Martin and Hornbeck, 1994) studies on sediment yield from natural and disturbed forested watersheds in the northeastern USA are limited, and the post-glacial landscape is assumed to be relatively insensitive to disturbance (Patric, 1976; Patric et al., 1984; Martin and Hornbeck, 1994). Recent studies nonetheless highlight potential changes in sediment yield related to climate variability and demonstrate persistent multi-year impacts from large-scale disturbances (Cook et al., 2015; Dethier et al., 2016; Yellen et al., 2016). Quantification of baseline or predisturbance conditions is difficult given the legacy of human land-use impacts. Identifying the erosional response to a disturbance is additionally difficult because of the time scales necessary to capture interactions with a suitable range of hydroclimatic conditions (e.g., Croke and Hairine, 2006). These inherent challenges, in combination with the scarcity of existing studies, result in much uncertainty about erosion and sediment yield variability in the northeastern USA, as well as other forested landscapes conditioned by Pleistocene glaciations. Consequently, this study seeks to answer the following questions: (1) What is the natural variability of sediment yield from a forested, post-glacial watershed in the absence of human disturbance? (2) How do land-use changes, including timber harvest and associated road construction, alter sediment yields and the sensitivity of the landscape to hydrologic disturbances? To answer these questions, we developed a continuous 1200-year record of sediment yield from the analysis of lake-sediment cores from northwestern Maine, USA. We assess this record in the context of regional hydrologic events and the timing and intensity of land cover alterations within the lake’s watershed, as reconstructed from historical topographic maps and aerial photographs.

2. Methods

2.1. Study area

Little Kennebago Lake (LKL) is 0.67 km² in area with a watershed spanning 135 km² of temperate mixed forest in the mountains of northwestern Maine (45.21 N, 70.77 W; Fig. 1). Common tree species include Picea rubens, Abies balsamea, Tsuga canadensis, Pinus strobus, Larix laricina, Thuja occidentalis, Betula alleghaniensis, Betula papyrifera, Fagus grandifolia, Acer saccharum, Acer rubrum, Quercus rubra, and Fraxinus americana. The watershed relief is 666 m, with a maximum elevation of 1209 m, and average basin slope of 19 percent. The annual mean precipitation is 135 cm, distributed evenly throughout the year. LKL’s large ratio of catchment area to lake area (201:1) amplifies the signal of terrestrial sediment input, while high gradient tributaries favor rapid routing of sediment to LKL (cf. Fryirs et al., 2007). Upstream lakes likely to interrupt sediment delivery to LKL are limited to the Seven Ponds area in the headwaters of the watershed. The straightforward geometry of the lake and river further simplifies the distribution of terrestrial sediment across the lake. LKL has a single deep basin with a maximum depth of 17 m (Fig. 1C). The Kennebago River is the primary source of surface inflow to LKL, entering from the north and exiting to the south. Given the size and depth of the lake, resuspension of sediment from the central basin is unlikely after initial deposition (cf. Håkanson and Jansson, 1983). Surficial materials in the region are generally characterized by ~5–10 m of basal till (sandy silt and clay matrix) with localized deltaic and kame terrace deposits in the vicinity of LKL (Borns and Calkin, 1977).

The LKL watershed has been and continues to be actively managed for timber harvest. In contrast to many areas of New England that experienced early forest clearance and conversion to cropland or pasture in the 17th–19th centuries (Foster and Aber, 2006), the remoteness of the watershed minimized human impacts prior to the late 1890s. Early Euro-American visitors were drawn primarily by hunting and fishing. Farrar (1878) describes good fishing at LKL and the Seven Ponds, and highlights the lack of roads accessing the region. The first dam (~4.6 m tall) on the Kennebago River (at the site of the present-day Upper Station Dam, downstream from LKL: Fig. 1B) was constructed in 1886 (Kaufman and Paradis, 1992). In 1891, the Kennebago Improvement Corporation was created with the purpose of maintaining the Kennebago River for log transport (State of Maine, 1893). It is likely that logging upstream of LKL began or intensified shortly thereafter. A 1907 description of the forests surrounding Kennebago Lake stated: “the length and difficulty of the [log] drives have prevented any considerable inroads into the spruce, which today remains practically as good a stand as it was fifty years ago” (Defebaugh, 1907, p. 69), suggesting that harvest intensity up until that point remained relatively low. The current 4.6-m high Upper Station Dam was constructed in 1932, primarily to facilitate log drives (Kaufman and Paradis, 1992). It increased water levels upstream as far as LKL. The dam was fitted for hydroelectric power generation in 1952 (Kaufman and Paradis, 1992). The last log drive occurred in 1952 (Palmer, 2004). Subsequently, timber would have been hauled away by truck, likely resulting in an expansion of logging roads around the mid–20th century. Presently, timber harvest continues throughout the upper Kennebago River watershed and remains the primary land use (Fig. 2). There is no evidence that the watershed was ever completely deforested. Current built infrastructure is limited to a network of unpaved (dirt) logging roads and a handful of seasonal camps on the shore of LKL and in the Seven Ponds area. Small dams (~2 m high) exist at the outlets of four of these lakes (Fig 1B). The headwaters location of these structures should minimize impacts on downstream sedimentation.

2.2. Sediment core analysis

We collected surface-sediment cores from the central deep basin (17 m; water depth; 45.135799 N, 70.770003 W) of LKL in June 2017 (core 17-1: 59 cm) and October 2018 (core 18-1: 70 cm). Recovery of an intact sediment-water interface was confirmed in the field. We observed undisturbed sediment overlain by clear water visible through transparent core barrels. A 142 cm
Fig. 1. (A) Map of the northeastern U.S. and adjacent Canada showing the location of the study watershed (panel B). USGS river gauging stations (closed circles; Dia, Diamond River, NH, USGS number 01052500; Car, Carrabassett River, 01047000; Swift River, ME, 01055000; Wild River, ME, 01054200), and NCDC weather station (open circles; Farm, Farmington, ME, GHCND US00172785) used in this study. Also shown is the PRISM Climate Group precipitation estimate for the U.S. on July 3, 2018 (blue shades). Base map is hillshading from ESRI. (B) Elevation map from a 10-m USGS DEM of the Little Kennebago Lake watershed (black line) showing dams (triangles) and other locations and features mentioned in the text. (C) Bathymetric map of Little Kennebago Lake, with 2015 NAIP orthophotograph in the background (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

A single-drive, piston-percussion core (core 17-3) was collected from the same location in June 2017 with partial overlap of cores 17-1 and 18-1. We split and described all cores prior to analysis of magnetic susceptibility at 0.5-cm intervals using a Bartington MS2E surface sensor. We obtained X-radiographs of cores and determined continuous, down-core elemental abundances at 1.0 mm resolution using an ITRAX scanning X-ray fluorescence (XRF) core scanner (Croudace et al., 2006). Cores were scanned using a Mo X-ray source operating at 30 kV and 55 mA with a 10 s exposure time. Percent loss on ignition (LOI) and dry bulk density ($\rho_{db}$) were measured on 1 cm$^3$ subsamples removed from the cores at 1-cm intervals following standard procedures (Dean, 1974). A continuous, composite sequence was constructed using data derived from analyses of cores 17-1 (LOI and $\rho_{db}$), 18-1 (magnetic susceptibility, X-radiograph, and XRF), and 17-3 (all measurements). We aligned overlapping core sections based on correlation of prominent layers visible in the split cores and distinct patterns in the measured data. The composite sequence used the upper 30 cm of cores 17-1 and 18-3 spliced to the section from 10 cm through 142 cm within core 17-3, resulting in a total length of 162 cm. We prepared 1 cm$^3$ subsamples for pollen analysis following standard procedures (Faegri and Iversen, 1989). Pollen residues were mounted in silicone oil and analyzed at 400x to 1000x magnification. We counted at least 300 pollen grains and
Fig. 2. 2015 NAIP orthophotomosaic showing a portion of the LKL watershed and recent areas of timber harvest.
spores of upland plant taxa for each sample and calculated percentage values relative to sum. Chronological control is based on radiotrace stratigraphy and

14C dating. We measured the activity of 137Cs, 210Pb and 214Pb in 1 cm thick, dried and homogenized sections of core 17-1 using a Canberra GL2020R low-energy gamma detector. We derived an age-depth model from the activity profile of excess 210Pb using the constant rate of supply (CRS) method (Appleby, 2008). We determined excess 210Pb by subtracting the 210Pb activity from the lowermost sample that was analyzed (from a depth 57–58 cm). We then validated the 210Pb age-model by comparing the CRS-derived age for the depth of peak 137Cs activity with the historically observed timing of peak fallout in 1963 (Appleby, 2008). Age control prior to 210Pb constraints was determined by accelerator mass spectrometry 14C dating of two terrestrial macrofossils and two bulk sediment samples. We calibrated all radiocarbon ages to calendar ages using the IntCal13 radiocarbon calibration curve (Reimer et al., 2013; Table 1). Our age-depth model for the composite sequence utilizes the CRS-derived 210Pb model for the upper 36.5 cm. We then linearly interpolate between the lowest 210Pb constraint at 36.5 cm and the radiocarbon age at a composite depth of 160 cm. The derivation of the final age model is discussed further in the Results section.

We examined temporal variations in suspended sediment yield for the LKL watershed based on the mass accumulation rate of clastic sediment (MARclastic) per unit area of lake bottom (g cm−2 yr−1) from:

\[
MAR_{clastic} = \frac{SR \times \rho_{db} (100 - LOI)}{100},
\]

where SR is the instantaneous bulk sedimentation rate (cm yr−1) defined by the slope of the age-depth model and \( \rho_{db} \) and LOI are the dry bulk density (g cm−3) and percent mass loss on ignition, respectively at corresponding depths. We converted values of MARclastic to estimates of suspended sediment yield (SSY) in Mg yr−1 km−2 using the equation:

\[
SSY = MAR_{clastic} \times \frac{LA}{CA} \times 10,000 \text{ Mg g}^{-1} \text{ cm}^2 \text{ km}^{-2},
\]

where LA and CA are the lake area and catchment area respectively. This method assumes a uniform MARclastic across the entire lake bottom (biasing towards an overestimate of sediment yields) and 100% trapping efficiency of sediment within the lake (biasing towards an underestimate of sediment yields). While these biases partially offset each other, we have no constraints on their cumulative impact and urge caution in comparing sediment yields determined in this study with those derived from other methods. Despite this inherent uncertainty in our absolute values of SSY, our method remains valid for assessing relative changes in the sediment yield from the LKL watershed over the timescales of interest to this study. This statement is based on the modest amount of observed sediment accumulation (~1.6 m) relative to the lake depth (17 m) being unlikely to substantially influence sediment focusing (i.e. the spatial pattern of accumulation rates across the lake) or the trapping efficiency of the lake.

2.3. Land cover change analysis

We quantified rates of timber harvest from 1958 to 2018 from historical aerial photographs and recent satellite images (Table 2) via a geographic information systems (GIS) analysis. Aerial photographs offered improved spatial resolution (1–3 m) and temporal span (back to 1958) relative to Landsat-based methods (e.g., Legaard et al., 2015). Orthophotomosaics and aerial photographs were downloaded from USGS EarthExplorer (https://earthexplorer.usgs.gov/). Satellite scenes from 2018 were obtained from Planet (Planet Team, 2017). The Maine Geological Survey provided access to paper copies of a series of aerial photographs from 1966 that covered 94 % of the LKL watershed. We scanned these photographs at 1200 pixels per inch. The resulting suite of images provided a time series from which to evaluate changes in land cover due to timber harvest over the past 60 years. These images provide maximum temporal resolution without sacrificing visual accuracy. For instance, we determined the spatial resolution of aerial photographs from October 1977 (original scale 1:80,000) was too low for analysis.

We created orthophotomosaics for each aerial photograph set (1958, 1966 and 1984; Table 2) using Agisoft Photoscan 4.0 after cropping text and fiducial marks from images. We measured coordinates of ground control points by finding common locations (such as road intersections) on the 2015 imagery, with an assumed accuracy of 2 m. Resultant orthophotomosaics had horizontal root mean square errors of 3–7 m, sufficient for visual comparison between images.

Table 1
Radiocarbon sample information. Included are all possible calibrated age ranges their probabilities based on the 1 sigma uncertainty of the radiocarbon ages.

<table>
<thead>
<tr>
<th>Lab Number</th>
<th>Composite Depth (cm)</th>
<th>Source Material</th>
<th>Radiocarbon Age (Years BP)</th>
<th>1 sigma Error</th>
<th>Calibrated Age Min (Years BP)</th>
<th>Calibrated Age Max (Years BP)</th>
<th>Calibrated Range Probability</th>
</tr>
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<tr>
<td>D-AMS 027048</td>
<td>94</td>
<td>twig</td>
<td>858</td>
<td>21</td>
<td>729</td>
<td>798</td>
<td>87.4</td>
</tr>
<tr>
<td>D-AMS 025458</td>
<td>102</td>
<td>bulk sediment</td>
<td>1449</td>
<td>39</td>
<td>1296</td>
<td>1402</td>
<td>95</td>
</tr>
<tr>
<td>D-AMS 027049</td>
<td>155.5</td>
<td>pine needles</td>
<td>1904</td>
<td>29</td>
<td>1741</td>
<td>1757</td>
<td>2.6</td>
</tr>
<tr>
<td>D-AMS 025459</td>
<td>160</td>
<td>bulk sediment</td>
<td>1197</td>
<td>29</td>
<td>1012</td>
<td>1020</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1056</td>
<td>1183</td>
<td>89.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1210</td>
<td>1229</td>
<td>4.1</td>
</tr>
</tbody>
</table>
analyzed to obtain a fractional harvest for each interval; division of harvest area by the time interval between images yielded a harvest rate (in km²/yr).

We quantified changes to the road network within the LKL watershed through time from digitized USGS topographic maps. Maps were available from 1931 to 1936, 1969 (for the eastern side of the study area), 1990 (for the center and western part), and 2018 (Table 2). The 1969 and 1990 maps were based on aerial photographs from 1966 and 1984, respectively, so we use these dates. We focused our analysis on official topographic maps rather than aerial photographs because they (1) are available over a longer interval, and (2) do not require interpretation of which roads were only temporary. However, to increase the temporal resolution, we used aerial photographs to identify when officially mapped roads were first evident. To avoid mapping temporary roads or skid tracks we did not map roads on aerial photographs that did not appear on later maps. Differences between the 1990 topographic map and the 1966 orthophotomosaic were used to estimate the 1966 network in the western and central portions of the watershed, which were not included in the 1969 map. Similarly, differences between the 1969 topographic maps and the 1984 orthophotomosaic were used to estimate the 1984 road network on the eastern side. We also used the 1958 orthophotomosaic to map the roads built by that time, by comparison with the 1966 network. The 1958 and 1966 road networks should be considered minimal. The 2018 topographic maps for the study area use a road network identical to the 2010 ArcGIS file available from the U.S. Census Bureau, so that dataset was used. In all cases, all of the roads shown on the maps were included in the digitized road networks; road-type classifications are included in Table 2. The 1931–1936 maps include “good pack trails,” which are included in the digitized road network. Trails are not shown in the study area on any of the subsequent maps. For each of the five mapped road networks we measured the total length of roads in the LKL watershed using ArcGIS.

2.4. Additional data sources

We gathered ancillary data on stream flow and precipitation from publicly available sources to compare the timing of recent sedimentary deposits with regional hydroclimatic events. No hydroclimatic monitoring stations exist in the Kennebec River watershed; we discuss the limitations of using regional data below. Specifically, we obtained peak stream flow records from the four nearest (36–83 km from LKL) U.S. Geological Survey (USGS) gauges with at least 50 years of continuous observations (Fig. 1A). Flows exceeding 10, 25, 50 and 100 year recurrence interval floods were identified based on published statistics (Hodgkins, 1999; Olson, 2009). We used daily precipitation data for Farmington, Maine (GHCND US000172765, 69 km from LKL; Fig. 1A) to derive peak annual rainfall from 1893 through 2018. Total precipitation (4 km spatial resolution) for 2018-07-03 was obtained from PRISM Climate Group, Oregon State University (http://prism.oregonstate.edu).

3. Results

3.1. Sedimentology, geochronology, and uncertainty

The 162 cm composite sequence of sediment recovered from LKL consists primarily of dark brown gyttja, with interspersed distinct light gray or tan layers (0.1–1 cm thick) of inorganic silt and clay (clastic) sediment (Fig. 3). Clastic layers are visible in the split core and X-radiograph and are characterized by reduced LOI and elevated magnetic susceptibility, ρm, and potassium content. A distinct transition occurs at 33 cm depth. Below, clastic layers are infrequent (5 layers occur between 33 and 162 cm), LOI averages 22 %, and magnetic susceptibility, ρm, and potassium content are all low and relatively uniform apart from the visible clastic layers. In contrast, the upper 33 cm contains at least 12 distinct clastic layers, average LOI is 18 % and magnetic susceptibility, ρm, and potassium content are all elevated relative to the lower portion of the record. Clastic layers in the upper portion appear in three clusters at 33–28 cm, 23–19 cm, and 15–10 cm. Core 18-2 includes 0.2 cm of clastic sediment as the uppermost deposit that is not evident in core 17-1, indicating additional clastic deposition between 6–2017 and 10-2018.

Chronology results indicate that our record spans at least the past 1200 years with varying rates of sediment accumulation over this period (Fig. 4). Peak 137Cs activity occurs at a depth of
Fig. 3. Optical image of split sediment core, X-radiograph (lighter shades of gray are more dense), and down core variations in magnetic susceptibility, percent loss on ignition (LOI; note reversed scale for X axis), $\rho_{db}$ and relative abundance of potassium (K). Clastic event layers are clearly visible in the split core and X-radiograph and correspond to increased magnetic susceptibility, reduced percent LOI, higher bulk density, and elevated K content.

Fig. 4. (A) Activity profiles of $^{137}$Cs, $^{214}$Pb, and $^{210}$Pb in near surface sediments. Error bars represent 1-sigma measurement uncertainty. (B) Constant rate of supply (CRS) derived age-depth for upper portion of record. Gray bar highlights the horizon of peak $^{137}$Cs activity in relation to the CRS derived age of the sediment at the depth (≈1960). (C) Age-depth models derived from $^{210}$Pb (triangles) and radiocarbon ages; solid red line reflects the best-estimate age-depth model using the lowest bulk sediment age (shaded blue), whereas the dashed red line is an alternative interpretation using only radiocarbon dates from terrestrial macrofossils as described in the text. 1 sigma probability distributions are given for each calibrated radiocarbon age. The step function in the age-depth model at 150 cm is inferred based on rapid accumulation of the clastic event layer at that depth. Gray shaded region represents the potential envelope of age-depth models that could be fit through available radiocarbon ages (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).
14–15 cm; the onset of detectable 137Cs occurs at 22–23 cm. The activity profile of excess 210Pb differs from a purely exponential decay curve, with reduced activity within intervals associated with the clusters of clastic layers identified above. Nearly constant 210Pb activity suggests little variation in the production of supported 210Pb despite potentially varying sources of sediment. Application of the CRS model to the excess 210Pb activity profile produces an estimate for the age of the peak 137Cs horizon (14–15 cm) of 1960. Despite large uncertainties inherent to 210Pb dating, agreement between the derived age of the 137Cs peak and accepted timing of peak 137Cs fallout (1963) suggests that the CRS model produces a reasonably accurate age-depth relationship with an estimated age of the lithologic transition at 33 cm of ~1906.

Below 33 cm, chronological control is provided by four radiocarbon ages (Table 1; Fig. 4). It is impossible to construct an age-depth model through all radiocarbon dates without inducing an age reversal. The lowest bulk sediment age is ~800 years younger than might be expected based on linear interpolation between the ages of the terrestrial macrofossils. In contrast, the upper bulk sediment age is ~400 years older than expected based on just the terrestrial macrofossil ages. This discrepancy makes assessing the reliability of any of the individual radiocarbon ages especially challenging. Re-deposition of old carbon is a distinct possibility in a lake fed by a large watershed. We feel that this is potentially more likely than an alternative scenario in which anomalously young ages are the result of sample contamination with young carbon.

Further constraints on the development of the full age-depth model are provided by the 210Pb results from surface sediments, where variations in accumulation rate are associated with distinct lithologic changes. In particular, increased accumulation rates are associated with intervals of more clastic sediment as might be expected if the clastic layers are the result of increased input of terrestrial sediment. Nearly uniform magnetic susceptibility, LOI, 137Cs, and potassium from 33 through 162 cm suggest little variation in composition and accumulation rates during this interval (aside from the 5 discrete clastic layers). Thus, an age-depth model requiring large changes in accumulation rate to fit the radiocarbon ages is unrealistic in the absence of corresponding changes in sedimentology. Accordingly, our final age-depth model linearly interpolates between the basal radiocarbon age and the 210Pb age model (Fig. 4C). A single 3 year step in the age-depth model was manually inserted for the clastic layer spanning 146.5 through 149 cm. While the actual deposition time of this layer is unknown, we chose 3 years as an approximation based on the assumption that the layer was likely initiated by an abrupt watershed disturbance that required at least several years to stabilize (cf. Cook et al., 2015). We made no further adjustments, as the thicknesses of other clastic layers were less than the resolution of data used to quantify MARclastic. This age-depth model produces a uniform linear accumulation rate prior to ~1900 (aside from the step at 146.5–149 cm) that is consistent with the sedimentology, and requires the smallest change in accumulation rate between the lower portion of the record and the upper portion constrained by 210Pb. We acknowledge that large uncertainty remains in the age-depth model but emphasize that our subsequent interpretation focuses primarily on variability within the portion constrained by 210Pb and only makes broad comparisons between this and earlier portions of the record. We nonetheless assess the impact of age model uncertainty on derived estimates of MARclastic, SSY, and event recurrence intervals below.

MARclastic and SSY both vary according to the SR derived from the age-depth model, and the LOI and 137Cs of the sediment (Eqs. (1) and (2)). Consequently, these data display identical patterns (Fig. 5) that differ only in their magnitude and units. For simplicity, we describe only SSY values. With the exception of a large spike at ~924 CE, SSY is nearly constant with a mean value of 2.0 Mg/km²/yr from the base of the core to ~1900 CE (33 cm below lake bottom). From ~1900 to 2018 (the core top) SSY averages 6.4 Mg/km²/yr with several prominent spikes as high as 19.6 Mg/km²/yr. For discrete clastic layers thinner than the 1 cm sampling interval at which 137Cs and LOI were determined, some degree of averaging occurs with the sediment bounding these layers. In addition, Sr values derived from the age-depth model are limited in resolution to several cm for the section of the record above 33 cm and are constant for the remainder of the record. Collectively, these factors result in calculated values of SSY associated with discrete clastic layers that likely underestimate actual yields during the deposition of those layers. This is especially likely for the four of the five clastic layers below 33 cm that are prominent in the sedimentological data yet barely evident in the SSY record (Fig. 5). While these factors indicate that peak SSY values should be interpreted with caution, decadal or longer term averages should be reliable for comparisons across different portions of the record.

Uncertainty in the radiocarbon constrained portion of the age-depth model affects estimates of sediment yield and any assessment of the recurrence interval of events responsible for the deposition of clastic layers within this section (determination of sediment yields above 33 cm, or ~1900, does not rely on radiocarbon ages). An age-depth model constructed using only the terrestrial macrofossils (Fig. 4C, dashed line) results in the oldest possible estimate of the basal age of the record (~82 to 39 CE) and an estimated mean SSY over this interval of 1.5 Mg/km²/yr. The best estimate age-depth model results in an estimated recurrence interval for deposition of clastic layers of 215 years; the alternative age model results in an estimated recurrence interval of 375 years.

The pollen record features high percentages of Betula (~40–50 %), with other tree taxa present at lower abundances, including Picea, Abies, Pinus, Tsuga, Alnus, and Fagus. Overall, forest composition was relatively stable over the last ~400 years. However, changes in the pollen percentages of several taxa indicate a shift in forest composition and an increase in disturbance after ~1900 CE (Fig. 6; full pollen results are available at https://doi.org/10.7910/DVN/RSDXOC). Picea and Tsuga declined in abundance, while Alnus and various weedy taxa (such as Ambrosia, Poaceae, and Asteraceae) became more prevalent. This pollen transition is coeval with increased SSY and frequency of clastic event deposits (Fig. 6).
is that the majority of the existing road network was in place by 1966 and approximately 40% of the roads were in place prior to the 1931. The most rapid expansion of the road network occurred between 1958 and 1966.

4. Discussion

The most prominent feature of the sedimentary record from LKL is the varying occurrence of the distinct clastic layers (Fig. 3). One of these layers was deposited between the collection of cores in June 2017 and October 2018, providing a valuable opportunity to examine their origin. Local camp owners described an intense rain event on July 3, 2018 that resulted in elevated turbidity within LKL and an associated plume of suspended sediment that traveled downstream to Kennebago Lake and beyond. We reviewed available rainfall observations to confirm that a locally intense rainfall event impacted a portion of the LKL watershed in the early morning of July 3, 2018 (Fig. 1). PRISM estimates of total July 3 precipitation within the LKL watershed range from ~3 to 8 cm with highest amounts in the southwestern part, in the vicinity of the Wiggle Brook and Bear Brook subbasins. Notably, rainfall was limited to ~1 to 2 h based on personal anecdotes and a review of available amateur weather station data archived at www.wunderground.com (station KMERANGE8 at Cupsuptic Lake recorded rainfall only from 02:00-03:09 h.). Six cm of rainfall within 1–2 hours in the LKL watershed is associated with a recurrence interval of 50–200 years (http://precip.eas.cornell.edu/). Suspended sediment in LKL is clearly evident in Landsat 8 imagery collected from the day of the rain event (Fig. 9). Our review of online satellite images showed declining concentrations of visible suspended sediment on July 3, 7, 9, and 11; another image from July 18 showed possible lingering suspended sediment, but LKL was clear by July 21 (Planet Team, 2017).

We observed evidence of flooding and erosion, including failure of culverts and bridge abutments, scarring of trees along channel banks, freshly deposited gravel bars bustling by vegetation, channel widening, and channel deepening, in the Wiggle Brook and Bear Brook subbasins in October 2018 (Figs. 1B and 9). In contrast, we noted only minor overbank deposition on the main stem of the Kennebago River, and saw no obvious signs of major flooding or significant mobilization of sediment during reconnaissance of Crowley Brook and its confluence with the Kennebago River. These observations suggest that flooding and erosion from the July 3 event was localized to the southwestern portion of the LKL watershed where estimated rainfall totals were the highest. Much of the observed erosion occurred on small (1–5 m channel width) first and second order, headwater streams where significant channel deepening occurred. On at least one tributary of Bear Brook, knickpoint migration upstream from a culvert failure resulted in stream incision of 1–2 m into glacial till underlying the modern alluvium (Fig. 8B–D). Mobilization of unweathered, clay-rich sediment from till is consistent with the fine particle size and enriched potassium content of the clastic layer deposited in 2018 (Fig. 3). Consequently, we interpret the discrete clastic layers found throughout the LKL record as a product of watershed erosion that mobilized unweathered glacial till. Extreme rainfall events are at least one of the triggers for this process.

The landscape surrounding LKL appears resistant to erosion from natural rainfall-runoff processes. Evidence for this includes the scarcity of event deposits recorded over the >1000 years prior to 1900, and the magnitude and intensity of rainfall required to initiate severe erosion and form a clastic layer within LKL from the July 3, 2018 rain event. The mean SSY prior to 1900 (2.0 Mg/km²/yr) provides an estimate of natural, background rates of erosion from an undisturbed forested watershed. This is low, but in the range of previous studies in the region. In a small catchment that had been

3.2. Land cover change analysis

Identification of areas impacted by logging in historical aerial photographs revealed varying harvest rates throughout the period of record. The earliest available photographs (1958) indicate at least some level of timber harvest over 46 km² (34 %) of the LKL watershed, mostly in the northern (upstream) portion (Figs. 7). This yields an average harvest rate of 0.6 km²/yr for the period from 1891 (when the Kennebago Improvement Corporation was formed) through 1958 (Figs. 7 and 8). Actual harvest rates likely varied over this interval and would be higher if harvest occurred in additional areas not evident in the 1958 images. The harvest rate was 0.4 km²/yr between 1958 and 1966, and increased to 0.9 km²/yr between 1966 and 1984. Harvest rates declined again between 1984 and 1998 (0.3 km²/yr) before beginning a steady increase from 1.2 km²/yr (1998 through 2007) to 4.1 km²/yr (2015 through 2018) – the highest harvest rates observed over the entire record. The cumulative area harvested from 1958 through 2018 represents 46.3% of the LKL watershed.

Quantification of road density within the LKL watershed indicates significant expansion of roads in the mid-20th century (Figs. 7 and 8). The earliest available maps from 1931 to 1936 include 44 km of roads within the LKL watershed (0.33 km/km²). This increased to 79 km of roads by 1958 (0.58 km/km²), and 103 km by 1966 (0.76 km/km²). The highest road density (118 km; 0.88 km/km²) appears in maps and photographs from 1984-1990. While our data record apparent fluctuations in road density over the past 50 years, we emphasize that the most robust observation...
re forested for 80–130 years, Ouimet and Dethier (2001) estimated background sediment yield for the mountainous terrain surrounding northwestern Massachusetts as <4.0 Mg/km²/yr. Total sediment yields from “undisturbed” forested watersheds studied at Hubbard Brook (New Hampshire) ranged from ~2.5 to 4 Mg/km²/yr (Borman et al., 1974; Martin and Hornbeck, 1994), with suspended sediment comprising ~5–20 % of the total yield. However, these “undisturbed” watersheds were previously logged and may be impacted by legacy effects. Patric (1984) suggested ~16.6 Mg/km²/yr as an upper limit for sediment yield from forested land in the eastern USA based on a summary assessment of available data at the time.

Peak SSY prior to 1900 CE is associated with the clastic layer at 924 CE (Fig. 5). The precise magnitude of this event is uncertain given the resolution of the age-depth model. However, the 2.5 cm thickness of this layer and its magnetic susceptibility, LOI, P Meadows, and potassium signature suggest that this was the most significant erosional event of the past ~1100 years, regardless of the precise SSY associated with it (Figs. 3 and 5). Collectively, the five clastic layers prior to 1900 suggest that the recurrence interval for extreme events capable of producing significant erosion on the undisturbed landscape is >215 years.

The sharp increase in SSY and frequency of clastic event deposits after ~1900 marks a transition in the landscape history of the LKL watershed (Fig. 5). The concomitant changes in pollen (increased weedy taxa; Fig. 6) and general agreement with the timing of historical constraints on the onset of logging in the LKL watershed point to land-use changes related to timber harvest as the cause of increased SSY and more frequent event deposits. Records of hydroclimatic variability, historical events, and both local and statewide timber harvest provide further insight (Fig. 8). Despite the clear link between extreme rainfall in July 2018 and subsequent deposition of a clastic event layer as described above, there is little agreement between the occurrence of extreme hydrologic events (extreme rainfall and/or flood events) and SSY during the period of overlapping records. Our hydrologic analysis is limited by the lack

Fig. 7. Maps of timber harvest and the road network through time in the Little Kennebago Lake watershed. (A) Areas of timber harvest interpreted from and displayed on a 1958 orthophotomosaic made from USGS aerial photographs. Road networks are from USGS 15’ topographic maps published in 1931–1936 and interpreted the 1958 orthophotomosaic. (B) Areas of timber harvest interpreted from sequential orthophotographs. Road networks from 1966 and 1984 are from 7.5’ USGS topographic maps and associated aerial photographs. Road network from 2010 is from U.S. Census Bureau data; it was also used on 2018 USGS 7.5’ topographic maps. Base is a hillshade image from a 10-m USGS DEM.
of local data and because both rainfall and streamflow may exhibit substantial spatial variability. However, extreme floods (or rainfall) impacting multiple sites simultaneously (such as observed in April 1987, August 2011 following Tropical Storm Irene, and at other times) reflect regional events that may be reasonably expected to have impacted the LKL watershed. The occurrence of additional, local extreme hydrologic events not observed in the regional hydrologic records are a further possibility. Thus it is especially noteworthy that no event deposits occur over the past >40 years (prior to 2018) despite numerous occurrences of simultaneous flooding and/or intense rainfall at multiple recording stations, including many of the largest regional flood events on record, and the possibility of additional unrecorded local extreme events (Fig. 8). While this disconnect may reflect the distance between the LKL watershed and the available hydrologic stations, the results nonetheless suggest that SSY variability over this portion of the record is not closely tied to hydroclimatic conditions. In contrast, the first abrupt increase in sediment yield ca. 1900 occurs shortly after the inferred onset of logging activity within the watershed and coincides with changes in the pollen record indicative of disturbance (Figs. 6 and 8). The subsequent decrease in SSY from ~1920–1933 coincides with a period of reduced statewide timber harvest (Barton et al., 2012), suggesting a slowing of local harvesting activity over the same period. The second peak in SSY in the mid-1930s through early-1940s follows the construction of the Upper Station Dam in 1932 (Kaufman and Paradis, 1992), and coincides with a statewide increase in timber harvest (Barton et al., 2012). Collectively, these factors are consistent with an intensification of local logging activity as the cause of increased sediment yield (Fig. 8).

Likens et al. (1970) demonstrated that the cutting of trees on its own is not a primary cause of erosion in northeastern forests. Consequently, processes related to how timber is transported and related land use changes, such as the construction of roads, provide a likely link between variations in harvesting activity and observed changes in SSY in the LKL watershed. Early 20th century timber harvest in the state of Maine relied on dragging or sliding logs downhill to the banks of rivers during winter and floating logs downstream in a series of log drives augmented by artificial floods during spring (Smith, 1972; Kaufman and Paradis, 1992). The two clusters of clastic deposition in LKL during the first half of the 20th century may reflect channel bank and bed erosion occurring during
series of individual log drives at times of more active timber harvest in the watershed, though we have no means to directly correlate individual deposits and log drives. The last log drive past Upper Station Dam occurred in 1952. Increased SSY and deposition of clastic layers in the 1960s through early 1970s must therefore reflect different processes. This third historical peak may reflect a rapid expansion of the road network and widening of existing roads in response to the transition after 1952 from in-stream log drives to hauling logs by truck. Another possible factor is the increased harvest rate for some period from 1966 to 1984 as evident from our aerial photograph analysis (Fig. 8). Active road construction and the presence of existing unpaved road surfaces are widely recognized as potential sources of increased sediment delivery either through direct erosion of the road surface or extension of the hydrologic network and alteration of hydrologic processes (e.g., Reid and Dunne, 1984; Montgomery, 1994; Wemple et al., 1996; Wemple and Jones, 2003; Luce and Black, 1999; Ziegler et al., 2000).

Mean SSY from the LKL watershed throughout the period influenced by logging activity (~1900 to present) is 6.4 Mg/km²/yr. This value is reasonably low for a forested watershed in the eastern USA (Patric, 1984), but the relatively modest 3-fold increase in sediment yield relative to the pre-logging conditions is consistent with results from clear cutting experiments in the region (Martin and Hornbeck, 1994). For comparison, SSY estimates from stream gauging in the region range from 9.98 – 136 Mg/km²/yr (Ames, 2018). More notable in the LKL record is the increased frequency of clastic layers after 1900 and the approximate order of magnitude increase in short-term SSY implied by these deposits (Figs. 5 and 8). Because extreme rainfall events needed to mobilize sediment are infrequent, quantifying the multiyear impacts of land use change from short term monitoring studies is often difficult. However, the general agreement between variability in SSY and the timing of activities related to timber harvest from ~1900–1970 suggests close coupling between land use changes and sediment delivery (Fig. 8). In contrast, SSY was nearly constant (or potentially decreasing) from ~1970 to 2017 despite increasing harvest rates over the past 20 years. Continued SSY above background levels since 1970 likely reflects elevated sediment delivery from existing roads, ongoing land use practices, and the legacy of early 20th century harvesting practices all having increased sediment availability throughout the watershed. The absence of clastic layers after ~1970 (until 2018) suggests that forestry best management practices (BMPs), implemented after passage of the Federal Water Pollution Control Act of 1972 (Clean Water Act; Phillips and Blinn, 2004) may have effectively reduced the occurrence of the most severe erosional events. The rain event and associated erosion that occurred in 2018 is difficult to judge. This event occurred while harvest rates were at their historical maximum and erosion was concentrated in a recently harvested

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**Fig. 9.** (A) Landsat image from 2018-07-03 (courtesy of the U.S. Geological Survey) showing highly turbid water within Little Kennebago Lake and flowing downstream into Kennebago Lake. Sources of the suspended sediment were traced to erosion in two subwatersheds of the upper Kennebago River: Wiggle Brook and Bear Brook watersheds. (B through D) Examples of erosion resulting from the 2018-07-03 rain event in the Bear Brook subwatershed of the Kennebago River. Culvert in (B) is ~1 m in diameter for scale. Base of vertical side channel walls in (B) indicates the approximately level of the stream channel prior to the 2018-07-03 event. 1.8 m tall person in (D) standing within incised channel below the pre-disturbance stream bottom.
portion the watershed (30% of the Bear Brook watershed was harvested after 2007; Fig. 7). However, the rain event was indisputably extreme and recently cleared areas showed no evidence of sheet or rill erosion. Concentration of flows by forest roads (e.g., Wemple et al., 1996; Wemple and Jones, 2003) and the failure of drainage culverts likely contributed to the extent of erosion that occurred within stream channels (Fig. 9). While the July 2018 event may have been anomalous, the frequency of extreme precipitation in the northeastern USA is projected to increase (Ning et al., 2015). Therefore, existing BMPs may not be adequate if rain events similar to the 2018 event become more common. Overall, the pattern of increasing timber harvest observed in the LKL watershed and the projections for increased precipitation in the region are consistent with observed trends in forest cover in other northern regions (Achard et al., 2006) and general projections for increased precipitation across high latitudes (Power et al., 2012).

The record of sediment yield from LKL provides a unique perspective on the impacts of land use change, as the watershed was largely undisturbed prior to the 20th century and forested land was never converted to agricultural or other uses. Studies in areas of more intense agricultural land use have documented larger impacts. In central Connecticut, Thorson et al. (1998) observed strong impacts to wetlands in which the 17th-18th century pulse of colonial disturbance continues to govern the modern sediment budget. Studies of small alluvial fans in agricultural areas of Vermont suggest that sediment yields during the past 200 years were higher than at any time during the prior 8000+ years (Bierman et al., 1997), having increased substantially (>100 times) from background levels (4-11 Mg/km²/yr) following land clearance and conversion to agriculture (Jennings et al., 2003). Studies of terrestrial sediment input to New England lakes record a more subdued erosional response to historical land use change (e.g., Bierman et al., 1997; Francis and Foster, 2001; Cook et al., 2015), possibly indicating that much of the sediment mobilized in response to Euro-American land use change remains on hillslopes rather than being transported through river corridors. Both Bierman et al. (1997) and Cook et al. (2015), in examining lakes in different regions of Vermont, describe a minimal response to historical land clearance in contrast to distinct episodes of erosion evident during the Holocene. Amherst Lake and its watershed in central Vermont (Cook et al., 2015) shares similar characteristics to LKL, however the Amherst Lake catchment was permanently settled beginning in the mid-18th century and land was converted to pasture prior to eventual afforestation. SSYs derived from values of MACclassic reported by Cook et al. (2015; 2.2 and 8.2 Mg/km²/yr pre and post 1900, respectively) are remarkably similar to our estimates for the LKL watershed. However, in contrast to the distinct human impact on sediment yield we describe, the recent increase in erosion in the Amherst Lake watershed was attributed predominantly to changing hydroclimate. This distinction highlights geographic variability in the response to disturbances related to both changing hydroclimatic conditions and land use alteration. Johnson et al. (2019) attributed variations in the presence and volume of legacy sediment deposits to differences in the upstream sediment supply, especially in the form of thick glacial deposits. Similarly, variations in sediment availability may be responsible for the differences observed in the sensitivity of the Amherst Lake and LKL watersheds to disturbances. The degree to which different watersheds have responded and will respond to changes in land-use practices and climate remains an important area of research on post-glacial, forested landscapes. It may be that the relatively modest impacts of timber harvest practices in the LKL watershed represent one end member, when compared with watersheds with more intense land-use change and/or greater sensitivity to hydroclimatic variability.

5. Conclusions

Little Kennebago Lake (LKL) preserves a continuous record of watershed erosion spanning the past >1200 years. Consistency among our SSY estimates and other regional studies utilizing stream monitoring or volumetric assessment of legacy deposits supports the interpretation of lake deposits as accurate records of terrestrial sediment yield. Thus our study provides the following answers to our original research questions. (Question 1) Background SSY from the LKL watershed was 2.0 Mg/km²/yr. Event deposits linked to erosion in the watershed upstream of LKL occur with a return period >200 years over the >1100 years prior to the onset of timber harvest, suggesting a landscape resilient to natural hydrologic disturbances. However, the single largest event deposit in the LKL record (at ~924 CE) occurred long before any Euro-American land use impacts, highlighting the potential for large natural variability in sediment yield. (Question 2) Following the onset of timber harvest in the LKL watershed, SSY increased threefold to 6.4 Mg/km²/yr and the return period of event deposits indicative of watershed erosion reduced by an order of magnitude to ~10 years. These findings demonstrate that human activities can influence SSY even in a moderately impacted watershed with low background erosion rates. Low SSY and a lack of event layers from the mid-1970s through 2017 suggests that forestry best management practices may have effectively reduced the occurrence of the most severe erosional events, despite increased rates of timber harvest over this period. However, the 2018 erosion event was a reminder that existing and expanding road networks combined with changing climate may make forested, post-glacial landscapes more sensitive to future disturbance.

Author contributions

All four authors wrote the manuscript and contributed ideas. TLC led the coring, sediment and hydrologic analyses. NPS led the watershed GIS analysis. WWO led the pollen analysis. KP conducted fieldwork and initial laboratory analyses.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

Funding for this research was provided by the U.S. Department of Interior Northeast Climate Adaptation Science Center (grant no. <GN1>-G12AC00001</GN2>), Worcester State Foundation, Boston College, and Harvard Forest, where TLC and NPS were based as Bullard Fellows for much of the duration of this project. In addition, we thank Beth Ames, Samantha Dow, Jim LeNoir, and Jeffrey Reardon for their assistance in the field; Jim Lukens and John Blunt for their hospitality while working in the area; Manisha Patel for laboratory assistance; Planet Lab for making their satellite imagery available; and Amber Whittaker from the Maine Geological Survey for providing access to archived aerial photographs. Data associated with this study are archived and freely available at https://doi.org/10.7910/DVN/BSXDOG.

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T.L. Cook et al./Anthropocene 29 (2020) 100232


