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EXAMINING VARIABILITY IN STREAMBANK EROSION RATES IN THE LAKE CHAMPLAIN BASIN, VERMONT

A Thesis Presented by

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Abstract

Bank erosion is a dynamic process with large variability in rates across the landscape. Although prior studies have investigated streambank and channel erosion rates on cross-section to sub-watershed scales, there is limited understanding of regional streambank erosion in the Lake Champlain Basin (LCB). Consequently, the role of erosion in watershed sediment budgets and the contribution of bank derived sediment and associated nutrients to degraded water quality in Lake Champlain is not fully understood. The goal of our work is to obtain refined rates of erosion in the LCB and to understand the source of bank erosion variability. To achieve this goal, this project compiles studies on bank erosion rates in Vermont to develop a regional dataset of erosion rates and associated stream attributes in the LCB. We quantified bank erosion rates for five field sites from LiDAR and field-surveyed cross-sections. Data from six previous bank erosion studies, that contained one or more observations were identified, creating a dataset of mass erosion rates for 190 individual stream reaches, with drainage areas that span from 0.1km^2 to 2730.9 km^2 in the LCB. The reaches were associated with Vermont ANR Stream Geomorphic Assessment data, populated with stream attributes, and analyzed to identify relationships between physical characteristics of the landscape and erosion rates. From our dataset, we found that erosion rates are highly variable, but that this variability can be described in part by drainage area, slope, incision ratio, and riparian vegetation cover. A better understanding of streambank erosion rates and important driving variables provides additional context for restoration practices and sediment deposition patterns on adjacent floodplains.

Introduction

Streambank erosion is a fundamental geomorphic process that can mobilize a considerable amount of sediment in watersheds (Hamshaw et al., 2019; Langendoen et al., 2012). When streams are in equilibrium, erosion and deposition are generally balanced (Noe et al., 2022). However, when streams experience disturbances, equilibrium may be disrupted, often elevating erosion rates. As a result, elevated sediment and nutrient loading to streams may occur and contribute to water quality issues downstream (Langendoen et al., 2012; Anderson et al., 2002) and destroy downstream habitats and biodiversity (Howard et al.,1998).

High sediment and phosphorus loads in the Lake Champlain Basin has led to the establishment of Total Maximum Daily Load (TMDL) by the EPA (EPA, 2016). Following agricultural land use, streambank erosion is estimated to be the second largest source of phosphorus to the lake for many of the State of Vermont's segments. As part of the TMDL's goal of allocating phosphorus sources, sediment loading from bank erosion must be addressed. Thus, there is an interest in maintaining healthy, naturally stable streams in the LCB to limit bank erosion and subsequently phosphorus in Lake Champlain.

Excessive erosion from stream migration can also greatly damage infrastructure (Garvey, 2012). After Tropical Storm Irene in 2011, the total damage to roads, bridges, and culverts from fluvial erosion was $175 to $250 million dollars (VT ANR, 2012). Just twelve years later, the State of Vermont experienced another widespread and damaging flood. The Great Vermont Flood of July 10th - 11th, 2023, was comparable and in some areas greater than Irene (NWS, 2023). As intense precipitation is expected to continue and to occur more frequently in Vermont and the Northeast (Picard et al., 2023), continuous geomorphic monitoring of rivers is becoming increasingly important to better constrain fluvial erosion rates and hazards and identify potential mitigation strategies (Hamshaw et al., 2019).

Identifying the variability in erosion across a watershed is vital to the development of sediment budgets, and in better targeting management actions that aim to improve water quality and reduce flood hazards (Noe et al., 2022). The State of Vermont has invested greatly into understanding the geomorphic condition and function of rivers and floodplains in Vermont, particularly with Stream Geomorphic Assessments and the introduction of the Functioning

Floodplain Initiative (SLR, 2023). However, these programs do not measure bank erosion explicitly.

Previous studies have presented bank erosion data for several distinct study areas within the Lake Champlain Basin (LCB). This study aims to compile these data into one regional dataset to facilitate data sharing and enable further analysis. Regional erosion datasets can help identify fluvial erosion hazards, and when contextualized with depositional measurements, stream loadings, and upland fluxes, they can help to constrain sediment budgets. Past work on floodplain deposition highlighted that drainage area, incision ratio, and slope were important factors for describing deposition variability at the watershed scale, but it leaves questions concerning bank erosion variability and the importance of erosion and deposition holistically (Diehl et al., 2023).

There are numerous factors that impact bank erosion rates. When more energy is available to transport sediment, as measured by stream power, higher erosion rates are likely (Church, 2002). Stream power scales to drainage area and slope, and both increasing drainage area and channel gradient have been attributed to higher bank erosion rates (Noe et al., 2022; Church, 2002; Gartner et al., 2015). Stream-flow peak intensity during floods and the duration of flood events can be a large driver of stream erosion as well (Julian and Torres, 2005). Further, large floods can have long-term impacts and can cause bank failure to continue at elevated levels after floods and during future floods (Ross et al., 2019).

Topography and land use can also influence bank erosion variability (Noe et al., 2022). In the Chesapeake Bay, urbanized land and pastureland in particular were found to be associated with higher bank erosion rates. Conversely, riparian vegetation can attenuate bank erosion rates (Noe et al., 2022; Zaimes et al., 2006). Disturbance history and stream geometries such as channel-floodplain connection have also been shown to influence stream erosion rates (De Rose and Basher, 2010). Additionally, bank soil composition can affect the erodibility of reaches, leading to erosion rate variability (Langendoen et al., 2012).

In Vermont, studies that have quantified streambank erosion have been motivated by a variety of objectives, including improved understanding of water quality impacts and better understanding of geomorphic and geotechnical controls on erosion. For example, both Ishee et al. (2015) and DeWolfe et al. (2004) focused on quantifying and understanding the relationship between phosphorus export and bank erosion in several streams in the LCB. At a smaller spatial and temporal scale, Ross et al. (2019) analyzed bank erosion and phosphorus after Irene on the Mad River to understand the geomorphic effects of extreme events on sediment and phosphorus loading. Garvey (2012) and Hamshaw et al. (2019) both focused on method development for acquiring bank erosion measurements using remote sensing and Unmanned Aircraft Systems (UAS) respectively, and in doing so, they also obtained bank erosion rates. Borg et al. (2014) and Jordan (2013) aimed to understand several of the drivers of bank erosion, with Borg et al. (2014) focusing on physical processes that cause bank failure on the Winooski River, and Jordan (2013) exploring landscape variation that impacts bank erosion variability on the Mad River. Additionally, Langendoen et al. (2012) used bank stability modeling in the Missisquoi watershed to understand how different scenarios may alter phosphorus export to Lake Champlain and how different variables affect bank erosion rates.

There are several ways to develop regional erosion datasets, including dispersed field sampling to capture watershed variability (Noe et al., 2022) and meta-analyses (Garcia-Ruiz et al., 2015). As long as there are sufficient data available, meta-analyses are less time-intensive and more accessible to conduct. However, they can also be challenging, since additional variability in data is added, such as differing methodology and measurement duration. Different methods are often used to answer distinct scientific goals, and as a result they have different strengths and weaknesses. For example, erosion pins and cross sections are capable of measuring bank change precisely in the field but are not feasible measurement techniques at large scales (Borg et al., 2014). Aerial imagery can be used to obtain measurements at large scales, and over longer timeframes, but only represent one-dimensional lateral migration and misses vertical changes (Jordan, 2013; Garvey, 2012). Broadly-available DEMs can capture three-dimensional streambank change but are often limited in their temporal resolution and may have significant vertical uncertainties (Hamshaw et al., 2019). Computational modeling of streambank erosion has much more uncertainty and is very scale-dependent (Garcia-Ruiz et al., 2015). On the Missisquoi and its tributaries, Langendoen et al. (2012) used the Bank-Stability and Toe-Erosion

Model (BSTEM) and reasoned that their calculated erosion rates were on the upper-bound of expected values but did not provide any comparison to field-measured values. Furthermore, when using different studies in a meta-analysis, it is important to note that they also often have different spatial and temporal resolutions, causing erosion rates to be averaged over different sized flood events and length-scales of adjustment (Garcia-Ruiz et al., 2015). Despite these sources of uncertainty, a well-constrained meta-analysis can reveal broad patterns in relationships between variables that are of practical importance for guiding management or shaping future research goals.

The goal of this project was to produce a spatially diverse dataset of erosion rates and stream attributes in the LCB to better understand sources of regional bank erosion variability. To do this, we have three objectives:

1) Measure bank erosion rates for five field sites.
2) Compile bank erosion measurements from past studies to develop a regional dataset of streambank erosion rates.
3) Evaluate and explore relationships between bank erosion and associated stream attributes.

Through exploring the effects of streambank erosion and associated stream attributes, we hope to develop a better understanding of river management needs in the LCB to improve water quality and ecosystem functions.

Methods

Field-measured erosion

We measured mass erosion rates (kg/m/yr) using LiDAR-derived DEM’s and topographic survey data at five sites in Vermont (Fig. 1). These sites are located within the Lake Champlain Basin, Vermont and are part of a long-term floodplain monitoring project focused on floodplain deposition (Diehl et al 2021; 2023). During the summer of 2023, cross-section data was collected at three sites (Lareau Site on the Mad River and Black Creek #1 and #2 on the Black Creek). Prior to field work, a desktop review was conducted at each of the sites to determine approximate cross section locations in dynamic areas that displayed visible channel migration and captured variability in stream morphology. Field teams surveyed cross-sections that spanned the river channel (top of bank to top of bank) using an Emlid Reach RS2 RTK GPS surveying system. We identified key parts of the stream bank and bed, being sure to capture changes in slope in the profile, so that an accurate cross section of the stream could be created. Survey data were post-processed using OPUS, an online service providing access to National Spatial Reference System coordinates maintained by NOAA (Soler & Wang, 2016), that we used to reposition the RTK base coordinates. Emlid Studio was then used to correct the cross-section points based on the OPUS-updated base coordinate.

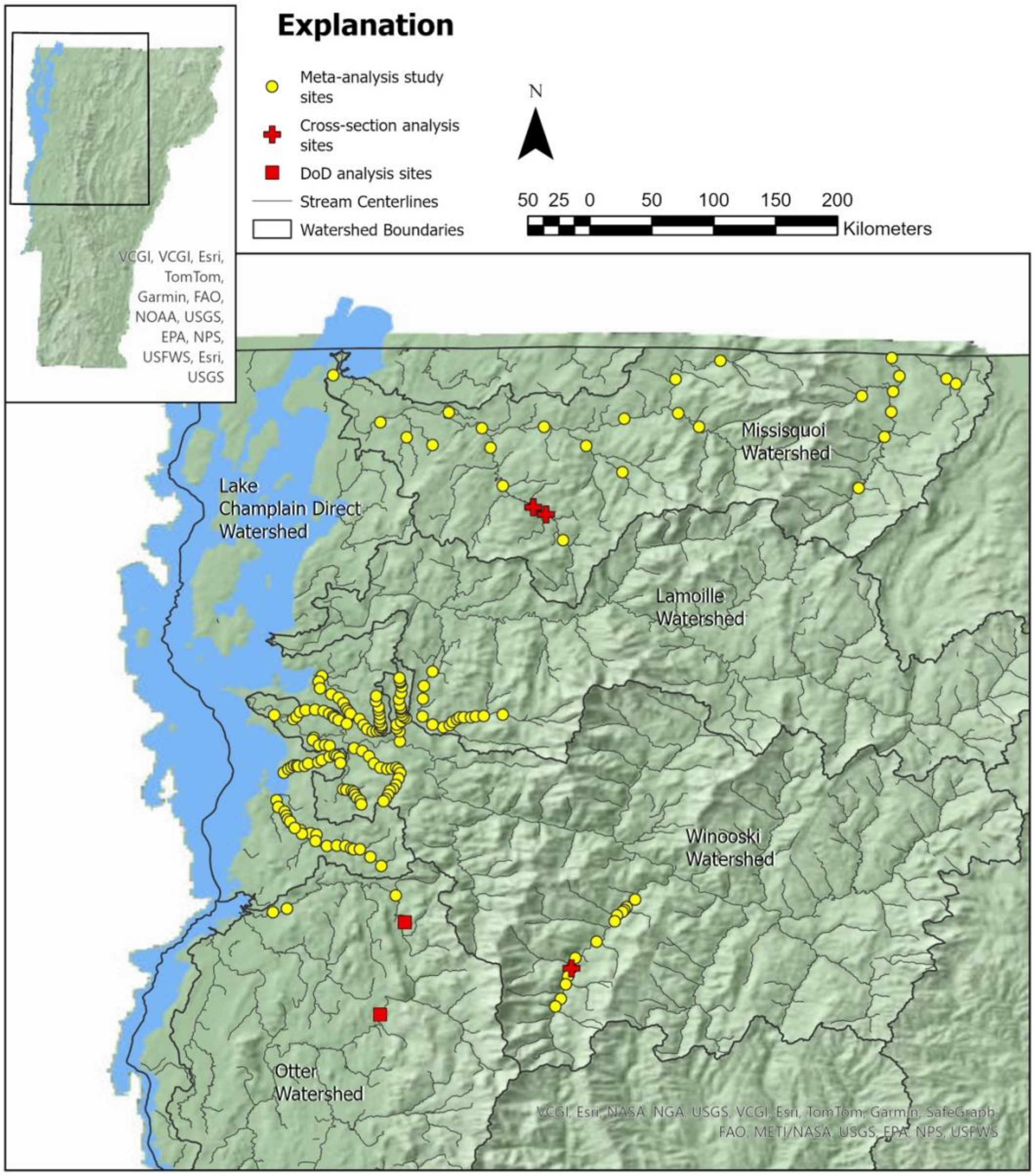


Fig. 1 The location of the 190 reaches represented in the bank erosion dataset.

In ArcGIS Pro, the corrected survey coordinates were overlayed onto the most recent LiDAR-derived DEM from the Vermont Open Geodata Portal (Quality Level 2). Elevations were extracted from the DEM, resulting in a matching set of survey and DEM points. The Mad River site utilized LiDAR data from 2013, and the Black Creek sites used LiDAR from 2017. The points representing the eroding streambank, defined by the toe of the slope and top of the bank, were identified, and the difference between the survey and DEM streambank-points were calculated for each cross section (Fig. 2). All cross sections can be found in the appendix. Then, the resulting cross-section specific values (in m^2) were averaged by site and divided by the number of study years, resulting in cross-sectional bank erosion rates (m^2/yr) for each site. To convert the cross-sectional erosion rates to mass erosion rates (kg/m/yr), we multiplied by a representative bulk density. A bulk density of 660 kg/m^3, measured on the Lemon Fair River (Roy et al., 2023), was used for the Black Creek sites and a bulk density of 1300 kg/m^3 from Ross et al. (2019) was used for the Mad River site.

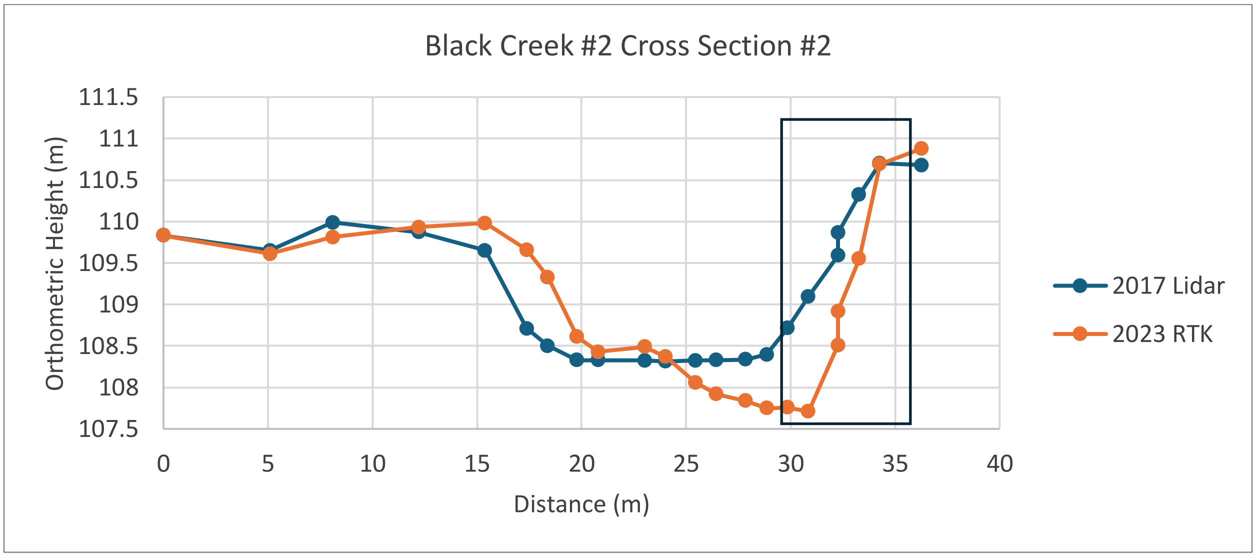
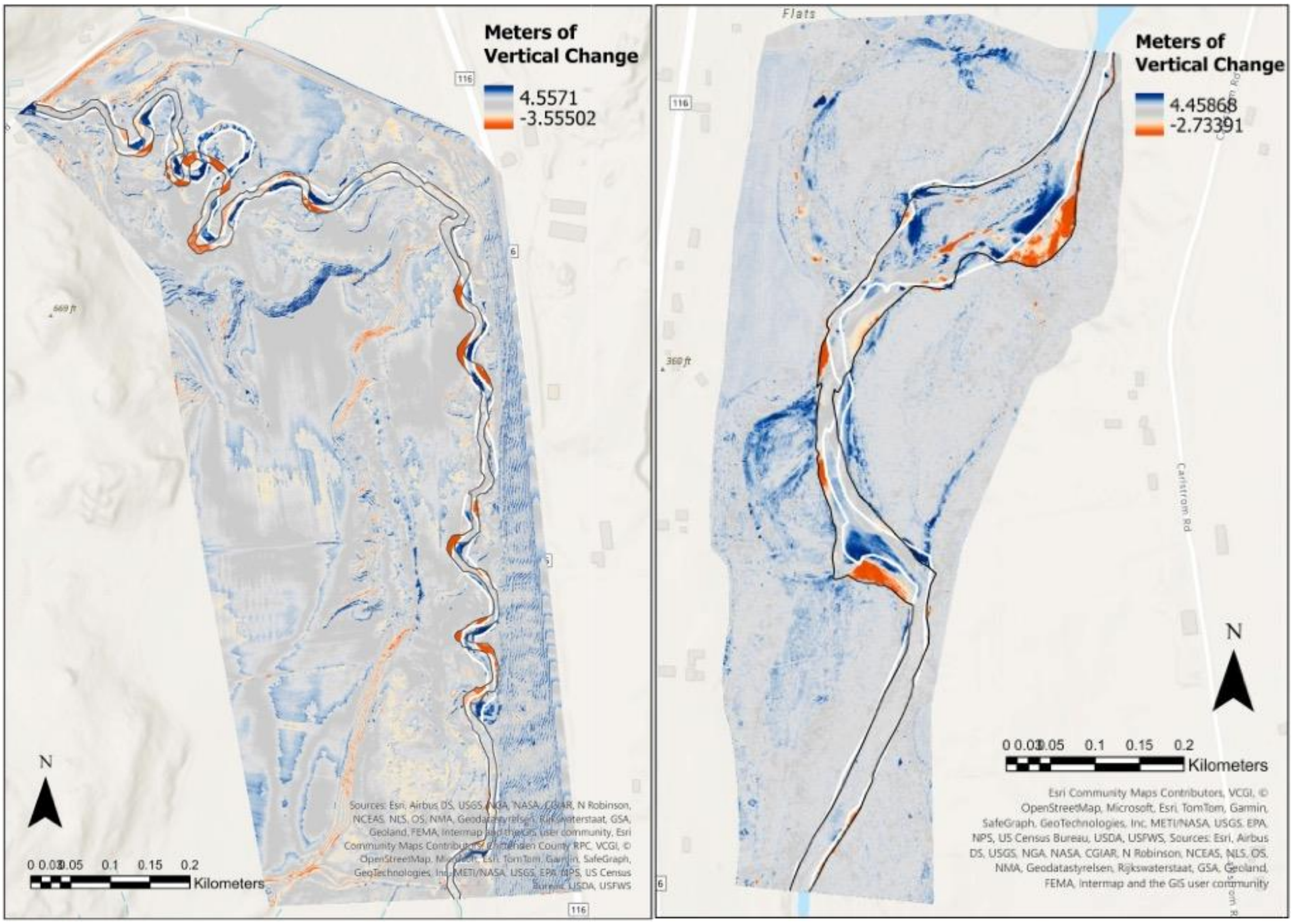


Fig. 2 An example of a cross section used to derive erosion rates. The box surrounds the points used for calculations, which extend from the top of the eroding bank to the toe of the eroding bank.

DoD-measured erosion

Due to the dynamic nature of the Lewis Creek and the New Haven River sites and availability of repeat LiDAR, DEMs of Difference (DoD) were computed in ArcGIS. UAS-LiDAR was flown by the UVM Spatial Analysis Lab at the New Haven River on November 22nd, 2023, and at Lewis Creek on April 14th, 2023. The Lewis Creek site was differenced with LiDAR collected in 2014, and the New Haven River site used 2017 LiDAR. The DoD was calculated by subtracting the elevation values of the older DEM from the elevation values of the newer DEM. Following the methodology of Garvey (2012), we digitized the 2014/2017 and 2023 channel boundaries while referencing the DEMs and ortho imagery, which we then used to identify areas of bank erosion (Fig. 3). We drew polygons representing bank erosion, which were defined as floodplain in the earlier DEM and channel in the 2023 DEM. We calculated zonal statistics for each polygon to derive volumetric erosion measurements (m^3), which were summed and used to calculate bank erosion rates. To get a mass erosion rate from volumetric erosion (m3), we multiplied by the bulk density, and divided by reach length (m) and period between LiDAR collection dates (yr). The bulk density of the Lewis Creek site was previously collected (1000 kg/m^3) (Roy et al., 2023) and we assumed that the Mad River bulk density was representative of soil properties at the New Haven River site (Table 3).



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, Chittenden County RPC, VCGI, © OpenStreetMap, Microsoft, Esri, TomTom, Garmin, SafeGraph, GeoTechnologies, Inc, METI/NASA, USGS, EPA, NPS, US Census Bureau, USDA, USFWS

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Fig 3. The Lewis Creek DoD (left) and New Haven River DoD (right). The black outline represents the 2023 stream channel boundary, and the white outline shows the older channel boundary. Polygons representing the extent of bank erosion were drawn in between the channel boundaries where the new channel was outside the older channel.

Meta-analysis of erosion rates in Vermont

To develop a dataset of mass erosion rates, we identified existing studies in Vermont that measure and report mass erosion rates (kg/m/yr), lateral migration rates (m/yr), or bank erosion loads (kg/m). In 2021, several studies investigating erosion rates throughout Vermont were compiled by Emily Mischler into a spreadsheet as a deliverable for the Functioning Floodplain Initiative (Underwood et al., 2021), which we used as a starting point for this analysis. Two studies were used from the initial spreadsheet, and 4 additional studies were identified and added to the dataset, yielding a total of 6 studies with distinct erosion rates for one or more stream reaches in the Lake Champlain Basin (Table 1). To extend the dataset, we added our topographic survey data and DoD measurements for an additional 5 reaches.

Table 1. All studies included in the bank erosion dataset and used for analysis.

Study	**Rivers Analyzed**	**Total # of Reaches**	**Years Studied**	**Methods Used**
Garvey, 2012	Browns River, Alder Brook, Allen Brook, Centennial Brook, Indian Brook, LaPlatte River, Potash Brook, Sucker Brook, Sunderland Brook	134	2004-2007	DEM of difference
Borg et al., 2014	Winooski	1	2006-2009	Repeat cross sections
DeWolfe et al., 2004	Lewis Creek, LaPlatte River, Browns River	9	2002-2003	Repeat cross sections
Jordan, 2013	Mad River	13	1995-2011	Imagery analysis
Hamshaw, 2018	New Haven River	1	2015-2016	Repeat cross sections
Langendoen et al., 2012	Missisquoi River, Black Creek, Hungerford brook, Trout River, Tyler Branch, Jay Branch, Mud Creek	27	1979-2010	Bank stability model
Flanzer A	Black Creek, Mad River	3	2017-2023; 2013-2023	Repeat cross sections
Flanzer B	Lewis Creek, New Haven River	2	2014-2023; 2017-2023	DEM of difference

From these studies, we extracted information to identify a common metric of bank erosion: mass erosion rates (kg/m/yr). DeWolfe et al. (2002) was the only study to explicitly report mass erosion rates, but Langendoen et al. (2012) analogously reported volumetric erosion rates (m^3/km/yr) along with bulk density allowing us to convert to mass erosion rates. The other 4 studies reported a combination of lateral migration rates (m/yr), normalized planform erosion (mT/m), cross-sectional erosion (m^2), and normalized change (m^2/m). Often, additional information (bank height, reach length, years, etc.) was needed to convert the given measurements into mass erosion rates and could be found in the study (Table 1). However, Hamshaw et al. (2018) and Jordan (2013) did not include bulk densities, a vital measurement needed to convert given erosion rates to mass erosion rates. We estimated bulk density for these using bulk density values for the Mad River reported by Ross et al. (2019) (1300 kg/m^3). In addition to mass erosion rates, we also identified the years monitored in each study as well as the methods used to obtain erosion rates, since a wide array of techniques were used to measure bank erosion. Collectively, these studies along with the mass erosion rates extracted from the studies serve as the base of knowledge for the meta-analysis.

Attributing the Dataset

For all values reported in the dataset, we identified the associated Stream Geomorphic Assessment (SGA) Phase 2 reach, which reflects a field verified determination of a geomorphically consistent stretch of river (VT ANR, 2004). Coordinates of reach center points were calculated using SGA reach databases found on the Vermont Open Geodata Portal. Drainage area (km^2), incision ratio, channel slope (%), agricultural land (%), and vegetated riparian area (%) were calculated as part of the development of SGA-based attributes for the Functioning Floodplain Initiative (SLR, 2023). Both agricultural area and vegetated riparian area were defined by the percentage of agricultural or vegetated riparian area within the river corridor, adjacent to the SGA reach. Reaches with incision ratios <1.3 were considered connected, and incision ratios ≥ 1.3 were considered disconnected from their associated floodplain. Channel slopes ≤ 0.002 m/m were considered low gradient and channel slopes > 0.002 m/m were considered high gradient. We also attributed each entry with its associated study duration and methodology. The method classifications used were DoD, bank stability model, repeat cross sections, or imagery analysis. Additionally, a simple classification of “moderate” or “large” flood was added to the database to roughly represent the largest flood events captured between the two repeat topographic measurements or captured in the modeled timespan. We categorized entries based on nearby gages, referencing either National Weather Service stage exceedance categories or flood frequency statistics (Olson et al., 2014). Floods were considered large if they exceeded the major stage or 20 year recurrence interval (calculated for each gage using a flow frequency analysis).

Data analysis

I summarized the dataset and looked for relationships between mass erosion rates and the attributes in Excel and JMP Pro 15. Initially, data were visualized using bivariate plots comparing mass erosion rate and various attributes. The distribution of variables was then evaluated to understand the spread of data included in the dataset. Using a combination of Spearman rank correlation coefficient analyses, two-tailed t-tests, and a one-way ANOVA to test the significance and relationship between variables were determined. In some cases, continuous variables, such as incision ratios, were further categorized and tested with t-tests and ANOVA tests to evaluate whether a threshold-relationship exists with erosion rates. For analysis of site variables (e.g., drainage area, incision ratio, slope, etc.), repeat measurements were averaged to eliminate duplicate reaches.

Results

Analysis of cross sections and DEMs of difference

Of the three sites where cross sections were analyzed, the Mad River site had the highest bank erosion rate (average of 1458.9 kg/m/yr). The Black Creek sites had lower erosion rates (average of 478.5 kg/m/yr at Black Creek #1 and 1041.4 kg/m/yr at Black Creek #2). Due to the varying number of cross sections taken at each site, different reach lengths were measured to derive erosion rates. The 10 Mad River cross sections were spread across 262 m, whereas the 2 Black Creek #1 cross sections spanned 38 m, and the 4 Black Creek #2 cross sections spanned 85 m. Each site had varying land-use/land-cover. The Mad River reach was 6.8% agricultural land and 62.3% vegetated riparian area and was considered disconnected from its floodplain (incision ratio of 1.63). It also had the steepest slope of the three sites at 0.97%. Both Black Creek sites were 14.1% agricultural land, but Black Creek #1 was 54.4% vegetated riparian area and Black Creek #2 was only 17.3% vegetated riparian area. Both reaches were considered connected to their floodplains, with incision ratios below 1.3. Black Creek #1 had a slope of 0.31% and Black Creek #2 had a slope of 0.06%.

The New Haven River and Lewis Creek reaches, where DoD's were analyzed, were highly mobile. Over the 6 year study period, the New Haven River reach had the highest bank erosion rate of any reach analyzed (3536.2 kg/m/yr). The reach measured was 2379 m long and was 23.1% agricultural land and 54.4% vegetated riparian area. It was moderately disconnected from its floodplain (incision ratio of 1.35) and had a slope of 0.47%. The Lewis Creek site had a lower mass erosion rate (877.6 kg/m/yr), which was analyzed over 9 years and 2362 m. The area surrounding the Lewis Creek reach is 11.7% agricultural lands and 45.6% vegetated riparian area. The stream in this area was connected to its floodplain (incision ratio of 1.26) and had a relatively high slope (0.40%).

Regional dataset of bank erosion rates

In all, we created a dataset of mass erosion rates and associated stream attributes for 185 unique stream reaches including 5 repeat observations. This dataset encompasses 20 streams in the LCB, with reaches concentrated in the Missisquoi and Winooski watersheds, and several other points distributed within the Lamoille, Otter, and Lake Champlain Direct watersheds (Fig. 1). There was variability in the methodology-used, duration, and years of measurements, and in the attributes tied to each stream reach.

Fourteen reaches were measured using repeat cross sections, which included 4 studies and 7 different streams. Thirteen reaches were measured with the imagery analysis method, but this method was only used by Jordan (2013) on the Mad River. DoDs were the most used method, with 136 reaches studied. One-hundred thirty-four of the reaches were from Garvey (2012), and I analyzed the two other reaches that used DoDs. The bank stability model was only used by Langendoen et al. (2012) and included 27 reaches from 7 streams.

Of the seven studies included in the bank erosion dataset, five studies (150 reaches) were considered to have short measurement durations (≤10yrs) and two studies (40 reaches) included long-term bank erosion measurements (>10yrs). The average study duration was 7.7 years, and the median duration was 3 years, with studies ranging from 1 year long to 30 years long. The years studied varied greatly as well and spanned 44 years; there was data from 1979 through 2023.

Additionally, 64 reaches (34% of dataset) had at least one large flood during the study period, and 126 reaches (66% of dataset) only had moderate floods during the study period. Irene, in 2011, and the 1998 floods, two record setting floods in many places, were captured and recorded in two of the studies.

Table 2. Summary statistics and distribution of each attribute.

Variable	**Mean**	**Median**	**Min**	**Max**	**Range**	**Std. Deviation**	**Skewness**
Mass Erosion Rates (kg/m/yr)	321.9	38.5	0	7511.4	7511.4	757.2	5.65
Drainage area (km^2)	152.4	25.3	0.1	2730.9	2730.8	407.5	4.5
Agricultural Lands (%)	20.3	19.6	4.1	80.4	76.3	11.4	2.06
Vegetated Riparian Area (%)	71.9	75.0	1.8	100.0	98.1	23.5	-0.68
Channel Slope (%)	0.507	0.324	0.001	4.47	4.469	0.637	2.87
Incision ratio	1.39	1.27	1.0	5.5	4.5	0.47	4.4
Reach Length (normalized by stream width)	110.8	89.9	2.0	528.0	526.0	91.4	1.94

Summary statistics of mass erosion rates and associated stream attributes can be found in Table 2. There is a wide range of erosion rates (0 – 7511.4 kg/m/yr) between the reaches included in this dataset. Several reaches analyzed in Garvey (2012) were reported to have no erosion, and Hamshaw (2018) reported the highest mass erosion rate on the New Haven River. The average mass erosion rate reported is 321.9 kg/m/yr, but the median mass erosion rate is 38.5 kg/m/yr. As such, the data is highly skewed to the right.

The dataset created represents small headwater streams up to large lowland rivers. Centennial Brook had the smallest drainage area (0.1 km^2), and the mouth of the Winooski River had the largest drainage area (2606.7 km^2). Smaller streams were over-represented in the dataset (skewness of 4.5).

Further, the slopes represented in the dataset were also skewed towards flatter gradients (skewness of 2.87). The Mad River consistently had the lowest percentage of agricultural land, and Hungerford Brook had by far the highest percentage of agricultural land (Table 2). Several streams were 100% vegetated riparian area, and Sucker Brook had the least vegetated area (1.8%). There were 104 reaches in the dataset that are considered to be connected to their floodplain (i.e., IR<1.3) and 86 reaches that are considered disconnected (i.e., IR≥1.3). Reach lengths were only obtained for 161 reaches, so the sample size is smaller but still had a range of 526 stream-widths long.

Factors that influence variability in bank erosion

Many attributes were found to have a weak but significant relationship with mass erosion rate.

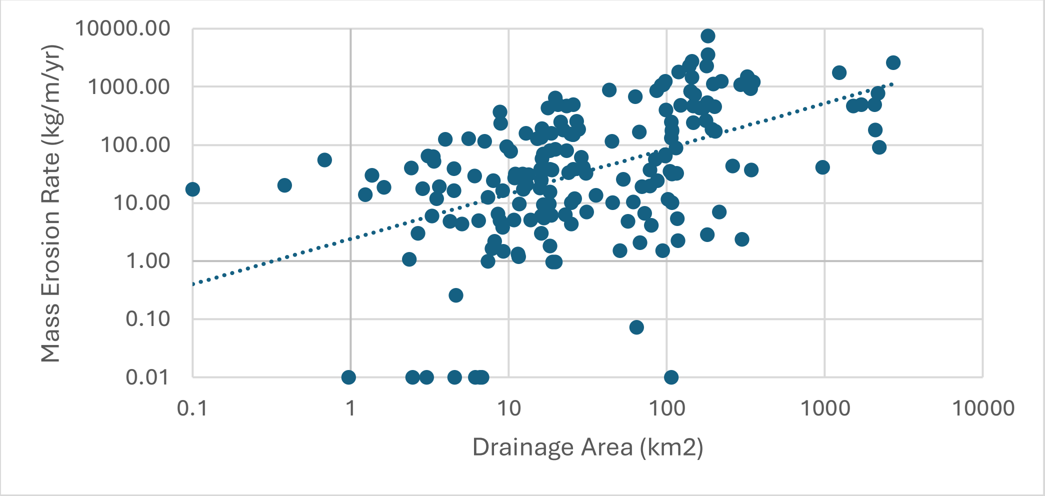

Fig 4. The relationship between drainage areas and mass erosion rates.

Drainage area had the most significant relationship to mass erosion rates when compared to all other attributes. Drainage area had a moderate and significant positive correlation ($r_s(185) = 0.55$, $p < 0.0001$; Figure 4). When categorized into higher and lower gradient environments, slope and mass erosion rates did not have a significant relationship ($p = 0.1416$), but continuously, slope had a weak but significant positive correlation to mass erosion rates ($r_s(185) = 0.17$, $p = 0.0194$). Both agricultural area ($r_s(185) = -0.24$, $p = 0.0010$) and vegetated riparian area ($r_s(182) = -0.28$, $p = 0.0002$) had weak but significant negative correlations. Additionally, as a continuous variable, incision ratio had a weak but significant positive correlation to mass erosion rates ($r_s(185) = 0.18$, $p = 0.0126$). However, when categorized, connected and disconnected reaches were not significantly different ($p = 0.7757$).

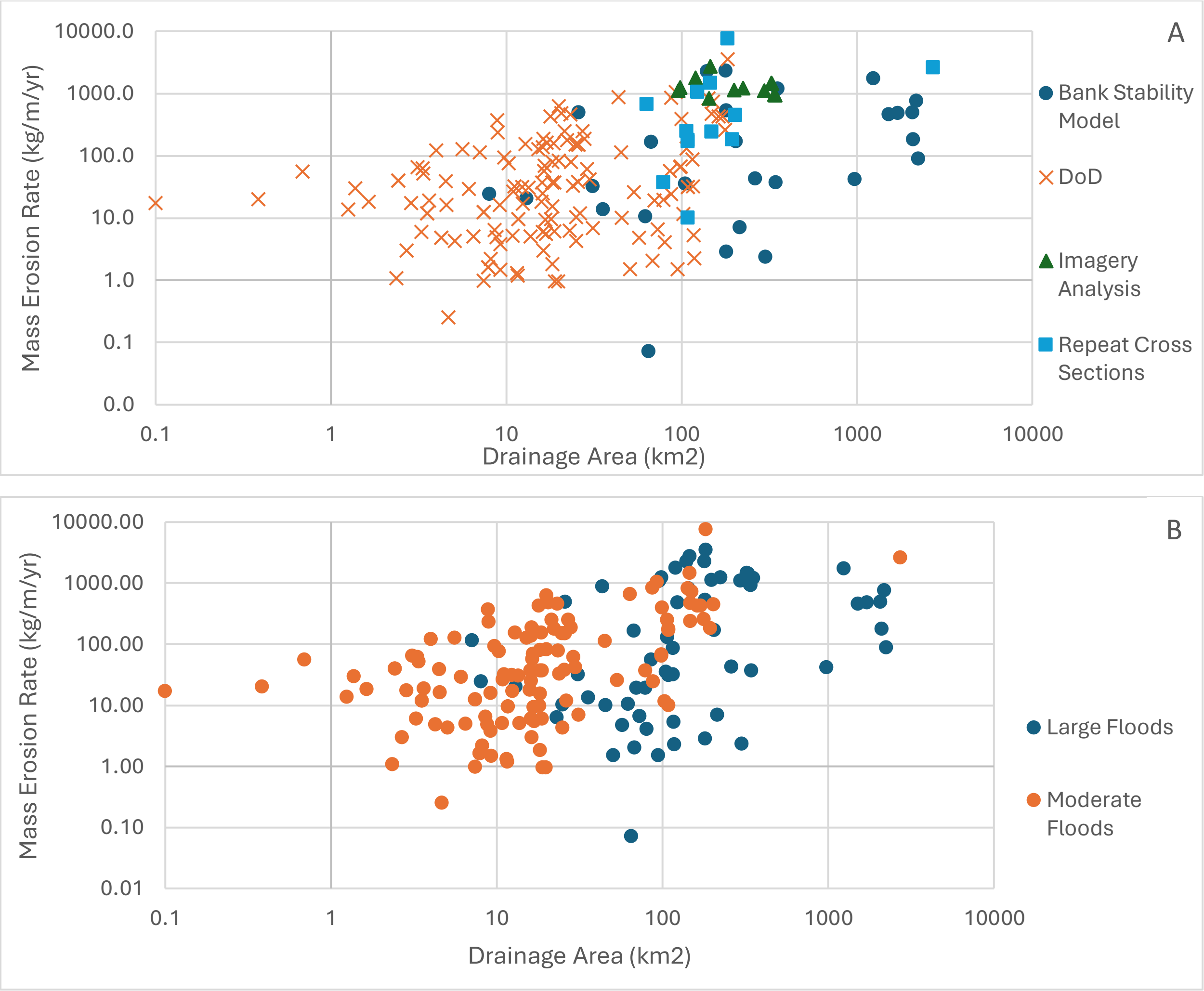

Fig. 5 (A) The relationship between methods and mass erosion rates, with respect to drainage area. (B) The relationship between flood size and mass erosion rates, with respect to drainage area.

Large floods produced, on average, larger erosion rates (545.6 kg/m/yr vs 208.4 kg/m/yr, for large and moderate floods, respectively) (t(120.9126) = -2.91, p = 0.0043). The reaches with large floods tended to be present in rivers with larger drainage areas and to originate from studies using imagery analysis and bank stability models (Fig. 5).

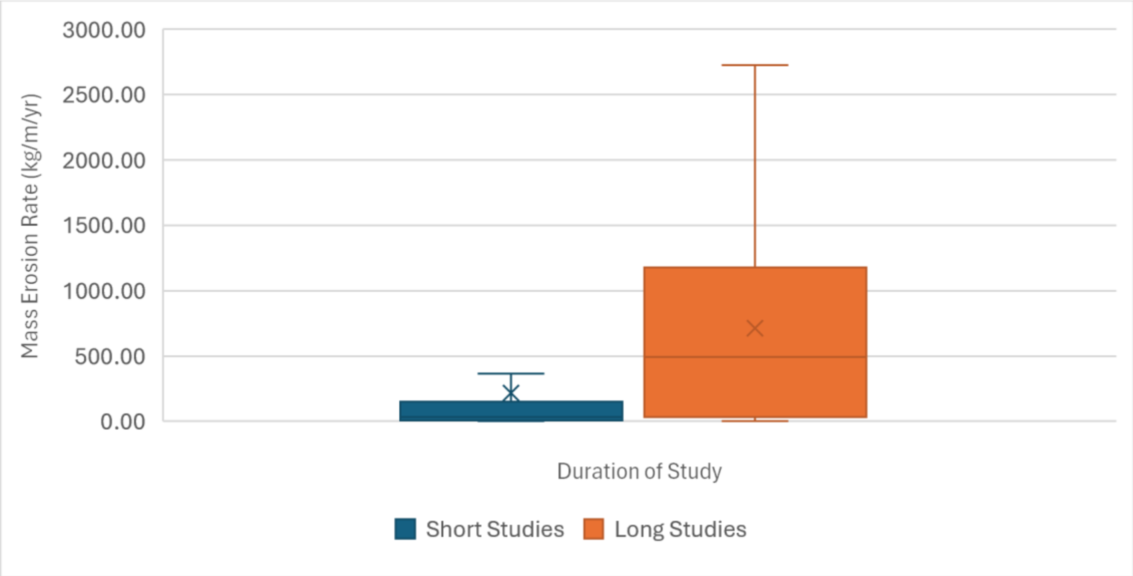

Fig. 6 The distribution of mass erosion rates by timespan, categorized as “short” and “long” studies.

The duration of studies did impact mass erosion rates. There was a weak but significant relationship between study durations and mass erosion rates as a whole ($r_s(190) = 0.26$, $p = 0.0003$), but when a threshold of either short (≤10 yrs) or long (>10 yrs) was analyzed, the correlation was stronger ($t(60.7045) = -3.75$, $p = 0.0004$)(Fig. 6). Longer studies also captured more large floods than shorter studies, since every long-study reach had a large flood, and 84% of short-study reaches only had moderate floods. Although a very weak relationship, reach length also had a significant but negative correlation with mass erosion rates ($r_s(161) = -0.22$, $p = 0.0050$). Additionally, while methodology appears to affect mass erosion rates ($F(3,189) = 19.58$, $p < 0.0001$), methodology is not evenly distributed across other important variables, such as drainage area (Fig. 5).

Discussion

Building an understanding of regional streambank erosion patterns requires an abundance of data, which is often difficult to acquire. The bank erosion dataset developed in this study drew upon a collection of studies across the Lake Champlain Basin (LCB), allowing us to identify rates across a large geographic area. As a result, we developed the first, readily-accessible regional streambank erosion dataset in Vermont, enabling us to better constrain erosion rates, work towards understanding the drivers of streambank erosion, and ultimately contribute to a more complete picture of geomorphic processes in the region that may inform better management of streams.

Potential drivers of bank erosion

One of the motivations of this study was to better understand not only the magnitude of erosion, but also the potential watershed and land use factors that influence variability in rates. We found that many variables, including drainage area, slope, land cover, flood size, and incision ratio have a significant correlation to mass erosion rates, but these relationships may be confounded in part by details of the study they were derived from including methodology, study duration, and reach length.

Drainage area, slope, and flood magnitude are directly related to stream power, so we would expect these variables to influence erosion rates (Church, 2002). As drainage area increases, so does stream power and the size of the stream, and as a result, the amount of material available to erode. Our finding that drainage area is an important variable in describing bank erosion rates is consistent with our expectations and with the findings of Noe et al. (2022) in the Chesapeake Bay. We found that steeper settings have higher bank erosion rates, which is consistent with Church (2002) as well. Large floods are more likely to be associated with higher bank erosion rates, that often persist for many years following a flood (Ross et al., 2019), although the exact relationship is not linear (Julian and Torres, 2005). While it appears that periods with large floods had higher mass erosion rates, observations of large events only exist on larger streams, so the effect of drainage area and flood size are potentially conflating, limiting our assessment of the role of flood magnitude.

Riparian vegetation has a well-documented influence on bank erosion variability, since it stabilizes streambank sediment, adds roughness, and aids in infiltration (Osborne and Kovacic, 1993; Langendoen et al., 2012). The negative correlation between percent riparian vegetation and mass erosion rates is consistent with what we would expect, indicating that erosion is lower with more riparian vegetation present. However, the negative correlation between agricultural areas and bank erosion is inconsistent with the literature, given that agricultural areas are typically associated with higher rates of bank erosion (Zaimes and Shultz, 2004; Noe et al., 2022). Our finding that areas with more agriculture have lower erosion rates may be influenced by an uneven distribution of agricultural land in the dataset or by other confounding variables. Incised rivers are a result of disturbances, and as channels evolve back into equilibrium, bank erosion widens the channel (Simon and Hupp, 1986). We found that more incised (i.e., disconnected) streams are associated with higher rates of bank erosion than those that are less incised and better connected to their floodplains.

While the development of a regional dataset can be a powerful way to look for trends, there are also challenges associated with differences in study design. Between studies, study duration and methodology had a large impact on erosion rates. Longer studies tend to be more representative of average erosion rates, since shorter studies can be influenced by whether or not there is a large event during the study period or not (Garcia-Ruiz et al., 2015). In our meta-analysis, longer studies tended to have more large events, and shorter studies mostly had moderate events, which could be a source of the positive correlation of duration-driven variability. For example, I found a mass erosion rate of 1458.9 kg/m/yr for reach 26_M12 on the Mad River and Jordan (2013) reported a mass erosion rate of 2724.0 kg/m/yr for the same reach. My measurement period was short and included only moderate floods, but the longer study of Jordan (2013) contained 2 large events (1998, 2011). Reach length as a function of stream width has a negative correlation, implying that shorter reach lengths have higher erosion rates. This could be because erosional features in longer reaches are spread out, whereas shorter measurement reaches may only include highly erosional features. For instance, for reach 26_M12 on the New Haven River, I found a mass erosion rate of 3536.2 kg/m/yr and Hamshaw (2018) had a mass erosion rate of 7511.4 kg/m/yr. However, my measurements were 91.4 stream-widths long and Hamshaw (2018) measured a reach of only 10.4 stream-widths long and captured an avulsion.

Although it is likely that the varying methodology and details of the studies used in our meta-analysis have an impact on calculated mass erosion rates, it is difficult to distinguish how specifically these factors would influence calculated rates. Garcia-Ruiz et al. (2015) found that methods are important for understanding some of the variability within worldwide soil erosion rates, but several other studies focused on bank erosion have found that there is little difference between GIS measurements and field-based measurements if used at appropriate scales (Hamshaw et al., 2019; Johansen et al., 2007). Since erosion rates derived from numerical model simulations have many assumptions that introduce additional uncertainties, they are highly reliant on field validation to understand how their uncertainties may contribute to erosion rate variability (Garcia-Ruiz et al., 2015). That said, since Langendoen et al. (2012) did not validate their model calculations and only reasoned through how their measurements may compare to field measurements, there is much more uncertainty in the mass erosion rates drawn from Langendoen et al. (2012). Thus, it is hard to draw conclusions on how methodology could have affected our dataset specifically.

Relationship between erosion and deposition drivers

When a river reach is in equilibrium, erosion and deposition are balanced (Noe et al., 2022). Based on regional average floodplain sediment deposition rates from Diehl et al. (2023) and regional average mass erosion rates from the bank erosion dataset, bank erosion (321.9 kg/m/yr) and floodplain deposition (156 kg/m/yr) appear to have similar orders of magnitude. However, it is important to note that these data sets sampled reaches representing different geomorphic reach types. Reaches in the deposition dataset of Diehl et al. (2023) were biased to unconfined, low-gradient (<0.0063 m/m) settings expected to demonstrate deposition, whereas the bank erosion dataset also included reaches with higher gradients.

Diehl et al. (2023) also identified several site and regional-scale factors associated with deposition variability. As with bank erosion, drainage area was found to describe some of the variability in measured deposition, with larger watershed areas receiving generally more deposition per stream length. Slope was also found to be an important driving variable in both regional deposition and erosion rates. In higher gradient settings (>0.002 m/m), floodplain deposition rates were higher, and we found that as channel slope increases, so does bank erosion. Diehl et al. (2023) also found that reaches with smaller incision ratios (well-connected to their floodplains) have higher rates of deposition, and reaches with larger incision ratios have lower rates of deposition. I found that smaller incision ratios have lower rates of bank erosion, and larger incision ratios have higher rates of bank erosion. This suggests that stream reaches that are disconnected from their floodplains likely have higher bank erosion rates and lower deposition rates, which opens questions of whether disconnected reaches contribute to downstream sediment loading and water quality issues at disproportionately high rates compared to connected reaches.

Restoration Implications

Understanding controls of bank erosion variability and the relationship between bank erosion and floodplain deposition in the LCB enables us to better target reaches in need of restoration and better inform restoration practices. Although there are several variables that cannot be physically altered (drainage area, slope, flood size, etc.), there are a number of variables that can be changed with restoration, such as riparian vegetation and stream-floodplain connectivity. Improving stream-floodplain connectivity has previously been found to be effective at reducing bank erosion (Christensen et al., 2024), but it could also aid in promoting sediment storage as well. We found that connected streams have lower mass erosion rates, and Diehl et al. (2023) found that connected streams also have higher rates of deposition on their floodplains. That said, it can be deduced that if floodplain connectivity in disconnected streams is restored, there might be less sediment mobilized from stream banks in the first place, and more sediment that could be deposited on floodplains rather than transported downstream. Riparian vegetation is also known to be an effective restoration technique (Higgisson et al., 2019), so the addition of riparian vegetation (which we found to attenuate bank erosion rates) coupled with increased stream-floodplain connectivity in disconnected reaches with minimal riparian cover could greatly aid in Vermont reaching its TMDL requirements.

Future work

Moving forward, if the collection of mass erosion rates developed through this project can be further constrained along with deposition rates, a sediment budget could be built for the LCB. The general trends found between bank erosion and deposition variability can also aid restoration projects by expanding our understanding of important variables that contribute to bank erosion, so more targeted management practices can ensue.

Conclusions

Through the compilation and analysis of a regional dataset, this study identified spatial trends in bank erosion rates that exist in the Lake Champlain Basin. We found that mass erosion rates were generally higher on rivers with larger drainage areas, higher gradients, and where streams were disconnected from their floodplains. We also found that areas with more riparian vegetation cover had lower mass erosion rates. However, methodology, study-duration, and measurement-reach length may be confounding and add uncertainty to our analyses of the effect of watershed and reach-scale trends in streambank erosion. We found similar trends and magnitudes in bank erosion rates and floodplain deposition rates, suggesting that there are spatial patterns between deposition and erosion that improve our understanding of both processes and could aid in river management. These findings highlight the importance of well-connected rivers and will help improve the understanding of sediment budgets in the LCB and support stream restoration work.

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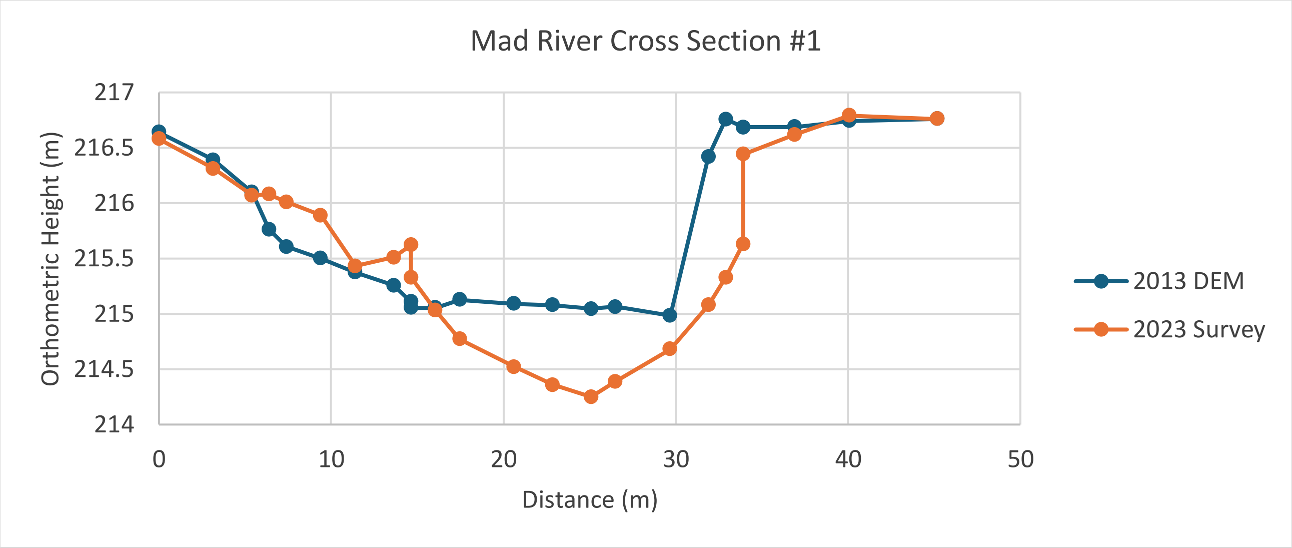
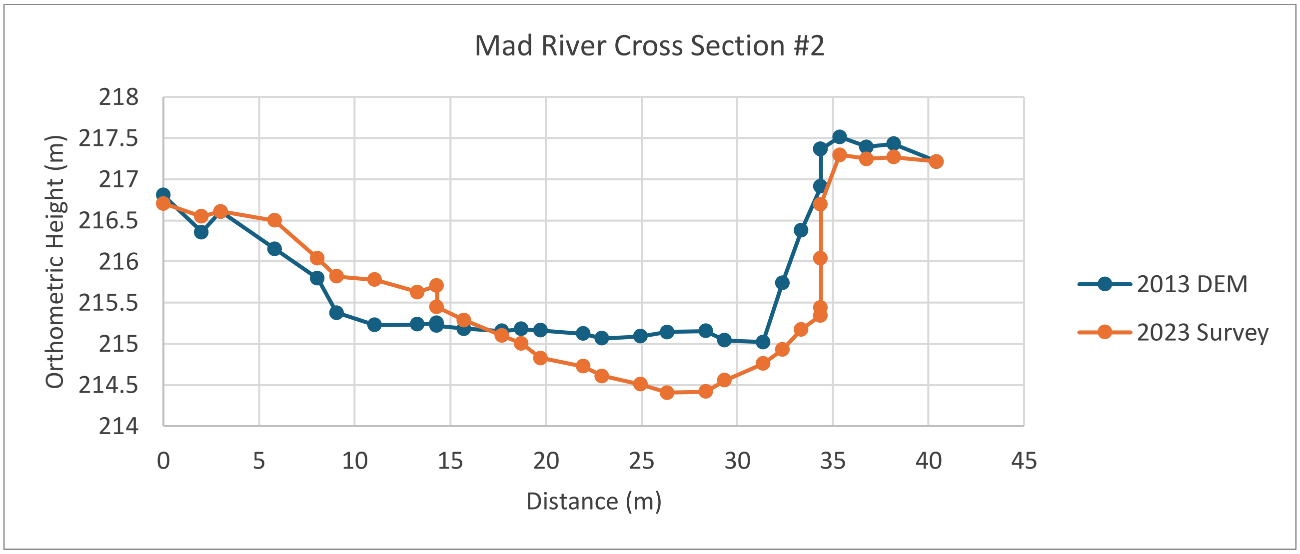
Appendix

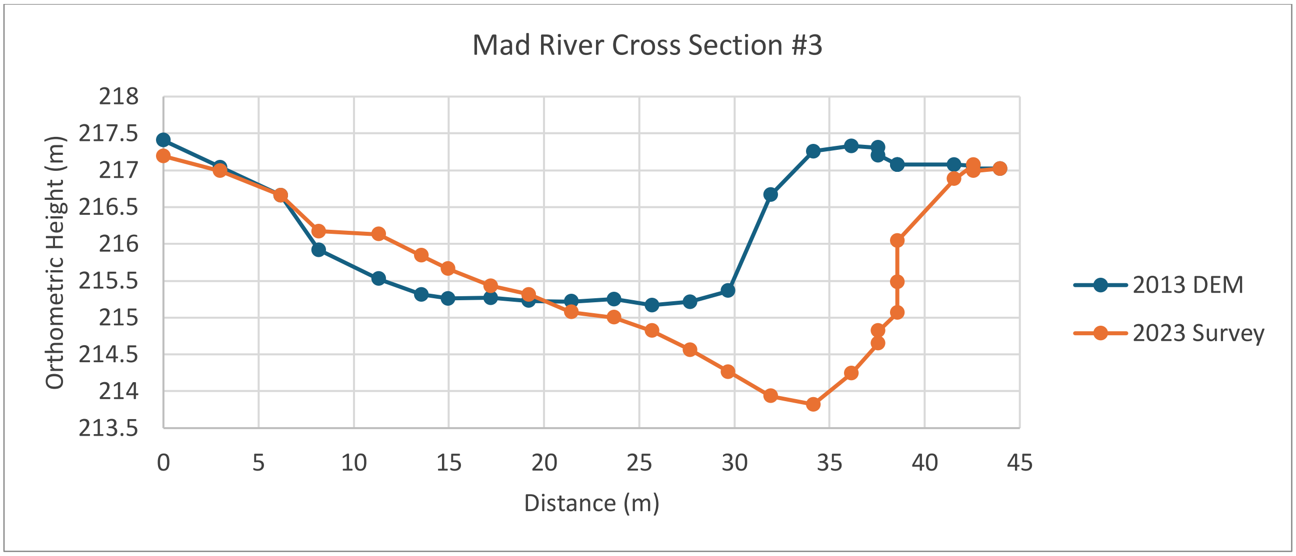
Table 3. Values extracted from each study and source of additional information needed to calculate mass erosion rates.

Study	**Information given in the study**	**Information sourced elsewhere**
Borg et al., 2014	• Bank height (page 1009, "Instrumentation and Measurements") • Total bank top retreat (m) (page 1011, "Cross-sectional Surveys") • Bulk density (page 1012, "Soil Properties")	• Reach length (approximated on Google Earth, using Fig. 1c as a reference)
DeWolfe et al., 2004	• Mass erosion rates (kg/m/yr) (Table 2)	
Garvey, 2012	• Normalized streambank erosion (kg/m) (Appendix A) • Normalized planform erosion (kg/m) (Appendix B)	
Hamshaw, 2018	• Cross-sectional net change (m^2) (Table 2.3, TLS data)	• Bulk density from Mad River (Ross et al., 2019)
Jordan, 2013	• Total normalized change in floodplain area (m^2/m) (Figure 8)	• Bulk density from Mad River (Ross et al., 2019) • Bank height assumed to be 1m (Ross et al., 2019)
Langendoen et al., 2012	• Soil loss (m^3/km/yr)(Table 6) • Bulk density (page 40)	

Mad River cross sections






Mad River Cross Section #3
Orthometric Height (m)
218
217.5
217
216.5
216
215.5
215
214.5
214
213.5
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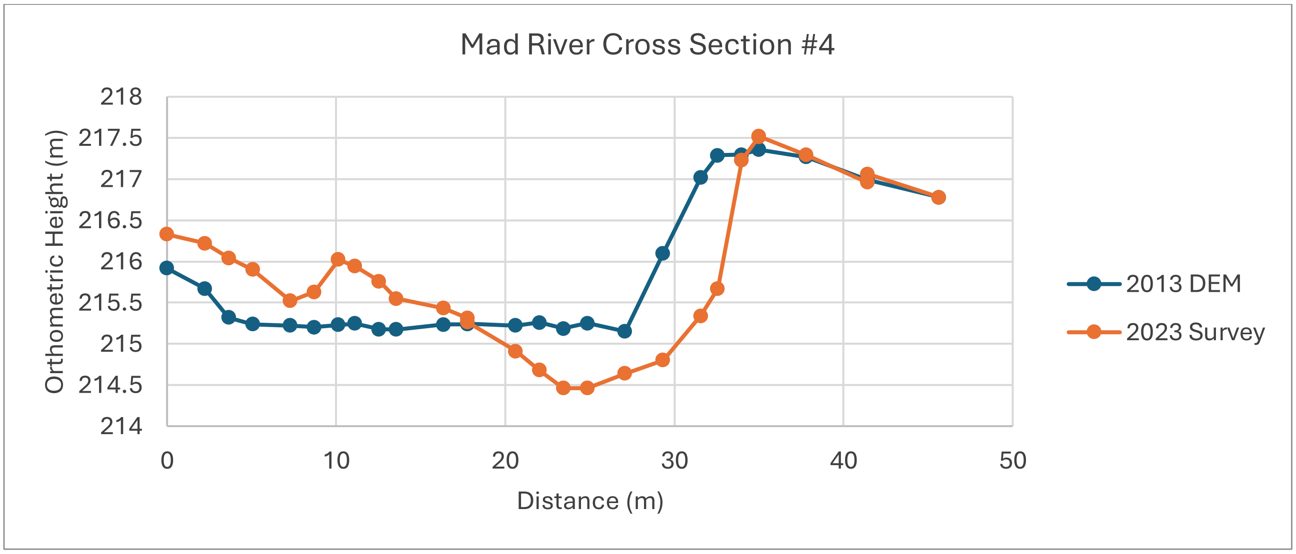
5
10
15
20
25
30
35
40
45
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #4
Orthometric Height (m)
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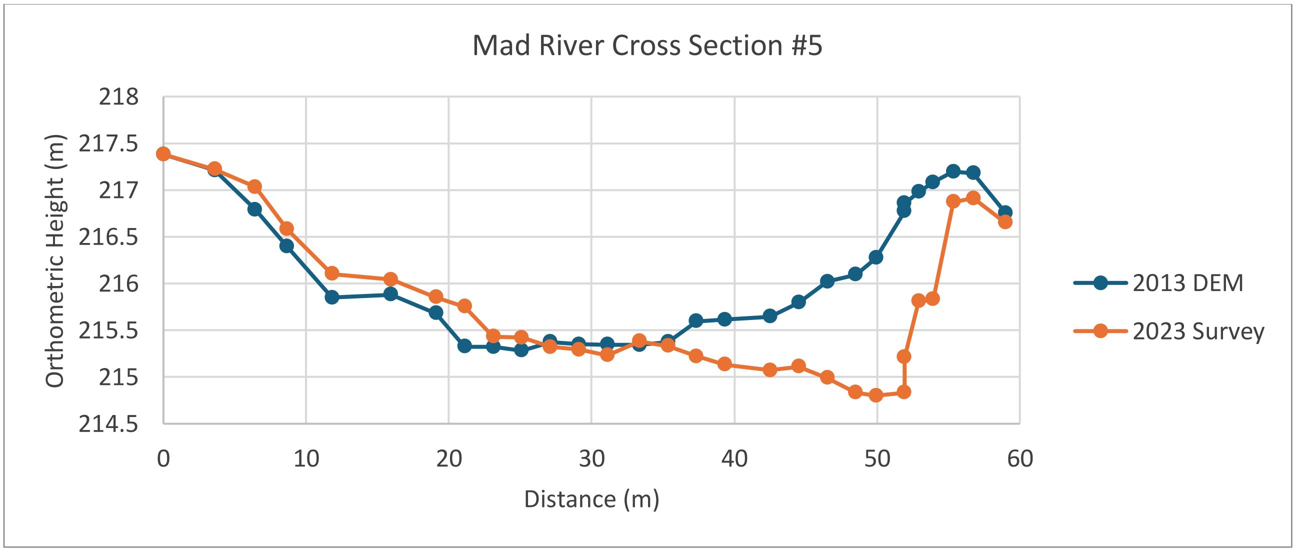
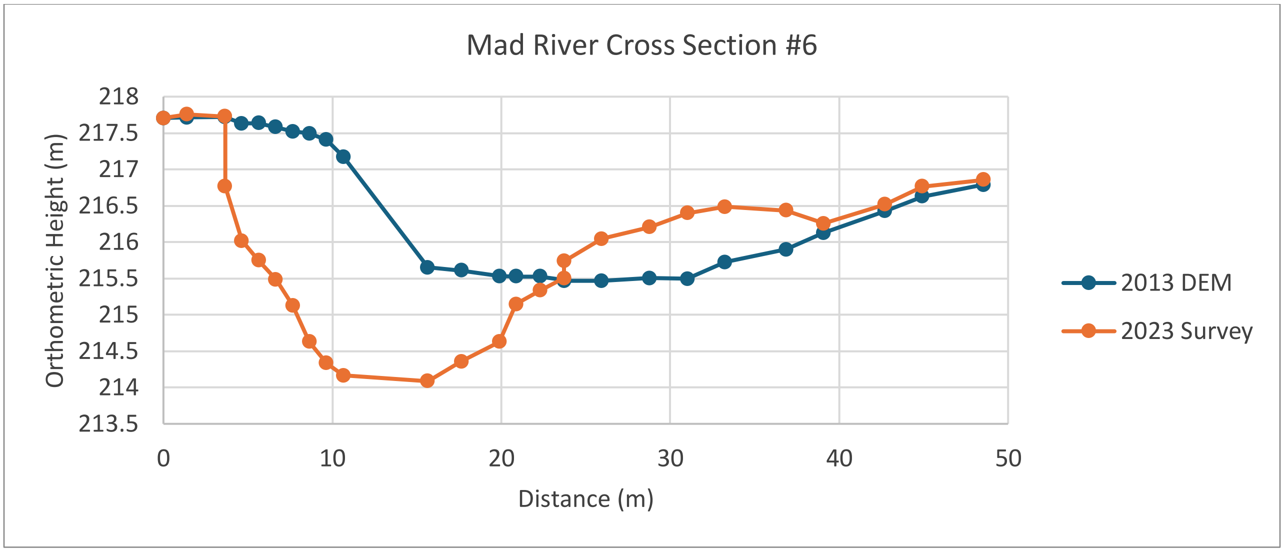
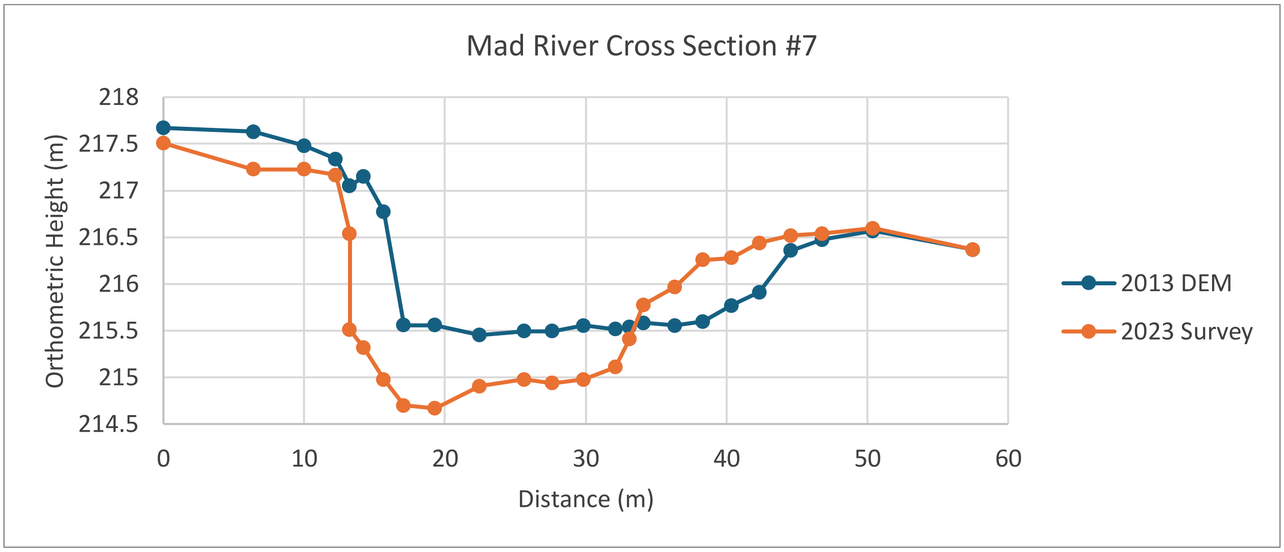
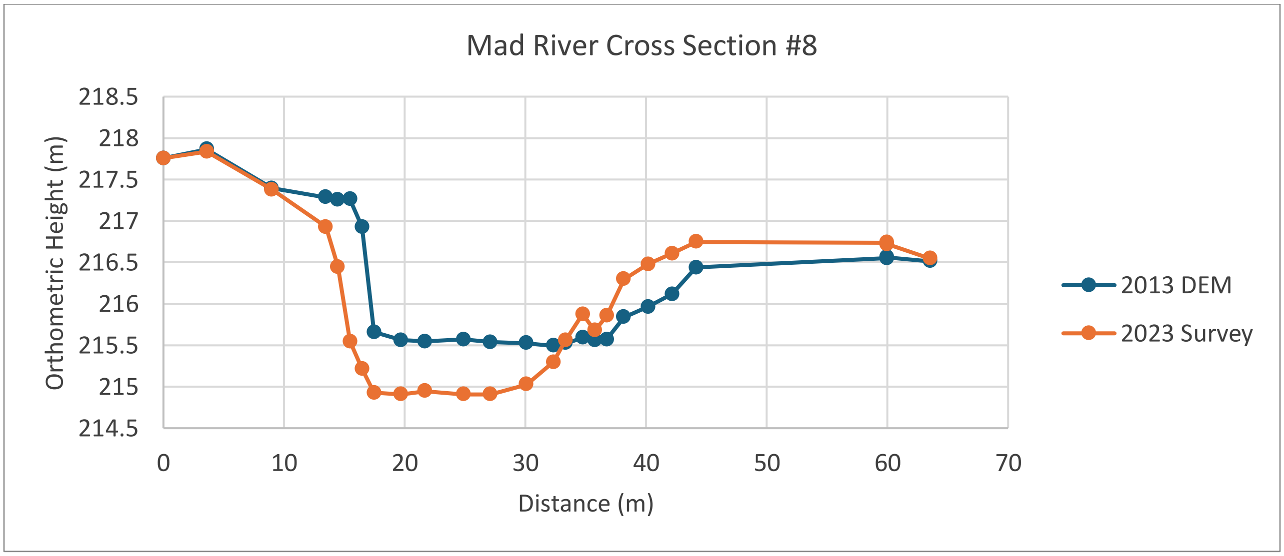
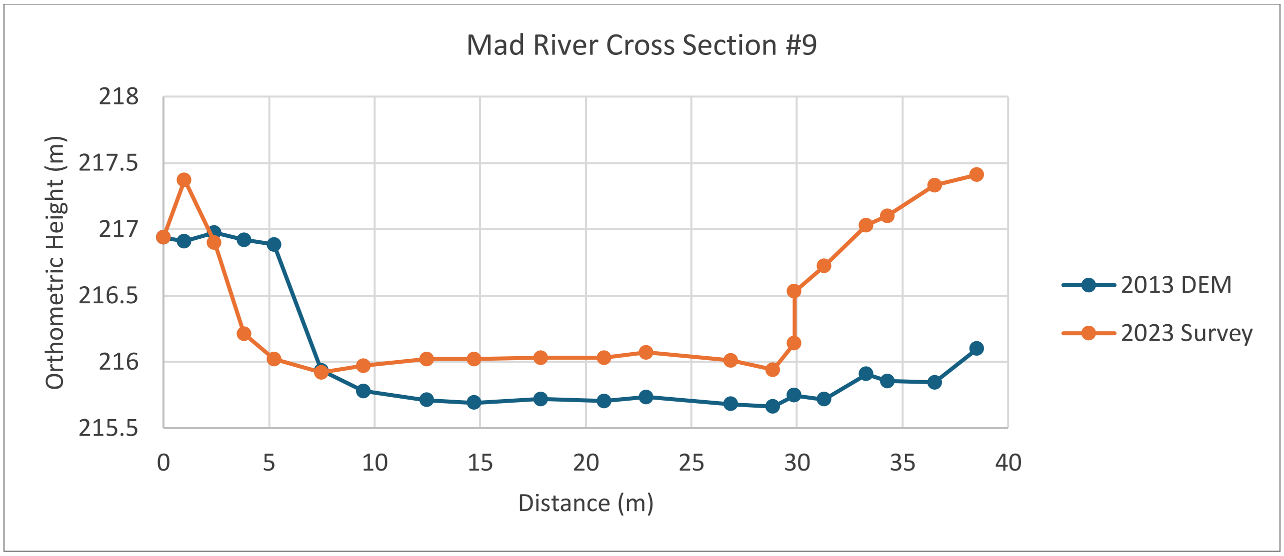
217.5
217
216.5
216
215.5
215
214.5
214
0
10
20
30
40
50
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #5
Orthometric Height (m)
218
217.5
217
216.5
216
215.5
215
214.5
0
10
20
30
40
50
60
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #6
Orthometric Height (m)
218
217.5
217
216.5
216
215.5
215
214.5
214
213.5
0
10
20
30
40
50
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #7
Orthometric Height (m)
218
217.5
217
216.5
216
215.5
215
214.5
0
10
20
30
40
50
60
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #8
Orthometric Height (m)
218.5
218
217.5
217
216.5
216
215.5
215
214.5
0
10
20
30
40
50
60
70
Distance (m)
2013 DEM
2023 Survey


Mad River Cross Section #9
Orthometric Height (m)
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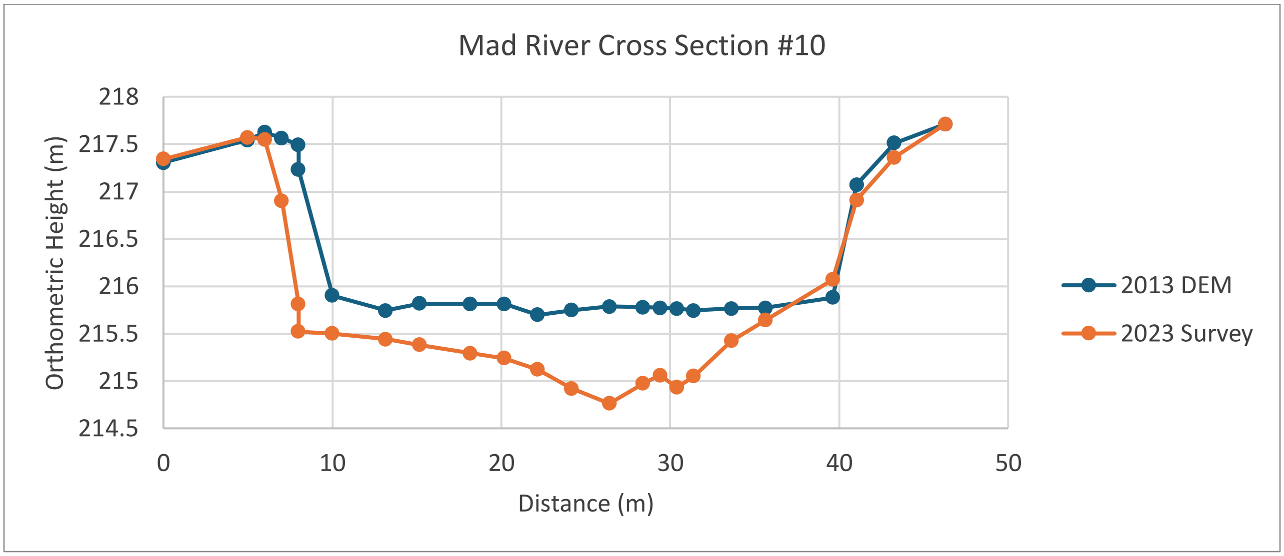
217.5
217
216.5
216
215.5
0
5
10
15
20
25
30
35
40
Distance (m)
2013 DEM
2023 Survey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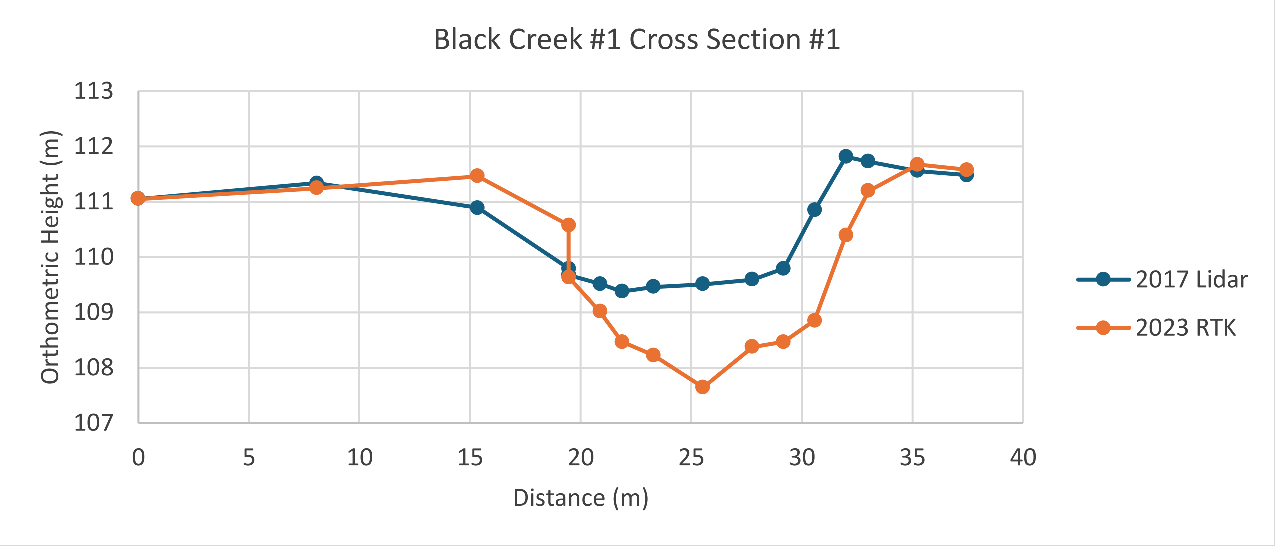
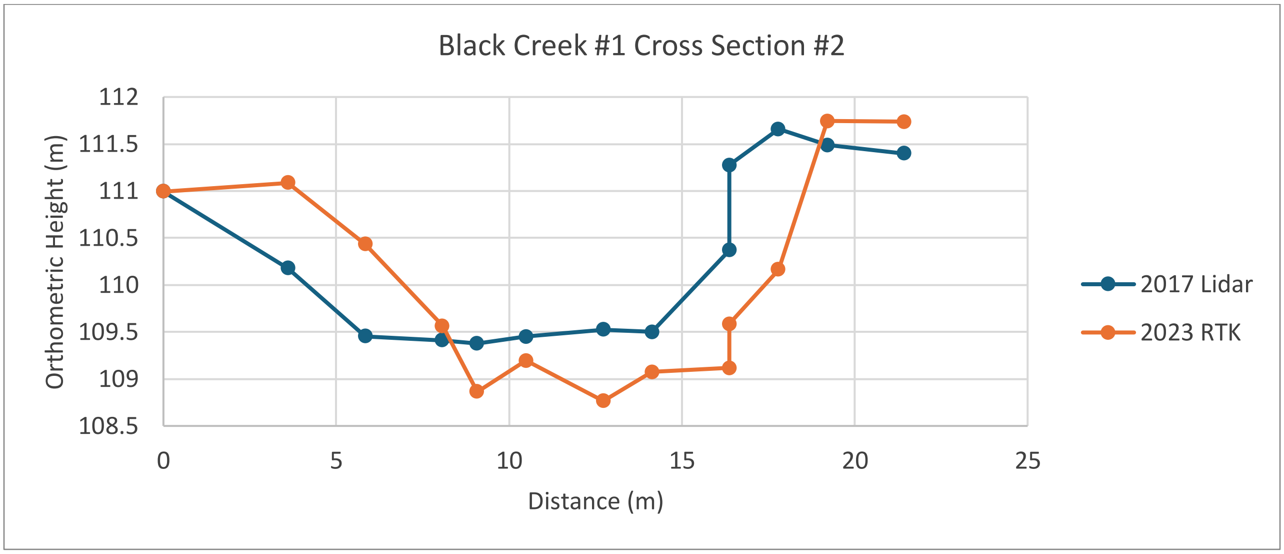
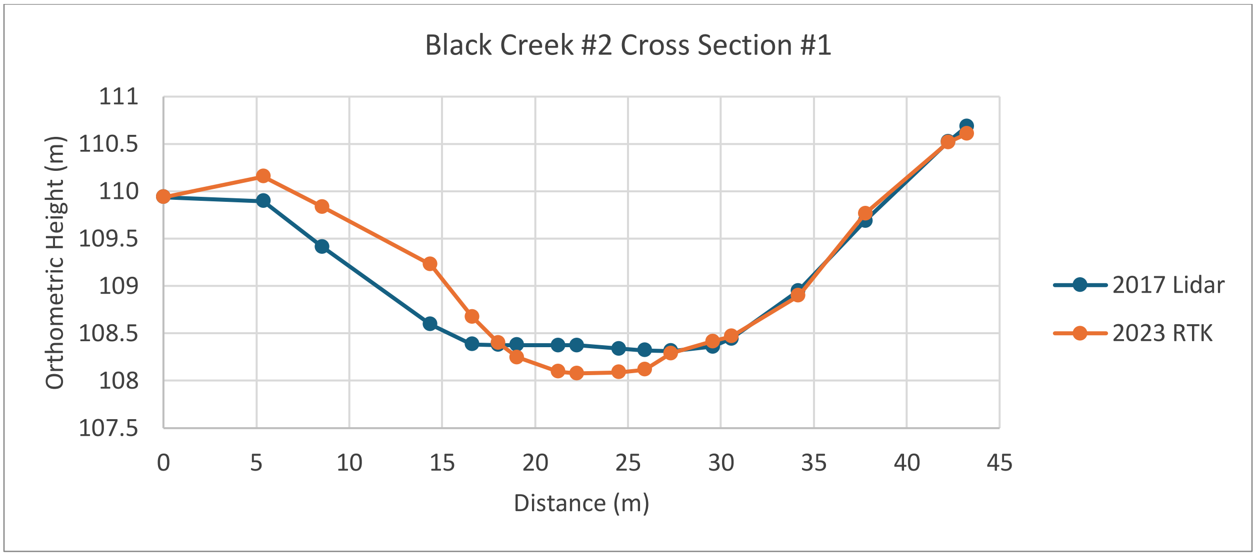
Orthometric Height (m)
218
217.5
217
216.5
216
215.5
215
214.5
0
10
20
30
40
50
Distance (m)
2013 DEM
2023 Survey

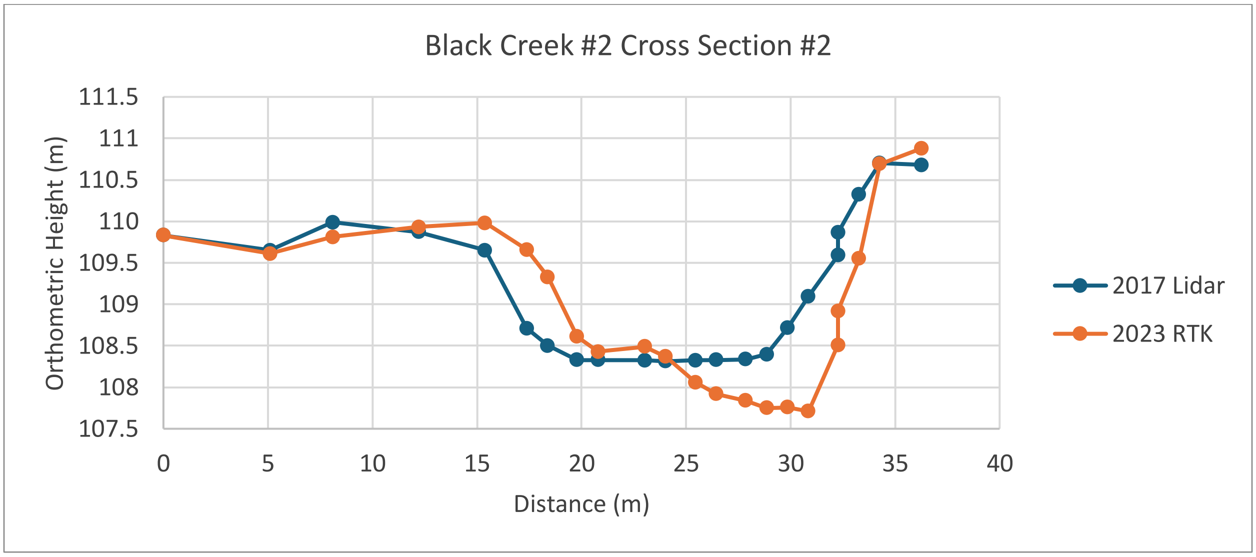
Black Creek #1 cross sections

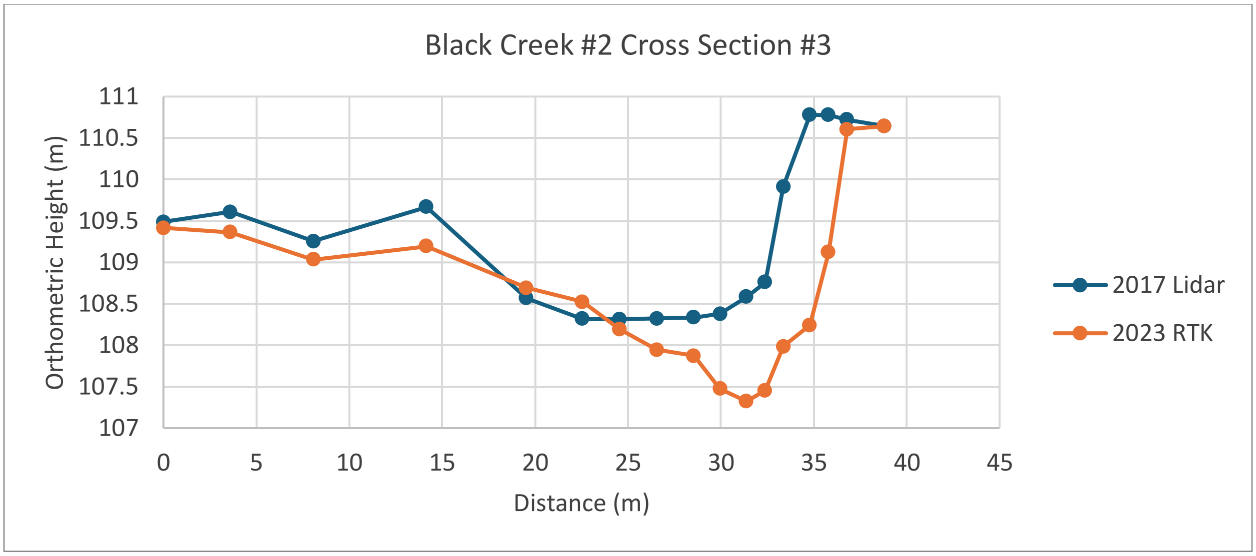


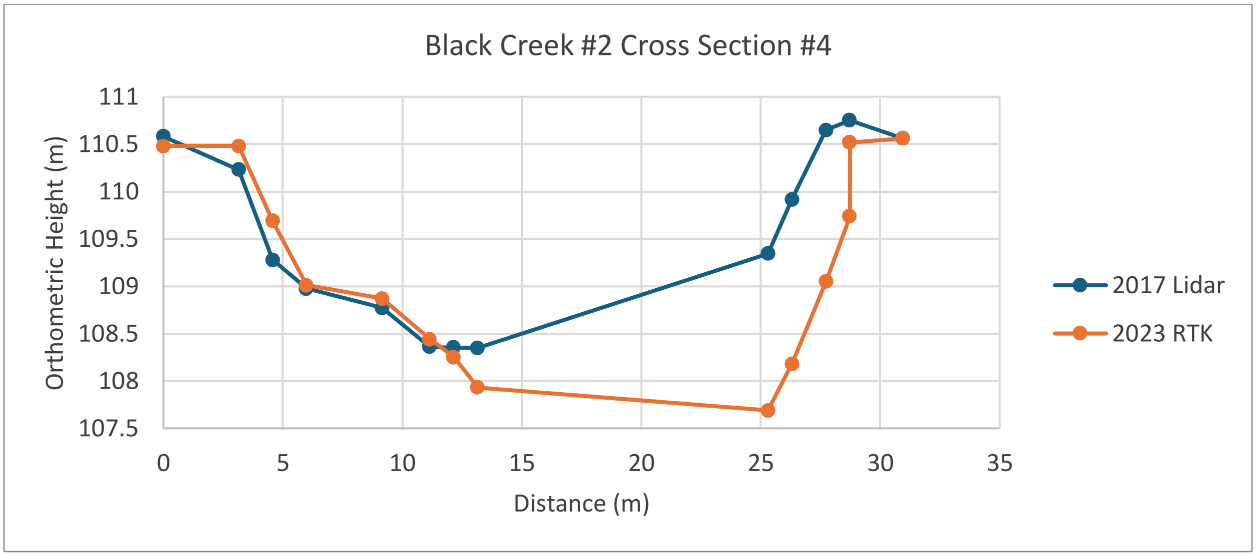


Black Creek #2 cross sections






Black Creek #2 Cross Section #3
Orthometric Height (m)
111
110.5
110
109.5
109
108.5
108
107.5
107
0
5
10
15
20
25
30
35
40
45
Distance (m)
2017 Lidar
2023 RTK


Black Creek #2 Cross Section #4
Orthometric Height (m)
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110
109.5
109
108.5
108
107.5
0
5
10
15
20
25
30
35
Distance (m)
2017 Lidar
2023 RTK