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An Analysis of River Channel Change Over Time in the Lamprey River

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Abstract

Flooding causes river channel change that threatens people and property. Due to climate change and urbanization, flooding events are projected to happen more frequently in the future, which will make the associated hazards worse. This project estimated the historical river channel change in the Lamprey River in southern New Hampshire. River channel change was estimated by delineating riverbank location on historical aerial photographs. The river channel change was compared to river width, curvature, and the number of 1.5-year flood events to explore the drivers of river channel change in the Lamprey River.

Introduction

Rivers naturally erode and deposit sediment, resulting in gradual changes in the position and shape of the river channel over time (Hickin, Nanson, 1984). This process is called river migration, and it occurs in almost every river. River migration can threaten infrastructure, such as bridges and dams, and property close to the riverbank (Rahman, 2013).

River migration occurs because of erosion and deposition, which increases during flooding events. Flood events can also cause property damage and are the most expensive natural disaster that northern New England faces (Csiki, 2020). Large floods occur infrequently but are powerful and very effective at moving sediment, thus creating erosion and deposition that will change the river channel. For example, following Hurricane Irene, the flow rate of the Connecticut River exceeded the flood magnitude of the 500-year return interval flood resulting in massive erosion and a sediment load of almost 500,000 tons of sediment per day (Yellen et al., 2014). Within specific tributaries of the Connecticut River, this single flood event mobilized the same amount of sediment that would have occurred over 10 to 40 years in the natural system

(Yellen et al., 2014). This example shows how much geomorphic work can be completed during a large flood event.

The geomorphic work that is completed during a flood depends on the magnitude and frequency of the flood. Infrequent floods of large magnitude do a massive amount of geomorphic work during the event but happen so infrequently that the average annual work may be small. Similarly, frequent floods of a small magnitude do very little work but happen frequently, also resulting in a small amount of average annual work. Wolman and Miller (1960) described a "maximum value" of the product of frequency and magnitude which described a flood that completed the most geomorphic work. They found that floods that are of a moderate magnitude and occur relatively frequently, such as the bankfull flood discharge (1.5-to-2-year return interval), complete the most geomorphic work over time (Wolman and Miller, 1960).

Flood frequencies have changed over the years, primarily due to climate change (Collins, 2014), which creates more intense rainstorms, and urbanization (Hollis, 1975), which routes water more effectively through the landscape because of impervious surface cover. Flood frequencies in many rivers in New England have increased, meaning floods of a certain magnitude are occurring more often than they were in the past (Collins, 2009). Specifically, in the Lamprey River, the 100-year flood magnitude has recently increased and is predicted to continue to increase in the future (Scholz, 2011).

To understand the amount of river channel change that a flood causes, the position of the riverbanks need to be measured. However, it is impractical to measure the position of the riverbank continuously and accurately in the field. To address this problem, remote sensing and satellite imagery have been used to estimate the river width and location using various techniques. For example, Gurnell (1997) used aerial imagery to look at the changing river width over time by using trees and mature shrubs as a proxy for the bank of the river. Schook et al. (2017) compared three different methods (channel cross sections, historical aerial photographs, and cottonwood transects at actively eroding river meanders) to assess river channel change over time and found that aerial imagery can be used to estimate river channel change if care is taken to ensure low georeferencing error. Finally, satellite imagery has been used to delineate riverbanks, such as in Frazier and Page (2000), who determined that a maximum-likelihood classification analysis was able to identify waterbodies with a 97.4% overall classification accuracy.

While there are many methods to delineate river channels using aerial imagery and remote sensing, this paper will specifically focus on manual riverbank delineation. Jordan and Wemple (2013) manually delineated the stream channel, point bars, and islands of the Mad River in Vermont for four different imagery dates. This allowed for the river channel change to be analyzed for the river with total annual river channel change greater than the resolution of the pixels. Aktar (2013) used a comparable manual delineation method to assess river channel change in three major rivers in Bangladesh (the Jamuna, the Ganges, and the Padma) by looking at the change in location of the riverbanks over time. This paper will follow a similar approach to these papers but will only focus on the delineation of the riverbank and vegetated islands.

This project aims to analyze the extent of river channel change in the Lamprey River over time and determine the relationship between river channel change, width, curvature, and flood frequency. The horizontal locations of riverbanks were manually delineated at multiple times from aerial imagery to explore their change over time. River width and curvature were also derived from the aerial imagery and compared to river channel change. Historical discharge from the United States Geological Survey (USGS) stream gauge system was used to determine the number of 1.5-year flood events to compare to the amount of river channel change.

Methods

Site Description

The study river is the Lamprey River in Rockingham Country, NH (Figure 1). The river flows into the Great Bay in Newmarket, NH. The drainage area of the Lamprey River upstream of the Macallen Dam is 211.62 square miles (StreamStats, USGS). The watershed has a maximum elevation of 1145 feet with an average basin slope of 6.25% (StreamStats, USGS). The watershed receives about 45 inches of rain and 66 inches of snow annually (StreamStats, USGS). The land cover of the watershed is 9.7% developed, 8.6% wetland, and 31.3% mixed coniferous deciduous forest (StreamStats, USGS). The USGS discharge gauge used for this analysis is USGS gauge 01073500, which is located in Durham, NH. The Lamprey River is highly regulated, with six dams located within the main channel (Dams of the Lower Lamprey).

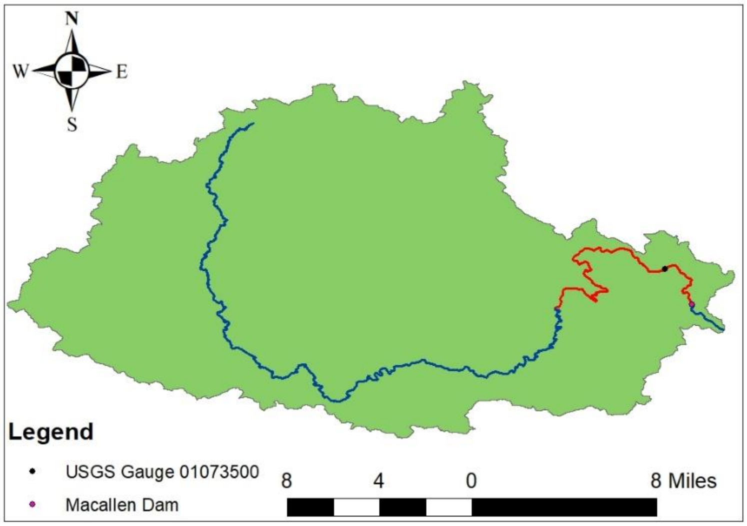


Figure 1: A map showing the Lamprey River watershed. The blue line is the total Lamprey River centerline, and the red line is the area that was delineated for this study. The pink dot is the Macallen Dam, where the delineations started, and the black dot shows the approximate location of USGS gauge 01073500, which was used for the flood frequency analysis.

Aerial Imagery Delineation

Aerial imagery was obtained and delineated within Google Earth. Four images were selected: from 1992, 1998, 2013, and 2018 (Table 1). These images were chosen because they were obtained during winter months (November-April), and the absence of leaves makes accurate delineation easier. Most of these images were obtained during periods when the Lamprey River had very similar discharge (Table 1), though the discharge at the time of the 1998 image was smaller. Depending on the resolution of the imagery, a different delineation scale was chosen and was consistent throughout the entire delineation (Table 1). The delineation scale for each image was chosen based on the resolution of the imagery. The older imagery from 1992 and 1998 had to be delineated at a larger scale because it was black and white, causing the bank, water surface, and trees to blend in with each other at a smaller scale (Table 1). The more recent imagery from 2013 and 2018 was delineated at a smaller scale because of increased resolution and color. This scale allowed for accurate delineation while keeping the distinction between structures (Table 1).

Table 1: Different imagery dates, the river discharge on the date the image was taken, and the scale for the manual delineation.

Imagery Date	**Discharge (ft^3/s)**	**Scale**
4/23/1992	446	1:3000
4/10/1998	213	1:3000
4/7/2013	490	1:1000
5/4/2018	401	1:1000

Manual delineation started just above Macallen Dam in Newmarket, NH. This dam was chosen as the starting point for manual delineation because the water level downstream of the dam is controlled mainly by tidal forces, making erosional and depositional processes in the reach different than the rest of the river. The aim of each delineation was to accurately map the riverbank, including any vegetated islands. The water's edge was not delineated as this can change greatly depending on the day and would not provide an accurate estimation of river channel change. The riverbank was located by attempting to look for sharp slopes towards the river which are located due to a change in ground cover from either water, bare sediment, or grass-like vegetation to permanent vegetation such as trees. The riverbank was delineated in this way because it should include the entire active channel up to the full bankfull width, which is reached by the water during a 1.5 to 2-year flood event. Therefore, a flood larger than the 1.5-year flood discharge is expected to top over the riverbank and reach the floodplain. The river centerline was delineated on the 1998 image by attempting to trace the exact center of the river. The 1998 image was chosen to delineate the centerline because it is the closest image to the center of the total date range. This centerline was only used for buffering, so the accuracy of the delineation is not as important. Once each delineation was completed, it was exported to ArcMap for further analysis.

River Channel Change Estimates

To allow for the exact same river reaches to be compared over multiples dates, a consistent frame of reference needed to be created, which started with splitting the 20.4-km-long 1998 centerline into 1 km pieces. The first 100 m of the centerline (closest to the Macallen Dam) and the last reach that was not a full 1 km were omitted from the analysis. The first 1-km reach was created just after the omitted 100 m to ensure that all the reaches were a full 1 km and started in the same location. The 1998 centerline was then buffered using the ArcMap buffer tool, with a buffer of 100 m and flat ends. Each 1 km 1998 centerline buffer polygon was exported as its own layer. These buffer polygons and the ArcMap clip tool were then used to clip the river channel polygon for each imagery date, resulting in 1-km-long river polygons that represented the exact same river reaches on different dates for comparison.

Once the river reach polygons for each imagery date were obtained, the ArcMap union tool was used between the same river reaches in different years to locate areas of no change, erosion, and deposition (Figure 2). This resulted in erosional and depositional areas. Erosional areas were defined as areas that were within the floodplain in an earlier image but were within the active river channel in a later image. Depositional areas are defined as areas that were within the active river channel in an earlier image but were within the floodplain in a later image. The erosional and depositional areas were measured using the ArcMap measure tool, which can measure lengths or areas of defined features. The total area and length of the river from endpoint to endpoint not accounting for curves (Figure 3) were also measured using the measure tool. The area values were divided by length (1 km) to get lateral erosion, deposition, and total change (defined as the total magnitude of lateral change, where erosion and deposition are not canceling forces), as well as width. The length (1 km) was divided by the actual length of the polygon measured endpoint to endpoint to produce curvature.

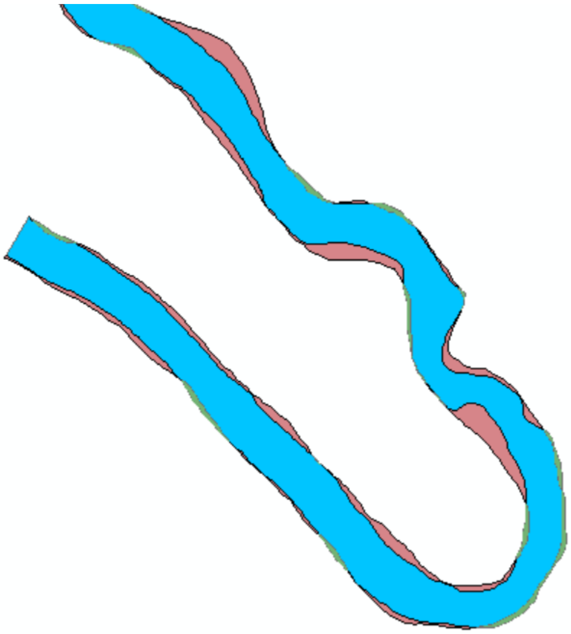
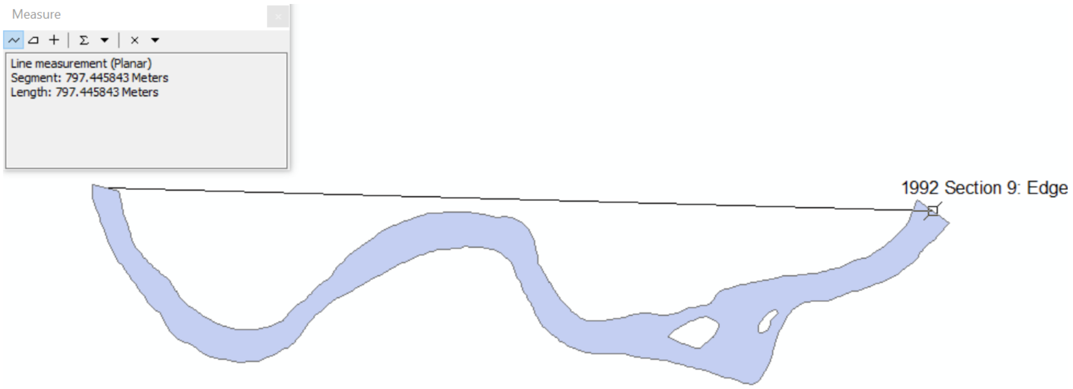


Figure 2: An example of the resulting union polygon between the 1992 and 1998 river delineations. The blue area is the part of the polygon that was the same in both images, which is the “no change” case. The red area are areas of erosion, which are areas that were within the floodplain in 1992 but were within the active channel in 1998. The green areas are areas of deposition, which are areas that were in the active channel in 1992 but were within the floodplain in 1998.



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Line measurement (Planar)
Segment: 797.445843 Meters
Length: 797.445843 Meters
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Figure 3: A screenshot showing how the length of each section is measured from endpoint to endpoint. Each section is 1 km long following the centerline but may be much shorter when measured this way due to the curvature of the reach (a reach with higher curvature will be shorter when measured this way).

Estimate of Error

To analyze the error within the manual delineation method, the same delineation process was repeated three times on each image in the same location. The 570-m-long reach chosen for error analysis was selected because it included a sharp bend and was heavily forested, making it a difficult location to delineate; therefore, error estimates should be interpreted as upper bounds. Using a similar process to the change estimates, a buffer was created from the centerline and broken into a 300 m section. The 300-m section was the largest section that could be analyzed while ensuring that each delineation started in the same location (like the other delineations, a starting and ending section needed to be omitted to ensure that each polygon started in the same location). For each of the four imagery dates, the riverbank was delineated three times and then clipped by the buffer to create the exact same river reach (12 reaches total). The union tool was used to analyze river channel change on every possible combination between each image date. For example, the union tool was used on the first delineation of the 1992 imagery and all three of the 1998 images. Then the union tool was used on the second delineation of the 1992 imagery and all three of the 1998 images, and so on, for 27 pairs total. The total, erosional, and depositional areas were measured and then divided by the length (1 km) to determine lateral change. The standard deviation of the lateral change estimated from each image combination was calculated to determine the error within the method for each image pair (error for the 1992-1998 delineations, for the 1998-2013 delineations, and for the 2013-2018 delineations).

Flood Frequency Analysis

A flood frequency analysis was conducted using 15-minute discharge data from USGS gauge 01073500 in Durham, NH (USGS Current Conditions), and analyzed in Python. The flood frequency analysis from the gauge was used as a proxy for the occurrence of floods throughout the entire watershed, even though the actual magnitude of the floods may be different in other parts of the watershed. Specifically, flood magnitude during an event is typically smaller upstream than downstream. The 15-minute (instantaneous) discharge was used because it represents all floods, including those that are large but have a short duration. The 1.5-year flood magnitude was calculated by ranking the annual peak historical discharge data and calculating the recurrence interval. The discharge with a recurrence interval closest to 1.5 was chosen as the 1.5-year flood magnitude. The 1.5-year flood magnitude was chosen for this analysis because it represents a relatively common flood of a medium magnitude, which has been shown to do the most geomorphic work within rivers (Wolman and Miller, 1960). If the instantaneous discharge had a local maximum above the 1.5-year discharge magnitude, it was counted as a peak. Any peaks within two days of another peak were omitted from the count because preliminary investigation confirmed that they were likely part of the same flooding event. Figure 4 shows an example of the hydrograph with a double peak. This is a good example of why peaks within 2 days of each other were omitted, because it is obvious from the figure that the heightened discharge is all from one event (Figure 4). The peaks were then organized into the water years that they occurred in to compare to the river channel change that occurred during the same period.

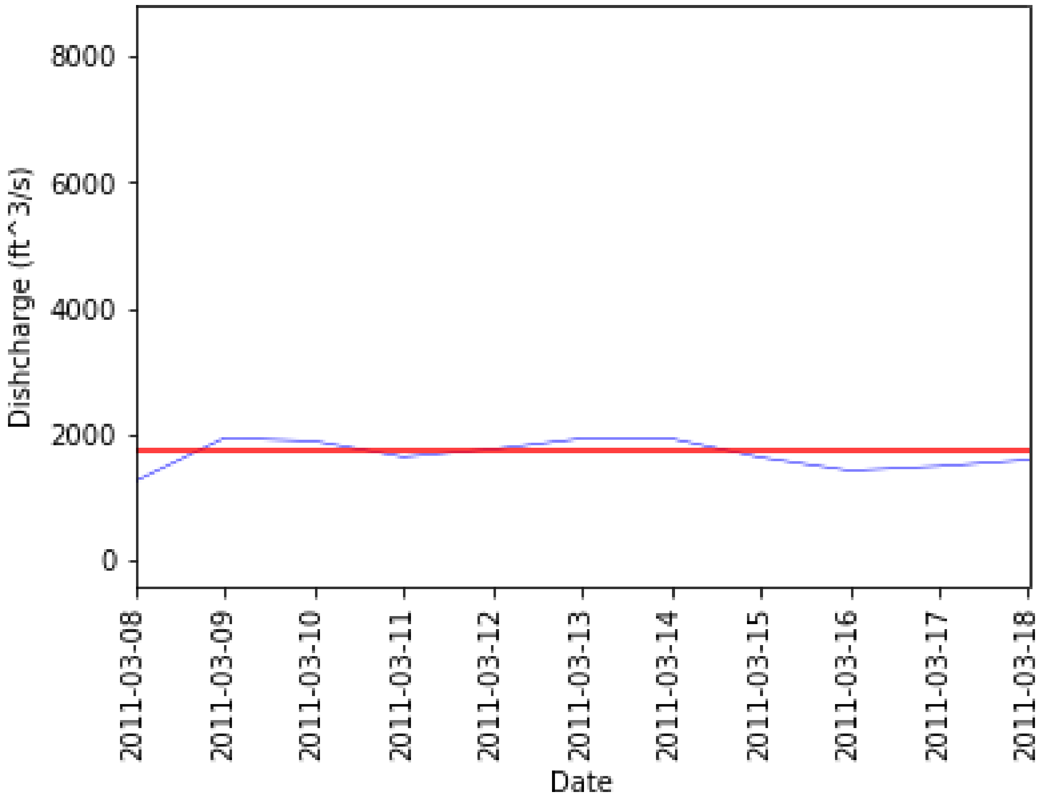

Figure 4: A hydrograph showing a single event that has two peaks over the discharge threshold, which shows why peaks within two days of another peak were omitted.

Statistical Tests

To determine if there was any relationship between river channel change, curvature, width, and the number of 1.5-year flood events, scatterplots were created comparing each pair of variables. Linear regression was performed on each scatterplot and the r^2 was recorded. The r^2 values were compared to the statistically significant values at an alpha of 0.05 to determine if there was a statistically significant relationship. An alpha value of 0.05 means that there is a 5% risk of concluding a relationship is significant when there is no relationship between the variables.

Results

River Change Estimates

The erosion, deposition, and total change values are highly variable depending on the reach (Figure 5). The overall average erosional and depositional changes over all reaches and time periods are 0.93 +/- 0.52 m/yr and 0.53 +/- 0.15 m/yr respectively. The error for the method calculated as standard deviation is 0.491 m/yr for erosion, 0.331 m/yr for deposition, and 0.368 m/yr for total change. Many of the change estimates fall outside of the calculated error, making it likely that there is actual change occurring in these areas (Table 2). The calculated error is also decreasing over time, which is likely caused by the improved imagery (Table 3). The first three reaches have eroded much differently compared to the other reaches (Figure 5). This is likely due to the large impoundment behind Macallen Dam.

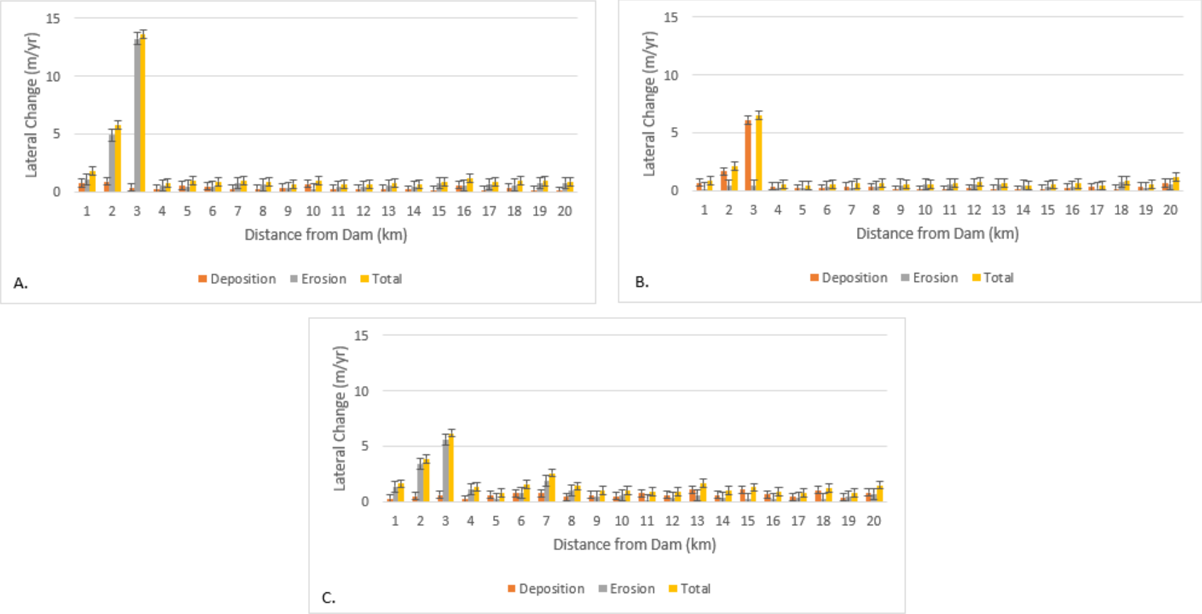

Figure 5: Bar graphs showing the erosional, depositional, and total lateral change for each period. A is from 1992 to 1998, B is from 1998 to 2013, and C is from 2013 to 2018.

Table 2: A table showing the calculated lateral change during the different time periods. Cells highlighted in green are greater than the associated error.

Reach	1992 - 1998 Lateral Deposition (m/yr)	1992 - 1998 Lateral Erosion (m/yr)	1992 - 1998 Lateral Change (m/yr)	1998 - 2013 Lateral Deposition (m/yr)	1998 - 2013 Lateral Erosion (m/yr)	1998 - 2013 Lateral Change (m/yr)	2013 - 2018 Lateral Deposition (m/yr)	2013 - 2018 Lateral Erosion (m/yr)	2013 - 2018 Lateral Change (m/yr)
1	0.7381667	1.041833	1.78	0.6876	0.168467	0.856067	0.2448	1.3566	1.6014
2	0.9063333	4.906	5.8123333	1.6528	0.422533	2.075333	0.4642	3.3894	3.8536
3	0.3673333	13.25	13.617333	6.1057333	0.425267	6.531	0.5662	5.611	6.1772
4	0.2725	0.511	0.7835	0.3759333	0.202133	0.578067	0.1794	1.131	1.3104
5	0.5288333	0.480333	1.0091667	0.1869333	0.274933	0.461867	0.5946	0.1948	0.7894
6	0.4573333	0.450167	0.9075	0.2085333	0.291	0.499533	0.7562	0.786	1.5422
7	0.2136667	0.736833	0.9505	0.3182	0.2786	0.5968	0.7562	1.8154	2.5716
8	0.2685	0.612167	0.8806667	0.3006667	0.304267	0.604933	0.4022	0.9714	1.3736
9	0.3511667	0.304	0.6551667	0.0427333	0.478067	0.5208	0.5604	0.4268	0.9872
10	0.69	0.253833	0.9438333	0.011	0.517533	0.528533	0.4658	0.5088	0.9746
11	0.2153333	0.427833	0.6431667	0.0926667	0.535733	0.6284	0.7476	0.1614	0.909
12	0.2373333	0.399667	0.637	0.1911333	0.542933	0.734067	0.5644	0.3016	0.866
13	0.219	0.494833	0.7138333	0.1469333	0.5066	0.653533	1.058	0.5798	1.6378
14	0.2021667	0.467667	0.6698333	0.0690667	0.416067	0.485133	0.5996	0.3634	0.963
15	0.1376667	0.724167	0.8618333	0.1385333	0.360667	0.4992	1.0956	0.1748	1.2704
16	0.5773333	0.561667	1.139	0.2760667	0.318733	0.5948	0.642	0.2174	0.8594
17	0.1668333	0.658167	0.825	0.3024667	0.1626	0.465067	0.3898	0.375	0.7648
18	0.3396667	0.591667	0.9313333	0.1301333	0.7402	0.870333	1.0212	0.2076	1.2288
19	0.1481667	0.763	0.9111667	0.3174667	0.245133	0.5626	0.3804	0.4242	0.8046
20	0.0808333	0.781167	0.862	0.636	0.5438	1.1798	0.8102	0.6616	1.4718

Table 3: The calculated error (m/yr) for each imagery date and type of river channel change.

	Erosion	Deposition	Total
1992 - 1998 Error	0.772199	0.4517041	0.45027
1998 -2013 Error	0.387361	0.4198357	0.433939
2013 - 2018 Error	0.312735	0.1222084	0.220844

When omitting the first three reaches, the overall average erosional and depositional change is 0.49 +/- 0.09 m/yr and 0.39 +/- 0.23 m/yr respectively. Since these impounded reaches seem to be behaving differently from the reaches upstream, they will be omitted from the rest of the analyses.

There does not seem to be a clear trend in the amount of river channel change over time, or a clear relationship between reach-scale river channel change, width, curvature, and 1.5-year flood events. The recorded r^2 are shown in table 2 and show that there are no statistically significant relationships, other than a relationship between erosion and 1.5-year flooding events (Table 4). This relationship is likely a type 1 error because there is a 5% chance of committing a type 1 error at an alpha value of 0.05 and the resulting conclusion, that there is a negative relationship between the number of floods and river channel change, does not agree with any other scientific papers on the subject (Guan et al., 2016; Molnar, 2001)

Table 4: Table showing the recorded r^2 values and the necessary r^2 value to be statistically significant at an alpha of 0.05. Statistically significant r^2 values are highlighted in green. The category column describes the relationship to be tested, the r^2 column shows the calculated value for the relationship, and the statistically significant r^2 column shows the r^2 needed for the relationship to be significant at an alpha of 0.05.

Category	r^2	Statistically Significant r^2	Category	r^2	Statistically Significant r^2
1992-1998 Erosion vs. Curvature	0.011	0.95	1998-2013 Erosion vs. Width	0.344	0.468
1992-1998 Deposition vs. Curvature	0.021	0.95	1998-2013 Deposition vs. Width	0.117	0.468
1992-1998 Total vs. Curvature	0.003	0.95	1998-2013 Total vs. Width	0.048	0.468
1998-2013 Erosion vs. Curvature	0.135	0.95	2013-2018 Erosion vs. Width	0.464	0.468
1998-2013 Deposition vs. Curvature	0.01	0.95	2013-2018 Deposition vs. Width	0.121	0.468
1998-2013 Total vs. Curvature	0.055	0.95	2013-2018 Total vs. Width	0.203	0.468
2013-2018 Erosion vs. Curvature	0.01	0.95	Erosion vs. # of 1.5-year floods	0.96	0.95
2013-2018 Deposition vs. Curvature	0.057	0.95	Deposition vs. # of 1.5-year floods	0.643	0.95
2013-2018 Total vs. Curvature	0.053	0.95	Total vs. # of 1.5-year floods	0.835	0.95
1992-1998 Erosion vs. Width	0.005	0.468			
1992-1998 Deposition vs. Width	0.042	0.468			
1992-1998 Total vs. Width	0.028	0.468			

Reach Scale Case Studies

The following section of this paper will document three delineated reaches from this study and analyze the effectiveness of the technique within the reaches as well as determine if the calculated river channel change within the reach can be seen within the imagery. For each case study, image A is the 2013 image with the 2013 delineation, image B is the 2018 image with the 2018 delineation, and image C is the 2018 image with the 2013 delineation. Figure 6 shows the first reach for analysis. Image A and B are delineated accurately and rarely separate from the bank location, aided by the lack of vegetation in this reach compared to other reaches on the Lamprey River. In image C, the areas labeled 1 and 3 are both areas that show the method at work. The 2013 delineation does not match the bank in the 2018 image. Area 1 looks to be an area of erosion, while area 3 looks to be an area of deposition. Area 2 is a location of potential error. In the 2013 delineation the riverbank in area 2 follows a straight line, while in the 2018 delineation there looks to be a cut into the bank. It is hard to determine from the aerial imagery whether that is real change or a delineation error, as there are shadows from the trees in that location (Figure 6).

Figure 6: A reach on the Lamprey River. Image A is the 2013 image with the 2013 delineation, image B is the 2018 image with the 2018 delineation, and image C is the 2018 image with the 2013 delineation. The labels 1, 2, and 3 on image C are areas of interest in this reach.

Figure 7 is the second reach case study. This reach shows another potential difficulty with manual delineation in the coniferous forest cover of the Lamprey River. The delineations in image A and B both seem to be accurate to the bank and the island, however there is a large discrepancy in area 1 on image C. In image A there does not look to be a cut in area 1, but there looks to be an obvious cut in image B. In this case, it is possible that there is a smaller cut hidden by the trees in image A, but it seems to have gotten much larger in imager B. Toward the bottom edge of area 1, there definitely looks to be an area of erosion, but the top of area 1 could be showing a delineation error due to the tree shadows (Figure 7).

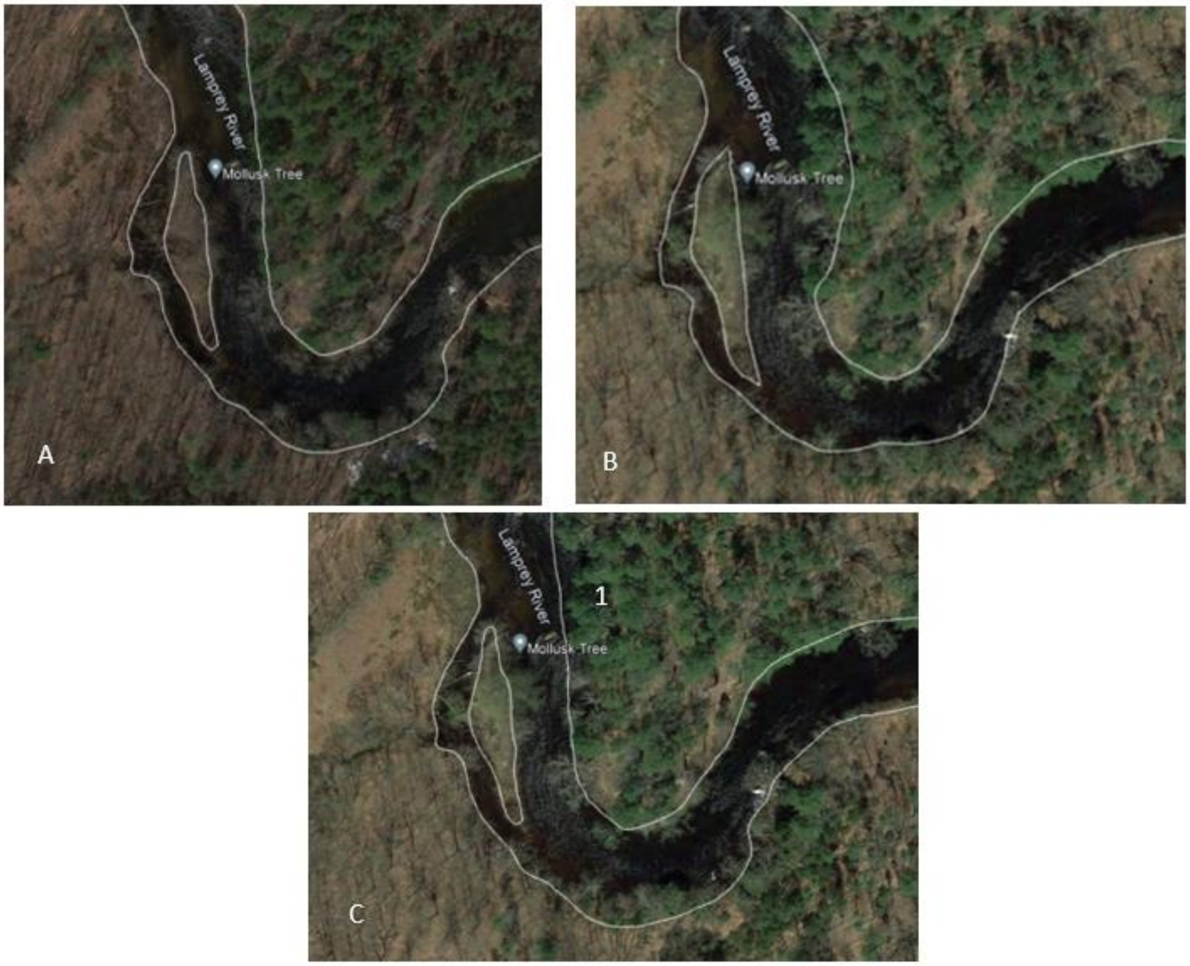

Figure 7: A reach on the Lamprey River. Image A is the 2013 image with the 2013 delineation, image B is the 2018 image with the 2018 delineation, and image C is the 2018 image with the 2013 delineation. Label 1 on image C is an area of interest in this reach.

The third and final reach for analysis is shown in figure 8. Areas 1 and 2 in figure 8 are both areas of interest that show real change in the reach. Area 1 looks to be an area that has had deposition and closed off the two sections of the channel shown in image C. While there are many trees in this area that make it hard to see this change, there looks to be a small, connected channel in image A that is no longer there in image B. Area 2 is an area with less tree cover that is accurately delineated on both images but does show a difference in the river channel. In area 2, there is a small area of both erosion and deposition (Figure 8).

Figure 8: A reach on the Lamprey River. Image A is the 2013 image with the 2013 delineation, image B is the 2018 image with the 2018 delineation, and image C is the 2018 image with the 2013 delineation. Labels 1 and 2 on image C are areas of interest in this reach.

Discussion

This method has shown that manual river channel delineation can be used to analyze river channel change over time in the Lamprey River in coastal NH, even in areas that have high forest cover. However, there were not any statistically significant relationships between river channel change, width, curvature, and 1.5-year flood events. This is likely due to the small sample size and can be improved upon with further research. However, this could also be due to an error within the method caused by the difficulty of delineating banks in areas with coniferous vegetation or the available frequency of leaf-off photographs. The availability of leaf off photos can be an issue if larger floods are driving the channel change within the Lamprey River. These floods could cause a large amount of change in a short time but would show up as much smaller change over time in the calculations due to the large time difference between the images. The result could also be due to an aspect of the Lamprey River, such as the clay-rich banks that may restrict sediment mobility, or downed trees, which may cause local river change effects that drive overall river channel change within the river. The local control of downed trees would be interesting to study for future work. The Lamprey River has a large number of downed trees, making it likely that the trees are causing extreme local influence on the river and may be a more important driver of river channel change than flooding, as the trees would alter the impacts of floods locally by acting as a block to the channel.

Manual river channel delineation on aerial imagery has many benefits. This method is easy to do with basic knowledge and skill in ArcMap (or another GIS program) and requires no field work. Assuming the GIS program has already been paid for, the method is very cheap compared to other methods. Also, all of the data is available remotely for free, which makes the method very quick. However, this method does have some disadvantages. The effectiveness of the method directly relates to the skill and attentiveness of the person delineating the river. Also, even though this method can work in areas with coniferous vegetation, the tree cover makes it very difficult to accurately locate the riverbank which results in more error. The error from the trees is mainly caused by the influence of shadows instead of an inability to see the riverbank.

The shadows from the trees can create areas that look like water in colored photos and can cause inaccuracies in the delineation.

From the above work, there seems to be no statistically significant relationship between the number of flooding events and river channel change, though this is contrary to the findings of many other scientific papers. The relationship between flooding and river channel change should change in the future as the environment begins to feel the impact of climate change, causing more frequent and larger flooding events.

Future research should expand this study to more rivers to analyze the effectiveness of this technique in other areas and to increase the sample size of the study to obtain more robust results. Since this would require much more analysis than what was provided in this paper, the creation of the river reaches in ArcMap should be automated to increase the efficiency of the analysis. This would also allow analysis at a smaller scale than the 1 km reaches used in this paper, which may be important for the Lamprey River due to local controls having the potential to control the river channel change. Future research should focus on these local controls, such as the influence of downed trees, invasive species such as Japanese Knotweed, hardscapes (such as riprap and bridges), and river bends. Downed trees may create local channel change by altering the impact of a flood by acting as a barrier. Japanese Knotweed may alter erosion within the reach by focusing more erosion on the knotweed patch because of poor root structure, and hardscapes may alter erosion by focusing the power of the river above or below the structure. Analyzing river bends in the Lamprey River to look for erosion and deposition would add to the overall study by determining if river channel change is focused in these areas. Because this study focused on larger reaches, a small bend with lots of change would be averaged over the entire reach, losing the specific impact of the bend on river channel change. Finally, future studies should complete field work to back up the conclusions drawn from this study and other future studies. The addition of field work will allow for the effectiveness of the method to be analyzed while adding further insights to the research.

Conclusion

Manual river channel delineation is a valid method for determining river channel change over time, even within rivers that have a high amount of forest cover, such as the Lamprey River. This study found that the Lamprey River is changing over time, with an overall average erosional and depositional change of 0.49 +/- 0.09 m/yr and 0.39 +/- 0.23 m/yr respectively. However, the drivers of this change could not be determined conclusively, shown by the fact that there were no statistically significant relationships between river channel change, width, curvature, and the number of 1.5-year flood events. More research needs to be done with a larger sample size to determine the cause of the river channel change and to further assess the validity of the method. Further research may look at the effects of local structures, such as downed trees, invasive vegetation, and hardscapes on river channel change to determine if they drive the river channel change in the Lamprey River. The historical trends of increasing flood frequency and river channel change are likely to continue in the future due to climate change causing more frequent, larger floods. This research, and further research that stems from this paper, could be used to aid river managers in the analysis of river channel change in their respective rivers as more frequent, large floods occur and enable them to protect their natural resources and the people within their watershed.

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