Stream Channel Migration of the Mad River between 1995 and 2011

Lindsay Jordan

Advisor: Dr. Beverley Wemple

Department of Geography

The University of Vermont

Spring 2013

Abstract

Rivers are constantly changing their shape through everyday erosion, seasonal changes in flow, flood events and changes in the land use on their banks. Significant changes in a stream channel can cause damage to roads, homes and businesses located along the channel. The pattern of settlement and topography of Vermont puts Vermont's infrastructure at a high risk for potential damage from flooding and erosion. Like many Vermont Rivers, the Mad River has undergone great change in the last few decades. This study uses the combination of aerial photography, Geographic Information Systems (GIS) and River Geomorphic Assessment (RGA) data to determine if there are specific locations along the Mad River that are more susceptible to change and what factors contribute to this change. Reach M09, M10, M13 and M15 were identified as reaches of major change. This study found that confined reaches, reaches with grade controls and reaches that contain or are near the intersection of a tributary are more likely to change.

Acknowledgements

I would like to thank my wonderful advisor, Beverley Wemple, for her constant support, vast knowledge and patience throughout this entire project.

Thank you to both Lesley-Ann Dupigny-Giroux and Donna Rizzo for providing me with wise and honest feedback along the way and for taking time in the busiest part of the year to be on my defense committee.

Thank you to Elizabeth Olliver for spending many sunny, summer days inside the computer lab with me as we tried hopelessly to deal with inexplicable software and data problems.

Thank you to Kristen Underwood for sharing her love of rivers with me and providing detailed answers to all of my frantic questions about the River Management Program data.

I also could not have done this research without the support of my family and friends. Thank you.

To my grandfather

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

Settling near a river is beneficial in terms of transportation, water supply, soil nutrients and food. However, rivers are not static entities. Stream channel migration refers to the lateral change experienced by a river through the processes of sediment erosion and deposition. The rate of stream channel migration is dependent on a wide variety of factors, both internal and external to the channel itself. These include, but are not limited to, the slope of the channel, the size and shape of bed material, confinement of the channel, the introduction of major tributaries, the presence of grade controls, flood events and land use (Gregory & Madew, 1982; Leopold, 1972; Ritter et al., 2002; Simon & Rinaldi, 2000).

The recent destruction in Vermont caused by Tropical Storm Irene brought a great deal of attention to the potential power of Vermont's rivers. According to data from the United States Geological Survey (USGS), Irene caused the worst flooding that Vermont had seen in 83 years. Rivers throughout the state experienced extreme amounts of erosion and channel change, in many cases causing damage to homes, businesses and roads. Understanding where a channel has changed in the past and why may help predict where the channel will change in the future. If this knowledge is used to help inform policy makers and direct mitigation strategies in communities, it could potentially help prevent future damage.

This thesis assesses the stream channel migration of a portion of the Mad River, in Moretown, Waitsfield and Warren, Vermont over a 16-year time period, from 1995 to 2011, in order to determine the locations of major change along this stretch of river and to determine what factors contributed to conditions that are conducive to change. The channel was mapped in each year based on aerial photography. Change was calculated using overlay tools in ArcGIS. Data available through the Vermont River Management Program and a Digital Elevation Model (DEM) of the area were used to determine what factors contributed to this change.

Chapter 2: Literature Review

Key Concepts in Fluvial Geomorphology

Geomorphology is the study of how landforms change over time. Different forces or processes act on a landscape and cause landforms to change, including wind, weathering, the movement of glaciers, water moving through a river and waves crashing against the coast. Geomorphic change can be a result of climatic, isostatic, tectonic or land-use change. These processes are behind the formation and change of every landform on Earth, whether it is a mountain, river, lake, canyon or rock (Ritter et al., 2002; Schumm, 1973).

Fluvial geomorphology is the study of rivers and how they work. Rivers depend on the idea that a balance exists between the earth's landforms and its processes. This balance is based on the force of energy acting on the landform and the resistance of the landform. It is altered when there are changes in either the force or the resistance. If the change is great enough, it can cause the system to be pushed beyond its limits or become unbalanced. The point at which the system becomes unbalanced is referred to as its threshold. Major responses in the system are likely to occur when these thresholds are crossed (Ritter et al., 2002). Stream channel change occurs when this balance is disrupted and the sediment within the river channel erodes or is deposited. Fluvial sediment erosion is the gradual wearing away of the edges and bottom of a stream channel as water passes over the sediment (Leopold, 1972; Stott, 2010). The two main drivers that can alter the balance of a river, and thus cause erosion to occur, are land use change and extreme floods. (Leopold, 1972; Ritter et al., 2002).

Stream Channel Migration

The details of stream channel migration vary from stream to stream, but in most cases it follows the same underlying process. As the water moves downstream, the fastest water moves to the outer bank of the bend, where the water is deepest. This section of the river is called the thalwag. The strength and speed of the flow determine how quickly it is able to erode the bank. The slower water flows along the inside of the bend. Because this water is slower, it deposits sediment that is too heavy for it to continue transporting. The build up of these deposits form the point bar (Ritter et al., 2002). As this process continues through time, the river will continue to cut into the outside bank and the point bar will continue to grow (Leopold, 1972). Soon vegetation will begin to grow on the point bar and it will become part of the floodplain. This causes the migration of the channel (Hooke, 1979).

The factors that influence stream channel migration can be loosely divided into two categories. The first category is based on the channel itself, such as the slope of the channel, the presence of natural or human-made grade controls, the presence of vegetation on the banks, confinement, parent geologic bed material and the abrupt change in drainage area at the confluence of the main stem and a tributary. The second category is made up of factors that are external to the stream channel itself, such as climate and land use in the drainage basin (Gregory & Madew, 1982; Leopold, 1972; Ritter et al., 2002; Simon & Rinaldi, 2000).

The slope of the channel affects the velocity of the water moving downstream. Sections of the river that have very steep slopes will have higher velocities and higher stream powers. If the stream power of a river is greater than the resisting force of the banks or bed of the stream channel, erosion can occur (Bagnold, 1973). Sudden changes in slope in a stream channel are called knickpoints or knickzones. Knickpoints are waterfalls while knickzones are areas that are steeper than other areas of the river. The section of a river directly before a knickpoint or knickzone is usually considered to be unstable and adjusting due to the change in baselevel (Bierman & Montgomery, 2012; Schumm, 1993). This can lead to channel change (Schumm, 1993). Human-made grade controls can have similar effects. In Simon and Darby's study in 2002, they found that human-made grade controls not only did not help stabilize the channel, but instead made it more unstable.

The presence of riparian vegetation can provide natural channel stabilization. The root structures of trees and other plants can hold in the bank material, making it less susceptible to erosion. Areas where vegetation has been removed from the banks often become unstable and are more likely to migrate at a faster rate. This introduces more sediment into the stream network, which can affect water quality (Martson et al., 1995; Simon & Rinaldi, 2000; Zaimes et al., 2006). McBride (2007) found in her study of Vermont streams that the removal of riparian vegetation could cause a channel to incise and become unstable, while reforestation along the banks of a river will cause the river to widen and eventually reach equilibrium.

Whether or not a stream channel is confined can greatly influence the rate at which stream channel migration occurs. A channel can be confined by either human-made structures or by geologic landforms. Bedrock channels erode significantly less quickly than an alluvial channel. Bedrock provides more resistance to the energy exerted on it by the flow of water (Ritter et al., 2002). Humans confine channels by placing rip-rap on the banks of the channels or other stabilizing structures. This is done in order to prevent damage to property from bank erosion. However, many studies have shown that preventing a channel from migrating in one reach may cause an increase in erosion downstream or upstream, because the energy in the water flow has not yet been released (Gregory & Madew, 1982).

The bed material of a river is another factor in the rate of erosion, deposition and migration. Generally, the average size of the bed material decreases from upstream to downstream. The velocity that any given material requires in order for it to be transported depends on the size of the material. The larger the material, the higher the velocity needed to transport it. Therefore, rivers or sections of rivers with smaller bed material are more susceptible to erosion than sections with larger bed material (Church, 2006; Ritter et al., 2002).

When a tributary meets a the main stem of a stream channel, it can add new types of bed material, debris such as fallen trees, sediment loads and a great deal of water (Benda et al., 2004). This sudden introduction of new water and material can cause change at and around the tributary junction. In many cases, alluvial fans form at these intersections causing a barrier that the water of the main stem must maneuver around (Benda et al., 2004). The amount that a tributary affects the morphology of the main stem is dependent on its size and its steepness, or in other words, its stream power (Seidl & Dietrich, 1992).

The Effect of Flooding on a Stream Channel

Many studies have shown an increase in flooding in the northeastern United States over the last century (Douglas & Fairbank, 2010; Kim et al., 2010; Villarini & Smith, 2010). Villarini and Smith (2010) found that maximum annual flood peak discharge was especially increasing in the northeastern United States. A study on streamflow variability looked at flood events between 1949 and 2008 in the Narraguagus River and the East Bear River in Maine. They found that between 1998 and 2008 there was a change in flood frequency over time of these two rivers. They especially noticed significant changes in flooding in 2004, 2006 and 2008 (Kim et al., 2010). Using a probability distribution of the changing flood frequency of seasonal flow, they found that flood potential has increased dramatically during August and September since 1949.

Flooding can cause significant change in a stream channel. Wolman and Miller (1960) stated that the entire character of a river, including geometry, sediment size, and riverbank stability, is controlled by how much water flows through it annually, and the magnitude and frequency of flood events. There is an on-going debate among researchers as to whether it is the infrequent high magnitude floods or the frequent but low magnitude floods that have higher geomorphic effectiveness (Bogaart et al., 2003; Gargani et al., 2006; Gilvear et al., 2002; Hack & Goodlett, 1960; Wolman & Miller, 1960).

Wolman and Miller (1960) argue that the annual or bi-annual floods events which are frequent but do not have high magnitudes do the most geomorphic work on a channel. Geomorphic work is loosely defined as the rate of sediment movement. A 100-year flood has a higher stream power and higher water levels than a 2-year flood. Higher water levels means the water flows at a higher velocity. Faster moving water is better able to pick up large pieces of bed material, which, when moving swiftly, can erode the banks and bottoms of rivers very easily (Gilvear et al., 2002). Therefore, Hack and Goodlett (1960) argue that a 100-year flood has a higher geomorphic effectiveness than annual flood events. However, Wolman and Miller (1960) believe that over time it is these 1-, 2-, and 3-year floods that, in fact, cause the most change to occur in a stream channel. This debate led to the idea that the absolute magnitude of a flow event does not necessarily determine whether or not a flood is effective or not. Miller (1995) stated that steep, mountainous regions are more likely than lowland areas to experience effective floods.

The Effect of Land Use on Stream Channel Change

Certain types of land use can contribute to a decrease in stream channel stability (Ward et al., 2009). With the combination of land use changes and climate changes, it is becoming increasingly more important to understand how land use can contribute to soil erosion. Stream channel migration is not only affected by the land use immediately beside the river, but land in the entire watershed. The type of land that precipitation moves through before it reaches the river channel determines the amount of water that gets soaked up by the ground and the rate at which runoff reaches the stream. The quicker the runoff reaches the stream channel, the more likely water levels will rise significantly causing increased erosion (Gregory & Madew, 1982). One of the most important elements of land use in relation to the rate of erosion and stream migration is the amount of vegetation along the banks of the river and in the drainage basin (Gregory & Madew, 1982).

Studies have shown that land use change can lead to changes in a stream's geometry. One study in Minnesota showed that urbanization caused the stream to become narrower and caused the banks to become steeper; however, this study did not find the rate of stream channel migration to be any different than natural variation (Leopold, 1972). Another study showed that human activity, such changing the river's natural course, the implementation of man-made riverbanks, deforestation, and the introduction of agriculture and grazing animals caused a river to change from a braided stream to a single-thread stream with higher stream channel stability (Marston et al., 1995). McBride (2007) found that the geometry of the channel changed with the removal of vegetation and changed again during the period of reforestation, until the channel stabilizes.

Modeling River Change

Many scientists have looked at different ways to model erosion and sediment transport in rivers. Bogaart et al. (2003) refer to two different types of models, a one-dimensional longitudinal river evolution model and a two-dimensional 'landscape evolution model.' The first uses erosion and sedimentation data to determine the extent of stream channel change, while the second uses a spatial grid to show the change in the landscape over time. Ghizzoni et al. (2006) used Digital Elevation Models (DEM) and a series of equations based on the stream width, depth, and hydraulic radius to map sedimentation and erosion processes in the Dora Baltea River basin. They found that mountainous regions are more prone to higher levels of erosion due to steeper elevation. A number of studies mention the difficulty of studying fluvial erosion processes because they are not uniform throughout all river systems (Bogaart et al., 2003; Peizhen et al., 2001).

The Use of GIS and Mapping in Relation to Stream Channel Migration

Many scholars have used Geographic Information Systems (GIS) to map and study stream channel migration and other related processes. In studies such as these, GIS is useful to show spatial variability, to present data in an easily understood way, to map significant changes in the landscape over time, and to analyze the data and maps. Digital elevation models are also useful in analyzing the three dimensional features of a landscape. GIS allows researchers to map changes in physical landforms and classify areas that share common attributes. For example, Ghizzoni et al. (2006) used GIS to map flood prone areas in a stream network. They created a map that demonstrated where in the stream network the river was stable, where erosion was occurring, and where sedimentation was occurring. Garvey (2012) used a combination of aerial imagery, LiDAR and GIS to measure soil mobility along the Brown's River in Vermont. She compared her GIS-based results to those of the Vermont River Management Program to determine whether such a methodology was comparable for determining which reaches of a stream are unstable.

Researchers often use GIS to perform different types of analysis on spatial data. Marston et al. (1995) used GIS analysis to generate statistics on how the river changed over time and statistics comparing the vegetation from the most recent year to the vegetation of 1991. Ghizzoni et al. (2006) used a DEM to determine the slope values of the area. Another study used GIS and DEMs to map large-scale erosion in rivers (Finlayson & Montgomery, 2003). With the DEM, they were able to study the topography of the landscape and estimate the amount of runoff in specific areas.

Chapter 3: Methods

Study Area

The Mad River watershed is 144 square miles and is located in Warren, Waistsfield, Moretown, Fayston and Duxbury, Vermont. The portion of the river studied in this research was 26 kilometers (approximately 16 miles) in length and ranges in elevation from 559 to 835 feet above sea level, according to the 10 meter Digital Elevation Model from the USGS National Elevation Dataset. According to a 2001 Landuse/Landcover Map created by the University of Vermont Spatial Analysis Lab, the Mad River Watershed is approximately 85 percent forest, 5 percent urban, 5 percent agriculture, and 5 percent other. The Mad River feeds into the Winooski River in Moretown, Vermont, which then flows into Lake Champlain. According to the Vermont River Management Program, this section of the Mad River has mostly alluvial parent bed material, with some ice contact, glacial lake and till deposits.

The Vermont River Management Program conducts Stream Geomorphic Assessments of rivers in Vermont, through the Vermont Agency of Natural Resources. These assessments are broken into three phases. Phase 1 is based on remote sensing data, Phase 2 on a rapid field assessment and Phase 3 on a survey-level field assessment. During Phase 1 of the assessment of the Mad River, the River Management Program divided the Mad River into 23 reaches. These reaches are lengths of the stream that are noticeably different from the portions both upstream and downstream of that section and can be determined based on the size of the stream, slope, confinement and geology (Vermont Agency of Natural Resources, 2009). For the Mad River, reach M23 is located at the headwaters of the river and M01 at the junction of the Mad and the Winooski rivers. The study area for this project spans from reach M05 to M17. 'M' signifies that the reach is part of the main stem of the Mad River and not a tributary. The major tributaries entering into the study area of the Mad River are, in decreasing size, Mill Brook, Shepard Brook, Dowsville Brook, Folsom Brook, Clay Brook, Welder Brook, Pine Brook and High Bridge Brook (Figure 1).

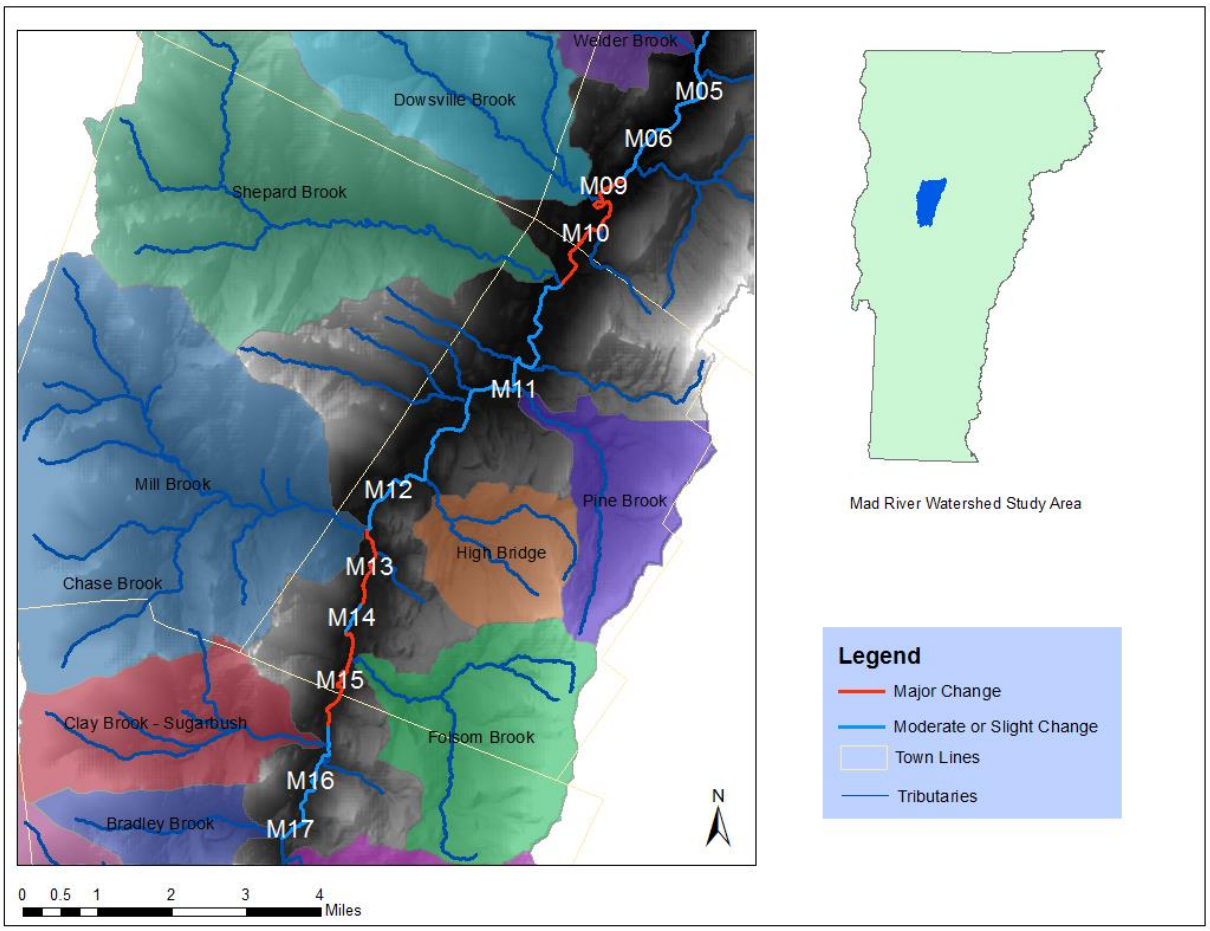


Figure 1: Map of the Mad River study area with tributary watersheds. Reaches labeled in red are reaches of major change. Labels for M07 and M08 are not shown in map due to their small size. They are located between M06 and M09.

Flood History

The USGS gaging station, located on the Mad River in Moretown, Vermont (#04288000) on reach M05, collects discharge and gage height data on a daily basis. This gaging station has collected stream flow data since 1927 (Figure 2). Annual peak flow data were collected from the USGS website for this research and used to create a flood history of the study area. Data were used to determine the recurrence intervals of annual peak stream flow between the water years 1928 and 2011. The recurrence interval of each peak flow was calculated using the following formula:

$$T = (n+1)/m$$

where n is the total number of years of record and m is the event rank (largest to smallest). According to the USGS, the mean peak flow for the years on record was 6, 616 cubic feet per second. Within the years studied for this research, floods at least one standard deviation above the mean occurred in 1996, 1998 and 2011 (Figure 2).

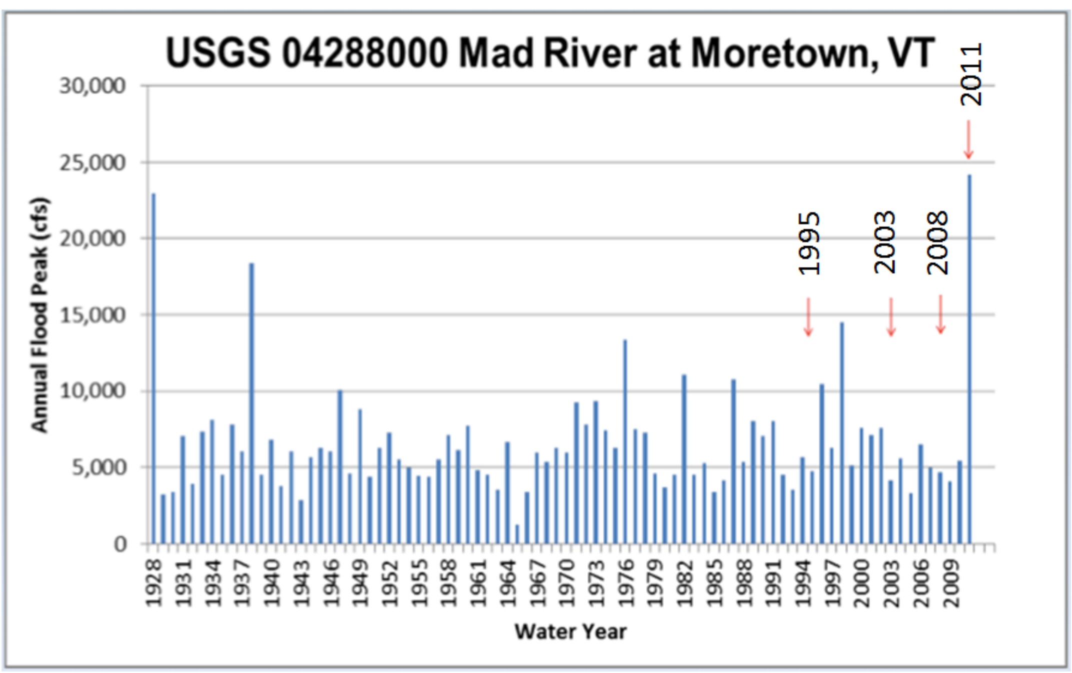


Figure 2: Annual peak flow at the USGS gaging station in Moretown, VT between the water years of 1928 and 2011. Red arrows indicate the years of imagery relative to flood events.

Aerial Photo Selection

Photos used in this analysis were selected based on availability. Photos were obtained from the Vermont Center for Geographic Information. The 1995 imagery is an orthophotograph and was acquired by the Vermont Mapping Program. The 2003, 2008 and 2011 are all from the National Agriculture Imagery Program (NAIP) and collected by the USDA (Table 1). The 1995 imagery has a 0.5-meter resolution and the NAIP imagery all have 1-meter resolutions. All of the image sets were georeferenced in the Vermont State Plane NAD83 coordinate system. A *Near Analysis* was performed within ArcGIS using 15 Ground Control Points (GCPs) to determine how much of an offset exists between image sets.

The exact dates of imagery collection are unknown, but the month within which each set was taken is listed in Table 1. The mean daily discharge during the month of April 1995 ranged from 173 cfs to 433 cfs, with a median of 248 cfs. For August 2003, it ranged from 43 cfs to 1,610 cfs, with a median of 109. For August 2008, the mean daily discharge ranged from 71 cfs to 2,060 cfs, with a median of 275 cfs. For the post-Irene imagery, between early September and late October 2011, it ranged from 94 cfs to 1,320 cfs, with a median of 210 cfs. The fluctuations of the flow in each month surrounding the imagery collection are shown in Figure 3.

Table 1: Table of photography dates, sources, scales and resolution of imagery. Medians of daily mean discharge were calculated using the daily discharges from the USGS gaging station in Moretown, VT for each day over a 30-day period for the 1995 imagery, a 31-day period for the 2003 imagery and 2008 imagery, and over 61-day period for the 2011 imagery.

Approx. Date of Photography	Source	Scale and Resolution	Median of Daily Mean Discharge (cfs)	Standard Deviation of Daily Mean Discharge (cfs)
Late April 1995	Vermont Mapping Program	1:5,000 (0.5 m)	248	67
August 2003	USDA Farm Service Agency Aerial Photography Field Office	1:40,000 (1 m)	109	289
August 2008	USDA Farm Service Agency Aerial Photography Field Office	1:40,000 (1 m)	275	502
Early September – Late October	USDA Farm Service Agency Aerial Photography Field Office	1:40,000 (1 m)	210	238

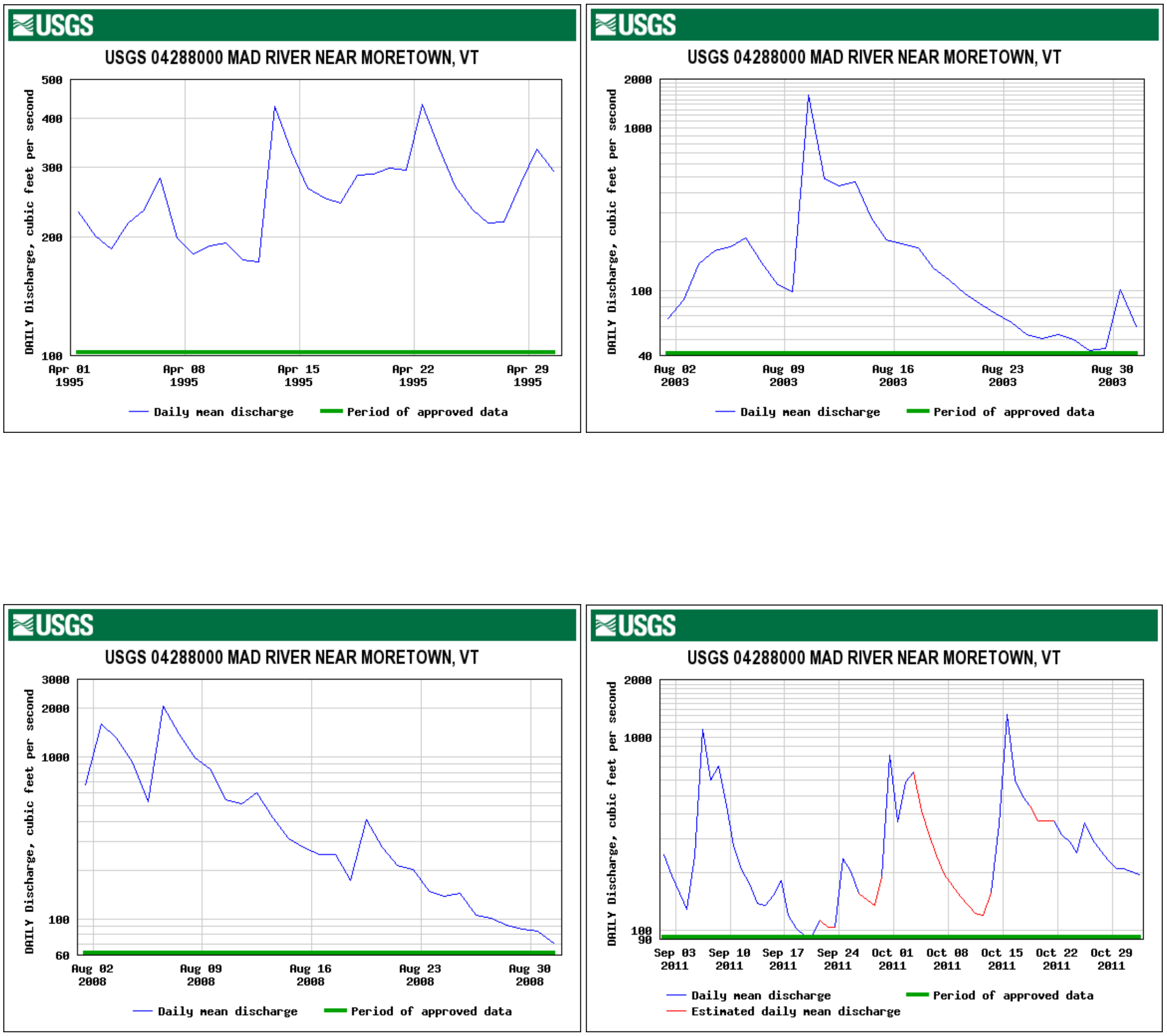


Figure 3: USGS Daily Discharge for the time period of the 1995 imagery, 2003 imagery, 2008 imagery and 2011 imagery.

Mapping and Calculating Channel Change

In order to map the channel change, a feature class was created in ArcGIS for each year of imagery. Using the imagery as a visual guide, the river was digitized with separate polygons for the stream channel, point bars and island (Figure 4). A series of unions between consecutive years were used to show the transitions between channel features in each pair of years. With the created union layers, the select by attribute tool was used to isolate specific types of changes, such as a change from point bar in 2003 to stream channel in 2008.

In order to calculate change by reach, a 60-meter buffer was created around the River Management Program layer of the centerline of the Mad River. This layer contains the location of the reaches. Unions were created between the buffered centerline layer and each of the unions of consecutive years. This allowed for a calculation of change by reach for each set of years. The type of each change was categorized into either depositional change or erosional change. For example, a change from stream channel in 2003 and island in 2008 was classified as depositional change. A change from floodplain in 1995 to stream channel in 2003 was classified as erosional

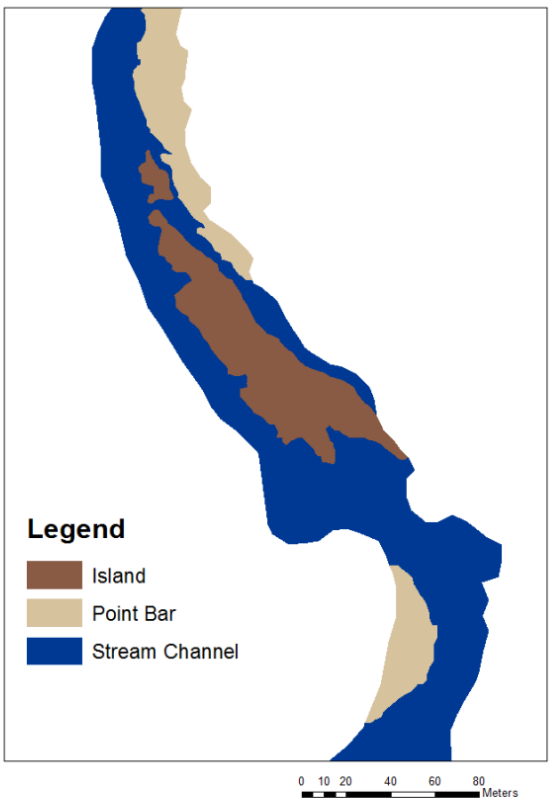


Figure 4: The 2011 channel with each feature type classified.

change. This was done for each set of years and between 1995 and 2011 in order to look at change over the whole study period. To determine which reaches were experiencing the most change, the total amount of change for each reach was divided by the reach's length. This provided an estimate of how much change was occurring in each reach without the length of the reach affecting the results. In order to determine approximately how much change was occurring annually within each study period, normalized change for each study period was divided by the number of years within that period. The total normalized change by reach from 1995 to 2011 was also calculated. A reach was considered to have significant change if its amount of total normalized change was above the 75th percentile of all reaches. A reach was classified as having moderate change if its amount of total normalized change was above the mean.

Creating a Longitudinal Profile of the Study Area

The creation of a longitudinal profile was based on the manipulation of the National Elevation Dataset 10 meter Digital Elevation Model (DEM) in ArcGIS. First, sinks in the DEM were filled in. Sinks are cells where there is no defined drainage direction. Before the DEM can be used, these imperfections must be fixed. Determining the elevation of the stream channel was a multi-step process using the *Flow Direction* tool, and then the *Flow Accumulation* tool in ArcGIS. The *Flow Direction* tool determines which direction water would flow if it landed on any given cell in the watershed. *Flow Accumulation* uses the flow direction raster to determine the number of other cells that flow into each cell. This raster helps to determine where the main stem of the river and its tributaries are, because their flow accumulation values are much higher than the cells around them.

In order to extract the elevation values along the river, an empty point feature class was created and points were constructed every 100 meters along the RMP centerlines layer of the

Mad River. Because there was slight discrepancy between the location of the highest flow accumulation and the RMP centerline layer, some points were adjusted so they lined up with the closest cell of the highest accumulation. Then the *Extract Values to Points* tool was used to find the elevation of each point along the river. The *Extract Values to Points* tool was also used to extract values from the *Flow Length* raster. This raster uses the *Flow Accumulation* raster to determine how far upstream each cell is. Now with both elevation data and length data for the study area of the Mad River, the data were imported into Excel and used to create the longitudinal profile. Elevation data were also extracted from points at the most downstream point of each reach to calculate reach slope.

Determining Changes in Drainage Area Between Reaches

The *Extract Values to Points* tool was also used to extract the flow accumulation values at the most downstream point of each reach. These values were multiplied by the cell size of the flow accumulation raster (100 square meters) in order to calculate the drainage area for that reach. Abrupt transitions in drainage area along the main stem indicate the confluence of a tributary.

Analysis of River Management Program Data

Data collected in Phase 1 of the River Management Program's Rapid Geomorphic Assessment were used to examine the presence of grade controls, geologic parent material and confinement in the study. Parent bed material and grade control data were displayed in a table to see if there was a relationship between grade control and the location of significant change in the river. A Wilcoxon signed-rank test was also run on the data to see if there was a statistically significant difference in normalized change for reach that were alluvial and other, and for reaches that had a grade control or did not. This test was used because the total normalized change data is not normally distributed. The River Management Program also assigns a confinement ratio to each reach based on the valley width divided by the channel width. This classifies each reach as narrowly confined (>1 and <2), semi-confined (>2 and <4), narrow (>4 and <6), broad (>6 and <10), and very broad (>10) (Vermont Agency of Natural Resources, 2009). Using the statistical package ‘R’, a test of correlation was run to see if there was a relationship between the confinement ratio and the amount of erosional change and between the confinement ratio and the amount of depositional change. Using the Wilcoxon signed-rank test again, the reaches were also classified into two groups (confined and unconfined) to determine if there was a significant difference in the means of normalized change in each group.

Chapter 4: Results

Hydraulic Conditions during Study Period

The five highest floods in the 85 year gaged history occurred in 2011 (23,600 cfs), 1927 (23,000 cfs), 1938 (18,400 cfs), 1998 (14,500 cfs) and 1976 (13,400 cfs). Photo sets used in this analysis span the time periods 1995 - 2003, capturing the flood of 1998, whose estimated recurrence interval is 21 years, and 2008 - 2011, capturing the flood of 2011, whose estimated recurrence interval is 85 years. The 2003 - 2008 time period captures only 1 – 3 year floods. Therefore, this study captures change during two time periods that contain high magnitude infrequent floods and one time period containing only low magnitude, but frequent flood events (Figure 5).

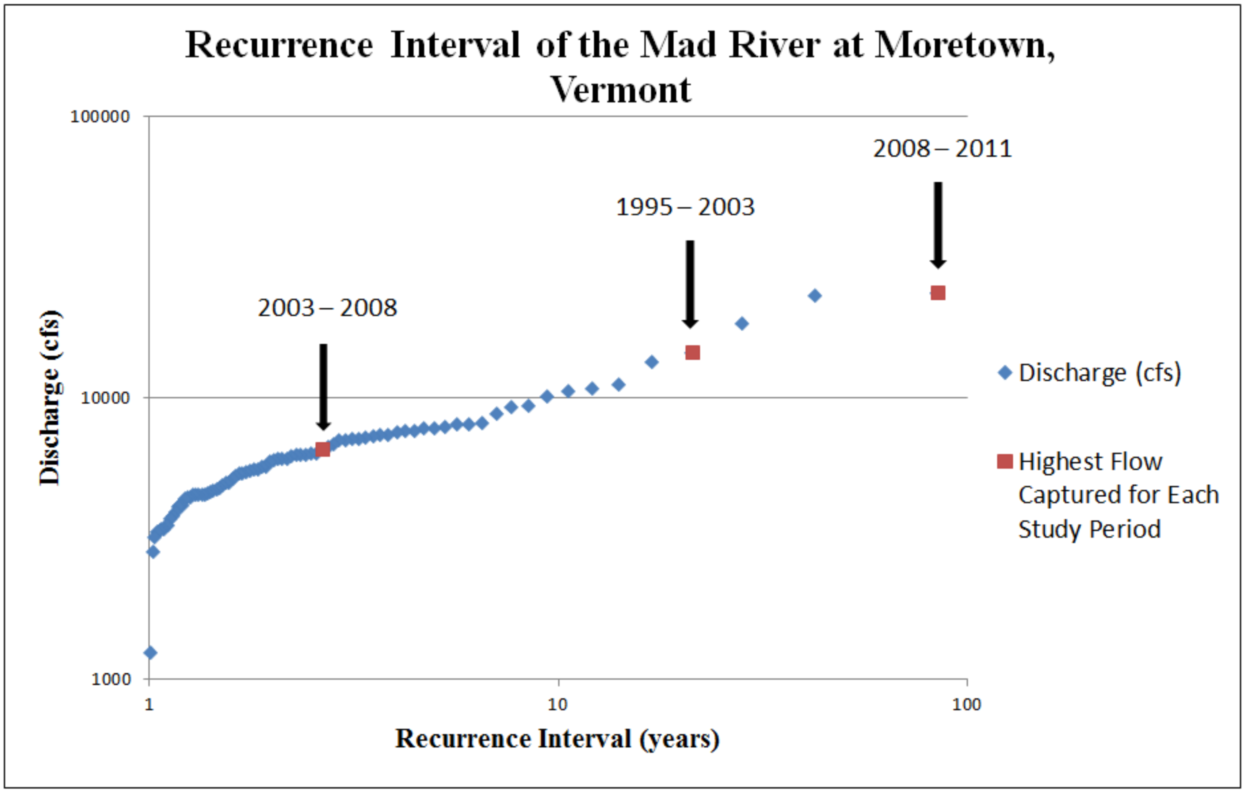


Figure 5: Graph of the recurrence intervals of the annual peak discharge in cubic feet per second at the gaging station in Moretown, VT.

Results of Near Analysis

There is an average of a 1.9-meter offset between the imagery sets, based on the *Near Analysis* of 15 ground control points in ArcGIS. The results of normalized change by reach show that no reach experienced fewer than 5 meters of lateral change. Therefore, the level of uncertainty is within the minimum amount of reach change.

Total Change within Studied Time Periods

The total amount of change that occurred between 1995 and 2011 from M05 to M17 of the Mad River was 872,665 square meters. The greatest change occurred between 1995 and 2003 with 325,805 square meters of total lateral change. This is followed by the 2008 to 2011 time period with 320,920 square meters and finally the 2003 to 2008 time period with 225,940 square meters. Tables were created that show the total area in square meters of each type of transition

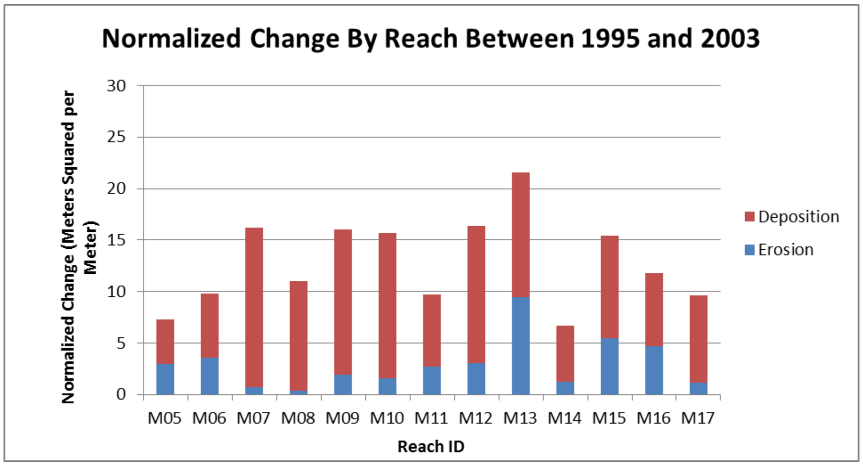
(Table 2). The majority of the change that occurred between 1995 and 2003 was depositional (77%). The change that occurred between 2003 and 2008 was 54% erosional and 46% depositional. Between 2008 and 2011, 67% of the change was erosional and 33% was depositional (Figure 6). The 2008 – 2011 time period experienced the most annual change, followed by the 2003 – 2008 period and finally the 1995 – 2003 period (Figure 7). Overall, the change during this study period (1995-2011) was 47% erosional and 53% depositional (Figure 8). The reaches that showed significant change (above the 75^{th} percentile) from 1995 to 2011 after normalizing them by reach length were M09, M10, M13 and M15 (Figure 9). M13 showed the most change with 60.7 meters squared of lateral change per meter.

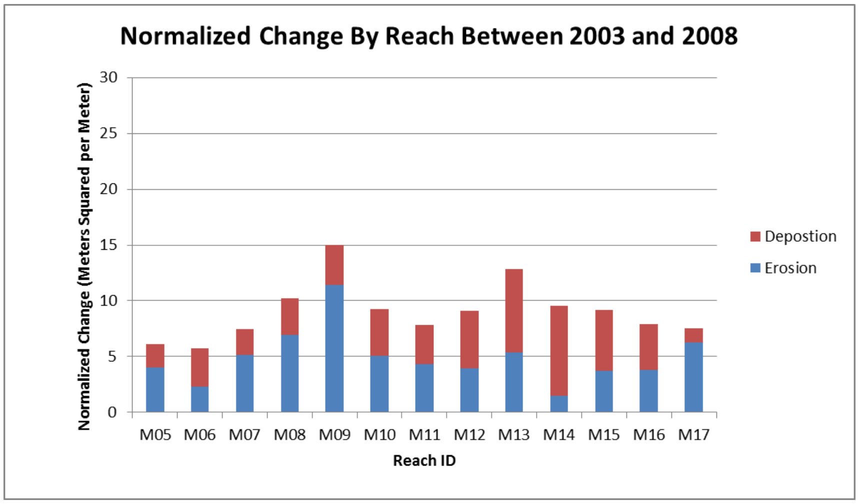
Table 2: Matrices showing of each type of change for each time period in square meters. Floodplain to floodplain is left blank in each table because the location of the floodplain was not digitized. Grey indicates no change. Blue indicates erosional change. Red indicates depositional change.

	Floodplain 03	Stream Channel 03	Point Bar 03	Island 03
Floodplain 99		56595	14398	123
Stream Channel 99	98032	507316	76185	8816
Point Bar 99	45190	16397	22953	1317
Island 99	2468	2011	4755	1664

	Floodplain 08	Stream Channel 08	Point Bar 08	Island 08
Floodplain 03		71968	7172	151
Stream Channel 03	58931	495744	21451	6192
Point Bar 03	21096	33065	63110	1021
Island 03	2	3978	1900	6039

	Floodplain 11	Stream Channel 11	Point Bar 11	Island 11
Floodplain 08		112748	67635	204
Stream Channel 08	36691	511516	50069	6672
Point Bar 08	5249	30964	49954	7466
Island 08	22	6942	5518	977





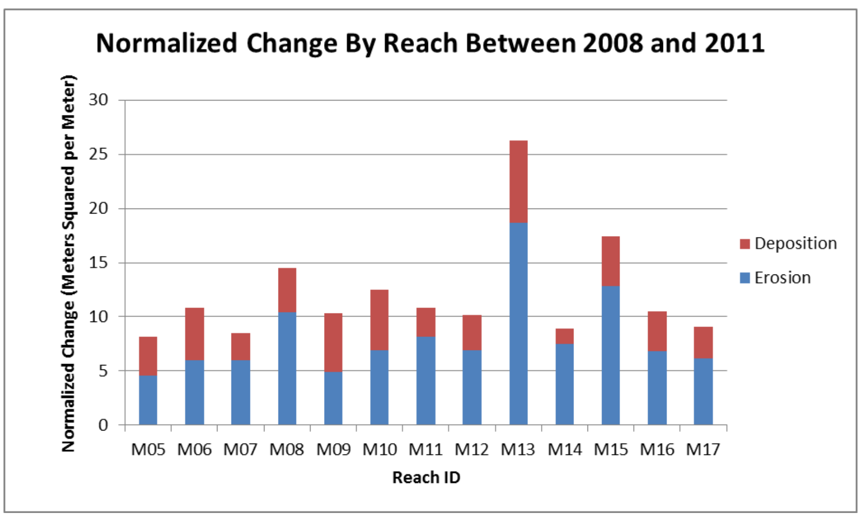
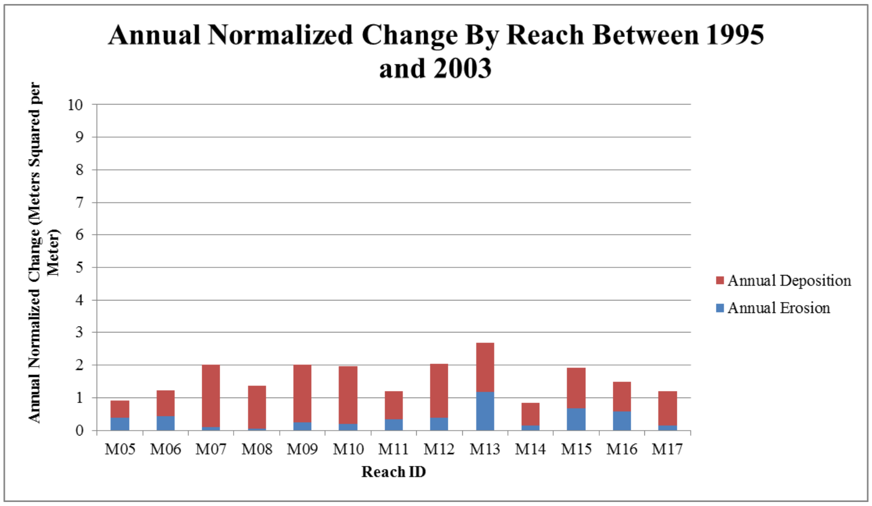
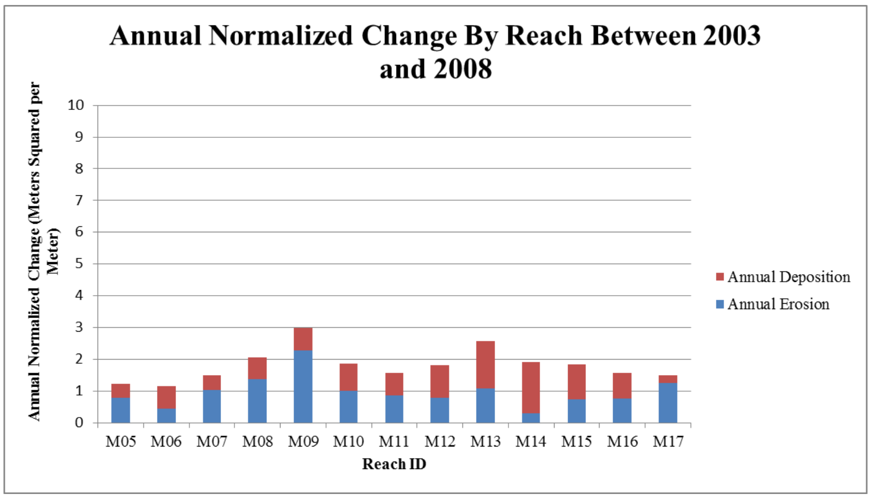


Figure 6: Each graph shows normalized change over the specified time period in each reach. The amount of change is broken down into either deposition or erosion.





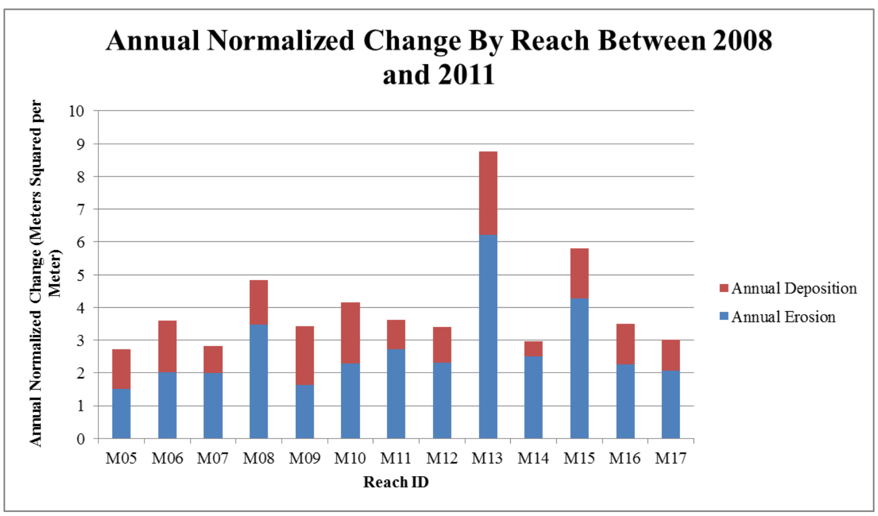


Figure 7: Each graph shows the approximate annual normalized change during each time period. Annual change calculated by divided normalized change by years in time period.

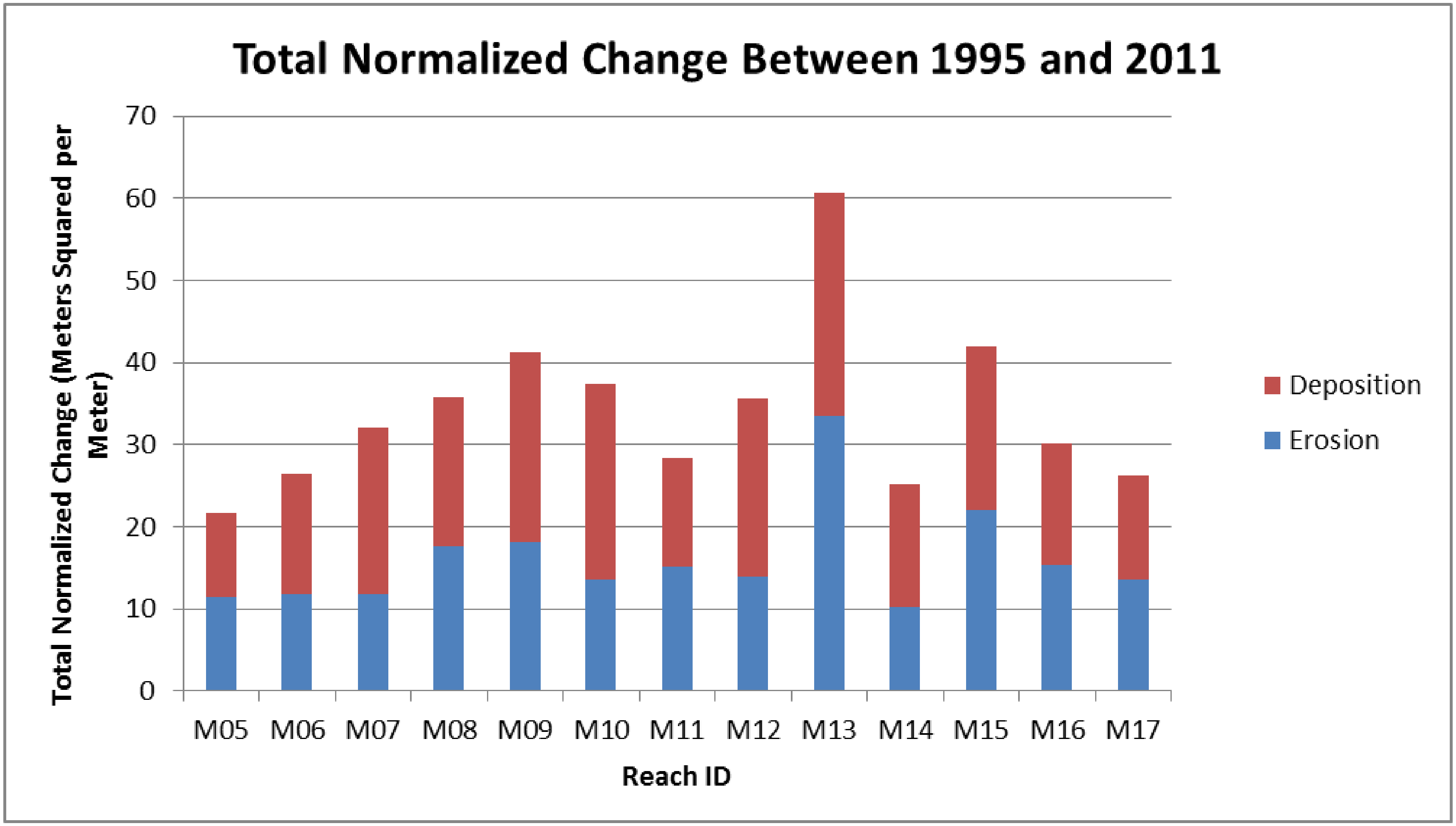


Figure 8: Normalized change by reach over entire time period.

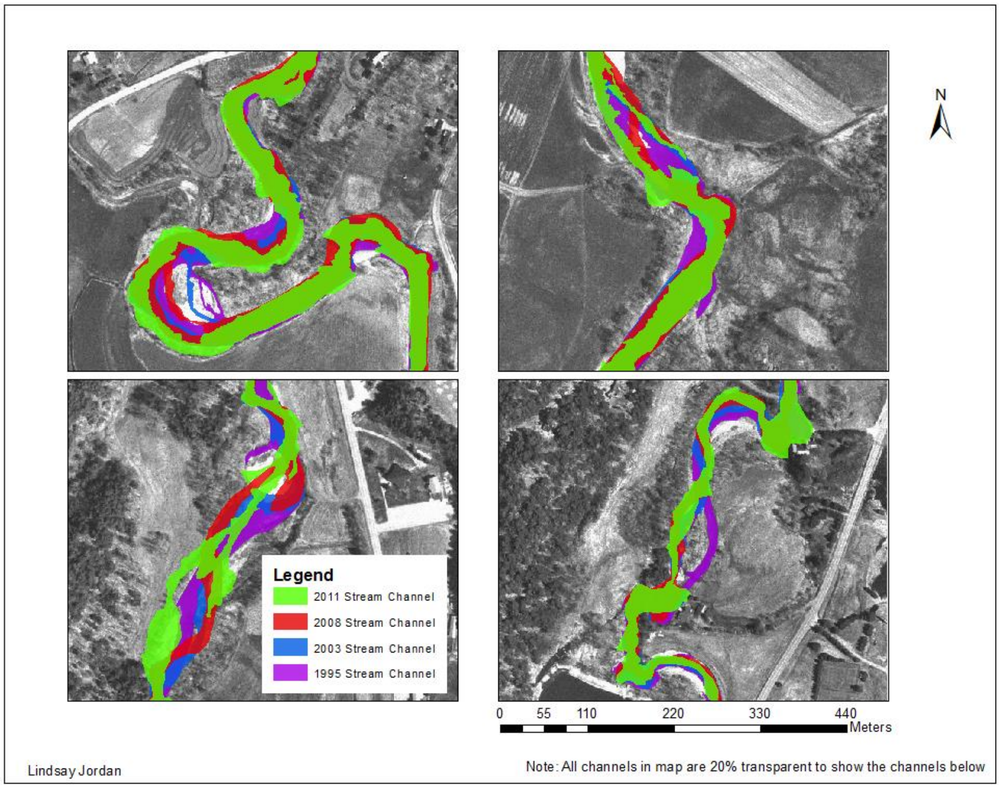


Figure 9: Maps showing movement of stream channel in the four reaches of major change. Map shows the cross over from M09 to M10 (top left), M10 (top right), M13 (bottom left) and M15 (bottom right).

Relationship between Slope of Reach and Amount of Normalized Change

The river follows the general pattern of steeper slopes upstream (M17) and flatter slopes downstream (M05). The movement from upstream reaches to downstream reaches is characterized by a general trend of flattening, with one section (between M07 and M08) of very steep slope (Figure 10). There was no correlation between the slope of a reach and the amount of normalized change per reach (Figure 11). However, two out of the four reaches of major change (M09 and M10) are right upstream of the M07 gorge (Figure 12). This gorge separates the steeper upstream reaches from the flatter downstream reaches.

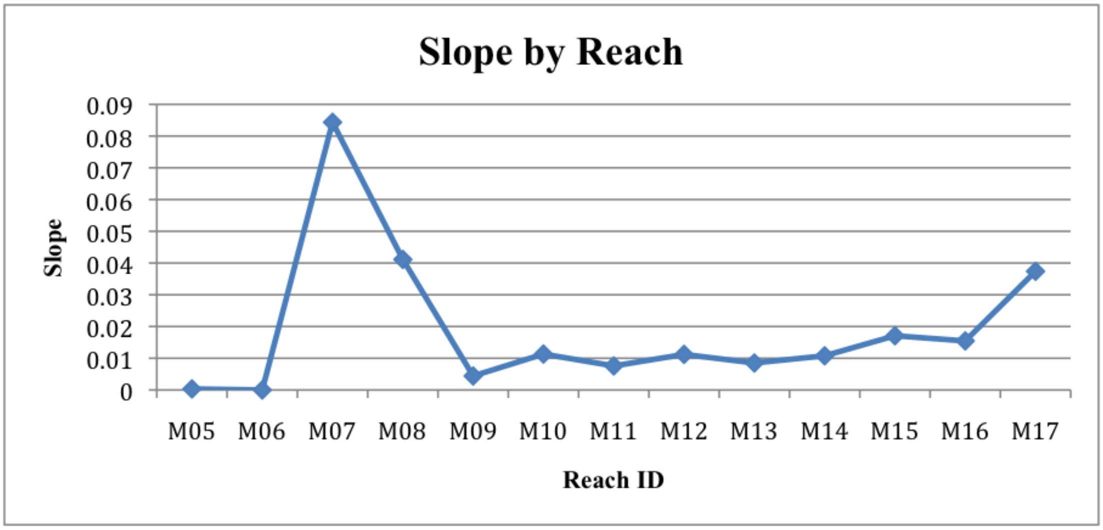


Figure 10: Channel slope of each reach. Gorge location in M07 and M08.

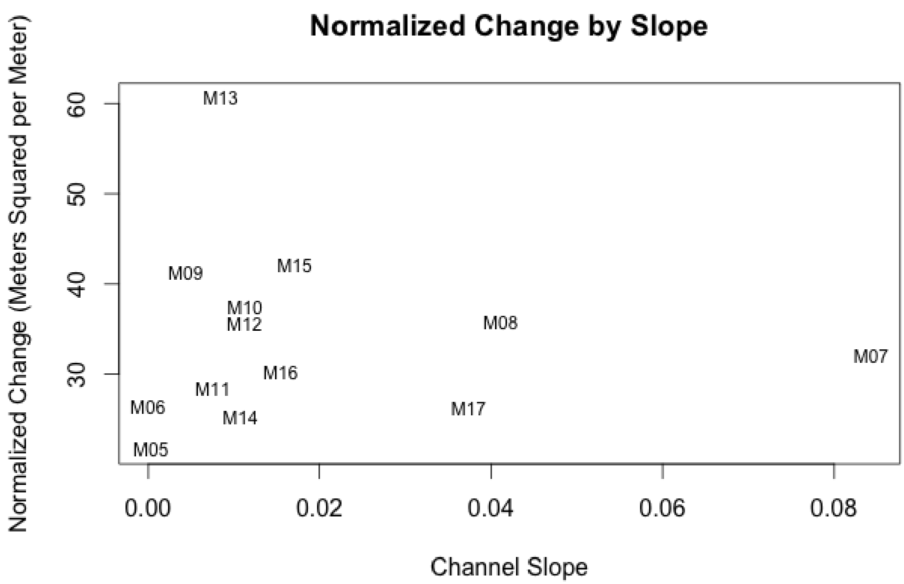


Figure 11: Scatter plot of normalized change by slope. There is no correlation between the two variables.

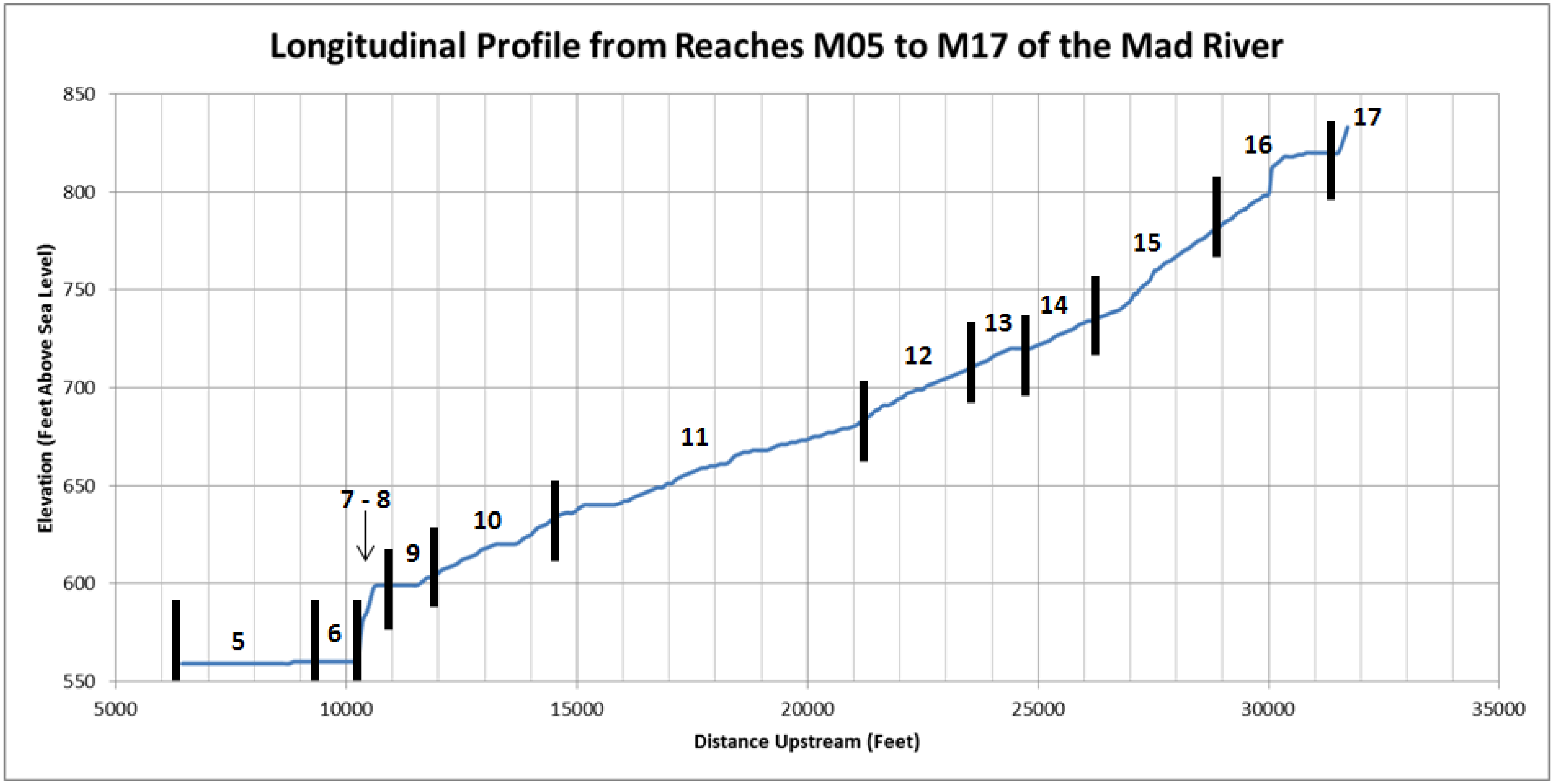


Figure 12: Longitudinal profile of the study area. Reach breaks are labeled by their number and separated by black markers.

Influence of Grade Controls and Parent Material on Reach Change

While the slope of a reach does not appear to have an effect on lateral change in this study area, the presence of a grade control and the type of parent bed material may have some effect (Table 3). Three out of the four reaches (M09, M13, M15) that show major change also have a grade control within the reach. Out of the six reaches that do not have grade controls only M10 showed major change. Three out of the four reaches (M10, M13, M15) were alluvial channels. While parent material and grade controls may have an effect on channel change, a Wilcoxon signed-rank test of the means of normalized change of reaches with grade controls and without grade controls showed that the means are not statistically different with a p-value of 0.2723. A Wilcoxon signed-rank test of reaches with alluvial bed material and other bed material showed that the means are also not statistically different with a p-value of 0.2246 (Figure 13, Figure 14).

Table 3: Matrix of grade controls and parent bed material. The 'Other' column consists of glacial lake, ice contact and till deposits. Reaches of major change are labeled in red.

	Alluvial	Other
Grade Control	M11, **M13**, **M15**, M16	M06, M07, **M09**
No Grade Control	M05, M08, **M10**, M12	M14, M17

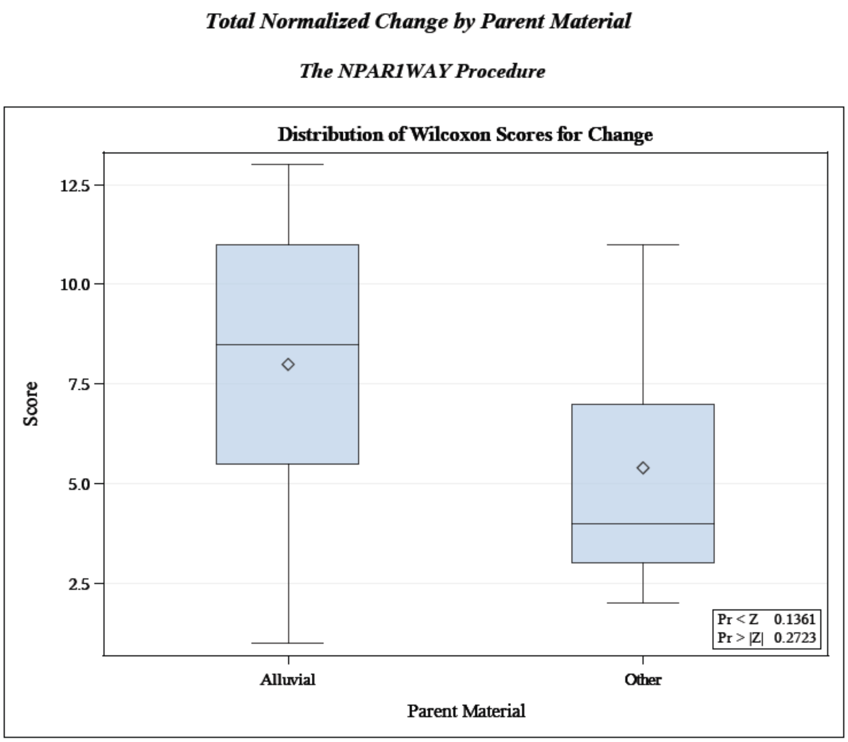


Figure 13: Boxplot of results of Wilcoxon signed-rank test of normalized change by parent material.

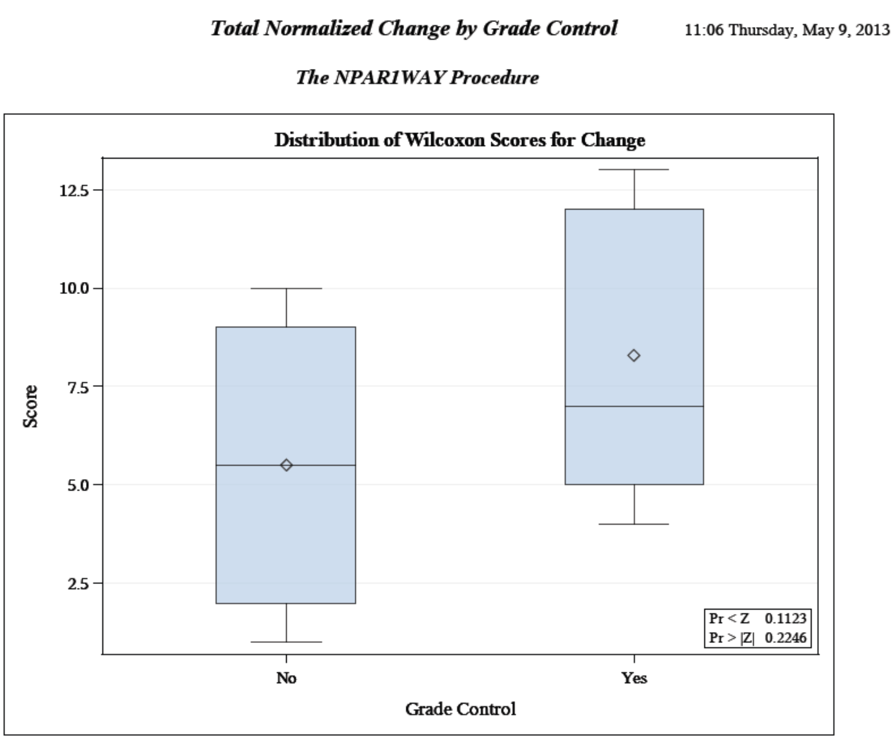


Figure 14: Boxplots of results of Wilcoxon signed-rank test for normalized change by grade control.

Influence of Tributaries on Reach Change

All four reaches of major change are located either at the junction, right upstream or right downstream of a major tributary. Dowsville Brook enters into M09. Shepard Brook enters into M10. Mill Brook enters into M12 approximately 180 meters downstream from the start of M13, a reach of major change. Folsom Brook enters into Reach M15, another reach of major change, and Clay Brook enters in to Reach M16 only 294 meters after the end of Reach M15 (Figure 1). The confluence of a tributary can be seen in large jumps in drainage area (Figure 15).

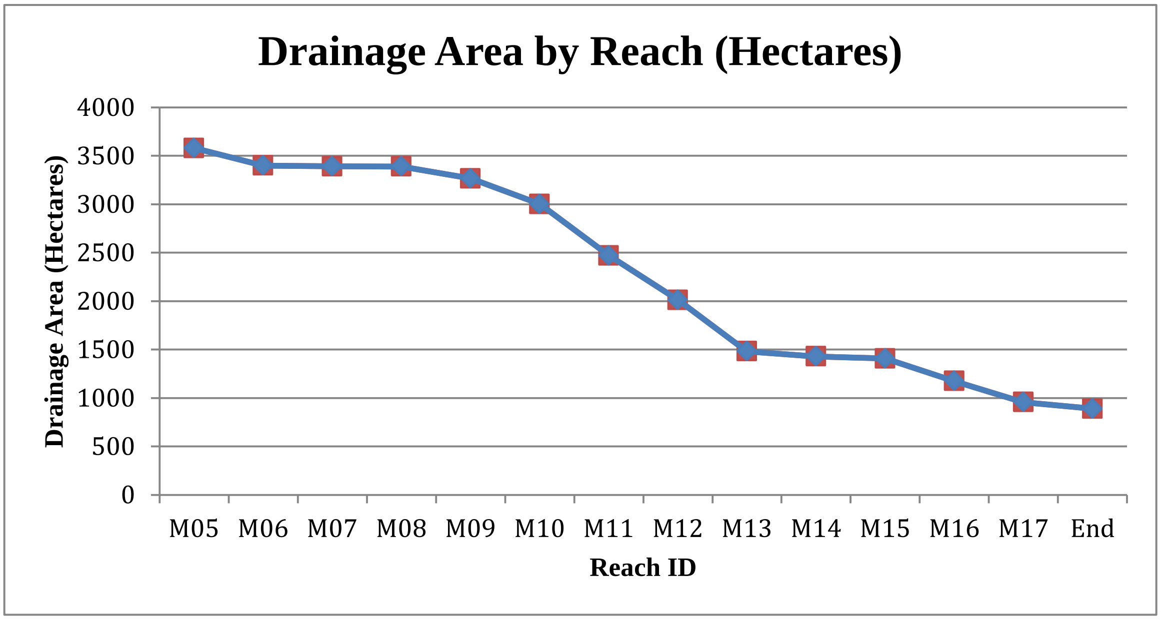


Figure 15: Drainage area at the downstream point of each reach.

Influence of Confinement on Reach Change

When comparing the River Management Program confinement ratios (Figure 16) for each reach, there was no correlation between confinement ratio and total normalized change for each reach between 1995 and 2011. There was a slight correlation between the confinement ratio and the amount of normalized erosion ($r = .5573$). There was no correlation between the amount of normalized deposition and the confinement ratio. In a Wilcoxon signed-rank test, there was no statistically significant difference between the mean of normalized change among unconfined reaches and confined reaches with a p-value of 0.7144 (Figure 17). However, the mean of normalized change in unconfined reaches (35 meters squared per meter) was higher than the mean of normalized change in confined reaches (32 meters squared per meter). The mean of normalized erosion in unconfined reaches (17 meters squared per meter) was also higher than in confined reaches (14 meters squared per meter).

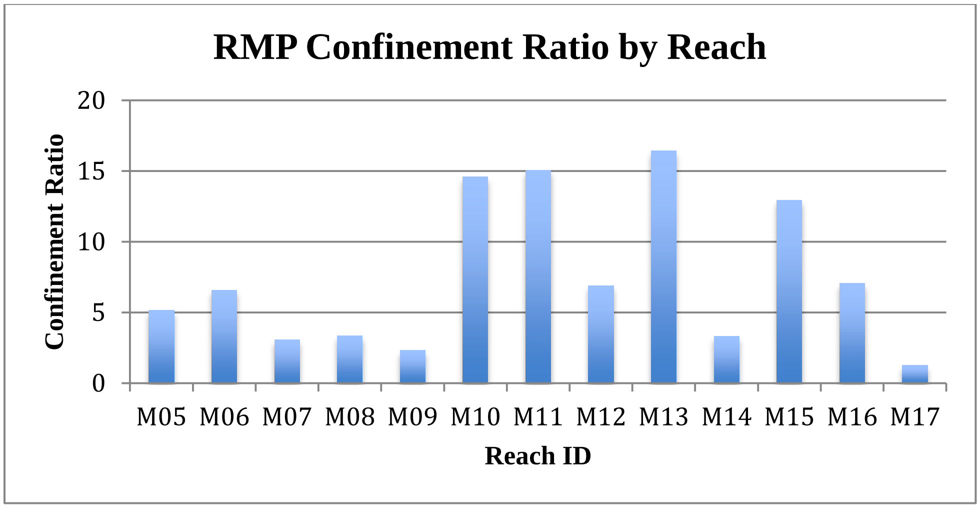


Figure 16: RGA Confinement Ratio by Reach. The greater the confinement ratio, the less confined the reach is.

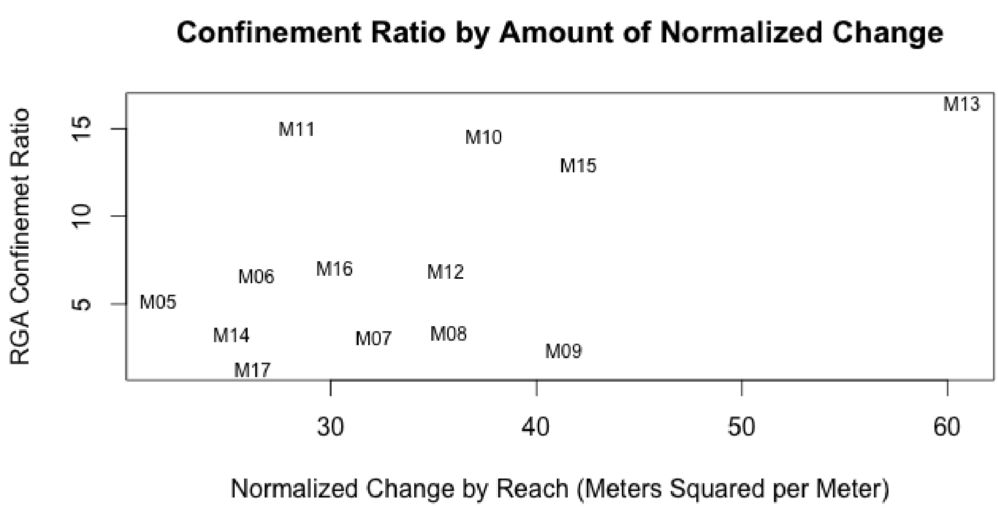


Figure 17: Scatterplot of RGA Confinement Ratio by Normalized Change.

Total Normalized Change by Confinement 11:06 Thursday, May 9, 2013

The NPAR1WAY Procedure

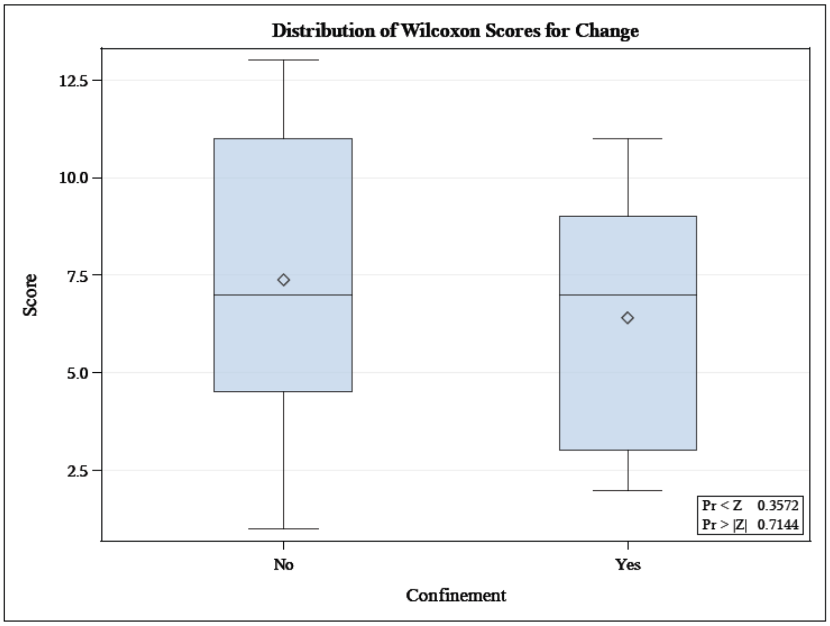


Figure 18: Boxplots of results of Wilcoxon signed-rank test of normalized change by confinement categories.

Chapter 5: Discussion

Studying rivers and channel change is not black and white. There are many factors that go in to whether or not a channel is vulnerable to change. Therefore, looking at any one factor alone may not provide clear results as to why one reach changes more than another. However, taking a step back and looking at the bigger picture of the river can provide insight into the processes going on in the river as a whole.

Geographical and Geomorphic Insights

While there was no correlation between the amount of normalized change and the slope of the reach, it does appear that the channel is changing upstream of the knickzone located in Reach M07. Both Reach M09 and M10 may be adjusting due to the change in baselevel downstream, which would correspond with the research done by Bierman and Montgomery (2012) and Schumm (1993). The presence of a grade control in three out of the four reaches of major change lines up with Simon and Darby's research (2002) that concluded that in many cases grade controls actually increase channel instability. Three out of the four reaches showing major change also have alluvial bed material.

In line with the research of Benda et al. in 2004, the reaches that showed the most change in this study were the reaches at or near major tributary junctions. The largest tributary in the study area, Mill Brook, with a watershed of approximately 19 square kilometers, intersects with the main stem of the Mad River slightly upstream of the start of M13, the reach showing the most overall normalized change. This coincides with the idea that the larger the tributary, the greater the effect it will have on the main stem of the river (Seidl & Dietrich, 1992).

The slight correlation between the confinement ratio and the amount of normalized erosion in a reach demonstrates that channels that are confined by either bedrock or human-made structures are less likely to erode their banks (Gregory & Madew, 1982; Ritter et al., 2002). In a larger sample size, this correlation would likely be stronger. Three out of the four reaches that showed major change (M10, M13 and M15) had high confinement ratios, meaning the majority of the reach was not confined.

Significance of Findings

The recent destruction in Vermont caused by Tropical Storm Irene brought a great deal of attention to the potential power of Vermont's rivers. Irene caused the worst flooding that Vermont had seen in 83 years. Rivers throughout the state experienced extreme amounts of erosion and channel change, in many cases causing damage to homes, businesses and roads. Living and building near a river has presented itself as possibly more dangerous than it once was.

As seen in the findings above, the most channel change occurred in time periods that included major flood events. The floods events of 1998 and 2011 (the two biggest flood events for the study area during the study period) both caused major damage to roads along the study area of the Mad River.

In June of 1998, the flooding damaged both Butternut Hill Road and North Road in Waitsfield. Butternut Hill Road runs along reach M15, a reach of major change. North Road runs along M10, another reach showing major change. According to the Waitsfield and Moreown Town Reports, damage repairs after the 1998 flood cost over $40,000 for Waitsfield and $76,000 in Moretown, totaling at least $116,000 for the study area.

During Tropical Storm Irene in 2011, there were road closings along VT Route 100 and 100B and Main Street. These closings ran along both M09 and M13, which were both classified as reaches of major change in this study (Figure 19). The American Flatbread in Waitsfield, located along the banks of the Mad River in Reach M13 suffered extreme damage. According to an article in the VT Digger (2011) the restaurant and surrounding inn and associated buildings were beneath seven feet of water during Tropical Storm Irene. Combined damage costs after the 2011 May flash flood and August tropical storm totaled at over $448,000 for Waitsfield. While road closings occurred in places other than the reaches classified as having major change, all four of the reaches specified caused damage to infrastructure during the study period.

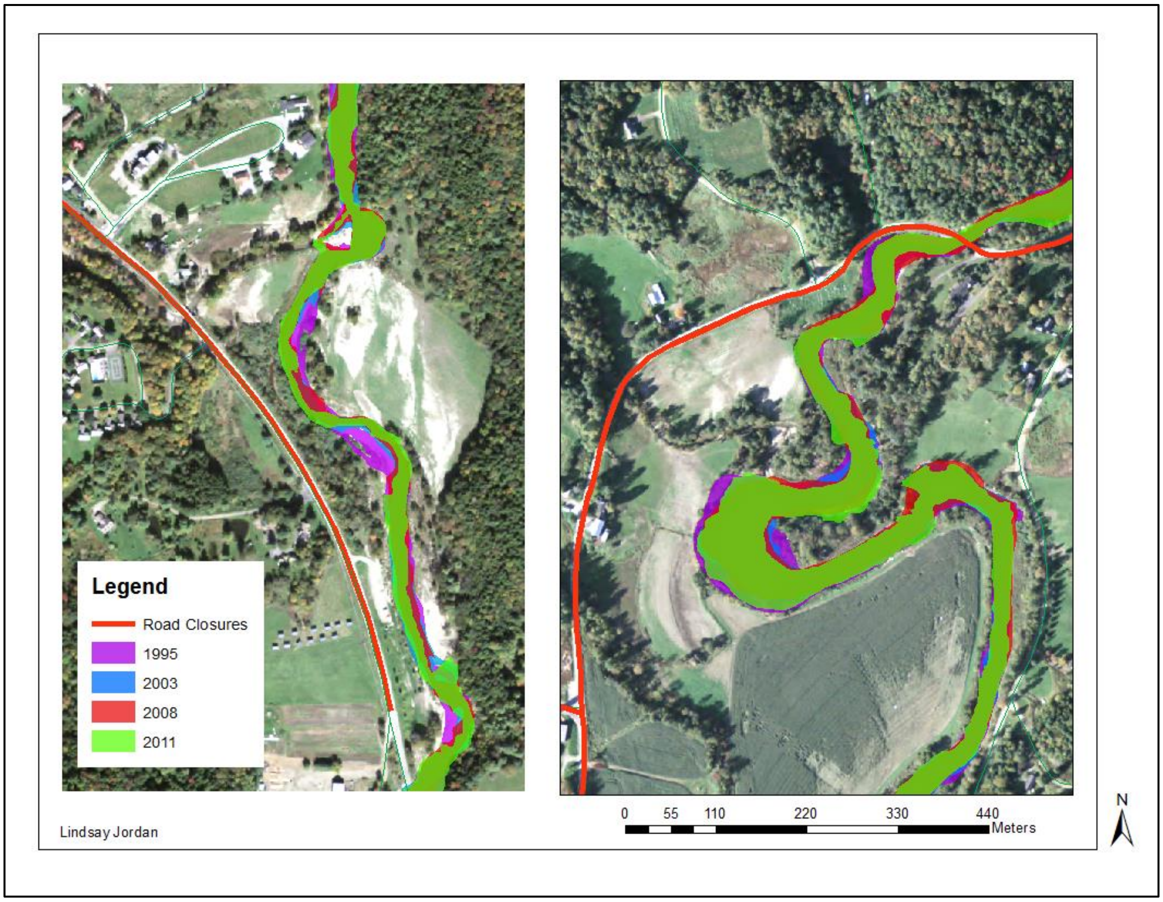


Figure 19: The map on the left shows the location of a road closure on Route 100 along reach M13. The map on the right shows the location of a road closure on Route 100B along reach M09.

In some places along the Mad River, especially near the reaches showing major change, it might be worth considering changing the road network in some way to put it further out of the way of the river. While it may seem like an unwanted cost at this point in time, it could potentially save considerable money in the future. Research in the Northeast has found that the 100 and 500-year floods are happening more frequently than they have in the past (Collins, 2009). This means that protecting the area against flood related damage should be a higher priority in the next decade. Therefore, the time and money that would go into planning and building roads further away from the river may be worth the effort in the long run, and prevent another $500,000 in damage in the next 20 years.

Limitations of Research

One of the main limitations of this study was the resolution of the imagery. The three sets of NAIP imagery all had 1 meter resolution, while the 1995 orthophoto had a resolution of 0.5 meters (Table 1). On the ground, 1 meter of river change can be significant change depending on its location. This coarse resolution may mean that some stable features were incorrectly digitized as changing. It also made the visual interpretations of some sections of the river difficult. Areas of exposed bedrock could sometimes be mistaken for sand bars or islands. If there had been more time for this study, it would have been beneficial to ground truth these difficult to interpret areas.

The fact that the exact dates of the images are unknown is another limitation of this research. If the imagery were taken on a high flow day in one year and a low flow day in another, the union between the two years would contain overestimated change. The time period within which the 2011 imagery was taken included a series of storm events. Most likely these images were collected on clear days after the high flow from storm events subsided, but if the flows were unusually high, it would affect the results.

Another source of overestimated change is the slight registration differences between the different year sets. If there were any error in their registration, then the offset would be included in the calculation of change. However, these offset errors are slight enough that they still preserve the locations of major change, even if the exact area of lateral change is not exact.

In the creation of the longitudinal profile, the elevation data were based on the 10-meter DEM. The points along the river were queried from the closest location of high accumulation. This means that there may be slight errors in the elevation values of each point along the stream. It would have been beneficial to double-check these values in the field, if there had been more time.

Suggestions for Future Research

In future research, either of this study area or other Vermont rivers, the addition of more imagery years, especially ones earlier in the 20th century would allow the researcher to look at longer term climatic or land use trends. The NRCS office in Berlin has aerial imagery from as far back as 1936 of the study area. With more years, there would be potential to see if the change was increasing over time, perhaps due to land use change, climate variability or human-induced climate change. This would be useful for predicting future change and preventing reaches from becoming unstable in the future. Looking at a longer time period would also allow the researcher to analyze the amount of change that occurs after high magnitude events and the amount of change that occurs slowly through annual flood events, and contribute to the on-going discussion of which has more of an effect on the river.

This study only focused on one portion of one river. In order to understand better what it going on all over the state or in rivers in general, it would be beneficial to look at multiple rivers in the same climate to see what factors affect their behavior. If there were reasons that a river exhibited different behavior from the results of this study, it could be possible to see what other factors might be influencing it, such as changes in land use around the river.

This study focused on the River Management Program assigned reaches. In some cases, especially in M09 and M10, areas of major change fell right at the cross over between the reaches. Some parts of the same reach may be experiencing more or less change than other parts of that reach. In order to see what the factors are influencing these smaller sections of the river, researchers could divide the river in 100-meter sections, for example, or manually determine sections based on where the most change is actually occurring in the river.

In future research, it would be useful to expand on the preliminary research on flood damage costs to both private and public property of this study. There is an abundance of data related to Tropical Storm Irene damages, but it is not all in one place. In a more in depth study, researchers could use a combination of town documents, aerial imagery, photos of damage sites, agricultural information and river change data to assess where exactly the worst damage occurred, what kind of damage it was, how much it cost, and which section of the river caused the damage. There could be a comparison between the areas of the river showing the most lateral change and the areas that caused the most damage.

Chapter 6: Conclusion

This study determined that four reaches (M09, M10, M13 and M15) experienced considerable change between 1995 and 2011. From the examination of these results in conjunction with both RMP data and DEM derived data, it appears that there are identifiable factors influencing channel change in this river. In this study area, the greatest channel migration occurred at the junction between the main stem of the river and a major tributary. Channel confinement may have also affected where channel migration occurred. The areas that were not confined experienced more channel migration than the areas that were not confined. While there was no correlation between the slope of a reach and the amount of change of that reach, two of the four sections of change were directly upstream of a knickzone or extreme change in elevation. Three out of the four reaches that exhibited major change also contained a grade control. Many factors determine how a river will behave and where it will experience change. This study has pointed to a few factors that may help determine where change might occur in other similar rivers or in this same study area in the future. This knowledge can be used to help mitigate the effect of major floods on public and private property in the future.

References

Arnell, N. W. (2004). Climate change and global water resources: SRES emissions and socio-economic scenarios. *Global Environmental Change*, *14*(1), 31-52.

Bagnold, R.A. (1973). The nature of saltation and of "bed-load" transport in water. *Proceedings of the Royal Society of London A 332*(1591), 473-504.

Benda, L., Poff, N. L., Miller, D., Dunne, T., Reeves, G., Pess, G., & Pollock, M. (2004). The network dynamics hypothesis: how channel networks structure riverine habitats. BioScience 54(5), 413-427.

Bierman, P., & Montgomery, D., (2012). Key concepts in fluvial geomorphology, Unpublished manuscript.

Bogaart, P. W., Balen, R. T. V., Kasse, C., & Vandenberghe, J. (2003). Process-Based modelling of fluvial system response to rapid climate change--i: Model formulation and generic applications. *Quaternary Science Reviews*, *22*(20), 2077-2095.

Church, M. (2006). Bed material transport and the morphology of alluvial river channels. *Annual Review of Earth and Planetary Science* 34, 325-354.

Collins, M. J. (2009). Evidence for changing flood risk in New England since the late 20th century. *Journal of the American Water Resources Association*, 45, 279–290.

Douglas, E. M., & Fairbank, C. (2010). Is precipitation in Northern New England becoming more extreme? *Journal of Hydrologic Engineering.*

Finlayson, D. P., & Montgomery, D. R. (2003). Modeling large-scale fluvial erosion in geographic information systems. *Geomorphology*, *53*(1-2), 147-164.

Gargani, J., Stab, O., Cojan, I., & Brulhet, J. (2006). Modelling the long-term fluvial erosion of the River Somme during the last million years. *Terra Nova*, *18*(2), 118-129.

Garvey, K (2012). Quanifying erosion and deposition due to stream planform change using high spatial resolution digital orthophotography and LIDAR data. (Unpublished doctoral dissertation). The University of Vermont, Burlington, Vermont.

Ghizzoni, T., Lomazzi, M., Roth, G., & Rudari, R. (2006). Regional scale analysis of the altimetric stream network evolution. *Advances in Geosciences*, *7*, 79-83.

Gilvear, D. J., Heal, K. V., & Stephen, A. (2002). Hydrology and the ecological quality of Scottish river ecosystems. *The Science of the Total Environment*, *294*(1-3), 131-159.

Gregory, K. J., & Madew, J. R. (1982). Land use change, flood frequency and channel adjustments. *Gravel-Bed Rivers. John Wiley, Chichester.*

Hack, J. T. & Goodlett, J. C. (1960). Geomorphology and forest ecology of a mountain region in the central Appalachians. *U.S. Geol. Surv. Prof. Paper, 34.* 66.

Hooke J. (1979). An analysis of the processes of river bank erosion. *Journal of Hydrology* 42: 39–62.

Kim, J. S., Jain, S., & Norton, S. A. (2010). Streamflow variability and hydroclimatic change at the Bear Brook watershed in Maine (BBWM), USA. *Environmental Monitoring and Assessment, 171*(1-4), 47-58. doi:10.1007/s10661-010-1525-1

Leopold, L. B. (1972). River channel change with time: An example: Address as retiring president of the geological society of America, Minneapolis, Minnesota, November 1972. *Bulletin of the Geological Society of America, 84*(6), 1845.

Marston, R. A., Girel, J., Pautou, G., Piegay, H., Bravard, J. P., & Arneson, C. (1995). Channel metamorphosis, floodplain disturbance, and vegetation development: Ain River, France. *Geomorphology, 13*(1-4), 121-131.

McBride, M. (2007). *Riparian reforestation and channel morphology: key driving mechanisms in small streams.* (Unpublished doctoral dissertation). University of Vermont, Burlington, Vermont.

Miller, A. J. (1995). Valley morphology and boundary conditions influencing spatial patterns of flood flow. *Geophysical Monograph, 89*. 57-81.

Peizhen, Z., Molnar, P., & Downs, W. R. (2001). Increased sedimentation rates and grain sizes 2-4 myr ago due to the influence of climate change on erosion rates. *Nature, 410*(6831). 891-897.

Ritter, D. F., Kochel, R. C., & Miller, J. R. (2002). Process geomorphology (4th ed.). Long Grove, IL: Waveland Press, Inc.

Schumm, S.A. (1973). Geomorphic thresholds and the response of drainage systems. *Fluvial Geomorphology*. 299-309.

Schumm, S. A. (1993). River response to baselevel change: implications for sequence stratigraphy. *The Journal of Geology 101*(2). 279-294.

Siedl, M. A., & Dietrich, W. E., (1992). The problem of channel erosion into bedrock. *Catena Supplement 23.* 101-124.

Simon, A., & Rinaldi, M. (2000). Channel instability in the Loess area of the midwestern United States. *Journal of the American Water Resources Association* 36: 133-150.

Simon, A., & Darby, S. E. (2002). *Geomorphology 40.* 229-254.

Stott, T. (2010). Fluvial geomorphology. *Progress in Physical Geography, 34*(2), 221-245.

Vermont Agency for Natural Resources (2009). Survey assessment: field and data analysis protocols. *Vermont Stream Geomorphic Assessment Phase 3 Handbook*. 8.

Villarini, G., & Smith, J. A. (2010). Flood peak distributions for the Eastern United States. *Water Resources Research*, *46*(W06504), 1-17.

VTD Editor (2011, August 30). Mad River Valley bears brunt of Irene damage in Central Vermont. *VT Digger*.
Retrieved from http://vtdigger.org/2011/08/30/mad-river-valley-bears-brunt-of-irene- damage-in-central-vermont/

Ward, P. J., van Balen, R. T., Verstraeten, G., Renssen, H., & Vandenberghe, J. (2009). The impact of land use and climate change on late holocene and future suspended sediment yield of the Meuse catchment. *Geomorphology*, *103*(3), 389-400.

Wolman, M. G. & Miller, J. P. (1960). Magnitude and frequency of forces in geomorphic processes. *J. Geol., 68*. 54-74.

Zaimes, G.N., Schultz, R.C., & Isenhart, T. M. (2006) Riparian land uses and precipitation influences on stream bank erosion in central Iowa. *Journal of the American Water Resources Association 42.* 83-97.