Quantifying Sediment Loading due to Channel Migration in Impaired and Attainment Watersheds in Chittenden County, VT

Introduction

Erosion can lead to the impairment of streams and pollution of receiving water bodies due to the high inputs of sediment, nutrients, and pollutants. High sediment loads can decrease water quality and have a negative impact on downstream habitat health and ecology (Howard et al., 1998). In addition to this major source of non-point source pollution, streambank erosion can have devastating effects on human infrastructure through flooding, destruction of roads and buildings, damage to bridges, and loss of farmland. Since 1973, Vermont has experienced thirteen major flood events at the state and regional level. Just five of these floods were estimated to have caused more than $50 million in damages (VT ANR, 1999). As of 2009, damages from flooding in Vermont cost more than $16 million per year (VT DEC ANR, 2009). As of 2004, 56,600 km of the 907,404 km assessed rivers and streams in the United States were classified as impaired due to sedimentation (USEPA, 2009). In Vermont more than 51 km of the 8,938 km of assessed waterways are classified as impaired due to sedimentation (USEPA, 2008). However, the importance of streambank erosion on Vermont's surface waters, in comparison to other sources of sediment (e.g. wind-blown sediment and that moved via runoff), has not been adequately quantified.

Vermont Geomorphic Assessment

The Vermont Agency of Natural Resources River Management Program (VT ANR RMP) has developed a three phase approach to assess and monitor Vermont's streams in order to better plan for future protection, management, and restoration of Vermont's streams (VT ANR, 2004). The first phase of this protocol utilizes remote sensing, topographic maps, aerial photographs, previous studies, and "windshield" surveys in order to delineate the watershed, define stream reaches, and assign a reference geomorphic condition based on valley landforms and geology. Phase II involves a Rapid Geomorphic Assessment (RGA) of the watershed on a reach by reach basis. A rating (Reference, Good, Fair, Poor) is assigned to each reach that explains the adjustment process from the historic condition (ie. without human impacts) of the stream to its current altered condition. A reference stream (rating of > 0.85) is in dynamic equilibrium while a "good" stream (rating 0.65 – 0.85) has experienced minor adjustment. A "fair" stream (rating 0.35 – 0.64) has had moderate adjustment, and a "poor" stream (rating 0 – 0.34) has experienced an extreme change from the reference stream type (VT ANR, 2004). Phase III involves additional field surveys only at select locations. VT ANR RMP estimates a time commitment of one to two months per watershed for the first phase, one to two days per mile of channel length for the second phase, and three to four days for every two meander wavelengths of stream channel for the third phase (VT ANR, 2004). With over 11,265 km of streams in Vermont and only 19% of the streams (2,172 km) mapped to date (Kline and Cahoon, 2010), the effort requires years, if not decades, to complete.

Streambank Erosion

Streams seek dynamic equilibrium, where a balance is achieved between sediment, discharge, and gradient in the stream system. Stream planform adjusts to this balance. The quantity and frequency of meanders depend on channel slope, substrate, and confinement. A lack of equilibrium due to changes in sediment supply, sediment size, slope, discharge, or the width to depth ratio can be due to either intense short term or smaller and cumulative long term disturbances in the watershed (Schumm, 2003; Shuster et al., 2005). This imbalance results in planform adjustment, channel widening, and either aggradation or degradation of the channel until the stream has again reached a dynamic equilibrium. These changes are assessed by comparing existing and reference streams and comparing stream attributes such as channel dimensions, stream pattern, profile, sediment transport, and sediment size distribution (VT ANR, 2004).

Streambank erosion can contribute a large amount of sediment to the stream, and is often the most significant source of non-point pollution in a stream, especially during storm events (Bull 1997, Howard et al 1998). Studies have shown that contributions due to bank erosion can range anywhere from as low as 0 - 5% (Roehl, 1962; Bull, 1997) to between 64 - 90% (Simon et al., 1996; Howard et al., 1998; Simon and Thomas, 2002, Simon et al., 2004) of the total sediment load. Most of the sediment entering streams due to streambank erosion originates from the main channel as opposed to tributaries, which are generally rocky and resistant to migration (Hansen, 1971). Hansen (1971) found that only an estimated 5-10% of the sediment load of the Pine River (MI) could be attributed to the contribution of sediment from tributaries. Roehl (1962) hypothesized that the type and texture of sediment sources, climatic variation, and other watershed characteristics influenced the relative contribution of streambank erosion. Ouyang and Bartholic (1997) add that basin slope and land use/land cover also play a significant role. In addition, water velocity, bank soil properties, and the amount of riparian vegetation factor into observed values for bank erosion (Bull, 1997; Howard et al., 1998).

Mapping and Assessing Stream Channel Migration

Studies of channel migration have often focused on specific reaches or on sections of streams primarily utilizing fieldwork (Bull, 1997; Howard et al, 1998; Vericat and Batalla, 2006; Zaimes et al 2006; Swanson et al., 2008), simulation models (Howard, 1992), numerial modeling (Darby et al., 2002), or predictors for stream channel migration such as stream power, valley slope, bankfull width, and mean annual flood (Nicoll and Hickin., 2009). However, in order to characterize an entire stream, a small number of observations must be extrapolated over a large area, and these methods can be time intensive and costly. Recent advances in remote sensing and the acquisition of high resolution aerial imagery and detailed, accurate elevation data derived from Light Detection and Ranging (LiDAR) can be utilized to map and monitor planform change and quantify sediment loading at the watershed level and across many watersheds over time at a relatively low cost and small time commitment. Thoma et al. (2005) found that surveying 1000m^2 of the steep banks of the Blue Earth River (MN), required 16 man-hours. However, two full LiDAR scans encompassing 56km of the river took just 8 hours over 2 days.

Historical maps and aerial imagery have long been used to document the changes in stream channel location over time (Hooke, 1977; Graf, 1983, 1984; Brizga & Finlayson, 1990; Leys and Werrity, 1999; Collins et al., 2003) and more recently GIS-based analysis of historical and aerial and satellite imagery have been used to monitor channel migration (Gregory et al., 1992; Downward et al., 1994; Micheli et al., 2004; Gordon and Meentermeyer, 2006; Meitzen, 2009; Wheeler et al., 2009). Aerial photography, frequently paired with field observations, has been used to target areas experiencing bank erosion (Howard et al., 1998). Johansen et al. (2007) found that a remote sensing approach to measuring and monitoring the condition of riparian corridors is more time and cost effective for larger areas than field observations. In addition, channel centerlines have also been used to measure and map changes in streams utilizing a GIS.

Mean annual lateral migration and erosion rates due to channel migration can be determined by creating polygons by intersecting stream centerlines from two different dates (Kirchener et al., 1998; Micheli and Kirchener, 2002; Micheli et al., 2004; Larsen et al., 2006; Constantine et al., 2009). Kirchener et al. (1998) created these “eroded area polygons” to define changing stream centerlines for the Kern River (CA) and found annual lateral migration rates between 0.25 and 3m.

One of the most challenging obstacles to overcome when mapping stream channels over time with two or more sources of imagery is that of registration error (Gurnell, 1997; Hughes et al., 2006). If there are small registration errors between images, changes in the stream channel that do not exceed the size of the error are unable to be detected while those that are detected may be underrepresented (Gurnell, 1997). Ground control points (GCPs) can be used to determine the offset between two image sources, which are usually geometrically distorted to some extent due to collection methods and the movement of the aircraft or spacecraft platform (De Leeuw et al., 1988). GCPs are placed at locations on each image that are easily identifiable such as bridges or building corners not tall enough to experience building layover. The horizontal distance between paired GCPs can be calculated to determine the offset between images. Many previous studies have used root mean square error (RMSE), the sum of the individual GCPs' error divided by the square root of the number of paired GCPs, to define image misregistration (Micheli and Kirchner, 2002; Urban and Rhodes, 2004; Hughes et al. 2006). Hughes et al. (2006) found that while RMSE is a good indicator of average error between images, it can lead to over- or under-estimation of true change. Other studies have used a set digitization scale (Yang et al., 1999) or manual adjustment of stream centerlines (Hughes et al., 2004) to limit the effect of image misregistration.

LiDAR

Light detection and ranging (LiDAR) technology provides very accurate elevation data that has many possible applications. Airborne LiDAR data is collected by firing laser pulses at the ground from an aerial platform and measuring the time between transmission and receipt of laser pulses reflected back (Bachman, 1979). There are multiple returns per pulse, each representing different heights at the surface. The first return pulses record the distance to the highest objects (ie. tree canopies or building roofs); the last return or bare earth pulses record the distance to bare earth. Data resolution is dependent on factors such as aircraft elevation and speed, laser pulse rate, scan width, scan rate, and vegetation cover (Thoma et al., 2005).

Traditional land surveys require large amounts of labor, money, and time while elevations determined by photogrammetric methods may be unreliable in forested or low relief areas because the aerial view cannot penetrate a dense canopy or accurately show areas with little definition in imagery (Franklin, 2001; Lefsky et al., 2002; Remmel et al., 2008). Many studies have tested the relative merits of using traditional DEMs or field collection with LiDAR-derived DEMs and found that the LiDAR-derived DEMs are more accurate and less costly than alternative methods (Webster et al., 2006; Murphy et al., 2008; Remmel et al., 2008; Hall et al., 2009).

Study Area

This analysis was carried out on 15 watersheds located in Chittenden County, Vermont (Figure 1). Of these watersheds, 9 are listed on the Vermont 303d list of impaired waters due to urban stormwater runoff, one is listed as impaired due to agricultural runoff, and 6 are classified as attainment watersheds (VT DEC, 2008). The LaPlatte River watershed is divided into two sections: the west is impaired due to agricultural runoff, and the east is an attainment or reference watershed (VT DEC, 2008).

The impaired watersheds range from 14-95% urbanized (Table 1). Englesby Brook, which drains into Burlington Bay of Lake Champlain, is overwhelmingly developed with 95% of the land use classified as urban (VT DEC Englesby Brook, 2009). Morehouse Brook, which is

88% urban, drains portions of the city of Winooski and the town of Colchester (VT DEC Morehouse Brook, 2009). The west half of the LaPlatte River is considered impaired due to agriculture; 51% of this nearly 80 km^2 watershed is classified as agriculture. Munroe Brook, located in Shelburne and South Burlington, is the smallest study watershed at less than 1 km^2.

The remaining study areas are attainment watersheds, which are those with streams that meet or attain Vermont water quality standards. In general these watersheds have more of their area covered by forested land than the impaired watersheds. Alder Brook has the highest urban land use of the study attainment watersheds at 52% urban (VT LCLU, 1992). Trout Brook has only 7% urban land use. Additional information about all watersheds is summarized in Table1.

Methodology

The objective of this study is to quantify the maximum potential sediment eroded due to streambank erosion (hereafter referred to as sediment loading) over time into 15 study watersheds in Chittenden County, Vermont. Sediment loading to streams due to streambank erosion will be assessed by analyzing very high spatial resolution aerial and satellite imagery within a GIS framework. In addition, lateral migration will be calculated between each two dates of analysis at the location of the center of each eroded area polygon. Processes to estimate sediment loading and lateral migration will be automated within ArcGIS ModelBuilder. Geospatial analyses will be performed using ArcGIS 9.3.1 (ESRI, 2009). Statistical analyses will be performed using SAS V8 (SAS, 1998).

Several sources of imagery and ancillary data were used to carry out the study objectives. The Vermont Mapping Program Digital Orthophotography Quadrangles (DOQ), acquired on April 25, 1999, depicted the baseline planform condition in the watersheds and was compared to imagery acquired in 2004 and 2008. Color-infrared (CIR) digital orthophotography (0.16m, 1:1250) was collected in May 2004 by the Chittenden County Metropolitan Planning Organization (CCMPO) and was used to depict the adjusted planform in the watersheds for 2004. In August 2008, 1m VIS/NIR digital orthophotography was collected by the USDA National Agriculture Imagery Program (NAIP) (1m, 1:5000) provided the basis for stream channel planform mapping in 2008. Stream centerlines digitized from the 1999 DOQ and acquired from the Vermont Hydrography Dataset published by the Vermont Center for Geographic Information (VCGI) were used to depict the baseline location for the stream centerlines. CCMPO 3.2m posting LiDAR elevation data (EarthData, Inc.) was used to determine bank heights, which were used to determine sediment loading. In addition, watershed and subwatershed boundaries, stream geomorphic assessment ratings, and geomorphic conditions were obtained from ANR RMP data (2005-2010, 1:5000).

LiDAR Elevation Data

LiDAR elevation points were used to generate DEMs to represent the ground elevation (bare earth) for each of the study watersheds. Two LiDAR datasets were utilized: a 3.2m systematic grid of last return points that represent bare earth (hereafter referred to as BE) and an irregular grid of points that show reflective surface (hereafter referred to as RS) or object heights, which represent the first return of the laser. Low lying nearby RS points were combined with BE points to create an enhanced DEM. A spatial join was performed in ArcGIS in order to overlay the two datasets (BE and RS), which created a horizontal distance field between adjacent points. The difference in elevation between the paired points was then calculated. Reflective surface points that fell within 1m horizontal distance and 0.25m vertical distance were considered representative of bare earth (after Pelletier, 2010). These select points were added to the existing BE dataset, creating a more robust BE elevation layer (hereafter referred to as BERS). To create a DEM, the Natural Neighbor method of interpolation was used with a 1m cell size (after Pelletier et al., 2007).

Quantify channel migration and sediment loss over time

1) Channel Migration – In order to determine how far a stream channel has migrated, stream centerlines were created by on-screen digitization of the center of the wetted channel through visual interpretation of digital orthophotography. Channel centerlines were digitized for all 15 watersheds utilizing CCMPO CIR (0.16m) digital orthophotography (acquired in 2004). In addition, centerlines were mapped for the LaPlatte River using USDA NAIP 1m digital orthophotography (2008). The remaining stream centerlines were not digitized using 2008 NAIP imagery because high riparian tree canopy cover in the imagery, which was collected in August, in most watersheds (30 - 100%) prevented accurate centerline digitization. All of the digitized stream centerlines were compared with VT Hydrography data, which includes stream centerlines in Vermont digitized from 1999 0.5m Vermont panchromatic DOQ. Stream channel migration, measured as the lateral shift of stream centerlines between any two dates of observation, was also measured for each stream. An automated approach was developed to compare the stream centerlines from 1999 to 2004 for all watersheds, and for three time intervals (1999-2004, 2004-2008, and 1999-2008) for the LaPlatte River (after Pelletier, 2010). Eroded area polygons, defined as the distance between stream centerlines between dates, were created (Figure 3). An automated model was developed in ArcGIS ModelBuilder to create these eroded area polygons, calculate areas of soil loss (m^3), and calculate lateral migration (m).

1a) Image to Image Registration – In order to remove locational bias when assessing stream channel migration over time, the horizontal distance between the same location on paired images was accounted for. To quantify registration error between images, 20 pairs of GCPs were digitized for each study watershed between dates of analysis. Each set of points was positioned on a fixed landscape feature easily identifiable in images (ie. building or sidewalk corners). Horizontal thresholds were chosen to represent the mean ± 2 SDs for all GCPs. The mean offset was computed for all image pairs (n=320 for 1999-2004 time series, n=40 for 2004-2008 and 1999-2008 time series) (Figure 2). These thresholds mean that 95% of all GCPs are located within 2m of their corresponding paired point for the 1999-2004 time series, 2.7m from their corresponding point for the 2004-2008 and 1999-2008 time series (LaPlatte River only).

The horizontal threshold was utilized to apply a corresponding sized buffer to the stream centerlines (digitized from the image source with the lowest locational accuracy). No directional bias in offsets between images was found, so an equidistant buffer was applied to the stream centerlines. For the 1999-2004 time series, a 2m buffer was applied to the 1999 stream centerlines. For the 1999-2008 and the 2004-2008 time series, a 2.7m buffer was applied to the 2008 stream centerlines. This buffered area was removed from subsequent channel migration or sediment loading calculations, thus removing locational bias for all subsequent calculations.

For each of the study watersheds, only the main channel of the watershed was digitized as it is assumed that the bulk of sediment entering the stream due to channel migration is occurring in these main channels since most tributaries are small, rocky, and resistant to migration. To test this assumption, all Indian Brook tributaries found in the 1999 VT Hydrography data were digitized from 2004 CCMPO for comparison. Sediment loading from Indian Brook, with and without all tributaries, were compared to determine if tributaries are a significant source of sediment.

1b) <u>Streambank Height</u> – To calculate streambank height the stream channel centerlines for both dates of analysis were clipped to erosional polygons, which were buffered by the image offset buffer previously erased from polygons to ensure overlap between centerlines and polygons. The LiDAR-derived stream channel heights were extracted and the mean value was calculated for the length of the stream bordering each eroded area polygon. The mean centerline heights were subtracted between dates of analysis in order to calculate streambank height.

2) Soil Volume Loss - In order to calculate soil volume loss, LiDAR-derived bank heights were used in conjunction with eroded area polygons. The mean bank height was multiplied by the observed area of soil loss due to streambank erosion for each time interval to calculate soil volume loss (m^3) as follows:

$$SVL = Area * BH$$

SVL= Soil volume loss (m^3)
Area= Area of eroded area polygon (m^2)
BH = Summed LiDAR-derived bank heights (m)

Where channel avulsions occurred, erosional polygons were manually edited to cover only the area where sediment was removed from the channel. Soil volume loss was summed by site, reach, and watershed.

3) Soil Sampling – Soil sampling was carried out in 4 of the study watersheds (Allen Brook (25 sites), Alder Brook (13 sites), Indian Brook (25 sites), and the LaPlatte River (13 sites)) to determine an appropriate value for soil bulk density. Bulk density (Mg/m^3), defined as the ratio of the mass of dry soil to the bulk volume of the soil from the core, will be used in the conversion of soil volume loss to soil mass loss (sediment loading) to streams due to channel migration. Bulk density sampling requires driving a metal core into the soil until the core is filled with soil but not compacted. Field sampling was carried out on randomly selected eroded

area polygons during the summers of 2009 and 2010 in collaboration with Dr. Don Ross and Eulaila Ishee (PSS / UVM). At each site soil samples were taken 1.5m from the streambank at two depths (mean depths: 3-11cm and 15-23cm) with 3 replicates 1m apart to ensure consistency. Samples were processed at the laboratory at the Plant and Soil Sciences Agricultural Science Building. To calculate bulk density, coarse fragments >2.0mm were removed, the remaining soil was oven dried for at least 8 hours at 105°C, and the soil and coarse fragments were weighed (after Grossman and Reinsch, 2002). The final bulk density value is the ratio of mass per volume of soil corrected for coarse fragments.

4) <u>Sediment Loading Calculations</u> – Sediment loading due to streambank erosion will be estimated for each of the study watersheds as a whole and on a reach by reach basis. To calculate sediment loading, field-collected soil bulk density and soil volume loss for all eroded area polygons were multiplied and summed per reach and watershed as shown in the following equation.

$$\text{Sediment loading} = \sum (\text{soil volume loss} * \text{bulk density})$$

The mean bulk density for all samples (adjusted for rock fragments) was determined to be 1.2 g/cm^3. This value was utilized for all subsequent calculations (after Thoma et al., 2005).

Results

Lateral Migration

Lateral migration, defined as the shift between stream centerlines between any two dates of analysis, was observed for each of the study streams though the rates varied between reaches and streams (Table 2 and Appendix A). The shift between centerlines ranged from 0m (Indian Brook and Morehouse Brook) to 93.21m (Centennial Brook) for the 1999-2004 time interval. The number of migrations ranged from 22 on Morehouse Brook to 513 on Indian Brook.

However, these migrations were widely varied in their area. The total area of the eroded area polygons range from 1,239.28 m^2 for Morehouse Brook and 24,821.25 m^2 for Trout Brook.

Sediment Loading

Sediment loading calculations also varied widely between streams and stream reaches (Table 3 and Appendix B). Patrick Brook had the lowest sediment loading estimate at 591.12 MT. Trout Brook had the highest sediment loading estimate at 51117.87 MT. However, most streams' sediment loading estimates fell between 2000 and 8000 MT. Sediment loading estimates were non-normally distributed with a median value of 3221.24 MT.

Discussion

Observed lateral migration rates and sediment loading calculations compared fairly well with those reported in current literature. DeWolfe et al. (2004) found lateral migration rates between 0.08m and 0.53m for 4 streams located in Vermont at 10 cross sections.

Barg et al (2003) found that Allen Brook had a total sediment load of 9744 MT/yr. Using this number as an average total sediment load value, our estimates show that streambank erosion accounts for 13.41% of the total sediment load if the quantified sediment load for Allen Brook (3633.36 MT) is divided by the 5 year interval between dates of observation. Although additional total sediment load values are unavailable for the additional study watersheds, this comparison helps to validate our estimates.

The sediment loading estimates that were generated represent the total potential sediment that has entered the study watersheds in response to stream channel migration over the specified time period. However, not all of this sediment is immediately carried downstream. Some of this sediment, especially sediment with larger grain sizes, may remain where it enters the stream or be deposited only a few meters downstream. More and more of this sediment will be carried downstream as time progresses and aggregates dissolve, especially during storm events. Therefore, our estimates are representative of the total sediment entering the stream during the specified time period that will eventually be transported downstream to the receiving waterbodies.

There are several sources of error that may affect our sediment loading and lateral migration estimates. The main source of this error is that of locational accuracy, which was accounted for by erasing a buffer equal to the mean ± 2 SDs of image offsets calculated from GCPs. However, minor sources of error that were not accounted for were that of digitization error, errors in the VT Hydrography dataset used to represent the location of the streams in 1999, manual correction of avulsions and channel shifts, and the fact that this model assumes that streambank sides are vertical at sites of streambank erosion. The final issue that we encountered was that the study streams were all fairly small and located in heavily wooded areas. In situations such as this tree cover often obscures the stream channel. This issue was minimized by using high resolution imagery collected in the spring before leaf out. These sources of error are minor and should not significantly affect estimates.

Our data can be used to guide future planning in the watersheds, to target restoration or management, and to assess the impacts of anthropogenic and natural alterations in the watersheds. This method can be used in the future as a model of channel change from its current and past state. The findings can also be correlated to stressors such as land use/ land cover, impervious surface, riparian vegetation, and proximity to damns. The method is ideal for future use as it is automated and can easily be updated as new data becomes available.

In addition, the method could be incorporated into VT ANR's RMP process. Their current methodology relies on only one date of observation, and the use of time series remotely sensed data could enhance their current products. VT ANR's goal for this program is to plan for future protection, management, and restoration of Vermont's streams (VT ANR, 2004). In order to predict how a stream will behave in the future, it is important to understand how it responded to similar stressors in the past.

LiDAR elevation data provides an effective and accurate means of assessing fluvial geomorphic conditions, even in areas of low relief or high tree cover. Our results demonstrate the usefulness of this data to allow the calculation of sediment loading estimates for an entire watershed. Previous methodology used to assess entire watersheds have generally extrapolated findings from a small area to the entire watershed. However, as our results show streams are dynamic and are not consistent longitudinally. LiDAR data allows for changes to be directly observed for the entire stream at a very high resolution; our DEMs had a resolution of 1m. Future research using multidate LiDAR data to quantify sediment loading between two time periods would further validate the usefulness of the data.

References

Bachman, C.G. (1979). Laser radar systems and techniques. Norwood (MA): Artech House.

Brizga, S. and Finlayson, B. (1990). Channel avulsion and river metamorphosis: The case of the Thompson River, Victoria, Australia. *Earth Surface Processes and Landforms*. 15: 391 -404.

Bull, L. (1997). Magnitude and variation in the contribution of bank erosion to the suspended sediment load of the river Severn, UK. *Earth Surface Processes and Landforms.* 22: 1109-1123.

Collins, B.D., Montgomery, D.R., and Sheikh, A.J. (2003). Reconstructing the historical riverine landscape of the Puget Lowland. In:Montgomery, D.R., Bolton, S.M., Booth, D.B., Wall, L. (Eds.), Restoration of Puget Sound Rivers. *University of Washington Press, Seattle, WA*: 79–128.

Constantine, C.R., Dunne, T., and Hanson, G.J. (2009). Examining the physical meaning of the bank erosion coefficient used in meander migration modeling. *Geomorphology*. 106: 242-252.

Darby, S.E., Alabyan, A.M., and Van De Wiel, M.J. (2002). Numerical simulation of bank erosion and channel migration in meandering rivers. *Water Resources Research*. 38(9): 1163-1186.

De Leeuw, A.J., Veugen, L.M.M., and Van Stokkom, H.T.C. (1988). Geometric correction of remotely-sensed imagery using ground control points and orthogonal polynomials. *International Journal of Remote Sensing*. 9(10-11): 1751-1759.

Downward, S., Gurnell, A., Brookes, A. (1994). A methodology for quantifying river channel planform change using GIS. *Variability in Stream Erosion and Sediment transport. Canberra Symposium*. 224: 449-456.

ESRI (Environmental Systems Research Institute). (2009). ArcGIS Desktop 9.3.1. (2009). Redlands, CA: *Environmental Systems Research Institute*. Computer software.

Franklin, S.E. (2001). Remote sensing of sustainable forest management. Lewis Publishers, Boca Raton, USA.

Gordon, E. and Meentemeyer, R.K. (2006). Effects of dam operation and land use on stream channel morphology and riparian vegetation. *Geomorphology*. 82(3-4): 412-429.

Graf, W. L. (1983) Flood-related channel change in an arid-region river. *Earth Surface Processes and Landforms* 8: 125-139.

Graf, W. L. (1984) A probabilistic approach to the spatial assessment of river channel instability. *Water Resources Research.* 20:953-962.

Gregory, K.J., Davis, R.J., and Downs, P.W. (1992). Identification of river channel change due to urbanization. *Applied Geography.* 12(4): 299-318.

Grossman, R. and Reinsch, R. (2002). The solid phase. P. 207-210. In J. Dane and G Topp (ed.) Methods of soil analysis. Part 4. Physical methods. SSSA and ASA, Madison, WI.

Gurnell, A.M. (1997). Channel change on the River Dee meanders, 1946-1992, from the analysis of air photographs. *Regulated Rivers: Research & Management*. 13: 13-26.

Hall, R.K., Watkins, R.L., Heggem, D.T., Jones, K.B., Kaufmann, P.R., Moore, S.B., and Gregory, S.J. (2009). Quantifying structural physical habitat attributes using LiDAR and hyperspectral imagery. *Environmental Monitoring and Assessment*. 159(1-4): 63-83.

Hansen, E.A. (1971). Sediment in a Michigan trout stream. Its source, movement, & some effects on fish habitat. *USDA Forest Service. Research Paper:* NC-59.

Hooke, J. M. (1977) The distribution and nature of changes in river channel patterns: The example of Devon. In: River Channel Changes (ed. by K. J. Gregory), 265-280. J. Wiley, Chichester, UK.

Howard, A.D. (1992). Modeling channel migration and floodplain sedimentation in meandering streams. *Lowland Floodplain Rivers: Geomorphological Perspectives*. John Wiley & Sons Ltd: 1-41.

Howard, A., Raine, S., and Titmarsh, G. (1998). The contribution of steam bank erosion to sediment loads in Gowrie Creek, Toowoomba. *Proc. ASSSI National Soils Conference, 27-29th April*, *Brisbane*: 491-493.

Hughes, M., McDowell, P., and Marcus, W. (2006). Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology.* 74:1-16.

Johansen, K., Phinn, S., Dixon, I., Douglas, M., and Lowry, J. (2007). Comparison of image and rapid field assessments of riparian zone condition in Australian tropical savannas. *Forest Ecology and Management*. 240(1-3): 42-60.

Kline, M. And Cahoon, B. (2010). Protecting river corridors in Vermont. *Journal of the American Water Resources Association.* 46(2): 227-236.

Larsen, E.W., Fremier, A.K., and Girvetz, E.H. (2006). Modeling the effects of variable annual flow on river channel meander migration patterns, Sacramento River, California, USA. *Journal of the American Water Resources Association.* 42(4): 1063-1075.

Lefsky, M., Cohen, W., Parker, G., and Harding, D. (2002) LiDAR remote sensing for ecosystem studies. *BioScience.* 52(1): 19-30.

Leys, K.F. and Werrity, A. (1999). River channel planform change: software for historical analysis. *Geomorphology* 29, 107– 120.

Meitzen, K.M. (2009). Lateral channel migration effects on riparian forest structure and composition, Congaree River, South Carolina, USA. *Wetlands*. 29 (2): 465-475.

Micheli, E.R. and Kirchner, J.W. (2002). Effects of wet meadow riparian vegetation on streambank erosion. 1. Remote sensing measurements of streambank migration and erodibility. *Earth Surface Processes and Landforms*. 27: 627-639.

Micheli, E.R., Kirchner, J.W., and Larsen, E.W. (2004). Quantifying the effect of riparian forest versus agricultural vegetation on river meander migration rates, central Sacramento River, California, USA. *River Research and Applications*. 20: 537-548.

Murphy, P.N.C., Ogilvie, J., Meng, F.R., and Arp, P. (2008). Stream network modeling using LiDAR and photogrammetric digital elevation models: a comparison and field verification. *Hydrological Processes*. 22(12): 1747-1757.

Nicoll, T. and Hickin, E. (2009). Planform geometry and channel migration of confined meandering rivers on the Canadian prairies. *Geomorphology*. 116: 37-47.

Ouyang, D. and Bartholic, J. (1997). Predicting sediment delivery ratio in Saginaw Bay watershed. *The 22nd National Association of Environmental Professionals Conference Proceedings. May 19-23, 1997*, Orlando, FL: 659-671.

Pelletier, K. (2010). Title TBD (Unpublished Master's thesis). University of Vermont.

Pelletier, K., Besaw, L., Morrissey, L., Rizzo, D. (2007). Investigating spatial interpolation of LiDAR data for analyzing fluvial geomorphic properties of streams. *American Geophysical Union, Fall Meeting 2007.* Abstract H43E-1667.

Remmel, T.K., Todd, K.W., and Buttle, J. (2008). A comparison of existing surficial hydrological data layers in a low-relief forested Ontario landscape with those derived from a LiDAR DEM. *Forestry Chronicle*. 84(6): 850-865.

Roehl, J.E., (1962). Sediment source areas, delivery ratios and influencing morphological factors, *International Association of Hydrological Sciences.* 59: 202-213.

Schumm, S.A. (2003). *The fluvial system*. The Blackburn Press, Caldwell, NJ.

Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E., and Smith, D.R. (2005). Impacts of impervious surface on watershed hydrology: A review. *Urban Water Journal*. 2(4): 263-275.

Simon, A., Rinaldi, M., and Hadish, G. (1996). Channel evolution in the loess area of the Midwestern United States. *Proceedings of the Sixth Federal Interagency Sedimentation Conference:* 86-93. Reston, VA. USGS.

Simon, A., and Thomas, R.E. (2002). Processes and forms of an unstable alluvial stream with resistant, cohesive, streambeds. *Earth Surfaces Processes and landforms*. 27: 699-718.

Simon, A., Langendoen, E., Bingner, R., Wells, R.R., Yuan, Y., and Alonso, C. (2004). Suspended-sediment transport and bed-material characteristics of Shades Creek, Alabama and Ecoregion 67: Developing water-quality criteria for suspended and bed-material sediment. *National Sedimentation Laboratory Technical Report*. 43: 150pp.

Swanson, K., Watson, E., Aalto, R, Lauer, W., Bera, M., Marshall, A., Taylor, M., Apte, S., and Dietrich, W. (2008). Sediment load and floodplain deposition rates: comparison of the Fly and Strickland rivers, Papua New Guinea. *Journal of Geophysical Research*. 113: F01S03

Thoma D.P., Gupta S.C., Bauer M.E., and Kirchoff, C.E. (2005). Airborne laser scanning for riverbank erosion assessment. *Remote Sensing of Environment,* 95: 493- 501.

Urban, M.A. and Rhoads, B.L. (2003). Catastrophic human-induced change in stream-channel and geometry in an agricultural watershed, Illinois, USA. *Annals of the Association of American Geographers.* 93(4): 783-796.

USEPA. (2008). Vermont 2008 water quality assessment report. *United States Environmental Protection Agency (USEPA).*

USEPA. (2009). National Water Quality Inventory: Report to Congress, 2004 Reporting Cycle. *United States Environmental Protection Agency (USEPA).* EPA 841-R-08-001.

Vericat, D. and Batalla, R., (2006). Sediment transport in a large impounded river: the lower Ebro, NE Imberian Peninsula. *Geomorphology*. 79: 72-92.

VT ANR (Vermont Agency of Natural Resources) (2009). Phase III handbook: Survey assessment field and data analysis protocols, *Vermont Agency of Natural Resources*.

VT ANR (Vermont Agency of Natural Resources) (2007). Phase I handbook: Watershed assessment using maps, existing data, and windshield surveys, *Vermont Agency of Natural Resources.*

VT ANR (Vermont Agency of Natural Resources). (2004). Stream geomorphic assessment protocols handbooks: remote sensing and field survey techniques for conducting watershed and reach level assessments. *Vermont Agency of Natural Resources.*

VT ANR (Vermont Agency of Natural Resources) (2003). Phase II handbook: Rapid stream assessment field protocols. *Vermont Agency of Natural Resources.*

VT ANR (Vermont Agency of Natural Resources). (1999). Options for state flood control policies and a flood control program. *Vermont Agency of Natural Resources Department of Environmental Conservation Water Quality Division.* Waterbury, Vermont.

VT DEC (Vermont Department of Environmental Conservation) (2009a). Notice documents Vermont Agency of Natural Resources Department of Environmental Conservation initial designation pursuant to clean water act: Englesby Brook. *Vermont Department of Environmental Conservation, Water Quality Division.*

VT DEC (Vermont Department of Environmental Conservation) (2009b). Notice documents Vermont Agency of Natural Resources Department of Environmental Conservation initial designation pursuant to clean water act: Morehouse Brook. *Vermont Department of EnvironmentalConservation, Water Quality Division.*

VT DEC ANR (Vermont Department of Environmental Conservation and Agency of Natural Resources) (2009). Regulating land use in flood hazard areas. *Vermont Department of Environmental Conservation River Management Program.* Town Fair 2009.

VT DEC (Vermont Department of Environmental Conservation) (2008). State of Vermont 2008 303(d) list of waters: Part A – Surface waters in need of TMDL. *Vermont Department of Environmental Conservation, Water Quality Division.*

Wheeler, P.J., Nguyen, T.T., Peterson, J., and Gordon-Brown, L. (2009). Morphological change at the Snowy River ocean entrance, Victoria, Australia (1851-2008). *Australian Geographer*. 40(1): 1-28.

Yang, X., Damen, M., Zuidam, R. (1999). Satellite remote sensing and GIS for the analysis of channel migration changes in the active Yellow River Delta, China. *International Journal of Applied Earth Observation and Geoinformation.* 1.2: 146-157.

Zaimes, G., Schultz, R., Isenhart, T. (2006). Riparian land uses and precipitation influences on streambank erosion in central Iowa. *Journal of the American Water Resources Association*. 42.1:83-97.

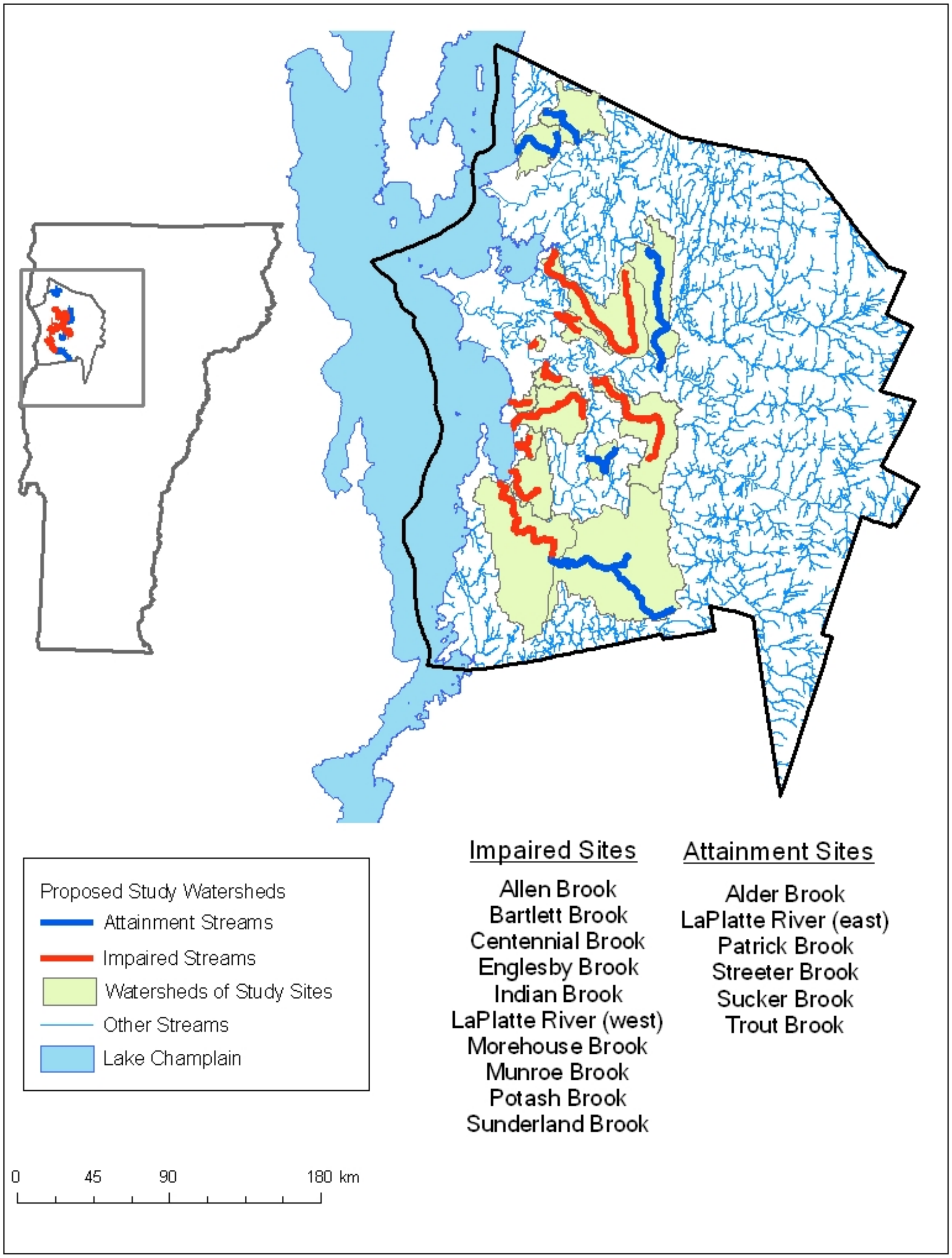

Figure 1. Fifteen study watersheds are located in Chittenden County, VT.

Table 1. Summary of the status, size, and 4 primary land cover/land use (LULC) classes for each study watershed. The dominant land use class(es) for each stream are shown in bold font.

Stream name	Status	Watershed Area (km^2)	Length of Streams (km)	LCLU (%)[1] Urban	Forest	Agricultural	Wetlands
Alder Brook	Attainment	26.7	16.5	**52**	38	<1	4
LaPlatte River	Attainment	57.4	14.7	17	**43**	30	5
Patrick Brook	Attainment	2.2	2.4	36	18	**37**	0
Streeter Brook	Attainment	16.2	6.2	15	**41**	17	23
Sucker Brook	Attainment	4.7	5.4	23	**46**	21	2
Trout Brook	Attainment	11.3	7	7	**59**	28	2
Allen Brook	Impaired	29	16.7	29	**32**	**32**	4
Bartlett Brook	Impaired	2.9	3.5	**64**	9	20	1
Centennial Brook	Impaired	3.6	3.8	**71**	16	4	2
Englesby Brook	Impaired	2.5	2.2	**95**	<1	1	0
Indian Brook	Impaired	31.1	27	33	**38**	17	6
LaPlatte River	Impaired	79.9	17.1	14	25	**51**	3
Morehouse Brook	Impaired	14.3	0.9	**88**	3	<1	0
Munroe Brook	Impaired	<1	5.2	29	24	**39**	3
Potash Brook	Impaired	18.3	11.2	**53**	10	29	2
Sunderland Brook	Impaired	5.79	5.24	**78**	10	3	2

[1] www.usgs.gov

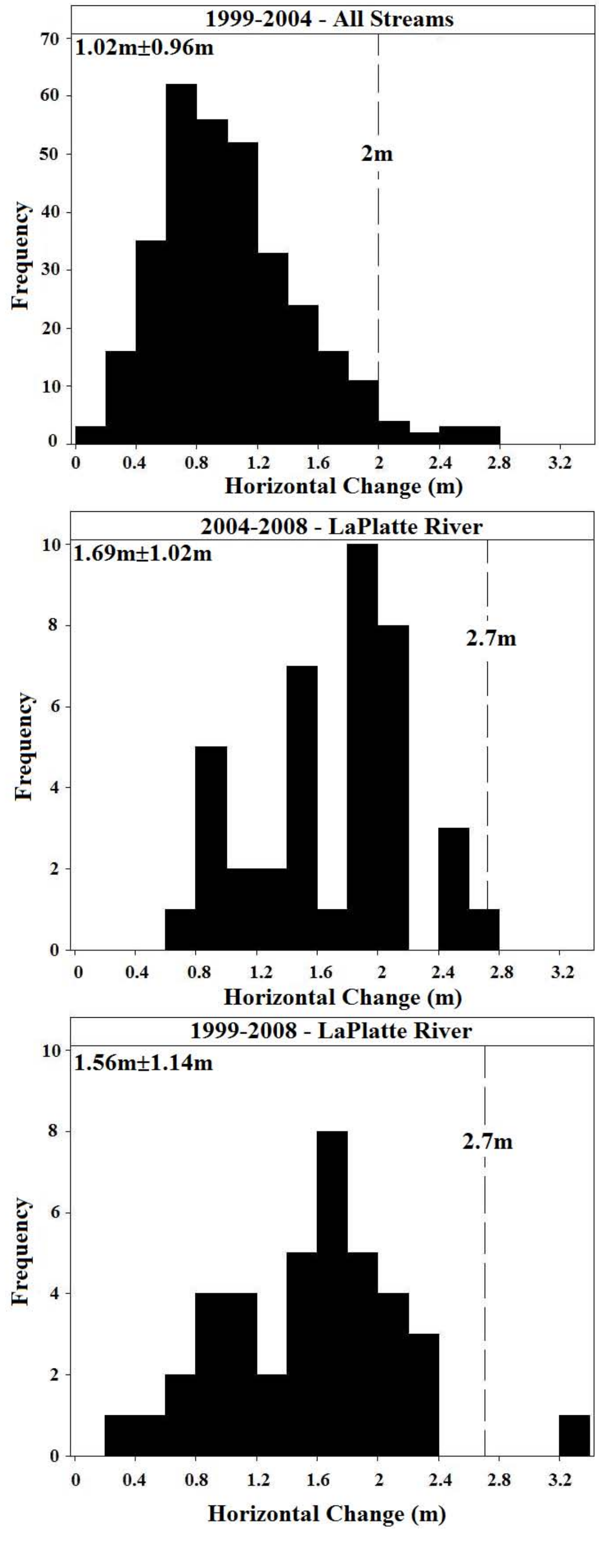

Figure 2. Histograms summarize the horizontal difference between paired GCPs for all watersheds (1999-2004, n=320) and the LaPlatte River (2004-2008 and 1999-2008, n=40). Mean ± 2 SDs are noted for each time series and represented with dashed lines.

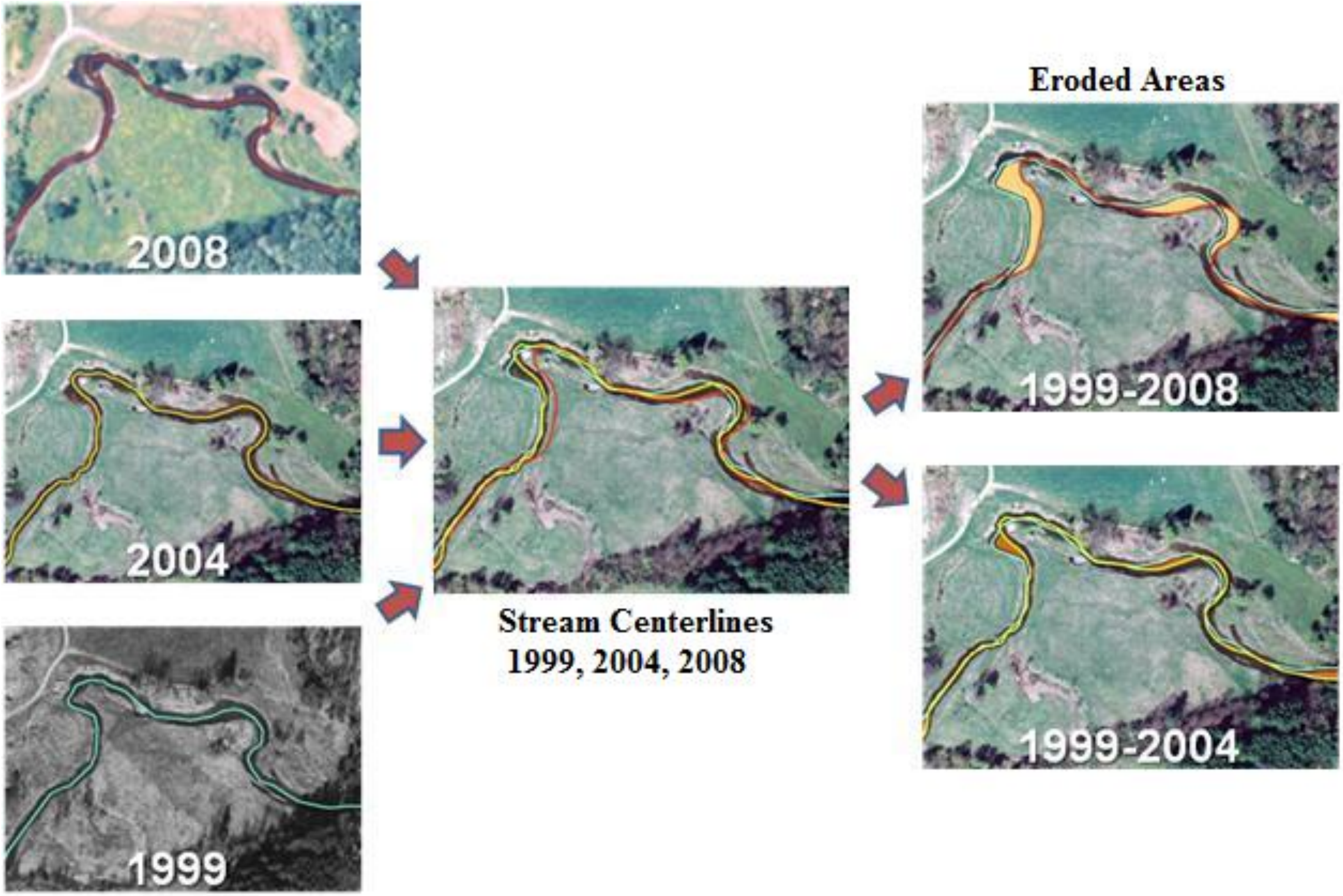

Figure 3. Stream channel centerlines were digitized for the 2004 and 2008 images and obtained from the VT Hydrography Dataset for 1999. The centerlines were then overlaid to map stream channel migration over time. The eroded area polygons are shown in gold for the 1999-2008 time interval and orange for the 1999-2004 time interval.

Table 2. Lateral migration summary statistics for study streams for all time intervals are shown in meters.

Stream Name	N	Mean	SD	Median	Sum	Minimum	Maximum
1999-2004 Time Period							
Alder Brook	343	1.83	2.52	0.97	627.28	0.002	14.35
Allen Brook	367	1.75	2	1.14	642.61	0.004	12.58
Bartlett Brook	67	2.92	3.23	1.71	195.57	0.01	11.07
Centennial Brook	54	6.77	19.33	1.1	365.31	0.04	93.21
Englesby Brook	58	2.52	1.76	2.06	146.11	0.08	7.61
Indian Brook	513	1.3	1.67	0.68	665.9	0	13.98
LaPlatte River (Attainment)	334	1.48	1.69	1.48	494.09	19.82	0.02
LaPlatte River (Impaired)	189	1.42	1.38	0.97	268.85	0.01	7.69
Morehouse Brook	22	3.67	4.09	1.85	80.65	0	11.65
Munroe Brook	138	2.19	2.63	1.07	301.62	0.004	11.26
Patrick Brook	52	1.56	1.65	1.09	81.25	0.03	7
Potash Brook	286	1.78	2.39	0.81	509.37	0.01	19.86
Streeter Brook	121	6.34	4.3	4.7	767.46	4	21.92
Sucker Brook	127	2.47	3.4	1.11	313.68	0.01	12.98
Sunderland Brook	125	2.46	2.7	1.51	307.12	0.05	17.07
Trout Brook	193	4.18	3.99	2.98	806.03	0.01	18.5
1999-2008 Time Period							
LaPlatte River (Attainment)							
LaPlatte River (Impaired)	188	2.96	7.52	1.65	556.96	0	100.31
2004-2008 Time Period							
LaPlatte River (Attainment)	274	1.6	1.92	0.88	438.01	0.003	10.17
LaPlatte River (Impaired)	189	1.45	1.38	1	274.2	0.01	7.69

Table 3. Sediment loading totals are shown for each of the study streams for each time interval.

Stream Name	Number of Erosional Features	Area of Erosional Features (m^2)	Sediment Loading (MT)
1999-2004 Time Period			
Alder Brook	343	14947.61	7881.50
Allen Brook	367	10978.92	3633.36
Bartlett Brook	67	6826.78	8254.87
Centennial Brook	77	2086.88	1125.67
Englesby Brook	58	6151.17	4661.79
Indian Brook	513	8804.48	1988.73
LaPlatte River (Attainment)	237	11152.51	980.60
LaPlatte River (Impaired)	189	8152.10	2809.12
Morehouse Brook	22	1239.28	2238.51
Munroe Brook	138	6313.75	2796.78
Patrick Brook	53	2164.69	591.12
Potash Brook	279	15830.71	9434.14
Streeter Brook	127	4938.09	7086.78
Sucker Brook	127	6873.02	1698.27
Sunderland Brook	125	4531.41	2277.59
Trout Brook	193	24821.25	51117.87
1999-2008 Time Period			
LaPlatte River (Attainment)	245	12052.36	6641.86
LaPlatte River (Impaired)	188	24493.86	5812.49
2004-2008 Time Period			
LaPlatte River (Attainment)	174	8768.81	5097.72
LaPlatte River (Impaired)	189	8152.10	2809.12