MDA priority setting in watershed restoration

Final report

September 2015

Project Investigator: Chris Lenhart

Co-P.I. John Nieber

Project Administration:
Heidi Peterson, Minnesota Department of Agriculture (MDA)

Funding provided from the Clean Water Fund as part of the Clean Water, Land and Legacy Amendment

BACKGROUND

Recent studies in the upper Midwest have shown that stream erosion is a major source of sediment in many Midwestern rivers (Yan et al., 2010; Lenhart et al. 2013; Belmont et al. 2013; Lauer et al. 2015) with negative impacts on instream water quality and aquatic life. While stream bank erosion is a natural process, the rates observed in parts of the Midwest exceed natural background levels. Flow levels have increased dramatically in recent years leading to increased disequilibrium in streams (Schottler et al. 2014).

With the ongoing assessment of impaired waters in Minnesota through the Total Maximum Daily Load (TMDL) process, and subsequent development of Watershed Restoration and Protection Strategies (WRAPS), there is need to reduce sediment input from channel sources in key areas and to prioritize actions for reduction of sediment and phosphorus loads to receiving rivers and streams. Targeted restoration and management actions can then be taken in the priority management zones both in the watershed and within the stream itself.

Project goals and research questions

A primary goal of this project was to develop tools to assist in the prioritization of management actions to reduce channel-derived sediment with the focus on the riparian zone. Numerous tools have focused on upland watershed management practices, but few have focused on the stream itself. Existing stream restoration/management prioritization tools utilize erosion calculators ranging in complexity from empirically-based indices to physical process-based models, such as Channel Evolution Model in Stream Restoration Strategies (CONCEPTS) (Langendoen and Alonso, 2008).

The second major goal of the project was to better understand the hydrologic drivers of stream bank erosion and the processes by which stream bank erosion occurs in three study areas. More specifically, we sought to understand the mechanical processes of bank collapse and hydrologic pathways, and water sources for flow contributing to the erosion events.

The specific project objectives were:

1. Estimate the natural/background/baseline erosion for representative channels in each of the sentinel watersheds.
2. Develop channel erosion assessment tools that are applicable to three regions of Minnesota, each region being represented by a study watershed within which the tools are developed.
3. Assess the hydrologic drivers associated with increased rates of stream erosion, and

4. Develop the decision support tool for prioritizing channel restoration and sediment reduction within the sentinel watersheds.

There is a strong need to develop an intermediate approach that utilizes empirically-based stream bank erosion indices applicable to the Upper Midwest, and Minnesota in particular, which is easily applied by local government agencies for TMDL load calculations and management plan development. TMDL load calculations require precise allocation for each source of a pollutant (Parry 1998 and EPA 2015). In the case of turbidity TMDLs, loads are typically divided into "upland" sources and channel sources. It is not practicable to develop time-consuming and complex hydraulic and sediment transport models for most projects. Complex models generally require a massive field data collection effort, followed by model calibration, which ultimately may not be more accurate than empirical methods. Therefore simple and reliable empirical channel erosion prediction methods are needed for estimating sediment loads for TMDL purposes.

To facilitate these estimates, region-specific channel erosion prediction graphs were developed for three different agricultural regions of Minnesota: the Driftless area in southeastern Minnesota, the Western Corn Belt Plains (geologically part of the Des Moines Lobe glacial till plain) in south central Minnesota and the Red River Valley in northwestern Minnesota. The Bank Assessment for Non-point source Consequences of Sediment (BANCS) equations were used for this purpose (Rosgen et al. 2006)(Appendix 1). The three study sites selected included the Whitewater River, Elm Creek and the Buffalo River, located respectively in each of the three ecoregions listed above (see Figure 1). These locations were selected because the predominant land-use is agriculture since the study was sponsored by the Minnesota Department of Agriculture. Secondly the study areas provided variety in the relative importance of different hydrologic and geomorphic processes related to stream bank erosion.

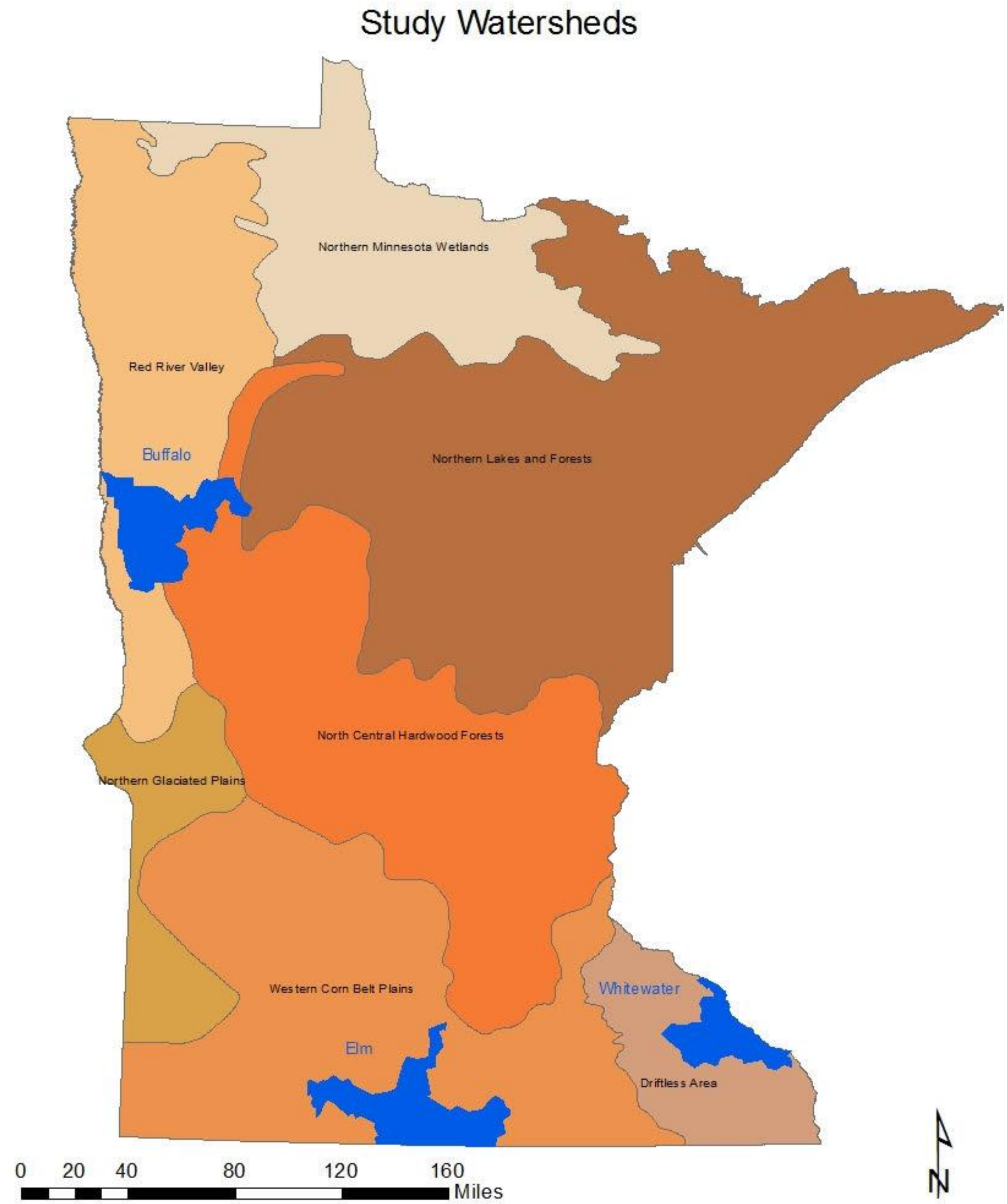


Figure 1. Research watershed locations. Three predominantly agricultural watersheds, Whitewater River, Elm Creek, and the Buffalo River, each representing a different ecoregion as shown above

The Whitewater River is located within the Driftless Area, a region of steeper topography that was not affected by the most recent glaciation. Draining to the Mississippi River, there is a flat plateau in the upper reaches of most Driftless region streams in Minnesota followed by a steep drop to the Mississippi River valley. The lower Whitewater River lies within alluvial sediment, much of which was deposited during the post-European settlement period (post 1850). This “legacy” sediment as it is often referred to, is sandy and easily eroded.

Elm Creek is contained within the Western Corn Belt Plains. This ecoregion has large areas of flat loamy soils deposited by past glaciers. The most common soil types are heavy silt to clay loams that are fertile and support productive agriculture. They typically have lower erosion rates than alluvial soil for example. Most of the ecoregion is flat to gently rolling, though it contains some steeper areas. In the Western Corn Belt Plains sediment sources to streams are thought to be dominated by field erosion. However substantial loading comes from the high stream banks and bluffs of some of the larger rivers (Lenhart et al. 2012a)

The Buffalo River is contained primarily within the Red River Valley ecoregion. This ecoregion was formed after Glacial Lake Agassiz drained about 10,000 years ago, leaving a large lake bed (originally over 170,000 square miles) of low permeability clay soil in much of northwestern Minnesota, northeastern North Dakota and southern Manitoba. A small portion of the Buffalo River headwaters is found within the Central Hardwood Forest Ecoregion. Streams in the southern Red River Valley have three distinct geomorphic settings: the outer relict beach ridge forming the eastern boundary of Lake Agassiz, the historical lake bed itself, and the moderately-steep transition zone between Lake Agassiz’s beach and bed.

METHODS

A three-tiered approach was used to develop a system to prioritize river reaches for restoration or management to reduce sediment loading, given as:

1. Tier 1: GIS and aerial photo analysis to determine long-term stream bank erosion rates using a lateral migration tool
2. Tier 2: Field data collection and verification using BEHI/BANCs to document processes, bank heights and materials: further focus on specific sites
3. Tier 3: Selection of specifics sites for restoration: site specific tool including cost / benefit, logistics, ecology and water storage benefits (Presnail 2013)

The methods used to provide scientific backing for the above approach are described in the following.

1. Determination of natural or "background" rates of channel erosion.

In order to determine lateral stream erosion rates and develop region-specific bank erosion prediction tools, the following approach was used. Background rates of lateral erosion were determined using an automated channel migration measurement tool developed by Mark Ellefson at the Minnesota DNR for use in GIS. The tool requires digitizing the center line of the stream for two different years. The distance the center line moved over the time period is measured in units of feet/year. Lateral migration measurements are lumped over of reaches hundreds of meters in length (200-400). There were over 100 river reaches measured for both Elm Creek and Buffalo, using the years 1991 and 2010 to determine lateral migration rates. For the Whitewater River, the time period of 2003 – 2010 was assessed due to the poor visibility of stream banks in the 1991 aerial photos (MN DNR 2015). The DNR conducted an in-depth watershed-based assessment on the Whitewater using the Watershed Assessment of River Stability and Sediment Supply (WARSSS)(Rosgen et al. 2006)

A second stream lateral migration tool was developed for this project (Titov 2015)(Appendix 2) which calculates lateral migration using a non-linear local alignment to minimize error in estimating local lateral migration. This tool was used to assess the results of the DNR lateral migration tool and identify ways to reduce channel migration measurement error at the local stream bank scale. The Dynamic Time Warping (DTW) based channel migration analysis tool yields a non-linear local alignment by solving the cumulative distance constrained minimization problem for a discrete set of migration points whereas all other tools estimate an average migration per section pre-defined by the user.

Most tools expedite this process by introducing a pre-processing step that involves stream channel segmentation into an equal number of parts. This effectively defines an affine (linear) transformation for distances along the stream channel. This linearity introduces a potential source of alignment errors if the stream channel does not migrate in a uniform way, i.e. some sections are more stable while other are extremely mobile. In this way, the DTW avoids many of the problems associated with the other methods that exist.

2. Methods for developing channel erosion assessment tools for Minnesota

Data was collected to assess how different Bank Erosion Hazard Index (BEHI)(see Appendix 1) and vegetation factors influence erosion rates using methods listed in Table 1. The field data collection also provided more precise information on bank height and channel material that cannot be obtained by aerial photos. The field data collection also improved our understanding of the mechanics of the bank erosion processes. BEHI parameters and vegetation composition and coverage were measured in 2012-2013 at 10 sampling sites within each of the 3 study watersheds for a total of 30 sites (see Underhill 2013 in Appendix 3 greater detail) distributed across the watersheds. Each of the 30 sites was at an outer bend in the river channel.

At each site a vegetation survey was conducted to measure species composition and percent cover. Each survey was done along a 300 foot long transect of the outer bend. Half meter square ($0.5m^2$) quadrats were used to measure ground layer vegetation density and species composition. Each quadrat was placed randomly every ten feet. In each quadrat relative percent of coverage was assessed with one hundred percent the maximum. A graded cover technique was used where values were recorded in 5 percent gradients, except for densities below 10 percent which were measured in one percent intervals. Bare space was included in order to estimate the amount of un-vegetated soil within the river reach. Plants were identified to the genus or species level if possible. Unidentified species were collected and identified later using supplemental material if possible. Trees, defined as any woody plant with a diameter at breast height (DBH) greater than 1/4 inch were also measured. If a tree stem grew within five feet laterally of the measuring tape the DBH was recorded. Bushes, with less than a 1/4 inch DBH were measured using the amount of area covered by the shrubs at breast height (CBH).

Near bank stress (NBS), an indicator of the erosive force of streams, was estimated at each site using method #2, one of the five (or is it six or seven) methods described in Rosgen et al. (2006). This method calculates NBS based on the tightness of river meanders relative to river width as defined by the relationship: *NBS = Radius of curvature / bankfull width.* The NBS score is then assigned a value from very low to extreme or 1 to 6 on the BANCS graph.

Together the NBS and BEHI values are plotted on a graph and used to predict bank erosion rates using the BANCS relationships (Rosgen 2006)(Also see Appendix 1). Using this data, combined with data on stream bank height and stream bank materials, a total volume of sediment from stream bank erosion may be calculated (Rosgen 2001) for either a section of river or the entire length of the river. If soil density data is available the total mass of eroded sediment may be calculated using local data or the value of 1.3 tons/cubic yard ($1.54\ g/cm^3$) which is typical for loamy alluvial soils common in the region.

Table 1: Data collected during 2012-2013 in relationship to BEHI and bank erosion processes at ten sites within each study watershed for a total of 30 sampling sites.

Category	**Data collected**
Bank Erosion Hazard Index (BEHI) variables	Bank height, bankfull height, bank angle, soil material, plant root depth and density (see Appendix 1)
Plant community composition and cover	Species composition, cover and frequency of plant species using a 0.5 m^2 quadrat at 10 locations along a transect parallel to the stream path
Root density	Root length, mass and volume data from herbaceous vegetation; WinRhizo software used to measure root diameter, length and volume (see Fig. 2)
Soil properties	Soil bulk density (to estimate mass of soil eroded)

Analysis of the effect of different BEHI variable components (e.g bank height, root depth) and vegetation properties on BEHI scores was assessed using linear regression (see Underhill 2013). The relationship between different physical variables (soil bulk density, watershed position) and the measured root density measurements also were assessed with linear regression. Box plots were used to display the mean and standard deviations of the BEHI data to identify potential statistically significant differences.

Field data on bank erosion rates was collected to help validate and further refine the aerial photo calculations and to document the timing and nature of stream bank collapses at 3 sites on Elm Creek and 7 sites on the Buffalo River. Resurvey of stream channels to measure erosion rates directly was done via survey of stream cross section and bank profiles along with bank erosion pins, (metal rebar inserted horizontally into the stream bank). The Minnesota DNR conducted extensive surveys over a period of seven years (2007-2014) in the Whitewater River (MN DNR 2015). The Elm Creek and Buffalo River sites were examined by University of Minnesota staff with assistance from the MN DNR on the Buffalo River from 2011 to 2014. Most field data collection was initiated in spring 2012 and continued through 2014 for this project.

Plant root data collection

Root depth and density data was collected for the BEHI and to get more accurate estimates of actual root density at the 30 sampling locations within the three study watersheds. Root samples were taken at the top of a stream bank one to three feet from the outside edge of the meander. Three depths were sampled for root density, 0-30 cm, 30-60 cm and 60-90 cm. These depths were chosen because previous research showed that typically > 90% of root mass is contained within the top 90cm of soil (Piercy and Wynn 2008). A sharp-edged 2” diameter PVC tube was used to extract the roots using a rubber mallet to drive it into the ground. The tube was then extracted and all the soil and attached particles, including roots, were stored in a ziplock plastic bag. Samples were then washed in the lab to remove excess soil. Root properties were measured using a plant root scanner and the WinRHIZO Pro software manufactured by Regent Instruments of Canada (http://www.regentinstruments.com/assets/winrhizo_about.html).

The program calculates the diameter of each individual root, total root length and the total area and volume of the roots. See Bauhus and Messier (1999) for a more detailed description of the tool and its application.

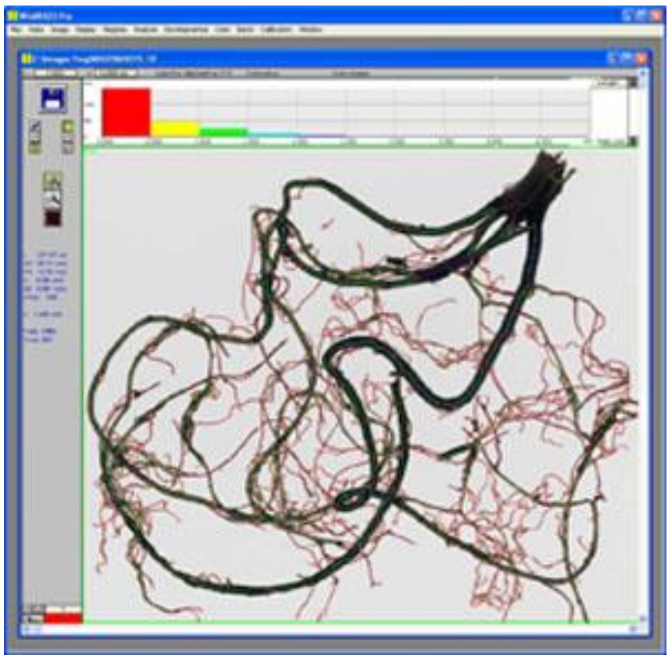


Figure 2. A plant root scan using a plant root tray and the WinRHIZO software. The software calculates several metrics related to root length, diameter, total volume and area. (http://www.regentinstruments.com/assets/winrhizo_about.html). Root density is measured as total root length of individual roots per volume of soil sampled (194 cm^3).

Data analysis of root data included quantification of the total root mass and root length density in each of the three depth categories (0-30cm, 30-60cm, and 60-90cm). Significance testing was done to test for differences between depth categories using the R Statistical software with results displayed as box plots.

Simulation of the effect of root depth on bank erosion hazard was conducted by inputting different root lengths (0.5, 1, 2, 3 and 6 feet) into the component of the BEHI equation to determine how root depth affects the ratio of plant root depth to bank height. Using the ratio of root depth to bank height, the following categories were used in the assessment; 0.0 - 0.05 (extreme), 0.05 – 0.14 (very high), 0.15 – 0.29 (high), 0.30 – 0.49 (moderate), 0.50 – 0.89 (low) and 0.90 – 1.0 (very low). The resulting graph provides a tool for determining where plant roots may play the biggest role in stabilizing stream bank.

Development of region-specific stream erosion indices

Currently there are only regional bank erosion prediction (BANCS) graphs for Yellowstone, Colorado and North Carolina. We collected BEHI data in the field in 2012-2013 to build regional graphs for Minnesota using the standard methodology. However the preliminary results did not show a strong correlation between BANCS predictions and observed stream bank erosion rates possibly because different people were collecting the data and because BEHI scores may change substantially from year to year as banks slumps or move. More experience was needed by the people doing the BEHI and NBS measurements to get accurate and consistent scores

Therefore we determined that reach averaged erosion rates using aerial photos was more accurate given the existing data. Overall this method is likely better at predicting stream bank erosion averages though it is less likely to accurately predict extremely high or very low erosion rates.

Two different approaches were used to develop new region-specific BANCS erosion indices for Minnesota. For Elm Creek and the Buffalo River the natural background or long-term channel migration rates between the years 1991-2010 were used to develop a modified BANCS graph for each watershed. The lateral migration data was summarized by migration rate in feet/year for the period between the two channel assessment times. Data is presented in tables by percentiles (20, 40, 60, 80, 90, 100) paralleling the 6 categories found in the BEHI/BANCS model (which include very low, low, moderate, high, very high and extreme). These categories represent annual stream bank erosion rates ranging from very low (typically < 0.1 feet per year) to extreme (typically 1 to 10 feet per year).

To adjust for the Near-bank shear stress (NBS) we took the observed rate of erosion from the Yellowstone BANCS graphs. The Yellowstone graph was developed in an area of glaciated soils and has been the most widely used for bank erosion calculations (Rosgen et al. 2006). The rate of NBS change was then applied to the Elm Creek and Buffalo lateral migration rates to obtain predictions for different NBS levels. Using this approach new relationships were made for Elm Creek representing the Western Corn Belt Plains (glacial till plains) and for the Buffalo representing the Red River Valley (Figure 1).

In the Whitewater River the Minnesota DNR team collaborating on the project used the standard Rosgen Methodology to develop a BANCS graph. They collected stream bank erosion data through re-surveying streams with different combinations of BEHI and NBS scores since the year 2007 (MN DNR 2015) at over 70 stream sites (Appendix 4).

Use of point bar vegetation and sediment deposition data to assess net transport of sediment

Streams that have relatively stable channel dimensions have a dynamic balance between deposition on point bars and lateral bank erosion over many years. Since sediment from bank erosion is frequently deposited locally and not always transported out of the river system entirely (Lauer and Parker 2008) it is helpful to estimate sediment deposition on point bars to determine how much sediment is being carried downstream. Sandbars that have perennial plants such as trees, shrubs and perennial grasses will hold down sandbar deposits whereas bare deposits will be more easily re-mobilized at high flows. Vegetation growth helps to initiate narrowing of the channel as shown in Stage 5 of the Channel Evolution Model (Figures 3a and 3b). Therefore areas of recent vegetation establishment, typically willow species (*Salix sp.*) and cottonwood (*Populus deltoides*) are indicative of recent depositional activity in rivers within the upper Midwestern U.S. (Figure 4)(Johnston 2003).

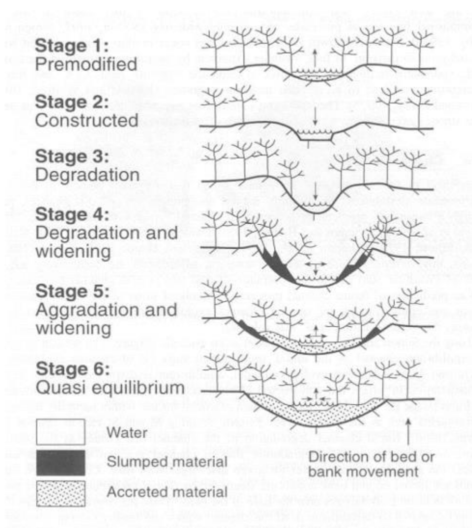


Figure 3a. The channel evolution model developed by Stanley Schumm and modified by Andrew Simon (Simon 1989). The diagram shows a river moving from a pre-modified state (Stage 1) through channel degradation and widening (stages 3-4) which can be caused by either flow increases, channelization or other increases in slope. As a river recovers in stage 5, re-vegetation starts to occur leading to narrowing back down of the channel and a return to a near equilibrium state (Stage 6) (Simon 1989).

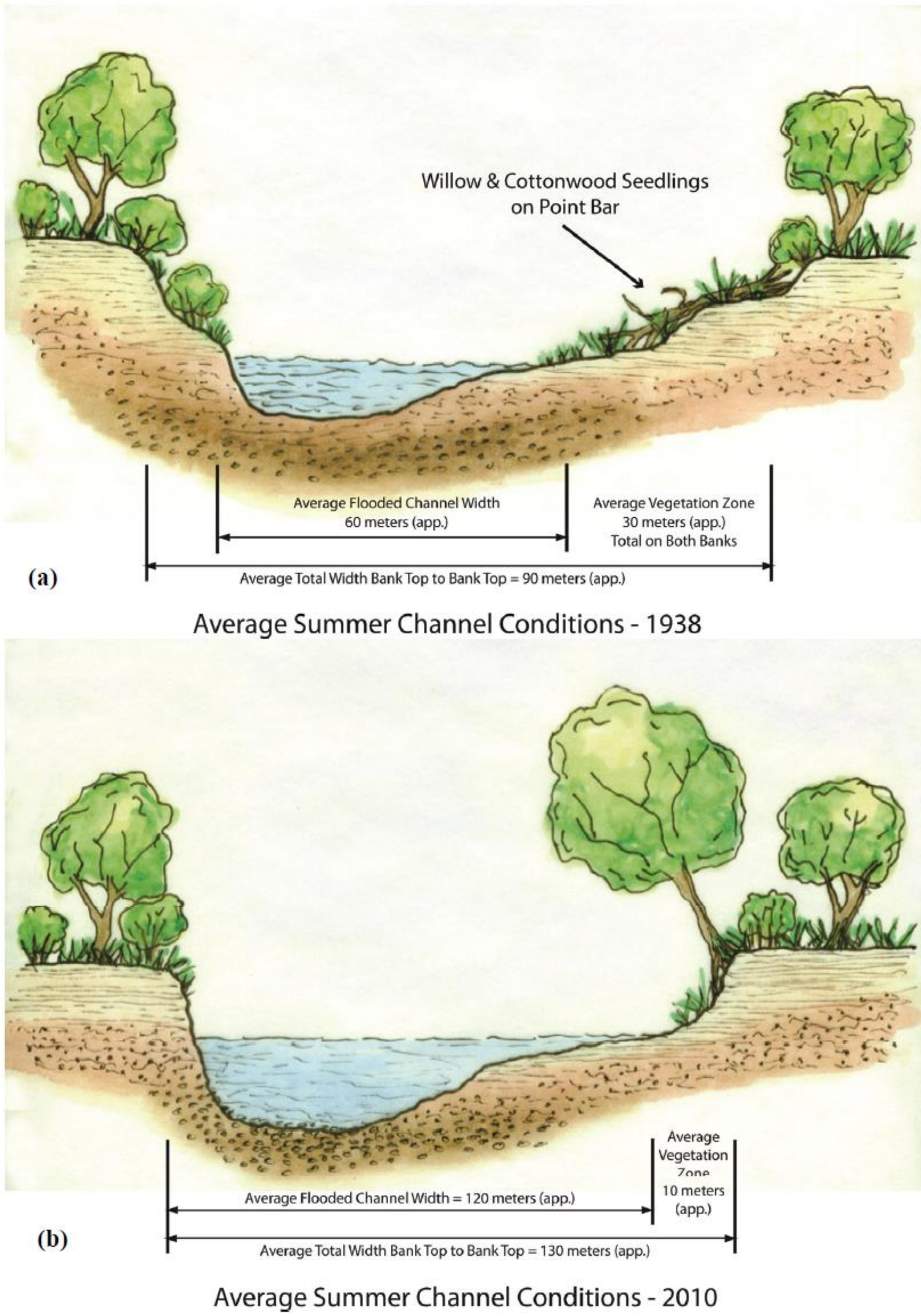


Figure 3b. Sketch showing the role of trees in channel narrowing which occurs in stages 5-6 of the Simon/Schumm CEM (drawing by Stephen Roos, University of Minnesota) (Lenhart et al. 2013).

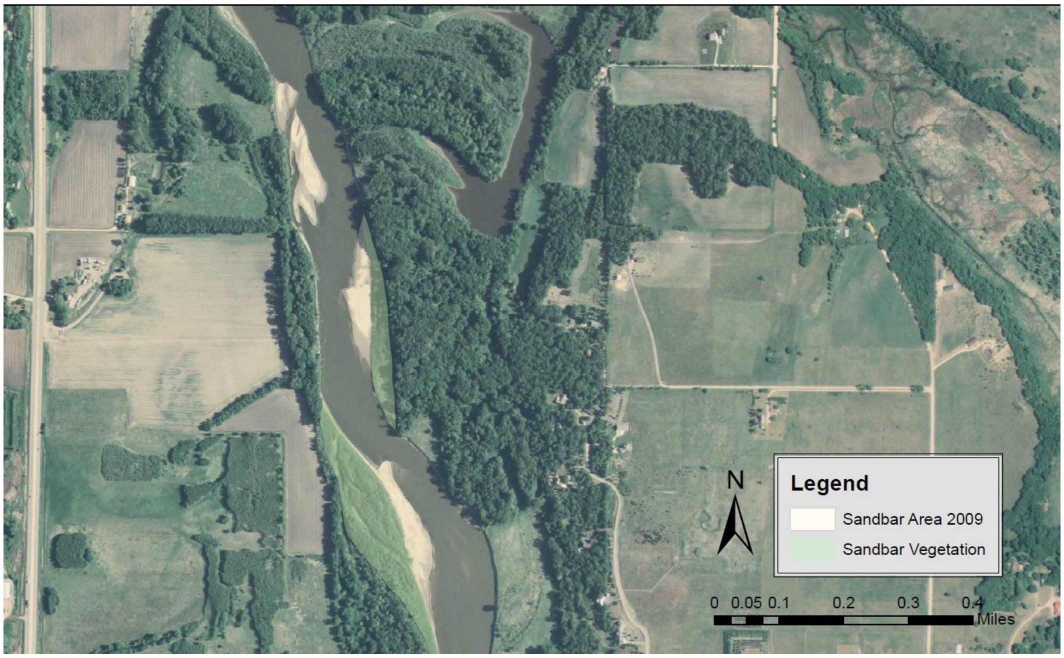


Figure 4. Areas in light green along the river margins above represent areas of recent willow and cottonwood growth on a river in southern Minnesota.

Data was collected at 8 different point bars on the Elm Creek, including sediment deposition rate, vegetation cover and species composition. Sediment deposition was measured using two methods: Soil excavation to the root collars of sandbar shrubs and placement of artificial turf mats put along sandbars of Elm Creek. Artificial turf mats squares, each 1400 square cm, were deployed during low flow conditions in late August and early September of 2013 at each field survey site. Turf mat squares, described in Steiger et al. (2003), are designed to trap deposited sediment left by receding flood waters, allowing for estimation of total volume of deposited sediment. Four to six turf mat squares were installed with 4 inch galvanized nails at each site from the water line to the top of the point bar.

Annual rates of sediment deposition were also estimated through the measurement of depth of sediment to root collar divided by age of sandbar willow sapling collections at each site. Locations of the root collar, or primary stem having developed since the time of establishment allows for accurate measurement of deposited sediment depth across a particular time frame. Approximately three to four measurements were taken in field at various distances along vegetation transects at each site. Associated willow saplings were collected and aged through the counting of rings under a dissecting microscope (Hupp, 1991). Due to its adventitious rooting capabilities, it is likely that sandbar willow saplings established at each site from both seed and advantageous reproduction. For this reason samples were collected on the largest present willow sapling or on individually growing species in order to accurately obtain depth to root collar measurements for each sample. Sediment particle size data was obtained from a study previously done in this location (see Rausch et al 2013 and Lauer et al. 2015). Plant species composition was recorded in quadrats placed along a transect running perpendicular to the river. Percent cover for each species was visually estimated in the quadrats.

Hydrologic data analysis was conducted to determine if prolonged high summer flows were inhibiting the colonization of sandbars thus leading to wider rivers and more sediment net sediment transport downstream (Triplett, 2014)(Appendix 5). Data was collected on the elevation of newly established vegetation relative to the stream's water surface. Historical stream flow data from the USGS and the MPCA gauge maintained at Martin County (years 2002-2008) were used in combination with cross-sectional data to estimate the magnitude of the "sandbar-submerging" flow and its duration. The historical streamflow record was then examined to determine if flow submergence was inhibiting colonization of woody plant species, based on known dates of seed dispersal.

The percentage of recent (<20 years) riparian vegetative growth covering sandbars was measured to provide a comparative metric for sandbar stabilization by woody plants, primarily by the species sandbar willow (*Salix interior*) but also cottonwood, silver maple and other willow species. Due to difficulties with observing forested areas in aerial photos along smaller rivers it was not possible to delineate these newly vegetated areas accurately along Elm Creek from the photos so estimates were made upon a larger nearby river, the Minnesota River, which Elm Creek eventually drains to.

An estimate of the total volume of sediment deposited within the permanently vegetated zone was made for Elm Creek using the deposition data and an estimate of the total area covered by *Salix* and cottonwood (*Populus sp*) species. The area of recent sandbar vegetation was multiplied by the mean sediment deposition rate on the sandbar multiplied by the soil density to obtain an estimate of the mass of sediment removed annually.

3. <u>Methods for assessing the hydrologic drivers of increased channel erosion in Minnesota</u>

Hydrologic and geomorphic data was collected in focused-site specific investigations of hydrologic pathways, bank erosion processes and channel evolution particularly in Elm Creek. Field techniques, modeling tools and GIS data used for the study are described in Table 2.

Table 2: Research methods used for hydrologic drivers of erosion component of the project		
Hydrology in the near-bank area		
Type	**Data collected and assessments completed**	**Dates**
Cameras across from stream banks	Images of stream bank shot every hour; bank collapsed timing; bank surface wetting	2012-13
Riparian wells	Water level, temperature and SC on the Buffalo River and Elm Creek.	2011-2014
Resurvey and bank pins	Sites at Elm Creek and Buffalo Rivers (Whitewater River done by the MN DNR)	2011-2014
BSTEM Bank Stability and Toe Erosion Model	Simulation of stream bank erosion processes and rates one reach of Elm Creek	Simulation for 2008 event
Sediment deposition as an indicator of net transport		
Sandbar physical and vegetative traits	Sandbar slope; soil texture, plant coverage and species composition along a transect	2013-2014
Deposition rates	Sediment deposit depth with age of trees or shrubs down to root collar (Hupp et al. ; Astroturf pads to capture on sandbars	2013-2015
Hydrologic drivers of erosion: Water pathways and sources		
Specific conductivity		
O and H Isotopes	Water samples collected from 10-12 sites along Elm Creek and different water sources (groundwater, tile and surface flow)	2011-2013
Soil and Water Assessment Tool (SWAT) model	A SWAT model developed for Elm Creek was utilized in the study	Modeled for year 2008

Direct observations and measurement of bank collapse include the use of motion-activated and time lapse cameras to capture bank collapse events and to observe changes in bank saturation on exposed stream banks. A digital camera (Bushnell® 8MP Trophy Cam, Led Trail Camera with Night Vision) was used because of its high resolution photos and rugged design suited for outdoor use. The camera was mounted on a steel bar on the river bank with a clear view of the opposite bank of the creek. The camera was located at a point where it would stay above flood stage, be safe (from vandalism), and possess a clear unobstructed view. A staff gauge was installed after these initial pictures were taken.

The camera was programmed to take still photos continuously on every hour both day and night, and has capacity to maintain run for more than one month continuously. Because of the distance of the study site from the Twin Cities, data was downloaded once a month.

Stream bank erosion mechanisms were documented at two banks along Elm Creek in spring and summer of 2012. The cameras were able to capture images of mass-wasting following undercutting of the banks on the falling limb of the hydrograph. The cameras also provided qualitative information on the location of groundwater tables within the stream bank which may contribute to mass-wasting via saturation. The cameras were installed in spring 2012 and collected hourly photos from April to August 2012 until they were destroyed by flood damage in.

a) Elm Creek, May 27, 2012 at high flow

b) Elm Creek, August 10, 2012 at lower flow

Figure 5. The game camera provided information on the timing of bank collapse relative to high flows, the slumping of upper bank materials and changes to the bank across seasons. a) The upper image shows Elm Creek on May 27, 2012 approximately 1 meter higher than the late summer flow on shown in the lower photo on August 10, 2012. Some slumping of the upper bank materials can be observed as well as seasonal regrowth of the vegetation.

Riparian-zone wells to investigate groundwater contribution to stream bank erosion

In order to better understand the role of groundwater seepage in stream bank erosion dynamics, riparian wells were placed to measure depth to groundwater, groundwater gradients and the presence of seepage through the stream banks which can contribute to bank collapse.

Two study sites were selected, one on lower Elm Creek and another in the middle Buffalo River near Hawley. Five wells were placed at Elm Creek along two transects perpendicular to the Creek while the Buffalo River had a transect of three wells.

Two inch diameter PVC, machine-slotted pipe wrapped in landscape fabric to reduce sediment infilling were placed at depths ranging from 1-2 meters. Within each well a Solinst Levelogger was suspended below the ground surface to a depth of 1 – 3 meters, depending on the depth to groundwater. Water level above the logger and temperature are recorded. A barometric logger was suspended in the air-space within one of the wells. The loggers were programmed to record data on 15 minute time intervals and placed in the field from approximately April to November during the years 2012-2014. A list of wells used in the Elm Creek watershed is in Table 3a.

Data provided by the loggers included depth to water table. From this data, groundwater gradients were calculated, measured as difference in water elevation/distance between wells. This information coupled with water level on the stream bank provides an indicator of the potential seepage force exerted on the stream banks that contributes to forces driving bank erosion.

Identification of flow sources using geochemical methods in combination with hydrologic data

To better understand hydrologic drivers of erosion in regions experiencing increased rates of channel change, it is helpful to understand the sources of water to stream flow and their relative contributions. Geochemical and isotopic tracers may be used to determine the origin of different water inputs and to develop a mixing model of different end members' contributions to streamflow, in combination with more limited hydrologic data collection. This approach contributes to substantial cost and time savings compared to a full-scale field hydrology study reliant on many groundwater wells, rainfall collectors and stream gauges. The end member mixing analysis (EMMA) procedure is described in more detail in Appendix 6.

Table 3. Location of monitoring wells and Specific Conductivity (SC) data collection in the Elm Creek watershed with the use of Solinst and Hobo automatic dataloggers.

Site name	Dates of sampling	Type of data	Location – Elm Creek watershed, Martin County, MN	Water sources
A1	2011-2014	Water levelogger in a 2” well	Stream bank well, Elm Creek at 300th Ave.	Primarily streamflow only; no Groundwater
A2	2011-2014	Manual measurements of water level only	Valley edge well, Elm Creek at 300th Ave.	Groundwater at very bottom of well only or dry
B1	2011-2014	Levelogger with SC data,	Stream bank well, Elm Creek at 300th Ave.	GW underflow through bank; streamflow into bank at high flows
B2	2011-2014	Water levelogger in a 2” well	Mid-valley well, Elm Creek at 300th Ave.	GW underflow; stream flow during large floods
B3	2011-2014	Levelogger with SC data,	Valley edge well, Elm Creek at 300th Ave.	GW underflow; stream flow during large floods
tile drain	2013-14	Levelogger with Hobo SC data logger	Elm Creek at 260th Ave.	Tile drainage only
Elm Cr at 159	2013-14	Levelogger with SC data,	On bridge pier at County Road 159 in Elm Creek	Streamflow
Surface gully	2013-14	Levelogger with SC data,	Elm Creek at 300th Ave.	Intermittent surface runoff

Specific conductivity (SC) measured in units of µs/cm, is useful as an indicator of the level of dissolved anions and cations in water which increases with greater residence time in the ground. This technique has been used to distinguish water sources in the Des Moines Lobe Glacial Till plain in Iowa by Smith (2011) and to separate snowmelt runoff from baseflow in the Colorado River basin by Miller et al. (2014). Smith found that water samples high in SC (>1000 µs/cm) are characteristic of groundwater while samples with low SC values (<50 µs/cm) are typical of rainfall and snowmelt. In watersheds with very rapid groundwater flow such as in karst environments, or in soils with low cation/anion binding ability the method is less useful in distinguishing surface from groundwater sources. This appears to be the case in some rivers within the Driftless areas of southeastern Minnesota where rapid infiltration and rapid through-flow in the subsurface occurs.

Water level and conductivity data was collected in the Elm Creek watershed using hand-held water chemistry probes (Hanna and YSI brands) in 2011-13 to identify the various water sources in the lower part of Elm Creek Watershed. This reconnaissance data collection effort provided the information needed to design and site a more focused data collection effort using SC dataloggers and water leveloggers.

More intensive data collection was done using Solinst Leveloggers in 2012-2013 along with Hobo conductivity loggers (Table 3). They recorded data at 15-minute intervals with locations across different water sources: groundwater wells, river flow (Elm Creek), a surface runoff gully and stream bank monitoring site. The datalogger at Elm Creek at Hwy. 159 provided a record of stream stage for 2013-2014. Using the past flow data collected at the Hwy. 159 site by the MPCA and Martin SWCD, a stage-discharge graph was developed.

Lamberton rainfall specific conductivity and isotope data collected as part of the National Atmospheric Deposition Program (NADP) is ongoing. The data is being collected as part of a national atmospheric water quality program and includes a large dataset from rainfall over many years (http://nadp.sws.uiuc.edu/ntn/). This dataset is representative of SC values in rainfall for the south central region of Minnesota.

In order to quantitatively apportion the sources of flow in Elm Creek a mixing model was developed for Elm Creek during periods without direct surface runoff occurring (Nieber et al. 2014)(Appendix 6). During this time period, SC and water level data were used to distinguish subsurface tile flow from groundwater.

The use of SC data for differentiating water sources to streams focused on Elm Creek. However hand-collected data using a water chemistry probe was collected at the Buffalo and Whitewater

Rivers to document SC levels in those rivers for comparative purposes and for determining the applicability of this approach in different regions of Minnesota. The SC data collected for the Whitewater River watershed is summarized in Table 3b.

Table 3b: SC data sources for the Whitewater River				
Site name	**Dates of sampling**	**Sample size**	**Location**	**Water source(s)**
Whitewater river and tributary sites	2011-2012	24	8 locations from headwaters of main branch to near river mouth	Stream flow
Finlay sub-watersheds *	2002	8435 (West Finlay), 19 (East Finlay)	Headwaters of the Whitewater*	Groundwater-dominated flow tributary to Whitewater
USGS gauge 05376800, Whitewater River	1975-1976	293	Whitewater main channel near Beaver, MN	Stream flow
NADP site WI98(National Atmospheric Deposition Program) Rainfall	2012	561	Wildcat Mountain, Wisconsin	Rainfall
*(see Green et al. 2007 and Johnson et al. 2010)				

SC data was also collected using the handheld Hanna probe on the Buffalo River at four dates in 2012-2013 (7/19/12, 8/31/12, 12/6/12, 6/11/13) to characterize the range of values observed in the main channel and upper tributaries but flow partitioning was not attempted for this watershed. Significance testing was conducted using a T-test to determine if significant differences exist between populations of water source categories in Elm Creek and the Whitewater River.

Isotopic data collection to develop water signature

The stable isotopes of hydrogen and oxygen are useful indicators of water source. The heavy isotopes of oxygen O^{18} and hydrogen (H^2 or deuterium) are concentrated in water that is exposed to evaporation. Therefore water from surface water bodies tends to plot to the right of the meteoric water line (Brooks et al. 2013), with higher concentration of O^{18} in particular. This tool has been used to characterize water sources in other parts of Minnesota including north central Minnesota (Lenhart et al. 2012b) and other locations in the United States such as the Colorado River basin (Miller at al. 2014). Other hydrologic and chemical indicators can be used to further corroborate findings from the SC and isotopic indicators including water temperature, other chemical species, position on hydrograph, and timing relative to storms. Isotopic data from Elm Creek was assessed to examine changes in water sources between sites within the watershed.

Simulation of bank erosion processes for comparison to observed erosion rates.

The Bank Stability and Toe Erosion Model (BSTEM), (Langendon and Alonso 2008) (http://www.ars.usda.gov/Research/docs.htm?docid=5044) was used to simulate bank erosion processes along a study reach in lower Elm Creek, where soil property (bulk density, particle size, critical shear strength and erodibility) and streambank erosion rate data from aerial photos and site monitoring was available. BSTEM works by calculating a Factor of Safety (F_s) based upon stream bank geometry, material strength, groundwater pore pressure and plant root reinforcement. It simulates toe scour from a high flow event and then recalculates F_s with the new bank geometry. A $F_s < 1.0$ is considered unstable, F_s between 1.0 and 1.3 is conditionally stable and $F_s > 1.3$ is called stable. The model calculates a volume of sediment caused by toe scour via stream flow and from mass-wasting when the F_s is exceeded. Sediment mass is then calculated by applying a value for soil bulk density for which we had local data.

Simulations were completed over the duration of one hydrograph on Elm Creek to estimate the total volume and mass of sediment eroded from a streamflow event observed in 2008 along a 120 m (394 ft) reach of Elm Creek. Input parameters including the bank/channel cross-section geometry, the erosion strength and shear strength properties of the bank, and vegetation characteristics (root depth and strength) on the bank. The 2.86 m (9.4 ft) stream bank was divided into five layers as well so that different properties could be entered for each soil layer.

The BSTEM assumes a steady state flow in the channel. To simulate conditions during a complete hydrograph the model was applied progressively to flows taken from the hydrograph divided into segments of uniform flow. The eroded soil volume may then be calculated for the event.

<u>Development of decision support tools for identifying sediment sources for channels and prioritizing management actions for sediment reduction</u>

Decision support tools were developed to provide practical tools usable by natural resources professionals in local and state government and consulting. A three-tiered approach was developed using the following approach:

Tier 1: GIS and aerial photos for "reconnaissance" level assessment of channel sources of sediment: Determine long-term erosion rates for streams in region using lateral migration tool(s)

Tier 2: Field data collection using BEHI/BANCs to document stream bank erosion processes, bank heights and materials: Develop regional bank erosion prediction tools to expedite calculations in TMDL studies and watershed management plans including WRAPs

Tier 3: Utilize a worksheet to rank practical, logistical, economic and related issues for stream restoration and stabilization projects. The Presnail (2013) stream restoration prioritization worksheet developed in conjunction with research in Elm Creek was used for this purpose

To gain landowner and LGU feedback a workshop was held in 2012 in Fairmont, MN. The purpose was to obtain input on landowner issues with implementing different riparian practices for sediment reduction in agricultural watersheds.

In 2014 six workshops were conducted across southern and western Minnesota to inform local landowners, local and state government agency staff and consultants about the tools and their application. The workshops were coordinated by the University of Minnesota-Extension along with CINRAM (Center for Integrated Natural Resources and Agricultural Management).

RESULTS

1. Natural background rates of channel erosion

The lateral stream migration rates measured using the Ellefson GIS tool are shown in Table 4.

Table 4. Lateral stream migration annual average rates for river reaches at our study sites over the time period 1991-2010 in feet/year*

Erosion rate descriptor	Percentile of erosion rate	Erosion rate in feet/year from aerial photos	Notes on site-specific information
Elm Creek			
very low	20%	0.33	Elm Creek is in the Des Moines Lobe glacial till plain, with moderately cohesive soils.
low	40%	0.41	
moderate	60%	0.49	
high	80%	0.57	
very high	90%	0.70	
extreme	100%	1.21	
Buffalo River			

very low	20%	0.45	The Buffalo River is in the Lake Agassiz plain (Red River basin) and has cohesive soils in the lower river with coarser loams in the middle to upper reaches
low	40%	0.51	
moderate	60%	0.61	
high	80%	0.69	
very high	90%	0.76	
extreme	100%	1.26	
Whitewater river			
very low	20%	1.08	The Whitewater River is in the Driftless area and has loamy somewhat cohesive soils in the upper watershed and non-cohesive alluvial soils in the lower river.
low	40%	1.40	
moderate	60%	1.83	
high	80%	2.15	
very high	90%	2.22	
extreme	100%	2.90	
Lateral migration rates from Rosgen et al. 2006 using Moderate NBS and variable BEHI scores from BANCS graphs for comparison			
Yellowstone			
BEHI score		Erosion rate ft/year	
very low		0.01	Data from the Yellowstone National Park region of Wyoming/Idaho/Montana; the area was influenced by alpine glaciation and/or volcanism
low		0.10	
moderate		0.28	
high – very high		0.76	
extreme		1.49	
Colorado			
very low		Not observed in data	Using Colorado USDA Forest Service data for streams found in sedimentary and/or metamorphic geology
low		0.07	
moderate		0.25	
high – very high		0.38	
extreme		1.07	

The data from Table 4 shows that all three study sites had higher rates of lateral migration than predicted by the commonly used Yellowstone BANCS graph in the very low to moderate BEHI score ranges (see Appendix 1). At higher BEHI scores the three sites were more similar to the Yellowstone graph values shown in Appendix 1.

Overall erosion rates were highest on the Whitewater River of the three study areas (Figure 6). It had 3 times the average Buffalo River lateral erosion rate and 3.2 times the average lateral erosion rate on Elm Creek with the 40-60th percentiles at 1.40 to 1.83 ft/year. Within the Whitewater rates were greatest on the lower Whitewater River with the extreme rate at 2.9 ft/

year and exceeding 10 fet per year on individual banks.   The lower Whitewater also had the highest bank heights meaning that sediment loading was greatest in those reaches.

Elm Creek did not demonstrate clear patterns in lateral erosion rates moving from the headwaters to the outlet of the watershed (Figures 7 -8). The mid erosion rates ranged from 0.41 to 0.49 ft/year (the 40th – 60th percentiles).

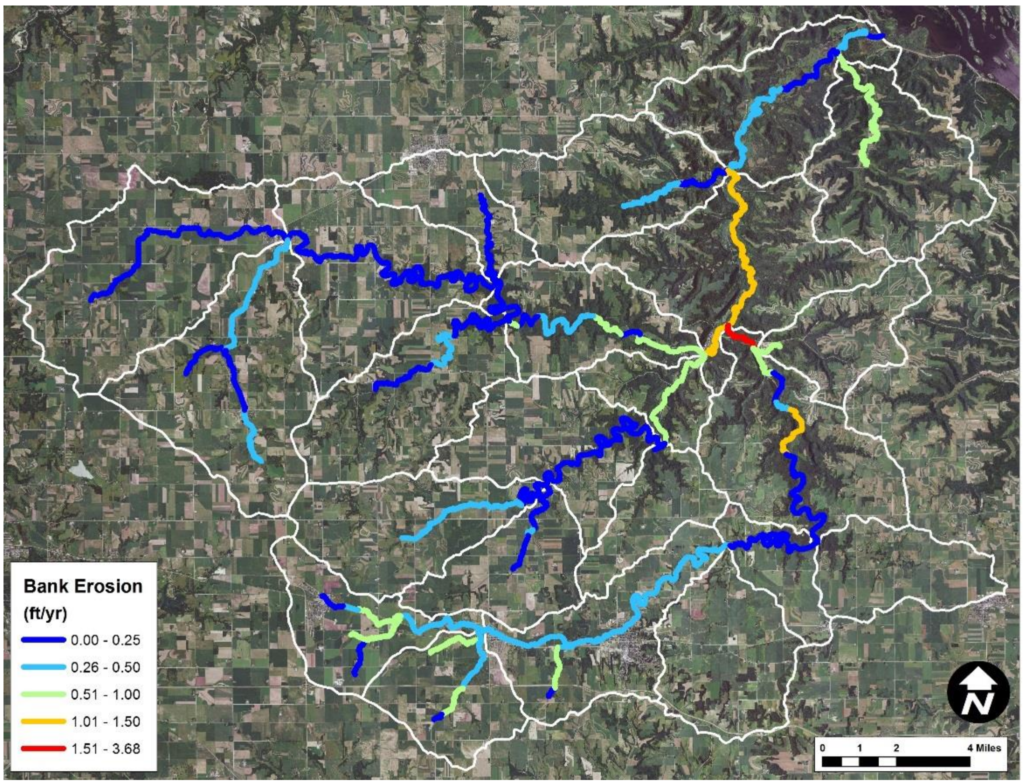


Figure 6. Lateral migration on the Whitewater River using the Ellefson GIS tool. Migration rates are shown in average feet year between 2003- 2011 with red and orange colors representing the highest erosion rates and blue the lowest.

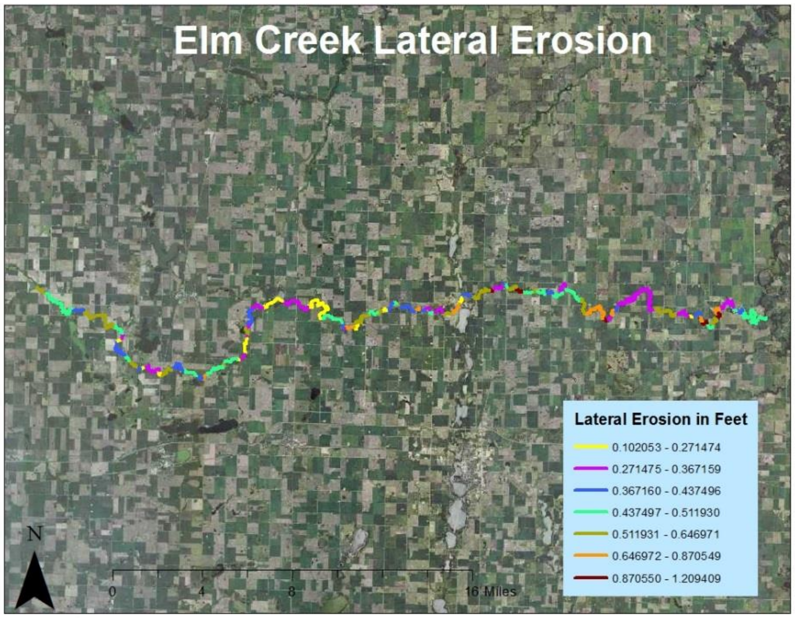


Figure 7. Annual average lateral erosion rate on Elm Creek using the Ellefson GIS tool. The starting point is near the headwaters in Jackson County to the west and ends at the river mouth near Winnebago, MN at the eastern end of the aerial photo.

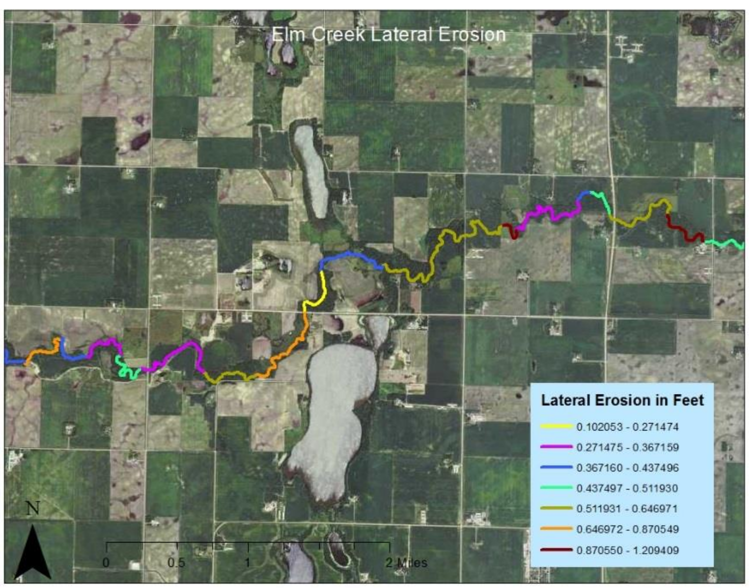


Figure 8. Close up section of Elm Creek average annual lateral migration from 1991-2011 using the Ellefson GIS tool. This section, located near the outlet of Martin Lake in the lower section of the river shows lateral migration rates ranging from 0.10 to 1.2 ft/year over the time period.

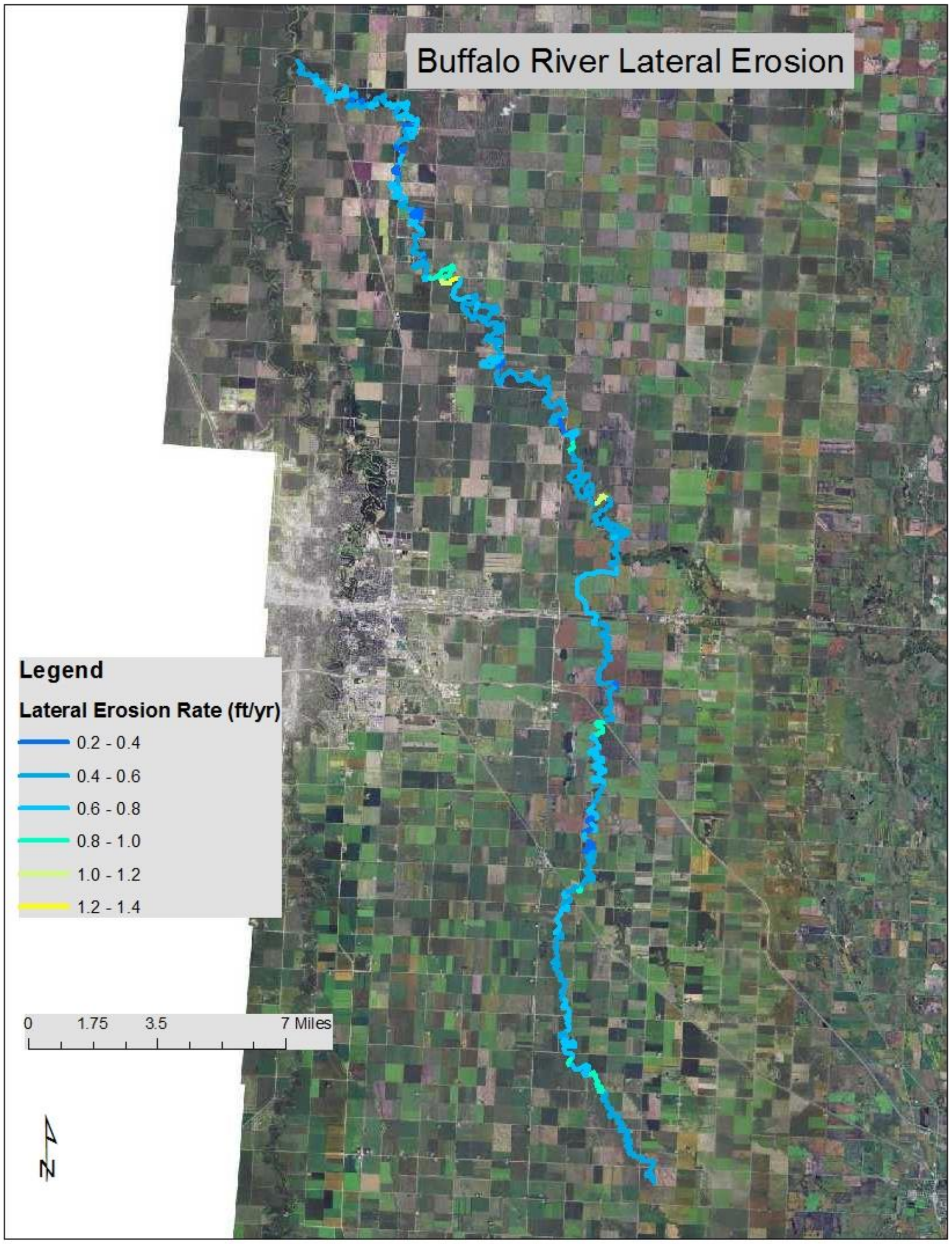


Figure 9. Buffalo river lateral migration rates in average ft/yr from 1991-2010 using the Ellefson GIS tool.

Lateral erosion rates on the Buffalo River were similar to Elm Creek in that the mid- lateral erosion rates were 0.51 – 0.61 feet year (the 40^{th} – 60^{th} percentiles (Table 4)). There were no distinct longitudinal trends in lateral erosion rate with reaches averaging between 0.2 ft/yr to 1.4 ft/yr (Figure 9).

The lateral erosion rate did not show distinct longitudinal trends along Elm Creek (Figure 10a). and displayed great natural variability up and down the river. The maximum erosion rates within each reach along the Buffalo averaged about 0.4 m/year (1.3 ft/yr) and did not display any obvious longitudinal trends (Figure 10b).

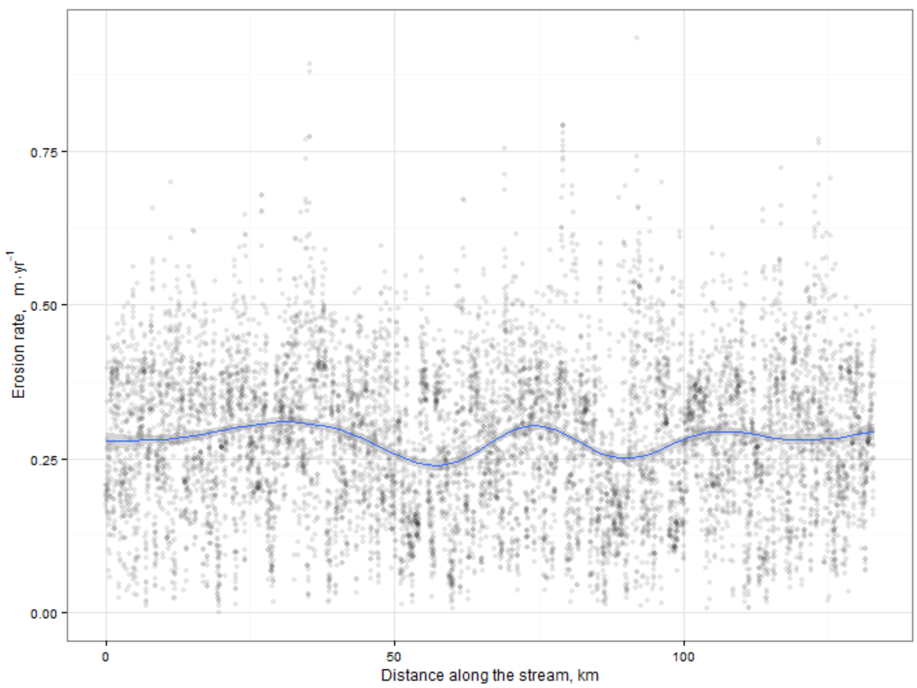


Figure 10a. Lateral erosion rates (m/yr) along Elm creek over the whole river length showing average bank erosion rates by river reach derived from the Ellefson GIS tool. The plot illustrates the high variability of erosion rates and the lack of apparent trend in the upstream to downstream direction.

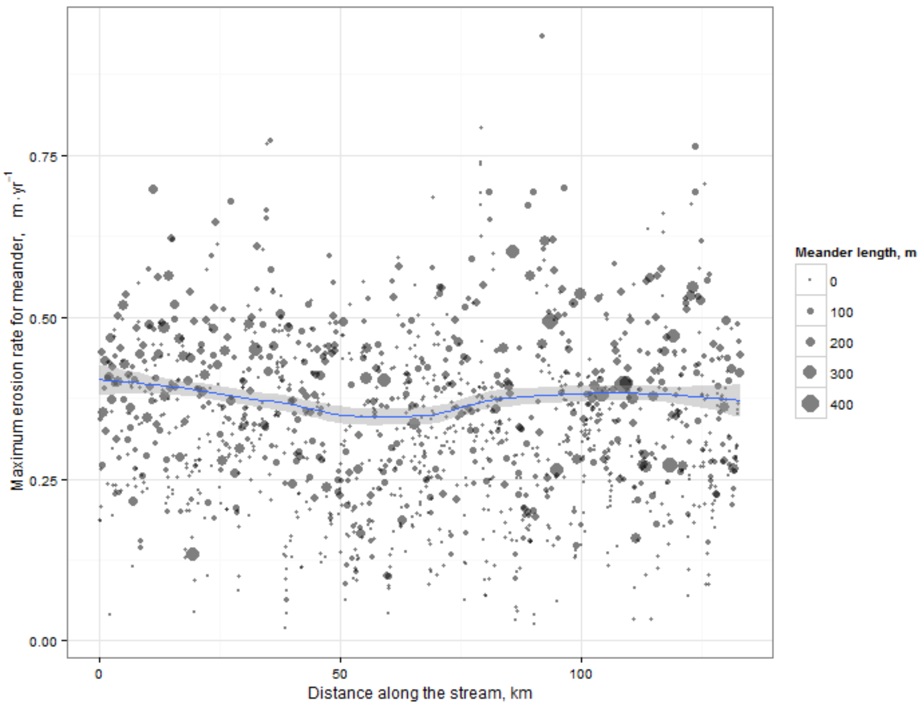


Figure 10b. Lateral erosion rates (m/year) along the Buffalo River by river length showing maximum erosion rate at outer bends within each river reach.

2. Prioritization tools and supporting data collection

<u>Data collection and component factors in support of the development of region-specific stream bank erosion prediction graphs.</u>

Field data collection of soil, geomorphology and vegetation parameters provided data on the factors influencing bank erosion rates and processes in the three study watersheds. BEHI scores were typically moderate (score 20-29) to high (score 30-39) at all three watersheds (Table 5 and Figure 11). 67% of the research sites (20 of 30) had very low to moderate near bank stress (NBS) values. Using the BEHI and NBS scores from the Yellowstone BANCS graphs in Appendix 1 yielded lateral erosion predictions of 0.04 to 1.32 ft/year for the study watersheds (Table 5). This was comparable to the rates of lateral migration observed in aerial photo analyses of the three rivers listed in Table 4 and shown in Figures 6-9.

Table 5. Research sites and data for BEHI data collection assessment of vegetation factors								
Site	River section	BEHI Rating	NBS Rating	Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Rate (tons/yr)*	Tons/year/linear ft
BU1	Upper	High	Very Low	0.17	300	7	347	0.06
BU2	Upper	High	Low	0.38	300	2.5	285	0.05
BU3	Upper	High	Moderate	0.38	300	4.5	512	0.08
BU4	Upper	Low	Low	0.05	300	5	77	0.01
BU5	Middle	High	Moderate	0.31	300	5	462	0.07
BU7	Middle	Moderate	High	0.33	300	4	392	0.06
BU8	Middle	High	High	0.58	300	6	1036	0.17
BU9	Lower	Moderate	High	0.42	300	6	757	0.12
BU10	Lower	High	Very Low	0.17	300	8	397	0.06
BU11	Lower	Very High	Very Low	0.17	300	10	496	0.08
EC1	Upper	Moderate	High	0.70	300	3.5	732	0.12
EC2	Middle	Low	Low	0.04	300	3	32	0.01
EC3	Upper	High	Low	0.25	300	3	225	0.04
EC4	Upper	Low	Very Low	0.03	300	8	59	0.01
EC5A	Middle	Moderate	Very Low	0.12	300	3	107	0.02
EC6	Lower	High	High	0.58	300	6	1036	0.17
EC7	Middle	Moderate	Low	0.15	300	7.5	344	0.06
EC8	Middle	Extreme	Low	0.42	300	9	1134	0.18
EC9	Lower	Very High	Very Low	0.17	300	7	347	0.06
EC10	Middle	High	Extreme	1.32	300	8.5	3371	0.54
WW1	Lower	Moderate	Very High	0.70	300	12	2509	0.40
WW2	Middle	Low	Very Low	0.02	300	8.5	44	0.01
WW3	Upper	Moderate	Very Low	0.12	300	5	178	0.03
WW4	Middle	Moderate	Very Low	0.12	300	8.5	303	0.05
WW5	Upper	High	Low	0.25	300	8	601	0.10
WW6	Middle	High	Very Low	0.25	300	7	526	0.08
WW7	Lower	Moderate	High	0.25	300	2.5	190	0.03
WW8	Upper	High	Moderate	0.38	300	11.5	1310	0.21
WW9	Lower	High	Extreme	0.87	300	15.5	4055	0.65
WW10	Upper	High	Extreme	0.87	300	5	1308	0.21
BU=Buffalo River, EC= Elm Creek, WW= Whitewater River **See Underhill (2013)(Appendix 3) for more detailed description of methods and analysis of results**								

The BEHI data did not show a significant trend in lateral erosion rate by river position longitudinally. Analysis of certain component BEHI factors indicated that bank height was one of the strongest predictors of bank erosion rate (Underhill 2013). NBS scores were low to very low in 53% of stream reaches, moderate in 10%, high to very high in 27% of reaches and extreme in 10% of reaches.

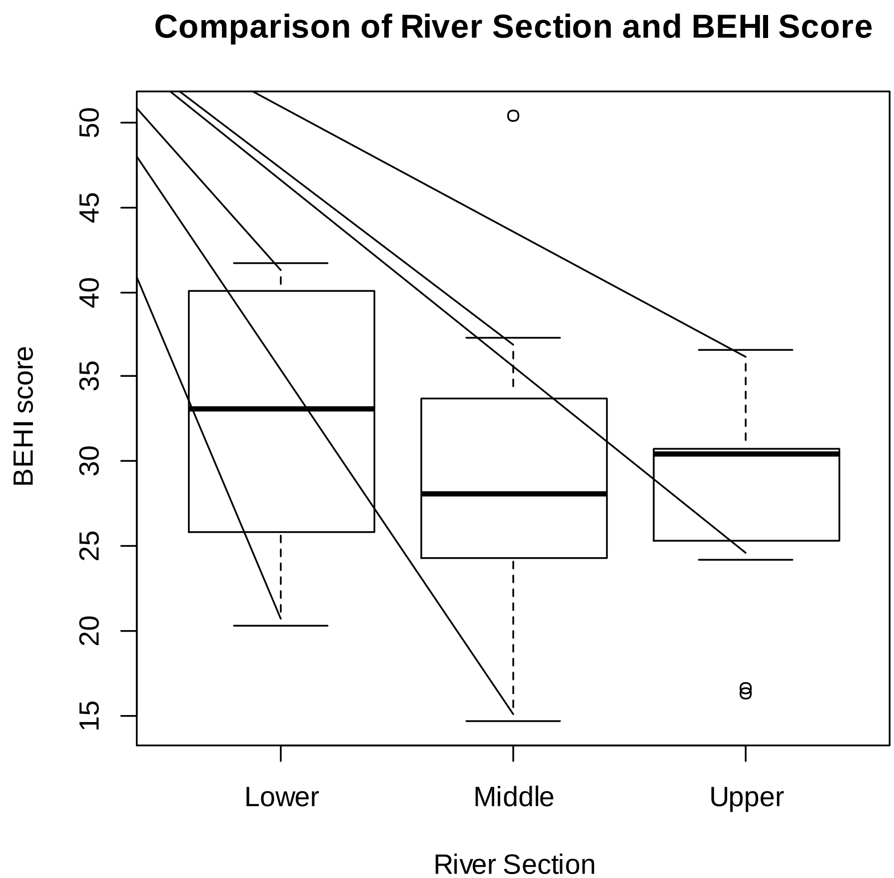


Figure 11. BEHI scores by longitudinal position at all 30 sites in the three study watersheds. There was no significant difference in BEHI scores by longitudinal river position when grouped as lower, middle and upper river sections. The box plots show the mean score as the bold line with error bars representing two standard deviations from the mean.

Although there were not large differences in lateral migration rate moving downstream in the Elm and Buffalo Rivers, bank height is known to increase in the downstream direction as demonstrated in regional curves developed for the southern Minnesota region that relate bank height to watershed area (Magner and Brooks), (Lenhart 2008). Increasing bank height often contributes to greater sediment loading rates from some lower river reaches. For example, Figure 12 shows increased sediment loading from the lower Whitewater River, where banks were frequently 10-15 feet high.

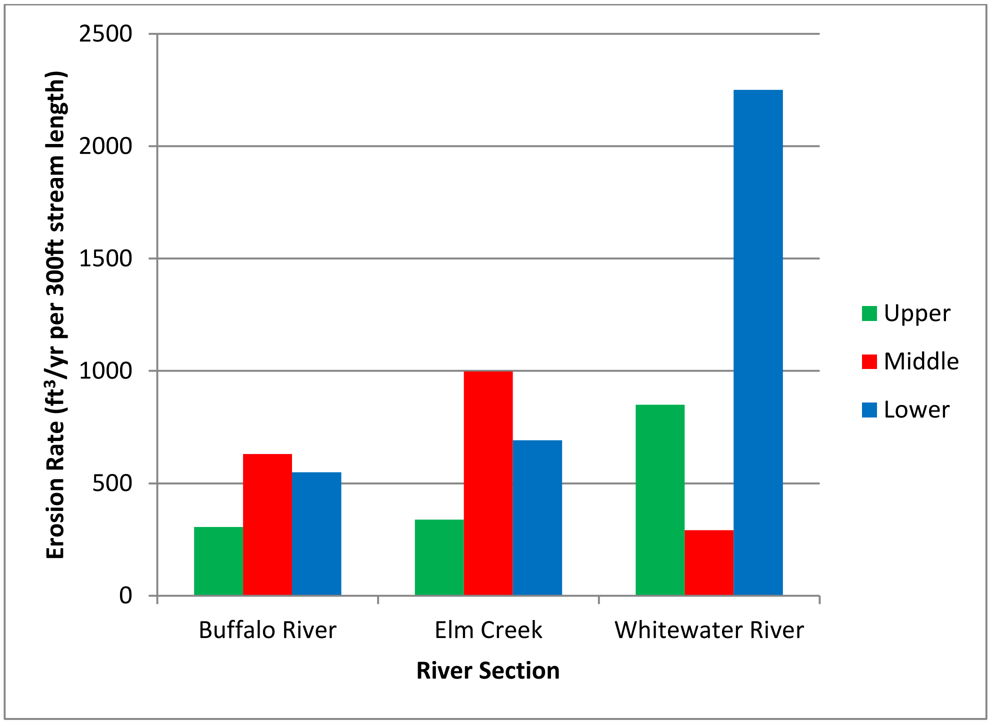


Figure 12 Erosion rates per 300 foot stream reach predicted by the BANCS graphs for the upper, middle and lower reaches of the three study sites (Underhill 2013)

<u>Role of vegetation in bank erosion rates and BEHI values</u>

Overall most of the study sites were dominated by herbaceous plant communities (Table 6 and Figure 13) with increasing forest cover found in the lower reaches.

Species composition data showed that the invasive reed canary grass (*Phalaris arundinacea)* was most abundant having the greatest coverage on 63% of the 30 sites. A scattering of other species were found with sedges (*Carex sp*.), goldenrod (*Solidago sp*.), violets (*Viola sp*.) and Virginia creeper (*Parthenocissus sp*.). The most abundant shrubs were sandbar willow (*Salix interior*), red-osier dogwood (*Cornus stolonifera*), honeysuckle (*Lonicera sp*.) and raspberry species (*Rubus sp*.).

Table 6. Plant community composition data for 30 stream bank sties in the Buffalo, Elm Creek and Whitewater watersheds*

Site	Dominant Vegetation Type	Dominant Herbaceous plant	Dominant Shrub species	Dominant Tree species	Tree Density (Trees/Acre)	Woody Plant Density (Equivalent Trees/Acres)
BU1	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	-	0	0
BU2	herbaceous	Reed Canary Grass (*P. arundinacea)*	Red-Osier Dogwood (*Cornus sericea)*	-	0	363
BU3	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	-	0	0
BU4	herbaceous	Reed Canary Grass (*P. arundinacea)*	Sandbar Willow (*Salix Interior)*	Boxelder (*Acer negundo)*	102	218
BU5	herbaceous	Reed Canary Grass (*P. arundinacea)*	Gooseberry (*Ribes spp.)*	Boxelder (*Acer negundo)*	29	174
BU7	Shrub	Reed Canary Grass (*P. arundinacea)*	Red-Osier Dogwood (*Cornus sericea)*	American Elm (Ulmus americana)	160	4011
BU8	Shrub	Reed Canary Grass (*P. arundinacea)*	Sandbar Willow (*Salix Interior)*	-	0	3052
BU9	Forest	Sedge (*Carex spp.)*	-	Green Ash (*Fraxinus pennsylvanica)*	567	567
BU10	Shrub	Reed Canary Grass (*P. arundinacea))*	Nannyberry (*Viburnum lentago)*	Basswood (*Tillia americana)*	392	945
BU11	Forest	Virginia Creeper (*Parthenocissus quinquefolia)*	Chokecherry (*Prunus virginiana)*	Boxelder (*Acer negundo)*	741	843
EC1	herbaceous	Tall Coneflower (*Rudbeckia Laciniata)*	Unknown Species	Silver Maple (*Acer saccharinum)*	102	116
EC2	Shrub	Reed Canary Grass (*P. arundinacea)*	Red-Osier Dogwood	Nannyberry (*Viburnum lentago)*	15	741

			(*Cornus sericea)*			
EC3	Forest	Reed Canary Grass (*P. arundinacea)*	Chokecherry (*Prunus virginiana)*	Boxelder (*Acer negundo)*	3765	3837
EC4	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	-	0	0
EC5	herbaceous	Reed Canary Grass (*P. arundinacea)*	White Mulberry (*Morus alba)*	-	43	43
EC6	Forest	Reed Canary Grass (*P. arundinacea)*	Sandbar Willow (*Salix Interior)*	Black Willow (*Salix nigra)*	538	872
EC7	Shrub	Black Raspberry (Rubus occidentalis)	Red-Osier Dogwood (*Cornus sericea)*	Boxelder (*Acer negundo)*	377	581
EC8	herbaceous	Cultivated Crop (Hay)	-	-	0	0
EC9	herbaceous	Reed Canary Grass (*P. arundinacea)*	Nannyberry (*Viburnum lentago)*	Boxelder (*Acer negundo)*	87	305
EC10	herbaceous	Horsetail (*Equisetum arvense)*	-	-	0	0
WW1	Forest	Reed Canary Grass (*Phalaris arundinacea)*	Honeysuckle (*Diervilla spp.)*	Boxelder (*Acer negundo)*	538	1061
WW2	herbaceous	Goldenrod (*Solidago spp.)*	-	Black Walnut (*Juglans nigra)*	73	73
WW3	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	Black Walnut (*Juglans nigra)*	15	15
WW4	Shrub	Violet (*Viola spp.)*	Honeysuckle (*Diervilla spp.)*	Basswood (*Tillia americana)*	363	654
WW5	Shrub	Reed Canary Grass (*P. arundinacea)*	Nannyberry (*Viburnum lentago)*	-	0	1380
WW6	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	Boxelder (*Acer negundo)*	15	15
WW7	Shrub	Reed Canary Grass (*P. arundinacea)*	Common Elderberry (*Sambucus canadensis)*	American Elm (*Ulmus americana)*	407	785

WW8	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	Boxelder (*Acer negundo)*	87	87
WW9	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	Boxelder (*Acer negundo)*	160	160
WW10	herbaceous	Reed Canary Grass (*P. arundinacea)*	-	-	0	0

BU=Buffalo River, EC= Elm Creek, WW= Whitewater River
Note-site BU 6 was eliminated from sampling list, so the BU site list goes to 11.
See Underhill (2013)(Appendix 3) for more detailed description of methods and analysis of results

Fifty-seven percent of the study sites (17/30) supported meadow type plant communities with little tree coverage. 43% were classified as woody-dominated with 8 shrub and 5 tree-dominated sites (Figure 13). Forested sites were more common in the lower river sections. Of the five sites classified as forest (defined as >435 trees/acre) boxelder (*Acer negundo*), black willow (*Salix nigra*) and green ash (*Fraxinus pennsylvanica*) were the most abundant tree species.

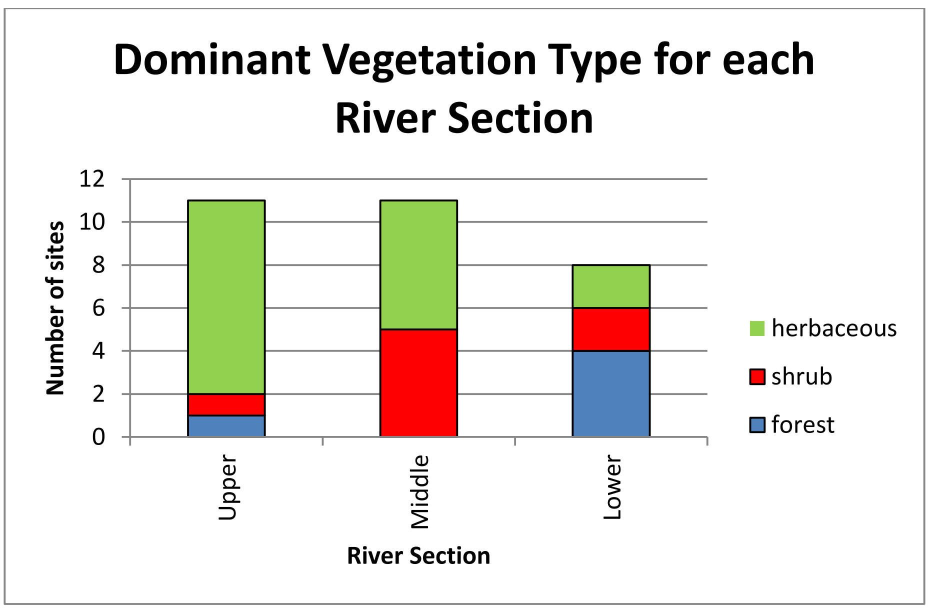


Figure 13 Vegetation type summarized for all thirty sample sites by river section (Underhill, 2013). Each river reach sampled was classified by the dominant life form type by coverage.

Overall root length densities ranged from 0.5 to 4.5 cm/cm^3. Data on root depth characteristics showed that approximately 80-90% of the plant root density (cm/cm^3) at the thirty study sites occurred in the top 30 cm (1 foot) of soil (Figure 14). There was very little herbaceous root density below 90 cm depth in the riparian areas sampled.

The observed root depth vs. bank height ratios when converted to BEHI sub-component scores would be mostly in the moderate to extreme categories where root depth extends less than 50% of the bank height (see root depth vs. study bank height in Appendix 1). Root density values measured via the plant root scanner would have ranged from low to extreme using BEHI metrics, but mostly in the moderate to very high bank erosion categories.

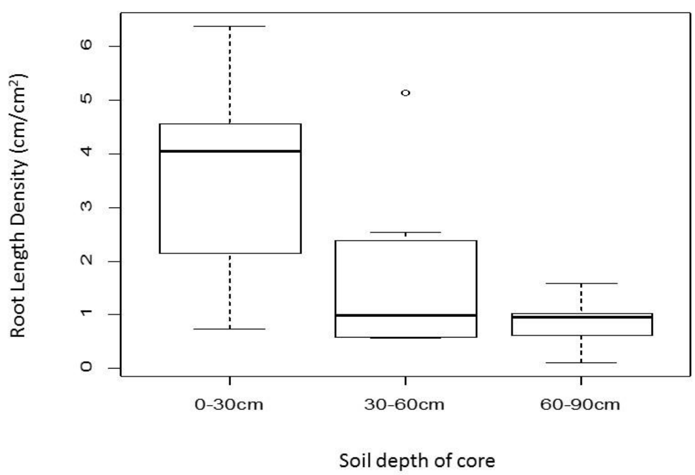


Figure 14. Root length density box plots for riparian areas in the 3 study watersheds. On the x-axis plant root density is shown as the length of roots (cm) per volume of soil (cm^3). The y-axis represents root density. The line in the middle of the box represents the mean value with error bars shown +/- 2 standard deviations.

Simulation of root effects on bank stability and potential for sediment load reduction

Figure 15 shows a simulation of the effect of root depth on bank erosion hazard and how it varies with bank height. Fig. 15 demonstrates that for typical root depths (< 2 feet) plant roots have very little impact on stream bank stability when bank heights exceed 14-15 feet. At that height the bank erosion hazard is high to extreme regardless of vegetation effects. Plant root depth can greatly decrease predicted bank erosion rates reducing banks to moderate or low bank erosion risk by adding as little as 0.5 feet of root depth. The reduction in bank erosion hazard is potentially important for stream banks with heights between three to ten feet.

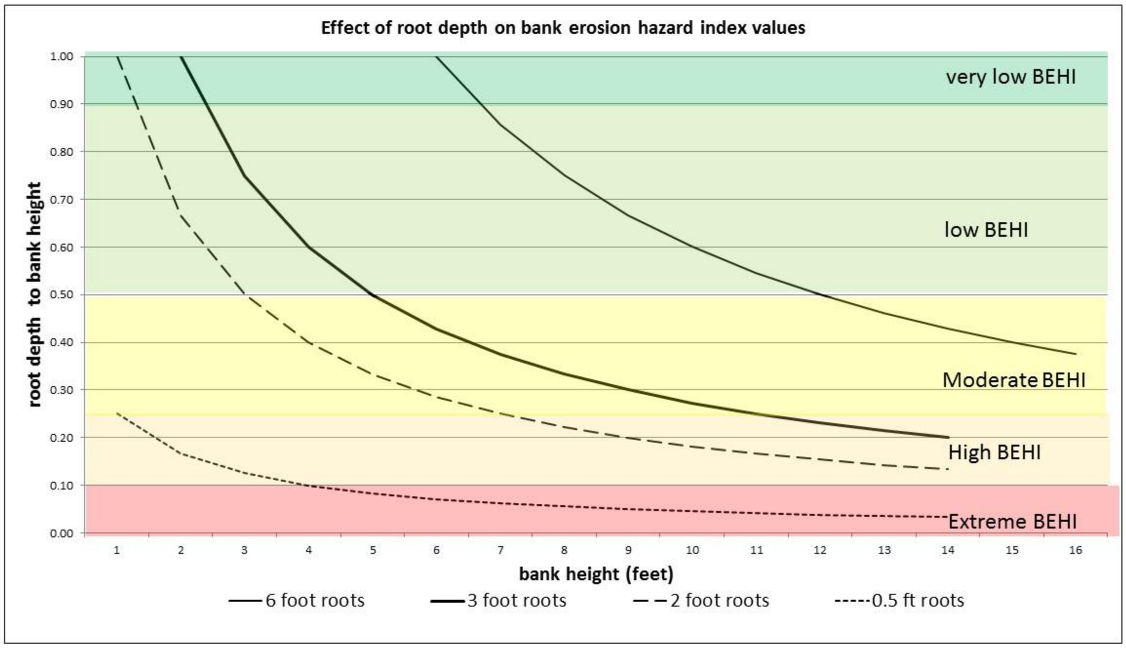


Figure 15. The role of root depth in stream bank stability. The ratio of root depth to bank height is shown on the y-axis with the bank height on the x-axis. The corresponding bank erosion hazard index (BEHI) score is grouped by color: red is extreme BEHI, orange is high, yellow is moderate, light green is low, and green is very low. This shows that as root depth increases bank erosion potential decreases. At stream bank increases vegetation has a decreasing ability to control bank erosion.

Regional annual stream bank erosion prediction graphs are presented in Figures 16, 17 and 18. Figure 16 shows the preliminary BANCS graph developed by the MN DNR for the Whitewater River based on field-collected data. Figures 17-18 show regional bank erosion prediction graphs developed for the Elm Creek and Buffalo Rivers representing typical streams in the south central Des Moines Lobe till plain and the Lake Agassiz plain / Red River basin. The latter two graphs were developed from lateral migration data obtained from aerial photos over a 20-year period, so they represent long-term average bank erosion rates.

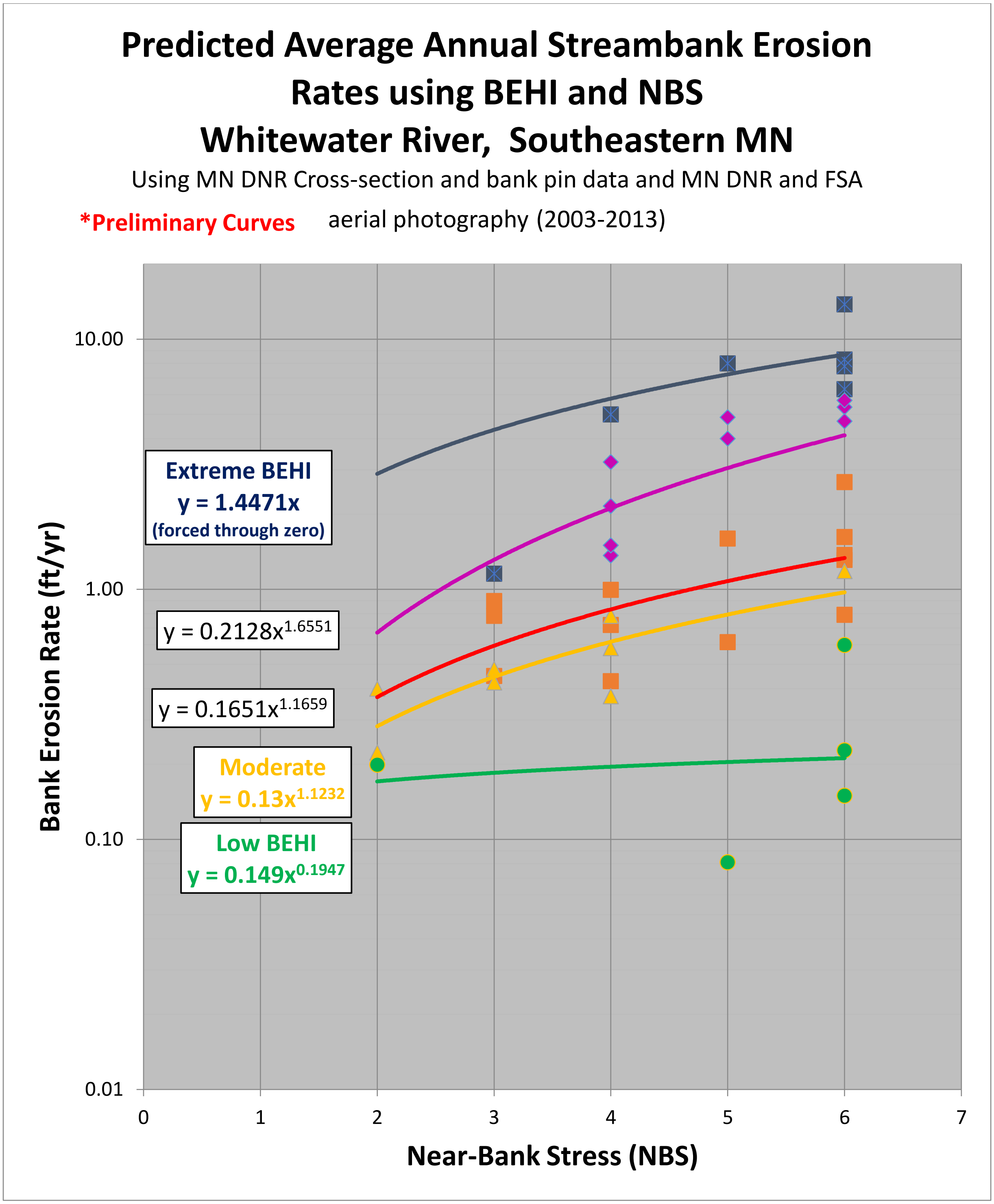
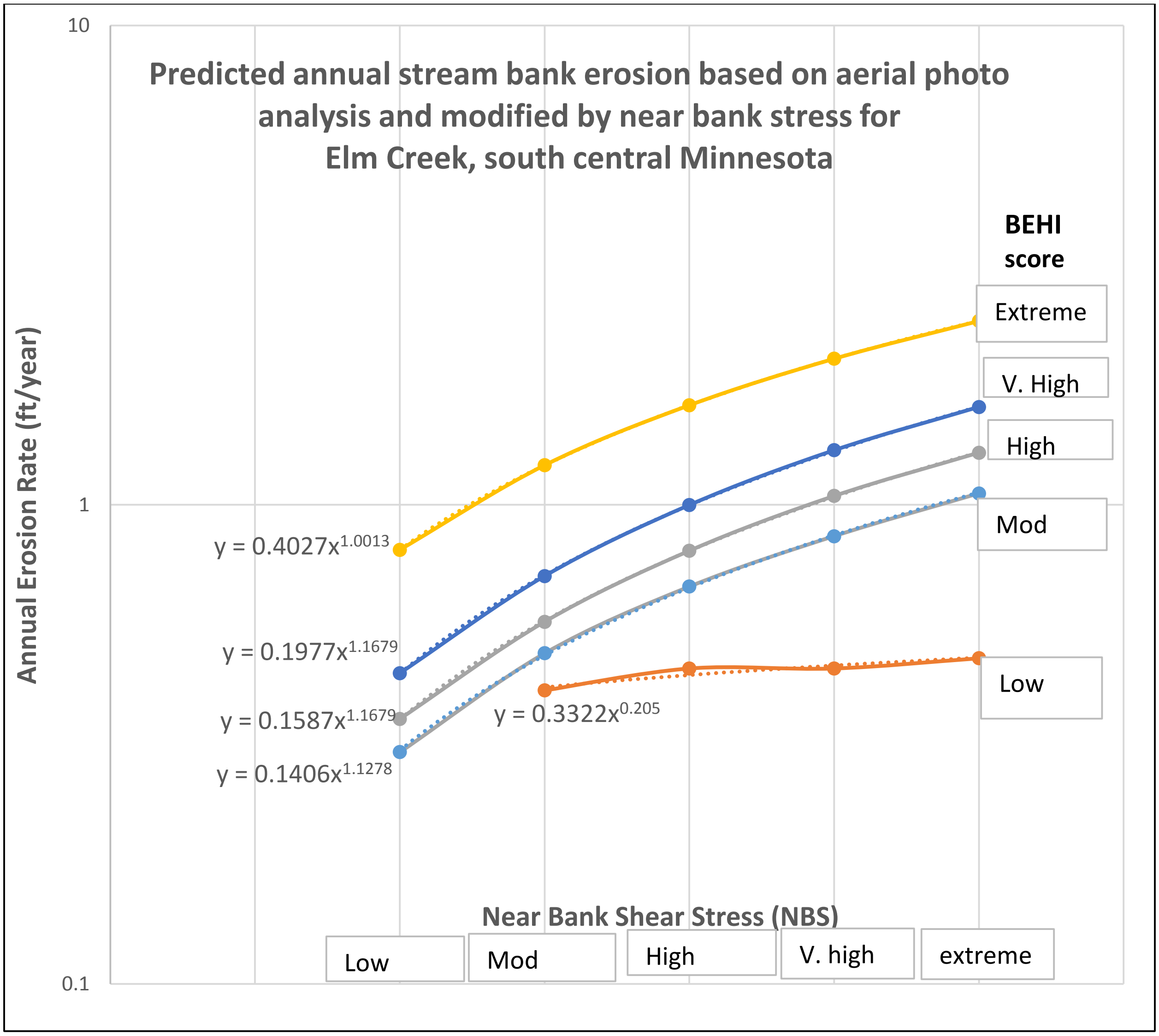
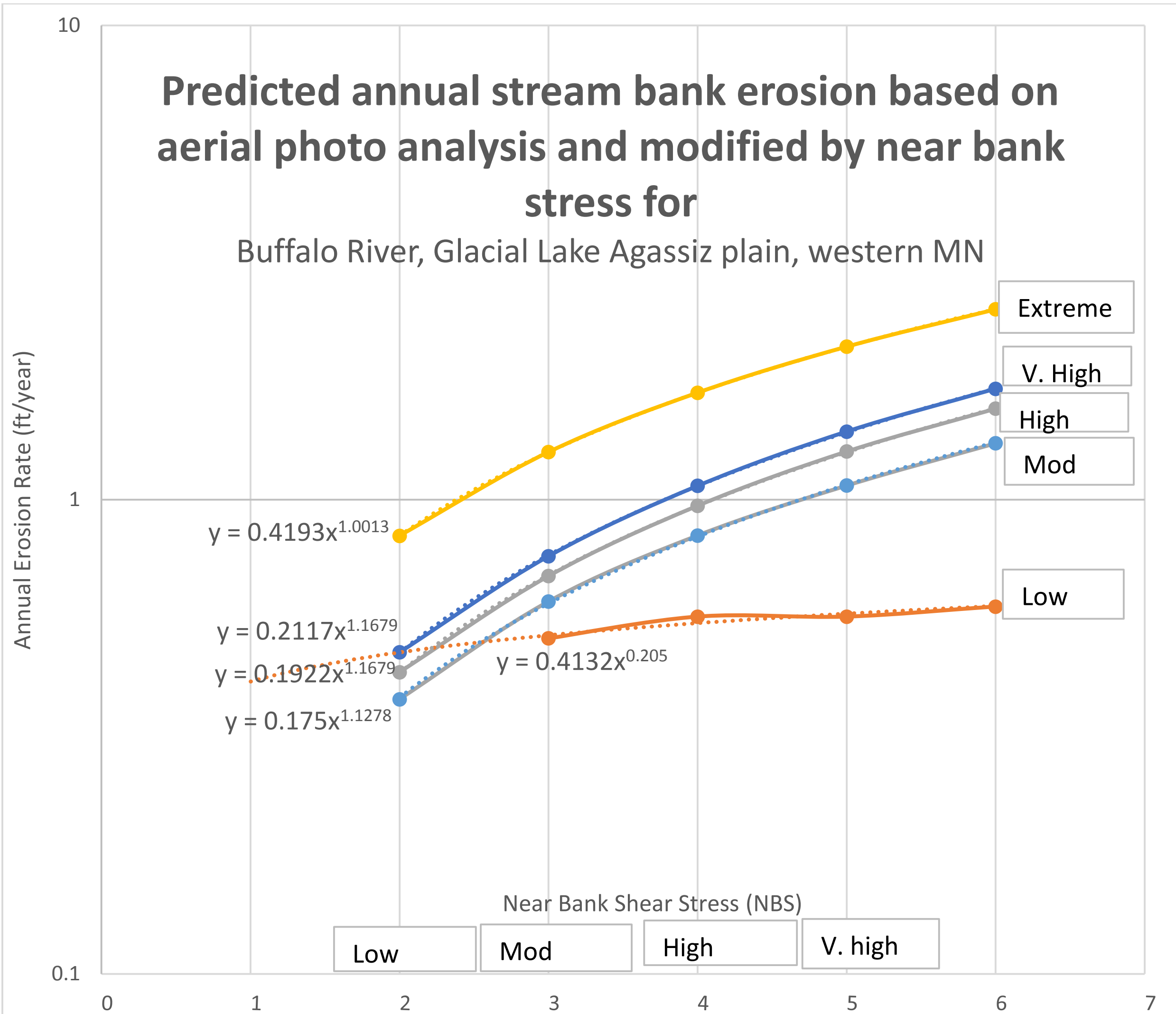


Figure 16. BANCS relationships for the Whitewater River, developed by the Minnesota DNR based on field monitoring of bank erosion rates for stream banks with different combinations of NBS and BEHI as shown by the points on the graph above.



Figures 17. Predicted annual average lateral erosion for Elm Creek. This graph was developed using lateral migration data from aerial photos (Table 4) and then adjusted for NBS using the slope of the lines from the Whitewater River graph shown above. Elm Creek is representative of streams in the Des Moines Lobe glacial till plain of southern Minnesota and northern Iowa. Stream bank soils are typically heavy silt or clay loams with some sandier loams in the lower parts of larger rivers.



Figures 18. Predicted annual average lateral erosion for the Buffalo River. This graph was developed using lateral migration data from aerial photos (Table 4) and then adjusted for NBS using the slope of the NBS lines obtained from the Whitewater River. The Buffalo River is representative of streams in the Lake Agassiz Lake plain located in western Minnesota with the Red River basin.

BSTEM stream bank erosion modeling results

Simulation of stream bank erosion was done using BSTEM for a 120m (394 ft) length of Elm Creek using data from a 2008 stream flow event. The predicted rate of erosion was 2.46 feet for a bankfull flow occurring in 2008 the entire length of the stream bank. Only fluvial erosion was predicted to have occurred via flowing water; no mass-wasting was predicted. The eroded volume totaled 256 m^3 (280 yd^3) approximately equal to a mass of 364 tons (with a density of 1.3 tons/cubic yard). The resulting bank profile was overhanging (>90 degree angle) and would've had a mass failure if additional flow days were simulated. Therefore the modeled numbers would have been even greater. In comparison the observed bank erosion rate in this reach averaged about 0.25 feet per year over the time period of 2007-2014; only 10% of the modeled rate.

Sediment deposition on sandbars

Sandbar deposition rates within the area of perennial woody plant establishment averaged 4.9 cm/ year with a range from 0.89 to 14.92 cm/year based on 17 samples measured on 8 points bars on Elm Creek (Figure 19 and Table 7). The willows ranged in age from two to five years so that the observed deposition rates represent the time period of 2008-2012. Total accumulated deposition (cm) during that time ranged from 3 – 60cm. There was little difference in rates within the sampling areas, as the $r^2 = 0.13$ for distance from the stream water line and sedimentation rate within the sandbar willow patches.

Data from the artificial turf sediment deposition pads is not presented here because most of the pads were either scoured away by flowing water on the un-vegetated portion of the sandbar and/or could not be relocated.

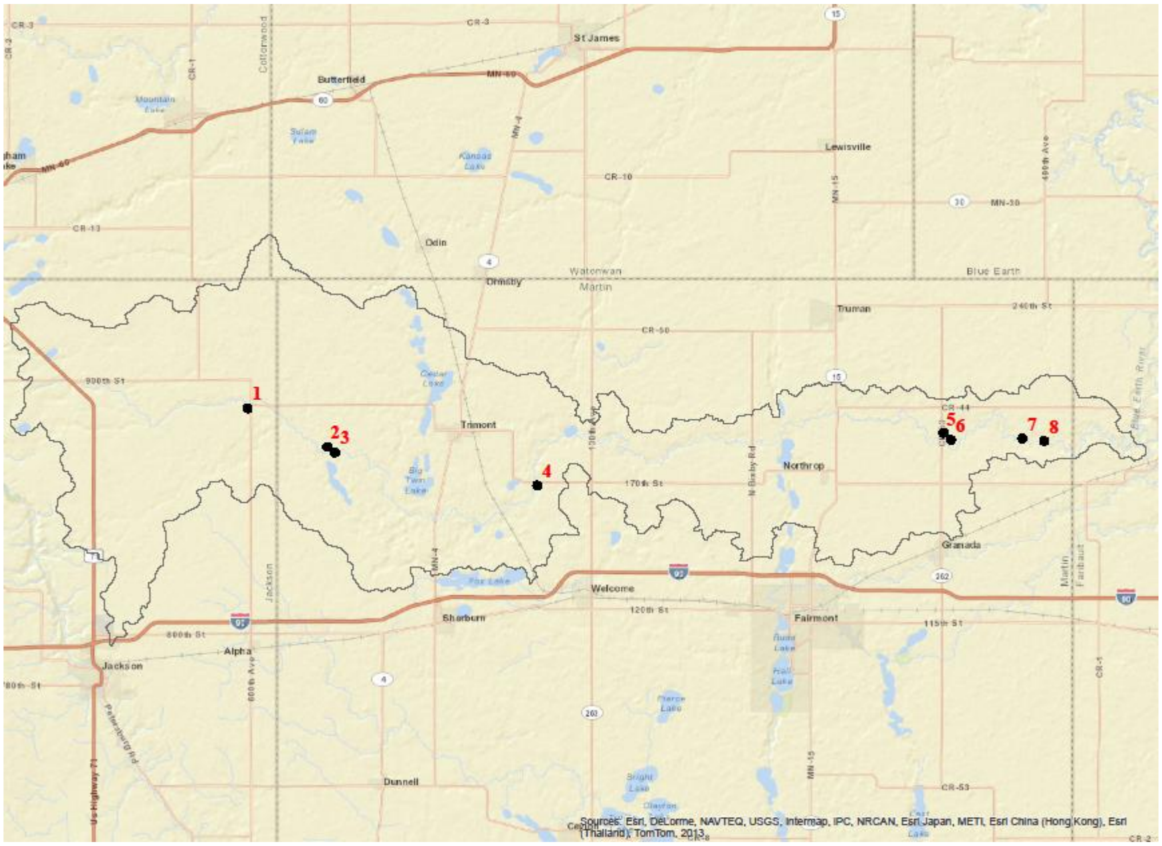


Figure 19. Sample site locations in the Elm Creek watershed for sandbar deposition (see Triplett 2014 for detailed methodology and results analysis). Deposition estimated were made using excavation down to the root collar of young sandbar willow shrubs (Table 7) and with sediment deposition pads.

Table 7: Deposition rates calculated on the vegetated portion of sandbars of Elm Creek Watershed. Rates were calculated by the depth of sediment accumulated along the stem of young (<20 years) willow shrubs. Sampling was conducted between August 2013 to September 2014 (Triplett 2014)(Appendix 5).				
Site	Willow Age (yr.)	Depth to Root Collar (cm)	Deposition Rate (cm/yr.)	Distance from Water Line (m)
1	4	9.53	2.38	2
	5	4.45	0.89	4
	5	9.53	1.91	8
2	No willows present	x	x	x
3	No willows present	x	x	x
4	4	9.53	2.38	5
	4	8.89	2.22	6
5	3	3.18	1.06	3
	2	6.99	3.49	3
6	3	24.13	8.04	5
	4	34.29	8.57	6
	3	3.81	1.27	8
7	3	3.18	1.06	1
	5	7.62	1.52	5
	4	59.69	14.92	5
	5	38.10	7.62	7
8	3	24.13	8.04	9
	3	41.28	13.76	10
	3	12.07	4.02	13

Composition and Frequency of woody plants

Seven woody plant species were found with three being the most frequent: sandbar willow, green ash and boxelder. Sandbar willow was by far the most frequently occurring woody plant in quadrat samples and had the greatest coverage, particularly in the sapling group which are young trees past the initial colonization stage and more likely permanent colonizers.

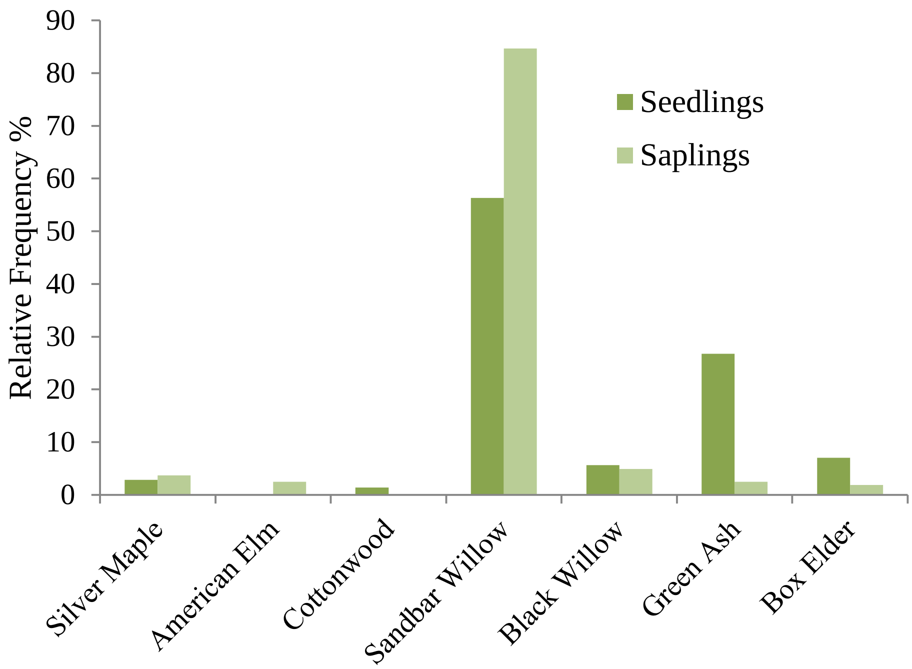


Figure 20. Woody plant species composition on sandbars of Elm Creek watershed. Seedlings are small newly established trees, less than 2 years old. Saplings are young trees that have survived several years and are much more likely to become mature, canopy trees in the floodplain forest after several decades.

Age of vegetation on sandbars in relation to channel evolution

Based on collected tree core data there were no trees greater than 30 years old found on the point bars (Triplett 2014). This indicates that the upper point bars succeed into floodplain forest during that time span at which point they are similar in elevation to the floodplain. At the increased elevation the point bars experience reduced flood frequency and deposition rates.

Effect of prolonged inundation on plant establishment and river width

Increased stream flow in rivers within the study area has decreased the timing and availability of sandbar areas for establishment of pioneer woody species on sandbars (Lenhart et al. 2013; Triplet 2014). The prolonged duration of stream flow submerging the sandbars was found to contribute to reduced tree establishment and increased growth of sandbar willow which has the advantage of spreading by clonal growth.

3. Hydrologic Drivers of Erosion Findings and Tool Development

Pathways and water sources of stream flow at study sites

Riparian well networks placed at the Buffalo River and Elm Creek sites provided data on the occurrence of groundwater near stream banks, its flow direction and how the gradient changes seasonally. The water levels and gradients in the wells indicated that groundwater entering the stream was not contributing substantially to bank erosion as it was occurring far down on the stream banks studied. Therefore detailed data analysis was not conducted since it appeared to be a lesser factor for stream bank erosion.

The well data combined with field observations showed that groundwater discharge to streams in the study areas was spatially discontinuous. At the Elm Creek site well A1 was dry except when surface water was flowing back into the bank. Well B1 received regular baseflow from groundwater. Based on this and other field observations it was determined that much of the area adjacent to the stream is not contributing to groundwater flow. Other findings included:

- Groundwater elevations fluctuate by as much as 1 – 2 meters in floodplains adjacent to Buffalo River and Elm Creek.
- Groundwater flow was well below the ground surface (1 – 3 m) at both sites and thus contributed to baseflow but did little to cause bank saturation and mass-wasting.
- At high flows in the spring and summer streamflow did reverse direction and infiltrate into the stream banks on several occasions. This would help to mitigate high flows or floods in some cases by providing temporary water storage.
- Further analysis would help fine-tune our understanding of groundwater dynamics in the riparian zone of these two streams.

The assessment of water sources in streamflow showed that geochemical methods can be used to clearly distinguish sources of water in the stream. Specific conductivity (SC) data in Figure 21 shows that large differences in SC values were found for groundwater, stream flow and rainwater. Groundwater flow, typically in the range of 1000 – 1400 µs/cm, is clearly distinguishable from surface flow in the Whitewater River (300-425 µs/cm) and rainfall on the lower right of the graph which averages 5-15 µs/cm.

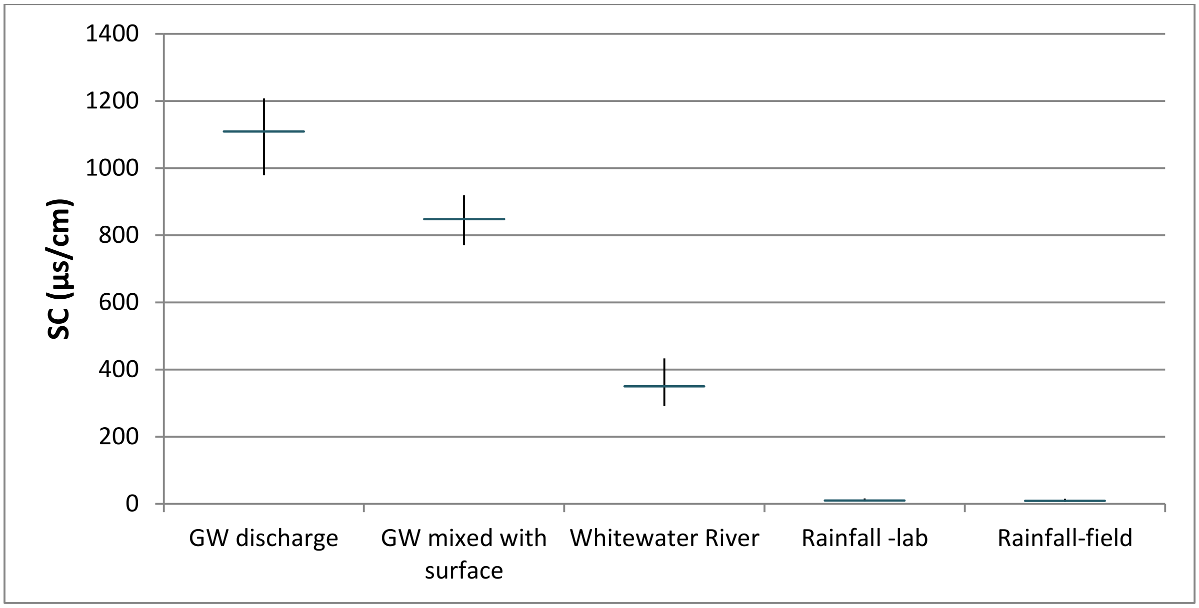


Figure 21. Specific Conductivity (SC) data for the Whitewater River watershed; data was collected from various sources including data loggers, USGS streamflow records and the National Atmospheric Deposition monitoring program. Plots show the mean as a horizontal line with error bars representing the 5^{th} and 95^{th} percentiles at the end points of the vertical lines (sample sizes ranged from 100s to 1000s of data points - see Table 3b).

Streamflow source separation using SC data in Elm Creek

SC data in Elm Creek displayed similar values for groundwater and rainfall as the Whitewater River. Conductivity data was used to separate subsurface tile flow from baseflow (groundwater feeding the stream) for a portion of 2014 in Elm Creek (Figure 22). The EMMA analysis showed that overall approximately 90% of the stream flow volume during this period originated from subsurface drainage flow. At low flow periods when storm events had not occurred for days or weeks the percentage of baseflow would rise to 35%

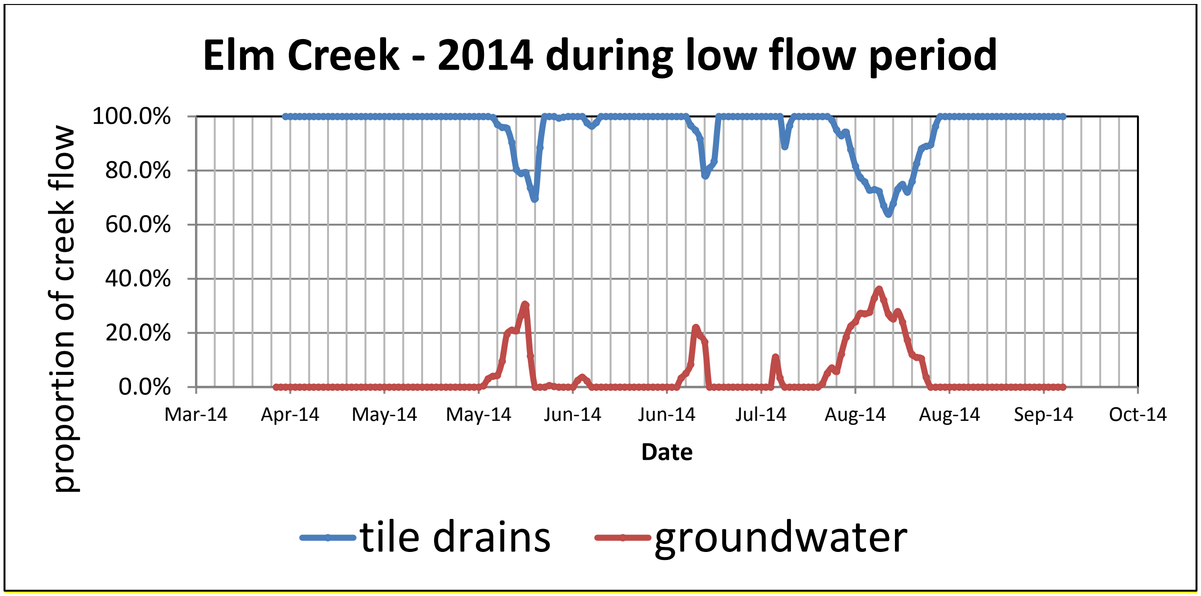


Figure 22. Stream flow separation using the EMMA approach described in Appendix 6. During low to average flows groundwater (baseflow) and tile drain flow comprise all of the stream flow in Elm Creek. This is the case for most of summer and fall - the unfrozen part of the year which is typically from March to December in southern Minnesota. Brief periods of surface runoff contribute during storm flow events most frequently from April to June. During the frozen period of winter there is usually almost zero stream flow.

The oxygen and hydrogen isotopes are good indicators of surface water evaporation as the heavier isotopes O^{18} and Deuterium (H^2) become concentrated in evaporated waters. In the case of Elm Creek it showed that much of the water in the creek was not from direct snowmelt runoff or groundwater recharge. Tile flow inputs dominated in the mid-flow ranges while in late summer as flow levels decline the water became more concentrated in O^{18} as the evaporation increased and flow from Martin Lake contributed more flow proportionally (Figure 23).

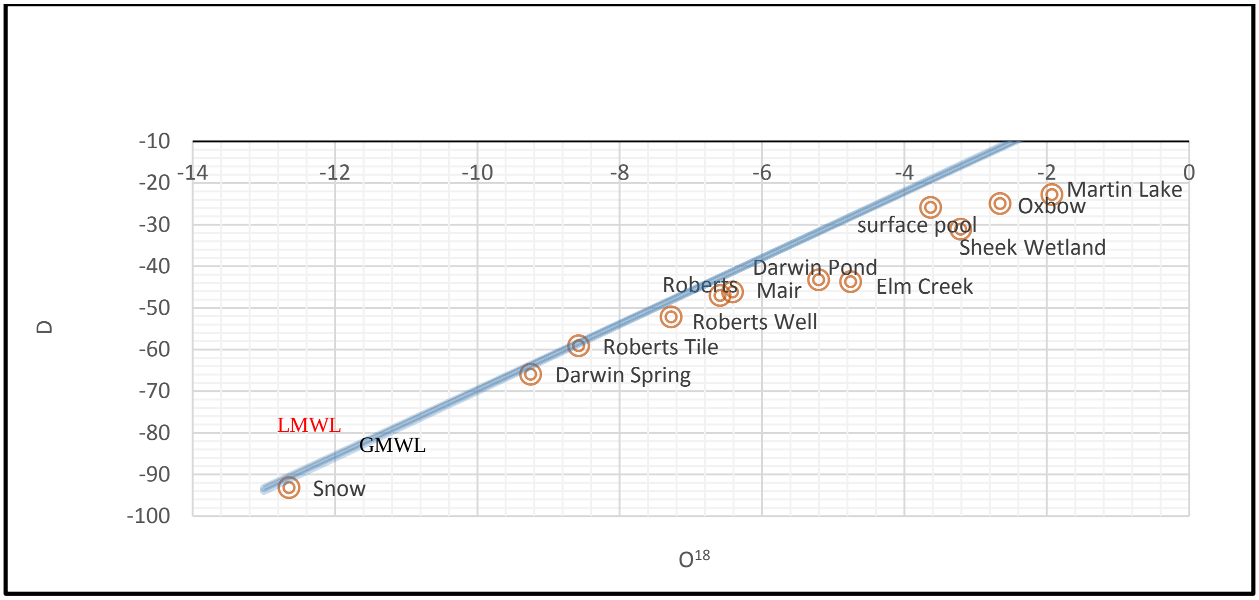


Figure 23. Oxygen-18 (O^{18}) and Deuterium (H^2) isotope data for Elm Creek showing the separation of water sources that contribute to stream flow. Water bodies exposed to evaporation tend to concentrate heavy isotopes such as O^{18}. Surface water bodies (Martin Lake, an oxbow, Sheek wetland and a surface pool) plot below and to the right of the local meteoric water line (LMWL) and the global meteoric water line (GMWL) while snow and deep groundwater plot toward the lower left of the graph along the line. The above values are averages from 2012-13 data for each site; therefore seasonal and spatial patterns are not represented in this plot.

The Soil and Water Assessment Tool (SWAT) was used to model flow sources in Elm Creek for comparison to the geochemical tools (mixing models) and hydrologic record. Based on flow data from 2008, SWAT estimated tile flow as 58% of the total annual streamflow volume, while baseflow was estimated at 20% and surface runoff 19% (Figure 24). Direct rainfall inputs and/or error accounted for the other 3%.

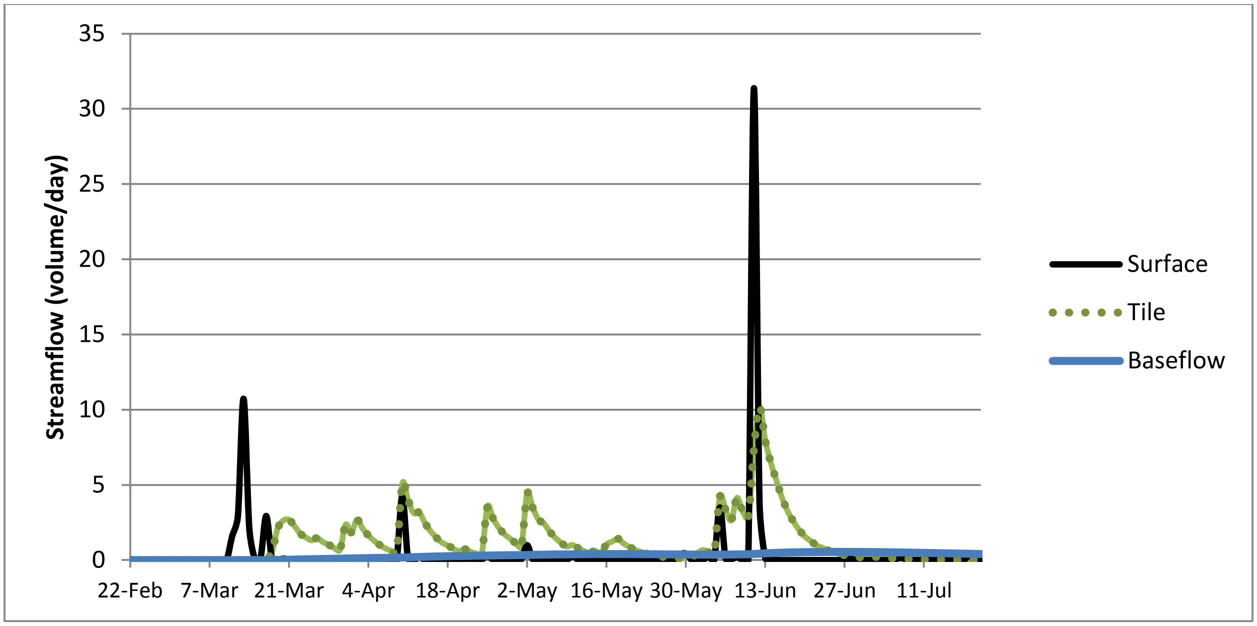


Figure 24. SWAT model of flow sources to Elm Creek showing relative contribution of tile flow, surface runoff and baseflow for the year 2008. Several surface water runoff events were predicted for March and June. Sub-surface flow was more evenly spread through the time period with smaller hydrograph peaks following storm events. Baseflow (groundwater) was predicted by SWAT to comprise 20% of annual flow.

4. Development of decision support tools

Public meetings summary

The 2012 Elm Creek meeting in Fairmont, Minnesota showed that rural landowners prefer riparian management practices over many upland management actions because they take less land out of production. Many other lessons were learned from this meeting about factors influencing landowner adoption of BMPs (Lenhart et al., in prep).

At the decision support tool workshops the three-tiered approach was presented (1.lateral migration tool to identify high sediment loading areas; 2. Field data collection and use of regional bank erosion prediction equations to validate predictions and increase understanding of bank erosion processes; and 3. Use of the Presnail stream restoration prioritization worksheet to identify potential restoration sites). The workshops were attended mostly by local government unit (LGU) staff and landowners in the summer of 2014. They provided valuable information on the needs of local government staff and practical issues with different decision tools. For example one point communicated by LGU staff was the need for simple empirical tools or indices that do not require tens or hundreds of hours of analysis time. Many of the channel erosion models such as BSTEM and CONCEPTS are too time-consuming to be useful for SWCDs or other local government staff. Even BEHI was thought to be too labor intensive by many LGU staff and consultants because of the time required for training and field data collection. There is a need for a rapid field estimates of BEHI and NBS to categorize large areas for sediment loading potential. This is the approach suggested in the watershed-based approach to estimating sediment sources and supply in rivers (Rosgen et al. 2006).

Meeting attendants also pointed to the increasing need for prioritization tools in order to provide objective criteria for state funding and other programs supporting implementation of watershed management activities. Many LGU staff and landowners felt that they could identify priority areas based on their own knowledge and approach yet the state is increasingly requiring the use of prioritization tools to justify management decisions.

DISCUSSION

The highest rates of lateral erosion were found in the Whitewater watershed, exceeding 10 feet per year in some outer bends in the lower Whitewater River (Mn DNR 2015). The lower Whitewater is comprised of very erodible sandy alluvium much of which originated from soil erosion in the uplands following European settlement (sometimes referred to as legacy sediment). In contrast the maximum rates of lateral bank erosion in Elm Creek and the Buffalo were less than 5 feet/year. Stream banks in the Des Moines Lobe till plain such as Elm Creek tend to consist of cohesive silt or clay loams that are more resistant to erosion than legacy sediment or more sandy alluvium. Similarly the Buffalo River lies in the Lake Agassiz plain of the Red River basin and tends to have more cohesive soils and thus lower erosion rates than the lower Whitewater. The upper portion of the Whitewater River had lateral erosion rates that were similar to Elm Creek and the Buffalo River.

Lateral erosion rates obtained from aerial photography (Table 4) are useful for obtaining average rates of channel erosion in a watershed at the stream reach scale (100-400m) or larger which is useful in TMDL load calculations. The use of statistical measures of long-term lateral stream erosion as a basis for the predictive regional stream erosion rate equations ensure that error will not be too great for river-wide averages. At the scale of local, individual stream banks less than 50m-100m in length may have much higher or lower lateral erosion rates than shown in Table 4 and Figures 6-9 as shown by the DNR research on the Whitewater River. GIS estimates provide little insight into geomorphic and hydrologic processes occurring at the smaller stream bank scale which is why field data collection and observation is necessary.

The BEHI/BANCS methodology does require substantial field data collection effort which provides a better understanding of the channel erosion processes and the role of different soil and vegetation parameters in erosion (Sass and Keene, 2012). In our BEHI data collection one of the key findings about vegetative conditions was that 80 - 90% of plant root density in stream banks in the study area occurred within the top 30 cm of soil (Underhill 2013). Consequently current riparian plant community characteristics are not optimally supporting bank stability. The shallow rooted exotic reed canary grass dominated on 63% of the sites, in contrast with the deeper-rooted native prairie plants and/or some native trees and shrubs.

Depositional data on sandbars

The sandbar deposition data in Table 7 were very high (1 – 15 cm/year) relative to other data for floodplains in the Minnesota River (Lenhart et al. 2013). Sandbars are important sinks for sediment in Elm Creek and likely many other Minnesota Rivers. Perennial vegetation establishment initiates fine sediment accumulation, point bar growth and succession towards a floodplain and can lead to channel narrowing (Figure 3b) reducing sediment supply from a river. Reduced woody plant establishment on point bars then may contribute to channel widening which has been observed over much of southern and western Minnesota (Schottler et al. 2014).

The woody species occurring most commonly on the sandbars was the shrub sandbar willow (*S. interior*) with reduced establishment of cottonwood trees. This has ecological and functional significance as shrubs are shorter lived than cottonwoods and have less deep roots. Regardless of species composition, the tree age on point bars is <30 years indicating a timescale of decades is required for a point bar to build itself up to the level of a new floodplain.

Hydrologic drivers of erosion

Both the geochemical methods (SC and isotopes) and the SWAT model indicate that tile drainage contributes the majority of flow volume in Elm Creek (from 58-90% during the non-frozen time period). There appears to be relatively little baseflow in Elm Creek as further evidenced by the low flow conditions that exist in late summer each year after the major tile drainage and lake outflow ends. Stream bank erosion events occur primarily during and shortly after higher flows but the volume of tile drainage flow may increase flow peaks depending on the timing of rain events. This is particularly true when large rain events occur on top of soils that are already saturated and tile drains flow is at a maximum.

In the Whitewater River stream flow is more of a mixture of surface and groundwater sources and there is little tile drain flow. The rapid subsurface flow in the Driftless area makes the separation of ground and surface water sources more difficult using SC data. There is not sufficient residence time in rapid-flow through situations such as karst for the SC values to become concentrated as they do with longer groundwater residence times.

There was insufficient SC data to separate out flow sources in the Buffalo River. However the large difference in SC of end members (groundwater and rainfall) observed in this region suggest that the method would be applicable in Lake Agassiz plain region as well.

Applications to management

Utility of new approaches and tools

This lateral migration tool identifies stream reaches with high sediment loading rates in a watershed. The work done here provides data on the ranges of lateral stream bank erosion rates that may be expected in a given region in streams with a similar geomorphic setting. Once areas of focus in a watershed are determined, then the region-specific bank erosion prediction graphs (Figures 16-18) expedite estimates of channel loading of sediment for TMDL studies when more detailed aerial photo or modeling analysis is not feasible.

Natural resource managers can then use the above information to determine appropriate watershed management or stream restoration/stabilization actions to address priority sediment-loading reaches. The Presnail stream prioritization worksheet may be used to weigh sediment load reduction along with practical, economic and logistical issues associated with stream restoration.

Deposition tool

The collection of sediment deposition data on pointbars provides a practical means by which resource managers can assess the net transport of sediment downstream. While pointbars are only one area where sediment is deposited in a stream valley, the vegetated portion is clearly a hotspot for deposition that can provide an indicator of the extent to which stream bank erosion is balance by deposition. MPCA and DNR field crews regularly collect field geomorphology data for TMDL projects and the deposition rate on pointbars would be another piece of data that they could easily collect to add to our overall understanding of the sediment budget.

Hydrologic drivers of erosion: water source assessment tool

The use of SC for separating sources of flow to streams has been greatly facilitated by the development of reliable SC dataloggers that make it possible to assemble large datasets continuously throughout the monitoring season. This makes it easier to separate out water sources with greater certainty and demonstrate statistically significant differences between different water bodies or sources. The SC method is particularly useful in areas where the major surface flow is snowmelt runoff (Miller et al. 2014) or excess surface runoff in spring as occurs in much of Minnesota. The method also works well in glaciated till plains (such as occurs in the Des Moines Lobe and other parts of the Midwestern U.S.) with longer groundwater residence time creating distinct SC signatures between groundwater, tile and surface sources (Smith 2012).

Some situations where the SC approach may create less useful results include urban areas where application of road salts or other pollutants may raise the SC in surface water runoff in watershed that often have little groundwater-fed base flow (Cooper et al. 2014). What is needed for more widespread application in Minnesota is a standardization of the water source assessment protocol for use in future projects by the MN MPCA, DNR and LGUs.

Project Outcomes – public meetings and trainings

As previously mentioned, a public meeting for landowners and local government staff was held in the Elm Creek watershed in 2012 to obtain landowner feedback on riparian management practices. Additionally UMN Extension helped to develop a series of workshops in southern Minnesota in 2014 to demonstrate the use and applications of the decision support tools, in coordination with the UMN Center for Integrated Natural Resources and Agricultural Management (CINRAM) (Table 8).

Aside from the public engagement / trainings a list of public presentations related to the project including lectures and poster presentations are listed in Appendix 8.

Table 8 Workshops on prioritization tools for the public. Workshops were run by University of Minnesota Extension with assistance from local partners, Martin SWCD, Rural Advantage, Pope County SWCD, MPCA and others. The focus of the workshops varied from technical presentations on the tools in Mankato and Marshal to discussion and field trips at Glenwood.		
Date	*Location*	*Activities at workshop*
4/8/14	Fairmont	Preliminary testing of models / tools for government staff, consultants and others
4/17/14	Montevideo	Preliminary testing of models / tools for government staff, consultants and others
6/24/14	Fairmont	Presentations followed by field trips to BMP sites
7/1/14	Marshall	Computer lab on use of prioritization tools
7/8/14	Mankato	Computer lab on use of prioritization tools
7/16/14	Glenwood	Presentations followed by field trips to BMP sites

Lessons learned and Future needs

Lateral migration tools and bank erosion rate prediction

It would be very helpful to have lateral stream migration rate maps over a larger range of the state. Digitization of the stream line in GIS is very time-consuming. However if representative streams could be assessed around the state and make available to the public much time and resources could be saved for government staff and consultants. Statewide characterization of lateral erosion rates would require more funding or dedicated work by university staff or students.

The regional bank erosion prediction graphs (Figs. 16-18) have only been tested in a few locations in Minnesota. Therefore further validation is needed of the Elm Creek, Buffalo and Whitewater graphs. In particular it will be helpful to see how well they predict lateral bank erosion rates for streams within the same region.

With the development of regional bank erosion prediction tools, TMDL managers and consultants can more easily calculate sediment load from streambanks. However phosphorus loading from stream banks needs to be examined more. Data is available from sources around the state which could facilitate estimates of phosphorus loading from stream bank erosion.

<u>Prioritization tools</u>

Application of three-tiered decision support approach needs to be examined in more locations. The first two steps (lateral migration tool and BEHI/BANCS field reconnaissance/data collection) are fairly straightforward. However the decision making about where to do stream restoration or stabilization or watershed management projects to reduce flow to streams is more complex involving social, economic and landowner adoption issues. The third phase of identifying and moving ahead with project sites as defined in the Presnail Stream Restoration Prioritization Tool (Presnail 2013) needs to be further tested beyond Elm Creek and streamlined.

Hydrologic drivers of erosion

The importance of tile drainage in the total stream flow volume was demonstrated in the flow source assessment for Elm Creek. Tools for storing and/or reducing the outflow of tile drain water need to be further developed. Related to the need to reduce flow from the watershed, the frequency and magnitude of stream bank erosion causing events needs to be better understood.. It is already known that most erosion is caused at high flows. But what water storage volume would need to be reduce such flows enough to reduce erosion is not well understood.

We collected preliminary data on hydrology in the near stream bank zone. However, riparian-zone hydrologic dynamics are still poorly understood in most cases. Further riparian zone hydrology research would help us understand the importance of bank storage in reducing flow at high water levels for example

Finally further training on the tools and methods generated by this project would be helpful for translating the knowledge generated by this project into practice.

Applicability to riparian buffer management

Data from this study shows that in many cases riparian buffers have low root depth and density. In addition to water filtration and bird habitat buffers can reduce sediment loading from bank erosion in situations where streambanks are comprised erodible material and root depth is limited. In the headwaters of many watersheds, stream banks are low (<1m high) and grasses provide dense cover over the entire stream bank surface (Abernethy and Rutherford 1998). Moving downstream, bank height increases and the probability of mass-wasting is greater. Vegetation has less impact on controlling mass-wasting on very high banks or bluffs greater 3 meters (Figure 15).

Practices that increase root depth and density particularly in mid-sized stream banks (1m-3m height) with erodible bank materials could help reduce sediment loading to rivers. In terms of management in Minnesota, our study suggests that control of reed canary grass actually could have stability and sediment & nutrient load reduction benefits in certain types of scenarios. Currently the effect of riparian vegetation type and rooting depth on bank erosion rates is being examined by two M.S. students at the University of Minnesota., Shanna Braun and Jennifer Oknich.

Acknowledgments

Funding provided from the Clean Water Fund as part of the Clean Water, Land and Legacy Amendment

The following people contributed greatly to this project:

- Adam Birr, Josh Stamper and Heidi Peterson provided project management for MDA
- Ben Underhill and Laura Triplett, graduate students who completed M.S. theses on the project in 2013 and 2014
- Jennifer Oknich and Shanna Braun, graduate students currently working on M.S. theses at the University of Minnesota with expected completion in fall 2015
- Kerry Holmberg, Jason Ulrich, Mikhail Titov, Michael Kramer, Justin Fasching, Haley Bauer and Caleb Arika provided technical assistance
- Minnesota DNR staff collaborated on the project, including:
    - Dave Friedl on the Buffalo River
    - Mark Ellefson assisted with his lateral migration tool that was used in this study and Kevin Zytkovicz provided valuable input to the project
- A National Science Foundation grant through Dr. Karen Gran at UM-Duluth partially supported Laura Triplett and the sandbar deposition research

References

Abernethy, B. and Rutherford, I. (1998). Where along a River's Length Will Vegetation Most Effectively Stabilise Stream Banks? *Geomorphology*. 23, pg. 55-75.

Bauhus J. & C. Messier. 1999. *Evaluation of Fine Root Length and Diameter Measurements Obtained Using RHIZO Image Analysis.* Agronomy Journal, Vol. 91, pp. 142-147.

Belmont, P., Gran, K. B., Schottler, S. P., Wilcock, P. R., Day, S. S., Jennings, C., ... & Parker, G. (2011). Large shift in source of fine sediment in the Upper Mississippi River. *Environmental science & technology*, *45*(20), 8804-8810.

Brooks, K. N., Ffolliott, P. F., & Magner, J. A. (2012). *Hydrology and the Management of Watersheds*. John Wiley & Sons.

Cooper, C. A., Mayer, P. M., & Faulkner, B. R. (2014). Effects of road salts on groundwater and surface water dynamics of sodium and chloride in an urban restored stream. *Biogeochemistry*, *121*(1), 149-166.

EPA, (2015). *What is a TMDL?* Website: downloaded July 29, 2015 http://water.epa.gov/lawsregs/lawsguidance/cwa/tmdl/overviewoftmdl.cfm,

Green, M. B., Nieber, J. L., Johnson, G., Magner, J., & Schaefer, B. (2007). Flow path influence on an N: P ratio in two headwater streams: a paired watershed study. *Journal of Geophysical Research: Biogeosciences (2005–2012)*, *112*(G3).

Johnson, G. (2010). Whitewater River Watershed National Monitoring Program Project. *Minnesota Pollution Control Agency*. Document number: wq-cwp8-12.

Johnston, C. A. (2003). Shrub species as indicators of wetland sedimentation. *Wetlands*, *23*(4), 911-920.

Langendoen, E. J., & Alonso, C. V. (2008). Modeling the evolution of incised streams: I. Model formulation and validation of flow and streambed evolution components. *Journal of Hydraulic Engineering*, *134*(6), 749-762.,

Lauer, J.W., Echterling, C., Lenhart, C.F., Belmont, P, and Rausch, R. (in press) 2015. Air-photo based change in channel width in the Minnesota River basin: Modes of adjustment and implications for sediment budget. *Journal of the American Water Resources Association*.

Lauer, J. W., and Parker, G. (2008). Net local removal of floodplain sediment by river meander migration. *Geomorphology*, *96*(1), 123-149.

Lenhart, C.F. 2008. *The Influence of Watershed Hydrology and Stream Geomorphology on Turbidity, Sediment and Nutrients in Tributaries of the Blue Earth River, Minnesota, USA. PhD Thesis*. University of Minnesota-Twin Cities.

Lenhart, C. F.,Verry, E. S., Brooks, K. N., & Magner, J. A. (2012a). Adjustment of prairie pothole streams to land-use, drainage and climate changes and consequences for turbidity impairment. *River Research and Applications*, *28* (10), 1609-1619.

Lenhart, C., Davidson, M., Brooks, K., Slesak, R., and D'Amato, A. (2012b). Hydrologic source characterization of black ash wetlands: Implications for EAB response. *Proceedings of American Water Resources Association* (AWRA). 2012 Summer Specialty Conference. Riparian Ecosystems IV: Advancing Science, Economics and Policy

Lenhart, C. F., Titov, M. L., Ulrich, J. S., Nieber, J. L., & Suppes, B. J. (2013). The role of hydrologic alteration and riparian vegetation dynamics in channel evolution along the lower Minnesota River. *Transactions of the ASABE*, *56*(2), 549-561.

Magner, J. A., & Brooks, K. N. (2005). Assessing agroforestry options for water quality using regional hydraulic geometry curves. In *Proceedings of 9th Association for Temperate Agroforestry*, Rochester, MN, June 12–15.

Miller, M. P., Susong, D. D., Shope, C. L., Heilweil, V. M., & Stolp, B. J. (2014). Continuous estimation of baseflow in snowmelt-dominated streams and rivers in the Upper Colorado River Basin: A chemical hydrograph separation approach. *Water Resources Research*, *50*(8), 6986-6999.

Minnesota DNR. (2015). *Whitewater River WARSSS* (Watershed Assessment of River Stability and Sediment Supply). Technical report by the Minnesota DNR, St. Paul, Minnesota.

Nieber, J. L., Lenhart, C. F., Holmberg, K., Ulrich, J., & Peterson, H. M. (2014). Hydrologic processes related to stream bank erosion in three Minnesota agricultural watersheds. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 0953).

Parry, R. (1998). Agricultural phosphorus and water quality: A US Environmental Protection Agency perspective. *Journal of Environmental Quality*, *27*(2), 258-261.

Piercy, C. and Wynn, T. (2008). Predicting Root Densities in Streambanks. *Journal of the American Water Resources Association*. 44(2), Paper No. J06044. doi: 10.1111⁄j.17521688.2008.00178.x

Pollen-Bankhead, N., & Simon, A. (2010). Hydrologic and hydraulic effects of riparian root networks on stream bank stability: Is mechanical root-reinforcement the whole story? *Geomorphology*, *116*(3), 353-362.

Presnail, M.L. (2013). *Prioritizing stream restoration: a decision support tool for use in restoring waters impaired by excess sediment in the Blue Earth River Basin of Minnesota* (M.S. thesis, University of Minnesota - Twin Cities).

Rausch, R., Lenhart, CF., Triplett, L. 2013. Ecohydrological investigations of Minnesota River sandbar vegetation. Conference paper: 98th ESA Annual Convention 2013, Minneapolis, Minnesota (poster).

Rosgen, D. (2001). A Practical Method of Computing Stream bank Erosion Rate, in Proceedings of the Seventh Federal Interagency Sedimentation Conference, Vol. 2, pp. II 9-15, March 25-29, 2001, Reno, Nevada

Rosgen, D. L., Silvey, H. L., & Frantila, D. (2006). *Watershed assessment of river stability and sediment supply (WARSSS)*. Wildland Hydrology: Pagosa Springs, CO.

Sass, C. K., & Keane, T. D. (2012). Application of Rosgen's BANCS Model for NE Kansas and the Development of Predictive Streambank Erosion Curves1.*JAWRA Journal of the American Water Resources Association*, *48*(4), 774-787.

Schottler, S. P., Ulrich, J., Belmont, P., Moore, R., Lauer, J., Engstrom, D. R., & Almendinger, J. E. (2014). Twentieth century agricultural drainage creates more erosive rivers. Hydrological Processes, 28(4), 1951-1961.

Simon, A. (1989). A model of channel response in disturbed alluvial channels.*Earth Surface Processes and Landforms*, *14*(1), 11-26.

Smith, E. A. (2012). *Spatial and temporal variability of preferential flow in a subsurface-drained landscape in north-central Iowa*. University of Minnesota, Ph.D. Thesis.

Steiger, J., Gurnell, A. M., & Goodson, J. M. (2003). Quantifying and characterizing contemporary riparian sedimentation. *River Research and Applications*, *19*(4), 335-352.

Titov, M. (2015). Channel migration tool. Located at website: http://mlt.github.io/QGIS-Processing-tools/channel-migration.html

Triplett, L. (2014). Variation in Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the Minnesota River Basin. M.S. Thesis, University of Minnesota-Twin Cities.

Underhill, B. L. (2013). *The influence of vegetation and root density on erosion for three streams in Minnesota*. M.S. Thesis. University of Minnesota.

Yan, B., Tomer, M. D., & James, D. E. (2010). Historical channel movement and sediment accretion along the South Fork of the Iowa River. *Journal of soil and water conservation*, *65*(1), 1-8.

Appendices

1. BANCS model.   A) Bank Erosion Hazard Index data sheet, B) Streambank erodibility variables used in BEHI, C) BANCS relationships for Yellowstone and Colorado (Rosgen et al. 2006)
2. Stream lateral migration tool developed by Mikhail Titov: Dynamic Time Warping (DTW) lateral migration tool available on the QGIS website
3. Underhill, B. L. (2013). *The influence of vegetation and root density on erosion for three streams in Minnesota*. M.S. Thesis. University of Minnesota-Twin Cities.
4. Whitewater River WARSSS report, Minnesota DNR, July, 2015
5. Triplett, L. 2014. *Variation in Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the Minnesota River Basin*. M.S. Thesis, University of Minnesota-Twin Cities.
6. End member mixing analysis for determining sources of water in stream flow.
7. Nieber, J. L., Lenhart, C. F., Holmberg, K., Ulrich, J., & Peterson, H. M. (2014, December). Hydrologic processes related to stream bank erosion in three Minnesota agricultural watersheds. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 0953).
8. A list of public presentations done on the priority setting in watershed restoration project.

Appendix 1. The BANCS model for prediction of annual stream bank erosion rates

The Bank Erosion Hazard Index (BEHI) data collection worksheet from Rosgen et al. (2006).

Worksheet 20. BEHI variable worksheet

Stream:	Cross Section:	Date:	Observers:

Bank Height/Max Depth Bankfull (C)

Study Bank Height (ft) A	Bankfull Height (ft) B	A/B = C

Root Depth/Bank Height (E)

Root Depth (ft) D	Study Bank Height (ft) A	D/A = E

Weighted Root Density (G)

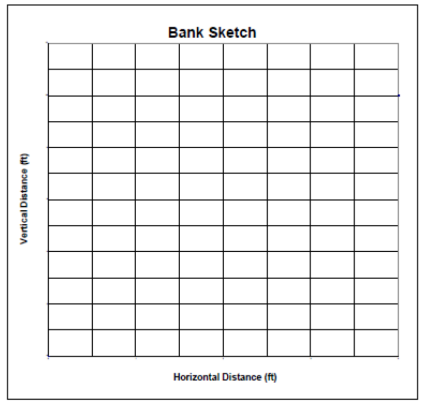
Root Density (%) F	F*E = G

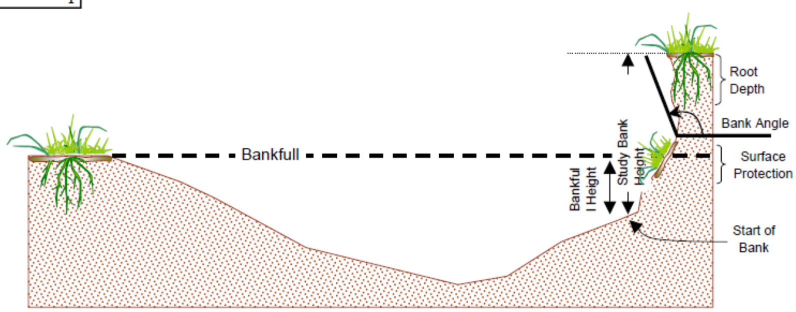
Bank Angle (H)

Bank Angle (Degrees) H

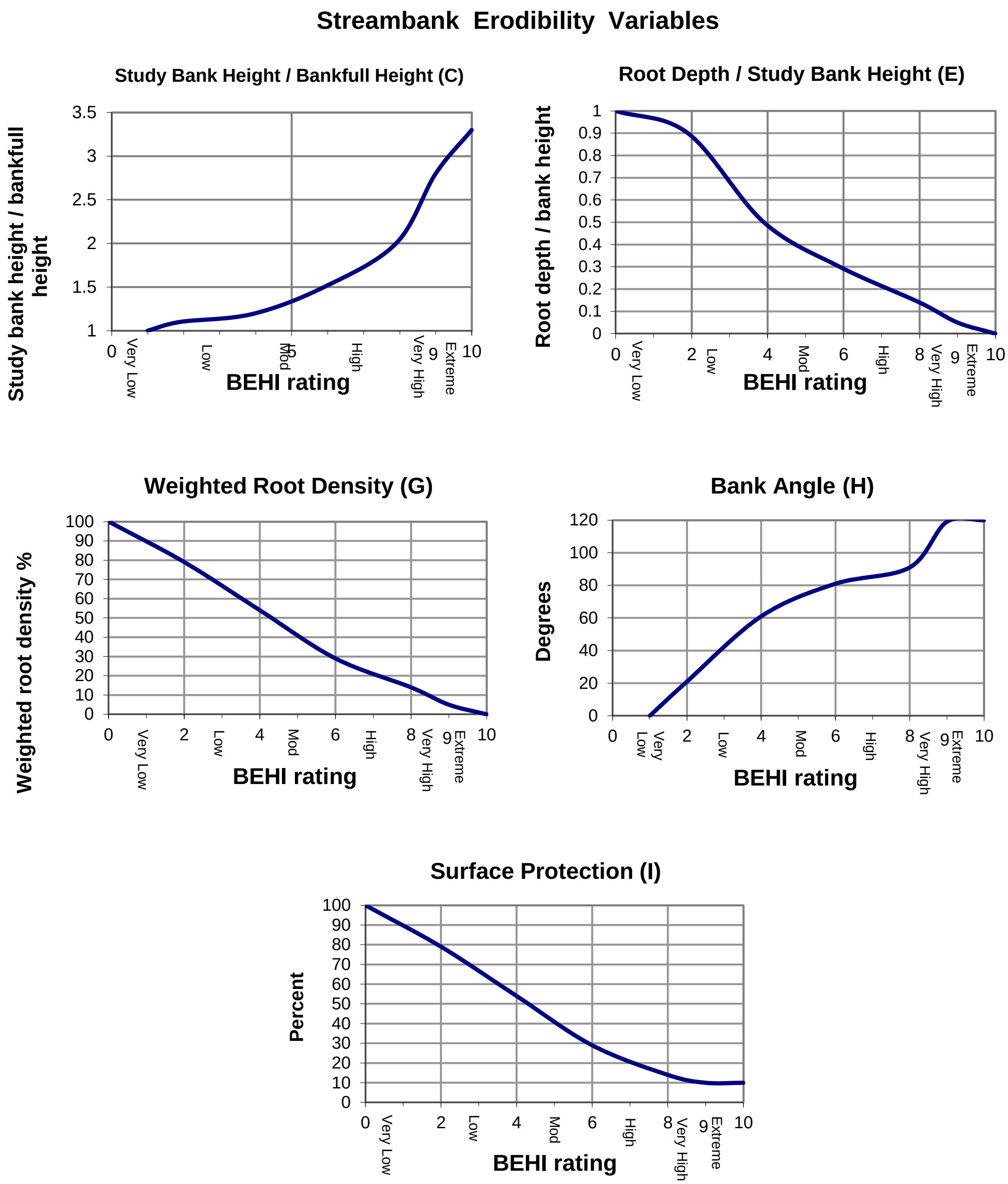
Surface Protection (I)

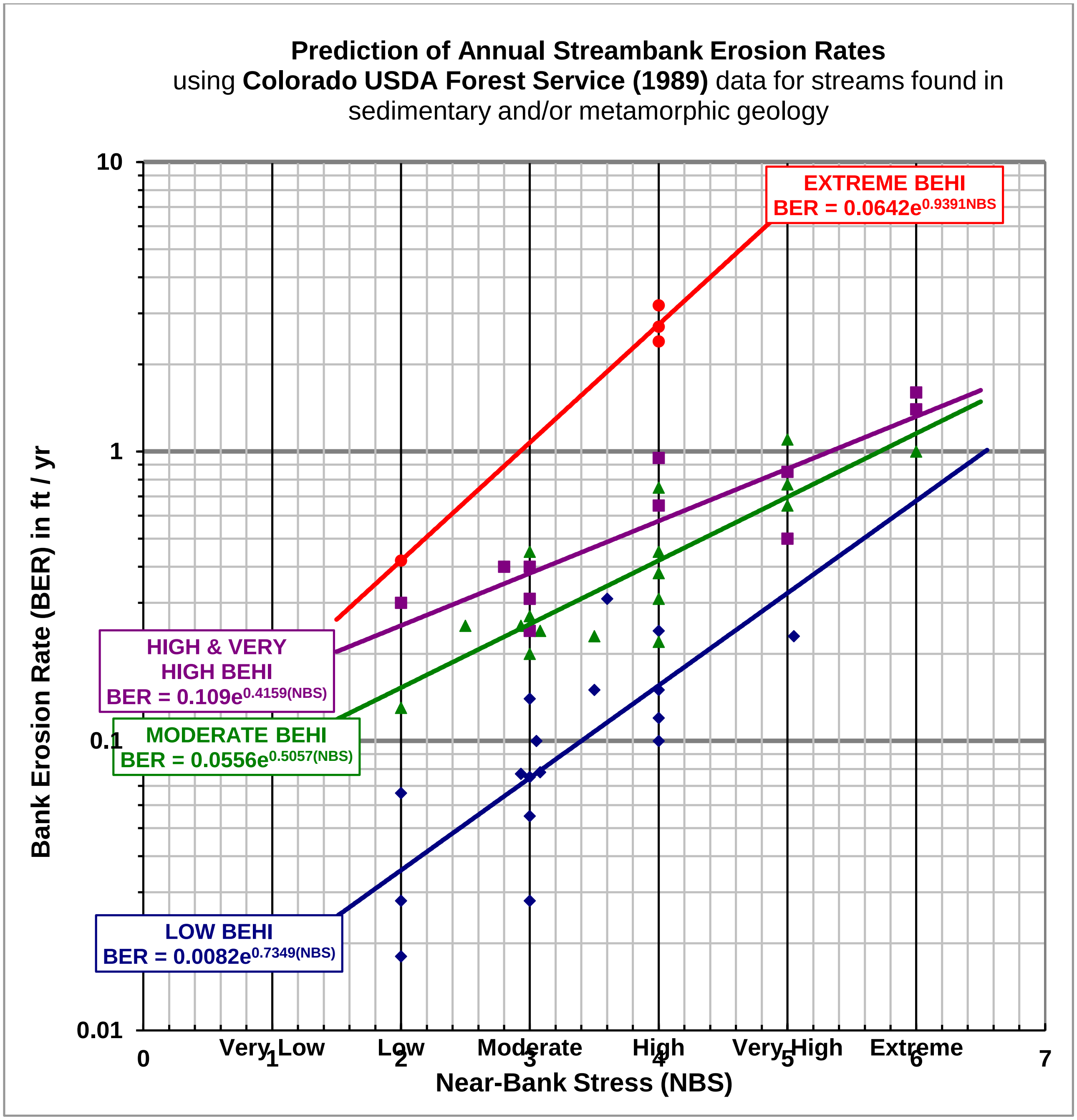
Surface Protection % I

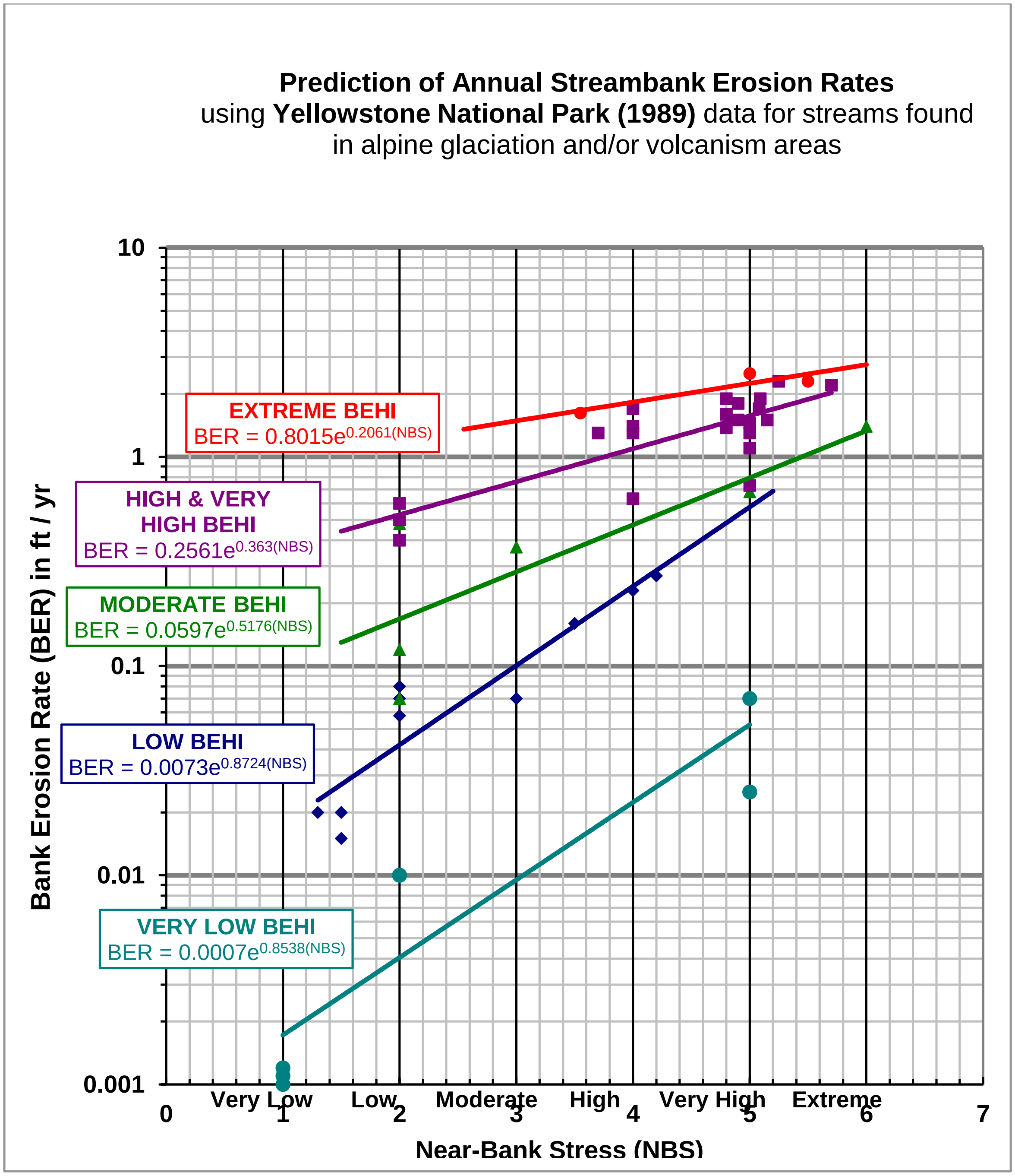




Components of the BEHI showing how the components from the worksheet above are scored. The subcategory scores are totaled to obtain a cumulative score for each stream bank assessed.



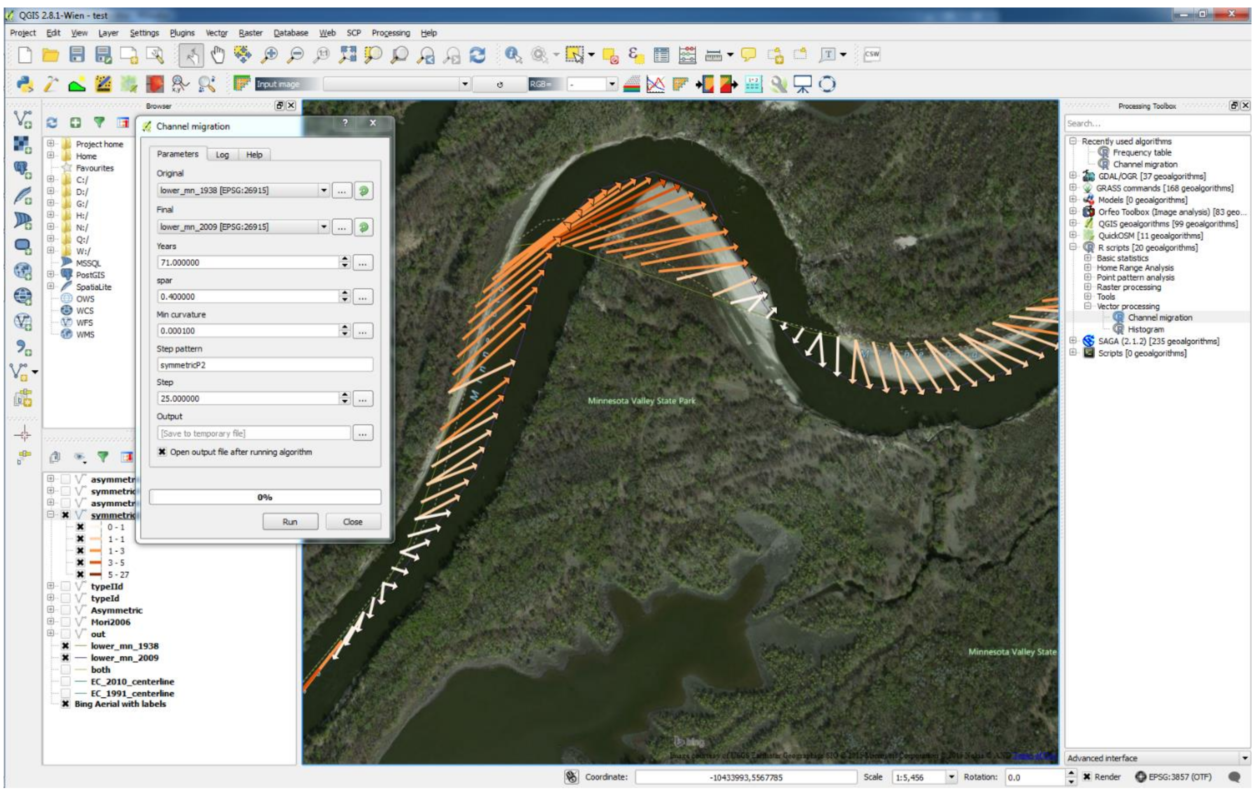

Prediction of Annual Streambank Erosion Rates
using Colorado USDA Forest Service (1989) data for streams found in sedimentary and/or metamorphic geology
EXTREME BEHI
BER = 0.0642e0.9391NBS
HIGH & VERY HIGH BEHI
BER = 0.109e0.4159(NBS)
MODERATE BEHI
BER = 0.0556e0.5057(NBS)
LOW BEHI
BER = 0.0082e0.7349(NBS)
Bank Erosion Rate (BER) in ft / yr
10
1
0.1
0.01
0
1
2
3
4
5
6
7
Very Low
Low
Moderate
High
Very High
Extreme
Near-Bank Stress (NBS)



Prediction of Annual Streambank Erosion Rates
using Yellowstone National Park (1989) data for streams found
in alpine glaciation and/or volcanism areas
EXTREME BEHI
BER = 0.8015e0.2061(NBS)
HIGH & VERY HIGH BEHI
BER = 0.2561e0.363(NBS)
MODERATE BEHI
BER = 0.0597e0.5176(NBS)
LOW BEHI
BER = 0.0073e0.8724(NBS)
VERY LOW BEHI
BER = 0.0007e0.8538(NBS)
Bank Erosion Rate (BER) in ft / yr
10
1
0.1
0.01
0.001
0
1
2
3
4
5
6
7
Very Low
Low
Moderate
High
Very High
Extreme
Near-Bank Stress (NBS)

Appendix 2. The Dynamic Time Warping (DTW) lateral migration tool available on the QGIS website, (Titov 2015).

A tool was developed to calculate lateral migration using a non-linear local alignment to minimize error in estimating local lateral migration. This tool was used to assess the results of the Minnesota DNR - Ellefson lateral migration tool and identify ways to reduce channel migration measurement error at the local stream bank scale. The Dynamic Time Warping (DTW) based channel migration analysis tool yields a non-linear local alignment by solving the cumulative distance constrained minimization problem for a discrete set of migration points whereas all other tools estimate an average migration per section pre-defined by the user. This should improve the accuracy of lateral stream migration prediction.



The tool can be obtained at this website:

http://mlt.github.io/QGIS-Processing-tools/

The Influence of Vegetation and Root Density on Erosion for Three Streams in Minnesota

A THESIS
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Benjamin Lawrence Underhill

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Christian F. Lenhart, John L. Nieber

August 2013

Acknowledgements

I would like to thank all of the individuals that have encouraged and assisted my graduate progress. My advisors, Chris Lenhart and John Nieber, as well as Rebecca Montgomery, have been valuable resources before, during, and after my thesis presentation. Their accumulated help has ensured I am consistent and thorough with all my research and data collection.

I am also very thankful for my wife, Stacy, without whose constant encouragement and helpfulness I could not have completed this project.

I would like to thank my family and friends for their support and understanding.

Finally, I would like to thank the Minnesota Department of Agriculture for the Prioritization Grant headed up by Adam Birr, who now works for the Minnesota Corn Growers Association, and Josh Stamper, which has helped to fund and provide guidance for my thesis project. I would also like to thank the DNR members that provided some data for the results, especially Dave Friedl.

Abstract

Streambank erosion is a growing concern in Minnesota as hydrologic conditions continue to change throughout the state. Plant root anchoring and surface protection from vegetation play a role in reducing erosion. The Rosgen Bank Assessment for Non-point source Consequences of Sediment (BANCS) method of erosion prediction uses both root density and surface protection to estimate the resistance of a streambank to erosion. In order to understand how different types of vegetation can influence parameters within the BANCS system thirty sites were selected in the Glacial Lake Plain, Glacial Till, and Loess regions. Root sampling and vegetation surveys revealed no correlation between root density and erodibility factors from the BANCS system. Data from this study can assist restoration efforts in these regions in order to improve or refine current practices, reduce erosion and improve water quality.

Table of Contents

List of Tables

List of Figures

Introduction

Excessive river erosion can change river morphology and create problematic conditions for aquatic animals and plants. Some erosion is natural and needed for some plants and animals. However, too much erosion destroys natural pools and riffles that many fish and insects need to reproduce, hunt, or hide from predators (Turbidity and TSS, 2013). Variation in depth and morphology allow a more diverse biotic community to survive (United States Environmental Protection Agency, 2012). Natural erosion rates can vary, but human induced increases in erosion cause loss of biodiversity and reduction in fish and insect numbers.

Erosion increases turbidity in the water by increasing the amount of particulate material in a stream (Lenhart et al., 2010a). Turbidity has many effects on human and other animals. It can cause species of fish and insects to decline due by interfering with their ability to hunt or forage. Turbidity reduces aquatic plant life by lessening the amount of light reaching the streambed (United States Environmental Protection Agency, 2012). Turbidity can also increase nutrient levels in a stream or lake, causing eutrophication and algae blooms (Turbidity and TSS, 2013). Increased costs can be transferred from drinking water and industrial companies to consumers because of additional filtration needed to remove particles in the water (United States Environmental Protection Agency, 2012). Rivers in Minnesota are experiencing increases in turbidity that cause harm and expense to humans and aquatic life.

River restoration efforts cost Minnesotans significant amounts of money every year (Lenhart et al., 2010b). These restoration projects occur where erosion is a major problem, especially where roads or houses become threatened. When personal property or roadways are threatened emergency restoration projects are enacted to protect citizens (DeWall, 2009). Often, these projects use costly materials such as, concrete and boulders, to stabilize a streambank with little regard to natural characteristics. Instead of waiting until emergency repairs are needed, vegetation can be used to stabilize a streambank before it reaches a critically eroded state.

Vegetation is known to be beneficial for restorations because it reduces erosion, provides habitat, and protects streambanks from freezing. Water expands when it freezes, causing damage to soil structure and reducing streambank cohesion (Wynn and Mostaghimi, 2006a). Plants can insulate the ground and reduce the expanse and damage caused by freezing. Plants that shade the river are valuable in providing habitat and cooling the water to temperatures that support some animal species, such as trout. Loss of trees and other plants along coldwater trout streams are a contributing cause of the decline in trout populations (Turbidity and TSS, 2013). Plants also reduce erosion on streambanks by increasing stability of the soil with their roots. Roots will penetrate into the ground and bind soil particles together, creating greater cohesion (Edmaier et al., 2011). However, inundation can decrease this stability. Roots can provide additional benefit by extracting excess water in the soil, increasing streambank stability (Shields et al., 2009). Roots may be the most important factor providing stability to streambanks.

Some erosion formulas consider roots when calculating erosion rates, for example Rosgen's Bank Assessment for Non-point Source (BANCS) erosion model uses root density and depth. Additional studies have been attempted to understand how roots provide support and where they can grow to provide the most benefit. The study outlined in this paper was designed to understand how plants and roots can be used for restoration efforts. In particular, understanding root density and root growth could provide valuable information for restoration activities that aim to prevent streambank erosion.

Chapter 1: Literature Review

Problem and Objectives

Streambank erosion rates have increased in Minnesota since European settlement in the 1850's (Beach, 1989). This human-induced erosion is much higher than natural rates. Restoration activities and conservation techniques have been developed to reduce erosion caused by human impacts. Erosion of streambanks in many parts of Minnesota are a major concern, since roads, bridges, property, and prime farm land can all be lost to high erosion rates caused by eroding streambanks (DeWall, 2009). Plant and root properties can provide support to streambanks, lowering erosion rates (Wynn and Mostaghimi, 2006b). However, little information is available about root patterns and density in riparian areas, so it is difficult to prescribe natural solutions to eroding streambanks. The priority of this study is to ascertain the usefulness of vegetation for restoration and conservation in rivers with high erosion rates.

This research aims to give insight into three aspects of stream erosion. First, the variation in root density across different environments in riparian areas is poorly understood and requires additional information. Different types of vegetation can exhibit wide ranges of root density and patterns depending on plant species, site characteristics, and many other properties (Piercy and Wynn, 2008). Understanding root properties can increase the efficacy and longevity of conservation and restoration practices. Second, using known plant and root properties, an erosion prediction tool can quantify differences in erodibility between river reaches. The framework for erosion prediction based on root characteristics already exists in the Watershed Assessment of River Stability and Sediment Supply (WARSSS) tool developed by David Rosgen (United States

Environmental Protection Agency, 2012). By using this framework and supplementing it with findings about vegetation and root properties an accurate prediction methodology can be used. Third, this study aims to provide insight for future restoration and conservation activities through the Minnesota Department of Agriculture (MDA). Results of the prioritization grant provided by the MDA can provide insight for local units of government and other organizations that wish to restore and protect streambanks.

Stream Erosion Prediction

Erosion is a normal process that occurs along streambanks in every natural river. However, erosion can become a problem when the rates of erosion accelerate and cause losses of land, increased turbidity, and degraded stream habitat. Erosion above the natural background is often due to human changes within a watershed. The WARSSS framework is useful in identifying reaches that have increased erosion by using the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model. Stability is defined in this framework as a river that "maintains its dimension, pattern, and profile without aggrading nor degrading" (United States Environmental Protection Agency, 2012). Human impacts often disrupt the balance of erosion and deposition to create an unstable stream. The BANCS model was developed for use on rivers in Colorado, but it is hypothesized that the same methodology may be used in other streams to estimate erosion potential (Rosgen, 2008). There are two regional curves for streams in Colorado based on geologic and geomorphic conditions of the landscape. For example, streams that flow through sedimentary derived soil erode at a different rate than streams in volcanic geology (Rosgen, 2008). Other regions have developed curves for different landscapes, such as the curve developed for parts of Pennsylvania and Maryland (White, 2001). Two separate parameters are used to calculate potential erosion rates; The Bank Erosion Hazard Index (BEHI) and Near-Bank Stress (NBS) (United States Environmental Protection Agency, 2012). High scores relate to higher predicted erosion rates, while smaller values indicate stable streambanks. BEHI and NBS can be correlated using a regional relationship curve to estimate erosion.

Two main methods, empirical data measurements and model estimation, are used to inform decisions about where conservation practices are needed. Models can be used to estimate the factors that influence erosion rates without field data collection. Model estimation requires expertise, background knowledge, and large amounts of time to accomplish. Empirical measurements, such as the BANCS methodology, use collected data to predict erosion rates. Empirical tools require field data collection to inform results. Empirical data collection is easier to use without expertise and directly relates to the watershed or region being measured. Accuracy can be obtained by models, but only if the physical properties of the watershed are very well understood. There are advantages and disadvantages to each method, but empirical measurements are usually more accurate and easier to obtain.

BEHI and NBS attempt to estimate the three forces that affect a streambank; shear stress, gravitational stress, and a cohesive force (Brooks et al., 2003). Shear stress originates from perpendicular forces such as flowing water through a streambed. Any features of the stream will be subjected to the force of moving water. These features of a stream are often expressed as the Manning's Roughness Coefficient. This is a simple value based on the channel features and vegetation used to calculate stream flow (Brooks et al., 2003). Channels with more features, such as debris, vegetation, or features of the channel bed, have more resistance to shear force and a higher Manning's Roughness Coefficient (Brooks et al., 2003). Vegetation is often the major factor in providing increased resistance to shear force.

Taller streambanks are at greater risk of collapsing due to stresses, such as gravity, from above (Brooks et al., 2003). Increased force from upper soil layers increases the stress from gravity while the cohesion remains the same, reducing the overall strength of the streambank. Additionally, water movement can reduce the cohesion of soil layers. Gravity causes water to move through streambanks from above, decreasing the cohesion between regions of a streambank. Separated regions are more likely to cause large portions of a streambank to fail (Abernethy and Rutherfurd, 1998). Objects on a streambank can also play a small role by increasing stress on a streambank, particularly if the object is heavy and large.

Cohesive strength is influenced by the amount of vegetation, amount of roots, and type of soil material (Brooks et al., 2003). These factors affect the ability of soil to bind together and resist outside forces. Streambanks with low cohesive strength are more vulnerable to every type of erosion. Plant roots increase the stability of a streambank by binding sediment; ensuring sturdier soils (Wynn and Mostaghimi, 2006b). Certain soils are also better at adhering to each other. For example, clay naturally binds with itself, causing it to be resistant to outside stresses (Natural Resources Conservation Science, 2013). Understanding the different stresses that affect a streambank is important for calculating erosion rates.

The first parameter for the BEHI tool uses the ratio of study bank height by the bankfull height (United States Environmental Protection Agency, 2012). This measurement is used as an indicator of potential change in the stream and the amount of incision present in the channel. Incision is an indication of greater erosion potential than normal for unstable streambanks. Larger differences between bank height and bankfull height increase the stress from gravity on streambanks (Brooks et al., 2003). Streambanks that have a high ratio of bank height to bankfull height, have higher rates of erosion (United States Environmental Protection Agency, 2012).

Vegetation can increase soil cohesion because of root structure and depth. Vegetation creates an underground net of roots that binds soil particles together which increases the resistance to shear forces (Wynn and Mostaghimi, 2006a). The next parameter in BEHI measures root depth because it determines the amount of protection and stability provided by plant roots (United States Environmental Protection Agency, 2012). Roots that reach deeper will be able to stabilize more of a streambank and lower the amount of erosion that occurs.

In classic root studies, large trenches were dug to examine plant roots in their natural environment. The study of roots began in prairie lands by J. Weaver (1968). The trenches dug by Weaver was 2.5 feet wide, five to ten feet long, and dug at least 5 feet deep, but as deep as 15 feet (1968). In prairie environments roots quickly grew to depths of 30 inches of more in one year of growth (Weaver, 1968). In these environments water is scarce and water tables are very deep; often many feet below ground. Prairie plants had reduced growing depths when nitrogen fertilizer was applied to the soil surface. Excess moisture caused roots to grow deeper, with fewer branches, unless the soil was inundated, the roots drowned without access to water (Weaver, 1968). Riparian environments are very different from prairie environments; water and nutrients are abundant and shallow (Abernethy and Rutherfurd, 1998). Roots cannot extend as deep because of a shallow water table that impedes growth. Likewise abundant nutrient availability causes root systems to branch laterally instead of deeper (Weaver, 1968). Therefore root depth is likely much lower in riparian areas than anticipated by previous studies in other environments.

The next parameter for the BEHI measurement is root density. A higher density of roots in a streambank the greater the stability and strength of that bank (Wynn et al., 2004). Short banks receive an abundance of dense roots, due to the limits of space and the easy availability of water. However, since riparian roots are often much shorter than prairie plants, root density can be low on tall streambanks. Weighted root density is the next parameter in the BEHI system (United States Environmental Protection Agency, 2012). Long, infrequent roots in a streambank result in a large value for root depth, but a low value for root density. Poor weighted root density scores, which involve both root depth and root density, are only achieved if both values are small (Rosgen, 2008). Root length and root density are both used to determine overall root stability provided to a streambank.

Bank angle is another indicator that can be used to estimate the stability and erodibility of a streambank in the BEHI system. Angles greater than 90 degrees indicate undercutting of streambanks (United States Environmental Protection Agency, 2012). Streambanks with higher bank angles are more vulnerable to mass failures. Mass failures are less likely to occur on streambanks with low bank angles because the gentle slope protects the inner streambank from erosion (United States Environmental Protection Agency, 2012).

Surface Protection is the next parameter for the BEHI measurement (United States Environmental Protection Agency, 2012). Aboveground vegetation provides cover from moving water, which Manning's Roughness Coefficient attempts to express (Brooks et al., 2003). This value is used as an estimate of the amount of resistance features of a stream channel have to flow. Fast moving water erodes soil easily, but surface protection, such as vegetation, reduces the speed of flowing water (Brooks et al., 2003). Vegetation is not the only material that can provide protection. Rip-rap, fallen trees, and rock weirs all provide protection to a streambank without relying on living vegetation. Herbaceous vegetation plays the most prominent role in protecting streambanks. Any protection will decrease erosion and increase the permanence of the channel (Rosgen, 2008).

The next BEHI parameter, bank material, is very important to consider when calculating the amount of erosion that occurs within a channel (United States Environmental Protection Agency, 2012). Soil type can affect the particle size, drainage, and cohesion of bank material (Natural Resources Conservation Science, 2013). Larger particles do not bind as easily, drain water more rapidly, and are more vulnerable to stress. Large soil particles have less attractive force. As a result, cohesion is very low and drainage is very high (Wynn and Mostaghimi, 2006b). The more sand present in a streambank the easier it erodes because it has much larger particles. Bulk density is often used as a surrogate measurement for particle size and cohesion. Larger bulk density values usually indicate smaller soil particles. However, certain soil types and other factors, such as compaction, can cause some soil to behave differently. Since sandy soils have less cohesiveness and drain quickly they are more prone to erosion .

The final BEHI parameter, stratification of soil materials, can indicate increased potential for erosion (United States Environmental Protection Agency, 2012). Different layers can erode at different rates, creating unstable conditions within a streambank. Water may flow between layers which can create regions of increased erosion and stress within a streambank (Shields et al., 2009). Other factors, such as soil type, bank height, and inundation increase the effect of stratification on erosion. Streambanks with stratified soil layers tend to have increased erosion rates and thus receive higher BEHI scores in the BANCS system (Rosgen, 2008).

The BEHI tool enables understanding about the conditions of a streambank. However, the amount of force exerted on a streambank is also needed to estimate an erosion rate. A streambank with a very low BEHI score could still experience large erosion rates if the shear force exerted on the streambank is very high (United States Environmental Protection Agency, 2012). The NBS tool uses seven different methods to quantify the amount of stress affecting a bank. Only one method is required to obtain an NBS rating, but multiple methods are useful. The methods increase in complexity from method one to method seven. Method one is easy and simple with little field work, but method seven requires specific field data and complicated calculations. The difficulty and complexity do not always correspond to increased accuracy (Rosgen, 2008). Instead it is important to use the most appropriate method to determine the magnitude of the shear force (Rosgen, 2008). Method two and five are the most appropriate methods to determine NBS on a stream bend. The other methods were not used in this study because they required other measurements or are less accurate for stream bends. NBS measurements are used to estimate the amount of shear stress affecting a streambank.

Method two uses the ratio of the radius of curvature to bankfull width of a stream meander to estimate Near Bank Stress (NBS). The radius of curvature is measured using a circle that has the same diameter as the bend of the stream as seen from an aerial photograph. This method only works on meanders, because the radius of curvature would be incredibly large for a straight channel, indicating a very small shear force. It is best used on sharp curves to estimate the potential for erosion due to directed flow. The tighter the curve, the more water will be directed to the outer bank, increasing the direct force on that streambank (Brooks et al., 2003) Water moves faster on the outside of a bend because the resistance to flow is less when it is further from the inside curve. Streambanks on the outer bend experience higher shear stress because the water is moving much faster (Brooks et al., 2003). That is why method two for estimating NBS can be a useful measurement even from aerial photographs. Method two is useful for computing erosion rates in many concerned reaches because of its simplicity and accuracy for curves.

Method five to calculate NBS uses mean bankfull depth and near bank maximum depth from a cross section taken in the field to calculate the stress applied to a bank. The near bank region is the closest third of the channel to the study bank. The ratio of near bank maximum depth to bankfull mean depth is used to gauge the amount of stress that affects a nearby streambank or streambed. Values of depth two to three times greater than the mean depth are indicators of increased stress and erosion in the near bank area (Rosgen, 2008). This measurement is useful for curves and straight sections, whenever most of the flow is deflected towards the outer third of the channel (United States Environmental Protection Agency, 2012). Deflected flow can be caused by curves, sandbars, or other obstructions in a river. Method five is used to measure NBS for areas with deflected flow.

In order to calculate final erosion rates an empirically derived graph is used to examine the relation between BEHI, NBS, and erosion rates. One axis contains erosion rates, while the other uses NBS ratings. BEHI and NBS are used to estimate the strength and stress of streambank, respectively. Therefore, the exact relationship on the graph depends on empirically derived results (Rosgen, 2008). Differences in erosion rates, streambank dynamics, and soil properties could all play a role in adjusting the number from the graphs designed by Rosgen (2008). That is why it is important to calculate a region specific graph for Minnesota, since no such curve currently exists for the Midwest region. Using the curves derived for Colorado may cause errors in the final erosion calculation due to the differences between Minnesota and Colorado.

Streambank Reinforcement

Vegetation can play many different roles in providing stability, but root depth and density are two of the most important factors that influence channel degradation. Herbaceous and woody plants provide different stability due to variations in size and strength of their roots. The maximum rooting depth for trees is greater than that for herbaceous plants, which is greater than herbaceous plants (Canadell et al., 1996). This maximum depth value differs based on biome; desert plants have a much deeper rooting depth plants in temperate environments (Canadell et al., 1996). Each type of vegetation is useful for preventing erosion, but the effectiveness can vary depending on root depth, root density, root size, or other factors. In order to understand this process it is important to understand how roots provide stability and whether herbaceous plants and woody plant roots differ.

Roots provide stability to streambanks from mechanical effects; they literally anchor the soil against erosive forces (Pollen and Simon, 2005). This has been widely recognized for many years, but the exact processes that provide this stability are poorly understood. Some of these processes could include soil buttressing, changing bank hydrology and actual reinforcement by roots in the soil (Abernethy and Rutherfurd, 1997). Individual root strength is often measured as tensile strength or the amount of force needed to break apart a single root when pulled. Measuring this type of strength requires a device that simply pulls on roots until they break. The amount of force required to break that root is the tensile strength. Using this simple measurement researchers and modelers have used tensile strength to calculate a failing point for a bank based on the suspected strength of the roots within that bank. However, simple models using tensile strength over predict the stability of soil with tree roots by 20-50% (Pollen and Simon, 2005) and soil with herbaceous roots by 600-1400%. In the simple model all the roots are assumed to break all at the same time at their maximum tensile strength with no pull out. Root strength is highly variable based on many factors, causing root reinforcement to be complex and highly variable (Pollen and Simon, 2005).

In simple models many factors of root behavior are ignored. Newer models allow smaller, weaker roots to break over time, before considering the stress on larger roots (Pollen and Simon, 2005). Each root in a soil area is not identical and has a different tensile strength. These differences are determined by size, density, and other factors (Pollen, 2006). Larger, denser roots have higher tensile strengths because they are more difficult to break from pulling. Other factors, such as inundation, can weaken a root so it has a lower tensile strength. Due to these differences, not all roots will behave the same when exposed to the same forces. Simple models do not consider the additional stress that occurs due to chronological breaking. As weaker roots break, the stress is reapplied to all other remaining roots (Pollen and Simon, 2005). These stronger roots are under more stress than thought by a simple model. Therefore, chronological breaking and root differences must be considered when estimating the strength of soil with different roots.

Simple models also assume that all roots reach their maximum tension before breaking. Stress is often concentrated in several areas on a streambank, not evenly distributed across the whole bank. Tensile strength can be misleading if the region where the root breaks is weaker than the rest of the root. Not all roots are straight in a streambank and will often straighten before breaking (Pollen and Simon, 2005). This straightening can redistribute stress and increase the strength of the soil. If the root straightens before breaking it should be able to absorb more force than predicted by simple tensile models (Pollen, 2006). Attempting to estimate the amount of reinforcement provided by roots can be difficult due to uncertainties in straightening, redistribution, and other factors.

Root pull out can also cause simple root strength models to over predict root stability (Pollen and Simon, 2005). The simple model assumes all the roots at the area of bank failure are not able to be removed from the soil. However, roots can be pulled out of a streambank, before breaking. The resistance to pulling out of a streambank is based on many factors; the largest factors are soil type, soil moisture, root orientation and surface area of the root (Wynn and Mostaghimi, 2006a). A threshold point where some roots may break, but others may pull out at less than their maximum tensile strength controls streambank stability (Pollen and Simon, 2005). In smaller plants with smaller roots, this can cause entire plant systems to be pulled out of the soil. Plants with longer roots are able to resist uprooting for much longer periods of time (Edmaier et al., 2011). Longer roots have increased surface area that interacts with soil, increasing the resistance to uprooting. Soil type plays an important role because it affects the amount of area that a root can anchor against. Soil with smaller particles will allow roots to anchor against more surface area of that soil, decreasing the amount of roots that are pulled out (Wynn and Mostaghimi, 2006a). Soil moisture decreases the cohesion of the soil itself, which can increase the rate of pulling out for roots. Orientation is important in resisting pull out, since it is easier to pull a root that is perpendicular to the bank face. Vertical roots can resist pull out much more easily because they have greater cohesion and more surface area to resist root pull out. Root pull out is affected by soil type, orientation, inundation, and surface area; which causes simple root breaking models to overestimate bank strength.

Root dynamics are important to understand because they assist in stabilizing streambanks. Predicting streambank resistance to erosion is not accurate when using tensile strength alone as a measure of stability (Pollen and Simon, 2005). Root size and density are better measures because they can give a more accurate idea of interactions between root stresses and resistances (Piercy and Wynn, 2008). Increases in surface area resist uprooting by increasing the force needed to remove root systems. This can vary based on soil type; smaller soil particles will provide more surface area for attachment. The ability of roots to straighten can also affect erosion by redistributing stresses (Pollen and Simon, 2005). Orientation plays a large role in the ability of a root to resist straightening and pulling out. Predicting the amount of stability provided to a streambank by root structures can be very difficult to calculate because of the various factors that influence root stability.

The stability of a streambank is affected by root structure and distribution which varies based on spatial and temporal differences. The spatial variability of root properties, such as size, density, and depth, depend on aboveground plant density, mineral deposition, water availability, and inundation frequency. Differences in sunlight can affect the spatial variability of plant growth, which in turn affects belowground growth (Wynn et al., 2004). Some soils contain more minerals needed by plants than others. Differences in soil minerals can affect how and where roots grow (Weaver, 1968). A small region of highly fertile soil could concentrate roots in one area. Similarly, water availability would influence the growth pattern of root systems (Pollen, 2006). Temporal variability can also change the root density in an area. Inundation plays a role in damaging roots during early spring floods. As the season progresses and sunlight increases, so does root growth. Root growth peaks in late August, then slowly senesces to prepare for winter (Kiley and Schneider, 2005). This pattern can be seen in any type of plant, both perennials and annuals; however annual plants have a much larger change in root density (Kiley and Schneider, 2005). This pattern can affect root density depending on the time of year.

Saturation and inundation within soil material has two main effects on roots. First, roots in saturated conditions cannot absorb oxygen. Oxygen diffuses very slowly through water, reducing the amount available in the soil while being unable to replenish oxygen supplies. Root strength decreases as the plant becomes oxygen starved (Pollen, 2006). Second, saturation reduces the stability of soils. Roots cannot grip the soil because water reduces the friction between surfaces (Wynn and Mostaghimi, 2006b). Increases in saturation reduce streambank stability after large flood events or periods of high rainfall.

The movement of moisture within a streambank can also have dramatic effects on stability. Small amounts of water that infiltrate and move laterally through soil exert pressure on nearby soil regions. The more water present in a region, the higher the pressure. Higher pressure often increases the chances of mass wasting events due to a smaller Factor of Safety (Shields et al., 2009). The Factor of Safety is a measure of the risk of failure of a streambank and is the shear strength of the soil divided by the shear stress of the soil (Brooks et al., 2003). The shear strength is the total strength of the soil and the shear stress includes gravitational and shear forces from water movement. Large values indicate stable streams while values near one indicate danger of bank collapse. Inundated soil has a smaller Factor of Safety because the numerator, or soil cohesion, is reduced while the denominator, or soil stresses, remains unchanged (Brooks et al., 2003). By dewatering a soil region, pore pressure decreases. This increases the shear strength of the soil, increasing the Factor of Safety (Shields et al., 2009). Vegetation will absorb water and effectively dewater a streambank through natural processes. If the bank is not inundated, vegetation can thrive throughout the growing season, which increases streambank stability by promoting root growth (Wynn et al., 2004). Rain and other sources of water are able to infiltrate or become absorbed by vegetation, reducing damage from floods or storms. Vegetation can be an important factor in increasing the overall resistance to erosion of a streambank by removing water.

Freeze-thaw cycles can destabilize soil structures and reduce cohesiveness from the expansion of ice crystals. Water that expands as it freezes, causing damage to the surrounding soil. Freeze-thaw cycles can be particularly damaging because the water will damage soils every time it freezes (Wynn and Mostaghimi, 2006a). Plants can reduce freeze-thaw damage by extracting water from the soil. This reduces the amount of water that can expand, thereby reducing the amount of damage caused during freeze-thaw cycles (Shields et al., 2009). The severity and amount of damage depends on climate and soil type (Wynn and Mostaghimi, 2006a). Regions with a greater number of frost prone days are more likely to experience freezing damage. This damage can be more or less severe depending on the soil type. Sandy soils have greater drainage and less moisture, whereas clay soils retain much of their moisture and are at a greater risk for frost damage.

Soil properties can have a vast influence on the susceptibility of a streambank to erosion and degradation. In many cases the most significant factor effecting streambank erodibility is the bulk density of the soil material (Wynn and Mostaghimi, 2006b). It is a composite measure that accounts for several soil properties such as drainage, soil cohesion, and root penetration. High bulk density soils tend to have smaller particle sizes, which creates higher cohesion and attraction between particles. Low bulk density soils drain water very easily, often creating dry conditions for plants. Moisture affects the ability of roots to provide stability and reduces damage from freezing (Pollen, 2006). Roots gain resistance to pull out when there is more surface area for root hairs to attach and anchor to (Wynn and Mostaghimi, 2006b). Deeper soils tend to have higher bulk density from compaction and gravitational forces where roots are also much scarcer (Piercy and Wynn, 2008). Large tree roots are greatly affected by the type of soil in which they grow. Trees that grow in thick soils, with high bulk densities, have much shallower root systems, often less than three feet deep (Crow, 2005). Lastly, freeze-thaw cycle and desiccation damage is related to the bulk density of a soil region. In soils with high bulk density, moisture can remain until freezing occurs. Due to the high cohesion and poor drainage of these soils, freeze-thaw cycles can be particularly damaging (Natural Resources Conservation Science, 2013). Since the soil drains very poorly, water is abundant, creating large areas of ice damage. Additionally, cohesion in these soils is much tighter, since the soil particles are much smaller. Disrupting these close knit soil particles can greatly decrease the cohesion (Wynn and Mostaghimi, 2006a). This can be contrasted with low bulk density, or sandy soils. These soils drain easily and how low cohesion so much of their water is lost, causing danger of desiccation instead to streambanks (Wynn and Mostaghimi, 2006a). Desiccation can also cause instability and increase the possibility of bank failure (Wynn and Mostaghimi, 2006b). Dry soils can fracture, causing loss of attraction between nearby soil particles. Fractured soil is unsteady and easily eroded, since it is detached from the remaining streambank. Therefore it is important to understand the soil properties of a streambank to understand how erosion can occur in that region.

Herbaceous vegetation can provide many benefits to short streambanks. Herbaceous roots tend to be small and dense, providing a network of stability for soil (Piercy and Wynn, 2008). Typical riparian species have short rooting depths, for example Horsetail (*Equisetum arvense*) has a maximum rooting depth of 3 meters and

Goldenrod species (*Solidago spp.*) typically have maximum rooting depths of 3.5 meters (Canadell et al., 1996). However, most of the nutrients and organic material in riparian areas is situated in the top thirty centimeters of the soil and root growth is most concentrated in the same top thirty centimeters (Kiley and Schneider, 2005). Below fifty centimeters of soil there is usually almost no root growth. Other studies have measured root depth to one meter, however the amount of roots at these depths is very small (Wynn et al., 2004). Soil properties, such as soil type, drainage, density, and inundation, can also influence the amount of root growth.

Other properties such as depth to water table, depth to an impermeable surface, season, and disturbance can influence herbaceous root density. Roots will only grow in an area if there are sufficient nutrients or water for plant growth. Root growth is very limited below one meter because nutrients are scarce and inundation is common (Wynn et al., 2004). A water table halts root growth because roots cannot retrieve nutrients or air while completely immersed in water. Instead they will grow near a water table to obtain nearby water. A shallow water table will cause roots to grow laterally instead of vertically (Weaver, 1968). Impermeable surfaces, such as bedrock, inhibit root growth in a similar manner.

Herbaceous root growth and density also change temporally. Root biomass growth peaks in late August as available sunlight and day length are maximized for plant uptake (Kiley and Schneider, 2005). As day length shortens and temperatures drop plants release seeds and senesce in order to avoid the harsh cold winter. Then, new seeds will grow in the spring and peak in August and prepare for the winter again. The depth and amount of roots will decrease as the season progresses until late August when senescence occurs, especially for annual plants (Wynn et al., 2004). Therefore, root mass can be highest mid-summer, and lowest during late fall and early spring.

Disturbances greatly affect the variability and abundance of herbaceous root density. This is caused by aboveground or belowground damage to soil properties. Freeze-thaw damage is an example of a belowground disturbance that reduces root abundance. Storms and fires are aboveground disturbances that can decrease the amount of vegetation and soil protection, which also reduces root abundance (Kiley and Schneider, 2005). Many factors can affect root growth, but impermeable layers, seasonal factors, and changes caused by disturbances have the most dramatic and long lasting effects.

There are many different ways to measure root growth, each with its own strengths and weaknesses. Root Volume Ratio (RVR) measures the total volume of all the roots present in a sample over the volume of soil in that sample (Wynn et al., 2004). This measurement was often used in older studies of root distribution. However, this measurement tends to bias larger roots. Larger roots have a greater volume individually, which increases the volume of the sample even though fewer root fibers exist (Wynn et al., 2004). Biomass is also often used to measure root abundance. Roots are weighed to obtain mass of just the biological matter, which will bias larger roots that have a greater mass. However, this measure can be determined as a ratio of root to shoot biomass (Zedler, 2007). This measure can give a better indication of the type of habitat and structure provided by individual species since different habitats and species require more or less root density. For example, species with high root to shoot ratios could be used for erosion control because they anchor soil better and are better protected from uprooting

(Zedler, 2007). Root Length Density (RLD) measures the length of roots in a volume of soil. RLD is advantageous because it is a better measure of the number of roots in a sample, without being affected by larger or heavier roots (Wynn et al., 2004). RLD is able to compare large root abundance and small root abundance without biasing larger, heavier roots.

Woody plant species have greater rooting depth, stronger roots and lower root density than most herbaceous plants. Woody plants, especially trees, extend their roots 3 m into the ground unless an impermeable surface or water table restricts growth. A majority of this root growth exists in the top 60 cm (Crow, 2005). While this is not as deep as trees are commonly believed to extend, it is deeper than herbaceous plants, which are concentrated in the top 30 cm or shallower (Wynn et al., 2004). This is due to many of the same factors that inhibit herbaceous root growth including inundation, an impervious surface, and soil type (Piercy and Wynn, 2008). Tree species can have very different root depths based on species characteristics. For example, aspen trees (*Populus spp.*) have a typical root depth of about 2.5 meters while walnut trees (*Juglans spp.*) can typically reach a depth of about 4 meters (Crow, 2005). The environment can greatly influence this depth, and maximum rooting depths may be much greater depending on soil properties. Maximum shrub rooting depths are typically shorter than trees, for example a group of shrubs known as bird cherries (Prunus spp.) have maximum rooting depths of about 2 meters (Canadell, 1996). Age is another characteristic that greatly drives tree root production. Older, larger trees have deeper and longer root systems than smaller, younger trees (Wynn et al., 2004). The age and amount of aboveground biomass can greatly affect the amount of belowground biomass for individual trees (Crow, 2005).

Since woody plant roots are longer, they must also be thicker to transport more nutrients and provide greater support to the plant. Thicker roots will provide greater stability to a streambank because the stress required to break, straighten, or pull out each root is much greater. However, the root density of woody plants is often lower than herbaceous plants. This could limit the effectiveness of woody roots, since the coverage provided by the thicker roots is much less.

It is important to understand soil properties, root differences, and bank stability factors because they can be used to improve restoration activities involving bank erosion. Restoration efforts can range from buffer species recommendations to entire channel re-meandering and engineering (DeWall, 2009). Vegetation can be used to stabilize streambanks for buffer strips, or in conjunction with a larger restoration project. Roots from plants can provide mechanical stability, reduce stress from inundation, eliminate damage from freeze-thaw cycles, and naturally regrow every year (Pollen and Simon, 2005). Vegetation and root structures can be used to stabilize soil eroding reaches depending on the size and type of restoration desired.

Restoration efforts using vegetation need to consider soil type when planning a stabilization project. Bulk density can explain much about soil conditions that affect erosion rates. Sandy soil with low bulk density values tend to erode more easily because they have low cohesion and poor soil structure (Wynn and Mostaghimi, 2006b). Roots will greatly enhance the cohesiveness and structure of these soils, because of the mechanical properties roots provide to streambanks (Pollen and Simon, 2005). Small, dense roots may provide the most benefit because they will stabilize erodible soils with network of roots in the top portion of the streambank (Wynn and Mostaghimi, 2006b).

Soils with moderate bulk density values will also benefit from roots. Cohesion and structure are stable in these soils, but frequent freeze-thaw cycles will disrupt this stability. Vegetation will reduce water availability and reduce the damage or stress caused from expanding ice (Shields et al., 2009). Shallow herbaceous roots will withdraw the most water in the top layers of the soil. Deeper roots would increase infiltration of water into deeper soils, away from streambanks (Zedler, 2007). Trees and herbaceous plants would decrease erosion in moderately dense soils vulnerable to freeze-thaw cycle damage (Wynn and Mostaghimi, 2006a). Clay and loamy soils would greatly benefit from vegetation that can remove damaging moisture and frost. However, soils with very high bulk density values are very stable and cohesive (Natural Resources Conservation Science, 2013). Roots do not penetrate well into this type of soil, but stability is already so high that vegetation may not improve stability, unless freeze-thaw damage is very prevalent. Therefore, vegetation will prevent different types of erosion, depending on the soil type and prevalent erosion issues.

Differences in River Qualities

Restoration efforts can vary along a river. Headwater reaches have different compositions and stresses than lower reaches of the same river. Three main erosion processes occur in each river corresponding to each section of the river. Subaerial processes dominate headwaters reaches, Fluvial entrainment dominates middle reaches and lower reaches are prone to mass failure. In order to reduce erosion each section requires unique restoration approaches to counteract the unique types of erosion.

The headwater reaches of a watershed are typically very small streams with short streambanks. Subaerial processes, such as wind thrown trees, increased stress from large woody debris, and freeze-thaw damage, dominate these reaches (Abernethy and Rutherfurd, 1998). Wind throw erosion occurs when trees or other large structures tip into the stream, usually due to wind. As they fall into the stream they uproot soil and deposit it in the stream itself (Abernethy and Rutherfurd, 1998). This type of erosion is common in headwater reaches because the water table is very shallow and freeze-thaw damage is common (Wynn et al., 2004). Since the streambanks are not tall enough to support deep root systems, tree roots cannot extend into the soil. Shallow root systems lead to unstable trees that are more easily knocked over during strong winds. Additionally, since the streams are often smaller, objects in the river can have a profound effect. Large woody debris can deflect flow from its normal path directly into a streambank (Abernethy and Rutherfurd, 1998). Large amounts of localized erosion will occur where large woody debris interferes with the normal flow of a stream. Freeze-thaw cycles can also significantly affect the stability of lower reach streams (Wynn and Mostaghimi, 2006a). Disruptions of soil structure can occur because moisture is available from a shallow water table. This moisture can cause damage during freeze-thaw cycles that reduces the stability of trees and soil. Freeze-thaw cycles break apart cohesive soils and uproot small plants (Abernethy and Rutherfurd, 1998). This can leave a streambank vulnerable and exposed during floods and storm events, increasing erosion from high flows. Headwater reaches need restoration efforts that address wind throw, flow deflection by large woody debris, and protection from freeze-thaw damage (Abernethy and Rutherfurd, 1998).

Middle reaches of a stream erode primarily from fluvial entrainment, or single particle erosion (Abernethy and Rutherfurd, 1998). The flow from upstream is more than headwater reaches, causing higher banks and faster flows. The shear stress from the water is not usually enough to erode entire sections of a river, however continuous erosion particle by particle causes slow, but steady erosion (Abernethy and Rutherfurd, 1998). Wind throw and large woody debris are usually not significant problems in these reaches because of the increase in stream size. Trees and other woody plants can extend their roots to a greater depth, making them less susceptible to toppling (Crow, 2005). Debris that is present in a river does not increase erosion as much because the increased width and depth allows flow to circumvent obstacles, instead of deflecting most of the flow into a streambank (Abernethy and Rutherfurd, 1998). Freeze-thaw damage can still affect these reaches depending on the soil type. Disruption of soil cohesion in the upper layers of the soil from frost damage can increase the amount of fluvial erosion occurring, especially during high floods (Wynn and Mostaghimi, 2006a). Sandy soils may not be as prone to this damage since the drainage is generally very high, but silty and clay soils are still vulnerable to freezing damage. These regions would likely benefit from a combination of woody and herbaceous plant material. Herbaceous plants can stabilize soil particles and protect streambanks from temperature changes. Woody plants provide strength during flooding or periods of heavy rainfall with larger and deeper roots (Wynn et al., 2004). Trees and herbaceous vegetation withdraw moisture along the entire bank face, reducing the amount of water in the soil that could cause damage during the fall and spring seasons. Middle reaches could benefit from a mixture of herbaceous and woody vegetation for restoration.

The lower reaches of a river are most susceptible to mass failure (Abernethy and Rutherfurd, 1998). Lower reaches of a river have very large flows as all the upstream flows become concentrated in the lower reach. This input of very water causes high banks and very wide rivers. Just as in the middle reaches, because of this height and width increase, large woody debris and wind throw erosion is not very significant (Wynn et al., 2004). As bank height increases, the bank is subjected to a larger amount of stress. These stresses are primarily from gravity and increases in water volume during high flows. This is because inundated soil loses shear strength, cannot bind as easily, and becomes more likely to fail (Pollen, 2006). Mass failure is a result of increased bank height and inundation from increased flow.

Different portions of a river are more vulnerable to mass failures. Outer bends of meanders are particularly vulnerable to mass failure because the amount of stress on the bank is greatly increased from deflected flow (Brooks et al., 2003). When the stress placed on a bank becomes too great, it can erode large amounts of sediment across a streambank. Additionally, stratified soil layers may play an important role in creating dangerous conditions where mass failures may occur (United States Environmental Protection Agency, 2012). When water that tries to percolate to the water table and meets a resistant layer, such as clay or bedrock, it is forced laterally out of a streambank (Pollen, 2006). The water inundates the streambank, causing instability, and increases the stress on nearby soil particles (Wynn et al., 2004). When a portion of a streambank erodes due to stratified layers, surrounding layers fail and erode as well. Predicting this type of failure is difficult because the seepage from stratification is imperceptible unless using special equipment. Infrared cameras can detect changes in temperature caused by water flowing laterally out of river, but little research has been done to estimate the frequency of this particular phenomenon. Due to the variety and range of stresses, it can be difficult to predict mass failure events for a large river.

Subaerial erosion often occurs in the headwaters, but other sections can experience this type of erosion, too. Subaerial processes are typically dominant when the water table is very high, therefore regions with a very shallow water table may be vulnerable to subaerial erosion (Abernethy and Rutherfurd, 1998). This may commonly occur when plant growth is impeded by an impermeable surface, such as bedrock, near the surface. The bedrock may create a water table that is very shallow in that region. Many other causes can increase the amount of subaerial erosion, such as a riparian wetland with a shallow water table, narrow or shallow streams due to soil type, and streambanks with very poor drainage (Wynn and Mostaghimi, 2006a). This framework for headwater erosion can be used in other parts of the river that have similar characteristics.

Middle reaches are primarily dominated by fluvial entrainment, but other reaches can be vulnerable to this type of erosion, too. The water table in middle reaches is often deeper than headwater reaches, but if a headwater area has a deep water table, then fluvial entrainment may become dominant (Abernethy and Rutherfurd, 1998). This can occur if the soil is sandy and drains well. Since the water drains quickly, the water table is deeper, shifting erosion towards fluvial entrainment. Likewise, shallow water tables on lower reach banks can shift erosion from mass wasting to fluvial entrainment. Since fluvial entrainment is a medium between subaerial and mass wasting processes, it can occur when the water table is not shallow and the stream is moderately sized.

Lower reaches are prone to mass wasting due to increased bank height, but this type of erosion can occur in other reaches. Reaches with very tall banks typically experience mass wasting due to the increased stress from gravity (Brooks, et al., 2003). However, if a stream in a headwater or middle reach has a tall streambank it can be prone to mass wasting as well. This often occurs when rivers erode into a valley wall causing bluffs to form. Stratification of soil layers can also decrease streambank stability and shift erosion towards mass wasting in smaller streams (United States Environmental Protection Agency, 2012). Large, unstable banks are prone to mass wasting, no matter which river section they occur.

Chapter 2: Root and Vegetation Differences in the Buffalo River, Elm Creek, and the Whitewater River

Introduction

Vegetation plays a large role in reducing erosion and improving streambank stability. Plants can provide surface protection that reduces damage from temperature changes and protects from freezing. Plant roots provide mechanical stability, reduce stress from inundation, and stabilize aboveground vegetation structure. Diverse root structures create unique differences in streambank stability, and soil strength depending on the type of vegetation. Understanding how plant and root properties can be used to inform restoration and land use activities would improve the effectiveness of conservation.

Information about root strength and soil properties are needed when considering restoration efforts in a stream reach. For larger banks it may be more beneficial to have longer, thicker roots that provide deeper and stronger support. Smaller banks may benefit more from smaller, denser roots that protect a streambank like a web (Abernethy and Rutherfurd, 1998). Soil type can have a profound effect on the erosion since dense soils are already resistant to erosion, but sandy soils may need additional protection to reduce erosion (Wynn and Mostaghimi, 2006b). Herbaceous vegetation and woody vegetation can play a role in both of these situations. They each have different advantages and disadvantages that are important to consider when attempting a restoration project.

In this study roots were extracted from the soil to understand differences between regions and vegetation types. BEHI values and BEHI parameters were used to test the relationship between roots, vegetation and erosion prediction. Additionally, root density was compared across regions, river sections, vegetation type, and soil properties to identify if any additional properties may influence erosion rates.

Hypotheses

H1: There is a larger quantity of roots present in the top 30 cm of the soil than any other depth of soil.

H2: There are more roots present in forested sites than shrub dominated sites, which have a greater amount than the herbaceous sites.

Materials and Methods

Site Characteristics

Three rivers are the main focus of this study; the Buffalo River, Elm Creek, and the Whitewater River. Each of these rivers resides in a different ecoregion of Minnesota; the Glacial Lake Plain of Northwest Minnesota, the Glacial Till region of South Central Minnesota, and the Loess region of Southeast Minnesota (Dingmann et al., 2012; United States Department of Agriculture, Blue Earth; United States Department of Agriculture, Buffalo-Whitewater). However, within each region three main subsections divide each river based on land use, soil type, elevation changes, and other differences. These differences change the amount and type of erosion that occurs.

The Buffalo River starts at Tamarac Lake and flows west 88 miles into the Red River of the North (Google Earth, "Buffalo River Sites", 2012). The South Branch of the Buffalo River starts in northeastern Minnesota, south of Barnesville, and flows north joining the Buffalo River near Glyndon. Precipitation rates in the Buffalo Watershed range from 21 to 25 inches annually (Dingmann et al., 2012). This rainfall is concentrated in the spring during snowmelt and heavy rains. The period of frost free days ranges from 111-136 days during the year (Dingmann et al., 2012). Much of the rest of year is prone to freezing, with freeze-thaw cycles prevalent during the spring and fall months. The three main sections of the Buffalo River are mostly influenced by the soil type, land use, and streambank size. The upper reach is dominated by natural landscapes and small rivers. The middle and lower reach contains agricultural land, with a corresponding increase in river size. The soil type transitions from sandy soils in the headwaters to clay in the lower reaches. In order to reduce erosion and understand the mechanisms behind every stress, each region in the Buffalo River needs to be studied separately. Flooding, freeze-thaw damage, land use, soil type, and vegetation are important considerations for each region of the Buffalo River to determine the possible erosion for each section.

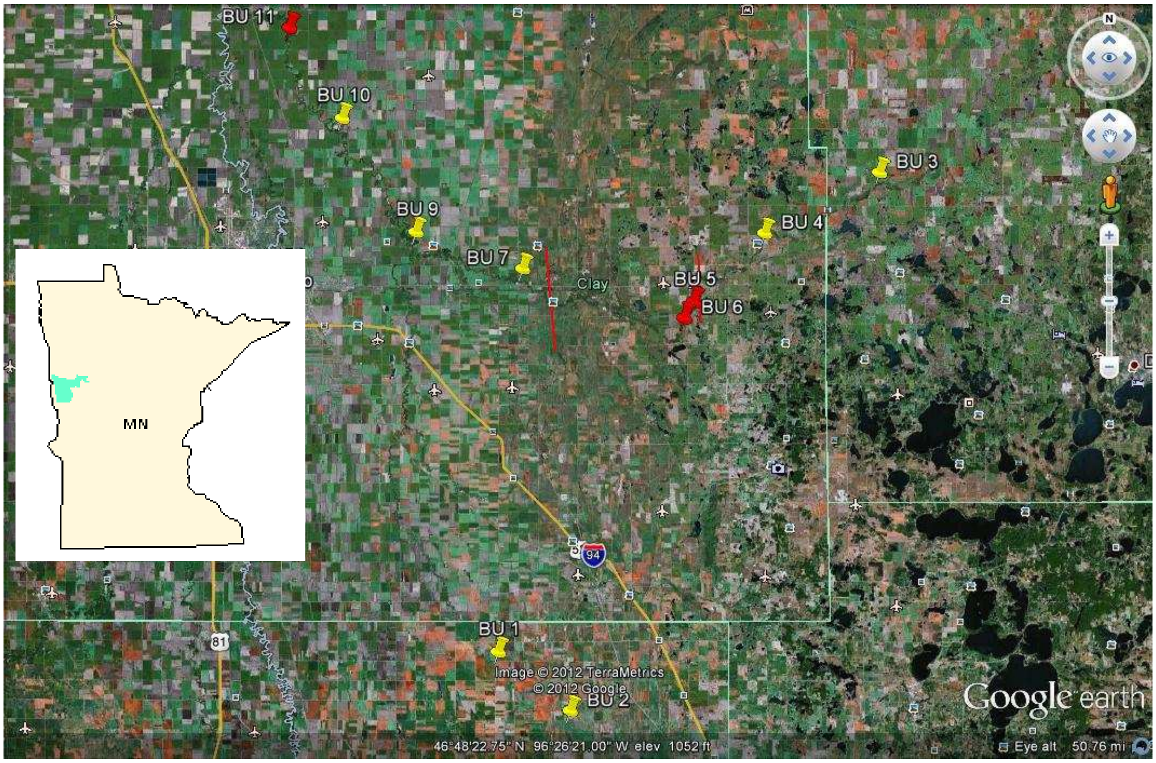


Figure 1. Buffalo River Watershed. The red lines denote the separation between river sections. (Source: Google Earth. "Buffalo River Sites." 46°48'22.75" N and 96°26'21.00" W. October 10th, 2012. Retrieved September 10th, 2012 and United States Environmental Protection Agency, 2013)

Buffalo river resides in three separate ecoregions of Minnesota in the northwest portion of Minnesota (see Figure 1). The headwaters reach of the Buffalo River consists mainly of prairies and woodlands with well drained soils (Dingmann et al., 2012). The most headwater portion of the Buffalo River exists in the Northern Lakes and Forests Ecoregion which consists of natural coniferous and hardwood forests (Dingmann et al., 2012). Most of the remaining headwaters area resides within the North Central Hardwood Forest Ecoregion of Minnesota (Dingmann et al., 2012). The geomorphology of this region is well drained sandy or silty moraine and other glacial deposits. Freeze-thaw damage is not widespread in this region because of the vegetation and sandy soils. Sandy soils drain water quickly and the natural vegetation actively removes water from the top layer of the soil, reducing the damage caused by freeze-thaw cycles. This region typically exhibits low erosion rates due to the small size of streams and the natural settings that provide stability from erosive forces.

The lower reaches of the Buffalo River differ greatly from the headwaters region because of changes in land use and soil type from naturally vegetated Glacial Till to agricultural Glacial Lake Plains near The Red River of the North (Dingmann et al., 2012). This change in ecoregion is very significant because it affects the hydrology and drainage of the landscape. The soil becomes very thick as small clay particles dominate the landscape. Water from the land cannot infiltrate into the thick clay soils, and it flows very slowly due to the flat terrain (Wynn and Mostaghimi, 2006b). Flooding and saturation are common (Dingmann et al., 2012). Thick clay limits the amount of vegetation growth, but also increases cohesion in the soil. Cropland and pasture compose a majority of the land use in the lower reaches, causing the dominant vegetation type to be crops such as corn and soybeans (Dingmann et al., 2012). Some natural grassland does exist in this region, providing protection against frequent flooding and runoff. The thick clay soils strengthen the streambank, but freeze-thaw cycles may damage soil structure since water drains very poorly in this region (Natural Resources Conservation Science, 2013). Land use and soil type play dominant roles in affecting the amount of erosion in the lower reach of the Buffalo River.

The middle reaches of the Buffalo River are a gradient of land use and soil type between the upper and lower reaches. The land use is mainly agriculture, but there are some regions of natural forest and prairie (Dingmann et al., 2012). Towns and state lands make up the majority of the remaining landscape. The soil in this region can vary from sandy outwashes to thick clay deposits (Dingmann et al., 2012). Many differences exist within the middle reaches of the Buffalo River, but erosion is usually highest in this part of the river. Soil type can vary, but often these soils are prone to erosion and freeze-thaw damage since drainage is poor. Agriculture and silty soils contribute to the instability of the streambanks in this region.

Elm Creek is an agricultural stream in sandy glacial till soil that flows from south central Minnesota east into the Blue Earth River (Google Earth, “Elm Creek Sites”, 2010). Precipitation in this watershed is consistently 27 to 31 inches annually (United States Department of Agriculture, Blue Earth). The landscape for this region consists of glacial till plains with short slopes and loamy soil with moderate drainage, except where prairie pothole wetlands form (United States Department of Agriculture, Blue Earth). Artificial drainage is common in many areas where prairie pothole wetlands historically occurred. The drainage has increased the hydrology of the stream, creating increased potential for unstable conditions. The dominant natural vegetation for this region is prairie grass, with little or no forested areas present (Lenhart et al., 2010a). The temperature can range from 105°F in the summer to -30°F during the winter (Minneosta Pollution Control Agency). Freeze-thaw damage is a concern for many regions that contain silty soil material because the soil drainage is often poor and moisture will collect and freeze during the winter (Wynn and Mostaghimi, 2006b). This river can be divided into three reaches based on land use and drainage area.

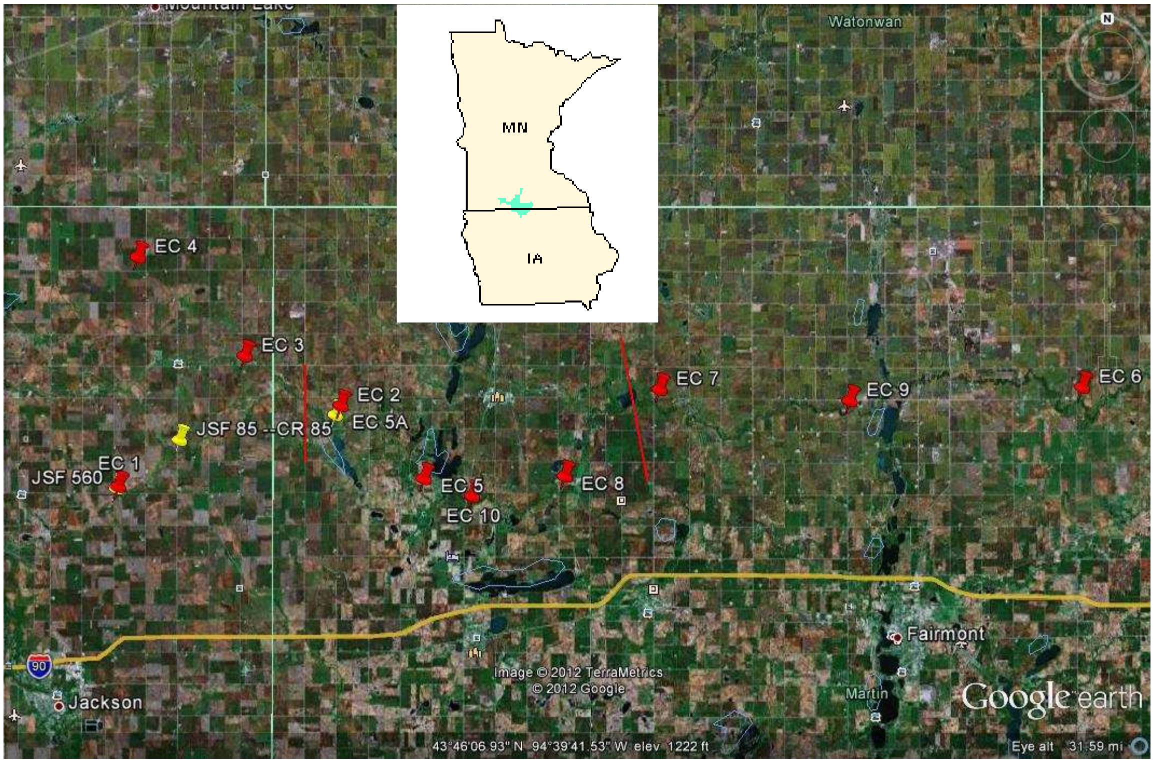


Figure 2. Elm Creek Watershed. The red lines denote the separation between river sections. (Source: Google Earth. "Elm Creek Sites." 43°46'06.93" N and 94°39'41.53" W. June 23rd, 2010 Retrieved September 10th, 2012 and United States Environmental Protection Agency, 2013)

The headwaters region of Elm Creek contains small tributaries with little drainage area. Drainage from nearby fields causes changes in hydrology, such as flash floods and increased water levels (Lenhart et al., 2010b). These changes cause reduced shear strength of soils as inundation and drying constantly affect the streambank. Inundation reduces the ability of soil particles to bind together and desiccation causes soil particles separate and fracture (Pollen, 2006). Freeze-thaw damage can be problematic if soil conditions stay wet during colder months.

The middle reaches of Elm Creek have taller streambanks because many of the small tributaries have joined into the main stem of the river with towns and farming making up the land use (Lenhart et al., 2010b). Since the soils are still loamy and prone to damage from various causes, the middle reach is very vulnerable to erosion. The increased flow from agricultural drainage increases the potential for erosion on unprotected streambanks (Lenhart et al., 2010a). Increased stress from inundation and shear forces causes bank instability in the middle reach.

The lower reach of Elm Creek has even taller banks and land use is still primarily agriculture (Minneosta Pollution Control Agency). This creates many problems similar to the headwaters and middle reaches, but on a much larger scale with greater flows and larger floods. Inundation of streambanks is common during high rainfall events and floods. This can decrease cohesiveness within the streambank until conditions change (Pollen and Simon, 2006). Freeze-thaw damage can be problematic for surface soil layers, but lower layers are insulated from damage by soil above. However, flooding and increases in hydrology upstream can create unstable conditions in the lower reaches of Elm Creek.

The Whitewater River begins east of Rochester and travels east into the Mississippi River just north of Winona (“Whitewater River Sites”, 2011). The land use and soil type of this river differs greatly from the previous two rivers since it lies mainly in the Loess Driftless region (United States Department of Agriculture, Buffalo-Whitewater).This region is characterized by many hills and valleys with shallow soils over bedrock with silty or loamy soil (United States Department of Agriculture, Buffalo-Whitewater). The Whitewater River receives between 31 and 33 inches of rain annually (United States Department of Agriculture, Buffalo-Whitewater). The soil is generally well drained, so this precipitation often infiltrates and flows into nearby streams through groundwater (United States Department of Agriculture, Buffalo-Whitewater). The average growing season is 150 days and much of the rest of the year is prone to frost or freezing damage (Johnson, 2010). Land use, vegetation, and stream power are affected by slope changes in this watershed. The headwaters region of the Whitewater River is very flat with glacial till soils, and slow streams. Agriculture and pasture dominate the landscape since the glacial soils are fertile. As the river moves east it steepens. The soils become the silty, windblown material typical of Loess regions (United States Department of Agriculture, Buffalo-Whitewater). Deposition and agriculture is rare in the steep middle reaches due to the increases in slope. Instead, natural forestland dominates the landscape because of the Whitewater State Park ("Whitewater River Sites", 2011). The lower reaches flatten out, changing the landscape and allowing agriculture to use the land again (Johnson, 2010). The soil accumulates some sediment from upstream as the river becomes a fertile floodplain. The soil is shallow in many places, but can be productive. Land use, vegetation, and soil type are all affected by the slope changes in the Whitewater River.

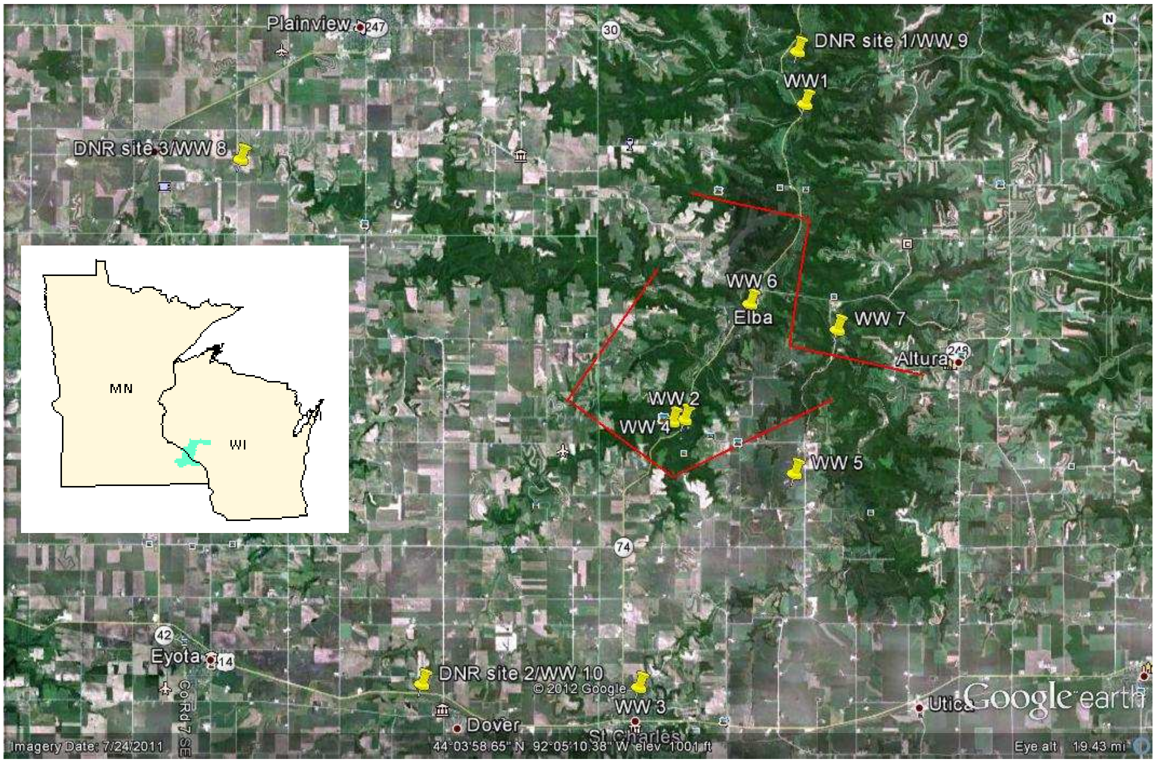


Figure 3. Whitewater River Watershed. The red lines denote the separation between river sections. (Source: Google Earth. “Whitewater River Sites.” 44°03’58.65” N and 92°05’10.38” W. July 24th, 2011. Retrieved September 10th 2012 and United States Environmental Protection Agency, 2013)

The Whitewater River resides in the southeastern portion of Minnesota (see Figure 3). The headwater reaches of the Whitewater River differ from the other reaches in elevation, land use, and soil type. This part of the river is significantly flatter with fewer elevation changes than the remaining river, causing slower streams with more meanders. The land use is primarily crop farming, pasture land, and towns (United States Department of Agriculture, Buffalo-Whitewater). The soils in this region are typically loamy or sandy, depending on smaller scale glacial or loess deposits (United States Department of Agriculture, Buffalo-Whitewater). The small streams in this area have small banks which allow stable streams that should require little restoration to exist. Very little shear force affects the streambanks due to the flat terrain. Some of the headwaters streams are affected by glacial deposits, creating various sandy or silty soil deposits (United States Department of Agriculture, Buffalo-Whitewater). These deposits influence the damage caused by freezing and the cohesive strength of the streambank.

The middle reach of the Whitewater River resides mainly in the Whitewater State Park, with corresponding changes in elevation, land use, soil type, and drainage area. As the river flows east towards the middle reaches, it increases in slope creating higher velocity streams (Brooks et al., 2003). As velocity increases, the shear strength of the water flow increases, increasing erosion rates. However, since the slopes are so steep, much of this region is not productive farmland. Natural landscapes reduce erosion by providing abundant protection from stresses and providing support to the soil. The soil in this region transitions from glacial till soils to loess windblown material (United States Department of Agriculture, Buffalo-Whitewater). This soil tends to be silts and loams that provide some stability, but are vulnerable to inundation and freeze-thaw damage. The natural vegetation and lack of human influence in the middle reach of the Whitewater River creates a stable river system.

The lower reach of the Whitewater River experiences an entirely different set of land use activities, elevation changes, and changes in soil type. As the river continues east into the lower reach the elevation flattens into a floodplain, becoming fertile lands for agricultural practices. In addition to scattered farmland, a road system runs adjacent to the river for much of the lower reach's path ("Whitewater River Sites", 2011). The streambank matieral remains windblown loess material., but as the river nears the Mississippi River, the soil layer becomes shallower, with karst causing instability and small landslides or sinkholes are possible (United States Department of Agriculture, Buffalo-Whitewater). The river increases to a very large size in this area, to accommodate for large flows from upstream and groundwater. These factors contribute to the lower reach being unstable and experiencing much erosion.

Field Data Collection

The three watersheds described above were chosen in order to evaluate differences in climate, vegetation, soil type, and ecoregion. Each watershed was divided into three sub regions; a lower, middle, and headwater region; based on differences of characteristics within each watershed. Each sub region received three sample sites and the final tenth sample site was used at each river to measure unique circumstances in the watershed, such as a city stream or a restored river section. Each site resided on a curve in order to test the erosion differences for similar reaches. Several sites were mapped before field data collection and on site analysis was used to determine site usability. Sites that were too difficult to reach, because of cliffs, thick forests, or distance, were excluded because of the large amount of equipment needed at each site. If the river was clearly on or near a house or farm field, permission was received before sampling started. Once the sites were selected, sampling and data collection could begin. See Figures 1, 2, and 3 for locations of sample sites.

Root samples were taken at the top of a streambank 1-3 feet from the outside edge of the curve in the river. Three depths were sampled in order to understand how root density changes with depth. The samples were taken every 30 cm in the soil. A PVC tube was used to extract the roots. The tube was hammered into the ground until it reached 30 cm. Then the tube was extracted and all the soil and attached particles, including roots, were stored in a plastic bag. This was repeated for 60 cm and 90 cm depths in the same hole. For thicker clay and silt soils or drier soils a bucket augur was used to extract the soil to the required depths. In these instances the radius and height of the soil excavated were carefully measured before being placed into a storage bag. Buffalo Site 7 and Whitewater Site 7 had impeding layers where an impervious layer restricted the progress of the PVC tube or augur, so deeper samples were not obtained. . Root samples were excavated from the ground, placed in a storage bag, and placed on ice until they could be returned to the University of Minnesota where they were frozen until sampled.

At each site a vegetation survey was conducted to measure the major plant communities and to assess which plants may provide stability to a streambank. Each survey was conducted using 300 foot long transect of the outer bend except for Buffalo site 7 which measured 220 feet. Half meter square quadrats were used to measure ground layer vegetation density and species composition. Each quadrat was placed randomly approximately every ten feet, except at Buffalo site 7, where the quadrats were sample at approximately 23 foot intervals. In each quadrat relative percent of coverage was assessed with one hundred percent coverage being the maximum. A graded cover technique was used where values were recorded in 5 percent gradients, except for densities below 10 percent which were measured in one percent intervals. Bare space was included in order to estimate the amount of un-vegetated soil within the river reach. Plants were identified to the genus or species level if possible. Unidentified species were collected and identified later using supplemental material if possible. Trees, any woody plant with a diameter at breast height (DBH) greater than .1/4 inch were also measured. If a tree stem grew within five feet laterally of the measuring tape the DBH was recorded.

Bushes, with less than a .1/4 inch DBH, were measured using coverage at breast height (CBH). Coverage measured the length of canopy that a bush provided in a small area. If there were multiple plants providing cover in a small area, it was noted while measuring CBH.

Many sites had woody vegetation, but it wasn't always clear what the dominant vegetation type was. If the density of tree stems was greater than a forest with trees planted 10 feet by 10 feet or 436 trees/acre, then it was considered a forested site. The stem equivalencies were derived from the Oak Ridge National Laboratory website (2008). The number of trees at each site was converted to an equal density of one acre and compared to the number of trees in a planted forest. The average DBH and standard deviation was also calculated to understand more about the measured trees.

Erosion rates were estimated using the WARSSS methodology, including BEHI and NBS measurements, outlined in the River Stability Field Guide (Rosgen, 2008). These measurements were performed on the outside bend of each site for consistent results. BEHI measurements involve seven separate parameters that are used to estimate the amount of erosion that may occur for a given streambank. These include ratio of bank height and bankfull height, root depth, root density, bank angle, surface protection, bank material. and soil stratification. These measurements were made by measuring bank height with an extendable rod and bank angle with a protractor tool. Root density was estimated visually on the bank face being studied. A broad region 5 feet wide was used to estimate the root density to the nearest 5 percent value. Surface protection was measured in the same area using the same methodology for vegetation covering the streambank. Then any other protection, such as woody debris, was included in the surface protection estimate for the same area. Bank material and stratification were estimated visually using soil cues and tactile estimates, such as color, amount of grit, and length of soil ribbon. An NBS value was also estimated using method 2 from aerial photographs. Method two requires measuring the radius of curvature of the stream curve to the width of the stream. Method 5 was also estimated at sites where cross sections were obtained using the ratio of bankfull depth to maximum near bank depth. The overall BEHI value and NBS value were used to calculate a final estimated erosion rate.

Soil cores were thawed and sieved using a No. 40 sieve, with openings 0.0165 inches (425 µm) and roots were sprayed with water to gently remove all the soil. In order to estimate root density a STD 4800 scanner and WINRHIZO software program were used to measure the root size and length. The WINRHIZO program calculated the length per volume of soil in centimeters per cubic meters (cm/m^3) and that value was converted into centimeters per cubic centimeters (cm/cm^3).

Bulk density samples were taken from the lower bank. These samples were pounded in the ground to a depth of 1-2 inches using a bulk density sampler of known radius and length. The bulk density samples were placed in plastic bags and transported back to the University of Minnesota where they were calculated by drying and weighing them. Some of the samples were frozen in storage until they could be dried and measured. Once all the data was retrieved, final calculations could begin. Many of the calculations were conducted using R statistical software. This software easily constructed ANOVA results using data obtained from this study. Microsoft Excel was used to construct other graphs and to obtain R^2 data for some calculations.

In order to estimate belowground biomass, the DBH measured during the vegetation surveys was used to estimate aboveground biomass. The DBH was estimated at the largest poosible value of .25 inches for shrubs. This should allow for the maximum amount of root mass at sites dominated by shrub plants. The aboveground biomass is calculated using the Jenkin's Model (Zhou and Hemstrom, 2009).

$$B_m = e^\wedge(b_0 + b_1 * \ln(DBH))$$

Where B_m is Aboveground biomass, DBH is the diameter at breast height in centimeters, and b_0 and b_1 are variables based on the species of tree used. This equation is most accurate for trees greater than 1 inch in diameter (Zhou and Hemstrom, 2009). Once the aboveground biomass was calculated it was converted into belowground biomass using a simple conversion of 25% of the aboveground biomass into belowground biomass (Cairns et al., 1997). This ratio can vary depending on tree type, species, soil type, water availability and nutrient availability. Using this belowground biomass estimate, tree root density can be compared between sites. Larger trees will have a much greater belowground biomass than smaller trees. Therefore, it is possible for a site dominated by very small trees to have a smaller belowground biomass than a site with few very large trees.

Results

Site vegetation composition is determined by many factors, ranging from disturbance to nutrient availability. Table 1 shows the dominant species and the sites where they are abundant. The dominant shrub species is the most abundant plant measured using CBH, while the dominant tree is the most abundant plant measured using basal area. Tree Density relates only the amount of trees present, while Woody Plant Density includes both trees and shrubs when calculating density. The dominant herbaceous species was Reed canary grass (*Phalaris arundinacea*), accounting for more than half of the herbaceous material at many sites in this study. Shrub species varied more than herbaceous species, but Red Osier Dogwood (*Cornus alba*) and Sandbar Willow (*Salix interior*) were the most common species seen in all three watersheds. Tree species did differ across the watersheds with Boxelder (*Acer negundo*) and Green Ash (*Fraxinus pensylvanica*) being the most common. Many other species were seen at the sites, but never in dominant amounts. These species include Smooth Brome Grass (*Bromus inermus*), Canadian Thistle (*Cirsium arvense*), Wood Nettle (*Laportea Canadensis*), Common Milkweed (*Asclepias syriaca*), Swamp Milkweed (*Asclepias incarnate*), and Common Buckthorn (*Rhamnus cathartica*)(see Appendix 2 for more information). Five forested sites were included in the study and the average tree DBH ranged from 7.41 inches to 0.8 inches. The standard deviation ranged from 7.2 inches to .5 inches. Eight sites were dominated by shrubs in the study. Seventeen herbaceous sites were present in this study, with the presence of trees and shrubs often ranging from absent to several trees along the transect.

Table 1. Plant Composition and Density for Each Study Site

Site	Dominant Vegetation Type	Dominant Herbaceous plant	Dominant Shrub plant	Dominant Tree	Tree Density (Trees/Acre)[1]	Woody Plant Density (Equivalent Trees/Acres)[1]
BU1	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	-	0	0
BU2	herbaceous	Reed canary grass (*Phalaris arundinacea)*	Red-Osier Dogwood (*Cornus sericea)*	-	0	363
BU3	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	-	0	0
BU4	herbaceous	Reed canary grass (*Phalaris arundinacea)*	Sandbar Willow (*Salix Interior)*	Boxelder (*Acer negundo)*	102	218
BU5	herbaceous	Reed canary grass (*Phalaris arundinacea)*	Gooseberry (*Ribes spp.)*	Boxelder (*Acer negundo)*	29	174
BU7	Shrub	Reed canary grass (*Phalaris arundinacea)*	Red-Osier Dogwood (*Cornus sericea)*	American Elm (Ulmus americana)	160	4011
BU8	Shrub	Reed canary grass (*Phalaris arundinacea)*	Sandbar Willow (*Salix Interior)*	-	0	3052

BU9	Forest	Sedge (*Carex spp.)*	-	Green Ash (*Fraxinus pennsylvanica)*	567	567
BU10	Shrub	Reed canary grass (*Phalaris arundinacea)*	Nannyberry (*Viburnum lentago)*	Basswood (*Tillia americana)*	392	945
BU11	Forest	Virginia Creeper (*Parthenocissus quinquefolia)*	Chokecherry (*Prunus virginiana)*	Boxelder (*Acer negundo)*	741	843
EC1	herbaceous	Tall Coneflower (*Rudbeckia Laciniata)*	Unknown Species	Silver Maple (*Acer saccharinum)*	102	116
EC2	Shrub	Reed canary grass (*Phalaris arundinacea)*	Red-Osier Dogwood (*Cornus sericea)*	Nannyberry (*Viburnum lentago)*	15	741
EC3	Forest	Reed canary grass (*Phalaris arundinacea)*	Chokecherry (*Prunus virginiana)*	Boxelder (*Acer negundo)*	3765	3837
EC4	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	-	0	0
EC5	herbaceous	Reed canary grass (*Phalaris arundinacea)*	White Mulberry (*Morus alba)*	-	43	43
EC6	Forest	Reed canary grass (*Phalaris arundinacea)*	Sandbar Willow (*Salix Interior)*	Black Willow (*Salix nigra)*	538	872

EC7	Shrub	Black Raspberry (Rubus occidentalis)	Red-Osier Dogwood (*Cornus sericea)*	Boxelder (*Acer negundo)*	377	581
EC8	herbaceous	Cultivated Crop (Hay)	-	-	0	0
EC9	herbaceous	Reed canary grass (*Phalaris arundinacea)*	Nannyberry (*Viburnum lentago)*	Boxelder (*Acer negundo)*	87	305
EC10	herbaceous	Horsetail (*Equisetum arvense.)*	-	-	0	0
WW1	Forest	Reed canary grass (*Phalaris arundinacea)*	Honeysuckle (*Diervilla spp.)*	Boxelder (*Acer negundo)*	538	1061
WW2	herbaceous	Goldenrod (*Solidago spp.)*	-	Black Walnut (*Juglans nigra)*	73	73
WW3	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	Black Walnut (*Juglans nigra)*	15	15
WW4	Shrub	Violet (*Viola spp.)*	Honeysuckle (*Diervilla spp.)*	Basswood (*Tillia americana)*	363	654
WW5	Shrub	Reed canary grass (*Phalaris arundinacea)*	Nannyberry (*Viburnum lentago)*	-	0	1380
WW6	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	Boxelder (*Acer negundo)*	15	15

WW7	Shrub	Reed canary grass (*Phalaris arundinacea)*	Common Elderberry (*Sambucus canadensis)*	American Elm (*Ulmus americana)*	407	785
WW8	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	Boxelder (*Acer negundo)*	87	87
WW9	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	Boxelder (*Acer negundo)*	160	160
WW10	herbaceous	Reed canary grass (*Phalaris arundinacea)*	-	-	0	0

[1]: Oak Ridge National Library, 2008.

Belowground Root Density was calculated using an empirical relationship derived from DBH and total aboveground biomass for forestry departments across many regions of the United States (Zhou and Hemstrom, 2009). Using this value a belowground biomass can be obtained. This number is in kg, but comparisons between sites can yield informative results about possible additions to root density values. Several sites; BU1, BU3, EC4, EC8, EC10, and WW10; had no tree or shrub plants, so the additional belowground biomass at these sites is zero. The greatest amount of biomass was at the herbaceous site EC 1 with 27,955.74 kg. This site also had the largest average DBH at 52.18 cm. WW3 had the second largest average DBH at 48.26, but there was only one tree at that site so the overall biomass remained low.

Table 2. Aboveground and Belowground Biomass of Woody Species at Every Site in the Study

Site	Dominant Vegetation	Aboveground Biomass (kg)[1]	Belowground Biomass (kg)[2]	Woody Species Average DBH (cm)
BU1	herbaceous	0.0	0.0	0.00
BU2	herbaceous	5.6	1.4	0.64
BU3	herbaceous	0.0	0.0	0.00
BU4	herbaceous	2157.4	539.4	9.88
BU5	herbaceous	208.7	52.2	1.86
BU7	shrub	1236.6	309.2	1.13
BU8	shrub	14.0	3.5	0.64
BU9	forest	9479.9	2370.0	18.82
BU10	shrub	15878.9	3969.7	14.39
BU11	forest	3864.1	966.0	10.23
EC1	herbaceous	27955.7	6988.9	52.18

EC2	shrub	13.7	3.4	0.67
EC3	forest	280.7	70.2	1.68
EC4	herbaceous	0.0	0.0	0.00
EC5	herbaceous	41.4	10.3	6.99
EC6	forest	4519.8	1130.0	4.48
EC7	shrub	4518.8	1129.7	10.01
EC8	herbaceous	0.0	0.0	0.00
EC9	herbaceous	1227.5	306.9	6.00
EC10	herbaceous	0.0	0.0	0.00
WW1	forest	3797.9	949.5	3.81
WW2	herbaceous	1632.3	408.1	19.91
WW3	herbaceous	1416.9	354.2	48.26
WW4	shrub	7714.4	1928.6	12.21
WW5	shrub	20.8	5.2	0.64
WW6	herbaceous	0.7	0.2	1.91
WW7	shrub	5616.2	1404.0	9.19
WW8	herbaceous	879.0	219.8	12.83
WW9	herbaceous	12209.7	3052.4	38.12
WW10	herbaceous	0.0	0.0	0.00

[1]: calculated using (Zhou and Hemstrom, 2009)
[2]: calculated using (Cairns et al., 1997)

The root length density measured in this study ranged from 0.11 cm/cm^3 to 6.38 cm/cm^3. The sample with the greatest root density was Whitewater site 6 at the 0-30 cm depth. The lowest root density was from Whitewater site 3 at a depth of 60-90 cm. For specific root density values see Appendix A: Raw Data from MDA Study. The root density values were significantly different between the 0-30 cm samples and the 30-60 cm samples (p-value= 0.0000001). The difference between the 0-30 cm samples and the 60-90 cm depth root samples was also significantly different (p-value= 0.000). There is no difference between the 30-60 cm sample and the 60-90 cm sample (p-value= 0.099) (see Figure 4). The average diameter for the 0-30 cm root sample is .3626 mm, the 30-60 cm average diameter is .3622 mm, and the average diameter for the 60-90 cm sample is .3778 mm (See Table 2 for individual values).

Table 3- Average Diameter of Root Samples for each Depth Category

	Average Diameter (mm)				Average Diameter (mm)		
Site	0-30cm	30-60cm	60-90cm	Site	0-30cm	30-60cm	60-90cm
BU1	0.3787	0.4856	0.4131	EC6	0.3173	0.3261	0.3149
BU2	0.3341	0.2909	0.4772	EC7	0.2487	0.3989	0.4294
BU3	-	0.3424	0.3505	EC8	0.2728	0.2477	0.2898
BU4	0.2767	0.3068	0.3114	EC9	0.3458	0.2781	0.3177
BU5	0.3773	0.3163	0.3229	EC10	0.2425	0.2363	0.3372
BU7	0.3576	0.4521	-	WW1	0.3745	0.4435	0.3915
BU8	0.4479	0.2903	0.2935	WW2	0.3503	0.2699	0.3737
BU9	0.3854	0.3575	0.3451	WW3	0.2921	0.4081	0.7114
BU10	0.4288	0.3539	0.2795	WW4	0.4810	0.5587	0.4995
BU11	0.4773	0.6694	0.5319	WW5	0.4507	0.3164	0.3720
EC1	0.3027	0.3186	0.5024	WW6	0.3307	0.2433	0.3195
EC2	0.2627	0.2836	0.2602	WW7	0.3181	0.3500	-
EC3	0.4427	0.3369	0.3033	WW8	0.3898	0.2727	0.2936
EC4	0.5804	0.4483	0.3764	WW9	0.4336	0.3281	0.4082
EC5	0.3330	0.3354	0.3367	WW10	0.2835	0.6002	0.4171

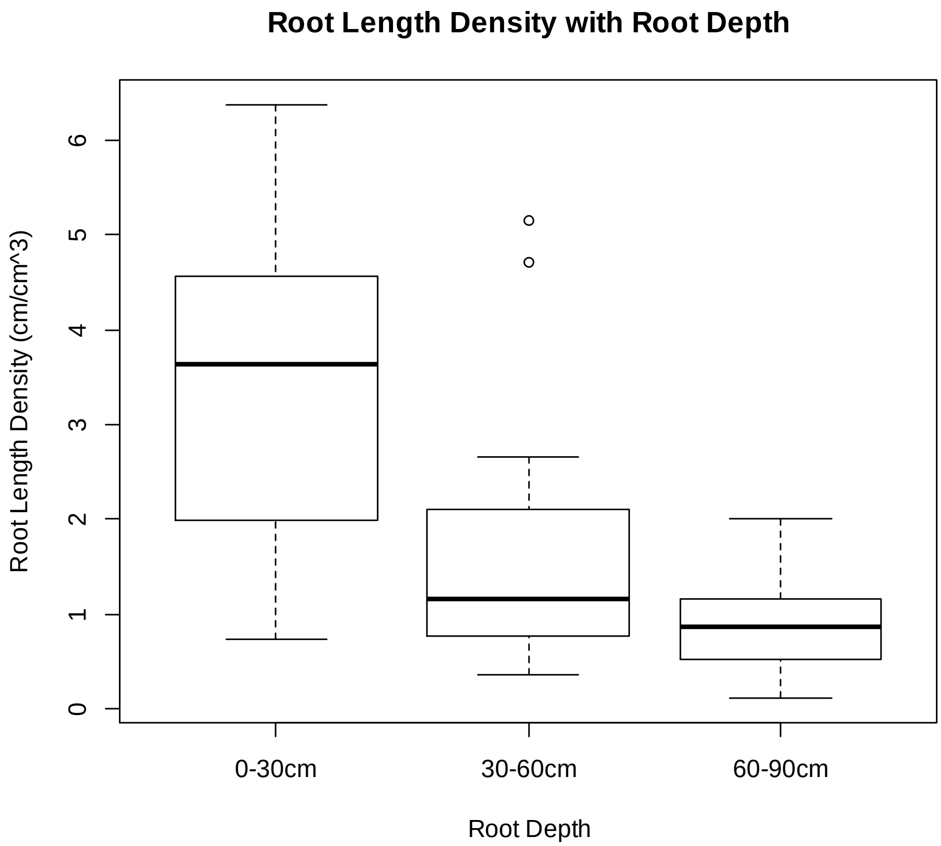


Figure 4. Differences in Root Length Density for each Sampled Depth Category

The RLD for each stream is similar (p-value= .51, see Figure 5). The difference between the RLD in the top 30 cm of each of the three streams is negligible. The average RLD in the top 30 cm is 3.4 cm/cm^3 in the Buffalo River, 2.9 cm/cm^3 for Elm Creek, and 3.8 cm/cm^3 in the Whitewater River. The Buffalo River and Elm Creek have very similar data points, while the Whitewater River has a much larger spread of data. This indicates larger differences in RLD in the top 30 cm at The Whitewater River than the other two rivers. However, the average RLD is still the same between all three rivers.

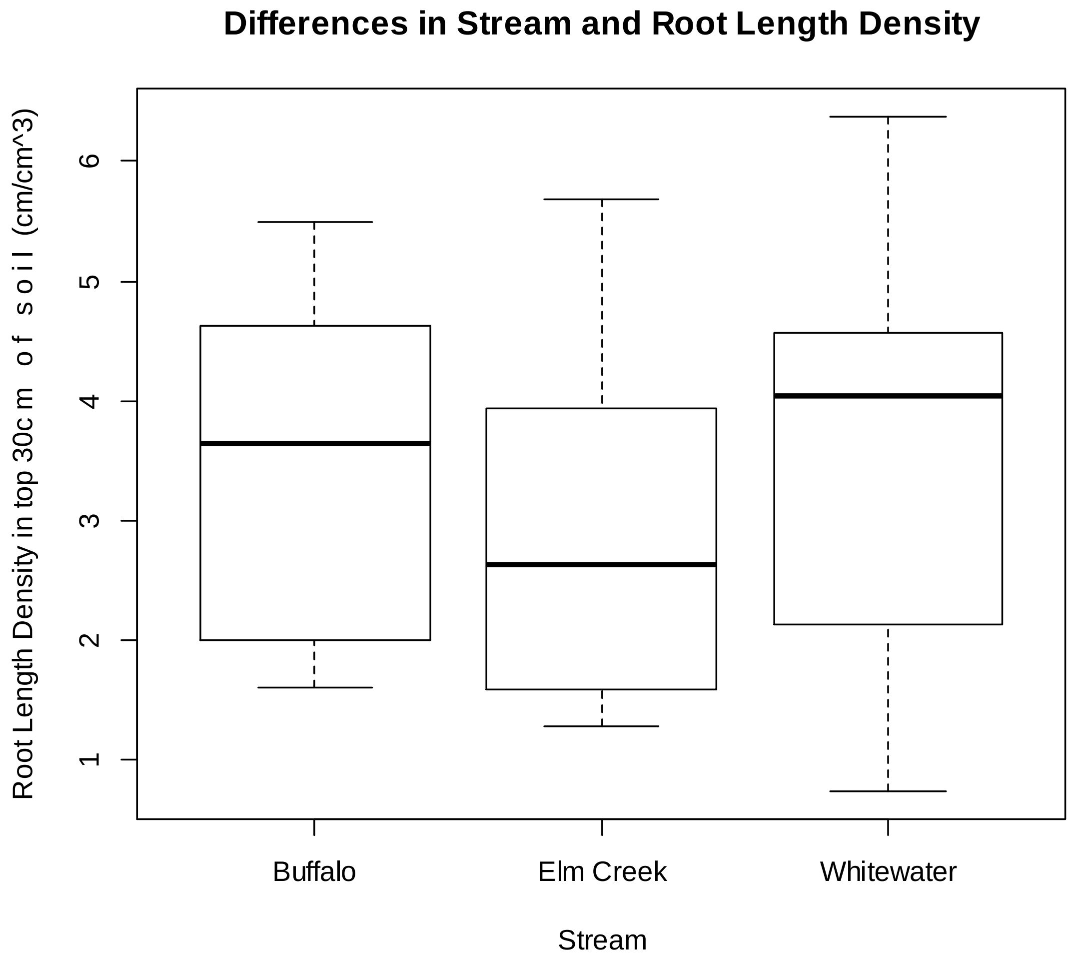


Figure 5. Root Length Density in the Top 30 cm of the Soil between Each River

Average RLD does not differ based on river section (p-value= .474, see Figure 6). The average RLD for the Buffalo River is 3.07 cm/cm^3, 3.81 cm/cm^3 in Elm Creek, and 3.10 cm/cm^3 in the Whitewater River. However, the middle and lower sections of the river contain some sites with much higher RLD in the top 30 cm of the soil. Even with these outlying data points, the difference between each of the three river sections varies very little on the Buffalo River, Elm Creek, and the Whitewater River.

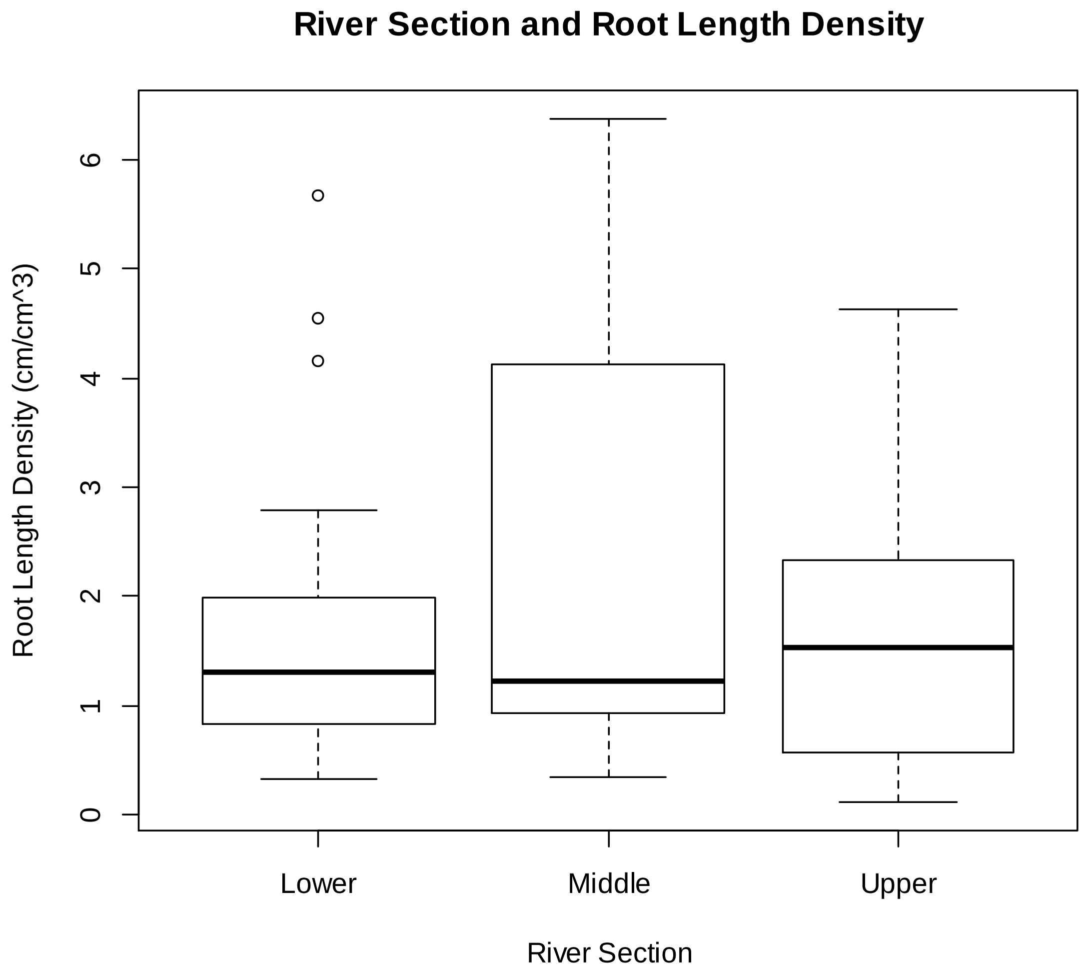


Figure 6. Comparison of Root Length Density in the Top 30 cm of the Soil for Each River Section from all three watersheds

The RLD in the top 30 cm of the soil does not differ between vegetation communities (p-value= 0.244). Careful inspection reveals that there is no significant difference between the herbaceous and forested sites in the RLD present in the top 30 cm of the soil (p-value= 0.887). There is also no difference between the amount of roots between the herbaceous site and the shrubs (p-value= 0.215) or the forested sites and the shrub sites (p-value= 0.651). The average RLD in the top 30 cm of the soil is 3.37 cm/cm^3 for the forested sites, 2.57 cm/cm^3 for the shrub dominated sites, and 3.75 cm/cm^3 for the herabaceous sites(see Figure 7).

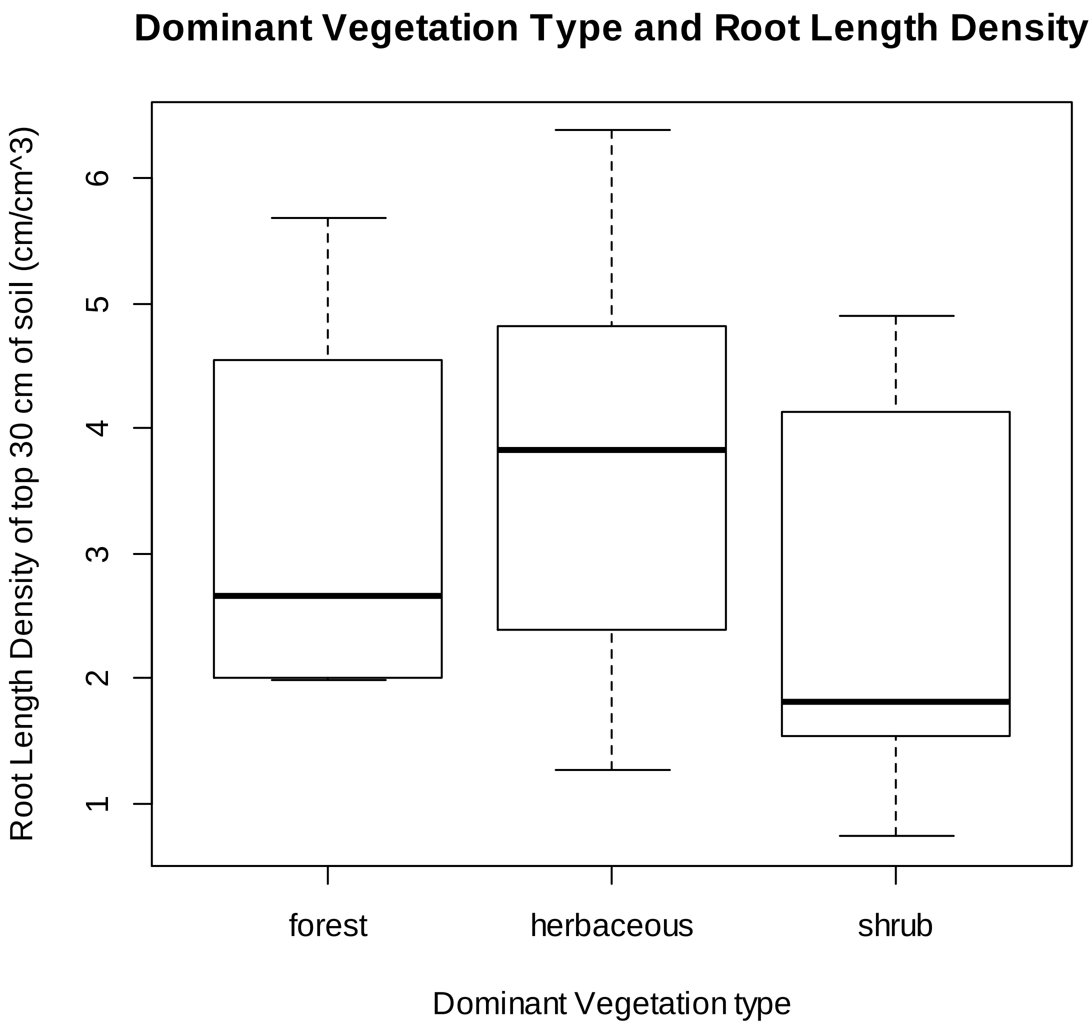


Figure 7. Root Length Density in the Top 30 cm of the Soil between Each Dominant Vegetation Type for All Thirty Study Sites

BEHI is an important tool used to estimate the amount of erosion occurring in a river section. Root density estimated by the BEHI tool should coincide with the sample RLD measured. However, there is little correlation between the root density estimated by the BEHI tool and the amount measured from root samples (see Figure 8). The samples and BEHI measurements were taken on the same bend but the scores do not seem related (R^2 value= .00007, p-value= .9653).

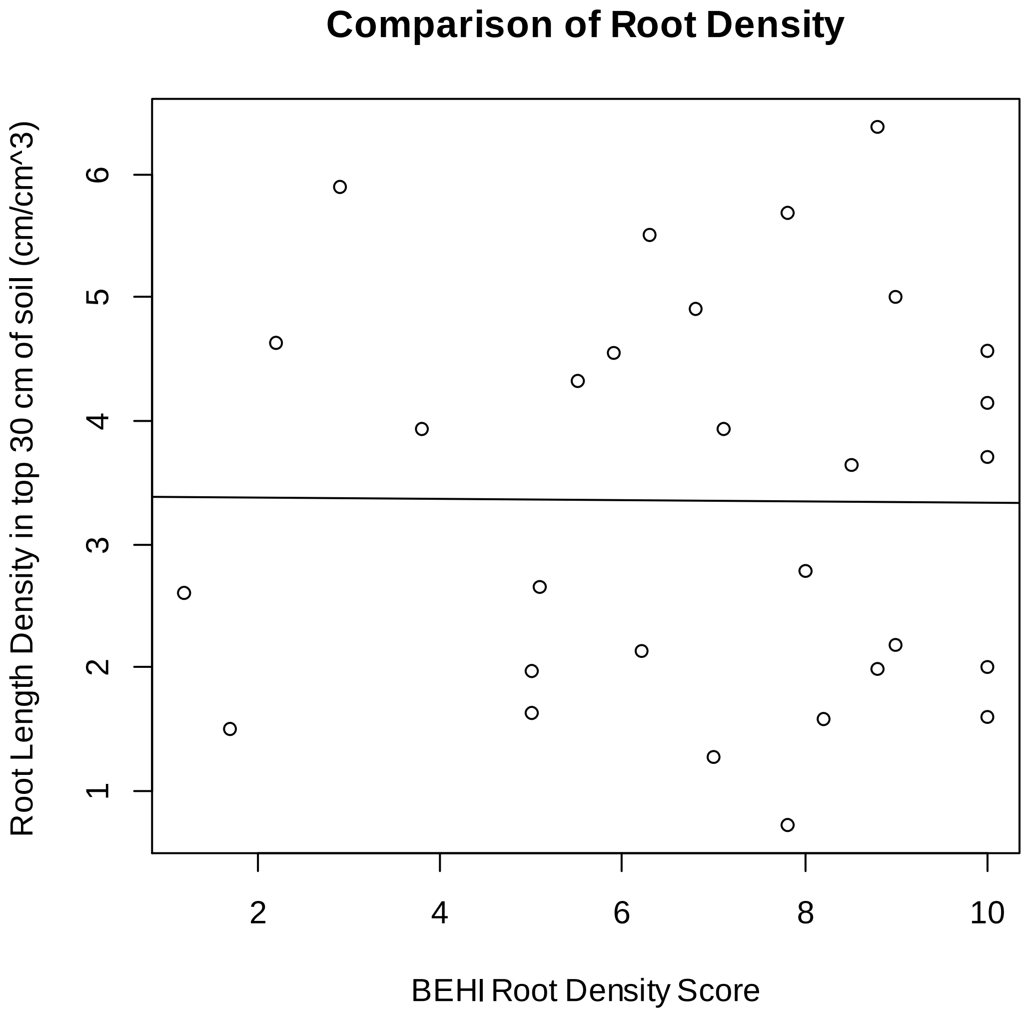


Figure 8. Estimated Root Density with the Bank Erosion Hazard Index (BEHI) Tool Compared to the Root Density Measured from Soil Cores at All Sites in the Study

Surface protection percent from the BEHI parameter and the vegetation type do not correlate (p-value=.937, see Figure 9).

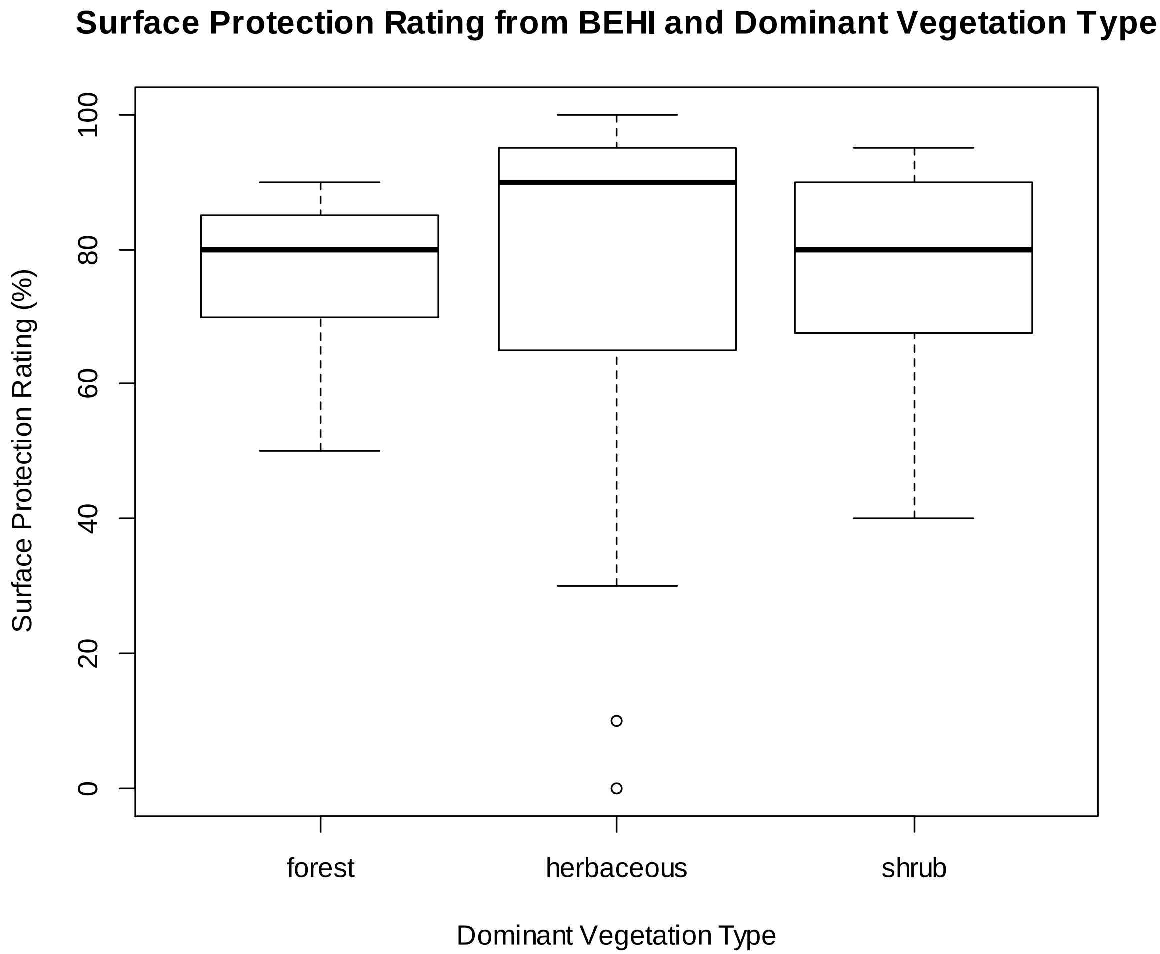


Figure 9. Surface Protection Rating Used in the BEHI Tool and the Relationship to Each Dominant Vegetation Type Measured at All Sites in the Study

Soil bulk density could affect the growth rate and patterns of plant roots, but there is no correlation between bulk density and root density. Figure 10 shows very little correlation between these two variables (r^2 value= .0027, p-value=.80). Five sites were removed due to unusually low values; however, this did not change the relationship between bulk density and RLD.

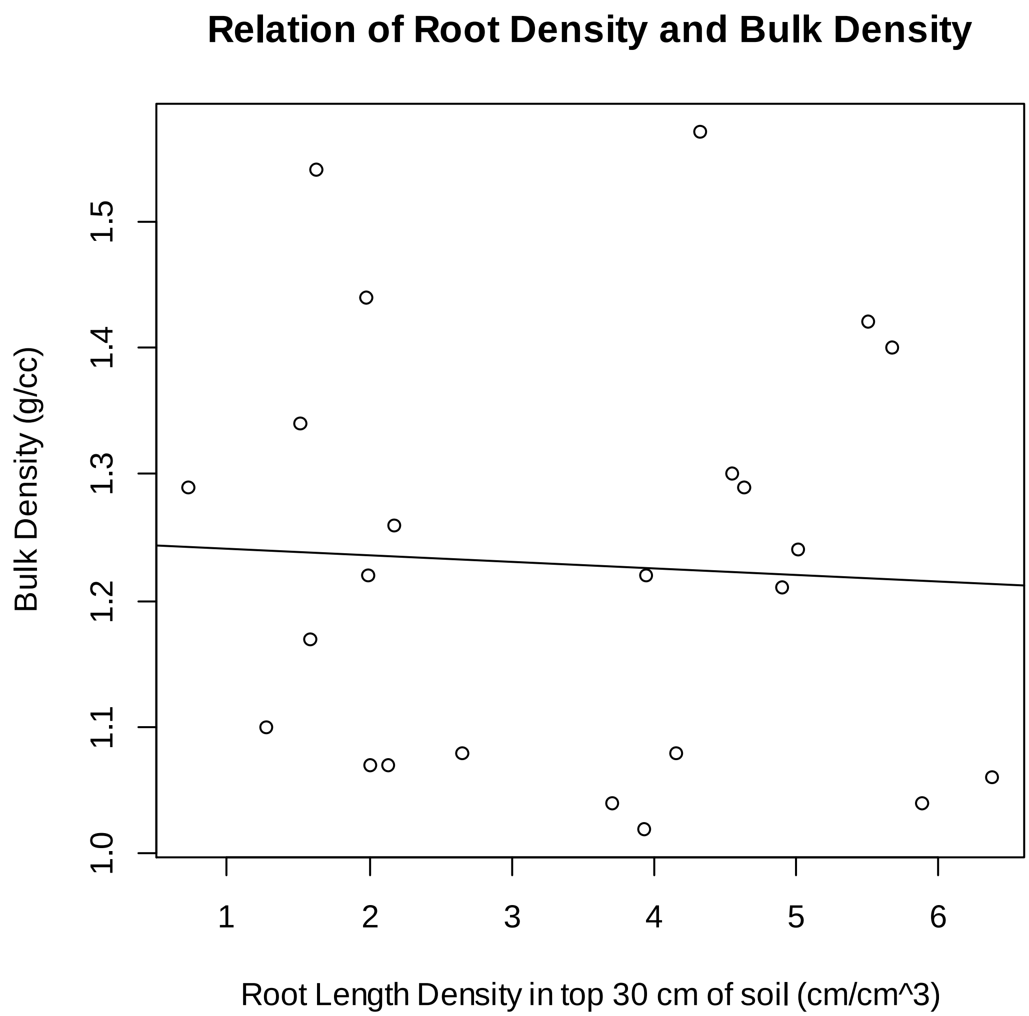


Figure 10. Measured Bulk Density and Root Length Density in the Top 30 cm of the Soil for All Sites Measured in the Study

Discussion

Human changes to the landscape have increased erosion rates and created the need for restoration activities (Beach, 1989). Understanding the relation between erosion rates, vegetation, and root density can be important in mitigating human caused changes to the landscape. Vegetation and plant roots play an important role in providing bank stability and reducing excessive erosion rates through reinforcement, dewatering, and other effects, but the importance of each process can be variable. It is important to understand the relation between all the factors that provide stability to a streambank in order to inform restoration activities.

Even though herbaceous root density differs depending on site specific differences, most of the root length is concentrated in the top 30 cm of the soil. Across all the watersheds and all the river sections in this study, RLD is always greater in the top 30 cm. This supports hypothesis 1, root density is greatest in the top 30cm of the soil, for every site in the study. There is no difference between the length of roots in the 30-60 cm samples and the 60-90 cm samples. Vegetation species and type does not affect the amount of distribution of roots in a soil profile. Wynn and Mostaghimi show evidence that bulk density is one of the most important factors relating to root growth (2006a and 2006b). However, little correlation between bulk density and root density found in the study suggest that soil compaction, soil density, or clay composition does not affect the density of root growth. For all factors root density was highest in the top 30 cm of the soil for this study.

Hypothesis 2 was not supported based on the evidence in this study. There was no correlation found between the amount of root density and type of vegetation at the study sites. Herbaceous plants, shrub dominated sites, and forested sites all provided similar amounts of root density within a streambank. Differences in dominant vegetation type indicate differences in site characteristics. This could be due to higher or lower amounts of nutrients, water, soil characteristics, or influences by humans. Even with all of these potential differences, root density did not differ between the sites, indicating that these factors do not cause differences in belowground density.

Tree roots are often measured as belowground biomass, which is not comparable to root density measures of length or volume. Larger trees have much greater biomass than smaller plants. Site EC1 has only seven trees and one shrub at this site, however, these trees are very large, the average DBH is 52.18 cm (20.54 inches), with the largest tree DBH being 139.12 cm (54.8 inches). Different root sizes would affect streambank stability through either support or dewatering. Very fine roots are used to extract water and nutrients from the soil, so sites dominated by very fine roots would reduce inundation more rapidly than sites dominated by larger roots (Pollen, 2006). Large roots, on the other hand, provide more structural reinforcement. Trees are much larger plants, and have correspondingly larger roots.

Natural forests usually have a diversity of tree sizes, some large and old, others small and young (Crow, 2005). BU9 and BU11 have large average DBH (7.41 and 4.7 inches, respectively) and larger standard deviations (5.5 and 3.0 inches, respectively), indicating the presence of both old and young trees. EC3 is a site containing mostly small, young trees. The average DBH is only .8 inches with a standard deviation of just .5 inches. The presence of only young trees indicates a disturbance or human impact that removed all the older trees. EC6 and WW1 likely have fewer human impacts because their DBH is higher (4.9 and 1.9 inches, respectively) and a standard deviation that is much higher (7.2 inches and 4.9 inches, respectively). This difference in size and variety could indicate recent disturbance and changes to the river caused by humans.

Shrub populated sites in this study had a slight trend towards less root density. This could be due to the lack of larger, woody roots collected and suppression of herbaceous plants. Allelopathy and competition could explain the slightly lower values in the shrub sites (Callaway and Ridenour, 2004). Chemicals produced by shrub plants could inhibit the growth of nearby herbaceous species. Competition could reduce the presence of herbaceous plants if a nutrient is limited in an environment. Shrub plants would be more efficient at obtaining or using this nutrient, causing nearby herbaceous plants to wither from lack of a vital nutrient (Callaway and Ridenour, 2004). Fewer nearby plants could result in lower root densities. However, this difference was not significant, so the differences could be explained simply by natural variability.

There is no correlation between the root density scores obtained from Rosgen's BEHI method and the root length density obtained from the soil cores. Individual parameters from the BEHI method do not correlate to observed values, either. Different vegetation types showed no consistent difference with the amount of surface protection provided. Since the BEHI test is an empirical tool used in conjunction with NBS to estimate erosion rates, it is not an indicator of the exact conditions at a site. RLD measured in the field and vegetation types may not relate to any of the BEHI parameters since BEHI is used mainly for comparison between sites and as an indicator of highly erodible sites, not to give a value for site conditions.

Many sources of error during sampling could have influenced the results from this study. Many of the tree roots were too large to be captured by the PVC tube method. This creates a bias towards shallow root systems. It is very difficult to know where root density may be higher or lower from simple observations. Much of the data for this study was taken between April and October and there is some risk for differences to occur due to seasonal variations. Disturbances such as ice damage, erosion, deposition, and compaction could reduce the amount of roots growing underground. Fertilizers or other nutrient inputs from nearby areas could increase root growth. These conditions would not be known before visiting a site and could cause variability in root growth and density. The sampling technique often required considerable effort to extract soil and roots from the PVC tubes; some roots may have been lost during this process. Additionally, very small roots may have not been captured by the sieve, biasing our results to those roots large enough to be captured. Scanning in the roots could have some error if roots overlapped or were not captured by the scanner. Based on the sampling and measuring of root density, some bias towards small, but not extremely small roots may have occurred.

Error in the bulk density samples may have arisen because of unusual values (see Appendix A), delayed measurements, and small spatial variations. Several of the bulk density values measured less than 1.00 g/cc when dried. These very light samples were discarded from the analysis, possibly changing the relationship between bulk density and root length density. Some samples were stored in sealed plastic bags inside a cooler and not dried and weighed until several months later. There may be some error associated with the breakdown of material in the freezer or after sampling. Finally, these sites consisted of alluvial material that could contain material originally deposited from another area by floods and water movement that would affect the bulk density values. Alluvial material in the study area is typically very low in organic matter, but small areas of buried organic material, such as muck and peat, could erroneously decrease bulk density values compared to the surrounding material.

The BEHI parameters and vegetation data was very similar is likely due to the abundance of Reed canary grass (*P. arundinacea*). Reed canary grass is an invasive species that can compete for space, nutrients, or water better than many native plants, especially in disturbed conditions (Callaway and Ridenour, 2004). The surface protection and root density data collected would be similar across all regions because it is measuring the same vegetative cover at nearly every site. The shallow dense root system of Reed canary grass could create a powerful bias in the root depth and density sampling because of the overabundance of one species. In order to understand the impact of different root structures and surface protection a variety of plant species is required.

Future studies can alleviate some of the discrepancies in this study by adjusting some of the methods and using alternate techniques. When retrieving soil samples for study, some error may have occurred due to compaction of soil in the tube and losses due to the difficulty of removing the compacted soil. Smaller depth intervals may help to reduce this problem and studies have used smaller sampling intervals (Piercy and Wynn, 2008; Wynn and Mostaghimi, 2006b; Wynn et al., 2004). Uncertainty also existed in the conditions of the sites before sampling in the summer. To better understand the amount of disturbance and inundation that may have occurred at each site an additional spring or winter visit could be useful to document factors that may influence root densities.

Increasing the sample size would likely not change the results of this study. Instead more careful site selection could be used to have equal number of sites for each vegetation type and to reduce the abundance of Reed canary grass (*P. arundinacea*) at selected sites. The uneven number of herbaceous, shrub, and forested sites may add errors to the data collection and analysis process. By using an equal number of sites for all three vegetation types, some of this error might be removed. Additionally, selecting sites with little Reed canary grass could be useful in identifying differences between native vegetation. In particular, herbaceous sites would benefit from an increase in diversity. By carefully selecting sites, not increasing the number of sites, some patterns may begin to emerge.

Tree root samples were not gathered in this study because of the PVC method bias towards smaller roots. Characterization of tree root densities and depths would benefit the results of this study. Tree root sampling can occur through several methods; tree tip-up measurements, trench excavation, and ground penetrating radar. Fallen trees are can easily be found in nearly every environment. By measuring the depth, size and density of fallen trees an estimate can be made of belowground root density. However, this process is likely to include much error since not all roots may still be attached to trees, soil upheaval may damage root structures, and fallen trees may have an atypical spread of roots, which cause the plant to fall. Trench excavation could accurately measure root density in the field, however it would be extremely difficult and labor intensive. Trenches may need to be many feet deep to capture all the roots in a vertical plane. Extent of lateral root spread would not be measured by this method. Ground penetrating radar may be the most useful in estimating belowground tree structure by capturing a three-dimensional image of root density with little excavation or surveying. However, ground penetrating radar devices may be expensive, bulky, and have problems with resolution making them unfavorable for field research. The lack of tree root measurements has caused some problems for this study and future studies should include methods of measuring tree root density.

Conservation practices can vary from simple vegetation management to large-scale in-stream restoration activities. The goal behind all of these practices is to reduce streambank erosion rates. However, this process needs to be conducted within a human impacted context. Even stable streams experience erosion; it is offset by equal amounts of deposition. Typically, human impacts change this balance by increasing erosion. It can be difficult to differentiate between natural high erosion rates and rates that have increased since human settlement. Several environmental cues can be used to judge if a river has experienced an increase in erosion. Nearby land use can affect streambank erosion by reducing vegetation and increasing stream flow through drainage or runoff. Changes in soil type can also indicate human impacts, for example the lower reaches of the Whitewater River experienced increased rates of deposition in the floodplain after human settlement from upstream soil types. Changes in vegetation can also be an indication of human impacts. In particular, natural forests and prairies have been converted to cropland and pastureland. Identifying where human impacts are greatest can allow targeted restoration and vegetation management to return erosion rates to their natural levels.

Conclusion

Most of the root growth occurred within the top 30 cm of the soil for all plant species and watersheds in this study, supporting hypothesis 1. Hypothesis 2 is not supported because there is no significant evidence that root density changes with vegetation type at my study sites. There was a slight trend for shrub dominated sites to have fewer roots than both herbaceous and forested sites, but it was not significant. BEHI values, root density, and surface protection did not correlate, either. BEHI cannot be used as an indicator of actual root density for streams in this study. The effect of many possible sources of error could bias this data. These errors are from sampling methods, measuring methods, and variability created by temporal and spatial changes.

The abundance of reed canary grass (*P. arundinacea*) likely plays a large role in creating similar results in this study. The shallow, dense root system commonly found at the study sites is likely indicative of Reed canary grass which was probably influencing root density values across watershed, vegetation type, and soil type.

Chapter 3: Vegetation and Erosion

Introduction

Vegetation can have a large impact on erosion rates in a watershed. Densely vegetated regions experience less erosion because of the support from plant roots, and surface protection. Vegetation communities are unique in different regions in Minnesota and across the globe, which can affect erosion rates within a watershed. Differences exist not only among rivers, but among regions of river, and when different vegetation is present. Erosion is a major concern because it can impact roads, bridges, houses, and public property (DeWall, 2009). In order to prevent erosion and reduce the need for costly restoration projects, efforts can focus on high risk areas with appropriate vegetation to improve the quality of a stream. This study conducted BEHI tests on 30 sites throughout Minnesota, 10 in the Buffalo River watershed, 10 in the Elm Creek watershed, and 10 in the Whitewater River watershed. Vegetation surveys, cross sections, and root samples were also taken at each site to compare to erosion rates estimated at each site to possible sources of protection and erosion reduction.

Each section of a watershed faces different types of erosion depending on certain qualities possessed by that section of the river. Headwaters reaches are most prone to subaerial erosion, middle reaches are affected mainly by fluvial entrainment, and lower reaches experience mass failure as the largest source of erosion (Abernethy and Rutherfurd, 1998). Since each region has different qualities and is prone to different forms of erosion, the most beneficial vegetation will differ. Headwater reaches should benefit most from herbaceous plant communities, erosion rates in the middle reaches should be reduced by shrub dominated landscapes, and lower reaches should benefit from forested land to effectively reduce erosion (Abernethy and Rutherfurd, 1998).

Herbaceous roots are shallow and dense (Canadell, et al., 1996). This would benefit short streambanks in headwaters reaches that have little area for roots to grow. Large woody debris and wind throw are such large problems in these regions that trees and other woody species would not provide much benefit (Abernethy and Rutherfurd, 1998). Herbaceous vegetation would be beneficial in reducing damage from freeze-thaw cycles and can provide a layer of insulation from temperature changes that might cause damage to streambanks (Pollen, 2006). Protecting the streambank from rapid temperature changes could be the best way to reduce freeze-thaw damage. Trees and other woody debris are the main source of erosion in headwater streams, and herbaceous plants would protect the bank from erosion and freeze-thaw damage.

Mass failure is a challenging problem in lower reaches because it occurs sporadically and is difficult to predict (Lenhart et al., 2010a). Predicting these events can be difficult because it is affected by the level of high flow during a flood, the type of soil in the streambank, the stress acting upon the bank, and the stratification of layers within a streambank. The higher and longer a flood, the more streambanks destabilize from inundation. In particular, large floods may saturate a streambank for many weeks, decreasing the shear strength of the soil and reducing root growth in a streambank. This is also dependent on the type of soil. Sandy soils become very vulnerable when inundated, whereas clay soils still retain much of their cohesion (Wynn and Mostaghimi, 2006a). Sandy soils, with low bulk density, cannot typically support taller banks. Clay is often so cohesive that it can support very tall banks before it becomes unstable. Some unstable clay soils and stable sandy soils exist, but generally sandy soils are less cohesive than clay soil. The proportions of sand and clay can be important for stability. Higher clay content imparts more cohesiveness and higher sand content lessens the stability of a bank face.

Each watershed is unique in soil type, stream size, land use, and many other factors. These differences can cause some reaches of a stream to have atypical erosion processes. The headwaters reaches in the Buffalo River are dominated by herbaceous and forested land (Google Earth, "Buffalo River Sites", 2012). In many areas this could increase erosion due to wetlands and shallow water tables. However, the soil can be sandy in some parts of this reach, creating dry conditions where trees would provide additional support (Dingmann et al., 2012). The middle reaches of the Buffalo River are prone to fluvial entrainment and mass failure in some locations. The soil type varies across this region from sandy to silty soils, therefore, trees and herbaceous plants could provide root stability, and freeze-thaw protection (Abernethy and Rutherfurd, 1998). Where sand and tall streambanks are present trees may be more beneficial. When silt and shorter streambanks are dominant, shorter rooting plants, such as herbaceous plants and shrubs, may be more beneficial. The lower reaches of the Buffalo River are made of thick clay, and tall streambanks (Dingmann et al., 2012). Tree and herbaceous plants may benefit these reaches the most. Trees could penetrate into the tall streambanks and provide stability, while the herbaceous material would protect the upper layers of soil from freeze-thaw damage. Buffalo River has unique characteristics that can shift the dominant type of erosion in each reach.

Sandy material is present in many parts of Elm Creek, possibly shifting the dominant type of erosion in some reaches. Loamy soils are also common, especially near wetlands or other low-lying areas. Herbaceous vegetation can be used to mitigate the effects of agricultural inputs, by slowing water movement, increasing infiltration, and providing protection from wetting-drying and freezing-thawing cycles (Wynn and Mostaghimi, 2006b). However, some areas with very sandy soils may benefit from deeper rooted vegetation. In particular, some areas of the middle reaches in Elm Creek have very tall streambanks composed of sandy material. Trees may provide the most benefit to these reaches where mass failure is possible.

The Whitewater River has many unique features that may promote different types of erosion. Headwaters reaches can be sandy, with deeper water tables, where trees and shrubs may reduce erosion better than herbaceous plants alone. The middle reaches of the Whitewater River have low erosion rates due to a dominance of naturally accruing grasses, shrubs, and trees. Several bluffs occur in this region, due to the steep slopes present, but existing trees can provide the most support in these reaches. The lower reach of this watershed has silty soils, tall streambanks, and many human impacts. Planting deep rooted vegetation, such as trees, can increase infiltration and reduce erosion from runoff due to human impacts (Shields et al., 2009). However, since the soil layers may not be very thick in some areas due to a shallow bedrock layer, herbaceous vegetation can also be planted to absorb water as it inundates shallow soil layers. Many factorsin the Whitewater River, such as agriculture, shallow water tables, and human impacts, could influence whether subaerial, fluvial entrainment, or mass failure is the dominant type of erosion.

Hypothesis

Each region would benefit more from a certain type of vegetation according to Abernethy and Rutherfurd (1998), with supporting evidence from other studies (Shields, et al., 2009; Wynn and Mostaghimi, 2006a; Wynn and Mostaghimi, 2006b; Pollen, 2006). However, the study by Abernethy and Rutherfurd was performed in Australia for a single watershed. If this trend is translatable across all watersheds similar trends should develop in Minnesota. Testing this hypothesis may not be possible with the current set of data, but trends can be analyzed to assess the possibility that this model would benefit regions other than Australia.

Materials and Methods

In order to determine site locations the same methodology mentioned in Chapter 2: Materials and Methods were used. Each river was subdivided into three sections based on differences in characteristics from the other sections of the river, such as drainage, soil type, and land use. These sites needed to be easily accessible and similar to each other for comparison. Once the sites were established, data and sample collection could begin.

Each site was tested to determine its erodibiliity using the BANCS system and River Stability Field Guide developed by Rosgen (2008). To be consistent, the outside bend was used to compare each stream section. Different properties, such as radius of curvature and stream width, can be compared for all sites in the study. In order to determine the first property of BEHI, bank height and bankfull height were measured on site. A cross section was measured using a laser level, measuring tape, and extendable rod. The bank height and bankfull height were established using the cross section.

However, if the river was too deep to measure a cross section, then the measurements were taken using an extendable measuring rod. During these measurements one person was required to travel to the bottom of the stream bank to determine the bankfull height using bankfull benches, rock discoloration, erosion patterns, or other distinguishing marks to estimate the level at which bankfull occurred. Bank height was also determined using the greatest near-bank increase since most streams were flowing above the minimum flow.

In order to understand more about a particular river reach a cross section can be useful in obtaining information. Measuring a cross section requires a measuring tape, a laser level, and an extendable rod, as outlined in the River Stability Field Guide (Rosgen, 2008). The tape is draped across the stream and used to measure horizontal distance. While the extendable rod and the laser level is used to accurately measure vertical distance. Changes in slope are measured using a combination of horizontal and vertical measurements. The final cross section measurement is very useful for obtaining bank height, stream width, maximum depth, cross sectional profile, and many other characteristics. These characteristics can then be used to classify the stream based on Rosgen classification or any other classification system.

After a cross section, bank height, and bankfull height were obtained, the depth of vegetation was determined by measuring the deepest roots with the extendable rod. This measurement used the depth of roots from the very top of the streambank to determine the depth of roots. However, if the vegetation cover was continuous from the top to another portion of the streambank, the depth included roots from the continuous vegetation. This measurement is designed to estimate the stability of the streambank. If there is a continuous blanket of vegetation on a bank, then the roots are contributing much stability to the streambank. However, if there are only patchy groups of vegetation down an otherwise barren riverbank, then those plants are excluded from the root depth measurement since they were not contiguous. Next, root density was visually estimated. The root density was estimated only for the portion of the streambank that had roots visible. All roots were estimated in the density measurement, except those below root depth. This approach was based on visual estimates, so it is subject to bias and over or under estimation. For this study a percent root density was agreed upon by all researchers and then recorded. Bank angle was estimated using a protractor tool. The measurements were taken at several points of the lower streambank and an average was used to determine the best bank angle description. The lower portion below the bankfull height was used because it was subjected to flows and gave a better indication of the stress affecting the streambank.

The amount of soil protected by vegetation or other material was estimated by determining the amount of barren streambank within a five to ten foot reach along the outside bend and considered surface protection. Other forms of protection exist, such as, woody debris from upstream that provides physical protection and deflects flow away from a streambank. This amount can be difficult to estimate if flow deflection is occurring, if not though, it is a rather simple estimation of exposed bank. Again, since this measure can be somewhat subjective, all researchers agreed upon a value to determine the amount of surface protection.

The final factors that can contribute to erosion are soil type and presence of stratification. Soil type can play a large factor in the cohesion of bank particles. Sand is highly erosive, with very little cohesion which tends to cause higher erosion rates. In the field, the soil texture is estimated and recorded. The presence of soil layers can also decrease stability and increase the chance of bank erosion.

Bank stability depends on many aspects, but roots provide stability and cohesiveness to a streambank. Little is known about the amount of roots in a streambank and which plants provide the best stability. In order to understand roots and vegetation better, root samples are needed and a vegetation survey is taken as outlined in Chapter 2: Materials and Methods.

In order to calculate the amount of erosion in a river reach BEHI, NBS, and bank height are needed. This process is outlined in the BANCS model (Rosgen, 2008). BEHI is used as an indicator of the strength of the soil and NBS indicates the amount of stress on the bank. A combination of BEHI and NBS values correlates to an erosion rate. This rate is multiplied by the bank length and height to predict the annual erosion rate in tons/ft/yr (Rosgen, 2008). The length for each site was 300 ft because that is the length that vegetation surveys occurred and to more easily compare the impact of bank height on erosion rates. Using these three parameters it is easy to identify where large amounts of erosion occur. The data was then entered into the R program and several ANOVA tests on single and multiple variables were run to test the relationship between different sets of data. Linear relationships were established using Microsoft Excel.

Root Length Density was measured as mentioned above in Chapter 2: Materials and Methods. A PVC tube was used to extract the roots from the streambank in 30 cm increments up to 90 cm deep. The collected samples were stored and frozen until processed at the University of Minnesota. Then the samples were thawed, sieved, and measured using a STD 4800 Scanner and WHINRHIZO software. The samples were compared using statistical software R.

Results

Each region and river section differs in many respects, from soil type to vegetation type to root density.

The BEHI value is based on parameters derived from Rosgen's River Stability Field Guide (2008) and determined through field observations. The smallest BEHI value was at Whitewater site 2 with an overall score of 14.7. The largest BEHI value was at Elm Creek site 8 with an overall score of 50.4. Large BEHI values indicate the potential for erosion is very high. The correlation of BEHI score and root density from the 0-30 cm depth were not significant (r^2-value= .0503, p-value= .2419, see Figure 11).

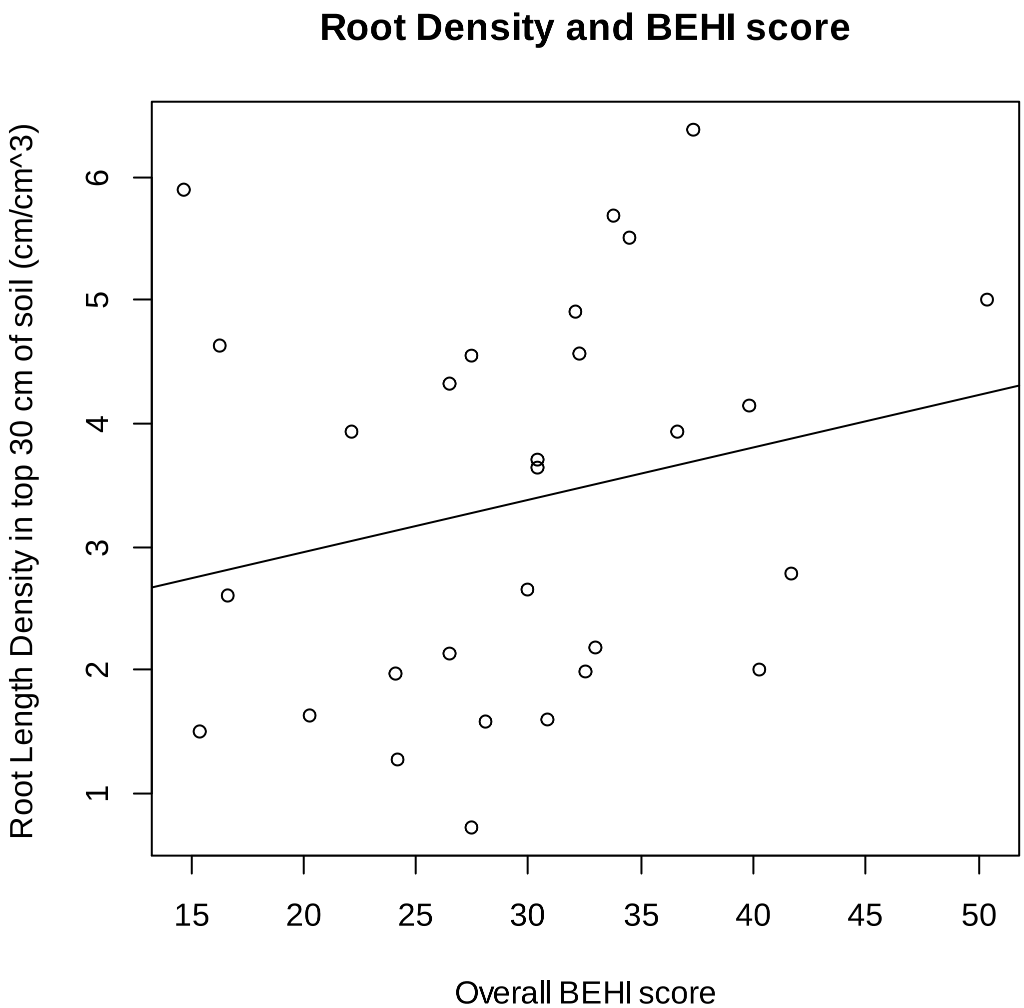


Figure 11. Relationship of BEHI scores and RLD in the Top 30 cm of the Soil

Different types of vegetation are expected to provide different protection and support to a streambank. In order to understand if forested land differed from herbaceous or shrub dominated landscapes, the estimated erosion potential was used to compare all three vegetation types. There was no significant difference between the BEHI score for each vegetation type (p-value=.682, see Figure 12) although large tree roots were not included in the analysis.

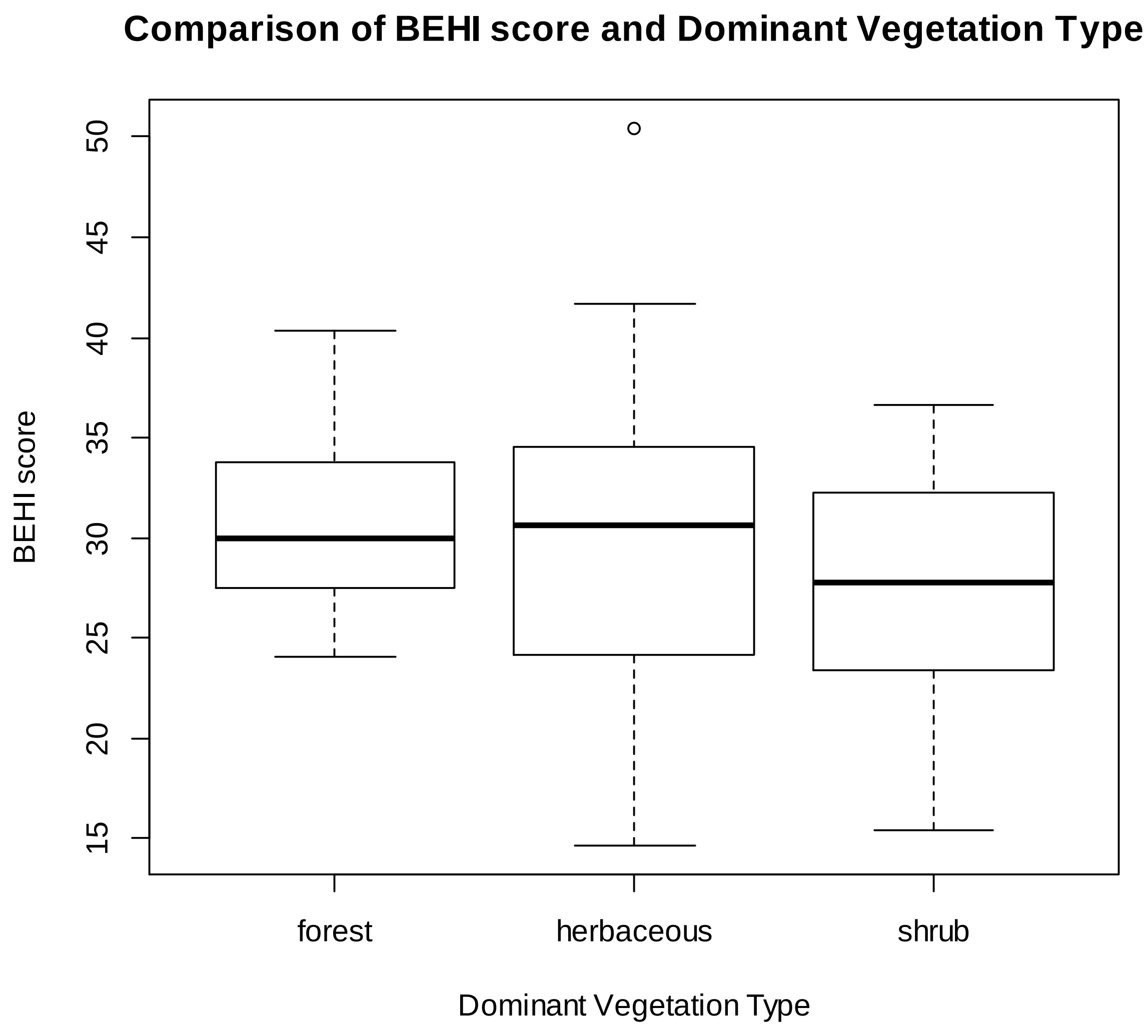


Figure 12. Comparison of BEHI Score and Dominant Vegetation Type Across All Study Sites

Each river was divided into three different sections, a headwater, middle, and lower section based on drainage area and geomorphic traits. Figure 13 shows the dominant vegetation community for each site across all watersheds. The headwaters reaches consist of many herbaceous plots of land. Middle sections contain the most shrub land, indicating a mixture of woody and herbaceous material. Lower sections vary greatly, but contain mostly forested sections. The sample sites were selected using other parameters besides vegetation type. In order to prevent bias in the sample selection vegetation type was not identified until after measurements and sampling were complete.

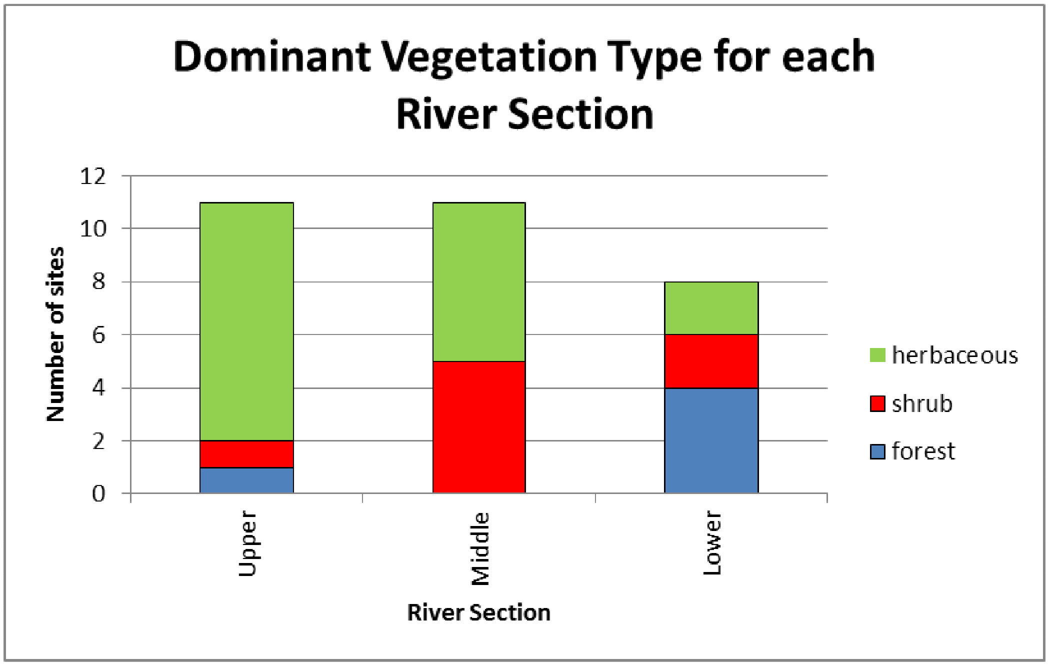


Figure 13. Dominant Vegetation Cover Based on River Section

Higher BEHI scores relate to more easily erodible streams and lower BEHI scores indicate stable streams. If BEHI score varies based on differences in land use and bank height, then scores should be consistently higher in lower reaches that have higher streambanks and often poor land use practices. However, BEHI scores were not found to vary based on stream section (p-value= .469, see Figure 14) for this study.

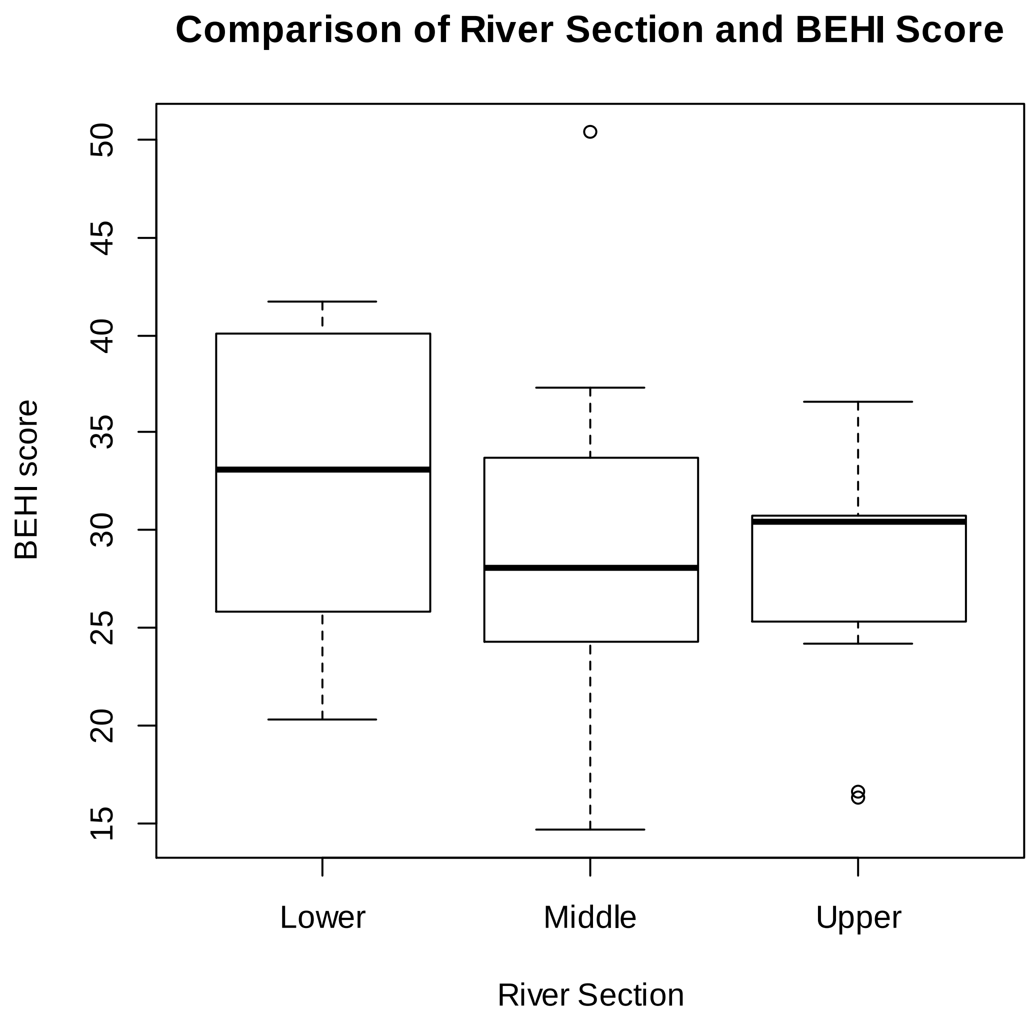


Figure 14. Comparison of BEHI Scores and River Section Across all Watersheds and Vegetation Types

The BEHI values did differ among vegetation types for each section. Some sections had lower BEHI scores, relating to lower erosion rates. Vegetation types that had higher BEHI scores should influence erosion rates for those specific sections. The upper or headwater reaches generally had lower BEHI scores when covered by herbaceous vegetation compared to forested reaches. The middle section had lower BEHI scores when covered by shrubs or small woody vegetation. The lower reaches had lower BEHI scores when covered with woody material such as trees or shrubs. The BEHI scores were much higher when covered with herbaceous material (see Figure 15).

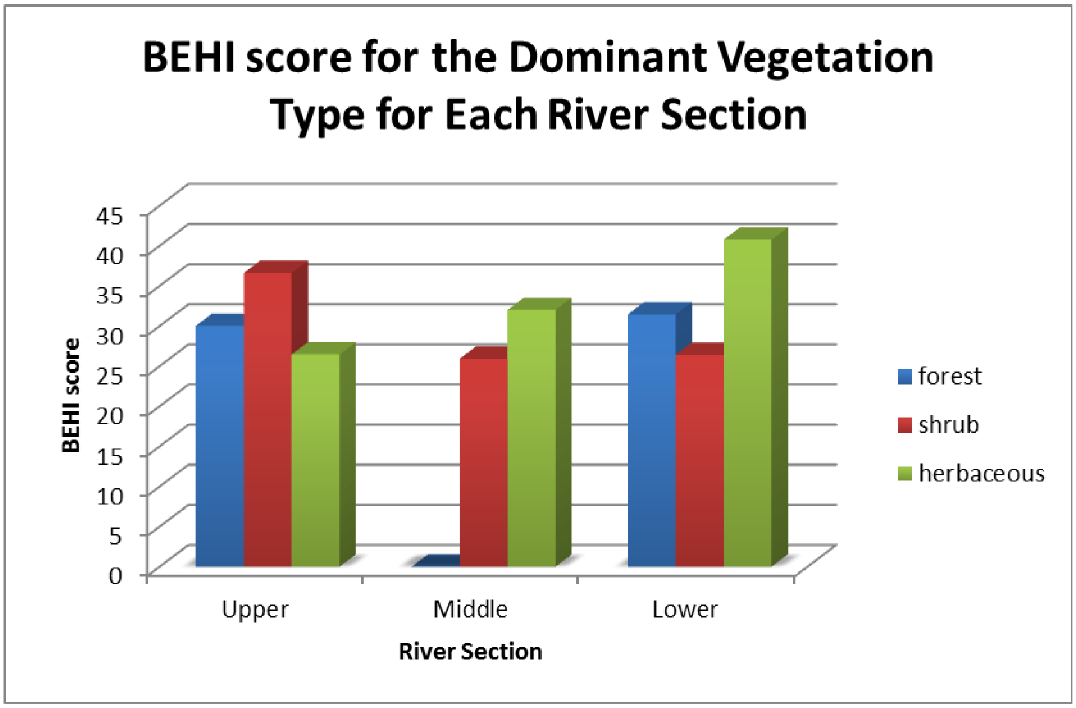


Figure 15. Comparison of BEHI Score and Dominant Vegetation Cover for Each River Section
Bars with values of 0 indicate no vegetation of that type was present in that section

The shear stress placed on a streambank by water flow should be independent of the quality and stability of the streambank. High BEHI scores should not correlate to any specific NBS score. This means a streambank with a very high BEHI score can have a high NBS score. However, high shear stress can increase the erosion on a streambank creating lower scores in categories such as bank angle and bank height. Increases in several composite scores could lead to an increase in the BEHI score. Overall, NBS scores showed a low correlation to BEHI ratings (r^2-value=.1265, see figure 16). There is a slight downward trend indicating high NBS scores could be influencing BEHI values, however, the relation is not significant.

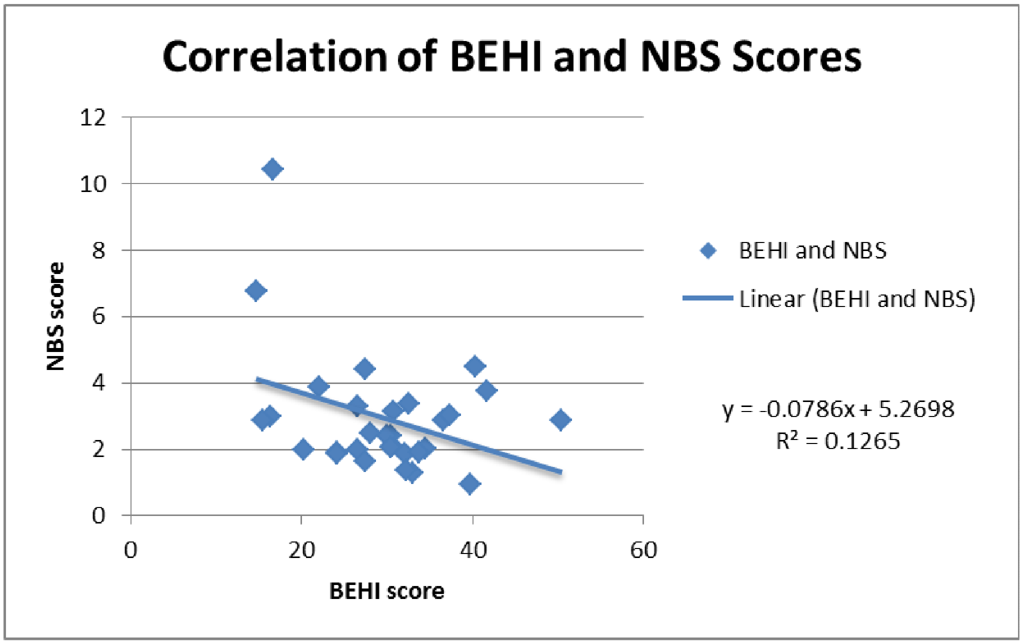


Figure 16. Comparison of BEHI and NBS Scores Across all Watersheds, Regions, and Vegetation Types

The final erosion rate is an average of the total amount of sediment that erodes from a streambank in one year (see Table 4). Each river section was averaged to estimate the total amount of erosion from each particular area (see Figure 17). This erosion rate was calculated using the sedimentary Colorado curve from the River Stability Field Guide (Rosgen, 2008). The highest erosion rate was predicted for the Whitewater River site 9 (WW9) at 195.24 tons/year. The lowest predicted erosion rate was at the Elm Creek site 2 reach (EC2) at 1.55 tons/year (see Table 4).

Table 4. Erosion Rates for Each Study Site

Site	River section	BEHI Rating	NBS Rating	Bank Erosion Rate (ft/yr)	Length of Bank (ft)	Bank Height (ft)	Erosion Rate (ft^3/yr)	Erosion Rate (tons/yr)
BU1	Upper	High	Very Low	0.165	300	7	346.95	16.71
BU2	Upper	High	Low	0.380	300	2.5	284.68	13.71
BU3	Upper	High	Moderate	0.380	300	4.5	512.42	24.67
BU4	Upper	Low	Low	0.051	300	5	77.23	3.72
BU5	Middle	High	Moderate	0.308	300	5	462.46	22.27
BU7	Middle	Moderate	High	0.326	300	4	391.68	18.86
BU8	Middle	High	High	0.575	300	6	1035.60	49.86
BU9	Lower	Moderate	High	0.420	300	6	756.55	36.43
BU10	Lower	High	Very Low	0.165	300	8	396.52	19.09
BU11	Lower	Very High	Very Low	0.165	300	10	495.65	23.86
EC1	Upper	Moderate	High	0.697	300	3.5	731.78	35.23
EC2	Middle	Low	Low	0.036	300	3	32.09	1.55
EC3	Upper	High	Low	0.250	300	3	225.38	10.85
EC4	Upper	Low	Very Low	0.025	300	8	59.26	2.85
EC5A	Middle	Moderate	Very Low	0.119	300	3	106.84	5.14
EC6	Lower	High	High	0.575	300	6	1035.60	49.86
EC7	Middle	Moderate	Low	0.153	300	7.5	343.96	16.56
EC8	Middle	Extreme	Low	0.420	300	9	1133.94	54.60
EC9	Lower	Very High	Very Low	0.165	300	7	346.95	16.71
EC10	Middle	High	Extreme	1.322	300	8.5	3370.58	162.29
WW1	Lower	Moderate	Very High	0.697	300	12	2508.94	120.80
WW2	Middle	Low	Very Low	0.017	300	8.5	43.60	2.10
WW3	Upper	Moderate	Very Low	0.119	300	5	178.07	8.57
WW4	Middle	Moderate	Very Low	0.119	300	8.5	302.73	14.58

WW5	Upper	High	Low	0.250	300	8	601.01	28.94
WW6	Middle	High	Very Low	0.250	300	7	525.89	25.32
WW7	Lower	Moderate	High	0.253	300	2.5	190.11	9.15
WW8	Upper	High	Moderate	0.380	300	11.5	1309.53	63.05
WW9	Lower	High	Extreme	0.872	300	15.5	4055.04	195.24
WW10	Upper	High	Extreme	0.872	300	5	1308.08	62.98

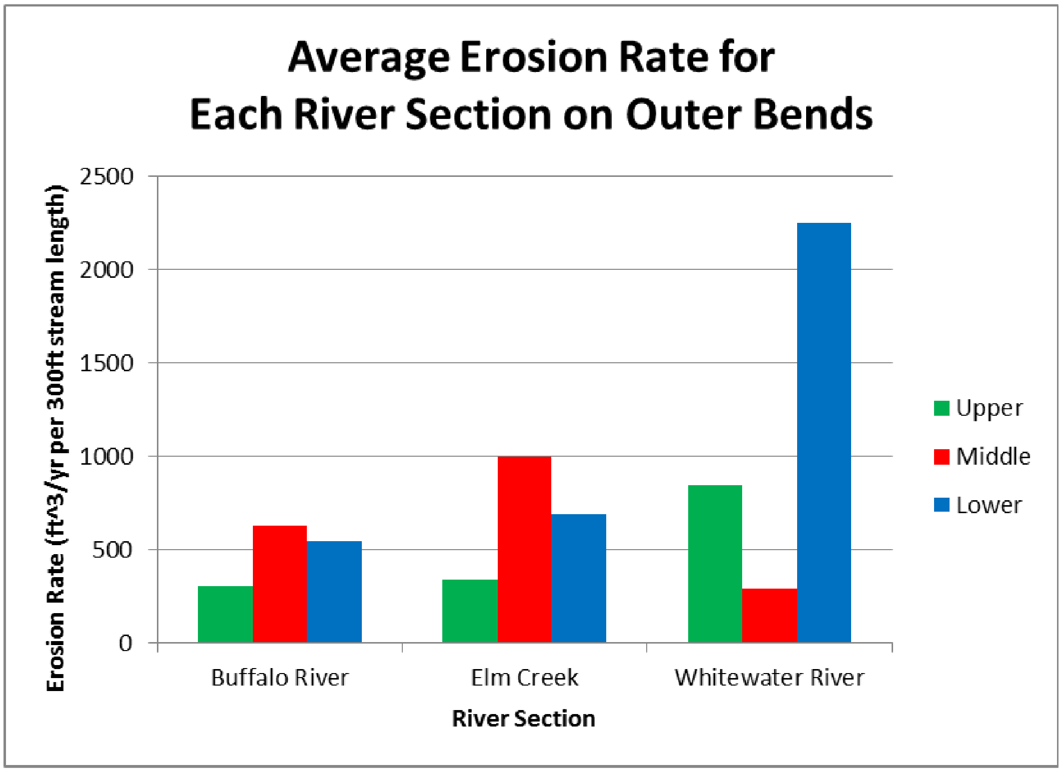


Figure 17. Comparison of the Average Erosion Rate for Each River Section Within Each River

Discussion

A BEHI score is a straightforward field method to estimate erosion problems on a river, which is made up of several different parameters. The relationship between each parameter and root density can be used to inform policy and technical decisions about restoration efforts and land use. Since vegetation and roots provide stability to a streambank, BEHI values should reflect the change in root density, however other parameters, such as bank height and bank angle may play a more significant role in the overall BEHI score. There seemed to be a slight upward trend in the results (see Figure 11), however, the overall BEHI scores did not correlate to RLD. Even though the result is not significant it is surprising to see an increase in BEHI score correlating to an increase in root density. Root density should increase the stability of a streambank and that should be reflected by a lowering of the BEHI value. Based on this evidence, BEHI root density values may not reflect actual root densities in the soil.

Herbaceous plants, shrubs, and trees have different sizes of roots because of differences in nutrient and water requirements. Roots from herbaceous plants are smallest because they are the smallest plants and require the fewest nutrients, while greater transpiration and nutrient extraction rates by trees could explain the differences in root size and structure (Brooks et al., 2003). An individual tree requires more nutrients than an individual herbaceous plant. This requires greater area to absorb nutrients and transport those nutrients to the leaves. As a result, there should be more herbaceous roots in the top 30 cm and tree roots should be more prevalent below 30 cm of soil. However, there is no significant difference between the RLD for the herbaceous root samples and forested root samples in this study. This is likely due to the sampling process that favored small herbaceous roots rather than larger, less abundant tree roots. High water tables could influence the distribution of roots in many areas. It could also be due to the extensive ground cover of herbaceous material, even in forested sites, that cause similar root profiles to appear. The land type also tends to be very similar in many regions. Shrub landscapes did show a small difference from the herbaceous and forested RLD. The reason for this difference remains unclear, but belowground competition or allelopathy could play a role in reducing root growth of herbaceous species (Callaway and Ridenour). It has been shown that some shrub species can inhibit or out compete herbaceous plant species (Callaway and Ridenour, 2004) This is not likely the case for all shrub sites in this study since there was no difference between root densities.

Vegetation is one of the most important aspects that influence erosion rates on the three streams in this study. Regions with greater amounts of undisturbed vegetation, such as the headwaters of the Buffalo River and the middle Whitewater River reaches, had much lower erosion rates. However, BEHI values did follow the suspected trend outlined in the hypothesis. Herbaceous sites generally had lower BEHI values in the headwater reaches. The lower reaches with forests had lower BEHI scores the herbaceous sites. Vegetation should be a significant factor because of its influence on surface protection and root reinforcement. It is possible that the type of vegetation planted in a certain reach does influence the erosion rate, even though root density, surface protection, and BEHI scores are not significantly different between categories.

NBS values are greater for incised channels, sharp curves, and steep slopes. This study measured NBS mainly using method 2, radius of curvature to bank width, and method 5 was used as a comparison as outlined in Rosgen's <u>River Stability Field Guide</u> (2008). Greater values of NBS represent greater stress related to the shape and contour of a river. This means that NBS scores should be unrelated to any of the other factors that independently measure bank strength. Figure 13 supports this hypothesis, since the r-value is very low and little relationship exists between BEHI and NBS. Erosion rates for reaches with low BEHI scores could still be high due to strong shear stress affecting the streambank. In these cases shear stress is the major cause of erosion and root and vegetation may only have a small effect on reducing erosion rates.

Soil type can have a profound effect on the efficacy and stability of certain vegetation. Since sand drains very easily, deeper rooted plants are needed to extract water from lower soil layers. Thick, clay soils may not require much vegetation and the vegetation that does grow would likely have shallow roots (Piercy and Wynn, 2008). As a result trees may not grow very well or be as beneficial in high density soils. Freeze-thaw cycles can greatly affect silty and clay soils in headwater and middle reaches. Regions that contain these types of soil may receive most of their streambank damage from freezing and thawing. Herbaceous material could become even more important to protect the soil with a layer of insulation and to remove excess moisture. Sandy soils do not retain moisture very well and do not have many problems with freezing and thawing. Soil type can be a very important factor in determining erosion rates for a portion of a river.

The soil type and elevation changes of a region greatly affect the amount of erosion that occurs. Region wide sediment changes can be important in providing the underlying soil structure of a streambank. For example, erosion rates are less in the lower part of the Buffalo River mostly because of a change in streambank sediment from sand in the headwaters to clay in lower reaches even though the streambanks are much higher. Changes in elevation also influence erosion by increasing stream power, shear force, and erosion rates. The Whitewater River has many steep areas, especially the middle reaches, but other sections of the river can change elevation rapidly. Flat regions will have much slower stream flow and lower erosion rates. Therefore, soil type and the elevation changes of a region are important in calculating erosion rates.

Many other factors can contribute to erosion rates and restoration needs in a watershed. The Buffalo River, Elm Creek, and Whitewater River differ in land use, soil type, and other characteristics. The Buffalo River has many different soil types that greatly influence the amount of erosion that occurs in many reaches of the river. Elm

Creek is homogenous in land use and soil type and erosion is caused mainly by changes in channel conditions, such as cross sections, bank height, and bankfull depth. The Whitewater River changes greatly in land use, elevation, and soil type, increasing erosion in certain areas of the watershed. Unique circumstances within and between the three watersheds contribute to the differences in erosion rates.

The Buffalo River has many natural settings in the headwaters where erosion rates are very low (see Figure 17). Natural forests and wetlands together with small bank heights reduce the amount of streambank erosion in this region. The middle reaches of the Buffalo River are prime agricultural lands. Therefore, many farms and small towns inhabit the landscape. Conservation practices can vary greatly, but typically erosion rates are very high in this region. Buffer strips are common, but often additional practices are needed to mimic a natural setting and reduce erosion rates to a natural and stable amount. As the river continues west, the soil becomes clayey which makes the river very resistant to erosion. The clay is so resistant to erosion in much of this region that minimal conservation practices can protect the landscape. Therefore in the Buffalo River, the middle reach experiences the largest erosion rates, due to soil type and land use influences.

In regions where the soil composition is uniform throughout the entire watershed, land use is the most important factor affecting erosion rates and BEHI scores. Farming is the main land use in the Elm Creek watershed. The middle reach of Elm Creek is most prone to erosion (see Figure 17) based on this study. High streambanks and other channel characteristics contribute to the amount of erosion that occurs. Land use contributes heavily to the increased erosion in these reaches; conservation practices are more common in the lower reach. Agricultural practices dominate Elm Creek, increasing flow from runoff and causing hydrologic changes downstream. Hydrologic changes can increase the shear force on banks downstream by increasing stream velocity. Due to the watersheds uniformity in soil type, the common agricultural land use, and increases in drainage area, the middle and lower reaches of Elm Creek are most prone to erosion (Lenhart et al., 2010a). Many stream bluffs exist in the lower reaches that were not captured in this study. This lack of information may explain why the middle reaches had a higher erosion rate. Otherwise, this may be due to the lack of nearby conservation practices, such as vegetative buffers. Changes in region specific characteristics, such as streambank height or soil conservation, can have a profound effect on erosion in the Elm Creek watershed.

Erosion on the Whitewater River is mainly influenced by soil type, geography, and land use. The headwaters reaches of the Whitewater River are dominated by glacial till soils, agricultural practices, urban land use, and flat geography. The flat land in the headwaters reduces the velocity of flow and shear force, but the sandy glacial soils in this region are prone to erosion. An agricultural practices increase flow downstream and reduces the amount of natural vegetation in the riparian area. The middle reaches are prone to more erosion because of the steeper slopes, but the land use in this area is mainly natural forests from the Whitewater State Park. Additionally, the stream runs through bedrock which is not easily eroded. Even though the stream is steep in the middle reaches, human impacts are low and erosion rates are correspondingly low. Naturally occurring vegetation and bedrock soils allow the formation of stable streams. The lower reach of the Whitewater River flattens again, creating a wide floodplain with sandy to silty alluvial soils deposited in the 1800's from poor fariming practices (Beach, 1998). This soil is more easily eroded than bedrock and the land use returns to agriculture. Even though the land is flat, increase flow from upstream agricultural practices increase the shear force on streambanks in the lower reach. Mass failure is common in the lower reach due to the instability of sandy soils with little natural vegetation. Therefore, in the Whitewater River, the most vulnerable reaches are the headwaters and the lower river due to land use and soil type.

The upper or headwaters reaches of all three rivers are dominated by herbaceous lands. Bias in the selection process could influence the results of this study. Many of the sites were near a road or farmland. Grass buffers or Conservation Reserve Program (CRP) land would increase the amount of herbaceous sites and possibly influence the results by mimicking natural landscapes. Herbaceous vegetation should provide more resistance to erosion in the headwaters because deep rooted plants will increase erosion through subaerial processes (Abernethy and Rutherfurd, 1998). In this study the herbaceous material averaged a lower BEHI score than the tree dominated sites for headwater reaches (see Figure 15). Trees have a tendency to become unstable and increase erosion through windfall actions (Abernethy and Rutherfurd, 1998). As trees fall into a river they bring sediment and increase erosion by redirecting flow into a streambank. Smaller plants with shallower roots will protect most of the streambank and remove excess moisture without providing large woody debris to increase in-stream erosion. Although this result is not definitive due to the small sample size and possible bias in site selection, it supports the idea that herbaceous plants will provide the most protection to headwaters sites in the three watersheds in this study.

Shrubs and herbaceous plants make up the middle reaches of each river in this study (see Figure 13). Bias in the site selection could have influenced these sites as well. Disturbances in the land near a road or farm could allow shrub plants to regrow more easily than trees or herbaceous plants. If disturbances have influenced the growth of shrubs at these sites, then the BEHI scores may not be accurate. Shrub dominated sites did have lower BEHI scores than sites dominated by herbaceous plants in the middle reaches (see Figure 15). Since the stream is larger and the streambanks taller, herbaceous plants may not provide adequate protection throughout the entire bank face of middle and lower reach sites. The herbaceous root systems may not be strong or deep enough to provide protection from fluvial entrainment that causes the most erosion in middle reaches of rivers. Small amounts of constant erosion occur at bankfull height or lower. Shrubs should extend their root systems deep enough into the soil to provide protection to these areas, whereas herbaceous plants should have shallower root systems. These results are not definitive, but the lend support to the idea that shrubs provide the most benefit to middle reach streambanks.

The lower reaches of each watershed contain some herbaceous, some shrub dominated, and many forested sites (see Figure 13). Selection bias may also be present in the lower reaches, since sites were picked to be near roads or farms. Trees may be dominant at these sites because of human impacts that have reduced the amount of disturbance, such as fire suppression and building fences. Woody sites have much lower BEHI scores herbaceous sites. Shrubs have a slightly lower BEHI average than forested sites in this study. Woody plants have a much deeper root structure than shrubs or herbaceous plants which can provide stronger support against mass failure events

(Canadell et al., 1996). This result is not definitive due to possible site bias, but it does support to the idea that trees would benefit the lower reaches of streams better than herbaceous or shrub plants.

Many factors can confound the trends shown above, such as missing tree data, the abundance of Reed canary grass, and error from sampling and measuring. Tree root data was not included in the RLD measurements, which could cause BEHI scores to differ, since they did include tree roots. Reed canary grass (*P. arundinacea*) was so dominant across the three watersheds, covering 22 of the 30 sites, that root densities may be similar based on similarities in species compostions, as discussed in Chapter 2. Using a small PVC tube to capture roots did not allow retrieval of tree roots or any other large roots in the soil. Error associated with sampling and measuring as mentioned in Chapter 2 could also influence the differences in root density.

The BANCS method of erosion prediction may be inaccurate because of the differences in land use, vegetation, and soil type that differ from the streams where it was designed. Since no region specific graphs or measurements have been made, calculations may be inaccurate. However, this erosion prediction method is designed to be empirical and requires calibration for each region in order to provide an accurate estimation. Increases in hydrology from runoff can cause higher flows increasing erosion rates while leaving BEHI values similar until equilibrium can be reached. Conservation farming and advanced stormwater practices can reduce the erosive power of high flows from agriculture, towns, and roadways, further confounding the relationship between BEHI and erosion rates. Conservation practices and hydrology changes can vary widely over a small area, causing BEHI values and erosion rates to vary greatly.

Soil and water conservation projects require many other considerations before implementation to reduce erosion rates in a region. Farming activities can influence the behavior of soils and increase the need for woody vegetation. Tile drainage could cause silty soils to drain quickly like sand. Fast, high flows caused by agricultural practices, such as ditching and tiling, can increase the need for woody vegetation. The water table will be much deeper with increases in shear force caused by increases in water velocity. Trees will strengthen streambanks with larger roots and can withdraw moisture from greater depths. Landowner considerations can affect the type of vegetation on a streambank. Herbaceous vegetation would be grown for grazing animals. Vegetation could be planted as habitat for desired species. For example, prairie birds and mammals could be attracted by planting grasses instead of trees. Many of these non-erosion based considerations must be included in conservation practices aimed at reducing erosion rates on streambanks.

The information obtained in this study could be useful for other studies and conservation practices. Other studies interested in riparian vegetation and erosion rates could benefit from learning about the significant causes of increases in erosion rates. Vegetation management, vegetation restorations, and in-stream hydrologic restorations could benefit in learning about the importance of different vegetation types and species on erosion rates. Information gleaned from this study could be useful to other researchers, restoration projects, and organizations that work to protect the stability of streams in Minnesota.

In order to verify the results of differences in effectiveness for vegetation depending on the river section additional research is needed. Further studies could focus on just vegetation and BEHI scores, allowing many site visits in a day. By focusing on one river, a complete picture of factors that affect erosion and BEHI scores would emerge. Comparisons of vegetation type and erosion could be more easily compared to river section with a larger sample size of sites. Additional data, such as land use, disturbances, proximity to a road, and soil type, would provide better information about human impacts. Expanding vegetation surveys and BEHI estimations to include more sites further from roads and other human impacts could provide further information about human caused changes for watersheds in Minnesota. Analyzing historical data for each of these watersheds could provide information about vegetation changes, erosion rates, and channel movement or degradation.

Application to other studies/projects

Conclusion

The hypothesis in this section could not be verified because of the complexity of the problem, but general trends can provide insight into possible relations that may reduce erosion rates in different sections of a river. Herbaceous vegetation received lower BEHI scores on the headwaters sections because small, dense plant systems reduce erosion from subaerial processes. Shrub dominated sites had the lowest BEHI scores among middle reaches since thicker, deeper rooting plants reduce erosion from fluvial entrainment. The lower river sites had the lowest erosion rates when populated by deep rooted woody vegetation which reduces erosion from mass failure. Each watershed behaves slightly differently. In the Buffalo River the middle reaches are the most vulnerable due to land use and soil type. Clay resists erosion in the lower reach and natural vegetation protects the headwaters reaches. The middle reaches have erodible soils with agricultural land uses increasing erosion rates. Elm Creek has particularly high erosion rates in the middle and lower reaches where stream size greatly influences the increases in erosion rates. Soil type and land use are similar across all reaches, with varying conservation techniques used in the middle and lower reaches. The increases in erosion stem from land use practices and stream bank height. The Whitewater River experiences high erosion rates in the headwaters and lower reaches. Again, this is primarily due to slope changes, soil type, and land use. The middle reaches are well protected by natural landscapes, but the other reaches are heavily farmed and contain sandy material. The lower reach experiences particularly high erosion rates due to increased bank height and poor land use practices.

Bibliography

Abernethy, B. and Rutherfurd, I. (1998). Where along a River's Length Will Vegetation Most Effectively Stabilise Stream Banks? *Geomorphology*. 23, pg. 55-75.

Beach, T. (1989). *Accelerated Sedimentation in Southern Minnesota*. (Doctoral Dissertation). University of Minnesota Library Non-Circulating Thesis Collection.

Brooks, K., Ffolliot, P., Gregersen, H., DeBano, L. (2003). *Hydrology and the Management of Watersheds*. Ch. 4, 8,9, 10. pg. 77-104, 189-251. (3rd Edition). Ames, IA: Blackwell Publishing.

Cairns, M., Brown, S., Helmer, E., Baumgardner, G. (1997). Root Biomass Allocation in the World's Upland Forests. *Oecologia*. 111, pg 1-11.

Callaway, R., and Ridenour, W. (2004). Novel weapons: invasive success and the evolution of increased competitive ability. *Frontiers in Ecology and the Environment.* 2(8): 436–443.

Canadell, J., Jackson, R., Ehleringer, J., Mooney, H., Sala, O., Schulze, E. (1996). Maximum Rooting Depth of Vegetation Types at the Global Scale. *Oecologia*. 108, pg. 583-595.

Crow, P. (2005). The Influence of Soils and Species on Tree Root Depth. *Forestry Commission.*

DeWall, Petra. (2009). Minnesota Department of Transportation. *Bridge Scour Evaluation Procedure for Minnesota Bridges*. Retrieved April 17, 2013, from http://www.dot.state.mn.us/bridge/documentsformslinks/hydraulics/ScourGuidelines_12-09.pdf

Dingmann, A., Niemela, S., Anderson, P., Butzer, A., Monson, B., Paakh, B., Frederick, J., Lundeen, B., Christopherson, D., and Parson, K. (2012). Buffalo River Watershed Monitoring and Assessment Report. *Minnesota Pollution Control Agency*. Document Number: wq-ws3-09020106b.

Edmaier, K., Burlando, P., and Perona, P. (2011). Mechanisms of Vegetation Uprooting by Flow in Alluvial Non-cohesive Sediment. *Hydrology and Earth Systems Sciences*. 15, pg. 1615-1627. doi:10.5194/hess-15-1615-2011

Google Earth. "Buffalo River Sites." 46°48'22.75" N and 96°26'21.00" W. October 10th, 2012. Retrieved September 10th, 2012.

Google Earth. "Elm Creek Sites." 43°46'06.93" N and 94°39'41.53" W. June 23rd, 2010 Retrieved September 10th, 2012

Google Earth. "Whitewater River Sites." 44°03'58.65" N and 92°05'10.38" W. July 24th, 2011. Retrieved September 10th 2012

Johnson, G. (2010). Whitewater River Watershed National Monitoring Program Project. *Minnesota Pollution Control Agency*. Document number: wq-cwp8-12.

Kiley, D. and Schneider, R. (2005). Riparian Roots through Time, Space, and Disturbance. *Plant and Soil*. 269, pg. 259-272. doi: 10.1007/s11104-004-0542-7

Lenhart, C. F., Brooks, K. N., Heneley, D., & Magner, J. A. (2010a). Spatial and Temporal Variation in Suspended Sediment, Organic Matter, and Turbidity in a Minnesota Prairie River: Implications for TMDLs. *Environmental Monitoring* *and Assessment, 165*(1-4), 435-447. doi:http://dx.doi.org/10.1007/s10661-009-0957-y

Lenhart, C., Suppes, B., Brooks, K., & Magner, J. (2010b). Riparian Corridor-Channel Restoration and Management in Elm Creek, Minnesota. *Ecological Restoration (North America), 28*(3), 240. Retrieved from http://login.ezproxy.lib.umn.edu/login?url=http://search.proquest.com/docview/754901515?accountid=14586

Lichvar, R. and Kartesz, J. (2012). *North American Digital Flora: National Wetland Plant List, version 3.0*. Retrieved April, 26th, 2013 from http://wetland_plants.usace.army.mil

Minnesota Pollution Control Agency. *Minnesota River Basin: Watonwan, Blue Earth, and Le Sueur River Watersheds.*

Natural Resources Conservation Science. *Web Soil Survey*. Retrieved April 17th, 2013, from http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx.

Oak Ridge National Library: Environmental Data Science & Systems. *Number of Trees per Acre and per Hectare by Various Tree Spacing Combinations.* (2008). Retrieved April 3rd, 2013 from http://www.google.com/url?sa=t&rct=j&q=stems+per+hectare+light+forest&source=web&cd=6&ved=0CEoQFjAF&url=http%3A%2F%2Fcta.ornl.gov%2Fbedb%2Fappendix_a%2FNumber_of_Trees_per_Area_by_Spacing_Combination.xls&ei=Mqs8Ufq6OebOyAHMsIGwDA&usg=AFQjCNER6aD_C9M0YrsiDD1UcweYg5wZDw

Piercy, C. and Wynn, T. (2008). Predicting Root Densities in Streambanks. *Journal of the American Water Resources Association*. 44(2), Paper No. J06044. doi: 10.1111⁄j.1752-1688.2008.00178.x

Pollen, N. (2006). Temporal and Spatial Variability in Root Reinforcement of Streambanks: Accounting for Soil Shear Strength and Moisture. *Catena*. 69, pg. 197-205. doi:10.1016/j.catena.2006.05.004

Pollen, N. and Simon, A. (2005). Estimating the Mechanical Effects of Riparian Vegetation on Stream Bank Stability Using a Fiber Bundle Model. *Water Resources Research*. 41(W07025).doi:10.1029/2004WR003801.

R Development Core Team. (2013). R Documentation. *R-Project.org*. Retrieved April 17th, 2013, from http://www.r-project.org/.

Rosgen, D. (2008). *River Stability Field Guide*. Fort Collins, CO: Wildland Hydrology.

Shields, F., Simon, A., and Dabney, S. (2009). Streambank Dewatering for Increased Stability. *Hydrological Processes*. 23, pg. 1537-1547. doi: 10.1002/hyp.7286

Turbidity and TSS. Lake Superior Streams. (2013) Retrieved April 17th, 2013, from http://www.lakesuperiorstreams.org/understanding/param_turbidity.html

United States Environmental Protection Agency- Water: Monitoring and Assessment *Turbidity: What is Turbidity and Why is it Important?* (2012).. Retrieved April 17th, 2013, from http://water.epa.gov/type/rsl/monitoring/vms55.cfm

United States Department of Agriculture: Natural Resource Conservation Service. *Rapid Watershed Assessment: Buffalo-Whitewater (MN / WI) HUC: 07040003*.

United States Department of Agriculture: Natural Resource Conservation Service. *Rapid Watershed Assessment: Resource Profile Blue Earth (MN/IA) HUC: 07020009.*

United States Environmental Protection Agency. *Surf Your Watershed* (2013).. Retrieved April 30th, 2013, from http://cfpub.epa.gov/surf/locate/index.cfm.

United States Environmental Protection Agency. *Watershed Assessment of River Stability and Sediment Supply (WARSSS).* (2012). Retrieved April 17th, 2013, from http://water.epa.gov/scitech/datait/tools/warsss/.

Weaver, J. (1968). *Prairie Plants and Their Environment*. Chapter 5. Underground Activities in Prairie, pp. 82-103. Lincoln, Nebraska: University of Nebraska Press.

White, K. E. (2001). Regional Curve Development and Selection of a Reference Reach in the Non-Urban, Lowland Sections of the Piedmont Physiographic Province, Pennsylvania and Maryland. *United States Geological Survey*. Retrieved from http://login.ezproxy.lib.umn.edu/login?url=http://search.proquest.com/docview/17343601?accountid=14586

Wynn, T. and Mostaghimi, S. (2006a). Effects of Riparian Vegetation on Stream Bank Subaerial Processes in Southwest Virginia, USA. *Earth Surface Processes and Landforms*. 31, pg. 399-413. doi: 10.1002/esp.1252

Wynn, T. and Mostaghimi, S. (2006b). The Effects of Vegetation and Soil Type on Streambank Erosion, Southwestern Virginia, USA. *Journal of American Water Resources Association*. Paper No. 04154.

Wynn, T., Mostaghimi, S., Burger, J., Harpold, A., Henderson, M., Henry, L. (2004). Variation in Root Density Along Stream Banks. *Journal of Environmental Quality*. 33, pg. 2030-2039.

Zedler, J. (2007). The Amazing Diversity of Root Forms among Native Wetland Plants University of Wisconsin: Madison. *Arboretum Leaflets*.

Zhou, X., Hemstrom, M. (2009). Estimating Aboveground Tree Biomass on Forest Land in the Pacific Northwest: A Comparison of Approaches. *United States Department of Agriculture.* Pacific Southwest Research Station, Research Paper PNW-RP-584.

Appendix A: Raw Data from MDA Study

Table 5. Information Used for This Study and the MDA Prioritization Study. The following information was collected at three different rivers in Minnesota, The Buffalo River (BU), Elm Creek (EC), and The Whitewater River (WW). There are several missing samples (denoted by -) where incomplete data was available. Bulk Density values below 1 g/cc were not included in the analysis. Each river has ten sample sites, there is no site BU6 on the Buffalo River. This data was collected and analyzed for this thesis project and the Restoration Prioritization Study funded by the Minnesota Department of Agriculture.

Site	Bulk Density (g/cc)	Vegetation Cover	BEHI Category	BEHI score	RLD (cm/cm^3) 0-30cm	RLD (cm/cm^3) 30-60cm	RLD (cm/cm^3) 60-90cm	Section	NBS rating	Erosion Rate (ft^3/yr per 300 ft)
BU1	0.79	Herbaceous	High	30.8	1.60	0.36	0.19	Upper	Very Low	0.1652
BU2	0.80	Herbaceous	High	30.4	3.64	0.51	0.21	Upper	Low	0.3796
BU3	1.43	Herbaceous	High	30.6	-	1.53	0.50	Upper	Moderate	0.3796
BU4	1.29	Herbaceous	Low	16.3	4.63	2.27	1.52	Upper	Low	0.0515
BU5	1.42	herbaceous	High	34.5	5.50	2.65	1.19	Middle	Moderate	0.3083
BU7	1.57	shrub	Moderate	26.5	4.32	4.71	-	Middle	High	0.3264
BU8	1.21	shrub	High	32.1	4.90	2.31	1.11	Middle	High	0.5753
BU9	1.44	forest	Moderate	24.1	1.98	1.31	0.78	Lower	High	0.4203
BU10	1.22	shrub	High	32.5	1.99	0.77	0.81	Lower	Very Low	0.1652
BU11	1.07	forest	Very High	40.3	2.00	0.58	0.33	Lower	Very Low	0.1652
EC1	1.10	herbaceous	Moderate	24.2	1.27	0.76	1.04	Upper	High	0.6969
EC2	1.34	shrub	Low	15.4	1.51	1.25	0.84	Middle	Low	0.0357
EC3	1.08	forest	High	30	2.65	0.74	1.53	Upper	Low	0.2504
EC4	0.45	herbaceous	Low	16.6	2.60	2.11	2.01	Upper	Very Low	0.0247
EC5A	1.02	herbaceous	Moderate	22.1	3.93	0.90	0.74	Middle	Very Low	0.1187
EC6	1.40	forest	High	33.8	5.68	1.11	0.87	Lower	High	0.5753
EC7	1.17	shrub	Moderate	28.1	1.58	1.02	0.34	Middle	Low	0.1529
EC8	1.24	herbaceous	Extreme	50.4	5.01	1.27	0.96	Middle	Low	0.4200

EC9	0.94	herbaceous	Very High	41.7	2.79	1.65	1.21	Lower	Very Low	0.1652
EC10	1.26	herbaceous	High	33	2.18	1.19	0.54	Middle	Extreme	1.3218
WW1	1.30	forest	Moderate	27.5	4.55	0.89	0.61	Lower	Very High	0.6969
WW2	1.04	herbaceous	Low	14.7	5.89	1.09	0.85	Middle	Very Low	0.0171
WW3	1.07	herbaceous	Moderate	26.5	2.13	0.55	0.11	Upper	Very Low	0.1187
WW4	1.29	shrub	Moderate	27.5	0.73	0.55	0.95	Middle	Very Low	0.1187
WW5	1.22	forest	High	36.6	3.94	1.78	1.03	Upper	Low	0.2504
WW6	1.06	herbaceous	High	37.3	6.38	5.15	0.95	Middle	Very Low	0.2504
WW7	1.54	shrub	Moderate	20.3	1.63	2.53	-	Lower	High	0.2535
WW8	1.04	herbaceous	High	30.4	3.71	2.39	1.57	Upper	Moderate	0.3796
WW9	1.08	herbaceous	High	39.8	4.15	0.86	1.32	Lower	Extreme	0.8721
WW10	0.79	herbaceous	High	32.3	4.56	0.58	0.27	Upper	Extreme	0.8721

Appendix B: Information about Commonly Found Vegetation

Table 6. Vegetation Information for Commonly Surveyed Species at the Study Sites.
The Indicator status refers to the natural habitat of each species. Species can be either adapted for upland, wetland, or a mixture of both habitats.
UPL- Obligate Upland species
FACU- Facultative Upland Species
FAC- Facultative Species
FACW- Facultative Wetland Species
OBL- Obligate Wetland Species

Common Name	Scientific Name[1]	Indicator Status[1]	Invasive to MN[1]
Herbaceous			
Swamp Milkweed	*Asclepias incarnata*	OBL	No
Common Milkweed	*Asclepias syriaca*	UPL	No
Brome Grass	*Bromus inermis*	UPL	Yes
Sedge	*Carex spp.*	UPL-OBL	No
Canadian Thistle	*Cirsium arvense*	FACU	Yes
Horsetail	*Equisetum arvense*	FAC	No
Wood Nettle	*Laportea canadensis*	FACW	No
Reed canary grass	*Phalaris arundinacea*	FACW	Yes
Virginia Creeper	*Parthenocissus quinquefolia*	FACU	No
Tall Coneflower	*Rudbeckia laciniata*	FACW	No
Giant Goldenrod	*Solidago gigantea*	FACW	No
Goldenrod	*Solidago spp.*	FACU-FACW	No
Stiniging Nettle	*Urtica dioica*	FAC	No
Violet	*Viola spp.*	FACU-OBL	No
River Bank Grape	*Vitis riparia*	FAC	No
Shrubs			
Red-Osier Dogwood	*Cornus sericea*	FACW	No
Honeysuckle	*Diervilla spp.*	FACU-FACW	Yes
White Mulberry	*Morus alba*	FACU	No
Chokecherry	*Prunus virginiana*	FACU	No
Common Buckthorn	*Rhamnus cathartica*	FAC	Yes
Gooseberry	*Ribes spp.*	FACU-OBL	No
Sandbar Willow	*Salix interior*	FACW	No
Common Elderberry	*Sambucus canadensis*	FACU	No

Nannyberry	*Viburnum lentago*	FAC	No
Trees			
Boxelder	*Acer negundo*	FAC	No
Silver Maple	*Acer saccharinum*	FACW	No
Green Ash	*Fraxinus pennsylvanica*	FACU	No
Black Walnut	*Juglans nigra*	FACU	No
Cottonwood	*Populus deltoides*	FAC	No
Black Willow	*Salix nigra*	OBL	No
Basswood	*Tillia americana*	FACU	No
American Elm	*Ulmus americana*	FACW	No

[1]: Lichvar and Kartesz, 2012

Whitewater River WARSSS

June 19, 2015

Contents

List of Figures

1 Watershed Overview

Hydrologic Impacts

The Whitewater River is a 320 square mile watershed formed as a result of glacial melt water repeatedly down-cutting the Mississippi River Valley. As the base level of the Mississippi River lowered, head-cuts propagated up the drainages flowing into into it. Watersheds like the Whitewater are still adjusting to this down-cutting. This adjustment is currently happening in the steep portion of the watershed, as seen in roughly the middle of the profile (**Figure 2**). The base-level lowering, in combination with a lack of recent glaciation has resulted in a well developed drainage. As a result, the watershed is lacking in wetlands. The relative lack of wetlands has meant the installation of less drain tile in comparison to similar agricultural areas in the state. Many portions of the upland perennial channels have been channelized/ditched however. This primarily happened around the turn of the century.

Agriculture is the primary landuse in the watershed with cultivated crops comprising 60% of the landcover (**Figure 1**). The conversion of the landcover from a prairie or savanna type cover to cultivated crops has undoubtedly led to increased runoff rates in the watershed. Because the hydrologic impacts of the historical land conversion happened so long ago, and the land use will no doubt remain predominately agricultural in nature, no future large-scale reductions or increases in runoff volumes should be expected. This does not mean that the channel morphologies are stable however. Adjustment to direct channel impacts like ditching/straightening/channelization are evident and ongoing. Although total runoff might not be expected to change significantly, flood timing and the flood magnitude could change with the application of channel stability remediation efforts. In general, these efforts would be the reconnection of the floodplain in ditched reaches or alterations to bridges and culverts, possibly impacting the flood pulse. This management strategy would be the replacement-modification-addition of the culverts in accordance to the principles discussed in Zytkovicz '' Murtada [Zytkovicz, Murtada2013].

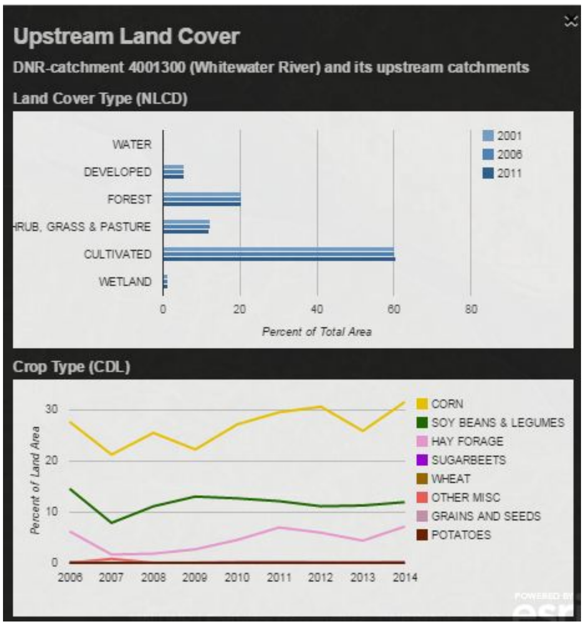


Figure 1: Whitewater watershed landcover [WHAF]

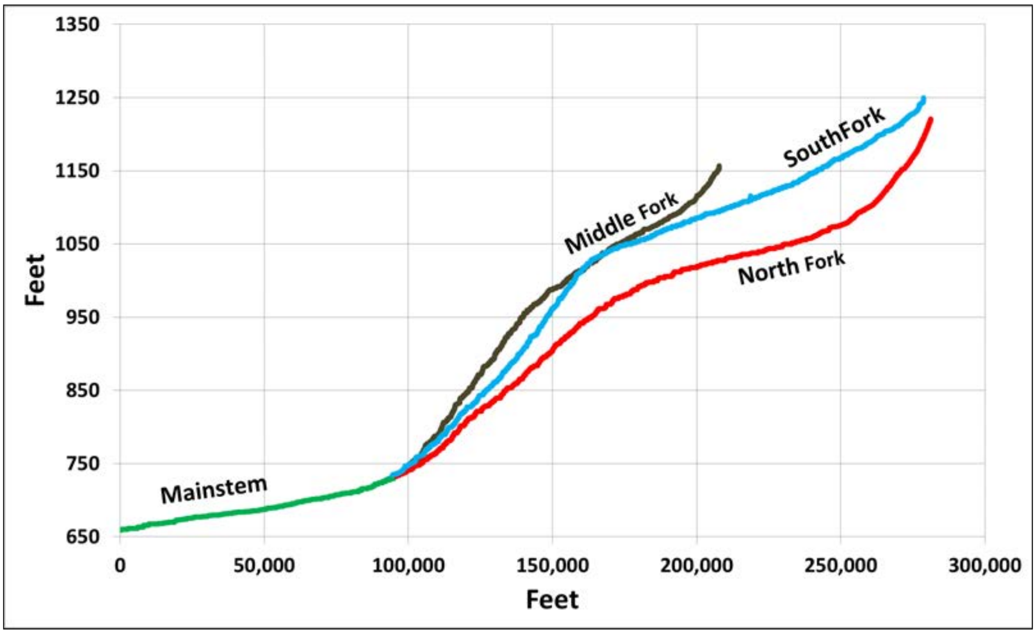


Figure 2: Whitewater Profiles

Soil Associations

Located roughly 80 miles South-East of the Twin Cities, the Whitewater watershed lies in the Paleozoic Plateau, also known as the "Driftless Area" (**Figure 4**). It is called this because the sediment left behind from glaciers is referred to as "drift' and the last four glacial advances have largely missed this area (**Figure 3**). Although there is evidence of previous glaciations, as on the western margin of the area where glacial till several feet thick can be found; these sediments are thought to be pre-Illinoian in age [Albert1994]. After the subsequent Wisconsinan glaciation receded, silts from the glacial outwash were carried by wind and deposited as loess on any exposed bedrock or remaining glacial till. The loess ranges in thickness from about 20 feet deep in the east on ridgetops by the Mississippi River to none at the western margins of the Driftless Area. Where the pre-Illionian till was not eroded away and the loess deposits did not cover it, glacial sediments are exposed and form the parent material of the existing soils. In the Whitewater watershed an area like this exists, covering most of the headwater areas of the South Fork of the Whitewater (**Figure 5(a)**).

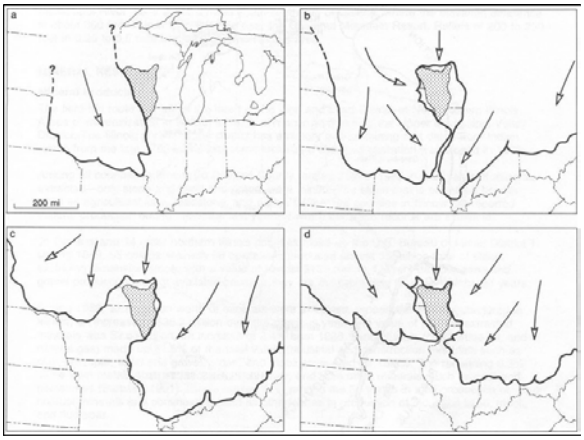


Figure 3: Driftless Area glaciations [Jefferson2010, Reinertsen1992]

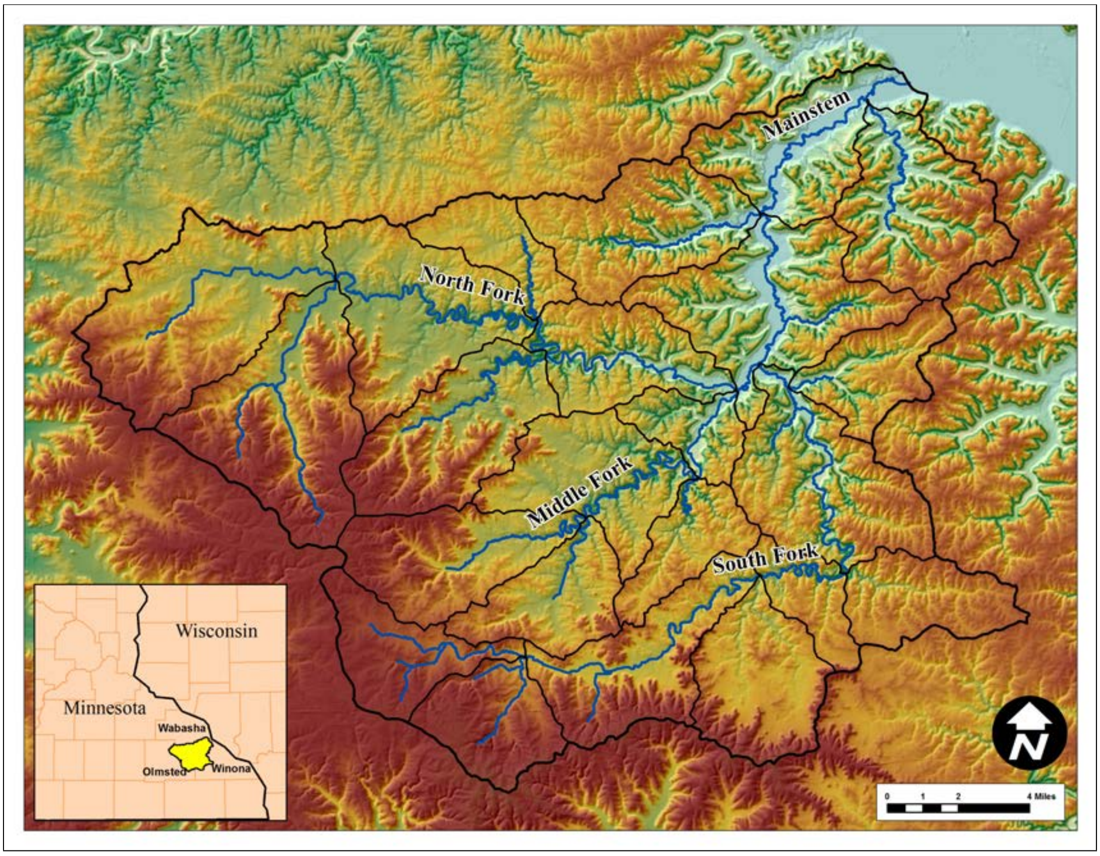
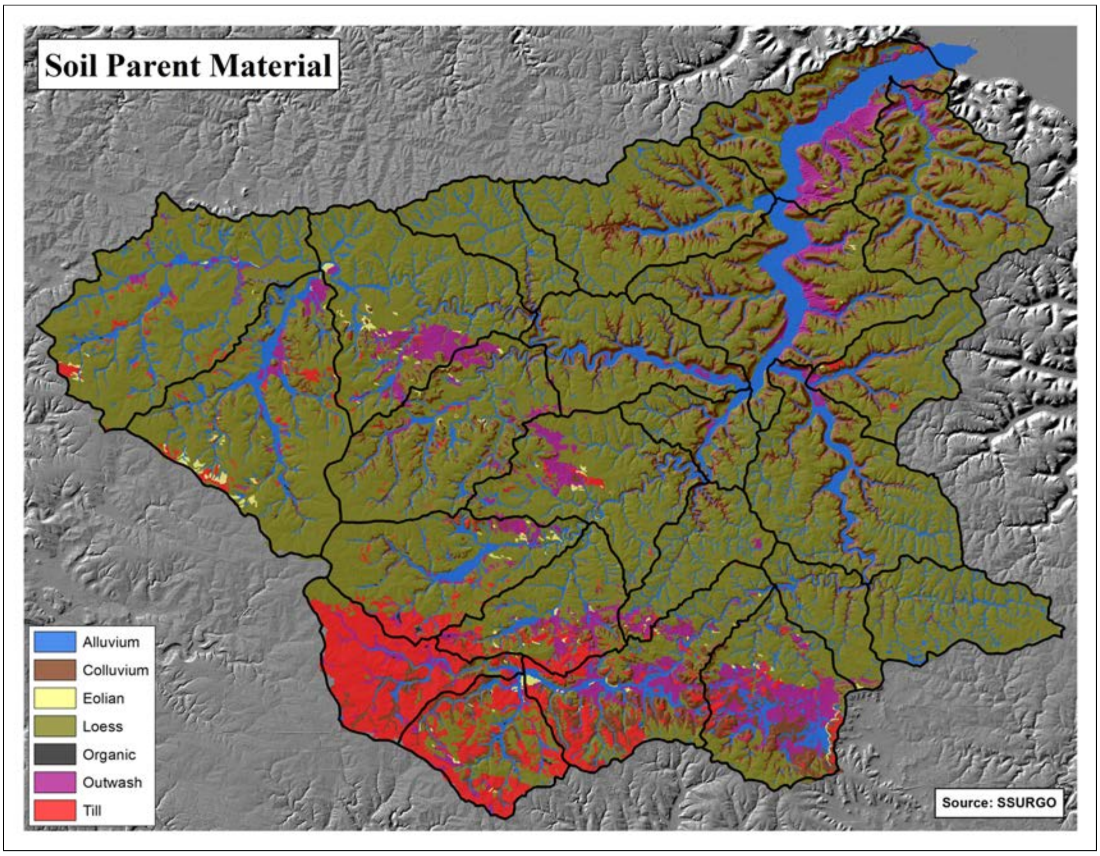
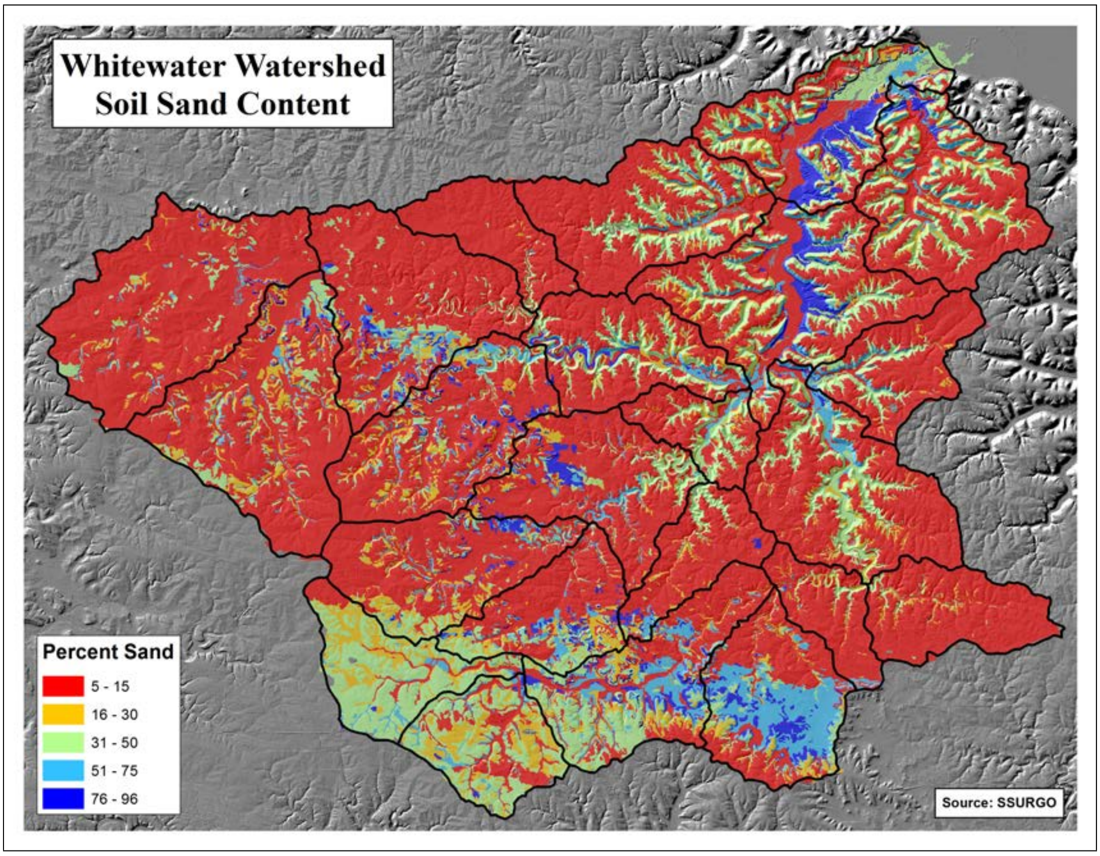


Figure 4: Watershed location and relief

The NRCS's General Soil Associations illustrate the layering and patterning of the soils in the watershed. As seen in **Figure 8** the Readlyn-Maxfield-Kenyon association depicts the underlying glacial till of the area comprising the upper portions of the South Fork. This association is very similar to the Racine-Floyd-Maxfield association mapped in **Figure 6**. These associations are congruous with the Racine-Floyd-Maxfield association making up the majority of the area. The difference mainly being the Racine-Floyd-Maxfield association is more deeply dissected. The remaining uplands of the North and Middle Fork's are dominated by silty loess. The Mt. Carroll-Port Byron-Lindstrom (**Figure 9**) and Mt. Carroll-Marlean-Arenzville (**Figure 10**) associations best represent these loess derived soils. They are mapped mapped as numbers 4 through 8 in **Figure 6**.



(a) Soil Parent Material



(b) Soil Sand Content

Figure 5: SSURGO Soils

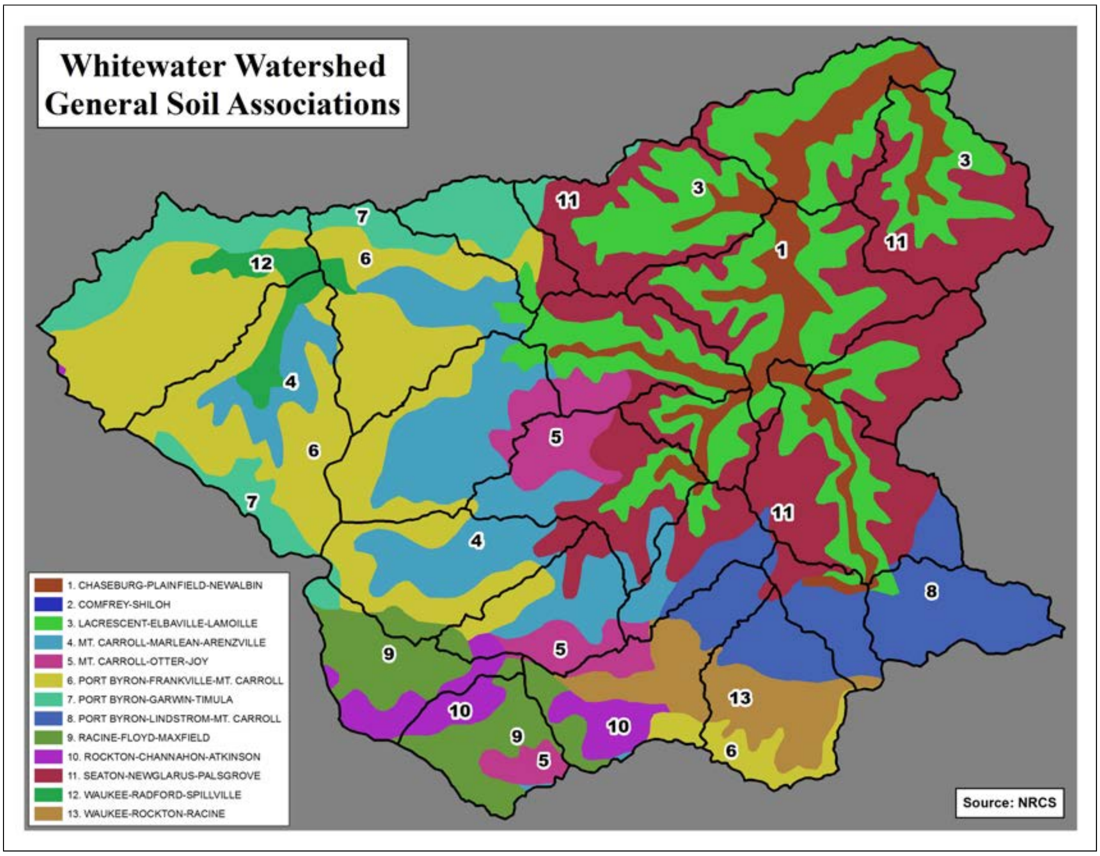


Figure 6: General Soil Associations

The conclusion to be drawn from looking at the county soil surveys is that the uplands of Whitewater Watershed is not homogenous. As seen in the SSURGO soil map (**Figure 5(b)**), the glacial till and outwash sediments are comprised of a much higher percentage of sand than the loess dominated areas. The alluvial sediments of the highly dissected bedrock valleys also contain a larger portion of sand. It could be expected that there will be two bedload sediment rating curves necessary to accurately capture the sediment loads in the Whitewater watershed. The first would be for the alluvial streams of the loess dominated uplands of the North Fork and Middle Fork. A second curve is likely necessary for the South Fork uplands, alluvial valleys in the dissected bedrock, the lower portions of the three forks, as well as the mainstem of the Whitewater. These four areas all appear to contain large proportions of sand.

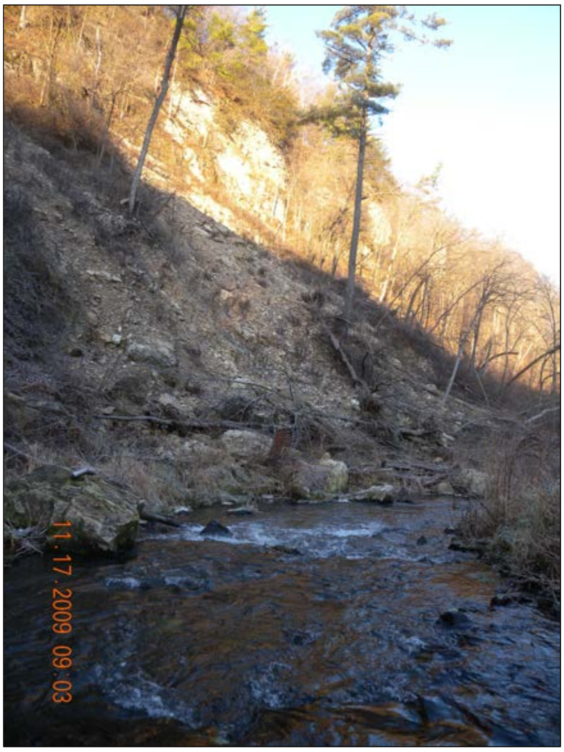
The glacial material can be seen in the field at various survey locations on the South Fork. The raw cutbanks of Site 008 (**Figure 7(a)**), located on near the headwaters of the South Fork, exhibits a dark-colored alluvial sediment overlying a light-colored glacial sediment that is comprised of primarily of sandy loam with embedded gravels. The channel bed consists of a large amount of sand with many, unsorted, gravels and cobbles (**Figure 7(b)**). Based on the competency calculation many of the larger stones prove too large for the stream to transport at a bankfull flow. It is therefore unlikely that these gravels and cobbles are being delivered from upstream. There are also no apparent eroding rock faces or colluvial slopes at the site or upstream that could be the source of these large particles. It can be said with high confidence that these large substrates are being accessed from the underlying glacial outwash or till. In contrast to the glacial material exposed at Site 008 on the South Fork, the cutbank of Site 025 near the North Fork headwaters exposes purely alluvial sediments and lacks the embedded gravels and cobbles (**Figure 7(c)**). The upland soils around Site 025 are almost exclusively loess derived, fine grained silt. The upland soils of Site 008 are mostly till and much sandier. In the lower portions of each of the three forks as well as the Mainstem of the Whitewater, the banks also have a higher proportion of sand in the banks (**Figure 7(d)**). This is primarily a result of these streams being on the receiving end of the deeply dissected landscape. It is here that large hillslope failures and ephemeral gullies transect the steep valleys. These are deliver large quantities of sand as they often occur on colluvial surfaces as seen in Figure **10**, **7(e)** and **7(f)**.

(a) Cut-bank in glacial sediments - South Fork

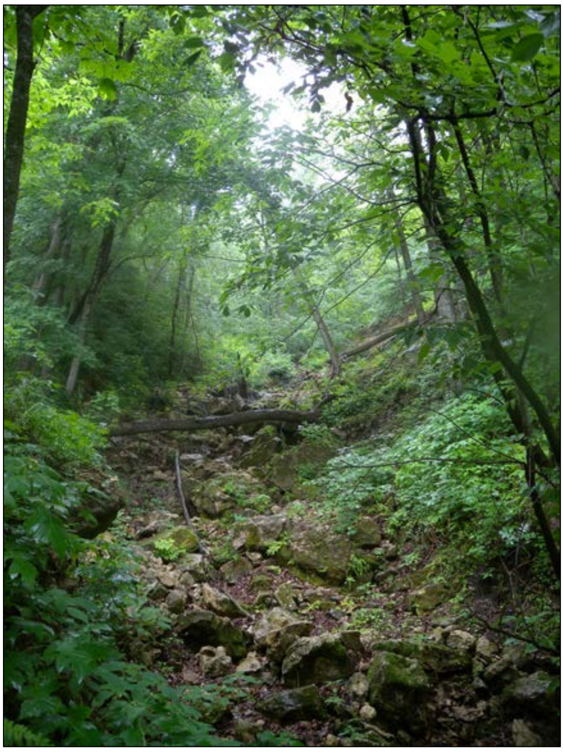
(b) Un-sorted glacial sediments - South Fork

(c) Cut-bank in silty alluvial sediments - North/Middle Forks

(d) Cut-bank in sandy alluvial sediments - Lower Valleys



(e) Hillslope failure - Deeply dissected valleys



(f) Debris torrent - Deeply dissected valleys

Figure 7: Typical near-channel sediments

Valley Types

Streams in the Whitewater River have valley types primarily consisting of VT C-CO-VS/US, C/U-BR-BC, C/U-AL-FD, U-AL-AF/IF, C/U-GL-TP and C-EO-LH. The perennial channels assessed are primarily limited to C-CO-US, C/U-BR-BC, C/U-AL-FD and C/U-GL-TP (**Figure 11**). Starting at the watershed divide and following the stream downstream, the classic progression of valley types encountered for the North and Middle Forks of the Whitewater River would proceed as follows. The landscape starts in flat to sloping eolian loess now converted predominately to agricultural fields. Most of these first order ephemeral streams start in VT C-EO-LH but due to the historical conversion of the prairies and savannas to row corps, much of the fine grained silt was eroded and deposited in the downstream valleys creating VT C-AL-FD. At this point most of the streams are ephemeral in nature. The magnitude of deposition increases downstream and these steep and narrow gullies give way to a more open valley of type U-AL-FD with a VWR of 7 or more. Continuing downstream, the valleys remain U-AL-FD but are characterized by lower slopes and expansive floodplain width with VWRs far greater than 7. Further downstream, the dissected bedrock begins to limit valley width pushing the valleys below the VWR threshold of 7. Moving down, the streams encounter the bedrock below and the valleys narrow and steepen. In these areas the VT's bounce back and forth between VT U-BR-BC, C-BR-BC, U-AL-FD and C-AL-FD with the C/U-BR-BC valleys encountered in the tight bends of the valley and C-AL-FD found in the straight sections between. The U-AL-FD valley type occurs occasionally in somewhat anomalously wide sections of the valley. At some point the streams exit the narrow valleys but maintain their gradient. In these wider valleys, VT U-BR-BC can still be found where the stream bumps up against the valley walls, otherwise VT U-AL-FD are typically found. As the major forks of the river approach the main stem of the river near the town of Elba, their slopes lessen and the floodplain width increases even more, forming VT U-AL-FD all the way to the mouth of the river.

The valley type sequence of the South Fork is very similar except that the soils are formed primarily from glacial till and outwash (parent material map). The extensive loess deposition found in the rest of the watershed largely missed this portion of the South Fork. Although the streams are now bound by alluvial material the bed of the channel is accessing these glacial sediments. These sediments are primarily sandy loam with minor fractions of gravel and clay. The City of St. Charles roughly marks the dividing line between the glacial and alluvial valleys. Everything upstream has been classified as glacial till valleys and downstream has been classified as alluvial valleys.

In the steeper, highly sinuous, bedrock dominated valleys typical of the Driftless Area, the typical meander in these types of valley has a long reach of riffle-pool morphology as it flows around the meander bend. This followed by an equally long pool. These features range in the neighborhood of 300-1000+ feet in length. At the end of these

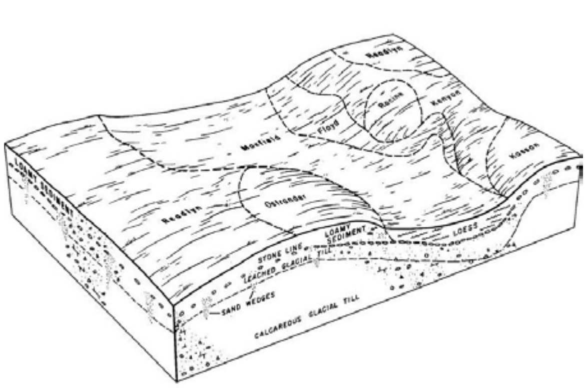


Figure 8: Readlyn-Maxfield-Kenyon association [NRCS-a]

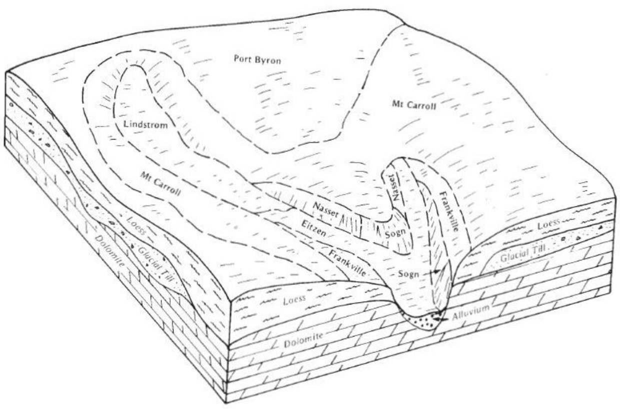


Figure 9: Mt. Carroll-Port Byron-Lindstrom [NRCS-b]

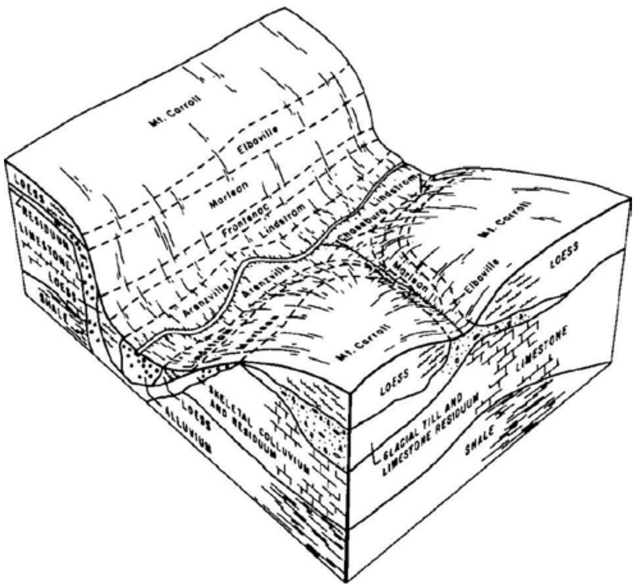


Figure 10: Mt. Carroll-Marlean-Arenzville association [NRCS-a]

extended pools are usually high W/d ratio "C" or "D" riffles. These riffles occur at the inflection point of the valley (where the channel crosses from one side of the valley to the other) in the same way as riffles occur at the inflection point of a meandering stream. Generally, the pattern repeats itself starting at this point. These mostly straight sections of river are classified as C-AL-FD. The survey data supports the separate classification of these valleys relative to the bounding bedrock morphology of the stream up and downstream.

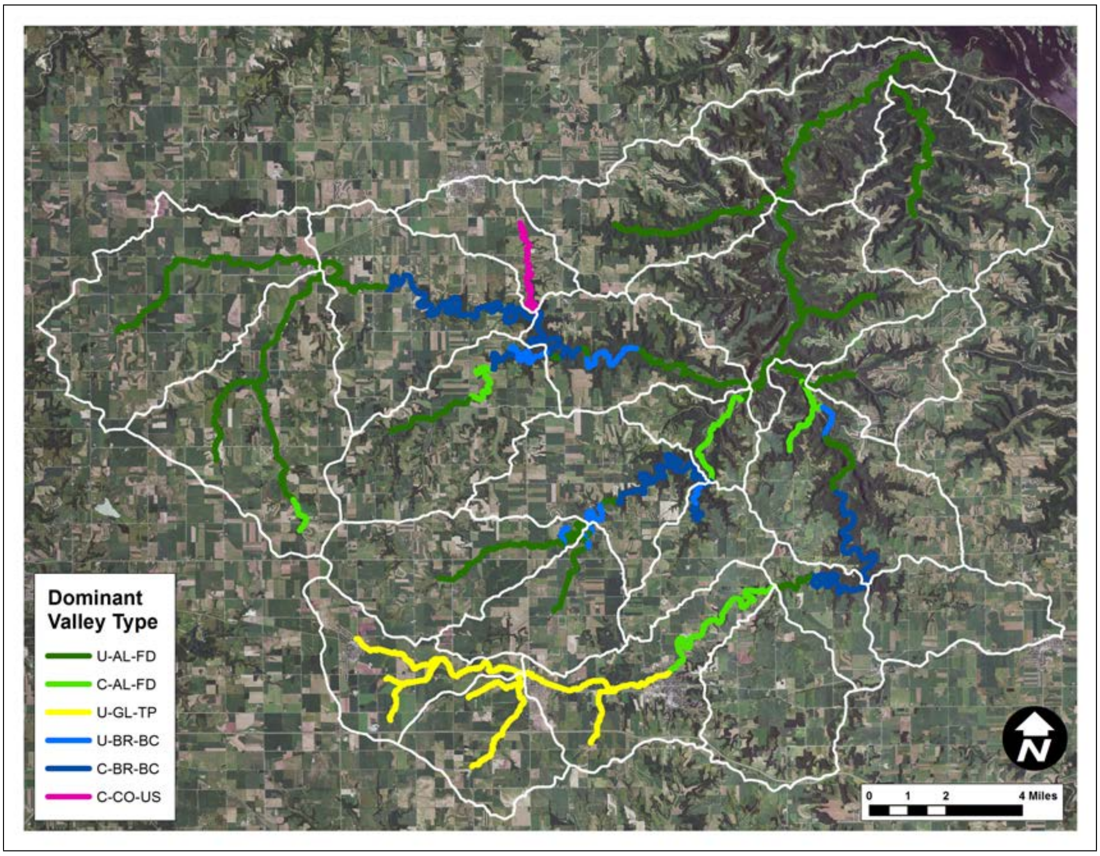


Figure 11: Whitewater Valley Types

At the inflection points of the valley the stream is usually not bound by valley walls and riffles in these locations tend to have higher width/depth ratios (25-35) than those found against the valley wall (15-25). The riffles on these portions of stream, while in a predominantly bedrock controlled valley, are classified as C-AL-FD. This stratification is made for purposes of assigning reference conditions correctly. Often found in the valley inflection points instead of a "C" channel is a "high W/d C" channel and possible a "D". The riffle form are often a transverse bar. A "C" type with a W/d ratio of 27 is considered reference for these riffles. The loss of stream power associated with these inflection points combined with the tremendous sediment loads delivered via hillslope failures initiated in large floods, ensure that large amounts of bedload are deposited here creating unstable "high W/d C" or "D" riffles at many locations. The accelerated deposition creates over-steep riffles, initiating lateral adjustment.

Floodplain Sedimentation

In the late 1930's, Dr. Stafford Happ of the Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS), established ranges perpendicular to the main valleys of the Whitewater River. Ground elevations were surveyed and soil borings made along these ranges to create cross sections of the floodplain including the pre-agricultural floodplain. Later in the mid 1960's he established more ranges that extended up all major tributaries of the Whitewater, as well as re-survey the previously established ranges. He established 94 ranges in all. In 1993-94 NRCS staff repeated the surveys. Because of these efforts it is possible to see how much the original floodplains have aggraded. This data was used to produce the time-trend cross sections shown in Appendix E. In general these cross sections show prolific floodplain aggredation.

The cross sections in the unconfined, terraced alluvial valleys of the upper portions of the Middle and North Forks make it apparent that there used to be a floodplain that existed at a lower elevation relative to the broader terraces comprising most of the valley floor. So much sediment has been deposited that now even the terrace

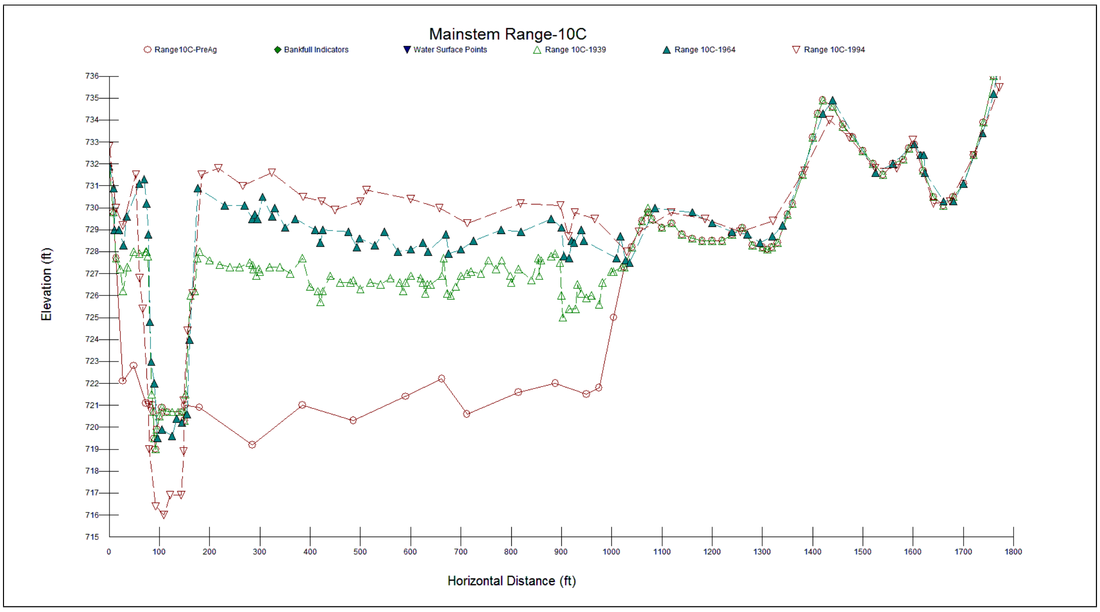


Figure 12: Historical Floodplain Aggredation

has been covered with fresh sediment. Any channels that had these lower and narrower floodplains between the higher and broader terraces saw the most extensive aggredation. In the glacial valleys of the South Fork the aggredation has been similar in scope, but the existence of terraces was not as common as in the other two Forks. In the deeper bedrock valleys the channels have largely maintained a stable shape but the floodplain has steadily risen. This shows how these streams have moved from an un-incised "C" channel to an incised "C", "B" or "F" type. The lower valley of each fork of river, before they meet the Mainstem channels have experienced large movements in their alignment either from rapid lateral migration or channel avulsion. This is evident in range 13A for example. It is in these reaches that the reference "C" channels are most likely to be found in a high W/d condition or even a braided "D" channel. Finally, Range 10C (**Figure 12**) depicts the extreme floodplain aggredation in the very flat Mainstem of the Whitewater River. The magnitude of aggredation ranges from around 15ft at the upstream end of the Mainstem and steadily decreases in the downstream direction to about 3ft at the mouth of the river.

2 Reaches

Distinct Reaches

The Whitewater consists of roughly 175 miles of perennial channel. These were divided into 110 distinct reaches of similar valley type (VT), stream type (ST) and gradient. In each reach there may multiple valley and stream types present, but typically one valley and stream type are dominant. Therefore the stream reaches do not represent a strict adherence to stream and valley type, but aggregated to reflect the general character of the channel. No two successive reaches will have all three criteria (VT, ST, slope) repeated. They may be of the same valley and stream type but distinguished as separate reaches because of a break in the general grade of the channel. Or slope and ST may be the same, but VT may change and etc. Dominant VT and ST were classified in a desktop procedure through interpretation of aerial photography and LiDAR data, as well as geology and soils maps/surveys. Desktop determinations were checked with field visits and geomorphic surveys. Channel gradient was extracted from LiDAR data. Disparate slopes were determined by the authors best judgment. A standardized statistical method of locating breaks of channel gradient was investigated but no techniques were found to be satisfactory to the investigators. It was found that in general the LiDAR derived channel slopes matched well with the surveyed water surface slopes.

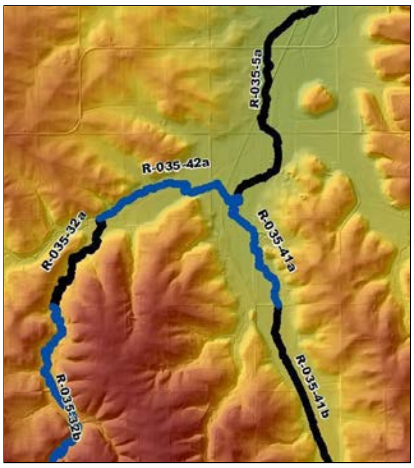


Figure 13: Reach naming

Each reach is given a unique identification code. An example of reach ID is "R-035-42a" as seen in (**Figure 13**). "R" is for reach, 035 is the last three digits of the Minnesota DNR's Minor watershed code. The last portion, "42a" consists of three parts. The "4" is a the Strahler Stream Order of the stream, the "2" means it is the second 4th order stream branch found along the main channel, starting from downstream in the Minor sub-watershed. The "a" means it is the first distinct reach, starting from downstream, on it's respective branch. Successive reaches would be labeled "b","c", etc. The 110 separate reaches and the Minor sub-watersheds (with ID's) they are located in are displayed in (**Figure 14**). The spatial extent of all reaches in a chosen Minor sub-watershed can be found in Appendix A.

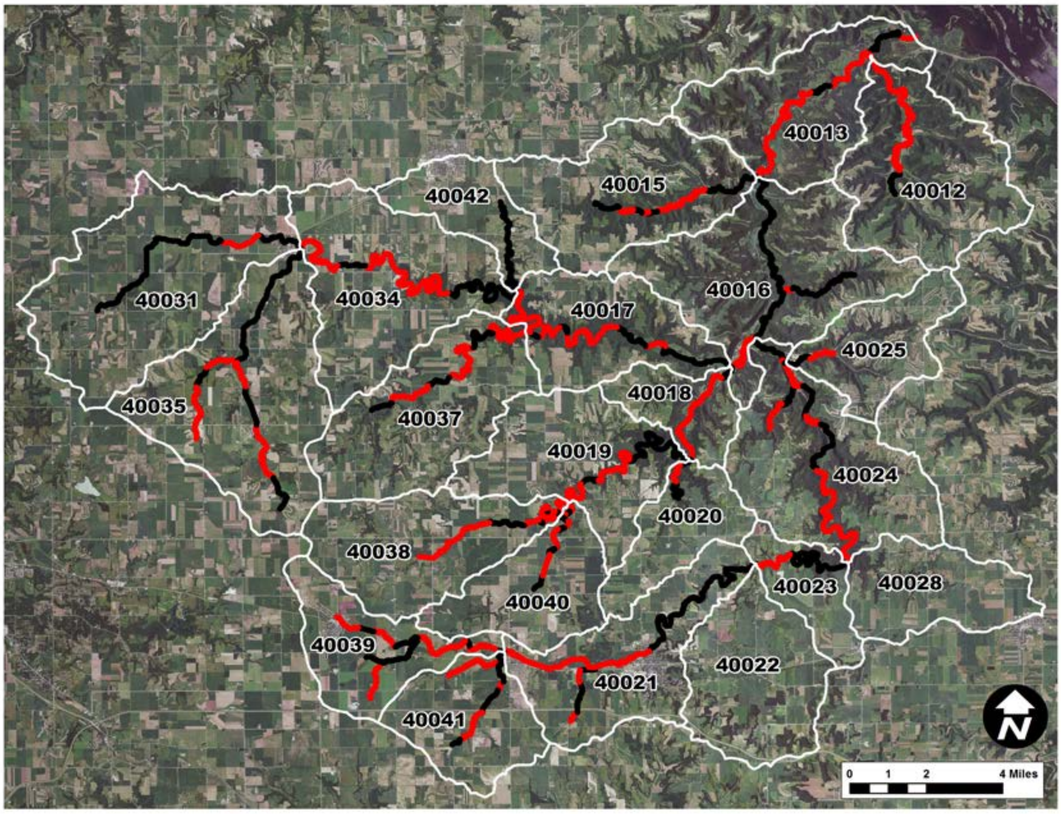


Figure 14: Minor subwatershed boundaries (white lines) and reaches (alternating red and black lines)

Stability

Pfankuch

Pfankuch stability ratings were scored at each survey site. If a reach had multiple survey sites and differing Pfankuch ratings, the Pfankuch rating that more closely matched the dominant or most prevalent condition was used to represent the entire reach (**Figure 15**). This was done for mapping purposes and stratifying the channels for later study. The survey sites retained their individual Pfankuch scores for the stability worksheets found in Appendices B and C. The Pfankuch ratings in conjunction with the VT/ST were used to pick the reference and representative sites discussed in Appendix B. By stratifying the channels by ST, VT and Pfankuch stability rating, one is able to use the correct sediment rating curves when estimating sediment delivery. To date, these rating curves are still under development in the southeastern portion of the state.

BANCS

In total, 87 miles of river were assessed using the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model [Rosgen1996, Rosgen2001]. The sediment loading estimates derived from this were extrapolated to 173 miles of stream. All estimates of erosion were made using the Colorado curve. Near Bank Stress (NBS) was visually estimated three ways; in the field, referring to field pictures or aerial photography. Calibration of visual estimates was done using surveyed banks, utilizing Method "5. Some banks required adjustments up or down in their BEHI score depending on the soil content found. The maginitude of the

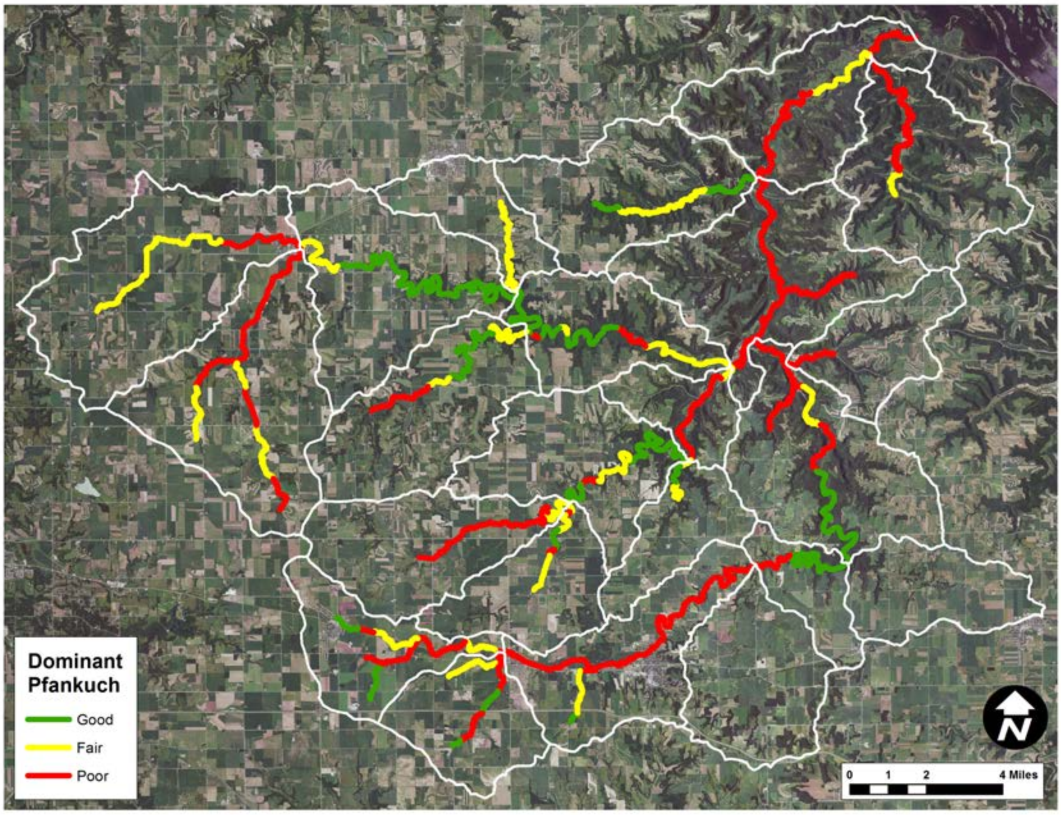
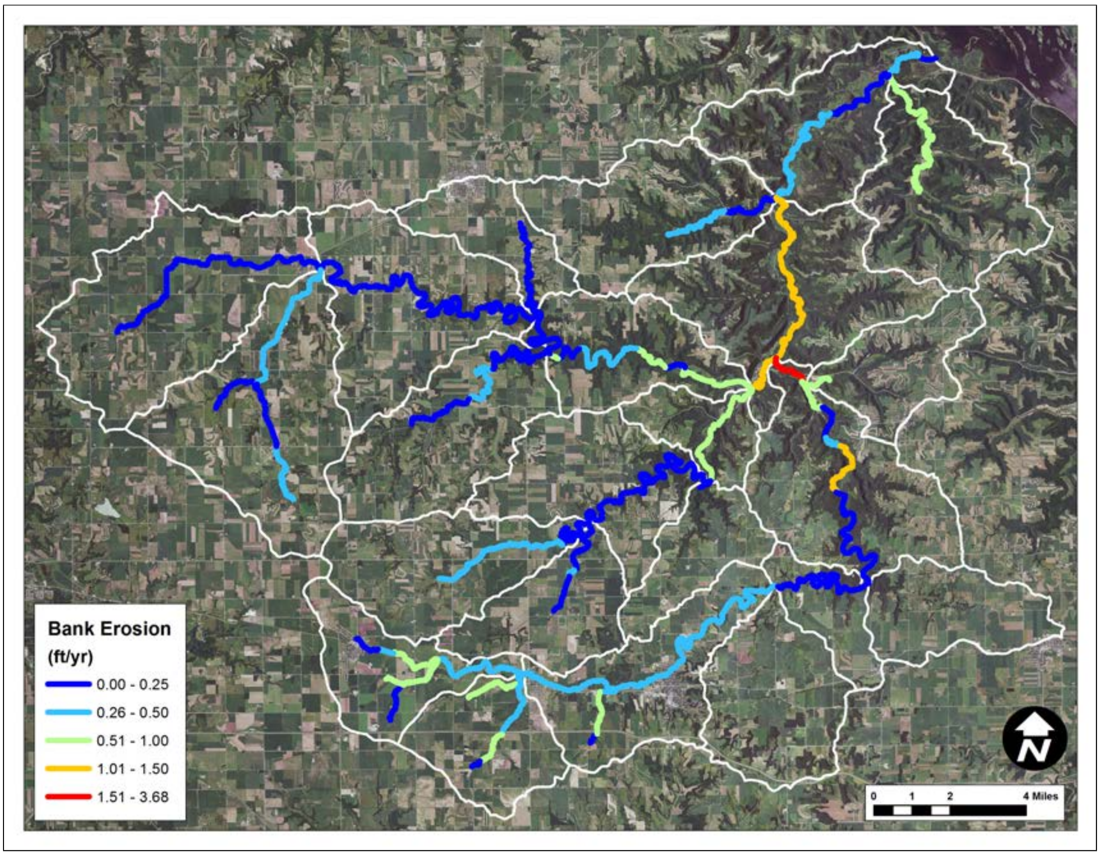


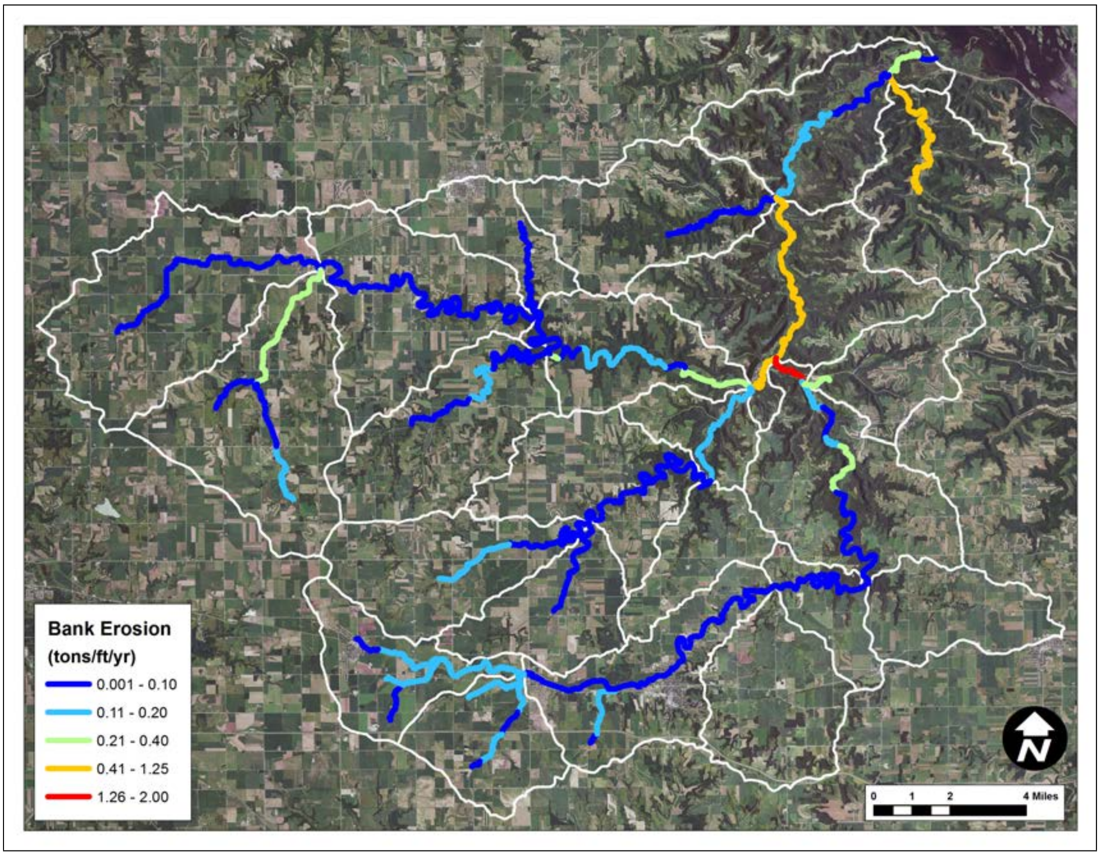
Figure 15: Dominant reach Pfankuch ratings)

adjustments were based on field measured erosion rates at monumented cross sections. Upward adjustments were made for sand content ranging from 5-20 points. BEHI scores were adjusted downward for clay and rock. Banks consisting of bedrock were assumed to exhibit zero erosion and were generally not rated in the streambank erosion summary forms found in Appendix C. However their length was included in the Total Stream Length used to calculate the erosion rate on a per foot basis. Bank heights were extracted from LiDAR. In general, this underestimates the study bank height because the LiDAR data does not penetrate the water's surface. Bankfull height was determined using survey data. The bankfull height was calculated as the distance from the low flow watersurface at the time of the survey to the bankfull elevation. In this way the bankfull height more closely matched the lower study bank height when using LiDAR. The result is a decent approximation of the study bank height/bankfull height ratio. It was found by the investigators that often the field estimate of bankfull in entrenched or incised channels would change to a significant degree after the data was worked up in the office. The process of using LiDAR and field photos to generate BEHI/NBS ratings allowed the rapid inventory of large reaches without having to measure or estimate bank heights, bankfull heights or bank lengths in the field. Although not a perfect system it avoids generating misleading estimates of bank height or length, particularly length. It also resulted in a spatially accurate GIS layer of eroding banks, including individual metrics comprising the BEHI and NBS ratings as well as hyper-linked field photos. This could prove useful if future adjustments are warranted in the erosion rates either from rating error or in-suitability of using the Colorado curve for erosion prediction. A preliminary southeast Minnesota region-specific curve has been developed. If warranted, the erosion rate estimates could be adjusted up or down if the regional curve is found to be statistically different from the Colorado curve.

Bank erosion estimates are shown in on a reach basis in Figures **16(a)** **16(b)**. Bank erosion estimates aggregated by Minor subwatershed can be found in Appendix A. Maps displaying individual rated banks can be found in Appendix A as well. In general, streams of the lower valleys are found to have higher lateral erosion rates. As discussed earlier in the "Soil Association" section, this is believed to be due to the higher fraction of sand in the banks. These larger channels also have naturally taller banks which limit the effectiveness of roots to stabilize the bank. Notable is the relatively large estimated reduction in the erosion rate in the mainstem occuring between the Minor subwatershed 40016 and 40013. The entire reach of the upstream portion exhibits an incision wedge in it's profile that is decreasing in the downstream direction. This means that is deeply incised at the upstream end and by the time it reaches Beaver Creek (Minor subwatershed 40015), the channel is only



(a) Mean lateral erosion rate by reach



(b) Bank-derived sediment loading by reach

Figure 16: BANCS estimated erosion rates

slightly incised. Although this is a natural condition of the channel, it becomes more pronounced the closer you move to reach R-013-7d. This is the location of a natural channel design restoration that reconnected the river with its floodplain. Below this reach the stream maintains its floodplain access until its confluence with the Mississippi. This reduction in estimated bank erosion rates is supported by bank erosion measurements taken at sites as well as time-trend aerial photography analysis.

3 Stream Types

Type "E"

Reference W/d ratios were selected for each potential stream type. The selected ratio was picked from a survey site that exhibited the most stable factors among the other similar sites. An intact riparian that was closest to its naturally occurring state was an important factor (**Figure 20**), as was a lack of incision and an unaltered pattern. Due to the widespread ditching/straightening efforts in the upper watershed, most streams are incised to some degree. This proved too much of a problem in the confined and unconfined alluvial valleys. It was determined that using the "E" reference site from an unconfined glacial till valley of the South Fork would be a better alternative than any location surveyed in the alluvial valleys in the Middle or North Forks. Many of the "E" channels have a channel succession scenario such as (**Figure 18**). Here the channel does not change stream type or even raise or lower its base level. It responds to the large influx of silty material delivered to it by aggrading its floodplain. This floodplain eventually turns into a terrace and the channel's degree of incision increases. The increased incision leads to increased bank erosion which leads to increased point bar formation. Because the point bar is built at the original floodplain elevation the channel creates a new floodway within its old floodplain, albeit at a narrower width than the original. This condition, and sometimes in combination with slight base level lowering from ditching or culvert impacts is typical for most "E" channels in the watershed. Due to the increased incision Figure 19(a) gives an indication of how far from reference the channels are from their potential W/d ratio by displaying their average W/d. Its apparent that most of the streams are on average, in an over-wide condition. The reference W/d ratio for all potential "E" channels in the watershed is then 8.8 (**Figure 19(a)**). This closely matches the mean W/d of all potential "E" channels in U-GL-TP valleys.

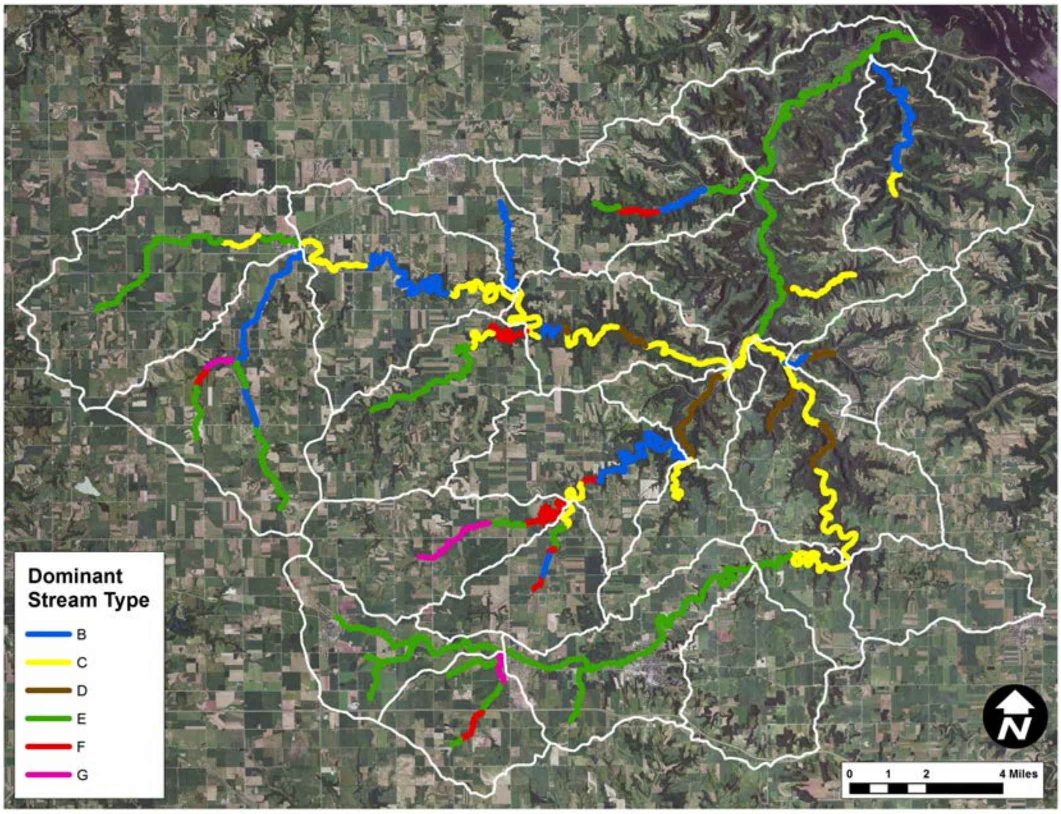


Figure 17: Whitewater Stream Types

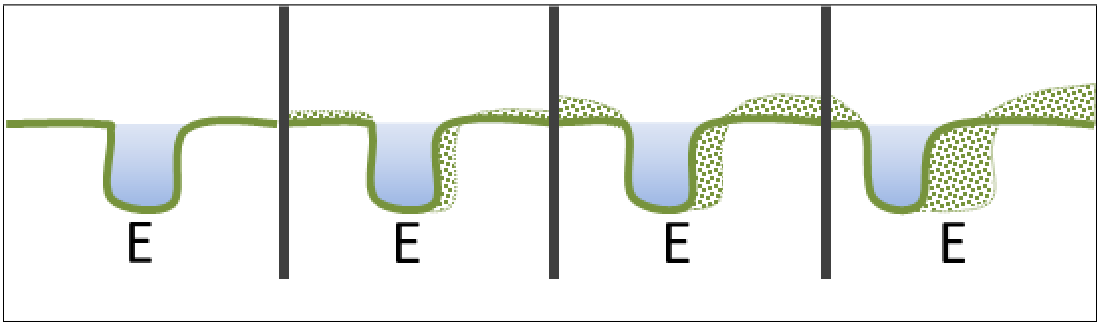


Figure 18: Incised E Succession

Type "C"

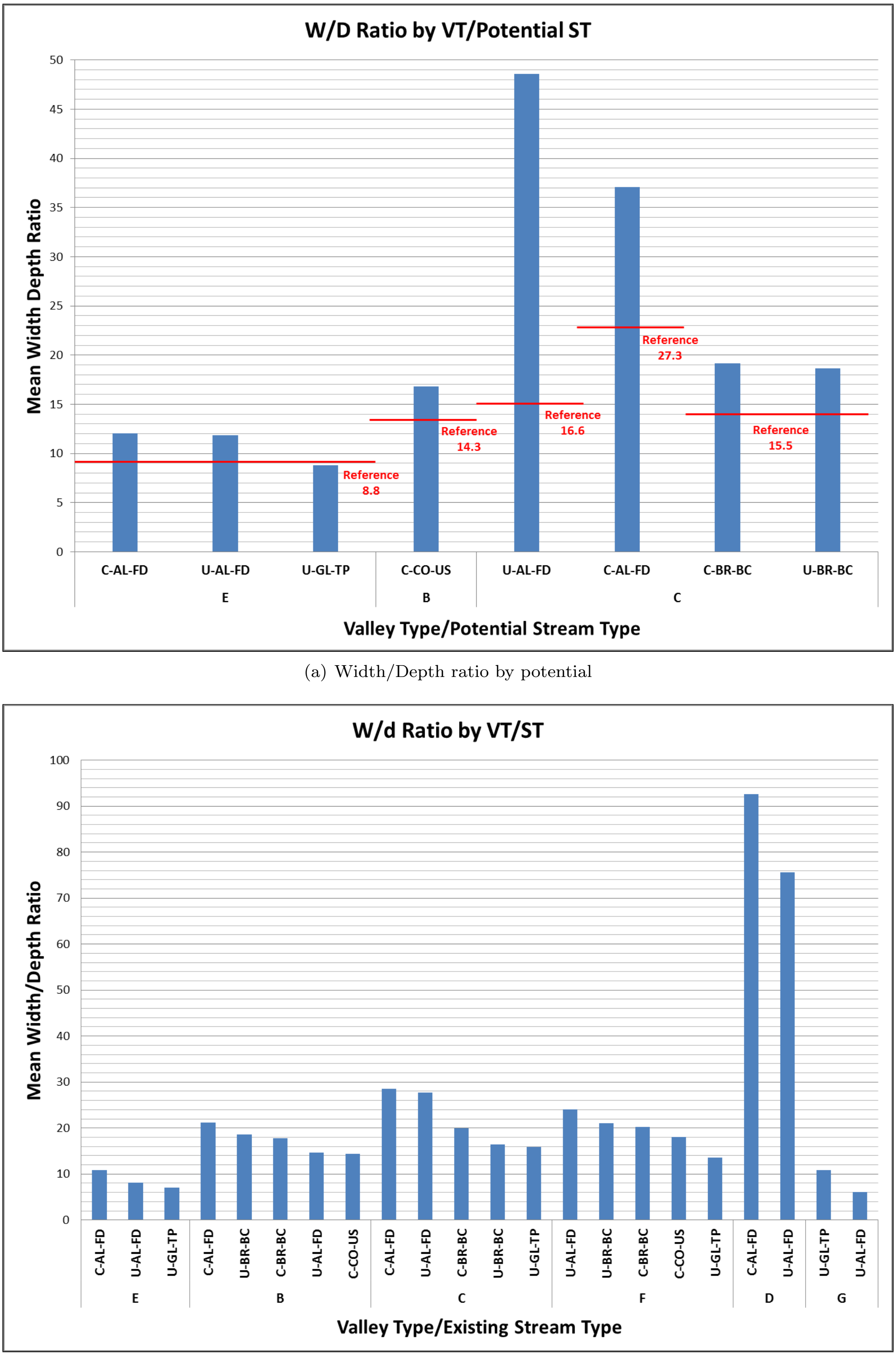
There are three different reference "C" types in the Whitewater watershed. One each for an unconfined alluvial valley (U-AL-FD), a confined alluvial valley (C-AL-FD), and one combined for a confined or unconfined bedrock controlled valley (C/U-BR-BC). The U-AL-FD "C" channels are fundamentally different than the C-AL-FD "C" channels as described earlier in the valley types discussion. U-AL-FD "C" types is the reference condition in the areas of the three forks that lie between the confluence with the Mainstem and the confined bedrock valleys upstream. On the Middle Fork for example, this would encompass the portion of the stream from where the Middle and North Forks meet, upstream to roughly the Whitewater State Park boundary. The reference W/d ratio of these channels is 16.6. The unstable form of these channels is either a high W/d "C" or "D" stream type. They are concentrated in the lower alluvial valleys of the three forks (**Figure 17**). It is in these locations where the steeper gradient of the deep valleys flatten out into the gentle slope of the lower main valley. These lower valleys are also impacted by present or historical riparian conversion. The loss of stream power and compromised boundary condition of the stream banks favor bed aggregation and channel widening. Looking to **Figure 19(b)**, the mean W/d ratio of the "D" channels stand out in how far they are departed from their reference condition

The C-AL-FD "C" channels exist on the straight sections of valley between the curving walls of the bedrock controlled valleys. These are typically very short stretches of stream and most often are only comprised of a few or less riffles. Because of they are located at the inflection point of the meandering valleys they are prone to recieving the most bedload deposition. For this reason they have a higher reference W/d ratio at 27.3. For the same reason the unstable form encountered is a high W/d "C" or even "D".

The unconfined and confined bedrock controlled valleys show no discernible difference in potential W/d ratio for a "C" channel at 15.5. Because these channels are bound on their cut bank by bedrock their only unstable stream type is not a "D" but an "F". Although this does not seem to negatively impact the stability of the portion of stream bound by bedrock, the increased flood water captured in the higher "F" channel may lead to instability in the reach below. Specifically, the C-AL-FD "C" channels described above.

Type "B"

The "B" channels of the confined colluvial valleys (C-CO-US) have a reference W/d of 14.3. These channels can also be found in a "F" type, but in general do not show significantly higher signs of instability. This is probably due to the high rock content found in the channel and banks of these valleys. These channels are also found between the bedrock controlled bends of the meandering valley. The distinction bewteen these reaches and the C-AL-FD reaches is that they typically have steeper, narrower valleys and are also smaller is size in terms of drainage area. Because the valleys are so narrow the stream banks are immediately bound by the colluvial material sloughed from the valley walls. This produces the U-shaped valley and gives the stream access to the large, stabilizing rocky material without creating large landslides source it. It is the large size and quantity of material entrained from sudden landslides and debris torrents that often create large instabilities in the C-AL-FD valleys. This some of this material can be transported further downstream or create a chain reaction of erosion that helps create some of the "D" channels of the lower valleys of the three forks.



(a) Width/Depth ratio by potential

(b) Width/Depth ratio by existing

Figure 19: VT/ST Existing-Potential W/d Ratios

Stream Type	Sensitivity to Disturbance[a]	Recovery Potential[b]	Sediment Supply[c]	Streambank Erosion Potential	Vegetation Controlling Influence[d]
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	very high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
DA4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

a Includes increases in streamflow magnitude and timing and/or sediment increases.
b Assumes natural recovery once cause of instability is corrected.
c Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.
d Vegetation that influences width/depth ratio-stability.

Figure 20: Rosgen Stream Type Management Interpretations [Rosgen1994, Rosgen1996]

Variation in Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the Minnesota River Basin

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

Laura Triplett

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Dr. Chris Lenhart, Dr. Joe Magner

January, 2014

Acknowledgements

Funding for this research was provided by the Minnesota Department of Agriculture as part of the Priority Setting for Restoration in Sentinel Watershed project, led by Dr. Chris Lenhart and Dr. John Nieber of the University of Minnesota in Saint Paul, Minnesota. Funding was also provided by the National Science Foundation Water Sustainability and Climate Program under the guidance of Dr. Karen Gran of the University of Minnesota Duluth.

Abstract

This study investigates the relationships between hydrologic regime and riparian vegetation establishment; specifically the impact of changes in hydrologic regime on the establishment of riparian vegetation in addition to exploration of associated sediment transport patterns. Recent flow increases within the Minnesota River basin have been associated with reductions in woody riparian vegetation establishment as a result of decreased point bar exposure time and increased scour at high flow. Reductions in riparian vegetation establishment may contribute to reduced sediment deposition; further promoting river widening and sediment loading. Field, geo-spatial, and stream flow data collection were completed within the Elm Creek and lower Minnesota River watersheds to further demonstrate and characterize the eco-hydrologic relationships between stream flow, vegetation establishment, and sediment transport within the Minnesota River basin.

Table of Contents

List of Tables

List of Figures

Part 1. Introduction and Research Overview

Over the past few decades, increases in stream flow have been observed within many upper Midwestern watersheds, including the Minnesota River basin (Lenhart et al., 2011a; Novotny and Stefan, 2007; Schilling and Libra, 2003). These increases can be attributed to changes in both climate and land-use, including increased precipitation and the expansion of subsurface tile drainage and annual row crop coverage (Zandlo, 2008; Zhang and Schilling, 2006). Channel adjustment has occurred within the Minnesota River basin in response to these changes in the form of channel widening and excess sediment transport (Lenhart et al., 2013; Schottler et al., 2014). Over 330 streams within the Minnesota River basin exceed turbidity standards and are listed as impaired by the Minnesota Pollution Control Agency (MPCA, 2008).

High levels of suspended sediment contribute to degradation of aquatic eco-systems including habitat destruction and sediment loading in downstream rivers (Waters, 1995). Inter-relationships exist between sediment transport and riparian vegetation including sediment scour and deposition on point bars (Corenblit et al., 2009; Bertoli et al. 2011; Gurnell et al., 2012; Lenhart et al; 2013). Additionally, alterations in stream-flow regime influence the establishment and survival patterns of riparian vegetation (Dixon et al., 2002; Johnson 1997). Component of a region's hydrologic regime are closely related to the establishment and survival patterns of riparian vegetation. These components include the timing, magnitude, and duration of base and peak flow events, as well as the rate of decline of the recession limb (Shafroth et al., 1998).

Recent studies have shown that changes in hydrologic regime within the region have contributed to reductions in woody riparian vegetation establishment (Lenhart at al., 2013). Prolonged summer flow duration and increased scour at high flow can contribute to vegetation mortality (Novotny and Stefan, 2007). High flows also lead to physical damage and removal of vegetation by ice and debris (Sigafoos, 1964; Yanosky, 1982). Additionally, excess sediment deposition occurring during large flood events serves to further inhibit vegetation survival (Hupp, 1988). Extended inundation can also lead to depletion of oxygen in the root zone and exhaustion of energy reserves necessary for vegetation survival (Gill, 1970; Whitlow and Harris, 1979; Stevens and Waring, 1985).

Exposed point bar sites following flood recession not only provide germination sites for woody vegetation, but also promote root elongation (Mahoney and Rood, 1991, 1992; Segelquist et al., 1993). More extreme flood peaks and recession rates may lead to extreme changes in soil moisture supply necessary for plant survival. Rood (1998), found that for survival of tree seedlings, the rate of water recession following a spring flood should not exceed the rate of root growth. For cottonwood (*Populus deltoides*), one of the fastest growing species in North America, the rate of root growth is approximately 2.5 cm/day (Rood and Mahoney, 2000).

Differing flow regimes and geomorphological characteristics within floodplain and point bar features lead to differing plant community compositions. Floodplains are generally flat surfaces located adjacent to the channel. The bank full stage, or point at which water begins to overflow the channel, is the elevation of the active floodplain. Most river systems experience overbank flow onto the floodplain every one to two years on average (Leopold et al., 1964). As a stream meanders down gradient over time, sediment is eroded or cut from one bank and deposited on the opposite side of the channel eventually causing lowering of the base elevation within a floodplain and the development of terraces, or abandoned floodplains (Brooks et al., 2013; Fitzpatrick et al., 1999).

Point bars occur at an elevation above base flow, but below bank full elevation and are characterized by annual spring flooding and heavy repeated erosion and deposition of materials. As deposited sediment, generally coarse sand and gravels, builds up on point bars during stream migration, point bar vegetation communities develop eventually leading to floodplain development and community succession. (Brooks et al., 2013; MNDNR, 2005; Wolman and Leopold, 1957) (Figure 1).

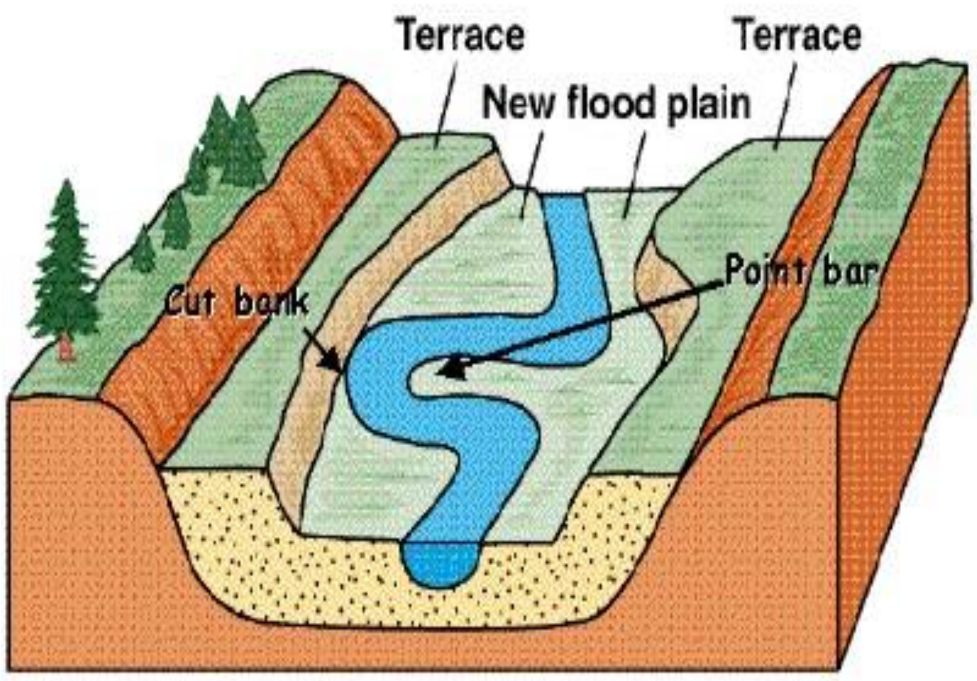


Figure 1. Floodplain, point bar, and terrace features within a river valley system.

Point bar vegetation communities are characterized by plants adapted to annual cycles of major natural disturbance. Species typically include perennial forbs and graminoids that are tolerant of erosion and inundation or annual herbaceous species that germinate rapidly on exposed sediments. Perennial species are generally limited to those that have well developed root systems or that are capable of adventitious rooting, such as sandbar willow *(Salix interior)* and black willow *(Salix nigra)*. Many species, including beggartick (*Bidens sp.*) and smartweed *(Polygonum sp.)*, both annuals forbs, produce seeds that remain viable buried in sediment until conditions are suitable for germination. Other annual grasses such as Creeping Lovegrass *(Eragrostis hypnoides)* or awned umbrella sedge *(Cyperus squarrosus)* are often abundant along river shores. Disturbance patterns within riparian plant communities also allow for rapid establishment of invasive species, such as reed canary grass *(Phalaris arundinacea)* (MNDNR, 2005).

Floodplain forest communities are present on occasionally or annual inundated sites and are dominated by deciduous trees tolerant of saturated soils, inundation, and frequent erosion and deposition of sediment. Characteristic species often are extremely mobile during some part of their life, using flowing water to disperse seed or producing seeds or propagules that remain dormant for extended periods of time. Some floodplain species also have physiological adaptations allowing for oxygen supply to submerged tissues, in addition to the ability to sprout new stems from the base of damaged ones. Actively flooded habitats are frequently dominated by silver maple *(Acer saccharinum)*, with occasional green ash *(Fraxinus pennsylvanica)*, American elm *(Ulmus americana)* or cottonwood *(Populus deltoides)*. Less frequently flooded habitats support mixed stands of silver maple, box elder *(Acer negundo)*, American elm, green ash, and cottonwood (MNDNR 2005; Smith, 2008).

Common woody species occurring on point bars and in floodplains present in this study include silver maple, American elm, cottonwood, black willow, sandbar willow, green ash, and box elder. Of these species, black willow and sandbar willow most frequently appear on point bar sites as saplings or shrubs, with occasional young pioneers of cottonwood or silver maple, while other species are generally observed within floodplain or terrace communities as adult trees (MNDNR, 2005; Smith, 2008).

Sandbar willow is especially adept at colonizing areas where the water table is near the surface and is a dominant riparian pioneer. This is especially true on exposed point bars created by receding floodwaters; seasonal flooding and sedimentation also strongly favor sandbar willow establishment. Sandbar willow, capable of developing roots from adventitious buds, can grow into dense thickets. Individual stems may grow and flower in just two or three years, but rarely live more than 12 years on average (MNDNR, 2005; Ottenbreit and Staniforth, 1992; Smith, 2008).

Black willow, although similar to sandbar willow, is better able to withstand inundation and sedimentation than other species (Gill, 1970; Pezeshki, 1998). This species transports seeds by both wind and water and is capable of developing roots from adventitious buds (Smith, 2008). Black willow has a dense root system excellent for stabilizing stream banks (Pitcher and McKnight, 1990). Black willow however, is brittle and easily subject to breakage (Fowells, 1965).

Silver maple, often dominant within floodplains, is of the earliest species to disperse seeds and to establish or to develop transplants. It is also a rapidly growing species, growing from ten to twenty-five cm per year. Where mature trees are present, seedlings are often abundant during the late spring, especially along the waterline (Geyer et al., 2010). On active floodplains, recruitment of silver maple saplings in the tree canopy seems to occur most often when it establishes within thickets of sandbar willow and cottonwood (MNDNR, 2005; Smith, 2008).

Cottonwood is among the fastest growing species in North America, growing as much as 80cm by autumn of the 1st year with a rate of root growth of about 2.5 cm/day (Rood and Mahoney, 2000). Cottonwoods produce massive amounts of seeds, transported by both wind and water, which reach numbers of up to 48 million seeds per tree (Cooper and Van Haverbeke, 1990). It is a relatively short-lived tree, seldom surviving more than 80 years. It has also been found to be relatively tolerant of drier sites (USDANRCS, 2002).

American elm, although producing fewer seeds as compared to silver maple or cottonwood, is more shaded tolerant and grows quickly when a canopy gap opens, developing a strong root system (Smith, 2008). American elm is tolerant of infrequent, short duration flooding during the growing season and is often more abundant on terraces or on less frequently flooded sites where replacement of silver maple by more shade tolerant trees, such as American elm, green ash or box elder is occurring (MNDNR, 2005).

Green ash is tolerant of moderate levels of spring flooding and sedimentation, but does not grow in permanently saturated soils and is intolerant of shade from surrounding trees. Although green ash is not considered to be a strong pioneer species within point bar or floodplain zones, it is a fairly early successional tree within upland habitats. Green ash is thought to be a tough, durable tree that rapidly colonized abandoned agricultural and urban land (Dickerson, 2002; MNDNR, 2005; Smith, 2008).

Within alluvial systems, box elder usually follows establishment of pioneer species including willow and cottonwood. Box elder can withstand moderate seasonal flooding of up to 30 days during the growing season, and is known to be an aggressive colonizer of degraded or abandoned land. Seeds will germinate in shade or full sunlight, but will begin to die off after one or two years if openings are not formed. Box elder seeds are light, large-winged, and widely wind-dispersed, and remain viable throughout the winter after ripening in the autumn and fall continuously until spring (Overton, 1990; Smith, 2008).

Woody riparian species commonly disperse seeds between April and August as determined from seed dispersal dates provided by Dixon (2002), Lenhart (2013), and Smith (2008). Peak seed dispersal windows for each of these species were compared to vegetation survey results and annual flow condition analysis. For purposes of analysis within this study, the growing season was considered to be April 15 through September

20 as determined by the earliest and latest seed dispersal dates provided in literature (Table 1).

Table 1

Seed Dispersal Windows of Common Woody Riparian Species

Species	Seed Release Date
Silver Maple	April 15 - June 15
Black Willow	April 15 - July 15
American Elm	May 15 - June 15
Cottonwood	May 15 - July 15
Sandbar Willow	May 15 - August 15
Green Ash	July 1 - September 10
Box Elder	August 1 - September 20

1.1 Background

The Minnesota River basin drains over 43,000 km^2, 80% of which is agricultural land, consisting mainly of corn and soybean. Due to its recent geologic history, the Minnesota River basin is primed to be a source of sediment with flat rolling glacial till plains and steep valley walls created by the rapid draining of glacial Lake Agassiz. The Minnesota River runs through a deep, wide alluvial valley comprised of fine textured silty to sandy loam. Tributaries of the Minnesota River, down-cut through upstream knickpoint propogation, consist mostly of finer-textured glacial till and glaciolacustrine soils (Gran et al., 2009; Lenhart et al., 2013; Matsch, 1983; Wilcock, 2009).

Today, the Minnesota River is the largest source of sediment to the Mississippi River in Minnesota (Engstrom et al., 2009). Large sediment loads to the Minnesota River and its larger tributaries have been found to come mainly from bluffs, which are defined as valley walls, as well as from terrace bluffs which are features that occur higher than the modern floodplain. Much of this sediment is thought to come from bluffs in steep knick zones of the Blue Earth River (Gran et al., 2009; Wilcock, 2009). Elm Creek, located in Martin and Jackson counties is a head-waters tributary of the Blue Earth River within the Minnesota River basin. Elm Creek, which drains about 700 km^2 is covered by 86% corn and soybean agriculture and is one of the greatest contributors of total suspended solids to the Blue Earth River as compared to other sub-basins of the Blue Earth River (Quade, 2000).

Land-use and climate changes over the last century within the Minnesota River basin have significantly altered the regions hydrology. These changes include the conversion of perennial prairie vegetation to annual row-crop agriculture, the expansion of subsurface tile drainage, and the loss of hydrologic storage (Leach and Magner, 1992) Conversion to annual row-crop agriculture reduces plant water use during the critical runoff period of April-June (Brooks et al., 2006). Over 90% of wetlands in the region have been drained, resulting in greater amounts of water being delivered to rivers (Miller et al. 1999). In addition, Lenhart et al. (2011a) found an approximate 10% increase in precipitation for the region between the periods of 1950-1979 and 1980-2008 and a 75% increase in mean annual flow.

Although the interactions between vegetation and fluvial geomorphology have been well established and accepted (Gurnell et al., 2012), the role of hydrology-vegetation interactions is not well understood within the Minnesota River basin specifically (Lenhart et al., 2013). Developing a better understanding of the patterns and characteristics of vegetation establishment, hydrologic regime, and sediment deposition within the Minnesota River basin would aid in development of management actions necessary to meet water quality standards (Baskfiled et al., 2012).

1.2 Related Research and Research Needs

Research has shown that altered vegetation-point bar interactions are associated with reductions in riparian vegetation establishment leading through decreased deposition on point bars and river widening (Dixon et al. 2002; Rood and Mahoney, 1995). Lenhart (2013), also demonstrated how altered hydrologic regimes influence the colonization of woody riparian species along the lower Minnesota River through the measurement of sandbar slope and elevation of riparian vegetation establishment where previous research has been done by Noble (1979). Plant elevation establishment was found to be about 2.5m higher on average than in 1979. With an average sandbar slope of 10% at sites surveyed within the study, this translated to about 25m of un-vegetated sandbar length that may have been vegetated prior to flow increases observed after 1979 (Lenhart et al., 2011a).

Similar studies have been completed within different watersheds dating back to 1984. Hickin (1984) published a paper documenting the influence of vegetation on river behavior and fluvial geomorphology. Since that time, research has found that the interactions among vegetation, flow, and sediment are key for the development of vegetated surfaces and for floodplain sediment deposition (Bertoldi et al., 2011).

Corenblit et al. (2009) showed that relationships between vegetation establishment and sediment transport are directly related to channel evolution.

Extensive research within completed within various Midwestern watersheds has shown how altered hydrologic regime influences the establishment of riparian vegetation, including work done by Dixon and Turner (2006) who demonstrated the effects of post-colonization flows on the recruitment success of riparian shrubs and trees through use of the recruitment box model. The recruitment box model, developed by Rood (1995), correlates appropriate flow conditions with peak seed dispersal times of woody vegetation. Additional studies completed by Rood et al. (2000, 2010), among several others have served to further demonstrate the relationships between hydrologic regime and riparian vegetation establishment (Alldredge and Moore, 2014; Gurnell et al., 2012; Shafroth et al., 2010).

Further research related to sediment transport and channel evolution has been completed within the lower Minnesota River basin. This includes work done by Lenhart et al. (2013) and Schottler et al. (2014), where the lower Minnesota River was found to have widened by 52% over the past 70 years. Lenhart et al. (2011b) also found stream cross-sectional area enlargement and loss of river length within the Elm Creek watershed, in addition to high levels of turbidity in a 2008 study. Additionally, Magner (2004) found channel enlargement throughout the greater Blue Earth River basin.

Sediment sources and delivery rates within the Minnesota River basin were identified by Wilcock (2009). Tributaries of the Blue Earth River, such as Elm Creek, were found to deliver more sediment to the Minnesota River than is transported out. This indicates that sediment storage is occurring within the Minnesota River valley. Lenhart et al. (2013) found high rates of deposition within the floodplain and backchannel cut-offs; little is known however about point bar deposition specifically within the study area. Although floodplain deposition has increased since 1850, it is thought that the basin may be less of a sediment sink than historically thought, due to decreased point bar deposition and reduced floodplain connectivity. Point bars within the lower Minnesota River basin may be trapping less sediment than historically thought, due to increased base and peak flows that more readily mobilize un-vegetated sediment (Corenblit et al., 2009; Magner et al., 2004).

1.3 Research Overview

This study investigates the relationships between hydrologic timing and riparian vegetation establishment; specifically the impact of changes in hydrology on the colonization of riparian vegetation. How do changes in hydrology, such as the timing and duration of base and peak flow events, affect the germination, recruitment and establishment of vegetation on point bars? Additionally, how are vegetation establishment and hydrologic regime patterns associated with sediment deposition patterns on point bars across time and space?

Field data collection, stream-flow analysis, and geo-spatial analysis were completed within the Minnesota River basin along the lower Minnesota River and Elm Creek watersheds. Field data collection included vegetation and soil surveys, which were then related to annual stream-flow patterns. Within the lower Minnesota River basin, available aerial photography was used to document change in point bar and riparian vegetation establishment over recent years which was then correlated to years of high or low flow. Woody age structure data was also collected and related to historical flow patterns within the lower Minnesota River basin.

Results from this study will help to provide an understanding of the eco-hydrologic relationships between flow, vegetation establishment, and sediment transport. This understanding will aid in meeting the goals of projects such as the Minnesota Department of Agriculture Priority Setting for Restoration in Sentinel Watersheds, aimed at reducing sediment related impairments within the Minnesota River Basin.

Part 2. Methods

The relationships between vegetation, flow, and sediment were explored through the collection of both field and geospatial data. Within this study, vegetation and soils data were related to available stream-flow and geomorphic data collected within the Minnesota River basin along the lower main stem Minnesota River and along a headwater tributary, Elm Creek. Seven field sites were sampled within the lower Minnesota River Basin (07020012) and eight field sites where sampled within the Elm Creek watershed (0702000909), as displayed in Figures 2 and 3. Field survey locations within each watershed were numbered starting from the furthest upstream site to the furthest downstream site; the coordinates of which are provided in Table 2.

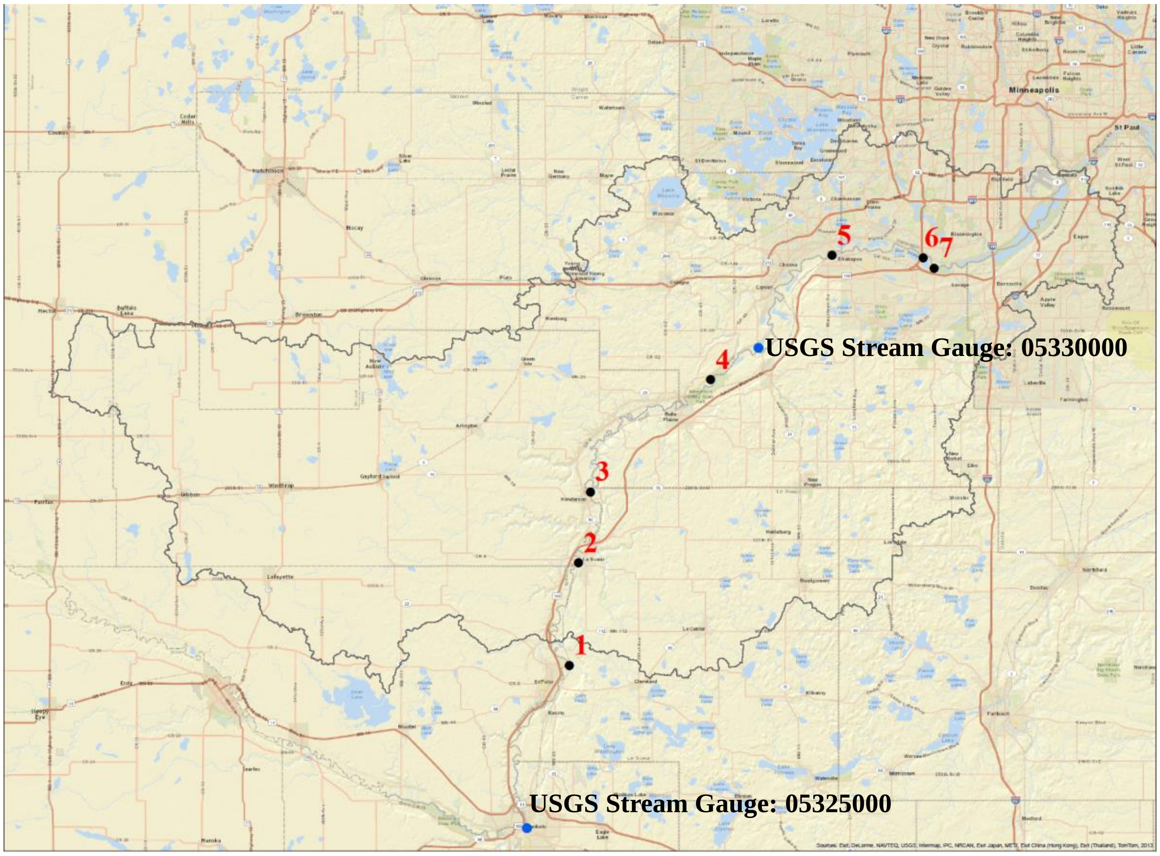


Figure 2. Field survey sites within the lower Minnesota River basin. N=7.

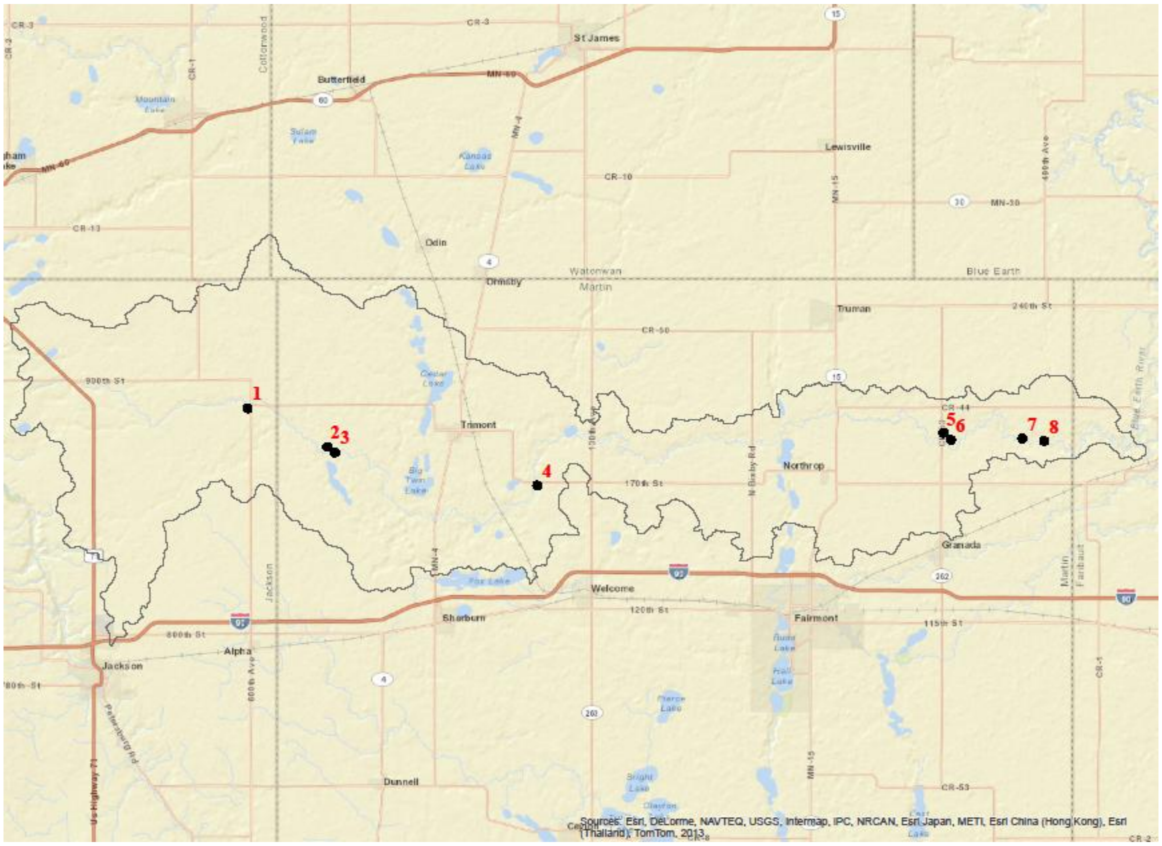


Figure 3. Field survey sites within the Elm Creek watershed. N=8.

Table 2

Minnesota River Basin Field Survey Site Locations

Watershed	Site	Northing	Easting
Lower Minnesota River	1	425507	4910799
	2	426756	4923392
	3	428305	4932128
	4	442950	4945740
	5	457708	4960897
	6	468683	4960548
	7	469991	4959234
Elm Creek	1	348956	4848514
	2	353869	4845909
	3	354009	4845771
	4	366616	4842729
	5	391827	4845997
	6	391945	4845691
	7	396485	4845718
	8	397822	4845525

Note. Coordinates are in NAD83 UTM 15.

2.1 Patterns of Vegetation Establishment

Vegetation surveys were completed within the study area during low flow conditions between late July and September of 2013. Surveys consisted of transects placed from the water's edge to the bank top documenting plant community establishment patterns on point bars. Age structure of woody vegetation was documented through the collection and analysis of tree core samples taken within the riparian zone. Vegetation establishment patterns were also analyzed using available aerial photography and Lidar data obtained from the Minnesota Department of Natural Resources MNTopo online Lidar application (MNDNR, 2014).

2.1.1 Transect Surveys

Along each meter of transect surveys, density of woody seedlings and saplings was documented within a distance of one half meter along either side of the transect. Within this study, a seedling was defined as a non-woody tree species approximately one to two years in age and a sapling was defined as a woody tree species less than three inches in diameter, often older than two or three years (USACE, 2009). Additionally, percent coverage of all species was recorded to the nearest percent within a half square meter quadrat every two meters along transects within the lower Minnesota River basin and along every meter within the Elm Creek watershed.

In order to document patterns of vegetation occurrence and dominance across each watershed, quadrat data was used to calculate relative frequency and relative coverage of species at each site across all quadrats, following methodology outlined by Curtis and McIntosh (1950). Formulas used for determination of relative frequency and coverage are displayed in Equations 1 and 2. Relative frequency of all woody seedlings and saplings was calculated, in addition to relative coverage and frequency of all forb, graminoid, and woody species. Relative coverage of annual versus perennial species, differing plant physiognomy groups, as well as adventitious rooting verse non adventitious rooting species was also calculated to further characterize point bar vegetation communities within the study area (MNDNR, 2005; Yadava and Supriya, 2006).

$$Relative\ Frequency = \left(\frac{Total\ Number\ of\ Individual\ Species\ Occurring\ in\ all\ Quadrats}{Total\ Number\ of\ all\ Species\ Occurring\ in\ all\ Quadrats}\right) \times 100 \quad (1)$$

$$Relative\ Coverage = \left(\frac{Total\ Percent\ Cover\ of\ Individual\ Species\ Occurring\ in\ all\ Quadrats}{Total\ Percent\ Cover\ of\ all\ Species\ Occurring\ in\ all\ Quadrats}\right) \times 100 \quad (2)$$

In order to document significant differences in occurrence of vegetation groups across all quadrats and sites within lower Minnesota River and Elm Creek transect surveys, an analysis of variance (ANOVA) test was used. This test, based on the null-hypothesis that species occurrence within each vegetation group is equal, was used to tests for significant differences between occurrences of varying species within vegetation groups including seedlings vs. saplings, late versus early seeding species, and species with adventitious rooting capability versus those without (Lock et al., 2005). The p-value, or strength of evidence against the null-hypothesis was set to the 0.10 confidence level within this study for determination of significance difference in species occurrence.

2.1.2 Elevation Establishment Patterns

Patterns of plant establishment were documented through comparison of average elevation of vegetation establishment above channel elevation at each study site within the lower Minnesota River basin and average vegetation elevation relative to water surface within the Elm Creek watershed. Average elevation of plant establishment at each site within both study areas was determined using 2010 and 2011 Lidar data and aerial photography. Although vegetation elevation values obtained using aerial photography and Lidar may have been altered by depositional events occurring since the time of actual vegetation establishment, these values still provide a picture of varying vegetation establishment patterns across the study area.

Channel elevations for each site within the lower Minnesota River basin were obtained from the nearest of N=19 2013 cross-sectional survey data provided by the United States Army Corp of Engineers (USACE) from St. Peter to Bloomington, MN (Figure 4). Although 2013 channel elevation data does not correspond exactly with 2010 and 2011 estimates of vegetation elevation, this still provides a representation of plant elevation establishment patterns at each site based on the best available data.

Cross-sectional data was only available within the Elm Creek watersheds at select locations prior to 2008. For this reason, 2010 and 2011 Lidar data was instead used to obtain estimates of water surface elevations at each site. As Lidar elevation data is limited by its un-ability to penetrate the water surface, water surface elevations were used to compare vegetation establishment patterns at each site, rather than actual channel elevations. This data still provides however, the best available evidence for varying vegetation establishment patterns across the Elm Creek watershed.

An analysis of variance test was again applied to test for significant differences in average elevation of vegetation establishment across sites with similar plant community structure or hydrologic regime, particularly sites dominated by sandbar willow verses those without. A 0.10 confidence level was used based on the null-hypothesis that significant differences in elevation of vegetation establishment do not occur between sites with varying characteristics.

Figure 4. 2013 cross-sectional survey locations within the lower Minnesota River basin. N=19.

2.1.3 Historic Elevation Establishment Patterns

Within the lower Minnesota River basin, modern vegetation elevation establishment data were compared to available historical elevation establishment data at three sites surveyed by Noble (1979), to document changes in plant elevation establishment between 1979 and now (Figure 5). Current vegetation elevation and slope data at each of these three sites was again obtained using available aerial photography and Lidar data (MNDNR, 2014). An estimate of change in length of un-vegetated sandbar was then calculated through the multiplication of modern sandbar slope to length of change in vegetation establishment elevation (Lenhart et al., 2013).

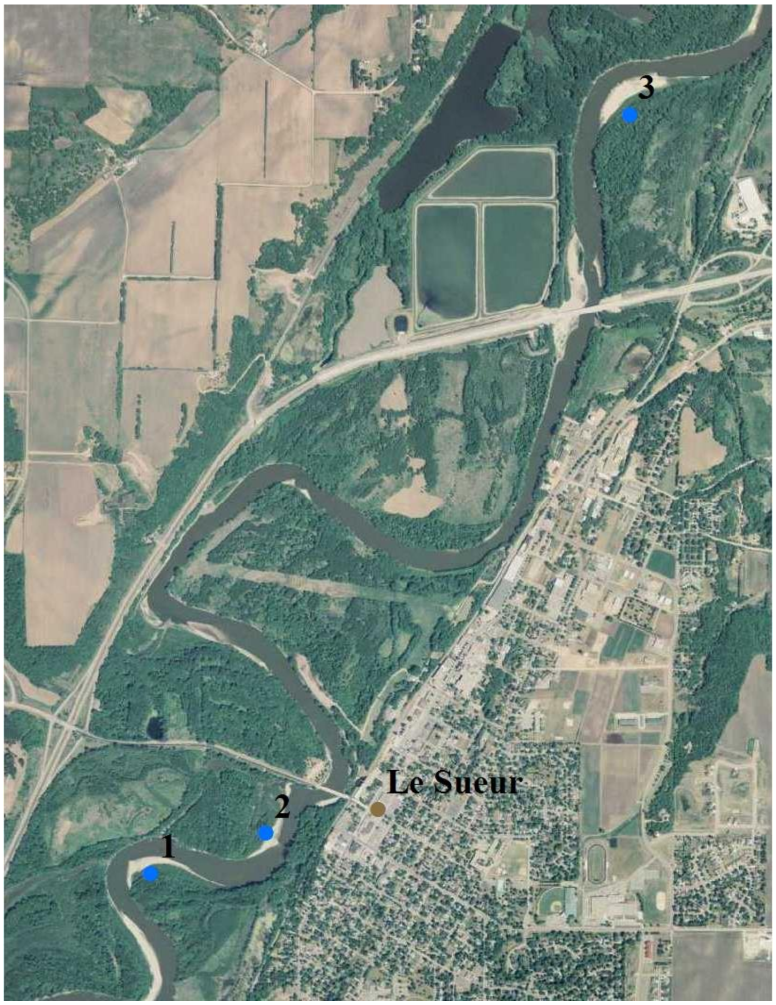


Figure 5. Noble (1979) sampling locations.

2.1.4 Woody Vegetation Age Structure Analysis

Tree core samples were taken during August of 2014 at six locations along the main steam lower Minnesota River basin from Saint Peter to LeSueur Minnesota using a Haglöf tree core sampler (Figure 6). Approximately five cores were taken within the riparian corridor at each site across a range of low to high diameter of representative species in order to document the range of age classes and species at each site. Three sampling locations were point bar sites, dominated by sandbar willow with some cottonwood and silver maple; whereas the other three sites were representative of floodplain forests dominated by silver maple with occasional box elder or American elm. Cores where collected at breast height along with associated diameter at breast height (DBH) measurements. Diameter measurements were then related to counting of tree core rings completed under a dissecting microscope in order to determine an age class for each sample.

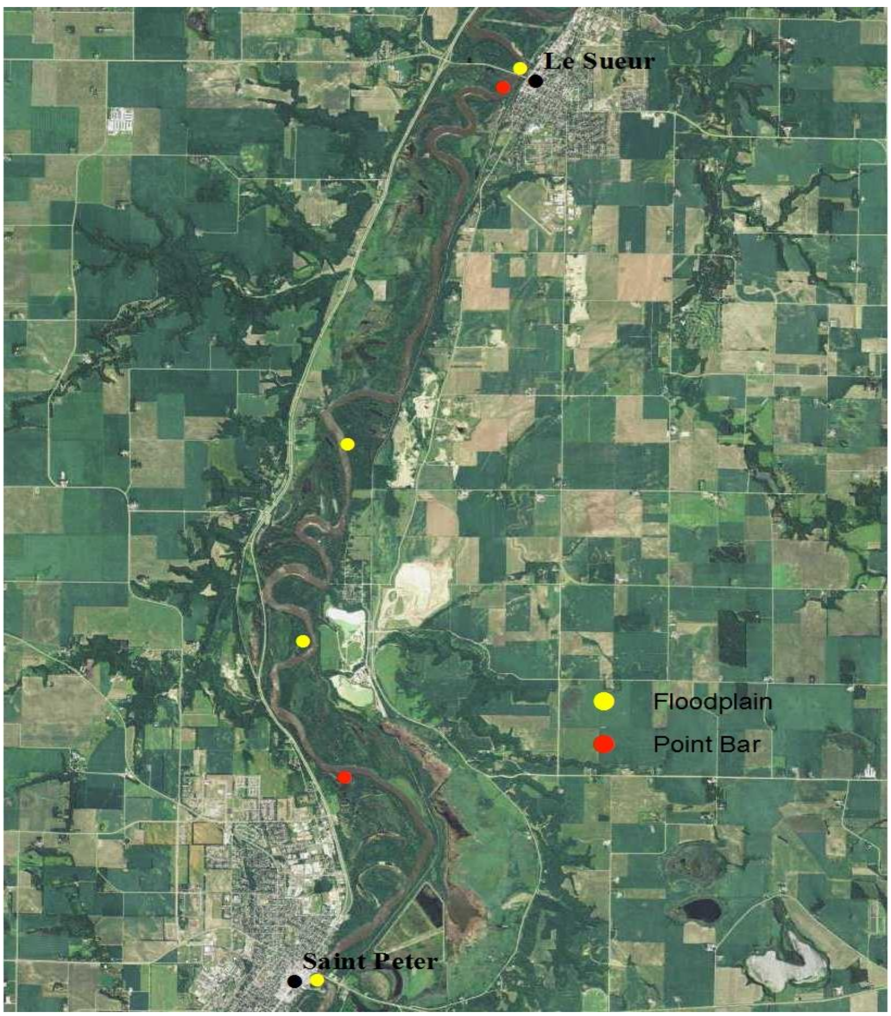


Figure 6. 2014 tree core sampling locations.

2.2 Patterns of Hydrologic Regime

2.2.1 Timing, Duration, and Magnitude of Base and Peak Flow Events within the Lower Minnesota River Basin

Timing, magnitude and duration of annual base and peak flow events were determined within the Minnesota River basin using annual stream discharge data from 2004-2013. Mean, maximum and minimum flow were determined during the growing season of April 15th to September 20th for each year, in addition to timing and duration of maximum flood peaks. The rate of recession of the flood peaks during each growing season was also calculated using a rating curve developed from available stage-discharge data within each study watershed. Hydrologic data was then compared to vegetation establishment data to document patterns of establishment during years of high or low flow.

Stream discharge data within the lower Minnesota River basin was obtained from the United States Geologic Survey (USGS) Current Water Data for Minnesota website at the Jordan, MN (05330000) and Mankato, MN (05325000) stream gauges (USGS, 2014). 2004-2008 stream discharge data within the Elm Creek watershed was obtained from a Minnesota Pollution Control Agency (MPCA) maintained gauge located just west of field survey site number 7 (Figure 3) and 2009-2013 data was obtained using a synthetic hydrograph based on available stream gauge data in adjacent watersheds (Lenhart, 2008). Historical stream flow data was also analyzed at the Mankato gauge during the years of 1940 and 2013 (Table 3). Average annual flows during each decade from 1940 to 2010 and from 2011 to 2013 were calculated, in addition to average magnitude and timing of maximum and minimum flows during each of those time periods.

Table 3

Lower Minnesota River Basin Stream Gauge Data Analysis Summary

Gauge Number	Location	Length of Data Record	Modern Data Analysis	Historic Data Analysis
05325000	Mankato	1903-2014	2004-2013	1940-2013
05330000	Jordan	1934-2013	2004-2013	N/A

2.2.2 Determination of Point Bar Submerging Flows and Growing Season Submergence

Point bar submerging discharge was determined at each field survey site in order to document timing and duration of point bar submergence and exposure during peak seed dispersal windows of riparian vegetation. These values were determined using available geomorphic cross-sectional data along the lower Minnesota River and Elm Creek watersheds. As previously shown in Figure 4, the closest of N=19 cross-sections were related to each site within the lower Minnesota river basin in order to determine submergence discharge and N=8 cross-sections taken during various years prior to 2008 provided by Lenhart (2008) were used within the Elm Creek watershed (Figure 7).

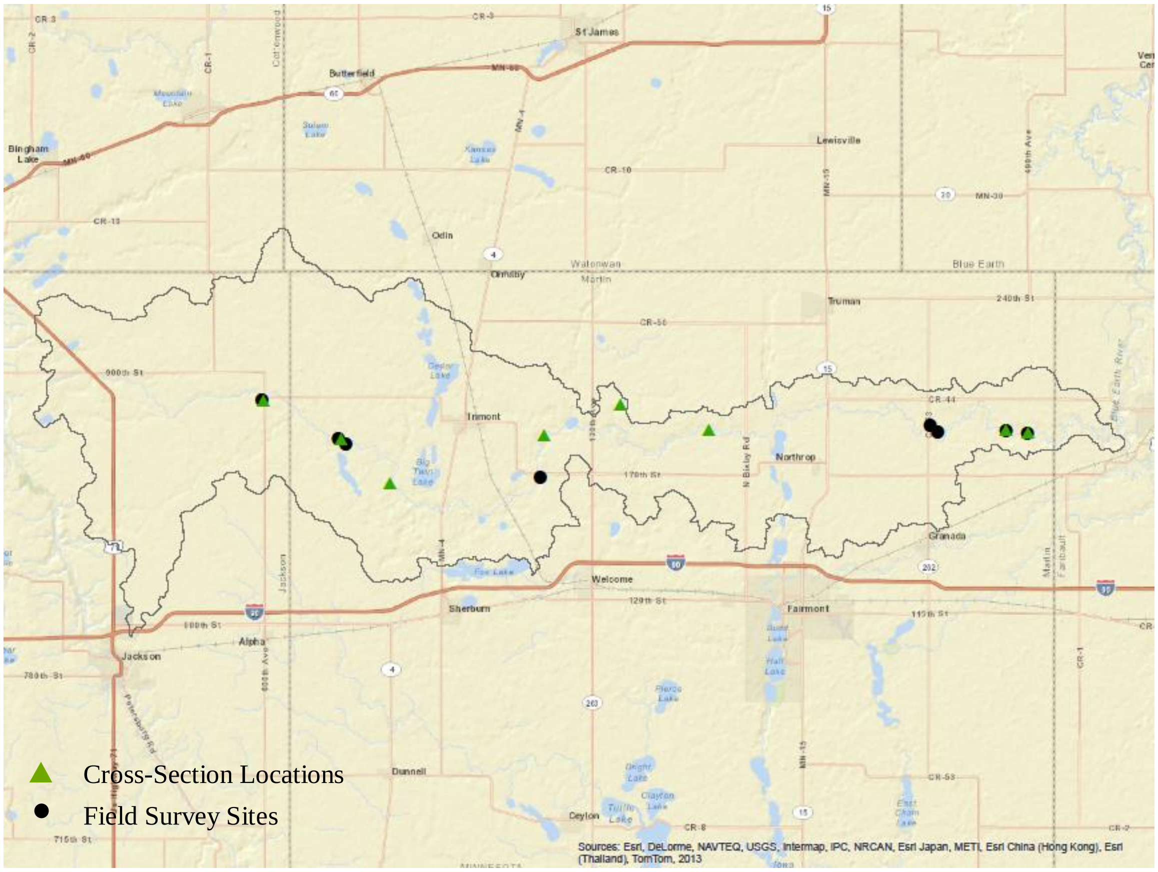


Figure 7. Cross-sectional survey locations within the Elm Creek watershed. N=8.

Historical cross-sectional data within the lower Minnesota River basin was obtained from the USACE. Although known to be taken prior to 1979, specific dates of these cross-sections were unavailable. Accurate coordinates of cross-sections were also unknown, but were geo-referenced to each other and known to occur within the lower Minnesota River basin. N=10 cross-sections taken from Mankato to LeSueur, MN, were analyzed to obtain an estimate of point bar submerging flows prior to 1979. Point bar submergence for the period of 1980-2013 was determined using the average of N=5 2013 cross-sections between Mankato and LeSueur as displayed in Figure 4. Decades of high or low flow were then related to tree core sample age class structure and historical elevation establishment data

Cross-sectional data were entered into the Spreadsheet Tool for River Evaluation, Assessment and Monitoring (STREAM) developed by the Ohio Department of Natural Resources (Ward, 2011). This tool, based on the Manning's equation (Equation 3), calculates a value for velocity (V) based on hydraulic radius (R) and channel slope (S), which is then multiplied by cross-sectional area to obtain an estimate of point bar submerging discharge. Total cross-sectional area was calculated with bank-full elevation set to match the elevation of the top of the point bar.

$$V = \frac{1.00}{n} {R_h}^{2/3} S^{1/2} \tag{3}$$

The value of the roughness coefficient, *n*, was calculated within the lower Minnesota River basin using available velocity and geomorphic field data obtained from the USGS Current Water Data for Minnesota website at both the Jordan and Mankato stream gauges and the value of the slope was obtained using Lidar data and aerial photography (MNDNR, 2014; USGS, 2014). From these calculated submergence discharges, percent of complete point bar submergence during the growing season of April 15th to September 20th was determined at each field survey site. Discharge data at Mankato, MN was used to determine submergence at sites 1-4 and data at Jordan, MN was used to determine submergence at sites 5-8 (Figure 2). Within Elm Creek, values for slope and Manning's coefficient were provided by Lenhart (2008).

2.3 Patterns of Sediment Deposition

2.3.1 Willow Age and Deposition Rate Estimation

Annual rates of sediment deposition were estimated through the measurement of depth of sediment to root collar divided by age of sandbar willow sapling collections at each site. Locations of the root collar, or primary stem having developed since the time of establishment allows for accurate measurement of deposited sediment depth across a particular time frame. Approximately three to four measurements were taken in field at various distances along vegetation transects at each site. Associated willow saplings were collected and aged through the counting of rings under a dissecting microscope (Hupp, 1991). Due to its adventitious rooting capabilities, it is likely that sandbar willow saplings established at each site from both seed and advantageous reproduction, for this reason samples were collected on the largest present willow sapling or on individually growing species in order to accurately obtain depth to root collar measurements for each sample. An ANOVA test was used, set at the 0.10 confidence level, to test for significant differences in deposition rate estimates and willow age structure between sites located in the lower verses upper regions of both watersheds.

2.3.2 Proportion of Vegetation Establishment to Point bar Area within the Lower Minnesota River Basin

Within the lower Minnesota River basin, the proportion of riparian vegetation establishment area to total point bar area was measured using GoogleEarth software. Measurements were taken at five locations from Mankato to LeSueur Minnesota using available aerial photography flown during low flow conditions in the years of 2003, 2006, 2009 and 2011 and averaged across each of the five sites. Change in average proportion of vegetation area across all sites was then related to varying flow patterns during the time periods of 2003-2006, 2006-2009, and 2009-2011. The scale of point bar area within the Elm Creek watershed and low resolution of available aerial photography made this analysis un-reliable within the Elm Creek watershed and was only completed within the lower Minnesota River basin.

A t-test was used within this data set in or order to analyze the significance of average change in proportion of vegetation to point bar area over the last decade, based on the null hypothesis that proportion of vegetation to point bar area is not significantly different across years of varying flow. The p-value or the strength of the evidence in favor of the alternative hypothesis was set to the 0.10 confidence level within this study for determination of significance change in proportion between 2003-2006, 2006-2009 and 2009-2011 (Lock et al. 2005).

2.3.3 Particle Size Characteristics within the Lower Minnesota River Basin

2012 particle size data available at field survey sites one, two, five, and six within the lower Minnesota River basin were obtained to document varying sedimentation patterns in associated with plant community and submergence characteristics at each field site. At all four sites, approximately N=10 samples were collected from the waterline to the bank top from 0-25cm and 25-50cm at sites one, five and six and from 0-25cm at site two. Within all sampling locations, at each site, total percent of vegetative cover and total cover of woody seedlings was recorded within a half square meter quadrat.

2.3.4 Sediment Trap Deposition Rate Estimation

Artificial turf mats squares, each 1400 square cm, were deployed during low flow conditions in late August and early September of 2013 at each field survey site. Turf mat squares, used by Steiger (2003), are designed to trap deposited sediment left by receding flood waters, allowing for estimation of total volume of deposited sediment. Four to six turf mat squares were installed with galvanized nails at each site from the water line to the top of the point bar. High flow conditions during 2014 left mats submerged at the time of re-survey at lower Minnesota River basin sites four, five and six and remain un-surveyed. Turf mat squares within the Elm Creek watershed also require re-survey.

Part 3. Results

3.1 Patterns of Vegetation Establishment

3.1.1a Seedling and Sapling Densities within the Lower Minnesota River Basin

Across all quadrats within lower Minnesota River basin transect surveys, higher relative frequency of saplings over seedlings was observed (Figure 8). This is particularly true at sites within the lower region of the watershed, such as sites two and three located near LeSueur and Henderson Minnesota (Table 4). The higher relative frequency of saplings over seedlings is due mainly to the dominance of sandbar willow, a species capable of adventitious rooting. In Figure 9, we see high relative frequencies of saplings of species capable of adventitious rooting including black willow and sandbar willow, while higher relative frequencies of seedlings of species without adventitious rooting are observed.

At sites two, three and five higher frequencies of cottonwood seedlings and saplings observed in association with high relative frequencies of sandbar willow. Sites two and five also had the only occurrence of silver maple saplings, in addition to high frequency of silver maple seedlings at site five. American elm and green ash were observed only at sites one, four and six which contained no sandbar willow. Silver maple seedlings were observed across all sites, aside from site six at Bloomington Minnesota. Site seven, also located at Bloomington Minnesota was the only site containing seedlings and saplings of black willow (Table 4).

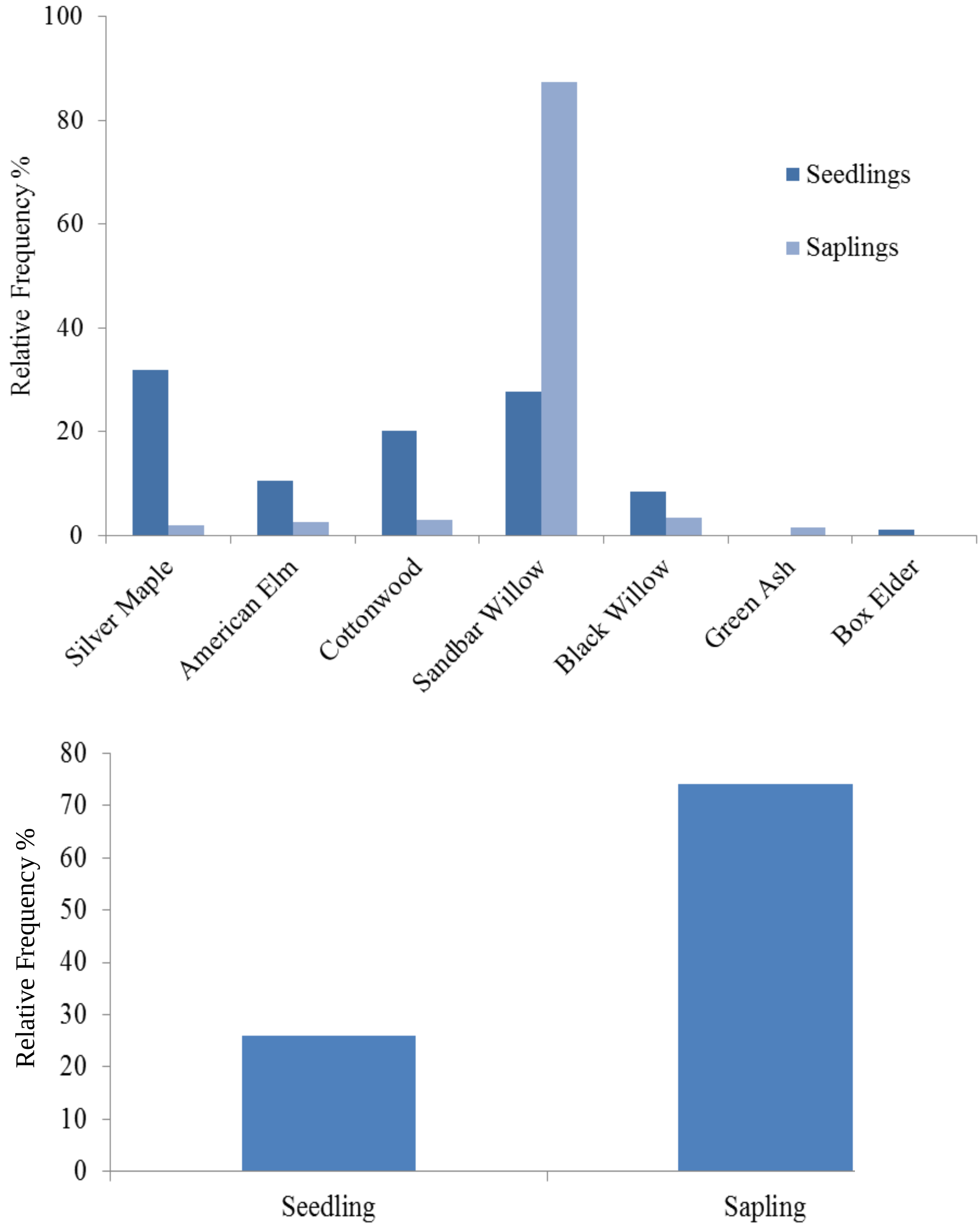


Figure 8. Relative frequency of seedlings and saplings within lower Minnesota River basin transect surveys. N=82.

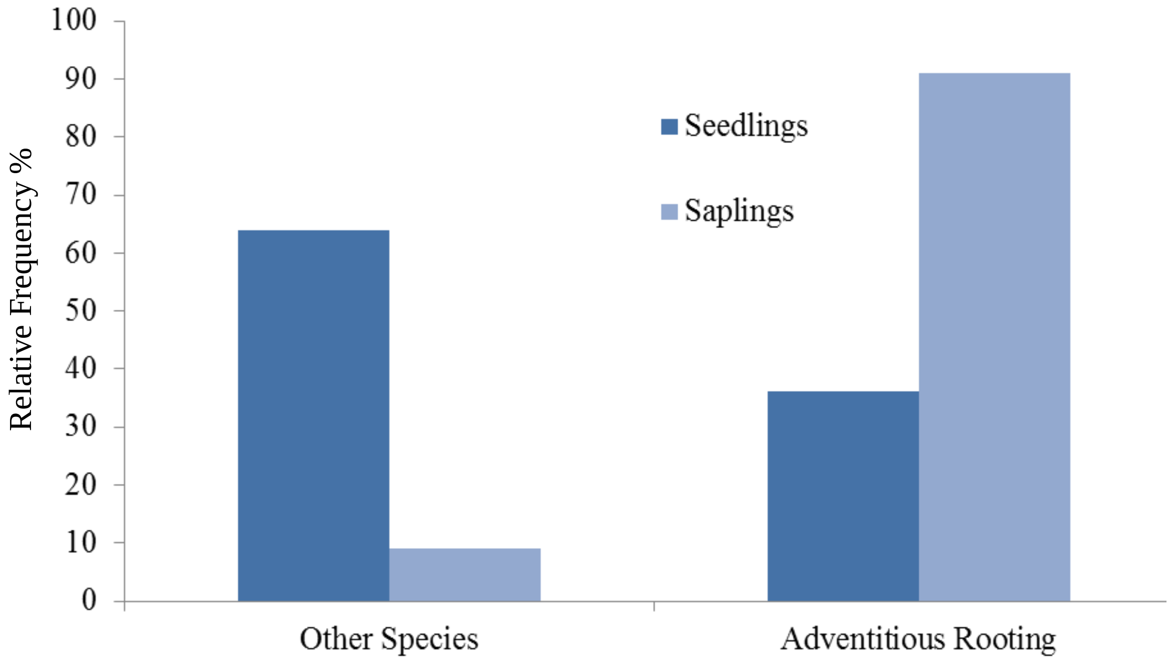


Figure 9. Relative frequency of seedlings and saplings with normal verses adventitious growth habits within lower Minnesota River basin transect surveys. N=82.

Table 4

Stem Density Across Lower Minnesota River Basin Transect Surveys

Species	Silver Maple	American Elm	Cotton-wood	Sandbar Willow	Black Willow	Green Ash	Box Elder
Site 1							
Seedling Density	2						
Sapling Density	2					1	
Site 2							
Seedling Density	1		2				
Sapling Density	2		4	102			
Site 3							
Seedling Density	1		15				1
Sapling Density				67			
Site 4							
Seedling Density	4						
Sapling Density		3				1	
Site 5							
Seedling Density	20		2	14			
Sapling Density	1		4	22			
Site 6							
Seedling Density		10					
Sapling Density		4				2	
Site 7							
Seedling Density	2			12	8		
Sapling Density				44	9		

3.1.1b Relative Species Coverage within the Lower Minnesota River Basin

Within the lower Minnesota River basin, we see an overall dominance of perennial species, mainly sandbar willow sapling and reed canary grass. High relative frequency and coverage of annual species including smartweed, Creeping Lovegrass, and cocklebur *(Xanthium strumarium)* are also observed, but to a lesser extent than sandbar willow and reed canary grass (Figure 10). As displayed in Table 5, all field survey sites are dominated by perennial cover aside from site four with sites one and six having the highest percent of perennial cover. Higher percent of bare ground was observed within the upper region of the watershed at sites one, two, and three as compared to sites in the lower region from Jordan to Bloomington, MN. Also displayed in Table 5, sites two, three and six are dominated by woody vegetation whereas other sites are dominated mainly by forbs and grasses.

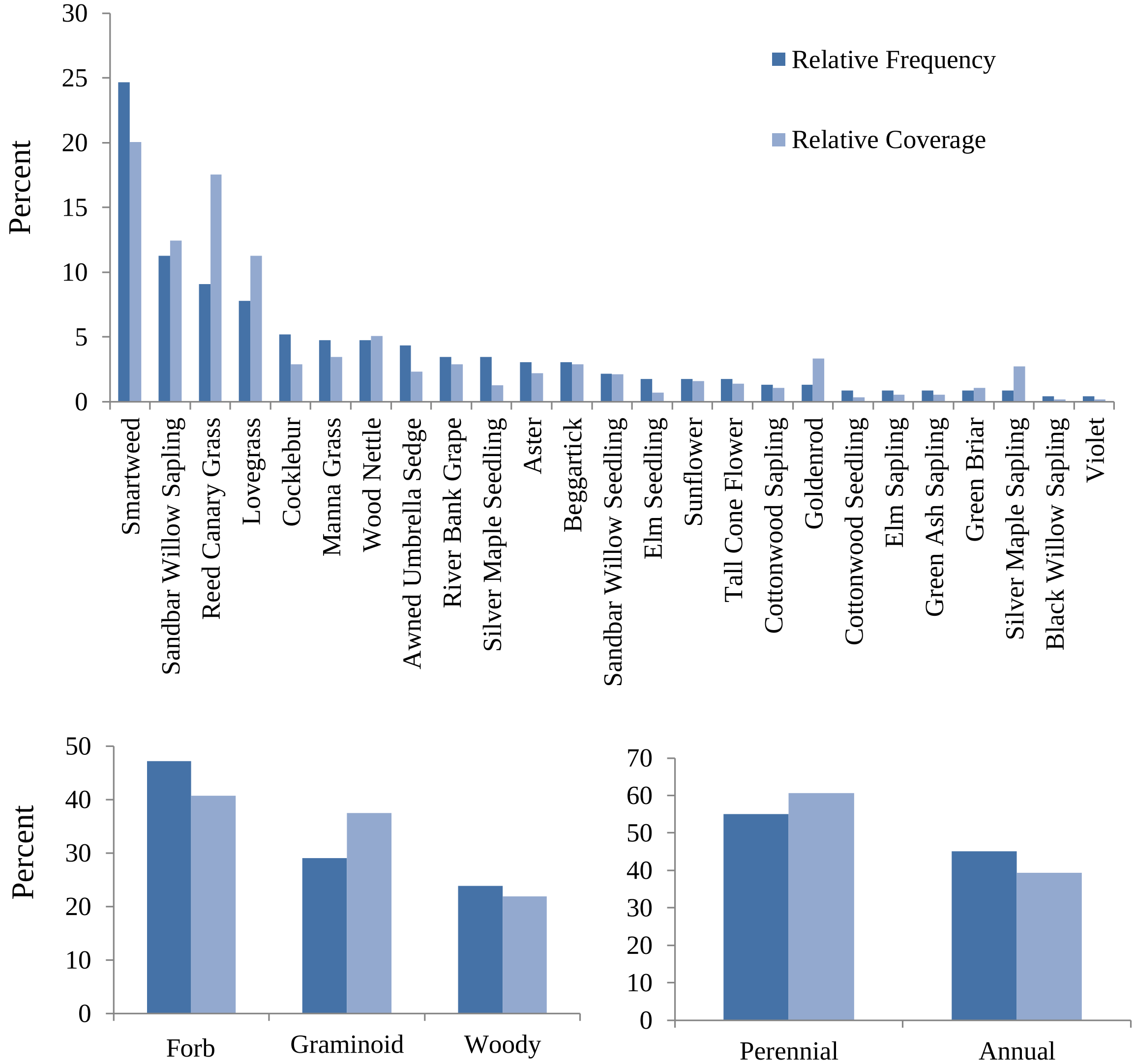


Figure 10 . Relative coverage and frequency of all species within lower Minnesota River basin transect surveys. N=82.

Table 5

Percent Species Coverage within the Lower Minnesota River Basin

Site	Bare	Annual	Perennial	Herbaceous	Woody	Graminoid
1	33	11	89	68	11	21
2	22	40	60	6	55	39
3	20	41	59	14	64	22
4	7	64	36	22	35	42
5	11	43	57	16	43	41
6	5	14	86	11	74	16
7	3	26	74	60	26	14

3.1.1c Lower Minnesota River Basin Transect Data Analysis

Analysis of variance tests between differing vegetation groups were completed on all species occurring within N=82 quadrats across the lower Minnesota River basin. As observed in Table 6, a significant difference was found between saplings of species with adventitious rooting capabilities including sandbar and black willow, and saplings without adventitious rooting capabilities at the 0.10 significance level. The same is true of seedlings of species with adventitious rooting capabilities versus seedlings without.

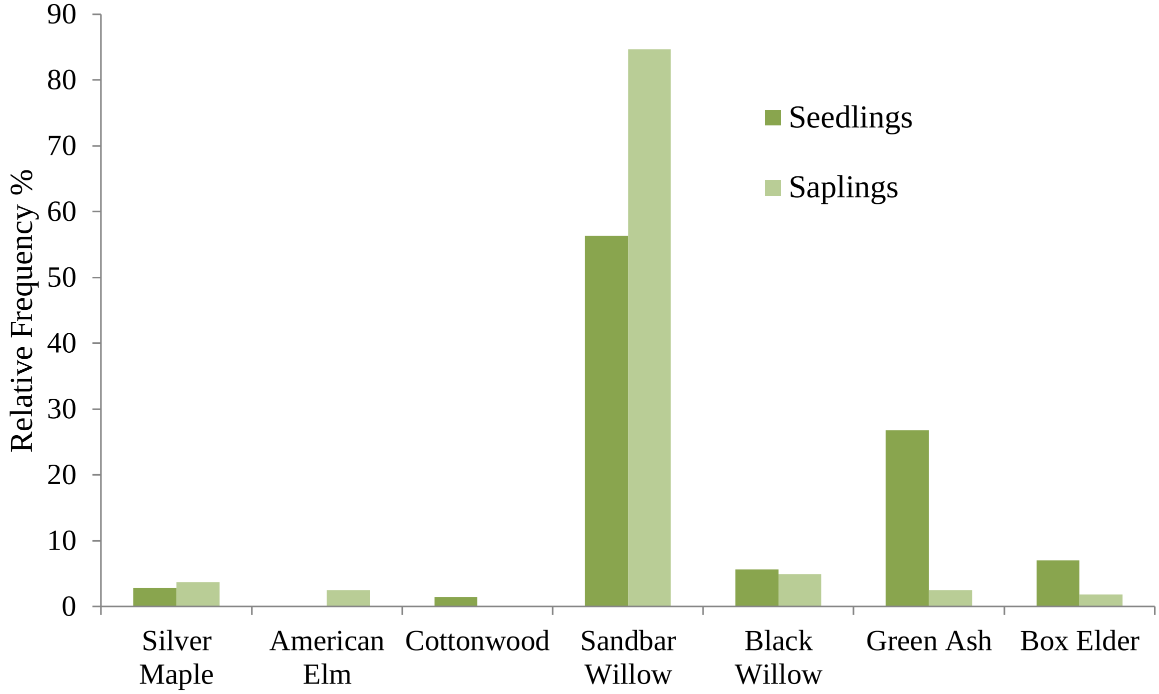
Table 6

Minnesota River Basin Transect Vegetation ANOVA

Group	P-Value
Seedling vs. Sapling Frequency	0.19
Early vs. Late Dispersing Seedlings	0.38
Early vs. Late Dispersing Saplings	0.29
Annual vs. Perennial Cover	0.74
Adventitious Rooting Seedlings vs. Without	0.07
Adventitious Rooting Saplings vs. Without	0

3.1.1d Seedling and Sapling Densities within the Elm Creek Watershed

As previously observed within lower Minnesota River basin transect data, vegetation data within the Elm Creek watershed saw higher relative frequency of saplings over seedlings, again dominated by sandbar willow (Figure 11). Higher relative frequencies of seedlings and sapling of species with adventitious rooting capabilities are observed as compared to those without (Figure 12). As displayed in Table 7, silver maple and American elm were observed only within the lower region of the watershed at sites six and seven, in addition to cottonwood seedlings present only at site 8. The occurrence of silver maple, American elm and cottonwood was associated with higher relative frequencies of sandbar willow at sites six, seven, and eight. Seedlings and saplings of black willow, green ash, and box elder were, in general, only observed at sites located within the upper region of the watershed where sandbar willow was absent such as at sites two, three, and four.



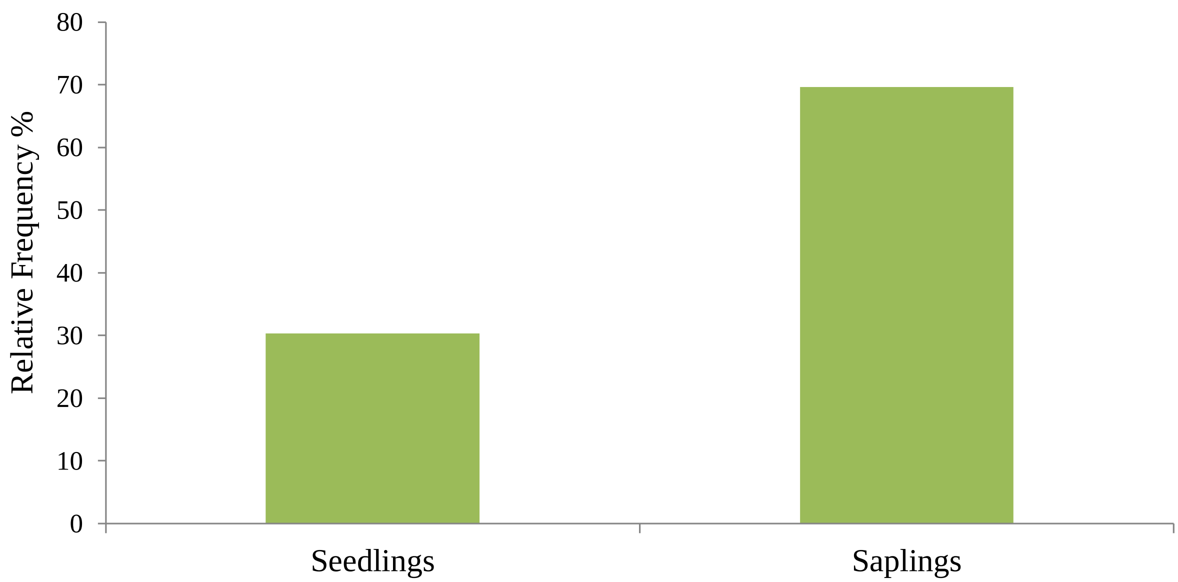


Figure 11. Relative frequency of seedlings and saplings within Elm Creek Watershed transect surveys. N=97.

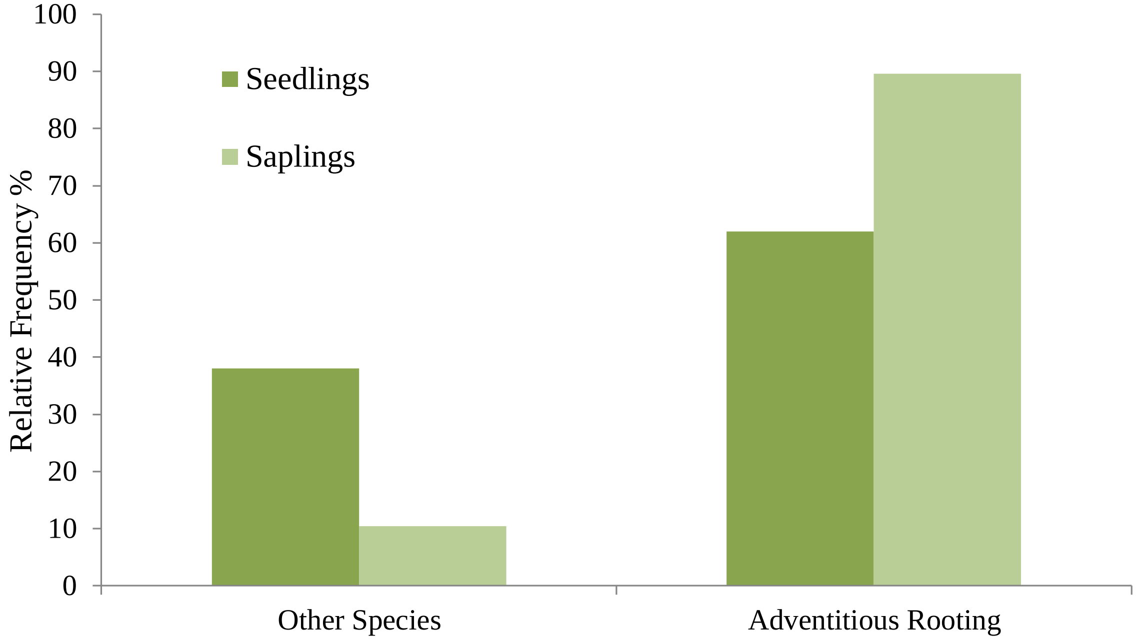


Figure 12. Relative frequency of seedlings and saplings with normal verses adventitious growth habits within Elm Creek watershed transect surveys. N=97.

Table 7

Stem Density Across Elm Creek Watershed Transect Surveys

Species	Silver Maple	American Elm	Cotton-wood	Sandbar Willow	Black Willow	Green Ash	Box Elder
Site 1							
Seedling Density				12		2	
Sapling Density				49			
Site 2							
Seedling Density							2
Sapling Density							
Site 3							
Seedling Density						3	2
Sapling Density							2
Site 4							
Seedling Density					4		
Sapling Density					8		
Site 5							
Seedling Density							1
Sapling Density							
Site 6							
Seedling Density				1			
Sapling Density		4		13			
Site 7							
Seedling Density	2			20		17	
Sapling Density	6			57		2	
Site 8							
Seedling Density			1	7			
Sapling Density				19			

3.1.1e Relative Species Coverage within the Elm Creek Watershed

Within the Elm Creek watershed, point bar vegetation surveys found higher relative frequency and cover of perennial species as compared to annual species across all field survey sites. This perennial cover is dominated mainly by reed canary grass as shown in Figure 13. This is particularly true at sites one, three, and seven where we see almost complete cover of perennial species (Table 8). In general, sites across the Elm Creek watershed were dominated by herbaceous species including forbs and graminoids. At sites one, three and seven, higher percent cover of woody species was observed as compared to other sites.

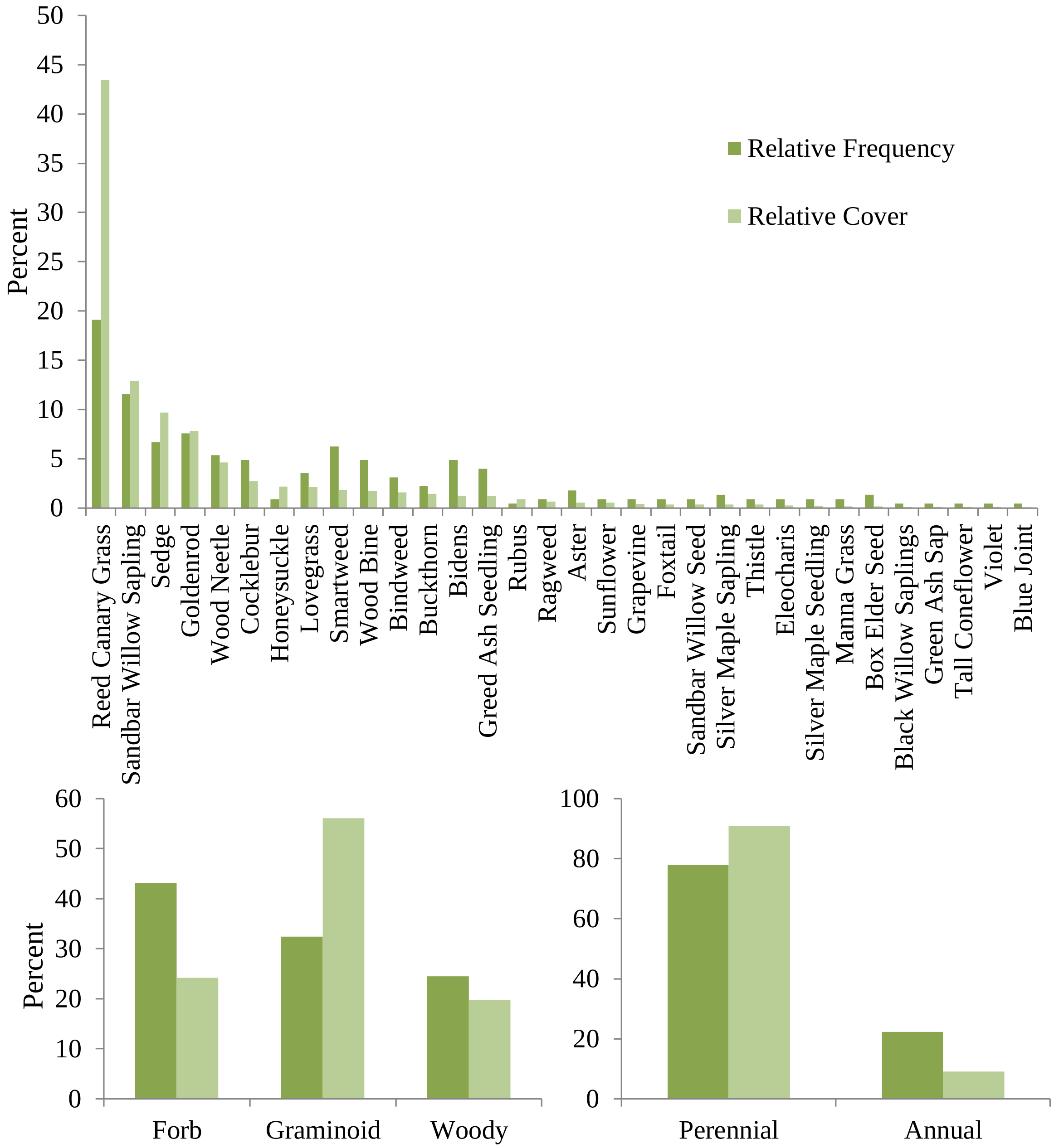


Figure 13. Relative coverage and frequency of all species within Elm Creek watershed transect surveys. N=97.

Table 8

Percent Species Cover within the Elm Creek Watershed

Site	Bare	Annual	Perennial	Forb	Woody	Graminoid
1	13	0	100	2	43	55
2	43	59	41	18	0	82
3	34	8	92	61	33	5
4	29	30	70	22	1	77
5	88	31	69	20	0	80
6	28	15	85	4	6	90
7	26	1	99	20	29	51
8	55	34	66	69	10	22

Note: N=97.

3.1.1e Elm Creek Watershed Transect Data Analysis

Analysis of variance tests were completed on occurrence of all species within N=97 quadrats across study sites within the Elm Creek watershed. Within this analysis, statistically significant differences were found between saplings of species with adventitious rooting verses saplings of species without adventitious rooting capability at the 0.01 significance level. In addition, a significant difference was found between cover of annual verses perennial species at the 0.05 significance level. No other vegetation groups were found to have significant differences in cover, aside from saplings of early verse late dispersing species which was just over the 0.10 significance level with a p-value of .11 (Table 9).

Table 9

Elm Creek Watershed Transect Vegetation Data ANOVA

Group	P-Value
Seedling vs. Sapling Frequency	0.19
Early vs. Late Dispersing Seedlings	0.4
Early vs. Late Dispersing Saplings	0.11
Annual vs. Perennial Cover	0.04
Adventitious Rooting Seedlings vs. Without	0.43
Adventitious Rooting Saplings vs. Without	0.01

3.1.2a Vegetation Elevation Establishment Patterns within the Lower Minnesota River Basin

As determined using available aerial photography and Lidar data at each field survey site, average distance of vegetation establishment relative to channel elevation is displayed in Table 10. Site five, at Shakopee Minnesota was found to have the greatest elevation of vegetation establishment relative to channel elevation followed by sites three and two at Henderson and LeSueur Minnesota. As previously displayed in Table 4, field survey sites two, three, five and seven had similar plant community composition as compared to sites one, four, and six. Sites two, three, five and seven, dominated by sandbar willow were found to have significantly higher elevation of plant establishment relative to channel elevation as compared to sites one, four, and six (Table 11).

Table 10

Vegetation Elevation Patterns within the Lower Minnesota River Basin

Site	Channel Elevation (m)	Ave. Vegetation Elevation (m)	Ave. Difference (m)
1	226	227(+/-.23)	2(+/-.23)
2	216	223(+/-.01)	7(+/-.01)
3	213	221(+/-.01)	8(+/-.01)
4	209	216(+/-.23)	6(+/-.23)
5	204	214(+/-.27)	10(+/-.27)
6	205	209(+/-0)	5(+/-0)
7	205	212(+/-.66)	7(+/-.66)

Table 11

Lower Minnesota River Basin Vegetation Establishment Elevation ANOVA

Site Numbers	Ave. Vegetation Elevation Difference (m)	P-Value
2, 3, 5, 7	8(+/-1.5)	
1, 4, 6	4(+/-2.1)	0.00

3.1.2b Historic Vegetation Elevation Establishment Patterns within the Lower Minnesota River Basin

Increases in elevation of vegetation establishment were found in comparison of data from three survey sites sampled by Noble (1979) to current elevation data obtained using Lidar. At each of the three study sites, elevation of vegetation establishment was found to have increased by approximately three to four meters. Through multiplying this difference to slope at each site, also obtained with Lidar data, estimates of length of newly un-vegetated sandbar since 1979 were obtained. Based on these estimates, approximately four to five meters of un-vegetated sandbar were found to have occurred since 1979 at each of the three study sites.

Table 12

Historic Lower Minnesota River Basin Elevation Establishment Patterns

Site	1979 Mean Elevation (m)	2013 Mean Elevation (m)	Mean Elevation Change(m)	Sandbar Slope (%)	Un-Vegetated Sandbar Length(m)
1	227.73	231.87	4.14	1.27	5.26
2	219.83	222.99	3.16	1.21	3.83
3	219.12	222.20	3.08	1.78	5.48

Note. Historical elevation data taken from Noble (1979).

3.1.2c Vegetation Elevation Establishment Patterns within the Elm Creek Watershed

As theory would suggest, we see both deceasing water surface and vegetation establishment elevations across study sites one through eight within the Elm Creek watershed. Elevation of vegetation establishment relative to water surface elevation is variable from site to site, with sites two and three having the greatest difference and sites one, four, seven, and eight having the lowest (Table 13).

As previously shown in Table 7, sites one, six, seven and eight are dominated by sandbar willow with some silver maple, American elm and cottonwood whereas sites two, three, four and five contain no sandbar willow with some green ash, box elder, and black willow. Sites dominated by sandbar willow, mostly occurring in the lower region of the watershed saw on average, statistically significant lower vegetation establishment elevations relative to water surface as compared to sites containing no sandbar willow (Table 14).

Table 13

Vegetation Elevation Patterns within the Elm Creek Watershed

Site	Water Surface Elevation (m)	Ave. Vegetation Elevation (m)	Ave. Difference (m)	Lidar Date	Flow (cms)	Submergence Flow (cms)
1	393.61	393.77(+/-.17)	.16(+/-.15)	4/21/10	8	6
2	380.48	380.83(+/-.18)	.35(+/-.16)	4/20/10	9	7
3	380.56	381.16(+/-.45)	.60(+/-.40)	4/20/10	9	7
4	359.92	359.98(+/-.1)	.11(+/-.07)	4/20/10	9	12
5	330.29	330.59(+/-.31)	.30(+/-.27)	4/21/10	8	17
6	329.97	330.31(+/-.09)	.34(+/-.08)	4/20/10	9	17
7	322.54	322.63(+/-.12)	.10(+/-.09)	4/20/10	9	17
8	320.94	320.95(+/-.03)	.02(+/-.01)	4/20/10	9	23

Note. N=5 at each field survey site.

Table 14

Elm Creek Watershed Vegetation Establishment Elevation ANOVA

Site Numbers	Ave. Vegetation Elevation Difference	P-Value
1, 6, 7, 8	.16(+/-.15)	
2, 3 ,4, 5	.34(+/-.32)	0.03

3.1.3 Tree Core Age Structure Analysis within the Minnesota River Basin

Based on ANOVA testing, tree core samples taken at six locations within the lower Minnesota River basin found significant differences in woody vegetation age structure between floodplains and point bars (Table 15). Within sampled floodplain habitats, tree ages ranged from 12-115 years with an average age of 55, whereas the average tree age on point bars was 17 years with a range of 10-30 years. Within both floodplain and sandbar sites, no species were observed to have established between the years of 1940-1959, with no species occurring during 1960-1979 on sandbar sites also (Table 16).

The highest proportion of point bar samples were found to have established during 2000-2009 with decreasing presence of species established during 1990-1999 and 1980-1989. Within floodplain habitats we see 29 percent of samples occurring prior to 1940 and 21 percent of samples then having established between 1960-1969 and 1970-1979. During 1980-1989 we see lower proportions of samples having established within floodplains at 14 percent, followed by seven percent of samples having established during 1990-1999 and 2000-2009 consecutively (Table 16). As displayed in Table 17, box elder and American elm were present only within flood plain habits and were not observed at point bar sites. The only occurrence of American elm was observed at site four in association with one of the oldest observed cottonwoods and with both silver maple and box elder.

Table 15

Tree Core Age Data Summary

Habitat Type	Age Range (yr.)	Average Age (yr.)	P-Value
Point Bar	10-20	17(+/-7)	
Floodplain	12-115	55(+/-34)	0.00

Note: N=9 point bar samples and N=14 floodplain samples.

Table 16

Tree Core Age Structure Data

Time Frame	Point Bar Samples (%)	Floodplain Samples (%)
>1940	0	29
1940-1949	0	0
1950-1959	0	0
1960-1969	0	21
1970-1979	0	21
1980-1989	20	14
1990-1999	30	7
2000-2009	40	7

Table 17

Tree Core Species, Age, and Habitat Data

Site	Age	Species	Habitat Type
1	40	Cottonwood	Floodplain
1	50	Cottonwood	Floodplain
2	10	Cottonwood	Sandbar
2	10	Cottonwood	Sandbar
2	10	Cottonwood	Sandbar
2	10	Cottonwood	Sandbar
3	28	Box Elder	Floodplain
3	38	Silver Maple	Floodplain
3	40	Silver Maple	Floodplain
3	45	Silver Maple	Floodplain
3	50	Box Elder	Floodplain
4	12	American Elm	Floodplain
4	93	Box Elder	Floodplain
4	93	Silver Maple	Floodplain
4	110	Cottonwood	Floodplain
5	18	Cottonwood	Sandbar
5	20	Silver Maple	Sandbar
5	20	Silver Maple	Sandbar
5	25	Cottonwood	Sandbar
5	30	Cottonwood	Sandbar
6	20	Cottonwood	Floodplain
6	33	Cottonwood	Floodplain
6	115	Cottonwood	Floodplain

3.2 Patterns of Hydrologic Regime

3.2.1a Timing, Duration, and Magnitude of Base and Peak Flow Events within the Lower Minnesota River Basin

As observed in Table 18 and Figure 14, higher average mean, maximum, and minimum flows occurred within the lower Minnesota River during the 2010 and 2011 growing seasons as compared to recent years. In addition to high relative average growing season flows, 2010 observed a high recession rate, 2.6 cm/day and short flood duration from its peak flood occurring late in the growing season. High rates of recession were also observed in 2012 and 2013, both approximately greater than the rate of root growth for most common riparian species including cottonwood, with a rate of root growth of approximately 2.5 cm/day (Rood and Mahoney, 2000). High flood recession may lead to extreme changes in soil moisture contributing to poor conditions for seedling and sapling survival. In general, flood peaks within the lower Minnesota River basin occurred between mid-March and mid-May aside from the 2010 and 2013 growing seasons when flood peaks occurred around late-June with relatively shorter flood duration and higher recession rates.

Table 18

Stream Flow Patterns at Mankato, Minnesota: April 15th-September 20th

Year	Average (cms)	Maximum (cms)	Minimum (cms)	Flood Peak	Flood Duration (Days)	Recession Rate (cm/day)
2013	227 (+/-194)	937	14	6/27	86	3.1
2012	119 (+/-130)	524	8	5/30	114	2.4
2011	485 (+/-263)	1150	95	4/15	159	1.0
2010	301 (+/-182)	977	80	7/1	63	2.6
2009	95 (+/-83)	362	9	4/15	159	1.5
2008	223 (+/-180)	612	13	5/5	139	1.8
2007	156 (+/-118)	419	16	4/15	119	1.8
2006	210 (+/-216)	753	16	5/4	140	1.8
2005	221 (+/-158)	674	36	5/15	89	2.1
2004	177 (+/-181)	663	24	6/14	87	2.5

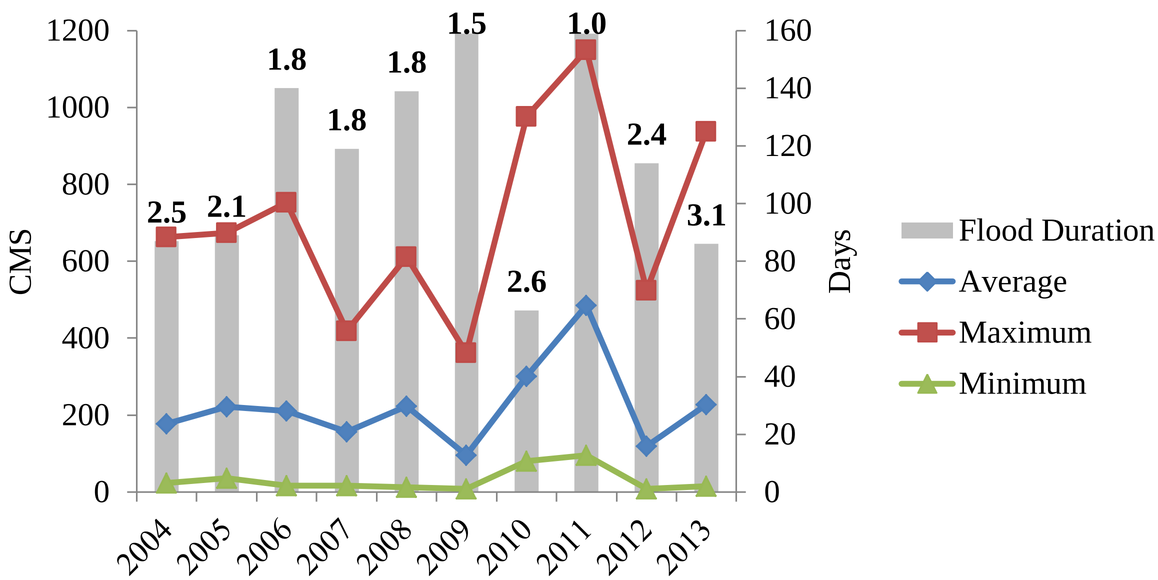


Figure 14. 2004-2013 growing season stream flow statistics, peak flood duration and recession rates (cm/day) in black at Mankato, MN.

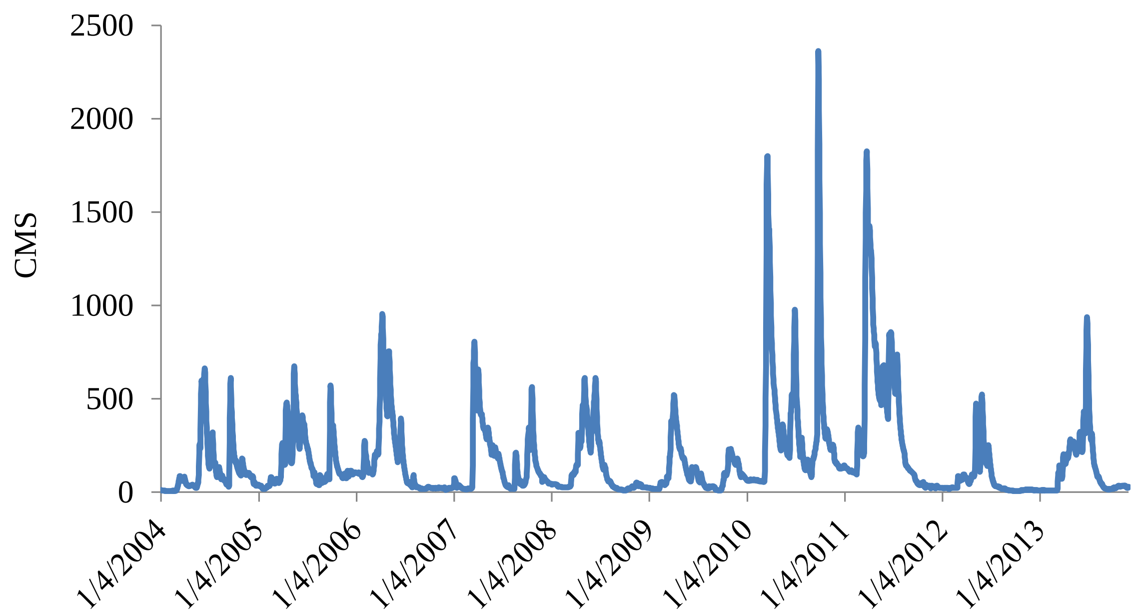


Figure 15. 2004-2013 stream discharge hydrograph at Mankato, MN.

3.2.1b Historic Timing, Duration, and Magnitude of Base and Peak Flows within the Lower Minnesota River Basin.

In general, higher average annual, maximum and minimum flows were observed in the decades following 1979 whereas lower flows were generally observed during decades between 1940-1979. 1960-1969 however saw extreme maximum flows and high relative average annual flows compared to other decades. On average, maximum flows generally occurred during late April to mid-May aside from 2010-2013 where maximum flows occurred during late June with average minimum flows occurring at varying dates across decades. The highest average annual, maximum, and minimum flows were observed during the decades of 2010-2013 and 1990-1999 (Table 19, Figure 16, Figure 17).

Table 19

Historic Flow Patterns at Mankato, Minnesota

Time Period	Ave. Annual Flow (cms)	Ave. Max Flow (cms)	Ave. Max Date	Ave. Min Flow (cms)	Ave. Min. Date
1940-1949	84 (+/- 113)	457	4/29	251	12-Apr
1950-1959	79 (+/-158)	667	5/12	187	18-May
1960-1969	107 (+/- 214)	953	5/14	247	9-Jun
1970-1979	89 (+/-119)	455	4/28	221	27-Jun
1980-1989	126 (+/-175)	614	5/19	545	29-Apr
1990-1999	207 (+/-244)	1006	5/12	796	12-Aug
2000-2009	135 (+/-205)	755	5/8	383	20-Aug
2010-2013	290 (+/-368)	1413	6/20	1082	23-Oct

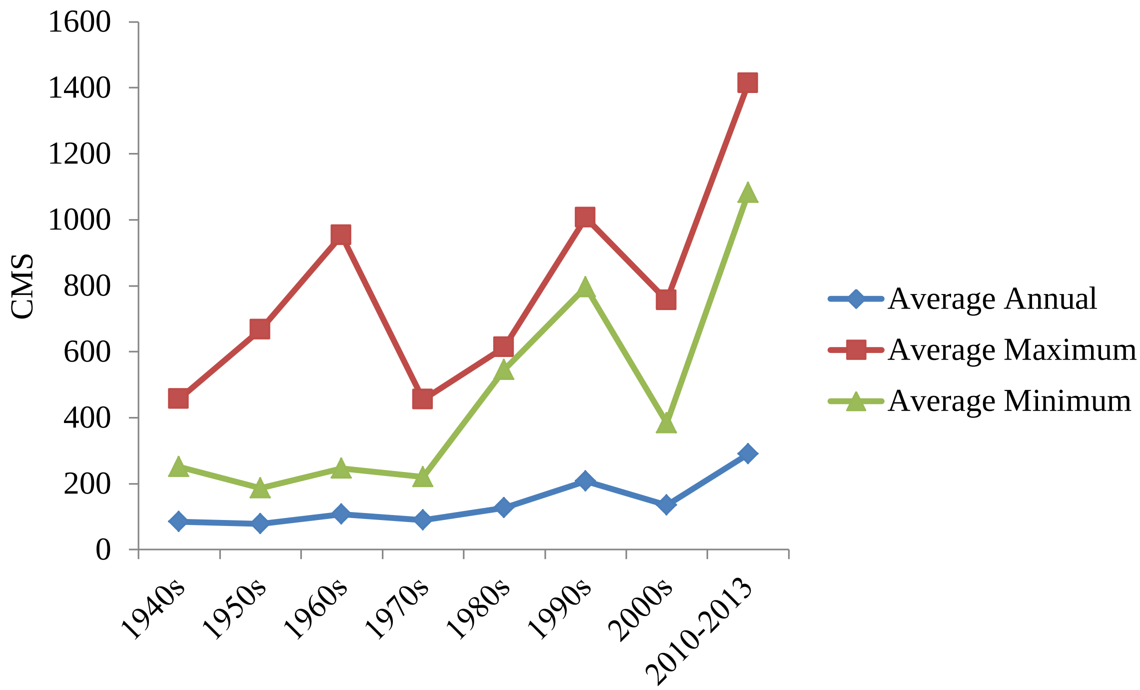


Figure 16. Historic stream flow statistics at Mankato, MN.

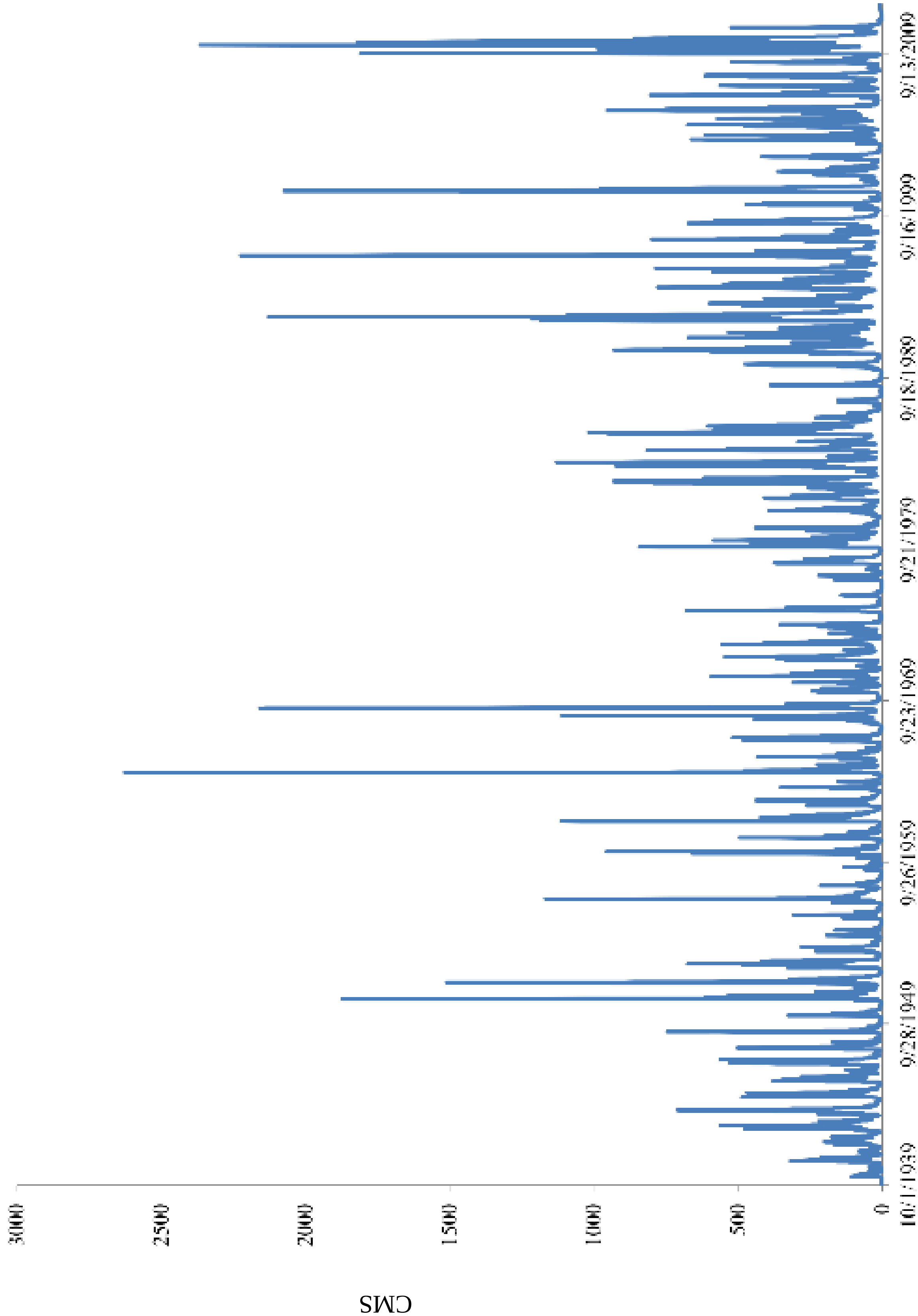


Figure 17. Historic stream discharge hydrograph at Mankato, MN.

3.2.1c Timing, Duration, and Magnitude of Base and Peak Flows within the Elm Creek Watershed

Within the Elm Creek watershed the highest mean growing season flows were observed in 2011 and 2010 with years of lower average flow occurring during 2009 and 2013. 2010 and 2012 however saw the greatest flood peaks. Extreme rates of recession and shorter relative flood duration were observed during the 2013 growing season. Timing of maximum flows is variable, generally occurring during mid to late June over the last five years and in late September of 2012. Timing of minimum flows was also variable over the last decade (Table 20, Figure 18, Figure 19).

Table 20

Stream Flow Patterns within the Elm Creek Watershed: April 15th-September 20th

Year	Average (cms)	Maximum (cms)	Minimum (cms)	Flood Peak	Flood Duration (Days)	Recession Rate (cm/day)
2013	3.4(+/- 4.3)	23.45	0	6/26	62	3.6
2012	5.1(+/- 9.3)	46.32	0.09	5/30	93	1.1
2011	10.1(+/- 8.8)	35.08	0.27	6/19	87	0.92
2010	7.4(+/- 7.8)	43.68	0.44	6/30	64	1.2
2009	1.4(+/- 1.3)	5.61	0.07	6/11	85	0.84
2008	6.5(+/- 6.7)	21.97	0	5/8	98	1.4
2007	2.8(+/- 3.6)	12.1	0	5/11	56	3.8
2006	6.6(+/- 9.0)	38.74	0.09	4/15	105	0.95
2005	7.1(+/- 8.0)	36.95	0.14	6/26	95	0.97
2004	5.1(+/- 6.1)	31.62	0.37	5/30	55	1.3

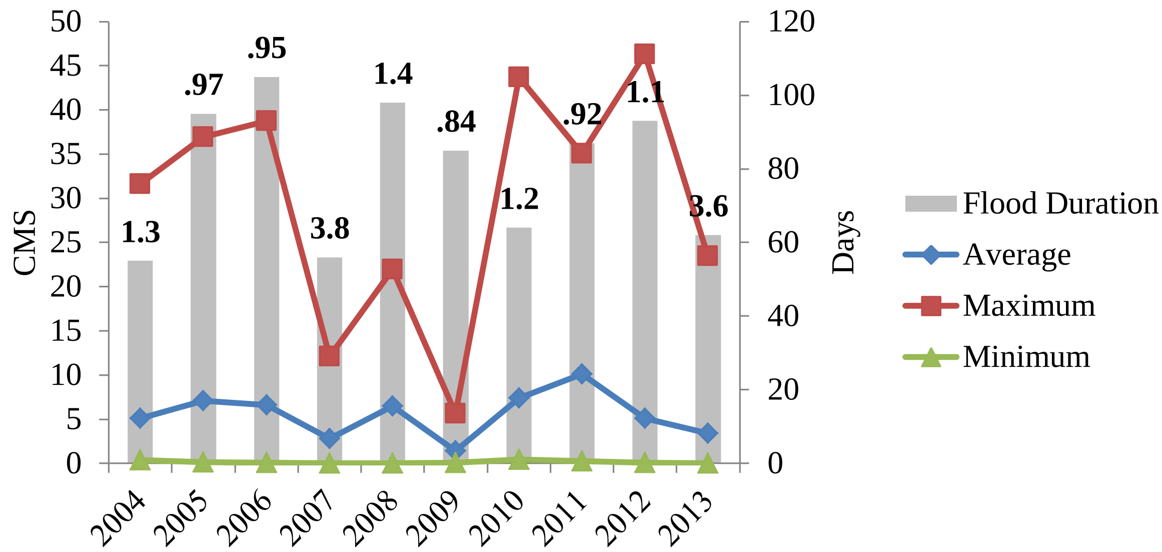


Figure 18. 2004-2013 growing season stream flow statistics, peak flood duration and recession rates (cm/day) in black within the Elm Creek watershed.

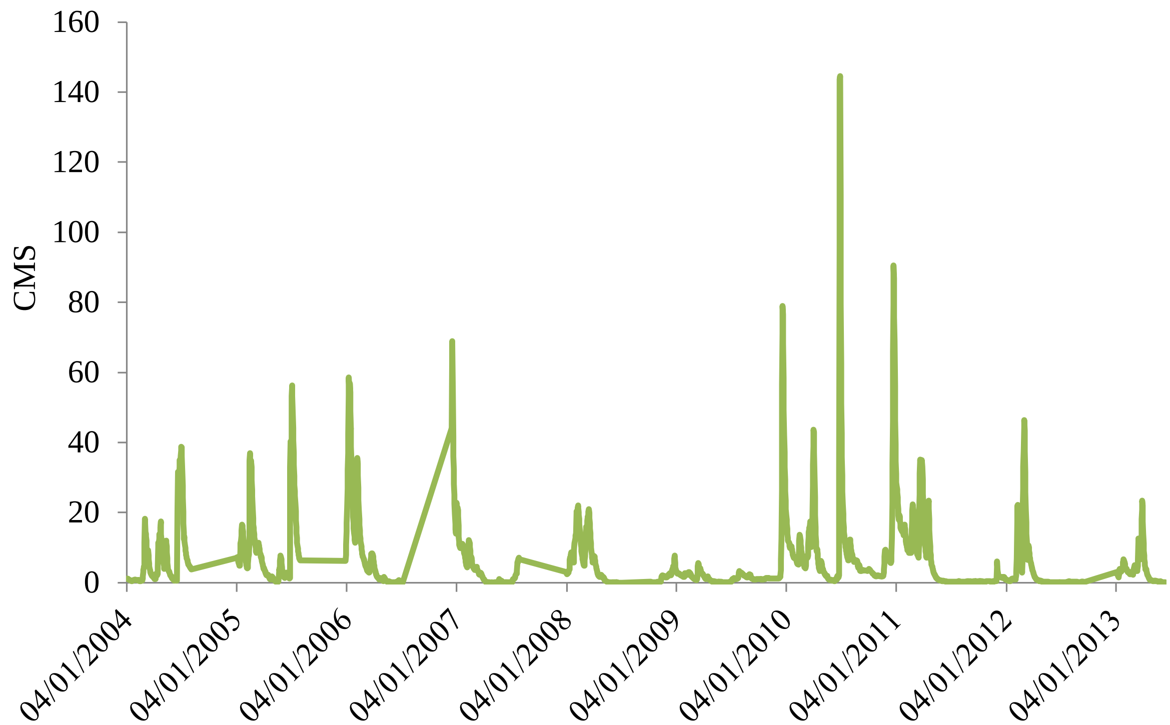


Figure 19. 2004-2013 stream discharge hydrograph within the Elm Creek watershed.

3.2.2a Point Bar Submerging Flows within the Lower Minnesota River Basin

Table 21 displays duration of complete point bar submergence over the last decade at each of the seven field survey sites within the lower Minnesota River basin. Across the basin, the greatest duration of point bar submergence during the growing season of April 15th to September 20th, was observed at all sites during the years of 2010 and 2011 with the lowest duration of point bar submergence occurring in 2009 and 2012. In general, sites 6 and 7, located at Bloomington, MN saw the greatest duration of complete point bar submergence followed by site one located at Saint Peter, MN. The lowest duration of point bar submergence was observed at sites 2 and 5 located at LeSueur and Shakopee, MN.

At sites two and five there is also point bar exposure until late June in 2013 whereas other sites where already completely submerged at the start of the growing season. These sites also saw exposure again in early July whereas other sites were completely submerged until late July or early August. During the 2012 growing season all sites were partially exposed at the start of the growing season with sites two and five again having smaller windows of complete submergence relative to other sites (Table 22).

Table 21

Lower Minnesota River Basin Point Bar Submergence: April 15th-September 20th

Site	Discharge (cms)	2013 (%)	2012 (%)	2011 (%)	2010 (%)	2009 (%)	2008 (%)	2007 (%)	2006 (%)	2005 (%)	2004 (%)	Ave.
1	126	67	35	86	87	25	62	53	49	61	44	57
2	501	7	2	52	13	0	8	0	13	6	11	11
3	166	62	26	78	81	19	54	48	47	53	33	50
4	177	62	34	80	72	21	57	48	48	59	38	52
5	636	7	0	41	6	0	0	0	11	5	6	8
6	70	76	53	100	100	57	71	65	59	84	6	67
7	70	76	53	100	100	57	71	65	59	84	67	73
Ave.		51	29	77	66	26	46	40	41	50	29	

Table 22

Point Bar Submergence Timing within the Lower Minnesota River Basin

Site	2013	2012	2011	2010	2009
1	4/15-7/30	5/6-7/3	4/15-8/30	4/15-9/20	6/38-9/20
2	6/24-7/5	5/29-5/31	4/15-6/7	4/15-7/8	N/A
3	4/15-7/24	5/6-6/14	4/15-8/18	4/15-9/20	5/14-9/20
4	4/15-7/26	5/7-7/4	4/15-8/20	4/15-9/20	4/15-5/18
5	6/28-7/8	N/A	4/15-7/10	4/15-7/11	N/A
6	4/15-8/17	4/21-7/15	4/15-9/20	4/15-9/20	4/15-7/22
7	4/15-8/17	4/21-7/15	4/15-9/20	4/15-9/20	4/15-7/22

3.2.2b Historic Point Bar Submerging Flows within the Lower Minnesota River Basin

As displayed in Table 23, duration of point bar submergence is higher, on average, during recent decades as compared to earlier decades. A step change in point bar submerging discharge is observed between 1970-1979 and 1980-1989. It is likely that this abrupt change is not accurate and that submerging discharge would vary across decades, but due to a lack of quality historical cross-section data within the lower Minnesota River basin changes in river cross-section and stage-discharge relationships across decades were un-accounted for. This data however, serves to show that duration of complete point bar inundation is currently greater than historically and allows for general comparison of growing season submergence durations across decades.

On average, point bars were found to be completely submerged for approximately thirty percent of the growing season, aside from 1990-1999 and 2010-2013 when submergence was observed for approximately 60 percent of the growing season. The lowest duration of point bar submergence was observed during the decades of 1950-1959 and 1940-1949. Increases in point bar submergence duration flowing 1980-1989 could be attributed to increases in base flow resulting from the use of tile drainage which increased significantly following the 1980s, in addition to significant increases in average annual precipitation (Fore, 2010; Lenhart et al. 2011a).

Table 23

Historic Point Bar Submergence at Mankato, Minnesota

Time Period	Submergence Discharge (cms)	Ave. Growing Season Submergence (%)
1940-1949	141	28.30
1950-1959	141	22.89
1960-1969	141	30.13
1970-1979	141	32.83
1980-1989	212	31.26
1990-1999	212	58.68
2000-2009	212	31.70
2010-2013	212	65.65

3.2.2c Sandbar Submerging Flows within the Elm Creek watershed

Within the Elm Creek watershed, we see the longest duration of complete point bar submergence at site one located within the upper region of the watershed with decreasing submergence duration going downstream to site eight where the shortest duration of complete point bar submergence was observed. Also observed within the lower Minnesota River basin, the 2011 and 2010 growing seasons saw the longest duration of complete point bar submergence, with the shortest submergence durations occurring during the 2009 and 2013 growing seasons (Table 24).

During the 2013 growing season later dates of complete submergence were observed at sites four through eight occurring during mid to late June, and earlier dates of complete submergence during late April at sites one, two and three. At sites one, two and three complete point bar submergence occurred until early July with complete submergence occurring only through late June at sites four through eight. Again during the 2011 and 2010 growing seasons we see earlier dates of complete submergence in addition to longer windows of duration at sites one, two and three as compared to sites four through eight. The 2012 and 2009 growing seasons saw nearly no complete submergence of point bars aside from short windows at sites one, two and three late during the growing season of 2012 (Table 25).

Table 24

Elm Creek Watershed Point Bar Submergence: April 15th-September 20th

Site	Discharge (cms)	2013 (%)	2012 (%)	2011 (%)	2010 (%)	2009 (%)	2008 (%)	2007 (%)	2006 (%)	2005 (%)	2004 (%)	Ave.
1	6	18	37	64	50	0	47	20	35	42	30	34
2	7	18	21	64	45	0	43	17	33	40	30	31
3	7	18	21	64	45	0	43	17	33	40	30	31
4	12	6	0	38	10	0	16	2	20	18	16	13
5	17	3	0	16	18	0	23	0	13	8	5	9
6	17	3	0	16	7	0	11	0	13	8	5	6
7	17	3	0	16	7	0	11	0	13	8	5	6
8	23	1	0	8	5	0	0	0	8	6	3	3
Ave.	13	9	10	36	23	0	24	7	21	21	16	

Table 25

Point Bar Submergence Timing within the Elm Creek Watershed

Site	2013	2012	2011	2010	2009
1	4/23-7/3	7/23-9/20	4/15-7/26	4/15/-7/27	N/A
2	4/25-7/4	8/17-9/20	4/15-7/26	4/15/-7/15	N/A
3	4/25-7/4	8/17-9/20	4/15/-7/26	4/15/-7/15	N/A
4	6/13-6/30	N/A	4/15/-7/22	6/13-7/9	N/A
5	6/24-6/29	N/A	5/23-7/4	6/18-7/6	N/A
6	6/24-6/29	N/A	5/23-7/4	6/18-7/6	N/A
7	6/24-6/29	N/A	5/23-7/4	6/18-7/6	N/A
8	6/26	N/A	6/17-6/28	6/27-7/5	N/A

3.3 Patterns of Sediment Deposition

3.3.1a Willow Age and Deposition Rate Estimation within the Lower Minnesota River Basin

Within the lower Minnesota River Basin we see on average, the highest rates of sediment deposition at site three located at Henderson, Minnesota. At this site we also see, on average, decreasing rates of deposition with distance from the channel in addition to increasing willow age. This is also true at sites two and seven located at LeSueur and Bloomington, MN. At site seven, we see the highest single estimate of sediment deposition rates occurring closest to the channel. At sites one, four and six no willow saplings were present for sampling. Site five, located at Shakopee, MN, saw the lowest observed rates of deposition (Table 26). Higher deposition rate estimates and willow ages were observed, on average, at sites 2 and 3 located within the upper region of the watershed as compared to sites 5 and 7 located within the lower region. This difference was not found to be significant based on ANOVA, but may prove to be significant if a larger number of sites were sampled (Table 27).

Table 26

Willow Age and Deposition Rate Estimation within the Lower Minnesota River Basin

Site	Willow Age (yr.)	Depth to Root Collar (cm)	Deposition Rate (cm/yr)	Distance from Water Line (m)
1	Absent			
2	3	21.59	7.20	80
	4	19.05	4.76	82
	5	10.80	2.16	88
3	5	67.31	13.46	65
	5	58.42	11.68	68
	7	88.90	12.70	75
4	Absent			
5	5	8.89	1.78	26
	5	10.16	2.03	28
6	Absent			
7	3	44.45	14.82	10
	4	11.43	3.81	13
	4	14.61	4.87	21

Table 27

Lower Minnesota River Basin Deposition Rate and Willow Age ANOVA

Region	Ave. Willow Age (yr.)	P-Value	Ave. Deposition Rate (cm/yr)	P-Value
Upper	4.83(+/-1.33)		8.66(+/-4.65)	
Lower	4.20(+/-.84)	0.32	5.46(+/-5.38)	0.32

3.3.1b Willow Age and Deposition Rate Estimation within the Elm Creek Watershed. Unlike what was observed within the lower Minnesota River basin, no clear pattern of sediment deposition rates was associated with distance from channel or with willow age. The highest rates of deposition were observed at sites seven and eight located in the lower region of the watershed. Site six, also located in the lower region of the watershed saw the third highest rates of deposition. Sites one through four, located within the upper region of the watershed saw, in general, lower deposition rate estimates as compared to sites within the lower region of the watershed. At sites two and three, no willow saplings were present for collection, and sites one and four saw deposition rate estimates ranging from approximately 1-2.5 cm/yr. compared to a range of approximately 1-15 cm/yr. at sites five through eight located within the lower region of the watershed (Table 28).

Higher estimated rates of sediment deposition are observed on average at sites five through eight located within the lower region of the watershed as compared to sites one and four located within the upper region, the difference of however was found to be statistically insignificant based on an ANOVA test. On average, greater willow age was found at sites within the upper region of the watershed as compared to the lower, the difference of which was found to be statistically significant (Table 29)

It is unlikely that deposition is occurring evenly across years as these data would suggest, but rather in events of deposition and erosion. These data do provide however, a general idea of the patterns of sediment deposition patterns across and within the Elm Creek and lower Minnesota River watersheds.

Table 28

Willow Age and Deposition Rate Estimation within the Elm Creek Watershed

Site	Willow Age (yr.)	Depth to Root Collar (cm)	Deposition Rate (cm/yr.)	Distance from Water Line (m)
1	4	9.53	2.38	2
	5	4.45	0.89	4
	5	9.53	1.91	8
2	Absent			
3	Absent			
4	4	9.53	2.38	5
	4	8.89	2.22	6
5	3	3.18	1.06	3
	2	6.99	3.49	3
6	3	24.13	8.04	5
	4	34.29	8.57	6
	3	3.81	1.27	8
7	3	3.18	1.06	1
	5	7.62	1.52	5
	4	59.69	14.92	5
	5	38.10	7.62	7
8	3	24.13	8.04	9
	3	41.28	13.76	10
	3	12.07	4.02	13

Table 29

Elm Creek Watershed Deposition Rate and Willow Age ANOVA

Region	Ave. Willow Age (yr)	P-Value	Ave. Deposition Rate (cm/yr)	P-Value
Upper	4.66(+/-.58)		1.73(+/-.76)	
Lower	3.5(+/-.85)	0.05	6.11(+/-4.85)	0.15

3.3.2 Sandbar Vegetation Change within the Lower Minnesota River Basin

Based on the availability of aerial photography flown during low flow conditions, the proportion of vegetation area to total point bar area was measured at five point bar locations from Mankato to LeSueur, MN using GoogleEarth software. The average proportion of vegetation area was than calculated across each site during the years of 2003, 2006, 2009, and 2011 to document overall increases or decreases in proportion of vegetation during years of low or high flow. The proportion of vegetation area to point bar area was found to have increased by approximately five percent during the years of 2003 and 2006 and by approximately thirty percent during the years of 2006 and 2009. Based on t-test results, average changes in proportion of vegetation during these time frames, which had lower average flows as compared to 2010 and 2011 were found to be statistically insignificant. During the higher flow years of 2009 and 2011 an observed decrease by approximately forty percent of vegetation area was found to be statistically significant at the 0.05 level (Table 30).

Table 30

Proportion of Vegetation Establishment Area to Point Bar Area

Year	Ave. Proportion Vegetation (%)	P-Value
2003	28	
2006	33	0.21
2009	65	0.11
2011	24	0.04

Note: N=5.

3.3.3 Particle Size Characteristics within the Lower Minnesota River Basin

2012 particle size data was collected at sites one and two located within the upper region of the watershed and at sites five and six located in the lower region of the watershed from the waterline to the bank top. In general, higher percent of sand was found at all sites in comparison to fine sediment, particularly at sites one and two which saw approximately 10 percent more sand on average as compared to sites five and six. At site one, approximately three percent more sand was found in samples taken from 0-25cm compared to samples at 25-50cm. At sites five and six greater proportion of fine sediment was found in samples taken from 0-25cm compared to those taken at 25-50cm (Table 31). On average, greater percent of sand and gravel verses fine sediment was found at sites within the upper region as compared to those in the lower region, the difference of which were all found to be significant based on ANOVA test results (Table 32).

Figure 20 displays the proportion of sand verse fine sediment in addition to associated percent vegetative cover and cover by woody seedling with increasing distance from the channel. At field survey sites one, two and five, increasing proportion of fine sediment is generally observed with greater distance from channel. At site one, little to no vegetative cover was found in quadrat surveys which was consistent with 2013 vegetation surveys (Table 4). At sites, five, and six increase and decreased in proportions of fine sediment are associated, in general, with increases in total vegetative cover. At site two, we observe increased in fine sediment from approximately 25m to 45m in addition to increasing vegetative cover along same distance from channel. The same is true at site five where increasing proportions of fine sediment and vegetative cover from about 10m to 35m, until nearly no vegetative cover in observed at 40m when the proportion of sand becomes greater than that of fines. Again at the six, we see increased vegetative cover at approximately 2m and 7m which are associated with increases in proportion of fine sediment.

Table 31

Particle Size Characteristics within the Lower Minnesota River Basin

Site	Depth(cm)	Ave. % Gravel	Ave. % Sand	Ave. % Fine
1	0 to 25	5(+/-6)	88(+/-10)	6(+/-11)
	25 to 50	9(+/-5)	85(+/-8)	6(+/-10)
2	0 to 25	4(+/-5)	89(+/-11)	7(+/-12)
5	0 to 25	0	65(+/-28)	35(+/-28)
	25 to 50	0	75(+/-21)	25(+/-21)
6	0 to 25	0	75(+/-18)	25(+/-18)
	25 to 50	0	81(+/-11)	19(+/-11)

Table 32

Lower Minnesota River Basin Particle Size Type ANOVA

Sites	Ave. % Gravel	P-Value	Ave. % Sand	P-Value	Ave. % Fine	P-Value
1, 2	6.13(+/-.06)		87.55(+/-.10)		6.31(+/-.11)	
5, 6	0	.00	73.76(+/-.21)	.00	26.24(+/-.21)	.00

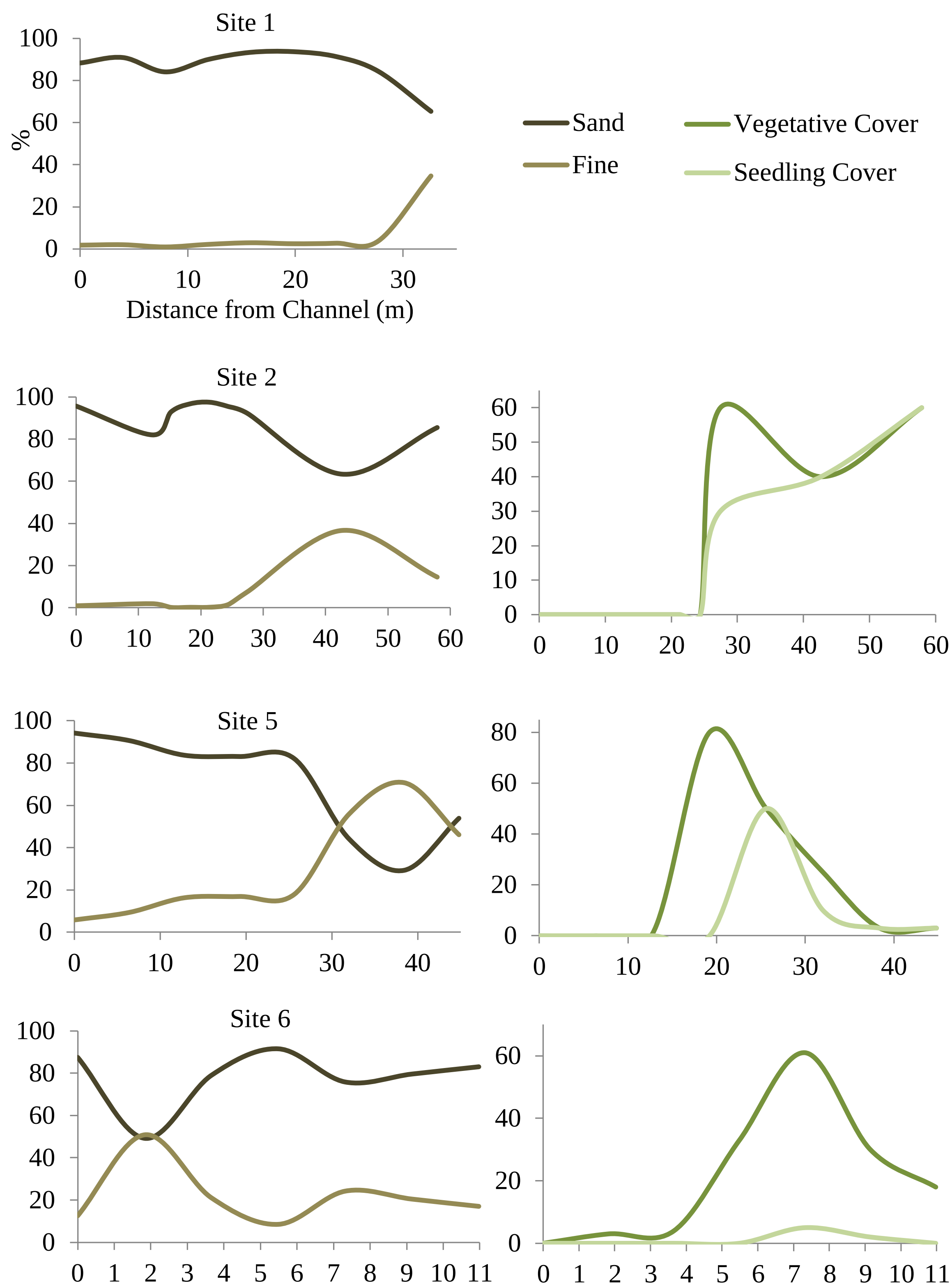


Figure 20. Percent sand verses fine sediment and percent vegetative coverage as a function of distance from water line within the lower Minnesota River basin.

3.3.4a Sediment Trap Deposition Rate Estimates within the Lower Minnesota River Basin

Turf mat squares placed at sites one, two, and three within the lower Minnesota River basin were unable to be re-located upon re-visit of point bar survey sites. Signs of heavy sediment deposition were evident at each of these sites in the forms of nearly buried sandbar willow saplings, and clear benches of fine deposited sediment. It is likely that the installed turf mat squares were buried too far under sediment to be recovered. This provides evidence that large deposition events often occur in association with large flood events, as observed during the 2014 growing season. Turf mat squares installed at sites four through seven were still submerged at the time of re-visit and need to be re-visited.

3.3.4b Sediment Trap Deposition Rate Estimates within the Elm Creek Watershed

Of the turf mat squares installed within the lower portion of the Elm Creek watershed, mats at sites five and eight were recovered. At site five, one turf mat located just at the bank top was found to be scoured and turned over with trace amount of sediment deposition less than .4cm deep on average, covering roughly 80 percent of the pad, which has an area of 1400 cm2. This translated to about .32 cubic centimeters per square centimeter deposited on average annually at this site near the bank top. The second mat recovered at site five, located closer to the channel, again had on average .40cm depth of sediment covering a 35cm2 area. Based on these values, it could be estimated that approximately .01 cubic centimeters per square centimeter were deposited on average annually at this site near the channel based on this mat.

Two mats were also recovered at site eight, again one located near the bank top and one located closer to the channel. Of the mat located closer to the channel, the average depth of sediment accumulated was approximately .77cm covering 50 percent of the 1400cm^2 mat. An average depth of approximately 3.15cm was found on 70 percent of the mat near the bank top. Based on these values, about .39 cm^3 of deposited sediment was estimated to occur near the channel and approximately 2.21cm^3 per square centimeter near the bank top. Mats at sites six and seven, located within the lower region of the watershed were either scoured out or too deeply buried in sediment to be recovered. Turf mats installed at sites one through four, located within the upper region of the watershed have not yet been re-visited.

Part 4. Discussion

4.1 Patterns of Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the Minnesota River Basin

Results from this study help to better understand and provide evidence for the relationships among vegetation establishment, hydrology, and sediment transport. Understanding these relationships and characteristics within the Minnesota River basin will aid in the development of management actions and the identification of priority management zones necessary to reduce sediment related impairments. Additionally, this work will provide baseline data and methodology for future work related to riparian vegetation, hydrology, and sediment within the Minnesota River basin.

4.1.1 Patterns of Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the lower Minnesota River Basin

4.1.1a Patterns of Vegetation Establishment and Hydrologic Regime

Across field survey sites within the lower Minnesota River basin, an overall higher relative frequency of saplings is observed as compared to seedlings (Figure 8). This is however skewed by the abundance of species with adventitious growth habit, mainly sandbar willow but also some black willow (Figure 9). Across lower Minnesota River basin transect surveys, willow saplings ranged from three to seven years in age indicating that sandbar willow, or adventitious rooting species established and survived during years of high flow, particularly 2008, 2010 and 2011 (Table 26, Figure 14).

Higher relative frequency of seedlings of species without adventitious growth habits were observed as compared to seedlings of species with adventitious growth habits (Figure 9). High relative frequencies of silver maple, American elm, and cottonwood were observed as compared to later successional species such as green ash and box elder. As shown in Figure 8, establishment of silver maple, American elm, and cottonwood saplings is also observed. It is likely that higher average flows observed during the 2010 and 2011 growing season served to leave behind exposed mineral substrates on point bars with abundant moisture and nutrients for plant regeneration (Table 18, Figure 14) (MNDNR, 2005). These new substrates likely allowed for rapid germination of seedlings during the lower flow years of 2012 and 2013. Saplings of silver maple and cottonwood observed in field surveys were likely established in 2012, germinating rapidly and surviving through the 2013 growing season.

Silver maple and cottonwood establishment was generally observed only at sites containing thick stands of sandbar willow, such as at sites two, three, and five. These sites also generally also saw higher elevation of vegetation establishment relative to channel elevation as compared to other field survey sites containing green ash and American elm such as sites one, four and six. At site five, which saw the highest vegetation establishment relative to channel elevation, saplings of silver maple are also observed that were not present at any other field survey site (Tables 4, 10, and 11). Sites two and five saw the lowest duration of complete submergence during the growing season over the past decade in addition to at least partial exposure well into the growing season allowing for rapid growth of earlier dispersing species such as silver maple and cottonwood (Tables 1, 21, and 22).

At field site one, nearly no woody seedling or sapling establishment was observed in addition to the smallest distance of vegetation establishment relative to channel elevation and relatively long duration of point bar submergence during the growing season. It is likely that vegetation establishing closer to the channel faces more damage from inundation as well as ice and debris hindering establishment vegetation establishment (Tables 4, Table 10, Table 21).

The comparison of vegetation area relative to point bar area across different years also served to demonstrate the relationships between vegetation establishment and hydrologic regime. During the years of 2003 to 2006, a slight increase in vegetation area to point bar area was observed, although found to be statistically insignificant. Between 2006 and

2009 an increase in proportion of vegetation area by approximately 30 percent was also observed, although still found to be statistically insignificant. During the 2007 and 2009 growing seasons, below average flows were observed particularly during 2009, creating more suitable conditions for vegetation established through decreased scour, inundation and sediment deposition. Between the years of 2009 and 2011, a statistically significant decrease in proportion of vegetation area was observed in association with above average flow during the 2010 and 2011 growing seasons. These data provide evidence for establishment of vegetation during lower flow years and inhibited vegetation establishment during higher flow years (Table 18, Table 30, and Figure 14).

4.1.1b Patterns of Hydrologic Regime and Sediment Transport

Patterns of decreased proportion of vegetation area to point bar area observed during high flow years also provide evidence for large depositional events occurring on point bars during years of high flow. In addition to increased mortality from prolonged inundation and increased scour, it is likely that vegetation is also being buried by large deposits of sediment associated with flooding further serving to inhibit riparian vegetation establishment (Table 18, Table 30, and Figure 14).

Sites two and three located within the upper region of the watershed saw higher rates of deposition as compared to sites five or seven located within the lower region of the watershed. At site three, higher rates of deposition were observed as compared to site two in addition to longer durations of point bar inundation again providing evidence of heavy sediment deposition occurring with flooding. Site three also observed fewer established saplings as compared to site two providing evidence that inundation and sediment can contribute to vegetation mortality. At field survey site seven, the single greatest measure of sediment deposition was observed in association with the longest observed complete point bar submergence relative to other field survey sites. Site seven also observed nearly no seedling or sapling of woody species aside from sandbar willow in addition to the only observed seedlings and saplings of black willow which is highly tolerant of heavy sedimentation as compared to other species (Table 4, Table 26, and Table 21).

4.1.1c Patterns of Sediment Transport and Vegetation Establishment

Although found to be statistically insignificant, estimated rates of sediment deposition were higher on average at sites within the upper region of the watershed as compared to those in the lower region. Higher average deposition rate estimates were generally associated with greater average willow age and age range providing evidence for the role of vegetation in sediment retention (Tables 26 and 27). Also displayed in Figure 20, increases in fine sediment at sites two, five and six are associated with increased vegetative cover further demonstrating the role of sediment in the trapping of fine sediment. Field survey site 1 also saw the lowest proportion of fine sediment and the highest proportions of sand and gravel in association with low vegetative cover as compared to other field survey sites.

Particle size samples taken at sites one and two observed significantly higher proportions of sand and gravel over fine sediment as compared to sites five and six located within the lower region of the watershed. Higher proportion of fine sediment as sites five and six were also observed in surface samples as compared to sub-surface samples providing evidence that deposition of coarse material is occurring within the lower region of watershed while fine sediment is being transported downstream. Sites four and six, located within the lower region of the watershed also observed green ash and American elm establishment with zero occurrences of sandbar willow indicating that little to no deposition is occurring. Site five, also located within the lower region of the watershed, saw lower deposition rate estimates and sandbar willow frequencies as compared to similar upper region sites in addition to greater proportions of fine sediment (Table 4, Table 31, Figure 20).

4.1.2 Historic Patterns of Vegetation Establishment and Hydrologic Regime within the lower Minnesota River Basin

Comparison of historical stream flow and vegetation establishment data within the lower Minnesota River basin served to further demonstrate the relationships between vegetation establishment and hydrologic regime across time. As displayed in Table 19, Table 23 and Figure 16, increases in average annual flow have occurred since 1979, in addition to increased duration of complete point bar submergence, particularly during the years of 1990 to 1990 and 2010 to 2013. Comparison of 1979 vegetation establishment elevations to modern elevations at three sites found average increases in vegetation establishment by approximately three to four meters at each site. This observed increase in vegetation establishment elevation is likely a response to higher river stage associated with flow increases (Table 12). Loss in length of un-vegetated sandbar is associated with easier mobilization of sediment may lead to increased sediment transporting and river widening.

Within tree core samples taken on point bar sites, ages ranged from ten to thirty years old and consisted mainly of cottonwood, with some silver maple. Within point bar sites, younger species of cottonwood were observed with no silver maple trees whereas older cottonwood trees where observed with silver maple trees (Table 17). No samples on point bar were found to have established prior to 1980 with increasing proportion of samples establishing during 1990-1999 and then 2000-2009. On floodplain sites, ages ranges from approximately 12 years to 115 years with no samples found to have established between 1940-1959. Decreasing proportion of floodplain samples were found to have established during each decade from 1960-1970. The only floodplains sample found to have established between 2000-2009 was an American elm species associated with the oldest observed samples of box elder, silver maple, and cottonwood (Table 16).

These patterns provide evidence for riparian vegetation succession from point bar to floodplain forest, where establishment of point bar vegetation lead to the development of floodplains. The observed absence of floodplain species having established prior to 1960 could be explained large flood events in the 1960s, particularly during 1965 which likely served to kill any establishing understory vegetation creating exposed, moisture and nutrient rich soil for establishment of vegetation beginning after 1965 and continuing until 2009 (Figure 17). It is likely that this same pattern may be observed in future years following large flood events during the 2010 and 2011 growing seasons in addition to high flood peak recession rates in 2013 (Figure 14).

4.1.3 Patterns of Vegetation Establishment, Hydrologic Regime, and Sediment Transport within the Elm Creek Watershed

Within the Elm Creek watershed, we again see a dominance of saplings over seedlings, in particular dominated by sandbar willow saplings (Figure 11). Higher relative frequencies of seedlings and sapling of species with adventitious growth habits, including sandbar and black willow, are observed as compared to those of species without adventitious growth habits (Figure 12). This is opposite of what was observed within the lower Minnesota River basin, where higher relative frequencies of seedlings without adventitious growth habits were observed over seedlings of those without (Figure 9). Within Elm Creek vegetation surveys willow ages ranged from two to five years old, with an average age of approximately four years indicating the establishment of species with adventitious growth habits established and survived during high flow years of 2010 and 2011. As observed within lower Minnesota River basin surveys, it is again likely that observed seedlings and saplings within the Elm Creek watershed established and rapidly germinated during the low flow years of 2012 and 2013 (Figure 18).

Overall, high relative frequencies of seedling of green ash and box elder were observed as compared to those of silver maple, American elm or cottonwood. We do however observe nearly even proportions of sapling establishment between all species aside from cottonwood and sandbar willow (Figure 11). In general, green ash and box elder were observed at sites containing no sandbar willow, such as sites two three and four located within the upper region of the watershed and at site five (Table 7). These sites also saw greater duration of compete point bar submergence as compared to sites dominated by sandbar willow which was also true within lower Minnesota River basin surveys (Table 4, Table 24, and Table 25).

As previously observed within lower Minnesota River basin transect surveys, the highest frequency of silver maple seedling and saplings was associated with the highest frequencies of sandbar willow. This was true at field survey site seven located within the lower region of the Elm Creek watershed. Also consistent with lower Minnesota River basin data, American elm and cottonwood establishment was also observed only in association with high relative frequencies of sandbar willow (Table 4 and Table 7). Sites six, seven, and eight located within the lower region of the watershed observed this pattern in addition to seeing the shortest duration of complete point bar submergence during the growing season (Table 24 and Table 25).

At sites one, two and three point bar exposure did not occur until late in the growing seasons of 2010, 2011 and 2013 likely creating unsuitable conditions for earlier seeding species such as silver maple, American elm or cottonwood. These earlier seeding species were not observed within upper region sites, but rather at lower region sites such as six seen and eight were point bar exposure was observed until late into the growing season during 2010-2013 allowing seeds of earlier dispersing species to reach exposed substrates and germinate rapidly (Table 25).

Sites dominated by sandbar willow, including site one, six, seven and eight saw significantly lower average vegetation establishment elevations relative to water surface elevation as compared to sites containing no sandbar willow. Sites dominated by sandbar willow with lower elevation of vegetation establishment, generally observed within the lower region of the watershed, saw shorter windows of complete point bar submergence as compared to those without sandbar willow establishing at higher elevations (Table 13, Table 14, and Table 25). Sites dominated by sandbar willow within the lower Minnesota River basin, also saw shorter durations of complete point bar submergence as compared to those without but were generally observed within the upper region of the watershed and saw significantly higher vegetation elevation established as compared to sites without sandbar willow (Table 4, Table 11 and Table 22).

Sites located within the lower region of the watershed saw higher average rates of sediment deposition as compared to sites within the upper region. As previously observed at sites within the upper region of the lower Minnesota River basin, these higher average rates of sediment deposition were associated with higher relative frequencies of sandbar willow. This again provides evidence for the role of vegetation in retention of sediment. These deposition patterns, in addition to the presence of pioneer silver maple and cottonwood species also may serve to demonstrate aggradation and development of point into floodplains occurring within the lower region of the Elm Creek watershed and within the upper region of the lower Minnesota River basin.

4.2 Research Limitations and Future Research Needs

Data within this will serve as a baseline for continued research to better document continued patterns of vegetation establishment, hydrologic regime and sediment transport across greater time frames and flow conditions. As field data within the study was collected during only one growing season, continued vegetation surveys completed across several growing seasons would serve to better illustrate the interactions between vegetation establishment and annual hydrologic regime and to strengthen study results. The same is true of associated sediment deposition rate estimate data. Additionally, sediment traps installed at sampling locations within both the lower Minnesota River and Elm Creek watersheds were not fully re-surveyed and could be monitored in future years to further document sediment deposition patterns across the study area.

Although data within this study serves to characterize and demonstrate the relationships between hydrologic regime, vegetation establishment and sediment transport within the Minnesota River basin, further or more refined data collection could have served to strengthen study results. Although available Lidar data and limited cross-sectional data provided some data on vegetation elevation establishment and stage-discharge relationships, geomorphic cross-section data taken along vegetation transect surveys at the time of surveys would have served to better illustrate the relationship between stream flow and vegetation establishment, including more exact vegetation establishment elevations and channel dimensions. Exact elevations of vegetation establishment at field sites could also have been related river stage elevations at each site.

Limited availability of cross-sectional data across various years also limited the strength of study results. Although providing an estimate of complete point bar submergence variability across field survey sites, cross-sectional data was only available within the lower Minnesota River basin during 2013 so did not account for any changes in stage-discharge relationships used to determine percent of growing submergence during each year of the last decade. The same is true of historical cross-sectional data used to document historical changes in submergence duration from 1940-2013, which was known only to have been taken prior to 1979. Within this study, durations of partial submergence were also not taken into account which may have further served to more fully represent the vegetation establishment patterns in association with hydrologic regime.

The methodology used within this study may serve as a baseline for future related work, although the methodology for exploring sediment transport patterns could be further refined. This is particularly true within the Elm Creek watershed, where aerial photography resolution was too low measure proportion of sandbar area to vegetation area with confidence and accuracy. As remote sensing technology continues to improve, higher aerial photography resolution and associated Lidar data may make this analysis possible within the Elm Creek watershed in future years.

The results of this study have provided evidence that sediment deposition is occurring within the Minnesota River basin, although the volume and extent of which is unknown or not well understood. Understanding the volume of sediment deposition occurring within the lower Minnesota River basin and the role of vegetation within that deposition would aid in development of sediment load reductions and associated management actions in tributaries of the Minnesota River as required by the Minnesota River Turbidity Total Maximum Daily Load (Baskfiled, 2012; Wilcock, 2009). Methodology such as estimating volume of deposited sediment per area using sediment traps, measuring changes in proportion of vegetation area to sandbar area, and determining depth of sediment to root collar could be further explored and applied across greater ranges of space and time to better characterize volumes and zones of sediment deposition.

4.3 Management Implications

Results from this study provide evidence for the relationships between vegetation establishment, hydrologic regime and sediment transport. As previously demonstrated by Lenhart et al. (2013) and as seen in result of this study, increases in flow observed after 1979 have been associated with decreased woody riparian vegetation establishment and increases in vegetation establishment elevation (Lenhart et al., 2011a). Within this study, large flood events have also been have also been associated with heavy sediment deposition events on point bars and associated decreased vegetation establishment. The role of vegetation in the trapping of deposited sediment has also been demonstrated within this study.

Management actions aimed at reductions in stream flow would lead to more suitable conditions for vegetation establishment which in turn would contribute to increased sediment retention, reduced river widening and increased floodplain connectivity and development. Reductions in stream flow could be accomplished through management actions including targeted restoration of riparian corridors or wetlands as well as increased cover of perennial vegetation (Brooks et al., 2013; Leach and Magner, 1992; Lenhart et al., 2011a, Lenhart et al., 2011b, Zedler, 2003).

Targeted riparian corridor restoration may prove to be a plausible option for stream flow reduction within agricultural watersheds. Construction of drainage ditches and culverts often accompany land-use changes within agricultural watersheds, further contributing to increased storm flow and sediment transport. Some hydrologic and ecological features or ditches may be improved through the use of alternative designs where ditches have previously been made. The two-stage ditch in particular serves to create a small floodplain within the overall geometry of a ditch which aids in buffering flow and sediment in addition to creating habitat for aquatic life (Brooks et al., 2013; Kramer, 2011).

Planting vegetated riparian buffers would also contribute to stream flow reduction through increased infiltration, transpiration and soil water storage, as well as through decreased surface run-off (Anderson et al., 2005; Schultz et al., 1995). Vegetated buffers also provide for stream-bank stabilization and are generally constructed with fast-growing species such as sandbar willow. Wetland restoration where previous wetlands have been drained for agriculture would also provide for increased hydrologic storage within the watershed, and it is often by law to replace wetlands that have been drained. Additionally, economic incentives exist for land owners interested in restoring their crop-lands to vegetative cover under the Conservation Reserve Program which compensates farmers for retiring land for ten years (Brooks et al., 2013).

Although these actions may be the most sustainable methods for stream flow managements, they may prove difficult within the Minnesota River basin as the watershed is predominately privately owned farmland. This farmland consists mainly of corn and soybean at a time when prices for these crops are at an all-time high. Additionally, private parcelization of land within the watershed makes large scale restoration more difficult. Such, further research and development into management actions aimed at stream flow control within agricultural watersheds would aid in improvement of water quality within the Minnesota River basin. (Coiner et al., 2001; Brooks et al., 2013; Lenhart et al., 2013; Nassauer et al., 2011; Santelmann et al., 2004).

References

Alldredge, B., & Moore, G. (2012). Assessment of riparian vegetation sensitivity to river hydrology downstream of a major texas dam. *River Research and Applications*.

Anderson, S. H., Udawatta, R. P., Seobi, T., & Garrett, H. E. (2009). Soil water content and infiltration in agroforestry buffer strips. *Agroforestry systems*, *75*(1), 5-16.

Baskfiled, P., Campbell, E., Dumalag E. (2012). Minnesota River Turbidity Total Maximum Daily Load Draft Report. MPCA Report wq-iw7-32b. St. Paul, Minn.: Minnesota Pollution Control Agency.

Bertoldi, W., Drake, N. A., & Gurnell, A. M. (2011). Interactions between river flows and colonizing vegetation on a braided river: Exploring spatial and temporal dynamics in riparian vegetation cover using satellite data. *Earth Surface Processes and Landforms, 36*(11), 1474-1486.

Brooks, K.N., D. Current & D. Wyse. 2006. Restoring Hydrologic Function of Altered Landscapes: An Integrated Watershed Management Approach. Pp 101-114 in: Tennyson, L. And P.C. Zingari (eds.). *Water Resources for the Future, Conference Proceedings, Porto Cervo, Sassari, Sardinia, Italy; 22-24 October, 2003, Watershed Management & Sustainable Mountain Development Working Paper 9.* FAO, United Nations: Rome.

Brooks, K., Folliott, P. & Magner, J. (2013) *Hydrology and the Management of Watersheds*. John Wiley & Sons.

Burns, R.M., Honkala, B.H.. Honkala, tech. cords. 1990. *Silvics of North America*: 2. *Hardwoods*. Agriculture Handbook 654. Washington, D.C. USDA, Forest Service.

Coiner, C., Wu, J., & Polasky, S. (2001). Economic and environmental implications of alternative landscape designs in the Walnut Creek Watershed of Iowa. *Ecological Economics*, *38*(1), 119-139.

Cooper, D.T., and D.F. Van Haverbeke. 1990. *Populus deltoides.* In *Silvics of North America:* 2. *Hardwoods*, R.M. Burns and B.H. Honkala, tech. cords., -42. Agriculture Handbook 654. Washington, D.C.: USDA, Forest Service.

Corenblit, D., J. Steiger, A. M Gurnell, E. Tabacchi, & L. Roques. (2009). Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Proc. and Landforms* 34(13): 1790-1810.

Curtis, J. & McIntosh, R. (1950). The interrlations of certain analytic and synthetic phytosociological characteristics. *Ecology* 31:434-455.

Devi, L. S., & Yadava, P. S. (2006). Floristic diversity assessment and vegetation analysis of tropical semievergreen forest of Manipur, north east India. *Tropical Ecology*, *47*(1), 89-98.
Dickerson, J. 2002. Plant Fact Sheet for Green Ash (*Fraxinus pennsylvanica* L.). USDA-Natural Resources Conservation Service, New York State Office, Syracuse, NY.

Dixon, M. D., Turner, M. G., & Jin, C. (2002). Riparian tree seedling distribution on Wisconsin River sandbars: controls at different spatial scales. *Ecological Monographs*, *72*(4), 465-485.

Dixon, M. D., & Turner, M. G. (2006). Simulated recruitment of riparian trees and shrubs under natural and regulated flow regimes on the Wisconsin River, USA. *River Research and Applications*, *22*(10), 1057-1083.

Engstrom, D. R., Almendinger, J. E., & Wolin, J. A. (2009). Historical changes in sediment and phosphorus loading to the upper Mississippi River: mass-balance reconstructions from the sediments of Lake Pepin. *Journal of Paleolimnology*, *41*(4), 563-588.

Fitzpatrick, F. A., Knox, J. C., & Whitman, H. E. (1999). *Effects of historical land-cover changes on flooding and sedimentation, North Fish Creek, Wisconsin*. US Department of the Interior, US Geological Survey.

Fore, Z. 2010. Tile drainage: Research results, economics, and where do we go from here. St. Paul, MN: University of Minnesota Extension Service.

Fowells, H. A. 1965. *Silvics of Forest Trees of the United States.* Agriculture Handbook No. 271. USDA Forest Service, Washington, DC.

Geyer, W. A., J. Dickerson, and J. M. Row. 2010. Plant Fact Sheet for Silver Maple (*Acer saccharinum* L.). USDA-Natural Resources Conservation Service, Manhattan Plant Materials Center, Manhattan, KS 66502.

Gill, C.J. 1970. 'The flooding tolerance of woody species—a review', *For. Abstr*., 31, 671–688.

Gran, K. B., P. Belmont, S. S. Day, C. Jennings, A. Johnson, L. Perg, and P. R. Wilcock. 2009. Geomorphic evolution of the Le Sueur River, Minnesota, USA, and implications for current sediment loading. *GSA Special Papers* 451: 119-130. Boulder, Colo.: Geological Society of America.

Gurnell, A. M., Bertoldi, W., & Corenblit, D. (2012). Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews*, *111*(1), 129-141.

Hickin, E. J. (1984). Vegetation and river channel dynamics. *The Canadian Geographer/Le Géographe canadien*, *28*(2), 111-126.

Hupp, C. R., & Simon, A. (1991). Bank accretion and the development of vegetated depositional surfaces along modified alluvial channels. *Geomorphology*, *4*(2), 111-124.
Hupp, C.R. 1988. 'Plant ecological aspects of flood geomorphology and paleoflood history', in Baker, V., Kochel, C., and Patton, P. (Eds), *Flood Geomorphology,* Wiley Interscience, New York, pp. 335–356.

Johnson, W. Carter. "Equilibrium response of riparian vegetation to flow regulation in the Platte River, Nebraska." *Regulated Rivers: Research & Management* 13.5 (1997): 403-415.

Knox, J. C. (2006). Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. *Geomorphology* 79(3-4): 286-310.

Knox, J. C. (1987). Historical valley floor sedimentation in the Upper Mississippi Valley. *Ann. Assoc. American Geographers* 77(2):224-244.

Kramer, G. (2011) *Design, construction and assessment of a self-sustaining drainage ditch.* MS Thesis. St. Paul, MN: University of Minnesota.

Leach, J., Magner, J.A. (1992). Wetland drainage impacts within the minnesota river basin. *Currents III*(2), 3-10.

Lenhart, C. F. (2008). *The Influence of Watershed Hydrology and Stream Geomorphology on Turbidity, Sediment and Nutrients in Tributaries of the Blue Earth River, Minnesota, USA*. ProQuest.

Lenhart, C. F., Brooks, K. N., Heneley, D., & Magner, J. A. (2010). Spatial and temporal variation in suspended sediment, organic matter, and turbidity in a Minnesota prairie river: implications for TMDLs. *Environmental monitoring and assessment*, *165*(1-4), 435-447.

Lenhart, C. F., Peterson, H., Nieber J. (2011a). Increased streamflow in agricultural watersheds of the midwest: Implications for management. Watershed science bulletin, 2011, 25-31.

Lenhart, C. F., Titov, M., Ulrich, J., Nieber, J., & Suppes, B. (2013). The role of hydrologic alteration and riparian vegetation dynamics in channel evolution along the lower Minnesota River. *Trans. ASABE*, *56*, 549-561.

Lenhart, C.F., Verry E., Brooks, K. & Magner, J. (2011b). Adjustment of prairie pothole streams to land-use, drainage and climate changes and consequences for turbidity impairment. *River Research and Applications* DOI: 10.1002/rra.1549.

Leopold, L.B., Wolman, M.G., and Miller, J.P., 1964, Fluvial processes in geomorphology: San Francisco, W.H. Freeman and Co., 522 p.

Lock, R.H., Lock, P.F., Morgan, K.L., Lock, E.F., Lock, D.F. (2013) *Unlocking the Power of Statistics*. Hoboken, New Jersey: John Wiley and Sons.

Magner, J. A., Payne, G. A., & Steffen, L. J. (2004). Drainage effects on stream nitrate-N and hydrology in south-central Minnesota (USA). *Environmental monitoring and assessment*, *91*(1-3), 183-198

Mahoney, J. M, and Rood, B. (1991). A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology*, 8:305-314.

Mahoney, J. M., & Rood, S. B. (1992). Response of a hybrid poplar to water table decline in different substrates. *Forest Ecology and Management*, *54*(1), 141-156.

Matsch, C.L., 1983, River Warren, the southern outlet of Lake Agassiz, in Teller, J.T. and Clayton, L., eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26, p. 232-244.

Miller, R.C. 1999. *Hydrologic Effects of Wetland Drainage and Land Use Change in a Tributary Watershed of the Minnesota River Basin: A Modeling Approach*. Master's of Science Thesis, University of Minnesota-Twin Cities, St. Paul, Minnesota, USA.

Minnesota Department of Natural Resources (MN DNR). (2014, January 1). *MnTOPO*. Retrieved July, 2013, from http://arcgis.dnr.state.mn.us/maps/mntopo/

Minnesota Department of Natural Resources Ecological Land Classification Program (MN DNR ELC). (2005). *Field guide to native plant communities: eastern broadleaf forest province.* St. Paul, MN: University of Minnesota Press.

Minnesota Pollution Control Agency (MPCA) (2008). Minnesota's impaired waters and total maximum daily loads. http://www.pca.state.mn.us/water/tmdl/index.html.

Nassauer, J. I., J. A. Dowdell, Z. Wang, D. McKahn, B. Chilcott, C.L. Kling, and S. Secchi. (2011). Iowa farmers' responses to transformative scenarios for corn belt agriculture. *J. Soil and Water Cons.* 66(1): 18A-24A.

National Park Service. (2014). *Eastern Cottonwood*. Retrieved from http://www.nps.gov/miss/naturescience/cottonwood.htm

Noble, M. G., (1979). The origin of *Populus deltoides* and *Salix interior* zones on point bars along the Minnesota River. *American Midland Naturalist*, 102(1): 59-67.

Novotny, E. V., & Stefan, H. G. (2007). Stream flow in Minnesota: Indicator of climate change. *Journal of Hydrology*, *334*(3), 319-333.

Ottenbreit, K. A., & Staniforth, R. J. (1992). Life cycle and age structure of ramets in an expanding population of Salix exigua (sandbar willow). *Canadian Journal of Botany*, *70*(6), 1141-1146.

Overton, R.P. 1990. *Acer negundo* L. *Boxelder*. Pp. 41-45, IN: R.M. Burns & B.H. Honkala (tech. coords.). *Silvics of North America*. *Volume 2*. *Hardwoods*. USDA, Forest Service Agric. Handbook 654, Washington, D.C.

Pezeshki, S. R., Anderson, P. H., & Shields, F. D. (1998). Effects of soil moisture regimes on growth and survival of black willow (Salix nigra) posts (cuttings). *Wetlands*, *18*(3), 460-470.

Pitcher, J. A. and J. S. McKnight. 1990. *Salix nigra* Marsh. Black Willow. *In* Silvics of North America. USDA-FS Agriculture Handbook No. 654. http://www.na.fs.fed.us/spfo/pubs/silvics_manual/vol ume_2/Salix/nigra.htm [online: cited 14 Nov 2008].

Quade, H. (2000). *Blue Earth River major watershed diagnostic report*. Blue Earth River Basin Implementation Framework. South Central Minnesota County, Comprehensive Water Planning Project. Mankato, MN: Joint Powers Board and Water Resources Center, Minnesota State University.

Rood, S. B., Braatne, J. H., & Goater, L. A. (2010). Responses of obligate versus facultative riparian shrubs following river damming. *River Research and Applications*, *26*(2), 102-117.

Rood, S., Kalischuck, A., Mahoney, J. (1998). Initial cottonwood seedling recruitment following the flood of the century of the oldman river, Alberta, Canada. *Wetlands*, 8, 557-570.

Rood, S. B., Mahoney, J.M. (2000). Revised instream flow regulation enables cottonwood recruitment along the St. Mary River, Alberta Canada. *Rivers*, 7(2), 109-125.

Rood, S. B., Mahoney, J.M., Reid, D. & Zilm, L. (1995). Instream flows and the decline of riparian cottonwoods along the St. Mary River, Alberta. *Canadian J. Bot*. 73(8): 1250-1260.

Santelmann, M. V., D. White, K. Freemark, J. I. Nassauer, J. M. Eilers, K. B. Vache, B. J. Danielson, R. C. Corry, M. Clark, S.Polasky, R. M. Cruse, J. Sifneos, H. Rustigian, C. Coiner, J. Wu, and D. Debinski. (2004). Assessing alternative futures for agriculture in Iowa, USA. *Landscape Ecol.* 19(4): 357-374.

Schilling, K., & Libra, R. (2003). Increased baseflow in iowa over the second half of the 20th century. *JAWRA*, *39*(4), 851-860.

Schottler, S. P., Ulrich, J., Belmont, P., Moore, R., Lauer, J., Engstrom, D. R., & Almendinger, J. E. (2014). Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes*, *28*(4), 1951-1961.

Schultz, R. C., Collettil, J. P., Isenhart, T. M., Simpkins, W. W., Mize, C. W., & Thompson, M. L. (1995). Design and placement of a multi-species riparian buffer strip system. *Agroforestry Systems*, *29*(3), 201-226.

Segelquist, C. A., Scott, M. L., & Auble, G. T. (1993). Establishment of Populus deltoides under simulated alluvial groundwater declines. *American Midland Naturalist*, 274-285.

Shafroth, P. B., Auble, G. T., Stromberg, J. C., & Patten, D. T. (1998). Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona. *Wetlands*, *18*(4), 577-590.

Shafroth, P. B., Wilcox, A. C., Lytle, D. A., Hickey, J. T., Andersen, D. C., Beauchamp, V. B., & Warner, A. (2010). Ecosystem effects of environmental flows: modelling and experimental floods in a dryland river. *Freshwater Biology*, *55*(1), 68-85.

Sigafoos, R.S. (1964). Botanical evidence of floods and flood-plain deposition, *US Geological Survrey Professional Paper* 485-A.

Smith, Welby. (2008). *Trees and shrubs of minnesota.* St. Paul, MN: University of Minnesota Press.

Steiger, J., Gurnell, A. M., & Goodson, J. M. (2003). Quantifying and characterizing contemporary riparian sedimentation. *River Research and Applications*, *19*(4), 335-352

Stevens, L.E. and Waring, G.L. (1985). The effects of prolonged flooding on the riparian plant community in Grand Canyon', in Johnson, R.R., Ziebell, C.D., Patton, D.R., Ffolliott, P.F., and Hamre, R.H. (Eds), *Riparian Ecosystems and Their Management*: *Reconciling Conflicting Uses*. First North American Riparian Conference, U.S. Department of Agriculture, Forest Service General Technical Report RM-120, Fort Collins, CO. pp. 81–86.

Tekiela, Stan. (2001). *Trees of Minnesota*. Cambridge, MN: Adventure Publications, Inc.

Underhill, B. 2012. The influence of vegetation and root density on erosion for Three Streams in Minnesota. Master's of Science Thesis, University of Minnesota-Twin Cities, St. Paul, Minnesota, USA.

United States Army Corps of Engineers (USACE). 2009. Interim Regional Supplement to the Corps of Engineers Wetland Delineation Manual: Northcentral and Northeast Region, ed. J. S. Wakeley, R. W. Lichvar, and C. V. Noble. ERDC/EL TR-09-19. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

United States Department of Agriculture - NRCS Plant Materials Program. 2002. Plant Fact Sheet for Eastern Cottonwood (*Populus deltoides* L.). USDA-Natural Resources Conservation Service, Manhattan Plant Materials Center, Manhattan, KS 66502.

United States Geologic Survey (USGS). (2014). *USGS Minnesota Water Science Center*. Retrieved July 1, 2014, from http://mn.water.usgs.gov/.

Waters, T.F., 1995. *Sediment in Streams: Sources, Biological Effects, and Control*. American Fisheries Society: Bethesda, Maryland.
Whitlow, T.H. and Harris, R.W. 1979. 'Flood tolerance in plants: a state-of-the-art review', *Technical Report E*-79 -2, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Wilcock, P. R., on behalf of the Minnesota River Sediment Colloquium Committee. 2009. Identifying sediment sources in the Minnesota River basin. MPCA Report wq-b3-43. St. Paul, Minn.: Minnesota Pollution Control Agency.

Wolman, M.G., and Leopold, L.B., 1957, River flood plains—some observations on their formation: U.S. Geological Survey Professional Paper 282-C, p. 87–109.
%

Yanosky, T.M. (1982). Effects of flooding upon woody vegetation along parts of the Potomac river flood plain. *US Geological Sur*6*ey Professional Paper* 1206.

Zandlo, J. (2008). Climate change and the Minnesota State Climatology office: Observing the climate. St. Paul, Minn.: University of Minnesota, Minnesota Climatology Working Group. Available at: http://climate.umn.edu/climatechange/climatechangeobservednu.htm.

Zedler, J. B. (2003). Wetlands at your service: reducing impacts of agriculture at the watershed scale. *Frontiers in Ecology and the Environment*, *1*(2), 65-72.

Zhang, Y., Schilling, K. (2006). Increasing streamflow and baseflow in Mississippi River since the 1940s: Effect of land use change. *J. Hydrol.* 324(1-4): 412-422.

Appendix: Vegetation Transect Data and Species List

Table 1

Lower Minnesota River Basin Transect Survey Seedling and Sapling Densities

Site	Transect Length (m)	Distance (m)	Species	Seedlings	Sapling	Tree DBH (cm)
1	90	82-83	Silver Maple	2		
		83-84	Silver Maple		1	23, 44
			Green Ash		1	
		84-85	Silver Maple			41
		85-86	Silver Maple		1	
		87-88	Silver Maple			38, 86
2	94	76-78	Sandbar Willow		13	
		78-80	Sandbar Willow		16	
		80-82	Sandbar Willow		19	
		82-84	Sandbar Willow		17	
		84-86	Sandbar Willow		11	
			Silver Maple	1		
			Cottonwood		2	
			Sandbar Willow		1	
		86-88	Cottonwood		2	
			Cottonwood	2		
			Sandbar Willow		6	
		88-90	Sandbar Willow		8	
			Sandbar Willow		1	
		90-92	Sandbar Willow		1	
			Sandbar Willow		4	
		92-94	Sandbar Willow		5	
			Silver Maple		2	11, 12
3	80	61-62	Cottonwood	2		
		62-63	Cottonwood	5		
		63-64	Cottonwood	5		
		64-65	Cottonwood	3		
			Sandbar Willow		2	
		65-66	Sandbar Willow		8	
		66-67	Sandbar Willow		10	
		67-68	Sandbar Willow		14	
		68-69	Silver Maple	1		

			Sandbar Willow		8	
		69-70	Sandbar Willow		9	
			Box Elder	1		
		70-71	Sandbar Willow		3	
		71-72	Sandbar Willow		6	
		72-73	Sandbar Willow		1	
		73-74	Sandbar Willow		1	11
		75-76	Sandbar Willow		1	
		76-77	Sandbar Willow		1	11
		77-78	Sandbar Willow		1	
		78-79	Sandbar Willow		1	
		79-80	Sandbar Willow		1	
4	42	29-30	Silver Maple	2		
		30-31	Silver Maple			73
		31-32	Silver Maple			15, 36
		33-34	Silver Maple			38
		34-35	Silver Maple	2		
		35-36	American Elm			15, 20
		36-37	Green Ash		1	
		38-39	American Elm		1	
		39-40	American Elm		1	
		41-42	American Elm		1	
5	42	24-25	Sandbar Willow	6		
		25-26	Sandbar Willow	3		
		26-27	Sandbar Willow	1		
		27-28	Sandbar Willow		1	
		28-29	Sandbar Willow		8	
		29-30	Sandbar Willow		5	
		30-31	Sandbar Willow		4	
			Cottonwood	2	3	
		31-32	Silver Maple	3		
		32-33	Sandbar Willow		2	
			Silver Maple	1	1	
		33-34	Cottonwood		1	
		34-35	Silver Maple	4		
		35-36	Silver Maple	3		
		37-38	Silver Maple	3		
		38-39	Sandbar Willow		1	
			Silver Maple	3		

		39-40	Sandbar Willow	1		
		40-41	Sandbar Willow	1	1	
			Silver Maple	2		14, 30
		41-42	Sandbar Willow	2		
			Silver Maple	1		72
6	22	8-9	Green Ash		1	
		11-12	Silver Maple			267
			American Elm		3	
		12-13	Green Ash		1	
		14-15	Green Ash			36
		15-16	American Elm	3	1	
		16-17	American Elm	3		
		17-18	American Elm	3		
		18-19	American Elm			39
		19-20	American Elm	1		27
		20-22	Box Elder			42
7	30	6-7	Black Willow	3	1	
			Sandbar Willow	1	1	
		7-8	Black Willow	3	2	
			Sandbar Willow		1	
		8-9	Black Willow	1	3	
			Sandbar Willow	1	3	
		9-10	Black Willow	1	3	
			Sandbar Willow		4	
		10-11	Sandbar Willow	2	4	
		11-12	Sandbar Willow	2	5	
		12-13	Sandbar Willow	1	3	
			Silver Maple	1		
		13-14	Sandbar Willow	1	3	
			Silver Maple	1		
		14-15	Sandbar Willow		3	
		15-16	Sandbar Willow		3	
		16-17	Sandbar Willow		3	
		17-18	Sandbar Willow		3	
		18-19	Sandbar Willow	1	2	
		19-20	Sandbar Willow		3	
		21-22	Sandbar Willow	3	3	
		28-29	Cottonwood			110
		29-30	Silver Maple			84

Table 2

Lower Minnesota River Basin Transect Survey Percent Species Coverage

Site	Transect Length (m)	Quadrat	Species	Cover (%)
1	90	1	Bare	100
		2	Bare	100
		3	Bare	100
		4	Bare	100
		5	Bare	98
			Unknown	2
		6	Bare	100
		7	Bare	98
			Smartweed	2
		8	Bare	100
		9	Bare	100
		10	Bare	100
		11	Bare	100
		12	Bare	100
		13	Bare	100
		14	Bare	100
		15	Bare	100
		16	Bare	100
		17	Bare	100
		18	Bare	99
			Smartweed	1
		19	Bare	98
			Smartweed	2
		20	Bare	100
		21	Bare	98
			Smartweed	2
		22	Bare	100
		23	Bare	100
		24	Bare	99
			Smartweed	1
		25	Bare	99
			Smartweed	1
		26	Bare	99
			Smartweed	2

		27	Bare	100
		28	Bare	95
			Smartweed	3
			Awned Umbrella Sedge	1
			Cocklebur	1
		29	Bare	97
			Smartweed	3
		30	Bare	100
		31	Bare	100
		32	Bare	100
		33	Bare	100
		34	Bare	100
		35	Bare	100
		36	Bare	100
		37	Bare	100
		38	Bare	100
		39	Bare	100
		40	Bare	100
		41	Bare	100
		42	Bare	75
			Litter	20
			Silver Maple Seedling	4
			Reed Canary Grass	1
		43	Bare	80
			Reed Canary Grass	17
			Aster	3
		44	Bare	95
			Reed Canary Grass	2
			Silver Maple Sapling	3
		45	Bare	75
			Silver Maple Tree	10
			Litter	5
			Reed Canary Grass	2.5
			Awned Umbrella Sedge	2.5
		46	Bare	65
			Litter	20
			Reed Canary Grass	15
2	94	1	Bare	100
		2	Bare	100

3	Bare	100
4	Bare	100
5	Bare	100
6	Bare	100
7	Bare	100
8	Bare	100
9	Bare	100
10	Bare	100
11	Bare	100
12	Bare	100
13	Bare	100
14	Bare	100
15	Bare	100
16	Bare	95
	Smartweed	5
17	Bare	95
	Smartweed	5
18	Bare	95
	Smartweed	5
19	Bare	100
20	Bare	100
21	Bare	100
22	Bare	100
23	Bare	100
24	Bare	100
25	Bare	100
26	Bare	100
27	Bare	100
28	Bare	100
29	Bare	100
30	Bare	100
31	Bare	100
32	Bare	100
33	Bare	100
34	Bare	100
35	Bare	100
36	Bare	98
	Smartweed	2
37	Bare	100

		38	Bare	100
		39	Bare	90
			Sandbar Willow Sapling	10
		40	Bare	90
			Sandbar Willow Sapling	10
		41	Bare	90
			Sandbar Willow Sapling	10
		42	Beggarticks	10
			Sandbar Willow Sapling	10
			Smartweed	10
			Cottonwood Sapling	5
		43	Bare	75
			Sandbar Willow	15
			Silver Maple Seedling	5
			Smartweed	5
		44	Bare	45
			Reed Canary Grass	40
			Sandbar Willow Sapling	10
			Cottonwood Sapling	5
		45	Reed Canary Grass	60
			Bare	20
			Sandbar Willow Sapling	20
		46	Bare	40
			Beggarticks	20
			Sandbar Willow Sapling	20
			Woodnettle	20
		47	Bare	35
			Beggarticks	35
			Sandbar Willow Sapling	10
			Woodnettle	20
3	80	1	Bare	98
			Smartweed	1
			Cocklebur	1
		2	Bare	100
		3	Bare	100
		4	Bare	98
			Cocklebur	2
		5	Bare	98
			Litter	2

6	Bare	98
	Litter	2
7	Bare	100
8	Bare	100
9	Bare	100
10	Bare	100
11	Bare	100
12	Bare	100
13	Bare	100
14	Bare	100
15	Bare	95
	Cocklebur	2.5
	Smartweed	2.5
16	Bare	100
17	Smartweed	97
	Bare	3
18	Bare	95
	Cocklebur	2.5
	Smartweed	2.5
19	Bare	100
20	Bare	100
21	Bare	98
	Awned Umbrella Sedge	2
22	Bare	100
23	Bare	95
	Creeping Lovegrass	2.5
	Smartweed	2.5
24	Bare	95
	Smartweed	3
	Fowl Manna Grass	
25	Bare	90
	Creeping Lovegrass	5
	Smartweed	5
26	Bare	90
	Creeping Lovegrass	7
	Smartweed	3
27	Bare	80
	Creeping Lovegrass	10
	Smartweed	10

28	Bare	80
	Creeping Lovegrass	10
	Smartweed	10
29	Bare	100
30	Bare	85
	Smartweed	15
31	Bare	75
	Creeping Lovegrass	30
	Cottonwood Seedling	2.5
	Smartweed	2.5
32	Bare	78
	Creeping Lovegrass	15
	Sandbar Willow Sapling	5
	Cottonwood Seedling	2
33	Litter	80
	Bare	10
	Sandbar Willow Sapling	10
34	Bare	90
	Sandbar Willow Sapling	10
35	Bare	40
	Litter	40
	Sandbar Willow Sapling	15
	Reed Canary Grass	2.5
	Smartweed	2.5
36	Bare	40
	Litter	40
	Aster	10
	Sandbar Willow Sapling	10
37	Goldenrod	40
	Bare	15
	Aster	10
	Sunflower	10
	Sandbar Willow Sapling	5
38	Reed Canary Grass	40
	Aster	20
	Bare	15
	Sunflower	15
	Sandbar Willow Sapling	10
39	Bare	45

			Goldenrod	30
			Aster	10
			Sunflower	10
			Reed Canary Grass	10
			Sandbar Willow Sapling	5
		40	Bare	45
			Goldenrod	25
			Sunflower	10
			River Bank Grape	10
			Aster	5
			Sandbar Willow Sapling	5
4	42	1	Bare	50
			Litter	50
		2	Bare	95
			Creeping Lovegrass	5
		3	Bare	75
			Creeping Lovegrass	15
			Smartweed	10
		4	Bare	70
			Creeping Lovegrass	15
			Smartweed	12.5
			Litter	2.5
		5	Creeping Lovegrass	60
			Smartweed	25
			Bare	25
			Awned Umbrella Sedge	5
			Litter	2.5
			Unknown	2.5
			Beggarticks	2.5
		6	Bare	75
			Creeping Lovegrass	20
			Smartweed	5
		7	Bare	65
			Creeping Lovegrass	20
			Smartweed	10
			Awned Umbrella Sedge	5
		8	Bare	60
			Cocklebur	15
			Smartweed	10

			Beggarticks	5
			Litter	5
			Woodnettle	5
		9	Bare	60
			Cocklebur	10
			Litter	10
			Smartweed	10
			Beggarticks	5
			Awned Umbrella Sedge	5
		10	Silver Maple Sapling	55
			Bare	43
			Litter	2
		11	Bare	60
			Litter	25
			Reed Canary Grass	20
			Smartweed	5
		12	Bare	60
			Litter	17.5
			Green Ash Sapling	10
			Reed Canary Grass	5
			Smartweed	5
			Silver Maple Seedling	2.5
		13	Bare	45
			Litter	20
			Litter	10
			American Elm Sapling	10
			Reed Canary Grass	10
			Woodnettle	5
		14	Bare	45
			Litter	40
			Woodnettle	15
5	42	1	Bare	100
		2	Bare	100
		3	Bare	100
		4	Bare	100
		5	Bare	100
		6	Bare	100
		7	Bare	100
		8	Bare	95

	Smartweed	2.5
	Cocklebur	2.5
9	Bare	95
	Cocklebur	3
	Smartweed	2
	Fowl Manna Grass	1
10	Bare	90
	Smartweed	8
	Fowl Manna Grass	2
11	Smartweed	60
	Bare	25
	Fowl Manna Grass	14
12	Bare	90
	Cottonwood Seedling	5
	Sandbar Willow Seedling	5
	Smartweed	5
13	Bare	40
	Fowl Manna Grass	30
	Smartweed	15
	Sandbar Willow Sapling	10
	Cocklebur	5
14	Bare	35
	Cocklebur	35
	Reed Canary Grass	15
	Sandbar Willow Sapling	15
15	Bare	20
	Cottonwood Sapling	20
	Fowl Manna Grass	20
	Awned Umbrella Sedge	20
	Smartweed	20
	Sandbar Willow Sapling	15
16	Reed Canary Grass	70
	Smartweed	15
	Bare	5
	Fowl Manna Grass	5
	Silver Maple Seedling	5
17	Bare	80
	Smartweed	20
18	Smartweed	45

			Bare	40
			Reed Canary Grass	10
			Silver Maple Seedling	5
		19	Bare	45
			Reed Canary Grass	40
			Smartweed	10
			Silver Maple Seedling	5
		20	Bare	45
			Reed Canary Grass	40
			Smartweed	10
			Silver Maple Seedling	5
		21	Bare	45
			Reed Canary Grass	40
			Smartweed	10
			Silver Maple Seedling	5
		22	Bare	65
			Woodnettle	20
			Sandbar Willow Seedling	10
			Silver Maple Seedling	5
6	22	1	Litter	70
			Bare	10
			Creeping Lovegrass	10
			Fowl Manna Grass	5
			Smartweed	5
		2	Bare	60
			Litter	15
			Awned Umbrella Sedge	15
			Creeping Lovegrass	5
			Smartweed	5
		3	Bare	70
			Litter	30
		4	Bare	50
			Litter	45
			River Bank Grape	5
		5	Bare	50
			River Bank Grape	40
			Green Briar	5
			Litter	5
		6	Bare	75

			Litter	10
			American Elm Seedling	5
			Green Ash Sapling	5
			Fowl Manna Grass	5
		7	Bare	70
			Litter	10
			Aster	5
			Fowl Manna Grass	5
			River Bank Grape	5
			Tall Cone Flower	5
		8	Bare	60
			Litter	20
			American Elm Sapling	5
			American Elm Seedling	5
			Tall Cone Flower	5
			Woodnettle	5
		9	Bare	45
			Tall Cone Flower	20
			Woodnettle	15
			Litter	10
			American Elm Seedling	5
			Violet	5
		10	Bare	40
			Green Briar	25
			Woodnettle	15
			Litter	10
			American Elm Seedling	5
			River Bank Grape	5
		11	Bare	60
			Woodnettle	20
			Litter	10
			Tall Cone Flower	10
7	30	1	Creeping Lovegrass	40
			Bare	30
			Fowl Manna Grass	10
			Awned Umbrella Sedge	10
			Smartweed	10
		2	Creeping Lovegrass	60
			Sandbar Willow Seedling	20

	Bare	10
	Beggarticks	5
	Smartweed	5
3	Bare	65
	Sandbar Willow Seedling	10
	Black Willow Sapling	5
	Sandbar Willow Sapling	5
	Smartweed	5
4	Bare	50
	Sandbar Willow Seedling	15
	Smartweed	15
	Litter	10
	Sandbar Willow Sapling	10
5	Sandbar Willow Sapling	70
	Bare	15
	Smartweed	15
	Litter	5
	River Bank Grape	5
6	Litter	35
	Sandbar Willow Sapling	30
	Reed Canary Grass	20
	Bare	15
7	Reed Canary Grass	75
	Sandbar Willow Sapling	10
	Bare	5
	Litter	5
	River Bank Grape	5
8	Litter	65
	Bare	20
	River Bank Grape	10
	Reed Canary Grass	5
9	Bare	85
	Litter	15
10	Litter	55
	Bare	40
	Woodnettle	5

Table 3

Elm Creek Watershed Transect Survey Seedling and Sapling Densities

Site	Transect Length (m)	Distance (m)	Species	Seedlings	Sapling	Tree DBH (cm)
1	8	1-2	Sandbar Willow	4	16	
		2-3	Sandbar Willow		3	
		3-4	Sandbar Willow	2	5	
		4-5	Sandbar Willow	3	12	
		5-6	Sandbar Willow	1	5	
		6-7	Sandbar Willow		3	
		7-8	Sandbar Willow	2	5	
			Green Ash	2		
2	10	5-6	Box Elder	1		
		8-9	Box Elder	1		
3	10	0-1	Silver Maple			11
		1-2	Silver Maple			11
		2-3	Green Ash		2	
		3-4	Silver Maple			11
		4-5	Box Elder	2		
		5-6	Box Elder		1	
		7-8	Box Elder	1	1	
4	14	5-6	Black Willow	1	2	42
		6-7	Black Willow	3	6	64, 89
5	13	0-1	Sandbar Willow	2	13	
		1-2	Sandbar Willow		6	
			Silver Maple	2		
		2-3	Sandbar Willow	5		
			Green Ash	3		
		3-4	Sandbar Willow	13		
			Green Ash	4		
			Silver Maple		1	
		4-5	Sandbar Willow		6	
		5-6	Sandbar Willow		7	
			Green Ash	3		
		6-7	Green Ash	1	2	
			Sandbar Willow		7	
		7-8	Sandbar Willow		5	
		8-9	Sandbar Willow		5	

		9-10	Sandbar Willow		1	
			Silver Maple		2	
		10-11	Sandbar Willow		2	12
			Silver Maple		3	
			Green Ash	3		
		11-12	Green Ash	1		
			Sandbar Willow		3	
		12-13	Sandbar Willow		2	
			Green Ash	2		
6	22	5-6	Cottonwood	1		
			Sandbar Willow	1	1	
		6-7	Sandbar Willow	2		
		8-9	Sandbar Willow	1	1	
		9-10	Sandbar Willow	2	7	
		10-11	Sandbar Willow		3	
		11-12	Sandbar Willow		6	
		12-13	Sandbar Willow	1	1	
7	10	7-8	Box Elder			14
		8-9	Box Elder		1	
		9-10	Box Elder			17, 26
8	10	4-5	Sandbar Willow	1	5	
		5-6	Sandbar Willow		8	
		9-10	American Elm		4	

Table 4

Elm Creek Watershed Transect Survey Percent Species Coverage

Site	Transect Length (m)	Quadrat	Species	Cover (%)
1	8	1	Reed Canary Grass	40
			Sandbar Willow Sapling	20
			Bare	10
			Woodnettle	10
		2	Reed Canary Grass	85
			Sandbar Willow Sapling	20
			Bare	5
		3	Sandbar Willow Sapling	90
			Reed Canary Grass	5
			Bare	5
		4	Sandbar Willow Sapling	85
			Reed Canary Grass	10
			Bare	5
		5	Bare	50
			Litter	30
			Reed Canary Grass	15
			Sandbar Willow Sapling	5
		6	Reed Canary Grass	40
			Sandbar Willow Sapling	35
			Bare	10
			Litter	10
		7	Reed Canary Grass	85
			Bare	5
			Litter	5
		8	Reed Canary Grass	70
			Sandbar Willow Sapling	15
			Bare	5
			Green Ash Seedling	5
			Litter	5
2	10	1	Bare	95
			Reed Canary Grass	2.5
			Smartweed	2.5
		2	Bare	95
			Beggarticks	3

			Awned Umbrella Sedge	1
			Smartweed	1
		3	Bare	90
			Cocklebur	10
		4	Bare	70
			Cocklebur	30
		5	Bare	60
			Cocklebur	40
		6	Reed Canary Grass	75
			Awned Umbrella Sedge	20
			Bindweed	5
		7	Reed Canary Grass	98
			Beggarticks	2
		8	Awned Umbrella Sedge	90
			Bare	7
			Bindweed	2
			Box Elder Seedling	1
		9	Awned Umbrella Sedge	60
			Reed Canary Grass	20
			Bare	15
			Beggarticks	5
		10	Awned Umbrella Sedge	70
			Reed Canary Grass	30
3	10	1	Bare	55
			Beggarticks	15
			Giant Ragweed	10
			Litter	10
			Cocklebur	5
			Fowl Manna Grass	2.5
			Woodbine	2.5
		2	Wood Neetle	45
			Ragweed	20
			bare	15
			Litter	10
			Green Ash Seedling	5
			Woodbine	5
		3	Goldenrod	55
			Buckthorn	15
			Sunflower	15

	Bare	10
	Litter	5
4	Bare	50
	Goldenrod	10
	Reed Canary Grass	10
	Sunflower	10
	Woodbine	10
	Buckthorn	5
	Litter	5
5	Bare	60
	Goldenrod	10
	Goldenrod	10
	Woodbine	10
	Reed Canary Grass	5
	Box Elder Seedling	2.5
	Woodnettle	2.5
6	Honeysuckle	70
	Bare	20
	Woodbine	10
7	Bare	50
	Reed Canary Grass	15
	Woodnettle	15
	Goldenrod	10
	Woodbine	7.5
	Box Elder Seedling	2.5
8	Raspberry	40
	Woodnettle	30
	Buckthorn	10
	Woodbine	10
	Bare	5
	Thistle	5
9	Woodnettle	30
	Buckthorn	25
	Bare	20
	Goldenrod	10
	River Bank Grape	10
	Woodbine	5
10	Bare	40
	Honeysuckle	30

			Buckthorn	10
			River Bank Grape	7.5
			Woodnettle	5
			Woodbine	5
			Bluejoint	2.5
4	7	1	Bare	45
			Awned Umbrella Sedge	25
			Smartweed	25
			Beggarticks	5
		2	Awned Umbrella Sedge	80
			Bare	5
			Beggarticks	5
			Fowl Manna Grass	5
			Smartweed	5
		3	Bare	95
			Black Willow Sapling	5
		4	Bare	45
			Reed Canary Grass	35
			Goldenrod	20
		5	Reed Canary Grass	55
			Bindweed	25
			Bare	10
			Litter	10
		6	Reed Canary Grass	95
			Bindweed	5
		7	Reed Canary Grass	80
			Bindweed	20
5	13	1	Bare	55
			Reed Canary Grass	30
			Sandbar Willow Sapling	10
			Goldenrod	5
		2	Reed Canary Grass	70
			Bare	15
			Sandbar Willow Sapling	10
			Silver Maple Seedling	5
		3	Bare	65
			Reed Canary Grass	20
			Green Ash Seedling	10
			Sandbar Willow Sapling	10

	Silver Maple Sapling	5
4	Reed Canary Grass	60
	Sandbar Willow Sapling	20
	Bare	10
	Green Ash Seedling	10
5	Reed Canary Grass	80
	Sandbar Willow Sapling	10
	Green Ash Seedling	5
	Bare	5
6	Reed Canary Grass	45
	Bare	30
	Sandbar Willow Sapling	20
	Green Ash Seedling	5
7	Bare	40
	Reed Canary Grass	30
	Goldenrod	10
	Sandbar Willow Sapling	10
	Green Ash Sapling	5
	Woodnettle	5
8	Reed Canary Grass	85
	Sandbar Willow Sapling	10
	Bare	4
	Green Ash Seedling	1
9	Reed Canary Grass	40
	Bare	25
	Bindweed	10
	Goldenrod	10
	Sandbar Willow Sapling	10
	Silver Maple Sapling	5
10	bare	15
	Sandbar Willow Sapling	15
	Woodnettle	10
	Goldenrod	5
	reed canary grass	5
	Silver Maple Sapling	5
11	Woodnettle	30
	Sandbar Willow Sapling	25
	Bare	20
	Reed Canary Grass	10

			Awned Umbrella Sedge	5
			Bindweed	5
			Goldenrod	5
		12	Sandbar Willow Sapling	60
			Bare	20
			Woodnettle	10
			Green Ash Seedling	7.5
			Beggarticks	2.5
		13	Sandbar Willow Sapling	40
			Bare	20
			Woodnettle	20
			Goldenrod	10
			Beggarticks	5
			Green Ash Seedling	5
6	11	1	Bare	90
			Awned Umbrella Sedge	2.5
			Spike Rush	2.5
			Creeping Lovegrass	2.5
			Smartweed	2.5
		2	bare	75
			Spike Rush	10
			Cocklebur	5
			Smartweed	5
			Awned Umbrella Sedge	2.5
			Creeping Lovegrass	2.5
		3	Bare	85
			Awned Umbrella Sedge	5
			Sandbar Willow Sapling	5
			Smartweed	5
		4	Awned Umbrella Sedge	75
			Smartweed	10
			Bare	5
			Creeping Lovegrass	5
			Sandbar Willow Seedling	5
		5	Bare	45
			Reed Canary Grass	30
			Sandbar Willow Sapling	15
			Aster	5
			Beggarticks	5

			Foxtail	5
			Smartweed	5
		6	Bare	60
			Sandbar Willow Sapling	15
			Cocklebur	10
			Sandbar Willow Seedling	10
			Beggarticks	5
		7	Bare	55
			Goldenrod	20
			Cocklebur	10
			Reed Canary Grass	10
			Aster	5
		8	Bare	45
			Goldenrod	30
			Aster	10
			Foxtail	10
			Violet	5
		9	Bare	50
			Goldenrod	50
		10	Bare	50
			Goldenrod	50
		11	Bare	50
			Goldenrod	50
7	10	1	Litter	50
			Bare	40
			Creeping Lovegrass	5
			Awned Umbrella Sedge	2.5
			Cocklebur	2.5
		2	Creeping Lovegrass	2
			Litter	55
			Cocklebur	3
			Bare	40
		3	Bare	50
			Litter	15
			Aster	5
			Cocklebur	5
			Reed Canary Grass	5
		4	Reed Canary Grass	45
			Bare	30

			Litter	20
			Beggarticks	5
		5	Bare	85
			Litter	10
			Reed Canary Grass	5
		6	Bare	95
			Litter	5
		7	Bare	95
			Litter	5
		8	Litter	60
			Bare	40
		9	Bare	80
			Litter	20
		10	Litter	60
			Bare	40
8	10	1	Bare	55
			Creeping Lovegrass	40
			Awned Umbrella Sedge	2.5
			Smartweed	2.5
		2	Bare	85
			Creeping Lovegrass	10
			Smartweed	5
		3	Bare	60
			Creeping Lovegrass	30
			Awned Umbrella Sedge	5
			Smartweed	5
		4	Reed Canary Grass	65
			Bare	10
			Sandbar Willow Sapling	10
			Cocklebur	5
			Sandbar Willow Seedling	5
			Smartweed	5
		5	Bare	60
			Reed Canary Grass	25
			Sandbar Willow Sapling	10
			Smartweed	5
		6	Reed Canary Grass	75
			Sandbar Willow Sapling	20
			Bare	5

7	Reed Canary Grass	100
8	Reed Canary Grass	100
9	Reed Canary Grass	100
10	Reed Canary Grass	95
	Tall Cone Flower	5

Table 5

Minnesota River Basin Transect Survey Species List

Common Name	Scientific Name
American Elm	*Ulmus americana*
Aster	*Aster sp.*
Awned Umbrella Sedge	*Cyperus squarrosus*
Beggarticks	*Bidens sp.*
Bindweed	*Calystegia sepium*
Black Willow	*Salix nigra*
Bluejoint	*Calamagrostis canadensis*
Box Elder	*Acer negundo*
Buckthorn	*Rhamnus cathartica*
Cocklebur	*Xanthium strumarium*
Cottonwood	*Populus deltoides*
Creeping Lovegrass	*Eragrostis hypnoides*
Fowl Manna Grass	*Glyceria striata*
Foxtail	*Setaria sp.*
Giant Ragweed	*Ambrosia trifida*
Goldenrod	*Solidago sp.*
Green Ash	*Fraxinus pennsylvanica*
Honeysuckle	*Lonicera sp.*
Ragweed	*Ambrosia artemisiifolia*
Raspberry	*Rubus sp.*
Reed Canary Grass	*Phalaris arundinacea*
River Bank Grape	*Vitis riparia*
Sandbar Willow	*Salix interior*
Silver Maple	*Acer saccharinum*
Smartweed	*Persicaria sp.*
Spike Rush	*Eleocharis sp.*
Sunflower	*Helianthus sp.*
Tall Cone Flower	*Rudbeckia laciniata*
Thistle	*Cirsium sp.*
Violet	*Violia sp.*
Woodbine	*Parthenocissus quinquefolia*
Woodnettle	*Laportea canadensis*

Appendix 6:
The End Member Mixing Analysis (EMMA) is a procedure used to separate out the water sources making up a flow at a particular location and time. The methodology is based on the following assumptions:

1. The tracer (chemical or thermal) level in a given source water does not change with time.
2. The tracer (chemical or thermal) is conservative, that is, it does not decay with time.
3. When multiple tracers are used the tracers need to have characteristic source concentrations that are completely independent of each other.

The number of distinct tracers required to identify the source waters depends on how many source waters need to be distinguished. EMMA equations used depend on how many sources of water need to be identified. The general principle is that if there are N source waters to be distinguished, then the number of tracers required is N-1. So, for example, if there are two source waters to be distinguished, then one needs to have one tracer. Three source waters will require two tracers, etc.

The EMMA equations consist of one mass balance equation for the water and one mass balance equation for each of the tracers. These equations are listed below for the case of two source waters, surface runoff and groundwater. For this case there is one tracer required as a minimum.

$$Q_s = Q_{sr} + Q_{gw} \qquad (6.1)$$

$$Q_s C_s = Q_{sr} C_{sr} + Q_{gw} C_{gw} \qquad (6.2)$$

where Q_s is the flow in the stream, Q_{sr} is the flow from the surface runoff, Q_{gw} is the flow from the groundwater, C_s is the concentration of the tracer in the streamflow, C_{sr} is the tracer concentration in the surface runoff, and C_{gw} is the tracer concentration in the groundwater flow.

For input to this system of equations one generally has the streamflow, the tracer concentration in the streamflow, and the characteristic tracer concentrations in each of the source waters. Given that information equations (1) and (2) are sufficient to be solved for the discharge contributions from the surface runoff and the groundwater.

If additional sources of flow are to be identified then those flows are added algebraically to equation (1), and additional mass balance equations for the additional required tracers are added to the system of equations. For example, if there are three source waters to be identified (e.g., surface runoff, groundwater, and tile flow), the system of equations is given by the following,

$$Q_s = Q_{sr} + Q_{gw} + \mathrm{Q}_{\mathrm{tf}} \qquad (6.1')$$

$$Q_s C_{s_a} = Q_{sr} C_{sr_a} + Q_{gw} C_{gw_a} + Q_{tf} C_{tf_a} \qquad (6.2')$$

$$Q_s C_{s_b} = Q_{sr} C_{sr_b} + Q_{gw} C_{gw_b} + Q_{tf} C_{tf_b} \qquad (6.3)$$

where Q_{tf} is the flow from the tiles, and the subscripts on the concentrations refer to the tracers (a) and (b).

APPLICATIONS

The model was applied to the Elm Creek stream flow data collected in 2014 during a period of non-storm flow as presented in the results and Appendix 7 - a poster presentation at the annual AGU meeting in San Francisco, CA in December, 2014.

Hydrologic processes related to stream bank erosion in three Minnesota agricultural watersheds

H23G-0953

Project partners

Christian Lenhart[1], John Nieber[1], Kerry Holmberg[1], Jason Ulrich[2] and Heidi Peterson[3]

Background

There has been widespread increases in stream flow across the agricultural regions of Minnesota and the Midwestern U.S contributing to increased rates of stream bank erosion. Increased subsurface drainage flow, land-use change and increased precipitation are thought to contribute. Yet many questions concerning hydrologic and geomorphic processes occurring at the stream bank zone remain unanswered. This study focuses on understanding the hydrologic drivers and processes involved in the increased rates of bank erosion observed in recent decades in many Midwestern streams (Schottler et al. 2014). Funding from the Minnesota Department of Agriculture (MDA) supported the study from 2011-2015.

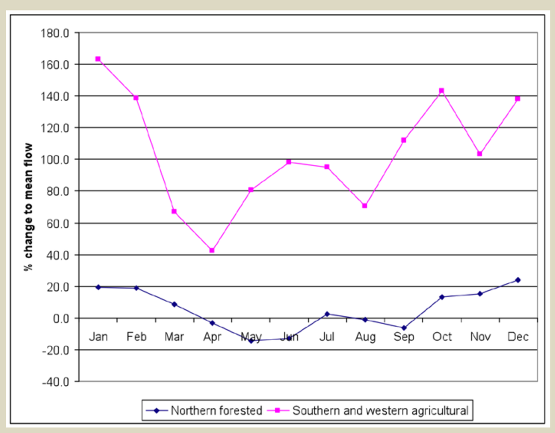


Figure 1. Stream flow increase in Upper Midwestern Rivers. Stream flow increases have occurred across many of the agricultural watersheds (pink) while forested watersheds in the northern Midwest (blue) have not experienced such increases (Lenhart et al. 2011)

Methods: hydrology

- Three watersheds with primarily agricultural land-use were studied (Figure 2)
- **Geochemical assessment of sources:** Oxygen and Hydrogen Isotopes H^2 or Deuterium (D) and δO^{18} (‰) & specific conductivity (SC) collected from groundwater, subsurface drain tile flow, surface runoff and rainfall. Data was used to determine "signatures" of different water sources to streams by plotting isotopic data relative to the Global Meteoric Water Line (GMWL). This information was used in combination with stream gage data to separate out sources of water in stream flow.
- **Riparian zone hydrology:** Wells installed in riparian zone of Elm Creek and Buffalo River, water level-loggers and conductivity probes recorded data on 15-minute intervals. Data allowed for identification of groundwater input zones and seepage gradients through the bank (Figure 3).

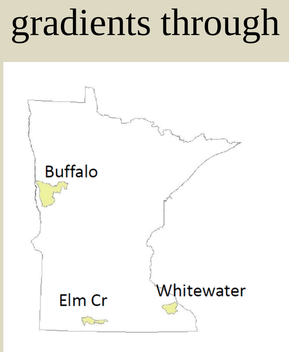


Figure 2. Study watersheds in in three different agricultural regions of Minnesota (Buffalo in the Red River basin, Elm Cr. in the Des Moines Lobe Till Plain and the Whitewater in the un-glaciated Driftless area)

Figure 3. Stream hydrologic and geomorphic monitoring using monitoring wells, remote cameras and channel re-survey.

- **Hydrograph separation** using geochemistry data concurrent with stream flow data from Elm Creek, stream flow was separated into base flow, subsurface tile flow and surface runoff. Using the standard *End Member Mixing Analysis* procedure to separate out two end members using SC as a conservative tracer. The application assumed the end members to have constant values of the SC set equal to the average of the SC of each end member measured during the period of study
- **Watershed hydrology modeling with SWAT:** The SWAT model was developed for the Elm Creek basin at a point containing 86% of the watershed area to obtain estimates of ground water, surface runoff and sub-surface tile drainage flow contributions to stream flow in Elm Creek for the period of 2004-2010.

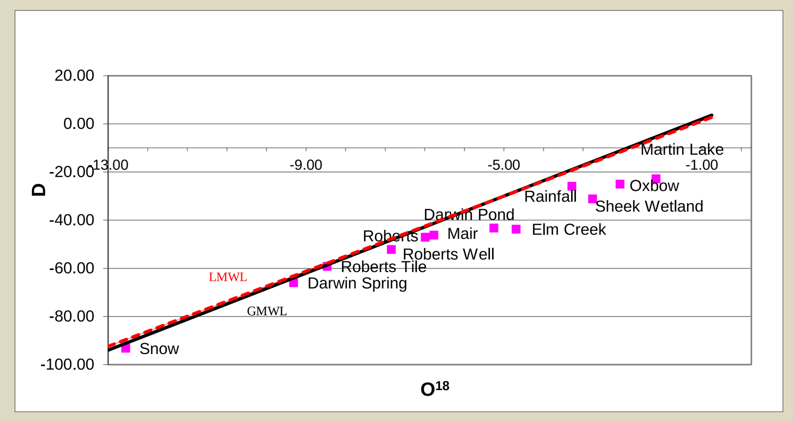
Methods: Stream erosion

- **Temporal distribution of bank erosion events** was obtained by monitoring bank erosion events at different stream bank sites within each of the study watersheds with collaboration of the Minnesota DNR staff between the years 2010-2014.
- **Processes of stream bank collapse:** resurvey of bank monitoring sites and field observations allowed for the characterization of bank collapse processes and the role of fluvial erosion vs. mass-wasting
- **The spatial distribution of lateral migration rates across river corridor:** using a lateral migration tool in GIS developed by Mark Ellefson of the MN DNR for the period of 1991 - 2011.

Results: water sources in stream flow

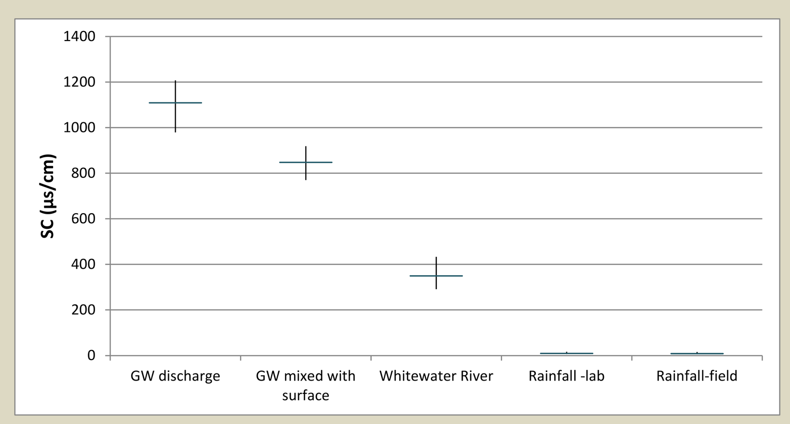
- O and H Isotopic data results show that stream flow in Elm Creek is distinct from surface water bodies (lakes, wetlands) which plot to the right of the global water line due to evaporation (Fig. 4).

Figure 4. Average δO^{18} vs D isotopes in Elm Creek over the 2012-2013 period. Lakes and wetlands exposed to evaporation plot to the right of the GMWL. Snow and groundwater are along the line to lower left.



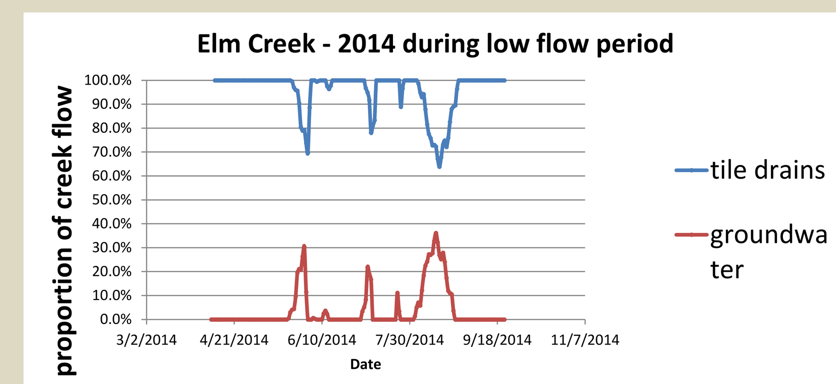
- SC data shows that water sources separate out distinctly particularly groundwater which has high SC values >800 µs/cm while rainfall is low (<50 µs/cm) (Fig. 5)

Figure 5. Specific Conductivity data from the Whitewater River watershed showing distinct SC signature of GW, rainfall and stream flow; similar ranges were found in the other two watersheds.



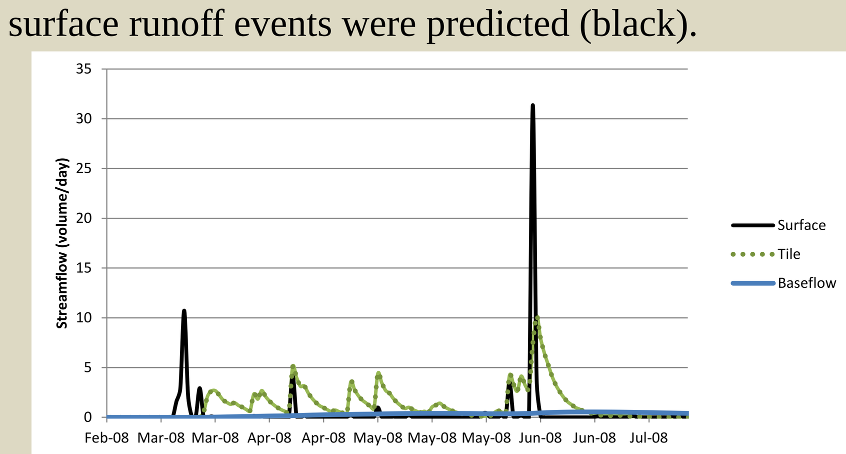
- The SC data used along with stream gauge data showed that surface runoff events occur infrequently and subsurface tile drain flow is the largest source of flow in Elm Cr. by volume. Baseflow comprised a small percentage of stream flow (Fig. 6).
- SC has an inverse relationship with stream flow. SC values approach 1000 µs/cm at baseflow and dip to < 400 µs/cm during storm events.

Figure 6. Hydrograph separation using SC data during a low-flow period to distinguish tile drain from vs. groundwater discharge to Elm Cr. Tile flow comprised 70-100% of stream flow.



- By total annual stream flow volume subsurface tile flow comprised 58% (green), surface flow 19% and base flow 20% (blue) in the simulation over the 2004-2010 period (Fig. 7)

Figure 7. Hydrograph components for Elm Creek based on SWAT simulations for the year 2008. Infrequent surface runoff events were predicted (black).



Results: hydrologic processes in the stream bank zone

- Monitoring well data showed that ground water seepage through the study banks had a gradual slope ($1 \times 10^{-2} - 1 \times 10^{-4}$ m/m) discharging low in the bank profile. It contributes to base flow but minimally to erosion. Seepage frequently wets the lower bank at two of the three monitoring sites and reduces plant rooting depth, thus contributing to bank erosion processes obliquely.
- In Elm Creek, groundwater inputs to the stream are patchy and limited; consequently streams in the Des Moines Lobe till plain are intermittent in stream flow; in contrast with the Whitewater River in the unglaciated region where baseflow is very high.
- At very high flows water flows, the gradient reversed from the stream into the banks at the Elm Cr. & Buffalo River. This occurred during summer and fall storm events when soil moisture was low.
- At most times seepage is occurring gradually low in the bank contributing to base flow but minimally to erosion. Spatial distribution of seepage: In Elm Creek and Buffalo Rivers, groundwater inputs are patchy and limited; most of the region is intermittent in stream flow (see flow duration)
- Bank monitoring in Elm Creek shows that most bank erosion occurs at high flows (>99%) or 1-year recurrence interval flood
- Lateral bank migration in GIS over the 1991-2011 time period showed high rates in the mid-lower Whitewater River while in Elm Creek bank erosion was fairly evenly distributed (Figure 8).

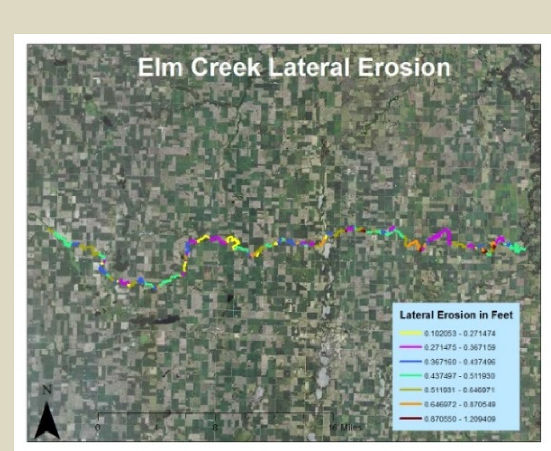
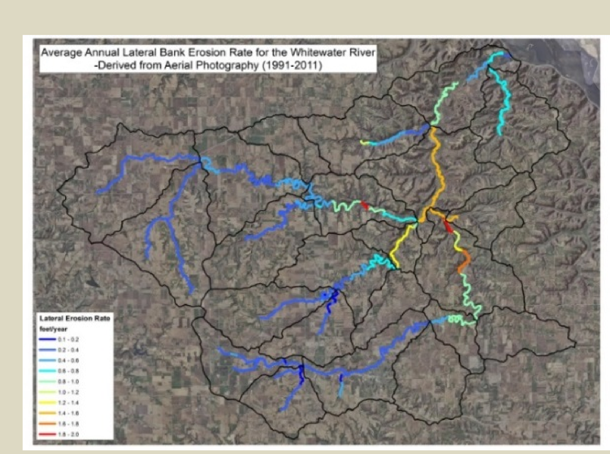


Figure 8a and b. Spatial distribution of lateral bank erosion between 1991-2011 in Elm Cr. (left) and Whitewater River (right). Higher rates are in red and orange. Elm Cr. averaged about (0.15 m/yr (0.5 ft/yr) while the Whitewater river had twice that with rate with some reaches averaging 0.6 m/yr (2 ft/yr)



Results: synthesis

- Most runoff occurs via the "saturation excess" process when soils are saturated particularly in spring in southern and western Minnesota. Many of the overbank flood events in recent years occurred in June in Elm Creek when subsurface drain flow and rainfall amounts are near the maximum (Fig. 9). Increasingly large fall flood events occur in the fall that are more climatically-driven.
- Most stream bank erosion is initiated by fluvial erosion processes
- Surface runoff events atop saturated soils drive most bank erosion events in the tile-drained Des Moines Lobe glacial till plains.

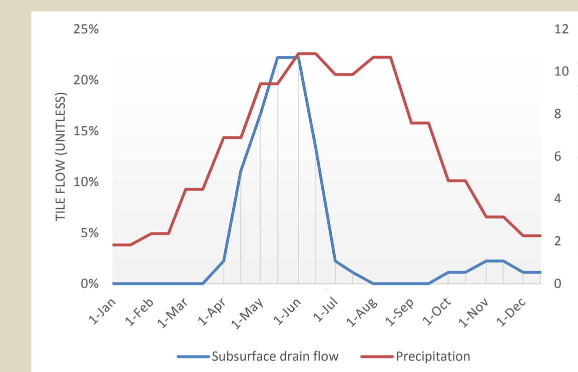


Figure 9. Mean monthly precipitation in the Elm Creek watershed (red) and typical subsurface tile drainage flow (blue) shown as % of total annual tile flow based on field monitoring data. The convergence of maximum tile flow and rainfall occurs from mid-May to mid-June here.

Applications to management

- Water chemistry tools are a useful addition to hydrologic studies that help with identification of flow sources. SC data loggers have transformed this approach by affordably providing continuous data at multiple locations.
- In Elm Creek, tile sources are largest by volume (58%) contributing to bank erosion particularly in spring when large rain events coincide with peak tile flows and saturated soils. In the Buffalo watershed tile drainage is less ubiquitous but expanding, while in the Whitewater tile drainage is minor.
- More water storage is needed in agricultural watersheds to reduce flows at key times via ponds, wetlands, perennial crops and tile control structures
- River management practices could include targeting most erosive reaches and using low-tech sustainable practices; and targeting high banks with erodible soils

Conclusions

- In the study area, the largest stream flow events are driven by rainfall occurring on top of saturated soils when tile drainage is at its peak discharge in the spring months of May to June.
- Flow sources are dominated by subsurface drain flow in the Des Moines Till plain, while tile drains are less important in other regions of Minnesota.
- SC is useful for separating flow sources where an inverse relationship with flow is found. Use of SC works less well where large inputs of salt or pollutants raise SC in surface runoff. O & H isotopes help to identify surface water sources that have undergone evaporation.
- Sub-surface tile flow drainage contributes to greater frequency of bank erosion-causing events particularly in the spring
- At the study sites bank collapse is driven by fluvial erosion with subsequent mass-wasting. Groundwater seepage plays a minor role at the study sites.
- Lateral rates of bank erosion were at a maximum in the Whitewater River where high stream power coincided with high, erodible stream banks.

Authors' afffiliations

[1] Ecological Engineering Group, Bioproducts and Biosystems Engineering Department, University of Minnesota, St. Paul, MN
[2] Emmons & Olivier Resources, Inc. Oakdale, Minnesota
[3] Minnesota Department of Agriculture, St. Paul, Minnesota

References

- Lenhart, C. ,Peterson, H. and Nieber, J. (2011). Watershed response to climate change in the upper Midwest: The importance of low and mean flow increases for agricultural watershed management. *Watershed Science Bulletin*, Spring 2011: 25-31.
- Schottler, S. P., Ulrich, J., Belmont, P., Moore, R., Lauer, J., Engstrom, D. R., & Almendinger, J. E. (2014). Twentieth century agricultural drainage creates more erosive rivers. *Hydrological Processes*, *28*(4), 1951-1961.

Appendix 8: Presentations on project

In addition to the public workshops mentioned in the report text, the following presentations were made or will be made based on research completed in this project.

Invited Oral Presentations

Lenhart, C.F. Prioritization of strategies to reduce ravine, bluff and stream bank erosion, MDA agricultural BMP meeting; Redwood Falls, MN, July 2012

Lenhart, C. F. and Nieber, J.N. Sediment and phosphorus loading from the Whitewater River and tributaries: Sources and Solutions**,** Driftless Area Symposium, La Crosse, WI, March 2013

Lenhart, C.F. --- University of South Dakota, Biology Department Seminar, November 2015

Contributed oral presentations:

Lenhart, C.F., Triplett, L., Gran, K. and Batts, V. 2015. Impact of hydrologic change on the riparian vegetation dynamics in the Minnesota River basin. Ecological Society of America (ESA) annual meeting, Baltimore, Maryland.

Poster presentations

Batts, V. A., Triplett, L., Gran, K. B., & Lenhart, C. F. (2014, December). Riparian Vegetation, Sediment Dynamics and Hydrologic Change in the Minnesota River Basin. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 3577).

Nieber, J. L., Lenhart, C. F., Holmberg, K., Ulrich, J., & Peterson, H. M. (2014, December). Hydrologic processes related to stream bank erosion in three Minnesota agricultural watersheds. In *AGU Fall Meeting Abstracts* (Vol. 1, p. 0953).

Triplett, L. 2014. Variation in hydrologic timing and riparian vegetation establishment within the lower Minnesota River Basin. Society for Ecological Restoration- Midwest Great Lakes (SER-MWGL) 2014 Annual Meeting, March 2014, St. Paul, MN