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).

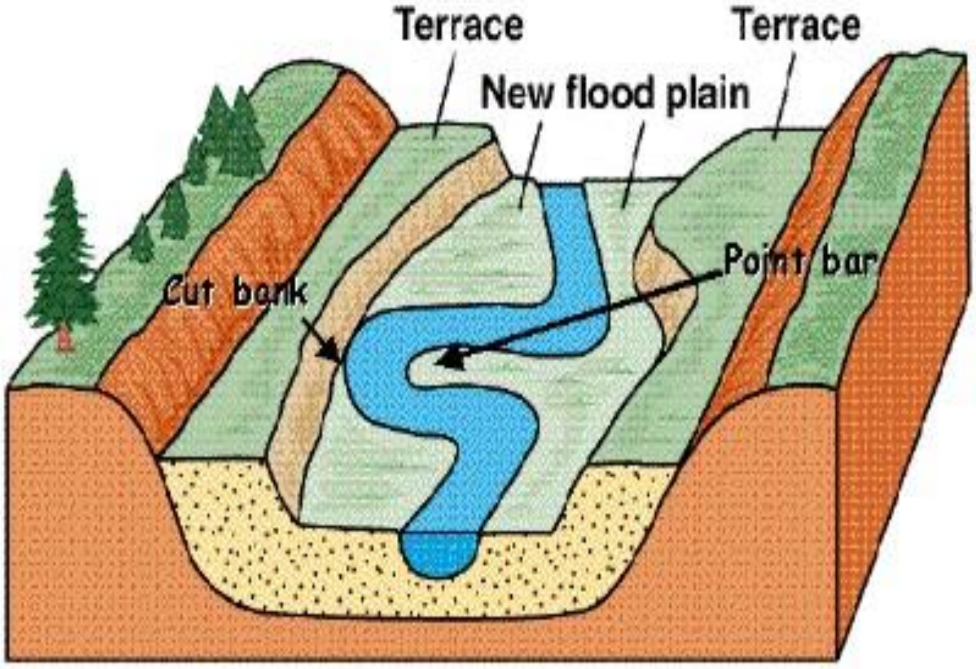


Figure 1. Floodplain, point bar, and terrace features within a river valley system.

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.

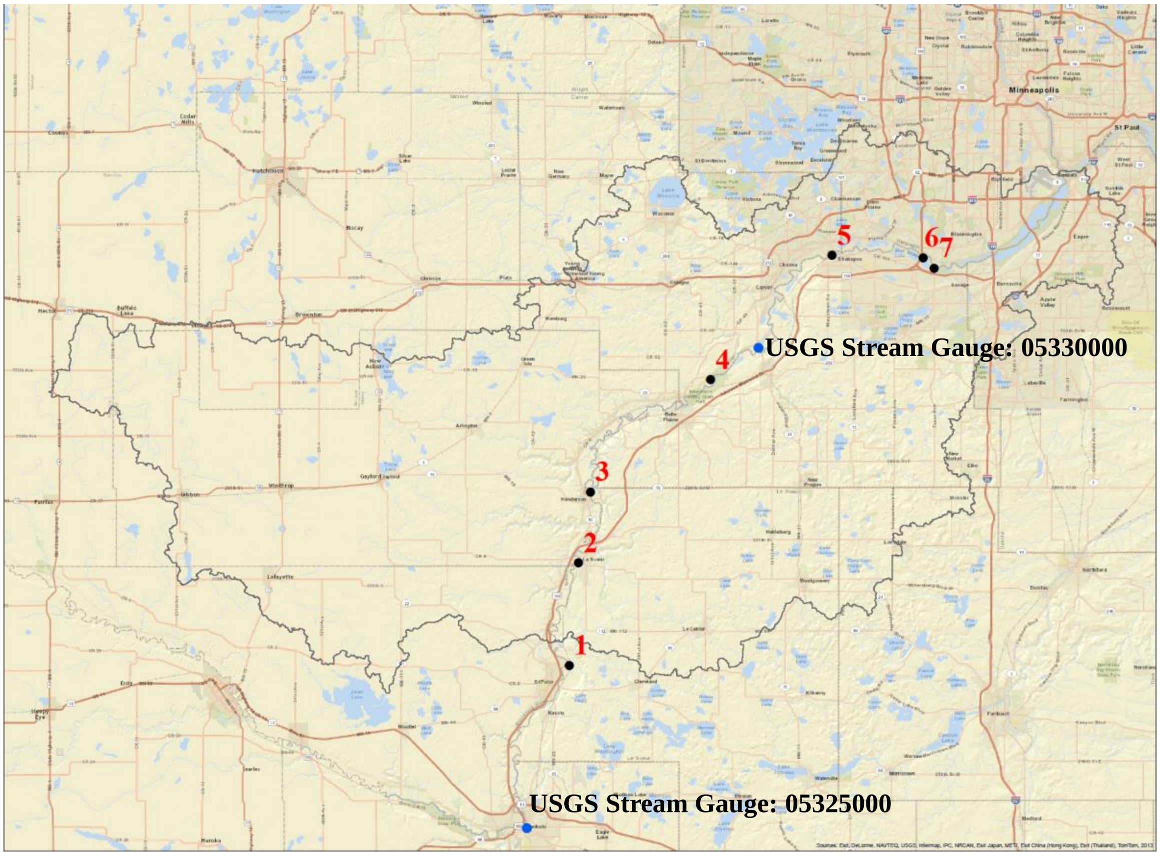


Figure 2. Field survey sites within the lower Minnesota River basin. N=7.

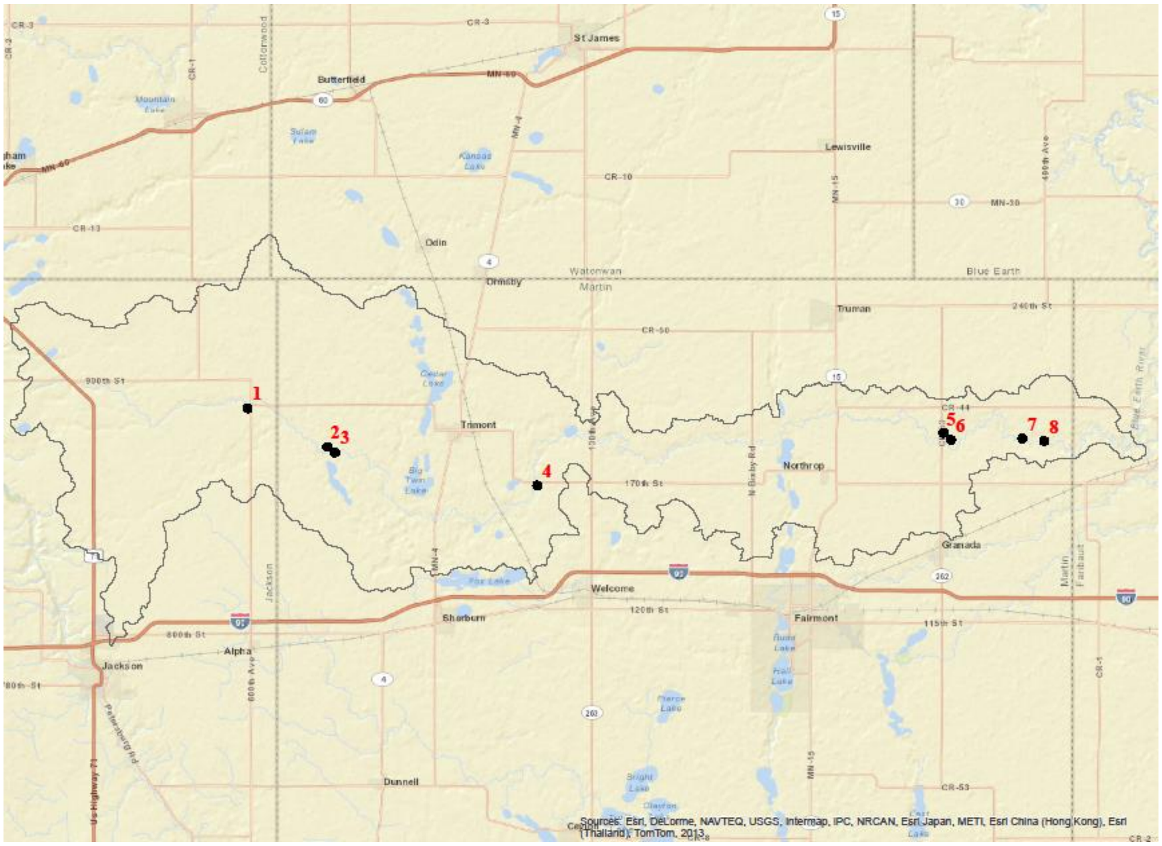


Figure 3. Field survey sites within the Elm Creek watershed. N=8.

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).

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

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

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.

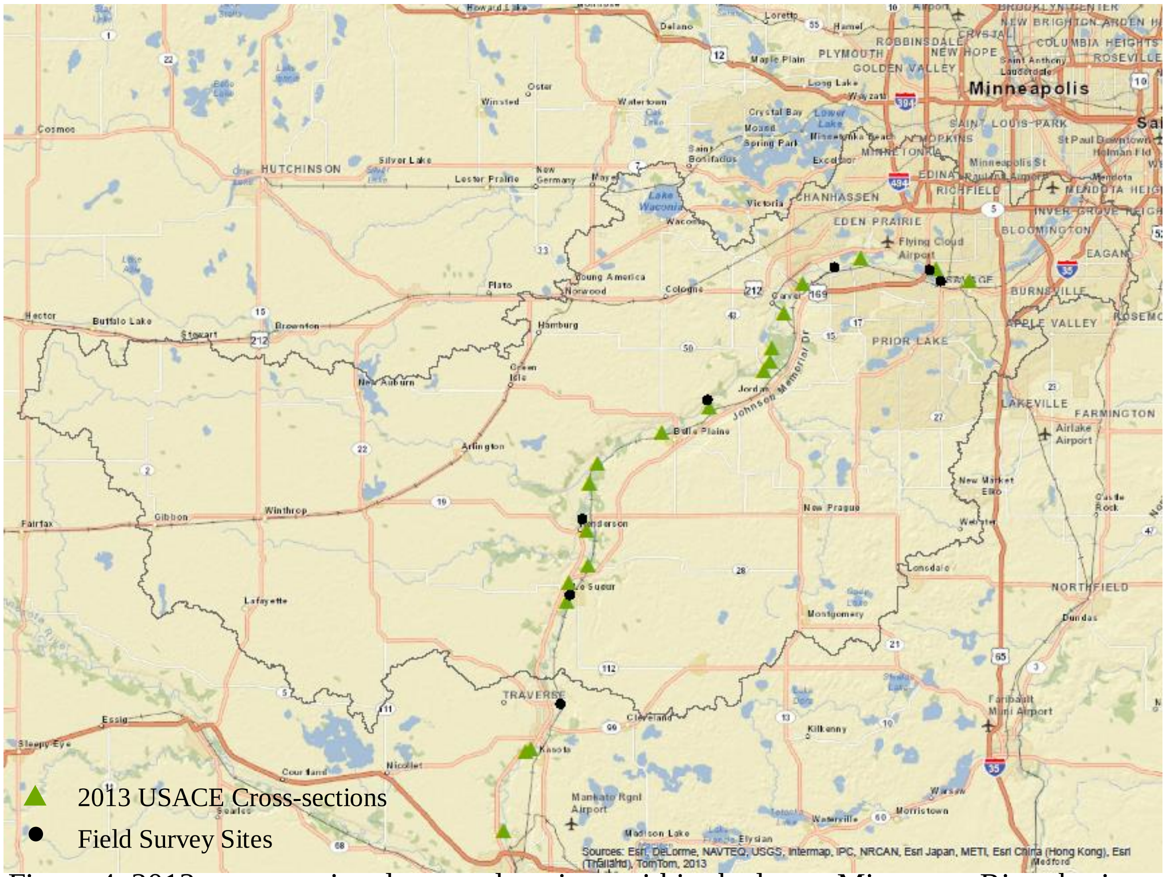
2.1.2 Elevation Establishment Patterns

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.



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, iPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013

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).

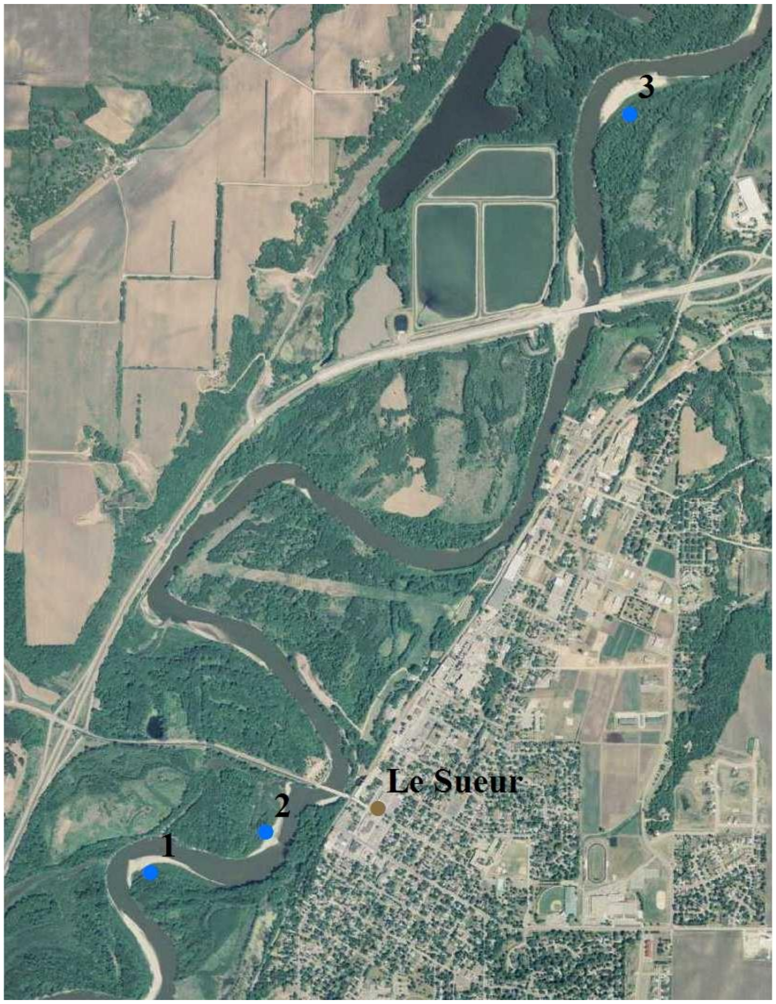


Figure 5. Noble (1979) sampling locations.

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.

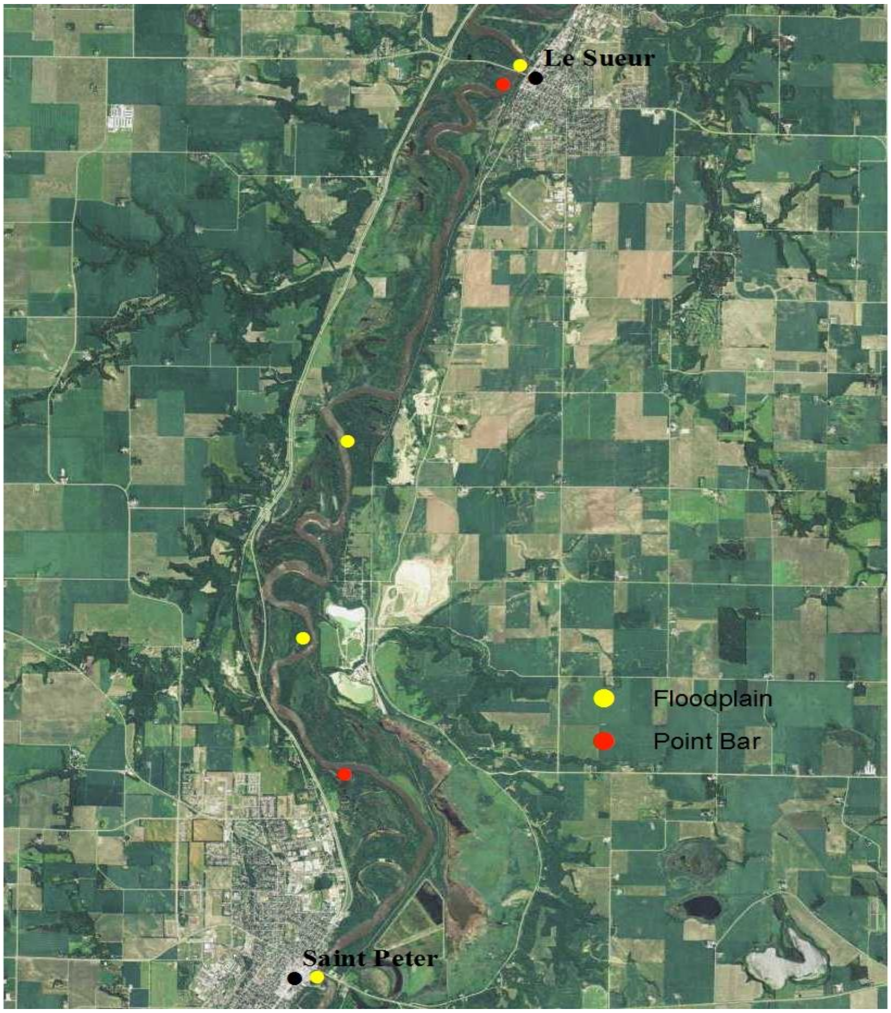


Figure 6. 2014 tree core sampling locations.

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.

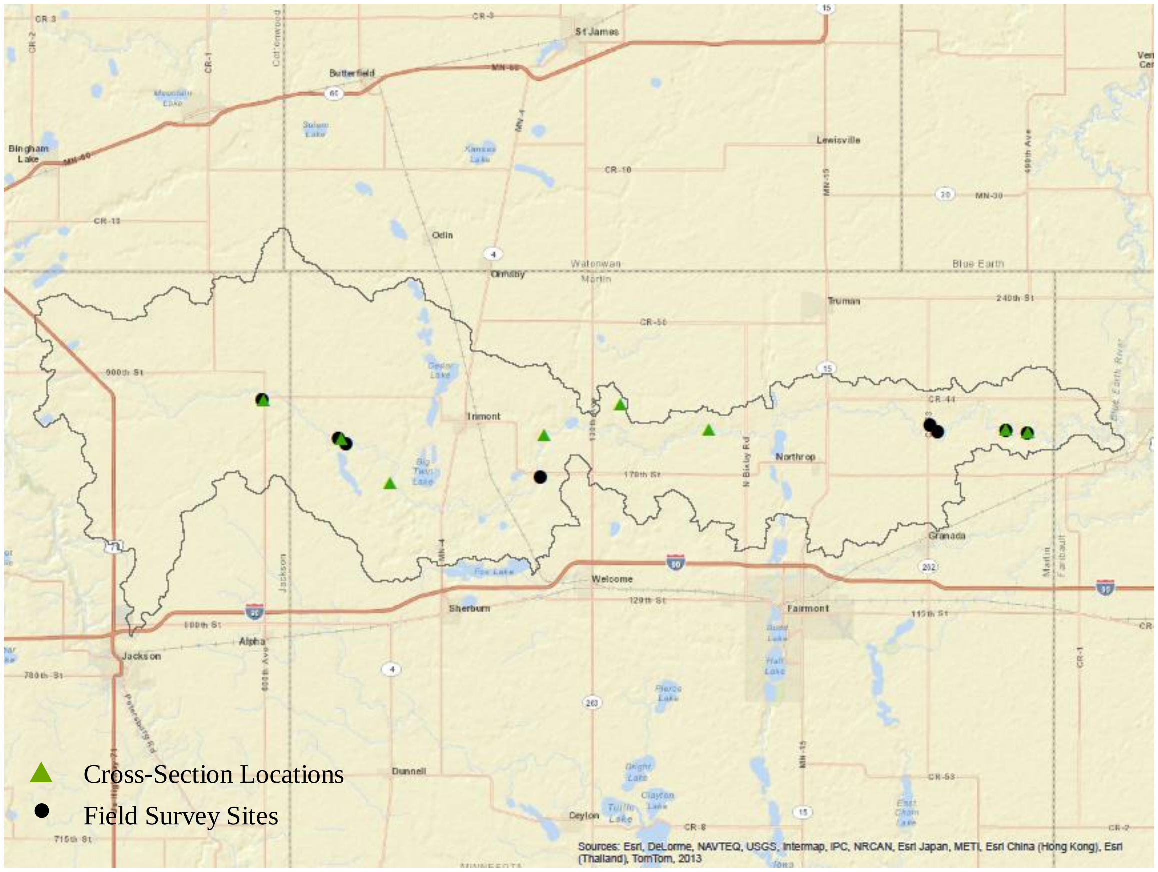
Table 3

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).



Sources: Esri, DeLorme, NAVTEQ, USGS, Intermap, IPC, NRCAN, Esri Japan, METI, Esri China (Hong Kong), Esri (Thailand), TomTom, 2013

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).

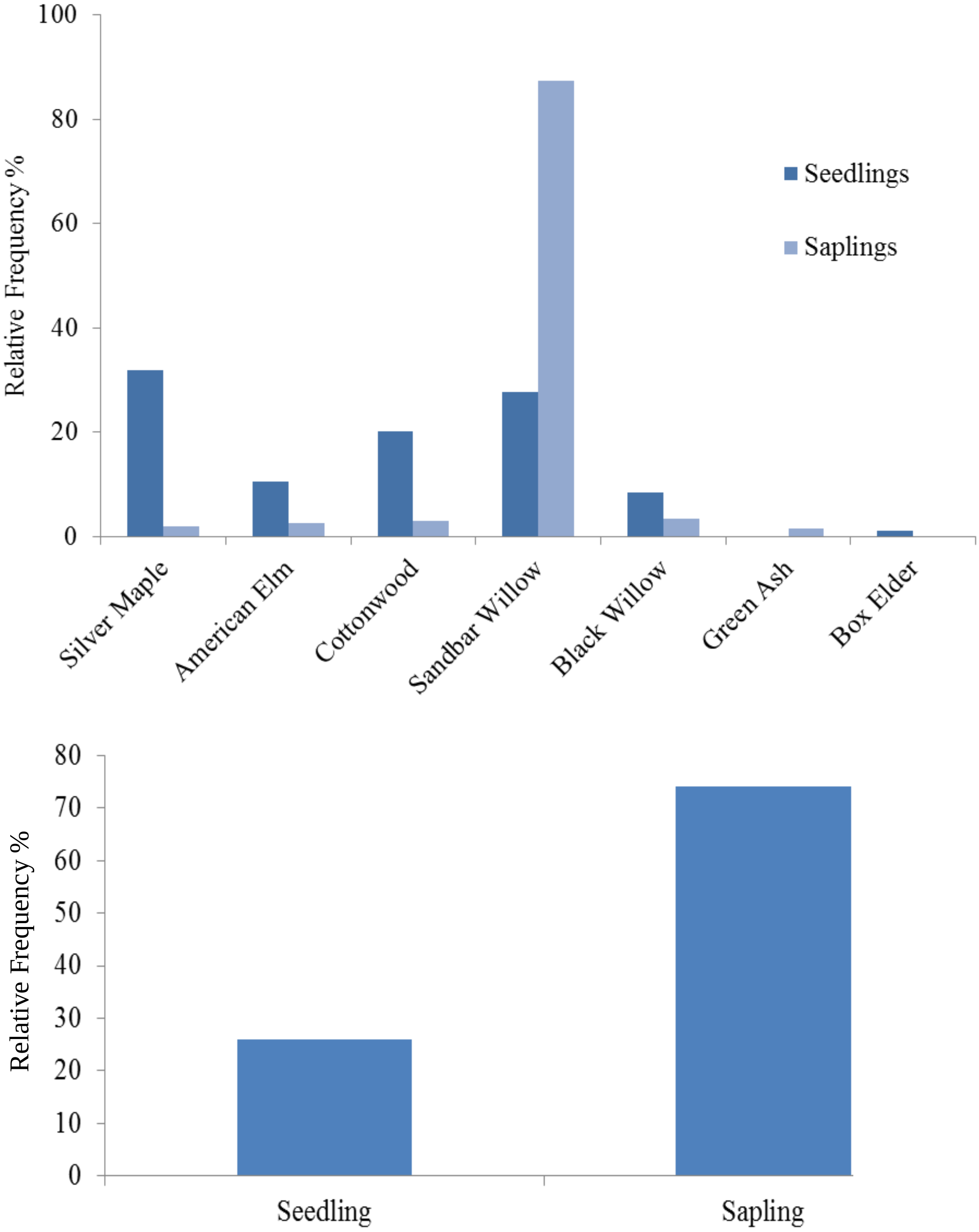


Figure 8. Relative frequency of seedlings and saplings within lower Minnesota River basin transect surveys. N=82.

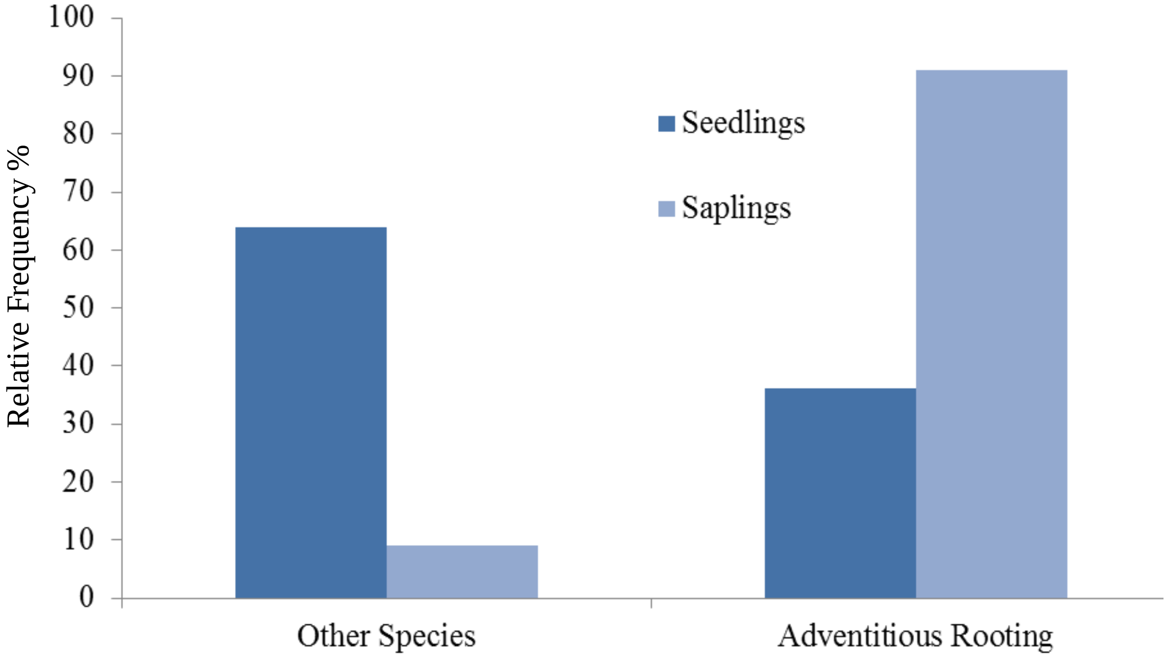


Figure 9. Relative frequency of seedlings and saplings with normal verses adventitious growth habits within lower Minnesota River basin transect surveys. N=82.

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.

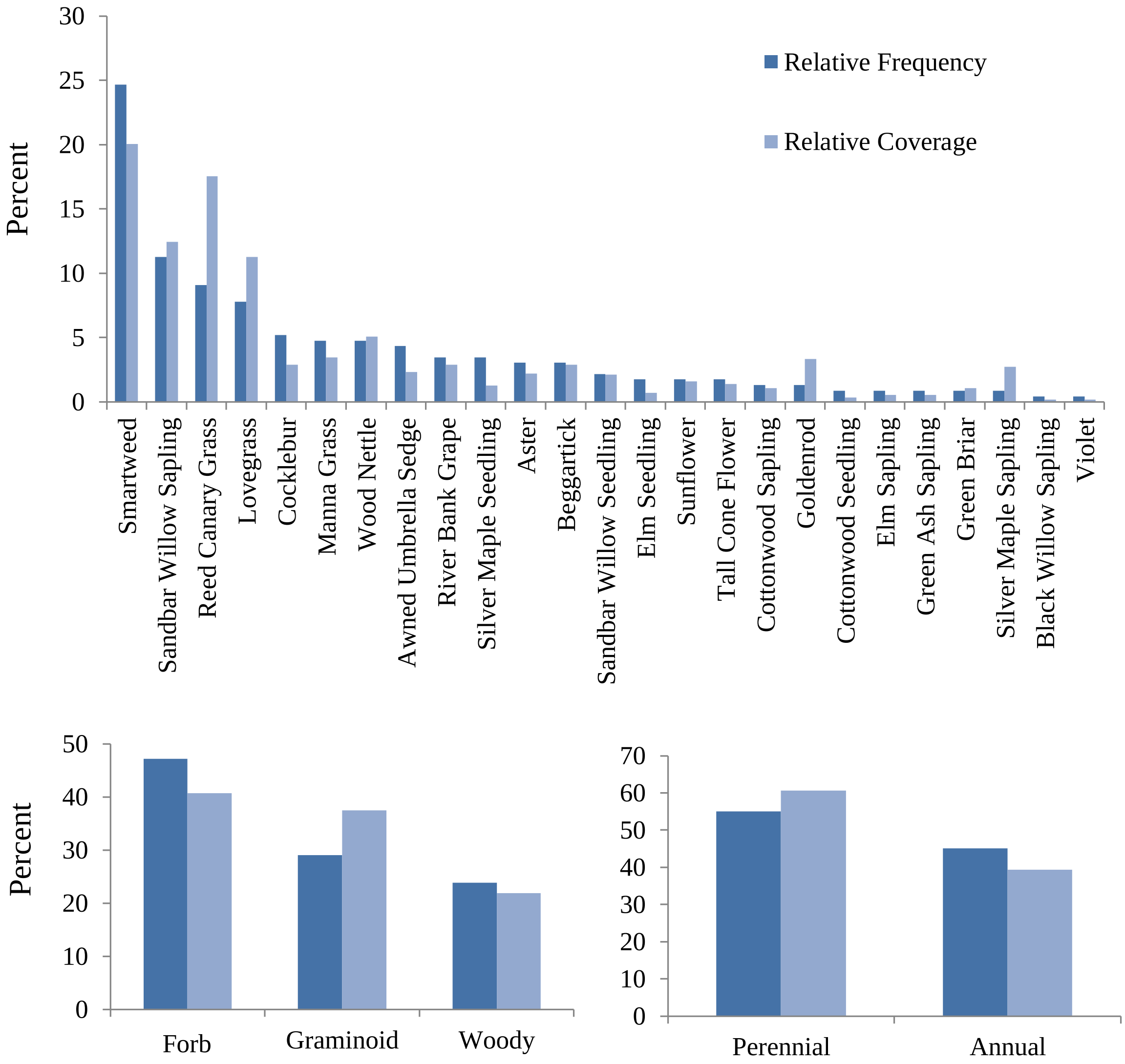


Figure 10 . Relative coverage and frequency of all species within lower Minnesota River basin transect surveys. N=82.

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.

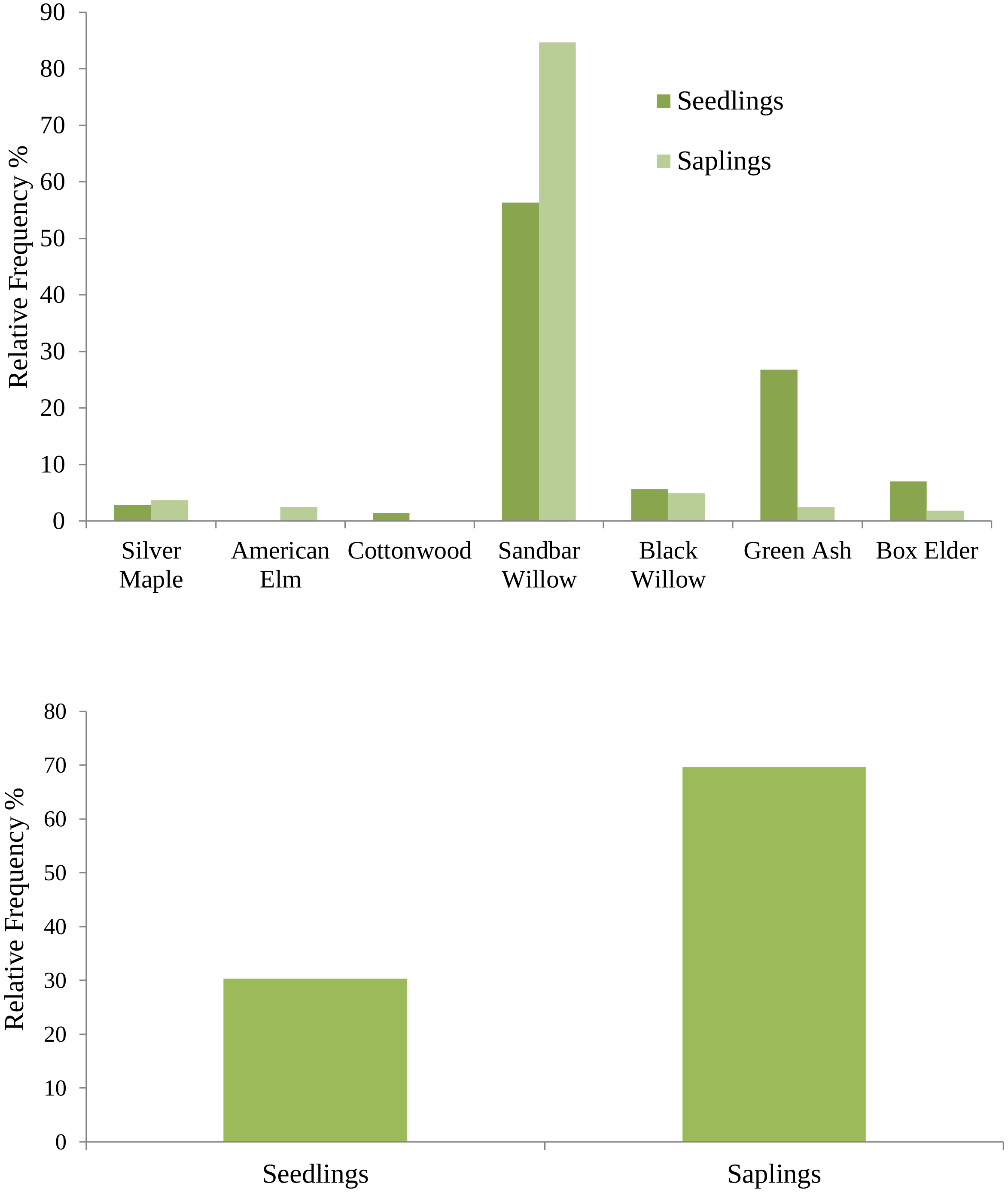


Figure 11. Relative frequency of seedlings and saplings within Elm Creek Watershed transect surveys. N=97.

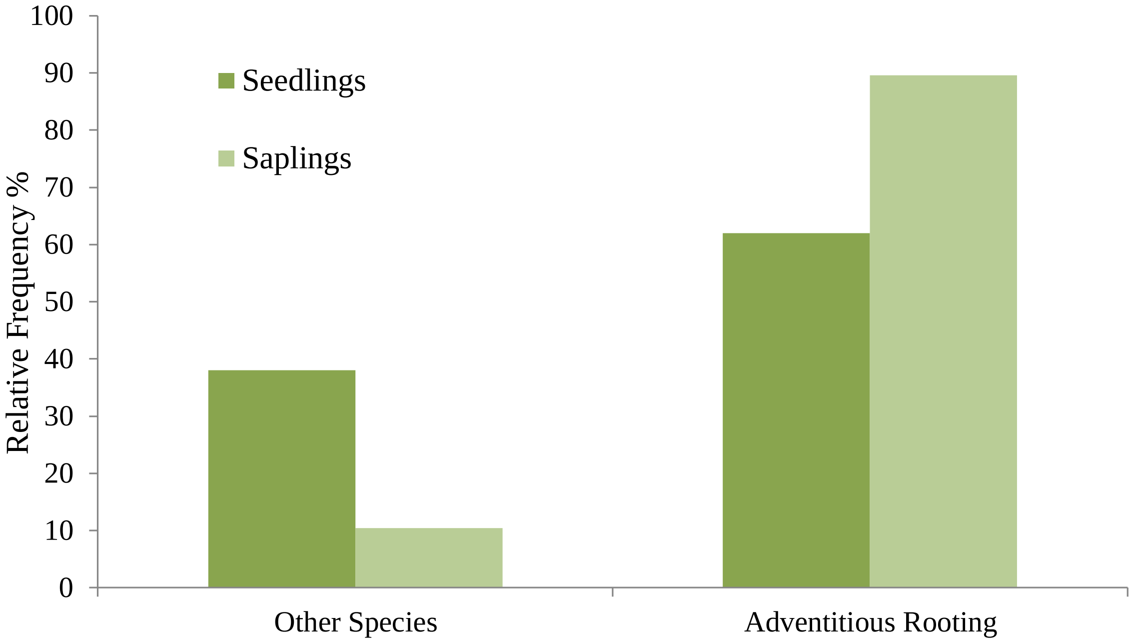


Figure 12. Relative frequency of seedlings and saplings with normal verses adventitious growth habits within Elm Creek watershed transect surveys. N=97.

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.

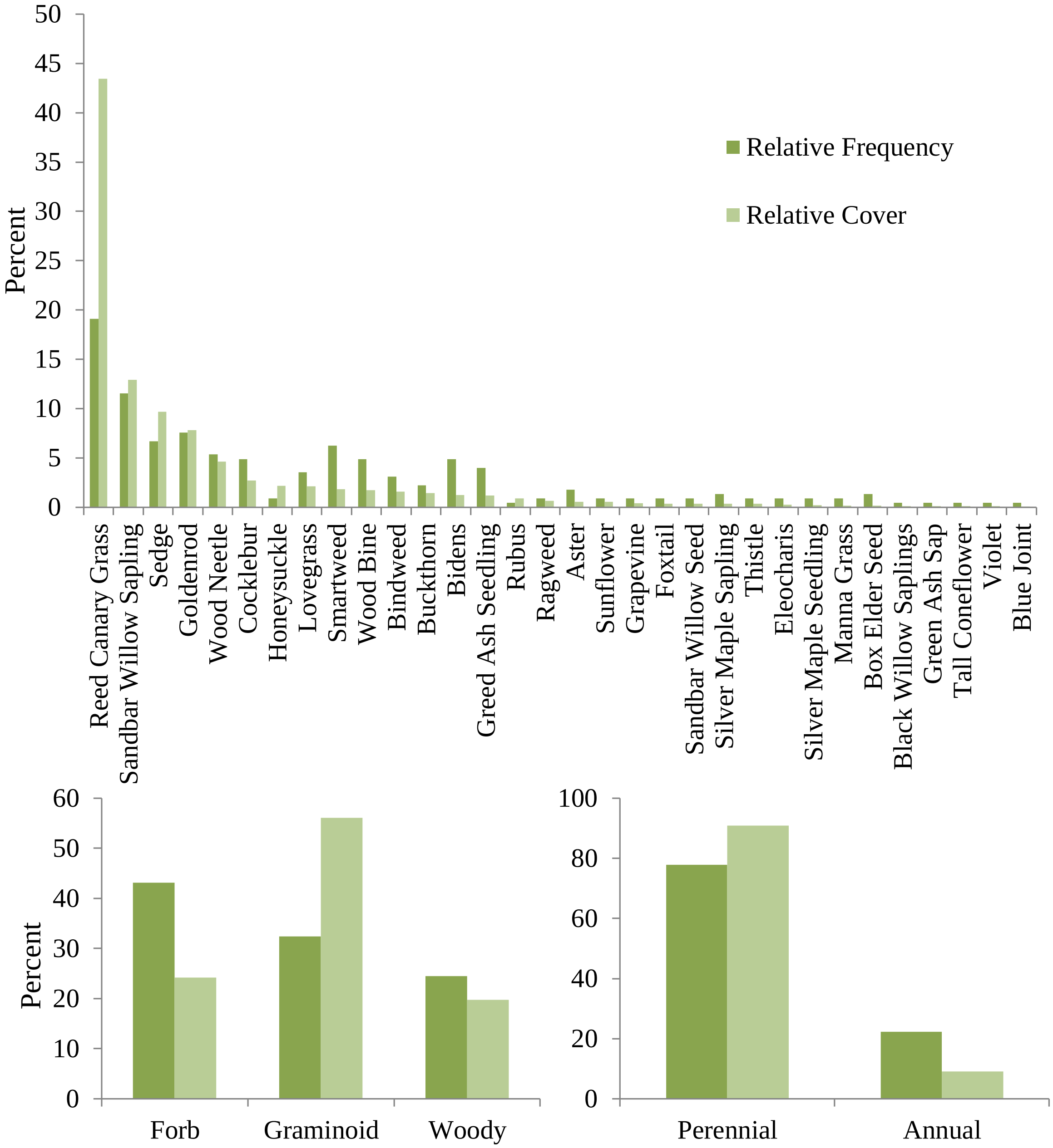


Figure 13. Relative coverage and frequency of all species within Elm Creek watershed transect surveys. N=97.

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

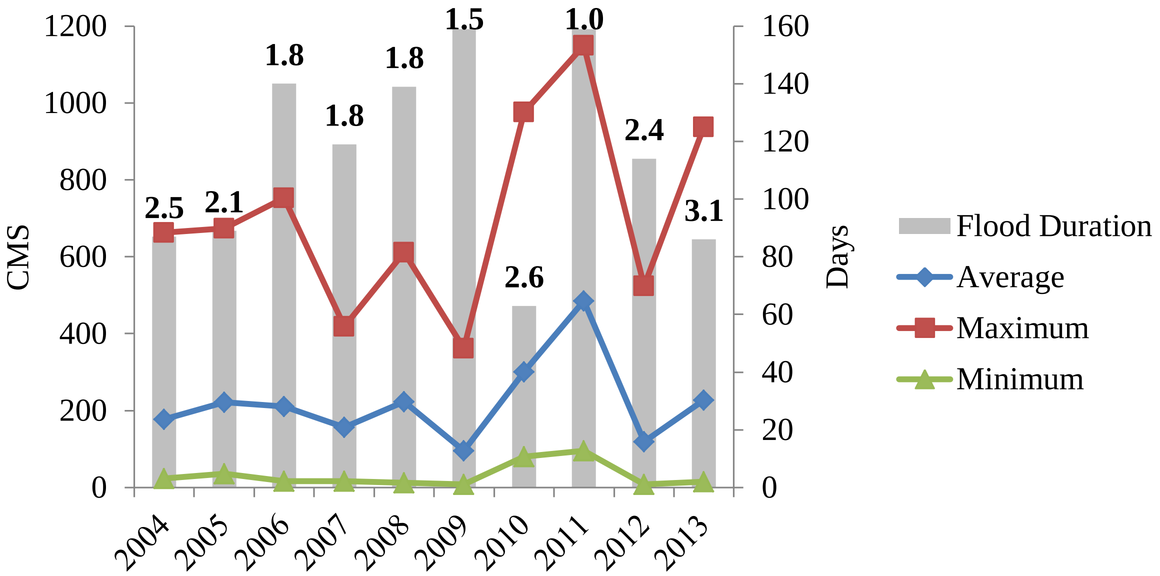


Figure 14. 2004-2013 growing season stream flow statistics, peak flood duration and recession rates (cm/day) in black at Mankato, MN.

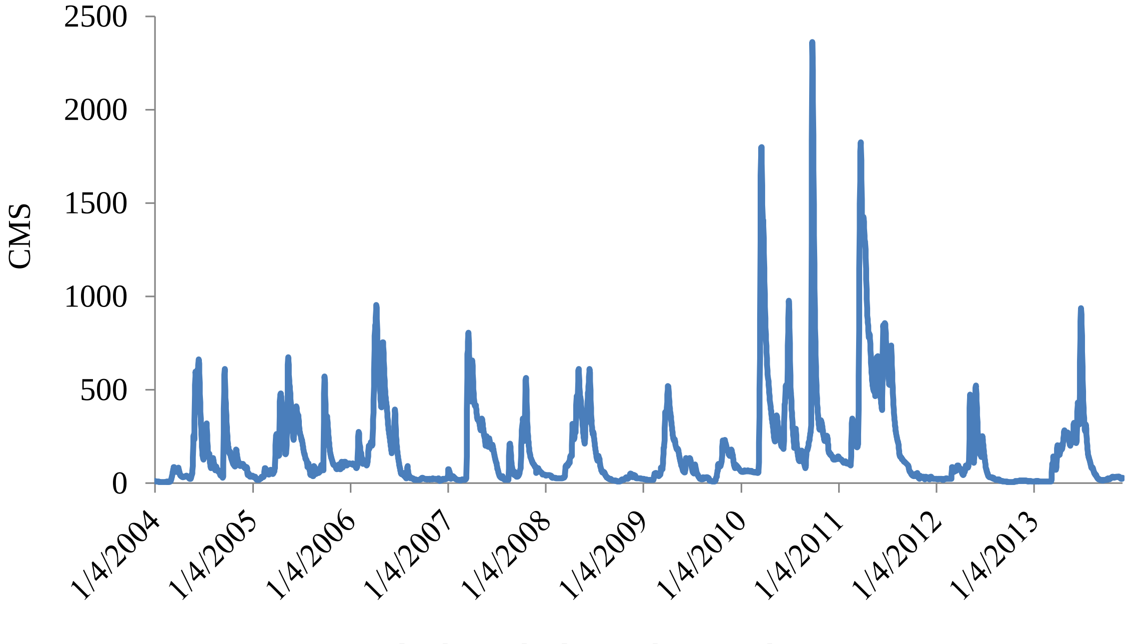


Figure 15. 2004-2013 stream discharge hydrograph at Mankato, MN.

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

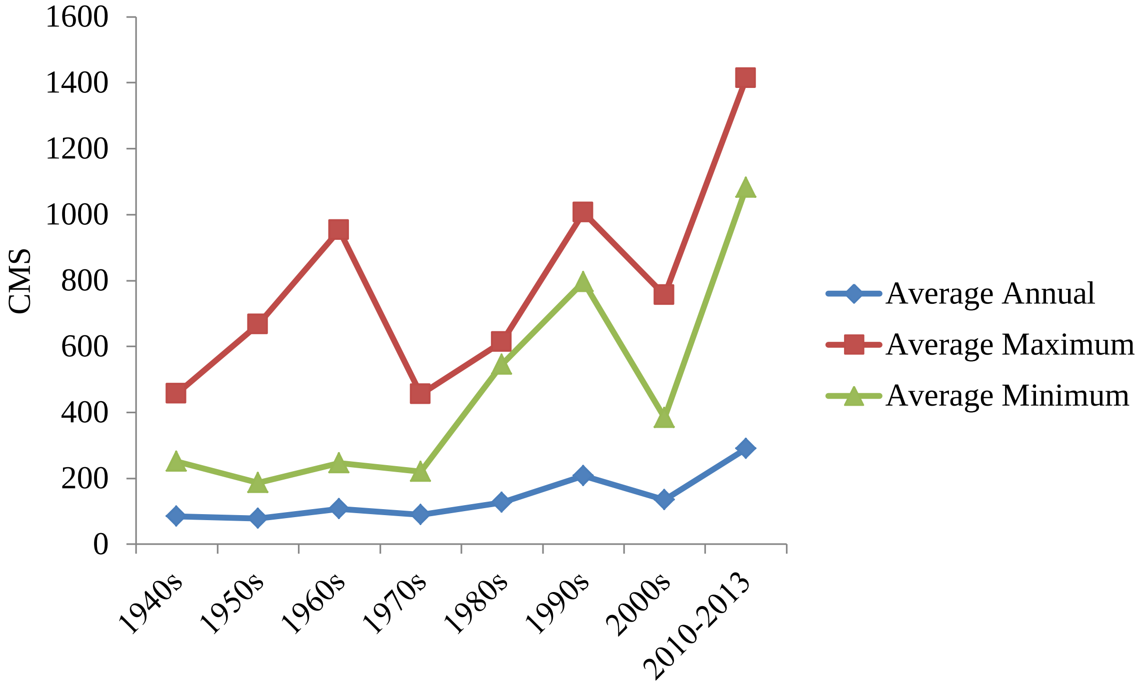


Figure 16. Historic stream flow statistics at Mankato, MN.

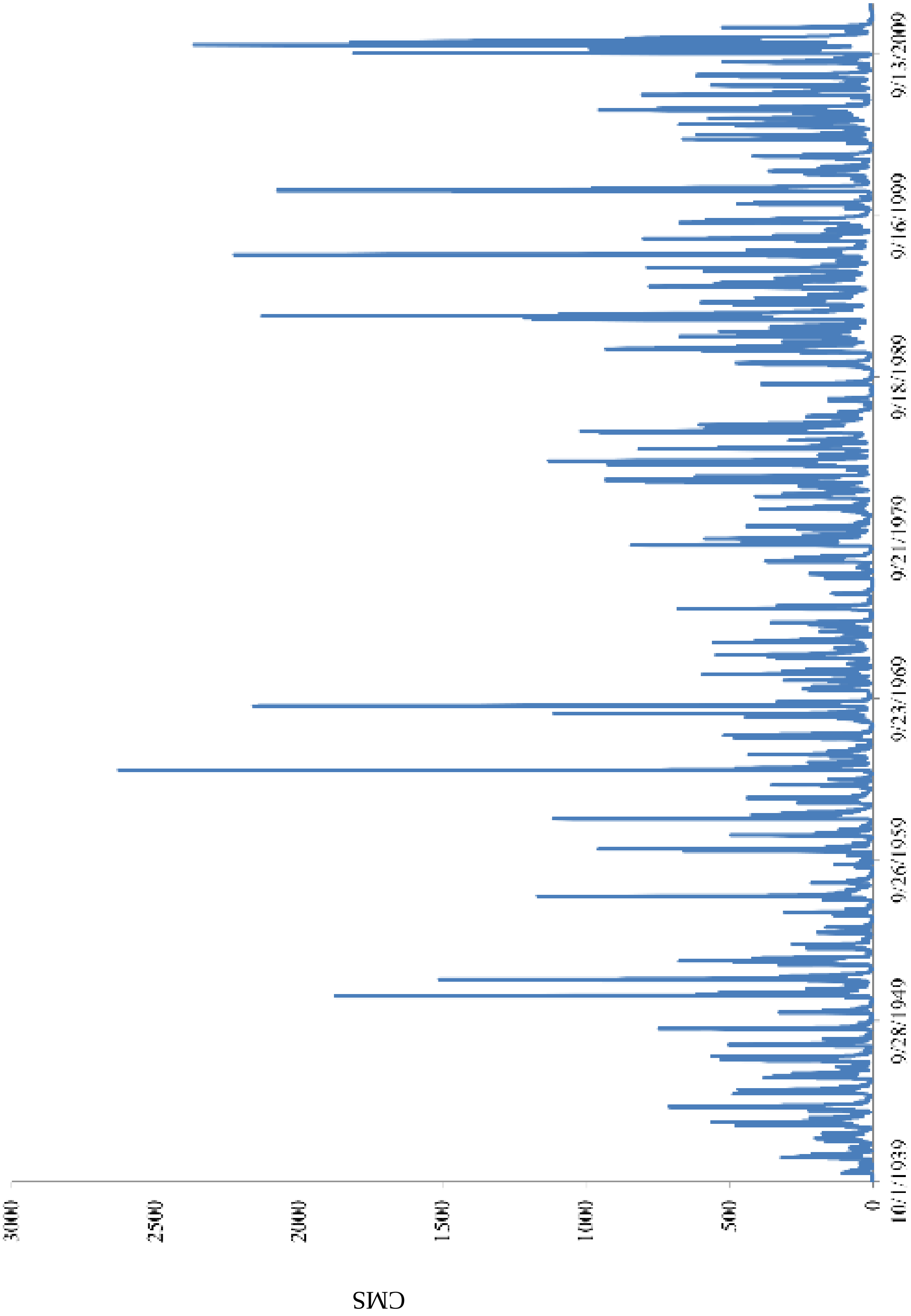


Figure 17. Historic stream discharge hydrograph at Mankato, MN.

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

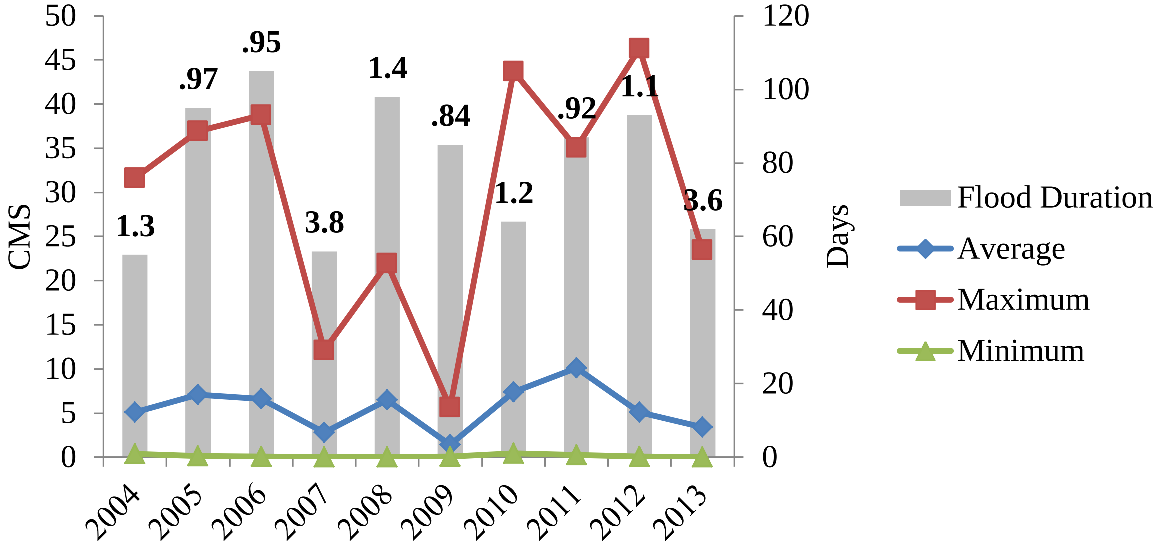


Figure 18. 2004-2013 growing season stream flow statistics, peak flood duration and recession rates (cm/day) in black within the Elm Creek watershed.

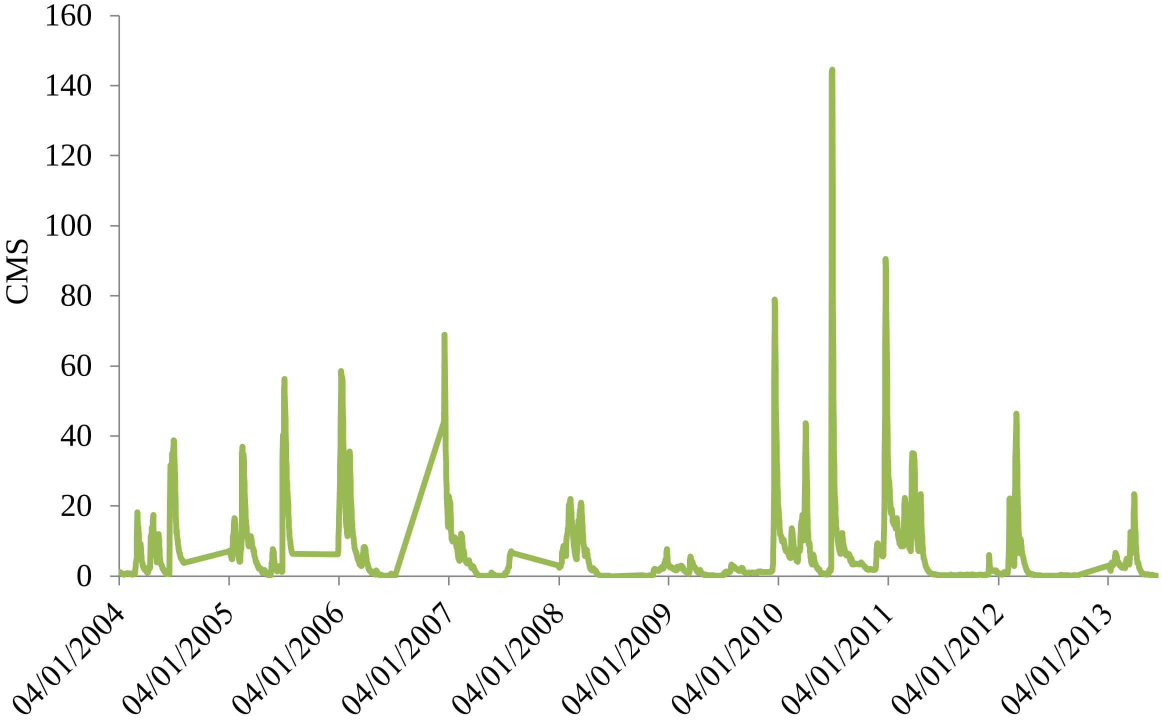


Figure 19. 2004-2013 stream discharge hydrograph within the Elm Creek watershed.

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

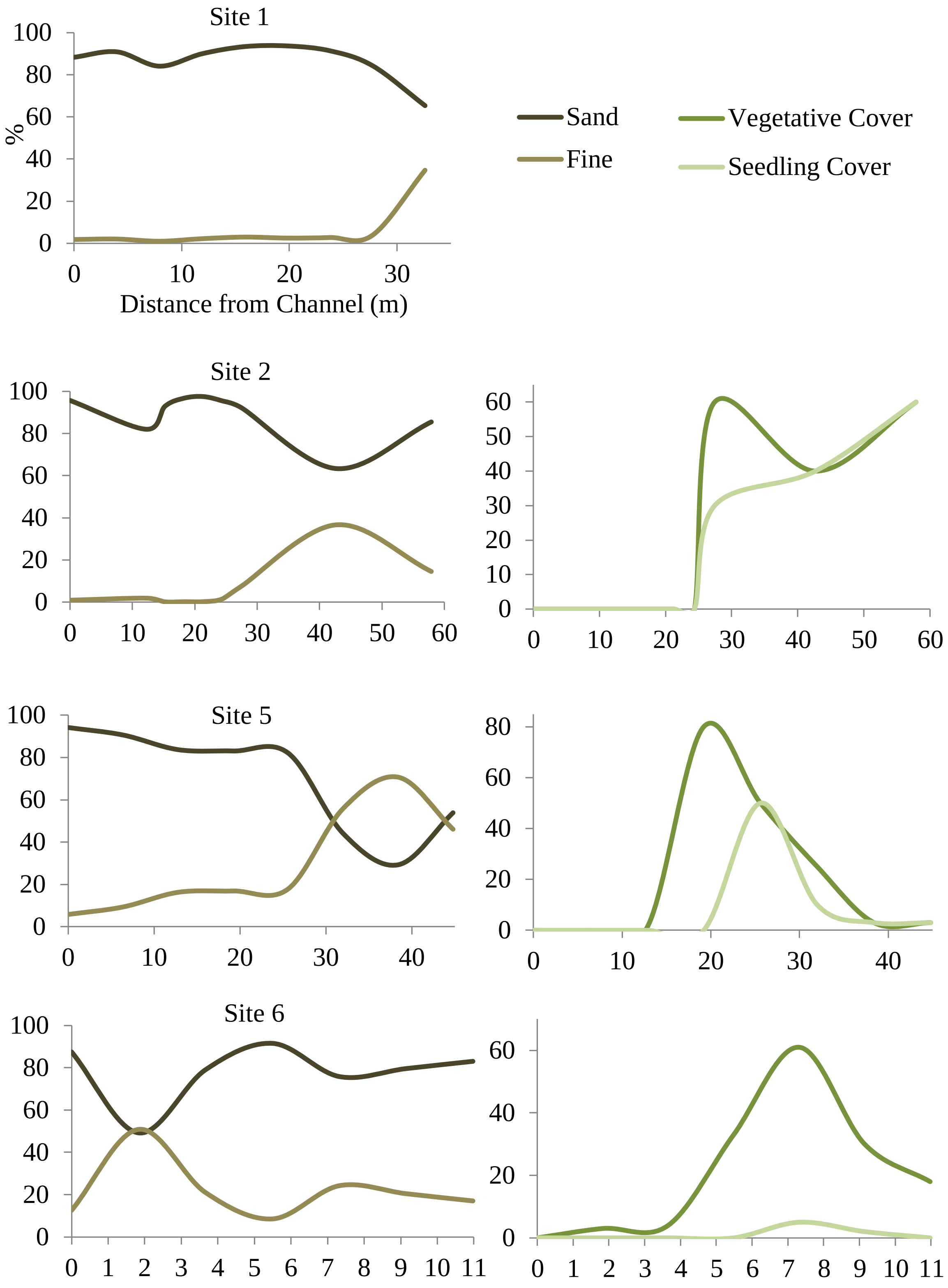


Figure 20. Percent sand verses fine sediment and percent vegetative coverage as a function of distance from water line within the lower Minnesota River basin.

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 $.39\ \text{cm}^3$ 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 Sur6ey 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*