Missouri River Basin Hydrology, Connectivity, and Geomorphology Assessment Report

wq-b7-01

MINNESOTA DEPARTMENT OF NATURAL RESOURCES:
DIVISION OF ECOLOGICAL AND WATER RESOURCES

October 10, 2014

Table of Contents

Table of Figures

List of Acronyms and Abbreviations

AUID = Assessment Unit Identification

BEHI = Bank Erosion Hazard Index

BHR = Bank Height Ratio

cfs = Cubic Feet per Second

DEM = Digital Elevation Model

DMC = Double Mass Curve

ft = Foot

GNIS = Geographic Names Information System

HUC = Hydrologic Unit Code

IBI = Index of Biotic Integrity

IWM = Intensive Watershed Monitoring

LiDAR = Light Detection and Ranging

MNDNR = Minnesota Department of Natural Resources

MNDOT = Minnesota Department of Transportation

mm = millimeter

MPCA = Minnesota Pollution Control Agency

NBS = Near-Bank Shear Stress

Q20 = 20 year discharge event

Q50 = 50 year discharge event

SID = Stressor Identification

SWUDS = State Water Use Data System

USGS = United States Geological Survey

W/D = Bankfull Width to Depth Ratio

WHAF = Watershed Health Assessment Framework

WHAT = Web-based Hydrograph Analysis Tool

WMA = Wildlife Management Area

WRAPS = Watershed Restoration and Protection Strategies

Executive Summary

The Missouri River basin in Minnesota drains 1783 mi^2 of predominantly row cropped and pastured land in the southwestern part of the state. The four Hydrologic Unit Code (HUC) 8 watersheds (Upper Big Sioux, Lower Big Sioux, Rock, and Little Sioux) that comprise the Missouri River basin in Minnesota became subject to the Minnesota Pollution Control Agency's (MPCA) Intensive Watershed Monitoring (IWM) process in 2011 to assess the overall health of the watershed and identify areas of interest that need to be protected or restored.

The "healthy watersheds" approach the MPCA and Minnesota Department of Natural Resources (MNDNR) have adopted assesses a five component framework. These five components of a healthy watershed consist of: hydrology, geomorphology, connectivity, water quality, and biology. All of these components are interrelated, and the disruption of any of them can result in undesirable consequences deeming the stream impaired for one or more condition. The MPCA is tasked with the responsibility to monitor and assess the biology and water quality in watersheds active in the IWM process while the MNDNR provides supplementary data and conclusions for the geomorphology, hydrology, and connectivity components.

Once all of these components have been evaluated, the MPCA creates a stressor identification (SID) document to show what stressors are causing current impairments within Assessment Unit ID's (AUID) in the study watershed. The SID document helps guide the Watershed Restoration and Protection Strategies (WRAPS); a guidance document for local units to implement clean water projects that will provide the most benefit to local resources.

This report analyzes the hydrology, connectivity, and geomorphology components of the Missouri River basin in Minnesota. Historical gage data on the Rock River, stream crossing data, and applied fluvial geomorphology assessments were analyzed in order to find relationships that would help understand water quality and biological impairments throughout the basin.

Poor riparian vegetation communities and improper stream crossing sizing were found to have an effect on geomorphic response throughout the assessed parts of the Missouri basin. Altered hydrology, though very well documented in other watersheds as a driver of geomorphic response in rivers, was inconclusive in the Missouri basin likely due to lack of long-term (>30 years) hydrological data. At geomorphology field sites with relatively undisturbed riparian vegetation, it appeared that geomorphic stability was much better than overgrazed reaches. Aerial photo analyses showed improper sizing of culverts and bridges also resulted in increased sediment supply and channel succession downstream.

In order to attain a healthy watershed status, the WRAPS process will have to address issues within the watershed. As important as restoration of disturbed sites is, focus must also be set out to protect undisturbed areas that appear to be near "reference" condition. The overall objective is to have a healthy watershed that sustains agriculture, groundwater, fish and wildlife habitat, biodiversity, recreation, and water quality in our landscape.

Introduction

Study Background

The Missouri River basin (Minnesota portion) drains 1783 mi^2 in southwestern Minnesota and consists of four Hydrologic Unit Code (HUC) 8 watersheds: Upper Big Sioux, Lower Big Sioux, Rock, and Little Sioux (Figure 1). The Missouri River basin is separated from the Mississippi River basin by a distinct feature along the eastern boundary known as the Coteau des Prairies. The Coteau is a plateau that is made up of glacial deposits and was bypassed by the last glacial sheet that created the prairie pothole region to the east, the Des Moines Lobe, and to the west, the James Lobe (Gilbertson 1990). The Coteau tapers off along the boundary between the Rock River and Little Sioux River watersheds, leaving more glacial lakes and a flatter landscape in the Little Sioux watershed than any of the others (Figure 1).

Nearly all of the streams in the Upper Big Sioux, Lower Big Sioux, and Rock River watersheds start at the Coteau and eventually spill into the Big Sioux River which discharges into the Missouri River near Sioux City, Iowa. Minor tributaries in Minnesota include: Medary Creek in the Upper Big Sioux watershed; Flandreau, Pipestone, Split Rock, Beaver, and Four Mile Creeks in the Lower Big Sioux watershed; Poplar, Mound, Ash, Mud, Kanaranzi, Elk, Champepadan, and Chanarambie Creeks as well as Little Rock River in the Rock River watershed; and Ocheyedan River, West Fork Little Sioux River, and Judicial Ditch #28 in the Little Sioux watershed.

In 2011, the Minnesota Pollution Control Agency (MPCA) began studying each of the HUC 8 watersheds within the Missouri River basin as a part of their Intensive Watershed Monitoring (IWM) schedule. The IWM process includes biological and water quality assessments, verification of old impairments, identifying new impairments, stressor identification (SID), and modeling to understand the watershed as a whole and what potential stressors are leading towards impairments. Culminating all of these data together, finding potential restoration and protection areas, and engaging citizens are part of the Watershed Restoration and Protection Strategies (WRAPS) process.

The analysis of a healthy watershed looks at a five component framework: hydrology, geomorphology, connectivity, water quality, and biology (Figure 2). The MPCA is in charge of collecting water quality and biology data in the Missouri basin while the Minnesota Department of Natural Resources (MNDNR) analyzes historical and current hydrological data, assesses the geomorphology and stability of rivers within the basin, and assesses connectivity (longitudinal, floodplain, and riparian). The remaining report will focus on these three components.

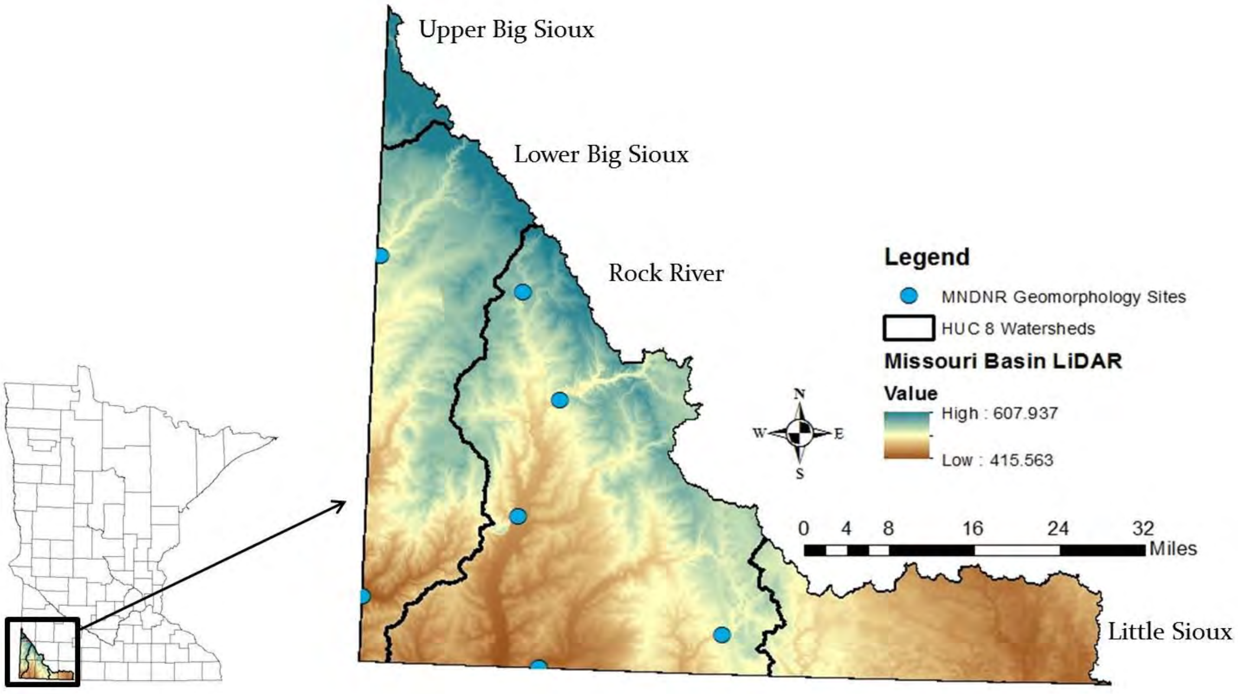


Figure 1. Spatial location of the Missouri River basin in Minnesota with Light Detection and Ranging (LiDAR) imagery.

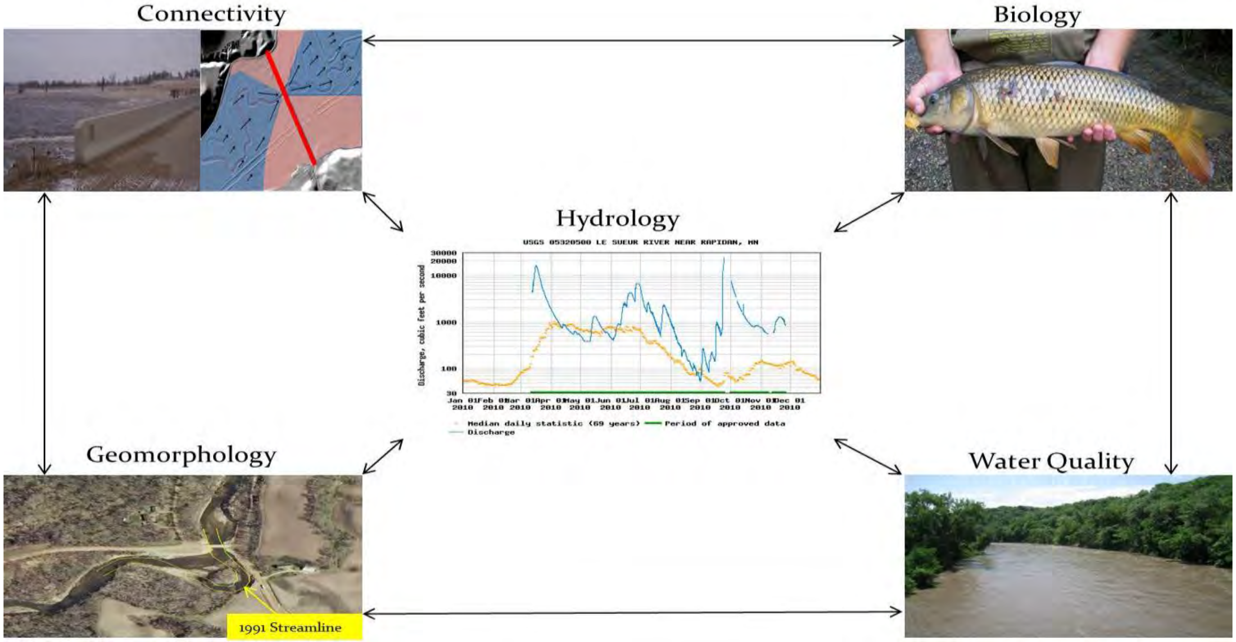


Figure 2. Five components measured to determine watershed health. All components are interrelated; a disruption of any of these can have an effect on the rest of the components.

Hydrology

Hydrologic conditions (e.g., precipitation, runoff, storage, annual water yield) and the disturbance of natural pathways (e.g., tiling, ditching, land use changes, and loss of water storage) has become the driver of many impairments in other Minnesota watersheds (MPCA 2012). These disturbances coupled with an increase in precipitation (total, frequency, and magnitude) have resulted in issues with: increased bank erosion, excess sediment, habitat degradation, and disturbance of natural flow regime. Moderating the effect of accelerated runoff from urban and agricultural landscapes is fundamental to addressing sediment and nutrient impairments in lakes, streams, and wetlands in Minnesota.

Given the geologic history of the Missouri basin, some of these disturbances are not as applicable. The Little Sioux watershed is an exception to the rest of the Missouri watersheds as it is part of the Des Moines Lobe with a flatter landscape and many lakes and wetlands. Since the Big Sioux and Rock River watersheds were not impacted by the Des Moines or James Lobes, natural water retention was never realized in comparison to watersheds within the Des Moines or James Lobes. Very few wetlands and lakes reside in the Rock and Big Sioux watersheds, and most that are located in these watersheds are a result of damming minor tributaries to create an impoundment or sand and gravel mines. However, agricultural producers still use tile as a means to dry out existing wet soils and precipitation changes are still prevalent.

Land use conversion from perennial vegetation alone has had an adverse effect on water storage. Perennial vegetation creates a higher storage capacity in the soil profile than row crop and pasture land uses. Every 1% increase in organic matter results in as much as 25,000 gallons of available soil water per acre (NRCS 2012).

In terms of total precipitation, the Missouri basin falls in the mid-range for Minnesota. The State Climatology Office (2012) reported that normal annual precipitation from 1981-2010 in the Missouri basin ranged from 26-29”. The State of Minnesota ranges anywhere from 21-36” depending on location, with the southeast corner receiving the most, and the northwest corner receiving the least. Increased precipitation trends over the past few decades have resulted in increased water yields in Minnesota rivers (Mark Seeley, Minnesota State Climatologist, personal communication). Precipitation changes alone could warrant changes in the other four components of a healthy watershed if nothing else had changed.

Connectivity

Connectivity is a principle component of a healthy watershed that incorporates many meanings. The term is widely used as a means of longitudinal connectivity in a river. Longitudinal connectivity is especially important for fish species as they make seasonal migrations to larger rivers or another overwintering area. Mussel species are also adversely affected by the inability for host fish species to migrate to potential habitats upstream.

Disruptions of longitudinal connectivity include: dams, waterfalls, perched culverts, or any structure that impedes seasonal migration of aquatic biota resulting in a negative impact on aquatic species, reflected in low Index of Biotic Integrity (IBI) scores. Dams on riverine systems have been documented to not only reduce species richness, but also increase abundance of undesirable species (Winston et al. 1991; Santucci et al. 2005; Slawski et al. 2008; Lore 2011).

Another use of the term connectivity relates to floodplain connectivity, or the ability of a stream to access its floodplain on a regular basis. Floodplains not only play a vital role in spawning habitat and refuge for aquatic biota, but also for nutrient removal and energy dissipation for river stability (Junk et al., 1989; Tockner et al., 2000). When a river degrades to a point where it can no longer dissipate its energy through floodplain access, it builds excess amounts of shear stress along both banks resulting in channel widening. This process makes the channel unstable and usually results in loss of habitat and biotic integrity until the stream can eventually reach a state of equilibrium once again.

Another important result of floodplain connectivity is the recharging of oxbows (i.e., filling up disconnected channel cutoffs with water). These oxbows provide critical habitat to many slack-water species, including the federally endangered Topeka shiners *Notropis topeka* that have been documented throughout the Big Sioux and Rock River watersheds (Nagle and Larson 2013). Once a channel has degraded to a point where it cannot access its floodplain, this critical habitat has been abandoned; potentially resulting in loss of species diversity.

One final component of connectivity that will be addressed is riparian connectivity. Riparian connectivity consists of bridges and culverts that disallow free migration of riparian and aquatic biota, as well as having proper riparian vegetative communities to sustain stream stability. Improper sizing of bridges/culverts not only removes access for the stream to reach its floodplain at the current location causing a bottleneck, but also impedes longitudinal movement of riparian animals which can result in incidental death from vehicle collisions while crossing roads. Zytkovicz and Murtada (2013) reported that improper sizing of bridges and culverts can also result in infrastructural damage due to loss of the river’s access to its floodplain.

Riparian habitat quality also is incorporated in the riparian connectivity section of this report. Not only does habitat quality pertain to habitat for terrestrial animals, but also provides refuge and spawning habitat for aquatic biota during flood events. In terms of stream stability, proper riparian vegetation is essential for many stream types in order to maintain or restore stability.

Geomorphology

Fluvial geomorphology, as addressed in this report, pertains to the way the land has formed and continues to be formed by flowing water (Leopold et al., 1964). The principle methods used in this study to describe the geomorphology follow the Rosgen (1994) classification system, where the dimension, pattern, and profile of the stream are all documented to classify the stream (Figure 3). Other measurements (e.g., bank height ratio, erosion rates, and sediment

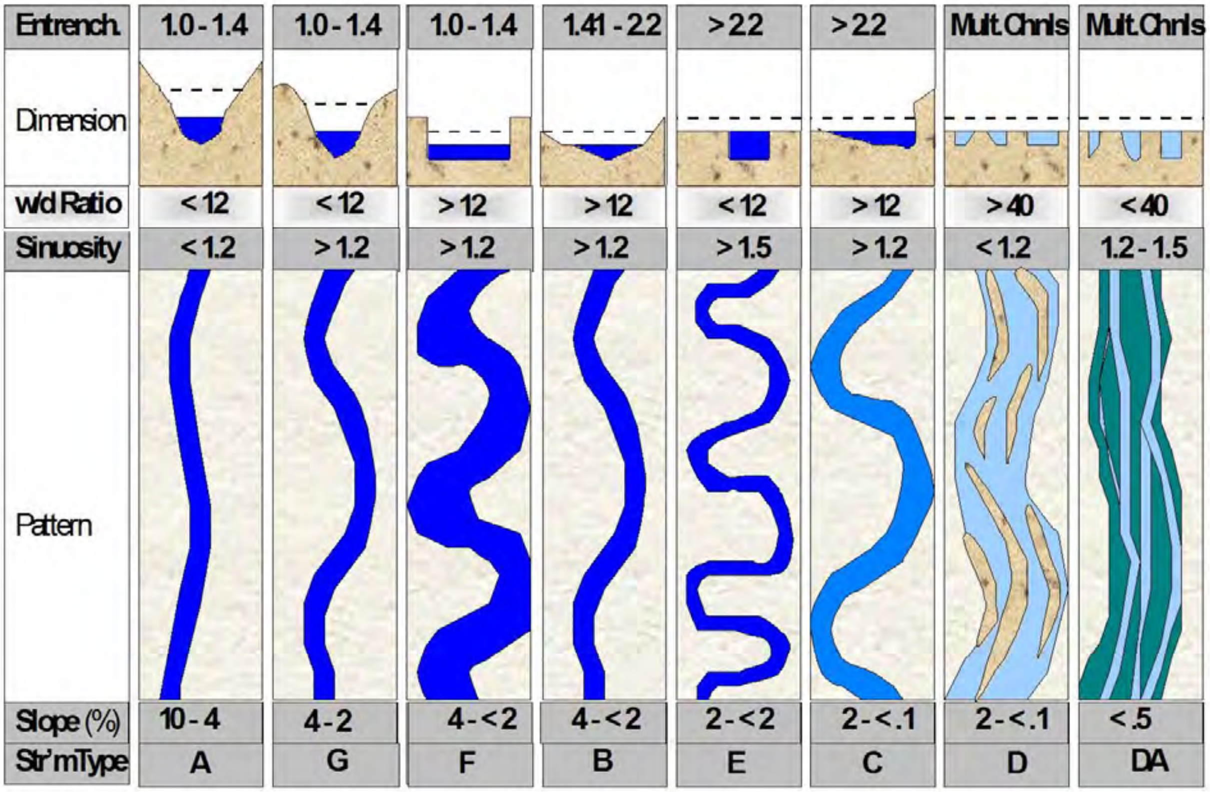


Figure 3. Explanation of the measurements used to classify a representative stream reach. Once there are established measurements of entrenchment, bankfull width to depth ratio, sinuosity, and slope at a riffle cross section in the representative reach, one can conclude what type of stream it is. Other measurements taken help determine if the stream is stable in its current state or if it is in a successional state to adapt to its current climate, hydrology, and land use (from Rosgen 1997).

competence) can help assess if the channel is stable or if it is in a transitional state (i.e., evolving to or from a disturbed channel type).

By definition, a stable stream is one that can transport the flows and sediment of its watershed over time in a manner that the stream maintains its dimension, pattern, and profile without aggrading or degrading (Rosgen 1996, Rosgen 2009). When other components of the healthy watershed are disturbed, especially hydrology and connectivity, it is likely to see a successional change in local rivers to adjust to the current conditions. Typically, a stream that is disturbed will lose habitat quality from an imbalance of sediment supply and sediment delivery resulting in biota and turbidity impairments in the stream.

Methods

Hydrology

In order to understand and evaluate the hydrologic processes within a watershed, several types of analyses are used to examine the relationships between flow (discharge) and precipitation. Groundwater levels and usage over time are also reviewed to detect trends and compare to surface water flow. The analysis methods can evaluate and measure changes within a system by reviewing statistical variations and trends over time.

Discharge Analysis

Flow data sets are collected by the United States Geological Survey (USGS) and MPCA/DNR stream gage network for nearly all of the HUC 8 watersheds in Minnesota. Most long-term (i.e., >30 years) gage sites are at or near the pour point of the watershed, either into a larger river, or another state. Site specific stream flow data are calculated using continuous stream stage measurements and periodic field-verified stream flow measurements. These data are plotted to allow for statistical analysis and are used to create hydrographs, flow duration curves, and other visual representations of the period of record.

Watershed discharge data can be used to review daily, monthly, seasonal, annual and long-term trends within a watershed and examine changes in the discharge characteristics such as periods of low or zero flow, flood frequency, base flow volume, and seasonal variability. Discharge data for the Rock River were reviewed from the Luverne (USGS/DNR# 83016001) and Hardwick (DNR# 83027001) gages.

Precipitation

Precipitation data analysis is based on the long-term data collection location nearest to the stream data collection site. All precipitation data are acquired through the "High Density Radius Retrieval" website maintained by the Minnesota State Climatology Office. Precipitation data are used to examine long-term trends within a watershed, and the relationship and response of discharge, runoff, and baseflow conditions relative to recorded precipitation totals. Long-term precipitation data were available at Luverne (Station #217012) in Minnesota.

Double Mass Curve Analysis

A double mass curve is an analysis based on a cumulative comparison of an independent and dependent variable. Double mass curves are useful in hydrological data as they allow examination of the relationship between two variables. This technique was used to compare precipitation and stream discharge relationships (annual and seasonal) and well elevation fluctuations relative to precipitation. When plotted, a straight line indicates consistency in the relationship while a break in the slope would mean a change in the relationship.

When used with long-term discharge data sets, the curve can demonstrate when the change in the relationship began to occur. All double mass curves presented are runoff (discharge/watershed area) and monthly precipitation in inches. All discharge values are converted to inches by dividing total volume by the watershed area (the annual discharge converted to acre–ft. and then to inches of runoff over the watershed). Additional information on double mass curve development and interpretation can be found on the following website: http://pubs.usgs.gov/wsp/1541b/report.pdf

Web-based Hydrograph Analysis Tool

The Web-based Hydrograph Analysis Tool (WHAT) was developed by Purdue University and designed to separate baseflow and direct runoff using digital filtering algorithms from user specified flow data. Data can be automatically uploaded from the USGS database or manually entered by the user. The analysis can be run over the entire period of record or for dates specified by the user. Subsets of the data can be used to look for a change in the relationship as indicated by the double mass curve or precipitation records. The WHAT tool examines the baseflow to discharge relationship for long-term and seasonal variations.

The supplied dataset is analyzed using a recursive digital filter, based on a groundwater system with "perennial streams with porous aquifers". The tool and additional information can be found on the following website: https://engineering.purdue.edu/~what/

Groundwater Usage

Permitted groundwater usage was reviewed to examine changes in type of usage and volume over time. Data were collected through the State Water Use Data System (SWUDS) from 1988-2011. The data were used to review total volume appropriated, volume appropriated by county, aquifer type, and well level fluctuations relative to precipitation.

Connectivity

Longitudinal Connectivity

Longitudinal connectivity was assessed in the Missouri River basin using desktop reconnaissance tools such as: ArcMap, Watershed Health Assessment Framework (WHAF), and Geographic Names Information System (GNIS). Since culvert inventories do not explain if they are perched or not, dams were the only barriers analyzed for this section.

Floodplain Connectivity

Flood-prone area (i.e., active floodplain) is defined as the area adjacent to the stream channel that is under water in flow events that are 2X maximum bankfull depth at the riffle cross section (Rosgen 1996, Rosgen 2009). Bankfull, as related to in this report, refers to the normal high water flow; usually relating to about the 1.5 year return interval flow. A field survey is needed to calibrate bankfull at the riffle within a reach and to find the flood-prone elevation. Thus, only sites that had geomorphology surveys were subject to floodplain connectivity analyses. If there was a wide flood prone area, width measurements were taken using LiDAR digital elevation models (DEMs) based off the flood-prone elevations measured through field survey.

Riparian Connectivity

Riparian connectivity analyses were done using ArcMap, WHAF, and Minnesota Department of Transportation's (MNDOT) bridges and culverts inventory. Number of culverts and bridges was split up within the Missouri River basin and also between sub-watersheds to get an idea of the abundance and density (bridges or culverts/mi^2). Limited aerial photo analyses were done to assess potential impacts of poorly designed culverts and bridges.

Riparian vegetation and habitat were qualitatively assessed at each field survey site. Type of vegetation, root depth, root density, and weighted root density (i.e., [root depth/study bank height] * root density) are all measured to help assess the quality of vegetation for that particular stream reach. Lack of quality in vegetation typically relates to poor stream stability and high sediment supply through bank erosion.

Geomorphology

Field Methods

After meeting with the Missouri River Basin Project Coordinator and MPCA staff, sites were established that would attempt to incorporate all stream type and valley type combinations found within the basin. Overall, seven sites were surveyed throughout the Lower Big Sioux and Rock River watersheds (Table 1). One site was added because it was a gage analysis site, and another site was added because of an interested landowner requesting further information about his site. The initial six sites were surveyed in July 2012 and revisited in July 2013, while the added site on Kanaranzi Creek was surveyed in November 2012 and revisited in November 2013.

At each site, elevation data were collected to describe the dimension, pattern, and profile of the reach. Since all of the survey sites had open canopy, a Trimble R6 receiver was used to calculate elevations based on its distance and angle from a number of satellites, which is corrected through a signal from a local base station.

In order to describe the dimension, pattern, and profile of the reach, a longitudinal profile at least 20X the bankfull width was surveyed at each site; consistent with the methods taught by Dave

Table 1. List of Missouri basin geomorphology sites and what Assessment Unit ID (AUID) they are located within.

Site Name	AUID
Kanaranzi Creek	10170204-517 (Norwegian Creek - MN/IA border)
East Branch Rock River	10170204-530 (Headwaters - Rock River)
Rock River	10170204-508 (Unnamed Creek - Champepadan Creek)
Little Rock River	10170204-512 (Headwaters - Little Rock Creek)
Chanarambie Creek	10170204-522 (Headwaters - Rock River)
Flandreau Creek	10170203-502 (Willow Creek - MN/SD border)
Beaver Creek	10170203-522 (Little Beaver Creek - MN/SD border)

Rosgen. The longitudinal profile consists of thalweg (deepest part of channel), water surface, bankfull, and low bank height (actual "floodplain", if located above bankfull) elevations throughout the reach in order to incorporate water slope, bankfull slope, channel bed features (e.g., pool, riffle, glide, run), and rate of incision (low bank height/bankfull height; if greater than 1). These data are necessary to help classify the stream using Rosgen (1994)'s stream classification system.

After completing the longitudinal profile, a riffle cross section was surveyed to analyze the width-to-depth ratio (bankfull width/average bankfull depth), entrenchment ratio (flood-prone width/bankfull width), flood-prone width, bankfull cross-sectional area, and calibrate bankfull elevations for the reach. Starting from the left bank (looking downstream), elevations were taken incorporating all changes in slope throughout the cross section. The entire flood-prone (2X bankfull) area was surveyed along the cross section, or the cross section was ended at a point where flood-prone width and entrenchment ratio could be calculated later in the office.

At most sites, a cross section was monumented within the study reach to be annually monitored for changes over time. Methods were similar to the riffle cross section, except benchmarks (rebar) were placed at the start and end of the cross section as a guide for annual resurveys. Typically this cross section also has a study bank where a toe pin is placed at the base of the study bank in the channel bed and 2-3 bank pins horizontally into the study bank so bank erosion can be assessed annually. At each of the study banks, the toe pin serves as a starting point for the study bank evaluation while the base of the edge pin on top of the bank serves as an ending point. The bank pins not only visually show the bank erosion, but help to validate our actual measurements versus the model estimates of change each year.

To estimate bank erosion within the sites, the Bank Erosion Hazard Index (BEHI) coupled with Near-Bank Shear stress (NBS) developed by Dave Rosgen (Rosgen 2001a) was used at each study bank along with other representative banks within the reach. The study bank at each reach is used to validate bank erosion model estimates. There are three established bank erosion models from Colorado, Yellowstone, and North Caroline; however, none of the models estimated actual conditions after one year of data so the Colorado model was used in all cases to remain consistent. Since the model used was developed in Colorado, measured bank erosion at each site will help develop a regional model for sites in southern Minnesota. Refer to Appendix 1 for results of each bank erosion model.

At each site, 100 active stream bed particles were measured (pebble counts) throughout the reach (for classification; Wolman 1954, Rosgen 2012) and 100 through the riffle cross section (for hydraulic analysis; Rosgen 2012). The D_{50} particle (i.e., 50% of particles are smaller than D_{50} particle) in the representative pebble count helps classify the reach. For example, a C4 stream is a C channel type with a reach D_{50} particle representing gravel substrate. The D_{84} particle in the riffle cross section is used to calculate roughness coefficients and bankfull discharge estimation.

After visually and physically surveying the study reach, a modified Pfankuch stability rating was assessed for each site. The Pfankuch stability rating is a qualitative assessment that estimates stability of the representative channel based on upper bank, lower bank, and channel characteristics (Pfankuch 1975; Rosgen 1996; Rosgen 2001b). After scoring each metric, a final score is calculated and an adjective rating is given (i.e., poor, fair, and good) based off of the potential stream type for the study reach.

Office Methods

Once the survey elevation data are collected out in the field, they are exported to an excel file using Trimble Business Center. The data are then copied from excel and imported into RIVERMorph Professional, version 5.1; developed by Stantec. Once all of the raw data collected in the field are entered into RIVERMorph; cross sections, longitudinal profiles, dimensional and dimensionless ratios, and other graphs can be generated in order to classify a representative stream channel. Radius of curvature, linear wavelength, and other pattern variables can be measured and calculated using the GIS tool in RIVERMorph.

In order to validate field bankfull calls, the USGS StreamStats tool is used to give drainage area, land use, and predicted flows with confidence estimates (Lorenz et al. 2009). Using RIVERMorph, one can estimate what the predicted bankfull (~1.5 year return interval) discharge is using measured water slopes and roughness coefficients, and if that falls near the StreamStats estimate, bankfull calls are validated.

Another tool being developed to help with bankfull call validation is a regional curve. Regional curves correlate a variety of variables, but the most commonly used is cross sectional area and drainage area. Other factors (e.g., slope, channel type) can affect how close a site is to the predicted cross sectional area, but most often this is a useful tool to get a good estimate of what the cross sectional area of the riffle cross section should be based off of drainage area. It is important to base these data by region because many factors can affect the dimension of the channel (e.g., precipitation, runoff potential, local geology).

ArcMap is another office tool used to assess geomorphological changes in stream reaches. Most often, the 1991 aerial photos are used to draw historical streamlines, and then overlaid on the most recent aerial photo. Aerial photo analysis can distinguish lateral stability (i.e., how much the channel has laterally migrated since 1991) and also if the channel appears to be changing its dimension or pattern.

Another use of ArcMap is the use of LiDAR data to create valley cross sections at the study reaches to help distinguish the type of valley the stream is in. Valley type defines the boundary conditions of the channel and helps predict lateral confinement. Other uses of LiDAR can relate to local slope conditions, stream power, terrain analysis, and historical depressional areas.

Results

Hydrology

Stream flow data in the Missouri River basin were collected at two separate gages on the Rock River: Luverne and Hardwick (Figure 4). Stream data collection at Luverne began in 1911 through the USGS, but was discontinued in 1914. The site was reestablished in the fall of 1996 and is currently operating. The Hardwick site was established in 1998 and is currently operating. Ideally a long-term data set (>30 years) would exist for all sites, allowing for in-depth analysis of changes over time; however, the Missouri River basin does not have that available in Minnesota. Long-term data allows for better analysis within a watershed and can help show trends or pinpoint when relationships changed.

Smaller data sets can still provide useful data to analyze for smaller, more recent shifts or changes within the period of record. The overlap within the period of record between the data sets available for both sites is 15 years, which allows for comparisons between the flow records between locations. However, determining the rates of change over time between the data collected in 1911 and the recent data can only be described in general terms.

Discharge Analysis

Discharge data for both locations were plotted from 1998 through 2013 (Figure 5). The general response of the watershed to precipitation events is similar. The total discharge volumes were similar from 2001 through 2013, likely due to close proximity of the sample locations and intermittent nature of some of the smaller river and streams in the watershed.

The Luverne site does include an additional watershed area of 105 square miles, which includes discharge from Champepadan and Mound Creeks. Precipitation received in the Champepadan watershed likely accounts for the significantly higher discharge peaks at the Luverne gage in 1998 and 2001. Based on linear trend lines applied to both data sets, the Luverne discharge is staying fairly consistent while the Hardwick discharge is increasing (Figure 5).

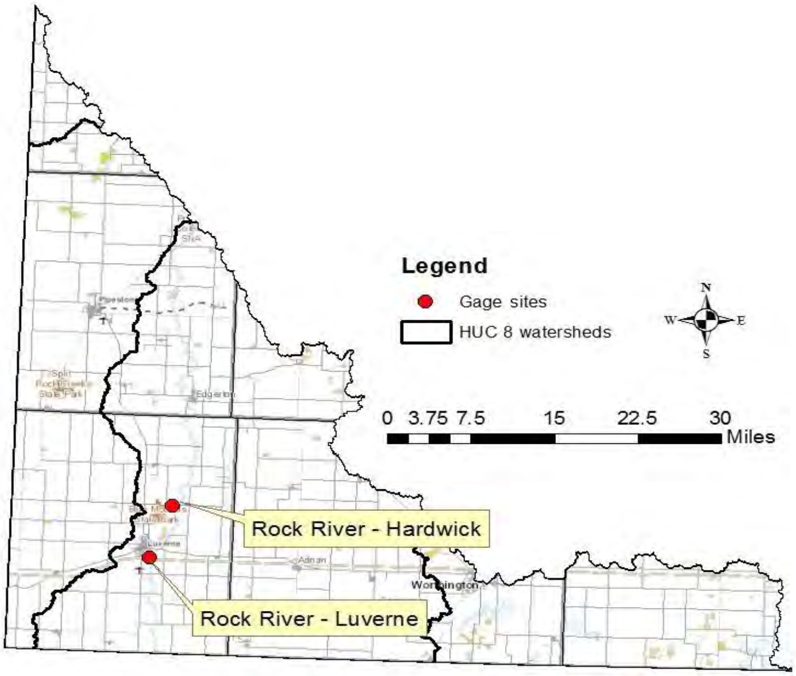


Figure 4. Location of stream gages in the Missouri River basin (Minnesota portion).

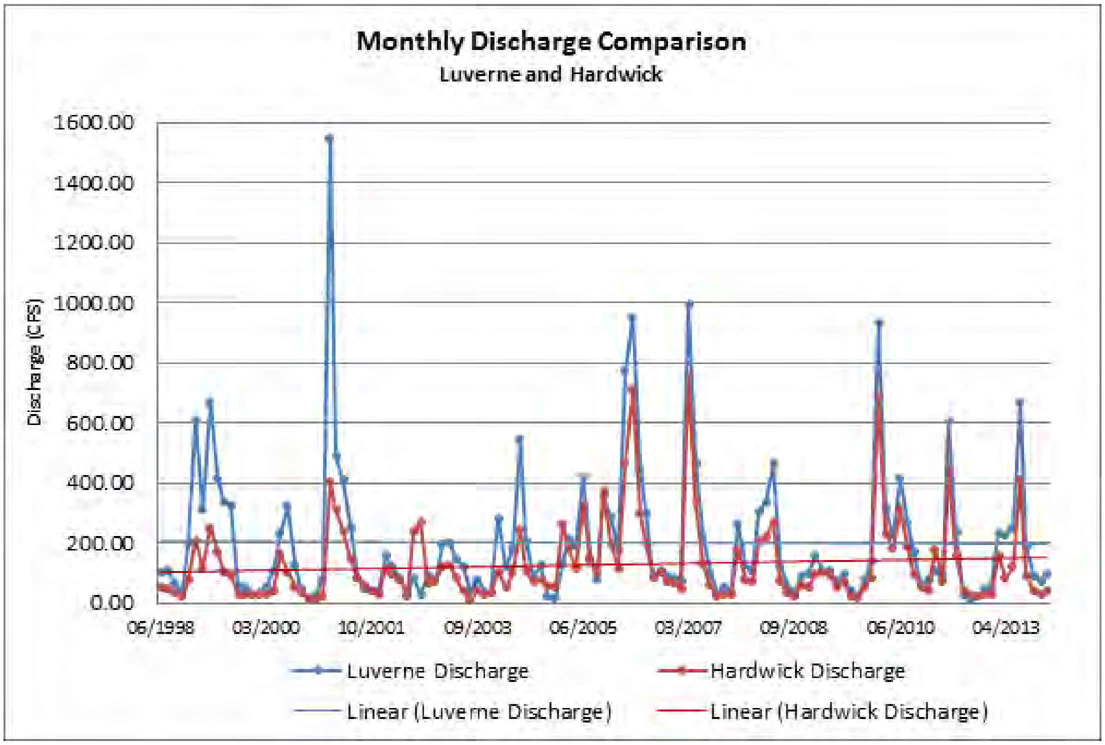


Figure 5. Monthly discharge comparison between the Luverne and Hardwick gages on the Rock River from 1998-2013 with trend lines.

Discharge data are also used to create a flow duration curve. Duration curves were used to examine the discharges and determine when a specific flow volume was exceeded or equaled in a given period, such as how often the flow volume exceeds high (10th percentile) and low (90th percentile) flow conditions for the watershed. With a large enough dataset, a relative frequency can also be calculated.

A flow duration curve was assessed for the Luverne and Hardwick gages for the period of record (Figure 6). Both curves have a relatively flat slope even at high flows, indicating longer prolonged events like snowmelt or other watershed storage may be moderating flood and high flow conditions. The relatively flat slope throughout the curve suggests the presence of surface or groundwater interaction. Due to the limited number of lake and wetlands within the Missouri watershed and lighter soils, groundwater interaction is the more likely candidate.

Even at low flow conditions (90th -100th percentile), no periods of zero/no flow have been recorded at the Luverne site, with very few zero/no flow conditions at Hardwick. This may indicate moderate perennial storage in the watershed.

Precipitation

Precipitation data collected at Luverne indicate the area had dry to drought conditions from 1910 until approximately 1940. Since then the yearly precipitation totals have been widely variable, and slowly trending upwards until approximately 2000. The late 1980s recorded higher than average precipitation while the early 2000s exhibited lower than average precipitation. Recent precipitation has been drier than normal, with the lowest recoded annual value in 2001 (10.92”). It should be noted that the second highest annual precipitation total was recorded in 2010 (40.91”), exhibiting how variable rainfall totals are in this basin on an annual basis. Even with the variability of the annual total values, the seven year average is largely within the 25th-75th percentile values, indicating a fairly stable precipitation in the region (Figure 7). Precipitation and discharge data are used to develop the double mass curve to examine the relationship between precipitation and discharge.

Double Mass Curve

Double mass curves (DMC) were developed for both the Luverne (Figure 8) and Hardwick (Figure 9) gage locations. Precipitation data for both sets were collected from the Luverne precipitation data station. Data specific to Hardwick were not available. Both site analyses were developed using data from April – October. Winter discharge volumes were not available until 2008 so they were not assessed given the short period of record. The curve for the Luverne sample site includes the USGS data collected from 1911 to 1914, and the MNDNR data from 1995 to 2013. The data collected from 1911-1914 generally shows smaller discharge volumes, with the exception of the 1914 flood event, which has the highest recorded peak discharge from the watershed; resulting in the low R^2 value of 0.76 (Figure 8). The Luverne gage double mass curve shows a fairly consistent linear relationship between runoff discharge and precipitation

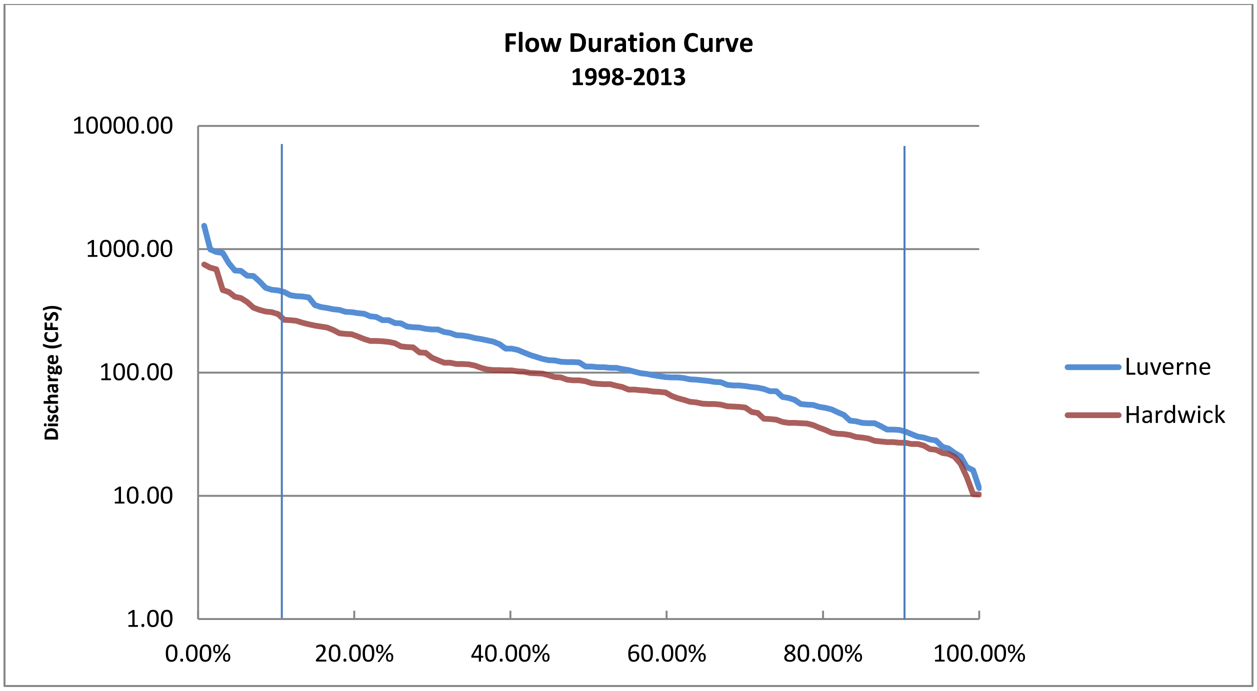


Figure 6. Flow duration curve for the Luverne and Hardwick gages for the period of record.

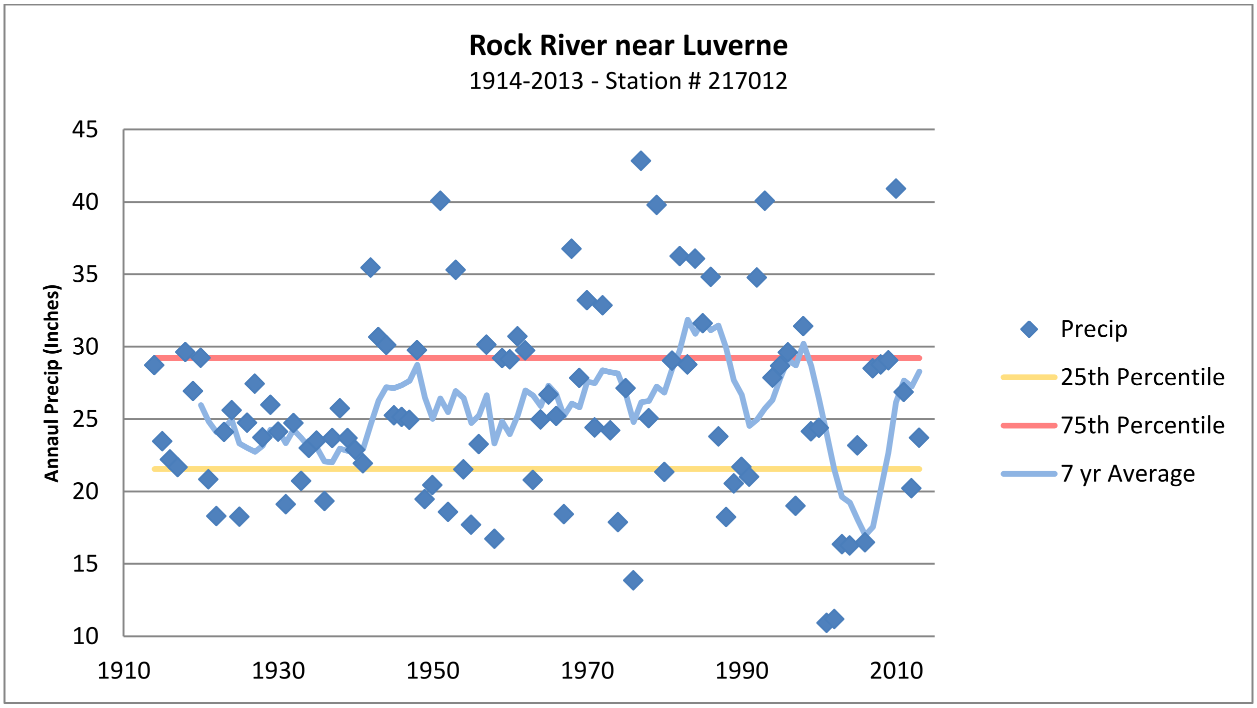


Figure 7. Annual precipitation totals in Luverne, MN from 1910-2013 with a moving 7 year average.

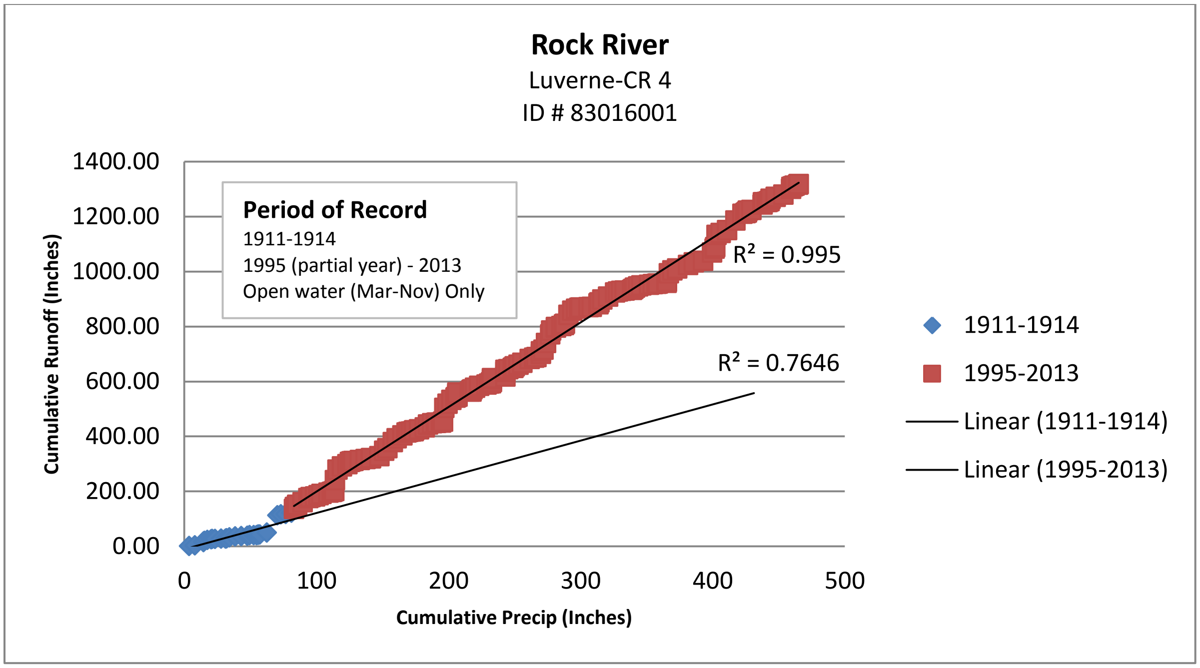


Figure 8. Double mass curve analysis for the Rock River gage at Luverne.

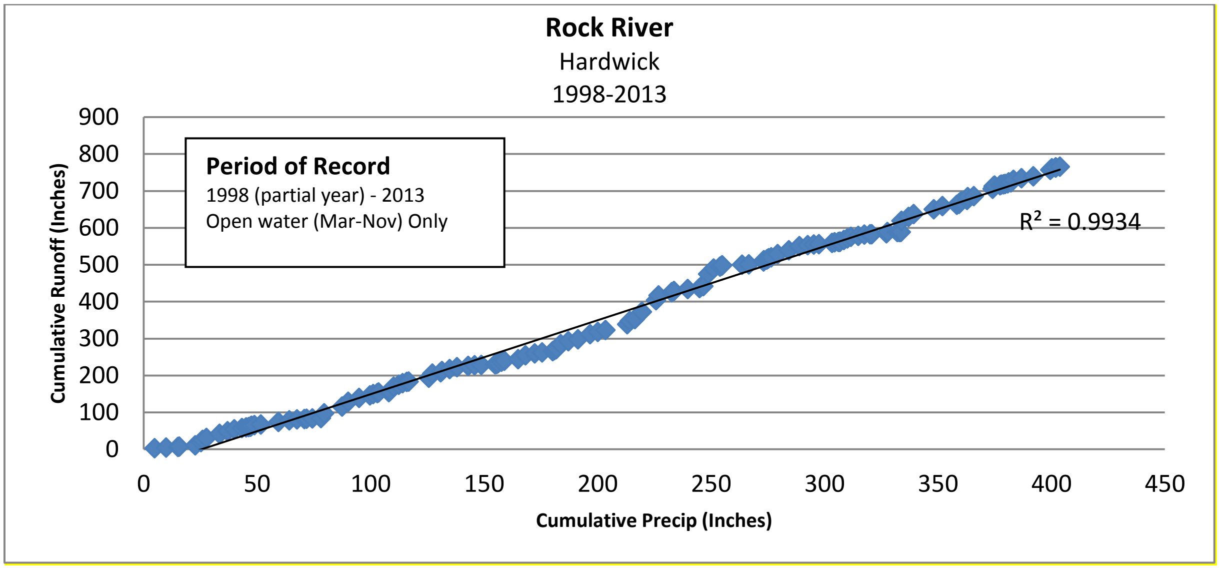


Figure 9. Double mass curve analysis for the Rock River gage at Hardwick.

during the 1995-2013 period of record, with the variability accounted for annual precipitation totals.

Due to the significant interval of time where discharge data were not collected, the analysis is limited and a specific time or total divergence in which the relationship changes is not known. However, the two datasets do demonstrate that the precipitation to discharge relationship is different between the two time frames. This change in the relationship could indicate that runoff is increasing relative to the amount of rain. Within the 1995-2013 dataset, both low and high annual precipitation volumes were recorded suggesting that a period of wet or dry conditions does not affect this relationship.

The curve for the Hardwick sample site includes MNDNR data from 1998 to 2013. The DMC plots out very similar to the Luverne data, with no change within the relationship found within the period of record (Figure 9).

Web-based Hydrograph Analysis Tool

The discharge data sets were analyzed for changes for runoff and baseflow conditions by uploading the data into the WHAT tool. Due to the short period of record, no significant increases or changes in the ratio of runoff or baseflow were detected (Figure 10).

Ground Water Usage

Groundwater usage for the watershed was reviewed by compiling all reported permitted usage. All permit data were collected through the SWUDS. The largest appropriation/usage category in the Rock River watershed is municipal waterworks, followed by rural waterworks (Figure 11). Rural waterworks has shown the most consistent upward trend in usage over time. Major crop irrigation reported levels were highest in 1998, and has stayed below 100 million gallons per year since 1992.

When the total appropriated volume was reviewed by county area, Rock County has the highest volume (Figure 12). This is likely due to the city of Luverne and municipal waterworks being the largest use in the area, combined with an increase in rural waterworks usage.

The type of aquifer used is also an important consideration when discussing discharge from the Rock River and groundwater/surface water interaction. The majority of the water being used is appropriated from relatively shallow wells, and is using the quaternary buried water table aquifers (Figure 13). Excessive pumping of the ground water aquifers may impact the Rock River, especially at periods of low flow, when ground water may be the majority of the baseflow input of the river. While still a small percentage, the use of quaternary buried artesian aquifers has been on the rise over the past decade (Figure 13).

In order to evaluate the potential impact on the water table from the usage, annual groundwater elevation range (max-min) over time was plotted in a double mass curve vs. precipitation from observation well number 51004 (Figure 14). Using the double mass curve technique eliminates

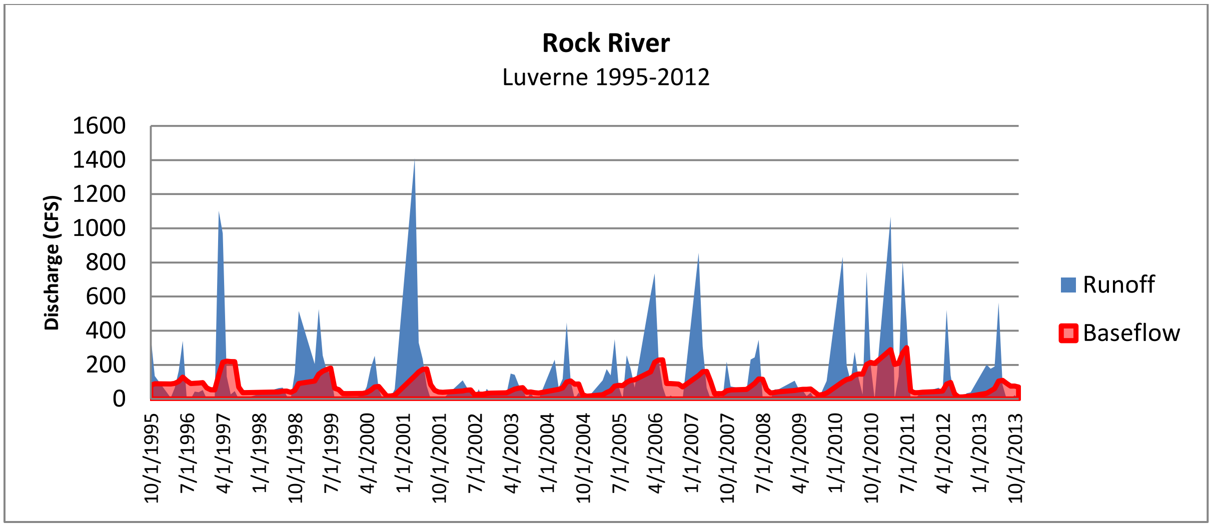


Figure 10. Calculated baseflow and runoff volumes using the WHAT tool for the Luverne gage.

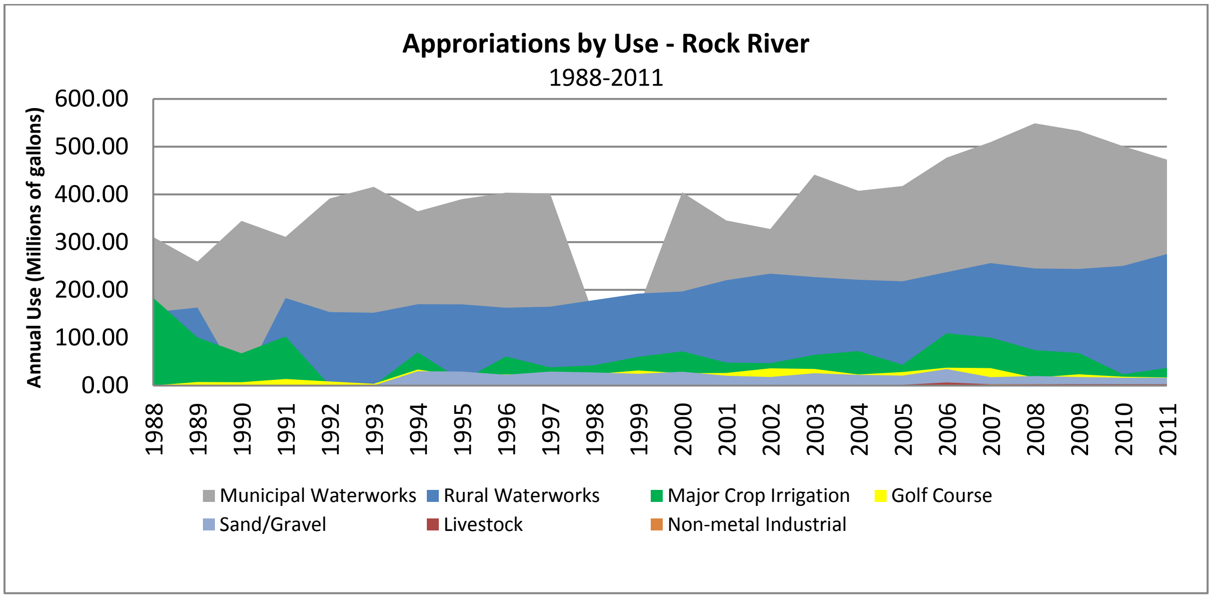


Figure 11. Water appropriation permitting by usage types from 1988-2011.

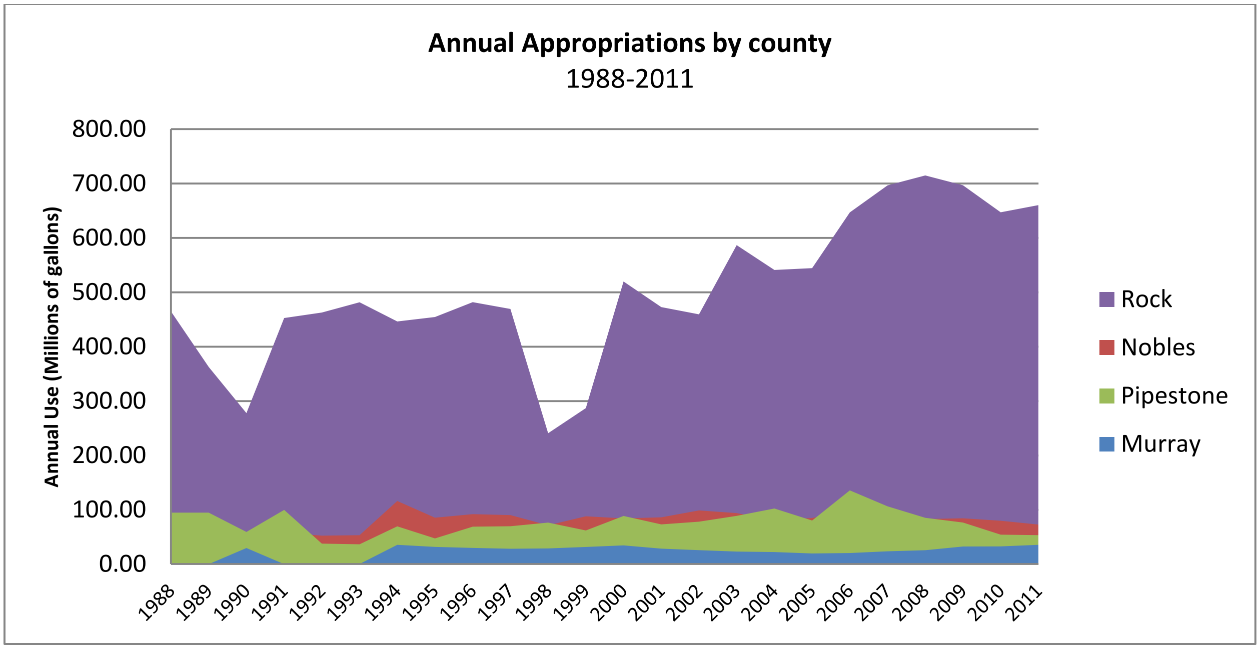


Figure 12. Annual water appropriation by county from 1988-2011.

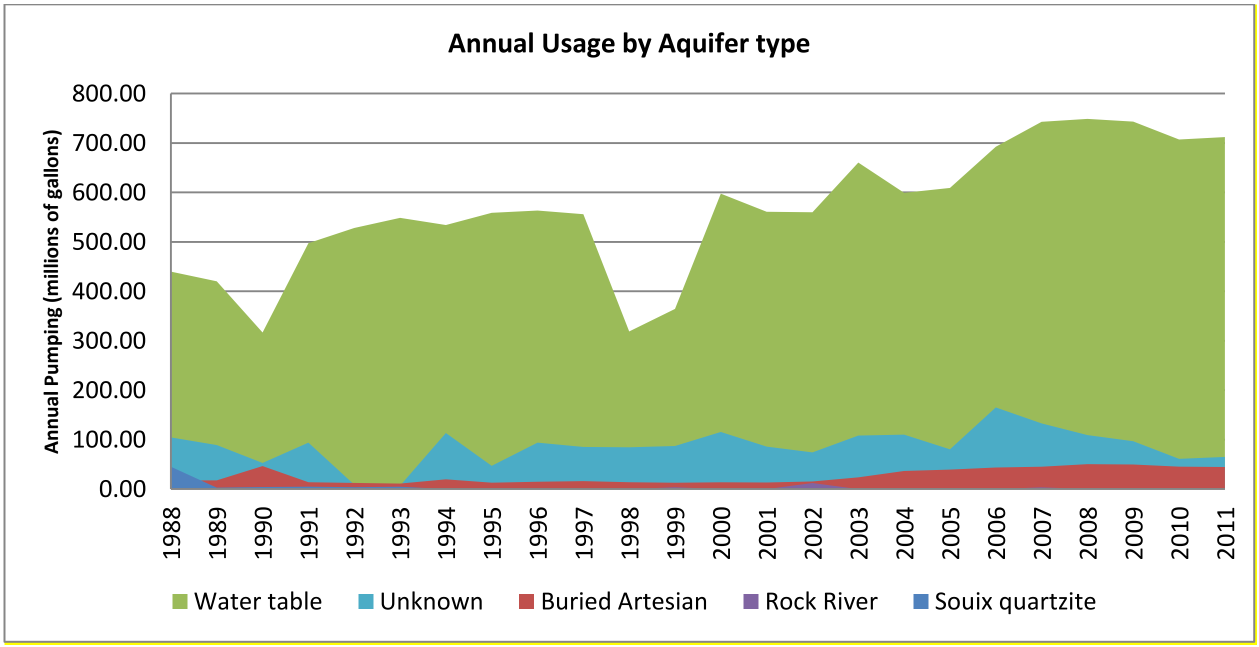


Figure 13. Annual water appropriation by aquifer type.

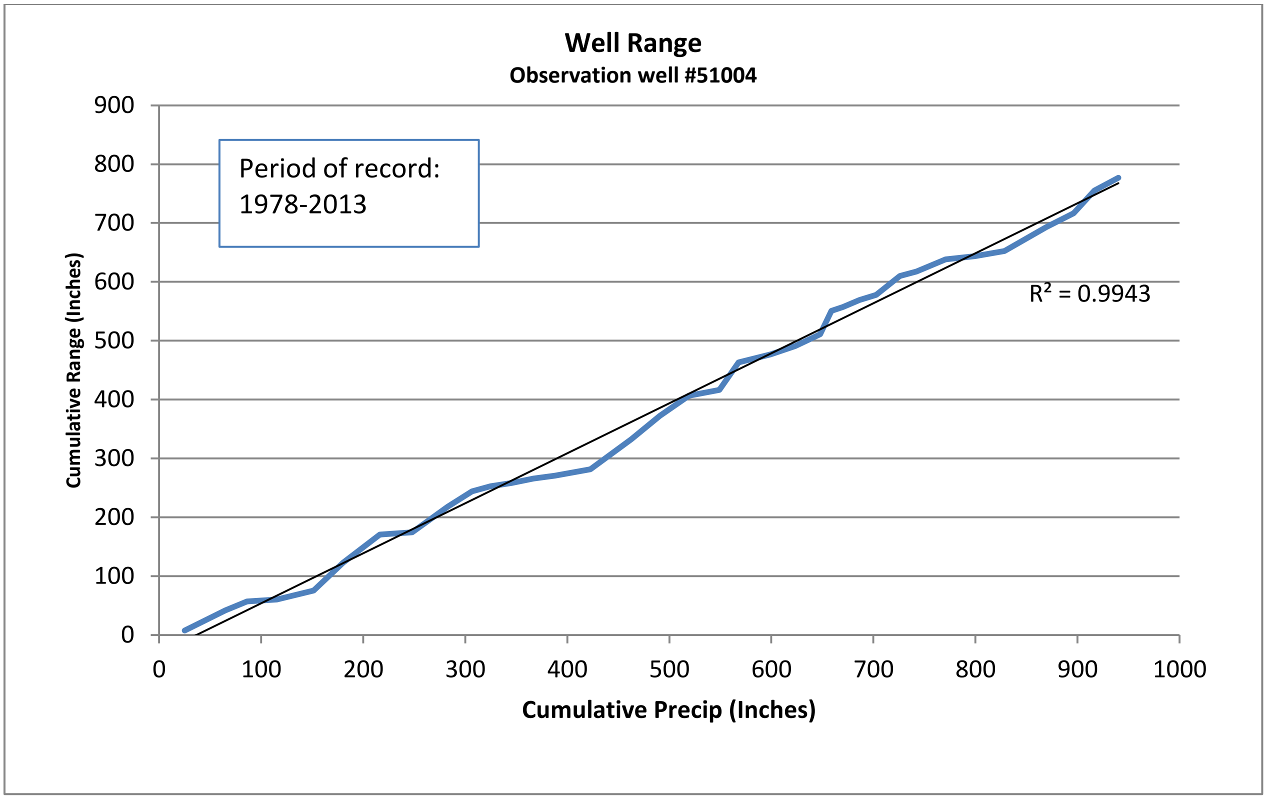


Figure 14. Groundwater elevation range double mass curve analysis from observation well #51004. The relative proximity to the 1:1 regression line helps show that there has not been a significant change in relationship during the period of record.

some of the natural variability often recorded in observation wells. While precipitation has been taken into account, it is important to note that climatic impacts have not been eliminated, because antecedent groundwater levels are very important in looking at fluctuations. Over the period of record of the observation well, no significant change in the relationship has been noted. That does not mean that this relationship will not change in the future based on changing land uses or appropriation volumes.

Connectivity

Longitudinal Connectivity

According to the GNIS database, there are eleven dams within the Missouri basin (2 in Lower Big Sioux, 5 in Rock, 4 in Little Sioux; Figure 15); however, one dam located on the Rock River near Luverne was replaced using a rock arch rapids design to allow fish passage in 2010. Outside of the replaced dam near Luverne, most of these dams are outlet control structures on lakes and small impoundments that likely do not affect MPCA fish community assessment sites. Zero waterfalls are documented on any of the main rivers in the watershed (Douglas 2011).

Floodplain Connectivity

Out of seven field survey sites, five were found to still have sufficient floodplain connectivity to recharge oxbows and provide refuge during high flow events. The two sites that appear to not be accessing their floodplains (Chanarambie Creek and Beaver Creek) are within an overly grazed pasture and row-crop agricultural riparian land use, respectively. Chanarambie Creek has had populations of Topeka shiners documented nearby the survey reach, where Beaver Creek only exhibits the shiners further upstream of the survey reach (Nagle and Larson 2013). At this time, Flandreau Creek shows minimal floodplain connectivity at the riffle cross section; however, along with Beaver Creek, StreamStats is currently unavailable for sites along the MN/SD border. Classification at these two sites is subject to change once StreamStats is updated.

At the Kanaranzi Creek survey site, the landowner was interested in assessing floodplain connectivity throughout his pasture to find protected calving areas and delineate rotational grazing scenarios. To estimate this, the “Interpolate Line” 3D analyst tool in ArcMap was utilized to create cross sections throughout the property. Using the validated bankfull elevation at the riffle cross section and extrapolating that throughout the reach with the measured water slope, the predicted flood-prone elevation for a 20 year discharge event (Q20; Figure 16) and a 50 year discharge event (Q50; Figure 17) were estimated at each of the LiDAR cross sections. These data were cross-checked with an engineering report and found to be very close to what the report estimated. Figure 18 shows the output of this method. Once all of the cross sections were analyzed, shapefiles were developed to show the landowner the approximate wetted perimeter of a 50 year discharge event and a 20 year discharge event so the landowner could find protected

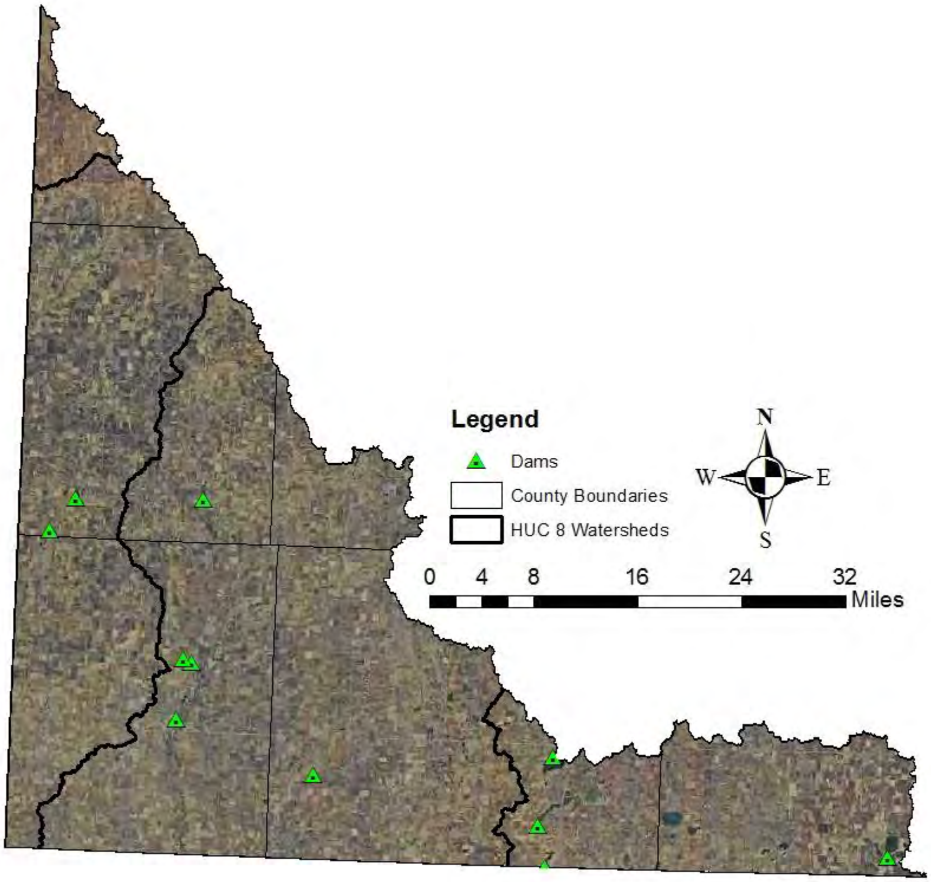


Figure 15. Location of dams in the Missouri River basin.

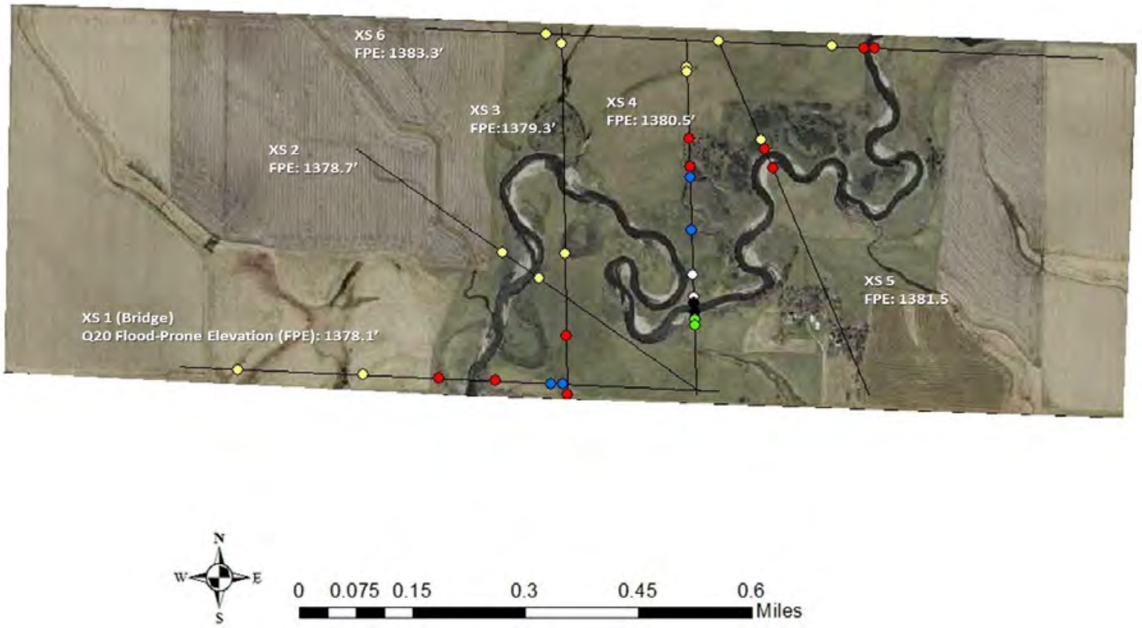


Figure 16. Aerial photo of the landowner's property on Kanaranzi Creek with Q20 flood-prone elevations (FPE). Each black line is a cross section created with LiDAR data. Flood-prone elevation is labeled at each of the cross sections, as well as colored dots that show areas within that cross section that are below the FPE. All cross sections were created from right (looking downstream) to left across the stream.

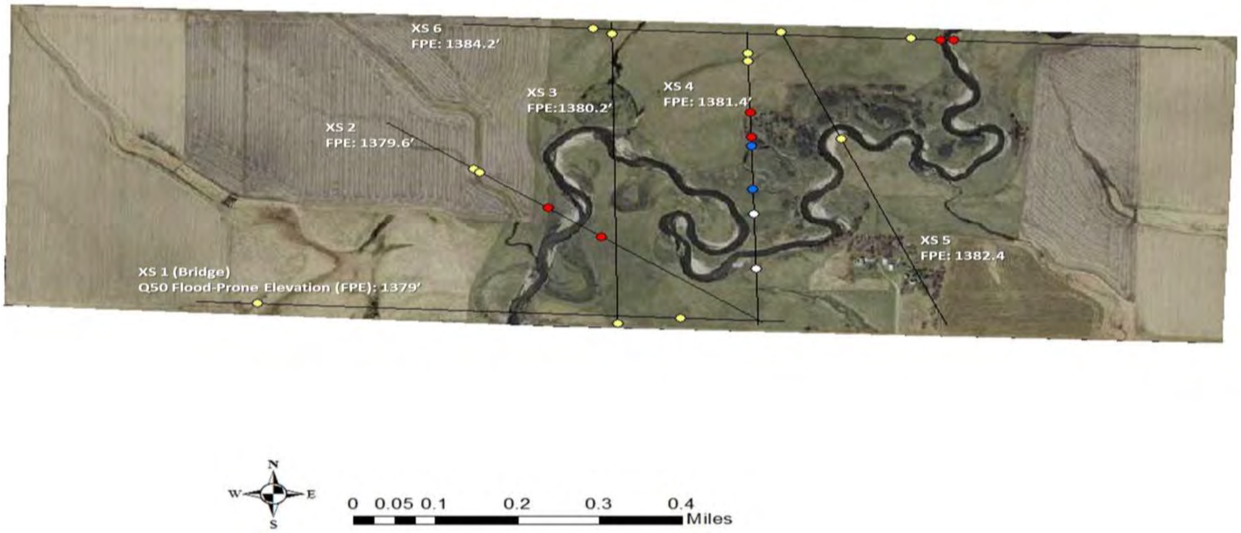


Figure 17. Aerial photo of the landowner's property on Kanaranzi Creek with Q50 FPE. Each black line is a cross section created with LiDAR data. Flood-prone elevation is labeled at each of the cross sections, as well as colored dots that show areas within that cross section that are below the FPE. All cross sections were created from right (looking downstream) to left across the stream.

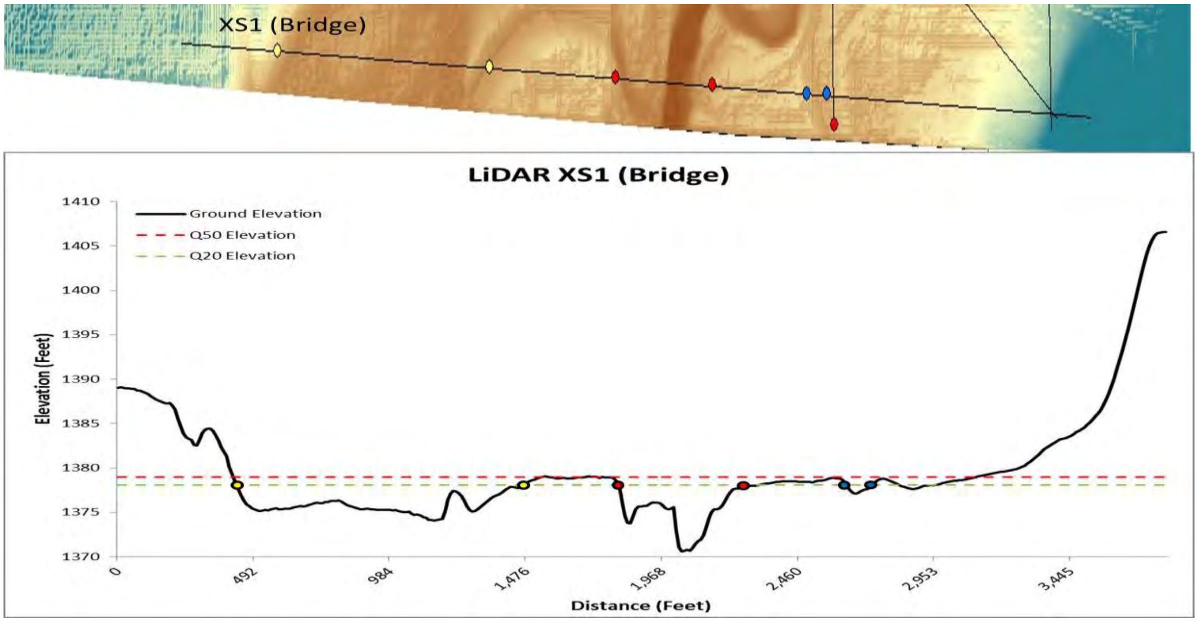


Figure 18. LiDAR cross section example from Kanaranzi Creek with output graph. Dots on the LiDAR image above correspond with dots on the elevation profile. The green dashed line shows the elevation of the Q20 flood event and the red dashed line shows the elevation of the Q50 flood event.

calving areas (Figure 19). These analyses could be used as a planning tool in future applications to find potential habitat restoration locations for Topeka shiners.

Riparian Connectivity

According to MNDOT's bridges and culverts layer in ArcMap, there are 530 bridges (0.30/mi^2) and 488 culverts (0.27/mi^2) in the Missouri River basin, 1018 stream crossings in total (0.57/mi^2; Figure 20). Table 2 details the density of bridges and culverts in each HUC 8 watershed in the Missouri basin. Given the density of crossings in this basin, proper sizing is important for streams to maintain stability. Improper sizing can lead to issues with moving sediment through culverts, and has adverse effects upstream and downstream (Zytkovicz and Murtada 2013; Figure 21).

Riparian vegetation was analyzed at each of the geomorphology survey sites using the BEHI model; especially bank height, root depth, root density, and weighted root density. Only two sites within the watershed that were surveyed had undisturbed vegetation; East Branch Rock River and Little Rock River. The Rock River survey site had mostly undisturbed riparian vegetation, but during the 2013 resurvey it was documented that some of the grasses were baled. Weighted root densities ranged from High to Extreme BEHI ratings at each of the sites, resulting in high susceptibility of erosion (Table 3).

Geomorphology

Out of seven survey sites, three are classified as "C" channels, two are classified as "E" channels, and two are classified as "F" channels (Figure 22). Results of each site are further explained in the following sections.

Kanaranzi Creek

Kanaranzi Creek (AUID 10170204-517; Norwegian Creek to MN/IA border) is currently impaired for fish and macroinvertebrate bioassessment (2013), while turbidity and *Escherichia coli* (*E. coli*) were listed in 2010. At the location of this survey site (near Minnesota/Iowa border; Figure 23), Kanaranzi Creek has a 193 square mile drainage area consisting of 84% cultivated crops, 10% perennial cover, and 6% "other" (WHAF 2013). Throughout the watershed, a majority of the riparian area is pastured while outside the stream's floodplain (usually >200' on both sides of the channel) is used for row-crop production.

At this site, Kanaranzi Creek is classified as a $C5_{c-}$ indicating that it is a low-gradient (water slope 0.07%) sand bed stream with point bar development, high outside banks, and good floodplain connectivity (Table 4). C5 stream types have a very high sensitivity to disturbance, fair recovery potential, very high sediment supply, very high streambank erosion potential, and riparian vegetation plays a significant role in maintaining stability (Table 5; Rosgen 1994).

The width-to-depth ratio at the riffle is 15.96 (Figure 24), relatively low for a C channel in an alluvial valley type; however, its tortuous meanders suggest that historically this stream was an E

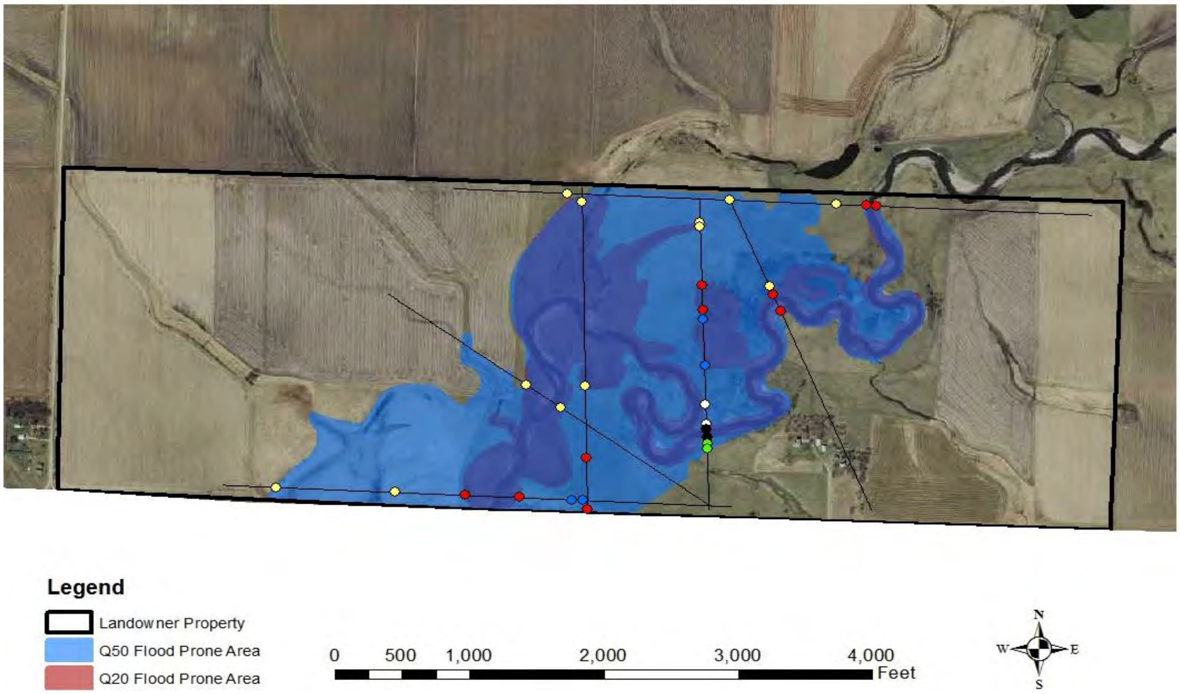


Figure 19. Polygons depicting the Q50 flood prone area (blue) and the Q20 flood prone area (red) delineated with LiDAR cross sections. Note that most oxbows in the reach appear to be recharged with the Q20 flood flows, but likely not on an annual basis.

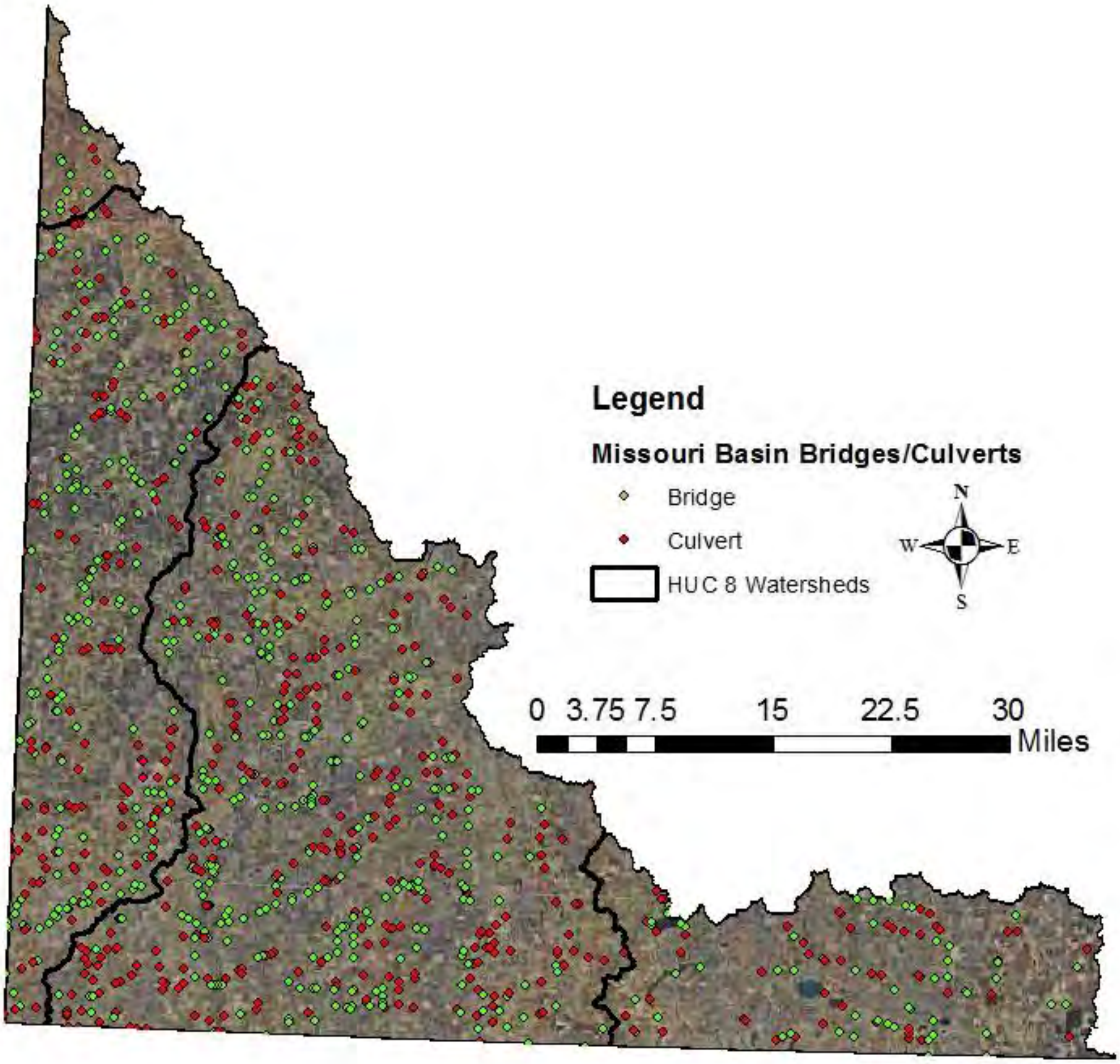


Figure 20. Location of bridges and culverts in the Missouri River basin.

Table 2. Number and density of road crossings in the Missouri basin broken down by HUC 8 sub-watershed.

	Watershed	Drainage Area (mi^2)	Number of Bridges	Density of Bridges (number/mi^2)	Number of Culverts	Density of Culverts (number/mi^2)	Total Road Crossings	Density of Road Crossings (number/mi^2)
	Upper Big Sioux	41	10	0.24	3	0.07	13	0.31
	Lower Big Sioux	511	174	0.34	134	0.26	308	0.6
	Rock River	910	293	0.32	297	0.33	590	0.65
	Little Sioux	321	53	0.17	54	0.17	107	0.34
Total		**1783**	**530**	**0.3**	**488**	**0.27**	**1018**	**0.57**

Figure 21. Aerial imagery of an oversized culvert on Kanaranzi Creek. The stream is flowing from right to left. Upstream of the culvert, the bankfull width is approximately 30 feet. The 4-barrel culvert is approximately 60 feet wide, affecting downstream bankfull widths to be twice as wide as upstream. Improper sizing of culverts can cause an excess amount of sediment downstream resulting in loss of habitat quality for a long distance downstream. Culverts should be properly sized to fit the bankfull channel and have flood relief culverts in the floodplain to handle high flows. Photo courtesy of Google Earth.

Table 3. Types of vegetation, bank and root characteristics, and corresponding BEHI rating for each weighted root density at Missouri basin geomorphology sites. Only two sites had relatively undisturbed riparian vegetation; E. Branch Rock River and Little Rock River.

Site	Vegetation Type	Bank Height (ft)	Root Depth (ft)	Root Density (%)	Weighted Root Density (%)	BEHI Rating
Kanaranzi Creek	Pasture Grass	8.9	2	5	1.12	Extreme
E. Branch Rock River	Unpastured Grasses	4	3	35	26.25	High
Rock River	Unpastured Grasses/Willows	12	2	20	3.33	Extreme
Little Rock River	Unpastured Grasses	8	3.5	35	15.31	Very High
Chanarambie Creek	Pasture Grass	9	1	10	1.11	Extreme
Flandreau Creek	Pasture Grass	10	6.5	35	22.75	High
Beaver Creek	Willows/Row Crop	10	0.5	5	0.25	Extreme

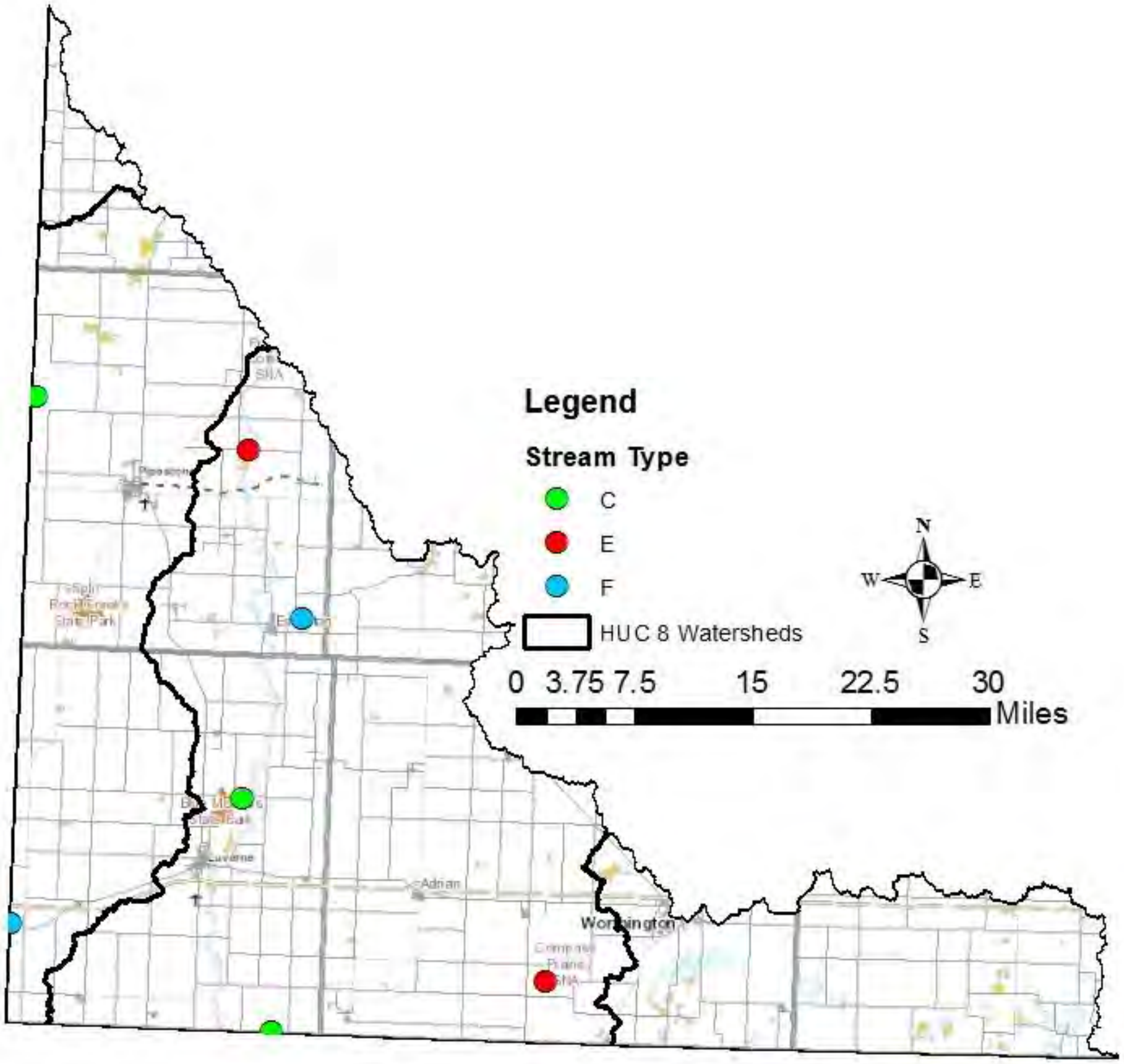


Figure 22. Location of MNDNR geomorphology survey sites with corresponding stream types.

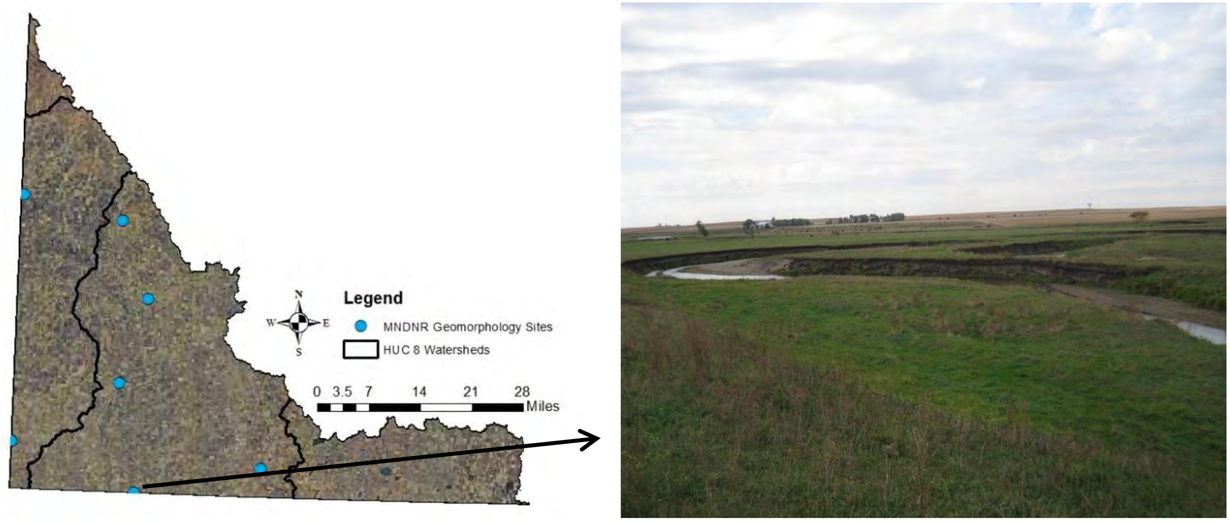


Figure 23. Location of Kanaranzi Creek geomorphology site in relation to the rest of the Missouri River basin.

Table 4. Baseline information about the Kanaranzi Creek geomorphology site.

Stream Information			
Stream Name	Kanaranzi Creek	**Drainage Area**	193 mi^2
AUID	10170204-517	**Stream Type**	$C5_{c-}$
HUC 8 Watershed	Rock River	**Valley Type**	8(c) Terraced Alluvial
County	Rock	**Water Slope**	0.0007 ft/ft
Township	Kanaranzi	**Sinuosity**	4.75
Section	33	**Erosion Estimates**	0.093 tons/foot/year
Range	44	**Pfankuch Stability Rating**	127 (Poor)

Table 5. Management implications for individual stream types (from Rosgen 1994).

Stream Type	Sensitivity to Disturbance [a]	Recovery Potential [b]	Sediment Supply [c]	Streambank Erosion Potential	Vegetation Influence [d]
A1	Very Low	Excellent	Very Low	Very Low	Negligible
A2	Very Low	Excellent	Very Low	Very Low	Negligible
A3	Very High	Very Poor	Very High	Very High	Negligible
A4	Extreme	Very Poor	Very High	Very High	Negligible
A5	Extreme	Very Poor	Very High	Very High	Negligible
A6	High	Poor	High	High	Negligible
B1	Very Low	Excellent	Very Low	Very Low	Negligible
B2	Very Low	Excellent	Very Low	Very Low	Negligible
B3	Low	Excellent	Low	Low	Moderate
B4	Moderate	Excellent	Moderate	Low	Moderate
B5	Moderate	Excellent	Moderate	Moderate	Moderate
B6	Moderate	Excellent	Moderate	Low	Moderate
C1	Low	Very Good	Very Low	Low	Moderate
C2	Low	Very Good	Low	Low	Moderate
C3	Moderate	Good	Moderate	Moderate	Very High
C4	Very High	Good	High	Very High	Very High
C5	Very High	Fair	Very High	Very High	Very High
C6	Very High	Good	High	High	Very High
D3	Very High	Poor	Very High	Very High	Moderate
D4	Very High	Poor	Very High	Very High	Moderate
D5	Very High	Poor	Very High	Very High	Moderate
D6	High	Poor	High	High	Moderate
DA4	Moderate	Good	Very Low	Low	Very High
DA5	Moderate	Good	Low	Low	Very High
DA6	Moderate	Good	Very Low	Very Low	Very High
E3	High	Good	Low	Moderate	Very High
E4	Very High	Good	Moderate	High	Very High
E5	Very High	Good	Moderate	High	Very High
E6	Very High	Good	Low	Moderate	Very High
F1	Low	Fair	Low	Moderate	Low
F2	Low	Fair	Moderate	Moderate	Low
F3	Moderate	Poor	Very High	Very High	Moderate
F4	Extreme	Poor	Very High	Very High	Moderate
F5	Very High	Poor	Very High	Very High	Moderate
F6	Very High	Fair	High	Very High	Moderate
G1	Low	Good	Low	Low	Low
G2	Moderate	Fair	Moderate	Moderate	Low
G3	Very High	Poor	Very High	Very High	High
G4	Extreme	Very Poor	Very High	Very High	High
G5	Extreme	Very Poor	Very High	Very High	High
G6	Very High	Poor	High	High	High

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

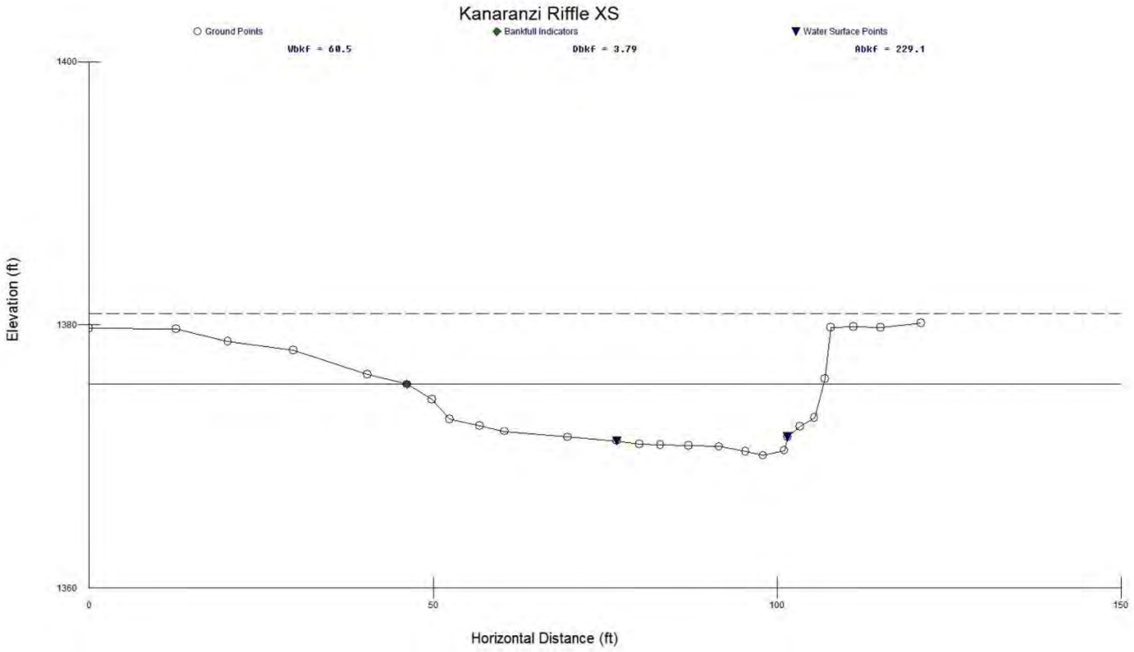


Figure 24. Riffle cross section at Kanaranzi Creek geomorphology site. Although there is still good floodplain connectivity, low bank height is only one foot lower than the floodplain elevation.

channel in its stable state that has evolved to a C channel. Bank Height Ratio (BHR) at this riffle cross section is 1.77, indicating that the channel is deeply incised at this location; however, other riffles throughout the reach had a lower BHR and were somewhat less incised. Raw banks at the site, Pfankuch stability rating, and aerial photo analyses suggest that this stream is going to continue widening out to a high width-to-depth ratio C and could likely go to an F stream type before reaching its stable stream condition again (Figure 25).

Evidence of this successional channel evolution is found in the shallow pools and fine active bed material while point bars and riffles show larger gravel materials. Sediment competence analysis from a bar sieve showed that the largest moveable particle is 40.5mm during a bankfull event, while the largest particle in the bar sieve was 55mm. Thus, Kanaranzi Creek does not have the competency or capacity to move the particles that are being delivered suggesting that the stream is aggrading. The longitudinal profile shows areas where pool filling is apparent as the reach has very poor pool quality until the bend near study bank 2 where a tight radius of curvature allows more shear stress to maintain a deep pool (Figure 26).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 696.61 cubic feet per second (cfs; U/U*) to 726.966 cfs (Manning's "n"). StreamStats analysis estimated the 1.5 year discharge to be 754 cfs with a 90% confidence interval between 464-1160 cfs (Table 6). Bankfull cross sectional area at the riffle is 229.1 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). These validations show bankfull calls for this reach are accurate.

A longer reach of Kanaranzi Creek was surveyed than normal (>20X bankfull width) because of a potential for future channel cutoffs that could turn the survey reach into an oxbow. Unlike many sites in the Missouri basin, continued annual resurveying of established longitudinal profiles and cross sections at this site are going to continue until the channel cutoff occurs to learn more about the processes involved. Survey points from 2012 to 2013 already show areas where there has been significant thalweg migration (Figure 27).

As previously stated, sediment supply from streambank erosion in Kanaranzi Creek is very high. The BEHI matched with NBS model estimated that this reach is contributing 0.093 tons of sediment (186 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 2,809' reach of stream delivers 261 tons of sediment (~26 dump truck loads) annually. At the two monumented cross sections the model is underestimating the amount of bank erosion in a normal year (Figure 28). The landowner explained that the reach has glacial outwash parent material with Loess soils incorporated making the banks highly erodible. This finding might support the conclusion that a model needs to be developed that pertains to the local geology of this site (Dave Rosgen, P.H., PhD; personal communication).

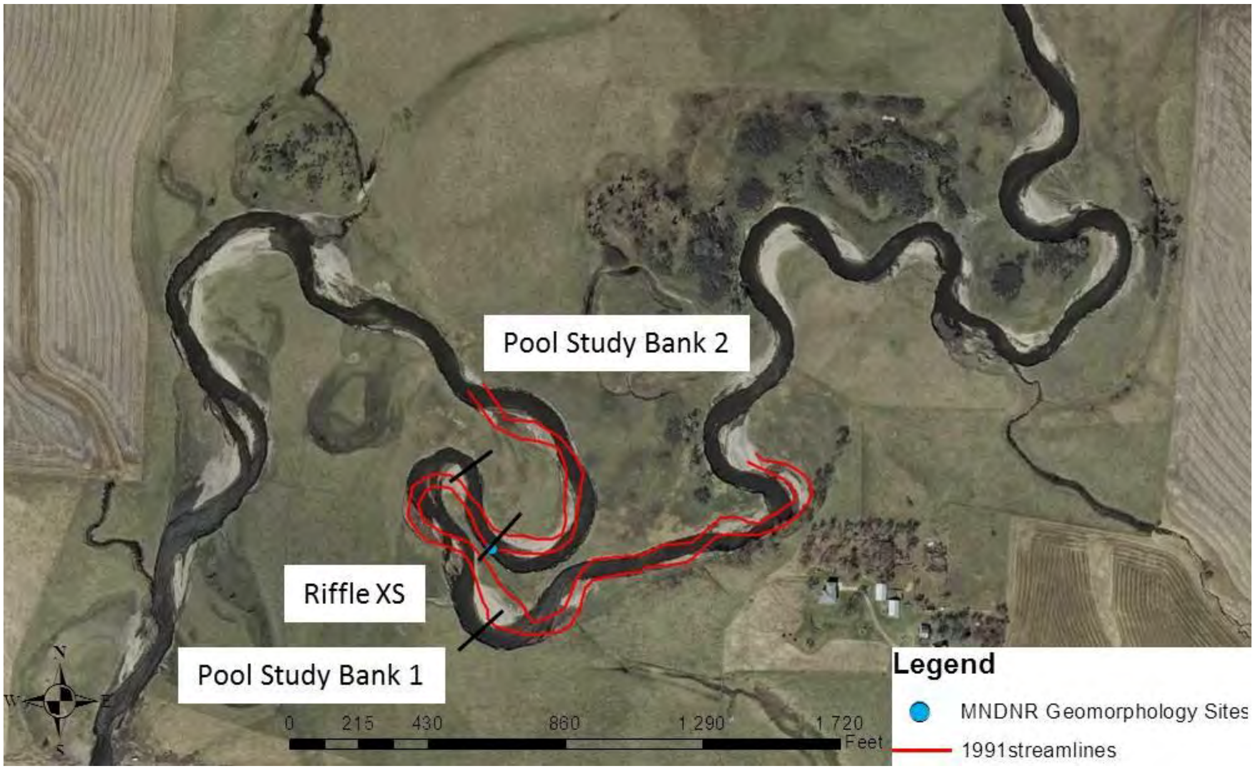


Figure 25. Aerial photo of Kanaranzi Creek geomorphology site with cross section locations and 1991 stream lines.

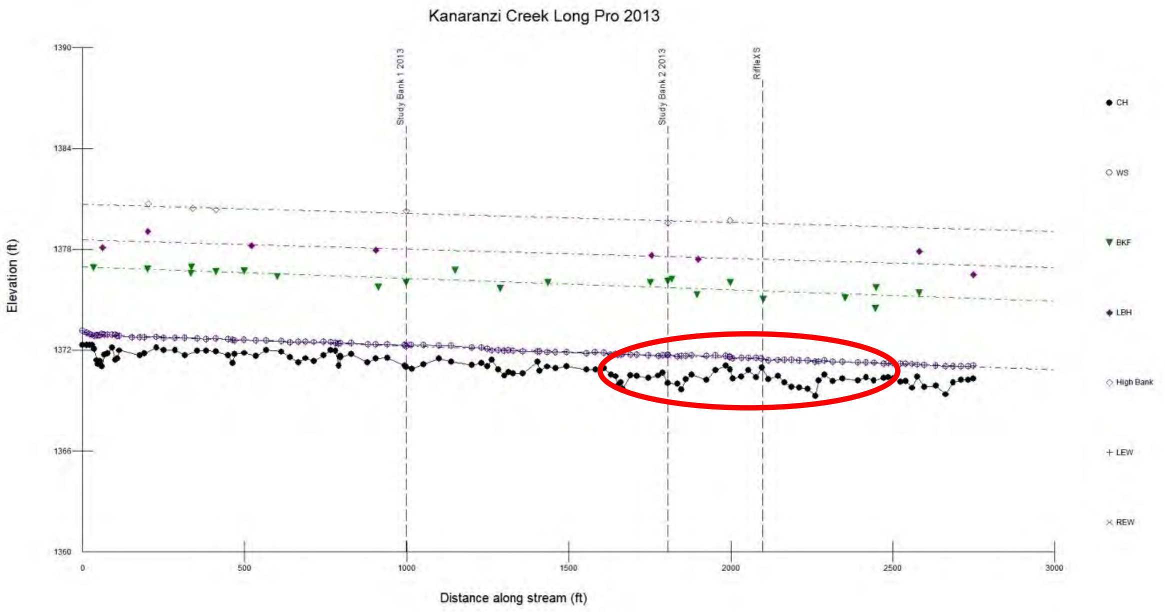


Figure 26. Longitudinal profile of the survey reach at Kanaranzi Creek. Note the lack of pool quality until the area of study bank 2 and downstream of the riffle cross section.

Table 6. Discharge estimation for all of the geomorphology sites based on riffle cross section and validation using the USGS StreamStats tool online.

Site	Estimated Bankfull Discharge Range (cfs)		StreamStats Estimate (cfs)	StreamStats 90% C.I.
	U/U* (Low)	Manning's "n" (High)		
Kanaranzi Creek	696.61	726.966	754	464-1160
East Branch Rock River	107.44	115.206	157	97.5-240
Rock River (Gage)	693.28	717.828	891	544-1390
Rock River (Riffle)	742.5	772.689	891	544-1390
Little Rock River	164.11	173.413	173	106-268
Chanarambie Creek	228.6	236.585	294	182-453
Flandreau Creek	71.6	74.1	n/a	n/a
Beaver Creek	157.55	163.047	n/a	n/a

Figure 27. Aerial photo (from Google Earth) of the Kanaranzi Creek site with 2012 and 2013 survey points. Notice the thalweg migration in the areas pointed out.

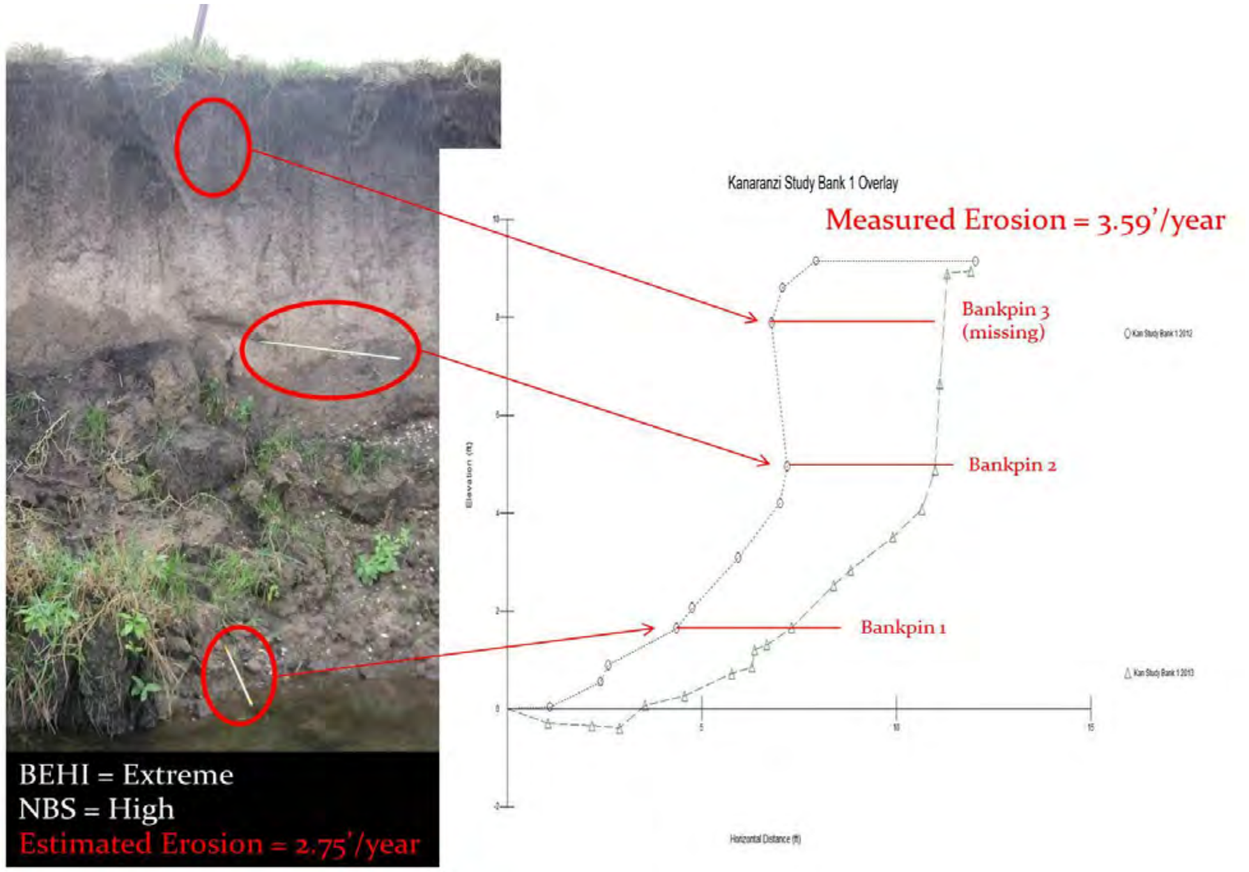


Figure 28. Visual of study bank used to validate bank erosion model by monumenting a cross section and installing three 4' bank pins into the bank. The model estimated there would be 2.75’ of bank erosion and actual bank erosion was 3.59’ in one year, with the top bank pin being completely removed from the bank. On the other study bank, the model estimated 1.074’ and measured 1.86’ of bank erosion; again, an underestimation.

Summary

Like many streams in Minnesota, anthropogenic activity has likely been the major cause for stream succession in Kanaranzi Creek. The geologic history of Kanaranzi Creek watershed makes soils more erodible, especially when riparian vegetation is sparse. Historical photo analysis showed that this stream has become wider and shorter since 1936, leading to excess bedload, pool filling, and increased stream slope. Geologic history and aerial photo analyses, coupled with field data collected over the past two years suggest that Kanaranzi Creek was historically an E channel that got wider and shallower becoming a high width-to-depth ratio C channel. Typically in this type of successional change, the stream will continue to widen until it can become once again a stable E channel within the base level of the current channel. This process could take many years and stream type changes before the stream creates its own equilibrium.

Very high sediment supply, lack of sediment competence and capacity, and pool filling observed at this site exhibit habitat degradation and may help explain the lack of fish and macroinvertebrates. Excessive bank erosion exhibited in our study bank cross sections and from aerial photo analysis likely helps explain the turbidity impairment classified within this AUID. Overall, this site appears to still be in a successional state of stability as sinuosity continues to decrease and slope increases, and is leading towards a less stable stream type. In order to restore the health of Kanaranzi Creek, implementation practices need to address the whole system (e.g., grassed waterways and buffers) instead of site-by-site (e.g., bank stabilization).

Management Recommendations for Kanaranzi Creek

The particular site surveyed on Kanaranzi Creek for this study has had a history of intensely grazed sections until the landowner proactively chose a better grazing approach with new renters. Now, the site is managed with rotational grazing practices that allow paddocks to re-vegetate before cattle are introduced. Historical overgrazing coupled with a few drier than average years and low base level flows in the channel led to undesirable riparian vegetation communities the few times the site was visited. Watershed-wide land use changes have likely led to a change in hydrology at this site over time, which has also increased the potential of bank erosion and other factors noted at this site. It is likely that the riparian vegetation changes paired with increased hydrology has made this channel evolve from a stable stream to one in disequilibrium. The best way to establish stability within this watershed would be to protect the banks with deep, dense rooted vegetation, and stabilize hydrology by implementing grassed waterways and contour terraces in high sloped uplands. Rotational grazing is a better practice than continuous grazing, and perhaps flash grazing (i.e., short-term grazing along the stream corridor at certain times of year) could be more beneficial for vegetation on stream banks. All of these practices coupled together could likely help realize the healthy watershed goals for Kanaranzi Creek.

East Branch Rock River

The East Branch of the Rock River (AUID 10170204-530; headwaters to Rock River) was just listed for its first impairment (macroinvertebrate bioassessment) in 2013. At the location of this survey site (in Terrace Wildlife Management Area, Pipestone County; Figure 29), East Branch of the Rock River has a 22.3 square mile drainage area consisting mostly of row-crop land use near the side-slopes of the Coteau. Land use in this catchment consists of: 62% cultivated crops, 32% perennial cover, and 6% "other" (WHAF 2013). As you approach this site on the Wildlife Management Area (WMA), it is difficult to see the stream channel with all of the tall grasses in the riparian area, especially in the middle of summer (Figure 29).

At this site, the East Branch is classified as an E4 indicating that it is gravel bed stream with a narrow, deep bankfull channel with good floodplain connectivity (Table 7). E4 stream types have a very high sensitivity to disturbance, good recovery potential, moderate sediment supply, high streambank erosion potential, and riparian vegetation plays a significant role in maintaining stability (Table 5; Rosgen 1994).

The width-to-depth ratio at the riffle is 7.77 (Figure 30), indicating that the channel is in fair to good condition and likely not in a successional state. Bank height ratio at this riffle cross section is nearly 1, indicating that the channel is stable and not currently incised. Highly vegetated banks at the site, Pfankuch stability rating, and aerial photo analyses also suggest that this stream has remained fairly stable (Figure 31).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 107.44 cfs (U/U*) to 115.206 cfs (Manning's "n"). StreamStats analysis estimated the 1.5 year discharge to be 157 cfs with a 90% confidence interval between 97.5-240 cfs (Table 6). Bankfull cross sectional area at the riffle is 28.9 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). These validations show that bankfull calls for this reach are accurate.

The BEHI matched with NBS model estimated that this reach is contributing 0.007 tons of sediment (14 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 308' reach of stream delivers 2.16 tons of sediment (~0.22 dump truck loads) annually. There was one study bank in this reach that was resurveyed in 2013. The Colorado bank erosion model predicted 0.153' of erosion and 0.736' of erosion was measured (Figure 32).

One potential concern with this site is the bridge located upstream of the study reach. Immediately downstream of the bridge there is an uncharacteristic pool for this stream that indicates the bridge is a stressor to channel stability (Figure 33). The bridge could be affecting the channel by improper sizing or by reducing the flood-prone area. Changes in dimension of the channel can disrupt sediment transport, resulting in excess deposition of fine materials.

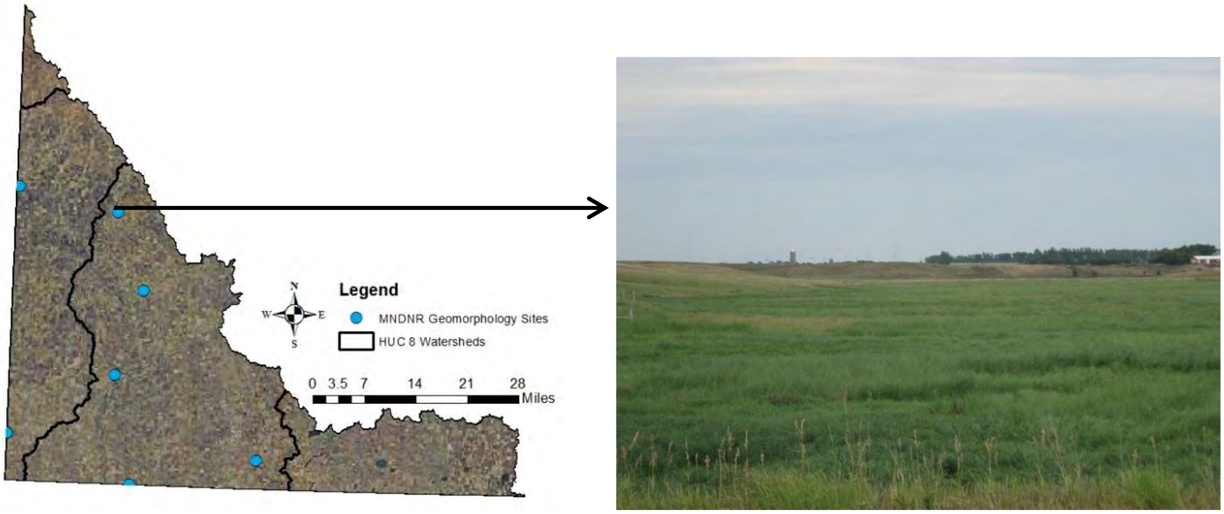


Figure 29. Location of the East Branch Rock River geomorphology site in relation to the rest of the Missouri River basin.

Table 7. Baseline information about the East Branch Rock River geomorphology site.

Stream Information			
Stream Name	E. Branch Rock	**Drainage Area**	22.3 mi^2
AUID	10170204-530	**Stream Type**	E4
HUC 8 Watershed	Rock River	**Valley Type**	8(c) Terraced Alluvial
County	Pipestone	**Water Slope**	0.0033 ft/ft
Township	Rock	**Sinuosity**	1.88
Section	31	**Erosion Estimates**	0.007 tons/foot/year
Range	44	**Pfankuch Stability Rating**	92 (Fair)

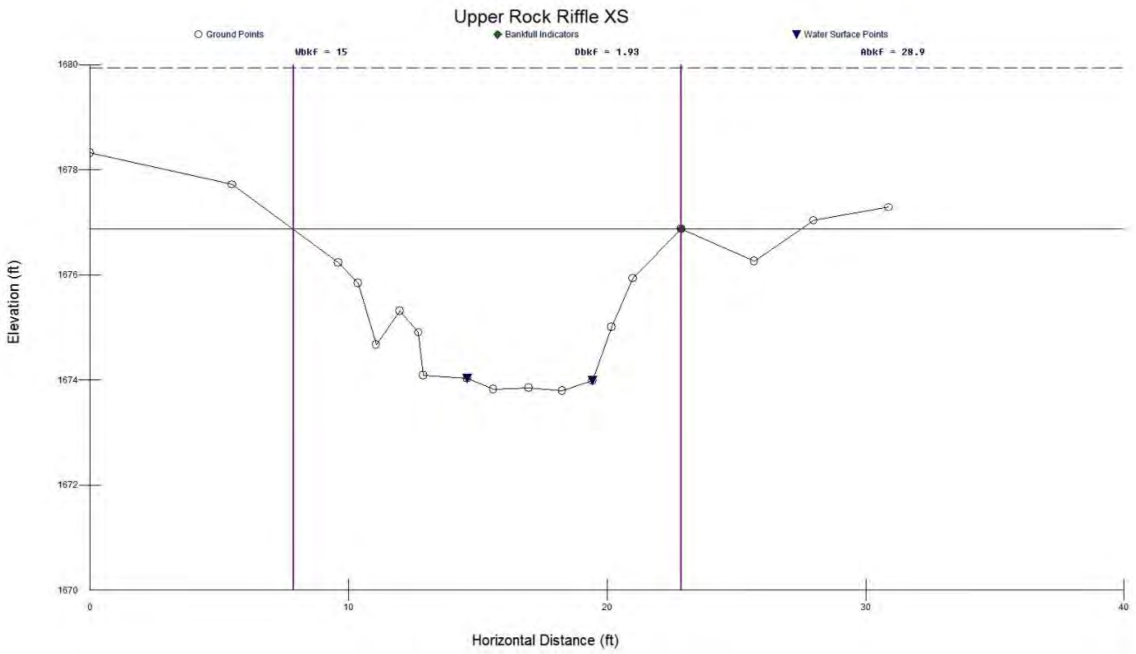


Figure 30. Graphical view of the representative riffle cross section in the survey reach at the East Branch Rock River site.

Figure 31. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

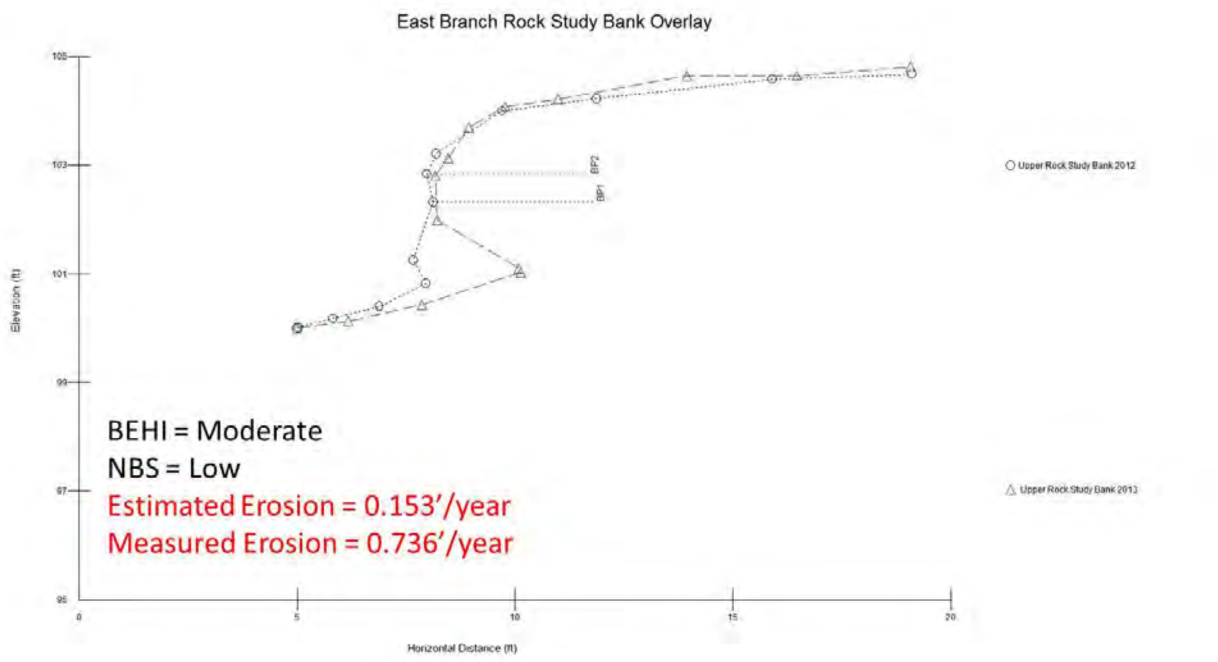


Figure 32. Study bank overlay for the East Branch Rock River site with estimated and measured erosion rates.

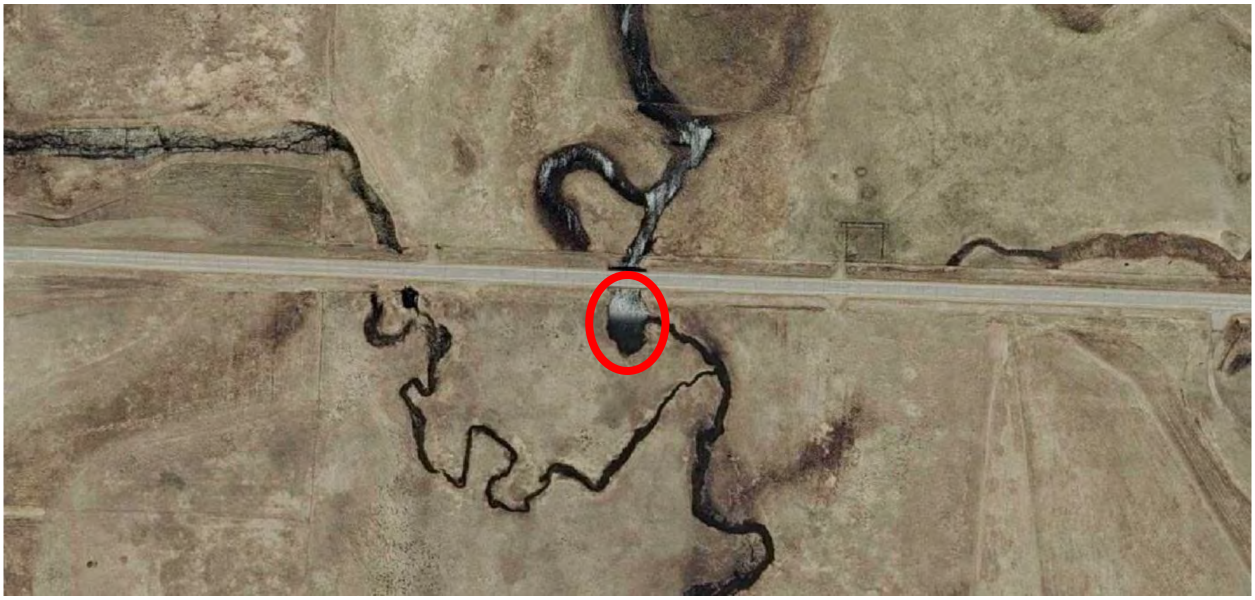


Figure 33. Aerial photo of oversized pool downstream of bridge, immediately upstream of the geomorphology survey reach.

Summary

Overall, this site appears to be the most stable out of all of the Missouri basin geomorphology sites based off of good W/D ratio, riparian corridor, and floodplain connectivity. It could potentially serve as a reference condition for this stream type and valley type combination. The current conditions could suggest why there are few impairments listed within this AUID. Lack of macroinvertebrates is likely caused by upstream sediment contribution as there were some areas with excessive fine material deposition, but other water quality factors that will be discussed in the MPCA SID report are also possible.

Management Recommendations for East Branch of the Rock River

Out of the small subsample of geomorphology sites surveyed in the Missouri River basin, the East Branch of the Rock River appeared to be the most stable. Since this site is located in a WMA, it is important that MNDNR staff continue to manage the riparian vegetation so the site does not become overgrazed or lose its vegetation quality. Ideally, the vegetation would include more native species than reed canary grass *Phalaris arundinacea*, but just having the vegetation there has shown to help maintain stability of the channel (Appendix 3). Also, upland management is critical to help the channel withstand potential hydrological changes from increased precipitation. Grassed waterways, contour farming, and terraces all help reduce surface runoff potential and consequent sediment inputs.

Rock River Gage (Hardwick)

The mainstem Rock River site (AUID 10170204-508; unnamed creek to Champepadan Creek) was just listed for fish and macroinvertebrate bioassessment, *E. coli*, and turbidity in 2013. At the location of this survey site (Hardwick Gage site; Figure 34), the Rock River has a 306 square mile drainage area consisting of 75% cultivated crops, 20% perennial cover, and 5% "other (WHAF 2013).

At this site, the Rock River is classified as a $C4_{c-}$ indicating that it is a low gradient, meandering, gravel bed stream with a wide bankfull channel, high banks on the outside bends, point bars on the inside bends, and good floodplain connectivity (Table 8). C4 stream types have a very high sensitivity to disturbance, good recovery potential, high sediment supply, very high streambank erosion potential, and riparian vegetation plays a significant role in maintaining stability (Table 5; Rosgen 1994).

The width-to-depth ratio at the riffle is 14.93 (Figure 35), a relatively low W/D ratio for alluvial valley types. Bank height ratio at this riffle cross section is nearly 1, indicating that the channel is stable and not currently incised. Although the riparian area is relatively undisturbed, Pfankuch stability rating and aerial photo analysis suggest that there is some instability in this channel and significant lateral migration (Figure 36).

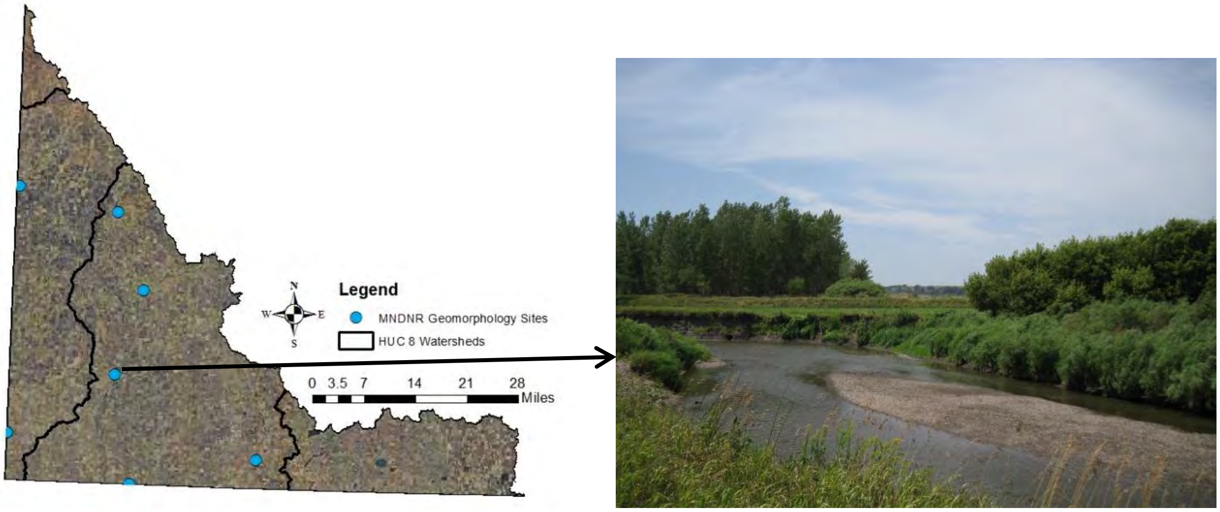


Figure 34. Location of the Rock River gage geomorphology site in relation to the rest of the Missouri River basin.

Table 8. Baseline information about the Rock River geomorphology site.

Stream Information			
Stream Name	Rock River	**Drainage Area**	306 mi^2
AUID	10170204-508	**Stream Type**	C4c-
HUC 8 Watershed	Rock River	**Valley Type**	8(c) Terraced Alluvial
County	Rock	**Water Slope**	0.0005 ft/ft
Township	Vienna	**Sinuosity**	1.42
Section	19	**Erosion Estimates**	0.038 tons/foot/year
Range	44	**Pfankuch Stability Rating**	125 (Poor)

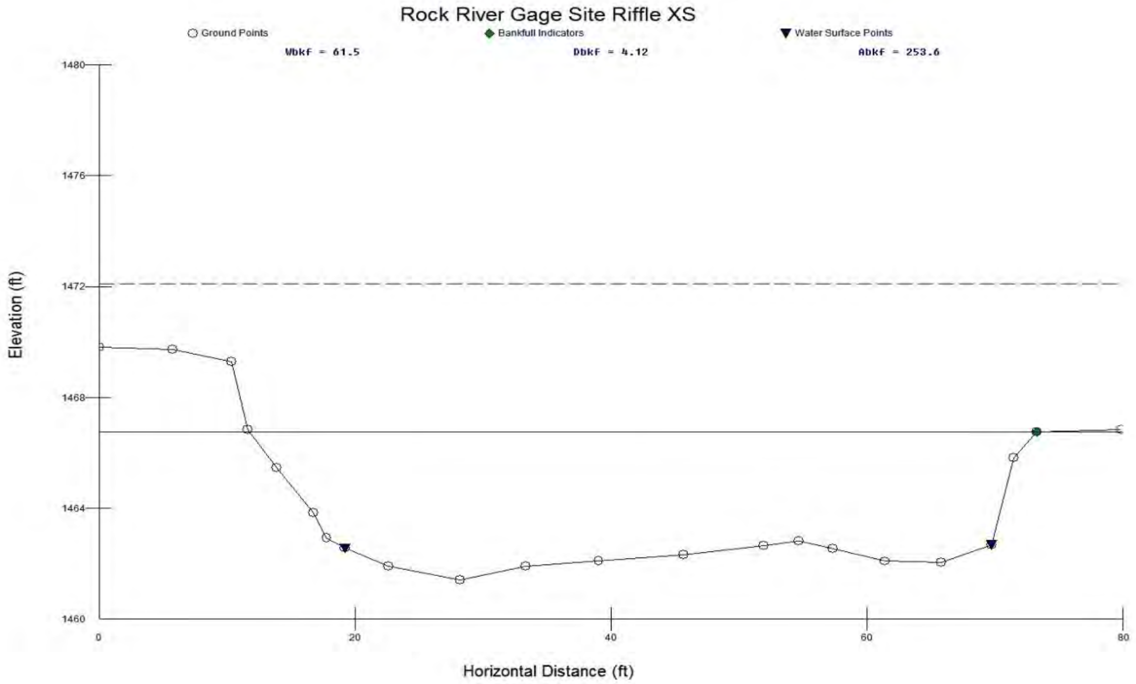


Figure 35. Graphical view of the representative riffle cross section in the survey reach at the Rock River site.

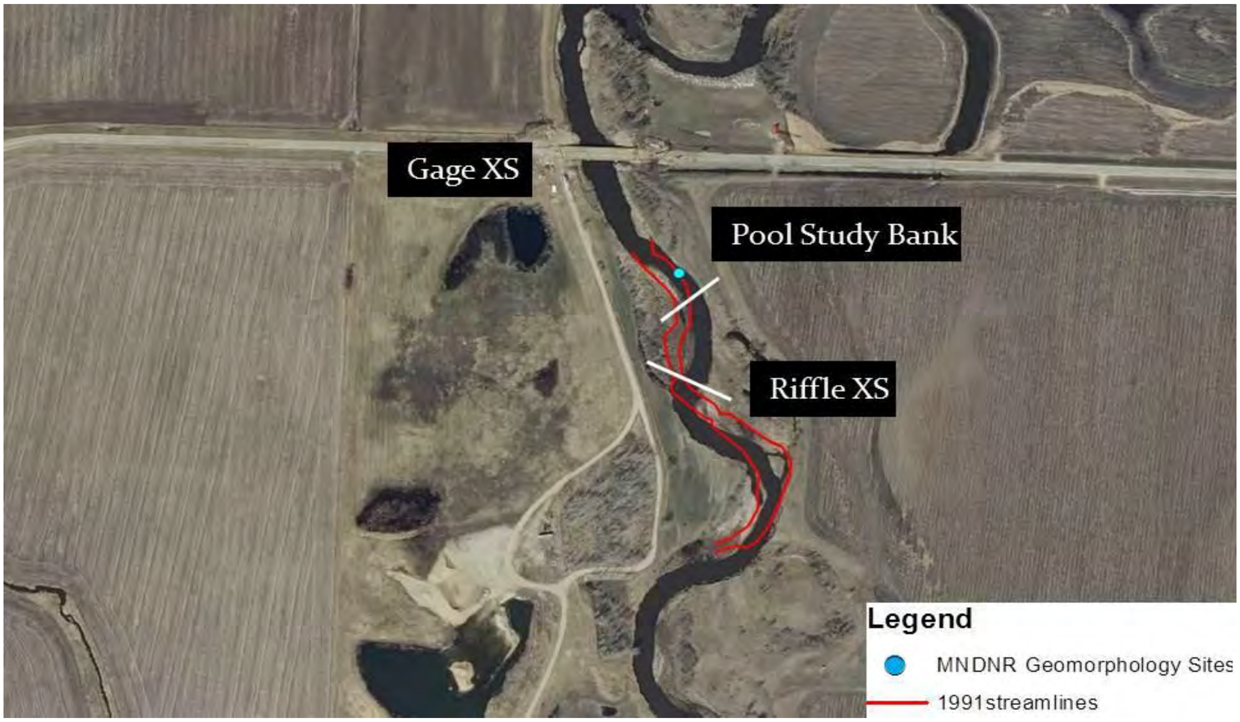


Figure 36. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

Since this was a gage site, a cross section was taken at the gage in order to analyze bankfull discharge at the gage location, and also at the riffle location. Discharge analysis at the riffle cross section estimated bankfull discharge to range from 742.5 cfs (U/U*) to 772.69 cfs (Manning's "n"). At the gage cross section, discharge analysis estimated a range of bankfull flows from 693.28 cfs (U/U*) to 717.83 cfs (Manning's "n"). Peak flow analysis from the gage data (6/1998-present) estimated the 1.5 year return interval flow to be 680cfs; resulting in the field bankfull estimation to be about a 1.7 year return interval flow.

StreamStats analysis estimated the 1.5 year discharge to be 891 cfs with a 90% confidence interval between 544-1390 cfs (Table 6). Bankfull cross sectional area at the riffle is 253.6 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). These validations show that bankfull calls for this reach are accurate. Bankfull indicators throughout the reach were apparent, so although the discharges appear to be higher than the measured 1.5 year return interval flow, they are still between 1-2 year events.

The BEHI matched with NBS model estimated that this reach is contributing 0.038 tons of sediment (76 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 1433' reach of stream delivers 54.45 tons of sediment (~5.4 dump truck loads) annually. There was one study bank in this reach that was resurveyed in 2013. The Colorado bank erosion model predicted 0.25-0.38' of erosion and 3.15' of erosion was measured, significantly higher than what was estimated (Figure 37).

Summary

Overall, this site appears to be fairly stable with good pool quality and satisfactory riffles for a low gradient stream. There were a few mid-channel bars with gravel materials suggesting there may be excess bedload and over-widening in spots. Lateral erosion has shown to be very active which could explain turbidity impairments, but pool filling was not evident at this site. It is likely that fish and macroinvertebrate communities are impaired for reasons other than explained by geomorphology and habitat quality; however, riffle quality in this reach was fair to poor so that may explain some of the issues. Other probable factors will be addressed in the SID report.

Management Recommendations for the Rock River at Hardwick

Although riparian vegetation quality is better at the Rock River (Hardwick) gage site than at Kanaranzi Creek, high bank erosion and sediment supply was still observed (Figure 37). Much of this was due to the lack of quality vegetation, root depth, and root density; resulting in a poor weighted root density and minimal bank protection (Table 3). Bank angles throughout this reach were also too high to maintain lateral stability. With many outside banks having angles of 90° or higher, the banks already were susceptible to high bank erosion.

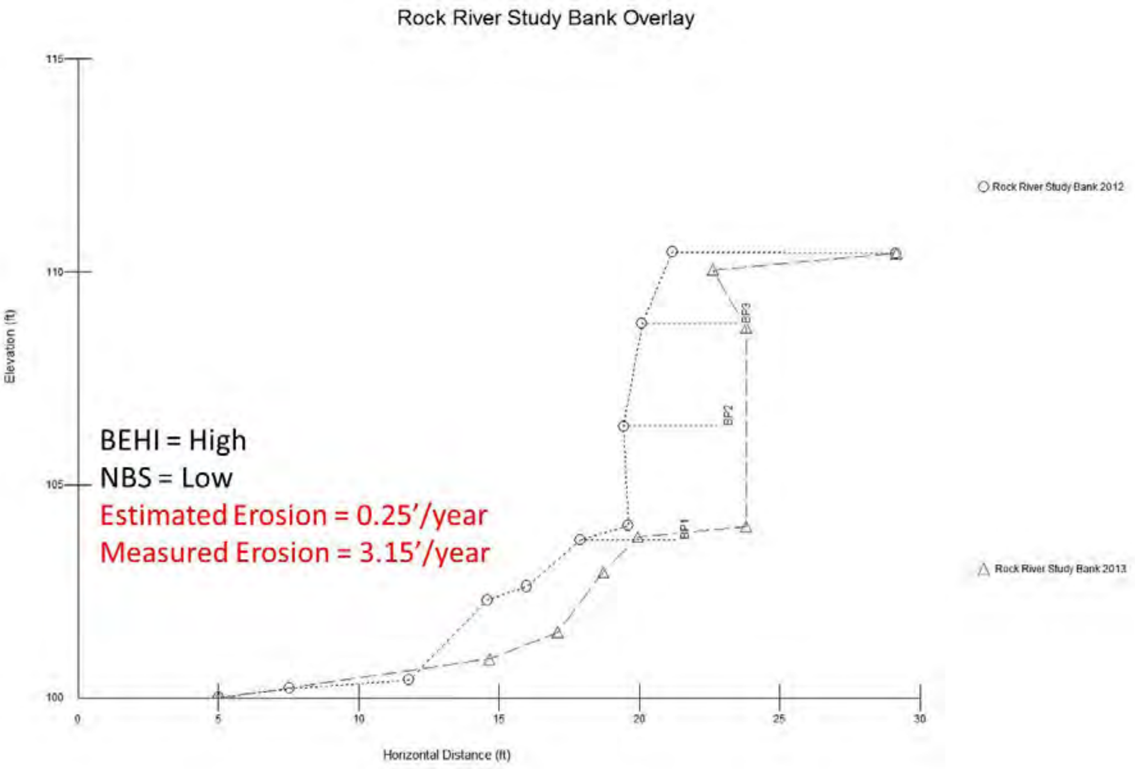


Figure 37. Study bank overlay for the Rock River site with estimated and measured erosion rates.

At sites like the Rock River gage, it is possible to implement bank protection using natural woody materials to protect the toe of the bank and reduce shear stress up against the bank; a practice known as toe wood protection (Appendix 3). When using toe wood, the purpose is to create bank stability by making a floodplain bench out of trees and woody material on an outside bend. This protects the toe of the bank, and also allows the river to deposit sediment and a seed source to grow natural vegetation on top of the bench. Although this has been shown to work in many cases, a systemic approach that includes better land use practices upstream is a more desirable strategy so it creates watershed stability instead of bank stability. Eroding banks tend to be a symptom of a larger issue in the Missouri River basin, and being able to address the larger issue can implement watershed-wide stream stability.

Little Rock River

The Little Rock River site (AUID 10170204-512; Headwaters to Little Rock Creek) was just listed for fish and macroinvertebrate bioassessment, *E. coli*, and turbidity in 2013. At the location of this survey site (~7.4 miles southwest of Worthington; Figure 38), the Little Rock River has a 33.9 square mile drainage area consisting of 85% cultivated crops, 9% perennial cover, and 6% "other" (WHAF 2013).

At this site, the Little Rock River is classified as an E4 indicating that it is a low gradient, gravel bed stream with a low width to depth ratio bankfull channel, typically vegetated banks and good floodplain connectivity (Table 9). E4 stream types have a very high sensitivity to disturbance, good recovery potential, moderate sediment supply, high streambank erosion potential, and riparian vegetation plays a significant role in maintaining stability (Table 5; Rosgen 1994). The width-to-depth ratio at the riffle is 8.96 (Figure 39), a relatively stable W/D ratio for alluvial valley types.

Bank height ratio at this riffle cross section is 1.22, indicating some incision, but the riffle cross section shows some possible floodplain deposition making that number higher than it really may be. Although the riparian area on the north side of this site is relatively undisturbed, the south side has row-crop agriculture nearly up to the stream banks in spots (Figure 40). The Pfankuch stability rating and aerial photo analysis suggest some instability in this channel, likely due to historical straightening to make the river go through the culverts at the road crossing (Figure 40).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 164.11 cfs (U/U*) to 173.413 cfs (Manning's "n"). StreamStats analysis estimated the 1.5 year discharge to be 173 cfs with a 90% confidence interval between 106-268 cfs (Table 6). Bankfull cross sectional area at the riffle is 48.5 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). These validations show that bankfull calls for this reach are accurate.

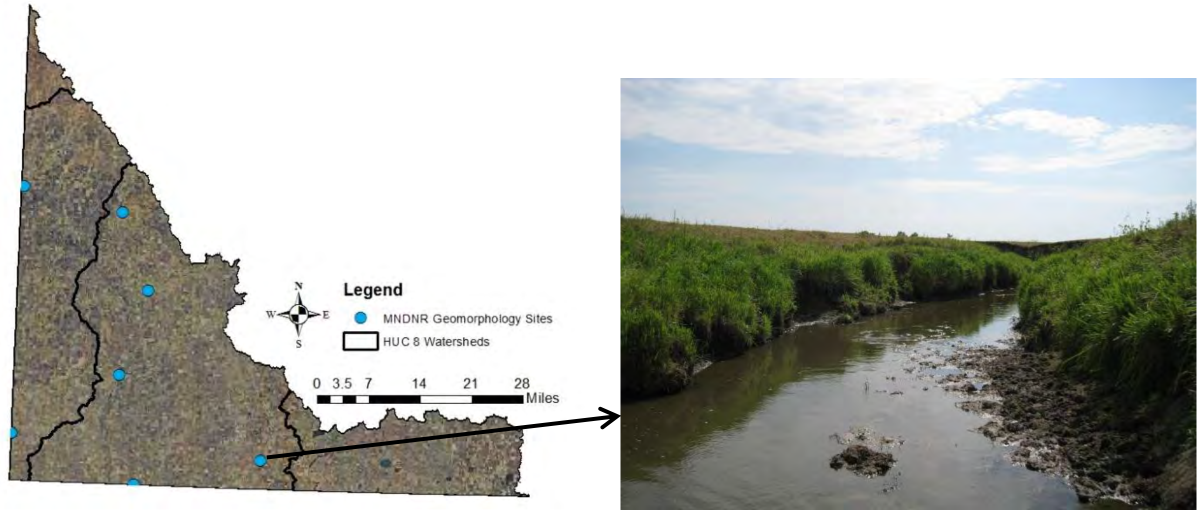


Figure 38. Location of the Little Rock River geomorphology site in relation to the rest of the Missouri River basin.

Table 9. Baseline information about the Little Rock River geomorphology site.

Stream Information			
Stream Name	Little Rock R.	**Drainage Area**	33.9 mi^2
AUID	10170204-512	**Stream Type**	E4
HUC 8 Watershed	Rock River	**Valley Type**	8(c) Terraced Alluvial
County	Nobles	**Water Slope**	0.00183 ft/ft
Township	Ransom	**Sinuosity**	1.16
Section	9	**Erosion Estimates**	0.0293 tons/foot/year
Range	41	**Pfankuch Stability Rating**	100 (Poor)

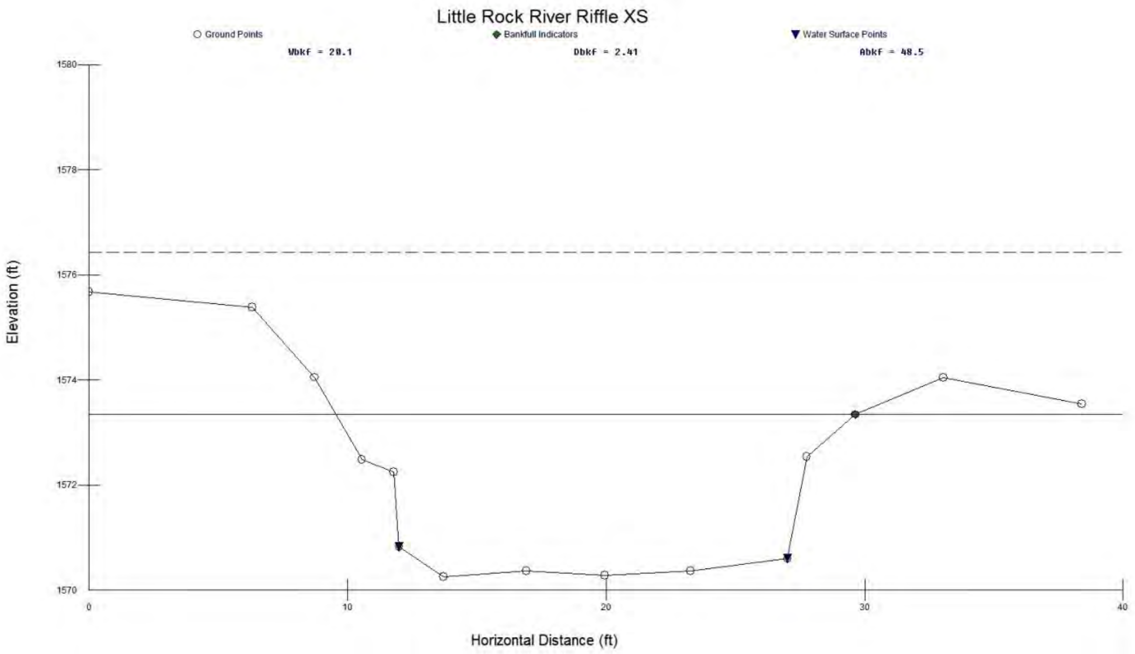


Figure 39. Graphical view of the representative riffle cross section in the survey reach at the Little Rock River site.

Figure 40. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

The BEHI matched with NBS model estimated that this reach is contributing 0.0293 tons of sediment (58.6 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 430' reach of stream delivers 12.599 tons of sediment (~1.25 dump truck loads) annually. There were no study banks in this reach to validate bank erosion estimates.

Summary

Overall, this site appears to be relatively stable for the Missouri River basin. Bank erosion is evident at this site using aerial photo analysis; however, it is possible that the channel is adjusting to being straightened to go through the culvert. Using LiDAR, it is apparent that the belt width (i.e., lateral extent of the stream in its valley; measured from outside bend to opposite outside bend) of the channel should be much wider than what it is near this road crossing (Figure 41). Historical photos from 1938 and 1954 show channel changes that took place (Figure 42). It also appears that the road crossing changed locations from 1954 to present along with the channelization. Data collected at this site show minimal influence on local impairments, suggesting there may be other stressors to this site leading to these impairments.

Management Recommendations for Little Rock River

Even though this site appears to be relatively stable compared to other sites, there are still practices worth considering that could potentially stabilize this reach. Two of the major concerns that affect stream stability at this site are culvert sizing and riparian land use on the south side of the stream. The road crossing immediately downstream of the study reach has four culverts; however, it appears that the two southern culverts are the only ones that transport water at normal to low flows (Figure 40). The amount of sediment deposited in the northern two culverts relates to the fact that the road crossing was built too wide for the bankfull channel, and the stream is developing a floodplain in the other two culverts. In order for a stream to maintain stability, it must transport the water and sediment of its watershed, so this site shows what happens when culverts are improperly sized. Ideally, sites like this would have a culvert large enough to handle the bankfull discharge, and then have floodplain relief culverts at the floodplain elevation to allow flood flows to stay on the floodplain and not be bottlenecked (Zytkovicz and Murtada 2013). An indirect impact of these culverts stems from the channelization of the stream that directed the flows straight into the culverts. Naturally, the Little Rock River is very sinuous, and in order to maintain stability it is continually working to be sinuous. Much of the lateral bank erosion noted in the study reach stems from this channelization that took place historically.

The other impact affecting stream stability is the lack of riparian vegetation on the south side of the channel. Row-crop agriculture typically only provides soil protection for 2-3 months of the year when rainfall is not common. Corn and soybeans also have poor weighted root densities that provide very little bank protection. Since the channel is an E stream type at this location, it is dependent on riparian vegetation in order to maintain or restore stability. Ideally, natural

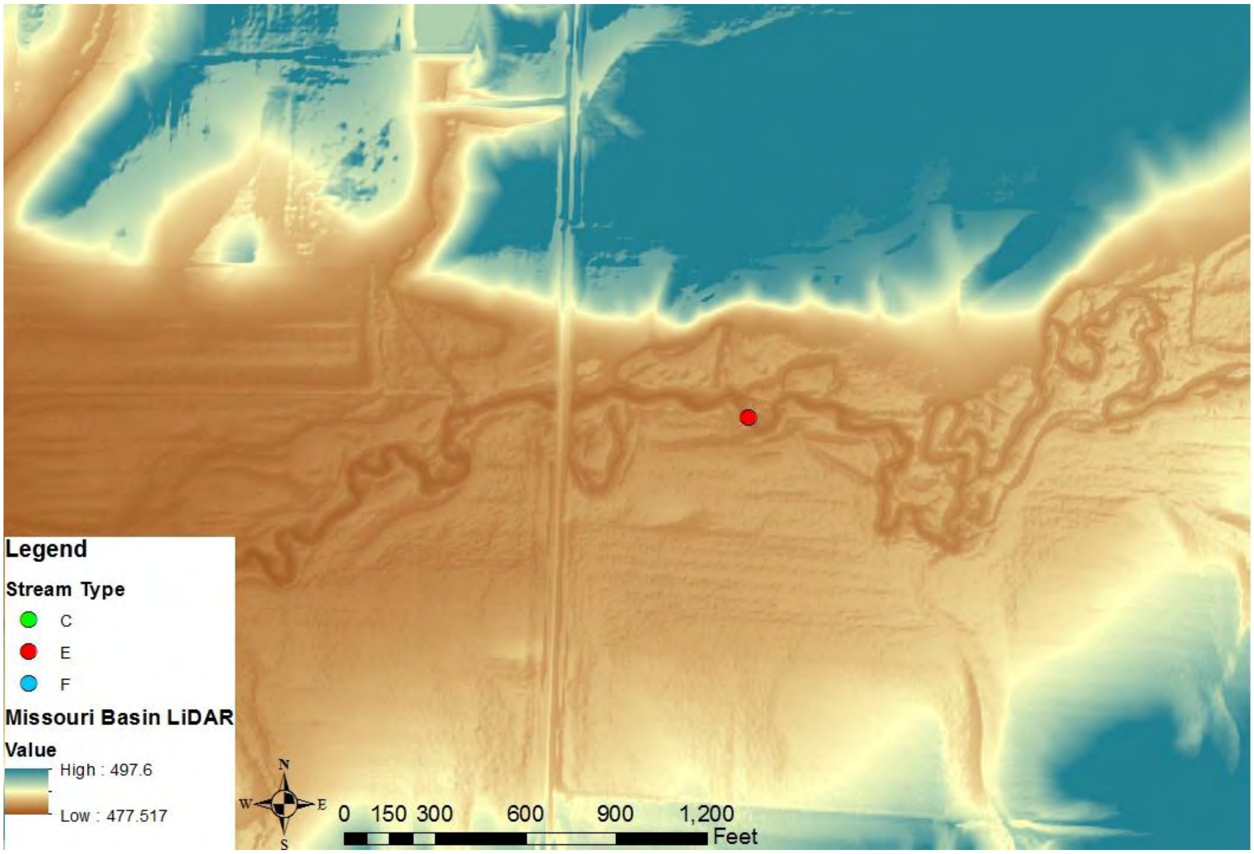


Figure 41. LiDAR imagery shows old meander scrolls in the study reach that had wider belt widths, more consistent with upstream and downstream than what is currently observed. This is likely due to straightening of the channel to go through the culverts under the road crossing.

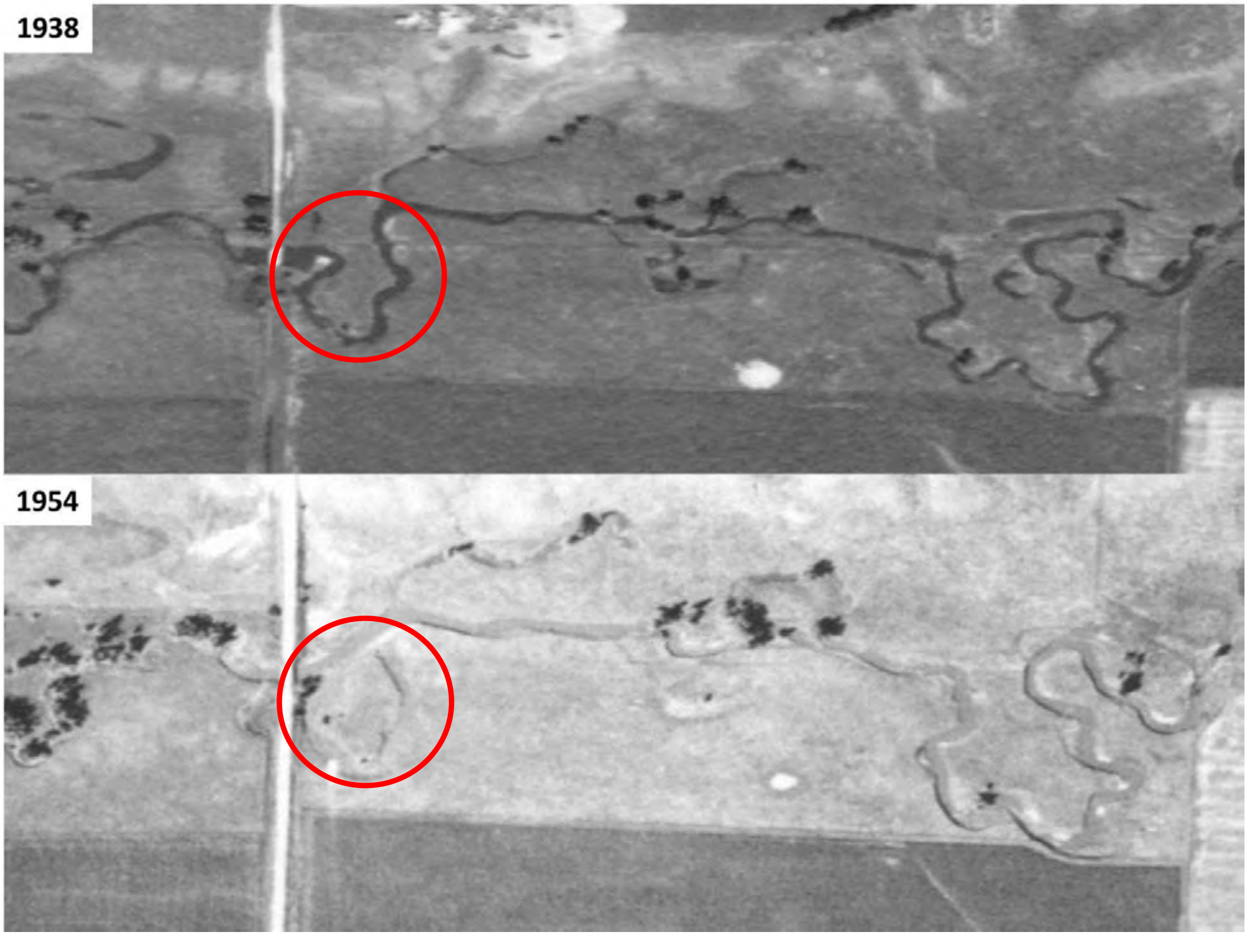


Figure 42. Comparison of the 1938 and 1954 aerial photos at the Little Rock River geomorphology site. Notice the abandonment of the channel (oxbow) immediately upstream of the road crossing from 1938 to 1954.

vegetation would be planted at least to the edge of the flood-prone area in order to make the Little Rock River healthier (Appendix 3).

Chanarambie Creek

The Chanarambie Creek site (AUID 10170204-522; Headwaters to Rock River) was just listed for fish and macroinvertebrate bioassessment, *E. coli*, and turbidity in 2013. At the location of this survey site (east of Edgerton; Figure 43), Chanarambie Creek has a 64.6 square mile drainage area consisting of: 69% cultivated crops, 25% perennial cover, and 6% "other" (WHAF 2013).

At this site, Chanarambie Creek is classified as an F5 indicating a fully-entrenched, wide and shallow bankfull channel with lateral instability and high bank erosion rates (Table 10). F5 stream types have a very high sensitivity to disturbance, poor recovery potential, very high sediment supply, very high streambank erosion potential, and riparian vegetation plays a moderate role in maintaining stability (Table 5; Rosgen 1994). Even though Nagle and Larson (2013) found Topeka shiners upstream and downstream of this reach, it is likely that they are not utilizing this site for spawning given the lack of floodplain connectivity and poor pool quality.

The width-to-depth ratio at the riffle is 14.64 (Figure 44), relatively low for F channels indicating that this site may have recently transitioned to this unstable stream type. Bank height ratio at this riffle cross section is 2.07, indicating that this channel is fully incised and has no access to its floodplain at 2X bankfull. Lack of riparian vegetation, Pfankuch stability analysis, and aerial photo analysis suggest that this channel is very unstable and will continue to widen out until it can make a new channel and floodplain within the existing channel (Figure 45).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 228.6 cfs (U/U*) to 236.585 cfs (Manning's "n"). StreamStats analysis estimated the 1.5 year discharge to be 294 cfs with a 90% confidence interval between 182-453 cfs (Table 6). Bankfull cross sectional area at the riffle is 63.6 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). These validations show that bankfull calls for this reach are accurate.

The BEHI matched with NBS model estimated that this reach is contributing 0.0166 tons of sediment (33.2 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 650' reach of stream delivers 10.79 tons of sediment (~1.08 dump truck loads) annually. However, the study bank at this location suggested that the bank erosion model's estimates were lower than what actual measurements were. The model estimated 0.25' of bank erosion at the study bank, and 0.975' of erosion was measured (Figure 46).

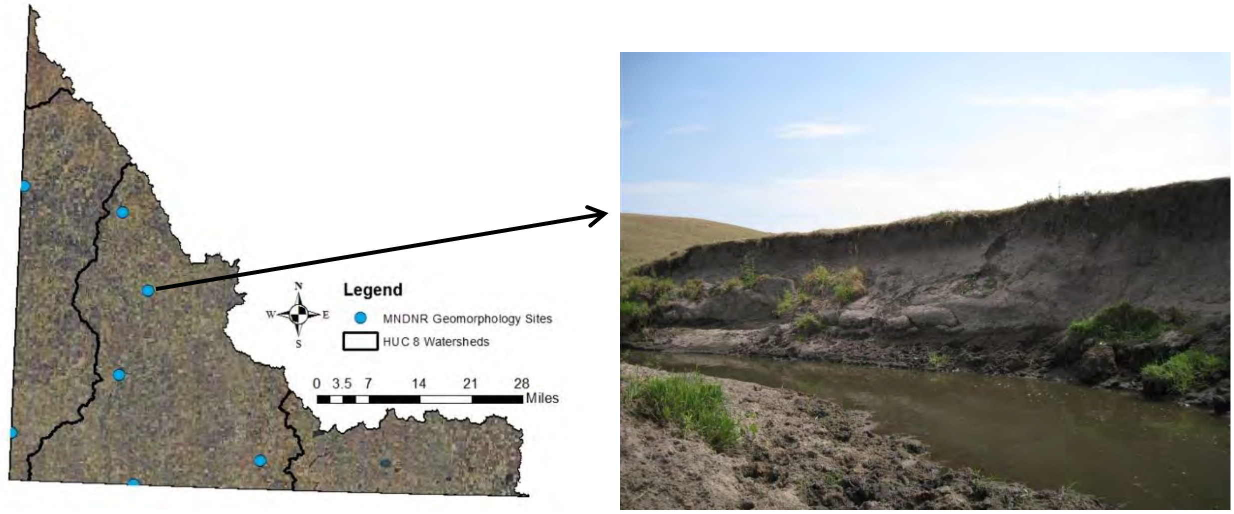


Figure 43. Location of the Chanarambie Creek geomorphology site in relation to the rest of the Missouri River basin.

Table 10. Baseline information about the Chanarambie Creek geomorphology site.

Stream Information			
Stream Name	Chanarambie C.	**Drainage Area**	64.6 mi^2
AUID	10170204-522	**Stream Type**	F5
HUC 8 Watershed	Rock River	**Valley Type**	8(c) Terraced Alluvial
County	Pipestone	**Water Slope**	0.0012 ft/ft
Township	Osborne	**Sinuosity**	1.9
Section	23	**Erosion Estimates**	0.0166 tons/foot/year
Range	44	**Pfankuch Stability Rating**	108 (Poor)

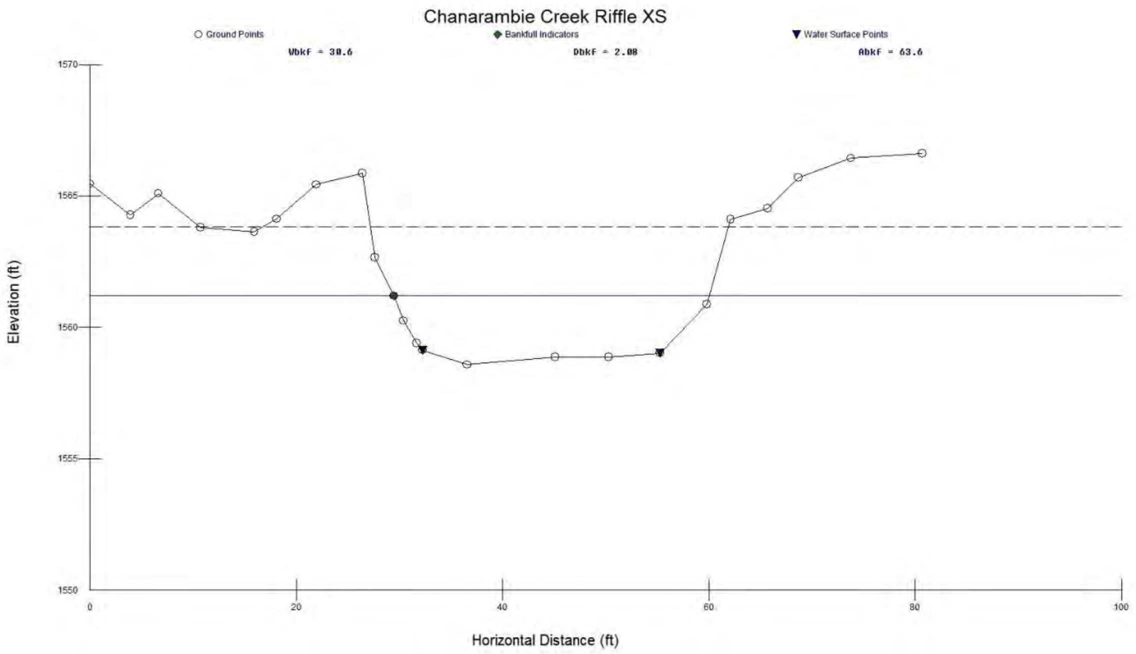


Figure 44. Graphical view of the representative riffle cross section in the survey reach at the Chanarambie Creek site.

Figure 45. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

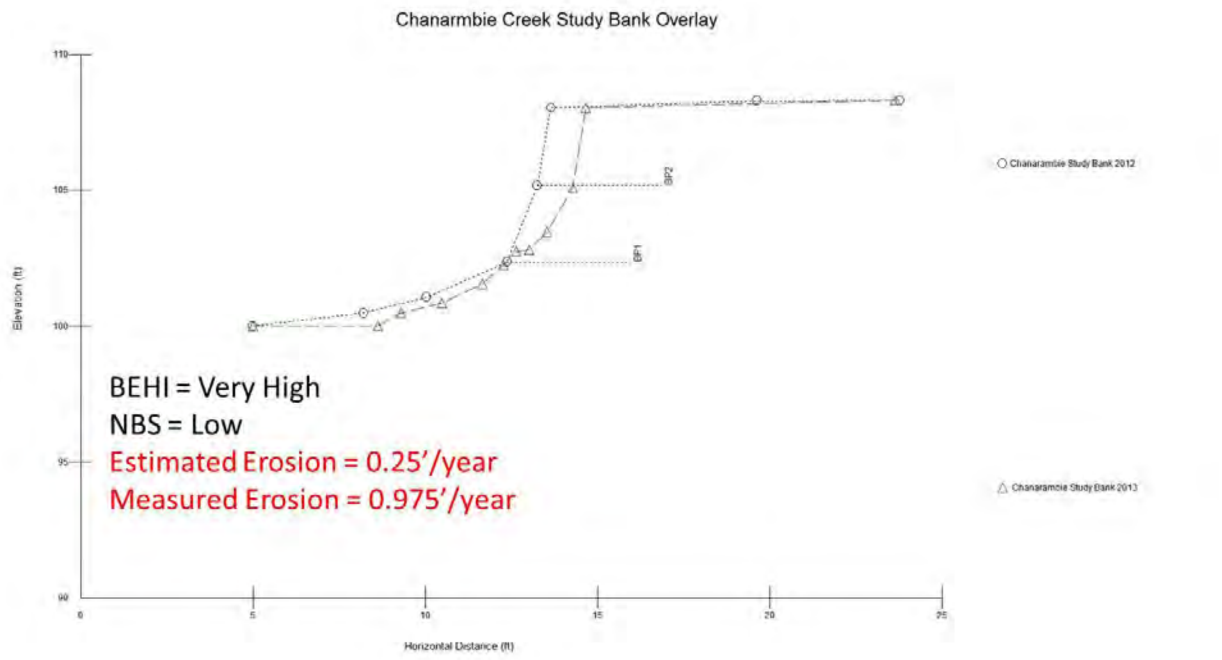


Figure 46. Study bank overlay for the Chanarambie Creek site with estimated and measured erosion rates.

Summary

Overall, the lack of riparian vegetation due to overgrazing appears to have set forth channel succession at this site. F channels are not the stable form for alluvial valleys, and they usually exhibit poor habitat quality, higher water temperatures, and excessive sediment supply resulting in poor aquatic communities and high turbidity. Since the tortuous meanders of the channel still remain from when this stream was likely an E channel type, it is likely that many of these meanders will be cut off and developed into disconnected oxbows. In the future, it is likely that the stream will continue to straighten and widen until a new floodplain can be created within the old channel. Until a new floodplain can be established, stability of Chanarambie Creek at the study site may not be realized.

Management Recommendations for Chanarambie Creek

Considering Chanarambie Creek is an F channel at the study site, there are few "quick fixes" that can be implemented to restore stability. As Table 5 states, F5 channels have poor recovery potential. However, like many of the pastured sites, restoring natural vegetation would be a good start to restoring stability within the study reach. Best management practices (e.g., grassed waterways, no till, etc.) implemented on the landscape could also relieve the stream from some of the changes in precipitation and flow regime that are currently taking place. In order to restore Chanarambie Creek to a healthy watershed, all of these practices will need to take place.

Flandreau Creek

The Flandreau Creek site (AUID 10170203-502; Willow Creek to MN/SD border) was just listed for fish bioassessment and *E. coli* in 2013. At the location of this survey site (1/2 mile east of MN/SD border; Figure 47), Flandreau Creek has an approximate drainage area of 92.3 square miles consisting of: 63% cultivated crops, 33% perennial cover, and 4% "other" (WHAF 2013). StreamStats has been used as a consistent tool for drainage area and discharge analysis for this watershed, however, the location of the Flandreau Creek site is not within StreamStats' area in Minnesota or South Dakota. At the time that this report went final, StreamStats still was not available.

At this site, Flandreau Creek is classified as a $C4_{c-}$ indicating that it is a low gradient, high W/D ratio bankfull channel with point bar deposition and high outside banks (Table 11). The stream type based off of the riffle cross section comes out as a B4, but was overridden because of possible low bankfull calls and the stream did not exhibit features related to a B channel (Figure 48). C4 stream types have a very high sensitivity to disturbance, good recovery potential, high sediment supply, very high streambank erosion potential, and riparian vegetation plays a significant role in maintaining stability (Table 5; Rosgen 1994).

The width-to-depth ratio at the riffle is 29.51 (Figure 48), which is very high for an alluvial valley type, suggesting there may be some disturbance in this stream or bankfull calls are low. Since bankfull has not been validated, bank height ratio of the cross section is likely incorrect at

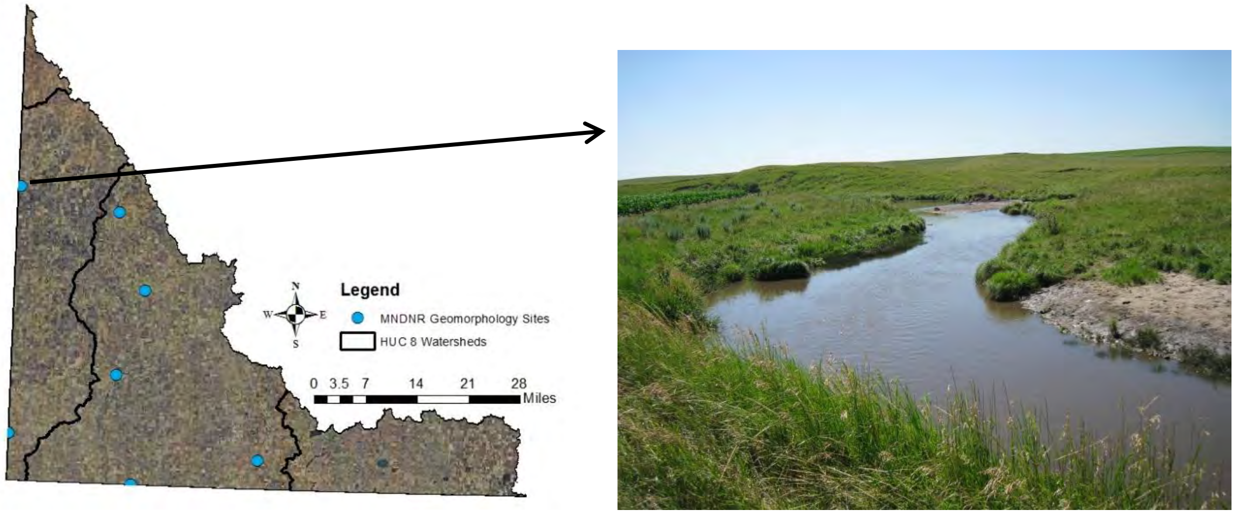


Figure 47. Location of the Flandreau Creek geomorphology site in relation to the rest of the Missouri River basin.

Table 11. Baseline information about the Flandreau Creek geomorphology site.

Stream Information			
Stream Name	Flandreau C.	**Drainage Area**	92.3 mi^2
AUID	10170203-502	**Stream Type**	C4c-
HUC 8 Watershed	L. Big Sioux	**Valley Type**	8(c) Terraced Alluvial
County	Pipestone	**Water Slope**	0.00016 ft/ft
Township	Troy	**Sinuosity**	1.6
Section	13	**Erosion Estimates**	0.0449 tons/foot/year
Range	47	**Pfankuch Stability Rating**	120 (Poor)

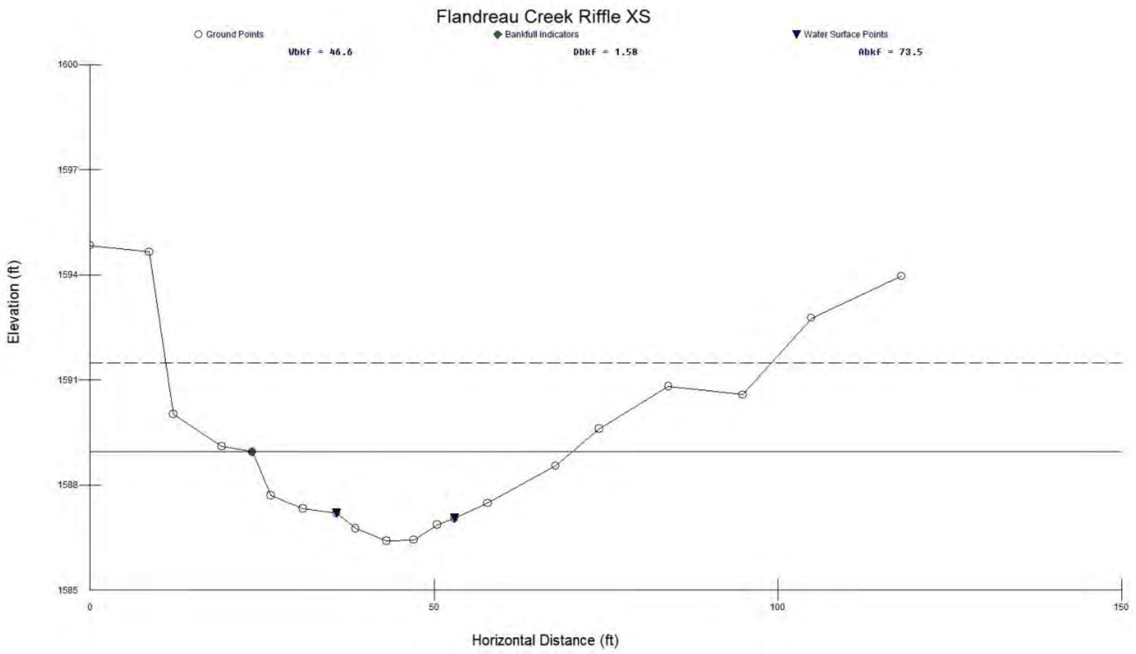


Figure 48. Graphical view of the representative riffle cross section in the survey reach at the Flandreau Creek site. Referencing the regional curve (Appendix 2), it appears the bankfull call is low on this cross section and will likely be raised.

this point. Lack of riparian vegetation, Pfankuch stability analysis, and aerial photo analysis suggest that this channel is in a successional state and not stable at this time (Figure 49).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 71.6 cfs (U/U*) to 74.102 cfs (Manning's "n"). Given the approximate drainage area of 108 mi^2, cross sectional area of 73.5 ft^2 is likely too low as it does not line up well with the regional curve (Appendix 2). Once StreamStats is finalized in this area, more confident bankfull estimates will be made (Table 6).

The BEHI matched with NBS model estimated that this reach is contributing 0.0449 tons of sediment (89.8 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 1056' reach of stream delivers 47.41 tons of sediment (~4.74 dump truck loads) annually. There were no study banks at this location to validate bank erosion estimates.

Summary

Overall, rotational grazing at this location has left the riparian area with relatively good vegetation in comparison to other observed pasture areas. However, there are many bare and over-widened areas within the reach from cattle entering the stream that are large contributors of sediment. While surveying at the site, the landowner discussed how the stream was much narrower and had deep pools (characteristics of an E channel) when he was growing up and fish like northern pike *Esox lucius* were abundant. At some point, the landowner began row-crop farming near the stream and noticed stream succession take place to a wider, shallower channel. Recognizing the effect land use changes had on the stream, the landowner began rotational grazing and establishing a more flourished riparian buffer (Todd Kolander, MNDNR District Manager, personal communication). Although it is difficult to see from aerial photos, Figure 50 shows the study reach in 1938, 1955, and 2011 to document any potential changes that have occurred during the landowner's life span. Figure 50 also shows how wide the channel is upstream of the bridge compared to the rest of the reach; a potential impact on stream stability. Case studies like this show how changes in riparian land use can have a direct impact on stream stability. Undesirable fish communities at this site could be a result of historical channel succession, and the fact that the stream is not in its stable form. It is likely that if the channel were to evolve back to a narrow, deep stream, it could benefit local fish communities.

Management Recommendations for Flandreau Creek

Given the deep pools, well vegetated riparian area, and gravel substrate, it appears that Flandreau Creek is beginning to restore itself to a stable stream type. Some areas like where the cattle have been accessing the stream could use more vegetation, but most of the stream has vegetated banks that show little cutting and erosion, also verified by aerial photo analysis. Depending on the finalized bankfull call, the rate of incision appears to be higher than what a stable stream would exhibit, so it is possible that grade control structures like cross vanes could improve floodplain connectivity and sediment transport.

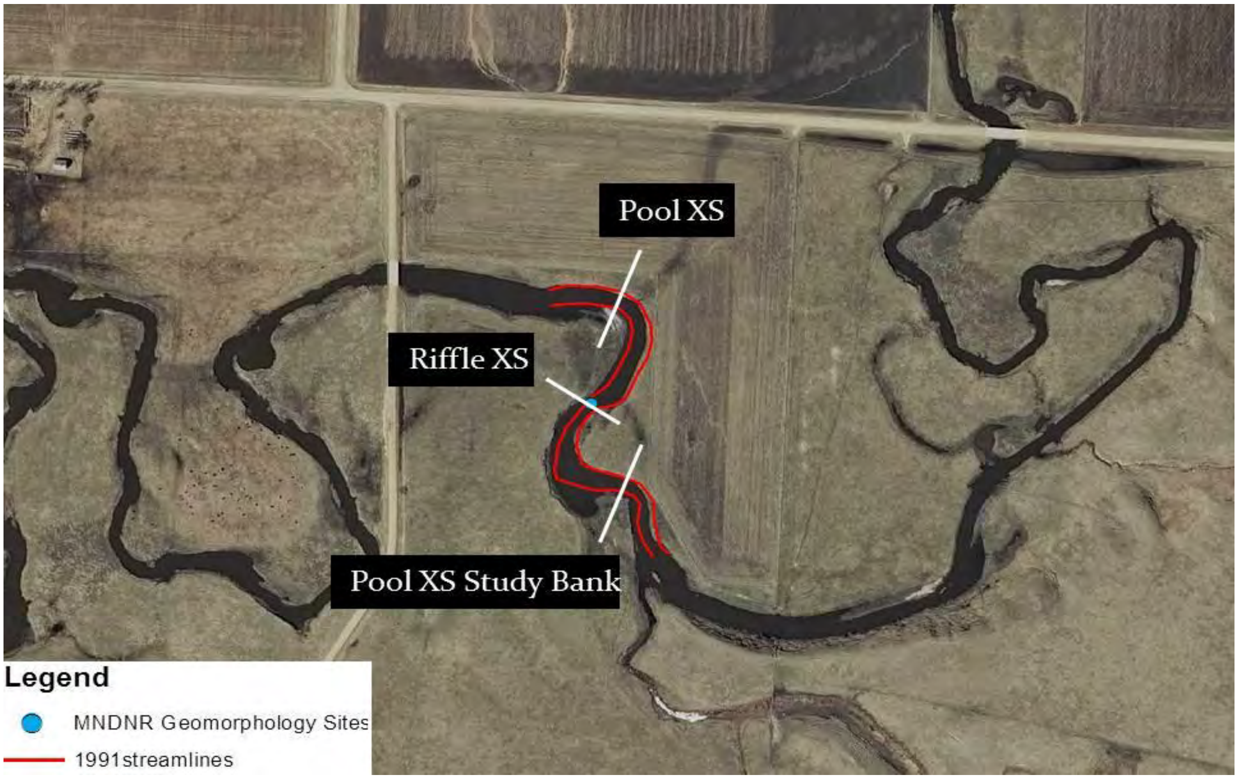


Figure 49. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

Figure 50. Aerial photo imagery from 1938-2011 of Flandreau Creek. The pattern of the channel is very similar in 1938 to what it is presently, and some areas appear to be narrower in the past, while others remain similar.

Beaver Creek

The Beaver Creek site (AUID 10170203-522; Little Beaver Creek to MN/SD border) was just listed for fish and macroinvertebrate bioassessment in 2013 and was previously listed for *E. coli* and turbidity in 2010. At the location of this survey site (MN/SD border; Figure 51), Beaver Creek has an approximate drainage area of 85.7 square miles consisting of: 81% cultivated crops, 13% perennial vegetation, and 6% "other" (WHAF 2013). StreamStats was not available in this area at the time that the report went final.

At this site, Beaver Creek is classified as an F5 indicating that it is a fully-entrenched, wide and shallow bankfull channel (Table 12). F5 stream types have a very high sensitivity to disturbance, poor recovery potential, very high sediment supply, very high streambank erosion potential, and riparian vegetation plays a moderate role in maintaining stability (Table 5; Rosgen 1994). Even though Nagle and Larson (2013) documented Topeka shiners far upstream of this reach, it is likely that they are not utilizing this site given the lack of floodplain connectivity and poor pool quality.

The width-to-depth ratio at the riffle is 20.49 (Figure 52), which is high for an alluvial valley type, suggesting there may be some disturbance in this stream or bankfull calls are low. Since bankfull has not been validated, bank height ratio of the cross section is incorrect at this point. Lack of riparian vegetation, Pfankuch stability analysis, and aerial photo analysis suggest that this channel is in a successional state and not stable at this time (Figure 53).

Discharge analysis at the riffle cross section estimated bankfull discharge to range from 157.55 cfs (U/U*) to 163.047 cfs (Manning's "n"). Bankfull cross sectional area at the riffle is 89.9 ft^2, which matches up well with the regional curves for the Missouri River basin and southern Minnesota (Appendix 2). The regional curve suggests that the bankfull call at the riffle is validated; however, final judgment will be made once StreamStats is finalized (Table 6).

The BEHI matched with NBS model estimated that this reach is contributing 0.0591 tons of sediment (118.2 pounds) per linear foot of stream bank annually using the Colorado erosion rate curve (Rosgen 2001a). These erosion predictions assume that this 650' reach of stream delivers 62.23 tons of sediment (~6.22 dump truck loads) annually. However, the study bank at this location suggested that the bank erosion model's estimates were much lower than what actual measurements were. The model estimated 0.25' of bank erosion at the study bank, and 2.81' of erosion was measured (Figure 54). Also, the thalweg migration from 2012 to 2013 was enough to bury the toe pin in the cross section resulting in potentially poor data because there was no monument on top of the bank due to the proximity of row crops (Figure 55).

Summary

Overall, the lack of riparian vegetation due to intense row crop agriculture at this site coupled with potentially altered hydrology appears to have set forth channel succession at this site. Much like Chanarambie Creek, Beaver Creek does not exhibit a stable stream type for its alluvial

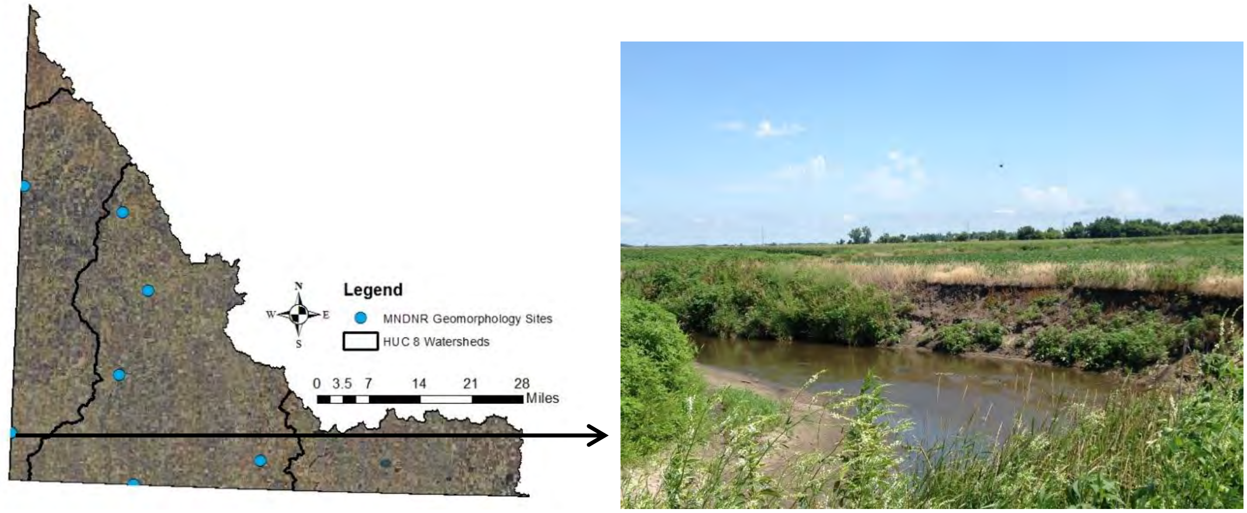


Figure 51. Location of the Beaver Creek geomorphology site in relation to the rest of the Missouri River basin.

Table 12. Baseline information about the Beaver Creek geomorphology site.

Stream Information			
Stream Name	Beaver C.	**Drainage Area**	85.7 mi^2
AUID	10170203-522	**Stream Type**	F5
HUC 8 Watershed	L. Big Sioux	**Valley Type**	8(c) Terraced Alluvial
County	Rock	**Water Slope**	0.00056 ft/ft
Township	Beaver Creek	**Sinuosity**	1.97
Section	34	**Erosion Estimates**	0.0591 tons/foot/year
Range	47	**Pfankuch Stability Rating**	137 (Poor)

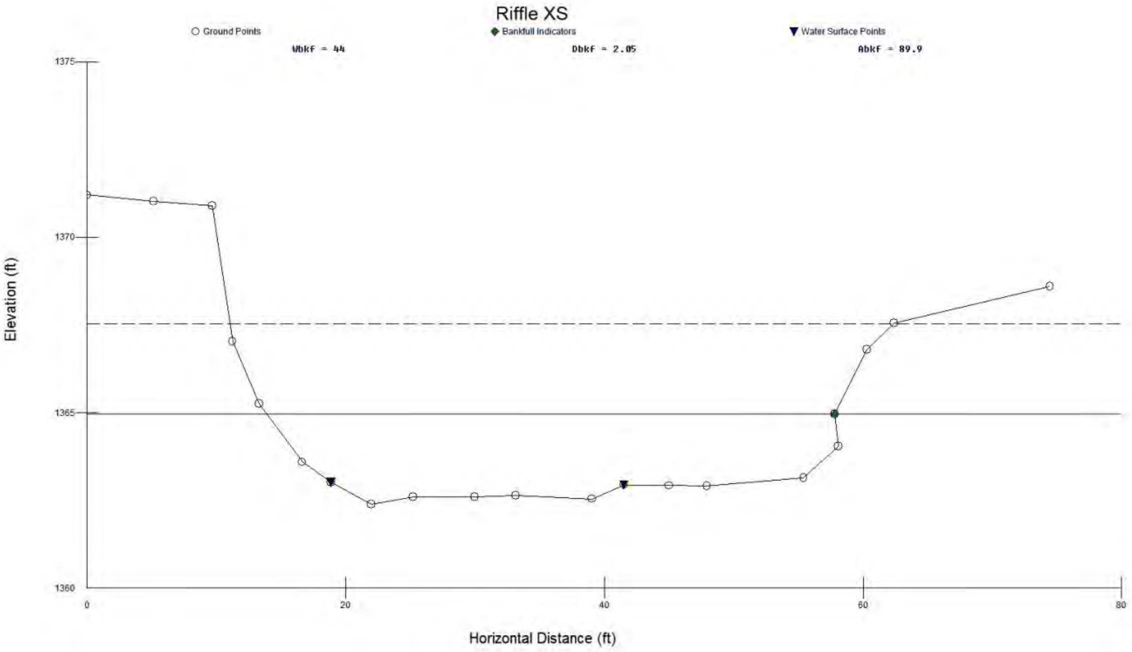


Figure 52. Graphical view of the representative riffle cross section in the survey reach at the Beaver Creek site.

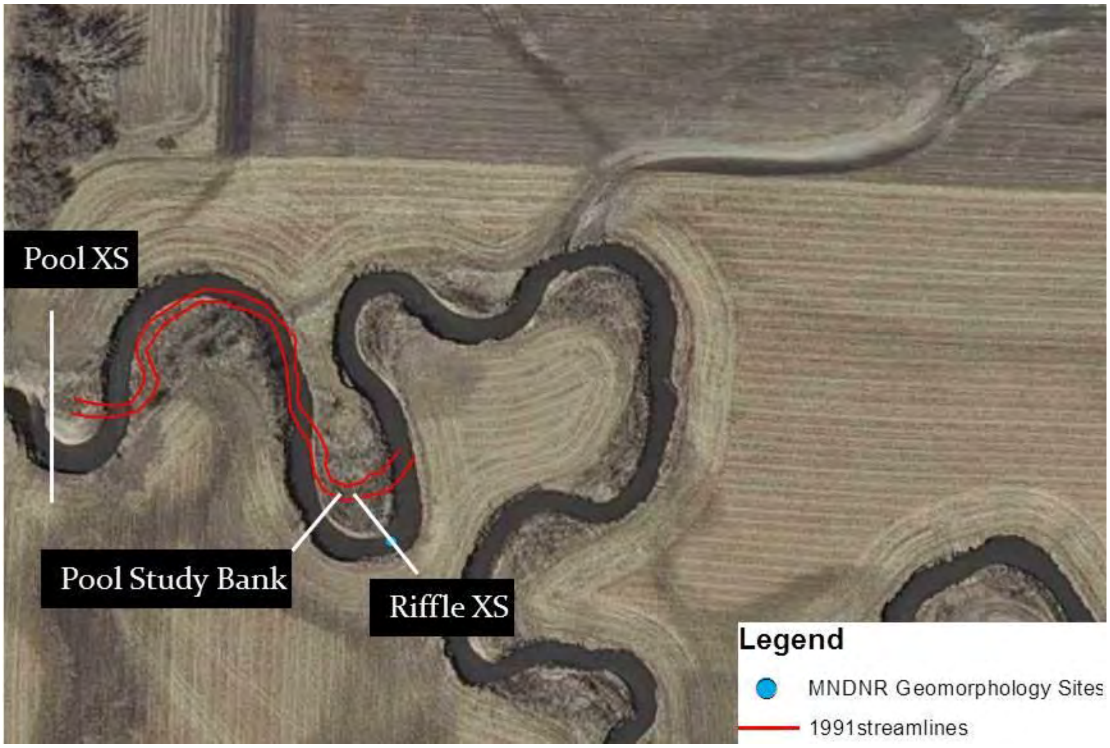


Figure 53. Aerial photo of the survey reach with labeled cross section locations and 1991 stream lines.

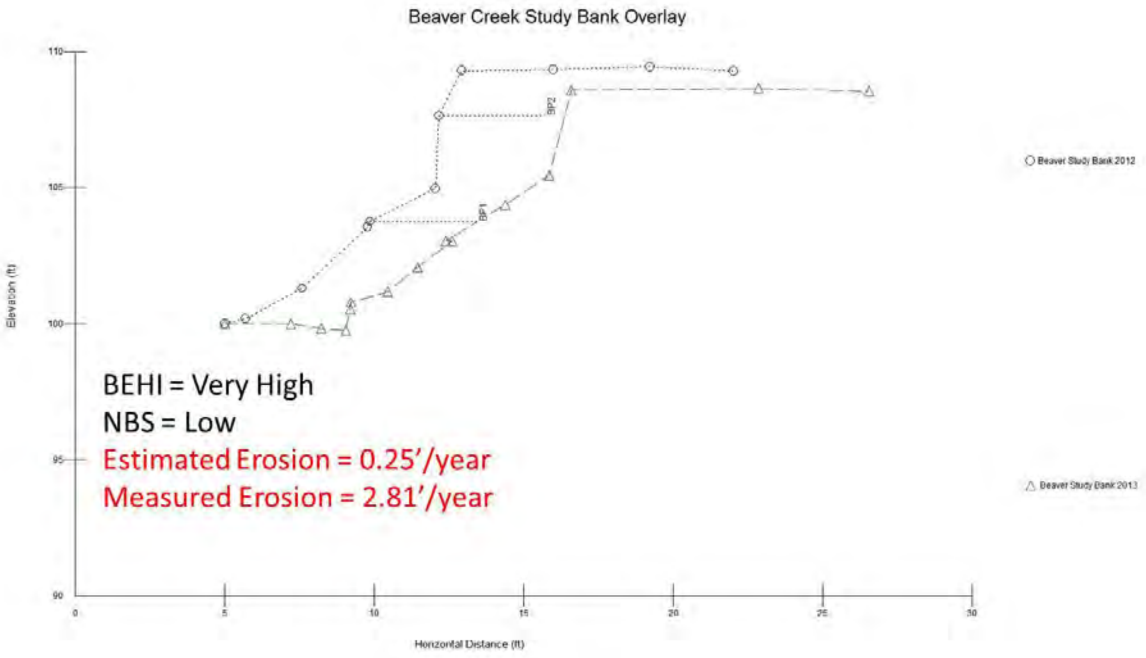


Figure 54. Study bank cross overlay for the Beaver Creek site with estimated and measured erosion rates. Both bank pins were missing when the cross section was resurveyed in 2013. There are some discrepancies with this cross section because the toe pin was buried from thalweg migration and the monument rebar was not there anymore.

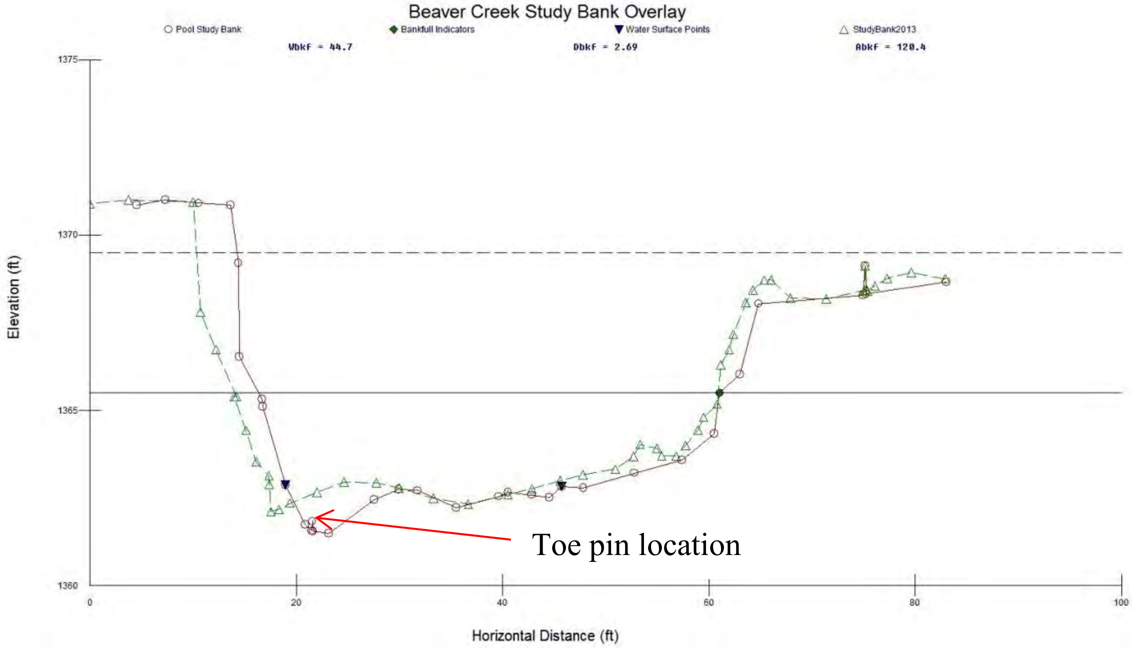


Figure 55. Study bank cross section overlay at the Beaver Creek site. Notice how the thalweg moved and buried the toe pin for the study bank.

valley. During the initial survey on Beaver Creek, blood worms (Chironomidae) were observed in large groups. Blood worms are typically very tolerant midge larvae that can withstand water quality issues that are related to F channels.

Management Recommendations for Beaver Creek

Given the instability of F channels, there are very few practices that can restore stability. Table 5 states that F5 channels have poor recovery potential, so it is important that a stream like Beaver Creek be restored as a system instead of a site. Like many of the sites in the Missouri River basin, improving the condition of the riparian vegetation would benefit stream health. Row-crop agriculture along the banks of Beaver Creek provides little or no bank protection, resulting in very high bank erosion measurements (2.81'; Figure 54). Now that the stream has reduced floodplain connectivity, it will continue to widen out until a floodplain can be created within the old channel.

Conclusions

Hydrology, connectivity, and geomorphology are three of the five essential components of a healthy watershed. If any of these components depart from natural or stable conditions, it is likely that the others will be impacted, as well as have a negative impact on biology and water quality within the impacted area. The Missouri River basin is no exception to this. Geology of the landscape, resulting in highly erodible soils and more surface runoff pathways, coupled with unnatural riparian and field practices has resulted in channel succession and instability at many sites. Geomorphology survey sites that have undisturbed riparian areas appear to be withstanding the increased precipitation better than those that have been overgrazed, however these sites are at smaller drainage areas than others and may be more resilient because of that.

Hydrologic analyses showed significant changes at the Luverne gage from the early 1900s to present; however, the short period of record (1911-1914) is too short to draw conclusions. More elaborate data collection from 1998-2013 shows no significant changes in hydrology; however, other watersheds show the significant change in DMC analyses around the late 1970s. Hydrologic data collection did not occur during this period of record, so it is inconclusive if this departure occurred in the Missouri River basin as it had in watersheds that naturally have more water storage.

Precipitation trends since the early 1900s showed that although erratic at times, the 7 year moving average typically stayed within the 25th and 75th percentile (Figure 7). Thus, it is likely that increased precipitation is also not resulting in recent geomorphological changes in the Missouri River basin as it is in other Minnesota watersheds.

The complex road network in this basin has resulted to a large density of stream crossings (0.57 road crossings/mi^2). With this many road crossings, it is likely that many of them are not sized correctly for the current bankfull channel or allow floodplain release. As shown in the culvert example (Figure 21), this can cause many issues downstream including increased sediment supply and habitat degradation.

The apparent channel succession that is occurring at many of the sites has led to pool filling and other habitat degradation that has likely resulted in the loss of fish and macroinvertebrate diversity. Many of the disturbed sites are also showing excessive bank erosion; likely resulting in many of the turbidity impairments measured in the basin. Access of cattle into the stream along with unsustainable nutrient management strategies likely has increased the abundance of *E. coli* in the basin.

Though a limited sample size, study banks throughout the basin consistently showed higher erosion rates than what the Colorado model estimated. Even though there are two other models; North Carolina and Yellowstone, these models were still underestimating bank erosion at the survey sites. In order to fully understand bank erosion in this basin, it is suggested that more study banks are installed at multiple levels of BEHI and NBS so a range of values will be able to be plotted. Once a good sample size is measured, a regional bank erosion model can be developed to help with further estimates.

Although historically this basin was extensively used by Topeka shiners, channel succession, oxbow filling, and loss of floodplain connectivity has resulted in the inability for some stream reaches to recharge oxbow habitats that the shiners prefer. Given the shiners are a relatively short-lived species, it is imperative that these oxbows are being recharged on an annual basis. Otherwise it is possible the shiners could access the oxbows and become trapped; disallowing their return back to the main channel. Future projects for habitat restoration could include grade control to build up the channel bed and allow more frequent oxbow recharging flow events or similar projects that allow better access to the floodplain. Riparian habitat management needs to be a top priority; sites that were surveyed, albeit a small number, have shown that erosion is minimized and stream stability is enhanced at sites that have undisturbed riparian areas.

Restoration and Protection Strategies

Throughout the Missouri River basin, there are multiple opportunities for restoration as well as protection. More detailed management recommendations can be found in each site's section in this report. It is important to restore these rivers with their watersheds in mind, instead of installing practices that prevent bank erosion on a small number of banks. As noted in this document, one of the main problems at many of the study reaches was lack of riparian vegetation density along with non-native species. Sites that were undisturbed showed much more resiliency to other changes that are taking place in the basin because they had natural protection with vegetation. Table 5 shows that nearly all of the stream types exhibited in this basin have a high sensitivity to disturbance (i.e., overgrazing of riparian area), and are also very dependent on riparian vegetation to maintain stability.

Another restoration practice would be resizing culverts and bridges to allow water and sediment movement throughout the basin. As shown previously, oversizing of culverts or undersizing of bridges can affect the river channel downstream. This can lead to excess sediment supply and habitat degradation, as well as block passage for riparian animals making them cross busy highways to migrate upstream or downstream. Proper sizing of road crossings and floodplain access are important to achieve stream stability. See Zykovicz and Murtada (2013) for further guidance.

Throughout the basin there are many opportunities to increase stream area by redirecting flows into old channels. For example, in Kanaranzi Creek there is a site where the stream lost 1.4 miles of stream channel in a small area because of a likely ditching project in the past (Figure 56). Areas like this where the old channel is still intact make great opportunities for stream restoration.

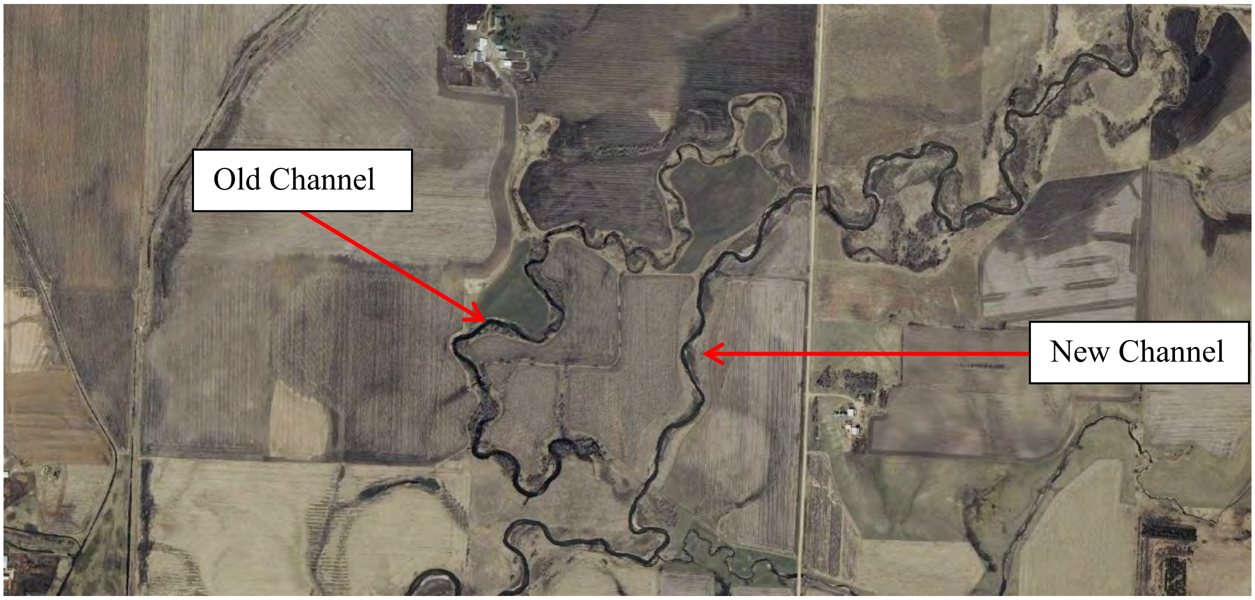


Figure 56. Historical channel cutoff on Kanaranzi Creek upstream of study site. The old channel measures out to be 10,708 feet, while the current channel measures out at 3,319 feet; a difference in 7,389 feet or 1.4 miles. Areas like this should be restored into their old channel in order to achieve higher water storage potential and maintain channel stability.

In many areas of the basin, locals have adopted the “J-hook” restoration practice to prevent bank erosion. This is a practice that can relieve shear stress along a bank that has a high erosion rate; however, when designed improperly J-hooks can cause more harm than good (Figure 57). It is important when looking at restoration opportunities, watershed professionals adopt a systemic approach and address sources (e.g., altered hydrology or grazing practices) of water quality issues as opposed to the symptom (e.g., bank erosion and channel succession). Appendix 3 gives guidance for proper implementation techniques given current stream stability and channel type.

Protection areas, although more sparse than restoration areas, still are found in this basin. Wildlife Management Areas, like at the East Branch of the Rock River site, provide stream stability by allowing riparian habitat to be undisturbed. Areas like this are of great value in a watershed that houses federally endangered aquatic and terrestrial species, and relies on stream stability and riparian vegetation to keep these species from being extirpated.

As a watershed, it is also important that practices are not put on the land that would increase stress on these systems. In order to realize the healthy watershed objective, it is important that everyone plays a part in holding some water on the landscape to allow for aquifer recharge, flood reduction, and water quality protection.

Figure 57. Aerial photo of a J-hook project on the Rock River that was designed outside of specifications made for J-hooks. This has resulted in issues with bedload deposition downstream of the 1st J-hook. Photo courtesy of Google Earth.

References

Douglas, B. 2011. A field guide to waterfalls in southern Minnesota. Gustavus Print Services: 48pp.

Gilbertson, J. P. 1990. Quaternary geology along the eastern flank of the Coteau des Prairies, Grant County, South Dakota. University of Minnesota Master's Thesis: 155pp.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems, p. 110-127 in D. P. Dodge: Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci. 106.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. Dover Publications, Inc. New York, NY. 522 pp.

Lore, J. G. 2011. Identifying stressors causing fish community impairments in the High Island Creek watershed. Minnesota State University, Mankato Master's Thesis: 176 pp.

Lorenz, D. L., C. A. Sanocki, and M. J. Kocian. 2009. Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on data through water year 2005. U.S. Geological Survey Scientific Investigations Report: 2009-5250. 54pp.

MPCA (Minnesota Pollution Control Agency). 2012. Pomme de Terre River watershed biotic stressor identification. Document number wq-iw7-36n. 166pp.

Nagle, B. C., and K. A. Larson. 2013. Topeka shiner monitoring in Minnesota: 2012-2013. Minnesota Department of Natural Resources Report: 121 pgs.

NRCS (Natural Resources Conservation Service). 2012. Unlock the secrets in the soil. See http://www.nrcs.usda.gov/Internet/FSE_MEDIA/stelprdb1143828.jpg. Visited 1/7/14.

Pfankuch, D. J. 1975. Stream reach inventory and channel stability evaluation (USDAFS No. R1-75-002, GPO No. 696-260/200). Washington, DC: U. S. Government Printing Office.

Rosgen, D. L. 1994. A classification of natural rivers. Elsevier, Catena 22:169-199.

Rosgen, D. L. 1996. Applied River Morphology. Wildland Hydrology. Pagosa Springs, CO. 385 pp.

Rosgen, D. L. 1997. A geomorphological approach to restoration of incised rivers. Proceedings of the Conference on Management of Landscapes Disturbed by Channel Incision: 11 pp.

Rosgen, D. L. 2001a. A practical method of computing streambank erosion rate. Proceedings of the Seventh Federal Interagency Sedimentation Conference 2: 9-15.

Rosgen, D. L. 2001b. A stream channel stability assessment methodology. In Proceedings of the seventh Federal Interagency Sedimentation Conference: Vol. 1 (p. II (9) – II (15). Reno, NV: Subcommittee on Sedimentation.

Rosgen, D. L. 2009. Watershed assessment of river stability and sediment supply (WARSSS): Second Edition. Wildland Hydrology. Fort Collins, CO. 610 pp.

Rosgen, D. L. 2012. Applied River Morphology: Training Manual. Wildland Hydrology, Fort Collins, CO. 268 pp.

Santucci Jr., V. J., S. R. Gephard, and S. M. Pescitelli. 2005. Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River, Illinois. North American Journal of Fisheries Management 25: 975-992.

Slawski, T. M., F. M. Veraldi, S. M. Pescitelli, and M. J. Pauers. 2008. Effects of tributary spatial position, urbanization, and multiple low-head dams on warmwater fish community structure in a Midwestern stream. North American Journal of Fisheries Management 28: 1020-1035.

State of Minnesota Climatology Office. 2012. Normal Annual Precipitation. http://www.climate.umn.edu/img/normals/81-10_precip/81-10_precip_norm_annual.htm visited 12/18/13.

Tockner, K., F. Malard, and J. V. Ward. 2000. An extension of the flood pulse concept. Hydrological Processes 14: 2861-2883.

WHAF (Watershed Health Assessment Framework). 2013. See http://arcgis.dnr.state.mn.us/ewr/whaf/Explore/. Viewed 1/7/2014.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120: 98-105.

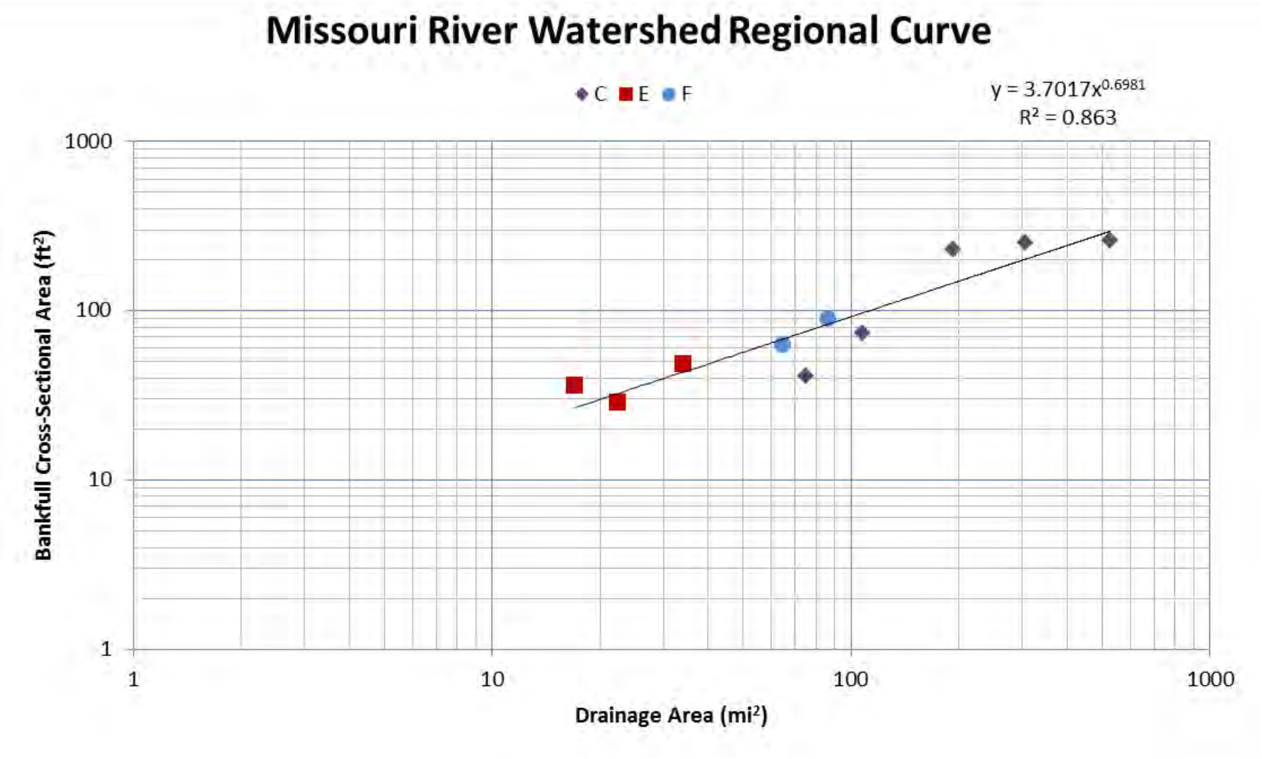
Wolman, M. G. 1954. A method of sampling coarse riverbed material. Transactions of the American Geophysical Union 35: 951-956.

Zytkovicz, K., and S. Murtada. 2013. Reducing localized impacts to river systems through proper geomorphic sizing of on-channel and floodplain openings at road/river intersections. Minnesota Department of Natural Resources: 56 pp.

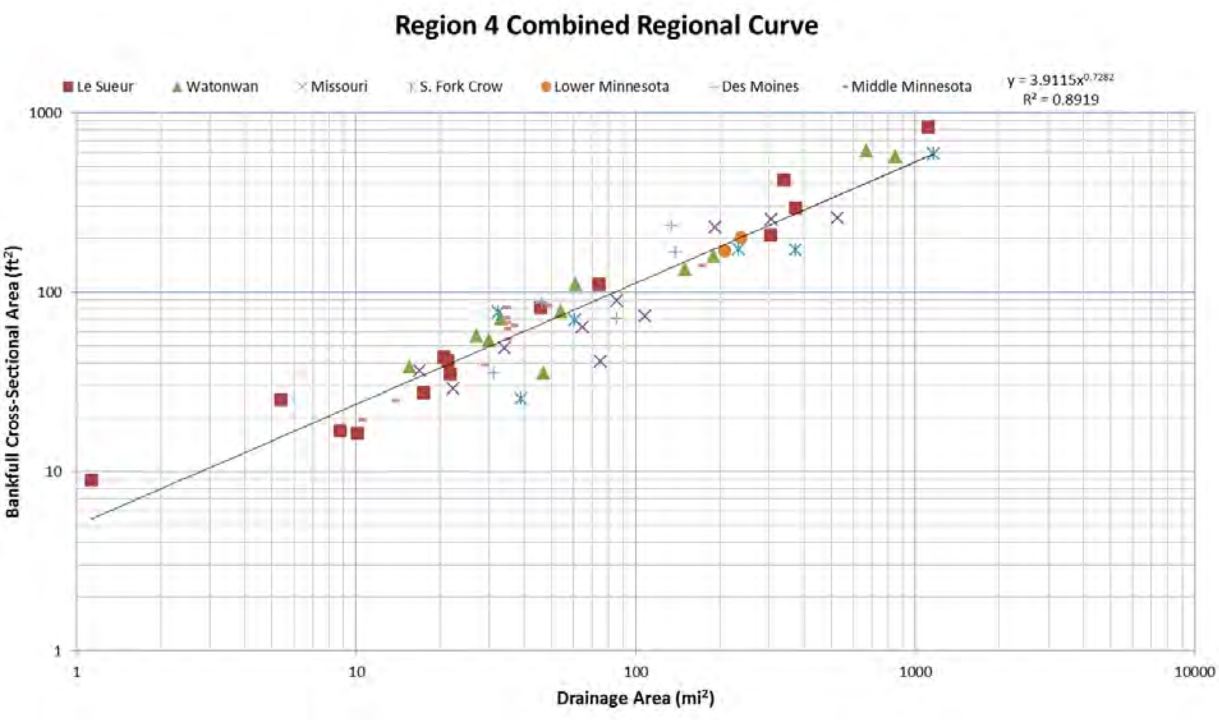
Appendix 1. Study bank locations within the Missouri River basin with BEHI and NBS ratings, predicted erosion rates for each model, and measured erosion at each site.

Site	Year	BEHI (Adjective)	NBS (Adjective)	Predicted Bank Erosion Rate (Colorado; ft/yr)	Predicted Bank Erosion Rate (Yellowstone; ft/yr)	Predicted Bank Erosion Rate (North Carolina; ft/yr)	Measured Erosion
Beaver Creek	2012	Very High	Low	0.25	0.529	0.6	**2.5774**
Beaver Creek	2013	Very High	Low	0.25	0.529	0.6	
Chanarambie Creek	2012	Very High	Low	0.25	0.529	0.6	**0.9752**
Chanarambie Creek	2013	Very High	Low	0.25	0.529	0.6	
Rock River	2012	High	Low	0.25	0.529	0.102	**3.139**
Rock River	2013	High	Moderate	0.38	0.761	0.16	
Upper Rock River	2012	Moderate	Low	0.153	0.168	0.03	**0.736**
Upper Rock River	2013	Moderate	Low	0.153	0.168	0.03	
Kanaranzi Creek SB1	2012	Extreme	Moderate	1.074	1.487	2.5	**3.5876**
Kanaranzi Creek SB1	2013	Extreme	High	2.747	1.828	3.8	
Kanaranzi Creek SB2	2012	Extreme	Moderate	1.074	1.487	2.5	**1.8641**
Kanaranzi Creek SB2	2013	Extreme	Moderate	1.074	1.487	2.5	

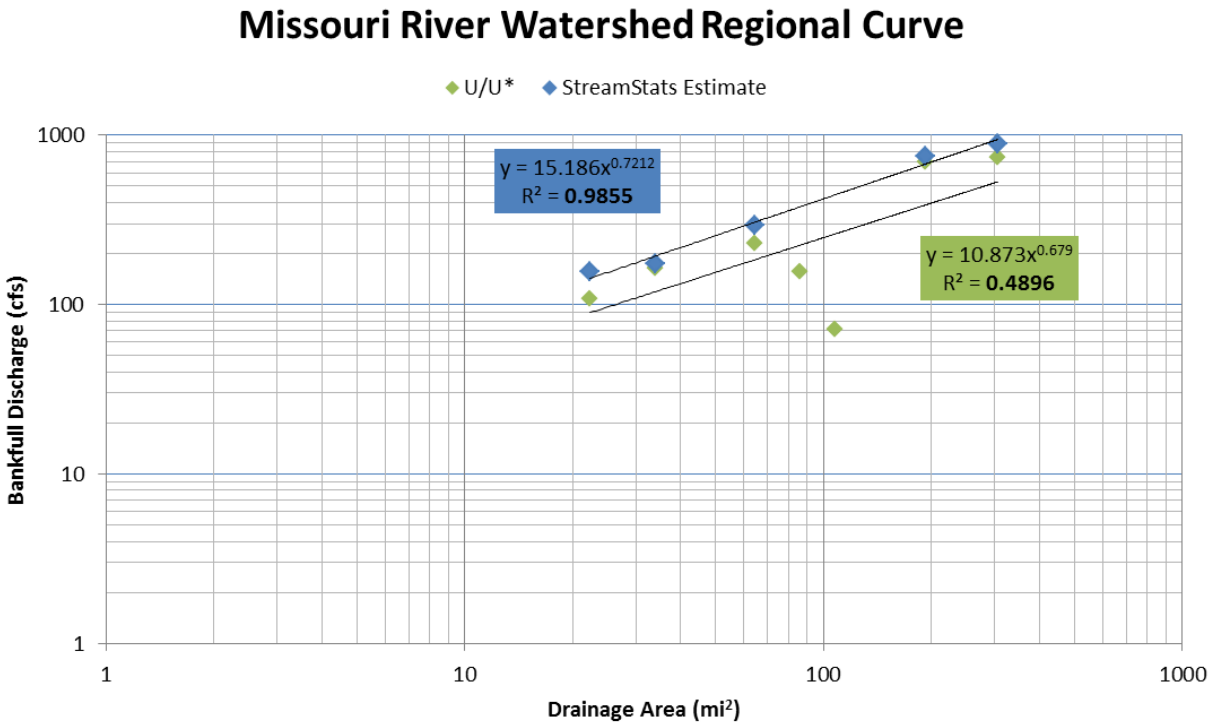
Appendix 2. Bankfull cross sectional area by drainage area for geomorphology survey sites in (a) the Missouri River basin and (b) southern Minnesota. Graph (c) plots bankfull discharge by drainage area in the Missouri River basin. The southern Minnesota curve is in development and some of the points still need to be validated.



(a) Missouri River basin regional curve by stream type; developed through MNDNR geomorphology surveys. Bankfull cross sectional area is taken at the representative riffle cross section at each site.

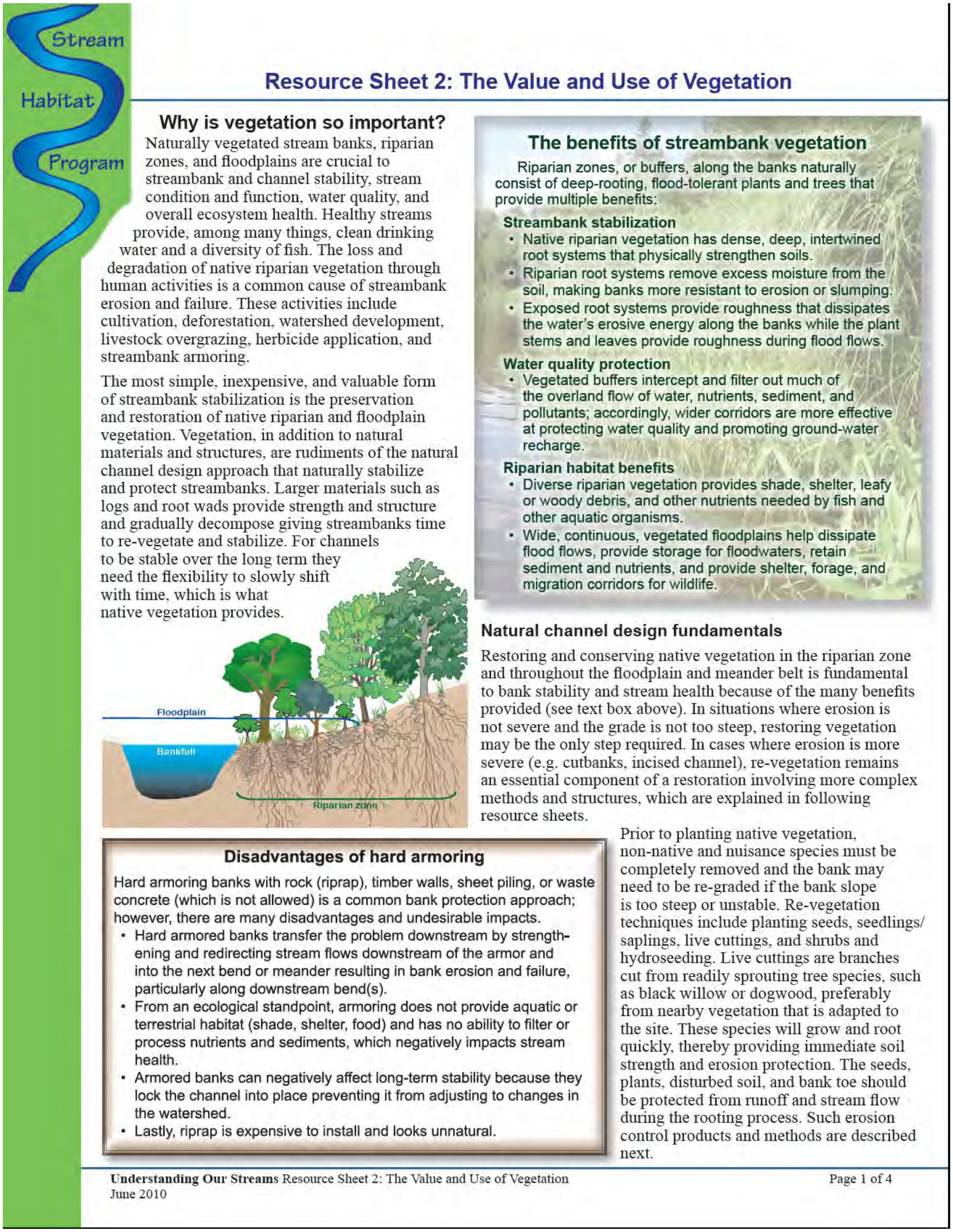


(b) Southern Minnesota regional curve by stream type; developed through MNDNR geomorphology surveys. Bankfull cross sectional area is taken at the representative riffle cross section at each site. This is a draft regional curve, and subject to change.



(c) Missouri River basin regional curve comparing bankfull (~1.5 year return interval flow) and drainage area. Green diamonds represent discharge estimates based off of the U/U* method, while the blue diamonds represent what StreamStats estimated for bankfull discharge at these sites. The two sites that appear low are Beaver Creek and Flandreau Creek. Both sites are unavailable for StreamStats analysis at this point.

Appendix 3. Documentation of implementation strategies, from the MNDNR Stream Habitat Program. PDF versions can be found at: http://www.dnr.state.mn.us/eco/streamhab/about.html.



Resource Sheet 2: The Value and Use of Vegetation

Why is vegetation so important?

Naturally vegetated stream banks, riparian zones, and floodplains are crucial to streambank and channel stability, stream condition and function, water quality, and overall ecosystem health. Healthy streams provide, among many things, clean drinking water and a diversity of fish. The loss and degradation of native riparian vegetation through human activities is a common cause of streambank erosion and failure. These activities include cultivation, deforestation, watershed development, livestock overgrazing, herbicide application, and streambank armoring.

The most simple, inexpensive, and valuable form of streambank stabilization is the preservation and restoration of native riparian and floodplain vegetation. Vegetation, in addition to natural materials and structures, are rudiments of the natural channel design approach that naturally stabilize and protect streambanks. Larger materials such as logs and root wads provide strength and structure and gradually decompose giving streambanks time to re-vegetate and stabilize. For channels to be stable over the long term they need the flexibility to slowly shift with time, which is what native vegetation provides.

The benefits of streambank vegetation

Riparian zones, or buffers, along the banks naturally consist of deep-rooting, flood-tolerant plants and trees that provide multiple benefits:

Streambank stabilization

- Native riparian vegetation has dense, deep, intertwined root systems that physically strengthen soils.
- Riparian root systems remove excess moisture from the soil, making banks more resistant to erosion or slumping.
- Exposed root systems provide roughness that dissipates the water's erosive energy along the banks while the plant stems and leaves provide roughness during flood flows.

Water quality protection

- Vegetated buffers intercept and filter out much of the overland flow of water, nutrients, sediment, and pollutants; accordingly, wider corridors are more effective at protecting water quality and promoting ground-water recharge.

Riparian habitat benefits

- Diverse riparian vegetation provides shade, shelter, leafy or woody debris, and other nutrients needed by fish and other aquatic organisms.
- Wide, continuous, vegetated floodplains help dissipate flood flows, provide storage for floodwaters, retain sediment and nutrients, and provide shelter, forage, and migration corridors for wildlife.

Natural channel design fundamentals

Restoring and conserving native vegetation in the riparian zone and throughout the floodplain and meander belt is fundamental to bank stability and stream health because of the many benefits provided (see text box above). In situations where erosion is not severe and the grade is not too steep, restoring vegetation may be the only step required. In cases where erosion is more severe (e.g. cutbanks, incised channel), re-vegetation remains an essential component of a restoration involving more complex methods and structures, which are explained in following resource sheets.

Prior to planting native vegetation, non-native and nuisance species must be completely removed and the bank may need to be re-graded if the bank slope is too steep or unstable. Re-vegetation techniques include planting seeds, seedlings/saplings, live cuttings, and shrubs and hydroseeding. Live cuttings are branches cut from readily sprouting tree species, such as black willow or dogwood, preferably from nearby vegetation that is adapted to the site. These species will grow and root quickly, thereby providing immediate soil strength and erosion protection. The seeds, plants, disturbed soil, and bank toe should be protected from runoff and stream flow during the rooting process. Such erosion control products and methods are described next.

Disadvantages of hard armoring

Hard armoring banks with rock (riprap), timber walls, sheet piling, or waste concrete (which is not allowed) is a common bank protection approach; however, there are many disadvantages and undesirable impacts.

- Hard armored banks transfer the problem downstream by strengthening and redirecting stream flows downstream of the armor and into the next bend or meander resulting in bank erosion and failure, particularly along downstream bend(s).
- From an ecological standpoint, armoring does not provide aquatic or terrestrial habitat (shade, shelter, food) and has no ability to filter or process nutrients and sediments, which negatively impacts stream health.
- Armored banks can negatively affect long-term stability because they lock the channel into place preventing it from adjusting to changes in the watershed.
- Lastly, riprap is expensive to install and looks unnatural.

Resource Sheet 2: The Value and Use of Vegetation

In choosing suitable native plant species, consider local habitat type (e.g. forest, prairie, wetland) and habitat components such as shade, soil type, moisture, and climate. Resources available to identify plant species suitable for various habitat types and desired purposes, such as erosion control, aesthetics, and wildlife habitat include: local nurseries, extension offices, soil and water conservation districts, the "Restore Your Shore" CD-ROM (info at http://mndnr.gov/restoreyourshore) and MN DNR website http://mndnr.gov/gardens/nativeplants. Vegetative stabilization has all the benefits of restoring native vegetation (strengthen and stabilize stream banks, runoff buffer, provide habitat, aesthetic value) in addition to low cost, low maintenance, lack of structural complexity, and endurance. Below is a list of plant species native to Minnesota that are recommended for streambank restorations.

Common name	Scientific name	Life form	Habitat
Blue vervain	*Verbena hastata*	F	W, UM
Canada anemone	*Anemone canadensis*	F	W, UM
Golden alexanders	*Zizia aurea*	F	W, UM
Grass-leaved goldenrod	*Euthamia graminifolia*	F	W, UM
Monkey flower	*Mimulus ringens*	F	W
Obedient plant	*Physostegia virginiana*	F	W, UM
Swamp milkweed	*Asclepias incarnata*	F	W, UM
Fowl manna grass	*Glyceria striata*	G	W
Fox sedge	*Carex vulpinoidea*	G	W, UM
Hardstem bulrush	*Scirpus acutus*	G	A, W
Porcupine sedge	*Carex hystericina*	G	W
River bulrush	*Scirpus fluviatilis*	G	A, W
Softstem bulrush	*Scirpus validus*	G	A, W
Tall manna grass	*Glyceria grandis*	G	W
Virginia wild-rye	*Elymus virginicus*	G	W
Basswood	*Tilia americana*	T	UM, UD
Black willow	*Salix nigra*	T	W
Red-osier dogwood	*Cornus sericea (stolonifera)*	T	W, UM, UD
Silver maple	*Acer saccharinum*	T	W, UM

Native Minnesota plant species recommended for stream bank restorations throughout the state (sorted by Life form then Common name).
***F**: forb (flower)* ***G**: grass or grass-like* ***T**: woody vegetation*
***A**: aquatic* ***W**: wet/transitional* ***UM**: upland moist* ***UD**: upland dry*

Natural materials and structures

Natural materials and structures can be used in addition to native vegetation to:

☆ protect seed & plantings from overland and stream flows,
☆ protect the toe of the streambank,
☆ prevent erosion on slopes,
☆ promote trapping of sediment,
☆ quickly develop dense roots and sprouts, & provide habitat.

The following six techniques are effective on small to medium streams. They are of moderate cost and can be installed by most landowners with a bit of direction. Landowners should consult an area hydrologist as project approval or a permit is required by the DNR and other agencies.

Biodegradable erosion control blankets (ECBs)

» Biodegradable ECBs are made of: jute (a vegetable fiber) mesh (*in photo*), coconut/coir fiber, straw, or excelsior (fine wood fiber) that are woven into a fiber matrix. ECBs are designed to temporarily provide erosion protection and assist with vegetation establishment as they degrade over 1-3 years leaving a vegetated bank. Products with polypropylene materials are not recommended because they do not degrade and can entangle wildlife in the rigid knitting.

× ECBs are placed over re-graded and re-seeded streambanks (use more durable netting for steeper banks). Wood stakes or live cuttings are used to secure the fabric in place (instead of metal anchor pins). Blankets should be installed promptly after the restoration to provide immediate erosion protection.

Resource Sheet 2: The Value and Use of Vegetation

Broadcast seeding and hydroseeding

» Broadcast seeding is the scattering of native seed mixes by hand or mechanically over prepared soil. Good seed to soil contact, protection (ECBs, mulch, oats or rye as a cover crop), and watering are important.

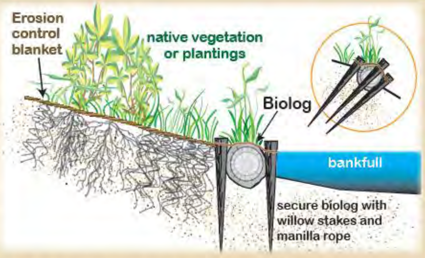
» Hydroseeding is a planting process that uses a mixture of water, seed, fertilizer, mulch, and tackifiers that is sprayed over renovated banks or slopes. Native seeds that are suitable to the habitat should be used in the mix. This mixture can be applied to the upper slopes, even on steeper slopes. The mixture should not be applied too close to the channel to avoid fertilizer from polluting the stream or seed from being washed away.

Staking and live cuttings

» Stakes and live cuttings from readily sprouting, local, healthy tree species such as black willow, dogwood, and alder are used to quickly vegetate restored streambanks. Staking can be applied on all types of banks and in addition to other techniques.

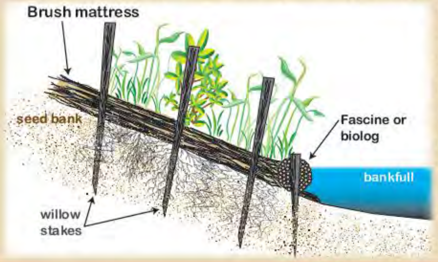
× The cuttings or stakes (branch sections without twigs or leaves) are cut and planted while dormant, late fall through early spring. Stakes are 2'+ in length and ½ - 3" in diameter with one end cut at a 45° angle. Stakes are planted 1 - 2' deep in soft soils or into a pilot hole in harder soils ensuring the stake is deep enough to reach permanently wet soils. Stakes are planted 1 - 2' apart depending on the size of the stakes to ensure successful survival and sufficient cover.

Biologs, coir fiber rolls, wattles, fascines



» Biologs and coir fiber rolls are made of coconut fiber, straw, or excelsior fiber. Wattles and fascines are cylindrical bundles of wheat or rice straw or cuttings. They are strong, flexible rolls (8-10' long, 8-12" diameter) of biodegradable material used to protect the toe of banks and to stabilize slopes . These structures work best where scour is not too severe and where flows will infrequently flow over the toe protection.

× The logs, rolls, or bundles are staked and tied into a shallow trench along the toe of the streambank to deflect flows and wave energy, retain sediment, and provide a stable structure for plant growth (substrate). Native vegetation is planted on and around the structures, then as the vegetation or cuttings becomes established, the natural materials will degrade in 2 to 6 years leaving a vegetated bank.



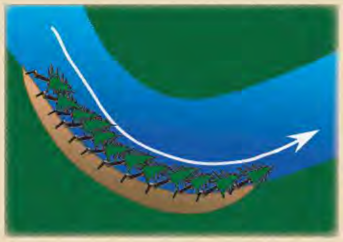
× Additional rows can be installed (placed in shallow trenches secured by wood stakes) upslope parallel to the toe of the bank for additional bank stabilization.

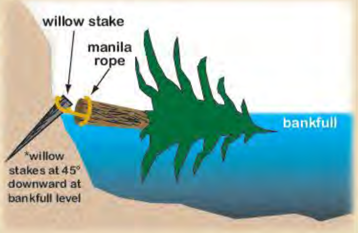
Brush mattresses

» Brush mattresses consist of a layer of interlaced dormant cuttings (e.g. willow, dogwood, alder) that are laid perpendicular to the toe and staked over a gently sloped streambank, often with a fascine or biolog at the base as toe protection.

× These structures work on most banks. They require good soil contact to support brush growth; base flows to keep the basal ends of the cuttings moist; and installation during the non-growing season, preferably early spring.

Tree revetments





» Tree revetments involve anchoring coniferous (such as Christmas trees) or hardwood trees along an outside bend where erosion is excessive.

× The trees are tied by the trunks with natural filament rope to wooden stakes placed at the bankfull level with the treetops pointing downstream. Tree revetments dissipate outside meander flows and collect sediment, thereby reducing erosion and promoting deposition.

× Tree revetments work best in small to medium streams with high sand or gravel loads because sediment deposition is important to the long-range goal of rebuilding and protecting the bank.

➪ These structures provide habitat and as they degrade and accumulate sediment they become a natural, structural part of the bank.

Resource Sheet 2: The Value and Use of Vegetation

Root wad revetments

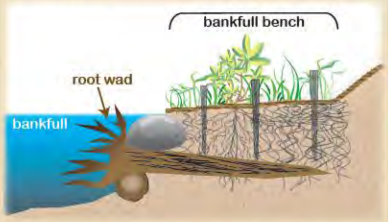
» Root wad revetments are more complex structures built into exposed cutbanks where erosion is actively cutting away the bank. These revetments commonly involve the construction of a bankfull bench to help accommodate and dissipate flood flows. This design is especially useful where there is infrastructure on the bank that needs to be protected from bank loss or slumping. These revetments can be scaled to the size of the stream (e.g., root wads can be stacked in large streams). They are not recommended in sandy soils where it is difficult to drive the trunks into the bank and the sand is more erodible.

× Large tree trunks with root wads are driven into a renovated cutbank so that the trunks angle upstream and the root wads are positioned below bankfull level directed into the flow. The trunks are secured with large boulders and a matrix of logs. Live cuttings are staked, natural vegetation planted or seeded, and erosion control fabric is staked on the bankfull bench and restored bank.

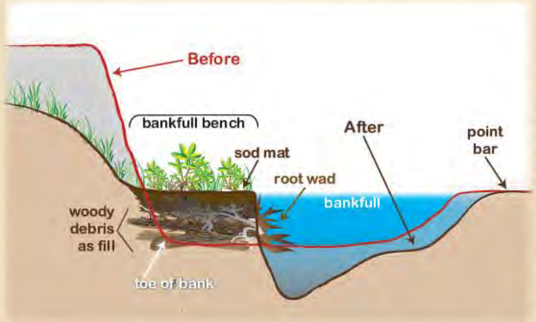
⇨These revetments protect the banks over a range of flows, provide substrate for invertebrates and refuge for fish, and will slowly degrade while becoming a natural part of the streambank.

Installation of root wads using an excavator to drive tree trunks into the bankfull bench (looking upstream).

**Variations of this design have been used through the years. For more specific design details see Applied River Morphology by Dave Rosgen, 1996.*



Root wad revetment and a revegetated bankfull bench built to stabilize a cutbank encroaching on Interstate 94, two years after construction (looking downstream).



Toe wood-sod mats *(see fact sheet for more details)*

» Toe wood-sod mats involve similar design elements to the root wad revetments. This approach can be scaled to all stream sizes.

× Cutbanks are renovated with a bankfull bench consisting of layers of logs, branches, brush, roots, and fill. Root wads can be incorporated to provide additional roughness and habitat. These layers are then covered with sod mats, willow cuttings, and transplants set at bankfull stage.

⇨ This structure design restores the connection to the floodplain with a bankfull shelf, restores channel dimensions, protects a once vulnerable and unstable cutbank, provides habitat (both aquatic and terrestrial), and is relatively inexpensive.

**Variations of this design have been used through the years. General design details are credited to Dave Rosgen of Wildland Hydrology.*

Review and advanced restoration designs

Bank restorations utilizing vegetation, erosion-control blankets, biologs, wattles, revetments, and mats or combinations thereof, can effectively protect and rebuild banks if properly placed and established. These approaches utilize all natural materials that do not artificially confine the channel, they are relatively inexpensive, and can be applied to all stream varieties (forested, prairie, steep, gentle, rocky, sandy). As explained in Resource Sheet #1, the cause(s) of stream instability and future watershed conditions should be considered. Most projects will need permits and professional assistance.

In some cases in-channel structures can also be used to protect restored or unstable banks. These include rock structures such as rock vanes, J-hooks, and riffles that are effective at properly slowing and deflecting flows from the streambanks. Installation of these structures requires professional assistance because proper placement is absolutely essential for successful streambank protection and restoration. This requires stream and watershed monitoring and assessments. These in-channel structures are explained in more detail in the following resource sheets.

Contact Information

DNR Ecological Resources:
Stream Habitat Program
Ecosystem Restoration
500 Lafayette Road, Box 25
St. Paul, MN 55155
(651) 259-5900

DNR Waters:
Public Water Permit Requirements
500 Lafayette Road, Box 32
St. Paul, MN 55155
(651) 259-5700

DNR website:
http://mndnr.gov

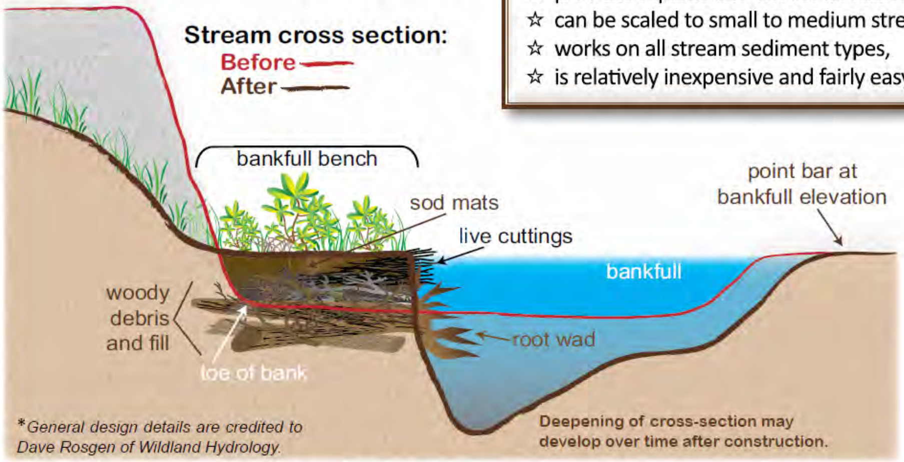
Stream Restoration: Toe Wood-Sod Mat

Purpose of a Toe Wood-Sod Mat

All streambank restoration project goals should be to: 1) restore channel function, dimensions and connection to the floodplain, 2) provide short-term protection that promotes natural long-term stability, 3) allow the channel to adjust over the long-term, 4) protect meanders (a.k.a., sinuosity) of a stream to prevent a meander cutoff. A toe wood-sod mat provides the opportunity to add stability, habitat, and streambank protection where it is needed.

The toe wood-sod mat is a preferred design because it:

- ☆ restores channel dimensions (width & depth),
- ☆ protects a once vulnerable and unstable cutbank,
- ☆ restores the connection to the floodplain with a bankfull bench,
- ☆ incorporates transplanted sod mat(s) and live cuttings that grow quickly and develop dense roots,
- ☆ utilizes all natural materials using local vegetation and sod,
- ☆ provides aquatic and terrestrial habitat,
- ☆ can be scaled to small to medium streams,
- ☆ works on all stream sediment types,
- ☆ is relatively inexpensive and fairly easy to install.



Construction of a Toe Wood-Sod Mat:

The cutbank is renovated by angling back the upper bank and excavating or filling in (depending on stream width and site restrictions) the lower bank with a bankfull bench. The bench consists of a bottom layer of logs, branches, brush, roots and soil as fill. Root wads can be incorporated to provide additional roughness and habitat. The fill is covered with a layer of live cuttings then with a top layer of sod mats and transplants set at *bankfull stage* (*the flow at which the channel fills the banks and just begins to overflow onto the floodplain*), which is level with the point bar. The stream bed may deepen with time as the stream develops its proper dimensions. In some cases, rock vanes may be installed up and downstream of the mat depending on how flow is impacted. A permit is needed from the DNR to construct a toe wood-sod mat. Permits may also be required from local and federal agencies. Contact your DNR Area Hydrologist for permit information.

Streambank restoration fundamentals:

Several factors need to be considered when proposing a streambank restoration project, like a toe wood-sod mat:

Evaluate the current and future watershed condition. Often, the presence of cutbanks indicates watershed-scale channel incision due to channel straightening, changes in the watershed that have introduced low-sediment water (dam, urbanization, tiling), or increased flood magnitude (see Resource Sheet #1). Before taking action, consider the purpose and scale of a restoration.

Determine if there really is an erosion problem. Channel erosion is natural channel adjustment to change. Occasional cutbanks are a natural stream feature that provide unique habitat. For example, a straightened ditch that is forming new meanders is adjusting towards a more stable form. Yet there are cases where local protection of infrastructure is necessary, and so determining if erosion is a problem is important.

Contact Information

DNR Ecological & Water Resources:

Stream Habitat Program
500 Lafayette Road, Box 25
St. Paul, MN 55155, (651) 259-5100

Public Water Work Permit Program
500 Lafayette Road, Box 32
St. Paul, MN 55155
(651) 259-5700

DNR website:
http://mndnr.gov

Toe Wood-Sod Mat: Construction Examples

Spruce Creek


Unstable bank encroaching on a picnic shelter. Toe of bank is eroding causing slumping and stream is overwide.


Construction of bankfull bench. A layer of woody debris and fill was placed along the bank toe then covered with live willow cuttings (in foreground).


Collection of local dogwood and willow sod mats with very dense root mats.


Placement of final layer of sod mats on the constructed bench at bankfull elevation.


Finished bank stabilization project: Vegetated bankfull bench and a graded streambank protected with erosion control blankets.

Buffalo River


Unstable bank and failing flood control dike protecting a mobile home park. The project started with the placement of woody debris and insertion of root wads.


The completed woody debris layer with incorporated root wads. The upper bank was regraded with a more gentle slope.


Dirt was added as fill and rooting material to the woody debris layer.


Locally collected red-osier dogwood and willow sod mats were placed on the constructed bench at bankfull elevation.


Project was completed with a vegetated bankfull bench and a re-graded upper bank seeded with native seed mix. New growth was thriving the next summer.