Evaluation of Minnesota River Physical Habitat Features

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Executive Summary

Project activity 2: Quantify physical habitat characteristics of the Minnesota River.

Project Objectives

- Quantify channel dimensions at twelve sites along the Minnesota River.
- Quantify additional physical habitat characteristics at twelve sites along the Minnesota River.

Significant Outcomes

- We quantified channel dimensions and physical habitat characteristics at twelve 2.0-5.5 km study sites located along the lower 402 km of the Minnesota River.
- Basic habitat surveys at 10 study sites included bathymetric mapping, longitudinal profiles, and woody debris surveys. Comprehensive habitat surveys at 2 study sites also included riffle cross section surveys.
- Average channel sinuosity of study sites was 1.34, varying from 1.05 to 2.76.
- Woody habitat (e.g., log jams, fallen trees) is prevalent in the Minnesota River, with percent of channel surface area covered with woody debris varying from 0.2% to 2.4%.
- Mean thalweg depth of the 12 sites was 3.45 m, varying 1.31–6.96 m.
- Riparian zone land cover is primarily wetlands, while the proportion of agriculture land cover increases at larger scales, accounting for approximately 78% of land in the Minnesota River watershed.
- Sediments in the Minnesota River Basin are highly erodible, consisting mostly of alluvium, till plain, and supraglacial drift complex which results in large amounts of sediment transport and deposition within the Minnesota River.
- Mean annual precipitation and the magnitude of single rain events is increasing throughout the Minnesota River Basin, resulting in increased mean discharge that impacts channel morphology and habitat complexity of the Minnesota River.
- Collection of baseline physical habitat data, coupled with continued monitoring, will provide insight into how the physical features and the Minnesota River ecosystem will respond to continued changes in climate, land use, and conservation efforts.

Abstract

Physical habitat has direct and indirect influences on biotic communities of riverine ecosystems. In alluvial systems like the Minnesota River, many factors influence physical habitat and geomorphology including watershed characteristics, underlying geology, climate, flow regime and human induced changes. The complex interactions between these factors often creates a dynamic mosaic of habitats, but some can also lead to homogenization of habitats. The Minnesota River landscape has many anthropogenic alterations (row crop agriculture and artificial drainage systems) and is experiencing changes in climate (increased precipitation and magnitude of single rain events) that impact the physical habitat of the river. The goal of this study is increasing understanding of physical habitat characteristics of the Minnesota River to provide insight into how future anthropogenic changes and climate changes may impact physical habitat and ecosystem health. During August 2016–August 2018, we quantified channel dimensions and other physical habitat characteristics at twelve sites along the Minnesota River. Habitat complexity varied widely among the twelve study sites with channel sinuosity varying 1.05–2.76, mean thalweg depth varying 1.31–6.96 m, and percent of woody debris coverage varying 0.18–2.38%. Land cover types varied at different scales among study sites, but in general, wetlands dominated land cover types at a local scales (e.g., riparian zone) while agriculture dominated land cover type at larger scales (e.g., greater than 500 m zone). Changes in land use and climate will undoubtedly impact physical habitat of the Minnesota River and subsequently the entire ecosystem, but the extent is unknown. The results of this study provide baseline measurements of physical habitat features that will allow for future quantification of changes.

Introduction

Rivers are dynamic landscape features strongly influenced by watershed characteristics (e.g., size, drainage density, slope, land use), climate, and underlying geology. These factors, along with human induced changes, ultimately determine the physical characteristics of these aquatic ecosystems that provide important habitat for many living organisms. In alluvial systems (i.e., banks and riverbed are composed of mobile sediments), like the Minnesota River, geomorphology is directly influenced by water discharge, sediment loads, and channel gradient (Call et al. 2017, Lauer et al. 2017). The flow regime and underlying geology (e.g., gradient, bed material) creates channel features, such as pools, riffles and runs, through erosion and deposition (Allan 2004); causes channel migration resulting in side channels and oxbows (Lauer et al. 2017); and maintains floodplain connectivity (Call et al. 2017). This results in a dynamic mosaic of habitat types and features.

Structural complexity of habitats has a direct influence on local species assemblages (Ward 1998). Interactions between complex and dynamic habitats and the habitat needs, life histories and dispersal abilities of biota, results in a greater diversity of species than in static habitats (Townsend 1989). Increased structural complexity (e.g., woody debris, depth variability) can also provide more diverse substrates (Bond and Lake 2005, Shields et al. 2006), increased foraging opportunities (Drury and Kelso 2000, Braccia and Batzer 2001), and refuge areas that reduce the intensity of interference competition and predator-prey interactions (Savino and Stein 1982, Willis et al. 2005). For example, Schneider and Winemiller (2008) reported that increasing habitat complexity

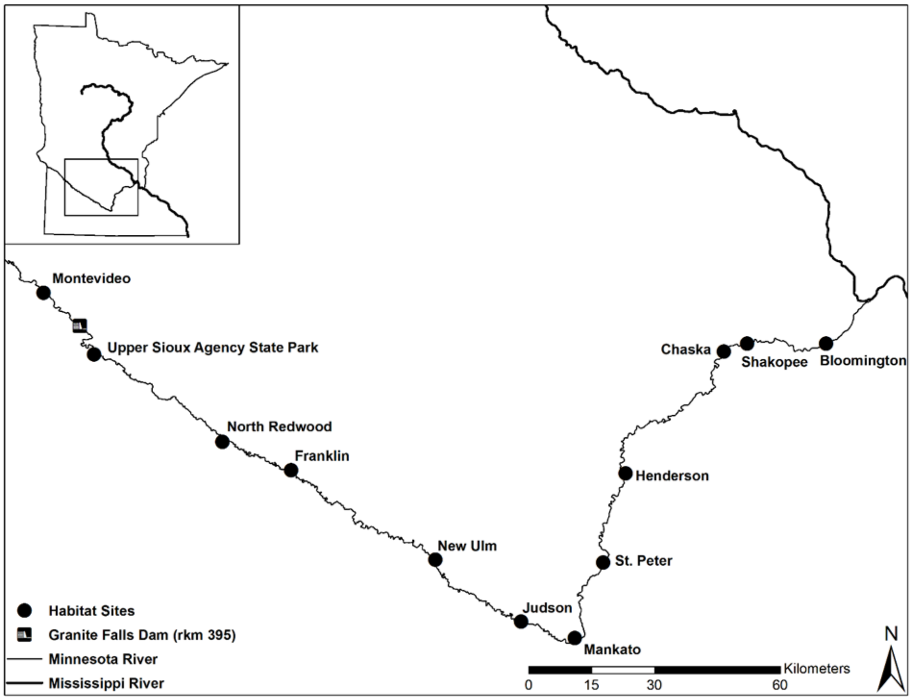

Figure 1. Location of twelve study sites where habitat surveys were conducted along the Minnesota River during August 2016–August 2018.

through the addition of woody debris in the Brazos River was associated with greater abundance and diversity of macroinvertebrates and fishes. Fish species have a wide range of spawning habitat requirements from course substrates in rapids (e.g., Lake Sturgeon *Acipenser fulvescens*) to aquatic macrophytes in sluggish waters (e.g., Bigmouth Buffalo *Ictiobus cyprinellus*), thus aquatic systems with complex and diverse habitats can support greater species diversity (Becker 1983, Chiotti et al. 2008, Bruch et al. 2016).

Since health of the Minnesota River ecosystem, including fish communities, is influenced by habitat features, our goal is to increase understanding of and quantify physical habitat characteristics. Ultimately, we hope to provide insight into how anthropogenic changes to the landscape along with changes in climate may impact the physical habitat of the Minnesota River and consequently ecosystem health. During 2016–2019, funding from the Environment and Natural Resources Trust Fund (ENRTF; lccmr.org) provided the Minnesota Department of Natural Resources (DNR) with the capacity to evaluate and quantify physical habitat characteristics of the Minnesota River.

Study Site

The Minnesota River Basin is approximately 44,030 square km^2 draining portions of Minnesota (38,205 km^2), South Dakota, and Iowa. The Minnesota River is a large 7th–8th order river (Strahler 1957) that flows approximately 515 km from Big Stone Lake on the Minnesota-South Dakota Border to its confluence with the Mississippi River in St. Paul, MN. The Minnesota River flows through a large valley formed by glacial River Warren as it drained glacial Lake Agassiz (Teller et al. 2002, Lepper et al. 2007). The creation of the Minnesota River Valley by glacial River Warren created a drop in base elevation (Groten et al. 2016, Lauer et al. 2017) which caused incision of tributaries through highly erodible layers of glacial sediments (consisting of clay, silt, and sand) that provides a significant amount of sediment to the system (Belmont 2011, Gran et al. 2011).

Along with sediments from tributaries, the Minnesota River has experienced an increase in discharge over the past century. The observed increase in discharge is likely

Table 1. Descriptive habitat characteristics of 12 Minnesota River study sites.

Site	River kilometer	Site length (km)	Percent woody debris coverage	Riffle cross section	Sinuosity	Mean thalweg depth (m)	Depth CV
Montevideo	402	2.0	0.67	Y	1.33	1.51	30.90
Upper Sioux	365	2.4	0.54	N	1.25	1.31	55.37
North Redwood	318	2.0	2.38	N	2.76	2.21	40.42
Franklin	289	3.6	0.82	N	1.43	2.69	33.29
New Ulm	222	5.5	0.86	N	1.18	3.63	40.81
Judson	185	4.4	0.18	Y	1.06	2.17	29.33
Mankato	167	3.9	0.70	N	1.15	2.92	39.77
St. Peter	141	3.4	0.84	N	1.10	4.25	64.40
Henderson	107	4.0		N	1.08		
Chaska	46	3.7		N	1.42	4.53	50.40
Shakopee	40	3.5	0.46	N	1.31	6.04	32.18
Bloomington	16	3.2	0.27	N	1.05	6.96	13.80

due to several factors including land use conversion, artificial drainage, and climate change. Historically, much of the basin was grassland and wetlands, but today the basin is dominated by agriculture (78% in row crop agriculture) with extensive surface and sub-surface drainage systems that allow for rapid removal of water from the landscape (e.g., tiles, drainage ditches; Musser et al. 2009, Belmont et al. 2011, Lenhart et al. 2011). Mean annual precipitation has also increased within the basin over the past several decades, leading to increased runoff and discharge (Musser et al. 2009, Gran et al. 2011, Schottler et al. 2014, Kelly et al. 2017). This increase in discharge has resulted in a more erosive river. For example, Lenhart et al. (2013) documented that the lower 167 km has widened by 53% since 1938 and shortened in length by 12% since 1854.

To improve understanding of Minnesota River geomorphology and physical habitat characteristics, we established twelve 2.0-5.5 km study sites where we quantified channel dimensions and physical habitat characteristics (Figure 1; Table 1). We selected sites along the Minnesota River to encompass spatial variability of habitat throughout the river, and also included sites where concurrent evaluations of Shovelnose Sturgeon *Scaphirhynchus platorynchus* and Paddlefish *Polyodon spathula* were occurring.

Methods

We established two types of study sites for quantifying physical habitat characteristics. At eight basic study sites we measured longitudinal depth profiles, developed bathymetric maps, and quantified instream woody habitat. At four comprehensive study sites, we also measured a riffle cross section. We surveyed longitudinal profiles and riffle cross section profiles using methods described in the fisheries stream survey manual (Minnesota Department of Natural Resources 2007) and by Harrelson et al. (1994). Additionally, we used aerial imagery and digital elevation models to quantify sinuosity, river valley cross section, and surrounding land use types for all study sites.

We measured channel cross sections by recording depths along a transect that crossed the river channel perpendicularly at a riffle. We used a precision laser level (Trimble SPECTRA Precision Laser LL500), survey rod outfitted with laser receiver (Trimble HR500 Laser Eye® Receiver), and precise GPS (Trimble GeoExplorer® 6000 Series) to record coordinates and elevation of the streambed or bank and water surface at 0.25–2.00 m intervals along the perpendicular transect. Cross section measurements were collected starting at bank full height along one bank to bank full height along the other bank.

Longitudinal profiles were developed by measuring streambed and water surface elevations along the thalweg of each study reach with a precision laser level (Trimble SPECTRA Precision Laser LL500), survey rod outfitted with laser receiver (Trimble HR500 Laser Eye® Receiver), and precise GPS (Trimble GeoExplorer® 6000 Series). Starting at the upstream end of the study reach, we drifted a boat through the study reach while maintaining position along the thalweg. We characterized the shape, depth, and lengths of streambed features (e.g., pools, riffles, runs) through longitudinal profiles by recording elevations every 10-20 m, or more frequently through areas of considerable change. We calculated average thalweg depth and coefficient of variation (CV) to better describe and compare habitat complexity among sites.

We increased accuracy of longitudinal and cross section profiles by differentially correcting GPS points with the GPS Pathfinder Office software (Trimble, Sunnyvale, CA). We processed each rover file containing Global Navigation Satellite System (GNSS) data using automatic carrier and code processing with a single base provider. GNSS data is both carrier-processed and code-processed, and the position with the best precision is selected for corrected position. Base stations were selected from base provider groups located closest to each habitat site. Following differential corrections, we exported corrected files as ESRI (Environmental Systems Research Institute, Inc., Redlands, CA.) shapefiles for further analysis in ArcMap (Environmental Systems Research Institute, Inc., Redlands, CA; v10.6). Average estimated accuracy for longitudinal and cross section profile points following differential corrections was ≤ 0.5 m for each site.

We collected bathymetric data at each study site using a Humminbird 898 sonar (Transducer model XHS 9 HDSI 180 T) and created interpolated bathymetric maps using the Humminbrid Autochart mapping software (Johnson Outdoors Marine Electronics, Racine, WI). We typically conducted bathymetric mapping during high water periods to allow for ease of navigation across the entire river channel. River levels were recorded from both upstream and downstream gages for reference when interpreting water depths at varying water levels. If gage height was not available, discharge (ft^3/sec) was recorded as a surrogate. We collected depth and corresponding location data with the Humminbird sonar unit while driving the boat 3-5 mph along five transects (left bank, left-center, center, right-center, right bank) parallel to the river bank. Depths in areas between transects were calculated through interpolation and extrapolation. Interpolation and extrapolation limits were typically set at 25 m and 5 m, respectively, but were increased if gaps occurred in created maps. We generated maps using the smooth/fast method in the AutoChart mapping software, which creates maps with an interpolation algorithm that results in smoother maps and reduced computation time.

We quantified woody habitat (e.g., log jams, fallen trees) within each study reach by estimating the aerial coverage (length x width), recording the GPS location and taking a picture of woody habitats throughout each study site. We calculated the percent of total aerial coverage by woody habitat within each study reach by dividing the entire surface area

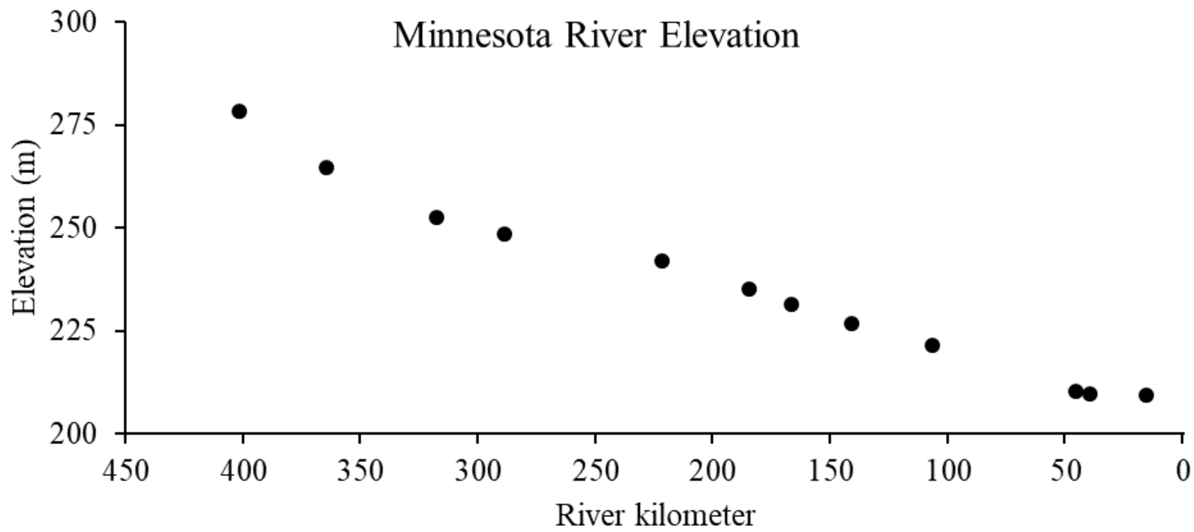

Figure 2. Minnesota River elevation (m) and river kilometer of habitat survey sites surveyed during this study. Elevation values based on MnTOPO LiDAR data.

of the study site by the sum of woody habitat surface area. We conducted woody habitat surveys during normal flow conditions, and acknowledge that aerial coverage changes with changing water levels.

Sinuosity for each habitat site was calculated using aerial imagery (Minnesota composite aerial photography, 2017 color FSA; MNDNR Quick Layers) and river centerlines in ArcMap (Esri, Redlands, CA; v10.6). Sinuosity is the ratio of stream length to valley length. River channel lengths for each site were based on channel centerlines (Stream routes – major river centerlines; MNDNR Quick Layers) in ArcMap. Valley lengths were determined from digitized valley lines from aerial imagery (Minnesota composite aerial photography, 2017 color FSA; MNDNR Quick Layers). Cutoffs (erosion across a meander loop that shortens and straightens the course of the river) within each site were also noted since they are directly related to reductions of sinuosity.

Minnesota River Valley cross sections were developed with LiDAR elevation data obtained from the MnTOPO website (http://arcgis.dnr.state.mn.us/maps/mntopo/). Using the “line elevation” tool, a transect was drawn from one side of the river valley to the opposite side of the river valley running through the study reach. Downloaded data contained UTM coordinates and elevation, and were used to create graphs displaying elevation and distance along the valley cross section transect.

Landscape scale land cover variables were also estimated for each habitat site. Land cover was quantified by first drawing concentric bands (50-, 500-, 1,000-, and 5,000-m) around each habitat site. Land cover data was provided by the Multi-Resolution Land Cover Consortium’s (MRLC) 2011 National Land Cover Dataset (NLCD; Homer et. al 2015). Land cover classes utilized for the riparian zone (i.e., 50 m band) were agriculture, forest-cover, wetlands, and human disturbance (e.g., urban development, and impervious surfaces). Land cover classes utilized for the broader bands were agriculture, forest-cover, wetlands, human disturbance, and open water. Land cover class percentages were calculated for each band surrounding each site using spatial analyst tools in ArcGIS.

Results

Table 2. Proportion of land use types at various scales for all study sites combined.

Land cover type	Mean	CV	Min	Max
Riparian zone – 50 m (%)				
Agriculture	19	119	0	80
Forest-cover	26	76	1	66
Wetlands	39	49	10	72
Human Disturbance	16	134	0	78
Watershed - 500 m (%)				
Agriculture	23	69	3	57
Forest-cover	15	87	3	51
Wetlands	25	45	6	46
Human Disturbance	20	103	3	76
Open water	18	61	6	42
Watershed - 1,000 m (%)				
Agriculture	27	71	3	60
Forest-cover	13	81	4	43
Wetlands	20	46	4	35
Human Disturbance	24	96	4	82
Open water	17	69	4	39
Watershed - 5,000 m (%)				
Agriculture	51	47	3	81
Forest-cover	10	49	2	24
Wetlands	8	39	5	13
Human Disturbance	24	96	5	74
Open water	6	67	2	15

Minnesota River Basin

We surveyed physical habitat characteristics and channel dimensions at twelve sites (from 7 rkm upstream of the Granite Falls Dam to 16 rkm upstream of the confluence with the Mississippi River) that encompassed spatial variability of habitat within the Minnesota River. One habitat site (Montevideo) was located upstream of the Granite Falls Dam, and the remaining 11 study sites were within the free flowing reach of river downstream of Granite Falls Dam (Figure 1). Study site elevation ranged from 278.5 m above sea level at the Montevideo site to 209.3 m at the Bloomington site with an approximate channel slope of 0.18 m/rkm (Figure 2). Channel sinuosity varied from 1.05 at the Bloomington site to 2.76 at the North Redwood site with a mean of 1.34 (Table 1). Valley width averaged 3.0 km and varied 1.1–8.1 km (See site specific figures, Montevideo 1–Bloomington 1) while flood plain width (distance between valley walls) averaged 1.7 km and varied 0.9–3.3 km (see site specific figures; Montevideo 1–Bloomington 1). Percent of woody debris coverage varied among sitse, with the greatest percent coverage (2.38%) at the North Redwood site and the lowest percent coverage (0.18%) at the Judson site (Table 1). Mean thalweg depth was 3.45 m varying from 1.31 m at Upper Sioux to 6.96 m at Bloomington (Table 1). Land cover types vary at different scales among all study sites. Wetlands are the dominant land cover type within the riparian zone and the 500 m band, representing 39% (CV=119) and 25% (CV=45) of the land, respectively (Table 2). Similar to land cover types, geology and sediment types vary by study site. In general, the Minnesota River channel flows through alluvium and bedrock, but differences in sediments exist at larger scales within the watershed (Figure 3). In the upstream portions of the Minnesota River Basin, sediments consist mostly of alluvium, bedrock, lacustrine, and till plain (Figure 3). Sediments in the middle and lower portions of the Minnesota River Basin consist of alluvium, bedrock, terrace, and supraglacial drift complex (Figure 3).

Site 1: Montevideo

The Montevideo site is the furthest upstream site located between the cities of Montevideo and Granite Falls and is the only study site located upstream of the Granite Falls Dam. The site begins approximately 800 m downstream of the Wegdahl county park boat ramp and continues downstream 2.0 km. We conducted a comprehensive survey at this site which included a riffle cross section,

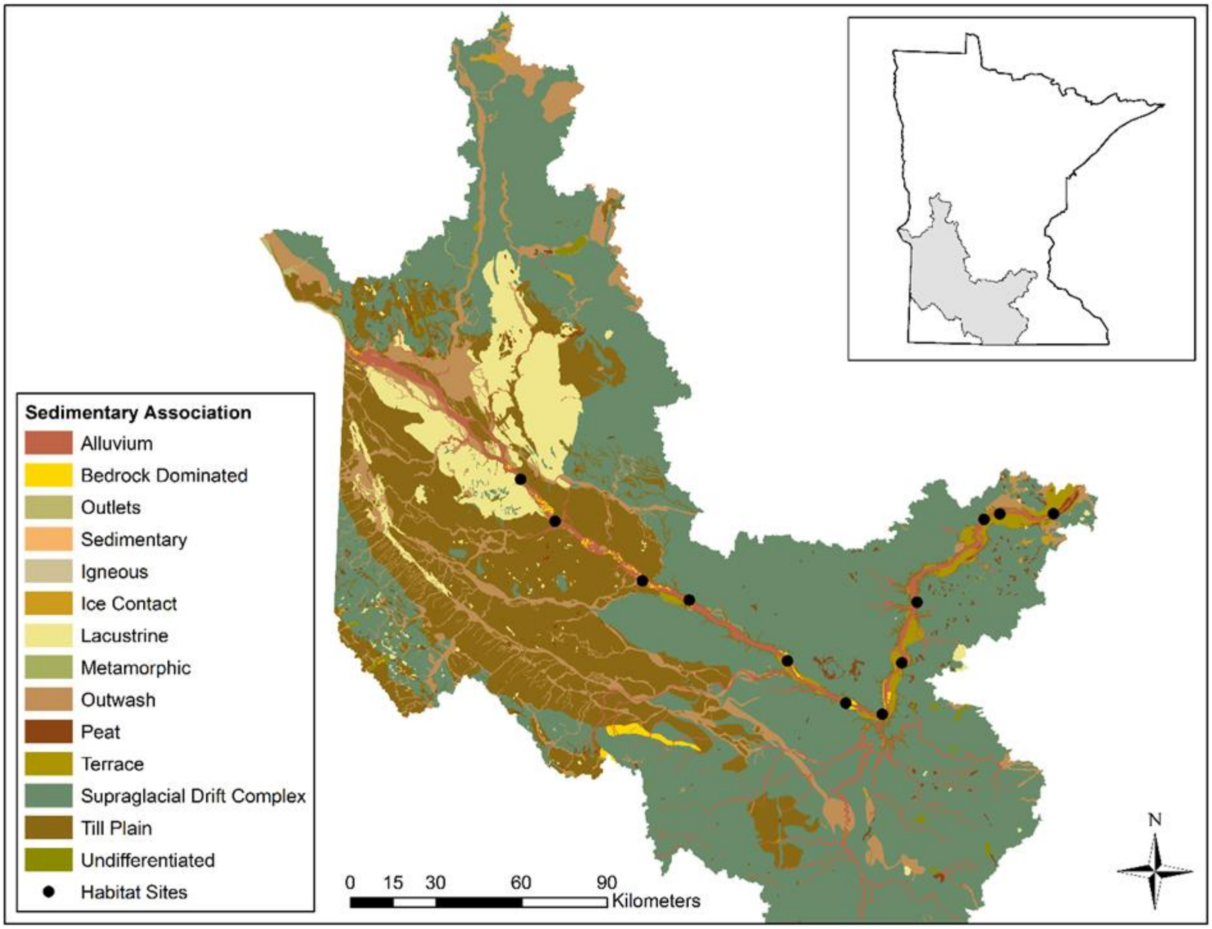

Figure 3. Sedimentary association of the Minnesota River Watershed and locations of twelve habitat study sites.

longitudinal profile, bathymetric map, and a woody debris survey. The longitudinal profile identified several pool, riffle, run sequences throughout the study reach (Montevideo 3). Pool habitats were associated with the meander bend located at the upstream section of the reach (Montevideo 5). Several riffles were located from the longitudinal profile and bathymetric mapping (Montevideo 3; Montevideo 5). Average thalweg depth was 1.51 m with a depth CV of 30.90, indicating a moderately uniform depth compared to other study sites (Table 1). The riffle cross section indicated that the thalweg was on the north side of the river, with a corresponding steep bank on the north side, and a shallow sloping bank on the south side (Montevideo 2). Sinuosity of the Montevideo site is moderately low (1.33) compared to other study sites (Table 1), but several bends are located upstream and downstream of the site. Woody debris was found throughout the site, and covered 0.67 % of surface area at the time of the survey (Montevideo 6; Table 1). Wetlands dominated the riparian zone (55%), with human disturbance being the second most common land cover type (33%) (Montevideo 4). Much of the human disturbance is attributed to Hwy 212, which runs along the south side of the study site. Land cover at larger scales is dominated by agriculture; 45% and 81%, for the 1000m and 5000m bands, respectively (Montevideo 4).

Site 2: Upper Sioux

The Upper Sioux site is located approximately 15.0 km downstream of Granite Falls Dam. The site begins at the Fredrickson boat ramp located off Pete's Point Road and continues downstream for approximately 2.4 km. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. The longitudinal profile identified two pools within the site, but the majority of the site is relatively shallow with an average thalweg depth of 1.31 m and a depth CV of 55.37 (Upper Sioux 2; Table 1). Based on the bathymetric map, the two pools are associated with sharp bends in the river channel, where bedrock outcrops cause the river channel to narrow (Upper Sioux 4). The site contains two riffles and the largest occupies approximately one-third of the site (Upper Sioux 4). With the exception of the sharp bend, the site is relatively straight, resulting in a low channel sinuosity value of 1.25 (Table 1). Woody debris is distributed throughout the site, including mostly small log jams and fallen trees, covering 0.54% of the total surface area (Upper Sioux 5; Table 1). Land cover in the riparian zone was dominated by wetlands (55%), with forest-cover (23%) and agriculture (22%) making up the remainder of the riparian zone (Upper Sioux 3). At the 500 m band, wetlands (33%) and agriculture (30%) make up the majority of land cover, with forest-cover decreasing to 15% and open water increased to 17%. Land cover in the larger 1,000 m and 5,000 m bands is primarily agriculture, 41% and 69%, respectively (Upper Sioux 3). Human disturbance at this site is low, varying from 4% in the 500 m band to 5% in the 1,000 and 5,000 m bands (Upper Sioux 3).

Site 3: North Redwood

The North Redwood site begins at the start of the side channel, approximately 1.2 km upstream from the North Redwood boat ramp, and ends at the confluence of the side channel with the main river approximately 2.0 km downstream of the boat ramp for a total site length of 3.2 km. The Redwood River enters the site from the south, approximately 800 m downstream of the boat ramp. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. Bathymetric mapping identified two pools associated with the County Highway 1/101 bridge, one pool upstream and one downstream, with the remainder of the site being uniform depth varying between 3.0 and 4.5 m (North Redwood 4). Although the Redwood River joins the Minnesota River within this site, we did not observe a sediment delta with the bathymetric map or longitudinal profile (North Redwood 4). Channel sinuosity of this site (2.76) is greater than at any other study sties (Table 1). Woody debris coverage is also greater at this site than any other study site, covering 2.38% of the total surface area (North Redwood 5; Table 1). Land cover in the riparian zone is primarily forest-cover (37%), agriculture (30%), and wetlands (27%) (North Redwood 3). Like most other sites, agriculture is the predominant land cover type at larger scales (500-5,000 m), varying from 42–63% (North Redwood 3). The wetland land cover type is the second most prevalent land cover type at larger scales, accounting for 26% in the 500 and 1,000 m bands, and 13% in the 5,000 m band (North Redwood 3).

Site 4: Franklin

The Franklin site extends approximately 3.6 km upstream from the Franklin boat ramp. The Franklin site contains two channel cutoffs where the river channel historically flowed. The upstream cutoff was created between 1955 and 1991 and has since filled in and only holds water during high water periods. The downstream cutoff was created between 1992 and 2003, and maintains connection with the river during most flow conditions. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. The longitudinal profile and bathymetric mapping identified several pool areas (Franklin 2; Franklin 4). One small pool was identified at the upstream end of the site, and two other larger pool complexes were identified along outside bends (Franklin 4). Average thalweg depth of the study site is 2.69 m with a moderate depth CV of 33.29 and a drop in water surface elevation of 0.27 m over approximately 800 m was identified during the longitudinal profile (Table 1; Franklin 2). Channel sinuosity of this site is moderate (1.43; Table 1). Woody debris is distributed throughout the site, with the majority of woody debris consisting of small brush piles or single logs, resulting in 0.82% of the total surface area (Franklin 5; Table 1). Land cover in the riparian zone and the 500 m band is dominated by wetland (57% and 46%, respectively) and agriculture (33% and 34%, respectively) (Franklin 3). Land cover in the 1,000 m band is similar to the riparian and 500 m bands; however, a shift towards more agriculture and less wetlands was identified (Franklin 3). This trend continues to the 5,000 m band, where 71% of land cover is agriculture (Franklin 3).

Site 5: New Ulm

The New Ulm site begins approximately 970 m downstream of the MN Hwy 15 bridge and continues downstream for 5.5 km ending just upstream from a railroad bridge. This stretch of river has gone through a considerable amounts of channel migration with several historic cutoffs. Within the New Ulm site, two channel cutoffs exist and were created between 1992 and 2003. These cutoffs provide oxbow backwater habitats that maintain connection with the main channel during most flow conditions. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. The longitudinal profile and bathymetric mapping identified a large riffle at the upstream end of the site, a small riffle towards the downstream end, and several pool areas (New Ulm 2; New Ulm 4). The pools are generally associated with cutoff locations and scour pools along outside bends (New Ulm 4). Average thalweg depth is 3.63 m with a depth CV of 40.81, which is moderate compared to other study sites (Table 1). The majority of the site is relatively straight, resulting in a low channel sinuosity value of 1.18 (Table 1). Woody debris is distributed throughout the site, including mostly single logs and small log jams, but a few large log jams are present at the downstream end. Total coverage of woody debris at the time of the survey was 0.86% of the surface area (New Ulm 5; Table 1). Many of the banks and point bars within this site are covered with small willows that are not included in the woody debris mapping, but likely provide cover and refuge for fish during high water events. The majority of the land cover within the riparian zone is wetlands (72%), followed by human disturbance (15%), forest-cover (9%), and agriculture (4%) (New Ulm 3). Percentage of wetlands at this site is high in the 500 and 1,000 m bands, representing 32% and 25%, respectively (New Ulm 3). The percent of human disturbance increases from 15% in the riparian zone, to 33% in the 500 m band, and 38% in the 1,000 m band (New Ulm 3). The observed increase in human disturbance at larger scales is due to the close proximity of the City of New Ulm, which is located along the south side of the river. Unlike many of the upstream sites, the percent of agriculture is low, except in the 5,000 m band where it comprises 58% of the land cover (New Ulm 3).

Site 6: Judson

The Judson site begins at the County Road 23 Bridge and continues downstream 4.4 km. Several creeks flow into this stretch of the river, creating several large deltas within the main channel. Areas of bedrock are scattered throughout the site, with more bedrock and large boulders present along the south bank. Steep banks line the south side of the river channel, while more gradual banks are present along the north side. We conducted a comprehensive survey including a riffle cross section, a longitudinal profile, bathymetric mapping, and a woody debris survey. The longitudinal profile and bathymetric mapping indicate that the majority of the site consists of riffles and runs, with pool habitat limited to several small pools ranging from 3.0 to 4.6 m depth (Judson 3; Judson 5). Mean thalweg depth is 2.17 m with a depth CV of 29.33 (Table 1). Based on water surface elevation readings collected during the longitudinal profile, the site is characterized as low gradient, dropping approximately 0.23 m from the start of the site to the end (Judson 3). Based on the riffle cross section, the channel is characteristic of a trapezoidal shape, with sloping banks and a generally flat stream bed (Judson 2). This shape is generally associated with engineered or modified channels, however, no such modification has occurred at this site. Generally, trapezoidal channels are effective at transporting water, but ineffective at transporting sediments. Percentage of woody debris coverage is lower (0.18%) than all other study sites (Judson 6; Table 1). This study site is relatively straight, with low channel sinuosity (1.06; Table 1). Agriculture is the predominant land cover type at all scales, varying from 80% of land in the riparian zone to 74% in the 5,000 m band (Judson 4). Wetlands are the second most common land cover type, varying 7–23%, with the greatest percent coverage within the 500 m band (Judson 4).

Site 7: Mankato

The Mankato site begins approximately 600 m upstream from the Land of Memories Park boat ramp and continues downstream for 3.9 km, ending at the Belgrade Avenue/Mulberry Street Bridge. It is important to note that much of this site has been highly modified. During the mid-1960's, floodwalls were constructed to reduce flooding in the city of Mankato and banks were riprapped to reduce erosion and channel migration. The resulting shape of the highly engineered channel is trapezoidal, which is poor at transporting sediment. Also of importance is the Blue Earth River, which joins the Minnesota River 1.1 km downstream from the start of the site. The Blue Earth River transports large amounts of sediment into the Minnesota River, creating a large delta and scour hole at its confluence. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. The longitudinal profile and bathymetric mapping identify several pool and riffle areas within the site (Mankato 2; Mankato 4). Pools are typically located along the outside bends, with one pool located at the confluence of the Blue Earth River and Minnesota River. One riffle is located downstream of the Blue Earth confluence, and the other riffle is located at the downstream end of the site (Mankato 4). Although much of the site has been modified for flood mitigation, a moderate depth CV was observed (39.77) with an average thalweg depth of 2.92 m (Table 1). Woody debris is mostly found in the upper half of the site, covering 0.70 % of the total surface area (Mankato 5; Table 1). Because much of the site is modified for flood mitigation, the channel is fairly straight, with a channel sinuosity measurement of 1.15 (Table 1). The Cities of Mankato and North Mankato, contributing to a large amount (49–82 %) of human disturbance at all land cover scales (Mankato 3), surround the site.

Site 8: St. Peter

The St. Peter site begins 300 m upstream from the Mill Pond boat ramp and continues downstream for approximately 3.4 km. The St. Peter site contains three old channel cutoffs. Two of the three cutoffs occurred prior to 1938 (oldest aerial photo available) while the other cutoff occurred between 1964 and 1991. The oxbow lake created by the most recent cutoff has since filled with sediment, and only connects to the main river channel during high flow events. We conducted a comprehensive survey including a riffle cross section, a longitudinal profile, bathymetric mapping, and a woody debris survey. A wide variety of habitats are identified throughout the site. Deep pool habitat is located throughout the upstream end of the site and several other small pool areas are scattered throughout the remainder of the site (St. Peter 2; St. Peter 4). A large riffle is located approximately 400 m downstream of the Highway 99 Bridge (St. Peter 4). Due to the wide variety of habitats throughout the site, the depth CV (64.40) is greater than all other study sites (Table 1). Percent of area covered by woody debris is moderate, accounting for 0.84% of the total surface area (St. Peter 5; Table 1). The City of St. Peter is located along the upstream end of the site, leading to high amounts of human disturbance within close proximity. Wetlands account for approximately 25% of land cover at smaller scales (riparian, 500 m, 1,000 m bands), but represent only 9% of land cover in the 5,000 m band (St. Peter 3). Forest-cover is highest in the riparian zone and decreases at larger scales while agricultural land cover is low at smaller scales and increases significantly at larger scales (up to 57% of land cover; St. Peter 3).

Site 9: Henderson

The Henderson site begins approximately 1.6 km downstream of the Highway 169 Bridge and continues downstream 4.0 km. The Rush River enters the site from the West, creating a large sand delta at its confluence. The confluence is also the location of a channel cutoff created between 1997 and 2003. A second channel cutoff is located at the downstream end of the site that includes at least two different oxbows created prior to 1937. We conducted a basic habitat survey including bathymetric mapping and a woody debris survey. Large areas of shallow water and a relatively narrow thalweg are present within the study site (Henderson 3) and channel sinuosity is low (1.08; Table 1). Forest-cover is the dominant land cover type at smaller scales, ranging from 66% in the riparian zone to 43% at the 1,000 m zone (Henderson 2). Agriculture replaces forest-cover as the dominant land cover type at the 5,000 m level, representing 56% of the land area (Henderson 2).

Site 10: Chaska

The Chaska site begins approximately 480 m upstream of the Hwy 41 Bridge and ends 3.7 km downstream. Most of the bends within the site are hard armored with riprap along the outside banks to reduce erosion. From the limited number of historic aerial photos, no major changes to the river channel have occurred since 1951. We conducted a basic survey at the Chaska site including a longitudinal profile, bathymetric mapping, and a woody debris survey. Bathymetric mapping and the longitudinal profile identifies several areas of pool habitat within the site, typically associated with outside bends (Chaska 2; Chaska 4). The majority of pool habitat varied in depth 6.1–7.6 m, with a deeper pool near the mid-point of the site with depths up to 13.7 m. Depth variability is high for this site (50.40), and is the third highest of all study sites (Table 1). Channel sinuosity is 1.42 (Table 1) and no recent channel migration activity is evident from historical aerial imagery. The Chaska site is near the Twin Cities metro area, so human disturbance levels are elevated compared to other upstream sites varying 19-38% of land cover (Chaska 3). Wetlands account for almost half the land cover in the riparian zone (48%), but quickly decrease at larger scale, accounting for only 6% at the 5,000 m level (Chaska 3).

Site 11: Shakopee

The Shakopee site begins at the Hwy 101 Bridge and continues downstream 3.5 km to the Shakopee Memorial Pond outlet. Similar to the Chaska site, no major changes to the river channel have occurred since 1947, but from field observations, the outside bank along the large meander bend is undergoing considerable erosion. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. Bathymetric mapping and the longitudinal profile identify several areas of pool habitat, varying in depth 6.1–9.1 m, with one deeper pool with depths up to 13.7 m (Shakopee 2; Shakopee 4). Average thalweg depth is 6.04 m with a moderate CV of 32.18 (Table 1). Sinuosity of the Shakopee site is moderate with a sinuosity value of 1.31 (Table 1). Much of the site is straight, with the exception of a large meander bend located at the downstream end. Woody debris cover is characterized as low-moderate, with 0.46% of the total surface area covered with woody habitat (Shakopee 5; Table 1). Like the Chaska and Bloomington sites, land cover is dominated by human disturbance (Shakopee 3). Forest-cover and wetlands are most prevalent in the riparian zone, accounting for approximately one-third of the land cover, but decrease at larger scales (Shakopee 3). Percentage of agriculture is low at all scales, accounting for 12–19% of land cover (Shakopee 3).

Site 12: Bloomington

The Bloomington site is the furthest downstream habitat site. We conducted a basic habitat survey including bathymetric mapping, a longitudinal profile, and a woody debris survey. The Bloomington site begins immediately downstream of the 35W Bridge, continues downstream for approximately 3.2 km, and ends at the Excel Energy plant warm water discharge. Unlike the other habitat sites, the Bloomington site is located in the 24 km barge navigation channel which is dredged to maintain a minimum depth of 2.7 m (U.S. Army Corps of Engineers 2007). To aid barge navigation, bends and passing points are often artificially widened and the 2.7 m channel is often dredged to depths of 3.5–4.0 m. As a result, sinuosity in this reach is low (1.05; Table 1), and much of the site is characterized by straight channels with hard armored banks to prevent channel migration. At the time of the survey, average thalweg depth was 6.96 m with a lower depth CV (13.80) than all other study sites (Table 1). Woody debris coverage (0.237 %) is low compared to most other study sites (Bloomington 5; Table 1). Land use immediately surrounding the site is mostly wetlands (41%) and floodplain forest (42%), but at larger scales is dominated by human disturbance (73.5%) (Bloomington 3). Bathymetric mapping and the longitudinal profile identify several pools or scour areas below the I-35W Bridge and downstream along the outside bend (Bloomington 2; Bloomington 4).

Discussion

Through funding provided by the ENRTF we established a baseline dataset of physical habitat features for twelve study sites along the Minnesota River. This dataset will be used to monitor future changes in physical habitat characteristics and inform understanding of the relationships between physical habitat and the aquatic organisms that inhabit the Minnesota River. The results of this study highlight the habitat diversity and complexity of the Minnesota River.

Habitat complexity and diversity varied widely among the twelve study sites. For instance, channel sinuosity varied 1.05–2.76 while the amount of surface area covered by woody habitat varied 0.18–2.38%. Mean thalweg depth of the twelve study sites was 3.45 m, with an average depth CV of 39.15, and varied 1.31–6.96. Specific sites varied from shallow, sinuous reaches with a diversity of substrates to deep, straight reaches dominated by fine sediments. The complexity and diversity of physical habitat within the Minnesota River is the foundation of a diverse ecosystem, including a fish assemblage of more than 90 species.

Physical habitat of the Minnesota River is impacted by both natural and anthropogenic changes such as land use alterations and shifts in climate. Yet, many other North American rivers have been impacted more heavily while some much less. For example, Minnesota River habitat complexity is greater than habitat complexity of the highly channelized rivers such as the lower Missouri River (Morris et al. 1968). Flow regulation on the Missouri River, along with channel stabilization structures (e.g., stone revetments and training dykes), have resulted in major reductions in aquatic habitat quantity (Morris et al. 1968) and habitat diversity and quality (Hesse and Sheets 1993). Shields et al. (2000) also reported that flow regulation by dams on the Missouri River has increased low flows by a factor of 2–3 and depressed high flows by 10–30%, resulting in bed degradation and reduced lateral migration. Although dams are present along the upper reaches of the Minnesota River, the lower 395 rkm is free flowing allowing for more natural river channel processes that promote increased habitat complexity. Although habitat complexity in the Minnesota River is likely greater than the highly modified Missouri River, it may be lower than more “natural” systems such as the Wabash River. The Wabash River is unique because the river channel has been relatively unmodified, but, the natural flow regime has been altered throughout the watershed due to reservoir release and agricultural impacts (Pyron and Lauer 2004; Pyron and Neumann 2008; Mueller and Pyron 2010). Like the Minnesota River, woody debris is a dominant habitat feature in the Wabash River, however, substrate diversity (medium-coarse sand, coarse sand, fine gravel, and silt) is greater in the Wabash River (Mueller and Pyron 2010; Zinger et al. 2013) compared to the Minnesota River which is dominated by medium and coarse sand (Grotten et al. 2016).

Continued shifts in climate will continue to influence physical habitat of the Minnesota River, and these impacts are likely exacerbated by the altered watershed. For instance, increased mean annual precipitation and increased magnitude of single rain events expected throughout the Minnesota River Basin will likely result in an even more erosive and dynamic river, potentially leading to more sediment deposition and habitat homogenization (Lenhart et al. 2011; Lauer et al. 2017). Increased sediment deposition and habitat homogenization has been shown to decrease the diversity of fish and invertebrate communities of rivers (Schneider and Winemiller 2008; Zeni and Casatti 2014), thus influencing ecosystem health and resilience.

In addition to a changing climate, land use practices associated with row crop agriculture ,such as artificial drainage systems, have also been shown to increase discharge within the Minnesota River (Schottler et al. 2014; Kelly et al. 2017). Agricultural land use has increased within Southern Minnesota since the early 1900's and currently accounts for approximately 78% of the land in the watershed (Musser et al. 2009). Coinciding with the increase in agriculture, artificial drainage has also increased. Kelly et al. (2017) reported that the percent of the Minnesota River watershed drained by subsurface tile increased from 19% in 1940 to 35% in 2012, and the percent of the watershed drained by ditches increased from 7% in 1940 to 10% in 2012. Subsurface drainage allows for rapid removal of water from the landscapes and reduces sediment inputs from fields by reducing surface runoff, but this has shifted sediment sources from erosion in fields and uplands to channel erosion (Belmont et al. 2011). Increased discharge and bank erosion will likely cause more channel cutoffs to form, resulting in a wider and shorter river.

Fortunately, conservation efforts are underway throughout the Minnesota River watershed that may mitigate some impacts from the changing landscape and climate, and ultimately promote a healthier Minnesota River watershed. For example, protecting important habitats such as floodplain forests and riparian vegetation, which provide important woody debris and bank stability, may reduce peak discharge through increased water retention and reduce sediment and nutrient inputs. Since much of the watershed has been converted to cultivated crops, many of the conservation efforts are focused on agriculture practices. The United States Department of Agriculture has several conservation programs such as the Conservation Reserve Program (CRP), the Conservation Reserve Enhancement Program (CREP), the Farmable Wetlands Program, and the Grassland Reserve Program (https://www.fsa.usda.gov/programs-and-services/conservation-programs/). These programs were created to improve environmental quality by protecting lands that might otherwise be used for agriculture. Other conservation efforts include buffer strips, cover crops, and redesigned drainage ditches. Conservation efforts are constantly evolving and benefits from individual efforts are difficult to quantify. Yet, through continued advancements in conservation practices and increased implementation, these efforts can improve health of the Minnesota River watershed and ecosystem.

Considerable evidence exists suggesting both quality and physical habitat complexity affects the overall composition of biological communities (Hynes 1968; Calow and Petts 1994). Integrative measures of stream condition, including index of biotic integrities (IBIs), are particularly useful for assessing overall stream health. Generally, higher IBI scores indicate healthier aquatic ecosystems, and are associated with greater species diversity. Physical habitat features that have been found to influence biotic community structure and diversity include but are not limited to substrate particle size and diversity (Shields et al. 2006; Thorp et al. 2006), amount of woody debris (Braccia and Batzer 2001; Schneider and Winemiller 2008), terrestrial and aquatic vegetation (Eadie and Keast 1984; Willis et al. 2005), and flow dynamics (Gorman and Karr 1978; Wood and Bain 1995). For example, Willis et al. (2005) reported that species diversity was positively correlated with habitat complexity and negatively correlated with discharge. The biological health of the Minnesota River is currently classified as being in good condition based on average fish IBI scores, but invertebrate IBI scores are indicative of poor biological condition (MPCA 2014; 2017). With the expected and observed changes is hydrology, climate, and land use within the Minnesota River Basin, changes in the biotic community and ultimately river health (IBI scores) are expected.

The extent of the impact that climate change, land use alteration, and conservation efforts may have on the physical habitat of the Minnesota River is unknown. Collection of baseline physical habitat data during this study, coupled with continued monitoring, will hopefully provide insight into how the physical features and ultimately the health of the Minnesota River will respond to future perturbations and conservation efforts.

Supplemental Material

Table S1. Upstream and downstream coordinates of 12 habitat study sites along the Minnesota River (separate file).

Table S2. Longitudinal depth profile along the thalweg of 12 Minnesota River study sites (separate file).

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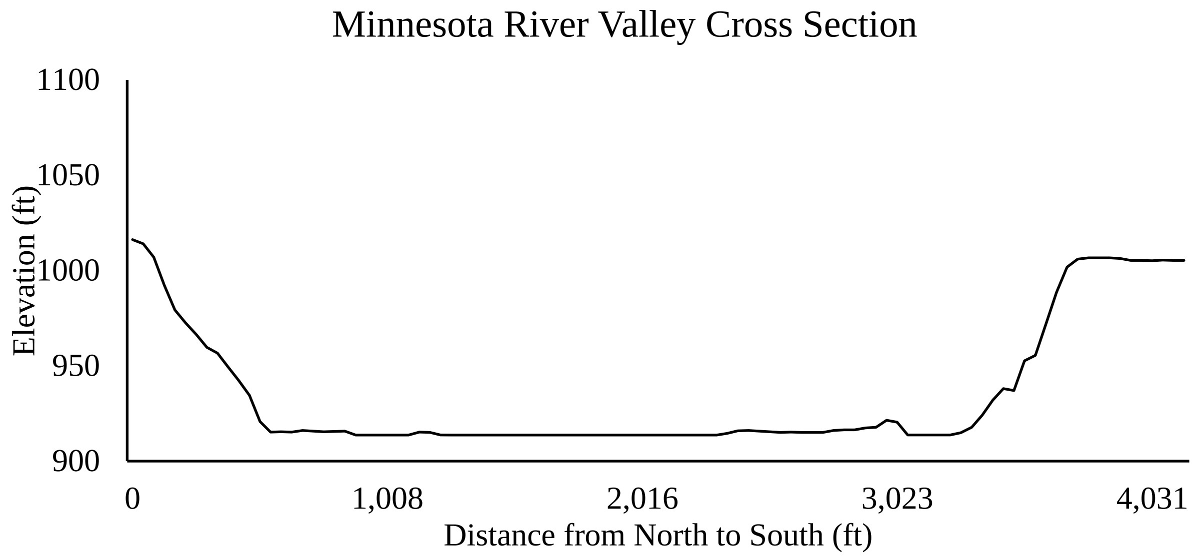
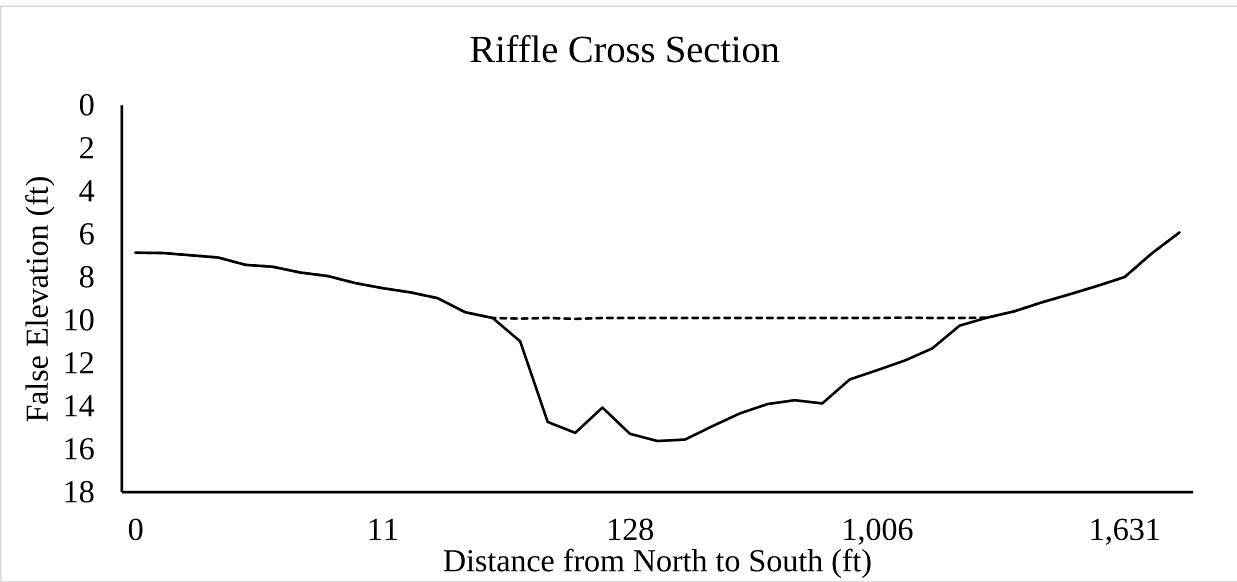
Site-Specific Tables and Figures

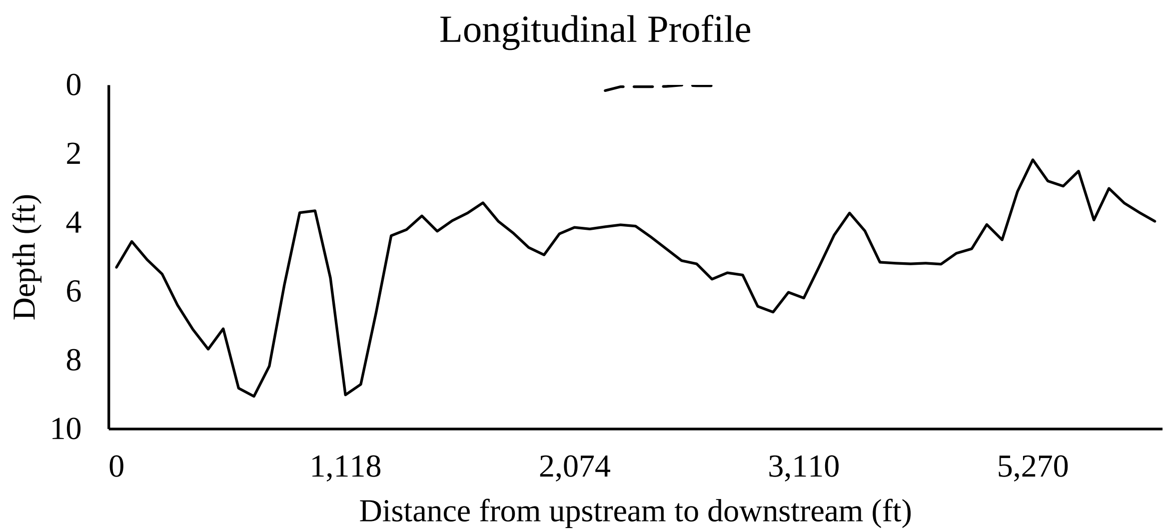
Site 1: Montevideo



Montevideo 1. Cross section elevation of the Minnesota River Valley near Montevideo, MN derived from LiDAR data.



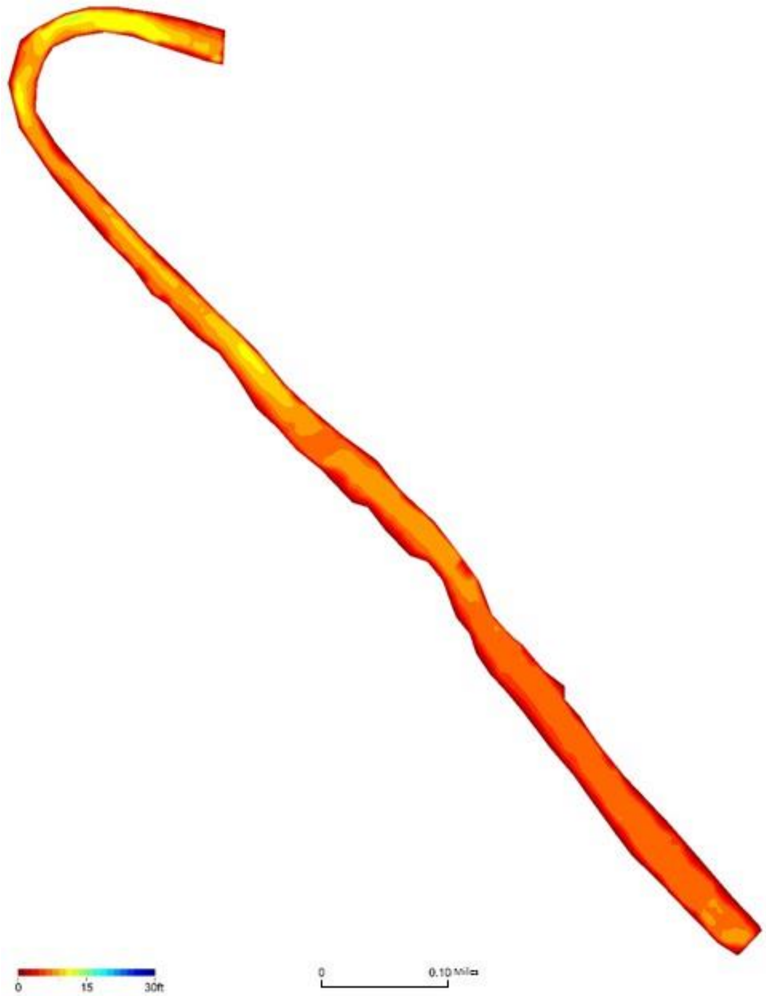
Montevideo 2. Surveyed cross section elevation of the Minnesota River at a riffle near Montevideo, MN.



Montevideo 3. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Montevideo, MN.

Montevideo 4. Land cover within concentric bands (i.e., 50–5,000 m) surrounding the Montevideo study site.

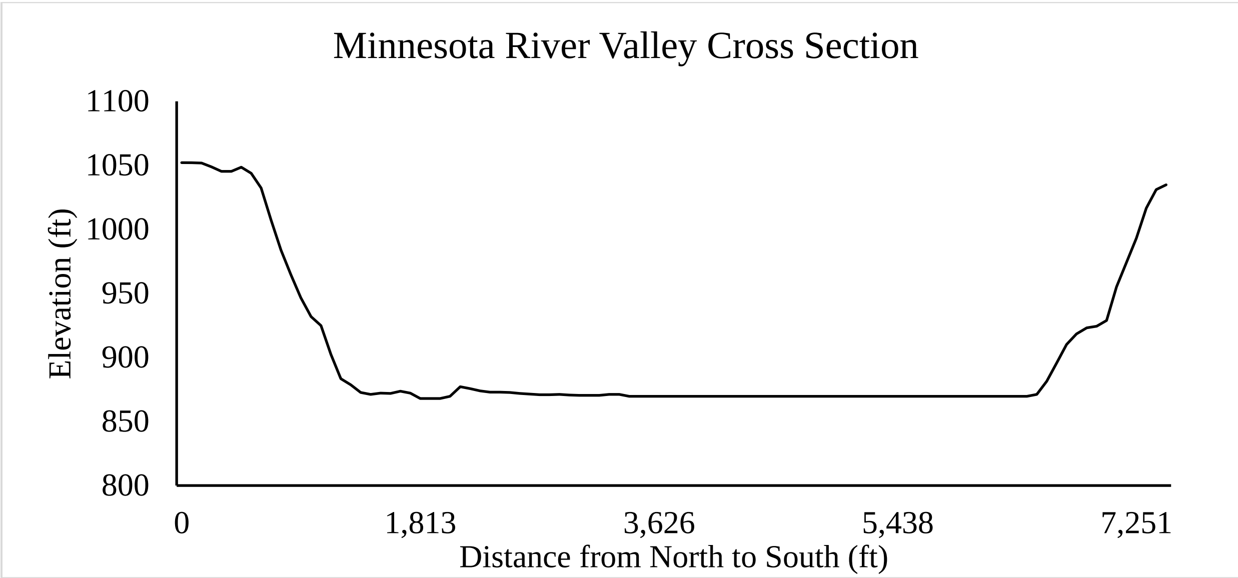
Montevideo		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	0	0
Forest-cover	18	12
Wetlands	86	55
Human Disturbance	52	33
Total	**156**	**100**
500 meter		
Agriculture	787	26
Forest-cover	167	6
Wetlands	1171	39
Human Disturbance	407	14
Open Water	467	15
Total	**2999**	**100**
1000 meter		
Agriculture	3441	45
Forest-cover	397	5
Wetlands	2272	30
Human Disturbance	634	8
Open Water	912	12
Total	**7656**	**100**
5000 meter		
Agriculture	86887	81
Forest-cover	2298	2
Wetlands	10080	9
Human Disturbance	5556	5
Open Water	2633	3
Total	**107454**	**100**



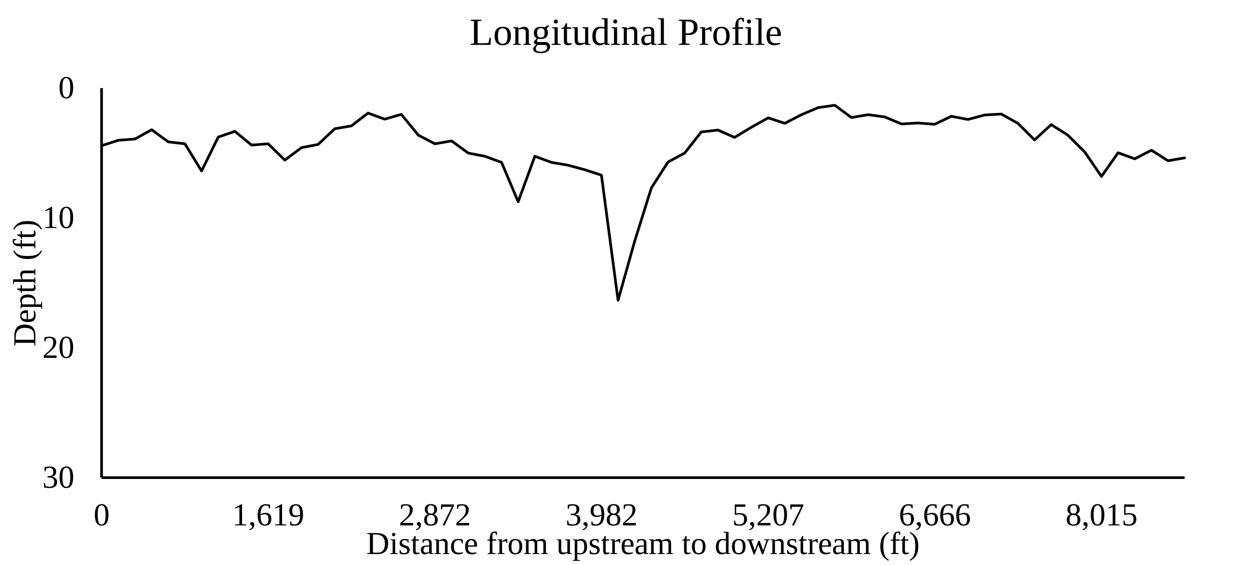
Montevideo 5. Bathymetric map of a Minnesota River study site near Montevideo, MN.

Montevideo 6. Map of the Minnesota River study site near Montevideo, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Upper Sioux



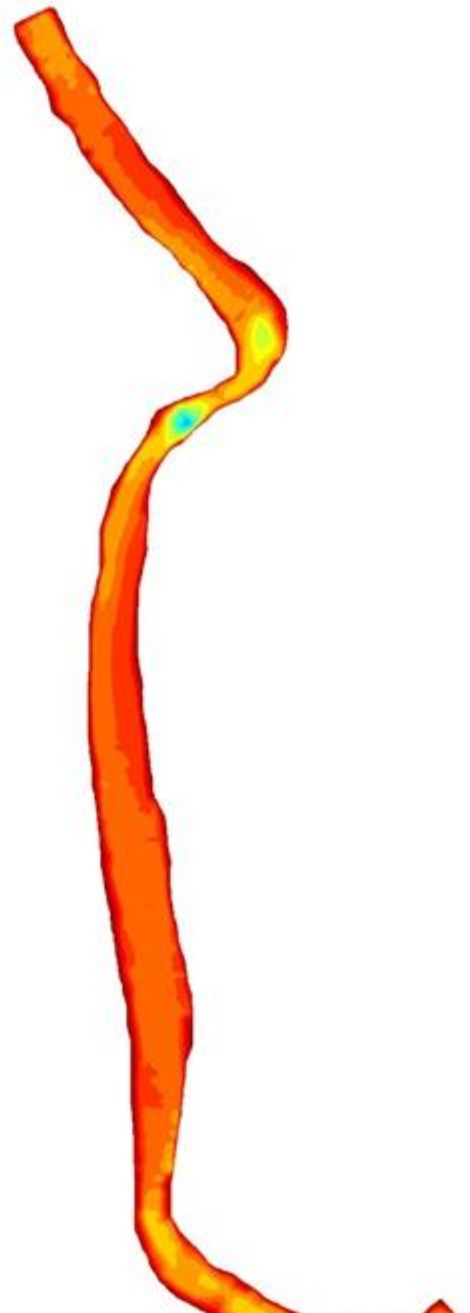
Upper Sioux 1. Cross section elevation of the Minnesota River Valley near Upper Sioux Agency State Park, Granite Falls, MN derived from LiDAR data.



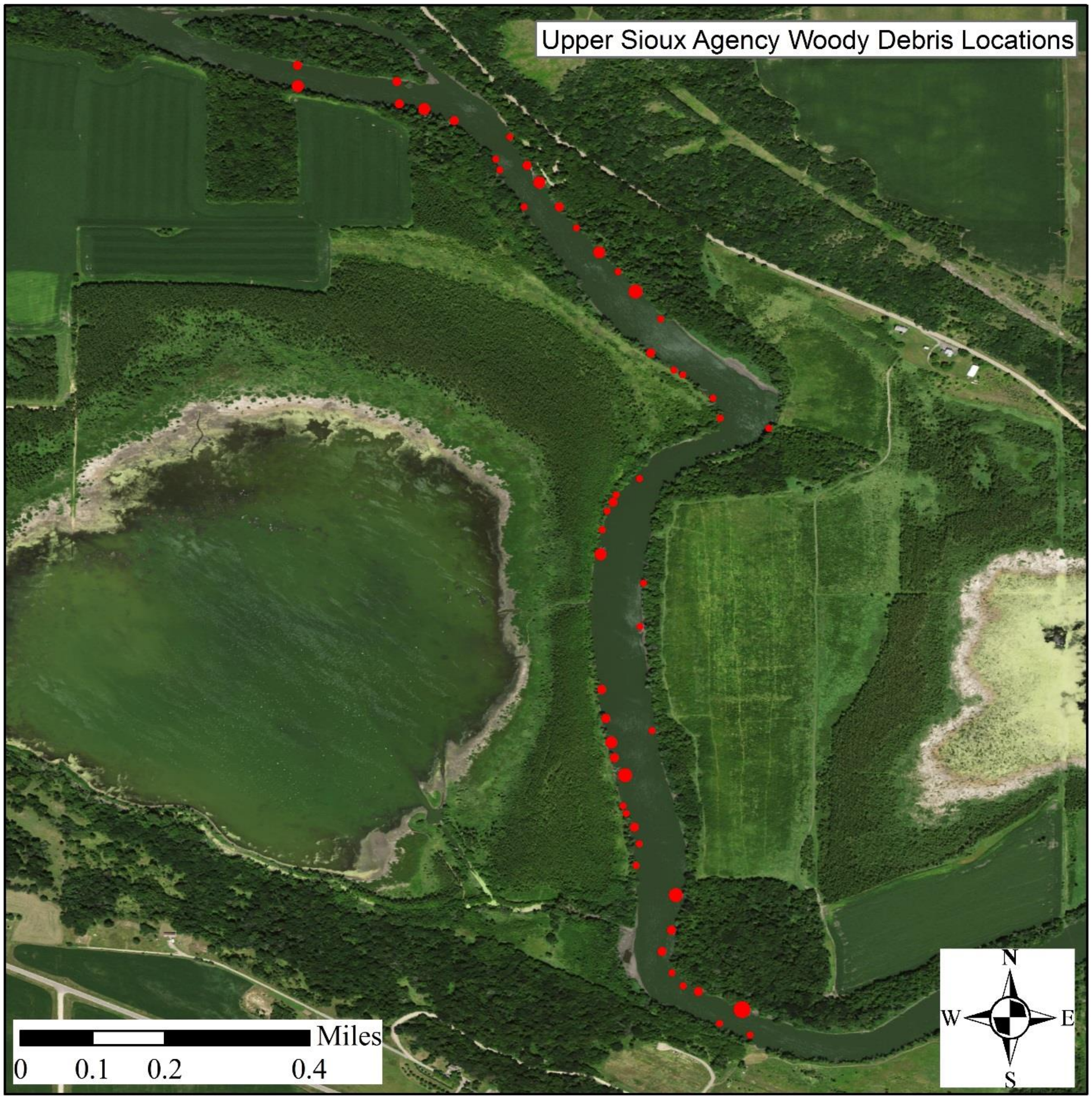
Upper Sioux 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Upper Sioux Agency State Park, Granite Falls, MN.

Upper Sioux 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Upper Sioux study site.

Upper Sioux		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	44	22
Forest-cover	47	23
Wetlands	112	55
Human Disturbance	0	0
Total	**203**	**100**
500 meter		
Agriculture	1074	30
Forest-cover	556	16
Wetlands	1177	33
Human Disturbance	139	4
Open Water	603	17
Total	**3549**	**100**
1000 meter		
Agriculture	3606	41
Forest-cover	950	11
Wetlands	2310	27
Human Disturbance	440	5
Open Water	1415	16
Total	**8721**	**100**
5000 meter		
Agriculture	77012	69
Forest-cover	9832	9
Wetlands	11991	11
Human Disturbance	7488	6
Open Water	5647	5
Total	**111970**	**100**

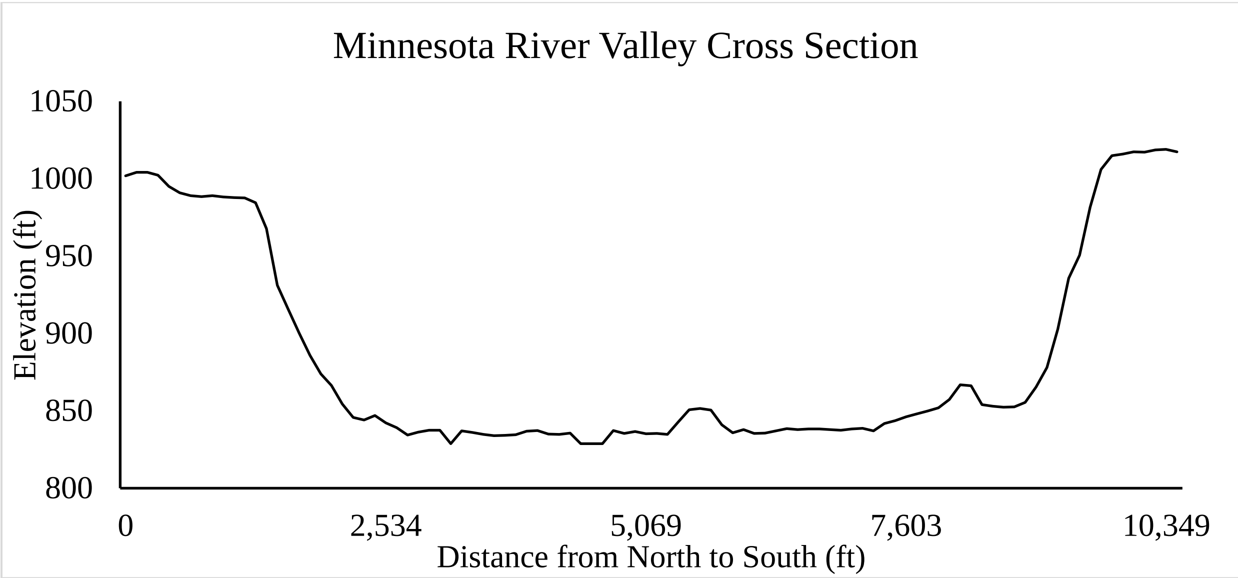


Upper Sioux 4. Bathymetric map of a Minnesota River study site near Upper Sioux Agency State Park, Granite Falls, MN.

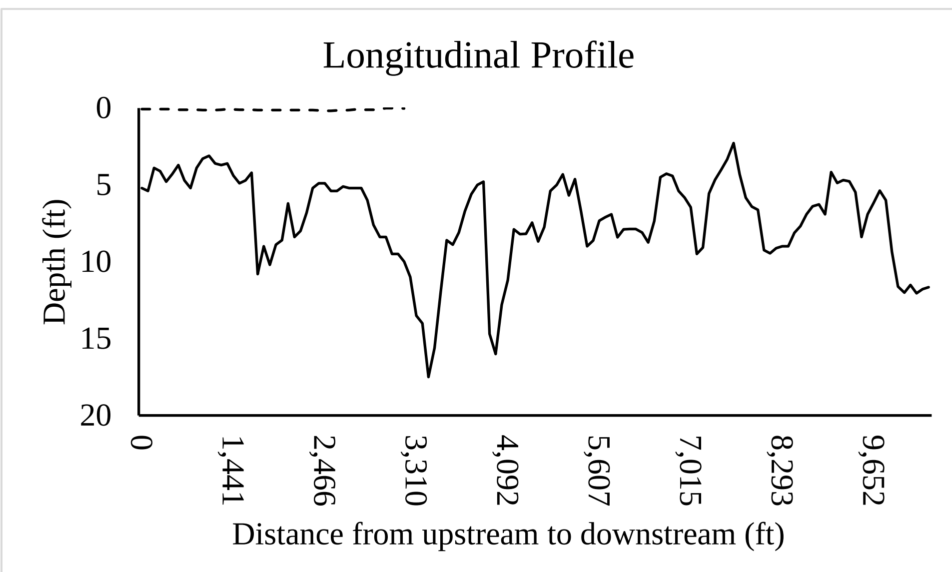


Upper Sioux 5. Map of the Minnesota River study site near Upper Sioux Agency State Park, Granite Falls, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 3: North Redwood



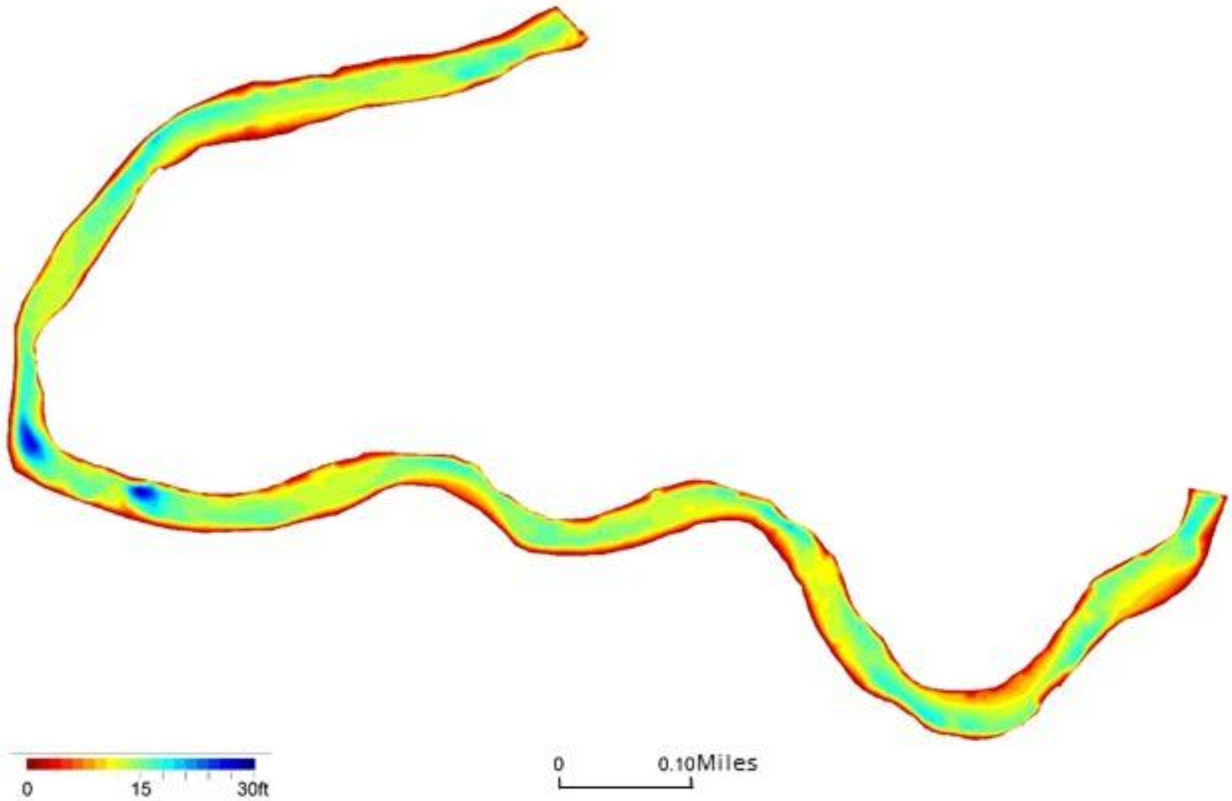
North Redwood 1. Cross section elevation of the Minnesota River Valley near North Redwood, MN derived from LiDAR data.



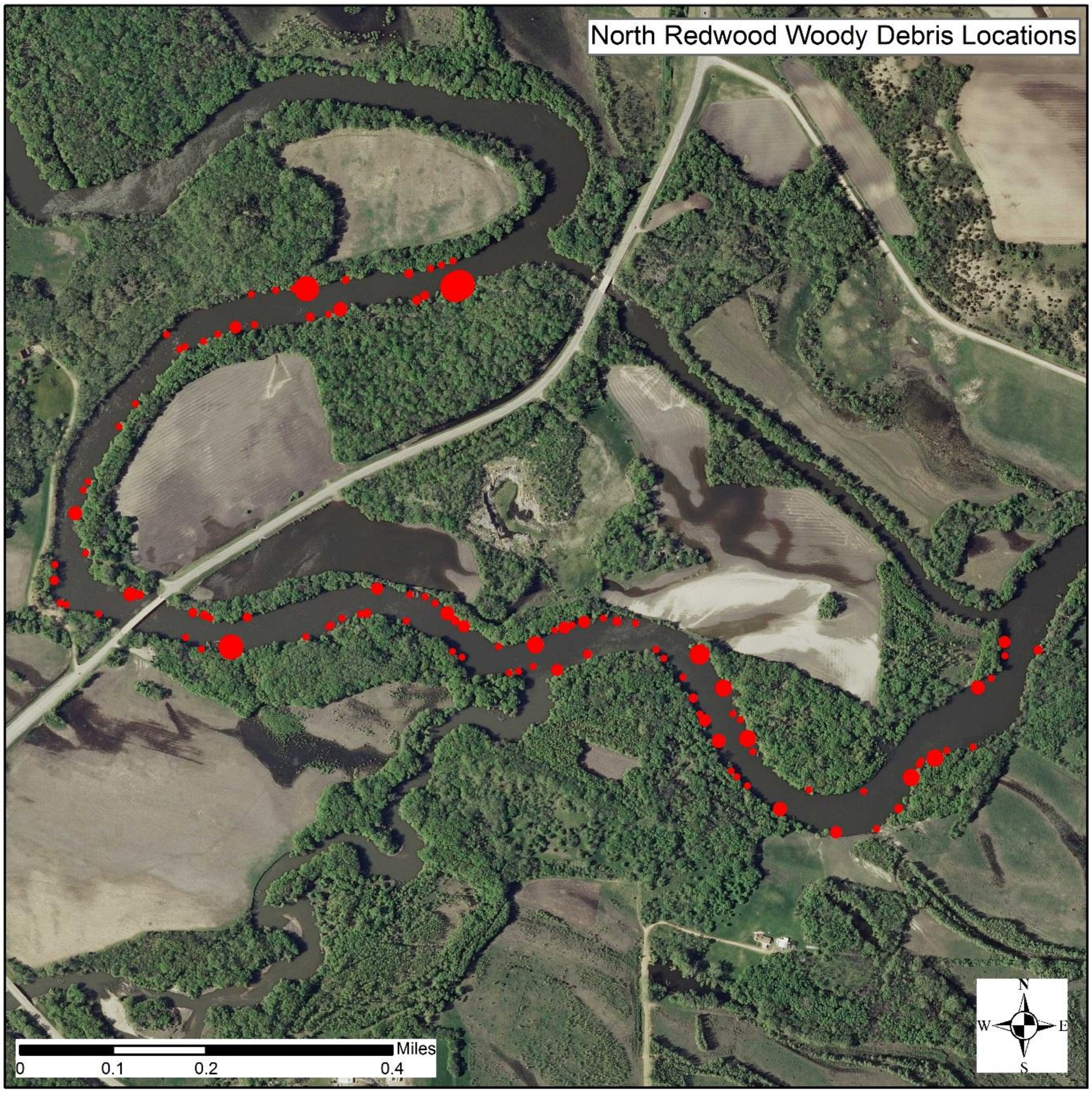
North Redwood 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near North Redwood, MN.

North Redwood 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the North Redwood study site.

North Redwood		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	74	30
Forest-cover	92	37
Wetlands	65	27
Human Disturbance	15	6
Total	**246**	**100**
500 meter		
Agriculture	1669	42
Forest-cover	656	16
Wetlands	1051	26
Human Disturbance	148	4
Open Water	458	12
Total	**3982**	**100**
1000 meter		
Agriculture	3933	43
Forest-cover	1385	15
Wetlands	2369	26
Human Disturbance	604	7
Open Water	779	9
Total	**9070**	**100**
5000 meter		
Agriculture	69913	63
Forest-cover	10611	9
Wetlands	14515	13
Human Disturbance	13101	12
Open Water	3507	3
Total	**111647**	**100**

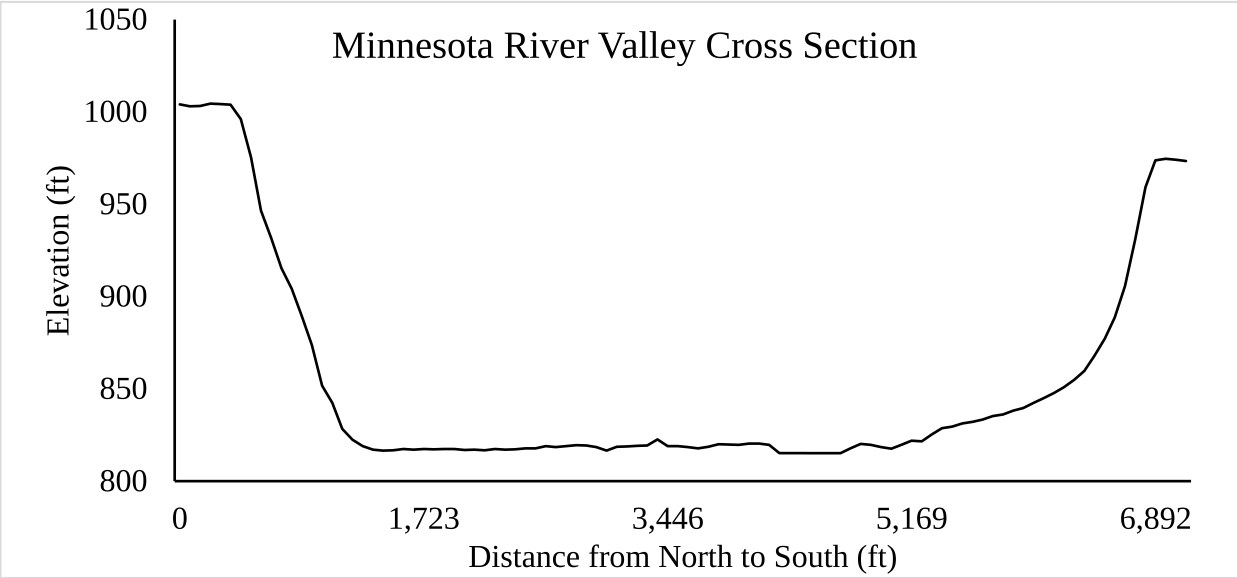


North Redwood 4. Bathymetric map of a Minnesota River study site near North Redwood, MN.

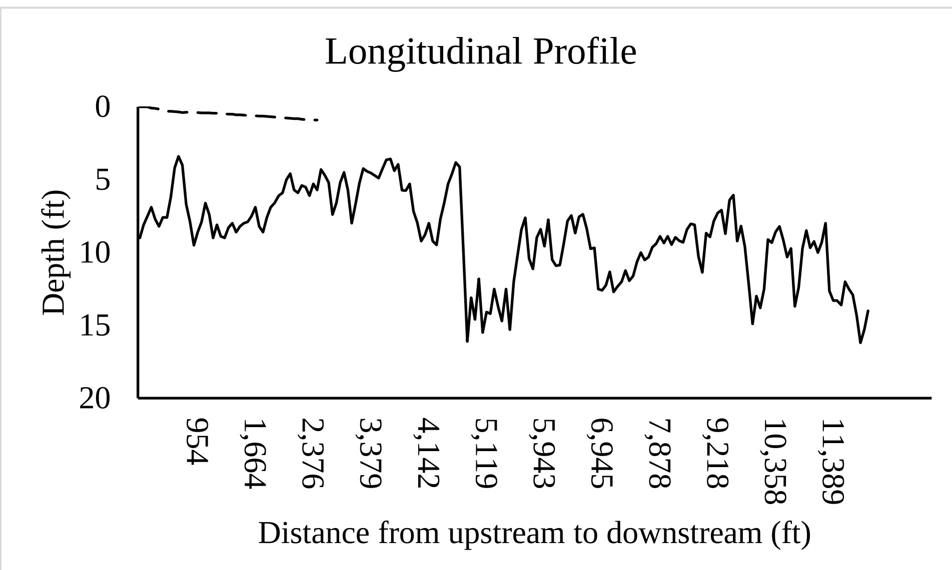


North Redwood 5. Map of the Minnesota River study site near North Redwood, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 4: Franklin



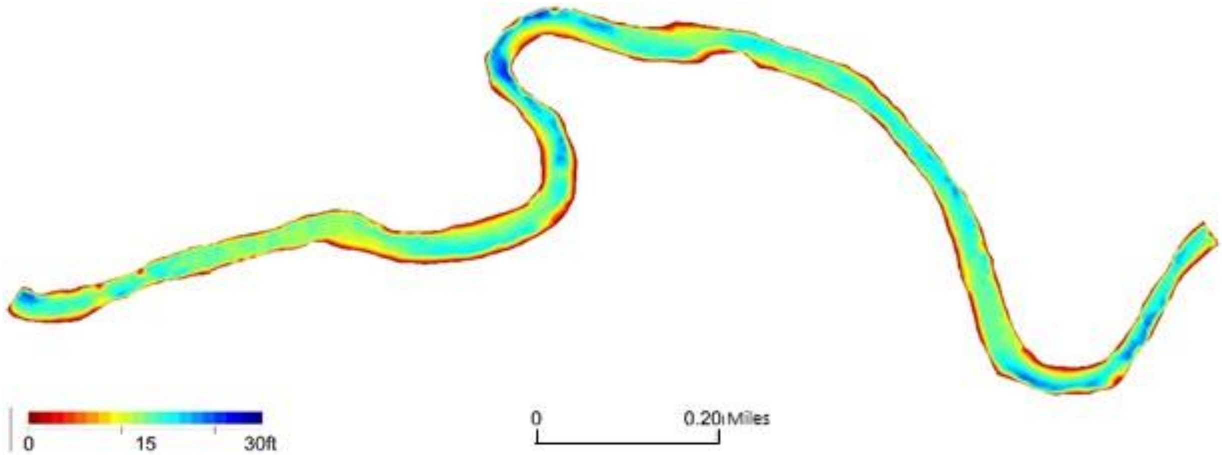
Franklin 1. Cross section elevation of the Minnesota River Valley near Franklin, MN derived from LiDAR data.



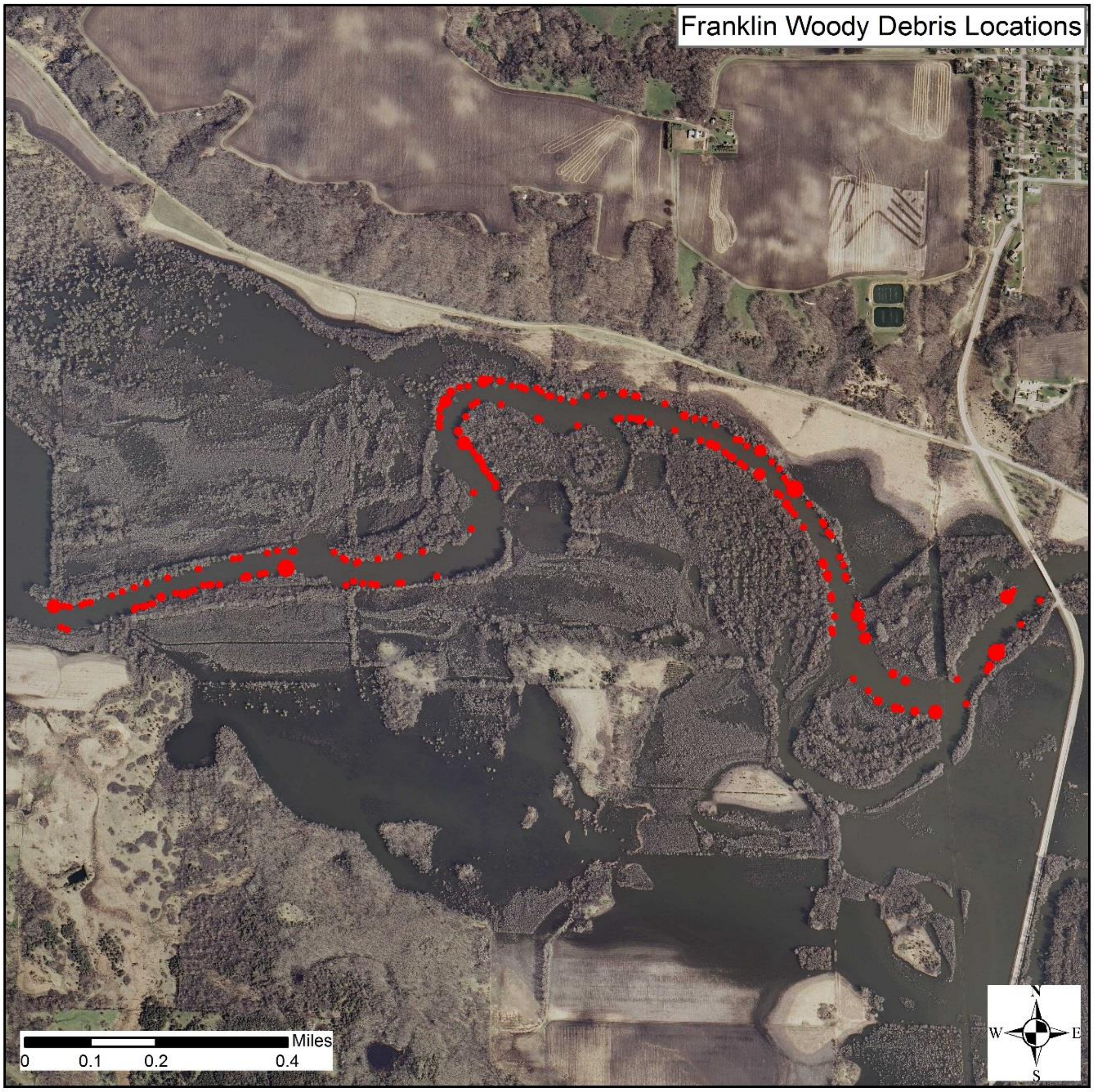
Franklin 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Franklin, MN.

Franklin 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Franklin study site.

Franklin		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	103	33
Forest-cover	25	8
Wetlands	180	57
Human Disturbance	5	2
Total	**313**	**100**
500 meter		
Agriculture	1570	34
Forest-cover	389	9
Wetlands	2084	46
Human Disturbance	168	4
Open Water	336	7
Total	**4547**	**100**
1000 meter		
Agriculture	4448	43
Forest-cover	1212	12
Wetlands	3689	35
Human Disturbance	411	4
Open Water	654	6
Total	**10414**	**100**
5000 meter		
Agriculture	84722	71
Forest-cover	8483	7
Wetlands	16008	13
Human Disturbance	6632	6
Open Water	3180	3
Total	**119025**	**100**

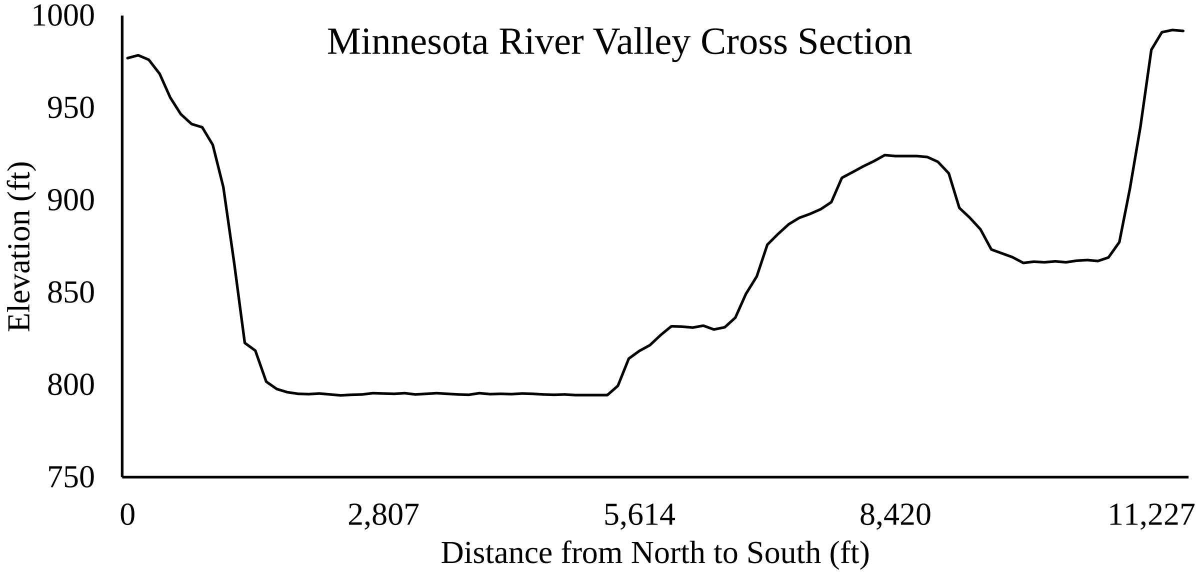


Franklin 4. Bathymetric map of a Minnesota River study site near Franklin, MN.

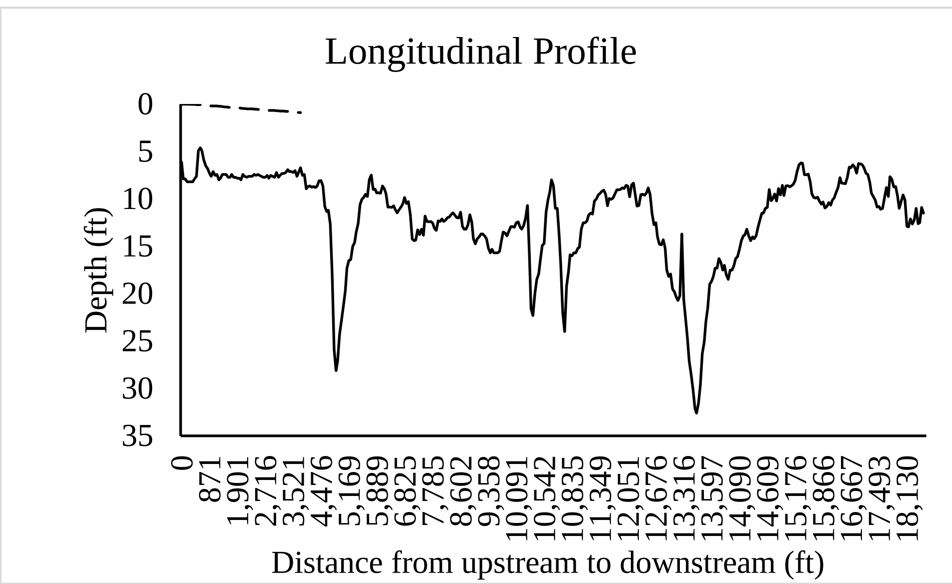


Franklin 5. Map of the Minnesota River study site near Franklin, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 5: New Ulm



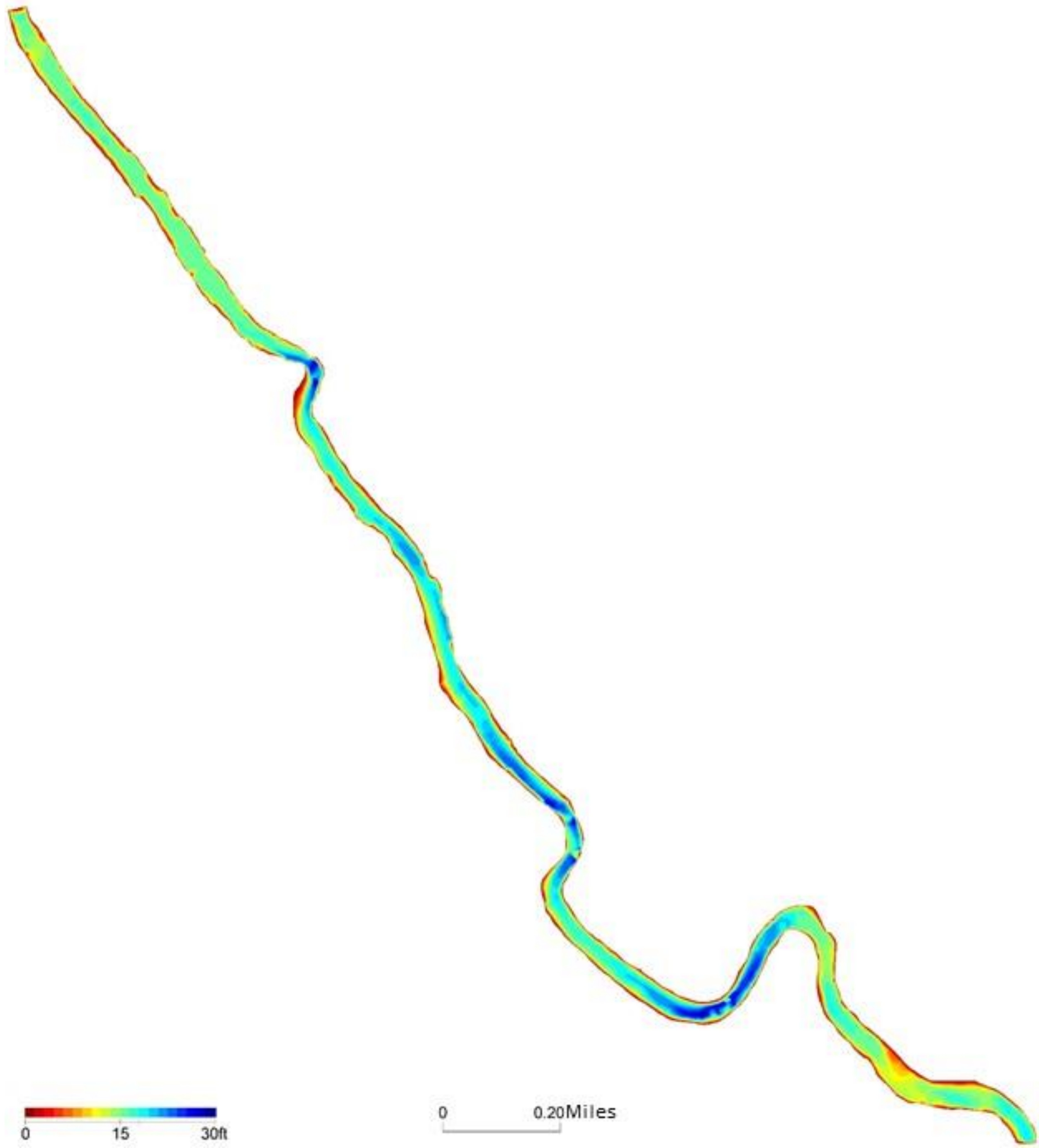
New Ulm 1. Cross section elevation of the Minnesota River Valley near New Ulm, MN derived from LiDAR data.



New Ulm 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near New Ulm, MN.

New Ulm 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the New Ulm study site.

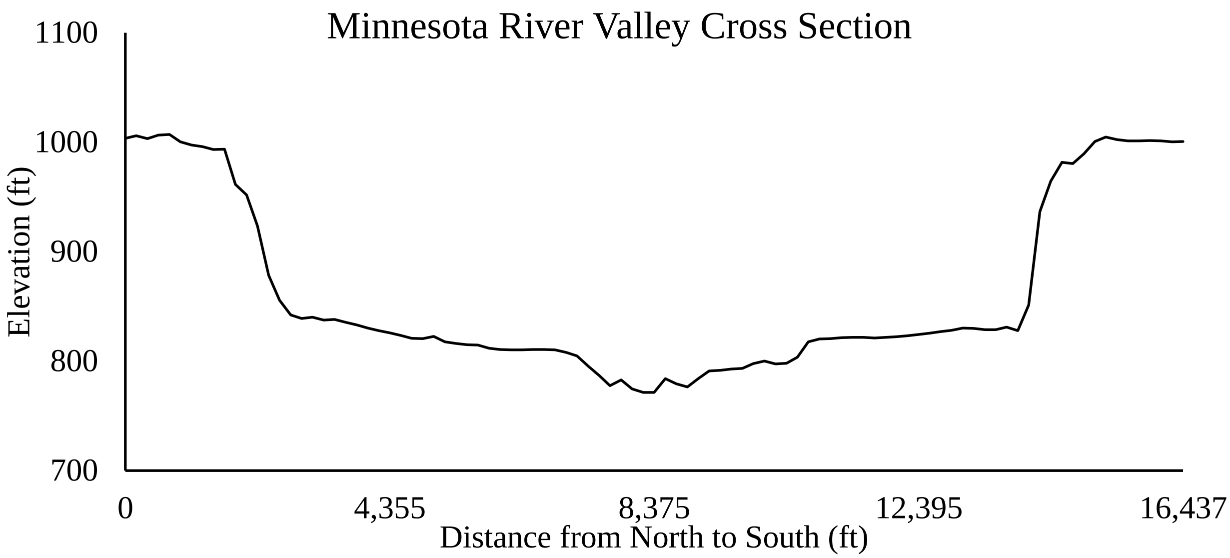
New Ulm		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	17	4
Forest-cover	34	9
Wetlands	275	72
Human Disturbance	57	15
Total	**383**	**100**
500 meter		
Agriculture	632	9
Forest-cover	501	8
Wetlands	2094	32
Human Disturbance	2150	33
Open Water	1193	18
Total	**6570**	**100**
1000 meter		
Agriculture	2021	14
Forest-cover	1152	8
Wetlands	3614	25
Human Disturbance	5444	38
Open Water	2233	15
Total	**14464**	**100**
5000 meter		
Agriculture	81432	58
Forest-cover	13787	10
Wetlands	15195	11
Human Disturbance	22320	16
Open Water	7729	5
Total	**140463**	**100**



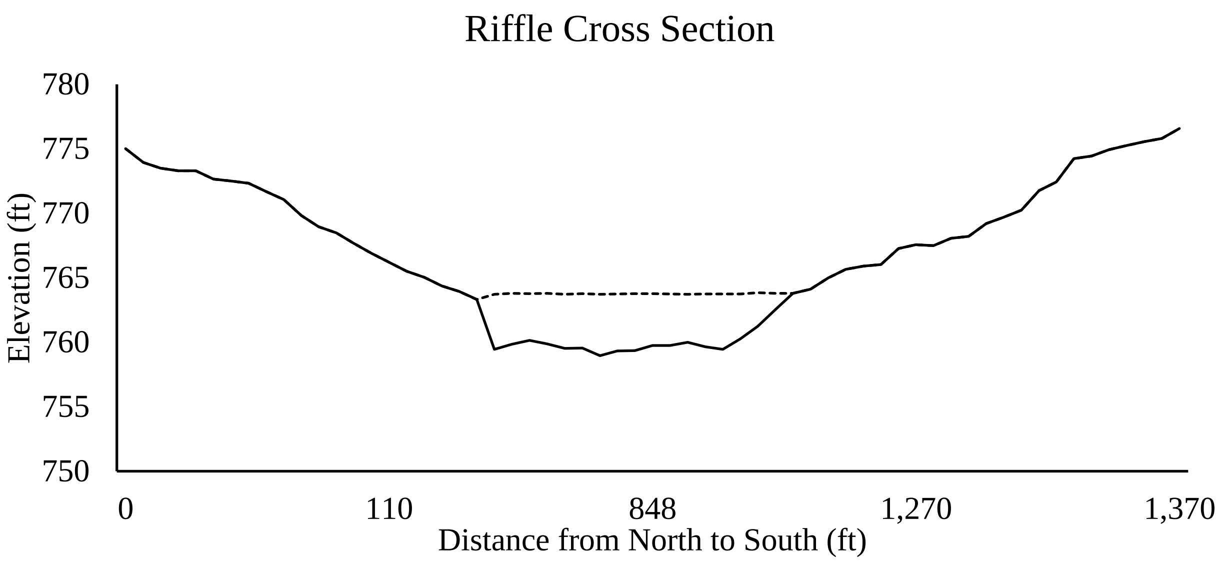
New Ulm 4. Bathymetric map of a Minnesota River study site near New Ulm, MN.

New Ulm 5. Map of the Minnesota River study site near New Ulm, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

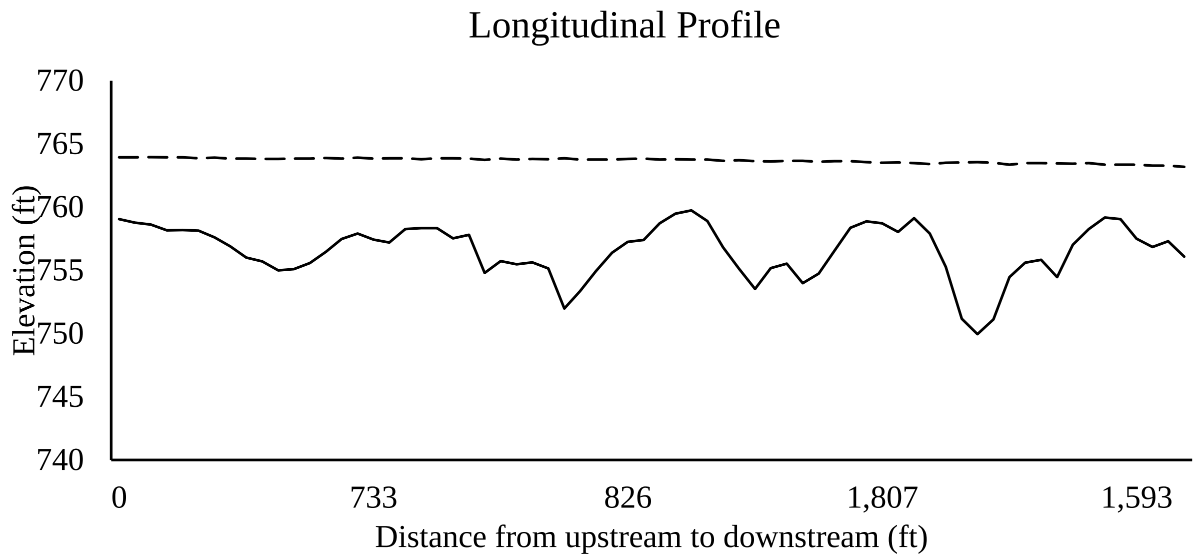
Site 6: Judson



Judson 1. Cross section elevation of the Minnesota River Valley near Judson, MN derived from LiDAR data.



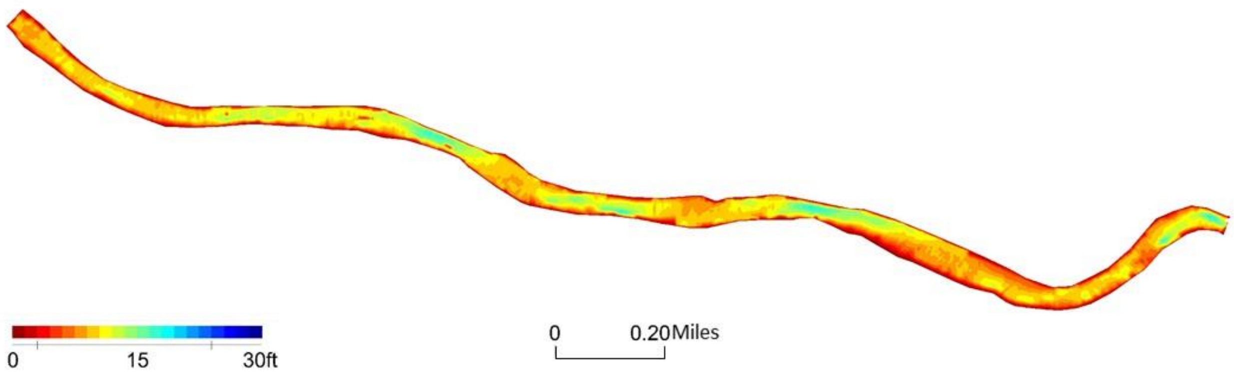
Judson 2. Surveyed cross section elevation of the Minnesota River at a riffle near Judson, MN.



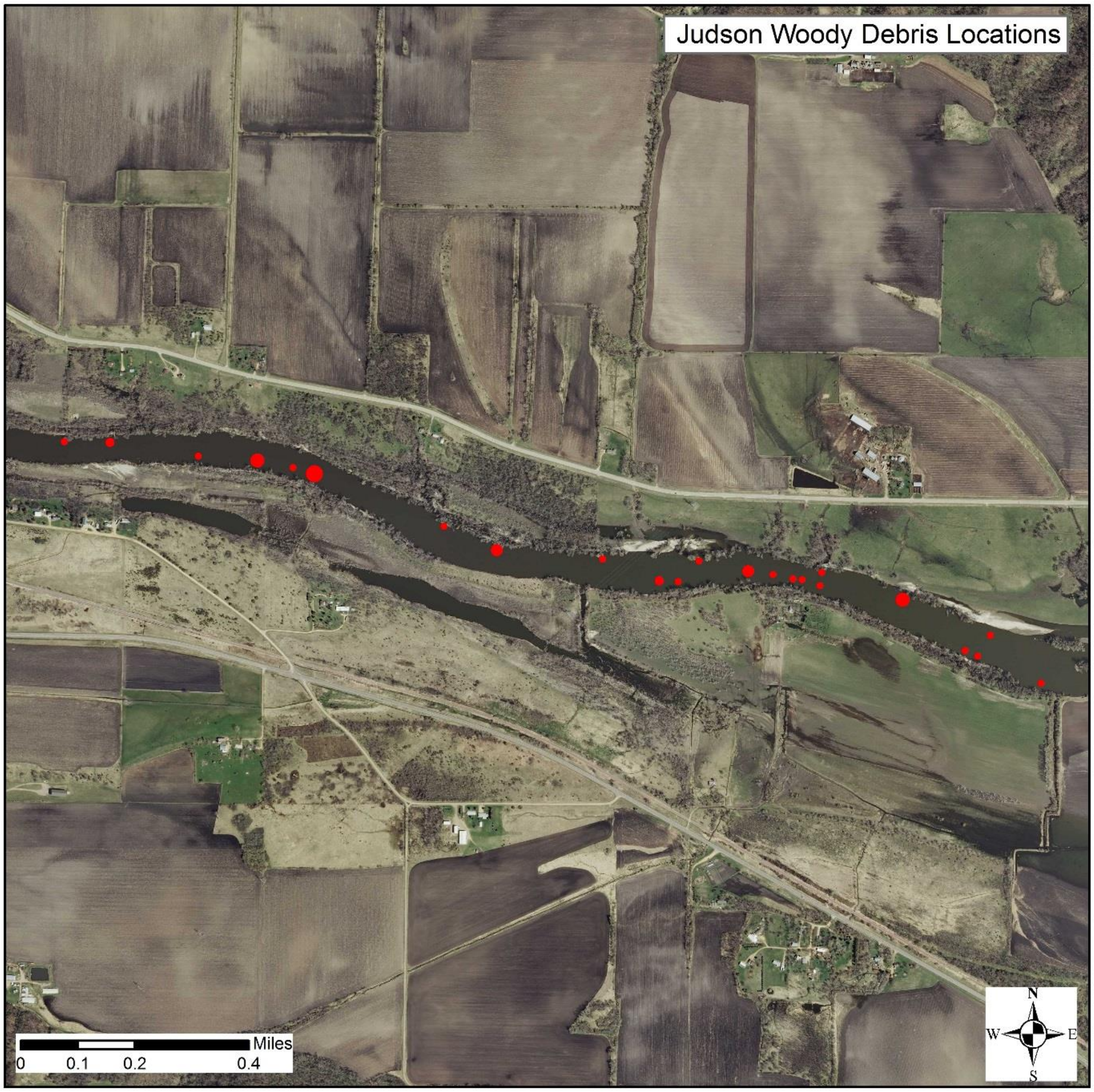
Judson 3. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Judson, MN.

Judson 4. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Judson study site.

Judson		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	296	80
Forest-cover	30	8
Wetlands	36	10
Human Disturbance	6	2
Total	**368**	**100**
500 meter		
Agriculture	3244	57
Forest-cover	352	6
Wetlands	1334	23
Human Disturbance	462	8
Open Water	329	6
Total	**5721**	**100**
1000 meter		
Agriculture	7913	60
Forest-cover	873	7
Wetlands	2743	21
Human Disturbance	1046	8
Open Water	571	4
Total	**13146**	**100**
5000 meter		
Agriculture	99712	74
Forest-cover	15449	11
Wetlands	9127	7
Human Disturbance	7998	6
Open Water	3033	2
Total	**135319**	**100**

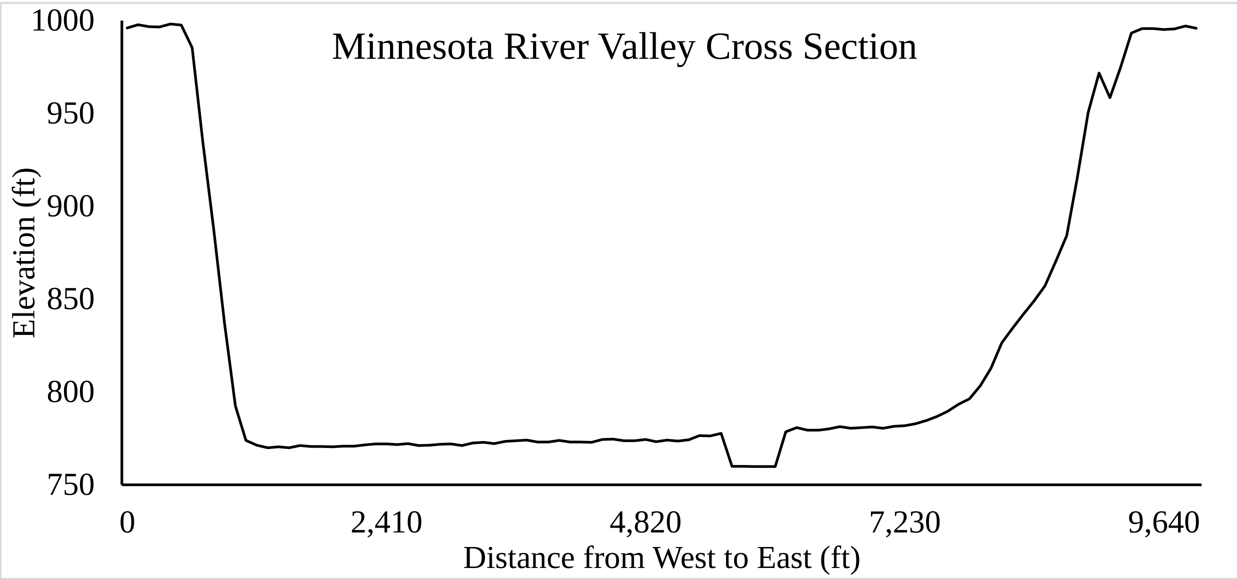


Judson 5. Bathymetric map of a Minnesota River study site near Judson, MN.

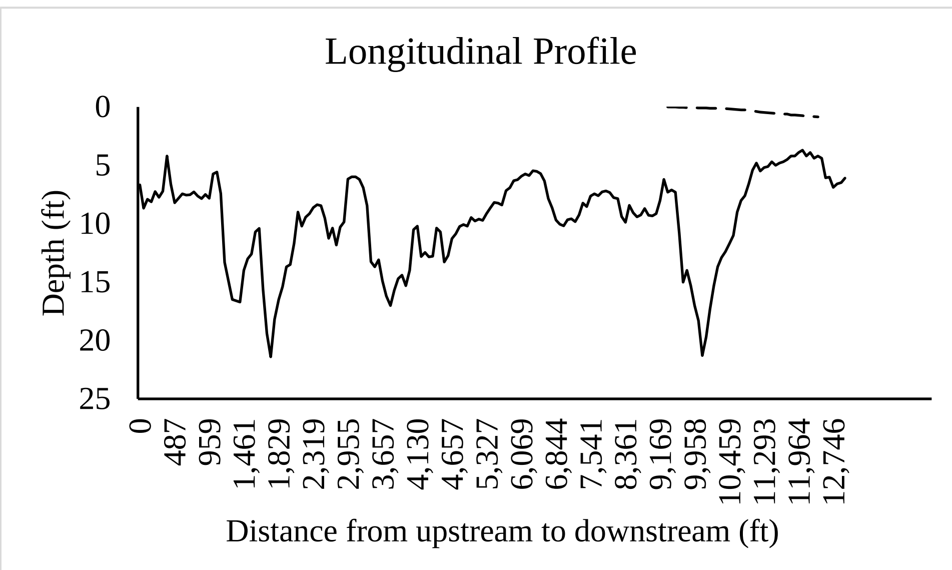


Judson 6. Map of the Minnesota River study site near Judson, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 7: Mankato



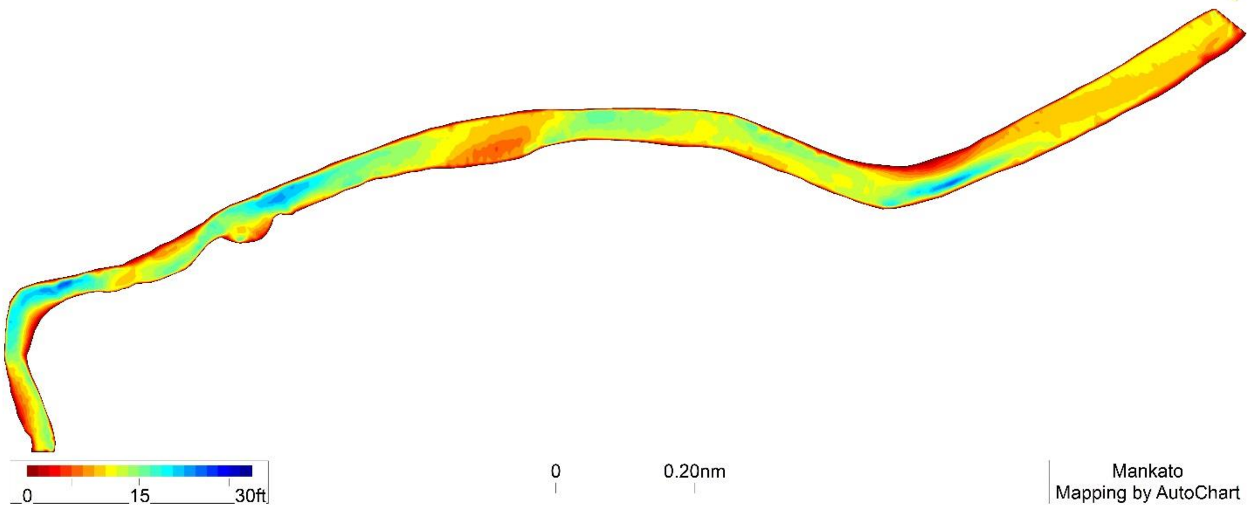
Mankato 1. Cross section elevation of the Minnesota River Valley near Mankato, MN derived from LiDAR data.



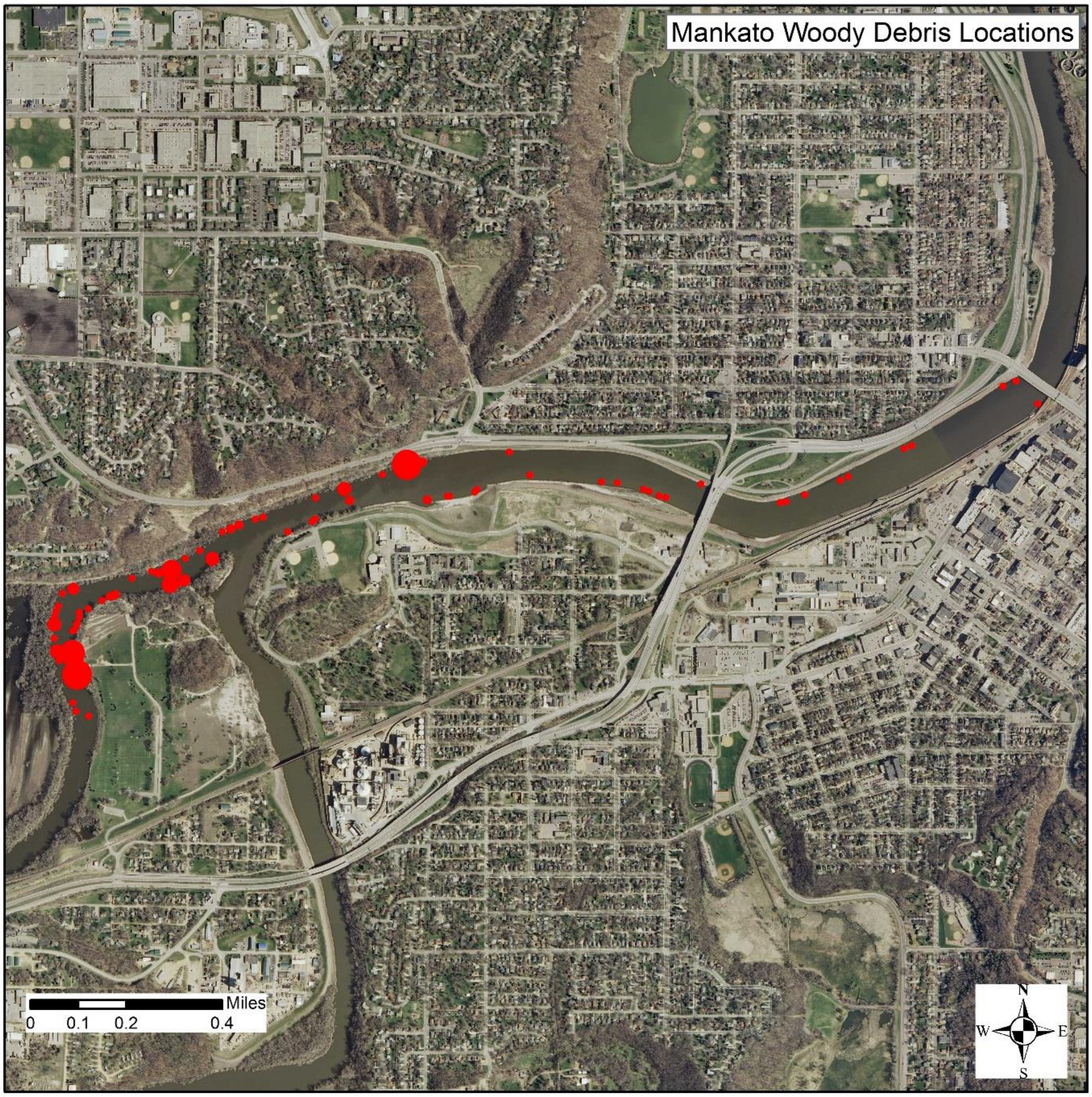
Mankato 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Mankato, MN.

Mankato 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Mankato study site.

Mankato		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	18	6
Forest-cover	2	1
Wetlands	42	15
Human Disturbance	224	78
Total	**286**	**100**
500 meter		
Agriculture	457	9
Forest-cover	137	3
Wetlands	276	6
Human Disturbance	3712	75
Open Water	328	7
Total	**4910**	**100**
1000 meter		
Agriculture	726	6
Forest-cover	410	4
Wetlands	429	4
Human Disturbance	9377	82
Open Water	505	4
Total	**11447**	**100**
5000 meter		
Agriculture	39049	31
Forest-cover	14039	11
Wetlands	6921	6
Human Disturbance	61501	49
Open Water	4221	3
Total	**125731**	**100**

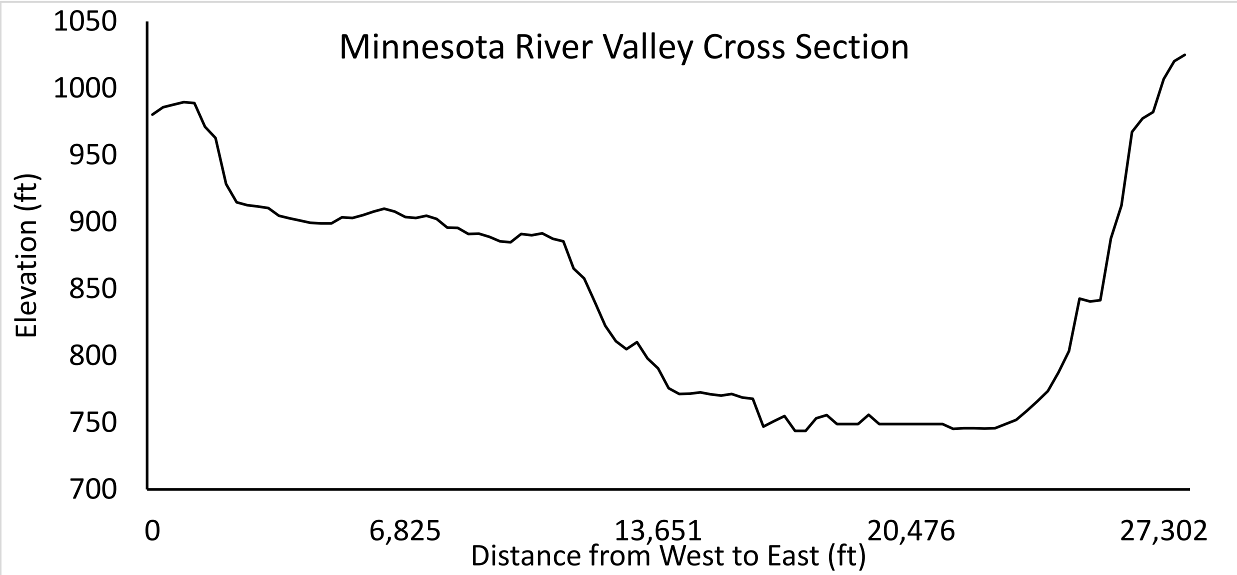


Mankato 4. Bathymetric map of a Minnesota River study site near Mankato, MN.

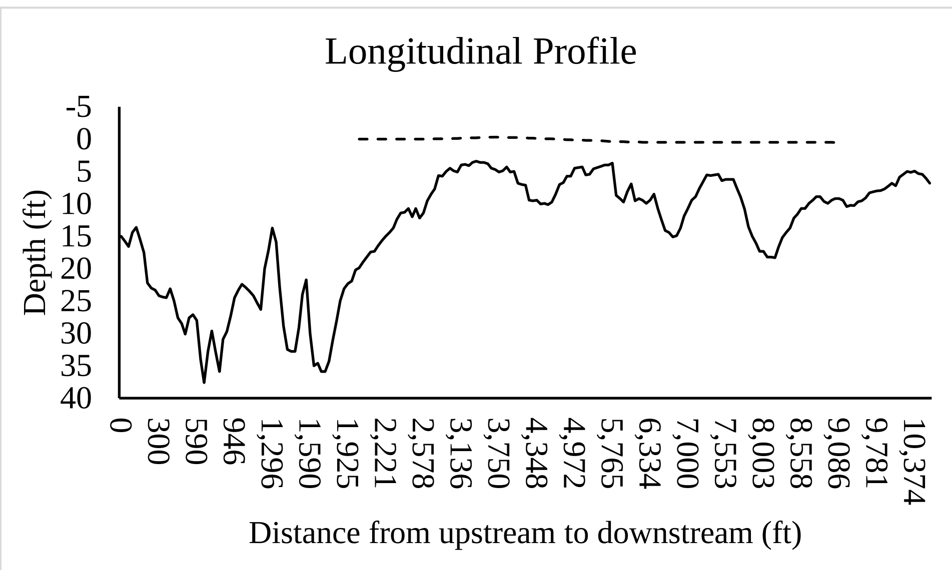


Mankato 5. Map of the Minnesota River study site near Mankato, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 8: St. Peter



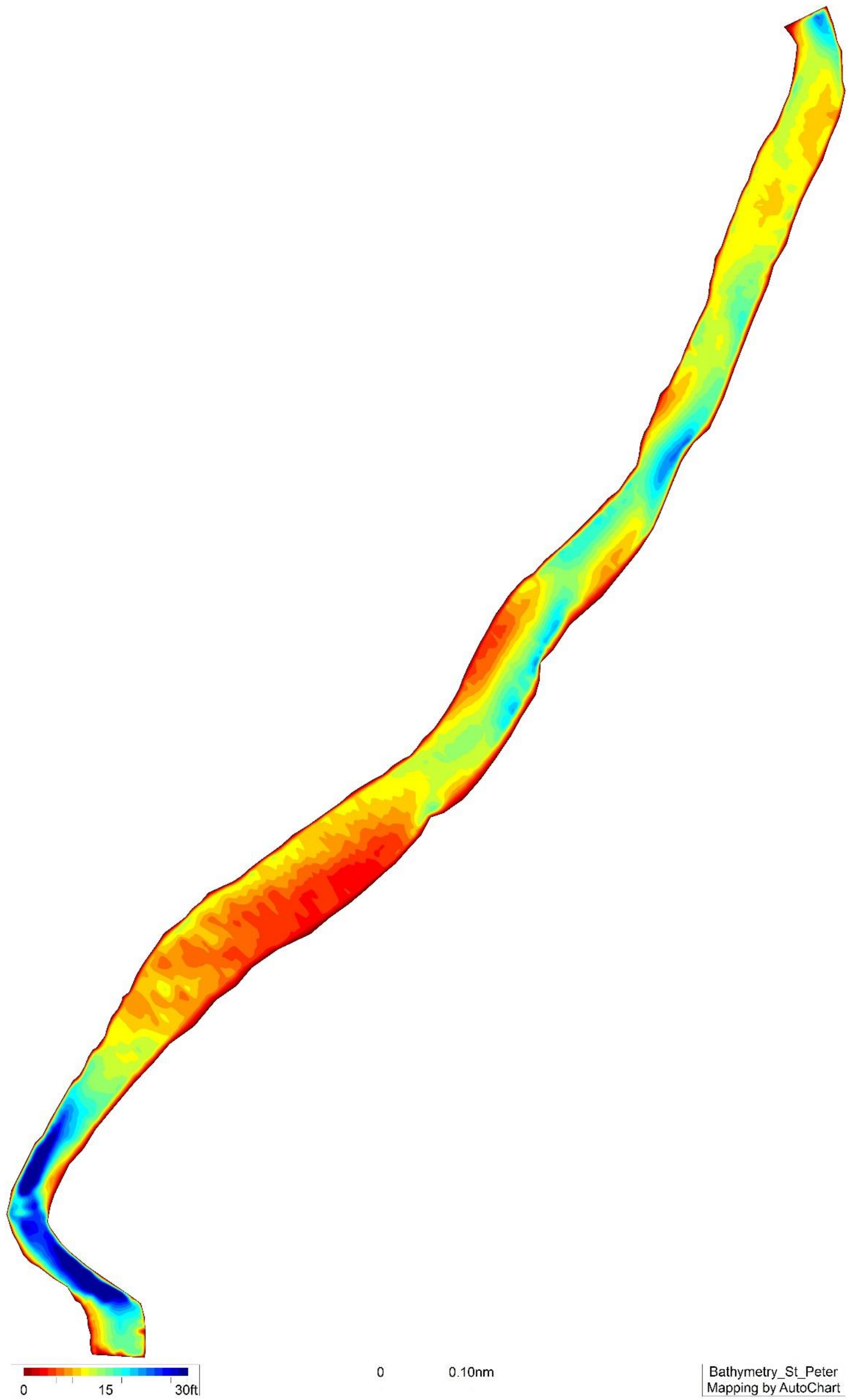
St. Peter 1. Cross section elevation of the Minnesota River Valley near St. Peter, MN derived from LiDAR data.



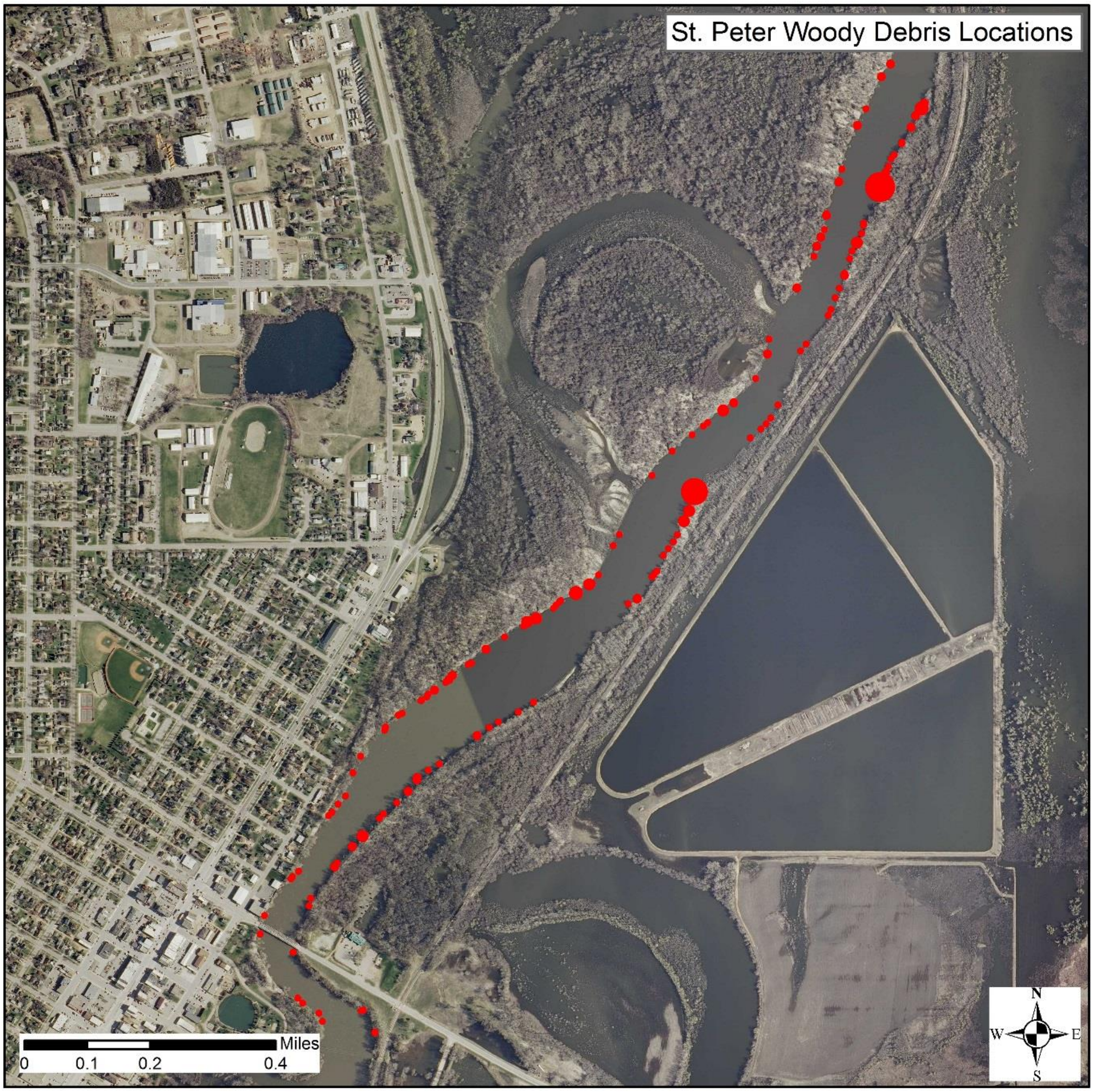
St. Peter 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near St. Peter, MN.

St. Peter 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the St. Peter study site.

St. Peter		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	17	6
Forest-cover	138	49
Wetlands	73	26
Human Disturbance	54	19
Total	**282**	**100**
500 meter		
Agriculture	311	7
Forest-cover	837	19
Wetlands	1070	24
Human Disturbance	969	21
Open Water	1292	29
Total	**4479**	**100**
1000 meter		
Agriculture	980	9
Forest-cover	1772	17
Wetlands	2570	24
Human Disturbance	2655	25
Open Water	2675	25
Total	**10652**	**100**
5000 meter		
Agriculture	66768	56
Forest-cover	14179	12
Wetlands	10368	9
Human Disturbance	18599	16
Open Water	8022	7
Total	**117936**	**100**

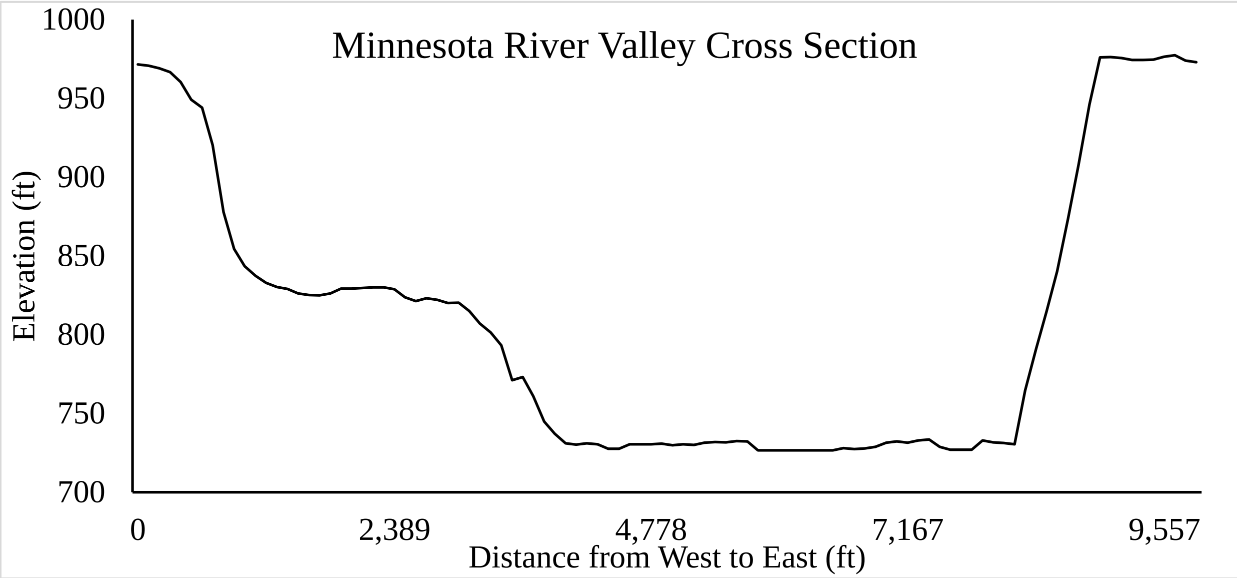


St. Peter 4. Bathymetric map of a Minnesota River study site near St. Peter, MN.



St. Peter 5. Map of the Minnesota River near St. Peter, MN showing locations of woody debris.

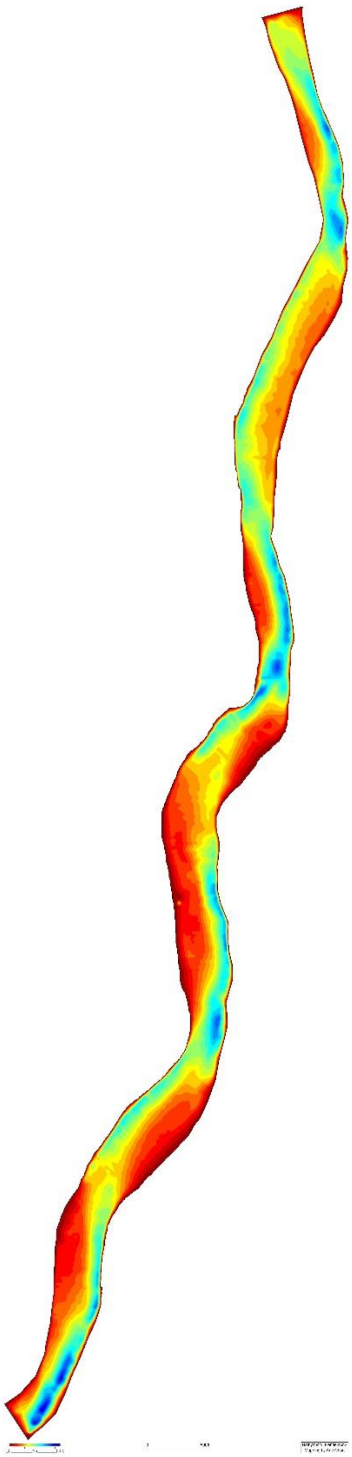
Site 9: Henderson



Henderson 1. Cross section elevation of the Minnesota River Valley near Henderson, MN derived from LiDAR data.

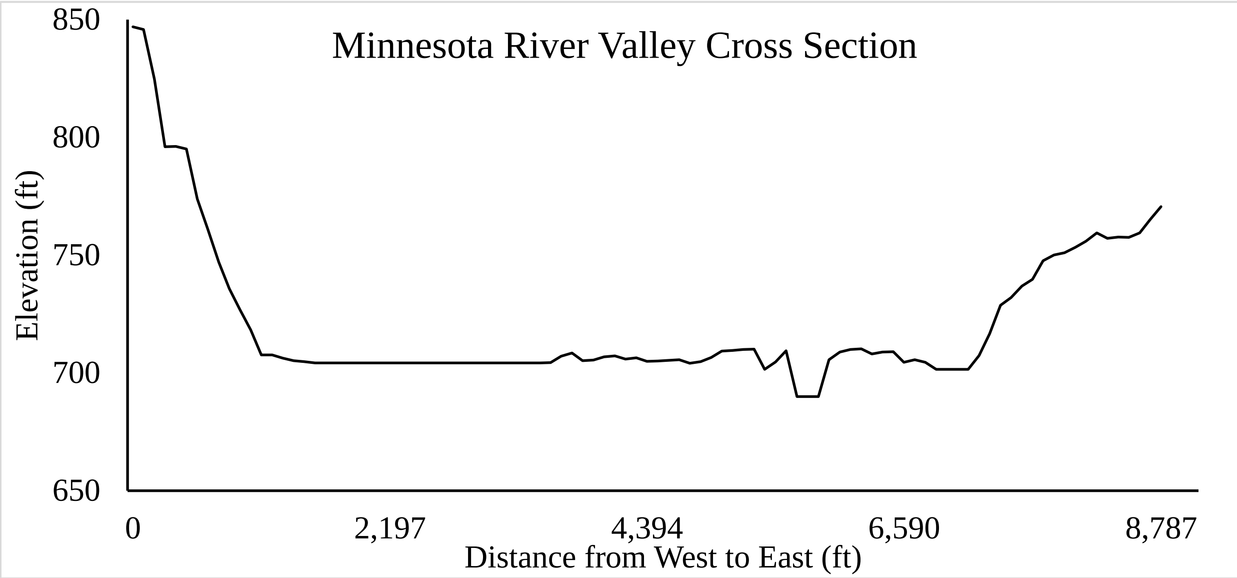
Henderson 2. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Henderson study site.

Henderson		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	19	8
Forest-cover	151	66
Wetlands	60	26
Human Disturbance	0	0
Total	**230**	**100**
500 meter		
Agriculture	923	19
Forest-cover	2522	51
Wetlands	628	13
Human Disturbance	161	3
Open Water	666	14
Total	**4900**	**100**
1000 meter		
Agriculture	3077	27
Forest-cover	4967	43
Wetlands	1307	11
Human Disturbance	861	8
Open Water	1221	11
Total	**11433**	**100**
5000 meter		
Agriculture	69360	56
Forest-cover	29350	24
Wetlands	6294	5
Human Disturbance	12272	10
Open Water	5578	5
Total	**122854**	**100**

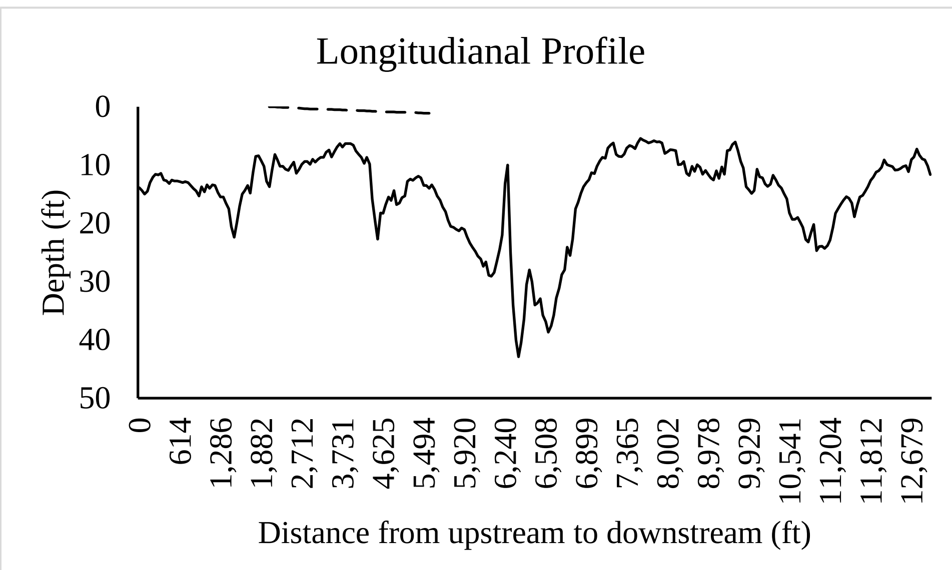


Henderson 3. Bathymetric map of a Minnesota River study site near Henderson, MN.

Site 10: Chaska



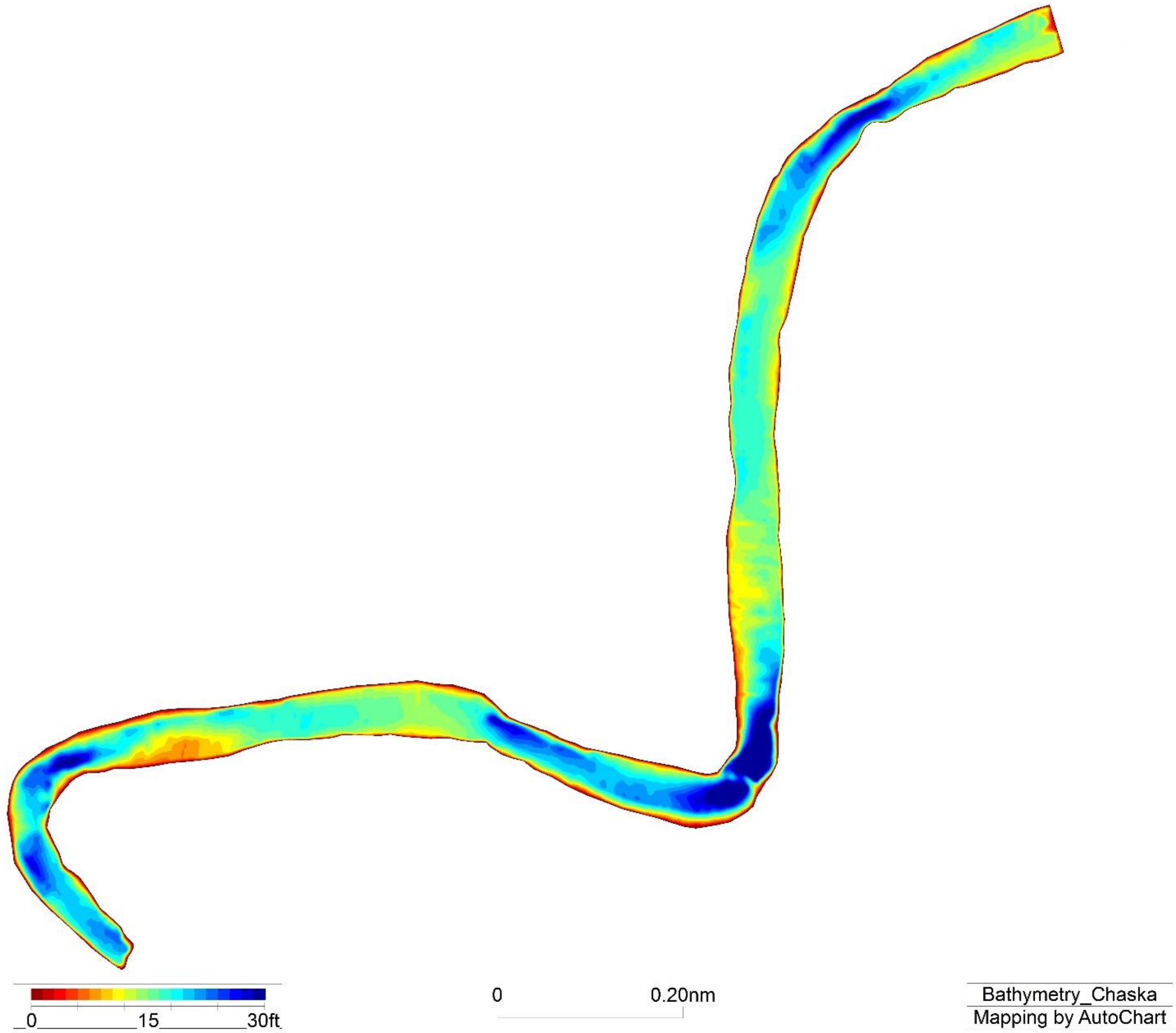
Chaska 1. Cross section elevation of the Minnesota River Valley near Chaska, MN derived from LiDAR data.



Chaska 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Chaska, MN.

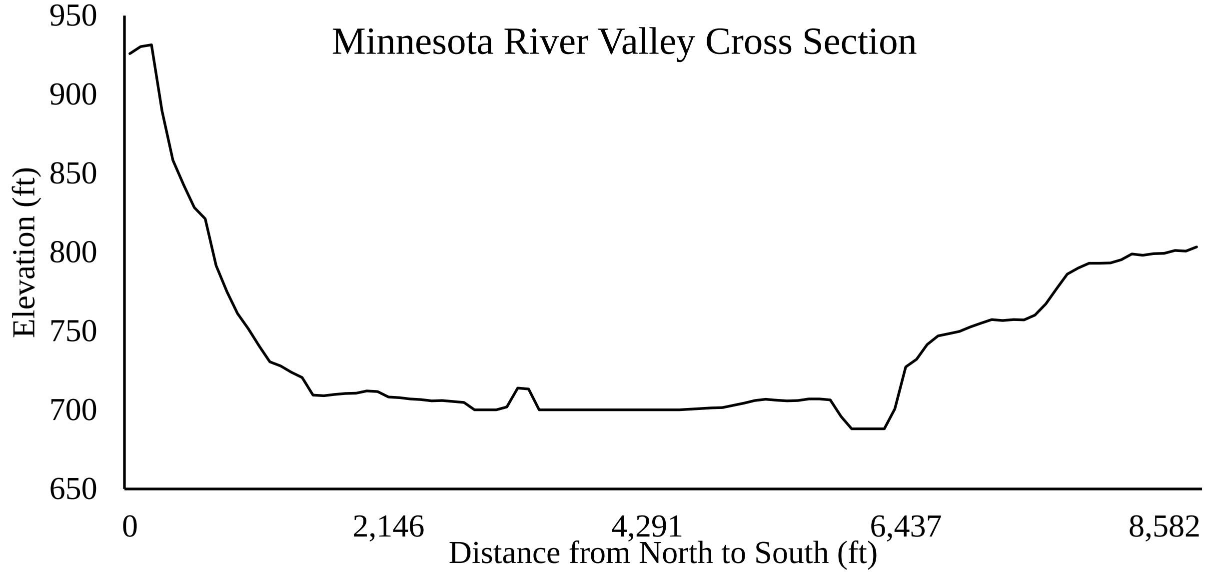
Chaska 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Chaska study site.

Chaska		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	29	10
Forest-cover	65	23
Wetlands	134	48
Human Disturbance	53	19
Total	**281**	**100**
500 meter		
Agriculture	901	19
Forest-cover	664	14
Wetlands	1186	24
Human Disturbance	1197	25
Open Water	868	18
Total	**4816**	**100**
1000 meter		
Agriculture	1866	17
Forest-cover	1160	11
Wetlands	1733	16
Human Disturbance	3620	33
Open Water	2584	23
Total	**10963**	**100**
5000 meter		
Agriculture	41769	35
Forest-cover	13198	11
Wetlands	6503	6
Human Disturbance	44723	38
Open Water	12093	10
Total	**118286**	**100**

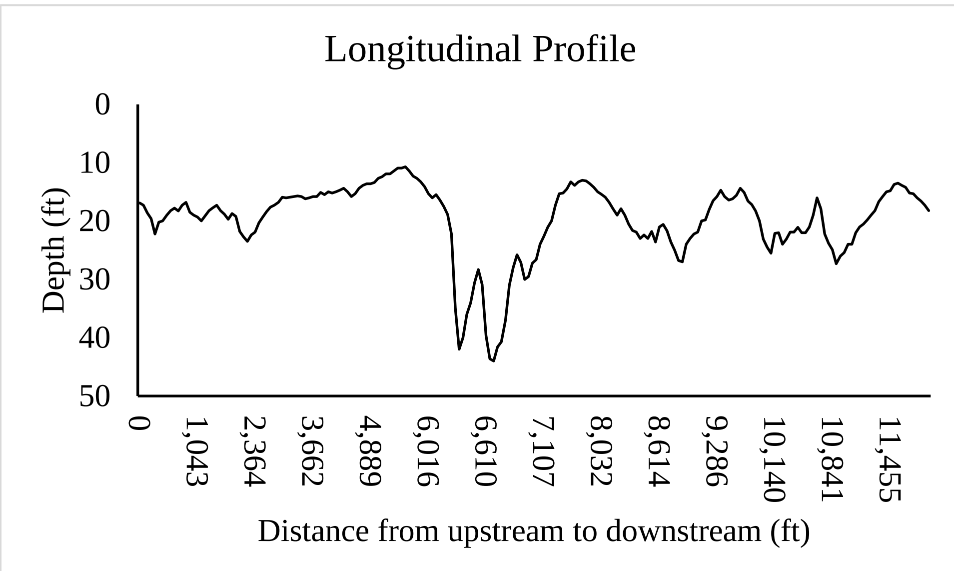


Chaska 4. Bathymetric map of a Minnesota River study site near Chaska, MN.

Site 11: Shakopee



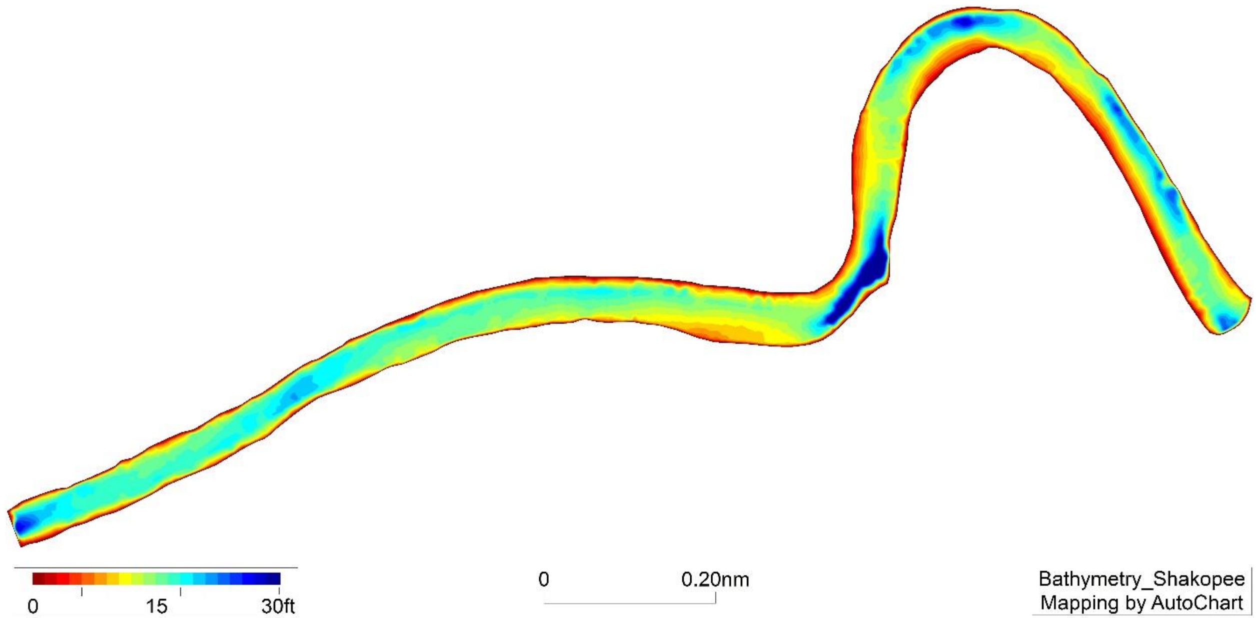
Shakopee 1. Cross section elevation of the Minnesota River Valley near Shakopee, MN derived from LiDAR data.



Shakopee 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Shakopee, MN.

Shakopee 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Shakopee study site.

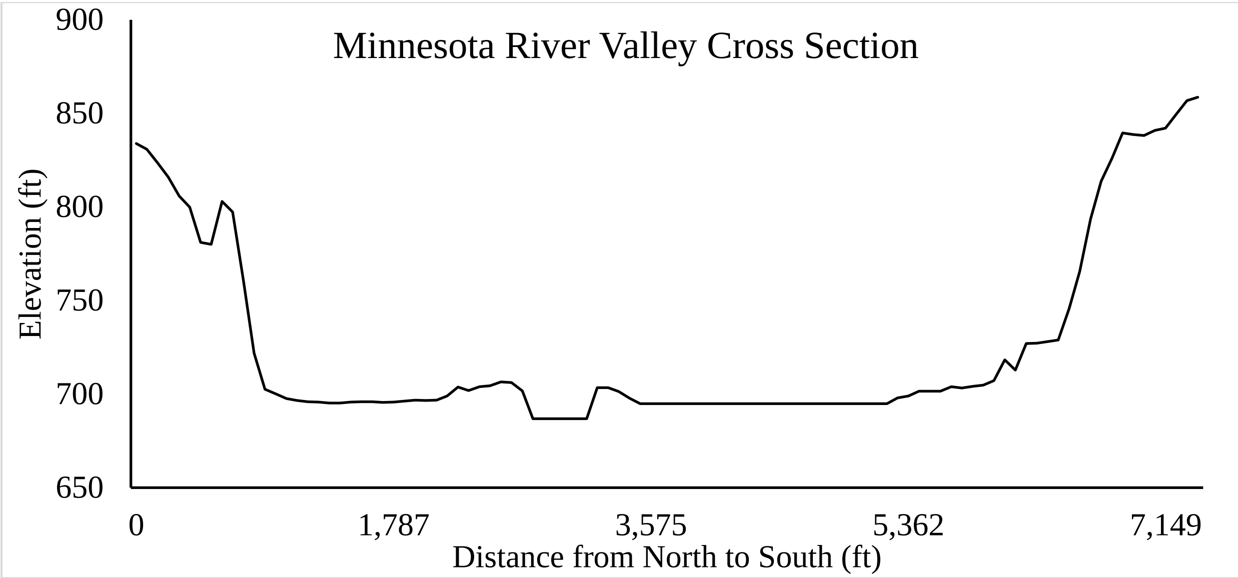
Shakopee		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	62	19
Forest-cover	127	38
Wetlands	110	33
Human Disturbance	32	10
Total	**331**	**100**
500 meter		
Agriculture	818	17
Forest-cover	538	12
Wetlands	720	15
Human Disturbance	1266	27
Open Water	1335	29
Total	**4677**	**100**
1000 meter		
Agriculture	1284	12
Forest-cover	956	9
Wetlands	1114	11
Human Disturbance	3754	35
Open Water	3552	33
Total	**10660**	**100**
5000 meter		
Agriculture	21886	18
Forest-cover	10929	9
Wetlands	5518	5
Human Disturbance	63287	53
Open Water	17608	15
Total	**119228**	**100**



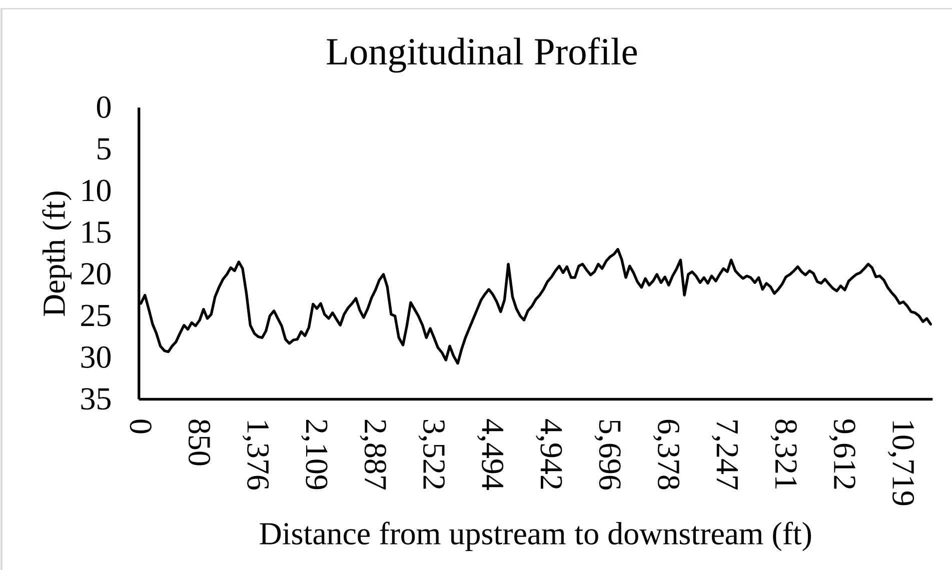
Shakopee 4. Bathymetric map of a Minnesota River study site near Shakopee, MN

Shakopee 5. Map of the Minnesota River study site near Shakopee, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.

Site 12: Bloomington



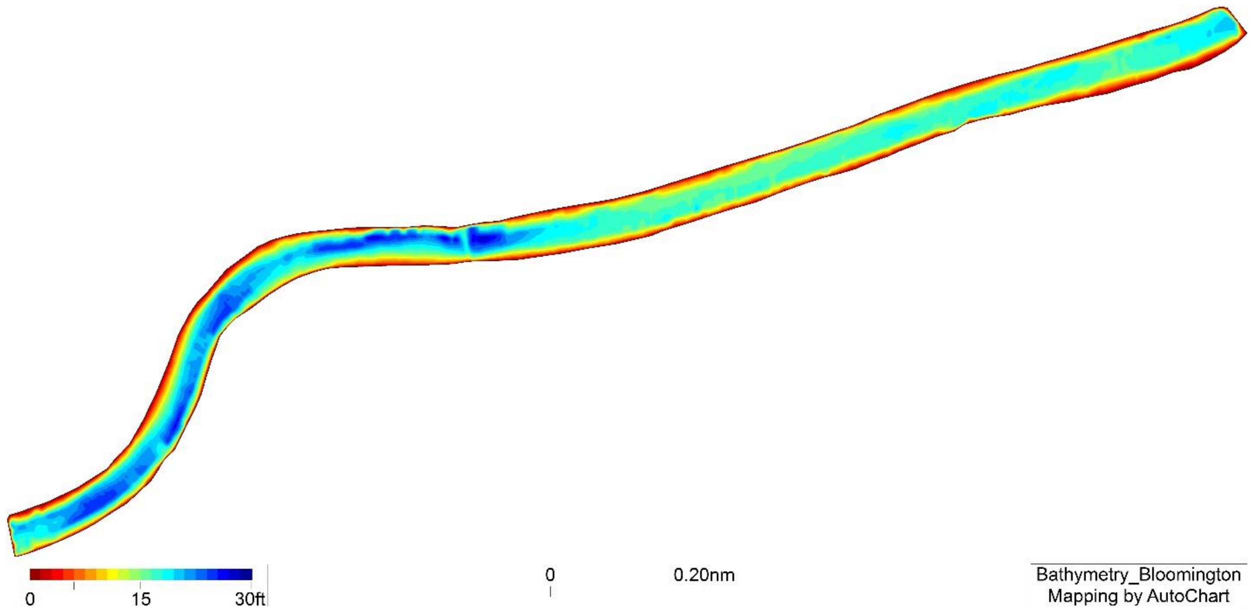
Bloomington 1. Cross section elevation of the Minnesota River Valley near Bloomington, MN derived from LiDAR data.



Bloomington 2. Longitudinal profile of the Minnesota River channel along the thalweg of a study site near Bloomington, MN.

Bloomington 3. Land cover within concentric bands (i.e., 50-5,000 m) surrounding the Bloomington study site.

Bloomington		
Land cover type	**Count**	**%**
Riparian Zone		
Agriculture	12	4
Forest-cover	133	42
Wetlands	131	41
Human Disturbance	40	13
Total	**316**	**100**
500 meter		
Agriculture	156	3
Forest-cover	820	18
Wetlands	836	18
Human Disturbance	884	19
Open Water	1992	42
Total	**4688**	**100**
1000 meter		
Agriculture	353	3
Forest-cover	1580	14
Wetlands	1442	13
Human Disturbance	3389	31
Open Water	4378	39
Total	**11142**	**100**
5000 meter		
Agriculture	3470	3
Forest-cover	8880	7
Wetlands	6635	5
Human Disturbance	90712	74
Open Water	13697	11
Total	**123394**	**100**



Bloomington 4. Bathymetric map of a Minnesota River study site near Bloomington, MN.

Bloomington 5. Map of the Minnesota River study site near Bloomington, MN showing locations of woody debris. The size of circles is proportional to the aerial coverage of woody debris.