FLOODPLAIN RESPONSE TO HISTORICAL LAND USE CHANGE ON THE UPPER BARABOO RIVER, WISCONSIN

by

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Abstract

Since the 1840s, Euro-American settlement of Wisconsin's Baraboo River watershed has had lasting effects on the landscape. This study examines the longitudinal and lateral changes in connectivity on the Baraboo River floodplain. Results show that shear stress, hydraulic radius, stream power, and water surface elevation within the longitudinal profiles each differ from presettlement conditions to modern conditions. The direct impacts include the presence of roads and railroad grades that disrupt the lateral connectivity of the floodplain. Water surface elevations increased since presettlement due to the confinement. Floods as large as the 500-year recurrence interval were found to be unable to overtop many artificially elevated highway and railroad structures, reducing the width of the modern floodplain. Floods with recurrence intervals between 1-10 years are also influenced by cross channel disturbances including bridge crossings and a grade control structure. The bridges constrict flow, and the grade control structure causes a drastic change in water surface elevation, similar to a dam. Flow is slowed upstream of the structure, and downstream flow expansions produce radical changes in velocity and power. Elsewhere, straightening of the river channel may have induced channel incision and promoted increased sediment transport from conversion of natural vegetation to agricultural land use. Understanding the river response to land use change improves future policy decision making with respect to restoration and rehabilitation.

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1.0 Introduction

Paddling down the Baraboo River, canoers and kayakers enjoy the picturesque landscape of wetlands, woodlands, pasture, farm fields, and prairie interspersed with cliffs of magnificent sandstone outcrops. The river's peaceful, slow pace allows patrons to relax and enjoy the ride. At one point, paddlers might notice jagged concrete blocks lining the banks, or notice bicyclists crossing old wooden bridges as the paddlers pass under the aging structures. While some may take note that the concrete blocks look unnatural or out of place, most move on in search of the view around the next meander.

As with everything else paddlers see while on the river, these irregularly-shaped concrete blocks, also known as riprap, are clues to the past which go unnoticed. While longtime local residents recall that the riprap replaced the old milldam in La Valle, they too might not notice the other human impacts on the landscape. In short, many people consider the Baraboo River to be a natural Midwestern river landscape and do not think twice about it. Dams were the only man-made structure sitting in the river, and since the dams have been removed, people believe that the river has been restored back to its natural state.

But what about the bridge crossings, pastures and farm fields? Are these components of the landscape natural? Many people are concerned about the future of rivers and the idea of restoration to natural conditions. The question then becomes, "what is natural?". The goal of this research is to quantify the change Euro-American settlement has had on the channel and floodplain morphology of the Baraboo River, and quantitatively estimate the impact it has on flooding characteristics. Also, more frequent incidents of high flow illustrated by the June 2008 flood serves as a baseline to estimate the upper limit impacts on the river, and the opportunity to estimate mobility in the system since dam removal. Interpreting the river's past is the key to understanding future change. This research will hopefully provide an understanding of the processes involved in historic river evolution to aid in rehabilitation or restoration efforts in the future.

2.0 Literature Review

2.1 Floodplains

Floodplains are naturally occurring features in river system morphology. Floodplains are formed as alluvial channels adjust their hydraulic geometry to transport water and sediment. Many terminologies exist to define floodplains according to a discipline's interests. Various existing definitions of floodplains reflect investigator's professional backgrounds and interests (Wolman and Leopold, 1957; Leopold et al., 1964; Freitag et al., 2009; Charlton, 2008; and Alexander and Marriott, 1999). Nanson and Croke (1992) review several floodplain definitions and attempt to classify definitions based on function. Nanson and Croke (1992) define a *genetic floodplain* as a horizontally-bedded alluvial landform separated from the channel by banks and created from a build up of sediment from flooding events. A *morphological floodplain* is represented by a description of its components rather than any classification. Shear stress and stream power can also be used to define an *energy based floodplain* classification (Hickin and Nanson 1984; Nanson and Croke, 1992; Simons et al., 1965).

Natural river floodplains are connected both laterally and longitudinally with the river channel. Longitudinal connectivity refers to the link between upstream and downstream sections of a river, and lateral connectivity refers to the link among a river, its floodplain, and surrounding slopes (Blanton and Marcus, 2009). As rivers adjust to the amount of water being supplied to them by precipitation events, spring meltwater, and groundwater, the amount of work and the potential to carry sediment or scour the banks will adjust as well. Through time, a river channel will constantly alter its sediment carrying capacity and planform through aggradation and/or degradation of its banks and bed. Floodplains form when stream flow becomes large enough to overtop the channel banks and deposit sediment. In addition to these driving factors, valley slope and confinement, substrate, and vegetation, also play a role in channel form and behavior (Charlton, 2008).

2.2 Floodplain Characteristics

Characteristic features found on the floodplain include levees, meander scroll bars, cut-offs, backswamps, and paleochannels. Each may or may not be found on any given floodplain, but they do help describe current processes as well as the processes that were prominent in the past. Floodplain characteristics do not remain constant throughout the watershed from the headwaters to the mouth. Slope, sediment supply, and stream power vary downstream along the longitudinal profile. Most river profiles are concave with gradients decreasing downstream, affecting stream power. Headwaters tend to supply more sediment to the river channel, and deposition is often favored downstream as the profile flattens out (Gilvear and Bravard, 1996). The constant cutting and filling of the river channel leads to a dynamic and active landscape.

Leopold and Wolman (1957) state that the two main variables controlling channel planform are discharge and slope. As the discharge in a river channel increases to bankfull, so too does the capability of eroding the concave cut bank of a meander. In turn this leads to a lateral migration of the channel. If the discharge becomes great enough to overtop the channel banks, vertical accretion will occur as sediment is deposited onto the floodplain.

2.3 Sedimentation and Driftless Area Floodplains

The Driftless Area of Wisconsin is located in the southwest portion of the state. During glacial periods, ice flowed around the Driftless Area, leaving the landscape untouched by the Quaternary glaciers and their drift. This area has a classic dendritic drainage pattern with steep slopes, gently sloped ridgetops, and deep valleys due to the underlying geology.

This physiography of the Driftless Area makes this region interesting to study because of its response to environmental change (Knox, 1987). Knox (1987) used trace metals to date overbank sedimentation in the Lead-Zinc District of the Driftless Area since Euro-American settlement to the area. In addition to dating, observations such as color and stratification indicated an environmental disturbance. Knox (1987) described the historical overbank sediments to be a yellowish brown color compared to very dark grayish brown of the underlying presettlement floodplain. The historical sediment displayed stratified bedding whereas presettlement sediment appeared massive as a result of bioturbation. Also the presettlement floodplain was relatively more clay-rich, while the historical sediment was silt and sand-rich.

Results of sediment dating show that rates and timing of overbank sedimentation differed between headwater tributaries and downstream trunk valleys. The initial sedimentation rates in all areas of the watershed may have been high from deforestation and the conversion to agriculture; however, valley-floor sedimentation rates in the headwaters began to decrease over time. Knox (1987) suggested that in addition to high sediment yields from land use, climatic events and feedback mechanisms were also at play creating decadal-scale changes in extreme sedimentation rates. Despite this observation, high sedimentation rates during the early 20th century are mainly attributable to little soil conservation such as contour plowing and terracing, which would reduce erosion on the fields and trap sediment. As soil conservation practices were implemented in the area, sedimentation rates were reduced.

The introduction of Euro-American agriculture to natural landscapes like the Driftless Area drastically changes the morphology of the landscape. More specifically, implementing agriculture into an area previously undisturbed will affect runoff and erosion of the area. Before Euro-American settlement, forests and prairies dominated the Driftless Area. Knox (2001) describes several reasons why agriculture accelerates runoff and increases soil erosion. A raindrop hitting bare soil from agriculture breaks up the natural soil aggregates, and reduces infiltration. Bare soil also reduces hydraulic roughness, which in turn increases surface runoff. Knox (2001) also states that cultivation and overgrazing causes compaction of the soils and depletes soil organic matter, which in turn decreases the porosity and permeability of the soil. The Little Platte River is one of many Driftless Area rivers to undergo changes since the onset of Euro-American settlement in the 1830s. The impact of agriculture increased flood magnitudes and their recurrence frequencies. In turn, this flooding led to increased channel width to depth ratios in headwater tributaries (Knox, 1977).

Rapid historical sedimentation is also noted in the Galena River basin (Magilligan, 1985). Not all sediment is flushed downstream, but much is deposited on the floodplain. The amount of sedimentation varied depending on valley width and drainage area changes. Wide valleys tended to have large accumulation of sediment, while narrow valleys did not. Magilligan (1985) states that despite soil conservation practices in the area, which would reduce the amount of sediment supplied, channel and floodplain responses to sedimentation occur rapidly.

Lecce (1996) also found that floodplain sedimentation increased in proportion to valley width, though it was also influenced by stream power and the development of historical meander belts. For instance, historical meander plains of the Blue River were located in the headwater and mid-basin reaches where stream power was sufficient to strongly accelerate channel migration. Lecce (1996) also found that large floods in the meander belts did not overtop the banks, sediment transport increased which eroded historical sediments, flood peak attenuation was reduced, and more sediment was transported downstream where the slope decreases allowing for deposition. Over time, stream power and flow depths will decrease as lateral migration increases and the meander belt widens.

Juckem et al. (2008) examine how climate and land management affect baseflow in a Driftless Area stream, suggesting the magnitude of change in stream baseflow before and after 1970 was most likely amplified by changes in land management. However, they found no significant correlation between land management practices and stream baseflow.

Nonetheless the study implies that land use extends beyond the river channel, and can affect the local hydrologic cycle as well.

3.0 Background

The Baraboo River watershed is located in south-central Wisconsin and flows from the headwaters to its confluence with the Wisconsin River covering an area of 609 square miles with a stream length of approximately 120 miles (Figure 1). The Baraboo River's headwaters lie in the Driftless Area of Wisconsin, an area of steep slopes, separating gentle ridges from flat-bottomed valleys (Martin, 1916). During the river's descent, the Baraboo River flows through the previous glaciated area downstream until it joins the Wisconsin River south of Portage (Attig and Clayton, 1990). The climate in the area is typical midlatitude humid continental, with seasonal flooding in March through May from snowmelt as well as flooding from thunderstorm systems (Doyle et al., 2003).

3.1 Study Location

The study site is located roughly midway through the Baraboo River watershed within the town of La Valle (T13N R3E) in Sauk County. The study area begins just downstream of the Dutch Hollow Road bridge crossing with the Baraboo River and continues downstream, passes through the village of La Valle, and ends upstream of Lake Redstone, just before County Highway V crosses the river (Figure 2). The study site was chosen based on the diverse land-use history of the area.

3.2 River Characteristics

Analysis of floodplain features guide understanding of how rivers work and helps identify events that formed the floodplain. According to Brierley (1996), geomorphic features are the building blocks of river systems. A qualitative description of channel and floodplain form is presented here in order to understand the processes at work within the Baraboo River.

Floodplains are formed through a combination of lateral and vertical accretion and are prone to reworking by various processes. The Baraboo River reach under study here has a characteristic ridge and swale topography. Active meandering on steeper slopes tends to be associated with higher sinuosity and leads to lateral instability. Neck and chute cutoffs induce instability by changing the river gradient and length (Brierley and Fryirs, 2005). Meandering rivers with backswamp floodplains are commonly characterized by extensive deposits of fine-grained overbank sediment near valley margins (Fisk 1944, 1947; Farrell, 1987; Woodroffe et al., 1993). The Baraboo River contains several lowland and tamarack backswamps allowing for sediment deposition to occur. According to Gundlach (1980) soil formation on the floodplain and meander belt is less prominent in the backswamps due to the continuously waterlogged soil. This is evident in the Fluvaquent and Fluvaquent-wet soils found in the swamps, which must be drained if cropland agriculture is to be practiced.

Floodplains have the natural ability to adjust, and depending on the sensitivity of the river, response time to environmental change can either be rapid or lagged. Valley width and slope are key factors that influence floodplain physical morphology (Brierley and Fryirs, 2005). The Baraboo River is a low gradient river and its intersection with key bedrock units provides valley confinement in certain areas along the profile. This indicates that the river is somewhat sensitive to change. The recovery potential in this area is low because after an extreme event such as a catastrophic flood, the proximity to bedrock limits the sediment supply and the capability for the river to adjust by aggradation and channel narrowing (Charlton, 2008).

Despite the bedrock valley confinement, the remaining floodplain in this system adjusts both by lateral and vertical accretion. Evidence of these processes is noticeable on the Baraboo River. Through Light Detection and Ranging (LIDAR), development of meander migrations or lateral accretion and other meander scars such as oxbow lakes can be determined. Field observations documented lateral accretion on the banks, most notably fresh sand deposition on the point bars and floodplain as a result of the June 2008 flood. The 2008 flood was estimated to have a 500-year recurrence probability (Fitzpatrick et al., 2008). Figure 2 shows valley constriction possibly related to faulting in the Cambrian bedrock (Attig and Clayton, 1990). Downstream, as the valley opens up, the river channel is freer to migrate laterally across the floodplain and the natural channel tends to be more sinuous (Figure 2). Figure 3 shows the effects of lateral migration processes with bank erosion on the far outer bank and deposition of sand on the inside point bar respectively.

3.3 Geology

Exposed bedrock of Cambrian age sandstones, most notably the Wonewoc and Eau Claire Formations, are found in the La Valle reach of the Baraboo River. The upper layer of the Wonewoc Formation, the Ironton Member, forms low, brown colored cliffs, while the

Galesville Member below is made of white sandstone. There are many outcrops of the Galesville Member, and the La Valle reach of the Baraboo River flows through this formation (Attig and Clayton, 1990).

Farther away and upslope from the Baraboo River floodplain is the Rountree Formation of the late Cenozoic. It contains clays, and sandy clays, which are residuum from the underlying Oneota dolomite of Ordovician age. Sandstones of the Jordan, St. Lawrence, and Tunnel City Formations of Cambrian age underlie the Oneota dolomite. Due to the different structure and cementation of each formation, erosion of the layers create a series of benches that form semicircular hillslope scallops, a distinct feature in the La Valle area (Attig and Clayton, 1990).

Also within the study area, the La Valle Fault, a slightly curved nine-mile fault line running east-west, created a 33 ft elevation offset of the Ironton Member. This fault is no longer active (Attig and Clayton, 1990).

3.4 Soils

The Baraboo River valley is filled with offshore sediment of the Big Flats Formation, which consists of locally derived hillslope sediment deposited on nonglacial water backflooded from Glacial Lake Wisconsin (Attig and Clayton, 1990; Clayton and Knox, 2008). As a result terraces above the modern floodplain consist of primarily quartz sand from the Cambrian sandstone formations, silt, clay, and chert nodules from the Oneota Formation, and silt and clay from the Rountree and overlying late Quaternary loess deposits (Attig and Clayton, 1990).

The soils of the modern floodplain are a mixture of Fluvaquents and Fluvaquents-wet. These soils are found on nearly level ground and subject to frequent flooding. These soils were formed on stratified silty, loamy and sandy alluvium. Fluvaquents are found on higher ground relative to Fluvaquents-wet, which means the water table is deeper beneath the surface, and the area is suited for trees, wildlife habitat and unimproved areas. Unlike the Fluvaquents-wet, which are mostly dominated by reed canary grass and not suitable for trees, Fluvaquents soil can be drained and used for agricultural cropping if protected from flooding. Surface runoff is slow for both soils, and water may be ponded in the Fluvaquents-wet (Gundlach, 1980).

Uplands of the study area are dominated by soils of the La Farge-Norden-Gale series. These soils are found on gently sloping uplands to very steep hillslopes, and formed in loess and in a thin layer of residuum from the underlying bedrocks. These soils are well-drained and have medium texture. Most areas with these soils are suitable for crops and pasture, but erosion from these practices is a major concern. Soils located in areas with steeper slopes tend to remain wooded (Gundlach, 1980).

3.5 Presettlement Land Conditions

Field notes from the Public Land Survey (PLS) section lines were used to reconstruct the vegetation cover along the Baraboo River prior to Euro-American settlement (Wisconsin Board of Commissioners of Public Lands, 2010). Survey notes of section lines that crossed the river were used since these notes most likely reflect the vegetation near the river channel, and the section lines traversed the floodplain. Schulte and Mladenoff (2001) note that the intention of the PLS was legal rather than scientific, so some tree species may be over-represented for a variety of reasons. First, some species were easier for surveyors to identify. Also species such as birch and willow, which are short-lived and susceptible to bifurcation, are generally omitted. Since trees noted were intended to serve as long term markers for identifying section lines, the surveyors also sought trees of a certain size. In general, the records are useful for interpreting land cover types, forest stand densities, and age cohorts of woody vegetation, but are less credible at very fine scales due to these concerns of representation and small sample sizes. Also a detailed map in Lange (1976) shows the general vegetation cover of the town of La Valle reconstructed from the original land surveys (Figure 4).

The PLS section line surveys were taken in the summer of 1845 in the town of La Valle. The interior lines of the township that crossed the river were examined. Exposed bedrock with relatively steep slopes is found upstream of the study area. Patches of white pine were most likely found on well-drained thin soil, whereas sugar maple, yellow birch and oaks were more common in areas likely to retain more moisture in the soil. Downstream of the bedrock constricted reach shown on Figure 2, the vegetation immediately adjacent to the river channel was marshland comprising of sedge meadows and wet prairies (Figure 4). Farther away from the channel, but still within the floodplain, oak woods were present in 1845. Oak woods and oak savannas prior to Euro-American settlement heavily dominated this region of Wisconsin and indicate that fire came through this area frequently (Curtis, 1959). As the river channel nears the present location of the village of La Valle, the center of the study area, the marsh vegetation covers a larger area of the floodplain along with hardwood and tamarack swamps. This mosaic of marsh and hardwood swamps continues downstream to the end of the study area with oak woods surrounding the swamps (Figure 4) (Wisconsin Board of Commissioners of Public Lands, 2010). This description of the landscape is indicative of what the vegetation cover was prior to 1845 and Euro-American settlement.

3.6 Euro-American Settlement

Samuel Karsterter was the first Euro-American settler to the town of La Valle in 1847. It wasn’t until the 1850s and 1860s settlers began to utilize the resources around them (Goc, 1990). Several saw mills were built along the river to process pine and hardwood in the uplands. Within the village of La Valle, J. F. Hamlin built a water mill dam in 1849 for grinding grain and flour (The History of Sauk County, 1880). This particular mill operated until 1980 and even provided electricity to the village at one point in time. The dam was a low head dam and created a backwater millpond called the La Valle Millpond. As people began to move in, forests were cleared and replaced with agriculture.

One hundred and forty people were counted in Sauk County’s population in 1840 and concentrated on the eastern side of the county adjacent to the Wisconsin River (Table 1) (The History of Sauk County, 1880). Euro-Americans still considered Sauk County to be wilderness in 1840, especially since the Ho Chunk Native American tribe dominated the area and made it difficult for Euro-Americans to move into tribe territory. Yet slowly, settlement in Sauk County continued and people began to move farther west from Sauk Prairie via the Baraboo River (The History of Sauk County, 1880).

Since the town of La Valle is located in the northwest part of the county, the early growth was slow because of its inaccessibility by road (Reedsburg Remembers, 1948). Generally this influx in settlement in the 1850s to the area is attributed to the opening of land for sale (The History of Sauk County, 1880). Settlers tended to migrate up the river valleys due to the relatively easy transportation, and fertile floodplain soil for farming (Ostergren, 1997). The railroad's arrival in 1872 in La Valle served as a catalyst of growth, allowing the village to establish several hotels and restaurants (Goc, 1990).

Table 1. Total Population. Empty cells indicate no data (data from The History of Sauk County, 1880; U.S. Census Bureau, 2009).

	1840	1850	1855	1860	1865	1870	1875	1990	2000
Sauk County	102	4371	13614	18963	20154	23868	26932	46975	55225
Town							1153	1104	1203
Village								487	326

The population of the county more than doubled between 1875 and 2000 (Table 1); however, the population of the town of La Valle changed little. The population density of Sauk County in 1840 was 0.12 people per square mile, but since most of the Euro-American population concentrated on the eastern side of the county, it is reasonable to assume that La Valle did not have a strong Euro-American influence (Table 2). The population of the town and village of La Valle is assumed to be zero in 1840 since Euro-American settlement of the area began in 1847. Although small populations of Ho Chunk lived in this area, little is documented regarding either population or land use impacts in the present-day town of La Valle. Population density in 2000 of the town is less than the county as a whole. The density of the town might actually be less when excluding the village of La Valle, which is home to roughly a third of the population of the township.

Table 2. Population Density (people per square mile) (data from The History of Sauk County, 1880; U.S. Census Bureau, 2009).

	Sauk County	Town	Village
1840	0.12	0	0
2000	66	35	779
Area	837	36	0.42

3.7 Modern Land-Use History

Forest covers approximately thirty-six percent of all Sauk County today (Figure 5). However, most of the forest cover is concentrated in the eastern part of the county within the Baraboo Bluffs. When examining the town of La Valle, agriculture dominates the floodplain of the Baraboo River with very few remnants of prairie grassland and forests on the steeper slopes (Figure 5). The forests of today are denser and comprised of more sugar maple, and basswood due to fire suppression that allows shade tolerant species to thrive (Sauk County Land Conservation Department, 2007).

Field surveys from October of 2009, described later, revealed that reed canary grass dominates the river floodplain immediately adjacent to the banks along with silver maple and basswood (Figure 6). Farther away from the channel, the floodplain is dominated by agricultural cropland. Crops are primarily corn and soybeans and are plowed adjacent to the river channel in areas with steep banks on one side of the channel (Figure 7). A remnant of the old millpond in the village of La Valle is still present. Sloughs located along the old

Chicago and Northwestern railroad grade, now the 400 State Trail, are also present on the floodplain.

3.8 Previous Research on the Baraboo River

Many studies on the Baraboo River have focused on dam removal. Five milldam structures have been removed and 120 miles of river have become free flowing (Jepsen, 2009). Doyle et al. (2003) examined channel response to the removal of the La Valle dam in 2001 and found that the initial response to downstream channel changes was the deposition of fine sediment along channel margins and on the inside of meander bends. Sand trapped behind the dam was mobilized downstream and temporarily altered the cross-sectional area. Upstream degradation on the channel occurred rapidly because the sediment was easily eroded due to the lack of sediment consolidation (Doyle et al., 2003; Greene, 2010). The study by Doyle et al. (2003) was one of the first to quantify the geomorphic changes following dam removal. However, the temporal scale of observations limits this study.

Fish habitat and mobility following the dam removal increased species richness and allowed free passage for fish to migrate upstream (Catalano et al., 2007). This is good news for fish, but the fishermen who once enjoyed plentiful fishing in the spillway below the dam now find the area less rewarding since fish and no longer congregate below a dam spillway (Jepsen, 2009).

Despite the quick response to geomorphic change following dam removal, the Baraboo River continues to respond and adjust its channel bed. Greene (2010) found that since dam removal the longitudinal profile has become smoother, but a grade control structure at the dam site affects stream hydraulics. Greene (2010) also estimated that the June 2008 Flood contributed to cumulative removal of slightly over a third of stored sediment from the grade control structure. Jepsen (2009) states that if the dam structure were present during the 2008 flood, the dam would have been overtopped, severely compromising its structural integrity.

An anomalously wet 2007 followed by the heavy rains in June 2008 caused the extensive 2008 flooding in the Baraboo River watershed. Fitzpatrick et al. (2008) examined the flood inundation of the Baraboo River at Reedsburg and Rock Springs. Gage data and indirect methods of obtaining flood heights were used to estimate the extent and magnitude of this flood. This study demonstrates how antecedent conditions impact flooding and the communities surrounding the floodplain.

Despite the attention the Baraboo River received in recent years regarding manipulation of its channel, little is known about the long-term effects of land use change. Therefore the goal of this research is to expand the temporal scale of channel and floodplain response to better understand the drivers of human induced land use change on the Baraboo River.

4.0 Methodology

In order to assess the influence of land use change on the upper Baraboo River floodplain, a combination of historical data, field data, and GIS was used in a computer model to study stream flow within the La Valle reach of the Baraboo River. Historical background data including aerial photographs of the watershed area were obtained, field surveys of the river channel were conducted of the La Valle reach, LIDAR and Geographical Information Systems (GIS) were used for floodplain characteristics, and HEC-RAS 4.0 (Hydrologic Engineering Center River Analysis System) and HEC-GeoRAS were employed to model stream flow.

4.1 Field Surveys

Field surveys of the Baraboo River channel and its banks were completed over several weekends during September and October 2009. Surveys began approximately three miles upstream from the former dam site in La Valle and ended approximately three miles downstream from the site (Figure 2). Surveys were completed using an auto-level instrument at each cross-section. Twelve river cross-sections were surveyed along the reach and were accessed by canoe. Temporary benchmark elevations were created at each cross-section and later tied to a known benchmark at the State Highway 58 Bridge in La Valle, and verified using LIDAR in GIS.

4.2 Historical Aerial Photographs

Aerial photographs from the years 1937, 1949, 2005, and 2008 were compared to note changes in land use and river pattern. Aerial photographs were georeferenced and compared in a GIS.

4.3 Geographical Information Systems

Light Detection and Ranging (LIDAR) data courtesy of the Land Conservation Department, Sauk County were added to the channel banks at each cross-section to extend the floodplain. A triangulated irregular network (TIN) was created from LIDAR bare earth points to create a surface with x and y coordinates, and z surface values in Environmental Systems Research Institute's ArcGIS. The resolution of the LIDAR bare earth points at this site is between one and two meters (3.28 and 6.56 feet). Field survey cross-sections were overlain onto the TIN, and floodplain elevation data were extracted using HEC-GeoRAS, an extension in ArcGIS. Channel banks surveyed in the field were matched with channel banks determined using HEC-GeoRAS and merged into one cross-section. For comparison purposes, this method of obtaining floodplain and channel cross-sections by merging datasets is still reliable despite potential error involved.

4.4 HEC-RAS

Model simulations of stream flow for presettlement and modern conditions were created using HEC-RAS 4.0. The twelve modified cross-sections from HEC-GeoRAS were imported into HEC-RAS and Manning's coefficient for roughness was added to each cross section floodplain and channel to reflect the vegetation and river character. A one-dimensional steady flow analysis was performed for both models and output of water surface height, stream power, channel shear stress, channel velocity, Froude number, hydraulic radius, and longitudinal profile were compared. Several simulations were performed and adjusted to best reflect the environmental setting for each model, and are discussed in detail later.

To estimate the amount of discharge for a particular recurrence interval for the HEC-RAS model, stream flow of a given recurrence probability was estimated using the PeakFQ-Flood Frequency Analysis based on the U.S. Geological Survey's Bulletin 17B (Flynn et al., 2006). This program uses the Pearson Type III frequency distribution to create estimates of instantaneous annual-maximum peak flows for certain recurrence intervals (Flynn et al., 2006). Since there is no gage at the La Valle study site, flows were estimated using the USGS gages at Hillsboro (gage #5404116), upstream of La Valle, and at Baraboo (gage #5405000), downstream of La Valle. Flow data from the Hillsboro gage are only available since 1988 and the large peak flows (100-year flood and 500-year flood) seemed out of proportion to its drainage area of 39.1 square miles. Flow data from the Baraboo gage are available since 1914 with a few years missing, and estimates of peak flows seem to reasonably reflect the drainage area. Peak discharge for the La Valle study site was then estimated using a peak discharge to drainage area ratio based on the Baraboo river gage data. Discharge estimated for the 1, 2, 5, 10, 25, 50, 100 and 500-year recurrence interval was routed through each cross-section.

Reliability of the peak flow estimates was checked against estimates conducted by Walker and Krug (2003) on Wisconsin streams using equations based on flood-frequency and drainage basin characteristics. The discharges at a given recurrence interval for both methods produced roughly the same estimates despite having different periods of record for the gage. This outcome indicates that the PeakFQ analysis of the Baraboo River is an acceptable approximation of peak discharge at the La Valle site.

5.0 Results

5.1 Analysis of Aerial Photographs

In order to observe recent changes in floodplain morphology, aerial photos from 1937, and 1949 were compared with aerial photos taken in 2005 and 2008 (Figure 2). The 1937 photos show a lack of soil conservation practices since no contour cropping is visible. However, evidence of common contour plowing and rotational strip cropping become noticeable in 1949 indicating significant improvement in land conservation practices by the late 1940s.

Aerial photographs taken in 1937 reveal that Hemlock Slough was a cutoff meander. It appears that when the Chicago and Northwestern Railroad built tracks, the tracks were constructed on the edge of the river valley floodplain just before steep slopes begin. However, the river valley constricts just downstream of what is now Dutch Hollow Road, and makes railroad construction less desirable in that area due to the confinement. As a result, the railroad must have carved a path through the hills at the narrowest spot avoiding the constriction of the narrow valley. The 1937 aerial photograph shows that there are several oxbow lakes on the northeast side and southwest of the railroad line, and the outermost looks fairly recent (Figure 2). Instead of building two bridges to cross the river, the railroad company probably diverted the flow to the southwest of the line, straightening the course of the river channel. Although the line is several feet above the riverbank, they must have created an outlet to relieve any possible flooding into the relic channel.

At the State Highway 33 (STH) crossing, the river was channelized. This appears in all photographs. In the 1937 photograph, there appears to be a road just south of STH 33 that also crossed the river. Although the STH 33 bridge was constructed in 1917, it is unknown whether the current road was the original road crossing the river in this area. The aerial photographs as well as LIDAR data suggest this other road may have been the primary river crossing prior to the STH 33 bridge. Since there are oxbow lakes surrounding the STH 33 bridge, the river meandered before the existence of the highway. It is also noticeable that the smaller road mentioned previously crossed the old channel twice. It is likely that the river was channelized to minimize the number of bridge crossings and act as a flood control on the river (Figure 2).

Other changes on the river channel include meander cutoff upstream of the present day slough. However, due to the lack of record, it is unknown whether this cutoff was a natural river progression, or an accelerated alteration from channel migration caused by placement of the railroad. Downstream of the slough, the main channel has migrated again, most likely in response to the railroad placement. The outline of the La Valle Millpond is still visible thanks to a dike created to preserve the pond (Jepsen, 2009). However, the pond looks more stagnant than it did in 1937. This is probably because the millpond is fed by a natural spring, and only the dike connects the river to the pond (Jepsen, 2009). The spillway has also increased over time with the removal of the dam in 2001. A neck cutoff appears to have formed downstream of the STH 33 and railroad bridge.

5.2 HEC-RAS Model

5.2.1 Presettlement

In order to mimic presettlement conditions, bridges and other structures were omitted from one of the hydraulic models. This included roads and the railroad bed that were built up above the floodplain causing some cross-sections to have elevated ground that constricted floodplain storage. Channel length between cross-sections 3 and 4, and cross-sections 9 and 11 were lengthened to reflect natural meanders prior to modern channelization (Figure 2). Several simulations were run and adjustments to Manning's roughness coefficient and the longitudinal profile were made to best simulate presettlement conditions. HEC-RAS was performed under steady flow conditions using normal depth with slope upstream and downstream slopes between 0.0002 and 0.0005, as well as known water surface elevation. The normal depth model and the known water surface elevation model varied little from each other. It is important to note that the fixed modern discharge was routed through the presettlement model.

5.2.1.1 Manning's Roughness Coefficient

The first simulation included a channel Manning's roughness coefficient of 0.035. This is based on the vegetation described in the area by the PLS prior to settlement. The vegetation on the banks probably had little influence on stream channel velocity, so estimates were based on channel and floodplain roughness values shown in photographs published by Barnes (1967). These photos imply overbank roughness coefficients were between 0.08 and

0.15. Several scenarios that altered both the channel roughness coefficient and roughness coefficients on floodplains were run to see if these variables had an effect on flow.

5.2.1.2 Longitudinal Profile Adjustment

Altering the channel roughness coefficient did not significantly alter the water surface elevation for any flow regime, velocity, or Froude number. However, after looking at the longitudinal profile, the elevation at cross-section 7 in La Valle was unnaturally too high. This particular cross section is located near the old milldam, which was removed and later rocks were filled there to preserve the downstream spillway (Jepsen, 2009). Since the simulation still reflected the modern profile, the elevation of cross-section 6 was lowered by nine feet to adjust for the raised bed. After review of the adjusted profile, cross-section 7 was raised by two feet in order to help smooth out the presettlement longitudinal profile. This was done to make the presettlement profile look naturally smoother and account for potential scouring that may have occurred downstream from historical dam influences.

Comparison of the longitudinal profiles with and without the modification to cross-sections 6 and 7 show that upstream water surface levels differ by approximately two feet at lower flow regimes, and water surface changed little at higher flow regimes (Figures 8 and 9). Downstream water surface levels stay fairly consistent between the two scenarios starting at cross-section 7. Upstream cross-sections show that low flow regimes were much more affected by the lowering of cross-section 6 reducing water surface elevation by eight feet. Before the correction, cross-section 6 was acting as a dam, allowing water to backup upstream causing the surface elevation to be higher than it would be under natural conditions.

5.2.1.3 Channel Velocity and Froude Number

After adjustment to cross-section 6, velocities throughout the whole profile increase. Again, since cross-section 6 causes water to back up without the adjustment, channel velocities are slow at high flows, around 1.2-1.4 feet per second for cross-sections 4 and 5, and as water flows through cross-section 6, channel velocity increases to almost 13 feet per second for the 500-year flow as it moves through the constriction and down slope. With the modification of cross-section 6 and 7, velocity at cross-section 6 drops to 3.7 feet per second for the 500-year flood and velocities at all flows smooth out across the entire profile, generally ranging between 2-5 feet per second.

The Froude number at cross-section 6 before adjustment reached critical depth for the one-year flow, exceeded 1.0 for the two-year flow, and was subcritical, but approaching critical depth for the remaining flow regimes. After the adjustment, Froude numbers throughout the profile increase and stays fairly consistent between 0.14 -0.33, never reaching values near critical depth (see Appendix-B).

5.2.2 Modern

Several simulations adjusting Manning's roughness coefficients and ineffective flow areas throughout the profile were run to see how the modern model reacted to these changes. Steady flow was calculated using normal depth with slopes between 0.0002 and 0.0005 as well as using a known water surface elevation. To compare the models of the modern environment with various roughness and ineffective flow, focus was placed on water surface elevation, velocity, and Froude numbers.

5.2.2.1 Manning's Roughness Coefficient

Initially, the modern simulation had a Manning's roughness coefficient of 0.05 in the channel, and floodplain roughness coefficients were estimated using the 2008 National Agriculture Imagery Program (NAIP) aerial photo to determine vegetation type. The roughness coefficient of 0.05 for the channel was chosen based on field observations and on illustrations in Barnes (1967). Several simulations varying channel roughness (0.035, 0.04, 0.045, and 0.06), and varying changes in ineffective flow at certain cross-sections were modeled to test the robustness of the model.

The HEC-RAS model from John Vosberg of the Land Conservation Department in Baraboo, WI, modeled flooding on the Baraboo River from Lake Redstone to Reedsburg, which is a reach located downstream of La Valle. His model used channel roughness coefficients of 0.05 to 0.065 to account for the numerous tree dams causing high roughness throughout the reach. Although there are several tree dams located throughout the La Valle reach, the numbers were not near the extent and magnitude that John Vosberg described in his fieldwork. Understanding coefficients used in other reaches help to explain and justify the channel coefficient of 0.05 chosen for the La Valle reach.

5.2.2.2 Water Surface Elevation

According to local resident Carol Czarnecki, the June 2008 flood flooded her home with water two feet deep and deposited sand on her property (personal communication, October 11, 2009). Based on her location near cross-section 12, the 2008 flood reached an elevation of 887 feet. The June 2008 flood is estimated to be a 500-year flood, so only simulations where the 500-year flood reached a height of 887 feet at cross-section 12 were considered reasonable.

The 100-year water surface elevation from simulations that met the 500-year flood height of 887 feet were then compared with the 100-year water surface elevations from The Federal Emergency Management Agency (FEMA) Flood Insurance Rate Map (FIRM) effective December 2009. Selection of heights using the FEMA map was based on proximity to surveyed cross-sections. Most 100-year water surface elevations at cross-sections in the simulations were fairly consistent with the 100-year elevation determined by FEMA. This step did not determine whether the modern simulations were considered acceptable to use, instead this step was a check to see if simulations were comparable to other models of the area.

5.2.2.3 Channel Velocity

Next, channel velocity at each cross-section was compared among the simulations to see how much the velocities varied from each other. Channel velocities at the cross-sections varied only slightly when ineffective flows were added. Ineffective flows areas are used to indicate downstream ponding where water velocity is close to zero (Brunner, 2001). Increasing channel roughness only seemed to decrease velocity of high flows near bridges. For example, when the channel roughness coefficient is set to 0.06, the velocities for the 100 and 500-year floods are two feet per second lower before entering the Highway 58 bridge than for a channel roughness coefficient of 0.05. Low flow velocities seem to be unaffected by changes in roughness coefficients. Decreasing the roughness coefficient to 0.045

increases the velocity in the channel, but causes the water surface elevations of the 500-year flood to dip below that of the 100-year flood, which should not occur in this reach based on observations from the June 2008 500-year flood heights.

5.2.2.4 Froude Number

A reason for the low Froude numbers might be due to the raised bed at cross-section 6, which is located near the old dam site. It causes water to backup upstream reducing the channel velocity, and causes hydraulic jump following the Highway 58 bridge. The Froude number is related to velocity, depth, and gravitational acceleration in the cross-section according to $F= V/\sqrt{(gd)}$ where V is velocity, g is acceleration due to gravity, and d is hydraulic depth. The Froude numbers in all simulations have fairly low values and only approach critical depth near STH 58 bridge (see Appendix-B). Different flows reach critical depth depending on the simulation. Generally, the one and two-year floods reach critical depth at cross-section 6 in all simulations, while larger flows have Froude numbers just below one. This suggests that the larger flows are more affected by the higher roughness coefficients on the floodplain.

Froude numbers at other cross-sections show very small numbers (see Appendix-B). To verify whether the Froude numbers calculated in the simulations are reasonable, Froude numbers for the 100-year and 500-year floods were calculated based on arbitrary velocities of 3-4 feet per second. Velocities were chosen to reflect a reasonable speed at which water would flow at these higher flows. All Froude number values tend to be fairly low for all simulations and flow regimes (see Appendix-C). Since the slope of the La Valle reach is so gentle, and flow velocities are relatively small upstream of bridges, the Froude number outputs on the La Valle reach look acceptable. Similar Froude numbers using HEC-RAS models of the La Valle reach and the Reedsburg reach of the Baraboo River were generated using results courtesy of John Vosberg from the Land Conservation Department, and from Greene (2010).

5.2.2.5 HEC-RAS Slough Calculations

Since HEC-RAS calculates flood heights from cross-section to cross-section, it can be difficult to include all aspects of the floodplain. For the case of the modern steady flow model, there is a slough located between cross-sections 3 and 4 that was not taken into account during the analysis. Hemlock Slough is roughly twelve acres with a maximum depth of twelve feet (Ball et al., 1971). As mentioned earlier, Hemlock Slough is connected to the Baraboo River floodplain via an outlet passing under the old Chicago and Northwestern railroad (400 State Trail) (Figure 2). According to Ball et al. (1971), a portion of the Hemlock Slough is a relic oxbow lake and was confirmed by the aerial photograph analysis.

Today, Hemlock Slough provides a recreational area for picnic goers, canoers, and fishermen, and provides wildlife habitat for fish and fowl. Although the slough may have originally been used for flood relief, it now appears to have little affect on flood events. Using LIDAR, the elevation of the normal low stage water height of the slough is 893.5 feet. This is well above the elevation of the one-year flood of 889.45 feet. A weir was constructed to help maintain habitat and recreation to the area. The maximum depth of the slough is twelve feet, so if the weir were to fail at maximum capacity, approximately 144 acre-feet of water would be released into the Baraboo River. This would increase volume between cross-sections 3 and 4 by sixteen percent for the two-year flood. However, it is unlikely the elevation of the water surface of the slough would be at maximum capacity during a two-year flood event. The slough is normally four feet deep, so by volume, 48 acre-feet could flow into the Baraboo River if the weir structure were to fail. During a 100-year event with the slough at maximum capacity, the volume of water would increase by three percent, or a 1.08 inch rise in flood water. For the immediate area, the draining of the slough could cause a surge in water velocity and power, scouring channels and increasing sediment transport. However, when considering the entire river reach, or even the entire watershed, Hemlock Slough will not significantly alter flow on the Baraboo River.

5.2.3 HEC-RAS Summary

The final presettlement model has a channel roughness coefficient of 0.035, floodplain roughness coefficients between 0.08 and 0.15, and adjustments to the longitudinal profile were made to reflect a more natural channel. After considering all the factors that might affect the modern model, the simulation that best reflects the La Valle reach is the simulation using a channel roughness coefficient of 0.05 without including additional ineffective flow areas.

5.3 Changes in Cross-Section Characteristics

The height and the horizontal extent of water surface elevation for presettlement and modern were compared. Water surface elevation heights for modern floods were higher than heights for the presettlement model at all cross-sections with one exception where the modern 500-year flood water surface height is lower than the presettlement height. This anomaly can be explained by the 500-year flow experiencing supercritical flow as it passes between the abutments of the railroad bridge increasing its velocity and decreasing flow depth (Figures 10 and 11). The modern flows at cross-section 11 are experiencing ineffective flow, which reduces the efficiency of water to pass through. The left overbank floodplain is blocked by the old railroad grade. This structure acts as a levee and forces the modern flow to be more confined. The presettlement floods have no restriction preventing the river from overtopping its bank and flowing onto the floodplain. This cross-section is located near a bluff, which reduces the right overbank floodplain for both models.

Upstream, roads that are built up above the floodplain floor to prevent flooding onto the road also act as levees preventing flow from spreading out onto the natural floodplain (Figures 12 and 13). Cross-section 1 has a horizontal floodplain approximately 2000 feet wide allowing for water to expand and deposit sediment onto the floodplain. However, with the road in the way, the modern floods can no longer spread out, so flood elevations rise and velocity and sediment transport increases.

In contrast, cross-section 2 is confined by a narrow valley about 600 ft across. Figures 14 and 15 show that both models are confined within the bluffs, and as a result the channel is straight in this section. Also flood elevations and horizontal extent of flooding are fairly similar in both models, so the lateral connectivity is not affected. Low flows for both models experience the same floodplain constriction and thus water surface elevations should be similar, but since modern heights are higher than presettlement, it appears that upstream modern flow is affected by longitudinal connectivity. The left bank shows historical sedimentation acting as a small levee on the floodplain. Since the presettlement model shows the historical sedimentation, it is likely that the left levee was several feet lower than the modern model allowing overbank flow for the lower flow floods. The boundary of the left floodplain ends short of a steep bluff covered with trees for both models. Cross-section 5 is somewhat confined by bluffs, but not confined by man-made structures (Figures 16 and 17). While presettlement low flows stay within the main channel, modern flows spill out onto the floodplain. The modern 25-year flood level is seven feet higher than the presettlement 25-year flood. Downstream of cross-section 5, modern flows encounter bridge constriction, and an elevated bed. The grade control structure causes water to pool and backup upstream, which explains the increase in flood height of the low flows. The presettlement flows might be slightly higher than true conditions due to historical sedimentation, and the presettlement recurrence intervals were probably smaller in magnitude than the modern recurrence intervals.

To get a better understanding of how flow through each cross-section impacts other cross-sections, figures 18 and 19 show a three-dimensional plot of the 2-year bankfull flood throughout the study reach. The presettlement model shows that upstream water barely overtops the banks when compared to the modern model. Because of the modern grade structure, the flow upstream is backed up and the velocity of the 2-year flood decreases. Despite the two bridges downstream of the grade structure, the flow does not seem to be affected by them, and water spreads onto the floodplain similar to the presettlement model.

The three-dimensional plots for the 100-year flood shows that the modern flood is constricted overall and unable to spread out onto the floodplain compared to presettlement (Figures 20 and 21). Although the modern constriction looks subtle on the plots, changes in water surface elevations reflect the constriction (as seen with cross-section 5). Cross-sections with higher water surface elevations tend to be cross-sections that are constricted or cutoff from the floodplain. Despite the freedom the presettlement flow has to spread onto the floodplain, the presettlement model shows constriction at cross-section 6. Since this is near the old dam site, the channel cross section is probably too channelized to reflect true presettlement conditions. This also suggests that in addition to cross-section 6, most cross-sections are probably too channelized to reflect a true presettlement channel.

5.3.1 Changes in Cross-Section Characteristics Summary

The presettlement floodplain roughness is much higher than the modern floodplain due to the change in vegetation. The shift from tamarack swamps to agriculture and reed canary grass along the banks has made the modern model hydraulically smoother. Channel banks have increased in height over time due to historical sedimentation. The presettlement channel depth was probably shallower than the modern model, but the cross-sections do not reflect this change since the presettlement cross-sections are based on the modern cross-sections. The modern floodplain has lost some of its lateral connectivity due to channel incision, and change in hydraulic roughness.

5.4 Hydraulic Characteristics

5.4.1 Channel Shear Stress and Hydraulic Radius

Channel shear stresses at the ends of the study reach are relatively low compared to the middle of the reach due to the HEC-RAS program's way of calculating energy loss through several iterations (Figures 22, 23, and 24). If more cross sections were available upstream, shear stress might increase at the end cross-sections. Upstream of the dam site, shear stress values are much higher in the presettlement model, while the modern model stress almost decreases to zero just before the graded structure near the former dam site. As soon as modern flow passes through STH 58 bridge, shear stress increases to five to seven pounds per square foot. After the dam site, shear stress for both models are between 0.1 and 0.4 pounds per square foot until flow encounters STH 33 bridge at which point modern shear stress increases while presettlement flow is not affected.

Shear stress is based on the equation $\tau_0=\gamma RS$ where γ is the specific weight of water and sediment, R is hydraulic radius and S is slope (Knighton, 1998). The slope of the La Valle reach varies between 0.0002 and 0.0005, which is very gentle and may contribute to the low values. Overall the shear stress is most likely dominated by the hydraulic radius, but also influenced by slope at some cross-sections. Hydraulic radius is the cross-sectional area divided by the wetted perimeter. As the hydraulic radius increases, the channel is considered to be more efficient (Charlton, 2008). The modern profile shows that there is a slight decrease in hydraulic radius immediately downstream of the former dam site (Figures 25 and 26). As channel velocity decreases coming out of the grade structure and confinement from the bridge, sediment will start to settle out and aggrade the bed. Cross-section 7 may also have sand accumulated from the June 2008 flood. This might decrease the overall depth of the cross-section, which in turn decreases the shear stress.

Removing components of the grade structure at cross-section 6 made some adjustment to the presettlement model shear stress, but the hydraulic radius at cross-section 7 unnaturally decreases in depth in comparison to the depths at surrounding cross-sections. The 400 State Trail currently acts as a levee for the modern profile allowing an increase in hydraulic radius, whereas the presettlement model is allowed to spill onto its floodplain decreasing the hydraulic radius. Since the presettlement model is based on modification of modern conditions, it is very hard to reproduce presettlement conditions without introducing other errors. Presettlement downstream cross-sections appear to be influenced by modern structures more than upstream cross-sections. Despite removing evidence of bridges and levees, a precise understanding of what the channel bed looked liked before settlement remains unknown. Channel depths were probably overall shallower due to less scouring from agricultural related erosion and runoff, and baseflow was probably greater.

Between cross-sections 7 and 8, the LIDAR data show several meander scars, which might suggest that this portion of the reach is sensitive to change. This change could be adjustment from straightening the river upstream of the dam site to build the railroad, adjustment from the construction, use, and removal of the dam, but it may also have adjusted from increased runoff due to agricultural practices since the 1850s. The Little Baraboo River joins the Baraboo River just upstream of cross-section 9. The added discharge to the Baraboo River could increase scouring of the channel bed, which would explain the increase in hydraulic radius at cross-section 9.

Presettlement hydraulic radius increases downstream. Since cross-sections were minimally altered, artifacts of modern land use are still present in the modeled presettlement channel, including scouring from bridges. If the amount of scouring from the bridges were known, adjustments to the presettlement model could be made to more realistically reflect past conditions. Hydraulic radius for the modern 500-year flood is relatively small, while the shear stress increases to 10.23 pounds per square foot because flow under the railroad bridge became supercritical. A momentum equation was used in the HEC-RAS model to calculate the Class B low flow through the railroad bridge because the water surface profile passed through critical depth in the bridge constriction and the normal low flow equation did not accurately depict what is actually happening to the flow (Brunner, 2001).

5.4.2 Channel Velocity

Channel velocity for the presettlement model varies between 0.96 – 6.41 feet per second for all flow regimes (Figures 27 and 28). In contrast, the modern model varies between 0.73 feet per second for the two-year flood just before flowing under the STH 58 bridge to 8.15 feet per second passing under the old railroad bridge. While the presettlement velocity stays fairly consistent throughout the reach, the modern velocities are highly variable.

On average presettlement velocities upstream are much higher compared to modern velocities. The grade control structure near the former dam site is itself acting as a dam, causing water to backup upstream and decreasing channel velocity. The modern 500-year flood slows to 1.08 feet per second before the grade control structure and then velocity increases to 13.4 feet per second under the bridge. Velocity for the two-year flood also increases to 8.15 feet per second going under the STH 58 bridge. After the bridge, modern velocities slowly start to climb as flow moves through the reach, and become slightly slower than presettlement velocities downstream.

5.4.3 Channel Power

Channel Power is the rate of doing work, or the rate of potential energy expenditure per unit length (Knighton, 1998). Stream power usually decreases downstream relative to the amount of water and sediment supplied (Lecce, 1997; Walling, 1983). Excluding cross-sections 1, 2, 11, and 12, presettlement stream power has a decreasing trend (Figures 29, 30, and 31). Cross-sections 1, 11, and 12 do not meet the trend because they reflect the iteration process HEC-RAS uses to calculate energy loss starting at one end of the reach. The power at cross-section 2 reflects channel confinement and is smaller than it might be otherwise. Power is generally less than four pounds per foot-second. Despite the increase in discharge downstream, power decreases around cross-section 10. This is likely due to a decrease in slope as a result of increased channel sinuosity after flow comes out of bedrock confinement near cross-section 9.

Modern stream power upstream gets no larger than two pounds per foot-second, and power relative to each flow regime is much lower than presettlement power. For example, the 500-year presettlement flood reaches 4.06 pounds per foot-second, while modern power at the same cross-section reaches 1.69 pounds per foot-second for the 500-year flood. Stream power for the one-year flood remains almost zero upstream and then increases to 10.65

pounds per foot-second through the STH 58 bridge. Downstream, the one-year flood stream power increases slightly from upstream values. All other flows also lose stream power just before the STH 58 bridge, and then due to the sudden change in slope elevation, power increases to 95.34 pounds per foot-second for the 500-year flood. The 500-year flood reaches its maximum power just after the railroad bridge causing power to spike to 166 pounds per foot-second. Aside from the 500-year flood, downstream modern values for stream power are similar to presettlement values.

5.5 Longitudinal Profile Comparisons

Since the presettlement longitudinal profile is derived from the modern profile, direct conclusions cannot be made about the differences in the profile elevation data. However, it is clear that the absences of bridges or dam structures in the presettlement model allows for a more continuous flow and a gradual decrease in water surface elevation through the profile (Figures 9, 33, 34, 35, and 36). One would expect a concave longitudinal profile for the presettlement model, and although this model shows a concave profile with areas of aggradation and scouring, no significance should be attached.

The modern profile shows a clear disconnect in longitudinal profile throughout the reach. Water surface slope upstream is reduced due to the grade control structure and water elevation suddenly drops as flow moves through the graded area.

5.6 Estimating Sediment Transport

Using Costa's (1983) diagram relating shear stress in Newtons per square meter to grain size in millimeters, estimates were made of the potential transported grain size for the 2, 10, 100 and 500-year flows (see Appendix-G). Table 3 shows two potential grain sizes for the presettlement and modern models converted from millimeters into feet. Grain sizes were calculated based on average shear stress for each flow, and the maximum shear stress reached for each flow to estimate grain size.

The presettlement average shear stress at low flows can transport sediment between 0.00197 ft and 0.00578 ft whereas modern low flows can transport sediment between 0.00332 and 0.00983 ft. The presettlement 100-year flood can transport sizes 0.00269 and 0.00629 ft on average whereas the modern 100-year flood can transport 0.00540 to 0.01265 ft on average. The modern 500-year flood appears capable of transporting grain size between 0.01157 to 0.02712 ft on average compared to 0.00284 to 0.00666 ft on average for the presettlement grain size.

Using maximum shear stress to calculate grain size for each flood event shows evidence of increasing channel capability to transport larger grain sizes. Presettlement maximum grain size at low flows vary from 0.00267 to 0.01005 ft. Maximum grain size for modern low flows vary between 0.02237 and 0.06172 ft. The modern maximum transportable grain size increases dramatically when using the maximum shear stress values to estimate grain size. The 500-year maximum grain size for presettlement is 0.01224 compared to 0.08989 ft. This difference in transport capability will change how the flood flows though the river system. The flows in this reach are capable of transporting medium sized sand grains at low flows to large pebbles in the largest flood event.

Table 3. Estimated Grain size using Costa (1983).

Estimated Sediment Transport
Baraboo River, La Valle, Wisconsin

Presettlement	Upper end values		Lower end values (better estimate of true grain size)	
Recurrence Int.	Maximum (ft)	Average (ft)	Maximum (ft)	Average (ft)
2	0.00626	0.00461	0.00267	0.00197
10	0.01005	0.00578	0.00429	0.00246
100	0.01201	0.00629	0.00512	0.00269
500	0.01224	0.00666	0.00522	0.00284

Modern	Upper end values		Lower end values (better estimate of true grain size)	
Recurrence Int.	Maximum (ft)	Average ft)	Maximum (ft)	Average (ft)
2	0.05244	0.00777	0.02237	0.00332
10	0.06172	0.00983	0.02633	0.00419
100	0.07763	0.01265	0.03312	0.00540
500	0.08989	0.02712	0.03835	0.01157

The disruption of the channel and floodplain connectivity is evident in the modern simulation. The large increase in grain size in the high magnitude flows is reflective of human impact. The high spikes in velocities and change in shear stress reflect the flows encountering human made structures. The maximum shear stress for each flow occurs where the STH 58 bridge crosses the river. Not only is the river channel experiencing constriction, the river also encounters a drastic elevation change from the grade control structure at the La Valle dam site. These two variables lead to drastic increases in velocity downstream and a backup of water upstream, which also affects shear stress. The sharp changes in shear stress do not occur in the presettlement model, and as a result of the fairly stable shear stresses throughout the reach, the maximum shear stresses are not much greater than the average shear stresses. This means that there are not big jumps in grain size and the presettlement channel may have been able to transport medium sized sand to small granules at different flows throughout the whole reach. In contrast, the influence on the modern flows from man-made structures cause some areas in the reach to transport large pebbles while other areas may only be able to transport coarse sand.

5.7 June 2008 Flood

The June 2008 flood was estimated to have a 500-year recurrence interval. Maximum grain size that this flood transported should fall between 0.03835 ft and 0.08989 ft pebbles. The Baraboo River system mainly transports silt/clay and sand. Boulders from hillslopes and bedrock are unlikely. Energy for the 500-year flood fluctuates in maximum sediment transport capability, making it unclear how much and what type of sediment is actually transported. However, an event of this magnitude can transport all sand grain sizes. Abundant fresh sand was found at cross-section 8 downstream from the dam site on a point bar (Figure 3). Flow below bankfull would not be able to carry all sand sizes, and bankfull could potentially carry all sand sized grains, but the sand would be in channel transport and not overtop the bank. The abundant fresh sand most likely came from the sediment trapped by the grade control structure and flushed downstream by the 2008 flood. Since the bed was raised, scouring upstream has occurred and a buildup of coarse sediments is creating a sediment trap similar to a dam (Greene, 2010). The 2008 flood picked up the sediment trapped upstream of the grade control structure and was carried downstream. Some of this sand was deposited on point bars as flow went through meander bends and slowed.

Vegetation is just starting to take hold on the sand deposits, which also supports the idea that the deposits are fairly recent and are not remnants immediately deposited following dam removal in 2001.

Trees must have also played a large role in the June 2008 flood. Canoeing throughout the study reach, one has to navigate around many tree dams. Fallen trees varied in size and shape, and the tree dams varied in size from one tree submerged with a few snagged branches to several trees densely packed sticking out of the normal flow water by a couple of feet and spanning several hundred feet (Figure 32). According to Beyond Boundaries, LLC, a local business, the tree dams were not present before the flood and portaging canoes was not necessary (personal communication, September 27, 2009). After the flood, parts of the reach were impassible. Most tree dams located within the study reach were cut just enough to let a canoe or kayak pass.

These trees, whether or not they were being transported downstream or blocking river movement, affected channel flow. Banks throughout the La Valle reach are not very stable in some places with silver maple and basswood growing on the edges. When high velocity flows come through, bank erosion can occur causing the trees to topple into the water. If the tree is small enough, sufficient stream velocities can transport it downstream, otherwise the tree will fall into the channel and alter streamflow.

While canoeing through the La Valle reach, observations of scouring had occurred upstream of tree dams, and in some cases deposition of fine mucky sediment occurred downstream of a tree dam. It is unclear from modeling how much of a role these tree dams have on river channel morphology, but it is evident that some degree of deposition is happening in the field. However, the large tree dams were not taken into consideration during the modern model simulations because preliminary model runs adjusting for increased channel roughness and inundation areas were tested, and did not show significant influences on river channel hydraulics compared to simulations without increased roughness.

6.0 Discussion

This study shows that throughout the La Valle reach of the Baraboo River, the last 165 years of Euro-American settlement have affected the river's lateral connectivity by cutting off access to the natural floodplain margins thus narrowing the floodplain, and its longitudinal connectivity by disrupting streamflow through bridge constriction, straightening, and alterations to the channel bed elevation. Variables used to identify changes in the river floodplain morphology include land cover, water surface elevation, shear stress, stream power, velocity, sediment transport, and channel migration.

6.1 Direct Human Impacts on the Floodplain

The major influences driving change of river and floodplain morphology include channel modification such as stream engineering via channelization, dam construction and removal; infrastructure such as roads, railroads, and communities driving the infrastructure; and restoration efforts. The following section describes changes to the river and floodplain that have a direct effect on the river system.

6.1.1 Channelization

Channelization is a term to describe alterations to a river, which include flood control, drainage improvement, navigation, and erosion control (Gregory, 2006; Knighton, 1998). The La Valle reach has experienced several forms of channelization as described in Knighton (1998). The most visually prominent channelization in the La Valle reach is cutting off of the natural meanders. This results in an increase in slope, and flow velocity of the channel. Increase in slope can increase the erosion potential (Winkley, 1982). This study could not determine whether degradation and incision occurred at surveyed cross-sections because of the limitation in reconstructing presettlement channel morphology. However, deepening and widening of the channel may have occurred over time allowing less water to overtop the banks as seen from cross-section 6 in Figure 21. Historical sedimentation on the banks as seen with cross-section 11 also can lead to deepening of the channel, but again limitations of reconstruction presettlement conditions include the historical sedimentation since it is unknown exactly how much overbank sedimentation has occurred at each cross-section.

Another type of channelization includes the removal of instream obstructions, which converts heterogeneous channel systems to homogeneous systems. Removing tree dams from the channel causes the channel geomorphic structure to lose complexity with natural changes in flow and decreases habitat availability (Abbe and Montgomery, 1996). It is also possible that removing obstructions could induce instability upstream and downstream (Brierley and Fryirs, 2005). A change in vegetation along the bank and increase in runoff from agricultural practices have contributed to the increased roughness in the channel, but a decrease in roughness on the floodplain. Removal of these structures within the channel in this study seems to have little impact on the river in comparison to other forms of channelization.

6.1.2 Infrastructure

Increasing population has lead to important transformations in the township surrounding the Baraboo River. As people move into an area, the need for better transportation routes is critical. When the Chicago and Northwestern Railroad was built through the village in 1872, it not only allowed for easier access to and from the township, but also altered the river valley (The History of Sauk County, 1880). Although the railroad is no longer in use today, it has a lasting impact on the river floodplain. LIDAR data and aerial photos verified old channel meander routes that were altered by the railroad.

The area directly northwest of the village of La Valle was an area of swamp hardwoods. When people constructed the railroad line, they moved the river channel away from the railroad to prevent erosion of the railroad bed. Because the railroad was built high enough above the floodplain, it acts as a levee. Portions of the river cutoff by the railroad are now sloughs. Not only does the railroad cut off the old channel, it affects moisture-loving vegetation by blocking flood access to the floodplain as mentioned in Gergel et al. (2002a).

The railroad also crosses the river multiple times disrupting the longitudinal connectivity. Connectivity controls channel evolution and can impact floodplain ecosystem structure (Blanton and Marcus, 2009). As seen from the HEC-RAS model, bridges constrict flow and thereby affect the hydraulic geometry, shear stress, and velocity. Gergel et al. (2002b) mentions that these alterations, in turn, can have an effect on aquatic species in the river system. This constriction of flow plus the added erosion and runoff from agriculture in the area increases scouring of the channel bed and may cause the Baraboo River to have more frequent overtopping of channel banks (Greene, 2010). Gergel et al. (2002a) show that while levees built on the Wisconsin River floodplain do not affect the flooding within the levee boundaries, areas outside the levees differ drastically in terms of the floodplain vegetation mosaic.

6.1.3 Restoration

In recent decades, environmental advocacy groups have led the charge to restore floodplains and river systems towards previous levels of width, sinuosity, depth, and native vegetation well-suited to riparian zones. But restoration goals come with unintended consequences, which challenge managers. Response to channelization can mean a loss in vegetation on the banks (Hupp, 1992). The conversion from a forest swampland near the bank edges to primarily reed canary grass and silver maple may lead to more instability of the channel banks and increase in the number of tree dams within the river reach. As a result, oftentimes river managers are left with negotiating a fine balance between removal of non-native species and increasing erosion.

The biggest restoration challenge in the La Valle reach has been the La Valle dam removal. While the grade control structure was created to preserve the spillway downstream after dam removal, the grade control structure seems to have the same effect that a dam would have on velocity, power, shear stress, and water surface profile. Greene (2010) also compares the graded structure to a dam, and sediment gets trapped and water backs up just as a dam would. However, unlike a dam, fish species are now able to migrate upstream (Catalano et al. 2007).

Instead of using the restoration to define stream manipulation, rehabilitation may be more appropriate (Shields et al., 2003). Dam removal was a restoration effort to open the river and the subsequent grade control structure was created to preserve the spillway for fishing (Jepsen, 2009). Although restoration occurred locally at the spillway, the term *restoration* when applied to the river reach does not convey the processes of returning the system back to a natural state. All stream flows react upstream and downstream to the grade control structure, which interrupts the longitudinal connectivity of the river channel and floodplain. As a result, the dam removal restoration should be properly termed *rehabilitation* to avoid implying that the river has been restored to truly natural conditions.

6.2 Indirect Human Impacts on the Floodplain

Since most of the presettlement vegetation in the La Valle river reach was oak savanna and other hardwoods, the shift from forest and savanna to agriculture disrupted the channel's sediment yields. Deforestation in favor of agriculture increases fine silt and clay sediment supplied to the river. Prior to agriculture, sediment in the river was dominated by lacustrine sand deposit and eroded sandstone bedrock. The sand was probably distributed onto the floodplain more frequently than sediment is now because roads act as lateral barriers cutting off sediment supply to the floodplain.

After the dam removal, most of the fine agricultural sediment was flushed downstream (Doyle et al., 2003). The grade control structure in place of the dam also acts as a sediment trap preventing movement downstream (Greene, 2010). However, large floods, like the June 2008 flood have the power to flush trapped sand downstream. Although large floods might not have an immediate impact on the floodplain besides sediment deposits in the short term, their periodic erosion of sediment could potentially aid lateral stream migration in the future.

Over time, shear stress and power have increased in the river reach. As a result, sediment carrying capacity generally increased between presettlement times and the present day. This accelerates erosion along cut banks causing greater instability in the future and leads to widening and scouring of cross-sectional area and more deposition of larger particles downstream.

6.3 Non-human Impacts on the Floodplain

Although not discussed previously, the hydrologic regime plays an important role in shaping river morphology. Increased precipitation both in intensity and duration as a result of climate change could have a major impact on the La Valle reach. The June 2008 flood shows the destruction that a flood of its magnitude can create for communities built along the floodplain, such as La Valle. If the presettlement channel were shallower than the modern channel, the June 2008 flood would have had an easier time overtopping the presettlement banks and depositing sediment on the hydraulically rough floodplain. As a result the modern 100-year flood might have been considered a 500-year flood for the presettlement period. If increasing channelization in conjunction with changes in hydrologic regime occur, the frequency of the 500-year flood may increase in the future, and its geomorphic effectiveness in eroding the landscape, cutting and filling meanders, and overbank deposition may increase.

7.0 Conclusion

This study looks at the morphologic changes on the Baraboo River comparing presettlement conditions to modern. It is clear that Euro-American development between the 1840s and the present has had an impact on the river system, both laterally and longitudinally. There is an increasing nationwide trend of river restoration back to natural conditions. With any riverway, an ongoing debate surrounds the time period to which the managers ought to restore the river. For example, should river managers aim to restore the river back to conditions prior to dam construction, railroad construction, before Euro-American settlement, before any indigenous settlement? In the case of the Baraboo River, dam removal was the first step to restoration making it one of the longest reaches of river to be restored to free flowing status (Jepsen, 2009). Although the river is flowing freely, bridges, channelization, grade structures, and riprap are all still impacting the river.

A clear definition of restoration needs to be established for rivers and watersheds. The Baraboo River is free flowing, but it does not reflect the more sinuous system it was 165 years ago. Now that the river has more longitudinal freedom, people are taking recreational advantage by canoeing, kayaking, and fishing on the river. Ideas of restoration to these recreational goers mean clearing the river of debris to allow for free passage (Jepsen, 2009). This will make things more convenient for canoeing but does not 'restore' the river since tree dams are a natural part of river morphology. Brierley and Fryirs (2005) suggest that the river cannot go back to the exact way it was before, and Cairnes (1987) questions the purpose of restoring a river system to pre-disturbance since river systems are dynamic; when change is constant, the results of a ‘restored’ river system will be modified by natural processes since rivers will continue to meander.

The biggest challenge in river restoration will be to determine what is best for the river system and the surrounding community. To truly restore the Baraboo River to presettlement conditions, all structures and evidence of human interaction with the river would need to be removed. With no restrictions, the river can move freely within its floodplain and aggrade and incise to find its equilibrium. However, this is unfeasible and scientists are left trying to come up with a balance. Each river system is unique and will react differently to outside disturbances. More research specific to the river system is necessary to build up the knowledge to determine efforts that need to be made to put the river in quasi-equilibrium without eliminating all human disturbances.

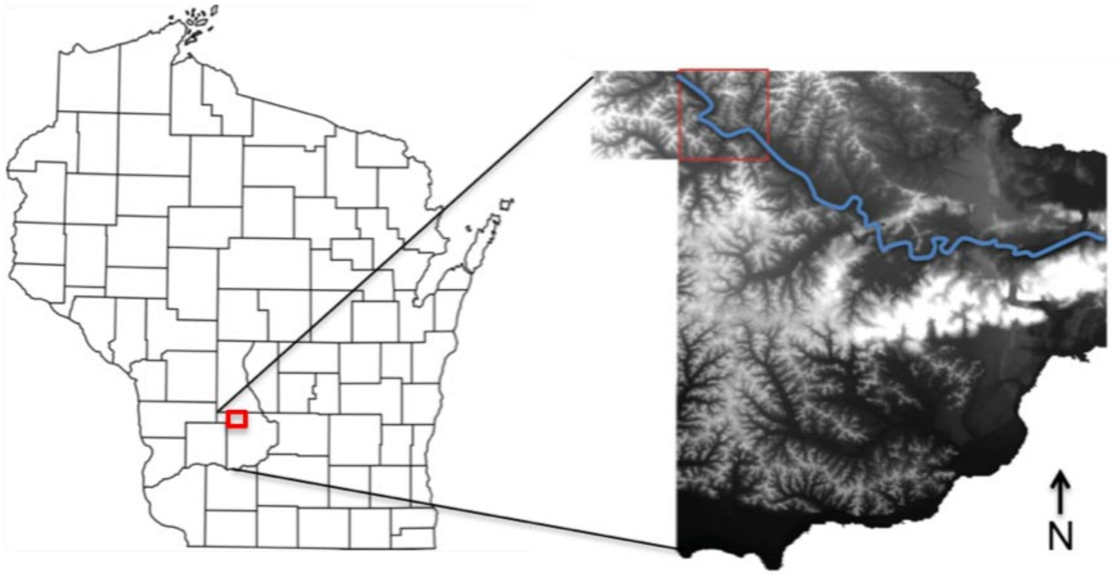

Figure 1. Map on left shows Sauk County relative to the state of Wisconsin, and within Sauk county, the diagram on right shows the Baraboo River in a simplified DEM with Baraboo River superimposed in blue and the boundaries of La Valle township in red.

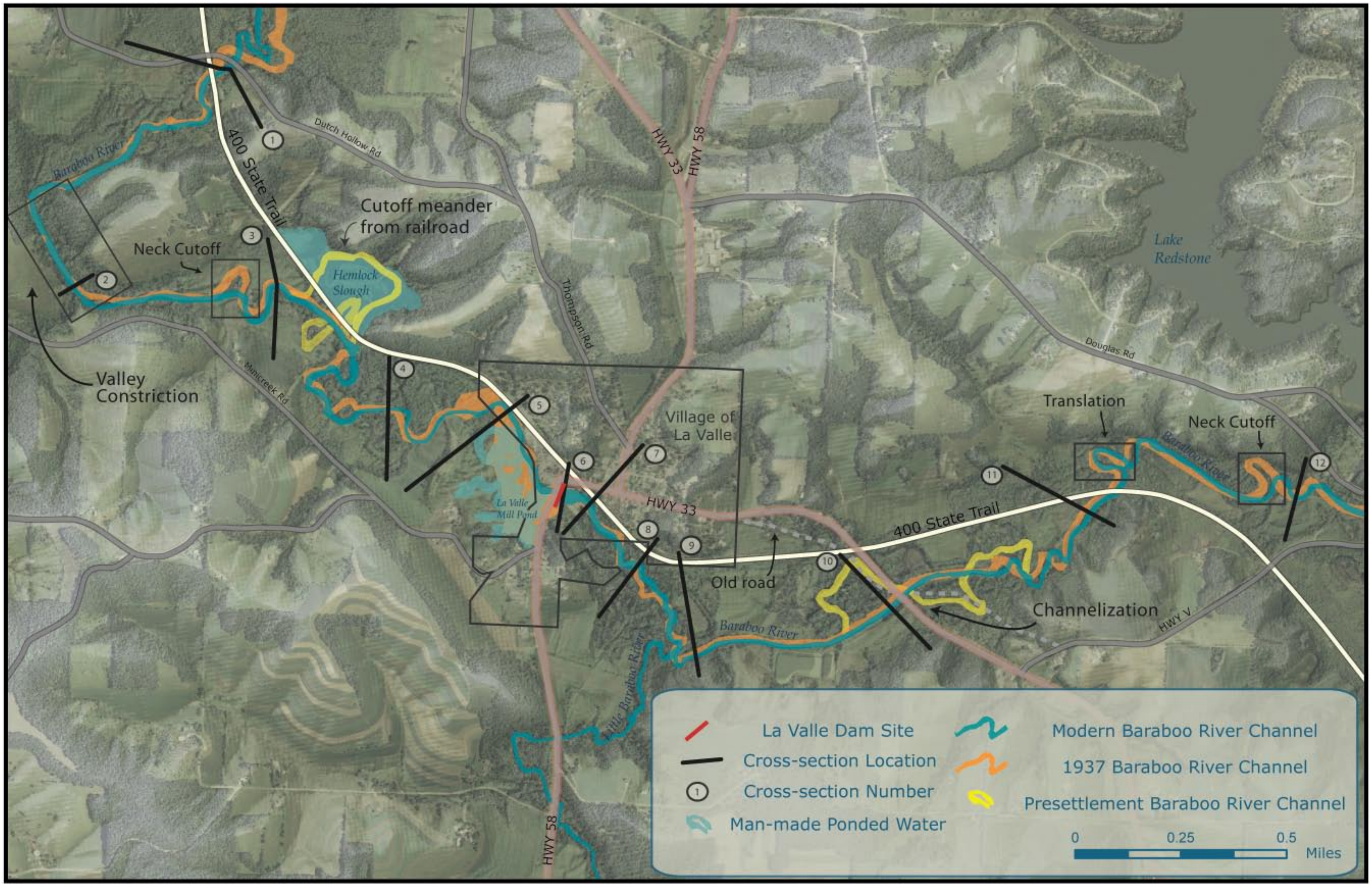

Figure 2. Detailed map of the La Valle reach.

Figure 3. The foreground shows sand deposits on the point bar, while the background shows the cut bank of a meander bend.

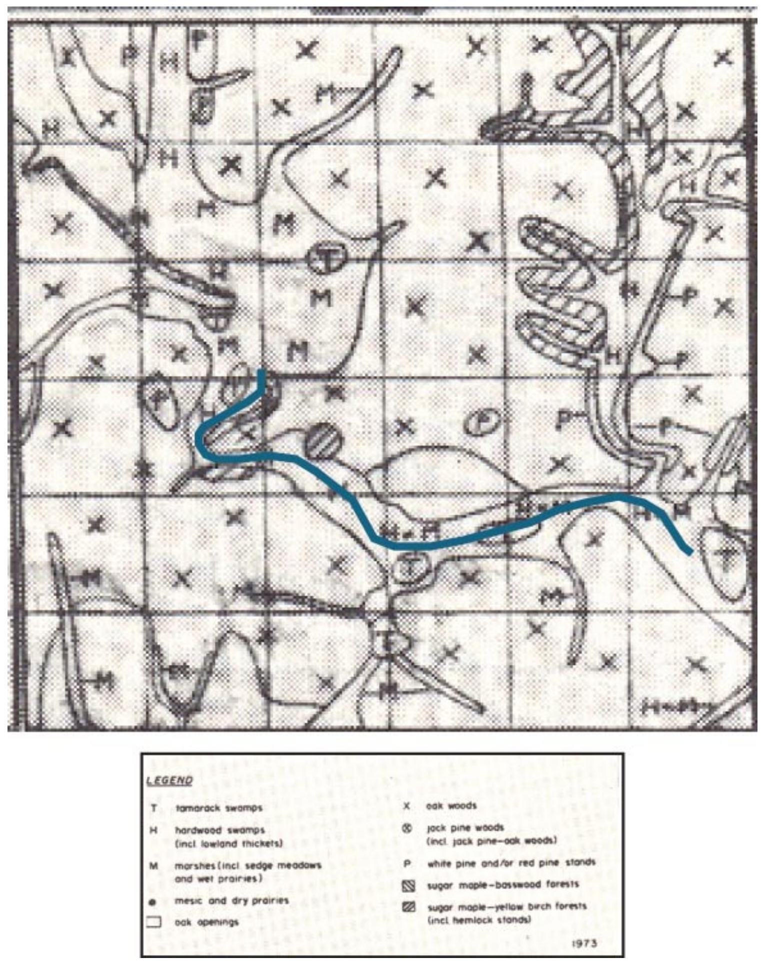

Figure 4. Presettlement vegetation of Sauk County, Wisconsin (from Lange, 1976).

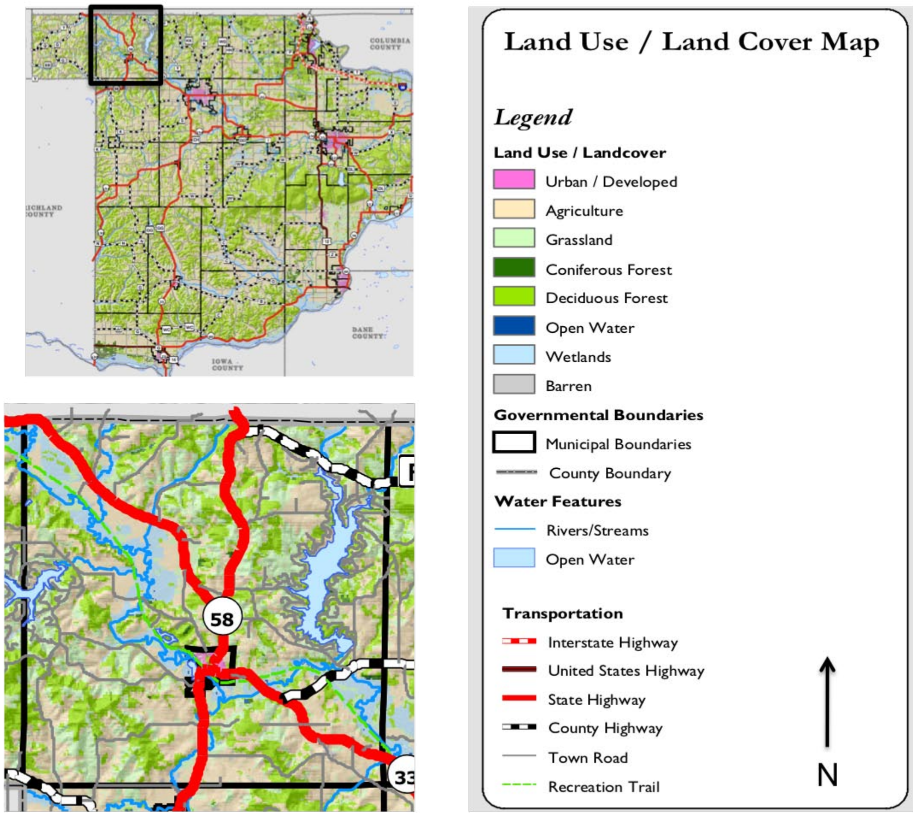

Figure 5. Current land use of La Valle, Wisconsin (taken from Sauk County Land Conservation Dept., 2007).

Figure 6. Reed canary grass lining the channel banks.

Figure 7. Cornfields growing up to channel banks.

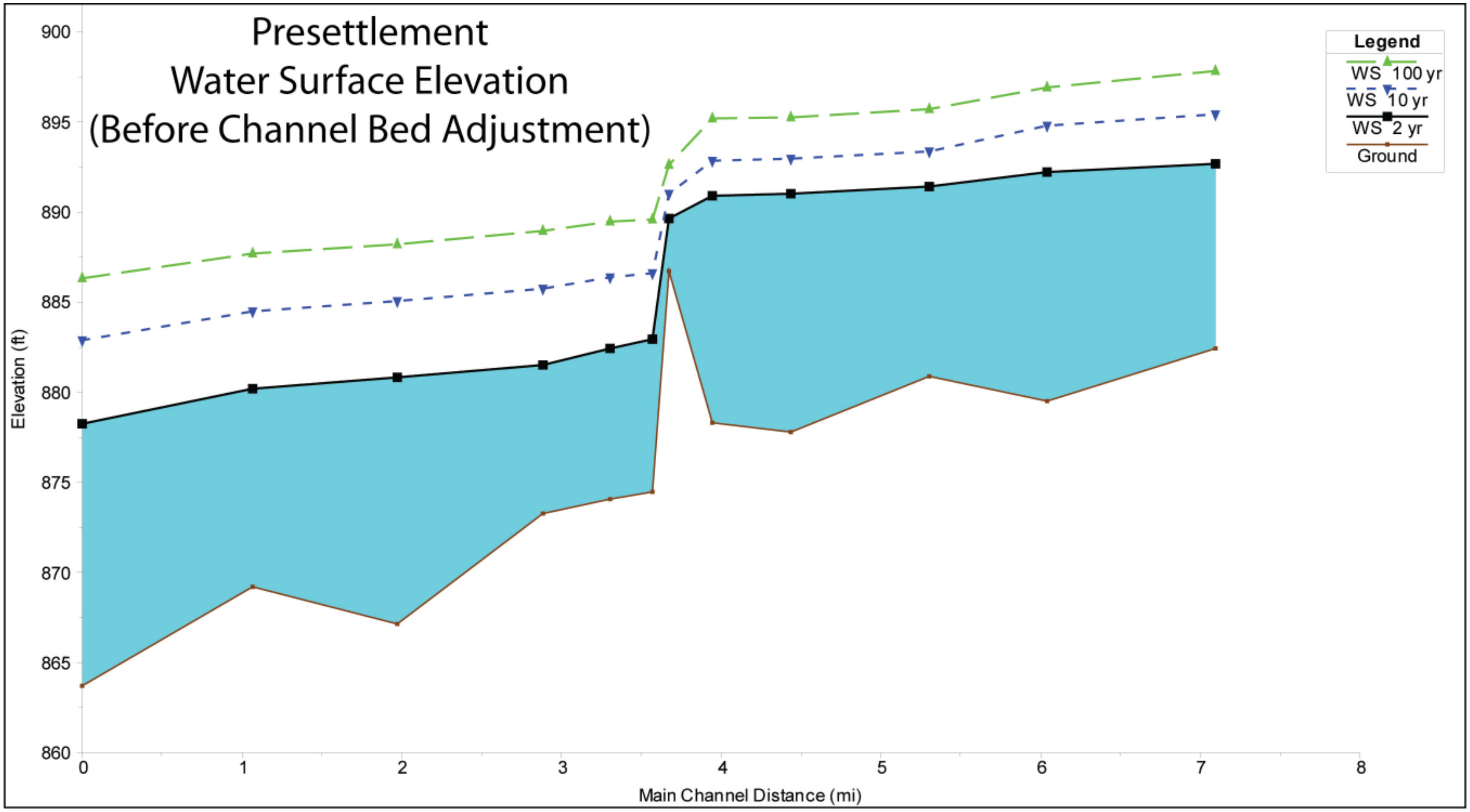

Figure 8. Presettlement longitudinal profile of water surface elevation before adjustment to channel bed at cross-sections 9 and 10.

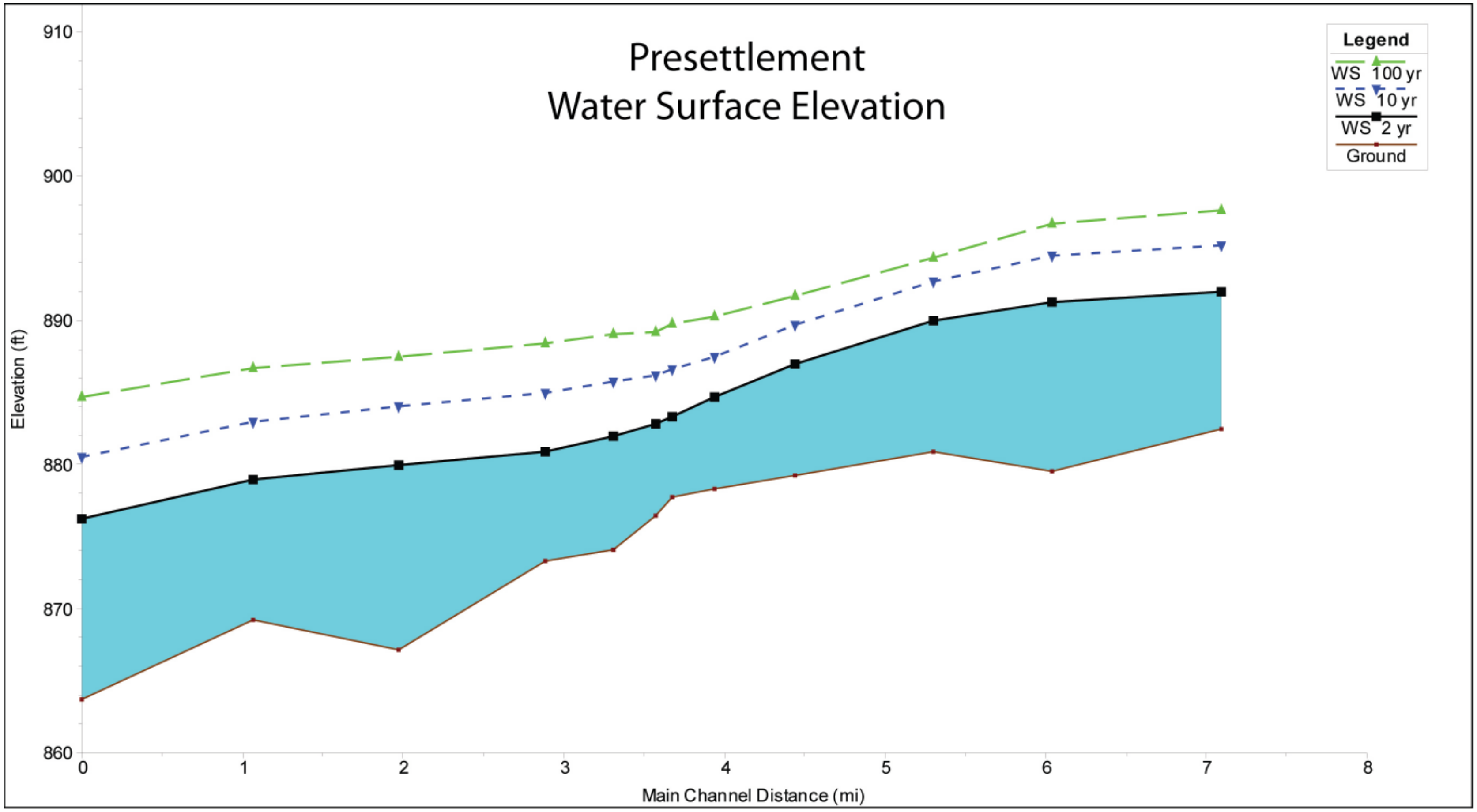

Figure 9. Presettlement longitudinal profile of water surface elevation after adjustments to cross-sections 9 and 10.

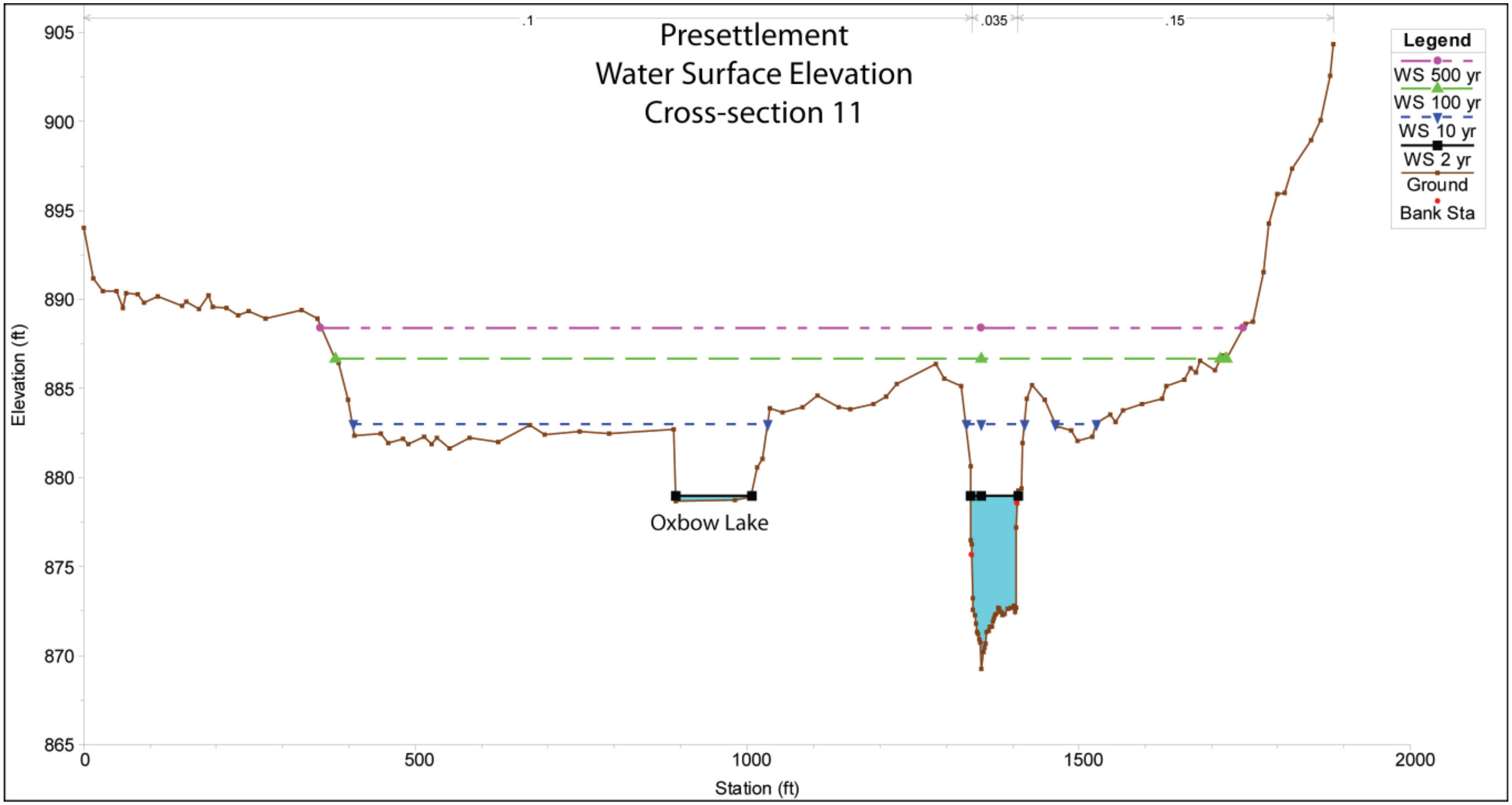

Figure 10. Presettlement water surface elevation at cross-section 11.

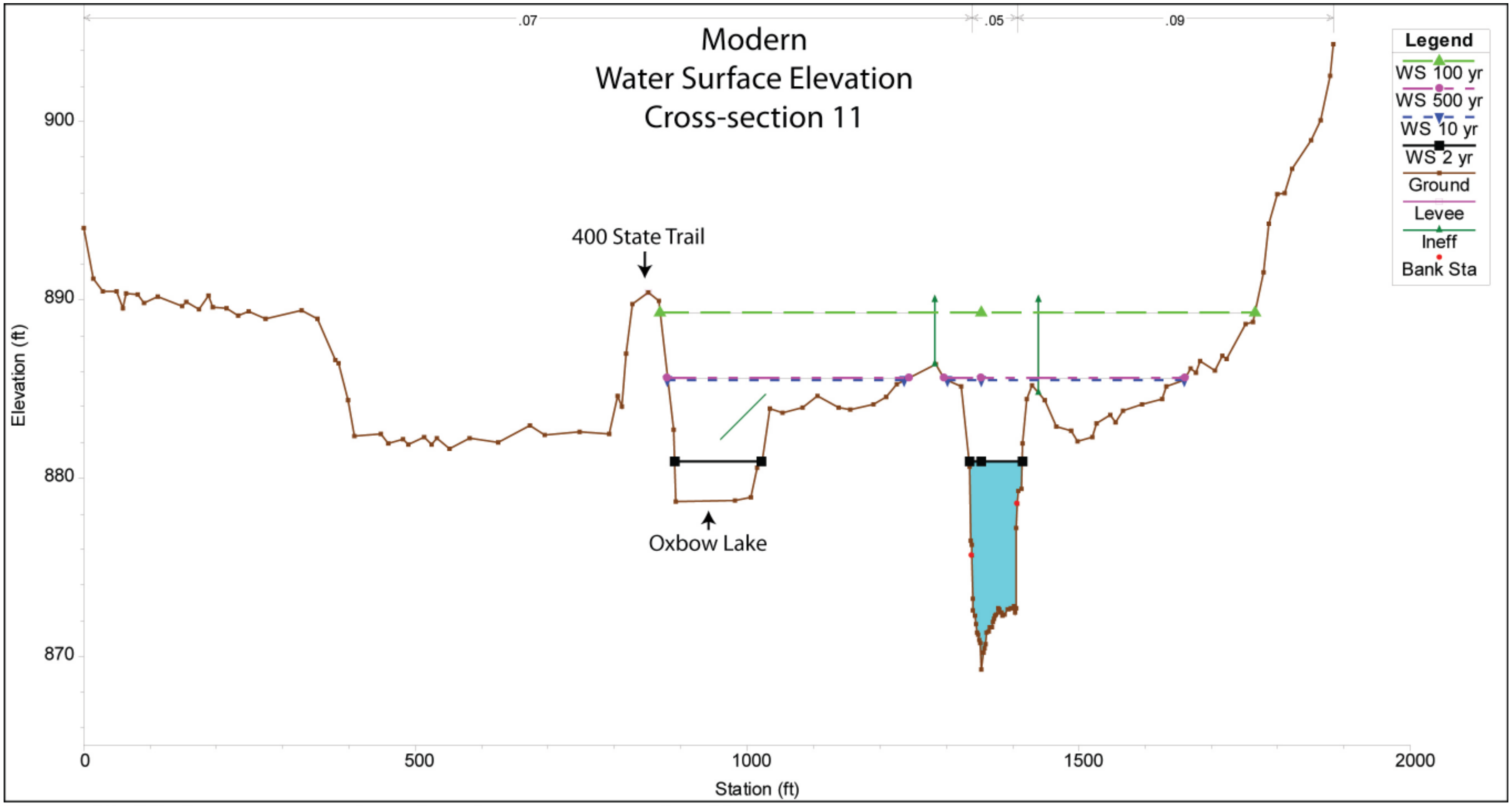

Figure 11. Modern water surface elevation at cross-section 11.

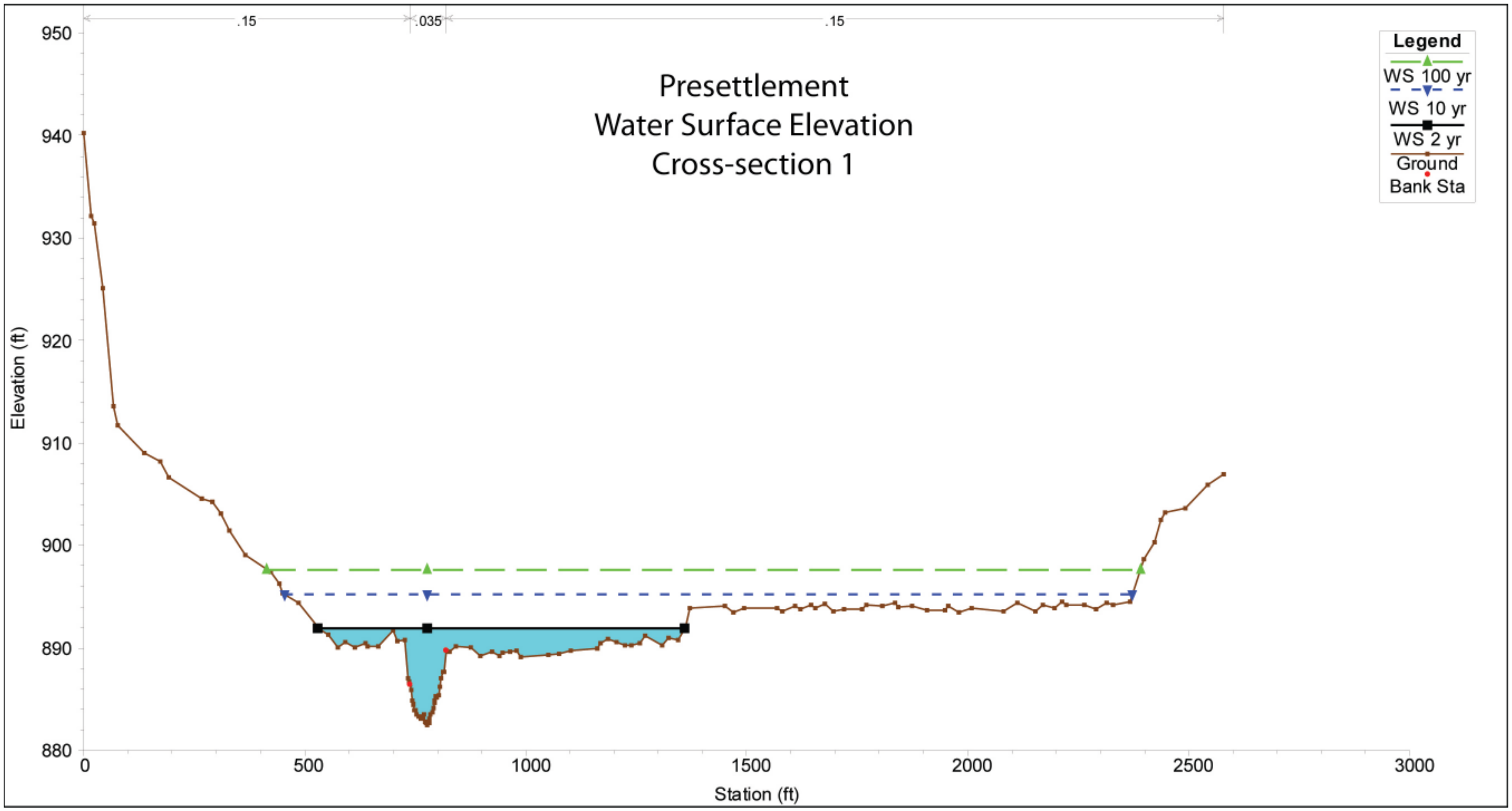

Figure 12. Presettlement water surface elevation at cross-section 1.

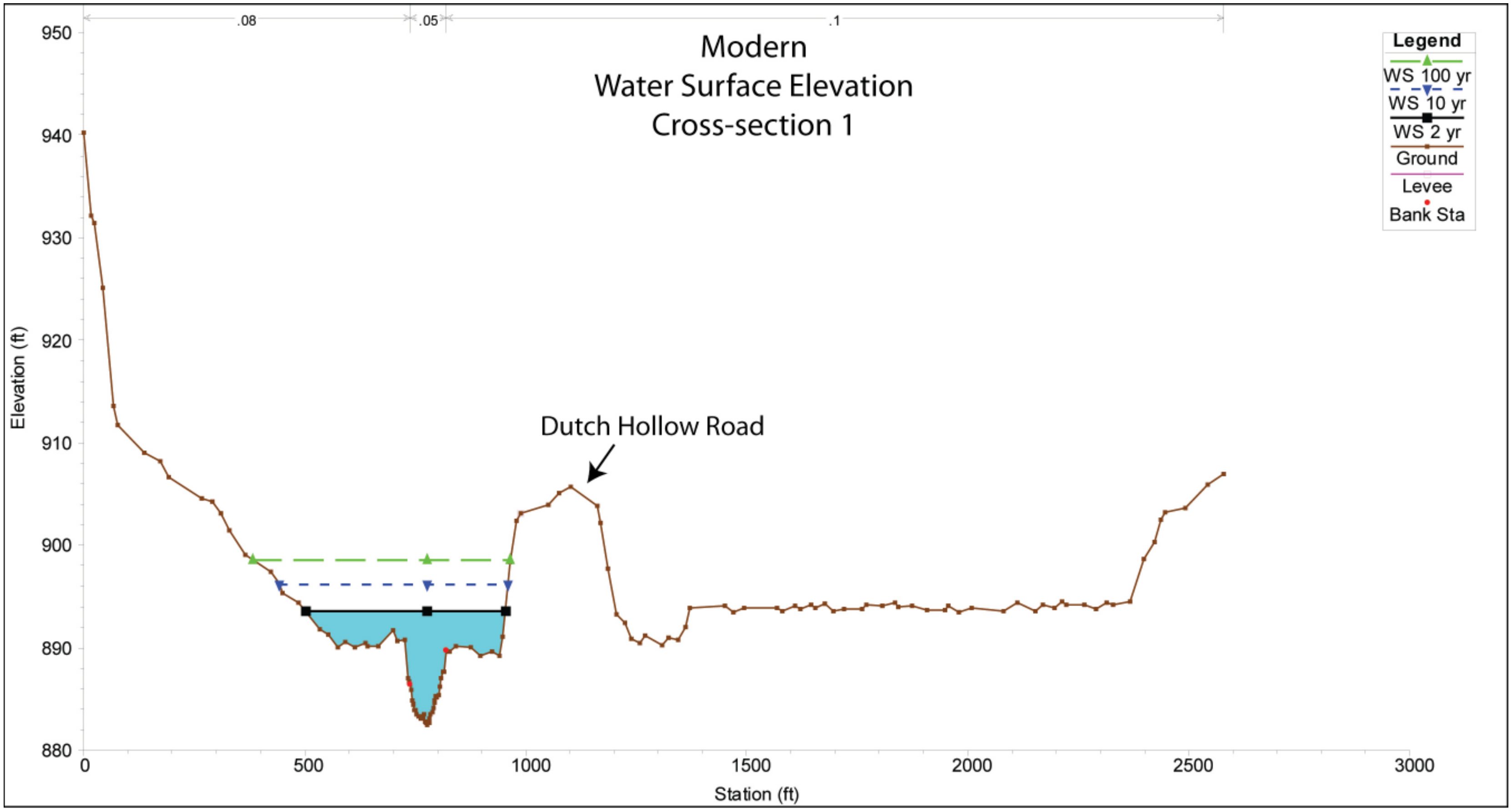

Figure 13. Modern water surface elevation at cross-section 1.

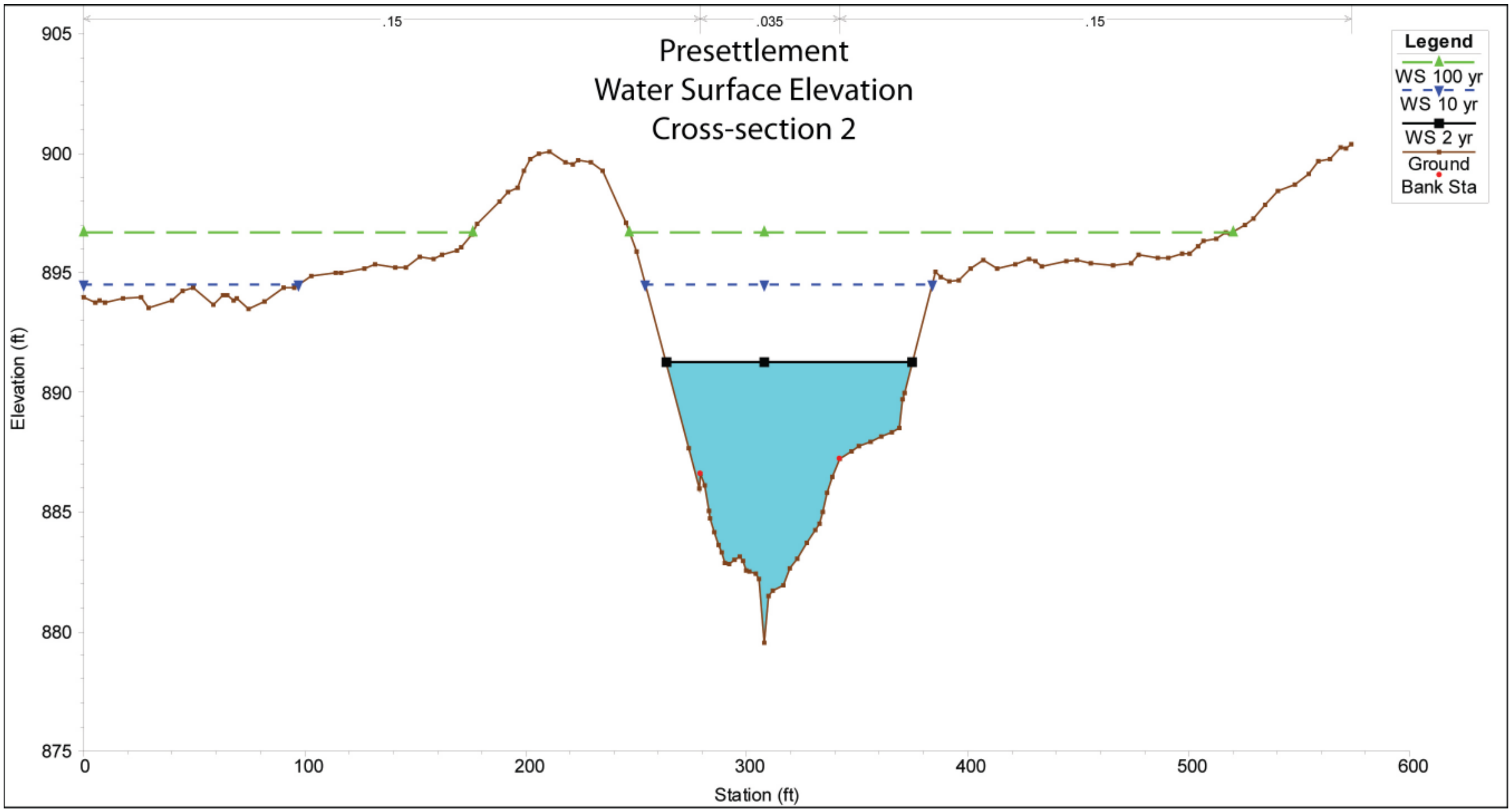

Figure 14. Presettlement water surface elevation at cross-section 2.

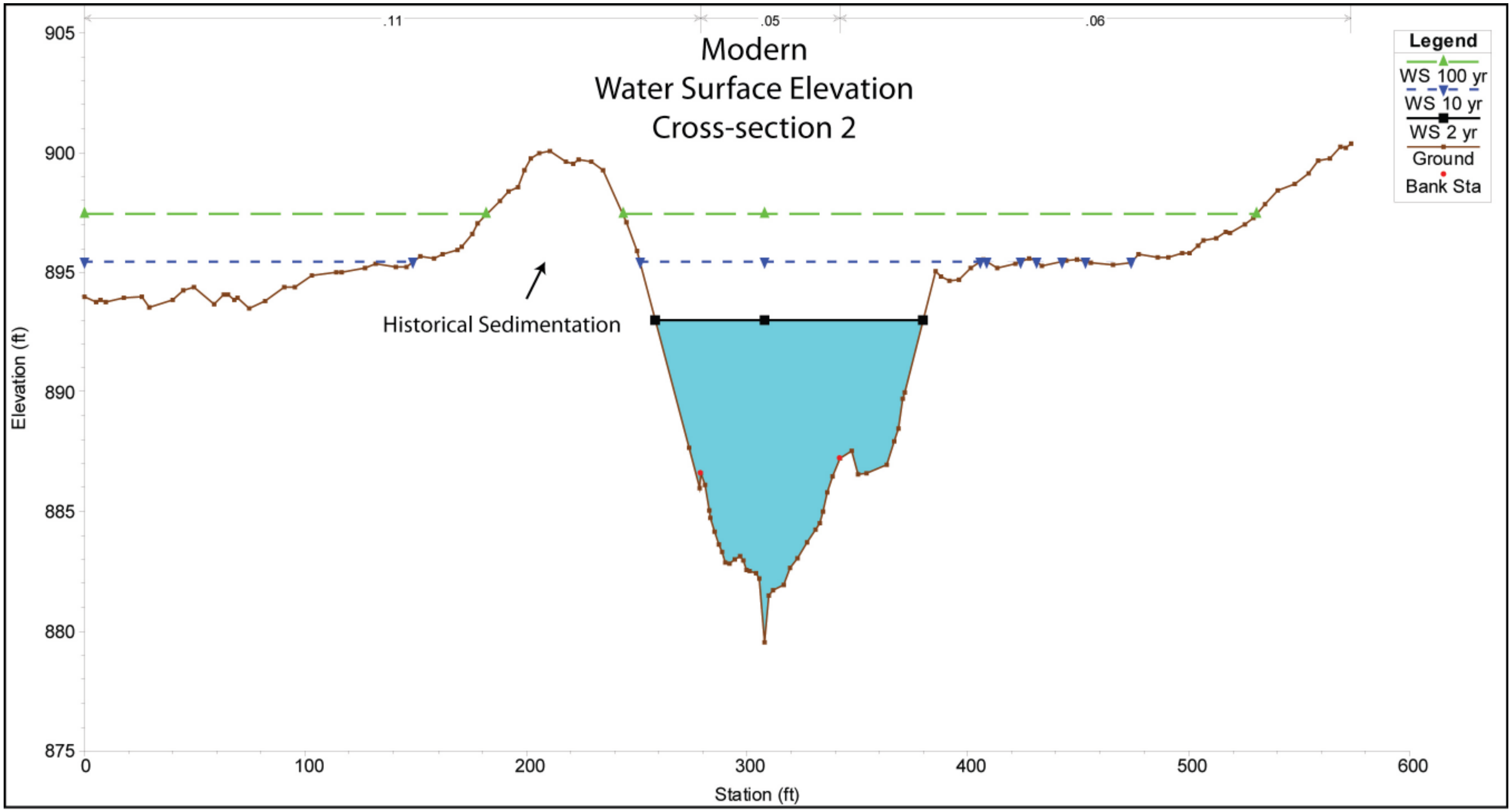

Figure 15. Modern water surface elevation at cross-section 2.

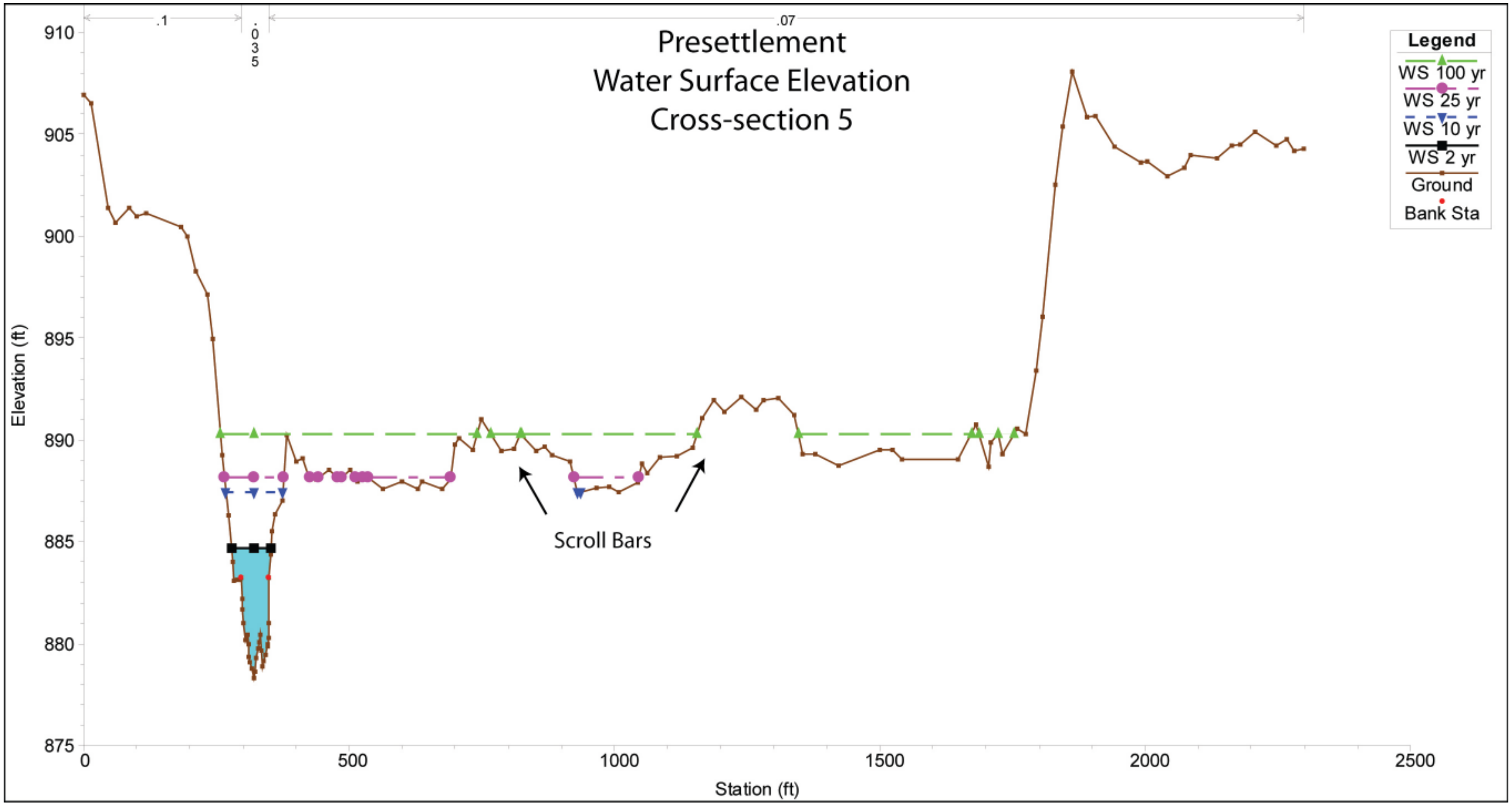

Figure 16. Presettlement water surface elevation at cross-section 5.

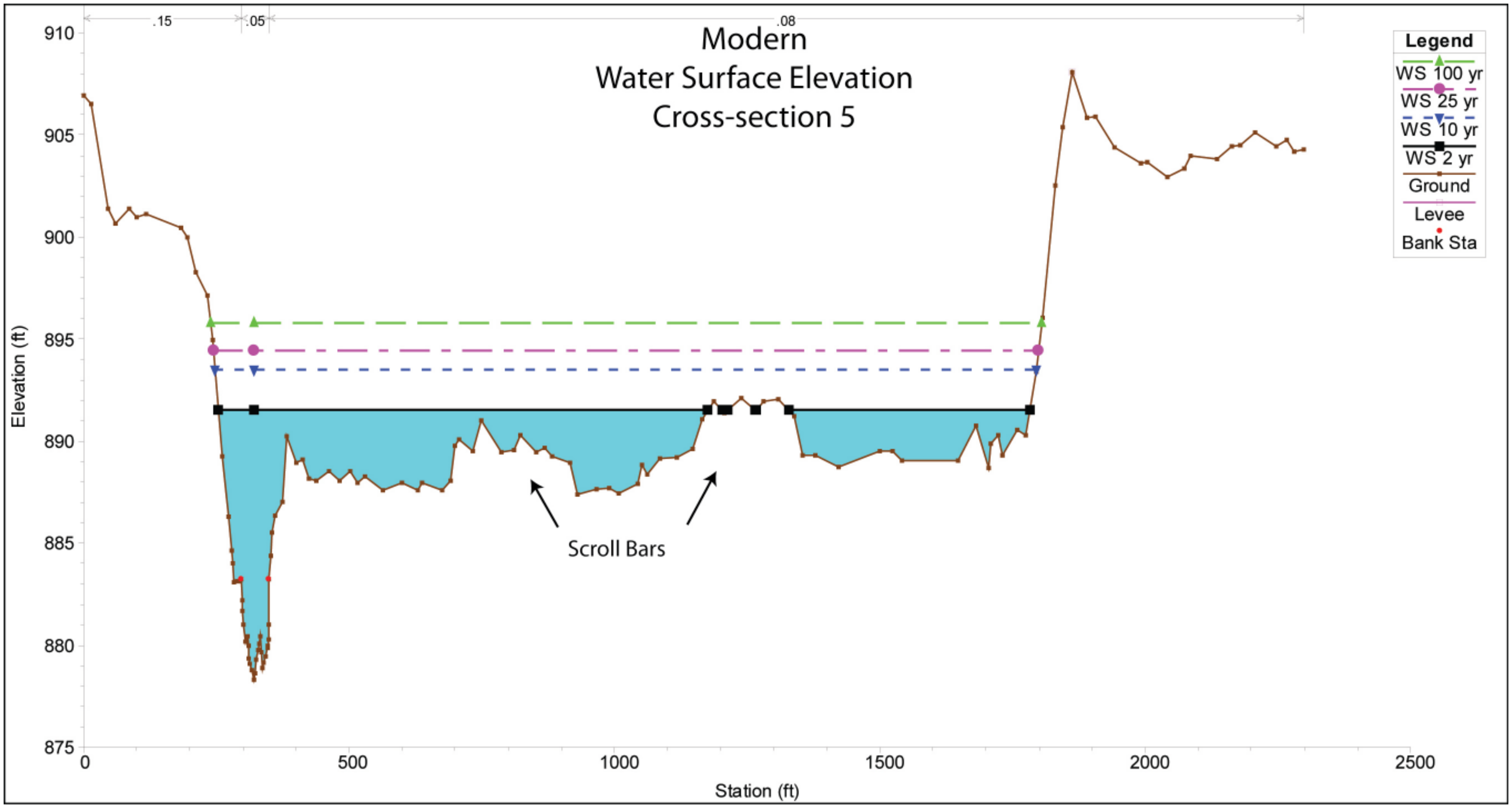

Figure 17. Modern water surface elevation at cross-section 5.

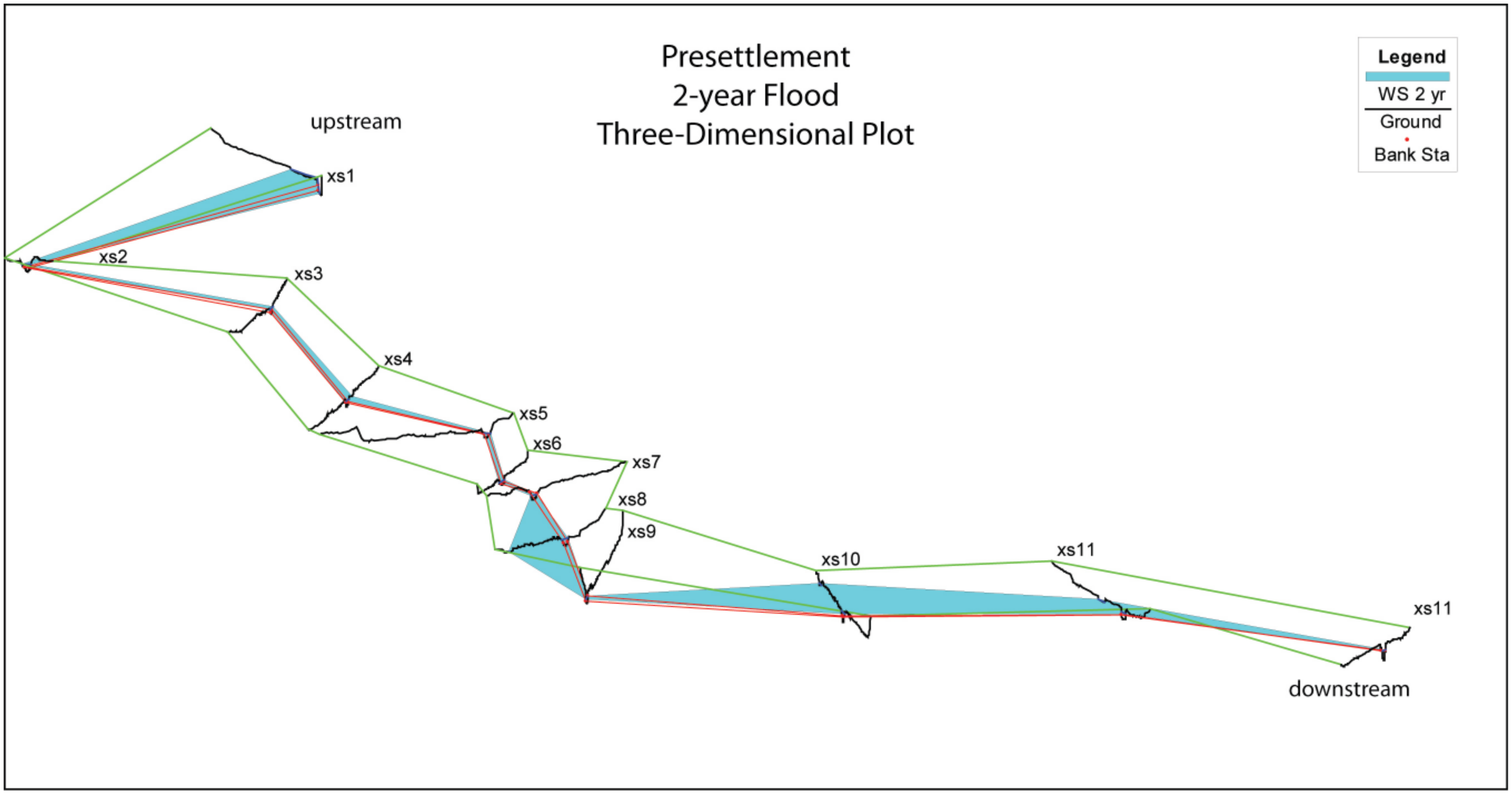

Figure 18. Presettlement three-dimensional plot of the 2-year flood.

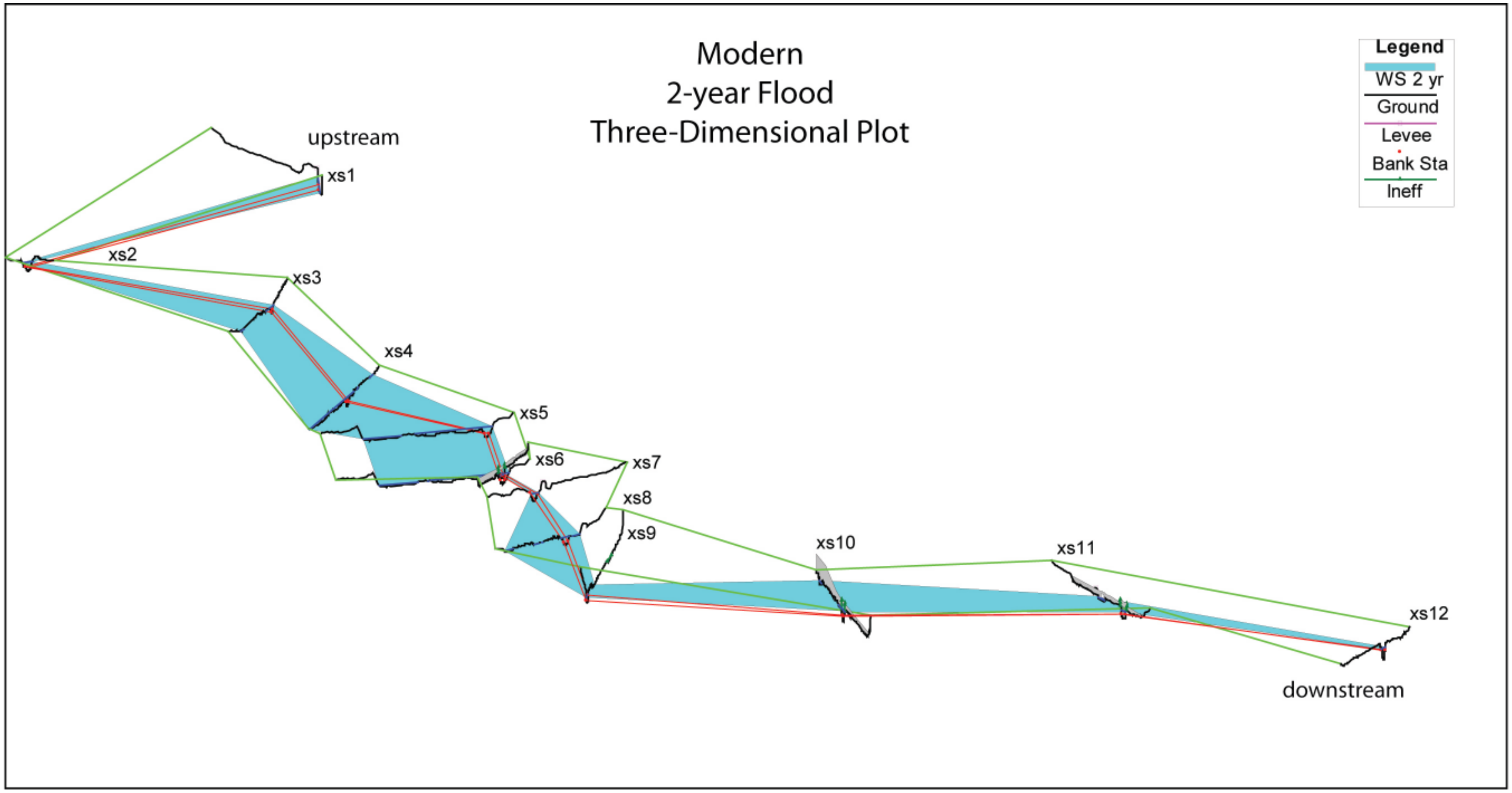

Figure 19. Modern three-dimensional plot of the 2-year flood.

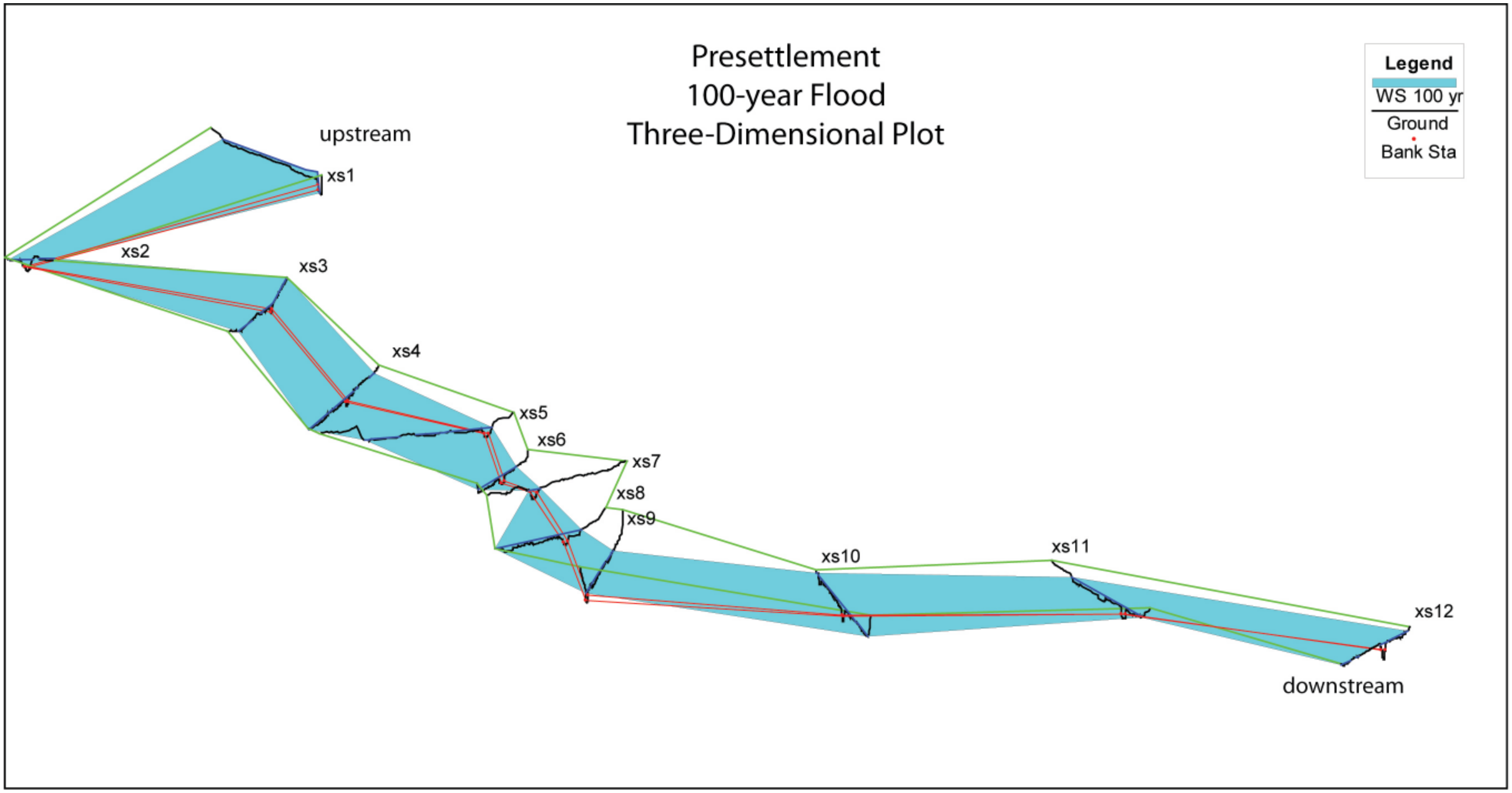

Figure 20. Presettlement three-dimensional plot of the 100-year flood.

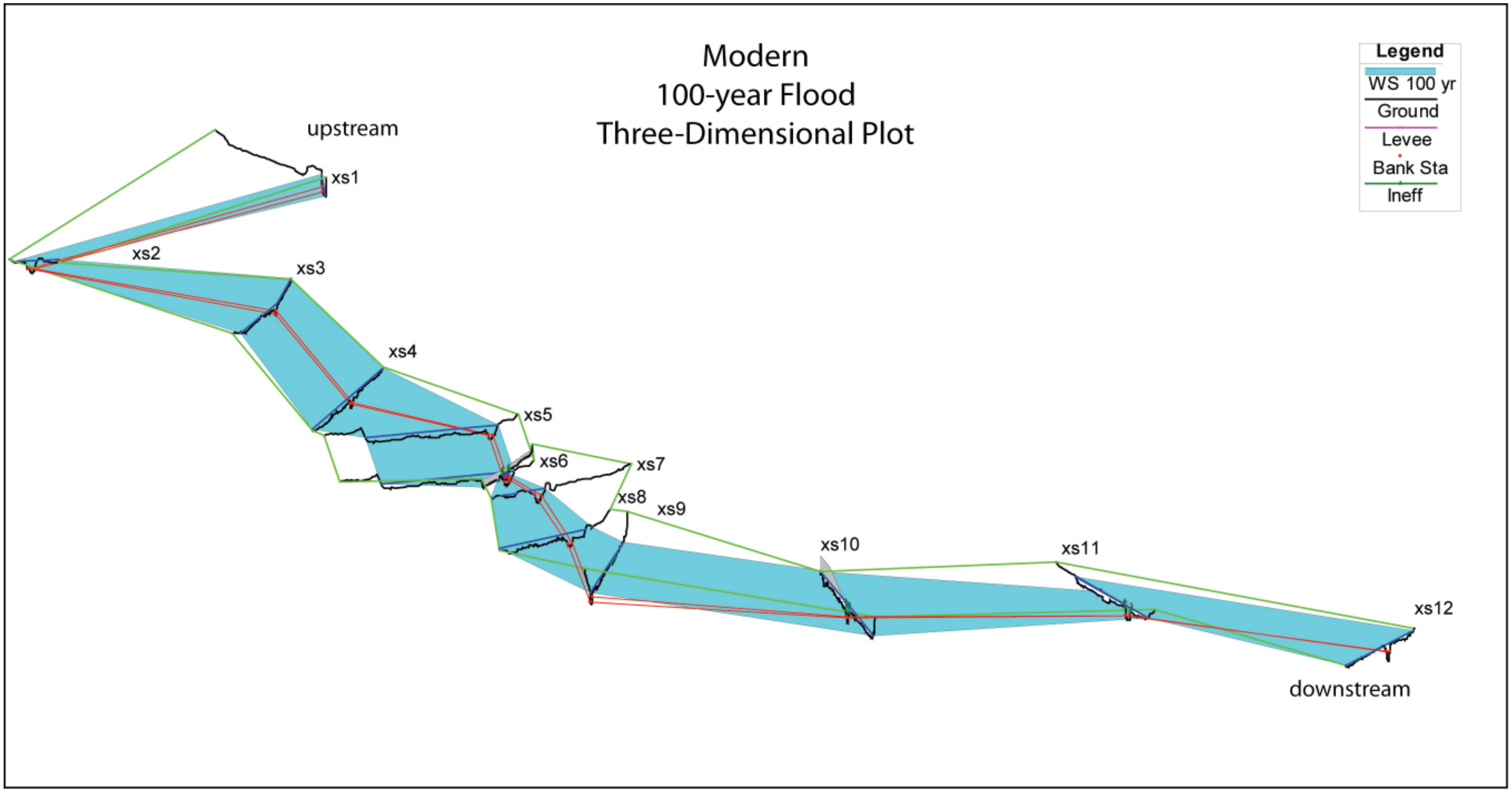

Figure 21. Modern three-dimensional plot of the 100-year flood.

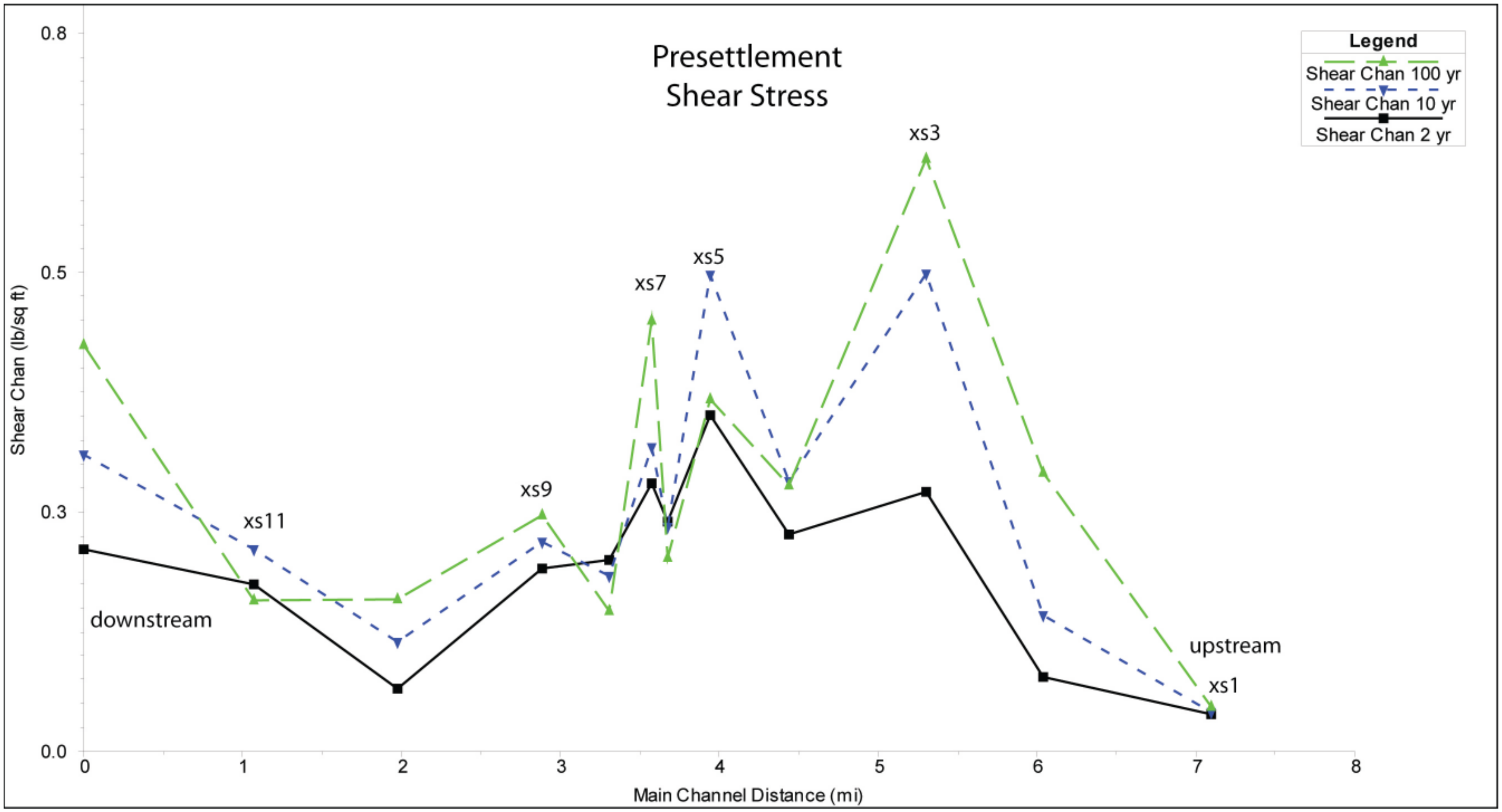

Figure 22. Presettlement Channel Shear Stress.

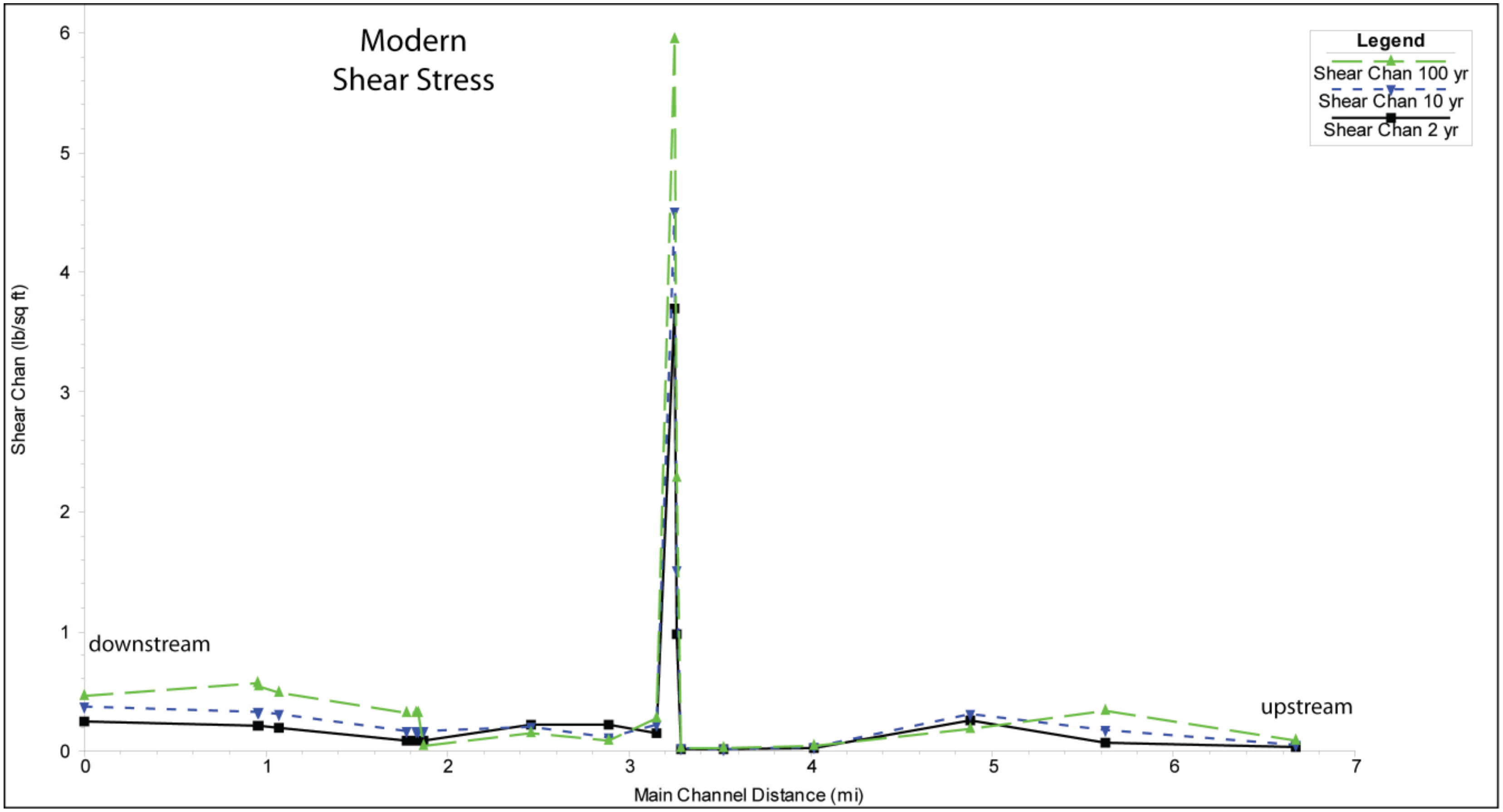

Figure 23. Modern Channel Shear Stress.

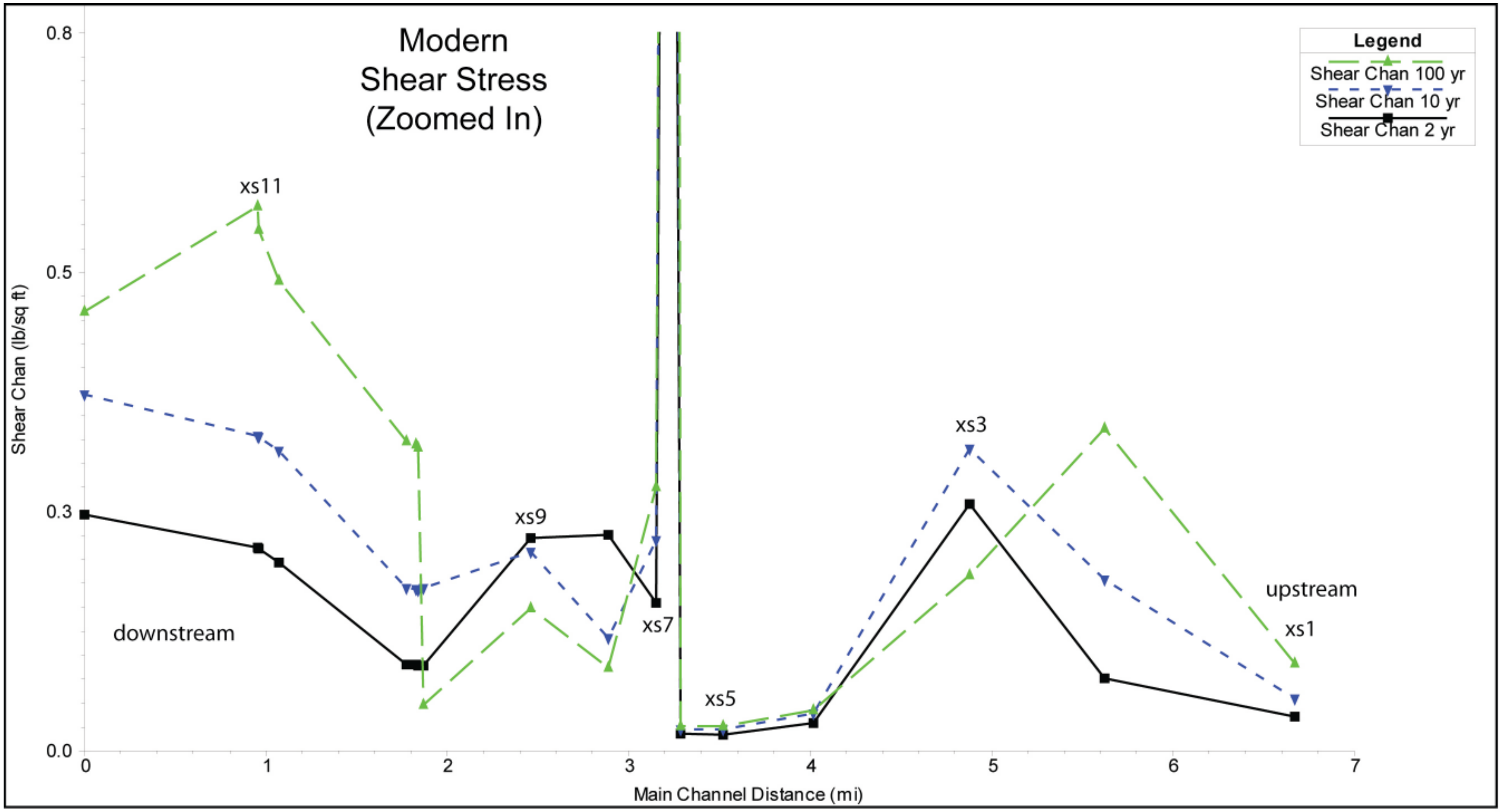

Figure 24. Modern Channel Shear Stress zoomed in to show lower values.

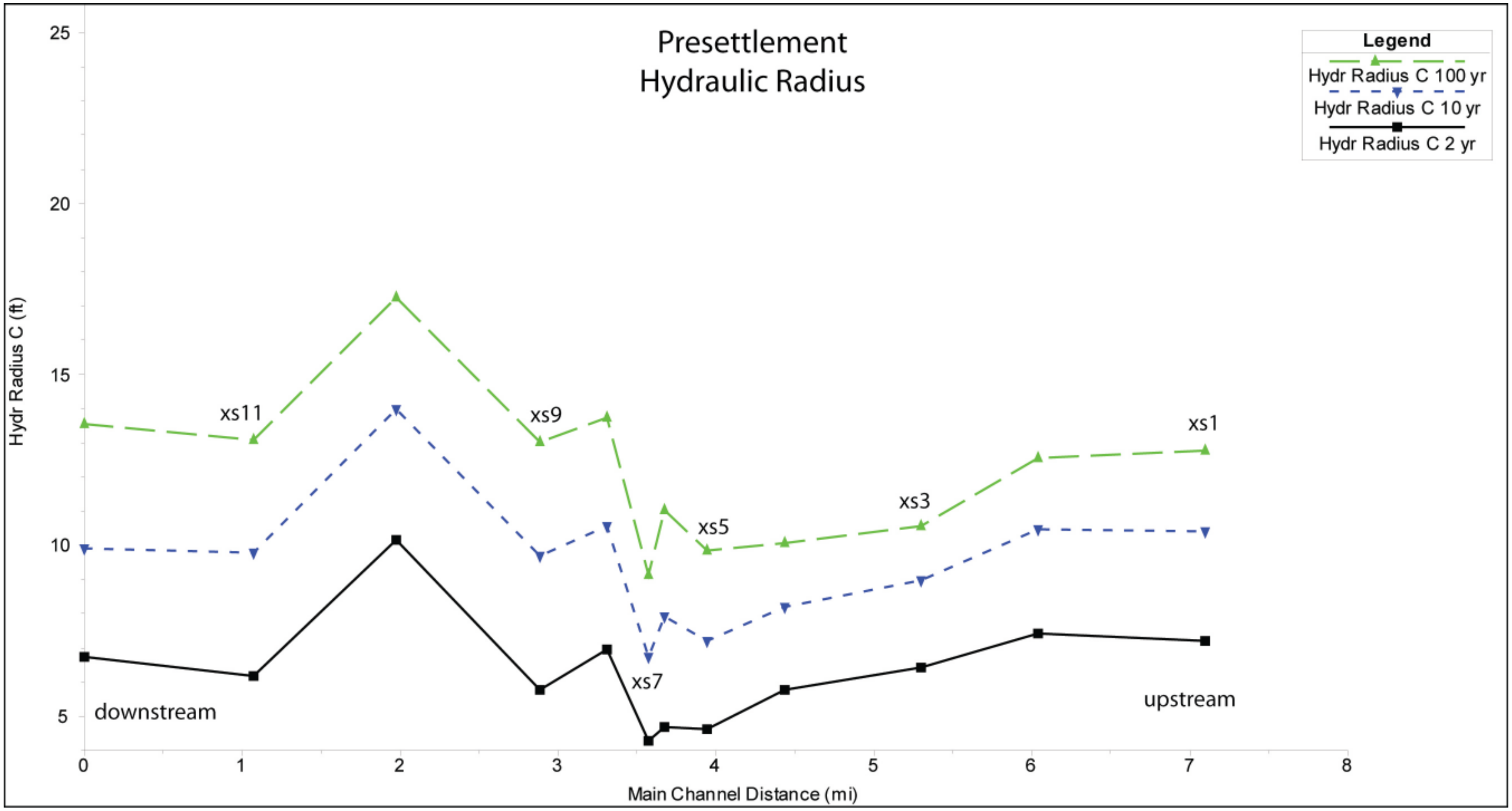

Figure 25. Presettlement Hydraulic Radius.

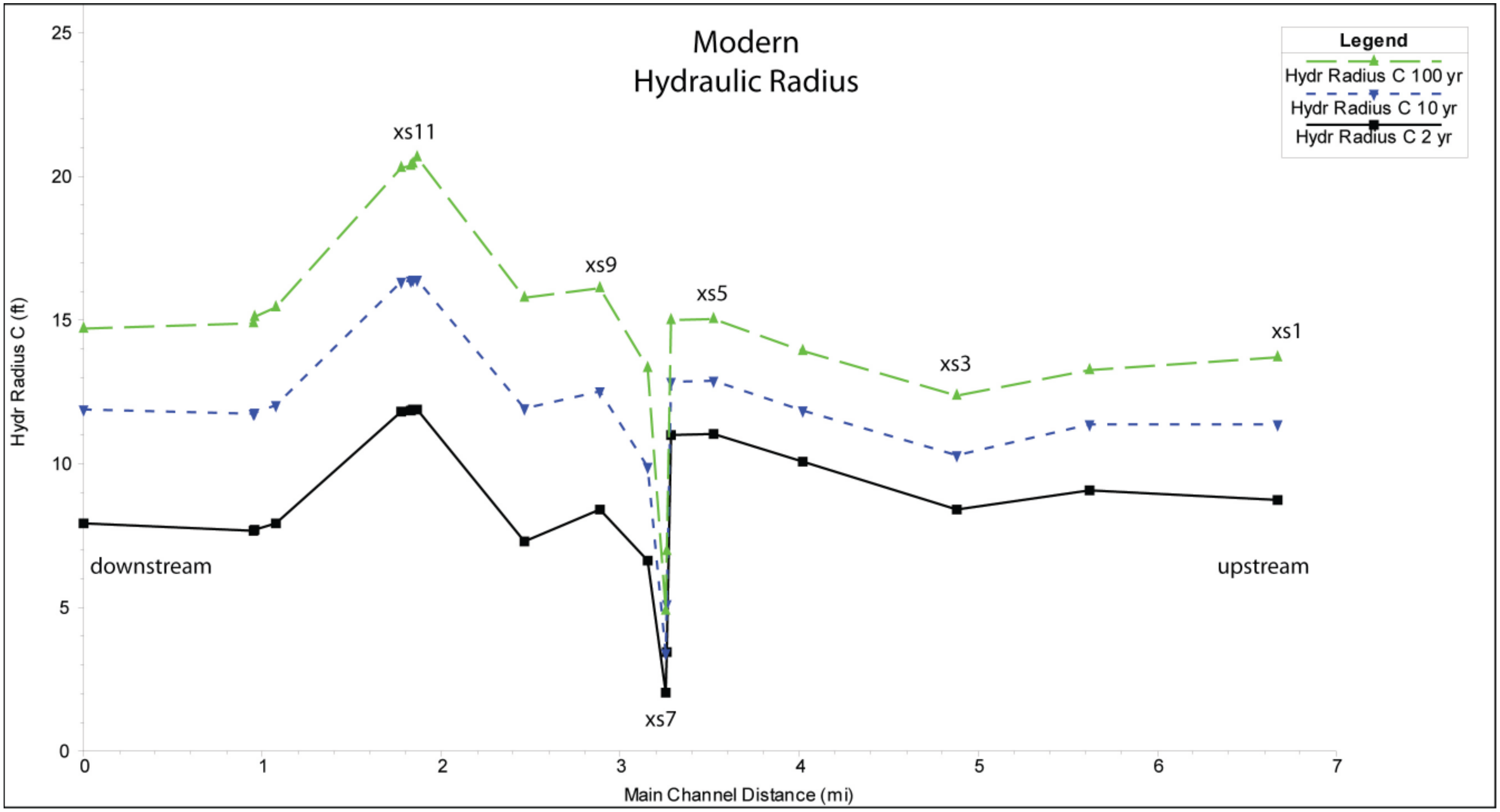

Figure 26. Modern Hydraulic Radius.

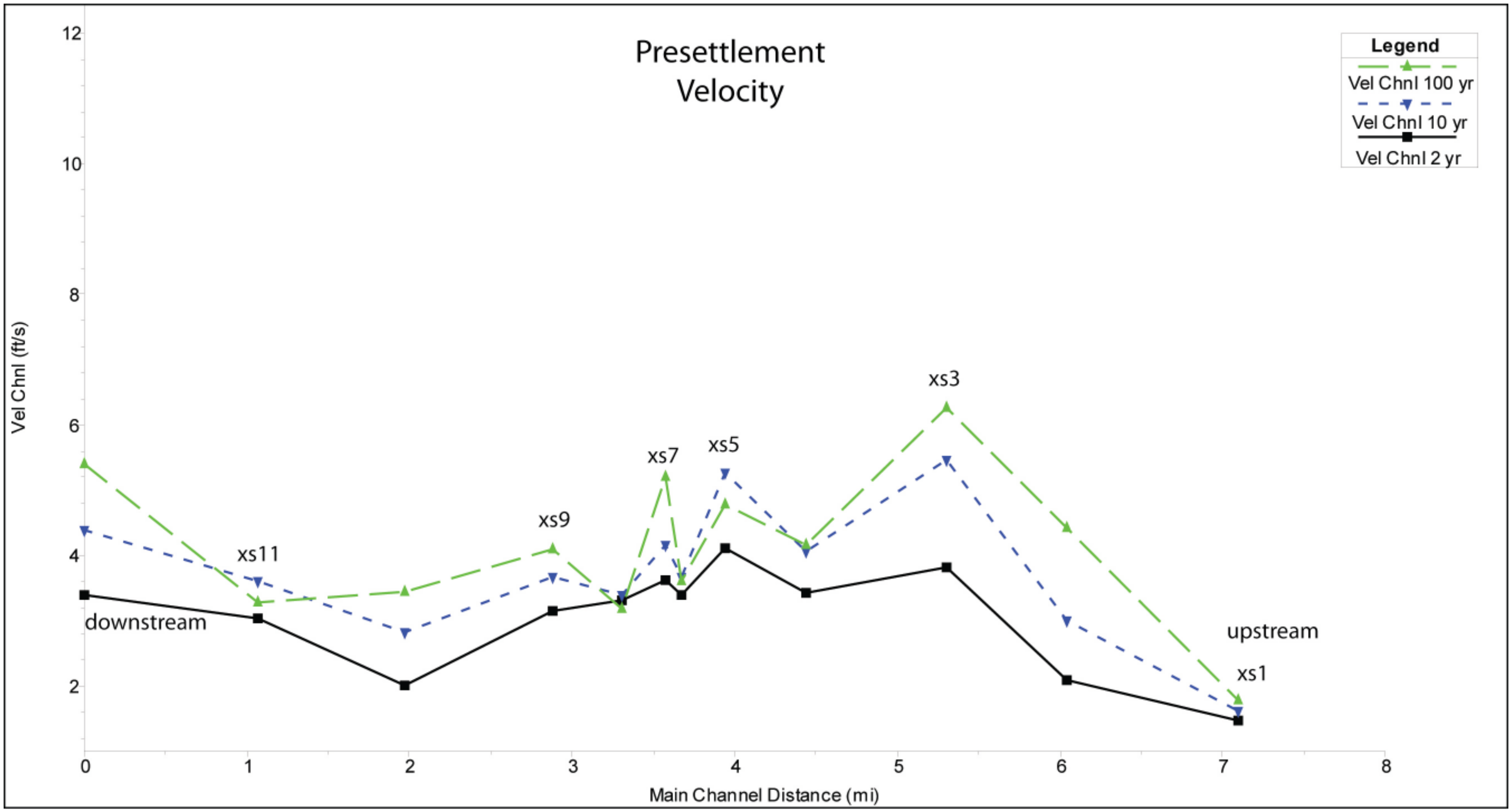

Figure 27. Presettlement Channel Velocity.

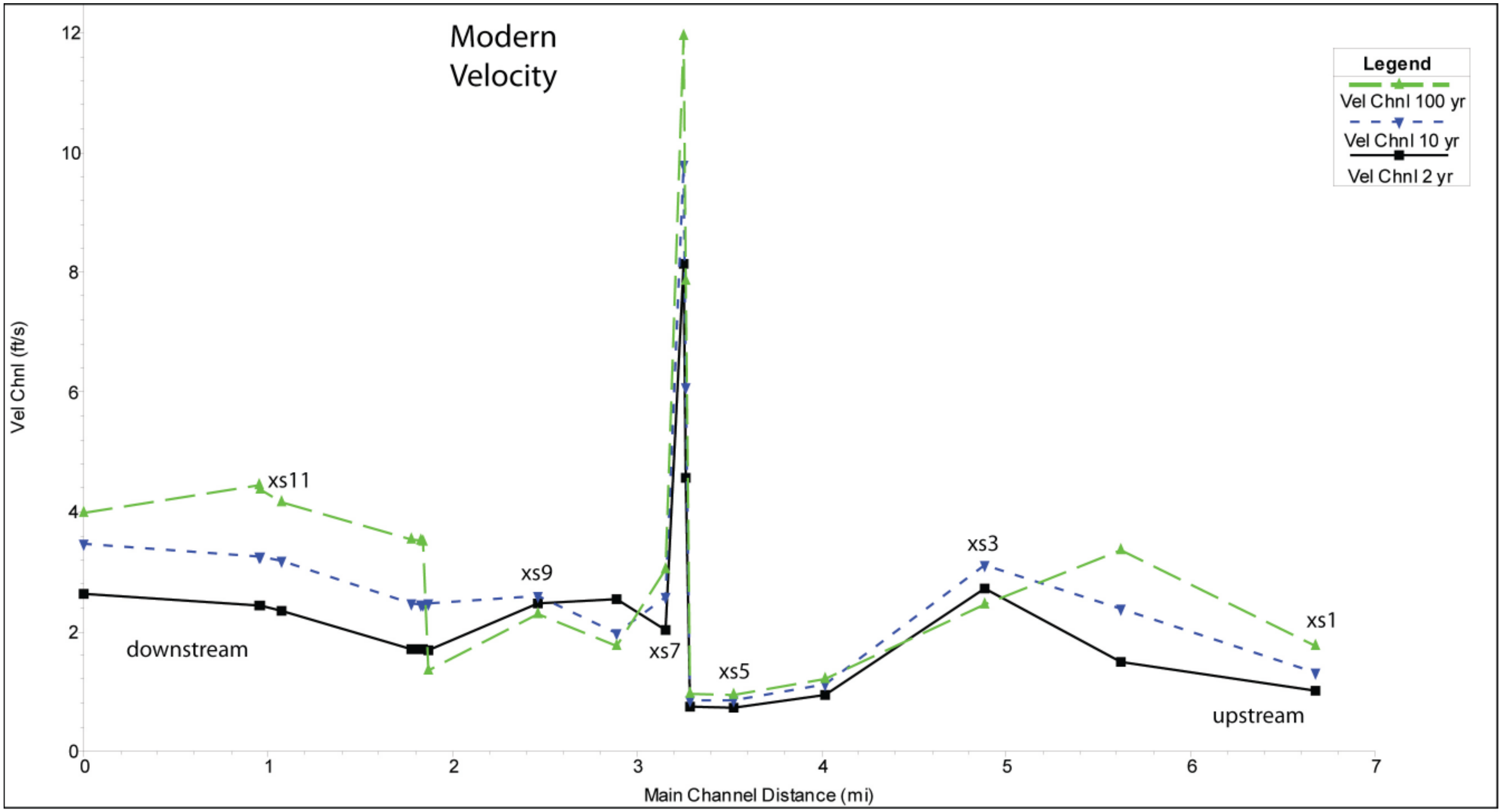

Figure 28. Modern Channel Velocity.

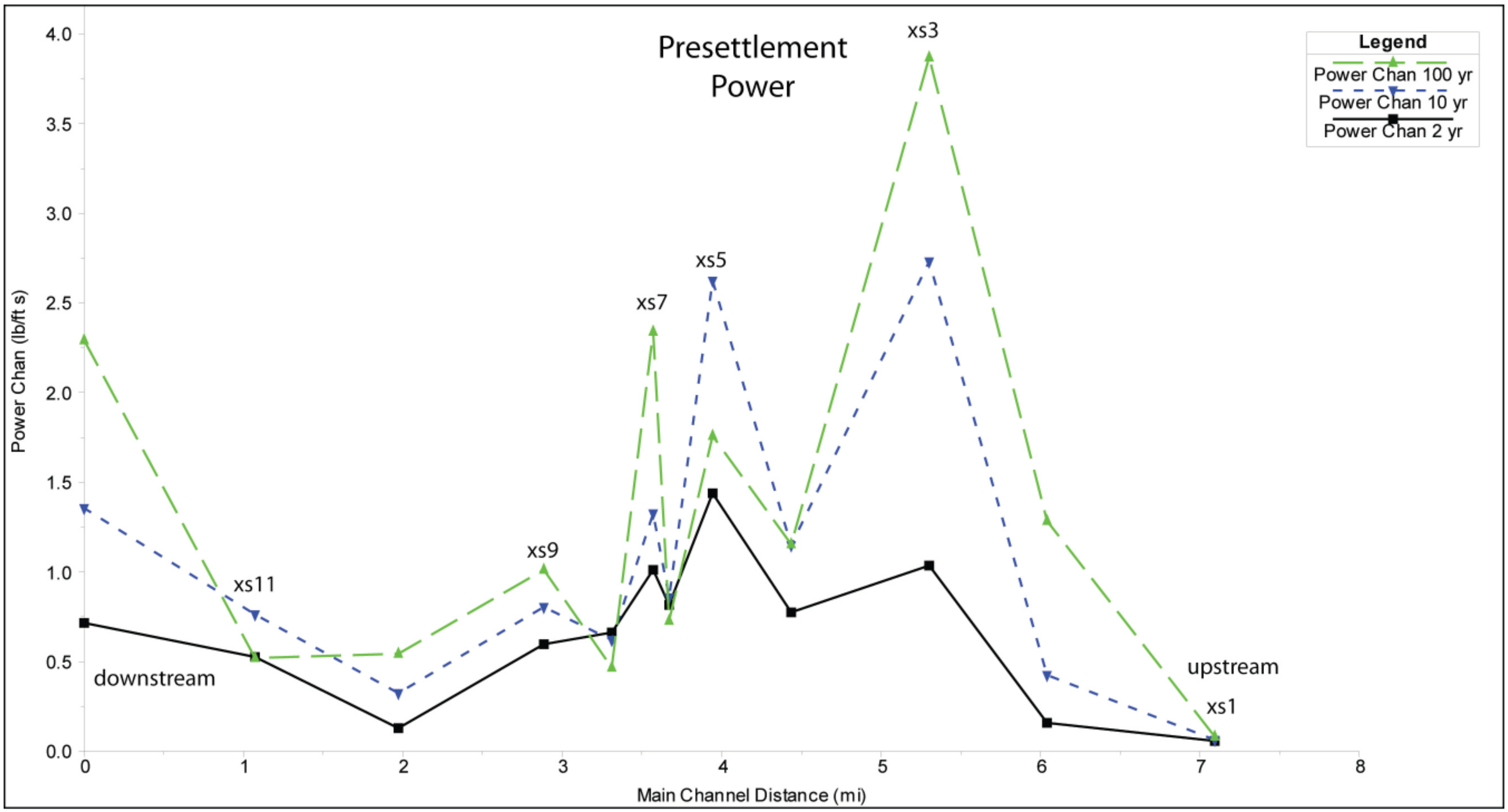

Figure 29. Presettlement Channel Power.

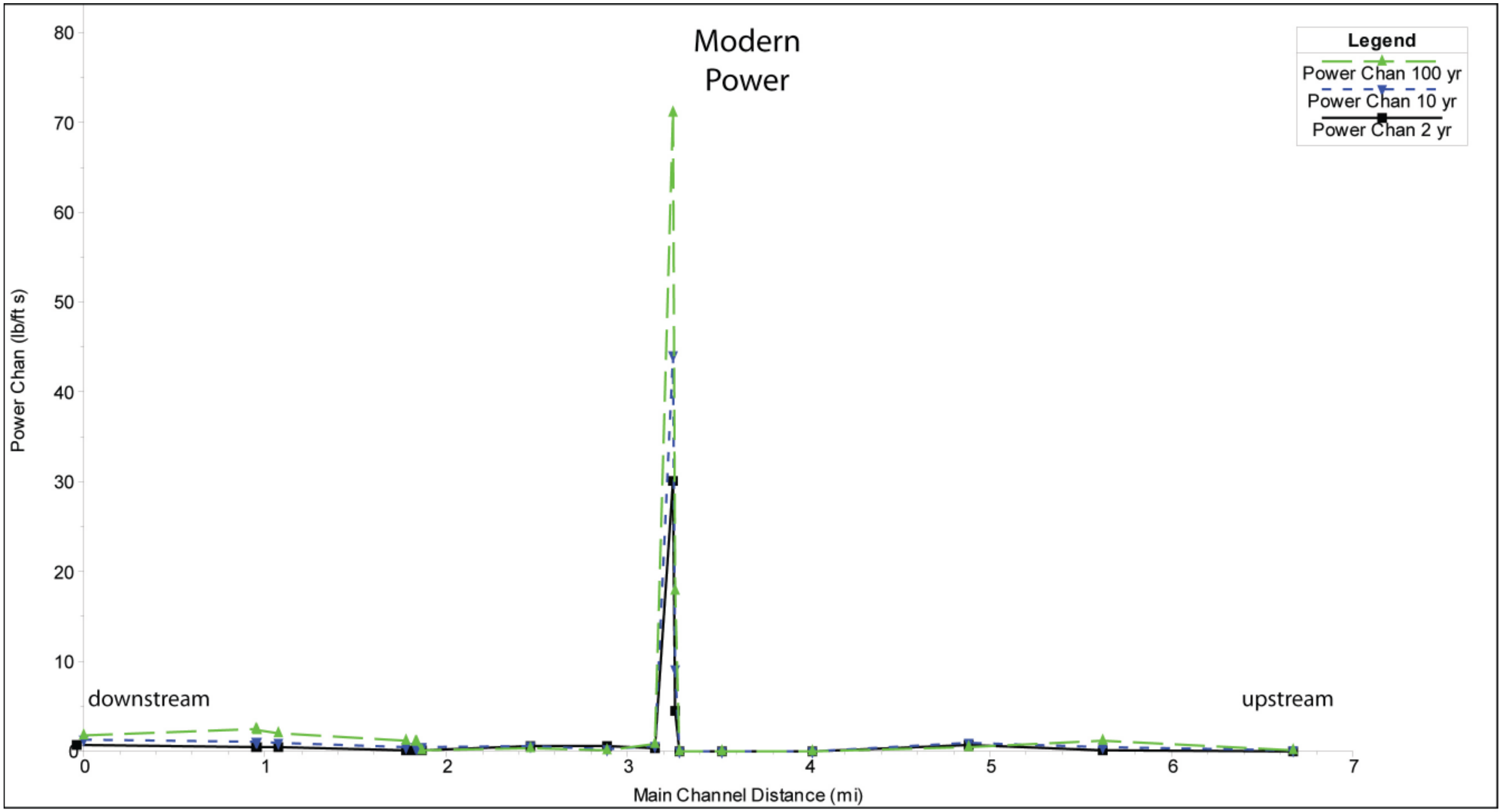

Figure 30. Modern Channel Power.

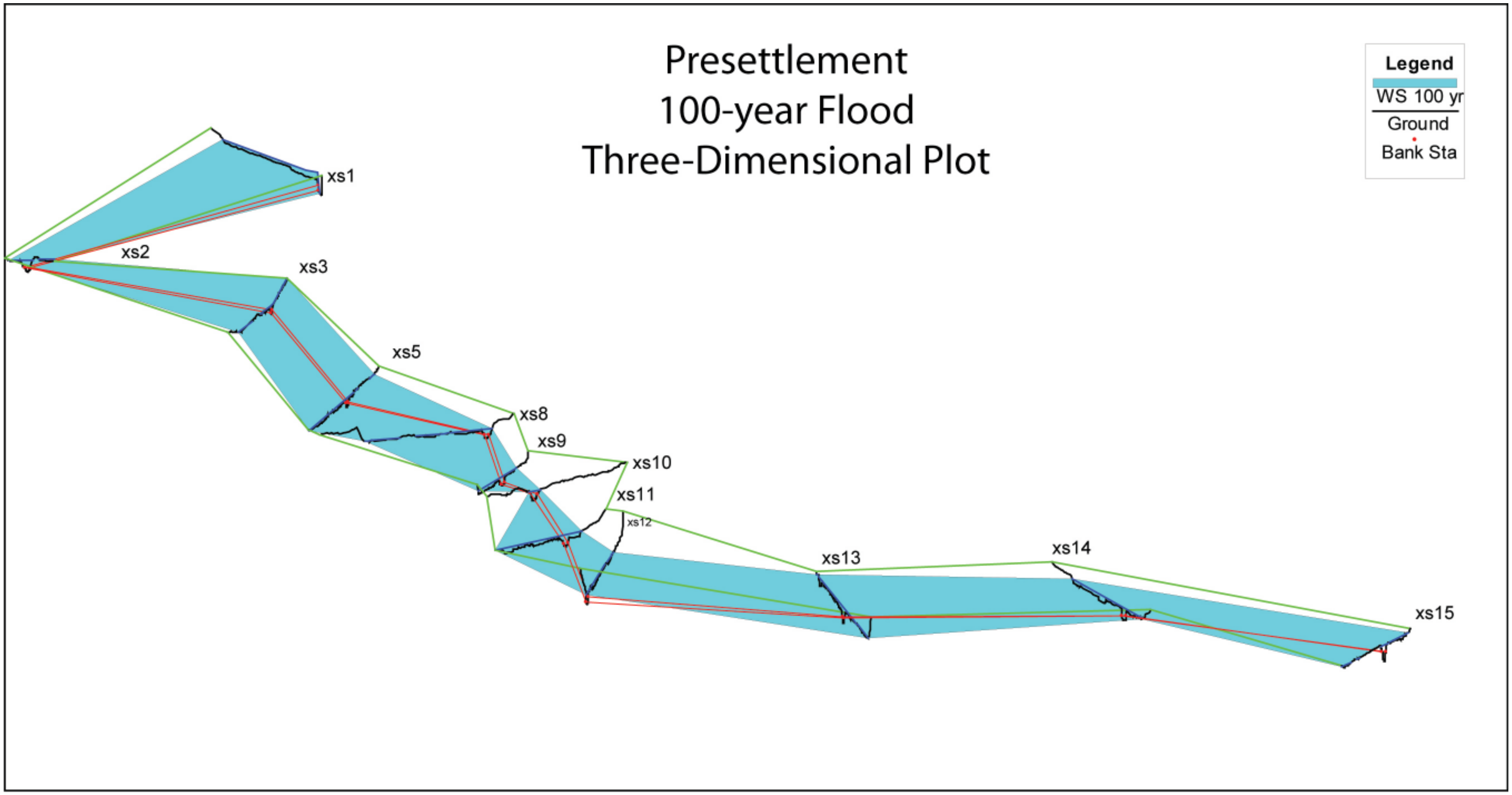

Figure 31. Presettlement three-dimensional plot of the 100-year flood.

Figure 32. Tree dam obstructing flow on the Baraboo River.

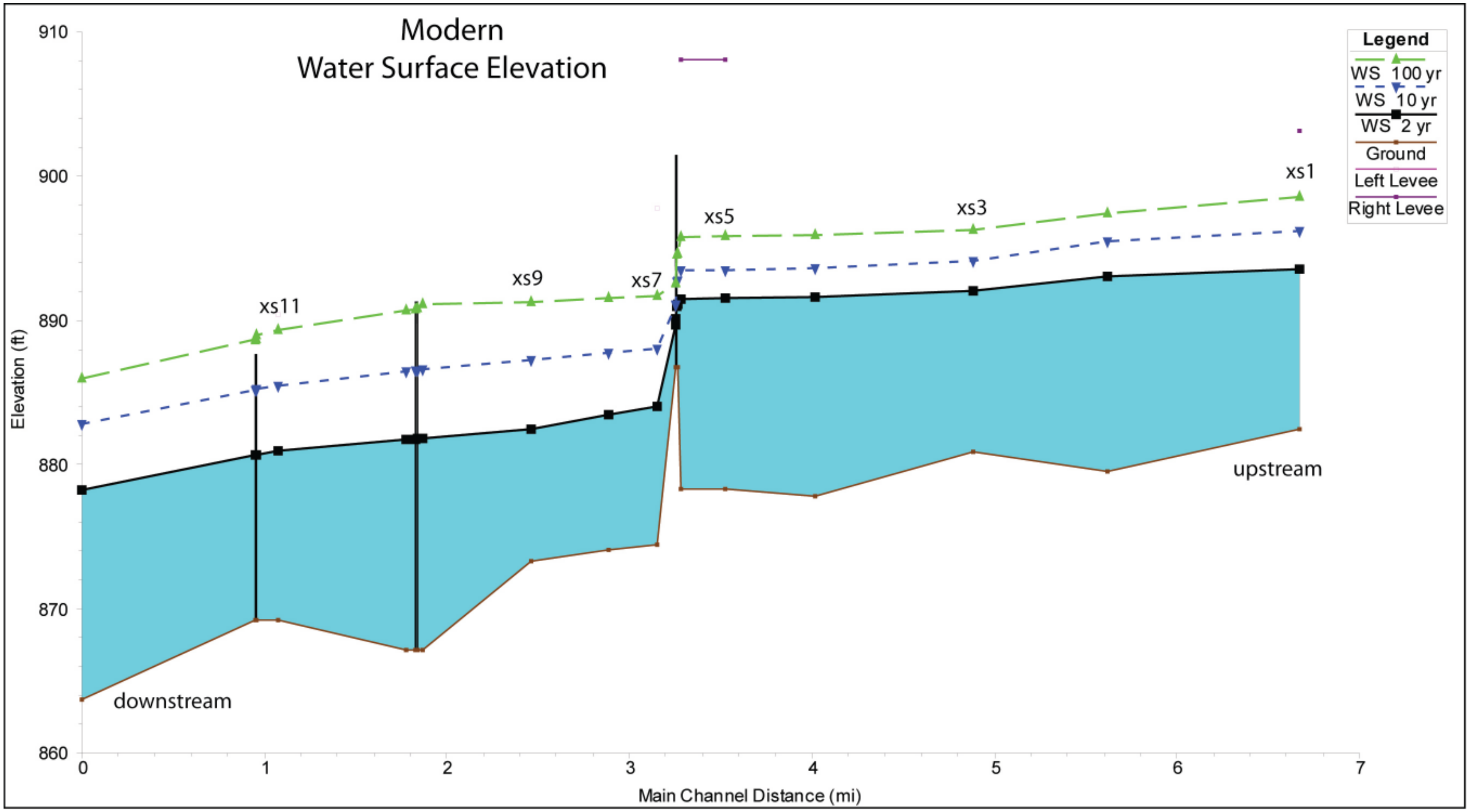

Figure 33. Modern longitudinal profile of water surface elevation.

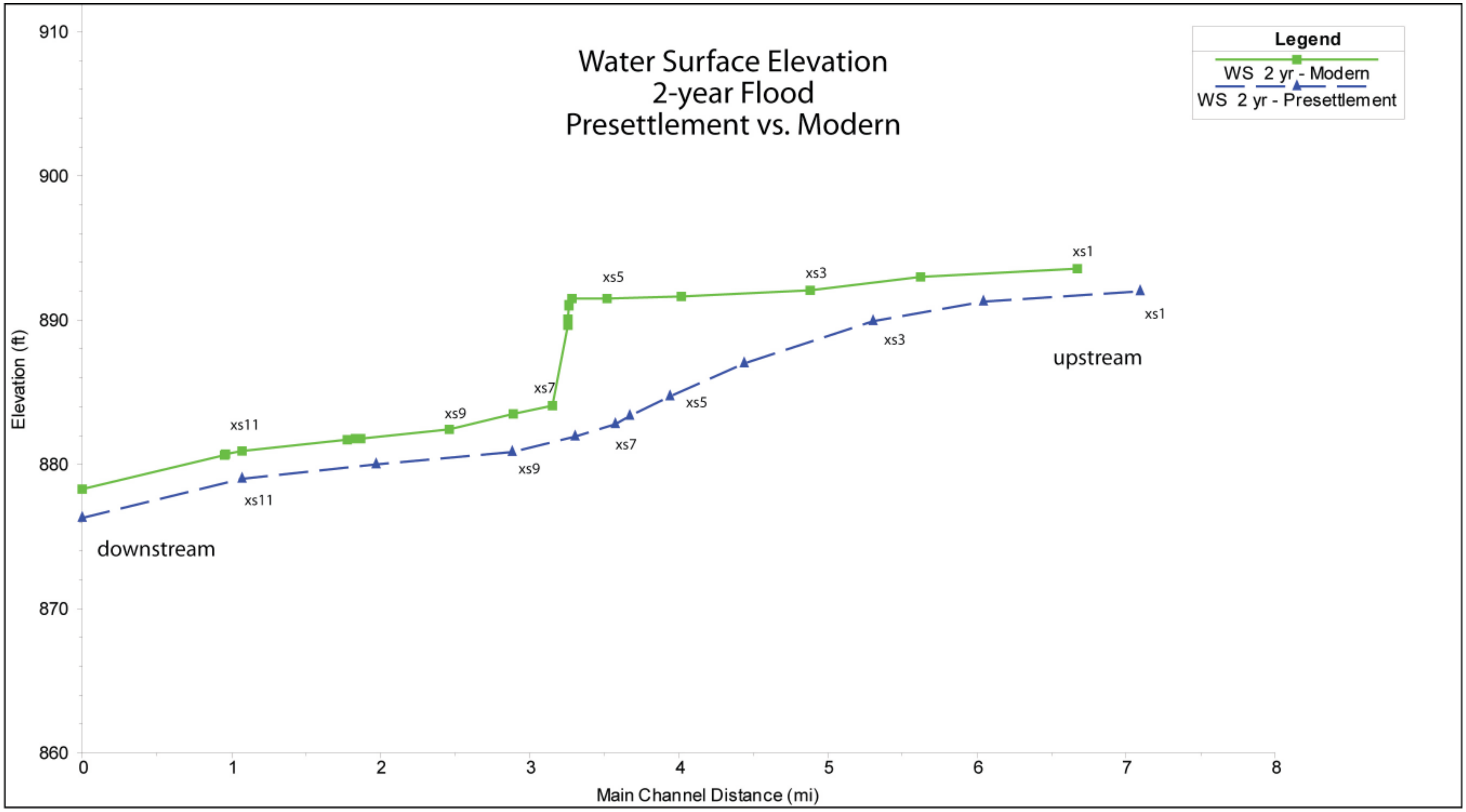

Figure 34. Water Surface Elevation Longitudinal Profile of the 2 -Year Flood.

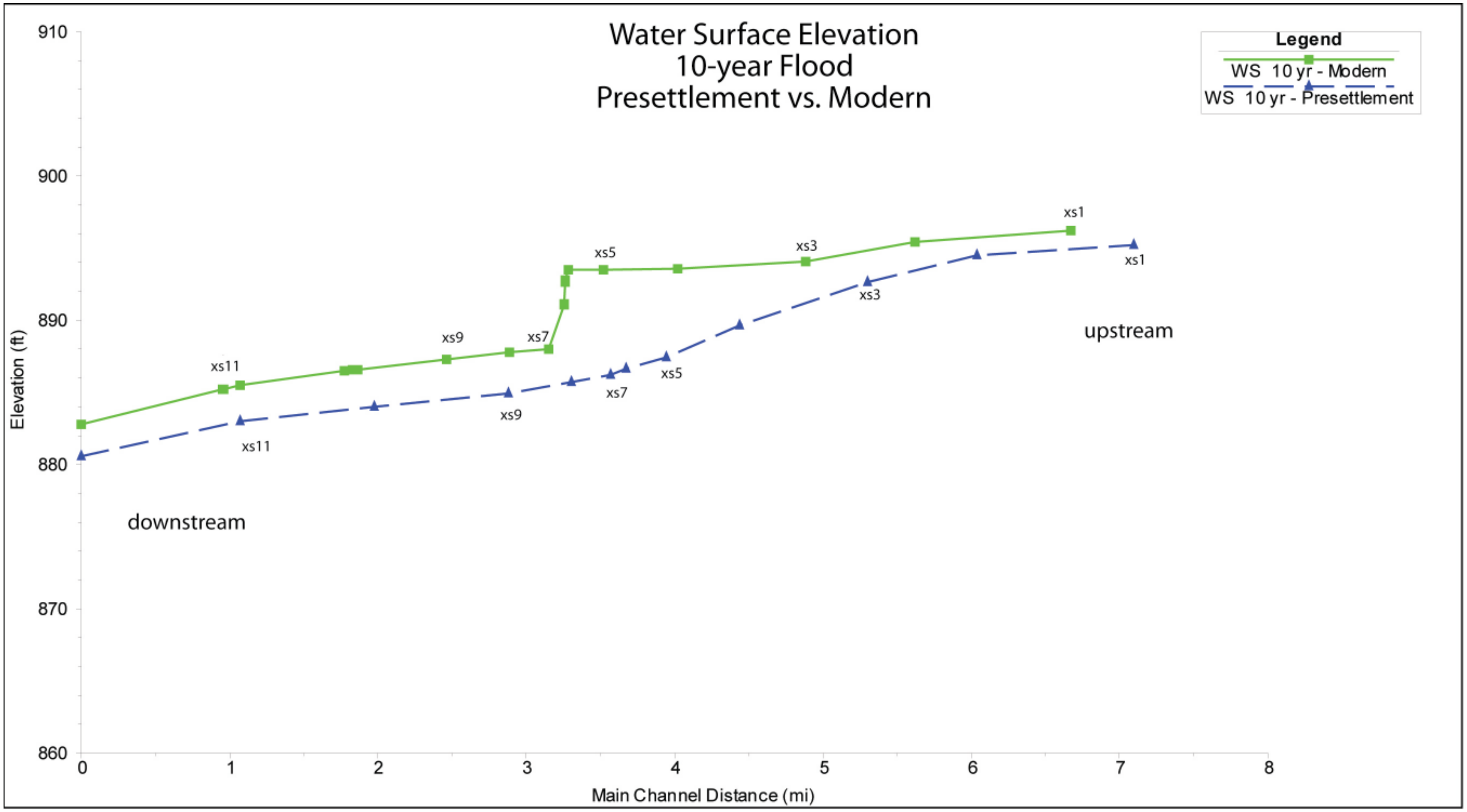

Figure 35. Water Surface Elevation Longitudinal Profile of the 10-Year Flood.

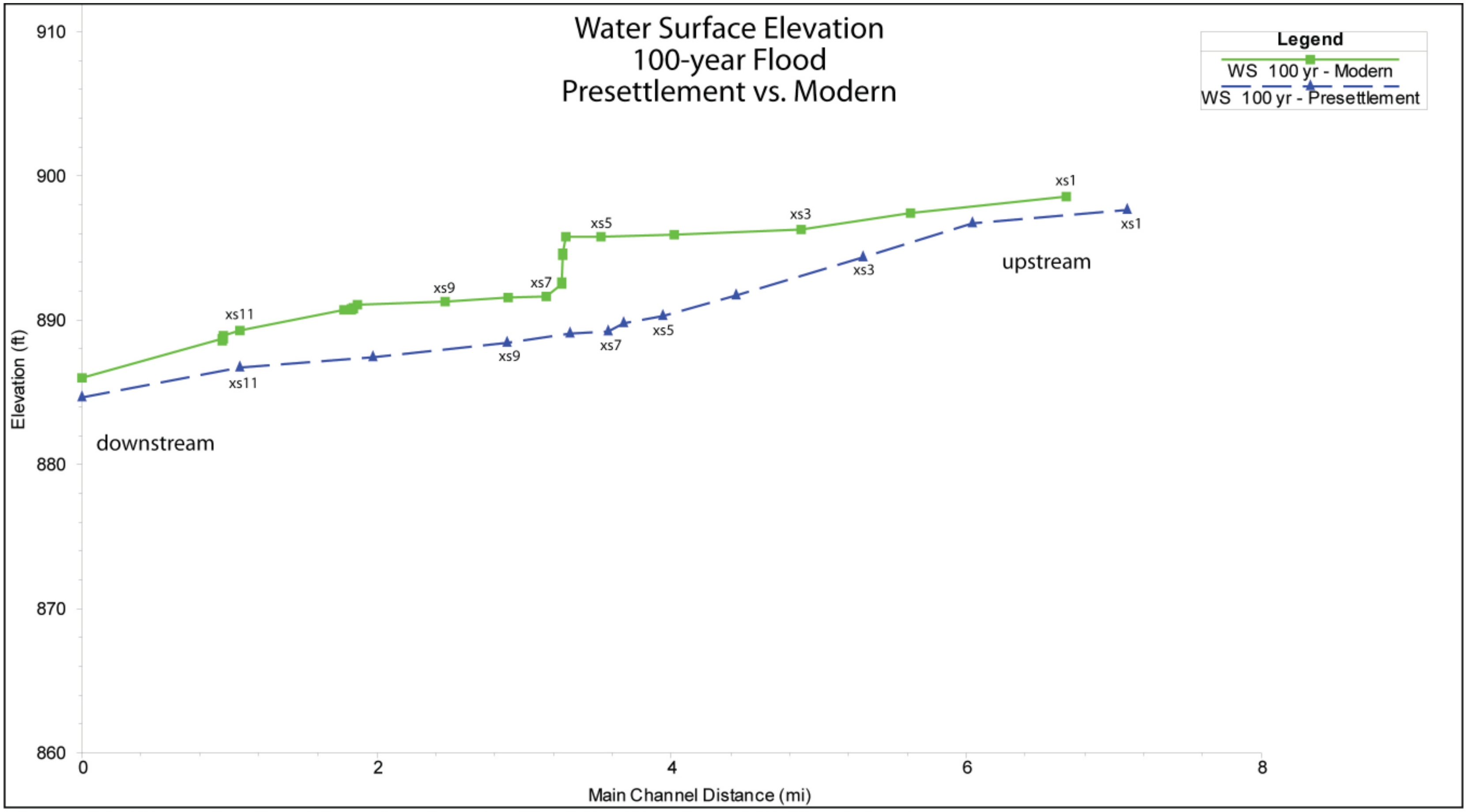

Figure 36. Water Surface Elevation Longitudinal Profile of the 100-Year Flood.

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Appendix - A

Velocity (ft/s)

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	1.47	1.62	1.78	1.98
2	2.09	3	4.42	5.39
3	3.82	5.47	6.26	6.41
4	3.42	4.06	4.16	4.19
5	4.1	5.27	4.77	3.83
6	3.4	3.67	3.61	3.66
7	3.62	4.16	5.21	6.14
8	3.32	3.4	3.19	3.36
9	3.14	3.68	4.1	4.25
10	2.02	2.82	3.44	3.73
11	3.04	3.61	3.28	3.31
12	3.39	4.38	5.4	5.83

Modern

Cross-section	2-year	10-year	100-year	500-year
1	1.01	1.31	1.75	2.06
2	1.49	2.39	3.35	3.88
3	2.72	3.11	2.45	2.41
4	0.94	1.11	1.2	1.33
5	0.73	0.85	0.95	1.08
6	8.15	9.8	11.95	13.42
7	2.03	2.58	3.04	4.05
8	2.55	1.97	1.76	2.36
9	2.47	2.59	2.3	3.21
10	1.7	2.46	3.5	4.94
11	2.35	3.19	4.16	7.92
12	2.64	3.47	3.99	4.19

Appendix - B

Froude Number

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	0.1	0.09	0.09	0.09
2	0.13	0.16	0.21	0.25
3	0.26	0.31	0.33	0.32
4	0.24	0.24	0.22	0.21
5	0.33	0.33	0.26	0.19
6	0.28	0.23	0.19	0.18
7	0.3	0.27	0.3	0.32
8	0.22	0.18	0.15	0.15
9	0.23	0.2	0.2	0.19
10	0.11	0.13	0.14	0.15
11	0.2	0.19	0.15	0.14
12	0.22	0.23	0.24	0.25

Modern

Cross-section	2-year	10-year	100-year	500-year
1	0.06	0.07	0.08	0.09
2	0.08	0.12	0.16	0.18
3	0.16	0.17	0.12	0.11
4	0.05	0.05	0.05	0.06
5	0.04	0.04	0.04	0.05
6	1	0.93	0.95	0.98
7	0.13	0.14	0.14	0.19
8	0.15	0.1	0.08	0.1
9	0.16	0.13	0.1	0.14
10	0.08	0.1	0.13	0.19
11	0.14	0.15	0.18	0.38
12	0.16	0.17	0.17	0.17

Appendix - C

Estimating Froude number using different velocities

Froude = V/sqrt(g/D)

	Actual		Estimated F using 3-4 ft/s		Estimated F using 4-5 ft/s	
xs1	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	2.04	2.36	3.00	4.00	4.00	5.00
Depth	13.58	15.12	13.58	15.12	13.58	15.12
Froude	0.10	0.11	0.14	0.18	0.19	0.23
xs2	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	3.69	4.16	3.00	4.00	4.00	5.00
Depth	13.72	15.11	13.72	15.11	13.72	15.11
Froude	0.18	0.19	0.14	0.18	0.19	0.23
xs3	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	2.92	2.62	3.00	4.00	4.00	5.00
Depth	13.20	14.78	13.20	14.78	13.20	14.78
Froude	0.14	0.12	0.15	0.18	0.19	0.23
Xs4	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	1.43	1.47	3.00	4.00	4.00	5.00
Depth	15.38	17.01	15.38	17.01	15.38	17.01
Froude	0.06	0.06	0.13	0.17	0.18	0.21
Xs5	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	1.13	1.20	3.00	4.00	4.00	5.00
Depth	16.02	17.66	16.02	17.66	16.02	17.66
Froude	0.05	0.05	0.13	0.17	0.18	0.21
Xs6	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	12.13	13.54	3.00	4.00	4.00	5.00
Depth	4.95	5.98	4.95	5.98	4.95	5.98
Froude	0.96	0.98	0.24	0.29	0.32	0.36
Xs7	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	3.49	4.55	3.00	4.00	4.00	5.00
Depth	13.21	13.69	13.21	13.69	13.21	13.69
Froude	0.17	0.22	0.15	0.19	0.19	0.24
Xs8	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	2.35	3.03	3.00	4.00	4.00	5.00
Depth	15.92	16.33	15.92	16.33	15.92	16.33
Froude	0.10	0.13	0.13	0.17	0.18	0.22
Xs9	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	2.96	3.96	3.00	4.00	4.00	5.00

Depth	15.40	15.56	15.40	15.56	15.40	15.56
Froude	0.13	0.18	0.13	0.18	0.18	0.22
xs10	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	3.85	5.49	3.00	4.00	4.00	5.00
Depth	20.21	19.60	20.21	19.60	20.21	19.60
Froude	0.15	0.22	0.12	0.16	0.16	0.20
xs11	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	4.66	8.43	3.00	4.00	4.00	5.00
Depth	16.06	12.79	16.06	12.79	16.06	12.79
Froude	0.20	0.42	0.13	0.20	0.18	0.25
xs12	**100 yr**	**500yr**	**100yr**	**500yr**	**100yr**	**500yr**
Velocity (ft/s)	4.82	5.12	3.00	4.00	4.00	5.00
Depth	15.82	17.20	15.82	17.20	15.82	17.20
Froude	0.21	0.22	0.13	0.17	0.18	0.21

Appendix - D

Channel Shear Stress (lbs / ft^2)

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	0.04	0.04	0.05	0.06
2	0.08	0.14	0.29	0.42
3	0.27	0.5	0.62	0.63
4	0.23	0.28	0.28	0.27
5	0.35	0.5	0.37	0.23
6	0.24	0.23	0.2	0.2
7	0.28	0.32	0.45	0.59
8	0.2	0.18	0.15	0.16
9	0.19	0.22	0.25	0.26
10	0.07	0.11	0.16	0.18
11	0.17	0.21	0.16	0.16
12	0.21	0.31	0.42	0.47

Modern

Cross-section	2-year	10-year	100-year	500-year
1	0.04	0.05	0.09	0.12
2	0.08	0.18	0.34	0.44
3	0.26	0.32	0.18	0.17
4	0.03	0.04	0.04	0.05
5	0.02	0.02	0.03	0.03
6	3.7	4.5	5.95	7.11
7	0.15	0.22	0.28	0.48
8	0.23	0.12	0.09	0.16
9	0.22	0.21	0.15	0.29
10	0.09	0.17	0.32	0.64
11	0.2	0.31	0.49	1.93
12	0.25	0.37	0.46	0.49

Appendix - E

Hydraulic Radius (ft)

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	7.21	10.4	12.78	14.07
2	7.42	10.48	12.56	13.59
3	6.44	8.97	10.56	11.4
4	5.78	8.2	10.06	11.08
5	4.61	7.19	9.85	11.37
6	4.69	7.92	11.03	12.73
7	4.26	6.73	9.14	10.6
8	6.95	10.56	13.73	15.32
9	5.77	9.71	13.02	14.66
10	10.16	14	17.24	18.86
11	6.17	9.77	13.08	14.65
12	6.74	9.91	13.56	15.2

Modern

Cross-section	2-year	10-year	100-year	500-year
1	8.75	11.38	13.7	15.04
2	9.07	11.37	13.25	14.32
3	8.4	10.3	12.36	13.45
4	10.06	11.86	13.92	14.97
5	11.02	12.87	15.02	16.09
6	2.05	3.42	4.88	5.74
7	6.64	9.9	13.35	13.6
8	8.4	12.51	16.13	16.29
9	7.29	11.92	15.78	15.7
10	11.88	16.4	20.46	19.99
11	7.93	12.02	15.45	12.15
12	7.91	11.9	14.7	15.8

Appendix – F

Power (lbs/ft-s)

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	0.06	0.07	0.08	0.11
2	0.16	0.43	1.29	2.27
3	1.04	2.73	3.87	4.06
4	0.77	1.15	1.16	1.14
5	1.44	2.62	1.76	0.87
6	0.82	0.86	0.73	0.73
7	1.02	1.33	2.34	3.65
8	0.66	0.62	0.47	0.53
9	0.6	0.81	1.01	1.09
10	0.13	0.32	0.55	0.67
11	0.53	0.76	0.52	0.52
12	0.71	1.36	2.29	2.77

Modern

Cross-section	2-year	10-year	100-year	500-year
1	0.04	0.07	0.16	0.25
2	0.11	0.43	1.13	1.69
3	0.7	0.98	0.45	0.41
4	0.03	0.04	0.05	0.07
5	0.01	0.02	0.02	0.03
6	30.12	44.13	71.06	95.34
7	0.31	0.57	0.84	1.96
8	0.58	0.23	0.15	0.37
9	0.55	0.54	0.34	0.93
10	0.15	0.41	1.11	3.15
11	0.46	1	2.04	15.29
12	0.65	1.29	1.83	2.07

Appendix – G

Estimated Sediment Transport
Baraboo River, La Valle, Wisconsin

Presettlement	Upper end values		Lower end values (better estimate of true grain size)	
Recurrence Int.	Maximum (mm)	Average (mm)	Maximum (mm)	Average (mm)
1	2.917	1.140	1.244	0.486
2	1.907	1.407	0.813	0.600
10	3.062	1.760	1.306	0.751
100	3.661	1.919	1.562	0.818
500	3.731	2.029	1.592	0.866

Modern	Upper end values		Lower end values (better estimate of true grain size)	
Recurrence Int.	Maximum (mm)	Average (mm)	Maximum (mm)	Average (mm)
1	9.793	1.398	4.178	0.596
2	15.982	2.369	6.818	1.011
10	18.812	2.995	8.026	1.278
100	23.661	3.857	10.094	1.645
500	27.399	8.267	11.689	3.527

Appendix - H

Water Surface Elevation (ft)

Presettlement

Cross-section	2-year	10-year	100-year	500-year
1	891.97	895.22	897.65	898.96
2	891.27	894.5	896.7	897.78
3	889.94	892.66	894.37	895.27
4	887	889.66	891.71	892.83
5	884.69	887.44	890.28	891.91
6	883.34	886.62	889.77	891.5
7	882.81	886.2	889.21	890.76
8	881.96	885.73	889.04	890.7
9	880.86	884.95	888.4	890.11
10	879.97	884.03	887.46	889.17
11	878.98	882.99	886.68	888.43
12	876.26	880.54	884.67	886.52

Modern

Cross-section	2-year	10-year	100-year	500-year
1	893.54	896.21	898.58	899.95
2	893.02	895.44	897.43	898.56
3	892.04	894.09	896.3	897.47
4	891.62	893.61	895.89	897.05
5	891.53	893.51	895.8	896.94
6	889.67	891.06	892.53	893.41
7	884.07	888.01	891.67	891.93
8	883.47	887.77	891.55	891.72
9	882.44	887.26	891.26	891.19
10	881.79	886.56	890.86	890.37
11	880.94	885.5	889.32	885.64
12	878.27	882.79	885.97	887.21