Red Cedar River Erosion and Habitat

Assessment Report

March 24, 2014

Prepared for:

Tainter Menomin Lake Improvement Association, Inc.

P.O. Box 185
Menomonie, WI 54751

Red Cedar River Erosion Partnership

RED CEDAR RIVER EROSION AND HABITAT ASSESSMENT
DRAFT REPORT

Prepared for:

Tainter Menomin Lake Improvement Association, Inc.
P.O. Box 185
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EXECUTIVE SUMMARY

Tainter Lake is a 1,690 acre reservoir located in north central Dunn County, Wisconsin created by the Cedar Falls Dam near Menomonie, WI. The lake is highly eutrophic and experiences severe summer algae blooms and poor water clarity, which are largely associated with elevated phosphorus concentrations. Additionally, sediment from the encroaching Red Cedar River delta has been filling the east end of the lake at a rough rate of 19 feet/year. Over 60 erosion sites have been identified along the channel within Dunn County (Dunn County LCD, 2008), including sites with adjacent infrastructure such as the Village of Colfax wastewater treatment facility. It is assumed that sediment from these erosion sites is responsible for the expansion of the delta. The combination of impacts has degraded water quality and ecological function, reduced access, impaired fishing and other recreational activities, and decreased aesthetics for residents living along its shoreline and potential visitors.

The Tainter Menomin Lake Improvement Association, Inc. (TMLIA), and its partners (Appendix H), aim to reduce both the sediment and phosphorus impacts to Tainter Lake. Because phosphorus is largely transported attached to fine sediment, and because the Red Cedar River is delivering relatively large volumes of sediment to the impoundment, limiting upstream erosion could potentially decrease both the nutrient and sediment inputs. By reducing erosion at critical sites along the river, they hope to effectively address both impacts. This study aims to identify and quantify erosion issues along the Red Cedar River upstream of Tainter Lake and identify potential treatment options. In part, it builds on an initial bank erosion survey completed by the Dunn County Land Conservation Division (2006).

For this study, the Red Cedar River banks within Dunn County were digitized on a series of aerial photographs, including photos from 1938, 1974, 1992, 2005, and 2012. The channels and photographs were overlaid in a Geographic Information System project (GIS; ESRI ArcGIS 10.1) in order to observe general trends in channel behavior and provide detailed data on channel change over the period between photographs. At the outset, the digitized bank lines suggested the channel could be divided into two reaches where 1) upstream of Colfax, WI, the channel is relatively stable, and 2) downstream of Colfax, the channel is relatively active. In both reaches, the channel is eroding banks at the outside of meander bends and depositing material on bars opposite of the erosion, which in general, is how similar rivers operate. However, along the downstream reach, the meander bends appear to be eroding banks at a higher rate. Additionally, the downstream channel has changed position (i.e., avulsed, cutoff) in the floodplain during large floods in the 1960s and 1980s, and is now trying to erode new meander bends.

The glacially-derived sands comprising the higher bluffs and lower floodplain soils have little cohesion, high permeability, and little ability to hold water to support vegetation at steep slopes, and therefore are easily mobilized. The air photo analysis shows that the river reach between Colfax and Tainter Lake has been very active via both meander migration and chute

cutoffs/avulsions over the last 75 years, and likely much longer (100s to 1000s of years). The erosion and subsequent sediment transport that would normally proceed downstream is being deposited at the upper end of the lake in the form of a delta. The process appears to be natural and consistent with river function.

Our analysis indicates that sediment is sourced within the project reach from two primary mechanisms, bluff erosion and channel cutoffs and subsequent adjustment. Erosion is occurring among several *bluff* sites where the river is interacting with higher valley wall. For relatively minor lateral erosion or channel migration a large volume of sediment is washed into river from the taller bluffs, especially at the Dobbs Landing Bend. At sites where the channel has avulsed and either cut or reactivated a new channel, a large volume of sediment is also put into downstream transport via the initial cut and subsequent meander establishment.

What has not been quantified is the total *load* of sediment carried by the river. Additional sources for this may be sediment sourced from normal bank scour at the interface of the channel and floodplain (non-bluff sites) and sediment delivered by tributaries. Temporary and permanent sediment storage within point bar and island deposits, or on the floodplain, also affect the total load that might reach Tainter Lake in any given year. Some attempt to discern the total load contributed to the Tainter Lake delta has been made and appears to range from a low of about 15,000 CY/year to 60,000 CY/year. Sediment volume from specific erosion sites upstream of Tainter Lake is estimated at approximately 50,000 CY/year, of which about 30% is from bluff sites. The Dobbs Landing site comprises 17% of the estimated total sediment volume from the assessed erosion and 58% of the estimated erosion at bluff sites.

This report indicates that deliberate and natural processes appear to be at work within the Red Cedar River and stopping, or even managing these processes on a large scale, will be difficult. It also indicates that reducing channel erosion will have little impact on the phosphorus inputs into Tainter Lake. In addition, the lake creates an unnatural condition within the river that will continue to collect sediment derived from the relatively active meander migration upstream. For this reason, we recommend sediment management efforts include an active plan within the delta itself, likely focused on dredging. However; although stopping the natural process at work above the lake isn't possible, the *rates* of sediment delivery to Tainter Lake might be influenced in the short term (decades). This action, in combination with sediment management at the delta, might present a reasonable approach to balancing the natural process with the less desirable consequences within Tainter Lake.

To begin the process of slowing the rate of sediment delivery, bluff stabilization including some combination of engineered riprap, rock or log barbs, log cribwalls, floodplain bench construction, and toe scour protection can be implemented. Bluff erosion protection does not provide protection against avulsion not related to the erosion control project. Dobbs Landing would be a primary location to begin, followed by bends adjacent to infrastructure, such as along the Colfax wastewater treatment facility, the Colfax School, or residences on the south side of the river in Colfax.

At all of the bluff erosion sites, we recommend providing either passive or active slope revegetation and installation of a vegetated buffer at the top of the slope. The vegetation should be native woody vegetation, forbs and grasses. Upper slope buffer vegetation will prevent runoff from concentrating; thereby limiting the potential for gullying and rilling on the slope face, and keeping extra sediment from reaching the channel. Gully erosion on the Dobbs Landing Bend (52) face has likely contributed as much sediment as many of the eroding banks elsewhere in the reach. The gullying may have been prevented by a buffer instead of the row crops that extend to the slope break.

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INTRODUCTION

Tainter Lake is a 1,690 acre reservoir located in north central Dunn County, Wisconsin. The lake was created by a hydroelectric dam at Cedar Falls in Menomonie, Wisconsin, that impounds the Hay and Red Cedar Rivers just downstream of their confluence. The lake is highly eutrophic and experiences severe summer algae blooms and poor water clarity, which are largely associated with elevated phosphorus concentrations. Phosphorus concentrations in the lake are often higher than 50ug/L. Additionally, sediment from the encroaching Red Cedar River delta has been filling the east end of Tainter Lake. The combination of impacts has degraded water quality and ecological function, reduced access, impaired fishing and other recreational activities, and decreased aesthetics for residents living along its shoreline and potential visitors.

The Red Cedar River drains approximately 1,480 square miles of mixed deciduous forest and agricultural land upstream of Tainter Lake. The area soils are primarily derived of glacial sands and gravels, which are often easily eroded by rivers and streams. Along the Red Cedar River, the banks are often steep, with exposed soil, downed trees, and little vegetation cover, indicating that the channel has been historically active.

The Tainter Menomin Lake Improvement Association, Inc. (TMLIA), and its partners (Appendix H), aim to reduce both the sediment and phosphorus impacts to Tainter Lake. Because phosphorus is largely transported attached to fine sediment, and because the Red Cedar River is delivering relatively large volumes of sediment to the impoundment, limiting upstream erosion could potentially decrease both the nutrient and sediment inputs. By reducing erosion at critical sites along the river, they hope to effectively address both impacts. This study aims to identify and quantify erosion issues along the Red Cedar River upstream of Tainter Lake and identify potential treatment options. In part, it builds on an initial bank erosion survey completed by the Dunn County Land Conservation Division (2006).

Existing Conditions

Physiologic Setting

The Red Cedar River Watershed encompasses over 1,890 square miles in west central Wisconsin. The river primarily flows south and southwest through Barron and Dunn Counties before finally joining the Chippewa River near Dunnsville, WI (Figure 1). The watershed encompasses a wide range of soils and landscapes ranging from low relief glacial till and sandy outwash areas, to loess-capped high relief sandstone uplands. The area receives between 30-34 inches of annual precipitation, with warm, humid summers and cold winters. Average snowfall is around 43 inches (NRCS 2004, 2008; WDNR 2014). Agriculture accounts for 58% of the landuse in the watershed, and forest land accounts for another 35% of the area, although forests covered 90% of the watershed in the late 1800s (NRCS 2008). Small industry, agriculture, forestry, outdoor recreation, and tourism drive the local economy (NRCS 2008).

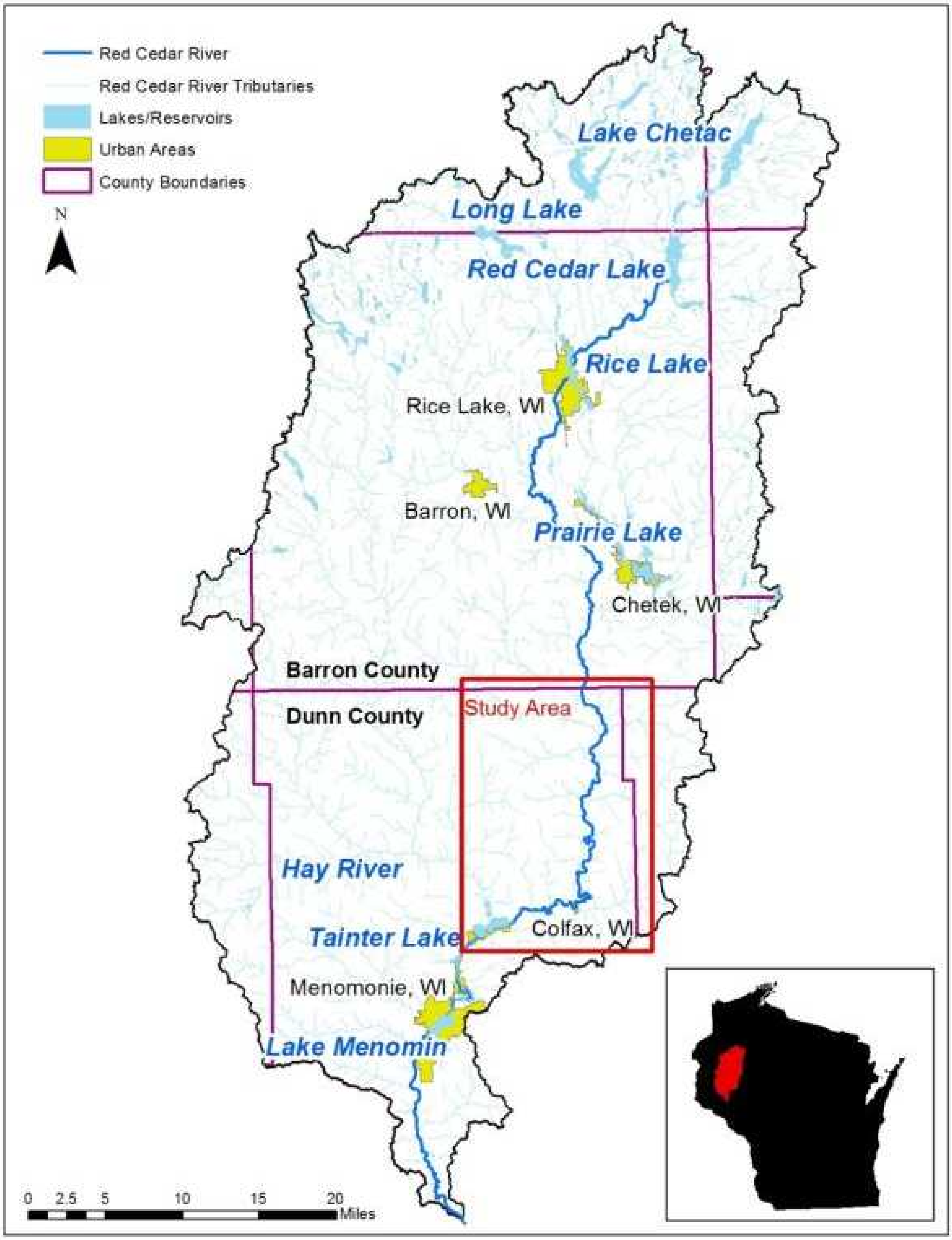


Figure 1. Red Cedar River Watershed (See Appendix A).

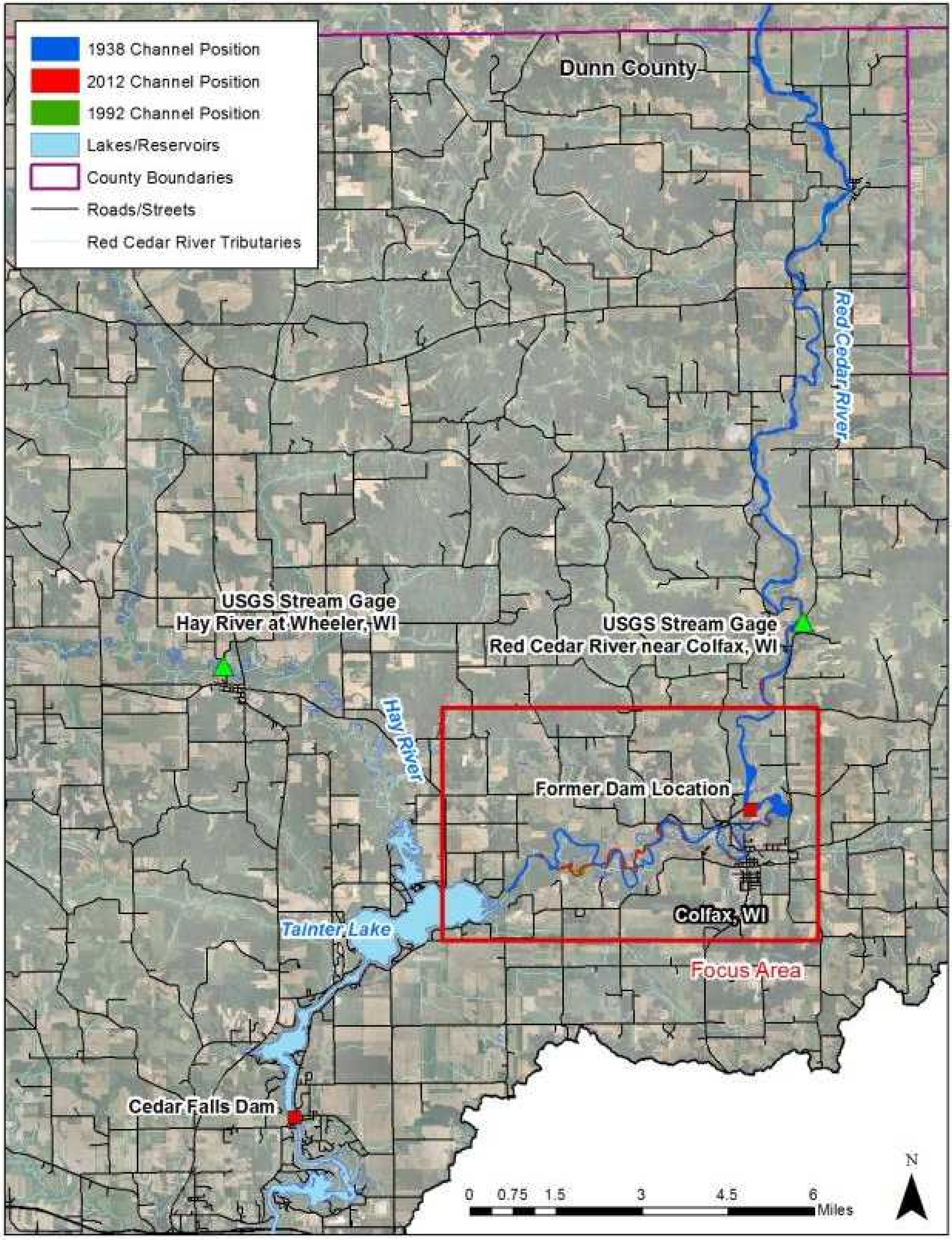


Figure 2. Red Cedar River Study Area, Dunn County, Wisconsin (See Appendix B).

Geology and Soils

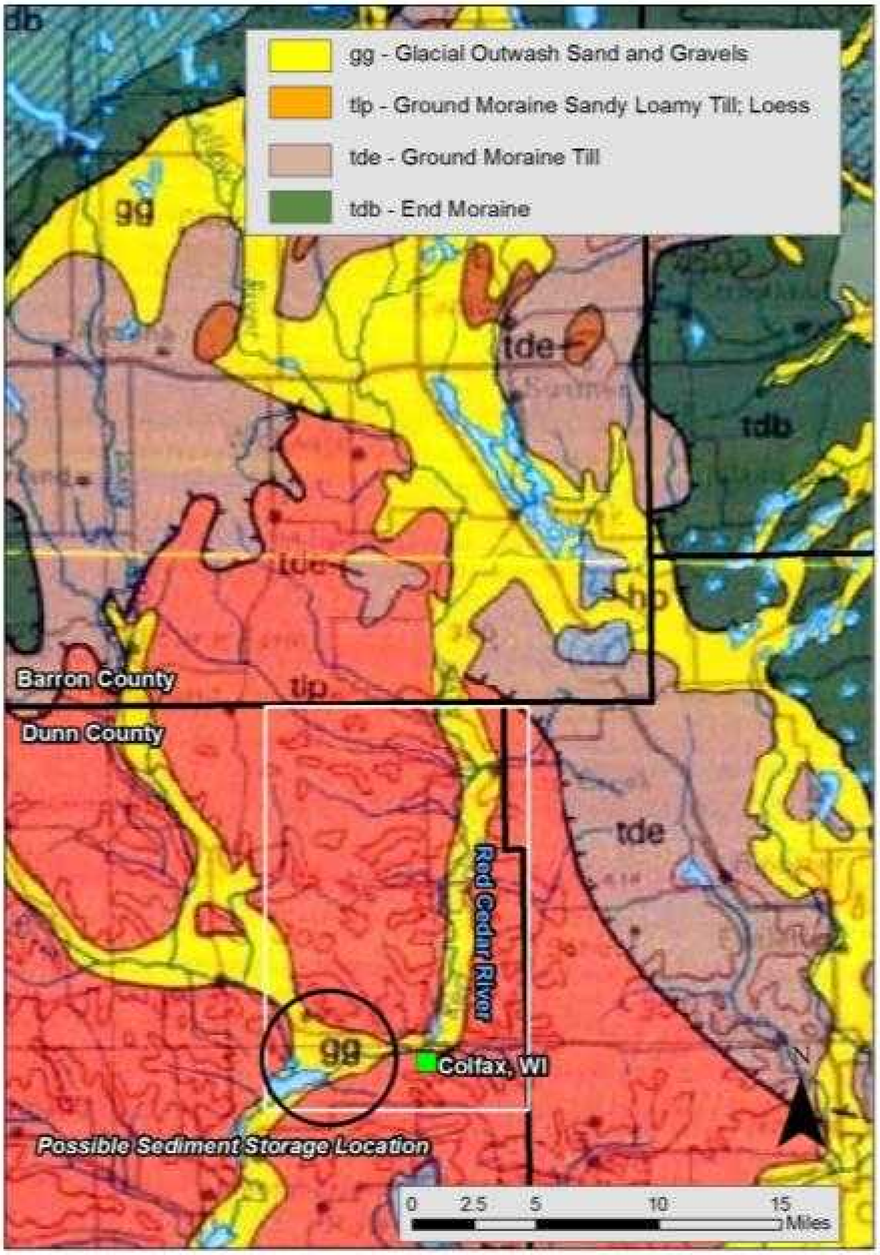


Figure 3. Quaternary Geology Map from Goerbel et al. 1983. The red box represents the study area and the black circle demarcates the confluence of the Hay and Red Cedar Rivers. Tlp – loamy soil formed in ground moraine materials, often over shallow bedrock. Gg – Glacial outwash deposits of sand and gravel.

The study area is largely focused on the southern end of the Red Cedar River, between the Dunn County Line in the north and Tainter Lake to the south (Figure 2). Along this reach, the landscape transitions from predominantly undulating till plains in the north to the more dissected, ridge and valley system more characteristic of the driftless area in the south. The hills are mantled in loamy soils formed in loess, silty and sandy alluvium, sandy and loamy colluvium, or sandy loam till (tlp; Figure 3). They range from excessively drained to somewhat poorly drained and generally have silt loam to loamy sand surface textures, moderate to rapid permeability, and moderate to low available water capacity. On the ridges, many of the soils are relatively thin over sandstone bedrock (NRCS 2004; 2008).

As glaciers retreated to the north, meltwater deposited sand and gravel along the major outwash channels, which now line the valleys of the Hay and Red Cedar Rivers (gg; Figure 3). As the rivers developed after the ice age, the channel cut through the sands and gravels, leaving the coarse material behind in terraces. The resulting bluffs are often associated with the excessively drained sand of the Plainfield soils and the sandy loam of the Forkhorn soil group which have developed in the terrace material. Stream cutting and deposition also formed swamps, sloughs, and marshes along the river floodplain. The floodplain soils formed in sandy and loamy alluvium or muck, range from moderately well drained to very poorly drained, and are subject to periodic flooding (NRCS 2004; 2008).

The surficial geology map indicates that the area enclosing the Hay-Red Cedar River confluence is wider than the valleys upstream of the confluence (Figure 3). This wider area may have allowed for additional sediment storage in this part of the system, or it may have supported a glacial lake. There is also the possibility that flood water and sediment deposition associated with alternating glacial outwash floods down the Hay or Red Cedar River forced the non-flooding branch to back up and deposit its excess sediment. This change may be partly responsible for the more active potion of the channel at the downstream end of the focus reach, but more study would be needed to understand the true cause of the increased activity.

Hydrology

A U.S. Geological Survey stream flow gage was located within the project area along the Red Cedar River near Colfax, WI (Site 05367500; http://waterdata.usgs.gov/wi/nwis/), located upstream of the village on County Highway M (Figure 2). The gage provided annual maximum flow (peak flow) data from 1914 through 1990 (Figure 4). More recent peak flow data were estimated using a regression equation formed by comparing measured floods on the Red Cedar River stream gage data and data for the same floods (by year) at an existing U.S. Geological Survey stream gage on the Hay River at Wheeler, WI (Site 05368000). The latter estimates appear to omit at least one significant flood in 2010 (Styer, personal communication).

Most of the historic annual peak flows range between approximately 2,000 and 10,000 ft^3/s (cfs), with large floods exceeding 15,000 cfs (1938, 1989, and 1965) and extreme floods exceeding 20,000 cfs (1934 and 1967). Table 1 provides the statistical return intervals for the annual peak floods. To estimate these flows, we fit the log-Pearson Type III (LP3) probability distribution (IACWD, 1982) to the annual peak flood data at the Red Cedar River gage. Results from similar peak flow analyses performed for FEMA (2011) are also provided in Table 1.

Figure 4. Annual peak flood magnitudes at the Red Cedar River near Colfax, WI stream gage (Site 05367500).

Table 1. Flood quantiles at the Red Cedar River near Colfax, WI stream gage (Site 05367500). The gage provided peak flow data from 1914 through 1990.

Return period (years)	1.43	2	5	10	25	50	100
Discharge (cfs)	4,310	5,680	8,910	11,300	14,600	17,250	20,055
Discharge (FEMA)				12,600		20,500	24,250

Hydraulics

The U.S. Army Corps of Engineers Hydraulic Engineering Center's River Analysis System (HEC RAS) model (HEC, 2010) was developed using total station survey data collected by the TMLIA and Dunn County Land Conservation Division in the autumn of 2013. The data were only collected along the section of river adjacent to the Colfax wastewater treatment facility, with the exception of one site downstream of Dobb's Landing. The reach included a bluff on the south side of the channel and extensive floodplain on the north, as well as a transition to a riffle and island at the downstream end. The bed material ranged from sand to coarse gravel, with small cobbles at the riffle head. Although the site may not be representative of the entire system, its similarities to other observed reaches allow for some insight into general hydraulic conditions.

The data were processed in both ArcGIS and Microsoft Excel in order to obtain distances between survey points and cross sections. In addition to the cross sections, survey points included thalweg positions used to create a reach alignment and longitudinal profile. Reach lengths between cross sections were measured along this alignment, as were overland flowpath distances.

In HEC-RAS, roughness values, (Manning's n; a measure of resistance to flow based on channel and bed materials and form) of 0.038 were assigned to the channel and 0.1 to floodplain. The channel roughness values were based upon Arcement and Schneider's (1989) predictions for gravel bed channels with moderate irregularity, little variation in channel cross section, and minor obstructions. In the floodplain, the roughness values were consistent with minor irregularities and obstructions and large vegetation (vegetation greater than floodplain flow depth).

The cross section geometry used in the model provided a conservative estimate of maximum water levels as the survey data was limited to the bankfull channel and flow above the bankfull elevation was not allowed to spill onto the entire floodplain on the north side of the channel (Figure 5). Consequently, predicted water surface elevations from the model were valid only up to the floodplain elevation. Above this elevation, the predicted water surfaces were artificially higher. The results of the hydraulic model indicate that the channel has a flow capacity approximating the 2 year return interval flood (Figure 5), which is within the expected range for gravel bed rivers.

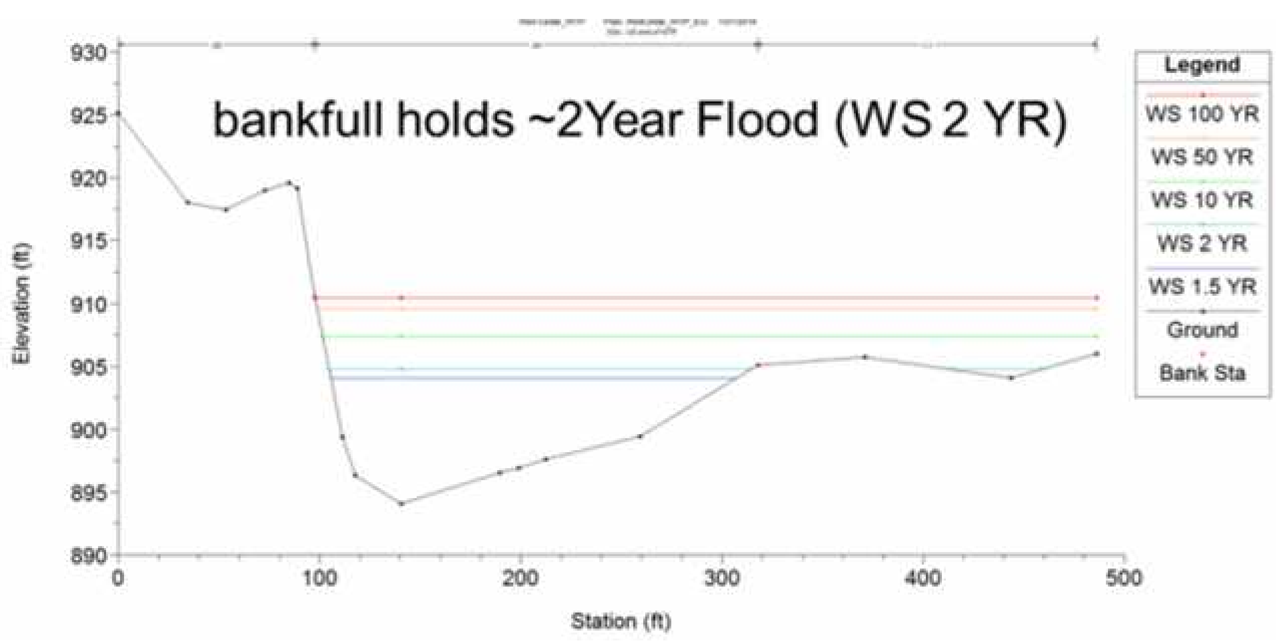


Figure 5. A cross section from the HEC RAS model at the upstream end of the wastewater treatment facility reach. Note that the channel bank tops (red dots) are reached during the 2-year flood. At the 100-year flood, less than 4 feet of water is on the floodplain.

In the waste water facility reach, the channel generates between 0.3 and 1.0 lbs/square foot of shear stress on the channel bed during a typical flood event (1.5 -2 year return interval; Figure 6). This shear stress can initiate transport of coarse gravel along most of the bed, and small cobbles at the head of the downstream riffle (station 220; estimated by Shields parameter; Julien, 2010). At larger flows (e.g., 50 – 100 year return intervals), the maximum shear stresses shift upstream and are capable of moving small to moderate sized cobbles. Overall, the HEC RAS analysis indicates the channel and bed sediment are, in general, adjusted to the hydraulics of *this reach*.

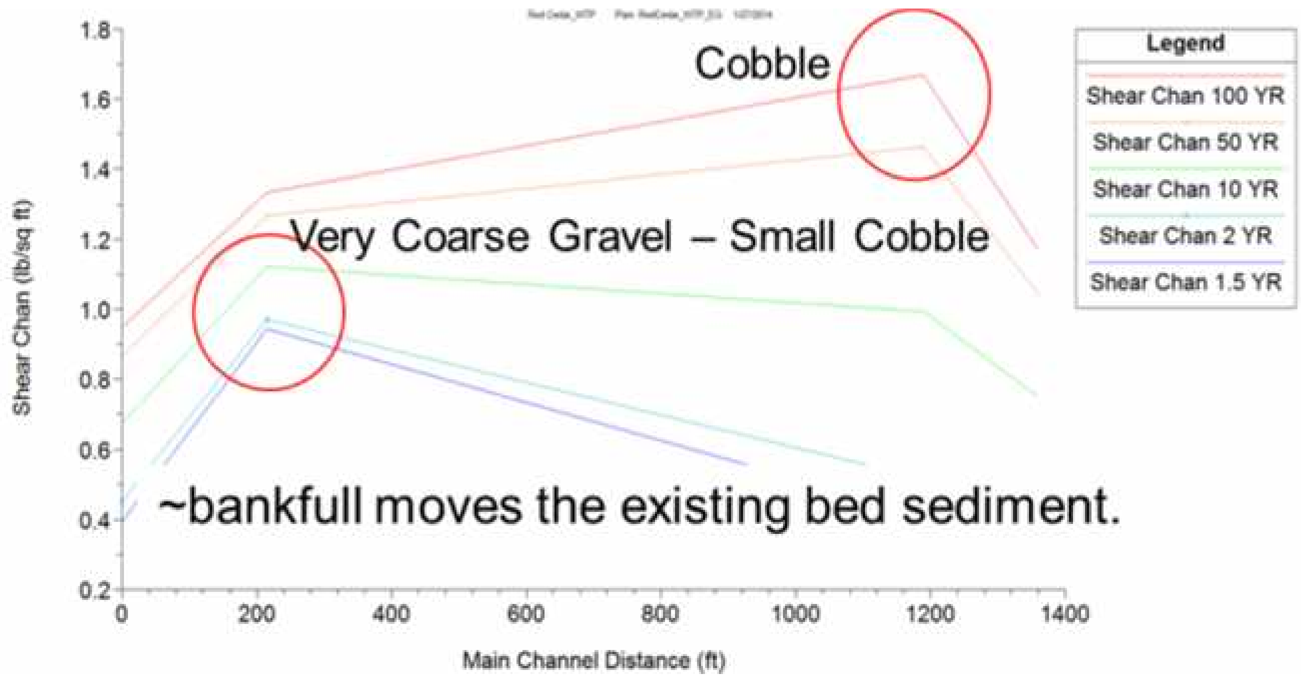


Figure 6. Shear stress results from HEC RAS model. At floods with recurrence intervals of at least 5 years, the shear stresses are large enough to mobilize coarse gravels. Extreme floods can move larger cobbles.

GEOMORPHOLOGY AND BANK EROSION

Rivers and streams evolve and adjust to efficiently pass the sediment and water delivered them from upstream. When the energy associated with the flow and channel slope balance the sediment load and bed material size, the channel is considered stable and in equilibrium (Figure 7). Although resilient, large or consistent changes in flood flows related to climate or management (e.g., dam operations) will likely result in a change in channel dimensions to accommodate the new conditions. Increases in flow will lead to erosion and a larger channel, and diminished flows will result in deposition and a smaller channel. Similarly, increases in sediment delivery will usually result in channel deposition and a decrease in sediment delivery often results in erosion along the bed and banks (Figure 7).

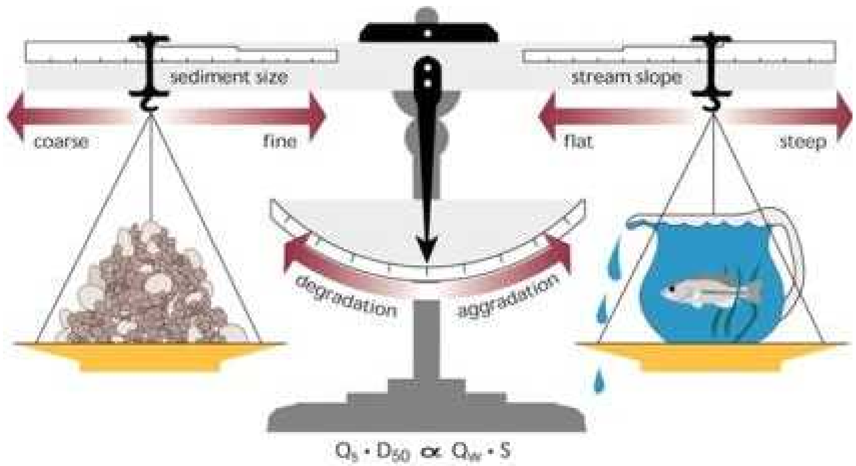


Figure 7. Lane's Balance – Channels in equilibrium balance their slope and flow capacity with their sediment load and sediment size.

Excessive channel migration or bank erosion can be a symptom of a hydrologic and/or sediment imbalance along a channel. Deposition in the channel often creates sand or gravel bars that force flow along banks, eroding them while creating a wider channel. Conversely, incising or downcutting channels often create over-steepened banks that result in failure. However, not all bank erosion is a sign of channel instability. Under equilibrium conditions, many channels still continually erode at the outside of bends while depositing a similar amount of material on point bars at the inside of the bends (Figure 8). This process is natural, and allows the channel to dissipate energy, maintain sediment in the channel, and yet still move stored sediment downstream. It also helps create and maintain a diverse floodplain environment.

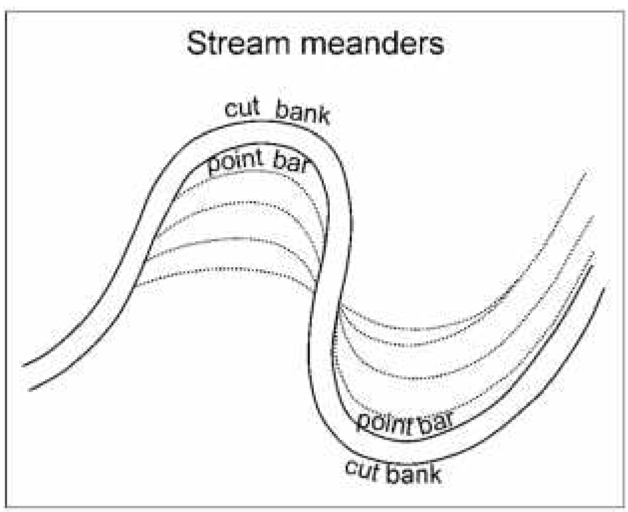


Figure 8. Typical meander bend dynamics in equilibrium systems. The channel erodes on the outside of bends and builds a point bar/floodplain on the inside of the bends.

One characteristic of meandering channels is that as bends get larger or tighter, the channel is getting longer. Therefore, the channel slope (i.e., *rise*/*run*) is decreasing because the *run* is getting larger as the *rise* stays the same. Everything else equal, a channel with a lower slope has a decreased ability to move water and sediment. When the length becomes too extreme, the meander loop is cutoff to bring the channel back into balance, either at the neck of the bend or through a chute through the floodplain, usually during a flood event. The occurrence of cutoff events, although sporadic, is a key component in the complex dynamics of meandering rivers (Camporeale, et al 2005). Cutoffs remove older meanders, limiting the number and shape of the bends, which stabilizes the river geometry around a general steady state, equilibrium planform shape. Meander bends also create a perturbation that impacts meander dynamics all along the channel. The energy configuration following the cutoff impacts meanders up and downstream, and a new pattern begins to develop in the chute channel. In these systems, the constant shifting of channel position often allows riparian flora and fauna, evolved to these conditions, to develop a diverse patchwork within the floodplain (Figure 9).

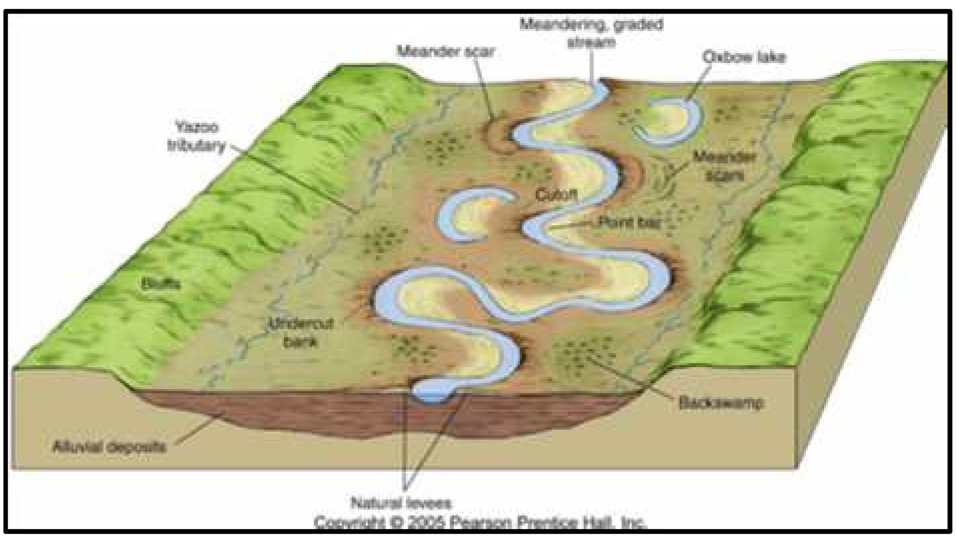


Figure 9. Typical meandering channel system with diverse floodplain habitats and consistent meander width through the valley walls.

General Fluvial Geomorphology- Red Cedar River

For this study, the Red Cedar River banks within Dunn County were digitized on a series of aerial photographs, including photos from 1938, 1974, 1992, 2005, and 2012. The channels and photographs were overlaid in a Geographic Information System project (GIS; ESRI ArcGIS 10.1) in order to observe general trends in channel behavior and provide detailed data on channel change over the period between photographs. At the outset, the digitized bank lines suggested the channel could be divided into two reaches based on the degree of channel stability and sinuosity. The change occurs at approximately the County Road MW crossing, just upstream of a former dam and impoundment (Figure 2). The upstream reach winds its way south through the farms and riparian forests of eastern Dunn County. The downstream reach bends to the west and heads through Colfax, WI, and then into Tainter Lake.

Although the upstream reach has experienced somewhat elevated rates of historic meander migration, its recent behavior (1992-2012) suggests it may be closer to achieving equilibrium with its sediment load and flows. The channel is eroding the outside of some of its bends, but it also appears that channel bars have grown and vegetated as well. In contrast, the downstream reach has exhibited much more meander migration, both recently and over the entire photo period of record. The downstream reach has also experienced multiple avulsions (i.e., chute cutoffs) where the channel has completely changed position in the floodplain. Because of the apparent differences in stability, the study focus shifted to concentrate on erosion in the lower reach (Figure 10).

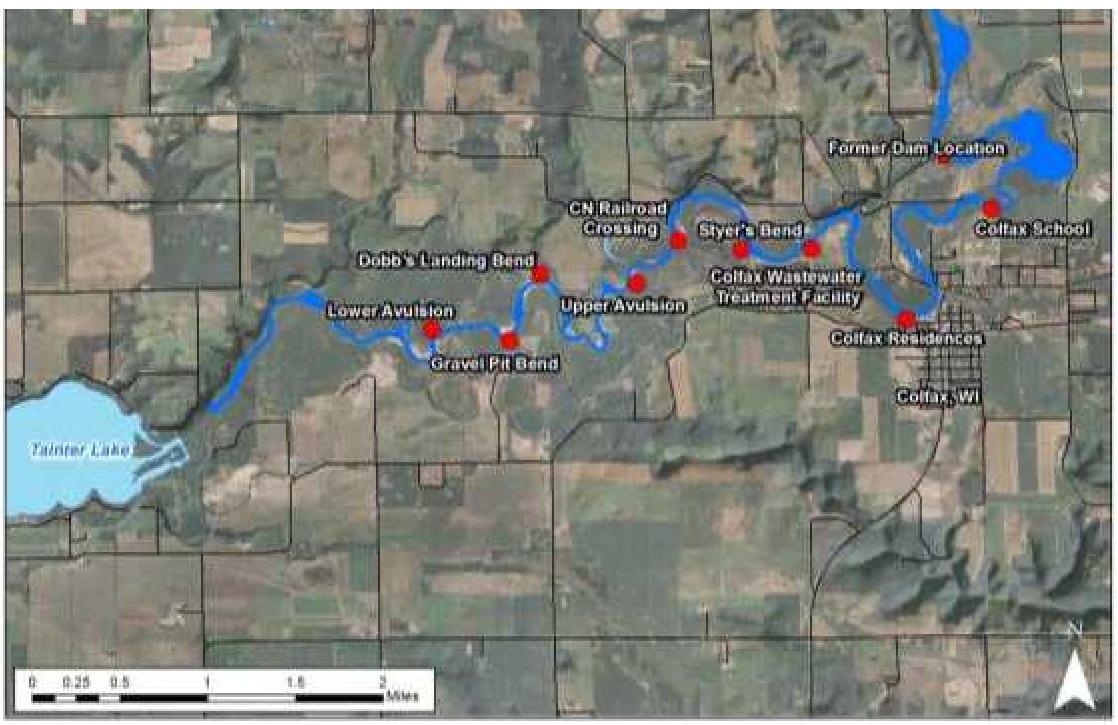


Figure 10. Active reach of the Red Cedar River between Colfax and Tainter Lake with general locations of important sites.

The sinuosity (i.e., channel length/valley length) along the focus reach increases to 1.8 compared to 1.4 along the upstream reach. Based on both field observations and the GIS data, mean channel widths are approximately 200 feet; however the GIS data predicts slightly higher mean width for the upstream reach (210 feet) than the downstream reach (195 feet). Mean bankfull depths observed at limited field locations were estimated at around 5 feet, but maximum depths are likely around 10 feet (Figure 5), and maybe higher in areas of severe scouring.

Based on survey data included in the Federal Emergency Management Agency (FEMA 2011) Flood Insurance Study for Dunn County, the average slope of the river within the county is 0.08%. There is a slight break in slope at station 224000 where the upstream reach gradient of 0.07% increases slightly to 0.09% along the downstream focus reach, further supporting the reach division (Figure 11). Along the downstream reach, the channel bed slope varies. For instance, it is relatively flat along the waste water treatment facility and downstream of Dobbs Landing Bend, but it is steeper downstream of the wastewater facility (Dale Styer's Bend) and through the straight reach where the chute cutoff occurred downstream of Dobb's Landing (Figure 12). These variations are likely related to shifts in sinuosity and sediment storage associated with cutoffs.

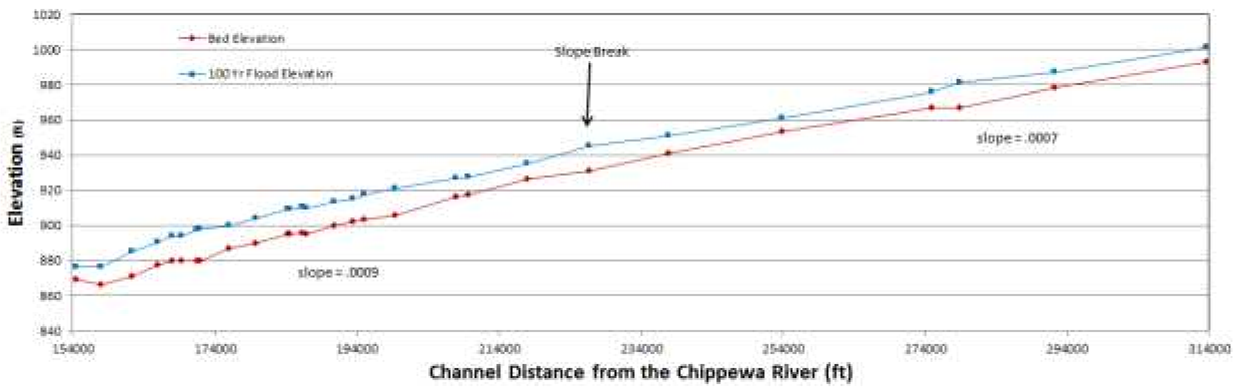


Figure 11. Long Profile of the Red Cedar River through Dunn County, WI. "Flood Elevation" represents the statistical 100 year return interval flood (from Dunn County Flood Insurance Study, FEMA 2008).

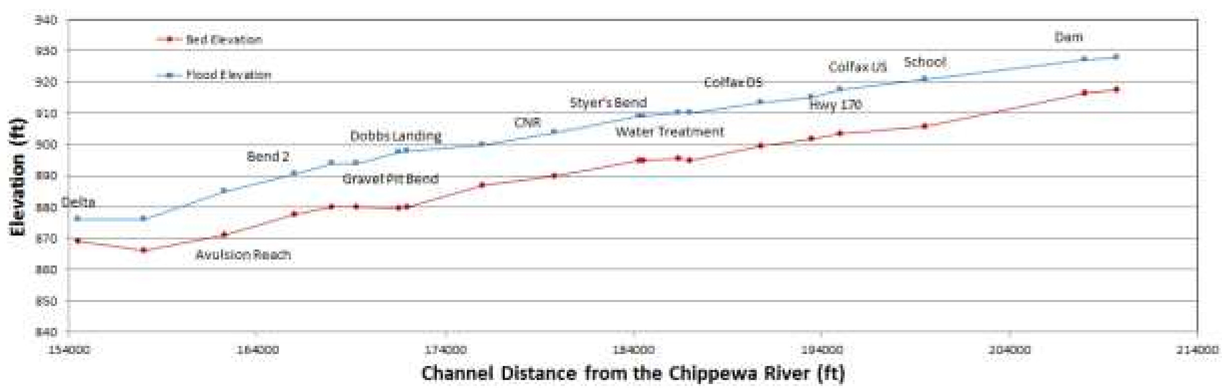


Figure 12. Long Profile of the Red Cedar River through the focus reach of the Red Cedar River study area, from the Tainter Lake delta to the abandoned dam upstream of Colfax to.

Field visits and photographs of channel margins indicate that much of the channel is bordered by lower elevation, sandy, floodplain deposits supporting riparian deciduous forests (i.e., floodplain banks). Most of the channel remains completely within the floodplain, which in the lower section features the Algansee-Kalmerville Complex of fine sandy loam and sandy loam. The soil is relatively deep and exposed to flooding and high water tables. Most of the documented erosion occurs within these soils along the floodplain banks (Figure 16).

Where the channel abuts the valley wall, it generally flows along 10 to 50 foot high, steep, sandy bluffs (Figure 13-15). The bluffs represent the exposed faces of terrace deposits comprising exposed glacial outwash sand and gravel left behind after the river downcut in response to glacial retreat. The bluff soils are primarily Plainfield Sand, with some Forkhorn Sandy Loam (Figure 16). The sandy loam often comprises the terrace treads and the exposed bluff face is usually the less developed Plainfield soil. Many erosion sites identified by the TMLIA and Dunn County Land Resource Department (2008) are associated with the bluff areas; however, erosion offsets at some of these sites, especially those characterized as sandy loam, are often less than at nearby floodplain sites.

The bluffs have little vegetation, presumably because the sand and gravel cannot hold enough moisture to support plant survival and possibly, because the surface materials are easily transported via sloughing or rotational failures, making plant establishment difficult. To some degree, the steep slopes and inability of the sand to hold water, and therefore support vegetation, lengthens recovery time and makes the banks appear worse than they actually are. However, many of the bluff sites are quite active as well, especially Dobbs Landing Bend (site 52) which contributes a significant amount of sediment to the system.

Additionally, the tops of the bluffs are commonly devoid of woody vegetation or native plants, leaving them susceptible to gullying and rilling. At many bluff erosion sites (e.g., Dobbs Landing Bend, Wastewater Treatment Facility, Co. Rd MW bridge) row crops and/or turf grass are planted to the edge of the slope, and large gullies have formed along the bluff face that likely contribute relatively large volumes of sediment to the channel in addition to the fluvial erosion. At the wastewater treatment facility, the cause of the gullies that formed in 2010 (Dale Styer, personal communication) is still unknown. They could be related to runoff, groundwater piping, or flow deflected into the bank during larger floods by adjacent bank protection works. Monitoring of the largest gully is being conducted by TMLIA.

Figure 13. Red Cedar River looking downstream along the wastewater treatment facility (left). The terraces are relatively high with sparse vegetation and the floodplains (right) are relatively low and well vegetated.

Figure 14. Red Cedar River looking downstream below the wastewater treatment facility. The terrace/bluff slopes are relatively high with sparse vegetation. The conifers on the left provide little bank protection and are being left along the bank and the opposing bar (right), which is forcing flow against the left bank.

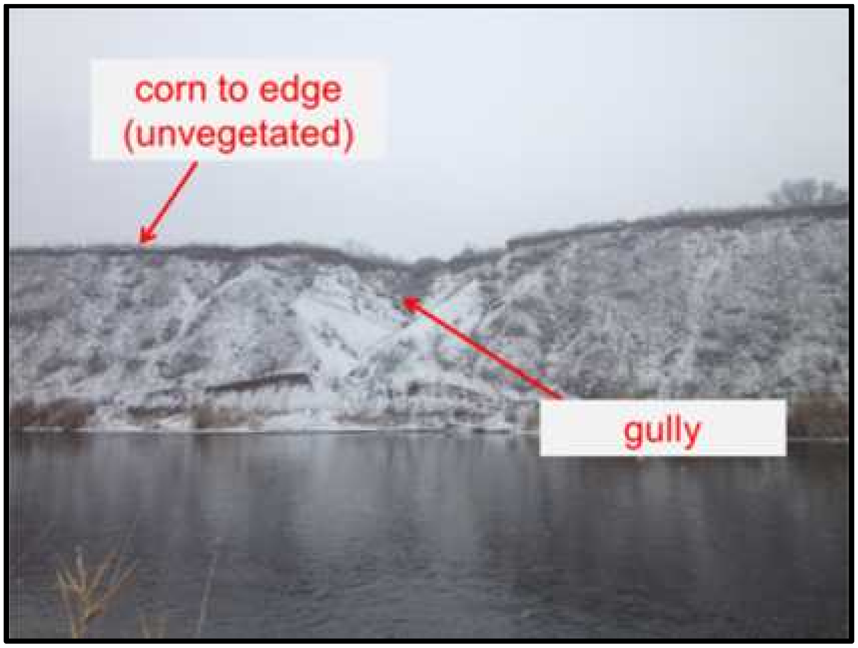


Figure 15. Red Cedar River looking downstream at the Dobb's landing bluff. The terrace/bluff slope is almost 50 feet high with sparse vegetation. Gullies have formed on the face of the bluff which is presumably related to surface runoff. The top of the slope is planted with row crops to the edge of the slope.

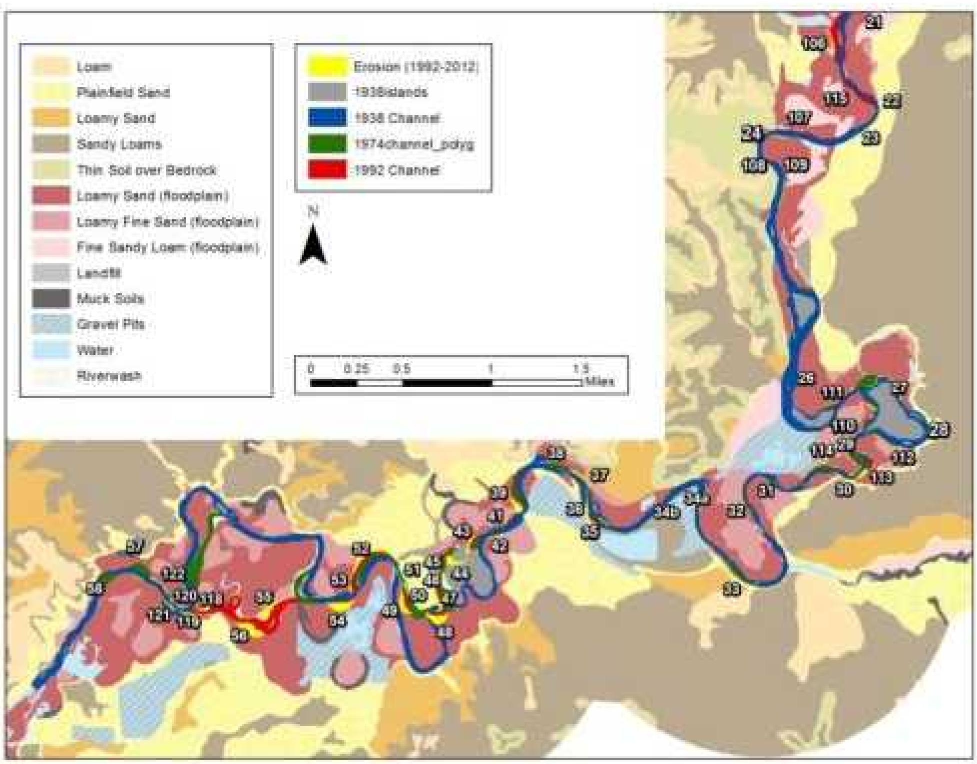


Figure 16. Soils and erosion sites along the Red Cedar River near Colfax, WI. The Channel and most of the major erosion sites are associated with floodplain sandy loams, whereas bluff faces are associated with poorly

developed sand soils.

Based on site observations, the channel bed primarily includes sand and gravel, with some cobbles, despite the sand entering the channel from bank erosion. The amount of sand increases moving downstream, where it is a large component of expanding point bars in cutoff reaches, and where it becomes the dominant bed material at the downstream end of the channel. In most subreaches of the focus channel, large woody debris does not appear to be a major component of the river environment. A few log jams were observed at individual sites, and individual fallen trees were observed on bars, but despite the relatively large amount of erosion, wood volume appears to be limited.

Red Cedar River Bank Erosion

Stream bank erosion inventories were conducted by the Dunn County Land Conservation Division (LCD) in the fall of 2006 on both the Red Cedar River and the Hay River upstream from Tainter Lake. This study estimated that the Red Cedar River was displacing 14,271 cubic yards per year and the Hay River was displacing 7,978 cubic yards per year. The eroding stream banks were inventoried for length, height, and angle of recession and located via GPS. The current study aimed to build on the LCD inventory by looking at system-wide channel planform dynamics and calculating erosion rates based on overlaying channel banklines digitized from sequential aerial photography.

Magnitudes of Erosion

Estimating erosion area and volume was a continuation of the air photo overlay used to identify erosion problems in the study reach. Banklines were drawn along the channel on each photograph, and then compared (Figure 17). Erosion areas were delineated as the area between banklines, so the 1992-2012 erosion is the planform (horizontal) area between the 1992 and 2012 banklines. The maximum offset is the maximum distance between the two banklines, and the average offset is the average distance between the lines, measured by dividing the area by the length of the bank. Erosion volumes were estimated by multiplying the erosion area by the height of the bank or bluff provided in the LCD (2006) bank inventory, or an estimated average height of 15 ft (Figure 17). The air photo based inventory conducted in this study included the entire river within Dunn County, as opposed to individual banks.

Although the air photos were matched to the 2012 image (georeferenced), they still included some error associated with the pitch and yaw of the airplane and georeferencing process. Additionally, bank delineation is often limited by the photographic scale, photo texture, differences in water level, overhanging vegetation, shadows, and other issues. The Red Cedar River banklines were digitized at a scale of 1500:1 on relatively high resolution, good quality air photos, and the channel banks are generally steep making delineation easier, but overall error is likely 10% and at individual sites where offsets are smaller than 5 feet, error might be greater than 100% (Mount et al., 2005; Swanson et al. 2010).

Overall erosion along the Red Cedar River in Dunn County amounted to 95 acres over the 1938-2012 photo period and roughly 40 acres since 1992 (Table 2). The estimated volume of sediment associated with the erosion is 3.5 million cubic yards and 1.0 million cubic yards for the 1938-2012 period and 1992-2012 period, respectively (based on field measurements of erosion site heights provided by Dunn County (2008) or an average bank height of 15 feet). In equilibrium systems, erosion should approximate deposition associated with bar and island expansion and floodplain accretion; however deposition is difficult to accurately measure on air photos and was not done as part of this study. Rough estimates suggest erosional area is about 20% less than depositional area, but the erosional volume is likely greater than that being deposited.

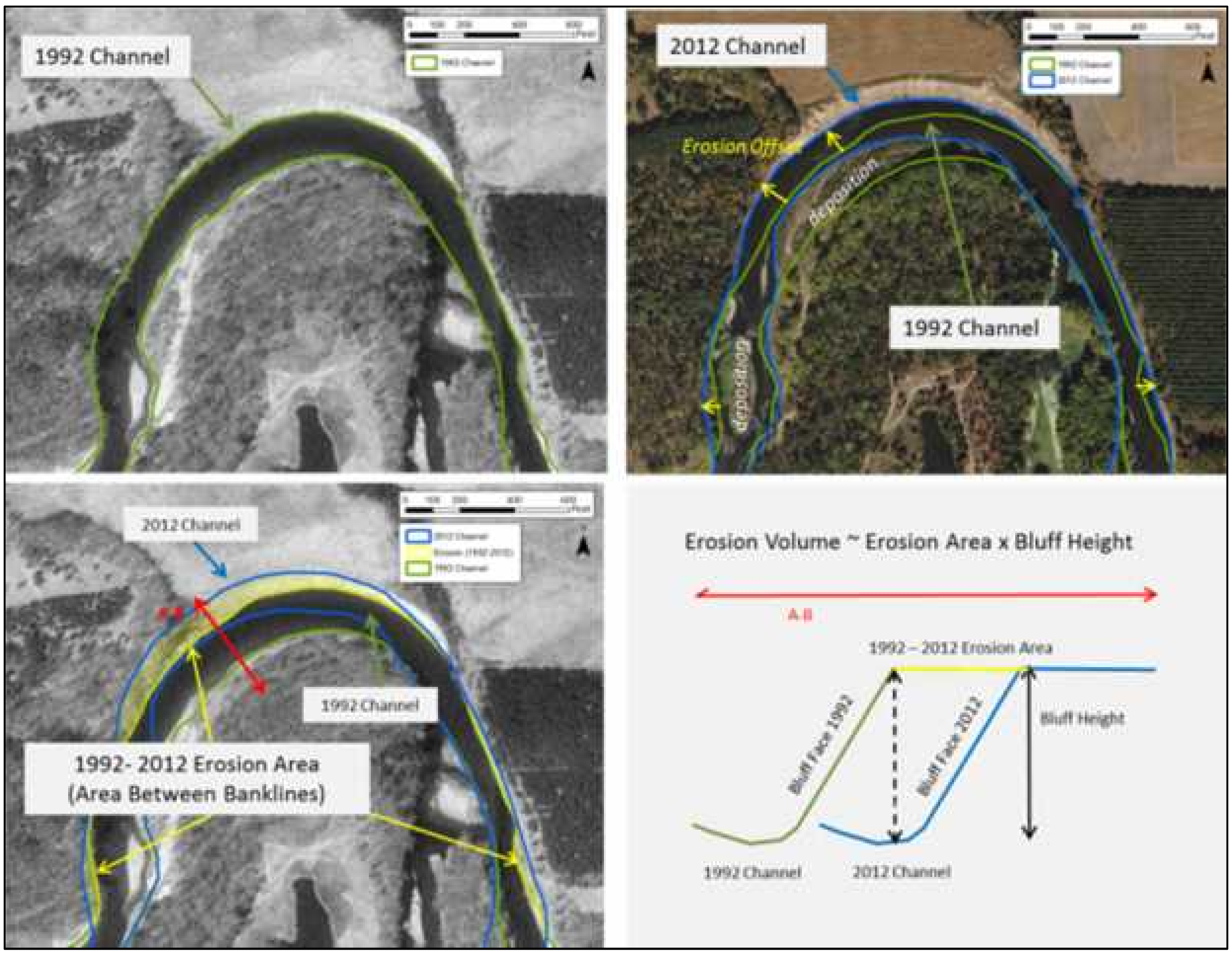


Figure 17. Estimation of Erosion Process. 1) Banklines were drawn along the channel on each photograph, and then compared. 2) Erosion areas were delineated as the area between banklines. 3) The maximum offset is the maximum distance between the two banklines, and the average offset is the average distance between the lines. 4) Erosion volumes were estimated by multiplying the erosion area by the height of the bank or bluff provided in the LCD (2006) bank inventory, or an estimated average height of 15 ft.

Average rates of offset for the 1992-2012 period were around 1 foot/year over all the delineated sites and overall rates of sediment input to the Red Cedar River were around 50,000 cubic yards/year. This estimated rate of sediment erosion is much higher than the rate predicted by the Dunn County survey of approximately 14,000 cubic yards/year. This discrepancy is largely related to a number of sites not being documented as part of the county's survey, which focused primarily on bluff erosion. Additionally, the erosion rates used in the county study, which used a maximum of 1 ft/year, were often underestimated (see Table 3 for rates at individual sites)

Table 2 also indicates that erosion rates for the 1938-1992 photo period were less than the erosion rates for the 1992-2012 period. The difference is likely due to relatively rapid adjustments occurring along the chute cutoffs in the downstream section of channel. In the earlier photographs, meander dynamics were more typical, with cutting at the outside of bends at rates near the mean. After the cutoff occurred, developing bends along the avulsions eroded material at rates almost twice those documented at bends located out of the avulsions and up to 7 times faster than the average erosion rate.

Table 2. Overall erosion magnitudes and rates for the Red Cedar River in Dunn County.

Photo Period	**Area**	**Area**	**Volume**	**Average Offset**	**Rate**	**Rate**	**Rate**
years	***square feet***	***Acres***	***cubic yards***	***feet***	***feet/year***	***acres/year***	***cubic yards/year***
1938-2012	5462600	95	3540600	57	0.8	1.3	47846
1938-1992	3692700	55	2514400	45	0.8	1.0	46563
1992-2012	1769900	40	1026200	26	1.3	2.0	51310

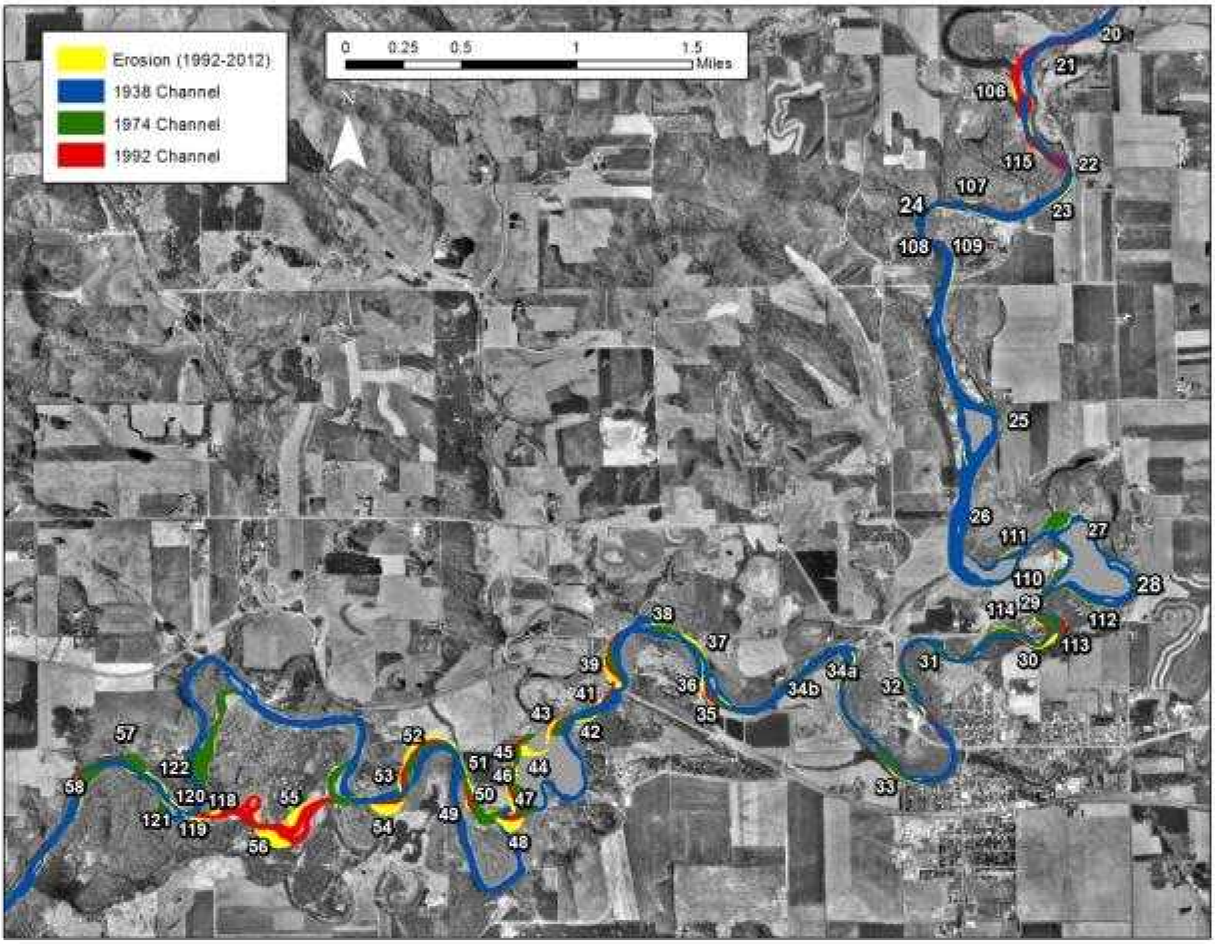


Figure 18. Erosion Sites along the focus reach of the Red Cedar River (1992-2012)

Erosion Sites and Processes

Figure 18 exhibits the major erosion areas, shown in yellow, along the lower focus reach of the Red Cedar River, through Colfax and down to Tainter Lake. The identification numbers, for the most part, are based on the erosion site numbers in the Dunn County (2006) study, although a few sites from the older study are lumped together, and there are some new sites, notably those numbered in the 100s. As suggested, erosion throughout the reach primarily occurs along the outside of meander bends. In general, the larger erosion zones begin at the downstream end of the wastewater treatment facility (Site 36) and continue to sites 57 and 58 (Figure 19).

Table 3 provides data describing erosion at the 60 bank locations with the largest amount of erosion in the reach over the 1992-2012 period. The five largest sites have all lost greater than 99,000 square feet, and the banks have retreated at an average rate ranging between 5 and 10 feet/year. The bend at Dobbs Landing, site 52, has contributed the most sediment to the system, losing an estimated 9,170 cubic yards per year since 1992, which is 17% of the estimated total. Eleven of the top 15 sites are associated with avulsions that occurred either in the 1960s or

1980s, and no site lying upstream of the focus reach makes the top twenty. In addition, sites where nearby infrastructure is a concern, such as the wastewater treatment plant (34b, 35), Colfax residences (32, 33), and the Colfax School (30) sites, have all exhibited some erosion, but at relatively low rates (<0.5feet/year). At the wastewater treatment site, riprap and vegetated groins have helped reduce erosion at the site, and similar bank protection measures have limited erosion through Colfax.

It is apparent that most of the recent erosion is concentrated in a relatively unstable reach of the Red Cedar River lying at the downstream end of the focus reach (Figure 19). In this stretch, the channel has experienced a number of chute cutoffs, with some likely occurring during the large floods in the 1960s and a substantial avulsion occurring sometime in the 1980s. The basic channel migration processes acting before or away from the cutoffs can be seen at many of the meander bends in the system (Figures 8, 9, and 21). The channel removes material at the toe of the bank, over-steepening or undercutting the upper material until it slides and (or) topples into the channel. At high, sandy, unvegetated bluffs, erosion occurs relatively easily and any vegetation on top of the banks or bluffs is moved as well. Through this action, the bends expand through the floodplain, elongating the channel and depositing finer material as they pass (Figure 21). At some point, the channel is hit by a large flood and the floodwaters find and erode a more direct path across the floodplain, often following old channel paths or side channels (Figure 21). In the case of the downstream avulsion, sediment deposition at a tight bend at the upstream end of the chute, as well as sediment inputs from several gullies along the previous channel position may have helped back up flood flows and force high water into its new position (Figure 21). Woody debris may have played a role in blocking and deflecting flow as well. The new, straighter, steeper section then begins eroding new meander bends at a relative fast rate, apparently cutting through the alluvial floodplain sand and undercutting and removing the riparian vegetation relatively easily (Figure 20 and 21). The finer material eroded from the banks (i.e., sands and silts) are carried downstream and deposited on expanding and aggrading point bars or in the Tainter Lake delta.

Channel change is generally controlled by changes in sediment or water moving through the system. However, the hydrology data do not indicate a trend in annual peak discharge and landuse does not appear to have changed much over the last 50 years. The presence of numerous meander scars in the floodplain at the downstream end of the focus reach indicates this section of the Red Cedar River has been active for over 100 years. The root cause of the changes documented in this stretch of the Red Cedar River are unclear and would require a broader investigation including a more detailed soils/geology study and more detailed examination of the impact of dam construction, logging, grazing, row cropping, and tile drainage on hydrology, channel dimensions, channel sediment, and hydraulics. Our focus is on recent trends and the future evolution of the river channel given the modern hydrologic and landuse regime.

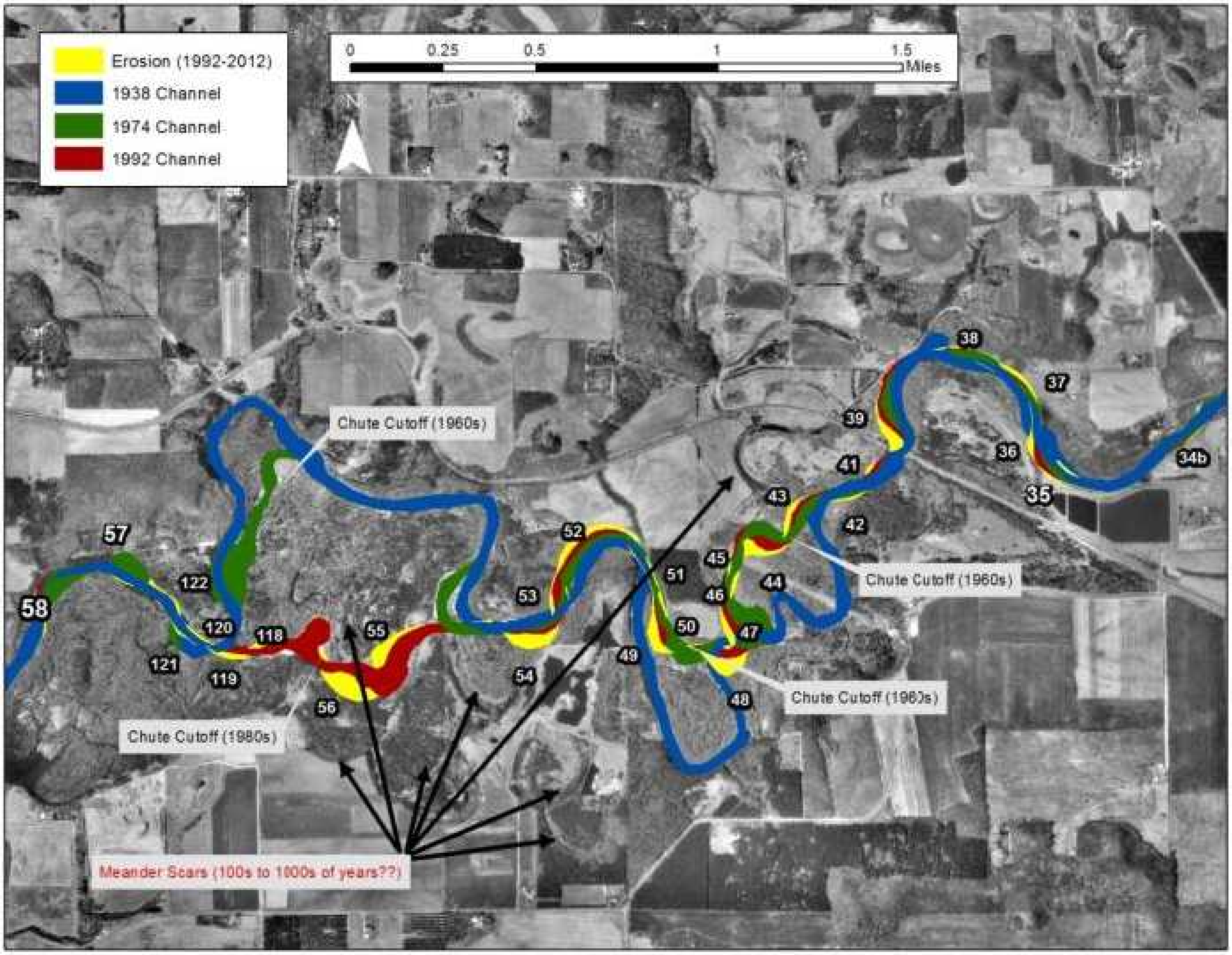


Figure 19. Erosion Sites along the focus reach, downstream of the Colfax wastewater treatment facility (1992-2012). This subreach has experienced multiple chute cutoffs since the 1960s, and relatively rapid channel adjustment along these sections since.

Table 3. Ranks, magnitudes, and rates of erosion for sites along the Red Cedar River in Dunn County. Gray rows denote sites associated with recent avulsions, white rows represent sites along the lower reach not associated with avulsions, and blue rows represent sites in the upstream reach (i.e., out of the focus reach).

Erosion Site	*Volume Rank*	*Area (ft^2)*	*Acres*	*Length (ft)*	*Max Offset (ft)*	*Mean Offset (ft)*	*Volume (CY)*	*Rate Mean Offset (ft/yr)*	*Rate Max Offset (ft/yr)*	*Rate Area (ft^2/yr)*	*Rate Volume (CY/yr)*	*Area Rank*	*Mean Offset Rank*
52	1	99034	2.3	1289	492	77	183397	3.8	24.6	4952	9170	5	7
56	2	177131	4.1	924	468	192	78725	9.6	23.4	8857	3936	1	1
48	3	109406	2.5	663	514	165	60781	8.3	25.7	5470	3039	3	2
49	4	84062	1.9	1696	404	50	46701	2.5	20.2	4203	2335	6	11
54	5	130858	3.0	809	481	162	38773	8.1	24.1	6543	1939	2	3
55	6	101776	2.3	976	371	104	37695	5.2	18.5	5089	1885	4	4
39	7	61700	1.4	758	258	95	27422	4.8	12.9	3085	1371	7	5
47	8	40950	0.9	673	136	61	27300	3.0	6.8	2047	1365	9	9
36	9	40549	0.9	1021	274	40	24029	2.0	13.7	2027	1201	10	15
44	10	63549	1.5	678	310	94	23537	4.7	15.5	3177	1177	8	6
118	11	39839	0.9	534	156	75	22133	3.7	7.8	1992	1107	11	8
51	12	19935	0.5	501	84	40	18459	2.0	4.2	997	923	17	14
119	13	32484	0.7	683	118	48	18047	2.4	5.9	1624	902	13	12
113	14	30684	0.7	925	304	33	17046	1.7	15.2	1534	852	15	20
37	15	31186	0.7	814	116	38	13861	1.9	5.8	1559	693	14	16
43	16	37411	0.9	688	157	54	13856	2.7	7.8	1871	693	12	10
27	17	17538	0.4	898	191	20	12991	1.0	9.6	877	650	20	31
30	18	6208	0.1	925	304	7	11495	0.3	15.2	310	575	43	57
106	19	18476	0.4	464	82	40	10265	2.0	4.1	924	513	18	13
33	20	9196	0.2	914	111	10	10218	0.5	5.6	460	511	32	49
2	21	26991	0.6	1261	224	21	8997	1.1	11.2	1350	450	16	27
9	22	9702	0.2	578	169	17	8984	0.8	8.5	485	449	31	36
18	23	15499	0.4	920	152	17	8611	0.8	7.6	775	431	23	35
23	24	17632	0.4	905	85	19	7837	1.0	4.2	882	392	19	32
17	25	13588	0.3	402	101	34	7549	1.7	5.0	679	377	26	19
46	26	15450	0.4	418	59	37	6867	1.8	2.9	772	343	24	17
104	27	12345	0.3	581	52	21	6859	1.1	2.6	617	343	27	28
29	28	9064	0.2	396	67	23	6714	1.1	3.3	453	336	33	26
105	29	11565	0.3	1550	567	7	6425	0.4	28.3	578	321	28	54
14	30	5502	0.1	453	30	12	6113	0.6	1.5	275	306	46	45
53	31	16009	0.4	641	83	25	5929	1.2	4.2	800	296	22	21
120	32	10319	0.2	524	49	20	5733	1.0	2.4	516	287	30	30
22	33	6136	0.1	433	78	14	5682	0.7	3.9	307	284	44	39
50	34	5408	0.1	229	45	24	5008	1.2	2.3	270	250	48	23
122	35	8791	0.2	379	66	23	4884	1.2	3.3	440	244	34	24
117	36	8681	0.2	1146	196	8	4823	0.4	9.8	434	241	35	53
34a	37	6429	0.1	1573	321	4	4762	0.2	16.0	321	238	42	60
3	38	7741	0.2	592	78	13	4587	0.7	3.9	387	229	37	42
15	39	7122	0.2	520	64	14	4220	0.7	3.2	356	211	39	40
8	40	4552	0.1	384	71	12	4215	0.6	3.5	228	211	52	46
4	41	14514	0.3	601	52	24	3763	1.2	2.6	726	188	25	22
121	42	6681	0.2	517	79	13	3712	0.6	3.9	334	186	40	43
103	43	6590	0.2	908	31	7	3661	0.4	1.6	330	183	41	56
58	44	4699	0.1	385	31	12	3481	0.6	1.6	235	174	51	44
42	45	11283	0.3	552	65	20	3343	1.0	3.3	564	167	29	29
1	46	17424	0.4	911	126	19	3227	1.0	6.3	871	161	21	33
107	47	5729	0.1	359	40	16	3183	0.8	2.0	286	159	45	38
109	48	5454	0.1	822	43	7	3030	0.3	2.2	273	151	47	58
41	49	7931	0.2	231	62	34	2937	1.7	3.1	397	147	36	18
114	50	5238	0.1	643	117	8	2910	0.4	5.9	262	145	49	50
38	51	7262	0.2	315	49	23	2690	1.2	2.5	363	134	38	25
116	52	4826	0.1	462	20	10	2681	0.5	1.0	241	134	50	48
26	53	4422	0.1	272	38	16	2457	0.8	1.9	221	123	53	37
111	54	4384	0.1	1176	104	4	2436	0.2	5.2	219	122	54	62
115	55	4173	0.1	314	23	13	2318	0.7	1.2	209	116	55	41
5	56	2723	0.1	347	60	8	1513	0.4	3.0	136	76	57	51
45	57	3969	0.1	209	34	19	1470	1.0	1.7	198	74	56	34
31	58	2315	0.1	1032	143	2	1372	0.1	7.2	116	69	58	63
20	59	2185	0.1	294	26	7	1214	0.4	1.3	109	61	59	55
34b	60	1571	0.0	149	10	11	1047	0.5	0.5	79	52	63	47
25	61	1640	0.0	261	18	6	911	0.3	0.9	82	46	60	59
112	62	1639	0.0	783	101	2	910	0.1	5.0	82	46	61	65
16	63	1584	0.0	208	20	8	821	0.4	1.0	79	41	62	52
32	64	1006	0.0	261	26	4	596	0.2	1.3	50	30	64	61
6	65	726	0.0	358	63	2	430	0.1	3.2	36	22	65	66

Figure 20. Red Cedar River at the gravel pit location downstream of the Dobb's Landing Bend (Site 54). The channel is undercutting woody riparian vegetation along the sandy floodplain bank on both sides of the river.

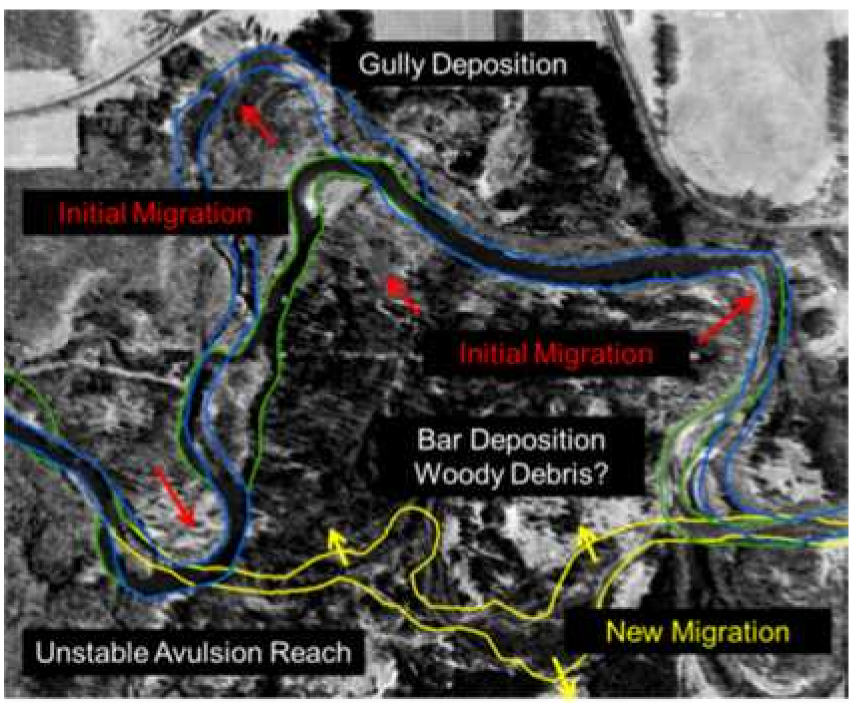


Figure 21. Channel adjustments at the downstream avulsion sight since 1938. 1938 (blue)-1974 (green)> Bends expand through the floodplain, elongating the channel and depositing finer material as they pass. 1974(green) – 1992(yellow)> The channel is hit by a large flood and the floodwaters find and erode a more direct path across the floodplain. Sediment deposition at a tight bend at the upstream end of the chute (right), as well as sediment inputs from several gullies along the previous channel position may have helped back up flood flows and force high water into its new position. 1992-2012> The new, straighter, steeper section begins eroding new meander bends at a relative fast rate.

Figure 22. The lower reach of the Hay River also appears to be active as it enters the Tainter Lake valley.

IMPACTS OF RED CEDAR EROSION

Delta Encroachment

A 2005 bathymetric study of Tainter Lake showed that 1,667 acre feet (8%) of the storage had been lost since 1960. This equals almost 2.7 million cubic yards of sediment deposited in Tainter Lake over that time period, or about 60,000 cubic yards per year. Figure 23 shows the expansion of the delta between 1938 and 2012. Although the data do not account for differences in water level, it suggests that the general planform area of the emergent delta, including distributary channels, increased from approximately 70 to 150 acres, and the delta has prograded into Tainter Lake an average of 19 feet/year (Table 4). Assuming a depth of 10 feet, the delta has stored an estimated1.3 million cubic yards of material since 1938, at a rate of 18,000 cubic yards per year. That rate increases to 32,500 CY/yr. It also appears the rate of expansion has tripled over that time. Delta expansion has diminished access to the east end of the lake and has reduced recreation activities as well.

Table 4. Estimates of delta expansion at the mouth of the Red Cedar River in Tainter Lake.

Photo Period	Area (ft^2)	Area (Acres)	Average Distance (ft)	Rate (ft/yr)
1938-1974	929000	20	370	10
1974-1992	864000	20	350	19
1992-2012	1754000	40	700	35
1938-2012	3547000	80	1400	19

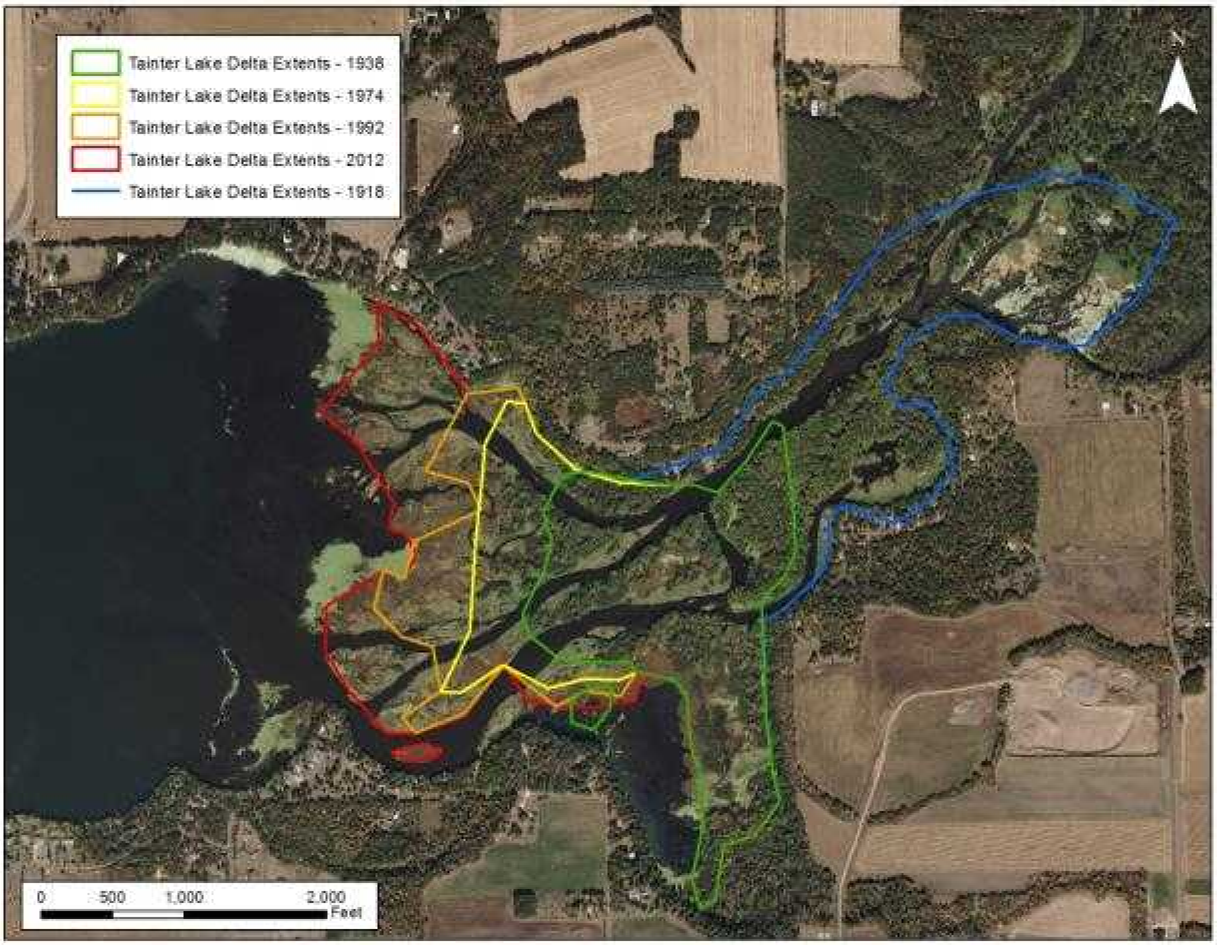


Figure 23. Expansion of the Red Cedar River delta into the east end of Tainter Lake (1938-2012).

Not all the eroded sediment from upstream ends up in the delta immediately, but estimated annual erosion volume and lake deposition rates indicate that a large percent of the material is passed through the system annually. Limiting erosion in the focus reach could slow the growth of the delta, but in order to greatly reduce the overall volume of material, work would be required over large subreaches of the channel. A long term program of bluff stabilization would have more impact on delta sedimentation than treating just a few channel locations. The possible exception is the Dobbs Landing Bend site (52), which contributes approximately 9,000 cubic yards of material to the channel per year, which is 17% of the estimated total in the study reach.

Phosphorus

Phosphorus is usually transported through river systems adsorbed to fine material such as silts, clays, and organics. It usually enters rivers via runoff, although some likely enters with eroded sediment. Modeling described later in the WDNR's 2012 Total Maximum Daily Load study for phosphorus in the Red Cedar River estimated the 9 year average total phosphorus load to Tainter Lake at 506,000 pounds per year. The inputs are primarily attributed to excessive application of manure and other fertilizers to agricultural fields, barnyard waste, and natural forest inputs. The phosphorus contributed to Tainter Lake via the Red Cedar River helps maintain elevated phosphorus concentrations in the lake (~50µg/L), which in turn, contributes to large algal blooms and vegetation growth.

In 2013, the TMLIA and Dunn County sampled bluff sediments at forested, urban, and row crop sites along the Red Cedar River focus reach for soil-bound phosphorus (i.e, soil samples, not water samples). The results showed phosphorus concentrations ranging from 79 ppm water extractable phosphorus (WEP; soil shaken in water for given time period) at the top of the slope to 17 ppm at the base, with an average concentration of 39 ppm (TMLIA 2013). Applying the mean concentration to the total estimated annual volume of erosion (1992-2012) predicts that bank retreat along the Red Cedar River contributes 5,700 pounds of phosphorus per year, or 1.1% of the expected total load (Table 5). Therefore, reducing erosion along the channel likely will not significantly impact phosphorus levels in Tainter Lake.

Table 5. Estimated Phosphorus loads attributable to Red Cedar River bank erosion based on soil concentration samples collected at the Colfax School bluff erosion site (30) by TMLIA in 2013.

	Sediment	*Sediment*	*Phosphorus*	*Phosphorus*	*Phosphorus*	
Locations	*Cubic Yards*	*kg*	*ppm (avg WEP*)*	*kg*	*lbs*	*% of total**
All Sites	51310	6.57E+07	39	2601	5723	1.1%
Dobbs Landing	9170	1.15E+07	39	465	1023	0.2%

**Water Extractable P* **506,000 lbs P*

BANK AND BLUFF EROSION SOLUTIONS

The primary performance goal for projects conducted along the Red Cedar River is to reduce erosion and downstream transport of eroded sediment. TMLIA and its project partners would like to accomplish this goal while meeting secondary aims of creating a natural looking solution that improves fish habitat.

More specifically, project criterion should include the following:

- Stabilize the toe of eroding bluffs to minimize soil loss contributing to dry granular flow and rotational failure of the upper slope (mass wasting) and encourage long-term (10+ years) vegetative stabilization of the bluff toe and face.
- Design the stabilization measures to withstand flood discharges up to 20,000 cfs.
- Allow the stream to adjust to floods at rates consistent with natural conditions
- Increase in-stream habitat complexity for fish and other aquatic and riparian habitat.

Possible erosion solutions range from traditional site treatments using large rock (riprap) to more bioengineered solutions that include the use of trees, vegetation, and rock to provide stabilization at the toe of the slope.

General Considerations for Bluff Stabilization

Bluff toe protection is constructed by building a floodplain bench that moves the toe of the slope away from the existing bluff. The floodplain bench adds weight to the bluff toe which helps to minimize mass wasting. The highest shear stresses are then encountered at the log or stone portion of the crib, and not at the bluff toe. Thus, the bluff stabilizes naturally and vegetation begins to move up the slope (Figure 24).

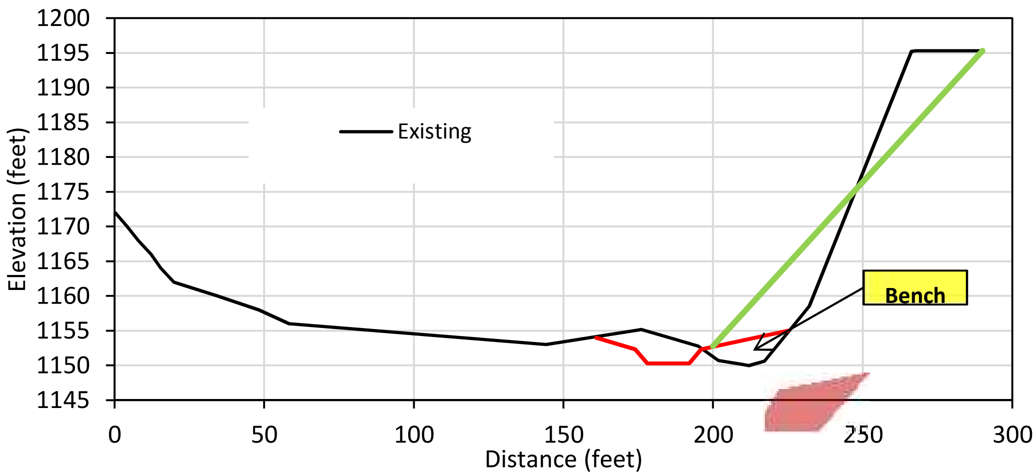


Figure 24. Existing, proposed and expected typical cross section at a typical bluff stabilization site. The existing ground (black line) shows the channel scouring at the toe of the bluff on the right side of the valley. The proposed channel (red line) will be excavated away from the bluff toe to allow room for placement of the treatmeant (riprap or cribwall) and to provide room for the upper bank material to slump over (green line).

In some cases, moving the channel away from the eroding bluff entirely may be more practical from both a construction standpoint and project effectiveness. Under this scenario, the inside bend of the meander is moved slightly inward and the excavated material is used to backfill the crib and floodplain bench (Figure 25). The constructed floodplain should then be planted with native trees, shrubs, and understory plants.

Constructing the treatment (cribwall or otherwise) will alter the dimensions of the observed bankfull channel geometry, essentially narrowing the channel. The top width of the stream will be narrowed by the width of the treatment. Typically, an equal, if not slightly larger area can be shaved from the opposing bank. In the latter case, the channel should be sized similarly, but slightly larger, than the existing channel. We propose adding this extra capacity as there is variability in the range of bankfull geometry and a larger, wider channel will initially produce less shear stress, limiting erosion concerns and trapping incoming sediment.

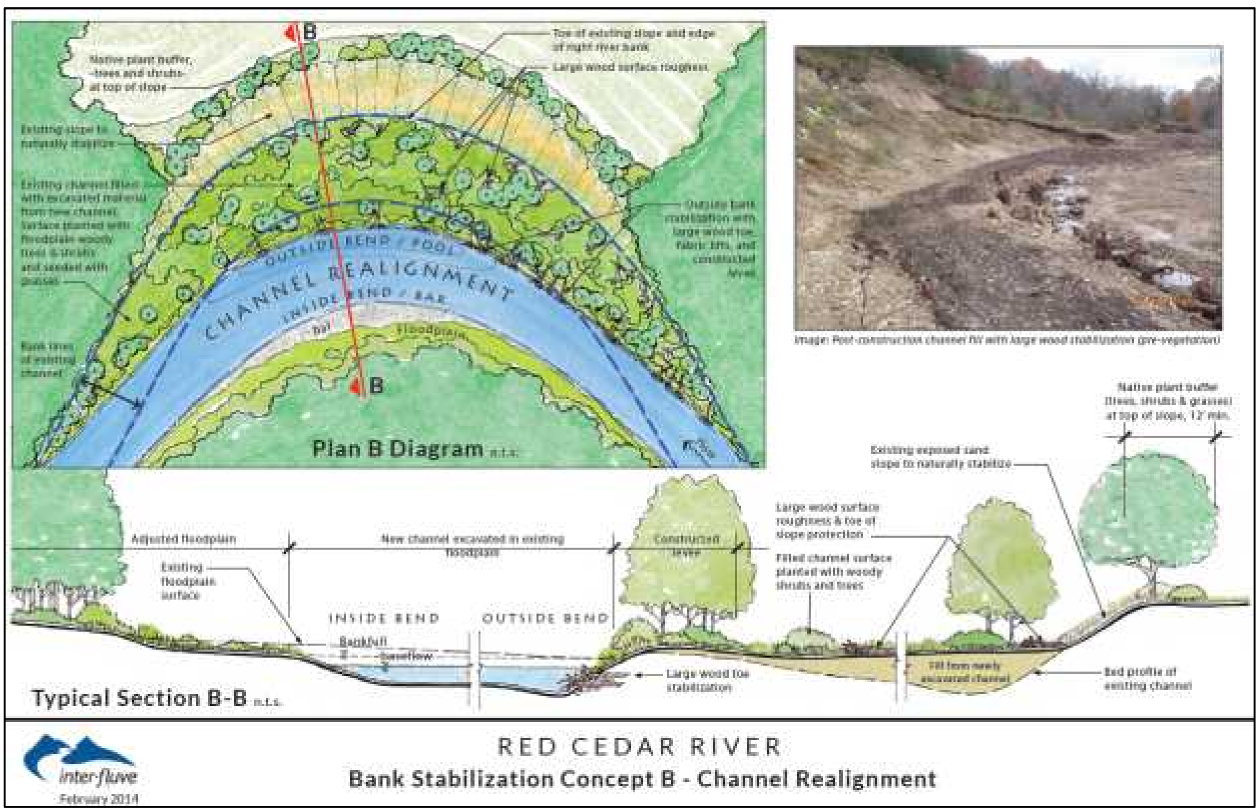


Figure 25. Planview schematic of a log cribwall stabilization project with a new channel constructed on the inside of the bend, and the existing channel filled and converted to floodplain.

Riprap Approach

Riprap can be an effective approach to stabilization as it is easily designed and contractors are familiar with its placement (Figure 26). In the past, site treatments along the focus reach of the Red Cedar River, and adjacent systems, have primarily used traditional riprap placement. Riprap has been proposed at the Colfax School site, placed at CTH Y and in Colfax, and along the wastewater treatment facility bank in conjunction with vegetated groins. The riprap appears to have been effective at the latter two sites, though thorough reviews of the projects were not conducted.

Riprap is typically placed from the top of the slope and allowed to roll down into the toe area of the slope, where stabilization is necessary. In some cases, riprap may require "keying" in to the toe to protect against scour, an element that can be investigated in design. Given the fine sands that are likely to persist at the toe of the bluff, a geotextile or similar filter design may be required to prevent winnowing of material from among the voids of the rock.

Drawbacks of utilizing riprap usually focus on the often unsightly aesthetics and detraction from the existing natural system. The latter can be somewhat mitigated by planting among the voids to develop a vegetative cover over the rock (Figure 27). Usually, the preferred plant is a live stake, easily threaded into the void spaces. However, frequent inundation often keeps perennial vegetation from establishing along the lower end of the slope and in the channel (Figure 28). Depending on water level fluctuations on the river, this may be a challenge. Habitat benefits are limited to near bank cavities for smaller fish to occupy. Wood placement along the riprap can be used to alleviate these issues.

Figure 26. **Riprap here was placed carefully from the bottom of the slope to preserve the existing trees. This may be possible at some sites where access is permits**

Figure 17: Examples of established vegetative riprap.

Figure 28: Water levels move up and down frequently at this site, keeping vegetation from developing among the riprap.

Although riprap will stabilize an eroding bank if sized and placed properly, use of rock, stone and similar “hard” materials on their own should generally be minimized in natural channel design. However, these materials should be used as part of planned structures such as ballast and anchor material for woody debris or to directly protect adjacent infrastructure (bridges, culverts, etc). Rock and riprap can also be used to construct groins or barbs into the channel. These structures protrude into the channel on an angle that forces the main part of the flow away from the bank and promotes deposition in the lee of structure (Figure 29). They have been used at the waste water treatment site in Colfax, and are a treatment option, in concert with other solutions, along the rest of the Red Cedar River.

Figure 29: Rock/riprap barbs forcing the flow to the right and catching sand on their downstream sides.

Large Wood Cribwall Approach

As an alternative or in combination with hard toe treatments like riprap, large wood placement meets multiple project performance criteria including the prevention of river migration into the bluffs, improving in-stream habitat, and allowing a more natural looking vegetated bank to develop over time.

Layout

In this case, wood placement refers to the use of engineered log cribs or log cribwalls. Cribwalls are a lattice-like structure of logs, placed both horizontally and vertically, with slash, local boulders, and soil intermixed within the log matrix (Figures 30 to 33). Logs exposed to wet/dry cycles are expected to decay in 15 to 30 years, and submerged wood can last as much as 200 years or more. As with any bioengineering treatment, by the time the structural elements have degraded, natural vegetation will have established and root structures make the bank stronger over time. Trees with vegetative reproduction qualities (e.g. black willow, cottonwood) can be incorporated into the structure, which then becomes a living entity with added structural stability from root growth. Boulders and cobbles can be added to the structure to provide self-armoring material for added toe protection long term.

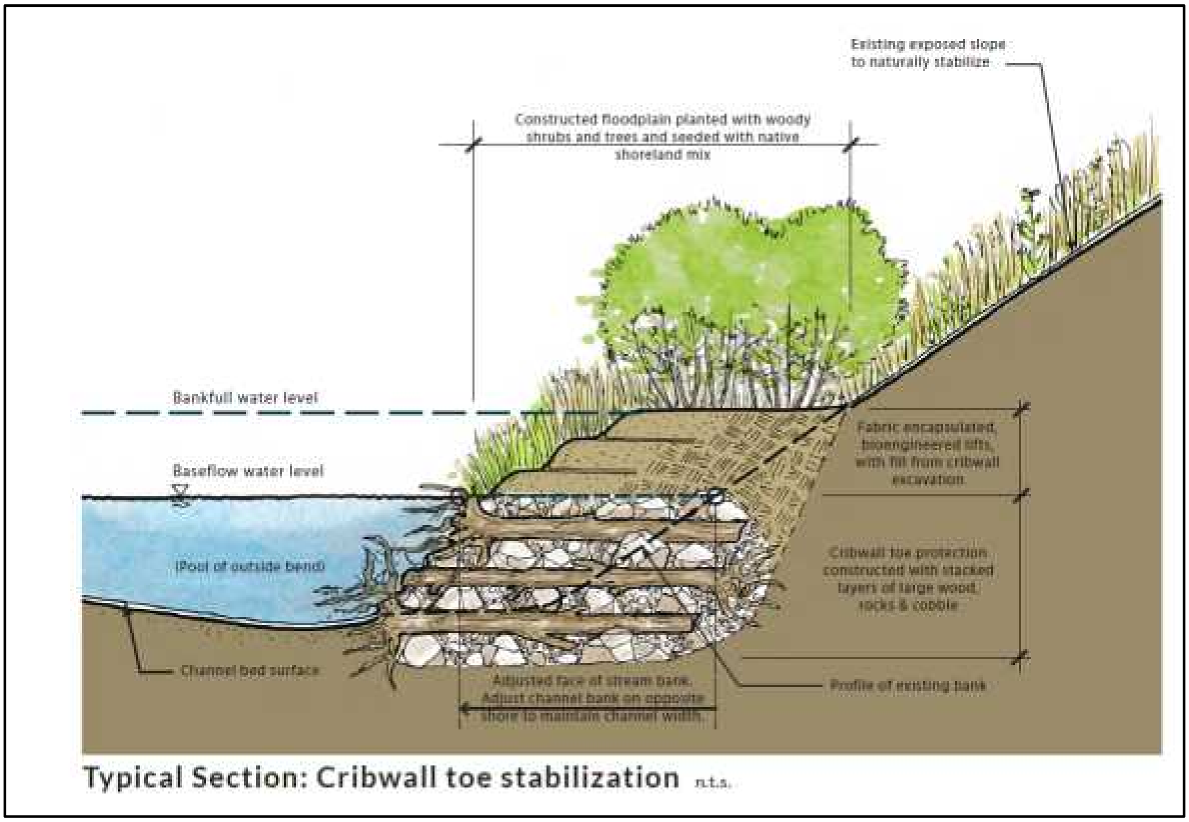


Figure 30. Schematic of a cross section through a log cribwall.

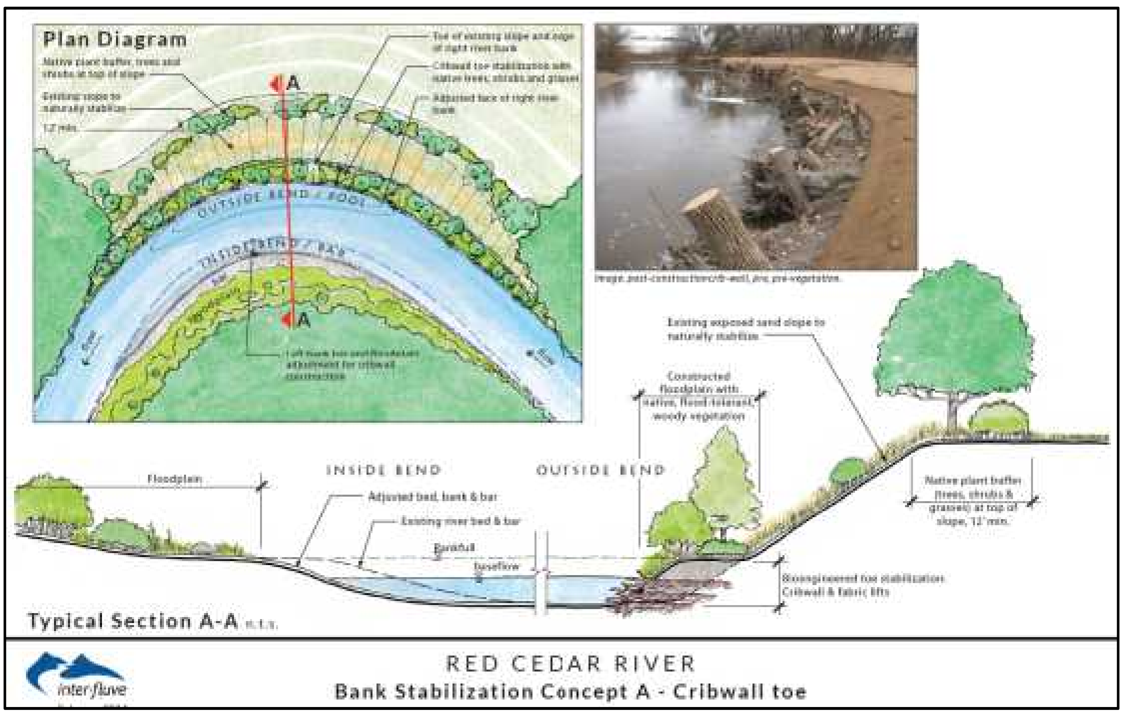


Figure 31. Planview schematic of a log cribwall stabilization project.

Figure 32. Example of a large wood cribwall under construction at the toe of a failing sand bluff in Minnesota. The space between the interlocking logs was filled by additional wood and rock, before being covered with soil. After construction, the bench will be planted with native vegetation.

Figure 33. Vegetation established on the bench and slope face behind the cribwall noted above.

Cribwalls are generally placed at the toe of the bank and extend into the channel, creating a bench along the bend (Figures 30-33). For most bluffs, the logs should extend from the beginning to the end of the exposed slope face and large wood should be tied into the exposed sediment to prevent overbank flows from scouring the area between the large wood cribwall and the bluff toe. The bottom elevations of the logs should extend below the channel bed to account for local scour and additional minor incision that may occur. With the bottom of the cribwall below the bed, the structure should not be undermined and will allow for some systemic degradation of the channel bed. Specific dimensions and plans for any proposed structures will be developed later in the planning process, during the design phase.

Finally, there are other materials and techniques that can be used to stabilize eroding bluffs and banks. Technical materials, such as geotextiles and(or) geocells (Figure 34) can be used to hold bank materials in place, although are generally not ideal for protecting the channel below the water line. Additionally, more intrusive, and more expensive, approaches can be taken, where the entire channel is realigned and regraded to a more stable form. This usually includes use of rock and wood structures for bank stabilization as well as grade control to keep the channel from downcutting. In addition to the expense, this latter option is usually not recommended along a naturally dynamic system with little adjacent infrastructure, like along the Red Cedar River.

Figure 34. Example of geocells being used along steep banks. The cells are filled with soil and then vegetated. They are usually used in concert with riprap or wood along the bank toe.

Project Risks

It is impossible to eliminate every potential risk with a proposed project. Projects are generally designed to be stable for specific failure modes; however, other geomorphic processes could occur along the Red Cedar River that result in destabilization of the stream such as extreme flood events, channel incision, or avulsions due to unpredictable natural events.

Large wood jams and riprap are usually designed to remain stable during all floods up to the estimated 100 year return interval flood (22,000 cfs in this case). In the case of riprap, the material is sized to withstand lift and drag forces generated by large flows, and they often include fabrics and filter material to slow the removal of fines behind the revetment. With woody debris, buoyant and drag forces are counterbalanced by ballast such as rock, soil, wood, driven piles and deadman anchors. Log piles as vertical pieces will be driven down adjacent to lateral pieces, preventing downstream movement and providing ballast (Figure 32). In river environments, both the riprap and wood structures have lifespans of 50 years or better, although in the case of wood, it is shorter if not permanently submerged. In both cases, woody vegetation establishment will greatly strengthen and prolong the lifespan of the structures.

Along the Red Cedar River focus reach, larger floods appear to create additional risks that are not always encountered at other sites. The main issue risk is associated with the chute cutoffs that occur in the lower valley. A new avulsion or cutoff, unrelated to the bluff protection projects, may result in the river taking a different path away from the constructed bluff or bank protection structures (Figure 35). The work could be left protecting a bank with no adjacent flow.

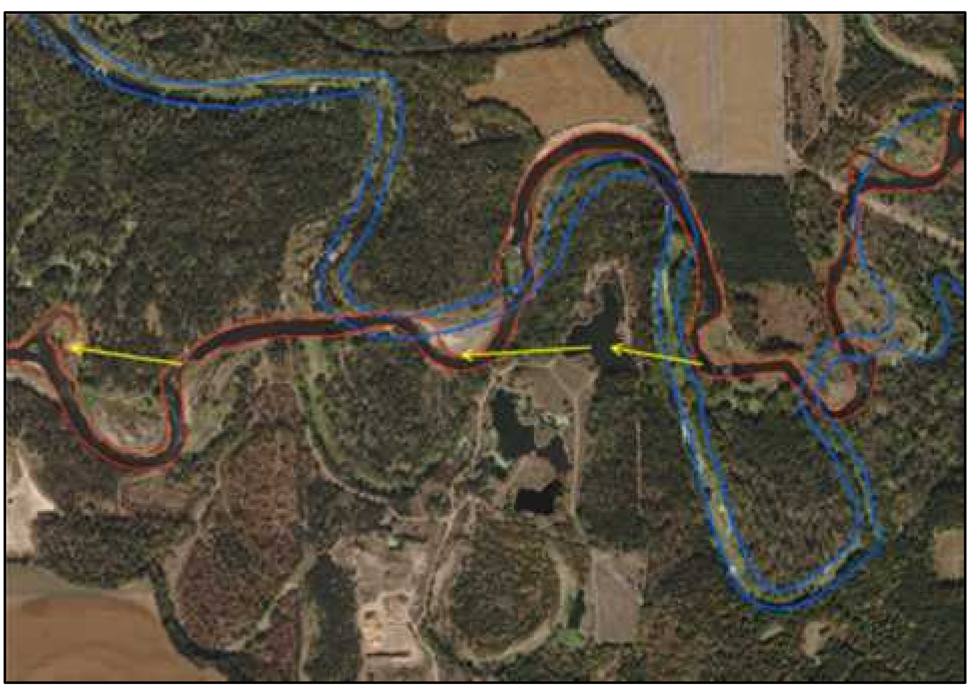


Figure 35. Potential avulsion/chute cutoff path along the existing channel. The gravel pits on the south side of the channel provide preferential pathways for floodwaters to cut a new position.

Project Costs

Costs for river projects vary widely due to a number of factors, including the availability of materials, the complexity of site access, the need and complexity of water management for in-channel work, the experience of the contractor, and economies of scale. Materials can be one of the biggest factors, in particular the local supply of wood and rock. Many projects have a ready supply of culled wood from local sources, whereas other projects require the contractor to harvest, transport, and install the wood which quickly drives unit prices to the high end of the spectrum. Understanding the logistics of locally sourcing materials will help narrow the costs specific to the Red Cedar River and move beyond the averages and ranges provided in this feasibility assessment.

Riprap or rock placement has long been the common bank protection treatment. The proposed work at the Colfax School site, which relies heavily on rock riprap, was estimated to cost around $145/cubic yard of placed rock. Table 6 provides similar estimates using an average cost, based on Inter-Fluve projects, of $120/cubic yard.

Table 6. Preliminary cost estimates for rock riprap revetment installation at specific sites along the Red Cedar River

Site	*Linear Feet*	*Bank Height (ft)*	*Live Stakes ($3/FF)*	*Placed Rock Costs ($120/CY)*	*Total Cost*
Dobbs Landing Bend	1800	8	$10,800.00	$192,000	$202,800
WWTP	1500	10	$18,000.00	$200,000	$218,000
Dale Styer's Bend	1000	10	$12,000.00	$133,333	$145,333
Colfax School	750	10	$4,500.00	$100,000	$104,500

Inter-Fluve has constructed cribwalls under a wide range and combination of circumstances. Two recent projects provide examples of the variance of costs associated with this work. Clark Creek was a low complexity project constructed by a WDNR construction crew in Fall of 2013. Logs were cut on site and staged by a private contractor at an approximate fee of $180/tree. WDNR habitat crews performed the work with their equipment and labor and Inter-Fluve provided oversight. Total treatment length was 3,100 Face Feet (treatment length x height = Face Feet) with +/- 400 logs. Cost was $32/Face Foot.

The Sheboygan River, WI project was built in Fall 2012 by a private contractor. It included a high level of complexity due largely to the need to dewater much of the site and deal with contaminated sediments. The city of Sheboygan supplied over 300 logs for the project. Contractor cost to install city supplied logs was $600/log vs. $920/log if the contractor sourced the logs, which was not done. A total of 2000 Face Feet were constructed. Costs were $90/Face Foot without the necessary dewatering and $153/Face Foot with the dewatering added.

For the purposes of cost estimating on the Red Cedar, we have assumed a mid-level unit cost of $60 /Face Foot for planning purposes. Fabric lifts are often typically added to allow vegetation establishment and prevent soil loss during floods. Fabric lifts are common components of projects and costs typically average about $25 / Face Foot for their construction (Table 7). As noted, additional design level investigation into site specific hydraulics, subsurface conditions, sources and logistics of materials, and discussion with local contractors can further refine the expected costs for specific to the sites on the Red Cedar.

Table 7. Preliminary cost estimates for log cribwall installation at specific sites along the Red Cedar River.

Site	*Linear Feet*	*Cribwall Height (ft)*	*FES Lift Height (ft)*	*Cribwall Cost ($60/FF)*	*FES Lift Cost ($25/FF)*	*Total Cost*
Dobbs Landing Bend	1800	4	2	$432,000	$90,000	$522,000
WWTP	1500	6	4	$540,000	$150,000	$690,000
Dale Styer's Bend	1000	6	4	$360,000	$100,000	$460,000
Colfax School	750	4	2	$180,000	$37,500	$217,500

The impetus for the investigation of the Red Cedar River was to slow the growth of the delta in Tainter Lake. Dredging provides a means to accomplish this goal and is included here briefly. Dredging consists of two primary types: 1) hydraulic dredging that sucks a sand/water slurry from the dredge area and pumps it to a dewatering area; and 2) mechanical dredging, which includes using a backhoe or other equipment to excavate sand and deposit it in a waste pile. Hydraulic dredging costs are dictated by the nature of the material and the associated distance and size of the dewatering area. Sand is readily dewatered and would be among the best materials to work with, reducing costs. The location of a permanent spoil area is the second component. If the delta itself could be used to decant and store the sand, costs would be lower. Dredging may be deemed a wetland impact, however, and material may require hauling to an offsite locale for disposal, thereby considerably increasing costs. The numbers used below assume $25/CY for hydraulic dredging with the spoils staying near the site, and $8/CY for mechanical dredging under the same assumption (Table 7). If material must be deposited far from the site, costs should be doubled or tripled depending on the distance.

Table 7. Preliminary cost estimates for dredging material from the Red Cedar River delta in Tainter Lake.

Dredging	*Cubic Yards*	*Hydraulic Dredging ($25/CY)*	*Mechanical Dredging ($8/CY)*
Entire Delta	1300000	$32,500,000	$10,400,000
Maintain Position (Annual)*	32500	$812,500	$260,000
Dobbs Landing Equivalent (Annual)*	9160	$229,000	$73,280

**based on 1992-2012 rates*

SUMMARY AND RECOMMENDATIONS

The Red Cedar River is actively eroding sediment from its valley, especially along the reach between Colfax, WI, and Tainter Lake. The sands comprising the bluffs and floodplain soils have little cohesion, high permeability, and little ability to hold water to support vegetation at steep slopes, and therefore are easily mobilized. The air photo analysis shows that this reach has been very active via both meander migration and chute cutoffs/avulsions over the last 75 years, and likely much longer (100s to 1000s of years). The erosion and subsequent sediment transport that would normally proceed downstream is being deposited at the upper end of the lake in the form of a delta. The process appears to be natural and consistent with the river function.

Our analysis indicates that sediment is sourced within the project reach from two primary mechanisms, bluff erosion and channel cutoffs and subsequent adjustment. Erosion is occurring among several *bluff* sites where the river is interacting with higher valley wall. For relatively minor lateral erosion or channel migration a large volume of sediment is washed into river from the tall bluffs. At sites where the channel has avulsed and either cut or reactivated a new channel, a large volume of sediment is also put into downstream transport.

What has not been quantified is the total *load* of sediment carried by the river. Additional sources for this may be sediment sourced from normal bank scour at the interface of the channel and floodplain (non-bluff sites) and sediment delivered by tributaries. Temporary and permanent sediment storage within point bar and island deposits, or on the floodplain, also affect the total load that might reach Tainter Lake in any given year. Some attempt to discern the total load contributed to the Tainter Lake delta has been made and appears to range from a low of about 15,000 CY/year to 60,000 CY/year. Sediment volume from specific erosion sites upstream of Tainter Lake is estimated at approximately 50,000 CY/year, of which about 30% is from bluff sites. The Dobbs Landing site comprises 17% of the estimated total sediment volume from the assessed erosion and 58% of the estimated erosion at bluff sites.

This report has indicated that deliberate and natural processes appear to be at work within the Red Cedar River and stopping, or even managing these processes on a large scale, will be difficult. In addition, Tainter Lake creates an unnatural condition within the river that will continue to collect sediment derived from the relatively active meander migration upstream. For this reason, we recommend sediment management efforts include an active plan within the delta itself, likely focused on dredging. However; although stopping the natural process at work above the lake isn't possible, the *rates* of sediment delivery to Tainter Lake might be influenced in the short term (decades. This action, in combination with sediment management at the delta, might present a reasonable approach to balancing the natural process with the less desirable consequences within Tainter Lake.

To begin the process of slowing the rate of sediment delivery, bluff stabilization including some combination of engineered log cribwalls, floodplain bench construction, and toe scour protection can be implemented. Bluff erosion protection does not provide protection against avulsion not related to the erosion control project. Dobbs Landing would be a primary location to begin, followed by bends adjacent to infrastructure, such as along the Colfax wastewater treatment facility (34b, 35, 36), the Colfax School (30), residences on the south side of the river in Colfax (33), or upstream of the CN Railway (39).

At all of the bluff erosion sites, we recommend providing either passive or active slope revegetation and installation of a vegetated buffer at the top of the slope. The vegetation should be native woody vegetation, forbs and grasses. Upper slope buffer vegetation will prevent runoff from concentrating; thereby limiting the potential for gullying and rilling on the slope face, and keeping extra sediment from reaching the channel. Gully erosion on the Dobbs Landing Bend (52) face has likely contributed as much sediment as many of the eroding banks elsewhere in the reach. The gullying may have been prevented by a buffer instead of the row crops that extend to the slope break. Similarly, gullying at the wastewater treatment plant may be prevented by leaving a strip of native riparian plants along the top of the slope.

Future planning and work for the Red Cedar River study area should include continued discussions with community leaders and residents about the erosion processes observed along the channel, their impacts to Tainter Lake, and potential solutions. Because of the natural activity of the channel in the study reach, alternatives and complements to bank protection projects, such as dredging and upland work should also be investigated. To advance any proposed in-channel projects, more detailed data will be required for permitting and design purposes. This information may include site specific material availability and costs, survey data, and hydraulic modeling. A broader inquiry into how projects will affect upstream flood elevations will also likely be required.

REFERENCES

Arcement, G.J., and V.R. Schneider. 1989. Guide for selecting Manning's roughness coefficients for natural channels and flood plains. U.S. Geological Survey Water-Supply Paper 2339.

Camporeale, C., P. Perona, A. Porporato, and L. Ridolfi. 2005. On the long-term behavior of meandering rivers. Water Resources Research, 41: W12403, doi:10.1029/2005WR004109

D'Aoust, S., and R.G. Milar. 2000. Stability of ballasted wood debris habitat structures. Journal of Hydraulic Engineering, 126(11): 810-817.

Dunn County Land Conservation Division. 2006. Tainter Lake Basin River Inventory Study.

Federal Emergency Management Agency (FEMA). 2011. Flood Insurance Study for Dunn County, WI.

Gorbel, J.E., D.M. Mickelson, W.R. Ferrand, L. Clayton, J.C. Knox, A. Cahow, H.C. Hobbs, and M.S. Walnut. 1983. Quaternary Geologic Mpa of the Minneapolis Quadrangle, United States.

Gurnell, A.M., H. Piegay, F.J. Swanson, and S.V. Gregory. 2002. Large wood and fluvial processes. Freshwater Biology, 47: 601-619.

Hydrologic Engineering Center (HEC). 2010. HEC-RAS: River analysis system. US Army Corps of Engineers, Version 4.1.

Interagency Advisory Committee on Water Data [IACWD]. 1982. Guidelines for determining flood flow frequency: Bulletin 17B of the Hydrology Subcommittee. U.S. Geological Survey, Office of Water Data Coordination, Reston, VA.

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

Mount, N.J., Louis, J., Teeuw, R.M, and Stott, T. 2003. Estimation of error in bankfull width comparisons from temporally sequenced raw and corrected aerial photographs. Geomorphology 56.1: 65-77.

Natural Resource Conservation Service (NRCS). 2004. Soil Survey of Dunn County, WI., United States Department of Agriculture, Natural Resources Conservation Service,in cooperation with the Dunn County Land Conservation Department and the Research Division of the College of Agricultural and Life Sciences, University of Wisconsin. Prepared by Theron Meyer.

Natural Resource Conservation Service (NRCS). 2008. Rapid Watershed Assessment – Red Cedar River Watershed.

Swanson, B.J., G.A. Meyer, and J. Coonrod. 2011. Historical channel narrowing along the Rio Grande near Albuquerque, New Mexico in response to peak discharge reductions and engineering: magnitude and uncertainty from airphoto measurements. Earth Surface Processes and Landforms 36.7: 885-900.

Tainter /Menomin Lake Improvement Association. 2013. Laboratory report on sediment phosphorus concentrations from UW Agricultural Extension Laboratory, Menominie, WI.

Wisconsin Department of Natural Resources (WDNR). 2014. The ecological landscapes of Wisconsin:an assessment of ecological resources and a guide to planning sustainable management.Wisconsin Department of Natural Resources, PUB-SS-1131 2014, Madison.

Wisconsin Department of Natural Resources (WDNR). 2012. Phosphorus Total Maximum Daily Loads (TMDLs) Tainter Lake and Lake Menomin, Dunn County, Wisconsin. Wisconsin Department of Natural Resources,Western District, Eau Claire WI. May 31, 2012.

GLOSSARY

Aggradation

The increase in land elevation due to the deposition of sediment. Aggradation occurs in areas in which the supply of sediment is greater than the amount of material that the system is able to transport

Alluvium

The loose, unconsolidated sediment which has been eroded by a stream or river, transported and reshaped, and then redeposited downstream.

Avulsion

The rapid abandonment of a river channel and the formation of a new river channel. Avulsions occur as a result of channel slopes that are much lower than the slope needed to maintain sediment transport and to efficiently pass flood flows.

Bankfull

The bankfull stage is associated with the flow that just fills the channel to the top of its banks and water begins to overflow onto the floodplain. It is often associated with flows that occur every 1.5 to 2 years, on average. Bankfull depth, height, width, slope, etc. are the characteristics of the channel at bankfull stage.

Colluvium

The loose, unconsolidated sediments that have been deposited at the base of hillslopes by non-stream associated hillslope processes, such as sheetwash, slow continuous downslope creep. Materials are usually a wide range of sizes.

Confluence

The junction where two rivers or streams join to become one.

Cutbank

The outside bank of stream or river bend which is continually undergoing erosion.

Cutoff

A meander cutoff occurs when a meander bend in a river is breached by a shorter channel that connects the two closest parts of the bend. This causes the flow to abandon the meander and continue straight downslope. Cutoffs are a natural part of the evolution of meandering rivers Avulsions, or chute cutoffs, are channels that form as meander cutoffs over relatively long distances, as opposed to only at the neck of the meander bend. The new channels usually capture an existing low point in the floodplain. The stagnant part of the river abandoned after the cutoff event will sometimes form an Oxbow lake.

Degradation

The lowering of a stream or river bed or floodplain through erosional processes. Degradation is characteristic of channel networks that are transporting more material than they are depositing.

Delta

A landform that occurs where the river flows into an ocean, sea, estuary, lake, or reservoir. The change in flow velocity (i.e., less energy) as the channel enters the larger waterbody results in the relatively rapid deposition of the materials carried by the river.

Deposition

The accumulation of sediment left behind as forces responsible for its transportation are no longer sufficient to overcome the sediments' weight and the friction with the bed.

Driftless Area

A region of Wisconsin, Minnesota, and Iowa characterized by deeply carved river valleys in bedrock valleys. The area's terrain results from escaping glaciation in the last glacial period.

Erosion

The process by which soil and rock are removed from hillslopes and floodplains by wind or water flow, and other activities. It general, erosion occurs when the driver, such as water flow, has enough energy to overcome the weight, friction, and attachment forces holding sediment or rock particles in place.

Eutrophic

The ecosystem condition where the addition of nutrients (e.g., nitrates and phosphates) to a waterbody leads to negative impacts. The impacts often include algal blooms, which result in oxygen depletion, which in turn, reduces productivity and diversity for other species such as fishes and macroinvertebrates.

Impoundment

A lake or pond formed behind a dam.

Loam

Loam is soil composed of sand, silt, and clay in relatively even proportions. Loam is considered ideal for agricultural uses because it retains nutrients well and retains water while still allowing excess water to drain away.

Loess

Sediment derived of accumulated fine, wind-blown silts and fine sands. They often form fine soils well suited to agriculture.

Meander Bend

A bend in a watercourse or river generally formed when the moving water in the river erodes the outer banks and sediment is deposited along the inner part of the river where the flow has less less energy .

Moraine

The accumulation of glacially eroded material. In ground moraines the till is left behind as the glacier rapidly retreats. They are usually characterized by gently rolling hills or plains. End moraines represent the maximum advance of a glacier. They are areas where the edge of the glacier was generally in the same place over a relatively long period, so the material moved in the ice, which generally acts as a conveyer belt for sediment, accumulated to form relatively high ridges and hills when the ice receded.

Permeability

The ability for water to move through a rock or soil.

Point Bar

A depositional feature made of sand and gravel that accumulates on the inside bend of streams and rivers, where the energy is reduced. Under equilibrium conditions, a point bar should grow at the same rate as the erosion on the opposing cutbank.

Reservoir

A lake or pond formed behind a dam

Return/Recurrence Interval

An estimate of the likelihood of an river flow (e.g. flood) to occur. It is a statistical measurement typically based on historic data denoting the average recurrence interval over an extended period of time, and is usually used for risk analysis. Channels are thought to evolve to pass annual floods with a 1.5-2 year return interval.

Riffle

A short, relatively shallow and coarse-bedded length of stream over which the stream flows at higher velocity and higher turbulence than adjacent stream sections.

Shear Stress

The force per area traveling parallel to the surface of the material. In rivers, it is primarily associated with the depth of slope of the flow. When the combination of the water's depth and gradient are large enough to overcome the weight, friction, and attachment forces of the sediment it flows over, then sediment transport can occur.

Sinuosity

A measure of a river or stream's bendiness or curviness based on the ratio of its channel length and its valley length (a perfectly straight channel has a sinuosity of 1).

Terrace

The remnants of a former floodplain surface of a stream or river formed by the downcutting of a river or stream channel, followed by the formation of a new river and floodplain system at a lower elevation, and the abandonment and lateral erosion of the former floodplain. Bluffs are usually areas where the existing channel is eroding terrace sediments.

Thalweg

The line of lowest elevation point along a river or stream, or the deepest part of the channel along its path.

Till/Glacial Till

Unsorted sediments deposited directly by glaciers as they retreat. Till materials are usually fine grained but vary widely from clays to mixtures of clay, sand, gravel and boulders.

Water Capacity

The amount of water that a soil can store that is available for use by plants.

APPENDICES

Appendix A. Red Cedar River Erosion Partnership Team

Appendix B. Red Cedar River Watershed

Appendix C. Red Cedar River Study Area, Dunn County, Wisconsin.

Appendix D. Erosion Sites along the upstream reaches of the Red Cedar River (1992-2012)

Appendix E. Erosion Sites along the focus reach of the Red Cedar River (1992-2012)

Appendix F. Erosion Sites along the focus reach, downstream of the Colfax wastewater treatment facility (1992-2012)

Appendix G . Soils and erosion sites along the Red Cedar River near Colfax, WI.

Appendix H. Schematic of a cross section through a log cribwall.

Appendix I. Schematic of a cross section through a log cribwall.

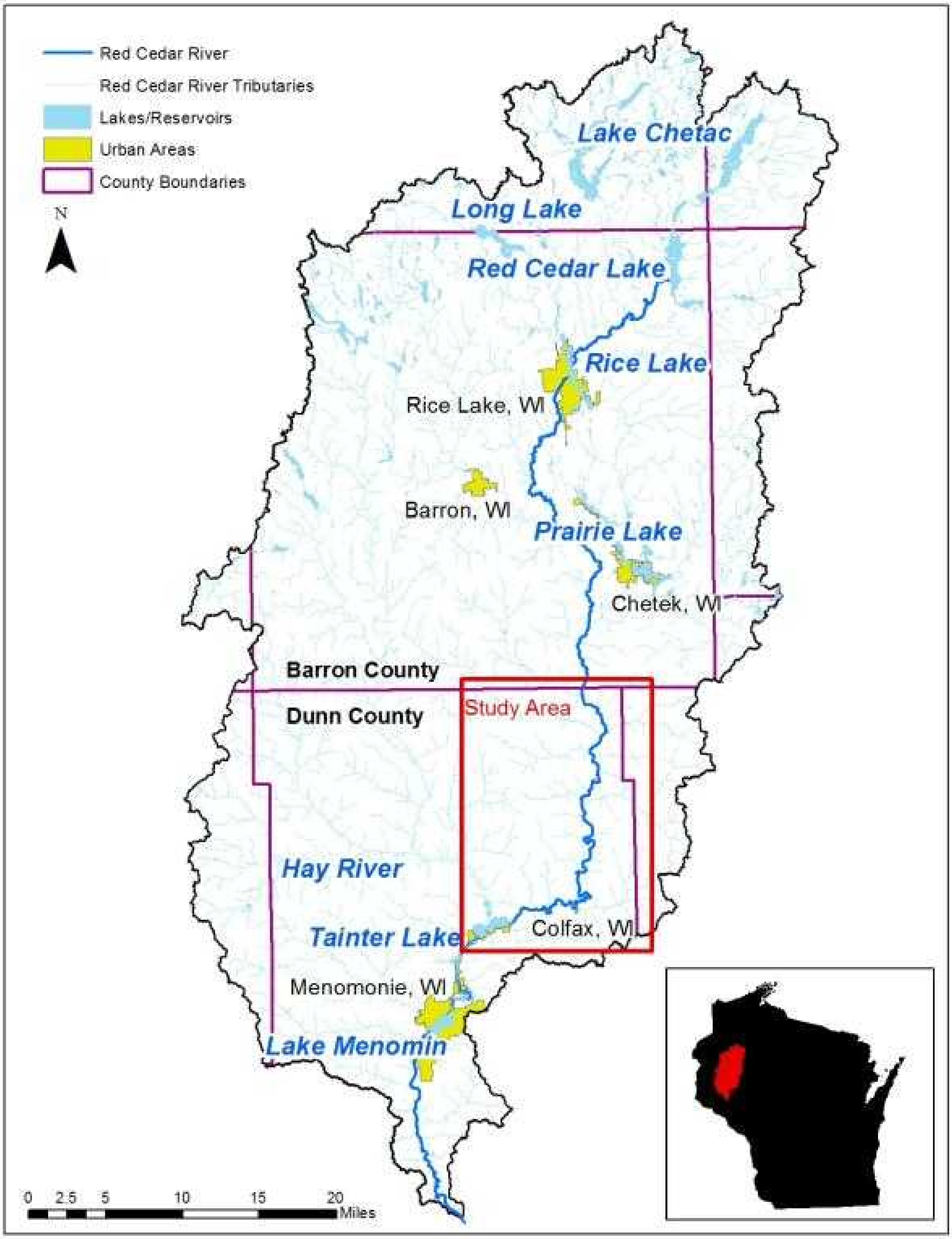
Appendix J . Planview schematic of a log cribwall stabilization project.

Appendix K. Planview schematic of a log cribwall stabilization project with a new channel constructed on the inside of the bend, and the existing channel filled and converted to floodplain.

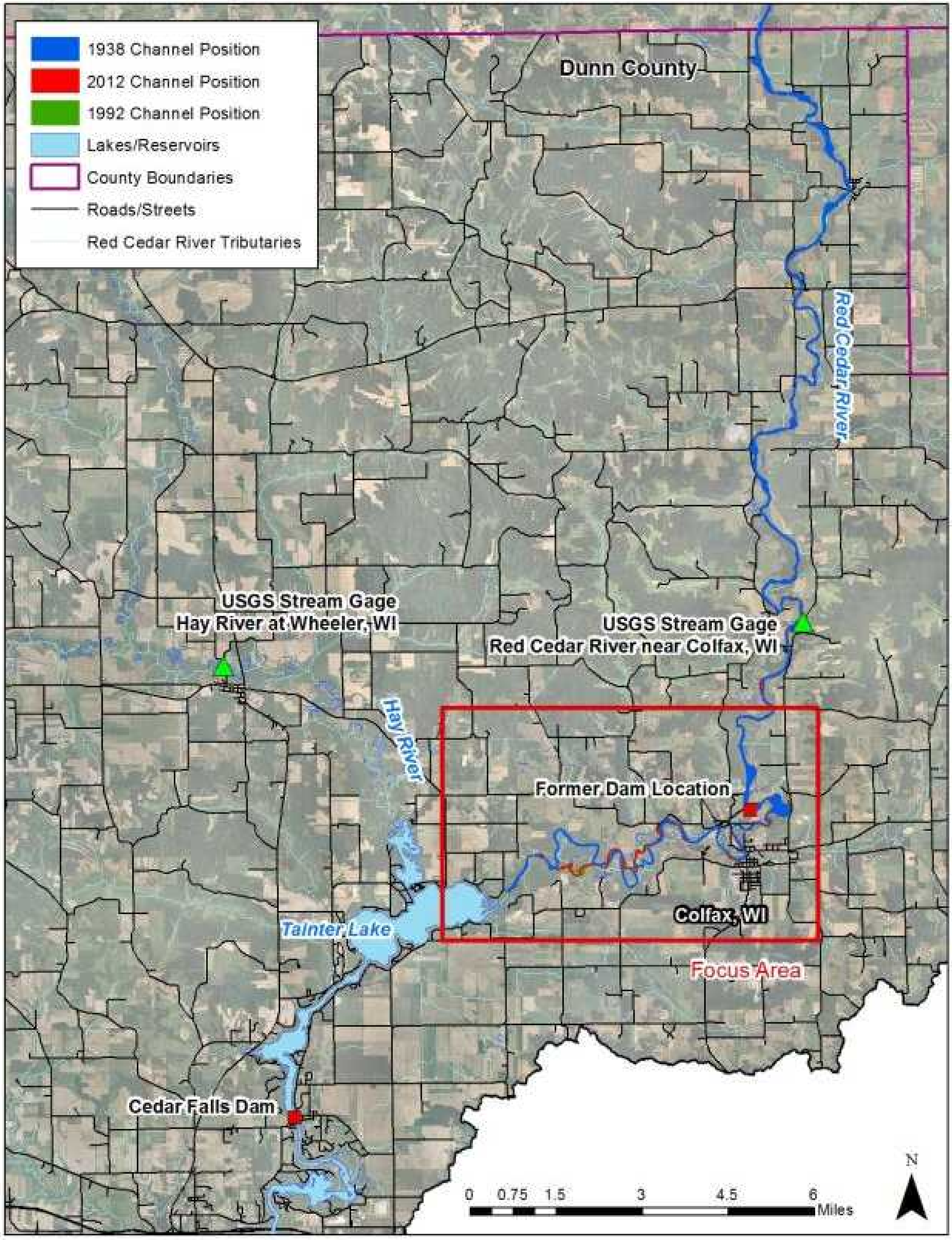
Last Name	First Name	Title	Affiliation
Campbell	Nathan	Regulatory Project Manager	US Army Corps of Engineers
DeFelice	Dustin	Water Regulations & Zoning Engineer	WI Department of Natural Resources
Engel	Marty	Fisheries Biologist	WI Department of Natural Resources
Gaetzke	Chris	Conservationist	Dunn County Land Conservation Division
Harings	Mark	Water Management Specialist	WI Department of Natural Resources
Kaner	Bob	Conservationist	Dunn County Land Conservation Division
Mosey	Mark	Science Teacher	Colfax High School
Prestebak	Dan	Conservationist	Dunn County Land Conservation Division
Selle	Andy	Fisheries Biologist/ Engineer	Inter-Fluve, Inc.
Sippl	John	District Conservationist	USDA Natural Resource Conservation Service
Sorge	Patrick "Buzz"	West Central Lake Coordinator	WI Department of Natural Resources
Sours	John	Trout Habitat Coordinator	WI Department of Natural Resources
Styer	Dale	Landowner	Landowner
Swanson	Ben	Fluvial Geomorphologist	Inter-Fluve, Inc.
Verdon	Ron	President, Landowner	Tainter Menomin Lake Improvement Association
Zerr	Dan	Natural Resources Educator	UW-Extension Regional Educator
Zien	Terry R.	Program Manager	US Army Corps of Engineers

UW-Stout Construction Honor Students provided surveying support for streambank and river cross-sections for this project.

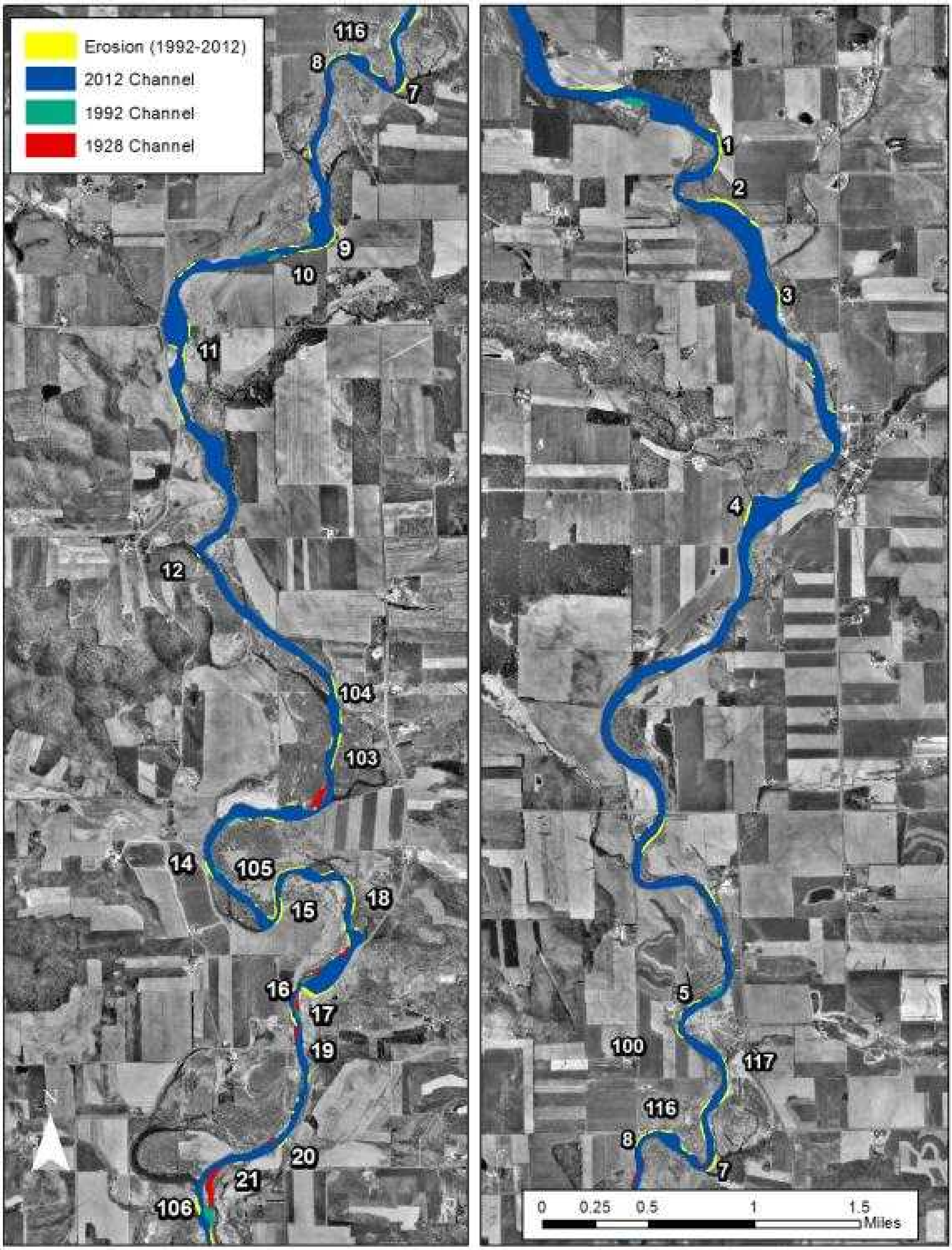
Appendix A. Red Cedar River Erosion Partnership Team



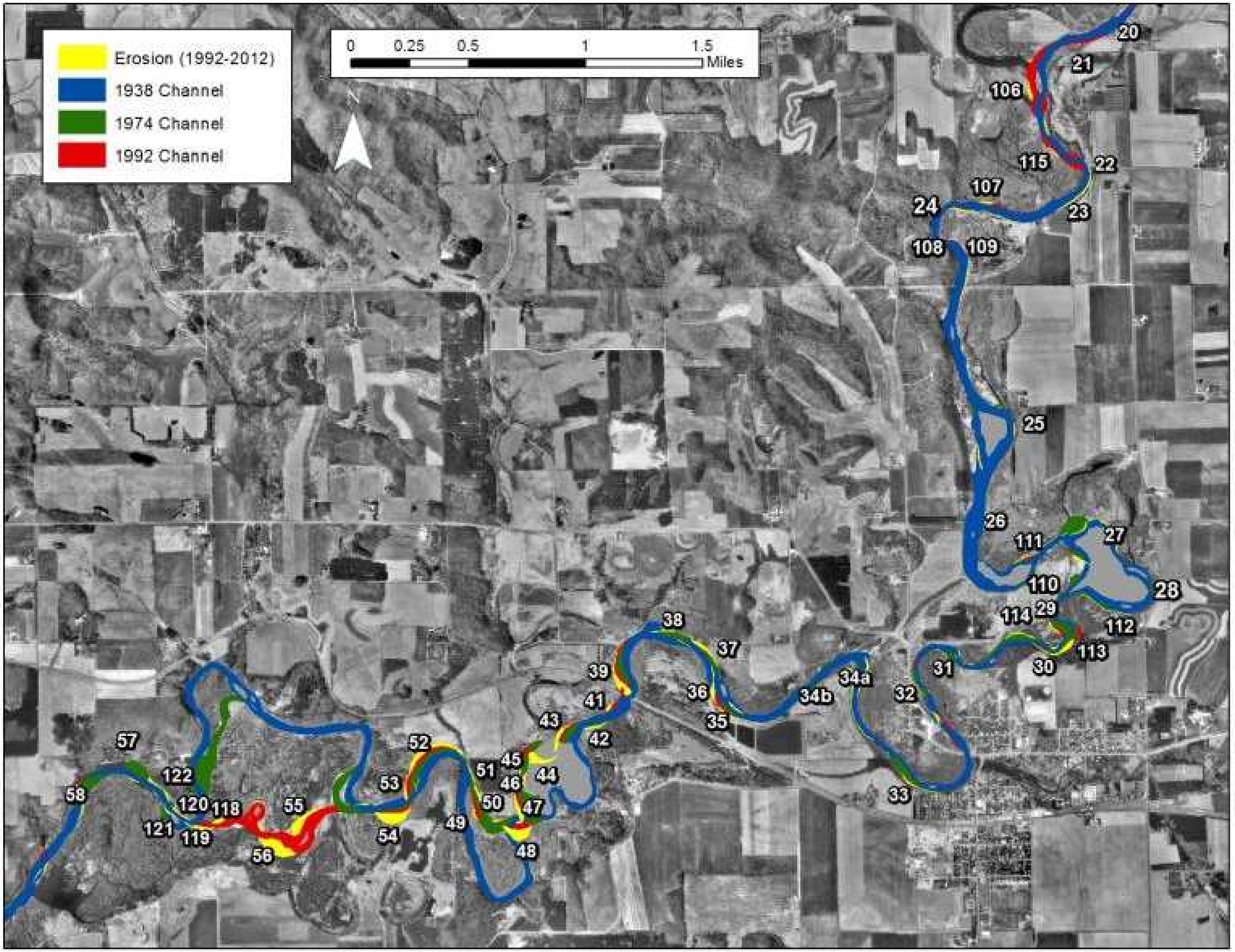
Appendix B. Red Cedar River Watershed



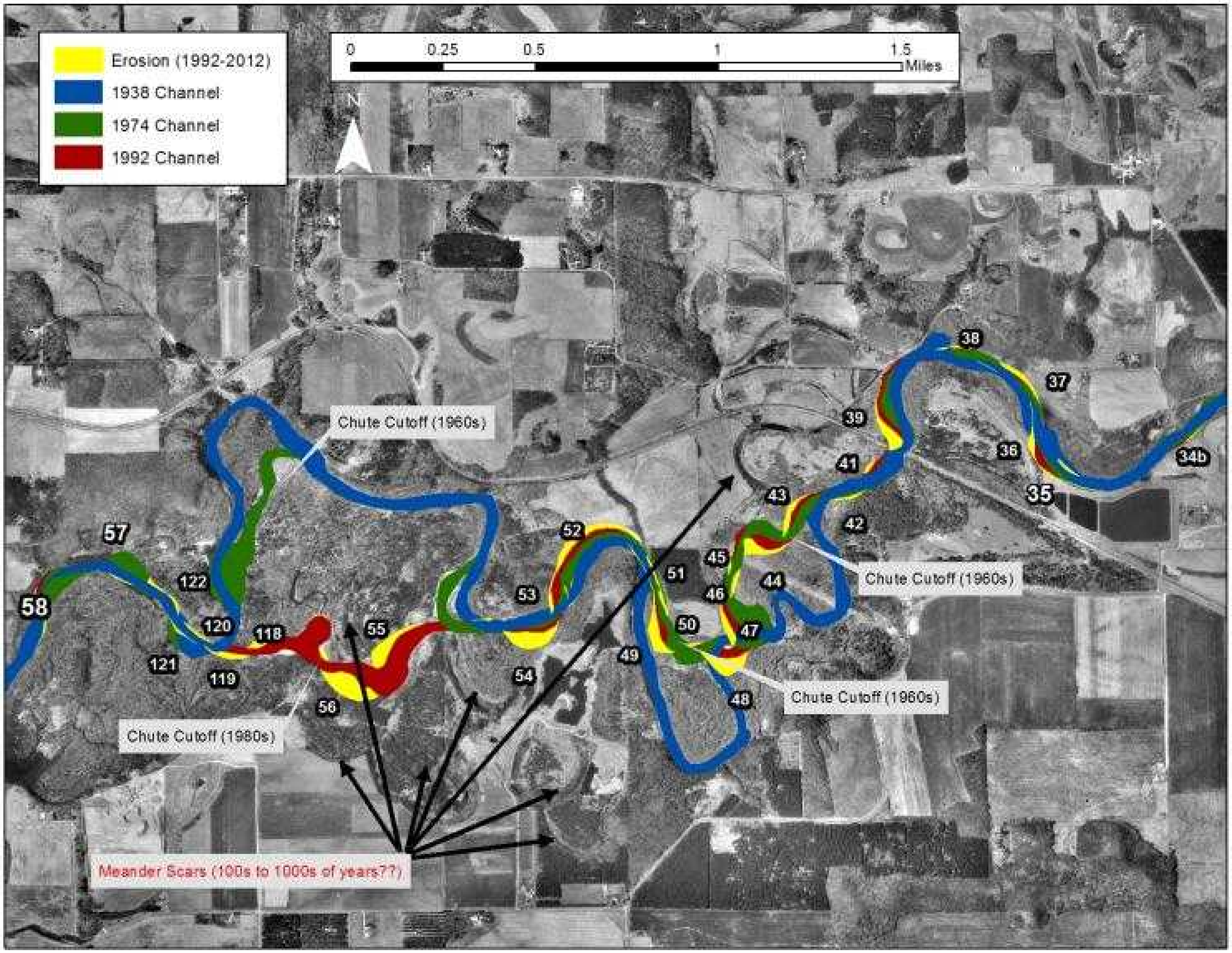
Appendix C. Red Cedar River Study Area, Dunn County, Wisconsin.



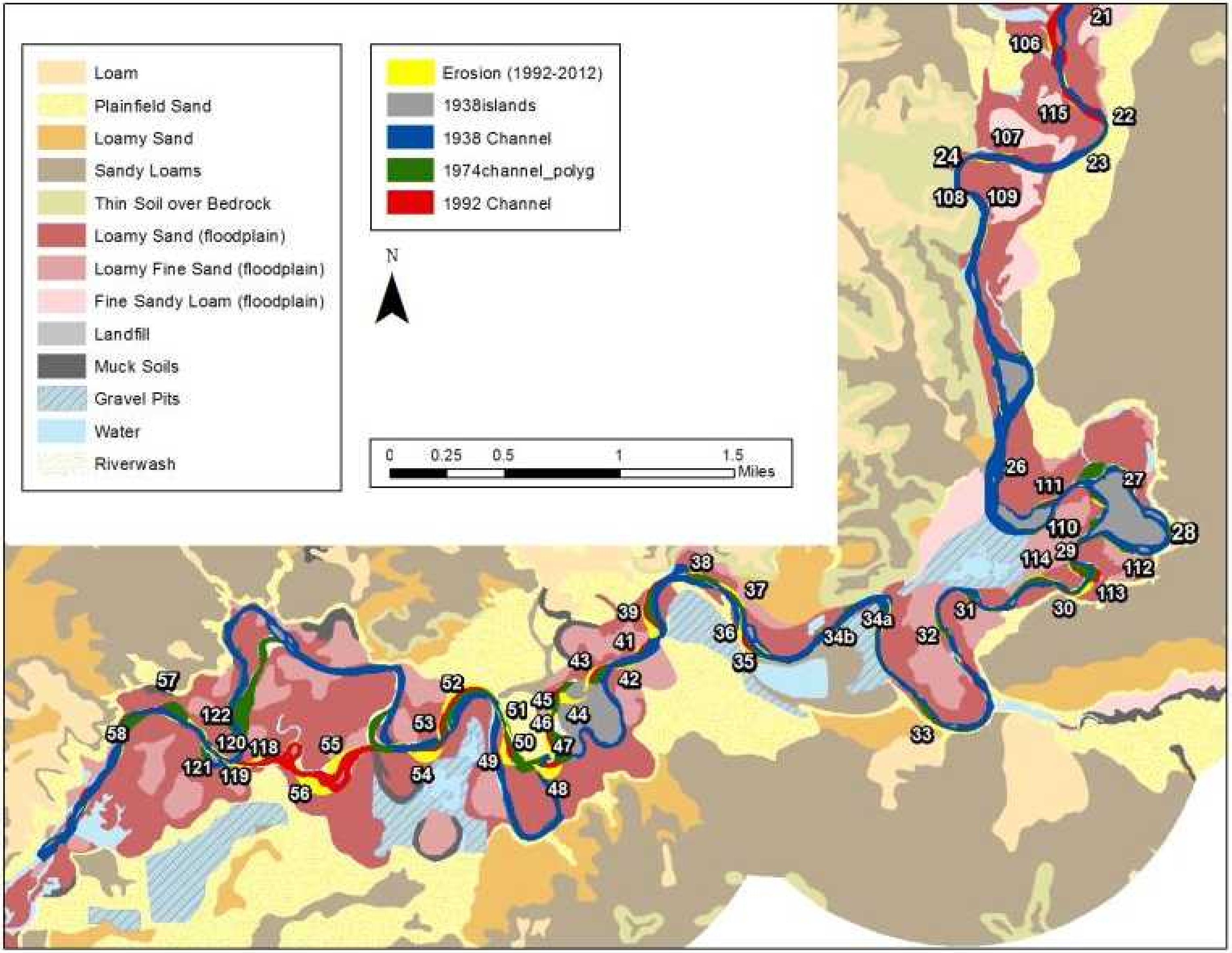
Appendix D. Erosion Sites along the upstream reaches of the Red Cedar River (1992-2012)



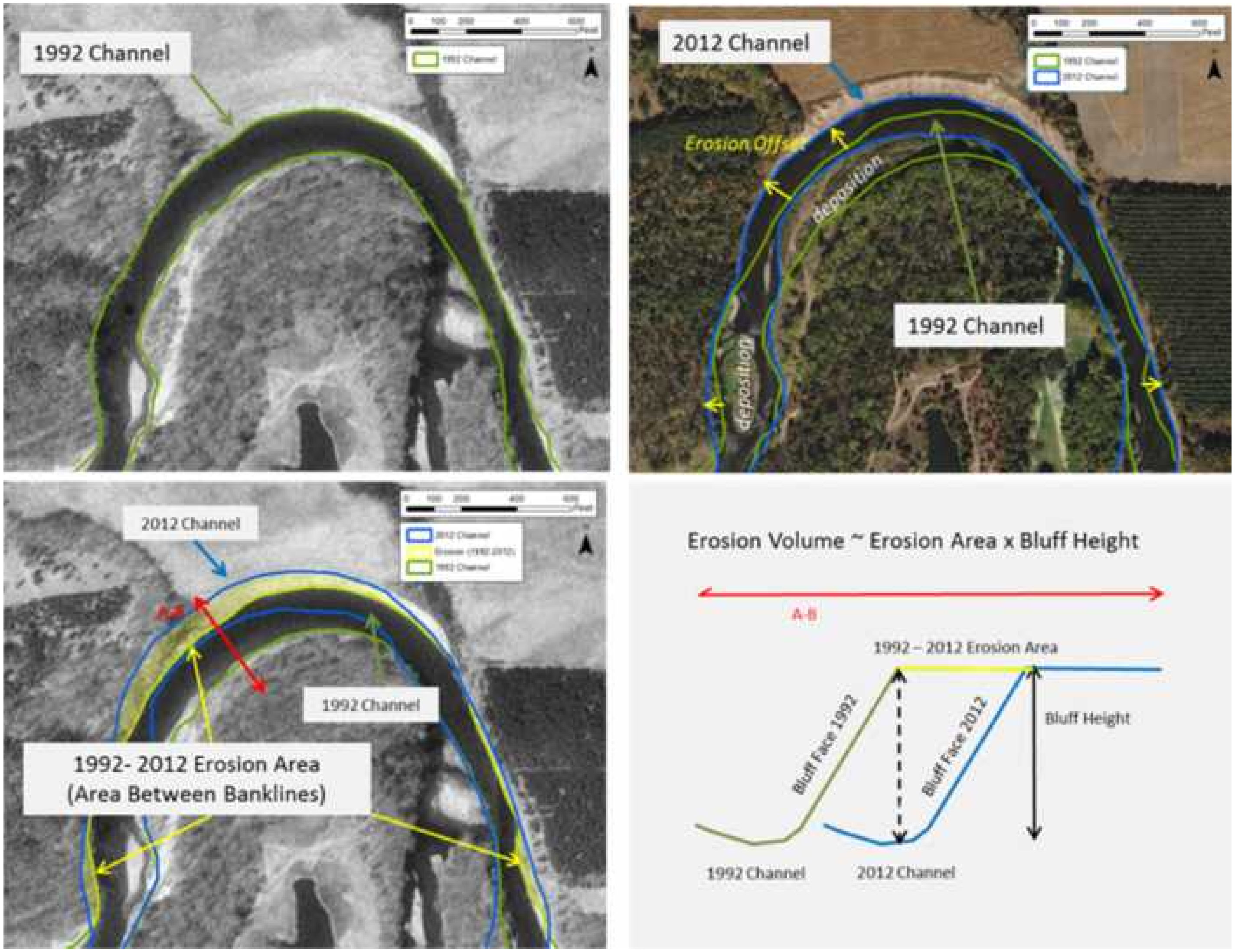
Appendix E. Erosion Sites along the focus reach of the Red Cedar River (1992-2012)



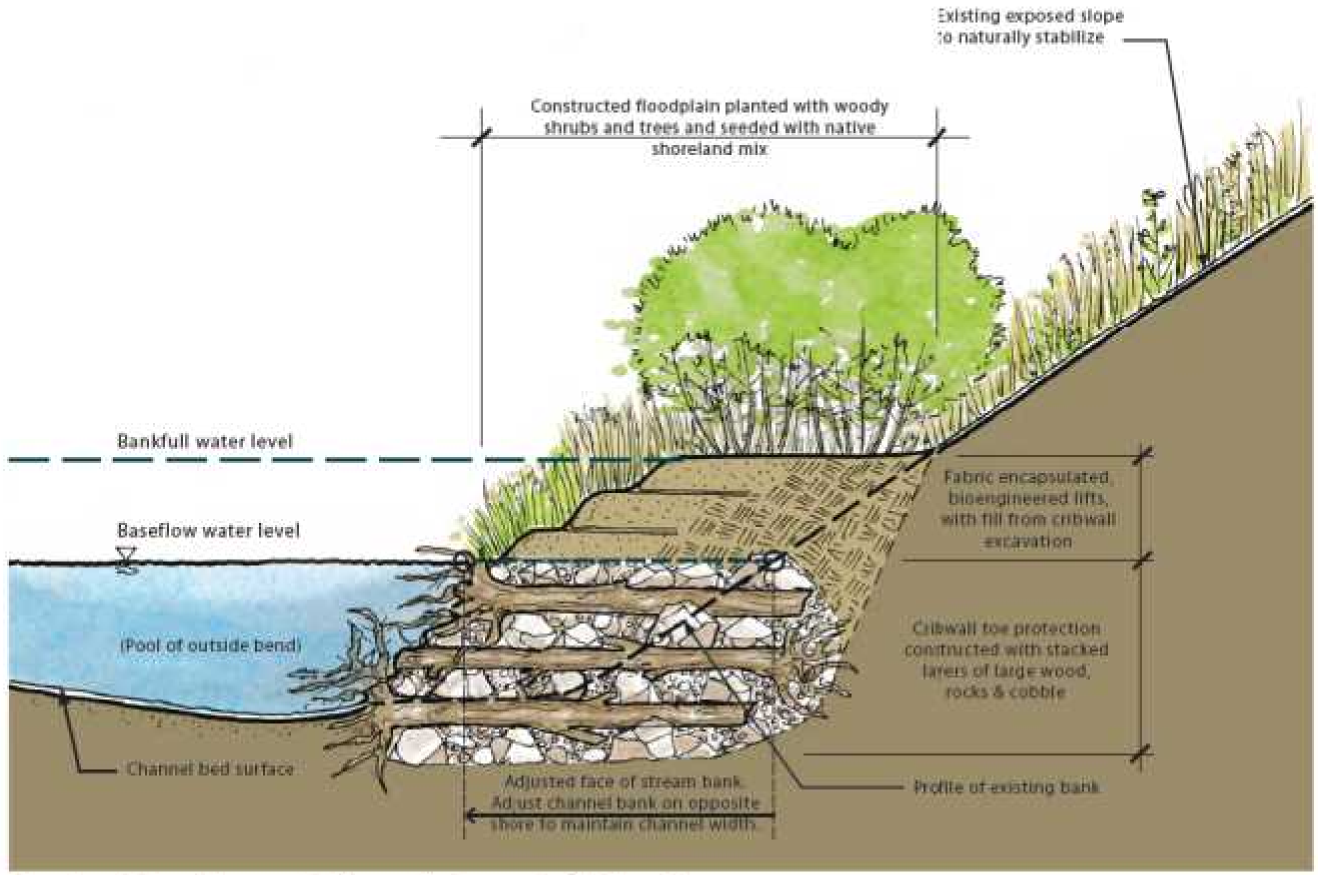
Appendix F. Erosion Sites along the focus reach, downstream of the Colfax wastewater treatment facility (1992-2012).



Appendix G. Soils and erosion sites along the Red Cedar River near Colfax, WI.



Appendix H. Estimation of Erosion Process. 1) Banklines were drawn along the channel on each photograph, and then compared. 2) Erosion areas were delineated as the area between banklines. 3) The maximum offset is the maximum distance between the two banklines, and the average offset is the average distance between the lines. 4) Erosion volumes were estimated by multiplying the erosion area by the height of the bank or bluff.

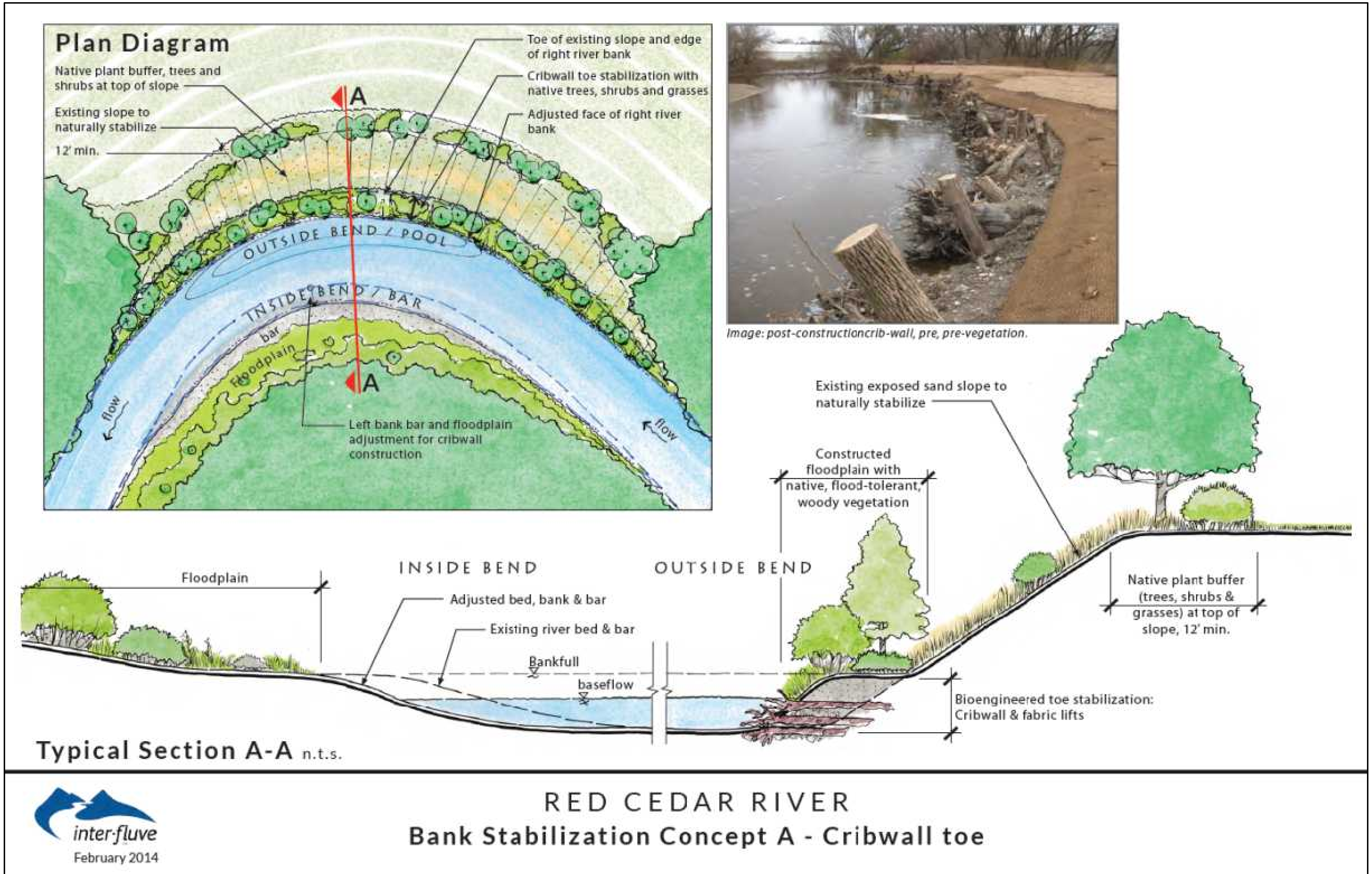


Typical Section: Cribwall toe stabilization n.t.s.

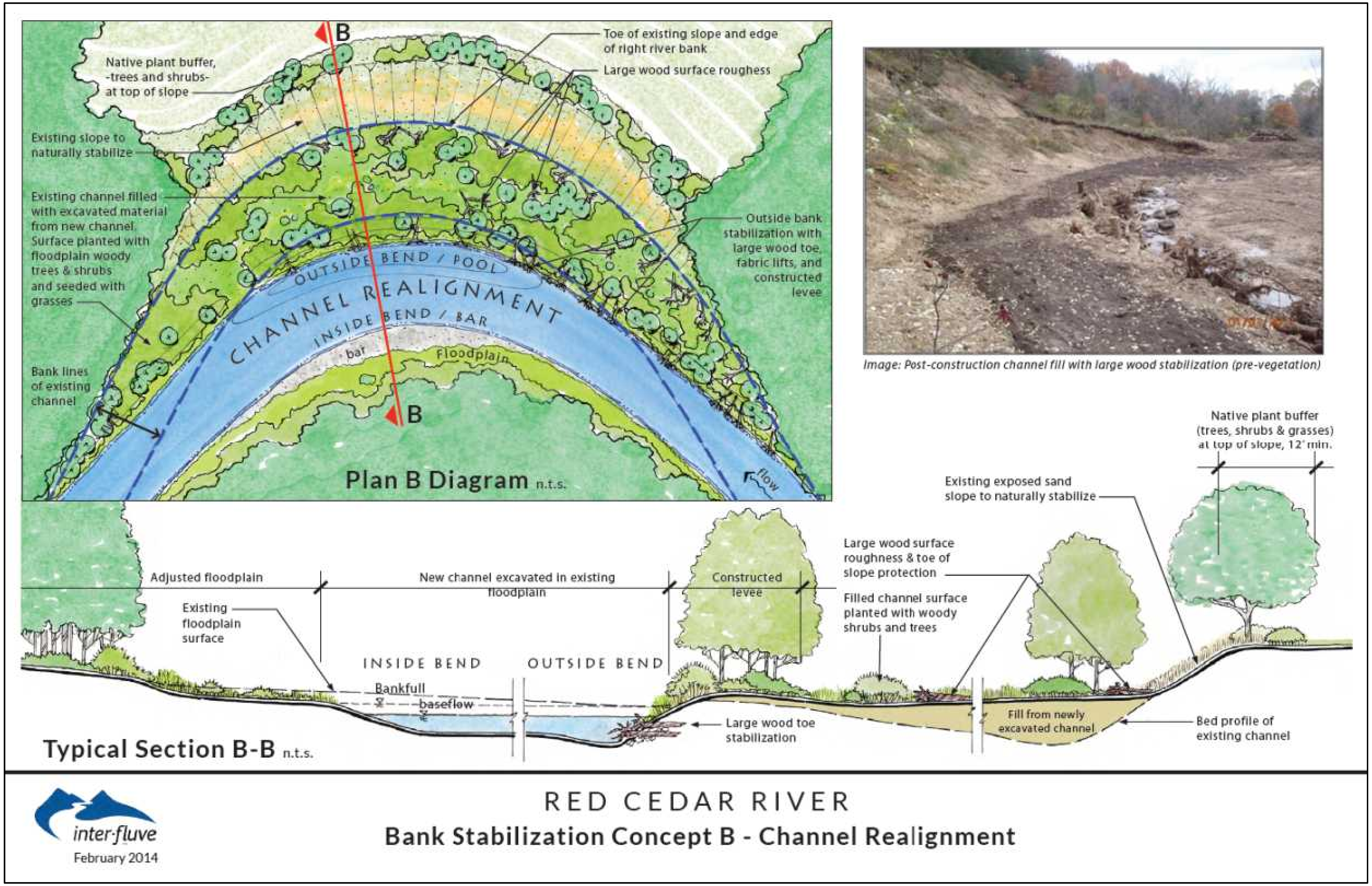
inter-fluve
February 2014

RED CEDAR RIVER
Typical Section: Cribwall Toe Stabilization

Appendix I. Schematic of a cross section through a log cribwall.



Appendix J. Planview schematic of a log cribwall stabilization project.



Appendix K. Planview schematic of a log cribwall stabilization project with a new channel constructed on the inside of the bend, and the existing channel filled and converted to floodplain.