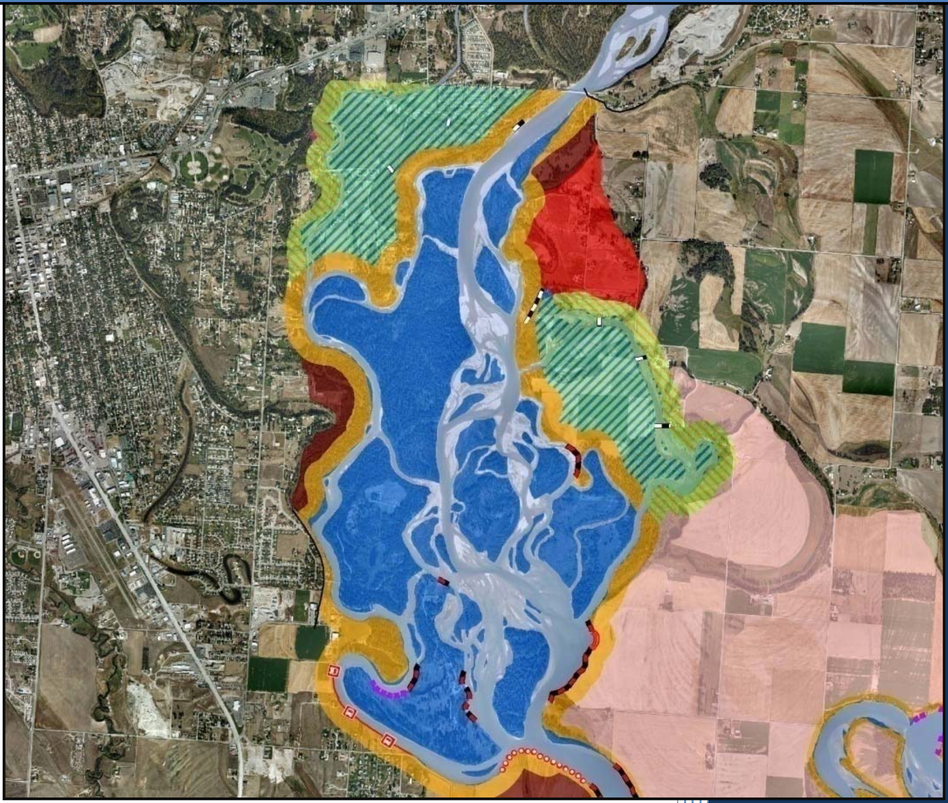
Flathead River
Channel Migration Zone Mapping



Final Report

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Table of Contents

List of Figures

List of Tables

1.0 Introduction

This report describes the development of a Channel Migration Zone (CMZ) map for the Flathead River from the Old Steel Bridge downstream to Flathead Lake. This effort is based on a contract between the Flathead Lakers and Applied Geomorphology Inc. (AGI) to provide a Channel Migration Zone analysis for 24 miles of the mainstem Flathead River, from approximately one mile from where the Highway 35 Bridge crosses Flathead River downstream to where the river flows into Flathead Lake. AGI teamed with DTM Consulting, Inc. (DTM) to perform this work.

1.1 Channel Migration and Avulsion Processes

From Old Steel Bridge to Flathead Lake, the Flathead River is an ***alluvial*** river, meaning it flows through sediment deposited by the river itself. As a result, the river is in a constant state of sediment reworking, as it builds point bars, erodes banks, and conveys sediment downstream (Figure 1). On actively meandering rivers such as the Flathead, these geomorphic processes are important for riparian vegetation communities, as the new bar surfaces provide colonization areas for young trees such as cottonwoods (Figure 2). Bank erosion also results in the recruitment of woody debris, which contributes to fish habitat quality and complexity (Figure 3).

Figure 1. Typical bank erosion into alluvial sediments, Flathead River.

Over time, any river that experiences bank erosion occupies a corridor that extends beyond its current channel boundaries (Figure 4). The width of this corridor is reflective of the rates of lateral shift, or ***migration***, that are characteristic of a given stream segment. Some stream segments, referred to as reaches, migrate relatively slowly due to low stream energy or erosion-resistant banks. Conversely, some segments migrate rapidly where the stream energy and sediment loads are relatively high and the erosion resistance of the channel perimeter is low.

Figure 2. Open gravel bars provide colonization surfaces for riparian vegetation, Flathead River.

Figure 3. Woody debris recruitment, Flathead River.

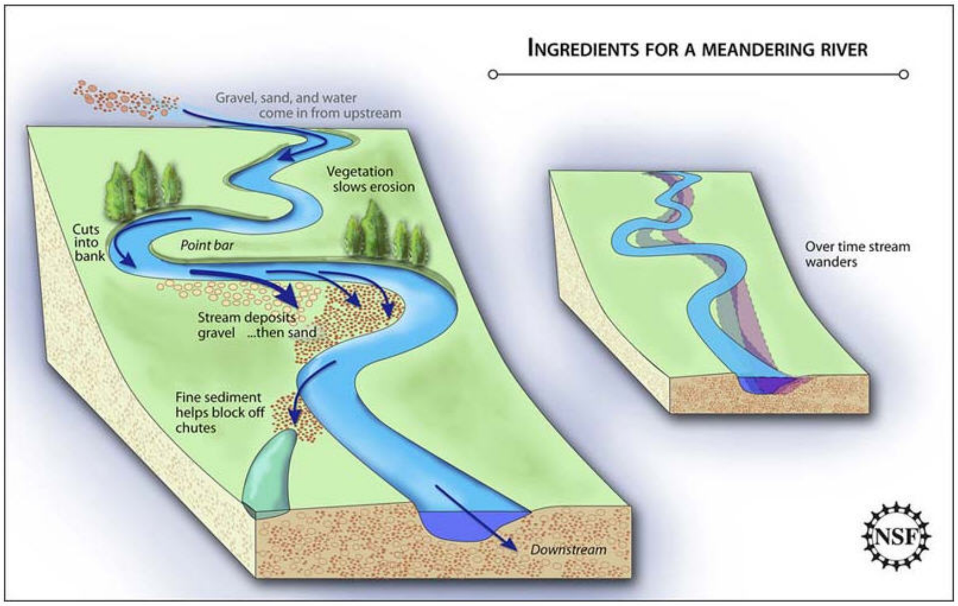


Figure 4. Schematic drawing of meandering river migration concept (www.berkeley.edu).

Whereas channel migration refers to the process of progressive lateral channel movement, ***avulsion*** refers to the capture of flow by a newly formed or previously abandoned channel segment. This process typically occurs during flood events, when overbank flows occupy and rapidly develop a new channel course. One primary example of avulsion on the Flathead is meander bend cutoff (Figure 5; Figure 6). Meander bends can cut off either due to migration, where the two limbs of a bend intersect through migration ("neck cutoff"), or by avulsion, where a new channel is excavated through the neck of the bend ("chute cutoff").

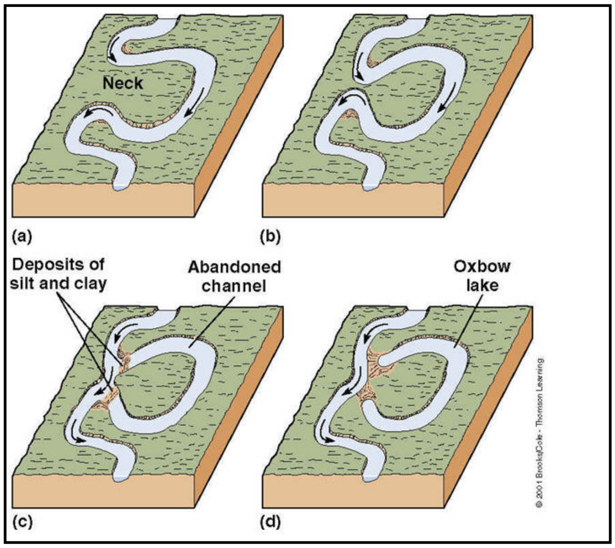


Figure 5. Schematic diagram of meander cutoff (www.uwsp.edu).

Figure 6. Meander cutoff, Flathead River.

The process of channel avulsion via development of chute cutoff is shown in Figure 7. This photo was taken from a helicopter by Montana Department of Natural Resources and Conservation (DNRC) staff during the 2008 flood on the East Gallatin River. The photo shows a typical bendway on the East Gallatin River, with floodwaters flowing over the core of the bend. On the downstream end of the bend (left side of photo), the overflows re-enter the main channel over a steep bank edge, creating a headcut. If the flood is large enough or long enough, the headcut will migrate up-valley through the core of the bend and excavate a cutoff channel. On this particular bend, the flood dissipated before cutoff occurred, resulting in a “failed avulsion”.

Figure 7. Example of the avulsion process, East Gallatin River May 2008 (DNRC).

In addition to bendway cutoffs, avulsions occur where long segments of channel relocate to new areas on the floodplain. These relocations may reflect capture of an abandoned channel, a tributary channel, or creation of an entirely new channel in the floodplain. These floodplain avulsions are less common than meander cutoffs, and require a certain degree of instability to occur. A more detailed description of these types of avulsions is contained within Appendix D.

1.2 The Channel Migration Zone Mapping Concept

Channel Migration Zone mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. As such, over a given time period, rivers occupy a corridor area whose width is dependent on rates of channel shift. The processes associated with channel movement include lateral channel migration and more rapid channel avulsion. The fundamental concept of CMZ mapping is to identify the corridor area that a stream channel or series of stream channels can be expected to occupy over a given timeframe. This CMZ study identifies areas prone to channel migration over the next 100 years.

In general, a Channel Migration Zone is composed of the following:

- Historic Migration Zone (HMZ) – the area of historic channel occupation, usually defined by the available photographic record.
- Erosion Hazard Area (EHA) – the area outside the HMZ susceptible to channel occupation due to channel migration or mass wasting.
- Avulsion Hazard Zone (AHZ) – floodplain areas geomorphically susceptible to abrupt channel relocation.
- Restricted Migration Area (RMA), areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features (also known as the Disconnected Migration Area, or DMA).

Rapp and Abbe (2003) define the CMZ as:

$$\boldsymbol{CMZ = HMZ + EHA + AHZ - RMA}$$

Thus, the CMZ is the sum of the historic footprint of all channels, areas of likely future erosion, and areas prone to channel avulsion, with restricted migration areas excluded from the corridor. This general definition allows for some flexibility in terms of both component definitions and the component inclusion in the CMZ. For example, one approach identified by the State of Washington is to use meander belt width and bendway amplitude to define the EHA, rather than measured erosion rates. This approach would be appropriate in channelized reaches where natural migration is largely inhibited. Also, whether or not the RMA is included in the CMZ requires a decision as to whether bank armor should be considered effectively managed, stable, and permanent. In the Flathead River CMZ, the RMA is highlighted but not excluded from the map as Rapp and Abbe (2003) proposed. The Flathead Technical Advisory Committee (TAC) decided to include the RMA in the Channel Migration Zone, as many stakeholders in other areas have. This inclusion of the RMA in the mapping was adopted because of uncertainties regarding the mapped extents, performance, and permanence of existing features such as bank armor that restrict migration.

1.3 Uncertainty

A 100-year channel migration corridor defines an area that a river's active channels are likely to occupy over the next century. As river systems are exposed to a myriad of influences that may affect migration rates, these corridor boundaries acknowledge a certain amount of uncertainty. FEMA (1999) noted the following with respect to predicting channel migration:

> …uncertainty is greater for long time frames. On the other hand, a very short time frame for which uncertainty is much reduced may be useless for floodplain management because of the minimal erosion expected to occur.

The intent of this mapping is to highlight those areas most prone to either migration or avulsion based on specific criteria developed from an assessment of historic channel behavior. In the event that the conditions experienced by the Flathead River over the last 50 years change significantly over the next century, uncertainty regarding the proposed boundaries will increase. These conditions include influences imposed by system hydrology, climate, lake level management, riparian vegetation densities and extents, and channel stability. Bank armor and floodplain modifications, such as bridges, dikes, levees, could also impact map boundaries.

For this study, a 100-year timeframe was selected to analyze the potential lateral migration of the Flathead River, which is typical for CMZ studies (WSDE, 2010). Suggested reasons for the adoption of this timeframe include the following:

1) 100-year floodplains are mapped to identify flood hazards due to inundation.
2) The availability of archival material used in the analysis commonly dates back around 100 years.
3) A century is sufficient time for growth of mature trees that could potentially affect channel process (King County, 2004).

Ultimately, however the 100-year timeframe reflects more of a policy decision than a scientific one; this window has proven to be a useful management framework for landowners and resource managers.

1.4 Relative Levels of Risk

Bankline migration and channel avulsion processes both present some level of risk to property within stream corridors. Although the quantitative probability of any area experiencing either migration or an avulsion during the next century has not been determined, their association with specific river process allows some relative comparison of the type and magnitude of associated risk. In general, the Erosion Hazard Area (EHA) delineates areas that have a moderate to high risk of channel occupation due to channel migration over the next 100 years. Such bank erosion can occur across a wide range of flows. As such, the risk is not solely associated with flood events, as channel migration commonly occurs as a relatively steady process. Avulsion tends to be a flood-driven process, and as such, risks identified by the Avulsion Hazard Zone (AHZ) are typically associated with infrequent, relatively rapid shifts in channel course that are commonly difficult to predict.

1.5 Potential Applications

The CMZ maps developed for the Flathead River identify areas prone to lateral channel shift over the next 100 years. These results are intended to support a myriad of applications. Potential applications for the CMZ maps include the following:

- Proactively identify future problem areas through documentation of active bankline migration;
- Identify restoration opportunities where bank armor has restricted the natural Channel Migration Zone;
- Provide a background tool to assess channel dynamics within any given area;
- Assist in the development of river corridor best management practices;
- Improve stakeholder understanding of the geomorphic behavior of this river system;
- Support planning decisions at local and county levels by identifying relative levels of erosion risk;
- Identify areas where channel migration easements would be appropriate;
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor; and,
- Help define long-term sustainable river corridor boundaries.

1.6 Disclaimer and Limitations

The boundaries developed on the Channel Migration Zone maps are intended to provide a basic screening tool to help guide and support management decisions within the Flathead River corridor and were not developed with the explicit intent of providing regulatory boundaries or overriding site-specific assessments. The criteria for developing the boundaries are based on reach scale conditions and average historic rates of change. The boundaries can support river management efforts, but in any application, it is critical that users thoroughly understand the process of the CMZ development and its associated limitations.

Primary limitations of this reach-scale mapping approach include a potential underestimation of migration rates in discrete areas that are eroding especially rapidly, which could result in migration beyond the mapped CMZ boundary. Additionally, site-specific variability in alluvial deposits may affect rates of channel movement. Mapping errors introduced by the horizontal accuracy of the imagery, digitizing accuracy, and air photo interpretation may also introduce small errors in the migration rate calculations. Future shifts in system hydrology, climate, sediment transport, riparian corridor health, or channel stability would also affect the accuracy of results, as these boundaries reflect the extrapolation of historic channel behavior into the future. As such, we recommend that these maps be supplemented by site-specific assessment where near-term migration rates and/or site geology create anomalies in the reach-averaging approach, and that the mapping be revisited in the event that controlling influences change dramatically. A sight-specific assessment would include a thorough analysis of site geomorphology, including a more detailed assessment of bank material erodibility, both within the bank and in adjacent floodplain areas, consideration of the site location with respect to channel planform evolution, and evaluation of influences such as vegetation and land use on channel migration.

1.7 Acknowledgements

This effort was performed for the Flathead Lakers through a contract between them and the Applied Geomorphology/DTM Consulting Project Team. Constanza von der Pahlen was instrumental in providing contract management and facilitating communication between the authors and project sponsors. Field support was provided by Mark Deleray, Pete Woll, Bailey Iott, and Russ Tinsdale. Patti Mason of Flathead Conservation District assisted us in identifying locations and extents of armor and dikes. Feedback from the Technical Advisory Committee (TAC) was critical in developing the maps. The project team extends its gratitude to all involved parties that facilitated this effort.

2.0 Physical Setting

The following summary of the Flathead River project reach geomorphology is intended to provide basic context regarding the physical conditions within the project reach. Because of the reach-scale approach to this project over approximately 24 miles of river, it is important to consider the variability in physical conditions that control river form and process.

2.1 Geology and Geomorphology

As previously described, the project reach of the Flathead River is underlain by young alluvial deposits (Figure 8). In the lowermost portion of the project reach, where the river abuts the eastern edge of the river valley near Sportsman's Bridge, a few bedrock exposures form the river's edge. This bedrock is comprised of Proterozoic-age Shepard Formation, which is part of the Belt Supergroup that is extensive in Montana. Outcrops of the Shepard Formation in Glacier National Park have been described as dolomite, siltstones, agillite, and quartzite, with several species of stromatolites (Fenton and Fenton, 1931).

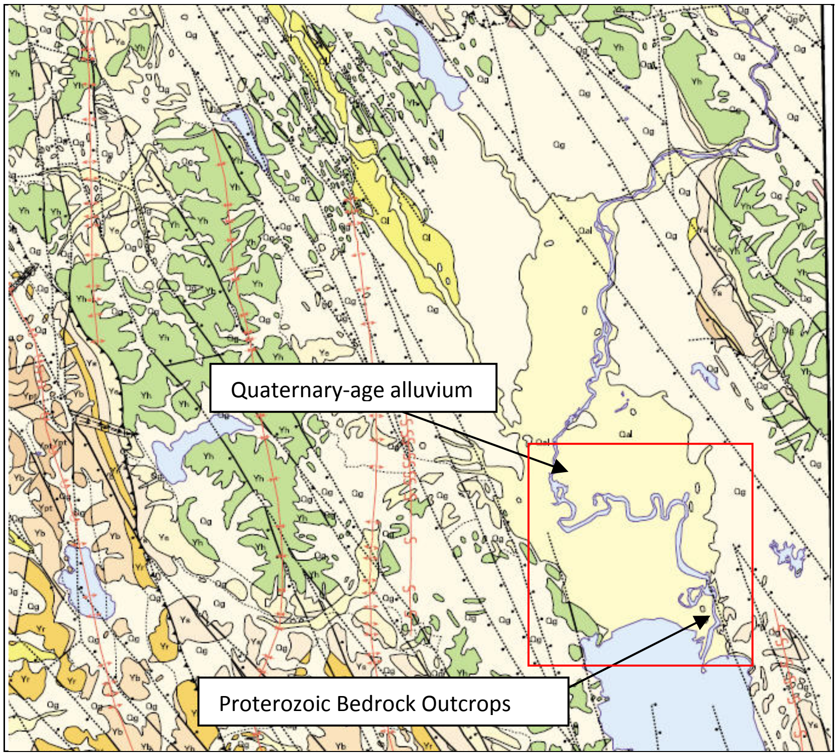
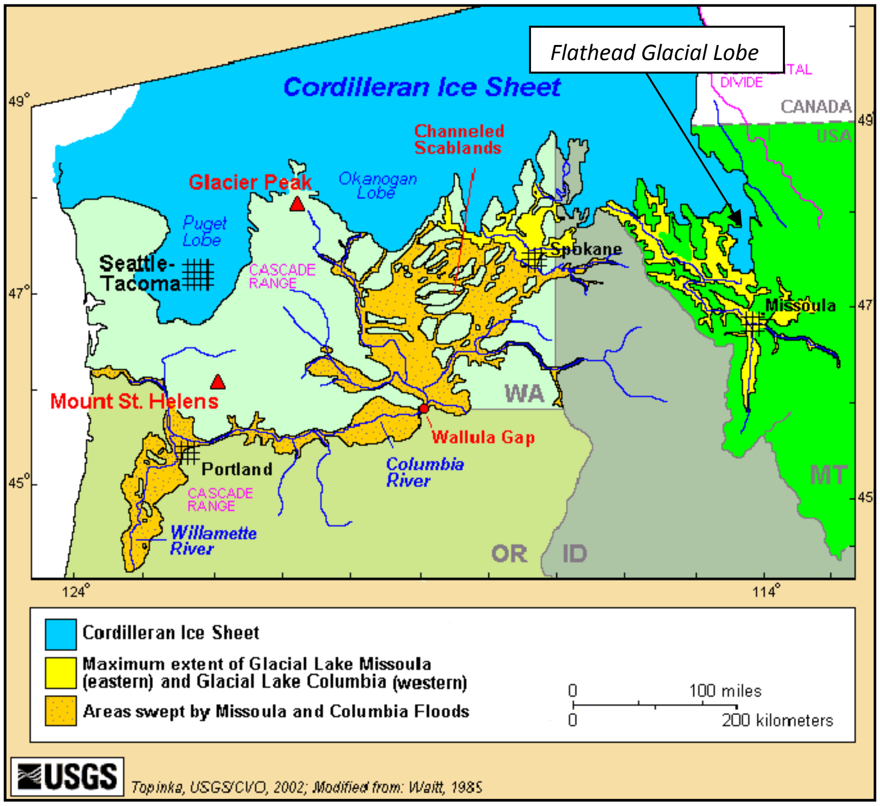


Figure 8. Geologic map of study area showing alluvial geology and localized bedrock outcrops of project reach (Harrison, et al., 2000).

2.1.1 Glacial History

The project reach lies in a glaciated river valley that was covered by the Flathead glacial lobe during the last ice age, approximately 10,000 to 12,000 years ago (Figure 9). This ice was over 4,000 feet thick near the Canadian border, tapering southward to a thin edge just south of Polson (Alt, 2001). The lake contains over 500 feet of syn- and post-glacial sediment, including till and overlying glaciolacustrine sediments (Hofmann, et al. 2006). Flathead Lake has been described as a topographic remnant of a stagnant ice block that has been maintained as a lake due to the relatively high elevation of the lake outlet (Alt and Hyndman, 1986). According to Benke and Cushing (2005), Flathead Lake is “of tectonic origin but modified by glacial scour”.



Topinka, USGS/CVO, 2002; Modified from: Waitt, 1985

Figure 9. Map of the maximum extent of the Cordilleran Ice Sheet showing the location of the Flathead Glacial Lobe (http://vulcan.wr.usgs.gov).

2.1.2 The Flathead Lake Delta

Within the project reach, the Flathead River flows through reworked glacial material and modern alluvium as it approaches and ultimately enters Flathead Lake. Prior to the completion of Kerr Dam in 1938, an exposed, vegetated delta was present where the

Flathead River entered the lake (Figure 10). Currently, the vegetated delta is gone, as the feature has been eroded and inundated (Figure 11).

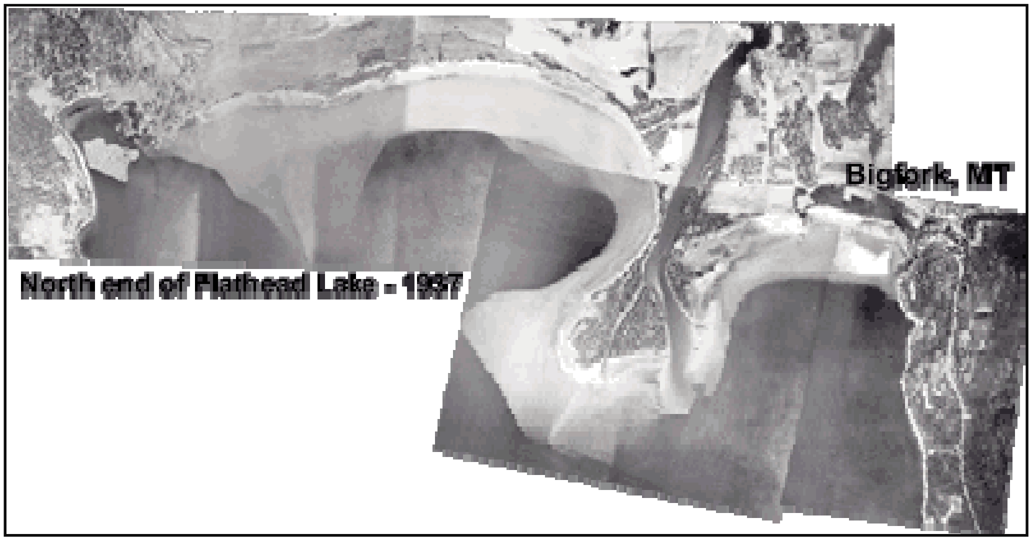


Figure 10. Imagery mosaic of 1937 delta (http://www.umt.edu/geosciences/COTC).

Figure 11. 2009 imagery of lowermost end of project reach showing the inundated delta at the mouth of the Flathead River.

Manipulation of water levels at Kerr Dam, on the Flathead River south of Flathead Lake, seasonally increases the lake level relative to its natural outlet elevation, and impounds water in the lowermost section of the project reach. Moore et. al. (1982) mapped a progressive loss of the delta expression through time (Figure 12), and recent erosion rates on the North Shore of Flathead Lake have been attributed to storm-generated waves and estimated at three feet per year (Devlin, 2007). Currently, erosion is a primary concern at the mouth of the river, as evidenced by several implemented erosion control projects including an extensive right bank gravel/wood “bush bundle” project that was designed to trap fine sediment and drive accretion, and enhance riparian vegetation densities on the banks (Figure 13; Devlin, 2007).

Figure 12. Changes in Flathead River delta, 1937-1987 (Moore, et al. 1982).

Figure 13. “Bush bundle” project installation near mouth of Flathead River.

2.1.3 **Erosion Mechanisms**

The Flathead River exhibits a complex mosaic of erosion processes due to the overlapping influences of fluvial erosion, saturated bank failure, and wave-induced erosion. In some cases, sites experiencing fluvial erosion are hundreds of feet long (Figure 14). In other situations, severe local erosion in an otherwise stable bank creates discreet scallop-shaped failures (Figure 15). These failures commonly occur along armored banklines, suggesting toe failure of the armor (Figure 16). In some cases these erosion sites correlate to meander scroll features that have been dissected by the modern channel course (Figure 17). Undercutting at the bank toe and topple failure of the upper bank is common (Figure 18).

Figure 14. Relatively long eroding bankline, Flathead River.

Figure 15. Localized severe erosion, Flathead River.

Figure 16. Severe scallop erosion of previously-armored bank, Flathead River.

Figure 17. Cross sectional view of eroding meander scroll deposit.

Figure 18. Lower bank undercutting, Flathead River.

Some bank failures within the project reach appear to be driven by gravitational failure of saturated banks (Figure 19). The exposure of saturated banks could be due to rapid changes in river stage, changes in lake level elevation, or floodplain irrigation.

Local residents have indicated that bank failure relates to lake levels in that different stages in the lower river expose variably erodible materials to stream energy. This vertical variability in bank materials is well-demonstrated by banks that host bank swallows, as the birds tend to dig their nests in relatively erodible horizons (Figure 20). Additionally, there is significant concern regarding erosion caused by boat wakes, storm waves, and wind-generated waves (Figure 21).

Figure 19. Saturated bank failure, Flathead River.

Figure 20. Bank exposure showing bank swallow preference for erodible stratigraphic horizons.

Figure 21. Recreational boating, Flathead River.

2.1.4 Project Reach Delineation

By defining project reaches, migration rate measurements can be spatially grouped so that calculated Erosion Hazard Area (EHA) values reflect processes associated with that specific river segment. This reach break delineation is a fundamental aspect of reach-scale CMZ mapping (WSDE, 2010). Reach breaks are generally determined using factors such as changes in confinement, gradient, or pattern, the presence of geologic or man-made constraints, and the locations of tributary confluences. For this project, migration rates were also used to help define reach breaks.

Based on similarities in geomorphic form and process, the project area between the Old Steel Bridge and the mouth is subdivided into three reaches (Table 1, Figure 22 through Figure 24). Reach 1 extends from Flathead Lake upstream for approximately 13 miles, to a point just above Church Slough (Figure 22). A LiDAR-derived water surface profile shows nearly flat water surface profiles in Reach1 (Figure 25). The lack of measureable slope reflects the limits of the LiDAR data resolution, hence are reported as <0.01%. Erosion rates in this reach are lower than those of upstream reaches, as reflected in the relatively small erosion polygons identified through the analysis of channel movement since the 1950s (Figure 22). Reach 2 is similarly flat, extending approximately 6.8 miles from Church Slough to a point 1.8 miles upstream of Foy’s Bend (Figure 25). Migration rates in

Reach 2 are notably higher than Reach 1 rates (Figure 23). Both Reach 1 and Reach 2 consist of a single thread meandering planform, with sinuosities (ratio of channel length to valley distance) of approximately 2.0. Based on the Montgomery-Buffington classification system, Reach 1 and Reach 2 would be classified as dune-ripple channel types, which are low gradient sand bed channels that are transport-limited. The FEMA flood insurance study (FEMA, 2007), shows that in these lower reaches, water surface slope increases with increasing river discharge.

Reach 3 extends from a point approximately 1.8 miles upstream of Foy's Bend to the Old Steel Road Bridge, the upstream limit of the project reach. Here, the channel is similarly transport limited. However, the channel planform is braided, the channel slope is steeper, with a water surface slope of 0.05%. Reach 3 is a pool-riffle channel type in the Montgomery-Buffington classification. Migration rates are relatively high in Reach 3 (Figure 24). It should be noted, however, that the Montgomery-Buffington classification system was developed for mountain drainage basins and does not explicitly include backwatered, lake-influenced channels (Montgomery & Buffington, 1997).

Table 1. Project Reach Descriptions

Descriptor	***Reach 1***	***Reach 2***	***Reach 3***
Location	Flathead Lake to just upstream of Church Slough	Just upstream of Church Slough to 1.8 miles upstream of Foy's Bend	1.8 miles upstream of Foy's Bend to Old Steel Road Bridge
River Mile	0-12.95	12.95-19.75	19.75-23.80
Channel Length (miles)	12.95	6.8	4.05
Sinuosity	1.94	2.12	1.24
Percent Slope (water surface slope from LiDAR data)	<0.01% (<0.5 ft/mile)	<0.01% (<0.5 ft/mile)	0.05% (2.4 ft/mile)
Typical Bed Material	Sand	Sand	Sand/Gravel
Dominant Roughness Elements	Sinuosity, bedforms	Sinuosity, bedforms	Bedforms
Dominant Sediment Sources	Fluvial, bank failure	Fluvial, bank failure	Fluvial, bank failure
Sediment Storage Elements	Overbank, bedforms, inactive channel	Overbank, bedforms, inactive channel	Overbank, bedforms
Confinement	Unconfined	Unconfined	Unconfined
Channel Type (Montgomery and Buffington, 1993)	Dune Ripple	Dune Ripple	Pool-Riffle (Braided)

Figure 22. 2009 air photo of Reach 1, showing numbered erosion sites used in CMZ analysis.

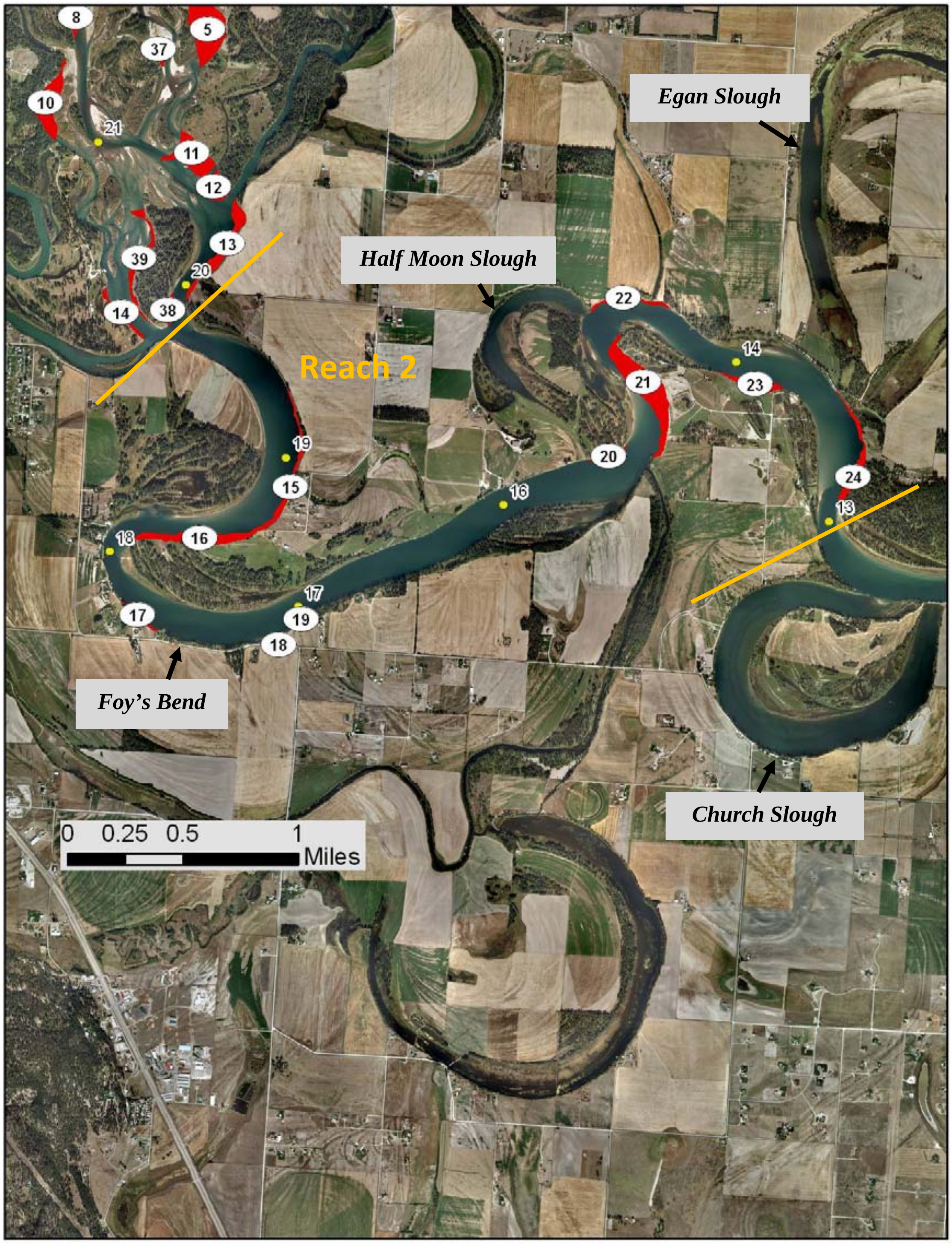


Figure 23. 2009 air photo of Reach 2, showing numbered erosion sites used in CMZ analysis.

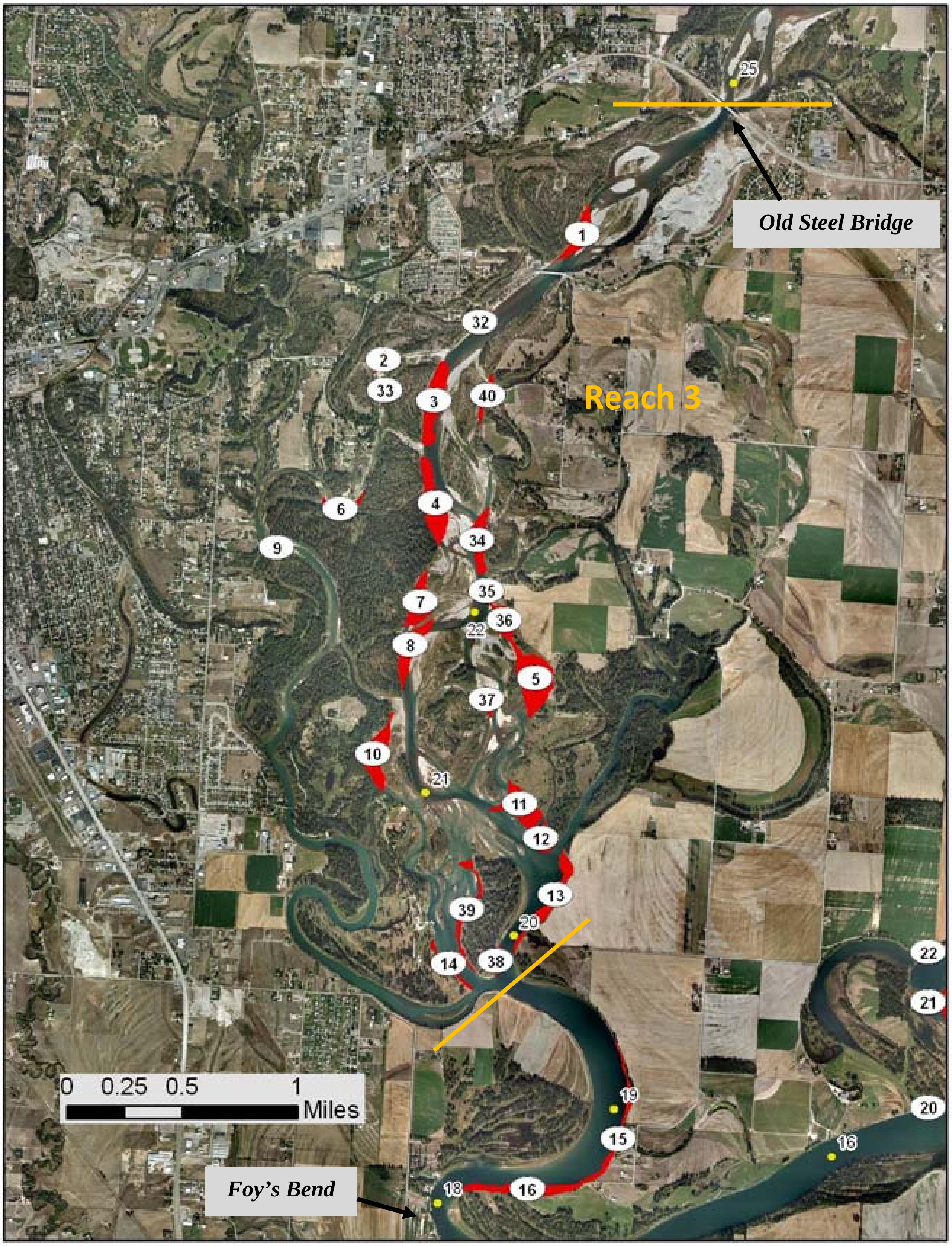


Figure 24. 2009 air photo of Reach 3, showing numbered erosion sites used in CMZ analysis.

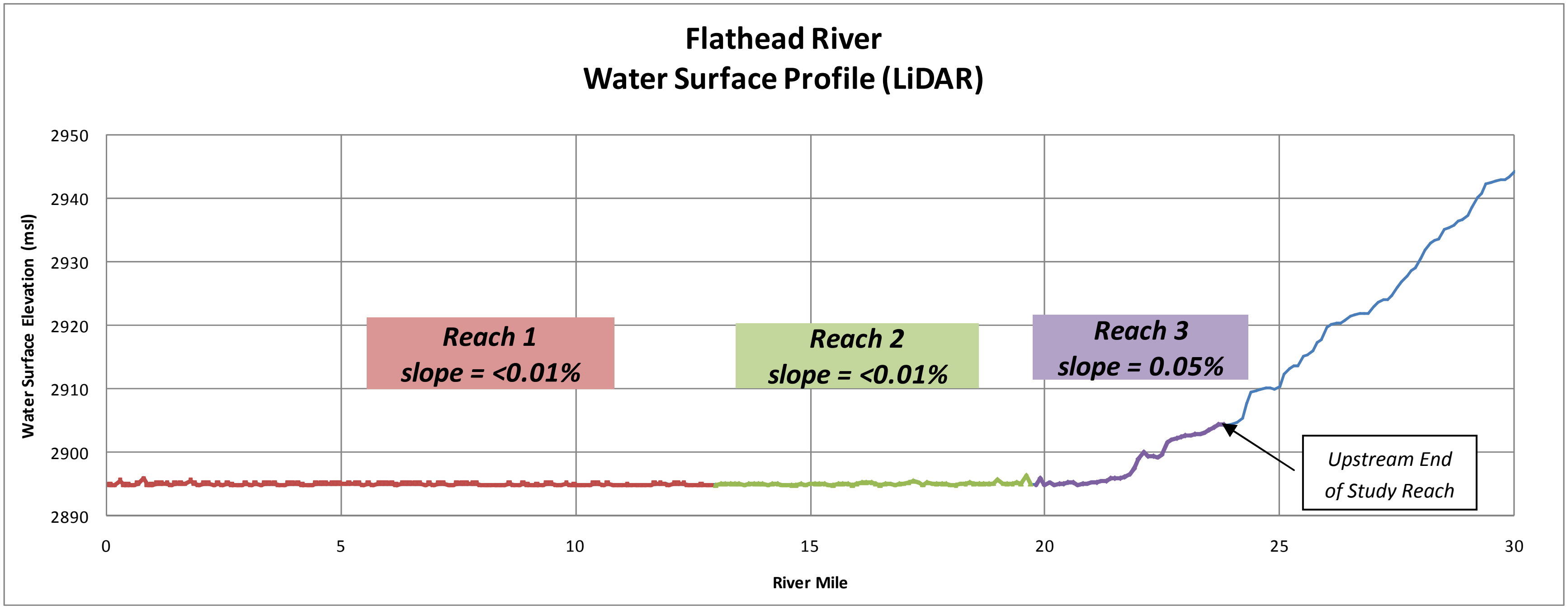


Figure 25. Water surface profile of project reach derived from the resampled 6-foot LiDAR elevation dataset.

2.2 Hydrology

Kerr Dam and Hungry Horse Dam have both altered the hydrology of the project reach. Kerr Dam is located near the outlet of Flathead Lake and its management affects the lake levels in the lowermost portion of the project reach. Hungry Horse Dam is a flood control reservoir located upstream of the project reach on the South Fork of the Flathead River.

2.2.1 Kerr Dam (1938) and Flathead Lake Water Surface Elevations

Kerr Dam is a hydroelectric facility located at the natural outlet for Flathead Lake, approximately five miles west of Polson. Operation of the dam, which began in 1938, raised the potential inundation level of Flathead Lake 10 feet above the natural outlet elevation (www.pplmontana.com). With flow management, the mean lake elevations with Kerr Dam in place have been approximately 4.8 feet higher than the pre-dam mean (Figure 26).

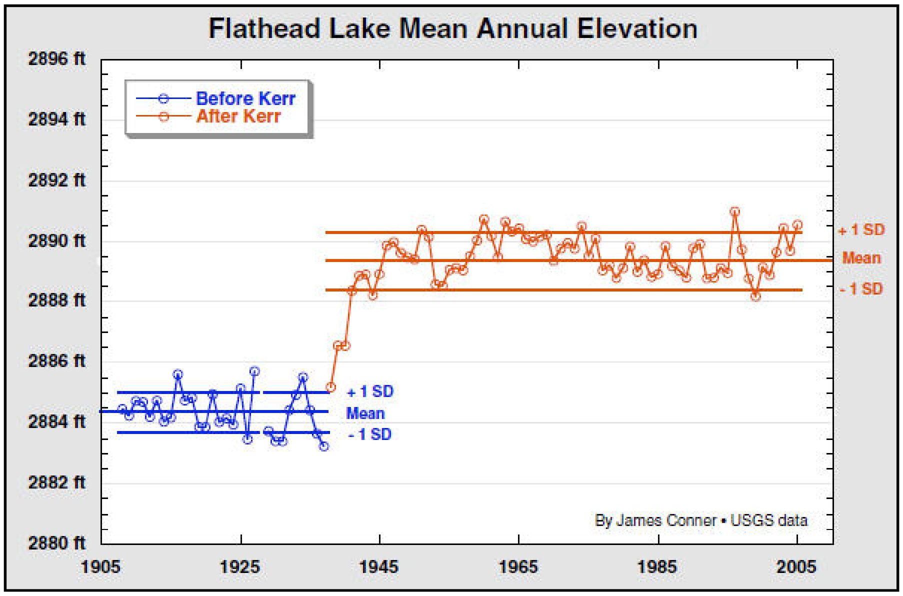


Figure 26. Flathead Lake elevations pre- and post-Kerr Dam (www.flatheadlakers.org).

Two USGS gaging stations record the level of Flathead Lake. These include gages at Somers (USGS 12371500) and at Polson (12371500). The Somers Gage record extends from 1928 to 1998, and the Polson record from 1909-2010.

At Somers on the northwestern corner of the lake, the annual pattern of lake level elevations changed dramatically from pre- to post- Kerr Dam conditions. Prior to completion of the dam, USGS lake level elevation data (USGS 12371500) followed a typical snowmelt hydrograph, indicating that lake levels were somewhat correlative to inflowing water volumes (Figure 27). Average lake levels peaked at approximately 2891 feet in June, and then continually dropped through the summer until October, when the average lake level elevations reached a minimum of 2882 feet. Following the completion of Kerr Dam, flows have been managed to sustain high lake levels through the summer months (Figure 28). Currently, average lake level elevations for the 1938-1998 time frame peak in July at approximately 2892.8 feet. Superposition of these two plots show that during the spring rise of May, lake level increases have remained relatively consistent through time, and that the average elevation values diverge in June, with the increased storage provided by Kerr Dam management evident (Figure 29).

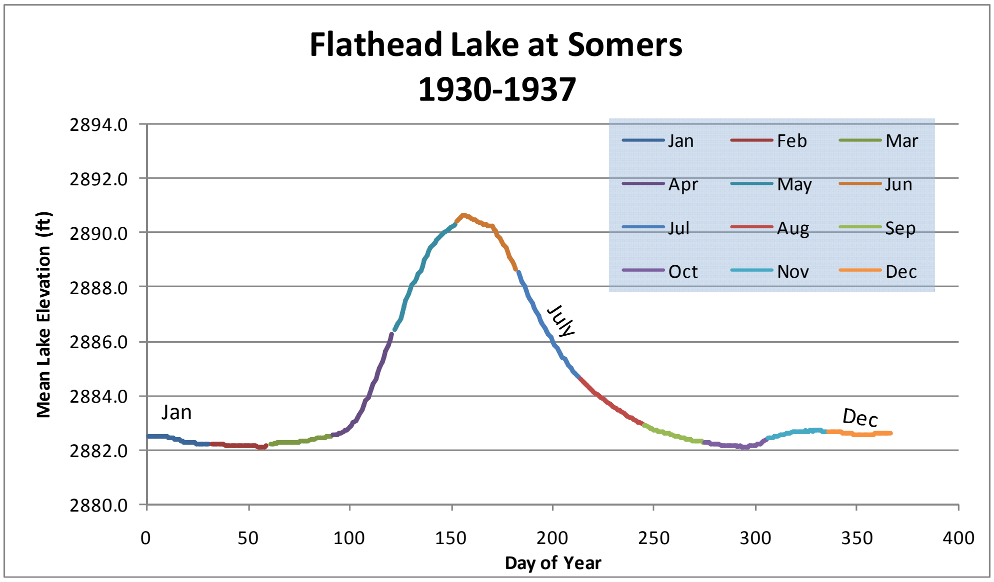


Figure 27. Mean daily elevation of Flathead Lake as measured at Somers for pre-Kerr Dam conditions, 1930-1937.

The typical high pool elevation in July of 2892.8 feet is lower than the elevation shown at the mouth of the river on the LiDAR-derived profile (2895 ft; Figure 25). This reflects a difference in datums for each data source, so their elevations are not directly comparable.

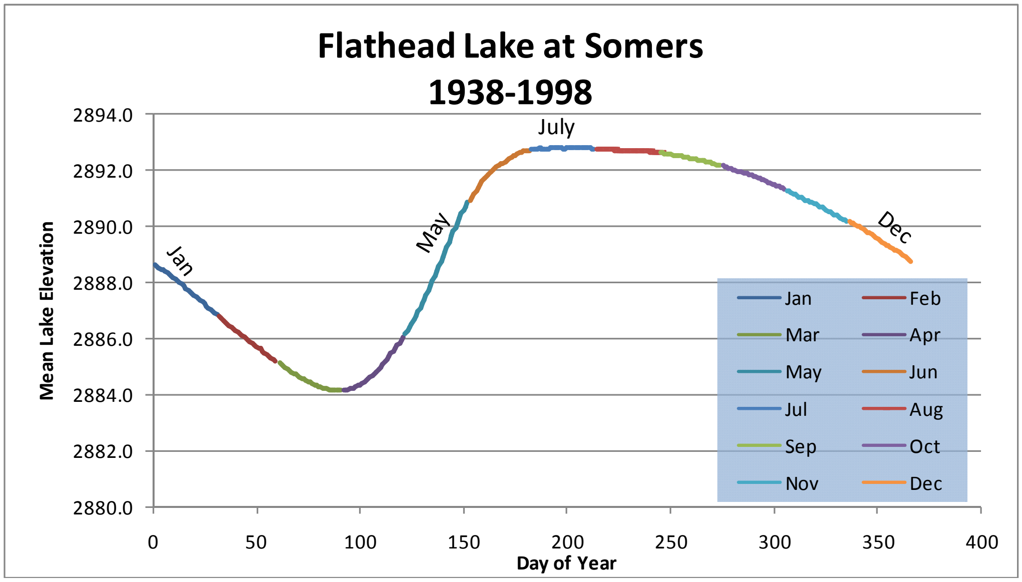


Figure 28. Mean daily elevation of Flathead Lake as measured at Somers for post-Kerr Dam conditions, 1938-1998.

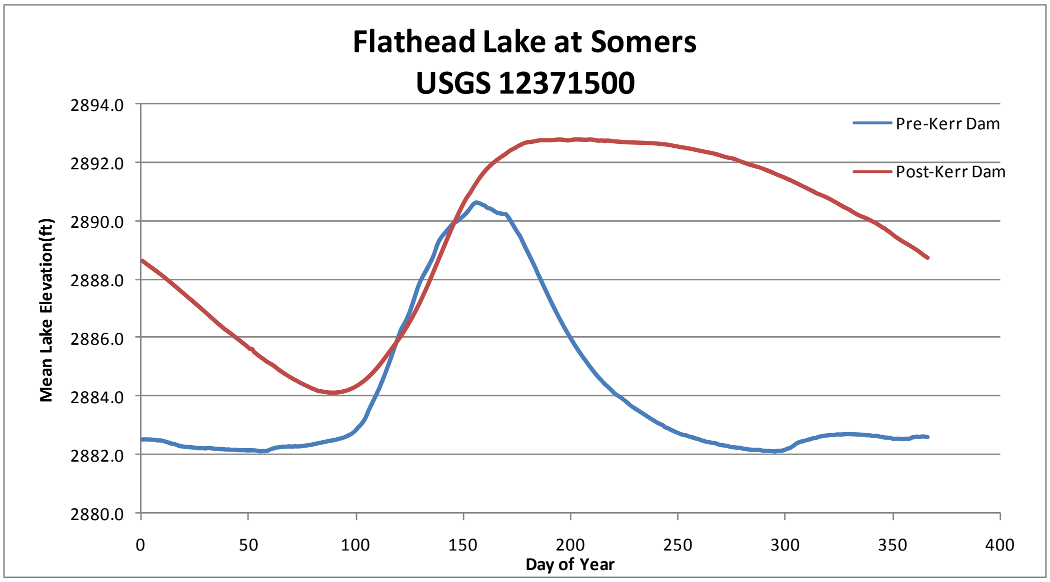


Figure 29. Superimposed Flathead Lake elevations at Somers showing pre-dam (1930-1937) and post-dam (1938-1998) conditions.

2.2.2 **Hungry Horse Dam (1948-1953)**

Hungry Horse Dam is located upstream of the project reach on the South Fork of the Flathead River, 20 miles northeast of Kalispell. The structure is 564 feet high, with a crest length of 2,115 feet (www.usbr.gov). Construction of Hungry Horse Dam was authorized in 1944, construction was contracted by 1948, and the work was completed by 1953. The dam has 2,982,000 acre feet of capacity specifically assigned to flood control. According to the US Bureau of Reclamation, the dam “helped minimize floods in the Flathead Valley and reduced peak discharges between the valley and Grand Coulee Dam by 10 to 25 percent, and at Portland, Oregon, by about 5 percent”. Hungry Horse Dam has had a significant impact on the mean annual hydrograph of the South Fork Flathead River below the dam (Figure 30). Pre-dam conditions (1911-1947) reflect a typical snowmelt hydrograph, whereas following dam closure (1954-2010), the spring pulse has been completely removed, and baseflow conditions have increased for the remainder of the year.

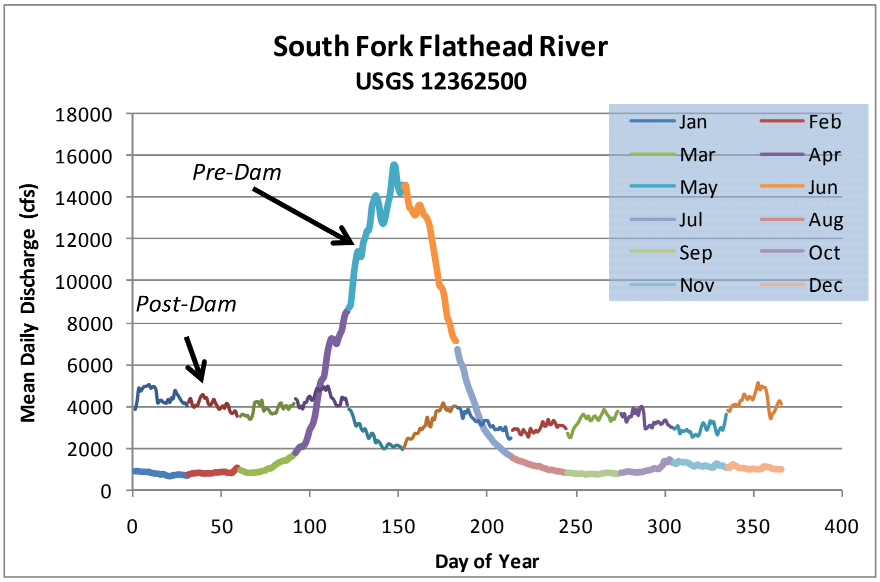


Figure 30. Mean annual hydrograph for South Fork Flathead for pre-dam (1911-1947) and post-dam (1954-2010) conditions.

The South Fork Flathead River is only one of three major contributors of flow to the project reach. The North Fork and Middle Fork of the Flathead River also contribute flows, and these drainages do not have reservoir impoundments. As a result, the mean annual hydrograph at Columbia Falls, downstream of the confluence of all three forks, still shows a strong snowmelt hydrograph signature (Figure 31). However, the mean annual peak discharge has been reduced by over 10,000 cfs from pre-dam to post-dam conditions. Hungry Horse reservoir thus has a significant impact on the hydrology of the project reach.

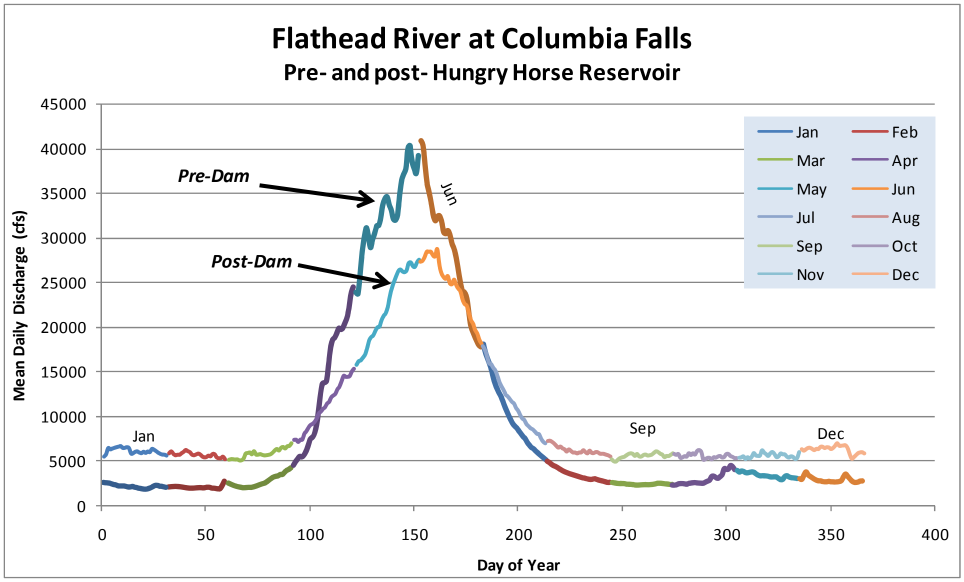


Figure 31. Mean annual hydrograph, Flathead River at Columbia Falls, pre-dam (1923-1947) and post-dam (1953-2009) conditions.

2.2.3 Flood History

Peak annual discharges for the Flathead River at Columbia Falls are shown in Figure 32. The largest flow on record at this station occurred on June 9, 1964, when the flow peaked at 176,000 cfs. The estimated 100-year discharge at this site is 84,200 cfs, indicating that the 1964 flood was over 90,000 cfs greater than the 100-year flood estimate. According to USGS flood frequency estimates at the gage, the event exceeded a 500-year flood. This event destroyed numerous bridges and many miles of railroad track and highway. Approximately 20,000 acres of land were flooded in the Flathead Valley and “areas up to a mile from the river were under four feet of water” (www.dailyinterlake.com).

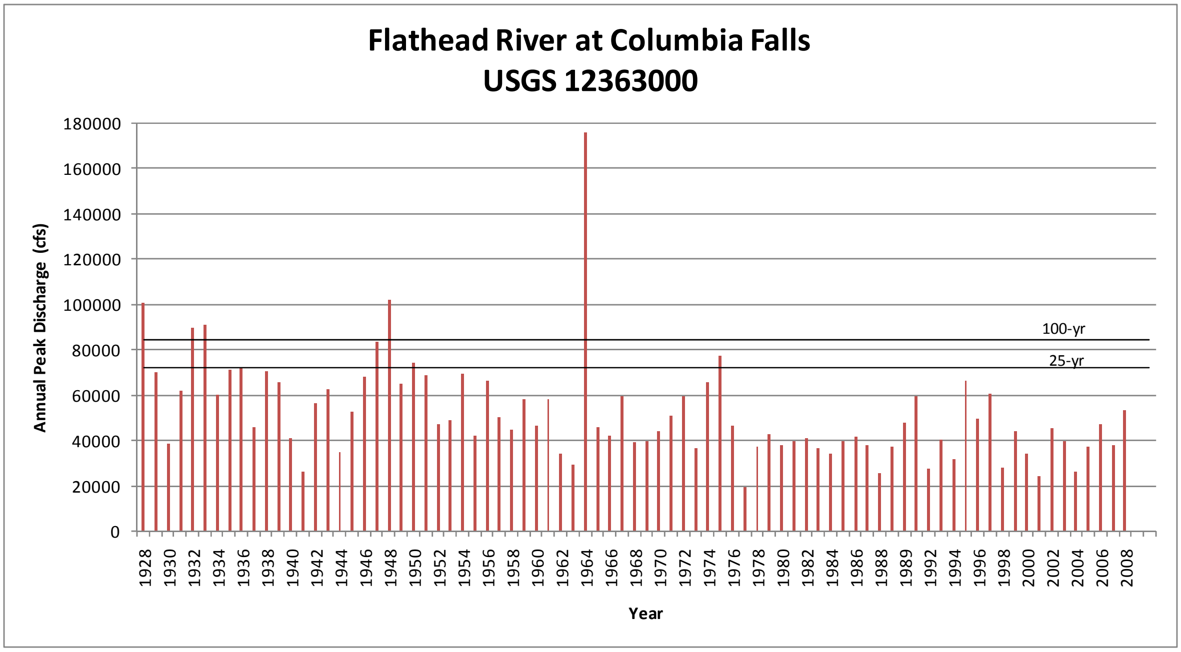


Figure 32. Peak annual discharge, Flathead River at Columbia Falls, 1928-2008.

Flood frequency discharges on the Flathead River have clearly been reduced by the operation of Hungry Horse Dam. Currently, the 500-year flood discharge at Columbia Falls is 97,800 cfs; over the period of record, this discharge has been exceeded four times (1894, 1928, 1948 and 1964). During the 25 year time frame that preceded the closure of Hungry Horse Dam, the Flathead River annual peaks exceeded what is now considered a 25-year event (71,900 cfs) a total of nine times (Figure 33). Over the last 55 years since the dam was completed the 25-year event has been exceeded twice (1964 and 1975).

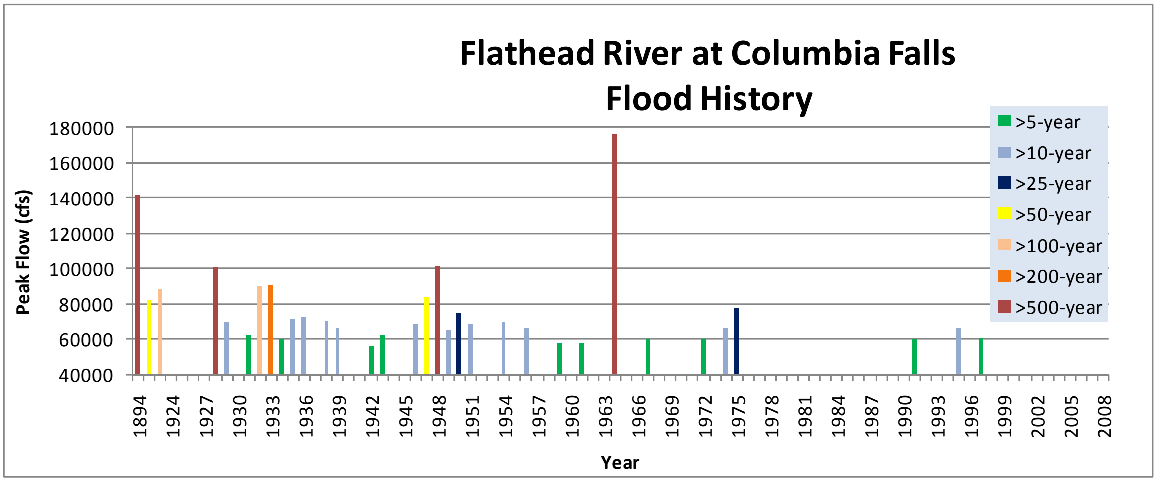


Figure 33. Peak floods that exceeded a 5-year event, Flathead River at Columbia Falls.

2.2.4 Flow Management and CMZ Mapping

Because both Kerr Dam and Hungry Horse Dam have affected the hydrology of the project reach, all of the analyses performed for the CMZ mapping effort are based on post dam conditions, to ensure that measured migration rates reflect the current hydrologic management scenario. That said, if management of either of these structures were to change significantly, then the analyses presented in this report should be revisited.

3.0 Methods

The methodology applied to the CMZ delineation are adapted from the techniques outlined in Rapp and Abbe (2003) as well as Washington Department of Natural Resources (2004). The Channel Migration Zone (CMZ) developed for the Flathead River is defined as a composite area made up of the existing channel, the historic channel since 1955 (Historic Migration Zone, or HMZ), and an Erosion Buffer that encompasses areas prone to channel erosion over the next 100 years. Areas beyond the Erosion Buffer that pose risks of channel avulsion are identified as “Avulsion Hazard Zones” (AHZ).

The primary methods employed in developing the maps include analysis of aerial photography using Geographic Information System (GIS) software, bankline digitization, migration rate measurements, and data analysis. The mapping information and measured rates of channel shift are then utilized to define historic channel locations and to define an erosion buffer to allow for future erosion. Once this buffer is established, areas beyond the buffer prone to avulsion are mapped, using supporting information derived from air photos, historic General Land Office survey maps, and inundation modeling results.

3.1 Imagery

Four series of aerial photographs (1956, 1978, 1990 and 2009) were used to evaluate changes in the morphology of the Flathead River over the last 53 years. The horizontal accuracy of each image data set is dependent on the methodology used to rectify the image set.

The 1956 and 1978 image sets were acquired in digital format from the USGS EROS Data Center. Mapcon Mapping of Salt Lake City provided orthorectification services using the 2009 six-foot LiDAR elevation model and the 2009 high-resolution aerial photography as a base (Montana DNRC, 2009). An independent assessment of the spatial accuracy of the orthorectified imagery performed by Technical Advisory Committee member Chuck Dalby indicated that the “resulting total error in horizontal positional accuracy for 1956 orthoimages is ±12.2 feet and ±16 feet for the 1978 orthoimages” (Dalby, 2010b).

The 1990 image set was created by the USGS as digital orthophoto quarter quadrangle (DOQQ) images and are served by the Montana State Library. The USGS performed the georeferencing process, and the images have a reported accuracy of ±8.2 feet. Complete metadata, including an accuracy assessment, is available at http://nris.mt.gov/nsdi/nris/doqq.html.

The 2009 imagery is a natural-color product created specifically for Flathead County. It provides a high-resolution (1ft) dataset for assessing modern-day channel morphology. Specifications and accuracy reports are available from the Flathead County GIS office.

3.2 GIS Project

The orthorectified air photos were compiled within an ArcMap GIS project to provide the basis for CMZ mapping. Other data included in the GIS project include one and six-foot LiDAR elevation data, roads, stream courses as depicted in the National Hydrography Dataset, scanned General Land Office Survey Maps which were obtained from Bureau of Land Management, floodplain mapping and geologic maps produced by the United States Geological Survey (Harrison et al., 2000).

3.3 Banklines

Banklines approximating a bankfull water condition were digitized for each year of imagery at a scale of 1:4,000. Bankfull is defined as the stage above which discharge commences to flow out onto the floodplain. There are many possible ways to delineate bankfull, including morphometric, sedimentary and discharge approaches (Riley, 1972). Despite the advantages offered by these methods, CMZ development requires identification of bankfull for past time periods where the historic ground condition can no longer be measured. Therefore, we typically rely on the extent of the lower limit of perennial, woody vegetation to define channel banks (Schumm, 1960; Mount & Louis, 2005). The bankfull extent reflects those portions of channels that are likely to convey typical spring runoff, thereby preventing the establishment of woody vegetation. Also used as boundaries are terrace margins and bedrock valley walls. Fortunately, shrubs, trees, terraces and bedrock generally show distinctive signatures on both older black-and-white as well as newer color photography. These signatures, coupled with an understanding of riparian processes, allow for consistent bankline mapping through time and across different types of imagery. Additionally, the acquisition of modern-day banklines via field-based methods, aside from not being feasible under typical time and budget constraints, would yield results that are not consistent with the accuracy of banklines obtained from historic photographs.

A few general rules were established for digitizing channels. A secondary channel must show physical connectivity with the main channel at both the upstream and downstream end under bankfull conditions. In Reach 3, several in-stream blockages constructed in side channels after 1955 were ignored as long as the feature met the morphologic criteria for a secondary channel.

Several sources of error can impact the accuracy of the digitized banklines: the horizontal accuracy of the imagery (Section 3.1), the ability to interpret the imagery, and the repeatability of the digitizing. While these factors can either compound or cancel out the positional error of the digitized banklines, the reach-averaging CMZ methodology effectively minimizes the impact of these errors, as the mapping is based on mean migration rates rather than any single value.

3.4 Migration Rate Measurements

Utilizing the GIS, the digitized banklines were evaluated for discernable channel shift since 1956.

Where migration was identifiable, vectors were drawn in the GIS to record that change. Within each area identified as an erosion site, three lines were drawn to represent migration within the polygon. These lines were drawn at the maximum migration distance of the polygon, then at a location approximately half way between the maximum migration line and the end of the erosion polygon, discounting narrow polygon tails. Each vector is attributed with reach, eroding site identification, geologic unit, vegetation type, and line length. A total of 183 individual migration vectors were created in the GIS to assess bankline migration during the 1956-2009 timeframe. The lengths of these vectors range from less than 30 feet in Reach 1 to as much as 815 feet in Reach 3. These vectors were then intersected with the banklines to develop a dataset consisting of the 183 vectors divided into 3 segments each (1956-1978, 1978-1990, and 1990-2009; Figure 34). This allows the assessment of movement over four distinct timeframes, including an overall 1956-2009 timeframe. In order to normalize the data, the vector lengths were converted to migration rates of feet per year.

In addition to the linear measurements of channel shift (vectors), the average displacement distance was calculated via polygon analysis. That is, mean migration rates for each erosion site polygon were calculated as the ratio of the polygon area to a line drawn along the polygon axis. The lines used to measure the polygon length were provided by Chuck Dalby of the project Technical Advisory Committee (Figure 35). The polygon method approximates the mean width of the erosion polygon area, reflecting only the 1956-2009 timeframe.

The results of both methodologies are provided in this document, and shown on the accompanying maps.

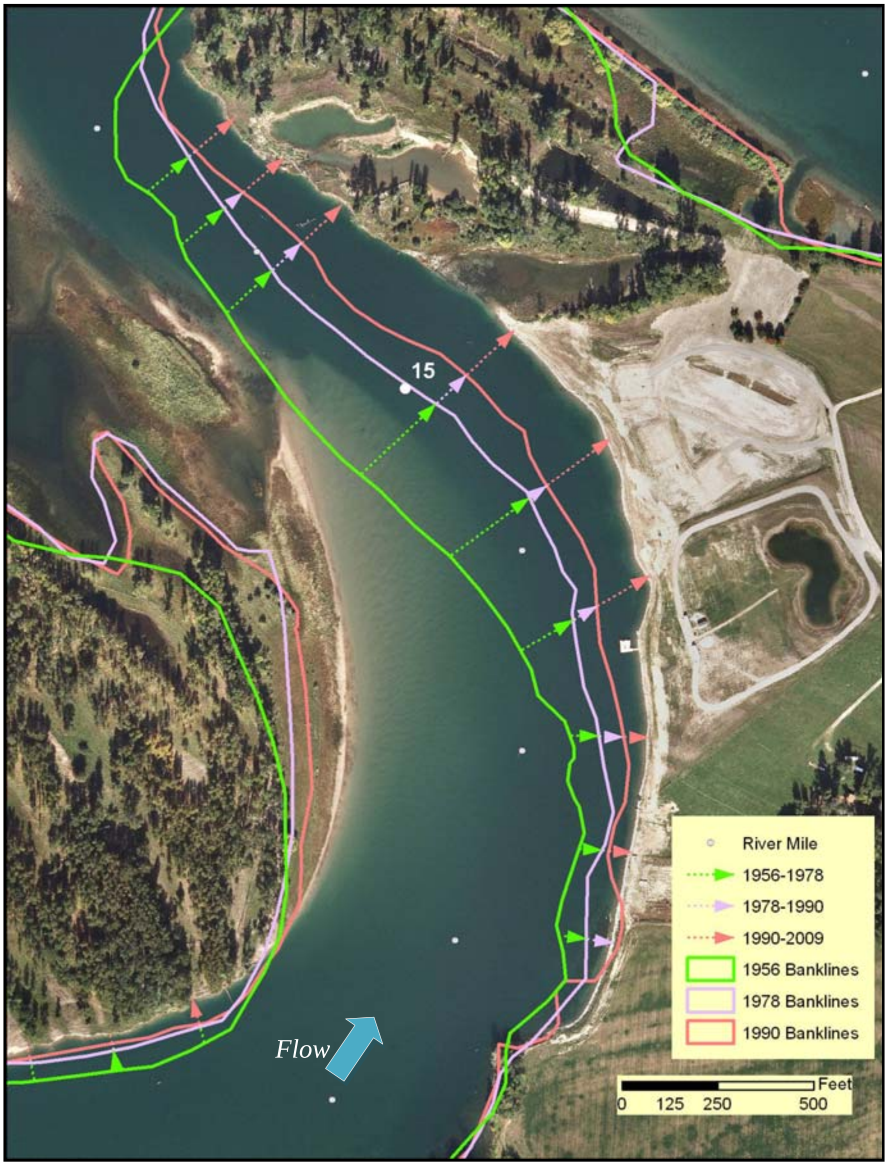


Figure 34. Segmented migration vectors, Reach 2; photo is from 2009.

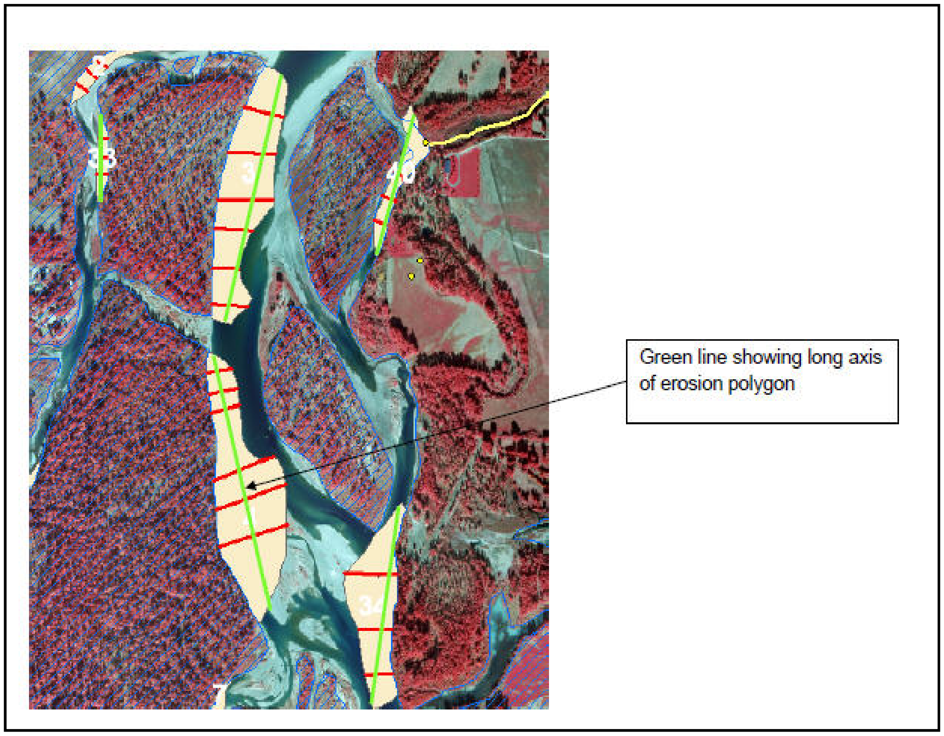


Figure 35. Erosion polygons with vector series (red) and polygon axes (green). From Dalby, 2010.

3.5 Inundation Modeling

Inundation modeling is a static model of inundation potential based upon Digital Elevation Model (DEM) data. The general technique involves creating a flood surface based on cross section elevations extracted from the DEM. This model surface is then intersected with the DEM to create a surface representing inundation depth. This is often used to approximate flood prone areas (e.g. areas where the flood surface elevations at a given stage are higher than the underlying DEM ground surface elevations are identified as flood-prone), but it also is a useful tool for identifying areas prone to avulsion. Areas of low elevation such as swales that may be reactivated through avulsion are highlighted in the resulting model. While anomalies in the DEM data, local structures, and the highly variable terrain complicate the model outputs, compelling results can still be developed.

For this study, six cross sections were defined along the study area. These cross sections were then intersected with the six-foot LiDAR DEM and the minimum elevation of each cross section where the cross section intersects the river was used to create the model surface. The resulting model surface is a series of planes, approximately coincident with the water surface elevations. Deviations between this surface and the LiDAR elevations represent potential water depth (Figure 36). The use of inundation modeling results in this study is described in more detail in Section 4.4.

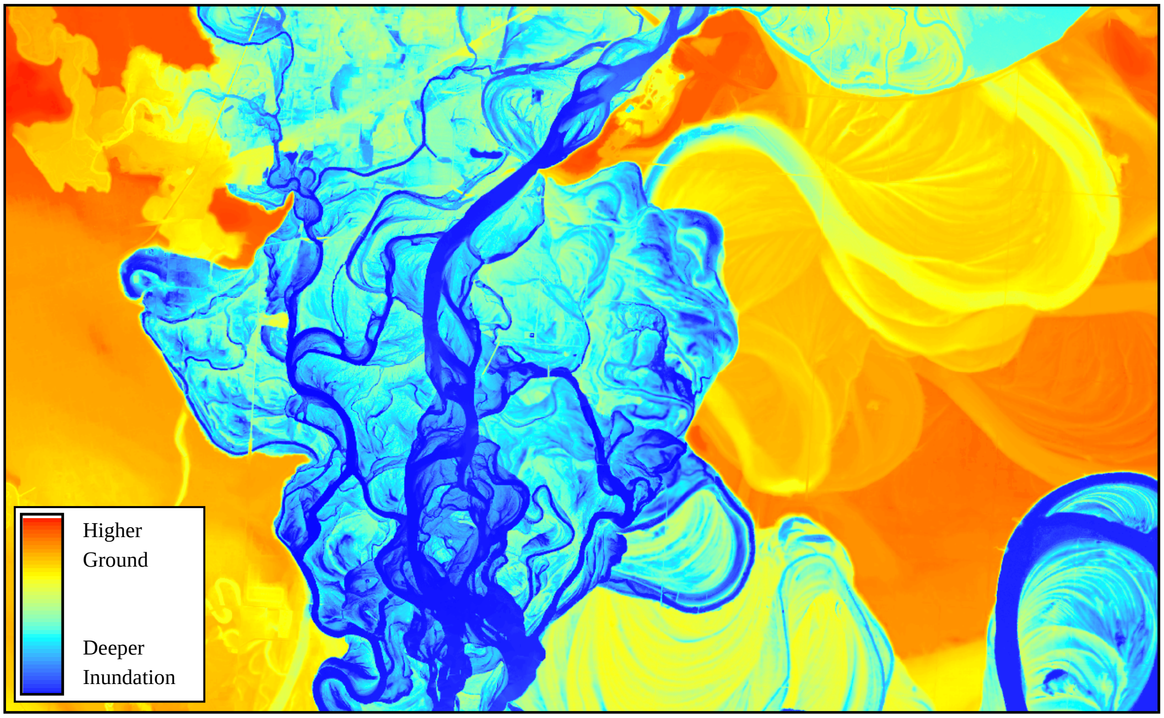


Figure 36. Inundation modeling output based on LiDAR topographic data, Reach 3.

3.6 Field Investigation

In late June of 2010, personnel from AGI and DTM traversed the entire project reach by boat. High resolution air photos were used for base mapping of bank armor, erosion sites, and general geomorphic/geologic features. Over 200 photographs were collected and located via Global Positioning System (GPS); these photos are contained within the GIS dataset. The work took place when lake levels were high, so lower bank erosion and lower bank armor segments were obscured, especially in Reach 1 and Reach 2. In Reach 3, only primary channel threads were mapped as numerous secondary channels were not navigable by boat.

4.0 Results

The channel migration zone (CMZ) developed for the Flathead River is defined as a composite area made up of the existing channel, the historic channel since 1955 (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA) that encompasses areas prone to channel erosion over the next 100 years. Areas beyond the EHA that pose risks of channel avulsion comprise the Avulsion Hazard Zone (AHZ). Lastly, those areas where migration has been restricted are highlighted as Restricted Migration Area (RMA).

4.1 The Historic Migration Zone (HMZ)

The HMZ is created by combining the bankfull polygons for each time series into a single HMZ polygon. The bankfull channel boundaries are the boundary between open channel and off-stream areas, including woody vegetation stands, vegetated floodplains, terrace margins, or bedrock valley walls. Thus, the HMZ contains all unvegetated channel threads that are interpreted to convey water under bankfull conditions (typical spring runoff), and as such, the zone has split flow segments and islands. Many of the larger islands have not had any active river channels since 1956, yet are included in the historic footprint of the HMZ. This inclusion of islands reflects the fact that the HMZ incorporates the entire river corridor area occupied by the Flathead River from 1956-2009. In some settings, where island areas are non-erodible, it may be appropriate to exclude these features from the CMZ. In the case of the Flathead River, these areas are comprised of young alluvial deposits in the active stream corridor that are prone to reworking and avulsion; hence, they have been retained in the CMZ.

For this study, the Historic Migration Zone is comprised of the total area occupied by Flathead River channel locations in 1956, 1978, 1990 and 2009 (Figure 37). The resulting area reflects 53 years of channel occupation.

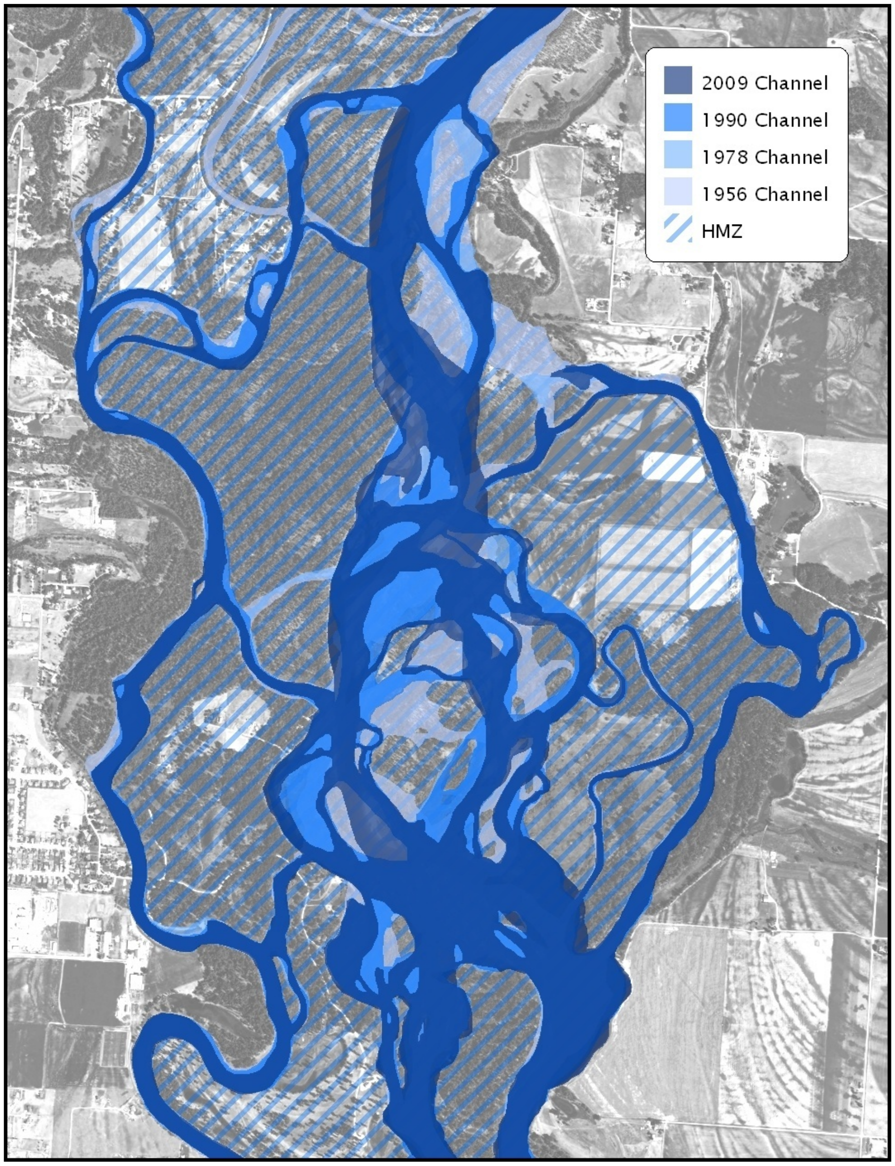


Figure 37. Flathead River HMZ

4.2 The Erosion Hazard Area (EHA)

Banklines and air photos were evaluated for channel shift between 1956 and 2009 within the GIS (Appendix B and Appendix C). The approach consists of measuring rates of movement within each reach and statistically analyzing those rates to develop an erosion buffer specific to each reach. This reach-scale assessment acknowledges that predicting movement at single sites along the 24-mile reach over the next century is at best difficult due to the non-linear nature of channel migration. As such, averaging over a reach scale provides an EHA on banklines that are not currently experiencing migration, assuming that the alluvial sediments are similarly prone to future bank movement throughout the reach. This is consistent with the Reach Scale approach outlined by the Washington Department of Ecology (WSDE, 2010).

4.2.1 Data Presentation: Box and Whisker Plots

Although the statistic utilized in developing the Erosion Hazard Area is the reach-scale mean migration rate, it is also instructive to consider the distribution of measured values relative to the mean. To that end, a series of statistics have been developed for each suite of migration rate measurements. These statistics for each data series are presented in graphical form as a series of box and whisker plots which reflect the following statistics for each dataset: minimum, 25th percentile, mean, 75th percentile, and maximum (Figure 38). Additionally, the 90th percentile value has been added to help identify the range of the most extreme (top 10%) of rate measurements. The box can be used to visually assess the concentration of data about the mean (50% of all measurements are within the box).

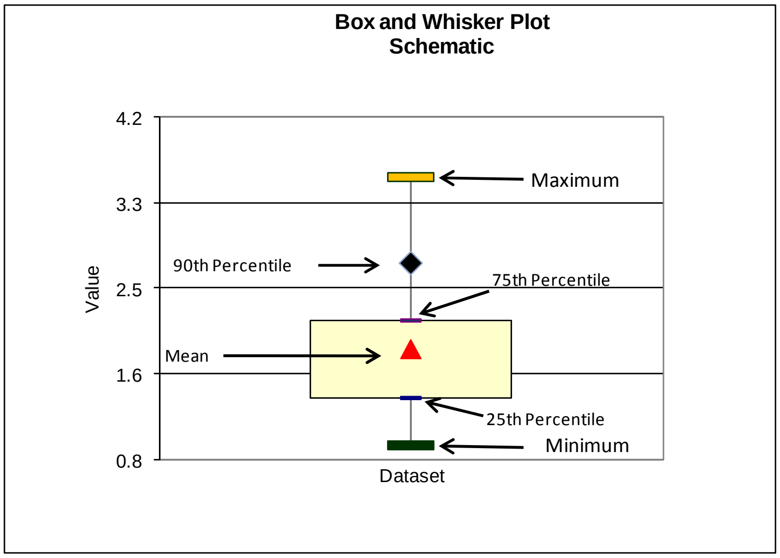


Figure 38. Box and whisker plot schematic showing relationships between graphics and statistics.

4.2.2 Reach 1

Reach 1 is characterized by low overall migration rates, with mean values for each timeframe of less than 2 feet per year (Table 2). Rates of movement were highest in the 1956-1978 timeframe, averaging 1.9 feet per year (Figure 39). The vector analysis method yielded slightly larger mean rates of movement than the vector approach. The mean 100-year migration distance for the vector approach is 13% greater than that derived from the vector analysis

Table 2. Summary statistics for channel migration, Reach 1.

Statistic	***Vectors***				***Polygons***	***1956-2009 Difference (Vectors vs Polygons)***
	1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-2009***	
25th Percentile	1.4	0.2	0.1	0.9	0.8	
Min	0.9	0.0	0.0	0.7	0.6	
Median	1.7	0.6	0.5	1.1	1.0	
Max	3.6	2.3	2.2	2.5	1.8	
75th Percentile	2.2	1.2	1.2	1.4	1.3	
N	13	13	13	13	7.0	
90th Percentile	2.7	1.5	1.9	1.8	1.6	
Mean	1.9	0.7	0.8	1.2	1.1	
Mean Migration Distance: 100 year timeframe (feet)	188	73	80	**123**	**107**	**13%**

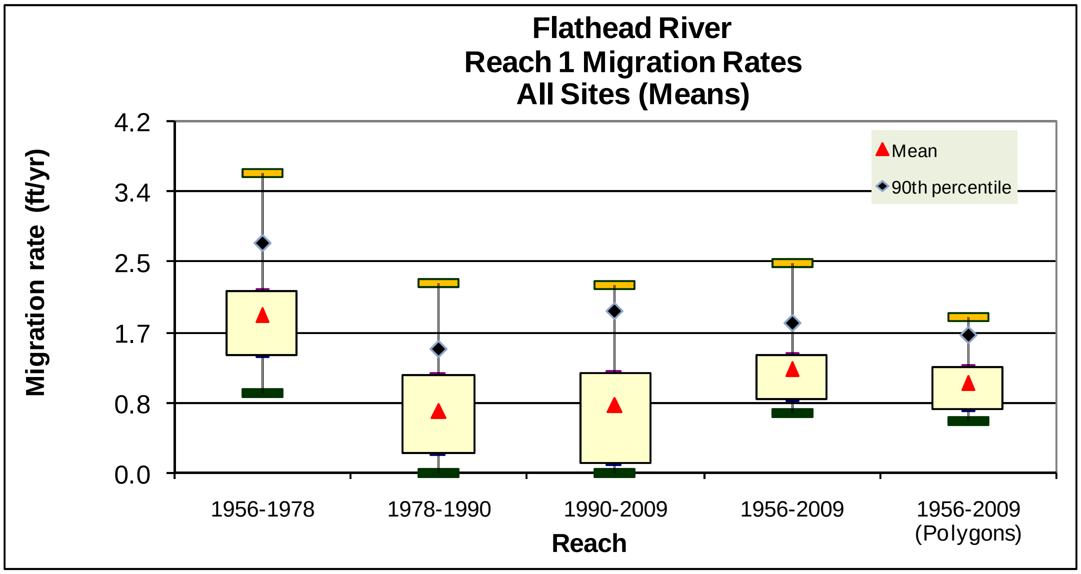


Figure 39. Reach 1 migration rates by timeframe.

If the migration rates are computed as a 100-year migration distance, the total anticipated migration distance, on average, is 188 feet using rates derived from the 1956-1978 timeframe. For the entire 1956-2009 timeframe, the 100-year anticipated migration distance is 123 feet for vector-derived rates and 107 feet for polygon-derived rates.

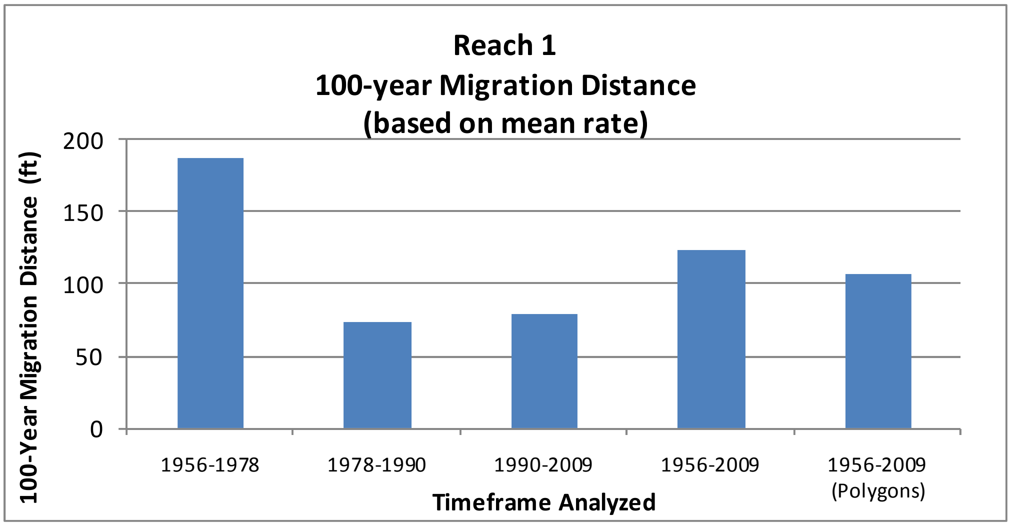


Figure 40. 100-year migration distances based on mean migration rates, Reach 1.

4.2.3 Reach 2

Reach 2 has notably higher migration rates than Reach 1. The break between the two reaches is based on an abrupt reduction in channel movement at approximately River Mile 13.0 (Table 3). Additionally, within Reach 2 there is a distinct difference in migration rates depending location of the site in a bendway. Migration rates are highest in areas of bendway compression, in that the fastest channel movement is typically on the upstream limb of a bend (polygons 16, 21, and 24 on Figure 23). In order to assess the affect of planform location on overall migration rates, vectors that are located in such areas of bendway compression were separated from the entire dataset and analyzed separately (Figure 41 through Figure 43). This then results in a different EHA for these specific areas.

Table 3. Summary statistics for channel migration on upstream limbs of bendways, Reach 2.

	Vectors				*Polygons*	*1956-2009 Difference (Vectors vs Polygons)*
Statistic	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***	***1956-2009***	
25th Percentile	1.7	2.5	2.1	2.8	2.6	
Min	1.6	0.7	0.4	1.2	2.3	
Median	3.1	3.9	3.9	3.2	3.0	
Max	10.3	7.8	9.5	9.2	6.8	
75th Percentile	4.4	5.7	5.4	4.7	4.9	
N	8	8	8	8	3.0	
90th Percentile	7.9	6.9	8.0	7.4	6.1	
Mean	4.0	4.1	4.2	4.1	4.0	
Mean Migration Distance: 100 year timeframe (feet)	401	412	422	**411**	**404**	**2%**

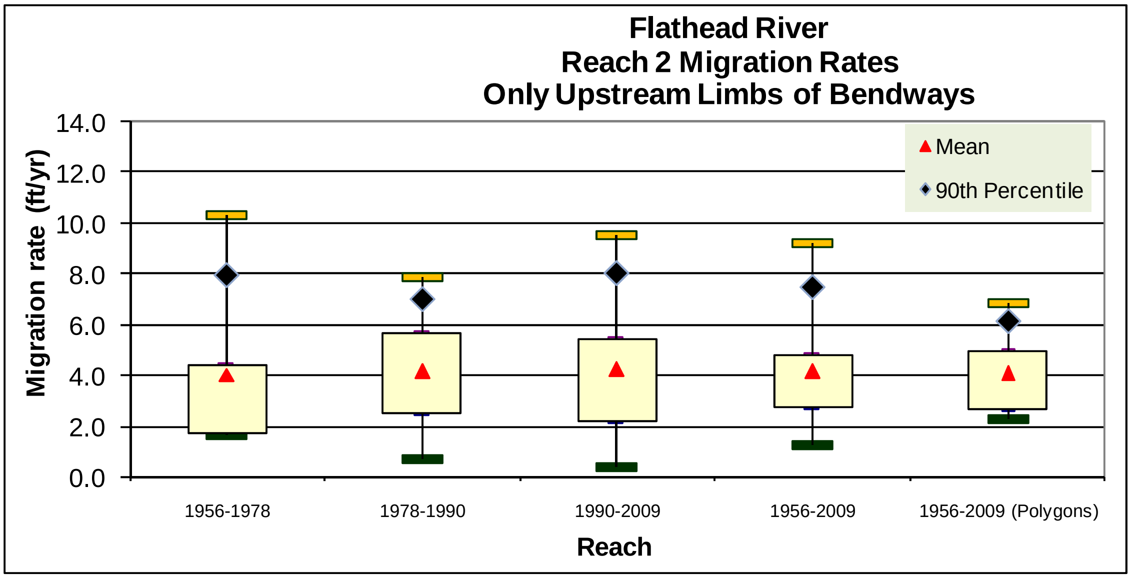


Figure 41. Summary statistics for compressing bendway sites, Reach 2.

Table 4. Summary statistics for channel migration on all other sites Reach 2.

	Vectors				*Polygons*	*1956-2009 Difference (Vectors vs Polygons)*
Statistic	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***	***1956-2009***	
25th Percentile	1.8	0.8	0.6	1.4	1.4	
Min	0.0	0.0	0.0	0.7	0.5	
Median	2.2	1.3	1.5	1.8	1.5	
Max	3.4	2.9	2.7	3.0	2.3	
75th Percentile	3.1	2.0	1.8	2.1	1.6	
N	11	11	11	11	7.0	
90th Percentile	3.2	2.4	2.5	2.2	1.9	
Mean	2.3	1.4	1.3	1.7	1.5	
Mean Migration Distance: 100 year timeframe (feet)	226	137	133	**172**	**146**	**15%**

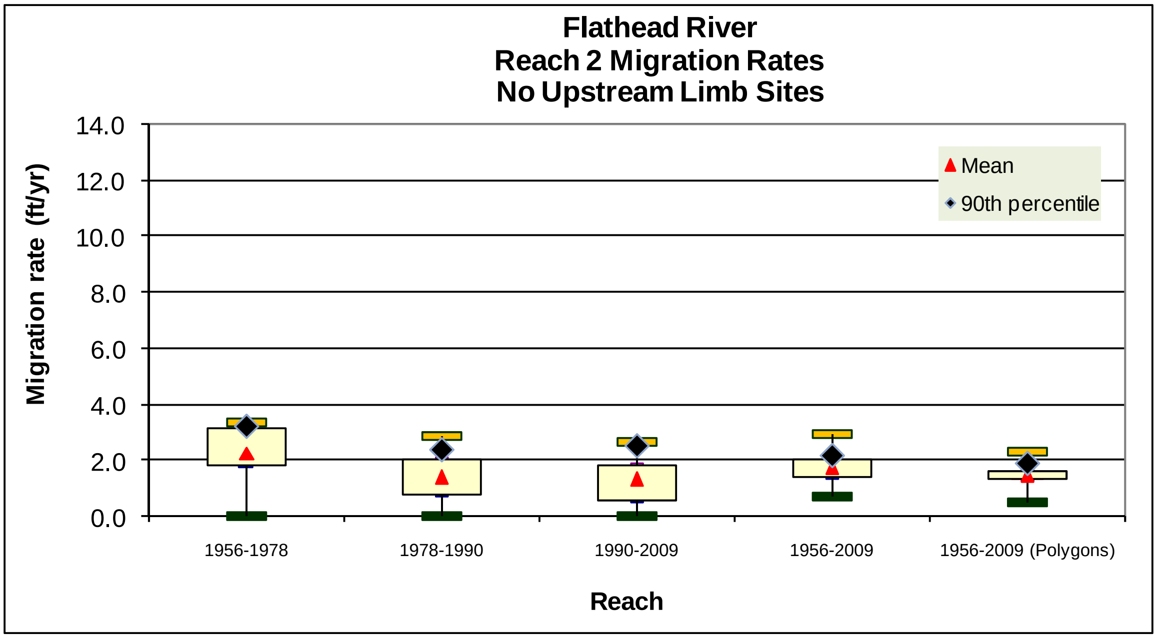


Figure 42. Reach 2 migration rates by reach for all sites other than upstream limbs of bendways.

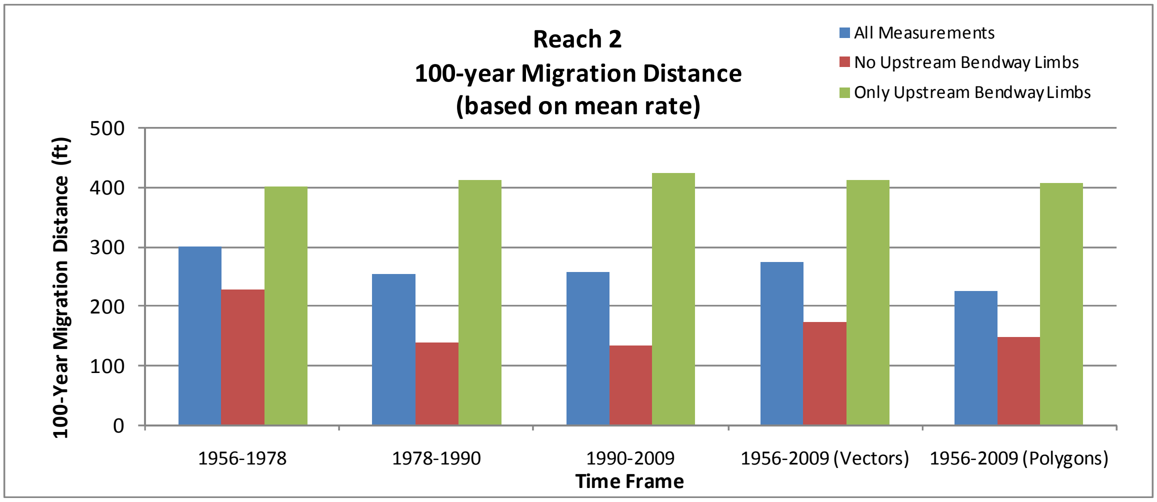


Figure 43. Reach 2 migration rates with bendway compression sites separated from all sites dataset.

4.2.4 Reach 3

Reach 3 has the most rapid migration rates in the project reach, with some sites migrating over 10 feet per year since 1956 (Table 5 and Figure 44). The majority of migration at many sites occurred between 1956 and 1978, which likely reflects impacts of the 1964 flood. For the 1956-1978 timeframe, which includes the 1964 flood event, the mean migration rate in Reach 3 erosion polygons was 6.9 feet per year. Long-term (1956-

2009) rates are somewhat less, averaging 4.6 feet per year. Polygon analysis depicts a mean rate of 4.1 feet per year for the same time period.

Table 5. Summary migration rate statistics for channel migration, Reach 3.

Statistic	*Vectors*				*Polygons*	*1956-2009 Difference (Vectors vs Polygons)*
	1956-1978	*1978-1990*	*1990-2009*	*1956-2009*	*1956-2009*	
25th Percentile	2.8	0.9	0.9	1.9	1.8	
Min	1.0	0.0	0.0	1.2	1.1	
Median	4.5	2.3	2.0	4.2	3.6	
Max	31.4	18.5	9.8	13.6	11.8	
75th Percentile	7.6	4.2	3.5	6.1	5.5	
N	29	29	29	29	22.0	
90th Percentile	12.8	7.4	6.9	8.0	6.8	
Mean	6.9	3.4	2.7	4.6	4.1	
Mean Migration Distance: 100 year timeframe (feet)	688	343	266	**459**	**411**	**10%**

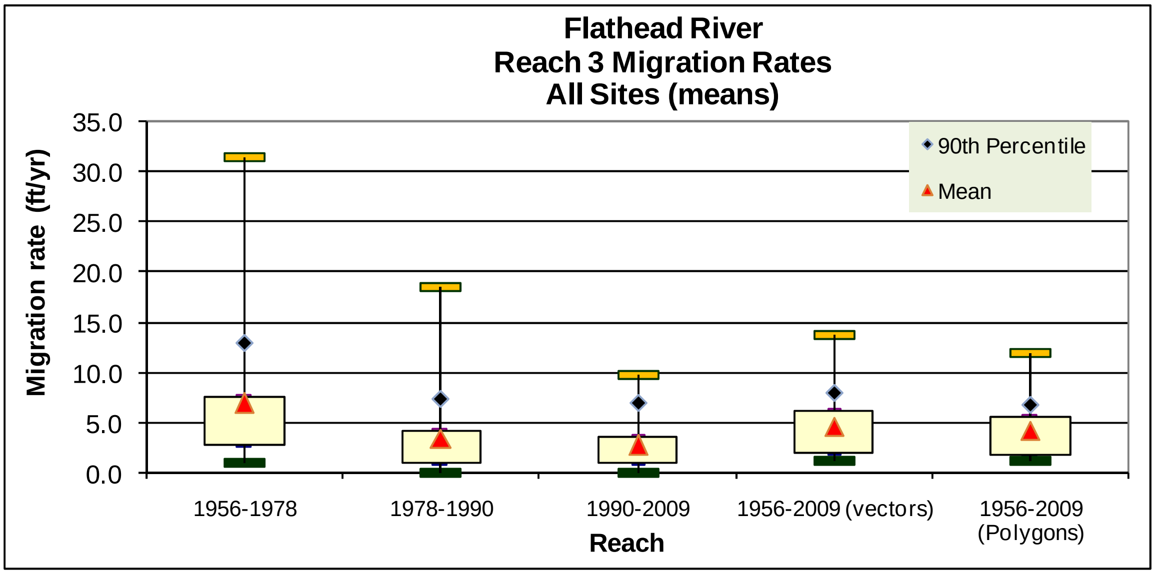


Figure 44. Reach 3 migration rates.

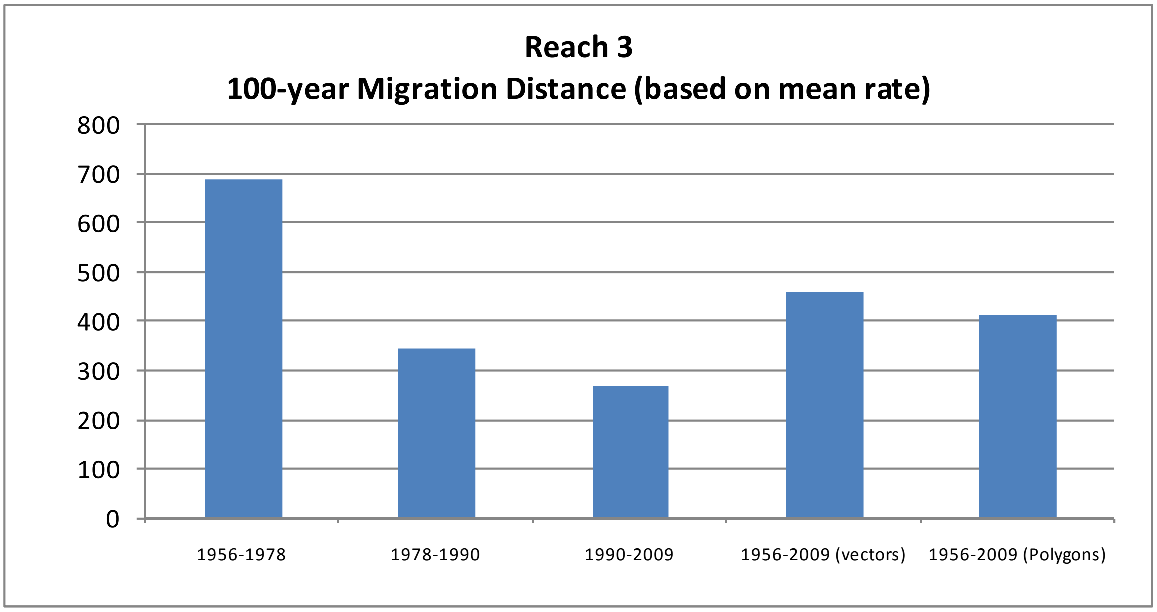


Figure 45. 100-year migration distances based on mean migration rates, Reach 3.

4.2.5 Geologic Controls on Migration Rate

An additional component of the EHA is the Geotechnical Setback, which is a setback placed on geologic units that may be prone to geotechnical failure. In the modern floodplain alluvium, any geotechnical setback that may be appropriate to accommodate the effects of bank saturation through irrigation, lake level management, or boat wake-induced erosion are included in the migration rate analysis. Beyond that, there are very few locations where the geology differs. These areas are identifiable by overlaying the geologic map of the area on a hillshade of the LiDAR elevation data. Geologic controls are located on the left bank just upstream of the study reach (upstream of Old Steel Bridge), and in the lowermost section of Reach 1. In Reach 1, these units are composed of bedrock and thus have been be clipped from the CMZ map. These areas are identified in the GIS files that accompany this report.

4.2.6 Erosion Hazard Area (EHA) Buffer Widths

One of the decisions required in establishing an Erosion Hazard Area (EHA) is to select the appropriate historic timeframe for defining typical erosion rates. On the Flathead River, migration rates were relatively rapid during the 1956-1978 timeframe, which likely in part reflects the influence of the 1964 flood. In discussions with the Technical Advisory Committee, it was decided that mean migration rates calculated for the longest timeframe (1956-2009) would most appropriately depict typical rates of change in the project reach anticipated over the next century. The resulting EHA widths, which reflect 100-year migration distances calculated using measured 1956-2009 rates of movement are shown in Table 6 and Figure 46. The polygon-based analysis consistently provides a slightly smaller EHA width, however the results are generally within 10% of one another. An example of the vector-based EHA placement against the 2009 banklines is shown in Figure 47.

Table 6. Erosion Hazard Area (EHA) buffers applied to CMZ maps.

Reach	***Vector- based 100 yr migration distance (ft)***	***Polygon- based 100 yr migration distance (ft)***
Reach 1 All Banks	123	107
Reach 2 (polys 16, 21, 24)	411	404
Reach 2 Remaining Banks	172	146
Reach 3 All Banks	459	411

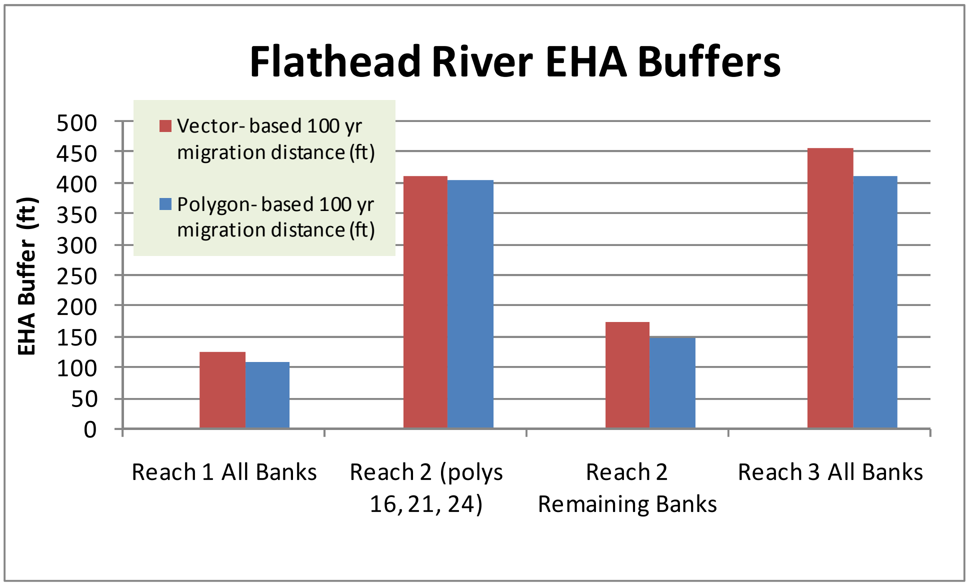


Figure 46. EHA buffer plot showing differences derived from vector and polygon approach.

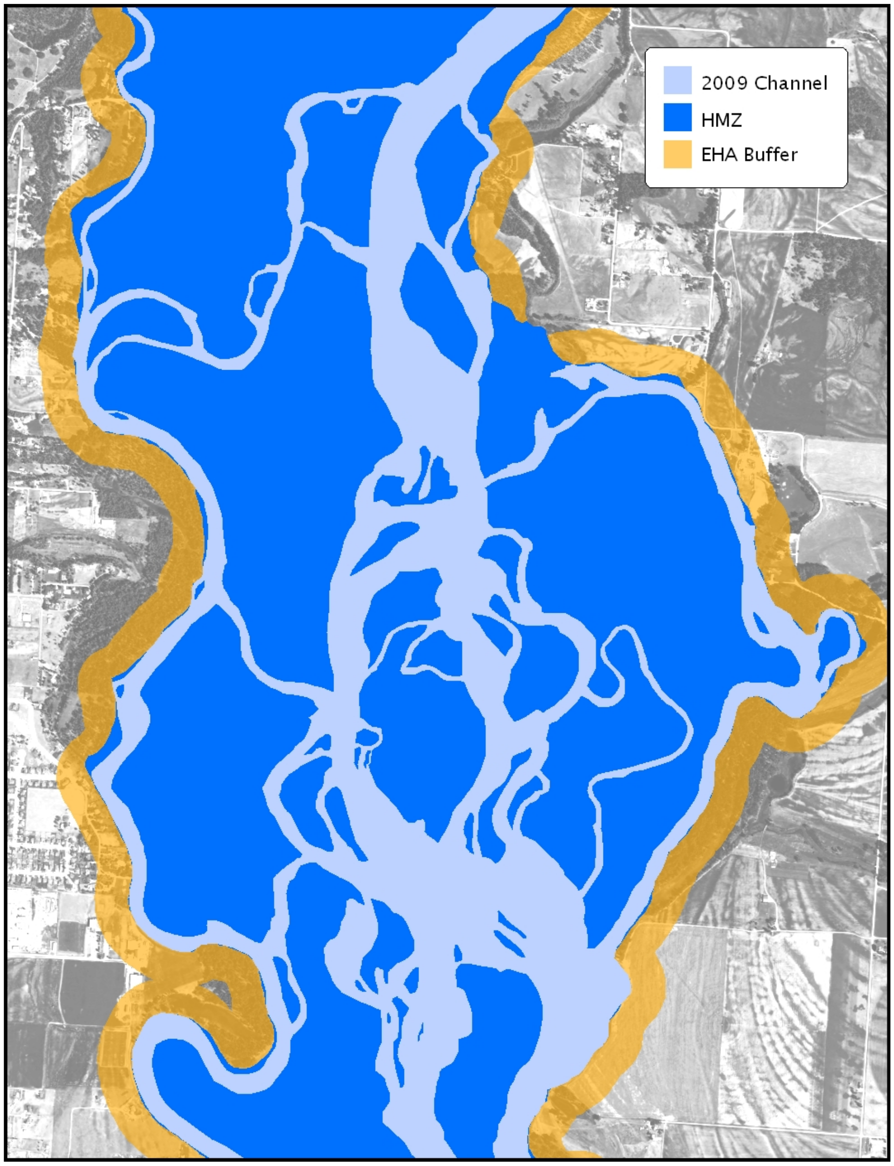


Figure 47. Vector-derived EHA buffers placed against 2009 banklines.

4.2.7 **Erosion Hazard Areas in Sloughs**

The erosion mechanisms observed on the Flathead River include fluvial erosion, saturated bank collapse, and erosion from wind- or boat- generated waves. Because the sloughs are in connectivity with the main river, and because the sloughs are popular for recreational boaters, the buffers generated for the river were also applied to the sloughs. This buffer will accommodate bank collapse from lake level changes, floodplain irrigation, or wave energy.

4.3 The Restricted Migration Area (RMA)

The Restricted Migration Area (RMA) includes areas of the natural CMZ that are isolated by dikes or bank armor. Whereas data were available to identify RMA areas affected by diking, there is no comprehensive bank armor inventory for the project reach. As such, only channel-blocking dikes define the RMA.

4.3.1 **Bank Armor**

Bank armor is extensive in the project reach, and may consist of old vehicles, concrete rubble, angular rock, rounded rock, pilings, or stone walls (Figure 48 through Figure 54). The bank armor may reflect multiple generations of bank treatment, and is commonly obscured by vegetation. During the field investigation, all visible bank armor was mapped to allow areas of RMA to be identified. However, it was apparent while in the field that numerous bank armor sites were not visible due to high lake levels or vegetation. As such, the mapped armor extents are incomplete. Due to the incomplete inventory, as well as the lack of information regarding the effectiveness of the armor in halting bank erosion, areas behind armor have not been specifically identified as RMA.

Figure 48. Quarried rock revetment obscured by vegetation, Flathead River.

Figure 49. Typical car revetment, Flathead River; note pilings in background from failed COE wood plank revetment.

Figure 50. Typical concrete rubble revetment, Flathead River.

Figure 51. Rock riprap reinforcement over older car body revetment.

Figure 52. Boulder armor and local erosion, Flathead River.

Figure 53. Bush bundles, Flathead River.

Figure 54. Stone wall revetment, Flathead River.

In support of an assessment of the temporal sequence of human modifications in the project reach, the following datasets have been developed:

1. A field inventory of bank armor. This dataset reflects bank armor elements that were visible at full pool conditions (June 30-July 1, 2010). As such, the dataset does not reflect those features exposed under lower flow/water surface conditions. However, it is anticipated that this dataset can be augmented by future mapping efforts.
2. Locations and dates of 310 permits as provided by Flathead Conservation District dating back to 1976. These permit references contain the permit number, permit type (e.g. bank stabilization) and date (year). The locations of the permits are fairly coarse, and there are commonly multiple records for a single armored bankline. As such, it is impossible at this point to associate a specific permit with a specific armor extent or the actual length of bank treatment.
3. Mapped locations with associated dates and site summaries provided by Flathead CD. Conservation District personnel met with local stakeholders to compile their knowledge of bank armor and dikes, and these mapped features have been integrated into the overall inventory.

Road prisms on the floodplain were coarsely evaluated with respect to their impact on flooding. At the scale of available flood mapping, there is no evidence that any major roads form the 100-year floodplain boundary.

4.3.2 **Dikes**

In Reach 3, both the eastern and western margins of the CMZ have been affected by channel blockages upstream (Figure 55). These areas are mapped as Restricted Migration Areas on the CMZ maps, and reflect those areas that were in the corridor in 1955, but subsequently restricted by those dikes.

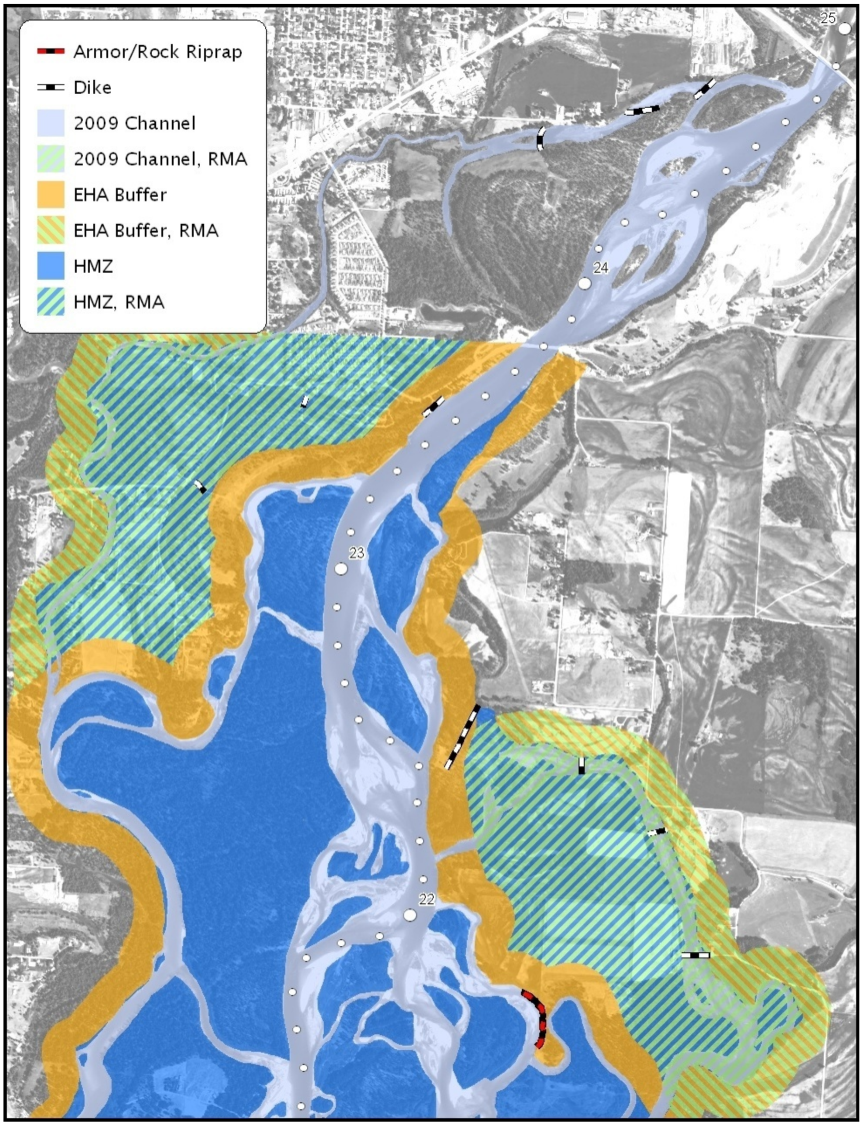


Figure 55. Restricted Migration Area (RMA) due to channel diking, Reach 3.

4.4 The Avulsion Hazard Zone (AHZ)

The Avulsion Hazard Zone (AHZ) includes the areas of the river landscape, such as secondary channels, relic channels, and swales that are at risk of channel occupation outside of the Historic Migration Zone (HMZ).

Avulsion hazards can be difficult to identify on broad floodplains, because an avulsion could occur virtually anywhere on the entire floodplain if the right conditions were to occur. Avulsion pathways were identified and mapped using criteria that identify a relatively high propensity for such an event. These criteria usually include the identification of high slope ratios between the floodplain and channel, perched channel segments, and the presence of relic channels that concentrate flow during floods. These features were identified for the Flathead River project reach using aerial photos and inundation modeling results.

Features that can help determine avulsion hazard areas include (WSDE, 2010):

- Low, frequently flooded floodplain areas with relic channels (Figure 56)
- Past meander-bend cutoffs
- Main channel aggradation, particularly medial bar formation or growth, in the upstream limb of a bend
- Lower elevation of relict channel than active channel bed
- Present and former distributary channels on alluvial fans, deltas, and estuaries
- Channels that diverge from the main channel in a downstream direction
- Creeks that run somewhat parallel to main channel

The GIS-based inundation model discussed in Section 3.5 was used to help identify potential avulsion pathways. These pathways were identified as low continuous swales visible on the inundation model output, and in some cases observed in the field (Figure 56). These pathways were then compared to FEMA flood mapping boundaries for the area, and to the mapped extent of 1964 flooding.

Between Kalispell and Flathead Lake, the Flathead River valley bottom is wide, low gradient, and contains extensive topographic swales that document ancient channel courses. Mapped features that create potential avulsion pathways at high discharges are shown in Figure 57. These pathways extend across much of the valley bottom below Foy’s Bend. When compared to maps of flood boundaries, it is clear that in many cases these features extend beyond the 100-year floodplain and into the 500-year floodplain. Thus, avulsions in this reach would likely require a flood event in excess of a 100-year discharge.

Figure 56. Floodplain swale, Flathead River.

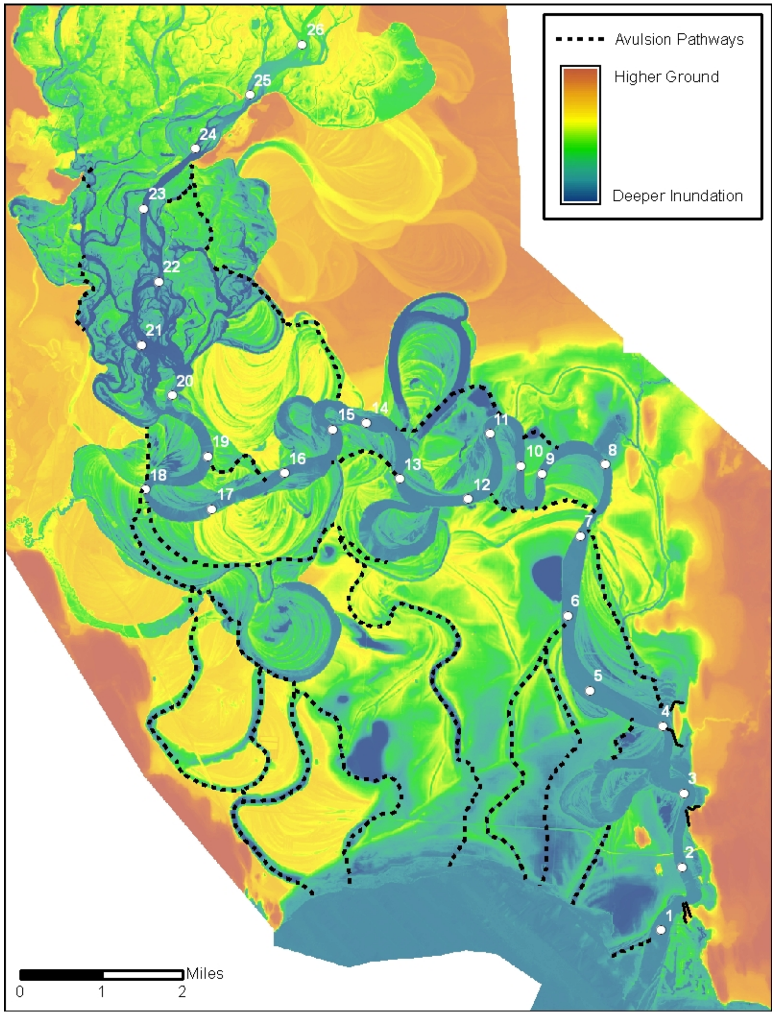


Figure 57. Potential avulsion pathways mapped on inundation model surface, Flathead River.

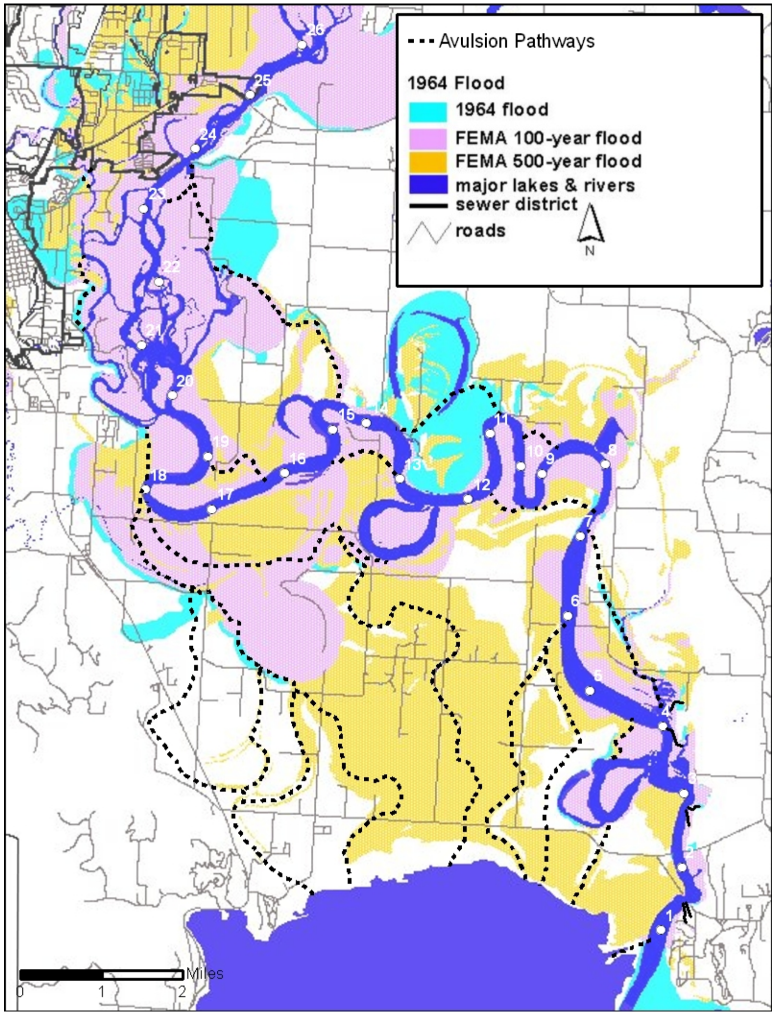


Figure 58. Avulsion pathways shown relative to flood boundaries, Flathead River.

Three different types of avulsion hazards have been mapped and are identified separately on the accompanying maps.

1. ***High Hazard***: Areas within the 100-year floodplain prone to meander cutoff.
2. ***Moderate Hazard***: Floodplain swales within the 100-year floodplain that show continuous flow paths and intersect the modern channel.
3. ***Low Hazard***: Continuous swales that are located out of the 100-year floodplain, but within the 500-year floodplain.

For a large scale avulsion to occur on the Flathead River, conditions must be met that create a threshold condition, and then a trigger must occur to drive the event (Appendix D). In the project reach, the creation of a threshold condition has likely been influenced by lake level management. Several management scenarios and their potential effects on avulsion events are described below.

1. When Flathead Lake is at high pool, avulsions in Reach 1 and Reach 2 are unlikely due to the lack of a steep topographic gradient between the river and the lake. Major flooding at high pool would simply inundate the floodplain, extending the lake margin up valley.

2. If a major flood event occurred at low pool, avulsions would be more likely to occur in Reach 1 and Reach 2, as overbank flows would be more likely to erode into the floodplain surface due to an increased topographic gradient between the river and the lake. It is interesting to note that the 1964 flood event inundated areas mapped as avulsion pathways, but no major avulsions occurred. This flood occurred in early June, when lake levels were almost at high pool (Figure 59). The event itself caused lake levels to rapidly rise approximately 2 feet before tapering off to the full pool level. If this event had occurred earlier in the year, the geomorphic response within the project reach may have been much more pronounced.

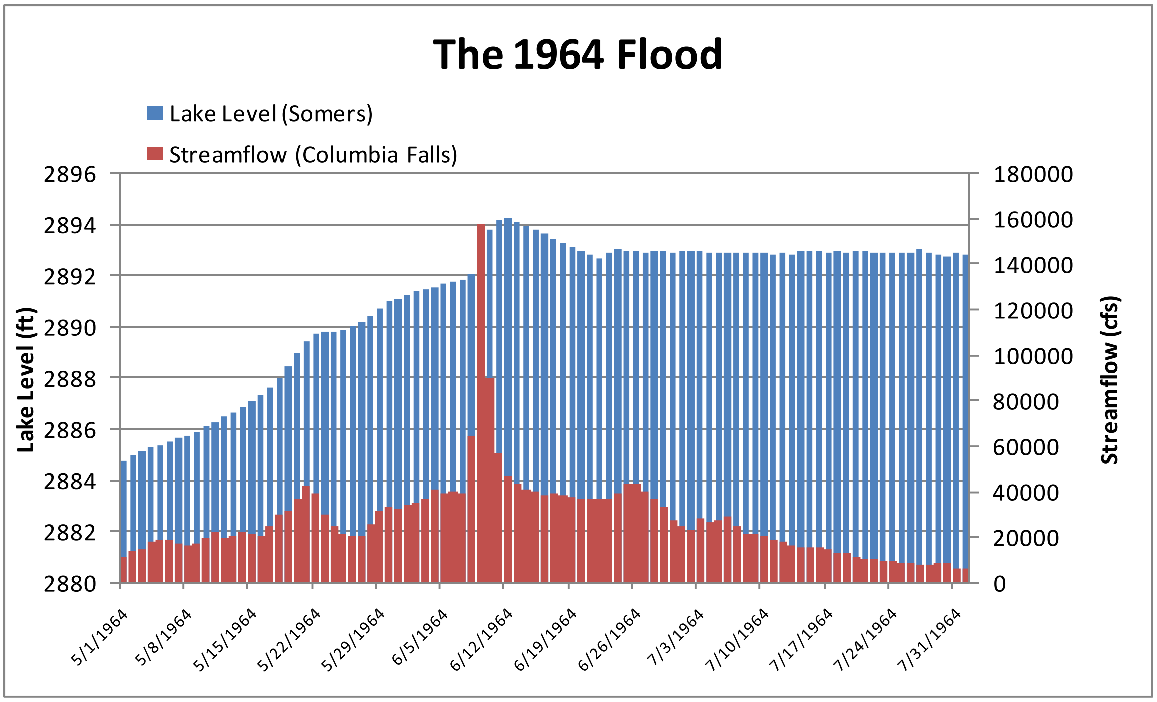


Figure 59. Comparison of lake levels (blue) and streamflow (red) during the 1964 flood.

3. As floods affect lake levels, floods with a very steep rising limb will have the most potential to cause an avulsion. One notable characteristic of the 1964 flood was its short duration; the event occurred when approximately 15 inches of rain fell over a 30-hour period in the upper Flathead drainage (State of Montana Natural Hazards Mitigation Plan, 2001). The peak of 158,000 cfs was reached on June 9. The day before and the day following had peak discharges at Columbia Falls of 64,400 cfs and 90,100 cfs, respectively. If this flood had extended over the floodplain to the lake at low pool, avulsion risk would have been significantly higher.

4. Another important consideration in assessing avulsion hazards is the sediment transport capacity through the project reach. Where sediment deposition is excessive and channel capacity is reduced, overflows are more frequent and avulsion risks increase. At high pool, the water surface flattens near the Reach 2/Reach 3 boundary. Sediment deposition downstream near Foy's Bend could then result in lost channel capacity and increased overbank flooding.

5. Although sediment deposition is likely accelerated at the Reach 2/Reach 3 boundary at high pool, there is also likely more significant scouring of this reach during low pool. Since Hungry Horse Reservoir was completed in 1953, winter

baseflows have approximately doubled (Figure 31). As these higher base flows occur at low pool, there is more opportunity for seasonal sediment flushing downstream.

Temporal and spatial issues related to river flow management, lake level management, and sediment transport are all important considerations in the evaluation of avulsion hazards on the Flathead River. These processes can be revisited and the mapping revised as appropriate, as additional research becomes available. This research includes the bathymetric study of the Flathead River that was recently performed by the Flathead Biological Station with the University of Montana.

4.5 Composite Map

An example portion of a composite CMZ map for a section of the Flathead River project reach is shown in Figure 60. The accompanying deliverable maps for the project reach are included on the project CD as PDF files.

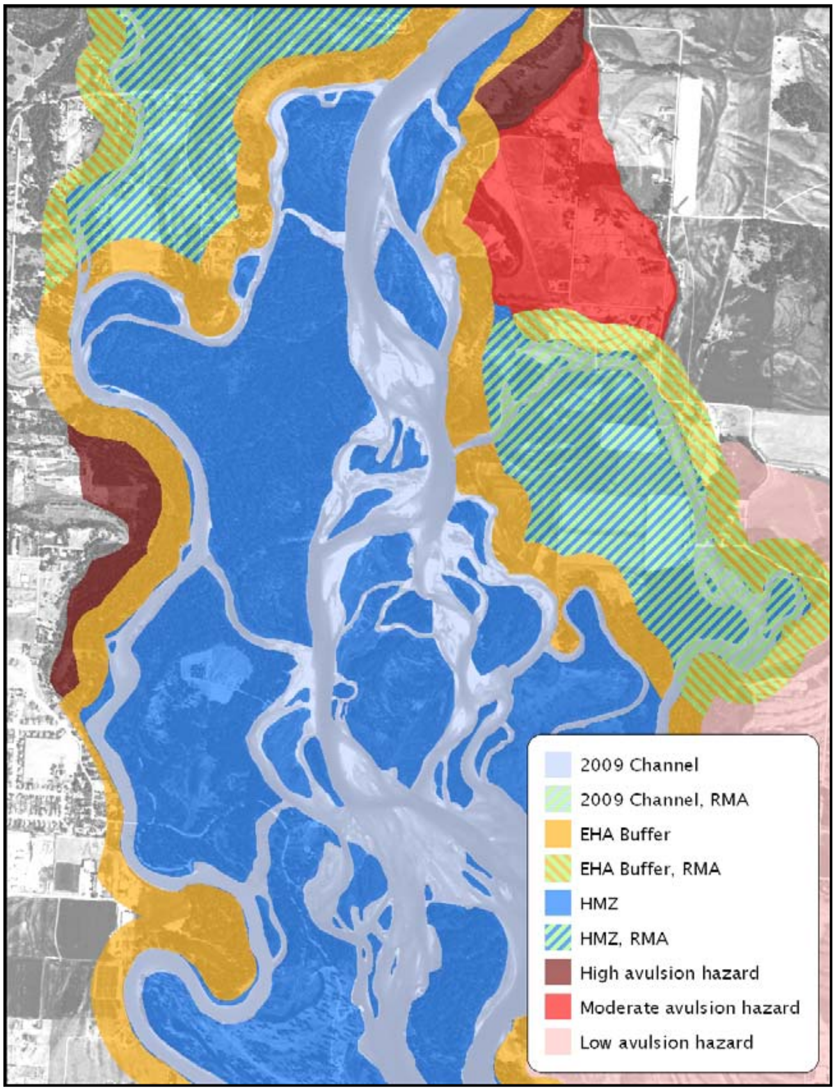


Figure 60. Composite Channel Migration Zone (CMZ) map example.

4.6 Comparison of Results with GLO Maps

The project GIS includes GLO plats that were surveyed between 1873 and 1893. These maps are shown with a CMZ overlay in Figure 61 through Figure 63. The comparison of the modern CMZ and the late 19th century mapping shows that in Reach1, the river currently follows its historic course, with the exception of the river mouth, where the channel has shortened and relocated to the west (Figure 61). This figure also shows the loss of land area on the north shore of the lake, as the pink CMZ edge follows the modern lakeshore. In Reach 2 (Figure 62) the channel CMZ closely follows the historic channel course, and in Reach 3, the western edge of the historic river corridor is effectively captured by the CMZ (Figure 63). More detailed comparisons of this mapping can be performed in the GIS; in general, however, the results indicate that the CMZ boundaries effectively capture over 100 years of historic channel movement.

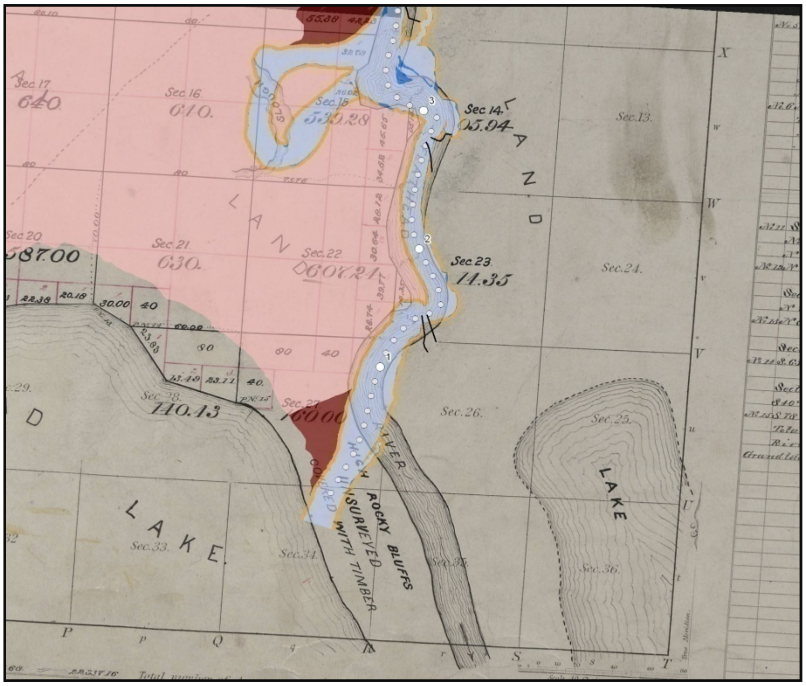


Figure 61. CMZ map overlay on General Land Office Survey Map, lower portion of Reach 1.

Figure 62. CMZ overlay onto General Land Office Survey Map, Reach 2.

Figure 63. CMZ overlay onto General Land Office Survey Map, Reach 3.

4.7 Deliverables

The products for this effort consist of a project data CD and maps that delineates the Channel Migration Zone for the Flathead River from the Old Steel Bridge to Flathead Lake. All new project data are supplied on CD in an ESRI Personal Geodatabase, along with PDF versions of the maps. Each Feature Class is accompanied by appropriate FGDC compliant metadata. All data utilize the Montana State Plane 1983 HARN meters coordinate system. A listing of datasets in the Geodatabase is found in Appendix A.

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6.0 Appendix A: GIS Datasets

Layer Name	***Description***
Avulsion_Pathways	Topographic features identified as potential avulsion pathways.
Bank_Inventory_2010	Visual inventory of bank features and protection performed from boat on June 30 and July 1, 2010.
banklines_1956	1956 banklines.
banklines_1978	1978 banklines.
banklines_1990	1990 banklines.
banklines_2009	2009 banklines.
CD_dikes_armor	Dike and armor locations furnished by the Flathead Conservation District.
CL_2009_Meas	Measured 2009 channel centerline.
CMZ	Composite Channel Migration Zone, including avulsion zones and restricted areas.
CMZ_boundary	Channel Migration Zone outer boundary only.
eroding_banks	Portion of 2009 bankline showing active erosion.
erosion_poly_bisect	Erosion polygon bisecting lines as furnished by C. Dalby.
erosion_polygons	Polygons derived from the 1956 and 2009 banklines representing total area of erosion.
FCD_310Permits	310 permits associated with riprap or bank stabilization projects.
HMZ	Historic Migration Zone
Migration_Vectors	Lines representing measured migration from 1956 to 2009.
photopoints	GPS points representing photos taken during fieldwork.
Reach_Designations	Project reaches.
RM_integer	Integer river miles.
RM_tenths	Tenths of river miles.

7.0 Appendix B: Migration Measurements (Vectors)

Reach 1

Reach 1 Polygon	*Site ID*	*Vector ID*	*Time Period (migration distance in feet)*				*Time Period (migration rate in ft/yr)*			
			1956-1978	*1978-1990*	*1990-2009*	*1956-2009*	*1956-1978*	*1978-1990*	*1990-2009*	*1956-2009*
25	25-1	25-1-A	17.0	5.9	8.5	31.3	0.8	0.5	0.4	0.6
	25-1	25-1-B	21.7	9.2	10.4	41.4	1.0	0.8	0.5	0.8
	25-1	25-1-C	27.8	5.3	6.2	39.3	1.3	0.4	0.3	0.7
	25-2	25-2-A	41.4	16.7	0.0	58.1	1.9	1.4	0.0	1.1
	25-2	25-2-B	58.4	15.4	15.7	89.5	2.7	1.3	0.8	1.7
	25-2	25-2-C	33.2	12.2	31.1	76.5	1.5	1.0	1.6	1.4
	25-3	25-3-A	39.2	18.3	6.5	64.0	1.8	1.5	0.3	1.2
	25-3	25-3-B	10.1	16.1	0.0	26.2	0.5	1.3	0.0	0.5
	25-3	25-3-C	20.6	7.1	0.0	27.7	0.9	0.6	0.0	0.5
26	26-1	26-1-A	67.6	0.0	0.0	67.6	3.1	0.0	0.0	1.3
	26-1	26-1-B	68.4	12.3	0.0	80.7	3.1	1.0	0.0	1.5
	26-1	26-1-C	44.2	16.4	0.5	61.1	2.0	1.4	0.0	1.2
	26-2	26-2-A	45.0	0.0	1.8	46.9	2.0	0.0	0.1	0.9
	26-2	26-2-B	37.8	0.0	11.5	49.3	1.7	0.0	0.6	0.9
	26-2	26-2-C	31.3	0.0	12.7	44.0	1.4	0.0	0.7	0.8
	26-3	26-3-A	44.7	0.0	0.0	44.7	2.0	0.0	0.0	0.8
	26-3	26-3-B	50.7	0.4	0.0	51.1	2.3	0.0	0.0	1.0
	26-3	26-3-C	40.9	12.2	0.0	53.1	1.9	1.0	0.0	1.0

Reach 1 Polygon	***Site ID***	***Vector ID***	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
27	27-1	27-1-A	28.8	5.3	3.1	37.2	1.3	0.4	0.2	0.7
	27-1	27-1-B	25.2	2.8	10.3	38.3	1.1	0.2	0.5	0.7
	27-1	27-1-C	40.5	0.0	0.0	40.5	1.8	0.0	0.0	0.8
28	28-1	28-1-A	41.2	16.1	38.0	95.3	1.9	1.3	2.0	1.8
	28-1	28-1-B	30.1	31.7	10.9	72.7	1.4	2.6	0.6	1.4
	28-1	28-1-C	21.7	33.5	18.9	74.0	1.0	2.8	1.0	1.4
29	29-1	29-1-A	59.6	0.0	0.0	59.6	2.7	0.0	0.0	1.1
	29-1	29-1-B	66.2	0.0	0.0	66.2	3.0	0.0	0.0	1.2
	29-1	29-1-C	54.2	1.7	0.0	55.8	2.5	0.1	0.0	1.1
	29-2	29-2-A	115.8	0.0	0.0	115.8	5.3	0.0	0.0	2.2
	29-2	29-2-B	110.0	39.4	36.9	192.2	5.0	3.3	1.9	3.6
	29-2	29-2-C	9.8	15.7	64.2	89.7	0.4	1.3	3.4	1.7
30	30-1	30-1-A	28.0	2.5	20.6	51.1	1.3	0.2	1.1	1.0
	30-1	30-1-B	27.0	0.0	25.1	52.1	1.2	0.0	1.3	1.0
	30-1	30-1-C	50.3	0.0	19.5	69.7	2.3	0.0	1.0	1.3
	30-2	30-2-A	20.1	12.8	42.4	75.2	0.9	1.1	2.2	1.4
	30-2	30-2-B	12.4	7.0	34.7	54.1	0.6	0.6	1.8	1.0
	30-2	30-2-C	30.0	0.0	34.2	64.2	1.4	0.0	1.8	1.2
31	31-1	31-1-A	44.3	1.4	38.5	84.1	2.0	0.1	2.0	1.6
	31-1	31-1-B	45.5	25.3	24.8	95.6	2.1	2.1	1.3	1.8
	31-1	31-1-C	52.5	0.0	64.0	116.5	2.4	0.0	3.4	2.2

Reach 2

Reach 2 Polygon	***Site ID***	***Vector ID***	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
15	15-1	15-1-A	59.3	0.0	0.0	59.3	2.7	0.0	0.0	1.1
	15-1	15-1-B	28.8	0.0	0.0	28.8	1.3	0.0	0.0	0.5
	15-1	15-1-C	41.1	1.0	0.0	42.2	1.9	0.1	0.0	0.8
	15-2	15-2-A	24.4	13.7	33.5	71.5	1.1	1.1	1.8	1.3
	15-2	15-2-B	50.8	20.1	30.2	101.1	2.3	1.7	1.6	1.9
	15-2	15-2-C	47.6	26.0	15.8	89.4	2.2	2.2	0.8	1.7
	15-3	15-3-A	51.2	8.9	0.0	60.1	2.3	0.7	0.0	1.1
	15-3	15-3-B	63.8	3.2	2.9	69.9	2.9	0.3	0.2	1.3
	15-3	15-3-C	54.0	33.6	8.5	96.2	2.5	2.8	0.4	1.8
	15-4	15-4-A	48.5	29.1	9.6	87.1	2.2	2.4	0.5	1.6
	15-4	15-4-B	69.0	29.1	8.3	106.4	3.1	2.4	0.4	2.0
	15-4	15-4-C	91.9	28.1	18.1	138.0	4.2	2.3	1.0	2.6
16	16-1	16-1-A	72.3	80.6	58.8	211.7	3.3	6.7	3.1	4.0
	16-1	16-1-B	40.8	138.1	48.6	227.5	1.9	11.5	2.6	4.3
	16-1	16-1-C	0.0	63.7	146.7	210.4	0.0	5.3	7.7	4.0
	16-2	16-2-A	5.7	33.4	89.3	128.4	0.3	2.8	4.7	2.4
	16-2	16-2-B	30.5	32.7	53.9	117.2	1.4	2.7	2.8	2.2
	16-2	16-2-C	76.8	29.1	42.1	147.9	3.5	2.4	2.2	2.8
17	17-1	17-1-A	99.6	12.1	4.4	116.1	4.5	1.0	0.2	2.2
	17-1	17-1-B	80.7	14.0	6.6	101.3	3.7	1.2	0.3	1.9
	17-1	17-1-C	41.6	4.5	19.1	65.3	1.9	0.4	1.0	1.2

Reach 2 Polygon	**Site ID**	**Vector ID**	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
18	18-1	18-1-A	0.0	5.4	12.6	18.0	0.0	0.5	0.7	0.3
	18-1	18-1-B	0.0	9.4	47.0	56.4	0.0	0.8	2.5	1.1
	18-1	18-1-C	0.4	8.7	24.6	33.7	0.0	0.7	1.3	0.6
19	19-1	19-1-A	40.5	17.0	35.3	92.8	1.8	1.4	1.9	1.8
	19-1	19-1-B	51.7	31.3	43.7	126.7	2.3	2.6	2.3	2.4
	19-1	19-1-C	27.7	38.2	37.7	103.6	1.3	3.2	2.0	2.0
20	20-1	20-1-A	47.2	12.1	35.4	94.7	2.1	1.0	1.9	1.8
	20-1	20-1-B	52.4	18.8	35.9	107.1	2.4	1.6	1.9	2.0
	20-1	20-1-C	44.7	7.3	70.5	122.4	2.0	0.6	3.7	2.3
21	21-1	21-1-A	58.9	71.7	0.0	130.6	2.7	6.0	0.0	2.5
	21-1	21-1-B	59.9	17.9	62.1	139.8	2.7	1.5	3.3	2.6
	21-1	21-1-C	74.9	64.8	65.5	205.3	3.4	5.4	3.4	3.9
	21-2	21-2-A	155.9	71.9	161.1	389.0	7.1	6.0	8.5	7.3
	21-2	21-2-B	255.5	55.2	206.7	517.4	11.6	4.6	10.9	9.8
	21-2	21-2-C	270.0	108.8	171.9	550.7	12.3	9.1	9.0	10.4
	21-3	21-3-A	162.1	105.4	145.3	412.8	7.4	8.8	7.6	7.8
	21-3	21-3-B	147.7	64.7	140.4	352.8	6.7	5.4	7.4	6.7
	21-3	21-3-C	142.4	23.6	134.2	300.2	6.5	2.0	7.1	5.7
22	22-1	22-1-A	51.4	29.2	5.6	86.2	2.3	2.4	0.3	1.6
	22-1	22-1-B	71.4	0.0	46.2	117.5	3.2	0.0	2.4	2.2
	22-1	22-1-C	78.1	26.4	39.2	143.7	3.5	2.2	2.1	2.7
	22-2	22-2-A	56.1	9.9	3.1	69.1	2.5	0.8	0.2	1.3
	22-2	22-2-B	32.6	0.0	43.7	76.4	1.5	0.0	2.3	1.4
	22-2	22-2-C	21.5	0.0	42.8	64.3	1.0	0.0	2.3	1.2

Reach 2 Polygon	***Site ID***	***Vector ID***	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
23	23-1	23-1-A	61.5	27.4	21.2	110.0	2.8	2.3	1.1	2.1
	23-1	23-1-B	50.4	45.1	45.6	141.1	2.3	3.8	2.4	2.7
	23-1	23-1-C	101.5	31.8	86.2	219.4	4.6	2.6	4.5	4.1
24	24-1	24-1-A	23.9	21.9	4.3	50.1	1.1	1.8	0.2	0.9
	24-1	24-1-B	30.7	33.7	0.0	64.4	1.4	2.8	0.0	1.2
	24-1	24-1-C	50.0	16.9	17.1	84.0	2.3	1.4	0.9	1.6
	24-2	24-2-A	70.6	50.2	10.2	131.0	3.2	4.2	0.5	2.5
	24-2	24-2-B	50.9	43.3	39.1	133.3	2.3	3.6	2.1	2.5
	24-2	24-2-C	98.0	33.6	56.4	188.0	4.5	2.8	3.0	3.5
	24-3	24-3-A	94.8	0.5	110.9	206.2	4.3	0.0	5.8	3.9
	24-3	24-3-B	69.2	24.4	95.3	188.9	3.1	2.0	5.0	3.6
	24-3	24-3-C	74.0	0.6	65.6	140.2	3.4	0.0	3.5	2.6

Reach 3

Reach 3 Polygon	***Site ID***	***Vector ID***	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
2	2-1-A	2-1	57.4	0.0	39.7	97.1	2.6	0.0	2.1	1.8
	2-1-B	2-1	64.5	7.2	45.0	116.6	2.9	0.6	2.4	2.2
	2-1-C	2-1	64.4	15.0	28.7	108.1	2.9	1.3	1.5	2.0
3	3-1-A	3-1	92.3	36.2	183.7	312.2	4.2	3.0	9.7	5.9
	3-1-B	3-1	142.9	52.7	182.9	378.6	6.5	4.4	9.6	7.1
	3-1-C	3-1	195.0	58.1	189.8	442.9	8.9	4.8	10.0	8.4
	3-2-A	3-2	64.8	61.4	178.4	304.6	2.9	5.1	9.4	5.7
	3-2-B	3-2	37.2	19.1	158.4	214.8	1.7	1.6	8.3	4.1
	3-2-C	3-2	165.1	20.0	101.0	286.1	7.5	1.7	5.3	5.4
4	4-1-A	4-1	151.1	0.0	50.6	201.7	6.9	0.0	2.7	3.8
	4-1-B	4-1	179.2	1.3	51.6	232.1	8.1	0.1	2.7	4.4
	4-1-C	4-1	171.0	27.5	40.0	238.5	7.8	2.3	2.1	4.5
	4-2-A	4-2	167.9	191.5	56.4	415.8	7.6	16.0	3.0	7.8
	4-2-B	4-2	235.6	241.3	97.7	574.6	10.7	20.1	5.1	10.8
	4-2-C	4-2	71.9	234.1	245.3	551.2	3.3	19.5	12.9	10.4
5	5-1-A	5-1	764.2	34.8	16.0	815.1	34.7	2.9	0.8	15.4
	5-1-B	5-1	747.8	12.9	26.4	787.1	34.0	1.1	1.4	14.9
	5-1-C	5-1	561.8	0.0	0.0	561.8	25.5	0.0	0.0	10.6
6	6-1-A	6-1	79.8	27.5	10.9	118.2	3.6	2.3	0.6	2.2
	6-1-B	6-1	106.7	62.5	53.4	222.6	4.8	5.2	2.8	4.2
	6-1-C	6-1	133.9	18.8	6.6	159.2	6.1	1.6	0.3	3.0

			Time Period (migration distance in feet)				*Time Period (migration rate in ft/yr)*			
Reach 3 Polygon	***Site ID***	***Vector ID***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
7	7-1-A	7-1	117.3	0.0	110.0	227.3	5.3	0.0	5.8	4.3
	7-1-B	7-1	238.5	11.2	18.3	267.9	10.8	0.9	1.0	5.1
	7-1-C	7-1	402.7	71.1	0.0	473.8	18.3	5.9	0.0	8.9
8	8-1-A	8-1	441.0	7.5	3.2	451.7	20.0	0.6	0.2	8.5
	8-1-B	8-1	324.9	7.6	24.6	357.1	14.8	0.6	1.3	6.7
	8-1-C	8-1	110.6	16.5	139.8	266.8	5.0	1.4	7.4	5.0
9	9-1-A	9-1	64.7	0.0	0.0	64.7	2.9	0.0	0.0	1.2
	9-1-B	9-1	99.7	0.0	0.0	99.7	4.5	0.0	0.0	1.9
	9-1-C	9-1	44.3	0.0	16.2	60.5	2.0	0.0	0.9	1.1
10	10-1-A	10-1	272.3	74.0	17.9	364.3	12.4	6.2	0.9	6.9
	10-1-B	10-1	242.0	234.6	41.3	517.9	11.0	19.6	2.2	9.8
	10-1-C	10-1	79.8	194.2	14.9	288.8	3.6	16.2	0.8	5.4
11	11-1-A	11-1	605.5	18.1	5.1	628.7	27.5	1.5	0.3	11.9
	11-1-B	11-1	520.3	37.3	0.4	558.0	23.6	3.1	0.0	10.5
	11-1-C	11-1	336.6	27.6	143.7	508.0	15.3	2.3	7.6	9.6
12	12-1-A	12-1	155.8	68.9	78.2	302.8	7.1	5.7	4.1	5.7
	12-1-B	12-1	103.8	39.9	192.1	335.8	4.7	3.3	10.1	6.3
	12-1-C	12-1	33.3	27.8	120.3	181.5	1.5	2.3	6.3	3.4
13	13-1-A	13-1	190.2	24.9	47.2	262.3	8.6	2.1	2.5	4.9
	13-1-B	13-1	178.4	34.5	68.5	281.5	8.1	2.9	3.6	5.3
	13-1-C	13-1	119.3	17.3	0.0	136.6	5.4	1.4	0.0	2.6
	13-2-A	13-2	33.6	47.6	105.5	186.6	1.5	4.0	5.6	3.5
	13-2-B	13-2	126.2	52.3	59.6	238.1	5.7	4.4	3.1	4.5
	13-2-C	13-2	126.2	53.1	35.9	215.2	5.7	4.4	1.9	4.1

Reach 3 Polygon	***Site ID***	***Vector ID***	***Time Period (migration distance in feet)***				***Time Period (migration rate in ft/yr)***			
			1956-1978	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
	13-3-A	13-3	56.7	17.3	0.0	73.9	2.6	1.4	0.0	1.4
	13-3-B	13-3	64.6	28.3	0.0	92.8	2.9	2.4	0.0	1.8
	13-3-C	13-3	50.6	33.9	15.5	100.0	2.3	2.8	0.8	1.9
14	14-1-A	14-1	56.2	91.0	0.0	147.3	2.6	7.6	0.0	2.8
	14-1-B	14-1	34.3	39.1	0.0	73.3	1.6	3.3	0.0	1.4
	14-1-C	14-1	51.4	22.3	9.1	82.8	2.3	1.9	0.5	1.6
32	32-1-A	32-1	100.6	0.1	13.2	113.8	4.6	0.0	0.7	2.1
	32-1-B	32-1	155.3	0.0	14.8	170.1	7.1	0.0	0.8	3.2
	32-1-C	32-1	131.8	0.0	13.7	145.5	6.0	0.0	0.7	2.7
33	33-1-A	33-1	55.5	28.7	0.0	84.2	2.5	2.4	0.0	1.6
	33-1-B	33-1	58.6	37.1	6.5	102.2	2.7	3.1	0.3	1.9
	33-1-C	33-1	8.9	39.5	47.5	95.9	0.4	3.3	2.5	1.8
34	34-1-A	34-1	273.8	4.7	123.4	402.0	12.4	0.4	6.5	7.6
	34-1-B	34-1	46.9	117.4	98.9	263.2	2.1	9.8	5.2	5.0
	34-1-C	34-1	0.0	140.4	76.7	217.0	0.0	11.7	4.0	4.1
35	35-1-A	35-1	74.0	0.0	63.5	137.5	3.4	0.0	3.3	2.6
	35-1-B	35-1	0.0	0.0	165.3	165.3	0.0	0.0	8.7	3.1
	35-1-C	35-1	60.6	31.6	9.2	101.4	2.8	2.6	0.5	1.9
36	36-1-A	36-1	230.8	112.9	7.5	351.3	10.5	9.4	0.4	6.6
	36-1-B	36-1	316.7	103.1	75.3	495.1	14.4	8.6	4.0	9.3
	36-1-C	36-1	289.0	65.6	0.0	354.6	13.1	5.5	0.0	6.7
37	37-1-A	37-1	135.5	0.0	80.2	215.7	6.2	0.0	4.2	4.1
	37-1-B	37-1	311.4	0.0	81.3	392.7	14.2	0.0	4.3	7.4
	37-1-C	37-1	231.1	0.0	63.1	294.2	10.5	0.0	3.3	5.6

			Time Period (migration distance in feet)				***Time Period (migration rate in ft/yr)***			
Reach 3 Polygon	***Site ID***	***Vector ID***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***	***1956-1978***	***1978-1990***	***1990-2009***	***1956-2009***
38	38-1-A	38-1	37.1	0.0	8.0	45.1	1.7	0.0	0.4	0.9
	38-1-B	38-1	26.9	4.5	59.6	91.0	1.2	0.4	3.1	1.7
	38-1-C	38-1	55.7	0.0	34.9	90.6	2.5	0.0	1.8	1.7
39	39-1-A	39-1	7.7	0.0	66.3	73.9	0.3	0.0	3.5	1.4
	39-1-B	39-1	155.0	0.0	0.0	155.0	7.0	0.0	0.0	2.9
	39-1-C	39-1	123.6	54.3	0.0	177.9	5.6	4.5	0.0	3.4
	39-2-A	39-2	0.0	126.1	32.5	158.6	0.0	10.5	1.7	3.0
	39-2-B	39-2	169.3	45.3	105.1	319.7	7.7	3.8	5.5	6.0
	39-2-C	39-2	127.4	0.0	57.1	184.4	5.8	0.0	3.0	3.5
	39-3-A	39-3	54.1	0.0	0.0	54.1	2.5	0.0	0.0	1.0
	39-3-B	39-3	60.9	0.0	3.5	64.4	2.8	0.0	0.2	1.2
	39-3-C	39-3	4.3	10.0	53.1	67.5	0.2	0.8	2.8	1.3
	39-4-A	39-4	28.9	79.0	0.0	107.9	1.3	6.6	0.0	2.0
	39-4-B	39-4	34.0	38.6	0.0	72.6	1.5	3.2	0.0	1.4
	39-4-C	39-4	0.0	91.7	0.3	92.0	0.0	7.6	0.0	1.7
40	40-1-A	40-1	61.4	35.3	8.5	105.2	2.8	2.9	0.4	2.0
	40-1-B	40-1	100.4	0.0	0.0	100.4	4.6	0.0	0.0	1.9
	40-1-C	40-1	101.3	0.0	0.0	101.3	4.6	0.0	0.0	1.9

8.0 Appendix C: Migration Measurements (Polygons)

Reach	***Polygon***	***Area (sq ft)***	***Bank Length (ft)***	***Area/Length (ft)***	***Mean Distance 1956-2009 (ft/yr)***	***Mean Rate 1956-2009 (ft/yr)***	***100-yr distance (ft)***
Reach 1	25	121560	3652	33.29	33	0.6	63
	26	110258	2444	45.11	45	0.9	85
	27	48548	1434	33.85	34	0.6	64
	28	101236	2054	49.29	49	0.9	93
	29	87519	861	101.65	102	1.9	192
	30	206046	3898	52.86	53	1.0	100
	31	119129	1555	76.61	77	1.4	145
Reach 2	15	258172	3497	73.83	74	1.4	139
	16	535061	3386	158.02	158	3.0	298
	17	83137	1317	63.13	63	1.2	119
	18	5504	223	24.68	25	0.5	47
	19	28231	460	61.37	61	1.2	116
	20	86330	934	92.43	92	1.7	174
	21	1053503	3641	289.34	289	5.5	546
	22	143535	2127	67.48	67	1.3	127
	23	196296	1787	109.85	110	2.1	207
	24	321637	3208	100.26	100	1.9	189
Reach 3	1	364975	1704	214.19	214	4.0	404
	2	60882	900	67.65	68	1.3	128
	3	613476	1981	309.68	310	5.8	584
	4	716486	2197	326.12	326	6.2	615
	5	887984	2370	374.68	375	7.1	707
	6	176178	1367	128.88	129	2.4	243
	7	384879	1578	243.90	244	4.6	460
	8	471965	1310	360.28	360	6.8	680
	9	34926	685	50.99	51	1.0	96
	10	557243	2310	241.23	241	4.6	455
	11	580762	1278	454.43	454	8.6	857
	12	171854	1035	166.04	166	3.1	313
	13	448624	3272	137.11	137	2.6	259
	14	126108	1633	77.22	77	1.5	146
	32	72247	784	92.15	92	1.7	174
	33	47075	695	67.73	68	1.3	128

Reach	***Polygon***	***Area (sq ft)***	***Bank Length (ft)***	***Area/Length (ft)***	***Mean Distance 1956-2009 (ft/yr)***	***Mean Rate 1956-2009 (ft/yr)***	***100-yr distance (ft)***
Reach 3	34	397195	1460	272.05	272	5.1	513
	35	60144	596	100.91	101	1.9	190
	36	310862	1367	227.40	227	4.3	429
	37	148515	829	179.15	179	3.4	338
	38	51956	794	65.44	65	1.2	123
	39	284435	3134	90.76	91	1.7	171
	40	125844	1297	97.03	97	1.8	183

9.0 Appendix D: Causes of Channel Avulsion

An avulsion is the sudden relocation of a channel into a new course. Aslan and others (2005) note that avulsions consist of two phases: first, conditions that set the stage for an avulsion are met (a threshold condition), and second, a triggering event such as major flooding occurs to drive the system over that threshold. The closer the river is to the threshold, the smaller the event needed to trigger the avulsion (Jones and Schumm, 1999).

Most research on avulsion processes have concentrated on the "topographic advantage" of newly formed avulsions relative to the abandoned channel segment. This typically reflects a tendency for a river to aggrade and become perched above its surrounding floodplain. This condition may cause the river to form a new channel at a lower elevation on the surrounding floodplain. On the Niobrara River in northeastern Nebraska, a series of avulsions occurred between 1995 and 1996. These events have been related to a ~10 ft base level rise and aggradation of the river in response to damming of the Missouri River just downstream (Ethridge et al., 1999). Following dam construction in the 1950s, the river aggraded for 43 years; at this point, the river reached a threshold condition, became avulsive, and entered a 2-year period of rapid change. Ice jams may have played a role in driving the avulsions (Ethridge et al., 1999).

Jones and Schumm (1999) described four types of conditions that lead a system toward an avulsion threshold. Two of the conditions reflect an increase in the ratio of the avulsion route slope (Sa) to the channel slope (Sc). As this ratio increases, a system approaches an avulsion threshold. Processes that increase this ratio may reflect a decrease in the channel slope or an increase in the floodplain slope. The most common process that decreases the channel slope is channel lengthening through meandering. The avulsion route slope can increase due to channel aggradation or deposition of natural levees on the channel margin. Other drivers for avulsions include hydrologic changes, sediment loading, and channel blockages such as sediment slugs, debris jams, and ice jams.

Ice jams are a common form of blockage on Montana's large rivers. Burge and Lapointe (2001) describe how abandoned floodplain channels create possible avulsion paths that can be activated by ice jam blockages. These authors also point out that the avulsion process typically fails when the avulsion course is longer than the main channel. Although long floodplain channels may flow due to ice jam induced flooding, passage of the ice jam results in abandonment of those channels and a failed avulsion. Where the avulsion course is much shorter than the main channel, however, the avulsion channel quickly becomes the primary thread.

Slingerland and Smith (2004) note that “floodplain channels are efficient, ready-made conduits for routing some or all flow away from diversion sites and thus comprise a common style of avulsion”. Over the past 5,000 years, avulsions on the Mississippi River occurred primarily through channel reoccupation. These authors conclude that the following factors promote avulsions:

1. Rapid aggradation of the main channels and resulting increased overbank flooding.
2. A wide unobstructed floodplain able to drain down-valley. This allows water surface slopes out of the main channel to remain steep. Pre-existing hydraulically efficient channels help in this regard.
3. Frequently occurring floods of high magnitude.

Jerolmack and Mohrig (2007) used a combination of field and laboratory data to show that avulsion frequency is related to the time required for the deposition of sediment equal to one channel depth, and that the relative rates of bank erosion and sedimentation define a stream’s tendency to avulse. Where sedimentation rates are high relative to bank erosion rates, the avulsion potential is increased. Alternatively, streams that migrate laterally at a relatively rapid rate are less likely to aggrade sufficiently to drive an avulsion.

Stouthamer and Berendsen (2007) concluded that there is currently no established means of accurately predicting avulsion events on alluvial streams. Slingerman and Smith (1998) concluded that for systems with sandy substrate, the critical slope ratio (Sa/Sc) for avulsion has been estimated to be approximately 5. A gradient analysis on the Mississippi River, however (Aslan et al., 2005), indicates that “significant local gradient advantages exist along the outer bend of virtually every meander of the modern meander belt (critical slope ratios typically exceed 30), and yet Mississippi avulsions are rare.” These authors concluded that on the Mississippi River, erodible substrate and floodplain channels play important roles in avulsion processes.

In the Rhine-Meuse delta of the Netherlands, an avulsion periodicity of ~500-600 years has been estimated (Stouthamer and Berendsen, 2007). Locations of avulsions on this system have been associated with sea level rise, local tectonics, and changes in discharges and sediment loads. Slingerland and Smith (2004) describe avulsion recurrence intervals as ranging from as low as 28 years on the Kosi River in India to up to 1400 years on the Mississippi River.