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TECHNICAL MEMORANDUM

To:	Peter Nielsen, Missoula County
From:	Applied Geomorphology and DTM Consulting, Inc.
Date:	October 7, 2009
In Regards To:	Clark Fork River CMZ Pilot

This technical memorandum describes the development of a 100-year Channel Migration Zone (CMZ) map for the portion of the Clark Fork River that extends from the Bitterroot River confluence near Missoula downstream to Huson, Montana. The objective of this write-up is to summarize the project methodology and to provide some context regarding results.

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 progressive channel *migration* and more abrupt channel *avulsion*. These processes and related hazards can be highlighted and presented by using the CMZ mapping techniques. For this effort, a 100-year timeframe has been adopted in developing the CMZ boundaries.

1.0 Site Conditions

The segment of the Clark Fork River evaluated in this mapping effort extends from approximately one mile upstream of the Bitterroot River confluence downstream to Huson Montana, a valley distance of approximately 13 miles (Figure 1). Within this reach, the river flows in a northwesterly direction, through an alluvial valley that is typically on the order of two miles wide.

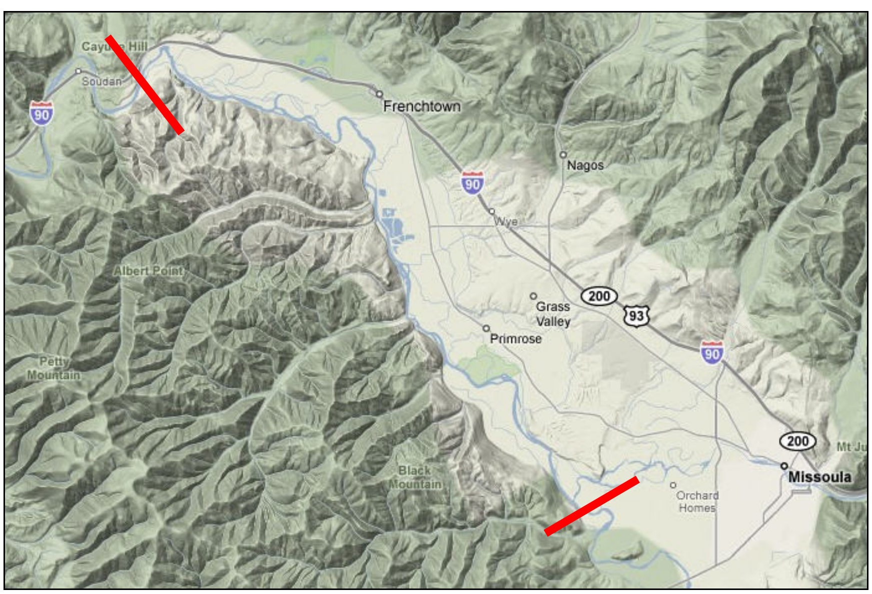

Figure 1. Project location map; red lines show limits of CMZ mapping.

Within the project reach, the Clark Fork River meanderbelt flows through young alluvial deposits and limited exposures of older terraces and alluvium that contain lake deposits, glacial deposit, and older stream deposits (Figure 2). The Quaternary-age terrace mapped in the valley bottom is described as typically 10 to 30 ft above the modern floodplain (Lewis, 1998). The city of Missoula is located on this terrace unit and additional exposures have been mapped on the margins of the river valley between Missoula and Primrose just north of Council Grove State Park. In addition to young alluvial deposits, much older bedrock commonly forms the margin of the stream corridor. Throughout much of the project reach, the river closely follows the western edge of the valley, marked by a steep wooded hillslopes that consist of Precambrian-age Belt rocks and Cambrian-age dolomites (Lewis, 1998). In general, the river corridor is geologically confined by hillslopes on its southwest margin and unconfined to the northeast.

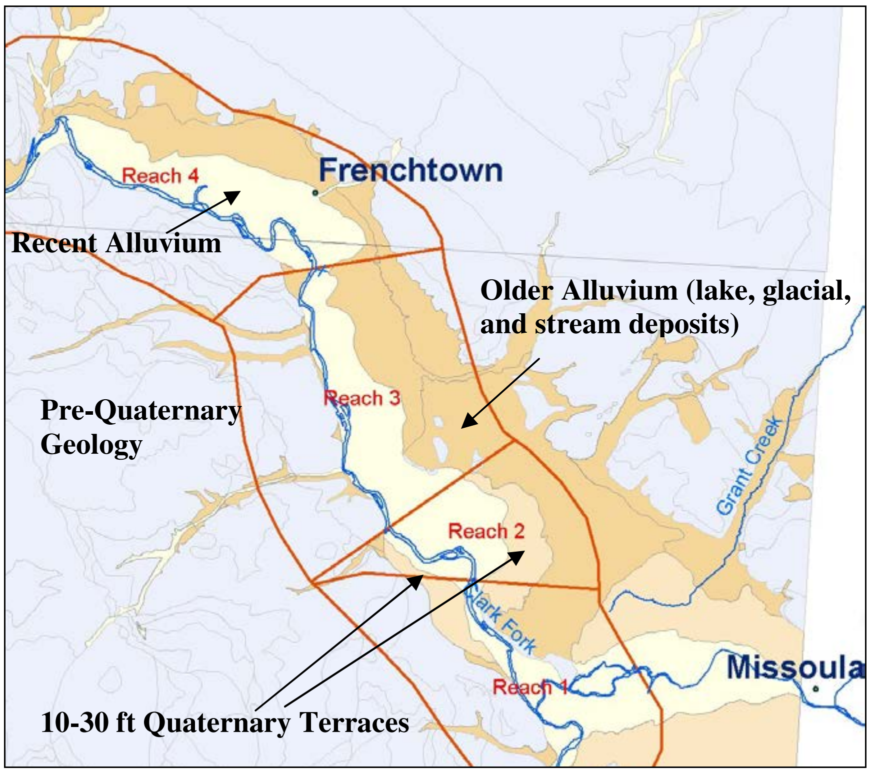

Figure 2. Generalized geologic map of study area showing project reaches.

Much of the active river corridor consists of undeveloped riparian forest. Primary land uses in the bounding floodplain area include agriculture and rural residential development. Near Frenchtown, the Smurfit-Stone Container Corporation plant includes numerous diked settling ponds that extend into the Clark Fork River floodplain. The contributing drainages on the west side of the valley have been extensively logged.

1.1 Project Reaches

Based on geologic controls and channel planform, the project area has been subdivided into four reaches (Figure 2). The reaches have been developed to better characterize trends in channel migration through the project reach. Migration rates have been identified in terms of their corresponding reach and the data have been statistically summarized on a reach scale (Section 3.2).

Table 1. Reach boundaries used to develop migration rate statistics.

Reach	*Primary Channel Length (mi)*	*Location*	*Description*
1	4.2	Bitterroot Confluence to Kona Bridge	Moderately confined with rural subdivision on left bank above Kona Bridge.
2	2.6	Kona Bridge to below Council Grove State Park	Dynamic split flow reach at Council Grove State Park; multiple wooded islands.
3	6.1	Below Council Grove State Park to 2.4 miles downstream of Schilling	Partially confined reach as river closely follows western bedrock valley wall; much of right bank is diked.
4	8.2	2.4 miles downstream of Schilling to Sixmile Creek confluence	Dynamic reach with wide meanderbelt and extensive abandoned channel network on floodplain.

1.2 Flood History

Whenever a Channel Migration Zone mapping effort is undertaken, it is important to consider the flood events that occurred during the time frame used to analyze historic channel migration rates. For this effort, migration rate calculations were made for the 1955-2005 time period. On the Clark Fork River, USGS gaging stations located both upstream and downstream of Missoula have recorded annual peak flows since 1930, so flood magnitudes are available for the analytical timeframe as well as 25 years prior. Upstream of Missoula, peak flows have exceeded 30,000 cfs a total of three times since 1930, and two of these events occurred since 1955 (Figure 3). These events occurred in 1948, 1964, and 1975, and their peak flows were 31,500 cfs, 31,700 cfs, and 32,300 cfs, respectively.

In 1908, a major flood described as the largest known event on the Clark Fork River has been estimated by the USGS at 48,000 cfs. The 1988 Flood Insurance Study for Missoula County (FEMA, 1988) describes this flood event as follows:

> The largest flood event known to occur in Missoula County was in May and June of 1908, and it involved nearly every major stream and river. Although gage records are few, newspaper accounts describe extremely high river stages that washed away houses, roads, and bridges and disrupted travel and communications for several weeks throughout the county. This great flood, caused by unseasonably warm temperatures combined with 33 consecutive days of rain, had an estimated peak flow for Clark Fork above Missoula of 48,000 cubic feet per second (cfs) at the Montana Power Company Dam in Milltown.

This event is not captured by the 1955-2005 series of air photos, and as a result, the channel shifts associated with this major flood are not directly reflected in the CMZ.

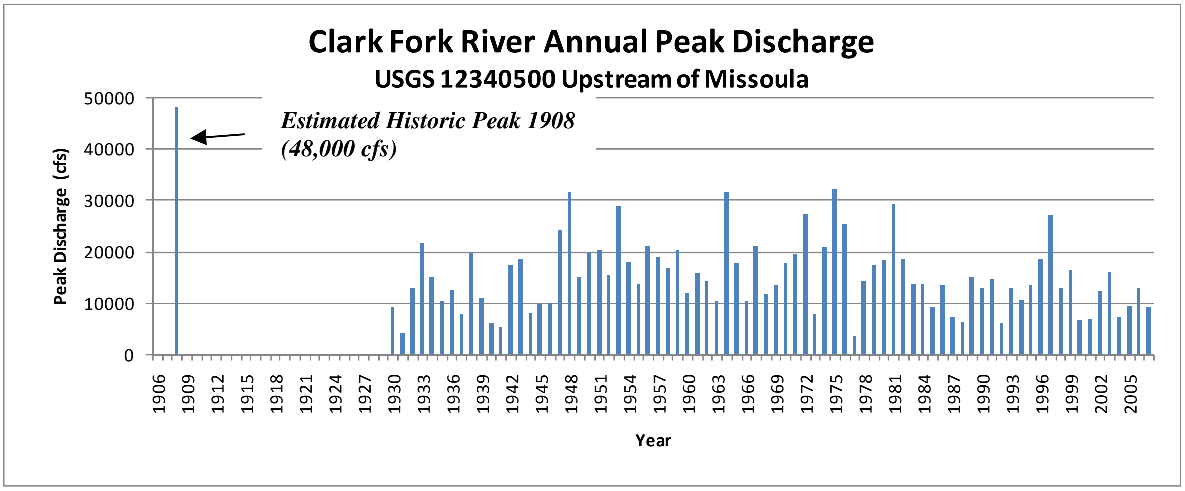

Figure 3. Annual peak discharges, Clark Fork River above Missoula, 1930-2007.

Just downstream of the Bitterroot River confluence, peak flows on the Clark Fork River have exceeded 50,000 cfs a total of three times since 1930, and two of those events are captured in the 1955-2005 migration rate analysis. The largest flood recorded between 1930 and 2007 occurred on May 18, 1997 and was measured at 55,100 cfs. No information was found regarding the estimated peak discharge below Missoula in 1908, however that event was likely the historic flood of record.

Flood frequency discharges developed for the 1988 FEMA Flood Insurance Study for the Clark Fork are shown in Table 2 (FEMA, 1988). A more recent flood insurance study for the area has adopted the same flood frequency discharges (FEMA, 2009). These flood frequency discharges list the 50-year flood event below Missoula at 58,000 cfs. A flood of this magnitude has not occurred within the system during the 1930-2007 period of record. Thus, the project reach has not experienced any flood in excess of a 50-year event since 1930. The 1997 peak flood of record was between a 10-year event and a 50-year event.

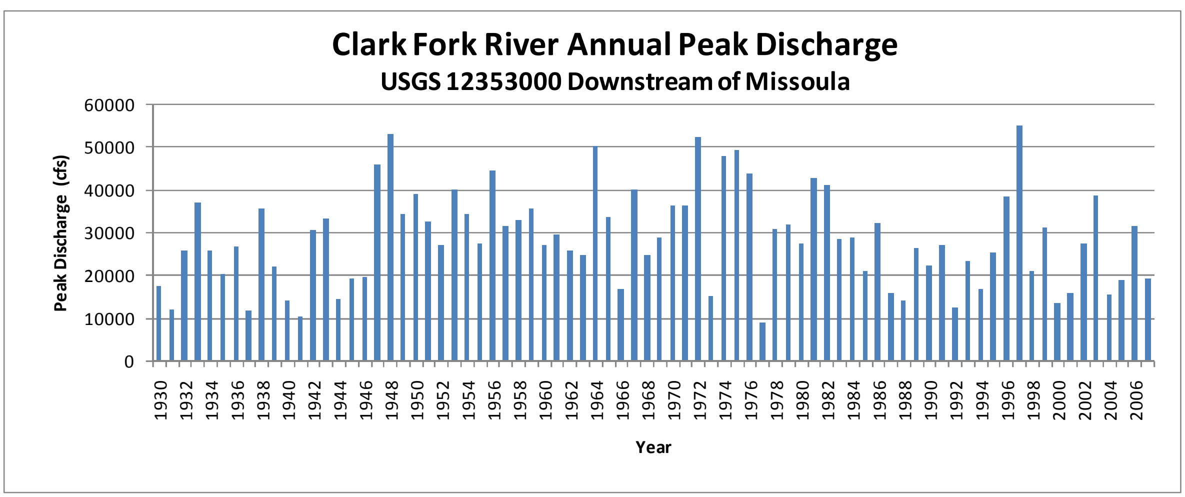

Figure 4. Annual peak discharges, Clark Fork River below Missoula, 1930-2007.

Table 2. Flood frequency discharges developed for 1988 FEMA flood mapping (FEMA, 1988)

Recurrence Interval	***12340500 Clark Fork River above Missoula (cfs)***	***12353000 Clark Fork River below Missoula (cfs)***
10-Year	27,000	47,000
50-Year	38,200	58,000
100-Year	42,500	64,000
500-Year	56,000	82,000

2.0 Methods

The methodology applied to the CMZ delineation generally follows 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 Clark Fork 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 Potential Zones" (APZ).

The primary deviation of the methodology used in this report and Rapp and Abbe (2003) is the treatment of pre-Quaternary age geologic units. Rapp and Abbe (2003) describe a methodology for applying a Geotechnical Setback (GS) to account for mass wasting that may occur beyond the Erosion Buffer area. They note that "generally, a GS determination is not necessary for vertical embankments composed of sound, well-indurated rock (such as a bedrock canyon), but it is potentially needed for vertical embankments composed of poorly indurated or fractured rock, and it is essential for embankments composed of unconsolidated materials (such as glacial outwash)." In this analysis, all pre-quaternary rock units have been excluded from the CMZ assessment, as the determination of geotechnical parameters and appropriate setbacks within these units is beyond the scope of this study. As such, concerns regarding slope stability on the valley walls should be considered on a site-specific basis.

The primary methods employed in developing the maps include air photo acquisition and incorporation into a GIS environment, 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 apply an erosion buffer to allow for future erosion.

2.1 Air Photo Acquisition

Three series of aerial photographs (1955, 1972 and 2005) were used to examine the evolution of channel morphology over the last 50 years. Photography from 1955 and 1972 was scanned and orthorectified by Mapcon Mapping, a division of OSI Geospatial, Inc. The 2005 imagery was provided by the US Department of Agriculture National Agricultural Inventory Program (NAIP). All aerial photographs were taken in mid-summer, after the annual spring rise had occurred. Additional air photos from 1997 were provided by Missoula County and used to assess flow patterns at flood stage.

The time frames that are bounded by the air photos include several flood events. This is important, because flood events can drive significant channel change and these flood-induced changes should be incorporated into any historical assessment of channel behavior. Between 1955 and 1972, floods exceeding 50,000 cfs downstream of Missoula occurred in 1964 (50,100 cfs) and 1972 (52,200 cfs).

The 1972 imagery was collected shortly after that June 3, 1972 flood event. Between 1972 and 2005, discharges exceeded 50,000 cfs only in 1997 (55,100 cfs). This flood event occurred during a period of relatively low peak flows (typically <25,000 cfs) between the mid-1980's and 2007 (Figure 4).

2.2 GIS Project Creation

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 detailed topographic data provided by Missoula County, roads, stream courses as depicted in the National Hydrography Dataset, scanned General Land Office Survey Maps which were obtained from Bureau of Land Management, recent FEMA floodplain mapping (FEMA, 2009), and geologic maps produced by the Montana Bureau of Mines and Geology (Lonn et al, 2007, and Lewis, 1998).

2.3 Bankline Digitization

For each suite of imagery, the bankfull channel margins were digitized in the GIS. In general, the bankfull channel reflects the active channel area that does not support woody vegetation. Its boundaries are delineated as the boundary between open channel and woody vegetation stands, terrace margins, or bedrock valley wall. These lines therefore generally reflect the lowermost edge of woody vegetation or unvegetated bedrock on the channel margin. In the 2005 imagery, there is substantial encroachment of young willows into the active channel corridor. These bars that support young riparian shrubs were included in the bankfull channel area, as comparison of air photos indicates that this encroachment is likely a short-term response to low peak streamflows that have been characteristic of the system since the mid-1980s (Section 1.2).

Within the Clark Fork project area, the floodplain contains numerous swale features (linear depressions) that represent abandoned channel segments. These features typically support non-woody wetland vegetation, and are sustained by groundwater. Where these features show continuity with the main channel and intermittent bare gravel, they were included in the mapped bankfull channel network. Other, isolated swales that do not show such continuity with the main thread were not included in the bankfull channel dataset.

2.4 Migration Rate Measurements

Within the GIS, the digitized banklines were evaluated in terms of discernable channel shift since 1950. Where migration was identifiable, vectors were drawn in the GIS to record that change. At each site of bankline migration, three measurements were collected, and the vectors were attributed with reach, eroding site identification, geologic unit, vegetation type, and line length. These measurements were then summarized by reach to determine appropriate reach-specific buffer widths to accommodate future shifts in channel location.

2.5 Avulsion-Prone Area Mapping

An avulsion is the sudden relocation of a channel into a new course. When water flows away from a primary channel, it will follow the most efficient course available. As such, avulsions are typically characterized by the relocation of a main river channel to an area of lower elevation. Avulsions can also occur into relic channels on the floodplain. A more detailed description of river conditions that drive avulsion events is contained in Appendix A.

The mapping of avulsion prone areas is inherently difficult without intensive modeling efforts supported by high resolution topography. The floodplain of the Clark Fork River is broad and low, with the mapped 100-year flood zone locally exceeding 2 miles in width. The floodplain is also dissected by numerous abandoned channel segments, many of which convey flow at higher discharges. Woody debris accumulations are common in the project reach, such that the potential for local channel blockage exists. All of these factors make it difficult to ascertain those areas prone to avulsion over the 100-year life of the CMZ. Over the past 50 years, relatively minor avulsions have occurred in Reach 4 that reflect bendway cutoff and chute channel formation during floods. These areas were relatively straightforward to map and consist of alluvial bendway cores that are captured in the Historic Migration Area.

Beyond the active meanderbelt, avulsions may occur in areas where the main channel is perched relative to the surrounding floodplain, or where the slope of the floodplain greatly exceeds that of the channel (Appendix A). Without detailed modeling of high resolution topography and floodwater inundation depths, these areas that might be prone to avulsion beyond the margins of the active meanderbelt are difficult to identify. For this effort, potential floodplain avulsion areas were mapped where distinct swales appeared to convey channelized flow in the 1997 flood photography, or where swales support long extents of groundwater and/or unvegetated substrate in the imagery. In general, the risk of occurrence of a floodplain avulsion is low relative to channel migration, as they tend to be rare events. Their locations may not be predictable, as they can be the result of a combination of channel instability (aggradation), high flows, debris jamming, or ice jamming. However, an effort was made to highlight areas where overflows may be channelized within existing topographic swales on the floodplain, and as such, may become reactivated during a flood.

3.0 Results

The channel migration zone (CMZ) developed for the Clark Fork 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 Potential Zones".

Channel Migration Zone (CMZ) = Historic Migration Zone (HMZ) + Erosion Buffer + Avulsion Potential Zone (APZ)

The following sections describe the individual components of the CMZ maps. These methodologies are adapted from those presented in Rapp and Abbe (2003) to accommodate the scale of the project area, available data sources, and the anticipated level of effort required.

3.1 The Historic Migration Zone

The Historic Migration Zone is based on a composite area defined by the channel locations in 1955, 1972, and 2005 (Figure 5 and Figure 6). The resulting area reflects the zone of channel occupation over a 50-year timeframe. The method for delineating the HMZ is to overlay the digitized polygons for the bankfull channel for each time series, and merge those polygons into a single HMZ polygon. The bankfull channel reflects the active channel area that is comprised of unvegetated substrate, and its boundaries are delineated as the boundary between open channel and woody vegetation stands, terrace margins, or bedrock valley wall. 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. All islands within the HMZ are included with the merged HMZ polygon.

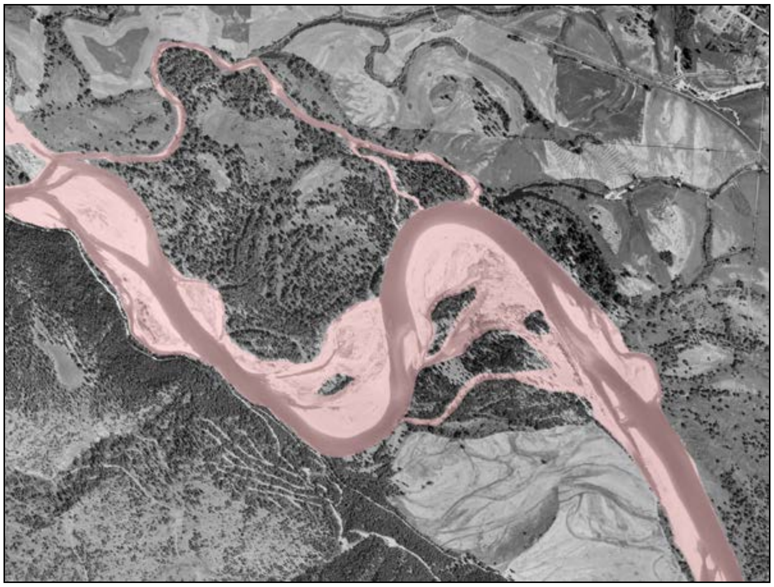

Figure 5. 1955 air photo and digitized bankfull polygons, Reach 4 near Frenchtown.

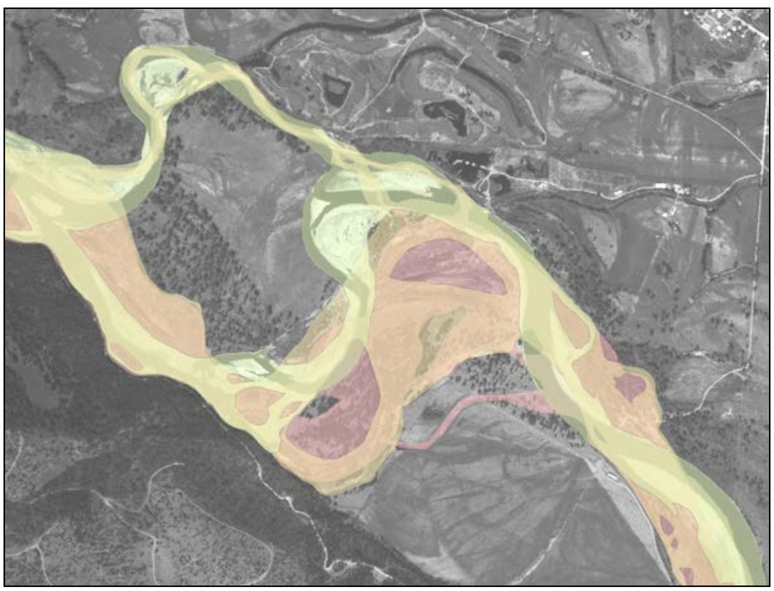

Figure 6. 2005 air photo and digitized bankfull polygons showing HMZ area, Reach 4 near Frenchtown (pink=1955, orange = 1972, and yellow = 2005).

Figure 7. 2005 air photo showing the composite HMZ boundary.

3.2 The Erosion Buffer

To address anticipated future migration beyond the historic corridor boundary, an Erosion Buffer has been added to the 2005 channel margin. This area is considered prone to channel occupation over the life of the CMZ (100 years) and is based on mean migration rates for a given channel segment or reach.

To determine the buffer distance, migration rates from 1955 to 2005 were measured throughout the corridor. A total of 126 measurements were made through the project reach (Figure 8). The rates were then statistically summarized by bendway and reach to approximate anticipated migration distances for a 100-year time frame (Table 3; Figure 1). The buffer distance was calculated as two times the mean migration rate for the entire reach. The general approach to determining the Erosion Buffer (two times mean 50-year migration rate) is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004). Figure 9 shows that the 100-year erosion buffer, when calculated as twice the mean 50-year migration distance, does not capture the maximum 50-year migration distances in any of the reaches. This indicates that there are areas where anomalously rapid bank migration has occurred, and that the buffer margins may be locally eroded through over the next 100 years. Typically, however, these areas of rapid bankline movement are within the Historic Migration Zone, and thereby captured in the CMZ.

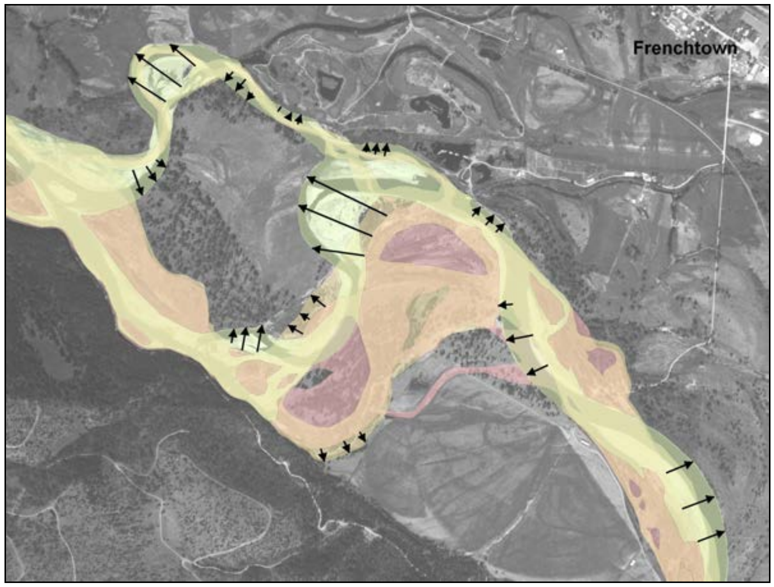

Figure 8. 2005 air photo and digitized bankfull polygons showing migration vectors, Reach 4 near Frenchtown (Red=1955, Orange = 1972, and Green = 2005).

For purposes of discussion, a second buffer width has been calculated and applied on the maps. This width represents two times the 75th percentile value for each reach, which is somewhat larger than the 2 times mean value (Figure 9). These two buffers have been applied to the 2005 banklines on a reach scale through the project area. The buffers based on the mean measurements range from 445 feet in Reach 1 to 864 feet in Reach 4, and those based on the 75th percentile value range from 465 feet in Reach 1 to 1129 feet in Reach 4 (Table 4).

Table 3. Statistical summary of migration rate measurements, Clark Fork River project reach.

Statistic	Reach 1 (ft)	Reach 2 (ft)	Reach 3 (ft)	Reach 4 (ft)
25th Percentile	144	128	131	180
Min	94	77	86	86
Median	170	223	190	385
Max	704	589	589	1219
75th Percentile	232	346	433	564
N	21	33	24	48
90th Percentile	415	453	458	861
Standard Deviation	149	148	155	302
Mean	222	257	263	432
Mean Plus 1 S.D.	371	405	418	734
Mean Plus 2 S.D.	520	553	573	1037
Mean Migration Distance: 50 year timeframe	222	257	263	432
Mean Migration Distance: 100 year timeframe	445	514	526	864

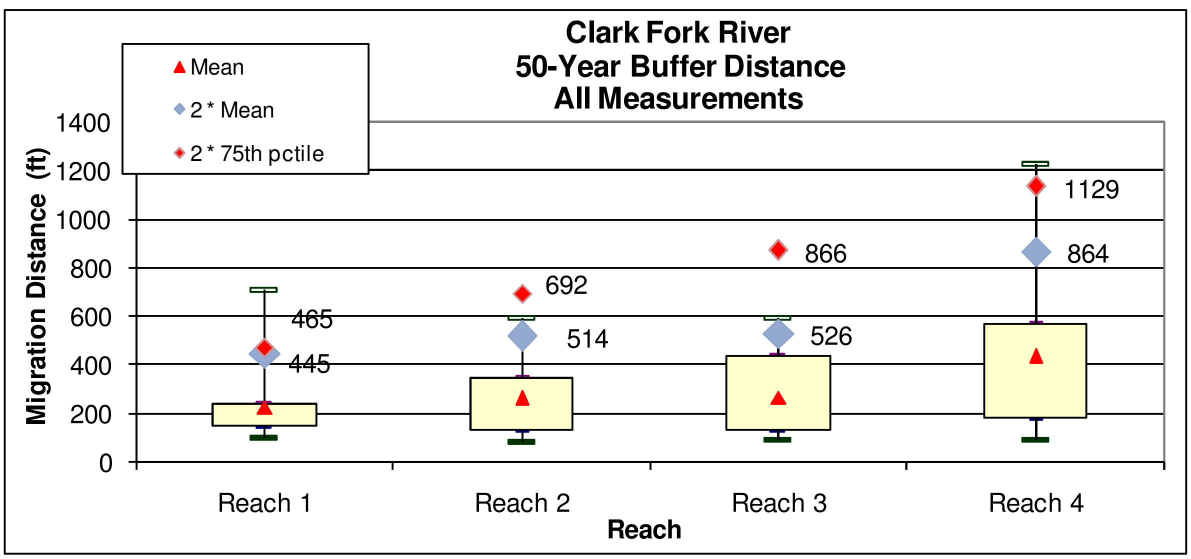

Figure 9. Box and whisker plot showing statistical summary of 50-year migration rate measurements; labeled values include twice the mean 50-year rate, and twice the 75th percentile value.

Table 4. Erosion Buffers applied to 2005 banklines.

Buffer Calculation	*Reach 1*	*Reach 2*	*Reach 3*	*Reach 4*
100-year buffer calculated as 2X Mean 50-year Migration Distance (ft)	445	514	526	864
100-year buffer calculated as 2X 75th percentile 50-year Migration Distance (ft)	465	692	866	1129

Although the extrapolation of measured migration rates to a 100-year timeframe is similar between this study and others, this effort included developing and applying buffers on a reach scale rather than the scale of a single migrating bankline. The reach-scale buffering approach provides a generalized long-term depiction of channel movement relative to approaches that apply site-specific buffers that are based on projected channel movement of an individual bank segment. In the near-term, this reach-scale averaging is likely to overestimate channel movement in places where active migration is currently slow or nonexistent, while potentially underestimating the short-term migration rates of areas in active phases of movement. However, due to the active planform of the Clark Fork River and the 100-year projected timeframe, reach scale buffer development may actually produce a more realistic depiction of the active channel corridor over 100 years. This suggestion is based on the fact that site-specific approaches commonly project linear migration directions and distances for a single eroding bank over a 100-year timeframe, which results in a continuing expansion of the existing planform for the next century. On the Clark Fork, this assumption is unrealistic due to the fact that migration rates and patterns vary with bendway shape, sediment load, flow conditions, ice effects, woody debris jams, and bankline integrity, such that single banklines are not likely to move at a constant rate over the scale of a century. Predictive modeling of these processes over 100-years is beyond the scope of this project, and likely impossible, which supports the reach-scale mapping approach.

3.3 Geologic Controls on Migration Rates

There were no areas identified within the project reach where migration was measured into materials other than young alluvium. As a result, there was no empirical basis to modify buffer widths based on geology. Where the alluvial buffer overlaps young sediments other than recent alluvium, the buffer was maintained throughout that unit (such as glacial deposits, lake deposits, and older stream sediments). Where the river abuts older geologic units, such as Proterozoic Belt rocks and Cambrian limestones, no buffer was applied, as migration into these units was not measureable, suggesting that they are not eroded by the river at a rate that is significant over 100 years. Any assessment of the retreat potential on the valley walls requires site-specific geotechnical analyses that are beyond the scope of this project.

3.4 Avulsion Hazard Zone

The avulsion hazard zone, which locally extends beyond the erosion buffers, reflects additional areas of the floodplain that show evidence of potential channel occupation over the next century. The avulsion hazard areas were mapped using the following general criteria:

1. Areas beyond the Historic Migration Zone and Erosion Buffer where flow paths captured on the 1997 flood imagery indicate channelized flow conditions and increased potential for channel formation and/or reactivation (Figure 10).
2. Floodplain swales that become proximal to the river in the event that the active channel migrates to the outer edge of the Erosion Buffer.
3. Areas where the floodplain slope will likely be steeper than the current channel slope in the event that the channel migrates to the edge of the Erosion Buffer.

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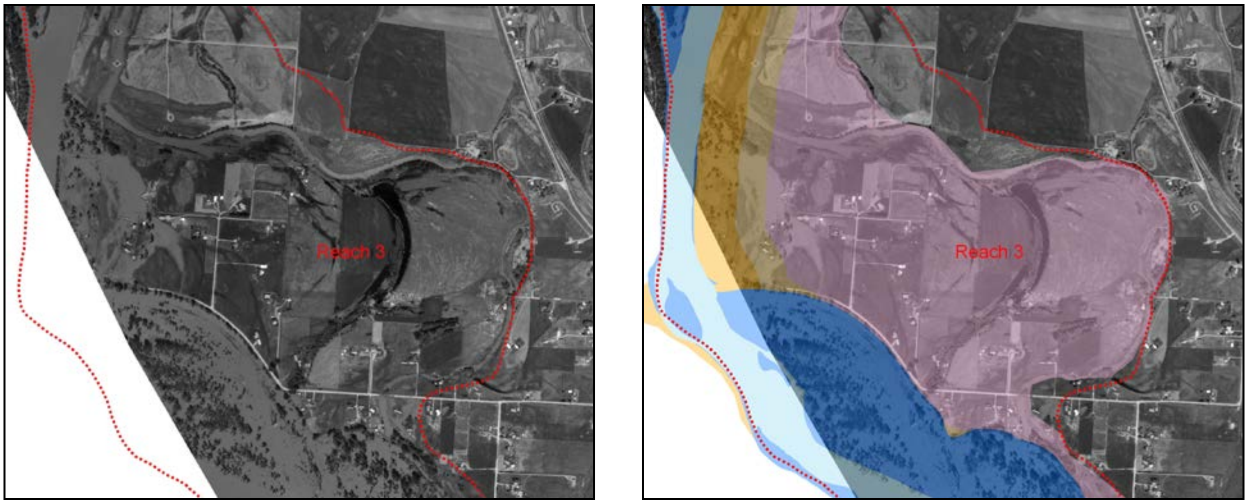

Figure 10. 1997 flood photo of portion of Reach 3 showing FEMA floodplain boundary (red dash) and channelized flow east of main river channel; resulting Avulsion Potential Area is shown on right.

As described in Section 2.5, mapping avulsion-prone areas is somewhat subjective without intensive analysis that is beyond the scope of this study. The approach taken in mapping avulsion-prone areas has been generally inclusive of much of the floodplain area for the following reasons:

1. Avulsions tend to be driven by large flood events and the project reach has not experienced a flood of a 50-year event or greater since 1930. As a result, there is a risk of underestimating the avulsion potential of the system using 1955-2005 aerial photography alone.
2. There is no evidence that any major avulsions have occurred since the GLO maps of the late 1800's, which includes the 1908 flood event (Section 4.2). However, land use changes since that time may make the system more prone to avulsion drivers including debris jamming and channel bed aggradation.

It is important to consider the methodology applied in defining avulsion prone areas when considering management applications of the CMZ maps. If the avulsion hazards are considered high priority with respect to overall land use management strategies, it may be appropriate to conduct a more detailed analysis of avulsion potential, or it may also be appropriate to consider the entire 100-year floodplain as avulsion-prone.

3.5 Physical Features Mapping

During the late summer of 2009, Missoula County employees inventoried physical features as seen from the river in the project reach, including bank armor and dikes. These features have the potential to affect channel migration rates and flooding extents. For this effort, these features were extended using air photos and incorporated into the mapping, but they were not evaluated in terms of their level of maintenance and associated level of performance. As such, the features are shown on the maps, but they do not affect the CMZ boundaries.

3.6 Composite CMZ Map

Channel Migration Zone mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. Over any given time period, rivers occupy a corridor area whose width is dependent on rates of bank erosion. An example of the CMZ mapping is shown in Figure 11. The map units developed in the process of creating these maps include the following:

1. ***Active Channel:*** The active channel is shown in LIGHT BLUE, and reflects the channel course in 2005.

2. ***Historic Migration Zone (HMZ):*** This unit is shown as BLUE on the map, and reflects the area where active channels of the Yellowstone have existed between 1955 and 2005.

3. ***Erosion Buffer:*** The erosion buffer is shown in ORANGE. This reflects a calculated erosion buffer based on over one hundred measurements of channel migration. The main orange buffer is twice the mean 50-year migration rate, and the lighter orange buffer that extends slightly beyond reflects twice the 75th percentile value measured for the 1955-2005 time frame.

4. ***Bedrock:*** Geologic units that are older than the valley bottom sediments are mapped as bedrock. These areas were not assigned erosion buffers or geotechnical setbacks, as any risk of erosion in these areas is highly site-specific and beyond the realm of this study.

5. ***Avulsion Potential Zone (APZ):*** Areas where topographic conditions suggest potential channel relocation or reactivation are mapped in PINK as the APZ. These areas reflect sites where during flood events, these channels are prone to reactivation or flooding.

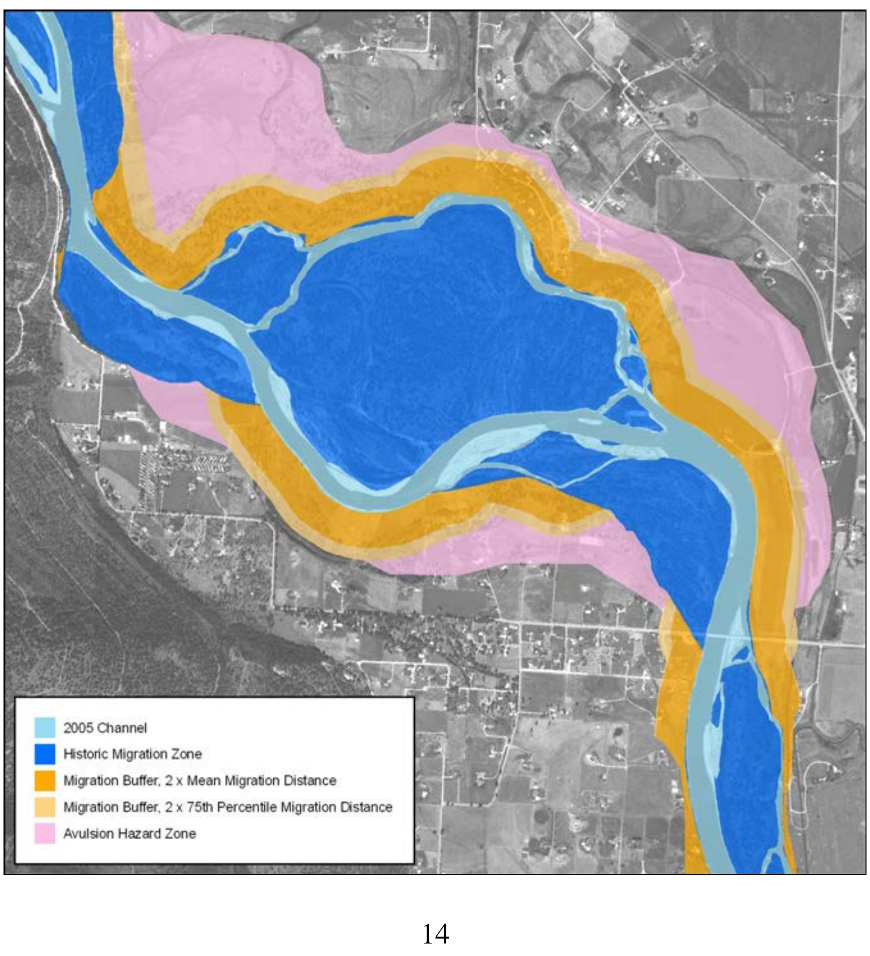

Figure 11. 2005 air photo with Channel Migration Zone map segment, Council Grove State Park.

4.0 CMZ Boundary Relationships to Other Mapping

Available mapping for the project reach includes recent flood boundary mapping (FEMA, 2009), as well as historic maps generated by the General Land Office (GLO) in the latter part of the 19th century. The following section describes the relationship between CMZ mapping and these other data sources.

4.1 Relationship to 100-Year Flood Boundary

The CMZ is generally contained within the mapped 100-year flood boundary (FEMA, 2009). Just north of Council Grove State Park, there is an area within the CMZ that is outside of the mapped 100-year floodplain (Figure 12). In these areas, the erosion buffer extends beyond the flood boundary, indicating that there is a risk of erosion into alluvial sediments beyond the 100-year floodplain margin. These erosion hazards also locally create a potential for avulsion where the buffers intersect floodplain swales or ditches.

In some areas, the difference in the 100-year floodplain and the CMZ boundary reflects differing levels of precision in mapping. Figure 13 shows such an area, where the avulsion hazard zone contains a floodplain swale that was locally excluded from the floodplain map.

In numerous places, the 100-year floodplain boundary extends beyond the CMZ. In these areas, flooding is predicted during a 100-year flood event, but there is no compelling evidence to suggest that the channel is likely to occupy that area over the next century.

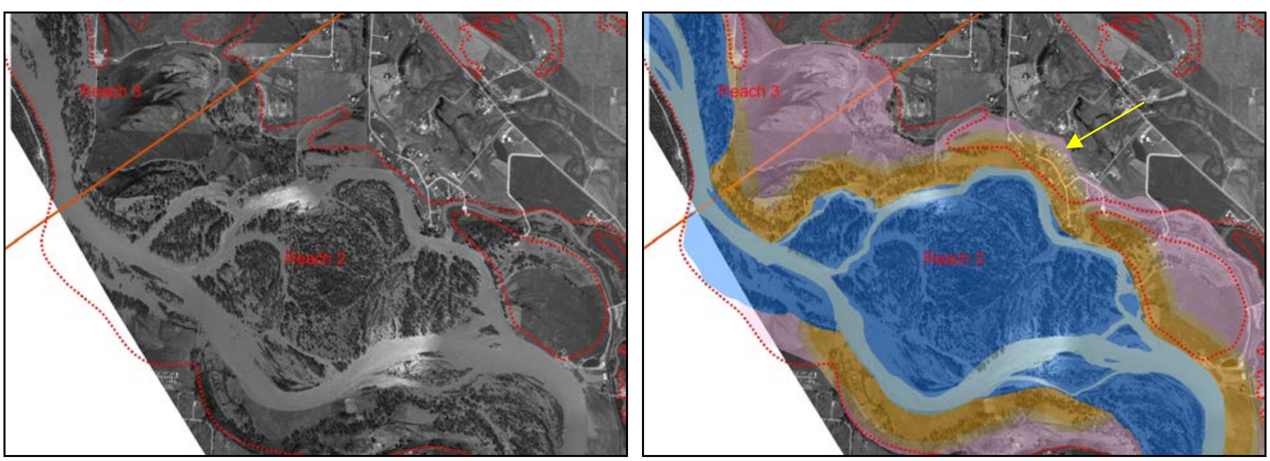

Figure 12. 1997 flood photography of Council Grove State Park showing flood boundary (dashed red line) on the left and the CMZ on right. Note the extension of the CMZ area beyond flood boundary (arrow), where erosion through the buffer would threaten a ditch.

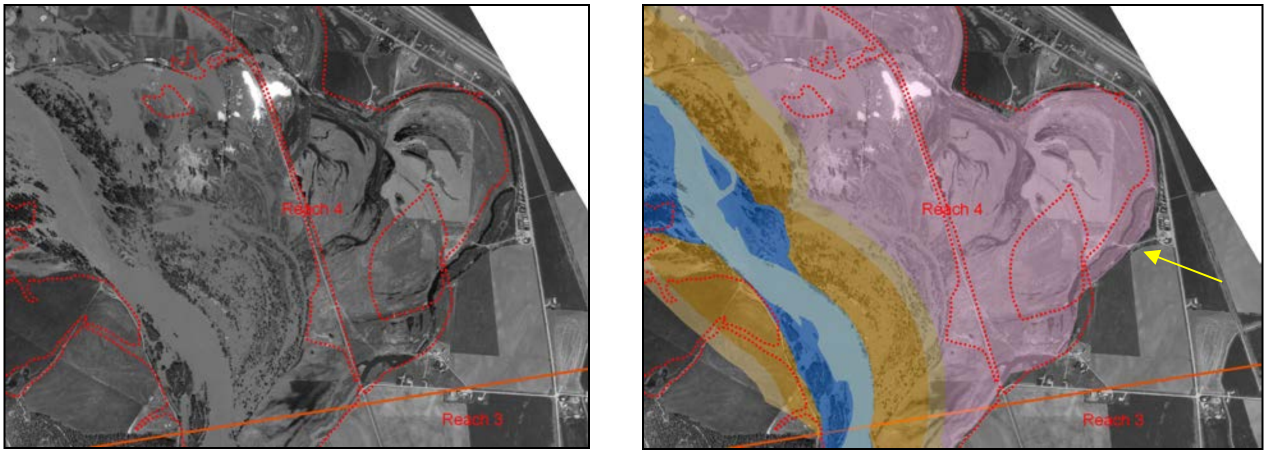

Figure 13. 1997 flood photography of a section of Reach 4 showing flood boundary (red dashed line) on the left and and the CMZ on the right. The APZ extends beyond flood boundary (arrow) following remnant channel course.

4.2 Relationship to GLO Mapping

The General Land Office (GLO) Survey maps for the area were brought into the GIS to compare channel locations in the late 1800's to the CMZ boundaries. Results indicate that the CMZ boundaries effectively capture the channel conditions of 140 years ago (Figure 14 through Figure 16).

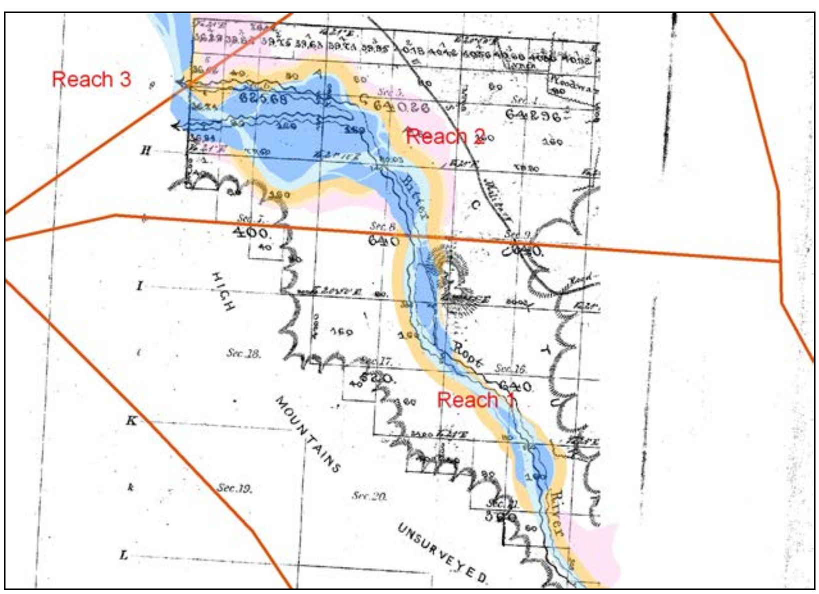

Figure 14. CMZ mapping over 1870 General Land Office Survey maps, Reaches 1 and 2.

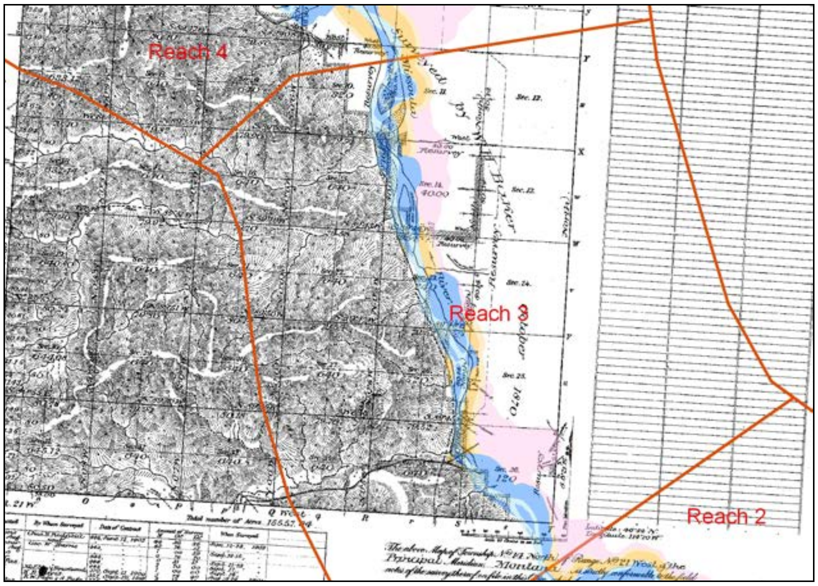

Figure 15. CMZ mapping over 1870 General Land Office Survey maps, Reach 3.

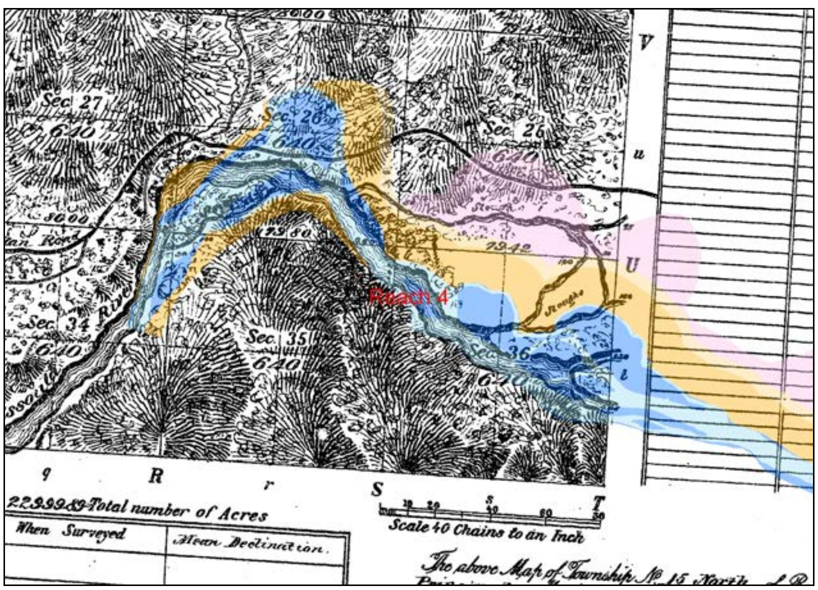

Figure 16. CMZ mapping over 1872 General Land Office Survey maps, downstream end of Reach 4, including the modern-day Huson area.

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6.0 Appendix A: 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 2 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 work on avulsion processes have concentrated on the “topographic advantage” of newly formed avulsions relative to the abandoned channel segment. This typically reflects 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. The Yellow River in China has experienced seven major avulsions in the last 2000 years (Slingerland and Smith, 2004). Avulsions on the Yellow River have been associated with aggradation of the river bed to an elevation several feet above the surrounding floodplain.

However, in some systems, this type of avulsion has occurred without such aggradation (Slingerland and Smith, 2004). 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.

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 (Group 1), or an increase in the floodplain slope (Group 2). Other drivers for avulsions include hydrologic changes, sediment loading, and channel blockages (Group 3).

Table 5. Causes of Avulsion (Jones and Schumm, 1999).

Processes and events that create instability and lead toward an avulsion threshold, and/or act as avulsion triggers		**Can act as trigger?**
Group 1. Avulsion from increase in ratio, Sa/Sc, owing to decreases in Sc	Sinuosity increase (meandering)	No
	Delta growth (lengthening of channel)	No
	Base-level fall (decreased slope)	No
	Tectonic uplift (resulting in decreased slope)	Yes
Group 2. Avulsion from increase in ratio Sa/Sc, owing to increase in Sa	Natural levee/alluvial ridge growth	No
	Alluvial fan and delta growth (convexity)	No
	Tectonism (resulting in lateral tilting)	Yes
Group 3. Avulsions with no change in Sa/Sc	Hydrological change in flood peak discharge	Yes
	Sediment influx from tributaries, increased sediment load, mass failure, wind-related processes	Yes
	Vegetative blockage	No
	Log jams	Yes
	Ice jams	Yes
Group 4. Other Avulsions	Animal trails	No
	Capture (diversion into adjacent drainage)	--

Sa is the slope of the potential avulsion course, Sc is the slope of the existing channel.

There is currently no established means of accurately predicting avulsion events on alluvial streams (Stouthamer and Berendsen, 2007). 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 and others, 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.

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.

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 se 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.