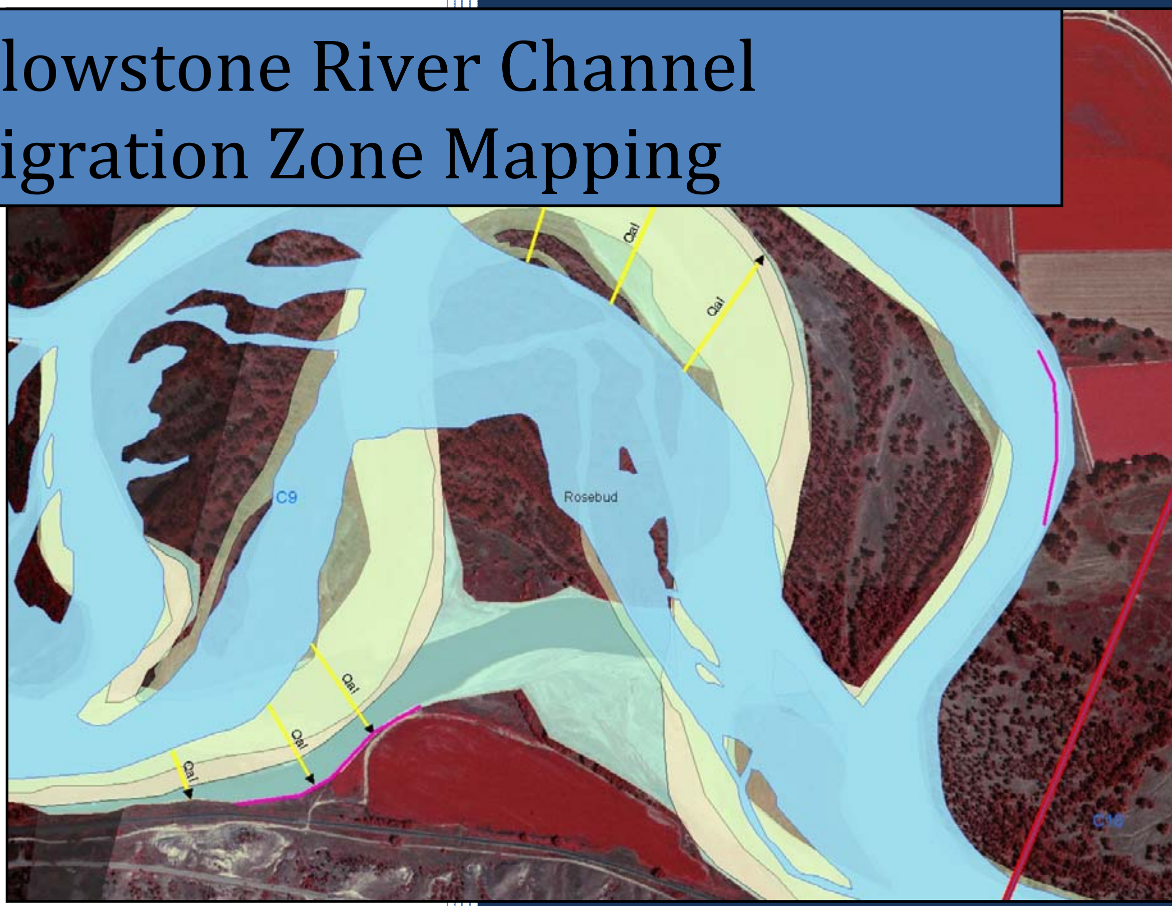
Final Report

Revised
February 20, 2009

Yellowstone River Channel Migration Zone Mapping



Prepared for:

Custer County Conservation District
Yellowstone River Conservation District Council

Tony Thatcher, Bryan Swindell
DTM Consulting, Inc.
211 N Grand Ave, Suite J
Bozeman, MT 59715
406-585-5322

Karin Boyd
Applied Geomorphology, Inc.
211 N Grand Ave, Suite C
Bozeman, MT 59715
406-587-6352

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1.0 Introduction

This report describes the development of a Channel Migration Zone (CMZ) map for the portion of the Yellowstone River that extends from the Gardiner near Yellowstone National Park, to its confluence with the Missouri River in McKenzie County, North Dakota. This mapping supports the Yellowstone River Conservation District Council in their efforts developing best management practices and performing a cumulative effects assessment of the Yellowstone River corridor.

1.1 Revisions to 2008 Report

This report contains revisions made to the original June 2008 document based on the incorporation of high-resolution Light Detection and Ranging (LiDAR) topographic data that has recently become available for all counties in the Yellowstone River corridor with the exception of Park County. In Park County, a photogrammetric elevation model supporting 2-foot contours was used in lieu of LiDAR data. The LiDAR data have been utilized for two primary purposes. First, the topographic data have been used to refine the mapping of Quaternary-age geologic units in the valley bottom. These revisions reflect an evaluation of the alluvial benches in the valley bottom in terms of their elevations relative to the river. The Yellowstone River valley bottom contains distinct terrace surfaces as well as less-pronounced alluvial surfaces that lie within the river's active floodplain. By evaluating cross sections using the LiDAR data, areas where terraces intersect the channel margin were identified with greater precision than mapping previously performed with aerial photography and published geologic mapping. Second, the high resolution LiDAR elevation data have been used to identify high flow channels that dissect the floodplain and may be prone to activation, or avulsion during flood events. As the LiDAR data collection method penetrates the tree canopy and represents a bare earth elevation surface, floodplain topography is much more evident on these maps than on air photos. The other main revision to this report is the inclusion of Park County mapping. The previous document that described Yellowstone River CMZ mapping did not contain the Park County portion of the Yellowstone River, which reaches from Gardiner to Springdale. As part of the effort to update the mapping, Park County has been included to provide consistent mapping between Gardiner, Montana and the river's mouth.

1.2 Channel Migration and Avulsion Processes

Along the majority of its extent, the Yellowstone River is an ***alluvial*** river, meaning it flows through sediment that has been deposited by the river itself (versus bedrock, concrete, etc.). As a result, the river is in a constant state of sediment reworking, as it builds point bars, erodes banks, and conveys sediment downstream. Over a given timeframe, the river thereby occupies a corridor that extends beyond its current channel boundaries. The width of this corridor is reflective of the rates of lateral shift, or ***migration***, that are characteristic of a given stream segment (Figure 1-1). Some stream segments, referred to as reaches, migrate relatively slowly due to low stream energy such as low slope, or where the channel flows through resistant boundary materials such as old river terraces or bedrock. 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.

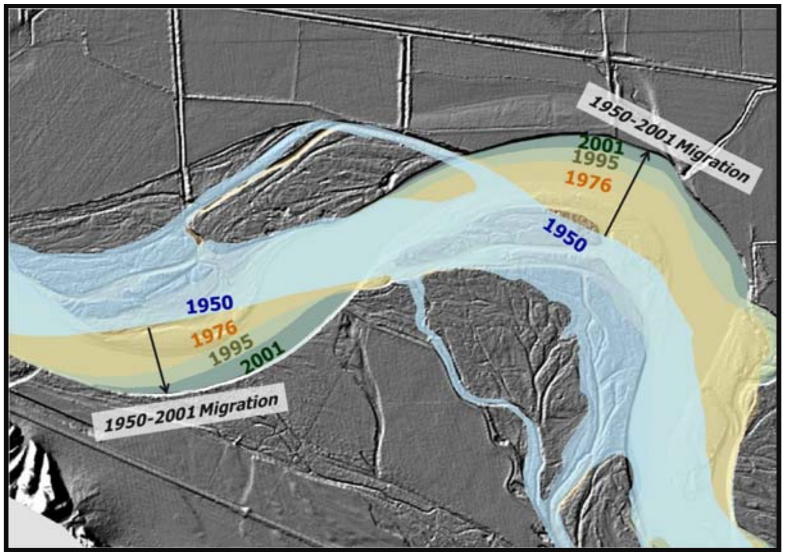

Figure 1-1. Example of progressive 1950-2001 meander migration at two sites in Rosebud County.

Whereas channel migration refers to the process of progressive lateral channel movement, ***avulsion*** refers to the rapid development of a main channel thread due to the "jumping" of the main channel. This process typically occurs during flood events. One primary example of avulsion on the Yellowstone is meander bend cutoff (Figure 1-2). In addition to bendway cutoffs, avulsions may occur where high flow channels enlarge and capture a main portion of the rivers flow. The process of rapid channel shift into a new primary channel, called ***avulsion***, differs from that of lateral channel migration in terms of process and frequency, and as such poses a different challenge in river management.

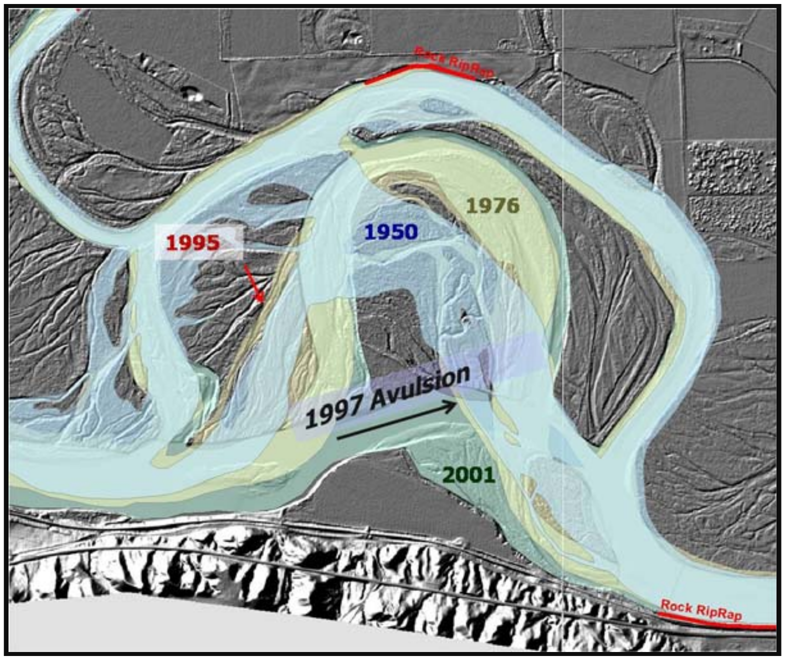

Figure 1-2. Example of a 1997 flood-driven avulsion via meander cutoff, Rosebud County.

1.3 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, which is captured in the map by the Channel Migration Zone (CMZ), and more rapid channel avulsion, which is described by the Avulsion Potential Zone (APZ). The fundamental concept of CMZ mapping is to identify the corridor area that stream channel or series of stream channels can be expected to occupy over a given timeframe. For this study, a 100-year CMZ was developed.

Because of a fundamental difference between avulsion and migration processes, high flow channels or bendways that appear to be at risk of avulsion are defined separately from areas at risk of channel migration on the maps. The Avulsion Potential Zone (APZ) is mapped as a distinct unit that extends beyond the core of the CMZ. This is primarily because the delineation of areas prone to avulsion is inherently more subjective than identifying migration-prone areas. Whereas the assessment of areas prone to erosion can be performed using measured rates of historic bank migration, avulsions tend to be less frequent, flood-driven, and more stochastic in nature.

1.4 Uncertainty

The adoption of a 100-year time frame for the CMZ boundaries creates a level of uncertainty with regard to the likelihood of channel occupation of specific areas within the CMZ over the next century. FEMA (1999) noted the following:

> …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.

For this study, a 100-year time frame was selected for the life of the CMZ. This criteria for projected channel movement was adopted because of the ecological implications of a 100-year time frame, as well as the fact that a 100-year CMZ has been most commonly adopted by other mapping efforts (Section 3.2). As the oldest cottonwood trees in the riparian zone are on the order of 100 years old, this time frame is considered likely to provide conditions necessary to develop diverse riparian age classes and locally support mature riparian forest.

Section 3.2 contains further discussion regarding the adoption of a 100-year time frame, as well as levels of uncertainty associated with reach-scale CMZ mapping.

1.5 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 floodplain 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 ***Channel Migration Zone*** 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. In contrast, ***avulsion*** tends to be a flood-driven process, and as such, risks identified by the ***Avulsion Potential Zone*** are typically associated with infrequent, relatively rapid shifts in channel course that are commonly very difficult to predict.

1.6 Potential Applications

The CMZ maps developed for the Yellowstone 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 and diking 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;
- Support the ongoing Cumulative Effects Study;
- Improve stakeholder understanding of the geomorphic behavior of this large river system;
- Support planning decisions at local and county levels by identifying relative levels of erosion risk;
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor; and,
- Help define long-term sustainable river corridor boundaries.

1.7 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 Yellowstone River corridor and ARE NOT intended to provide regulatory boundaries or override site-specific assessments. The criteria for developing the boundaries are based on reach scale conditions and average historic rates of change. These criteria do not reflect any intended regulatory application. The boundaries can support river management efforts, but in any application it is critical that users thoroughly understand the process of their development and associated limitations.

Primary limitations of this reach-scale mapping approach include the potential for an underestimation of short-term migration rates in discrete areas that are eroding especially rapidly, as well as limitations in mapping of site-specific geotechnical attributes of banklines. As such, it is recommended that these maps be supplemented by site-specific assessment where near-term migration rates or site geology and associated bankline retreat rates create anomalies in the reach-averaging approach.

1.8 Acknowledgements

This effort was performed for the Yellowstone River Conservation District Council (YRCDC) through a contract between the Custer County Conservation District and the DTM Consulting/Applied Geomorphology Project Team. Nicole McLain and Carol Watts were instrumental in providing contract management and facilitating communication between the authors and project sponsors. Feedback from the YRCDC and the YRCDC Technical Advisory Committee (TAC) was critical in developing the maps. We especially extend our thanks to YRCDC TAC members Warren Kellogg

(NRCS) and Jim Robinson (DNRC), as well as Karl Christians of DNRC for providing insightful review and discussion of the draft submittal. The project team extends its gratitude to all involved parties that facilitated this effort.

2.0 Physical Setting

The following summary of the Yellowstone River corridor geology and geomorphology is intended to provide basic context regarding the physical conditions within the project reach. Because of the large scale of this project (approximately 564 miles of river), it is important to consider the variability in physical conditions that control river form and process. Much of this information is derived from the report entitled Geomorphic Reconnaissance and GIS Development, Yellowstone River, Montana: Springdale to the Missouri River (AGI and DTM, 2004).

2.1 Regional Geologic History

From Gardiner, Montana, to Springdale, the Park County segment of the Yellowstone River flows through the Rocky Mountain physiographic province. The rocks exposed along the banks of the Yellowstone River in Park County range from Archean gneisses in Yankee Jim Canyon that are over 2.5 billion years old, to numerous recent landslides and glacial outwash terraces. The geomorphology of the Yellowstone River through Park County is strongly affected by outwash terraces that formed during a series of glacial episodes over the last 150,000 years. These terraces are largely exposed in the northern portion of the Paradise Valley, between Mill Creek and Carter's Bridge. Within and downstream of Livingston, the river is intermittently confined by Cretaceous-age sedimentary and volcanic rocks.

From Springdale, Montana, to its mouth, the Yellowstone River flows through what is known as the Northern Great Plains physiographic province, a broad surface that slopes eastward from the Rocky Mountain Front towards the Missouri River. Throughout its course, the Yellowstone River is strongly affected by the bedrock geology of the Northern Great Plains, which largely consists of sedimentary rocks that are Cretaceous and Tertiary in age (65 to 150 million years old). These rocks formed when uplift of the Rocky Mountains drove extensive erosion of the growing mountain range, and eastward transport of sediment. This material was then deposited as extensive layers of sand, silt, and organic matter on the gently sloping terrain.

During Pliocene time (over 2.5 million years ago), river systems began to dissect the Northern Great Plains, exposing the accumulated layers of sandstone, shale, and coal. At this time, the ancestral Yellowstone River drained northward to Hudson Bay (Wayne and others, 1991). When continental glaciation began about 2.5 million years ago, ice repeatedly blocked the easterly flowing rivers, causing them to form lakes, spill across divides, and form new courses. At one point, a lobe of the ice sheet extended as far south as Intake, blocking the course of the Yellowstone River (Howard, 1960), and forming Lake Glendive near present-day Glendive. Lake Glendive eventually reached upstream of Miles City to near Hathaway. About 20,000 years ago, the ice sheet retreated to the north, shifting and dropping the elevation at the river's mouth. This base level lowering caused the river to downcut into its valley fill, resulting in the formation of a series of terraces that bound the river today (Zelt and others, 1999). These terraces are important components of the Channel Migration Zone delineation, as the lowermost terraces commonly form the margin of the river, and are prone to erosion.

2.2 Valley Wall Geology

The Yellowstone River flows through a well-defined river valley that has eroded through sandstone, shale, and coal. The variability in rock types along the river course has resulted in major variations in valley width (AGI and DTM, 2004). Where the valley wall is made of shale, the valley tends to be relatively wide. A plot showing this correlation is shown in Figure 2-1. In this figure, each bar represents a 3-mile length of valley; the Valley Mile (VM) referencing reflects the valley distance upstream from the mouth of the Yellowstone Missouri River confluence. Each 3 mile segment has been attributed by the primary geology at the margin of the river valley. The yellow bars represent a series of shale units between Billings and Park City (Valley Mile 294-327), where valley is typically over 2.5 miles wide. The Bearpaw Shale, depicted as red columns on Figure 2-1, can be correlated to valley floor widening from Huntley to Pompey's Pillar (VM 261-288), in Mission Valley (VM 212-230), and in Hammond Valley (VM 199-206). Towards the river mouth, the Tongue River member of the Fort Union Formation is similarly associated with a relatively wide valley bottom. Whereas shales are typically associated with valley bottom widening, the narrowest valley bottom in the study reach occurs between Springdale and Park City, where the valley walls are comprised of resistant sandstone of the Hell Creek Formation.

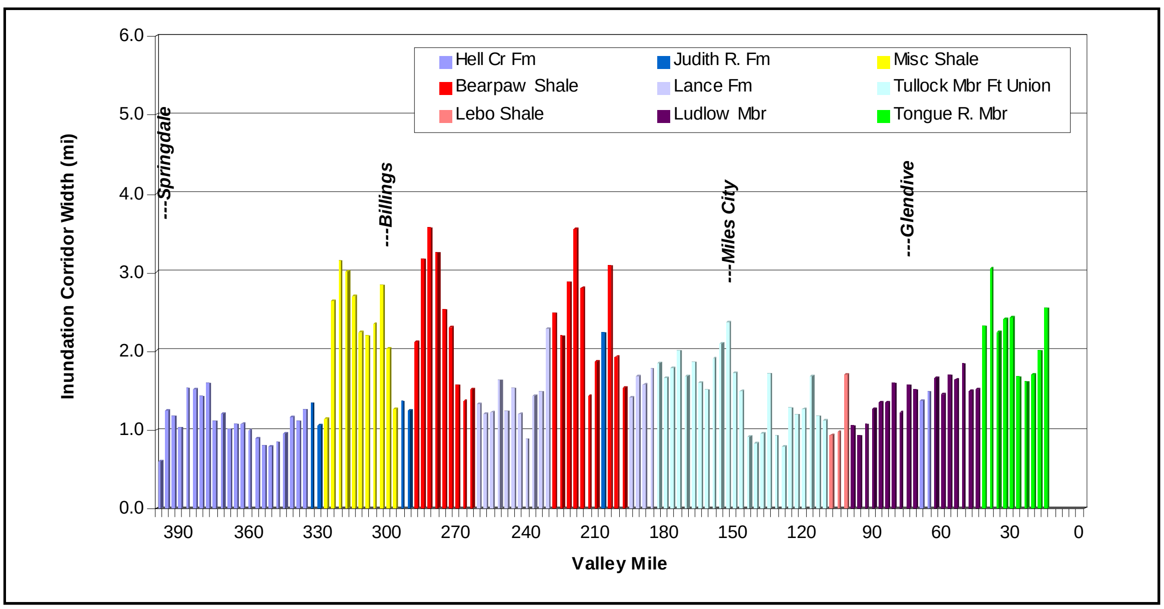

Figure 2-1. Valley bottom width and associated valley wall geology, Springdale to mouth.

2.3 Quaternary Terraces

As described in Section 2.1, the Yellowstone River has eroded the Northern Great Plains landscape over the past few million years. On most river systems, this process of vertical downcutting to form a stream valley is characterized by periods of active incision that are separated by periods of relative stability. During these periods of relative stability, the river migrates laterally, forming a floodplain. When incision resumes, downcutting of the river below its floodplain perches that surface as a terrace. Most river terraces are abandoned floodplain surfaces, which is why they tend to be flat, and draped by stream deposits (Figure 2-2).

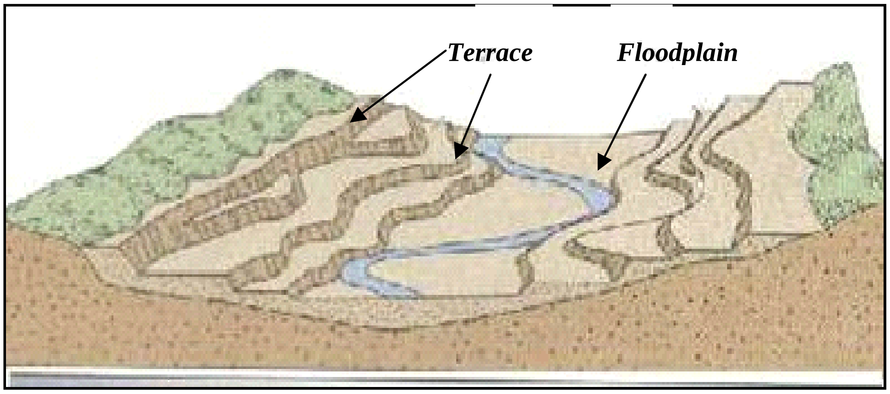

Figure 2-2. Schematic diagram of a typical river valley floodplain and terrace configuration (unt.edu).

Quaternary-age terraces along the Yellowstone River valley extend from the lower river upstream to the Paradise Valley (Figure 2-3). The terraces are typically coarse-grained sediments that were deposited during a period of extensive alpine glaciation in the upper watershed (Zelt and others, 1999). Individual terrace surfaces tend to converge in the upstream direction, which reflects the progressive entrenchment of the lower reaches of the river. The same high terrace surface that is approximately 380 feet above the river near Glendive, is only 120 feet above the river near Billings. In the vicinity of Billings, five distinct Pleistocene-age terrace units have been mapped above the elevation of the modern river and its alluvial deposits (Lopez, 2000;Table 1).

Table 1. Descriptions of mapped terraces in the vicinity of Billings (Lopez, 2000).

Geologic Map Unit	*Thickness (ft)*	*Estimated height above floodplain (ft)*	*Reference in Channel Migration Zone*
Qat1	20-40	10-20	LT: “Low Terrace”
Qat2	40-60	20-40	HT: “High Terrace”
Qat3	20-30	50-90	None
Qat4	20	200-300	None
Qat5	20	400-500	None

The only two terraces that have been identified as directly influencing the Channel Migration Zone boundaries are the Low Terrace (LT; Qat1) and the High Terrace (HT; Qat2). None of the higher terraces were identified as forming actively eroding margins of the modern river corridor; these high terraces are typically either hundreds of feet away from the river, or characterized by a gravel veneer over bedrock, perched well above the active channel.

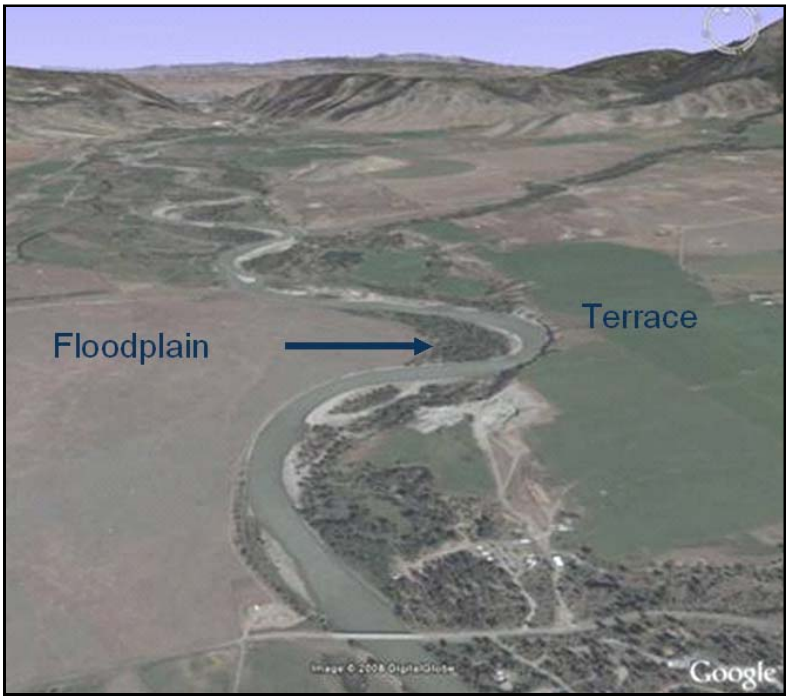

Figure 2-3. River floodplain and terrace downstream of Pine Creek Bridge in the Paradise Valley, Yellowstone River.

2.4 River Morphology

Koch (1977) concluded that in the mid-1970's, the general character of the Yellowstone River main stem was very similar to that observed during the William Clark expedition of 1806. This general characterization consisted of anabranching (abundant side channels) and braided reaches with gravel bars, and intervening reaches with very few islands and minimal gravel bars.

As part of the 2004 Reconnaissance Report (AGI and DTM, 2004), the river was subdivided into 67 reaches between Gardiner and the Missouri River. These reaches average approximately 7 miles in length, and are classified in terms of geomorphic conditions such as stream pattern (number of side channels, sinuosity), and confinement (presence of bedrock). Since the 2004 Reconnaissance Report was completed, Park County has been similarly subdivided into 21 reaches. Appendix A contains a list of project reaches and their general locations. The classification scheme utilized in the reach assessment is summarized in Appendix B.

In Park County, the Yellowstone River flows through major geologic controls from Gardiner to Point of Rocks, where channel migration rates are minimal, and the riparian corridor is very narrow. Below Emigrant, the channel is more dynamic, although locally confined by both low and high terraces. Spring creeks in the Paradise Valley occur on both sides of the main channel. This area is prone to major sediment loading from the terraces during flood events. Through Livingston, the river is confined by extensive armor and dikes. Downstream of Livingston near Mission Creek, wooded islands, open bars, and active bankline migration are common.

Between Springdale and the Yellowstone River/Missouri River confluence, the physiography of the Yellowstone River and its tributaries transitions from steep, confined mountainous areas to plains conditions. As part of the geomorphic reconnaissance study (AGI and DTM, 2004), this portion of the river corridor was subdivided into four regions (Figure 2-4).

- Region A: From Springdale to the Clarks Fork confluence near Laurel, the river contains a total of 18 reaches. These reaches are typically anabranching (supporting long side channels separated by the main channel by wooded islands), as well as braided (supporting split flow channels around open gravel bars). The reaches are typically "partially confined", indicating that the bedrock valley wall commonly affects one bank of the river. The low terrace commonly follows the channel edge, and a few exposures of high terrace form the modern channel margin.
- Region B: Between the Clarks Fork confluence and the Bighorn River confluence, the river contains 12 reaches. Reach types are variable, ranging from straight to braided. Similar to Region A, bedrock valley wall controls are intermittent. Both low terrace and high terrace features locally form the channel bankline.
- Region C: Between the Bighorn River and the Powder River, Region C consists of a lower gradient system that supports a wide range of reach types. A total of 21 reaches have been identified in Region C, and these reaches range from unconfined, multi-thread channels in the Mission and Hammond Valleys, to highly confined areas downstream of Miles City.
- Region D: Below the Powder River confluence, Region D contains 16 reaches. The uppermost segments of this region, from the Powder River to Fallon, are closely confined by bedrock valley walls. Downstream of Fallon, confinement is reduced, and broad islands are common.

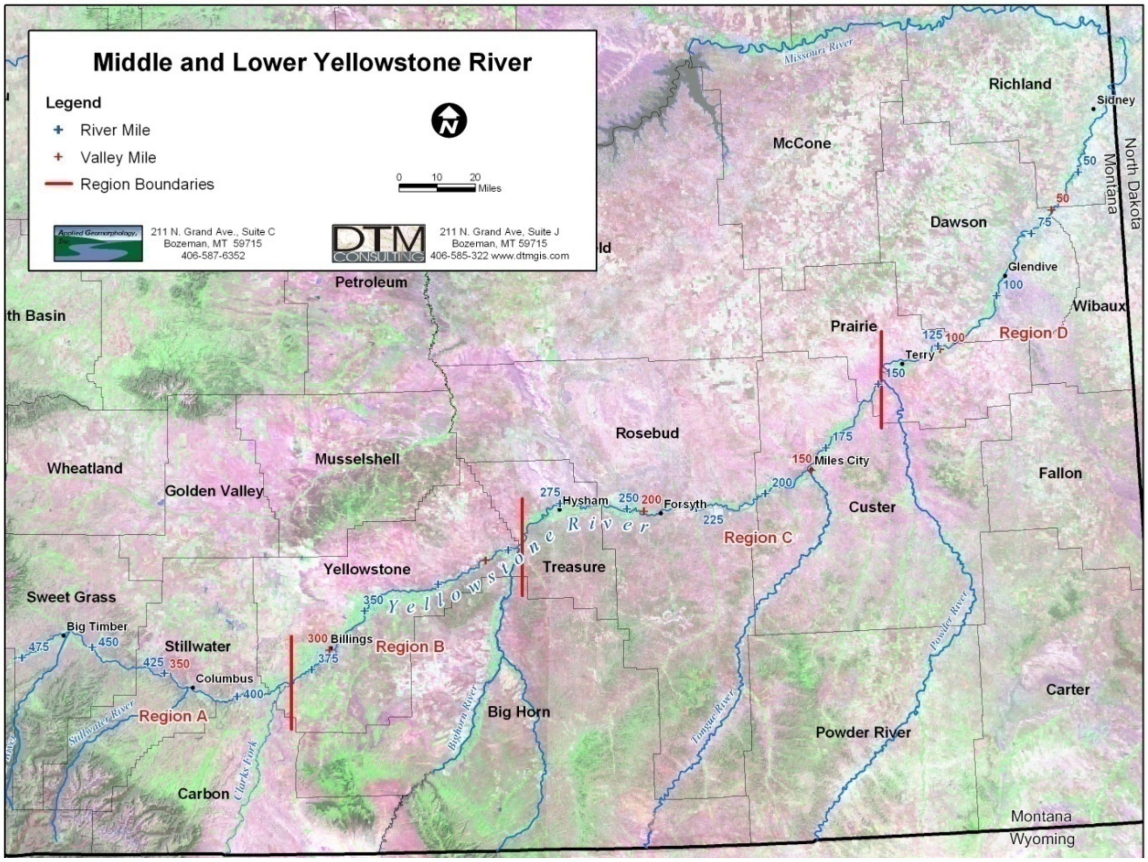

Figure 2-4. Regional geomorphic zones of the Middle and Lower Yellowstone River.

3.0 Methods and Results

The methodology applied to the CMZ delineation generally follows the techniques outlined in Rapp and Abbe (2003). The channel migration zone (CMZ) developed for the Yellowstone River is defined as a composite area made up of the existing channel, the historic channel since 1950 (Historic Migration Zone, or HMZ), and an Erosion Buffer that encompasses areas prone to channel erosion over the next 100 years. Areas within this CMZ that have been isolated by constructed features such as armor or floodplain dikes are attributed as "Restricted Migration Area" (RMA). Beyond the CMZ boundaries, outlying areas that pose risks of channel avulsion are identified as "Avulsion Potential Zones".

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

Restricted Migration Area (RMA) = Areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features

The following sections describe the methodologies for developing 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 (HMZ)

The Historic Migration Zone is based on a composite area defined by the channel locations in 1949-1951, 1976, 1995, and 2001 (Figure 3-1). 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.

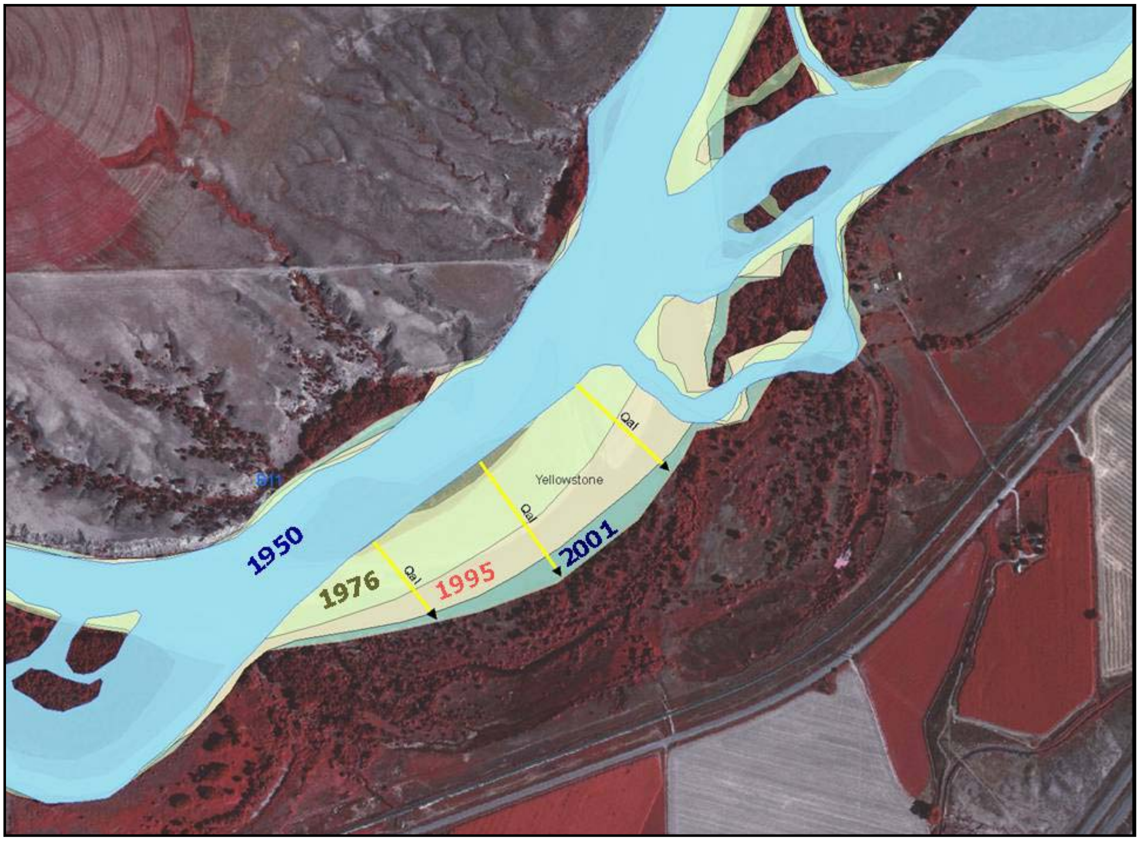

Figure 3-1. Composite Historic Migration Zone (HMZ) showing bendway migration from 1950-2001; migration lines are shown as arrows.

3.2 The Erosion Buffer

To address anticipated future migration beyond the historic corridor boundary, an Erosion Buffer has been added to the 2001 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 1950 to 2001 were measured throughout the corridor. The rates were then statistically summarized on a reach scale to approximate anticipated migration distances for a 100-year timeframe. 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).

FEMA (1999), concluded the following, which also supports the average migration rate approach:

> Because of limitations in data availability and model capabilities, it is extremely difficult to reproduce detailed time variation of stream movement; however, it is entirely feasible to analyze channel history and infer trends in the stream alignment and average migration rates.

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 approach was initially adopted as the most feasible means of mapping the 564-mile project reach with available resources. The results suggest that this reach-scale approach provides a more generalized long-term depiction of channel movement relative to approaches that apply buffers on the scale of active eroding banklines. In the near-term, this reach scale averaging is likely to overestimate channel movement in places where active migration is currently slow or nonexistent, and potentially underestimate the short-term migration rates of areas in active phases of movement. However, due to the active planform of the Yellowstone 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 bendway-scale 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 Yellowstone River, this assumption is unrealistic do to the fact that migration rates and patterns vary with bendway shape, sediment load, flow conditions, ice effects, and bankline integrity, such that single banklines are not likely to move at a constant rate over the scale of a century. Empirical observations of aerial photography indicate that over the past 50 years, there are areas where bendways have begun to form within straight channel segments, and areas where actively migrating bends have slowed down, changed direction, or cut off. 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.

Using a reach-scale approach to calculate erosion buffers, approximately 2000 individual measurements of channel migration were recorded in the project GIS. Three measurements were collected at each site, and each vector was attributed in terms of reach, location (river mile), geologic unit, distance, and time frame. An example of a single bendway migration site measurement is shown as three migration lines in Figure 3-1. A reach with labeled vector lengths is shown in Figure 3-2.

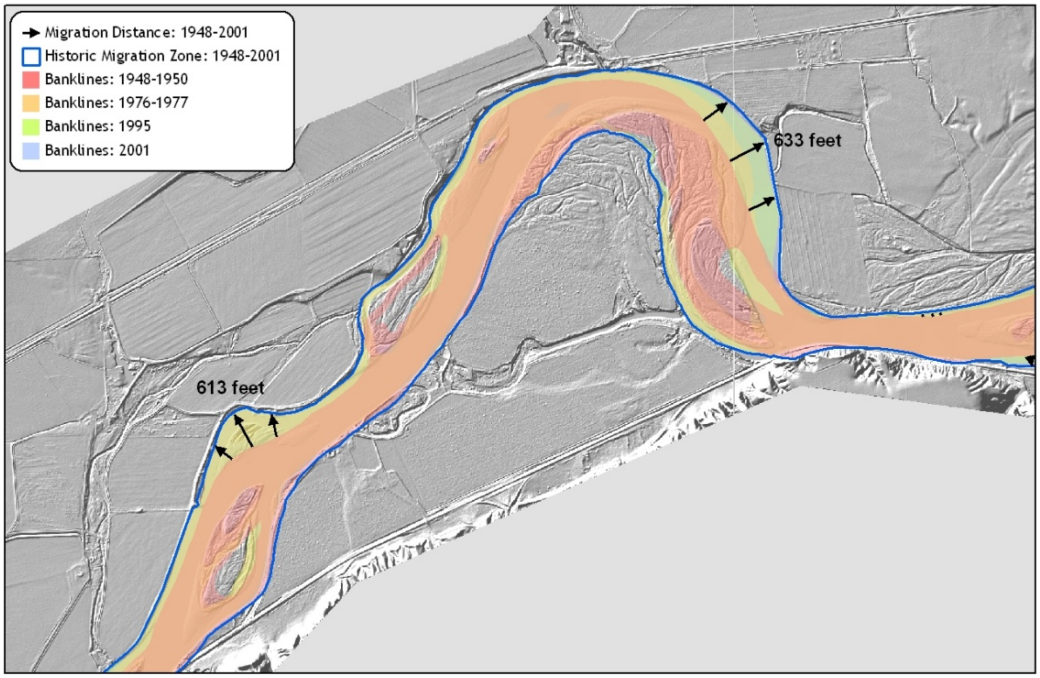

Figure 3-2. Migration vectors, showing length of longest site vector in feet.

3.2.1 Geologic Controls on Migration Rate

Any given area that the Yellowstone River has eroded over the past 50 years may consist of alluvium, terrace, or bedrock materials. For this study, very little migration was measureable into the bedrock valley walls, hence these units were excluded from the analysis. The Low Terrace (LT) and High Terrace (HT), however, show some cases of active erosion by the river. In order to effectively assess the potential for channel migration into these units, they were mapped in the GIS, and then any migration lines that extended into these units were attributed as such. The data for these sites, which reflect channel migration into terraces, were then summarized as an independent dataset.

The geologic mapping of terraces on the river margin relied on existing geologic maps, air photos, and high resolution LiDAR-derived topography. This mapping effort was challenging due to the variable heights and expression of these surfaces on the air photos. The recent acquisition of LiDAR data for the entire corridor has greatly facilitated terrace mapping, and several areas were field checked to correlate mapping results to ground conditions. Although LiDAR data improves the ability to map these terraces remotely, some surfaces may be inappropriately identified. Areas where a terrace surface intersects the bankline for only a short distance are most prone to being mis-mapped. It is therefore critical to note that these maps are intended to provide a best-effort screening tool, and that field observations can be used to refine buffer widths at specific sites if necessary.

The units mapped in the GIS include HT (High Terrace), LT (Low Terrace) AL (alluvium), and B (Bedrock). A schematic cross section showing the configuration of alluvium, terraces, and bedrock is shown in Figure 3-3. Bedrock (B) intermittently forms bluffs along the river's edge, and these bluffs are typically taller than the high terrace (HT). The most common material bounding the river channel is alluvium (AL), which is that material deposited and frequently reworked by the river. This alluvium, or floodplain area, includes both the active riparian corridor and slightly higher alluvial bottomlands. Where the river migrates beyond the edge of the alluvium, it commonly encounters the low terrace (LT), which is 10-20 feet above the alluvial bottom. This surface supports extensive agriculture in the corridor, and the railroad commonly follows its edge where it is in contact with the lower elevation floodplain. Locally, the river has eroded laterally to the edge of the high terrace (HT), which is at least 20 feet higher than the alluvial river bottom.

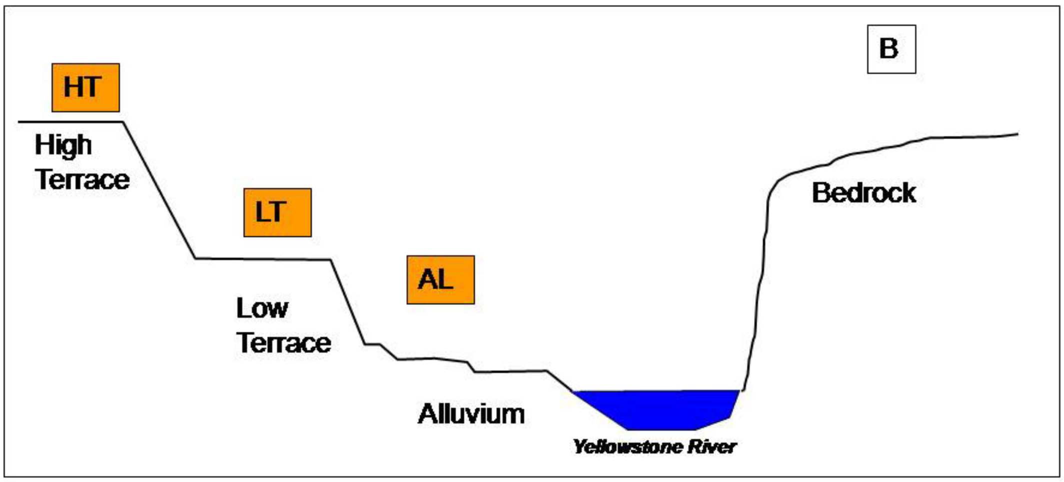

Figure 3-3. Schematic Cross Section showing geologic units addressed in CMZ development.

3.2.2 Migration Rate Statistics

The measured migration distances were statistically summarized by reach. Appendix A contains a list of project reaches and their general locations, and a summary of the geomorphic classification scheme is included in Appendix B. Appendix C contains box and whisker plots showing the range of measurements for each reach, and a list of resulting erosion buffers applied to the 2001 bankline is contained within Appendix D.

Active channel migration into the terraces was not widespread enough to be measurable in every reach. As such, the terrace erosion measurements were averaged between reaches, and applied on a regional scale. In a few reaches, where terrace erosion sites are minimal and measured rates of channel migration into alluvium are low, the alluvial buffer is applied as the maximum value for any geologic map unit.

The resulting erosion buffers applied to each reach are shown in Figure 3-4. The values shown are in meters, and reach-specific values reflect measured migration rates through alluvium. The buffer value, which is for a 100-year timeframe, reflects twice the mean 50-yr migration rate distance shown in Appendix B. Single values were developed for the LT and HT terrace values for each region (Park County, Region A, Region B, Region

C, and Region D). The high terrace (HT) was not identified as present within the CMZ boundaries of either Region B or Region C.

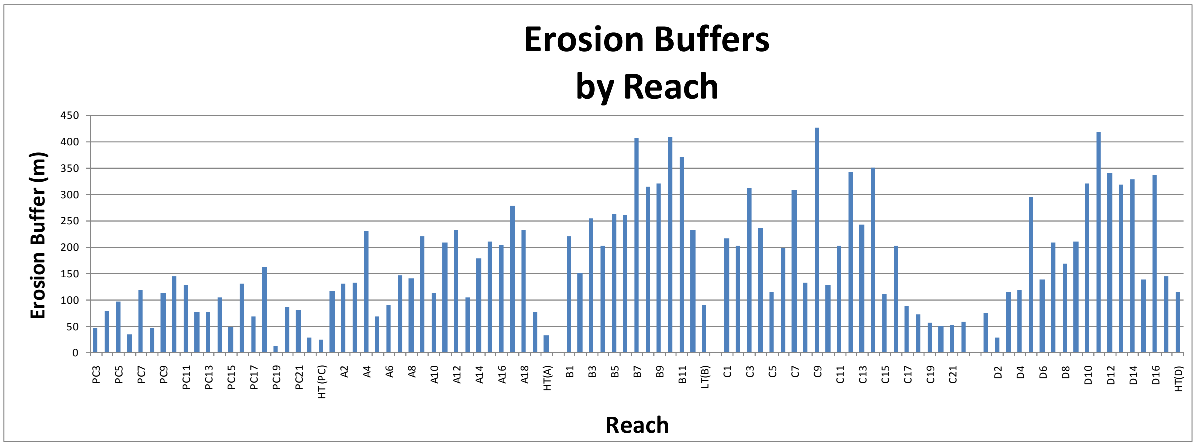

Figure 3-4. Erosion buffers applied to 2001 channel margin, Yellowstone River project reach.

Where the river abuts older terraces, and migration into that terrace is of concern, it would be prudent to perform a more site-specific assessment to define the geotechnical character and associated erodibility of that deposit. A reconnaissance level field assessment was performed to help define the average geotechnical characteristics of the geologic units that comprise the margins of the Yellowstone River corridor, however a complete field assessment of terrace extents and erodibility was beyond the scope of this project.

An example of the erosion buffer added to the 2001 channel margins is shown in Figure 3-5. Typically, the buffer applied to the AL deposits (recent river alluvium) is greater than that applied to either the low or high terrace (LT or HT, respectively). Where the channel abuts older bedrock units, no buffer was applied. Although these units may be prone to gradual erosion or perhaps mass failure, these processes are site specific and beyond the scope of this project. As such, it is critical to note that hazards likely exist where the river abuts geologic units older than Quaternary-age alluvium and terraces, but that these hazards should be addressed site-specifically.

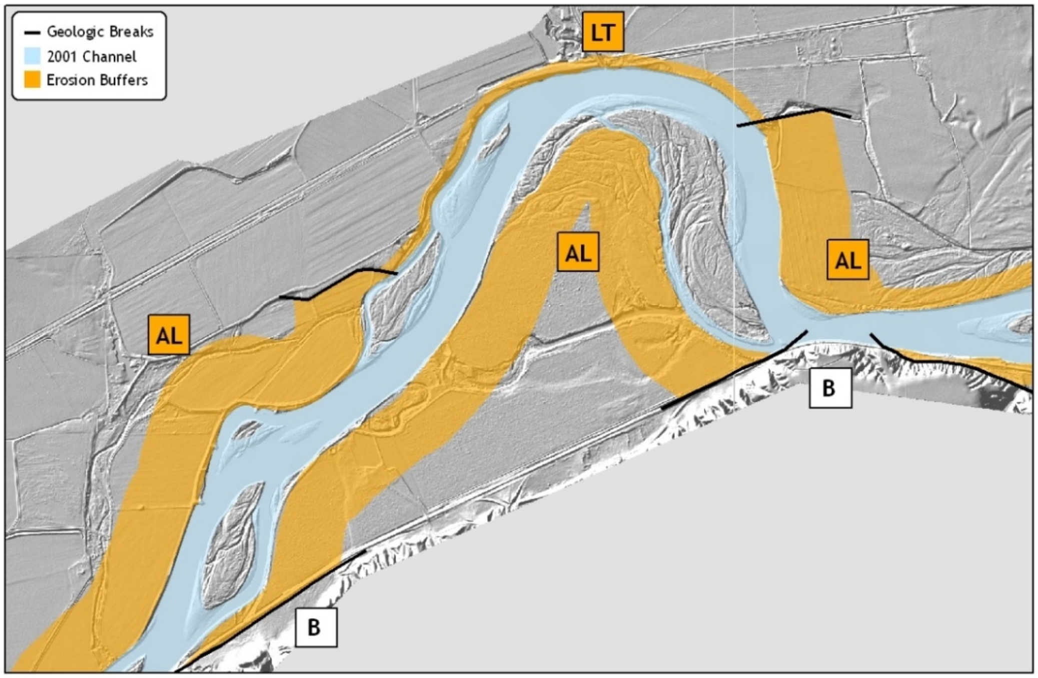

Figure 3-5. Erosion buffers applied to 2001 channel margin.

A summary of calculated erosion buffer widths by reach type shows that the confined channel types (CM and CS) have the smallest erosion buffers, which means the lowest measured rates of migration (Figure 3-6). The partially confined straight reaches (PCS) typically represent a straight channel that is flowing against a bedrock valley wall, also show low rates of channel shift. In contrast, braided, meandering, and anabranching channels all have much higher rates of migration and associated buffer widths. These data suggest that relatively high rates of lateral migration on the Yellowstone River occurs in numerous reach types, and that no single reach type accommodates the majority of channel movement.

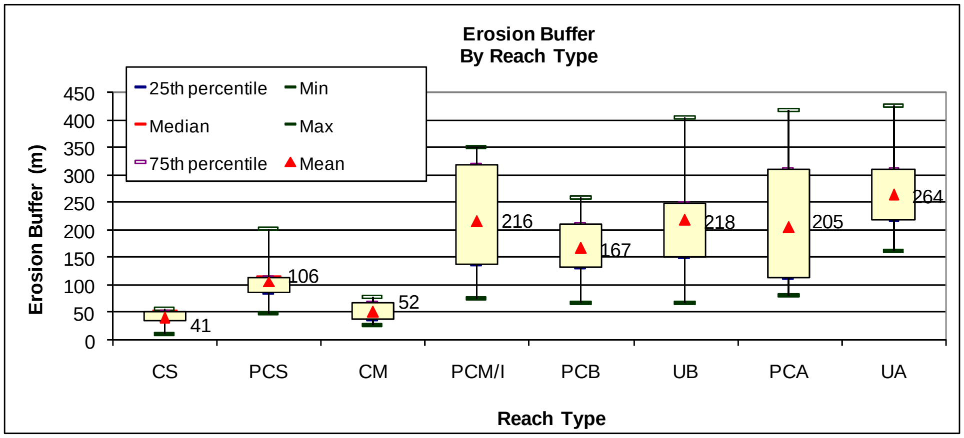

Figure 3-6. Statistical summary of erosion buffer widths by each reach type; average values are labeled.

3.3 The Restricted Migration Area

In an effort to control lateral erosion of the Yellowstone River, bank protection has been placed in areas of concern. The extent of bank armor within each reach ranges from 0% to almost 50% of the bank length (AGI and DTM, 2004). The effect of this armor is to restrict natural patterns of channel migration. As such, areas within the CMZ may not be wholly accessible to the river due to the erosion resistance of the armored bank. The Restricted Migration Area refers to areas within the CMZ that have been isolated by man-made structures (Figure 3-7). These features may include bank armor, dikes, embankments, levees, or bridge abutments. The Restricted Migration Areas are identified on the accompanying CMZ maps, and it is intended that in the future, a detailed, quantitative assessment of restricted area will support the Yellowstone River Corridor cumulative effects assessment.

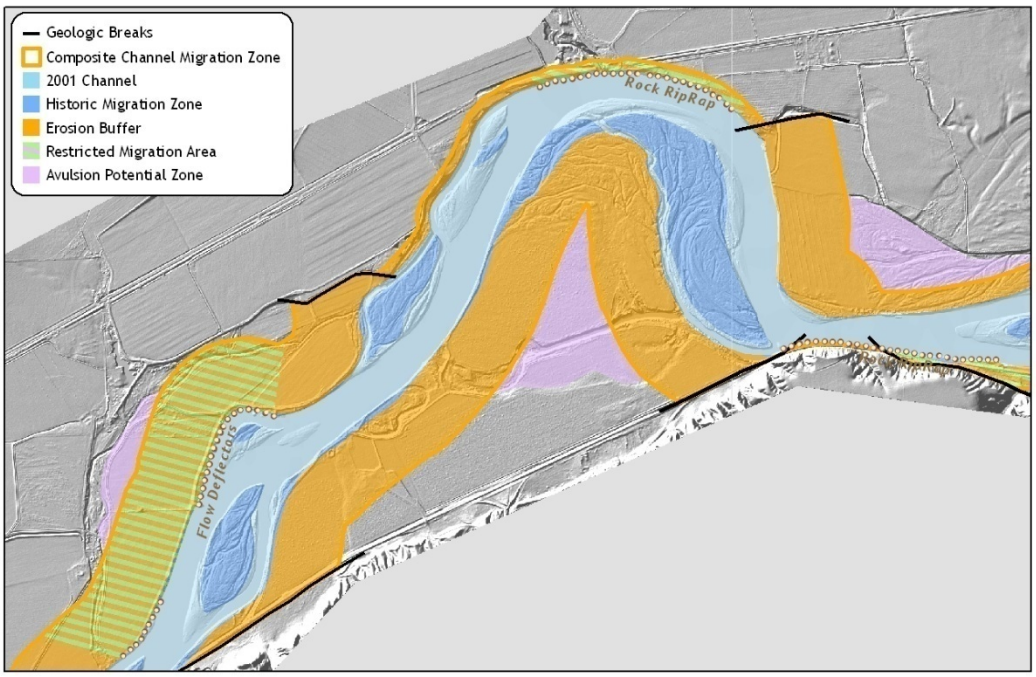

Figure 3-7. CMZ showing Restricted Migration Areas (cross-hatched) and Avulsion Potential Areas (pink).

A preliminary summary of the GIS data indicate that the channel types that tend to contain the most islands (anabranching: PCA and UA, and meandering with islands: PCM/I), collectively have the largest extent of CMZ acreage in the project reach (Figure 3-8). However, the braided channel types, which are characterized by extensive split flow around open gravel bars, have the greatest proportion of migration area that is restricted by bank armor and levees (Figure 3-9). These data represent a summation of all acreage within a given reach type. It is also instructive to assess the range of results calculated for each individual reach. A box and whisker plot of the data shows the minimum, 25^{th} percentile, median (labeled), 75^{th} percentile, and maximum for the dataset represented by each reach type (Figure 3-10). For most classification types, at least one reach exhibits an excess of 20 percent of CMZ restriction by armor, levees, or dikes. The

Partially Confined Straight (PCS) reach that is over 25% restricted is located immediately above Huntley Diversion dam (Reach B4); this may exemplify the relationship between infrastructure and CMZ isolation by riprap.

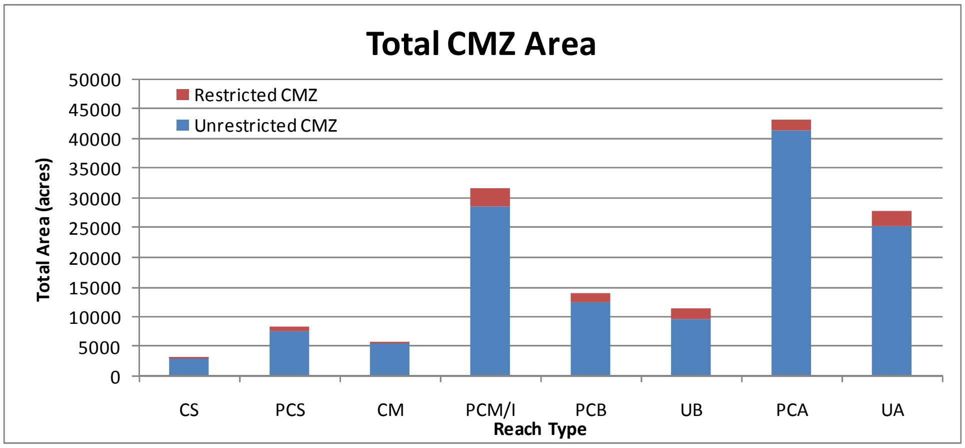

Figure 3-8. Total channel migration zone area by Reach Type.

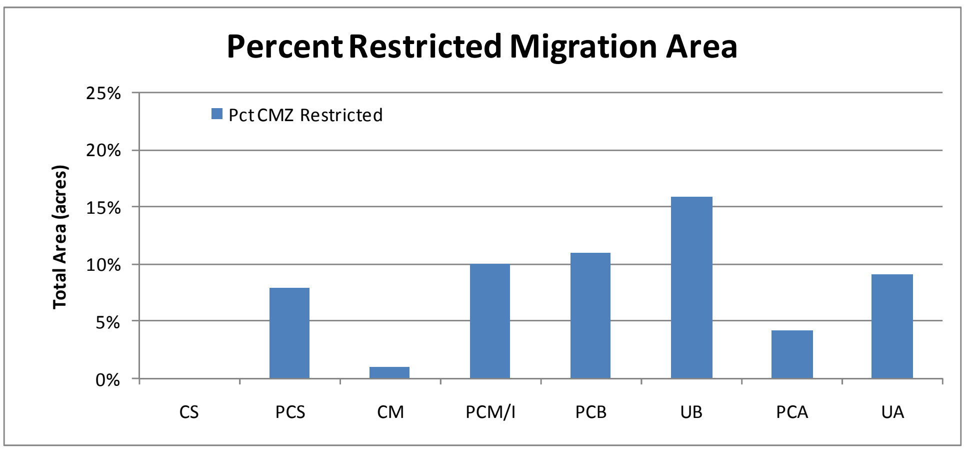

Figure 3-9. Percent of restricted migration area by reach type (total of all acreage).

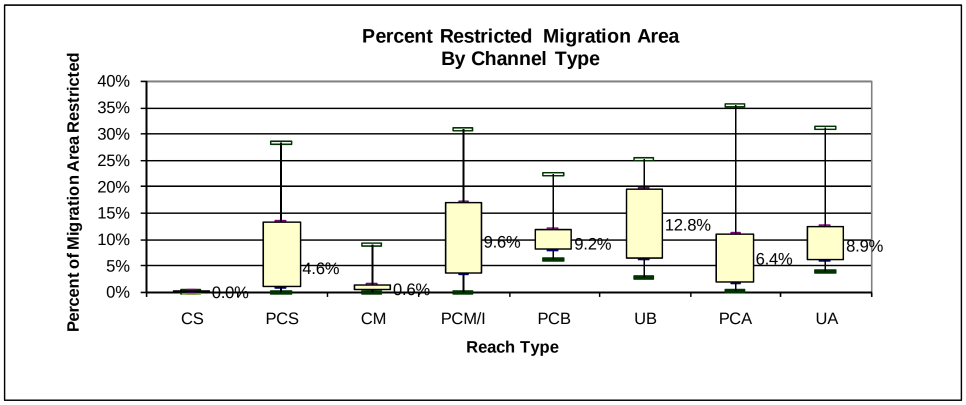

Figure 3-10. Statistical summary of percent restricted migration area by reach type; based on individual reach data (median values are labeled).

3.4 The Avulsion Potential Zone (APZ)

In many places, the Yellowstone River migrates laterally across its floodplain as a distinct, persistent channel course. However, mapping of historic channel movement on the Yellowstone River indicates that there are places where the river has historically "jumped" channels, or avulsed, due to a range of processes including natural erosion, flood events, and ice jamming. This process, which may be natural or driven by human activities in the stream corridor, creates additional risk of erosion within the river corridor. To address this risk, an avulsion potential zone (APZ) has been developed for the Yellowstone River corridor.

The Avulsion Potential Zone is based on digitized channel courses that are evident beyond the boundaries of the CMZ. It includes areas where discernable floodplain channel remnants are within the active valley bottom; and additionally, areas where bendways are geomorphically mature and appear prone to cutoff. The methodology for determining the APZ is to digitize channel remnants and bendways that are prone to cutoff, and highlight those areas beyond the CMZ where these features exist (Figure 3-7).

3.5 The Restricted Avulsion Potential Zone

In numerous areas, overflow channels that have been mapped as part of the Avulsion Potential Zone have been blocked by flood control features such as dikes and levees. Where these features clearly block channels and thus prevent their activation, the Avulsion Hazard Zone has been cross-hatched to indicate that it is restricted (Figure 3-7).

3.6 Composite Map

An example portion of a composite CMZ map for a section of Treasure County is shown in Figure 3-11. The accompanying deliverable maps for the project reach are presented by county and included on the project CD as PDF files.

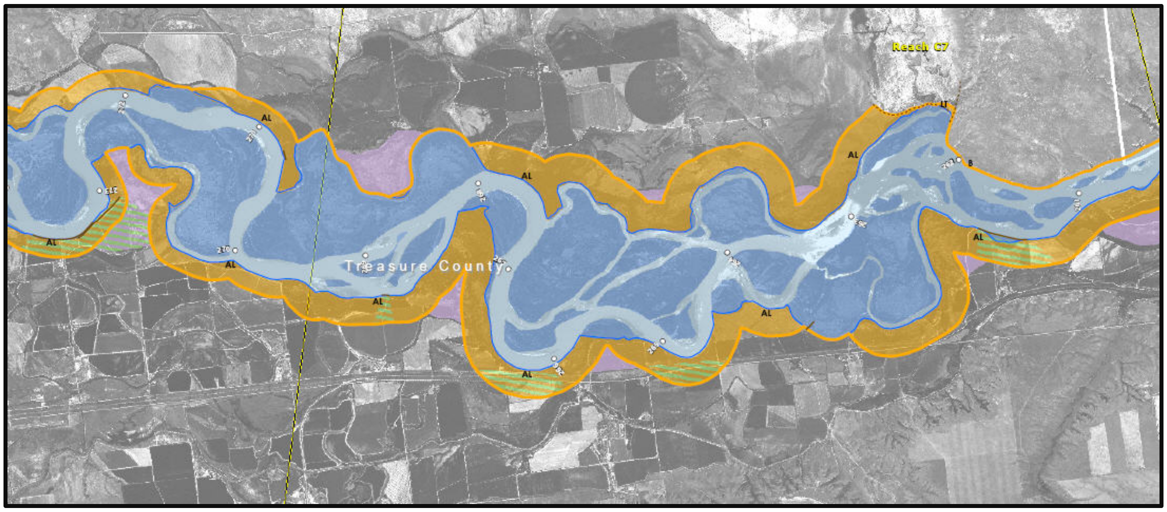

Figure 3-11. Composite Channel Migration Zone on 2005 NAIP imagery.

3.7 Deliverables

The products for this effort consist of a project data CD and a series of county-level maps that delineate the Channel Migration Zone for the Yellowstone River from Park County to the Missouri River. All new project data are supplied on CD in an ESRI Personal Geodatabase, along with PDF versions of the county-level maps. Each Feature Class is accompanied by appropriate FGDC compliant metadata. All data are in Montana State Plane NAD83 coordinates, in meters.

4.0 References

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Appendix A. Reach Lengths, Classification, and General Location

Table A- 1. Summary of reach types and geographic location

Reach Identification	*Length (km)*	*County*	*Classification*	*Comments*
PC1	7.6	Park	CS: Confined Straight	*Gardiner*: confined
PC2	5.0	Park	CM: Confined Meandering	Confined meandering above Yankee Jim Canyon
PC3	16.6	Park	CS: Confined Straight	Some bar formation at Corwin Springs; closely confined through Yankee Jim Canyon
PC4	5.8	Park	CM: Confined Meandering	To *Point of Rocks*; limited migration and narrow CMZ
PC5	6.2	Park	PCA: Partially confined anabranching	Increasing migration rates below Carbella Bridge
PC6	6.9	Park	CM: Confined Meandering	Confined
PC7	9.9	Park	PCA: Partially confined anabranching	*Emigrant*; relatively dynamic corridor
PC8	20.3	Park	CM: Confined Meandering	*Pray*; closely confined by Quaternary terraces
PC9	3.1	Park	PCA: Partially confined anabranching	To *Pine Creek Bridge*; wide corridor with
PC10	5.6	Park	PCM: Partially confined meandering	*Pine Creek to Jumping Rainbow*; dynamic reach with extensive diking to protect spring creeks
PC11	3.8	Park	PCA: Partially confined anabranching	Wide anabranching channel with extensive bank protection
PC12	3.2	Park	PCM: Partially confined meandering	To *Carter's Bridge*
PC13	2.5	Park	PCB: Partially confined braided	Canyon section below Carter's bridge
PC14	5.6	Park	PCA: Partially confined anabranching	*9th Street Island, Livingston*; extensive armor and diking
PC15	2.9	Park	PCS: Partially confined straight	*Livingston*
PC16	6.9	Park	PCA: Partially confined anabranching	Dynamic reach downstream of Livingston; active bankline migration
PC17	3.2	Park	PCB: Partially confined braided	*Highway 89 Bridge*
PC18	8.5	Park	UA: Unconfined anabranching	Mission Creek section; dynamic
PC19	4.4	Park	CS: Confined Straight	Confined by terraces and north valley wall
PC20	7.2	Park	PCS: Partially confined straight	Minimal planform complexity in canyon
PC21	3.7	Park	PCA: Partially confined anabranching	To Springdale; numerous islands
A1	5.4	Sweetgrass	PCB: Partially confined braided	*Springdale*: Low primary sinuosity; large open bar area; extensive armoring

Table A- 1. Summary of reach types and geographic location

Reach Identification	*Length (km)*	*County*	*Classification*	*Comments*
A2	11.1	Sweetgrass	UB: Unconfined braided	*Grey Bear* fishing access
A3	8.6	Sweetgrass	PCB: Partially confined braided	Upstream of *Big Timber*; Hell Creek Formation valley wall
A4	5.6	Sweetgrass	UB: Unconfined braided	To *Boulder River* confluence; encroachment at Big Timber; extensive armor
A5	5.2	Sweetgrass	UB: Unconfined braided	Low Qat1 terrace on right bank
A6	4.8	Sweetgrass	PCS: Partially confined straight	Channel closely follows left valley wall
A7	15.9	Sweetgrass	PCB: Partially confined braided	*Greycliff*: Narrow valley bottom with alluvial fan margins
A8	8.2	Sweetgrass	PCB: Partially confined braided	Floodplain isolation behind interstate and R/R
A9	6.2	Sweetgrass Stillwater	UA: Unconfined anabranching	To *Reed Pt*; extensive secondary channels in corridor
A10	6.9	Stillwater	PCS: Partially confined straight	Channel closely follows left valley wall
A11	11.2	Stillwater	PCB: Partially confined braided	High right bank terrace with bedrock toe; *I-90 bridge* crossing
A12	9.8	Stillwater	PCB: Partially confined braided	To *Stillwater* confluence
A13	5.8	Stillwater	PCA: Partially confined anabranching	*Columbus*; extensive armoring, broad islands
A14	12.5	Stillwater	PCA: Partially confined anabranching	Valley bottom crossover
A15	9.5	Stillwater, Carbon	PCB: Partially confined braided	Follows Stillwater/Carbon County line
A16	12.4	Stillwater, Carbon	PCA: Partially confined anabranching	*Park City*: Major shift in land use, and increase in valley bottom width
A17	10.4	Yellowstone Carbon	UA: Unconfined anabranching	To *Laurel;* WAI Reach A
A18	3.8	Yellowstone	UA: Unconfined anabranching	To Clark Fork; land use change to row crops; WAI Reach A
B1	24.6	Yellowstone	UB: Unconfined braided	Extensive armoring *u/s Billings*; WAI Reaches B,C,D
B2	9.8	Yellowstone	PCB: Partially confined braided	*Billings*; WAI Reach E
B3	7.0	Yellowstone	UB: Unconfined braided	Wide corridor d/s *Billings*; WAI Reach F
B4	6.1	Yellowstone	PCS: Partially confined straight	Channel closely follows right valley wall; extensive bank armor
B5	12.0	Yellowstone	UA: Unconfined anabranching	*Huntley:* includes *Spraklin Island*
B6	9.9	Yellowstone	PCB: Partially confined braided	Channel closely follows left valley wall

Table A- 1. Summary of reach types and geographic location

Reach Identification	*Length (km)*	*County*	*Classification*	*Comments*
B7	13.9	Yellowstone	UB: Unconfined braided	Unconfined reach
B8	14.7	Yellowstone	PCA: Partially confined anabranching	*Pompey's Pillar*
B9	7.5	Yellowstone	UA: Unconfined anabranching	Meander cutoff isolated by railroad
B10	11.6	Yellowstone	PCM: Partially confined meandering	Encroached
B11	13.1	Yellowstone	PCA: Partially confined anabranching	To *Custer Bridge*
B12	7.3	Yellowstone	UA: Unconfined anabranching	To *Bighorn River* confluence
C1	9.5	Treasure	UA: Unconfined anabranching	From *Bighorn* confluence: Includes 1 mile of left bank valley wall control; Extensive bank protection.
C2	8.9	Treasure	PCB: Partially confined braided	To *Myers Br* (RM 285.5); Railroad adjacent to channel on valley wall; low sinuosity
C3	7.6	Treasure	UA: Unconfined anabranching	To *Yellowstone Diversion*: very sinuous; large meanders, extensive bars; historic avulsion
C4	6.1	Treasure	PCB: Partially confined braided	Below *Yellowstone Diversion*
C5	5.1	Treasure	PCS: Partially confined straight	*Hysham*
C6	9.1	Treasure	UA: Unconfined anabranching	*Mission Valley*
C7	14.7	Treasure	UA: Unconfined anabranching	*Mission Valley*
C8	10.4	Treasure Rosebud	PCS: Partially confined straight	Rosebud/Treasure County Line
C9	17.2	Rosebud	UA: Unconfined anabranching	*Hammond Valley*
C10	11.0	Rosebud	PCM: Partially confined meandering	*Forsyth*
C11	18.3	Rosebud	PCM/I: Partially confined meandering/islands	To *Cartersville Bridge*
C12	16.2	Rosebud	PCM/I: Partially confined meandering/islands	*Rosebud*; numerous meander cutoffs
C13	10.8	Rosebud	PCM/I: Partially confined meandering/islands	Valley bottom crossover
C14	19.6	Rosebud Custer	PCM/I: Partially confined meandering/islands	Series of meander bends
C15	6.0	Custer	PCS: Partially confined straight	Very low riparian vegetation
C16	11.6	Custer	PCM/I: Partially confined meandering/islands	to *Miles City*
C17	7.2	Custer	PCS: Partially confined straight	*Miles City; Tongue River*
C18	5.2	Custer	PCS: Partially confined straight	Channel follows left valley wall

Table A- 1. Summary of reach types and geographic location

Reach Identification	*Length (km)*	*County*	*Classification*	*Comments*
C19	17.9	Custer	CS: Confined straight	Confined
C20	12.2	Custer Prairie	CS: Confined straight	Confined
C21	15.2	Custer Prairie	CM: Confined meandering	To *Powder River;* confined
D1	19.5	Prairie	CM: Confined meandering	To *Terry Bridge*; confined
D2	17.0	Prairie	CM: Confined meandering	To *Fallon, I-90 Bridge*; confined
D3	13.4	Prairie Dawson	PCS: Partially confined straight	Hugs right bank wall; into Dawson County
D4	17.7	Dawson	PCM/I: Partially confined meandering/islands	
D5	20.3	Dawson	PCA: Partially confined anabranching	Long secondary channels; to *Glendive*
D6	8.9	Dawson	PCM/I: Partially confined meandering/islands	*Glendive*
D7	12.3	Dawson	PCA: Partially confined anabranching	
D8	16.4	Dawson	PCA: Partially confined anabranching	To *Intake*
D9	5.6	Dawson	PCM/I: Partially confined meandering/islands	Downstream of *Intake*
D10	18.3	Dawson Wibaux Richland	PCA: Partially confined anabranching	Vegetated islands
D11	10.3	Richland	PCA: Partially confined anabranching	*Elk Island:* Very wide riparian; marked change in channel course since 1981 geologic map base
D12	21.9	Richland	PCA: Partially confined anabranching	Secondary channel on valley wall; Sinuous; long abandoned secondary channel
D13	13.8	Richland	PCM/I: Partially confined meandering/islands	
D14	23.1	Richland, McKenzie	PCM/I: Partially confined meandering/islands	Into *McKenzie County, North Dakota*: High sinuosity
D15	9.6	McKenzie	PCM/I: Partially confined meandering/islands	
D16	11.9	McKenzie	US/I: Unconfined straight/islands	*To mouth*: low sinuosity; alternate bars; vegetated islands

Appendix B. Channel Classification Scheme

Table B- 1. Channel classification

Type Abbrev.	*Classification*	*n*	*Slope (ft/ft)*	*Planform/ Sinuosity*	*Major Elements of Channel Form*
UA	Unconfined anabranching	12	<.0022	Mult. Channels	Primary thread with vegetated islands that typically exceed 3X average channel width
PCA	Partially confined anabranching	18	<.0023	Mult. Channels	Partial bedrock control; Primary thread with vegetated islands that exceed 3X average channel width
UB	Unconfined braided	6	<.0024	Mult. Channels	Primary thread with unvegetated gravel bars; Average braiding parameter generally >2 for entire reach
PCB	Partially confined braided	13	<.0022	Mult. Channels	Partial bedrock control; primary thread with gravel bars; Average braiding parameter generally >2
PCM	Partially confined meandering	4	<.0014	>1.2	Partial bedrock control; main channel thread with point bars; average braiding parameter <2
PCS	Partially confined straight	11	<.0020	<1.3	Partial bedrock control; low sinuosity channel along valley wall
PCM/I	Partially confined meandering/islands	11	<.0007	Mult. Channels	Partial bedrock control; sinuous main thread with stable, vegetated bars
CS	Confined straight	5	<.0001	<1.2	Bedrock confinement; low sinuosity
CM	Confined meandering	7	<.0008	<1.5	Bedrock confinement; sinuous; uniform width; small point bars
US/I	Unconfined straight/islands	1	<.0003	<1.2	Low sinuosity with vegetated bars

Appendix C. Channel Migration Measurement Results

Figure C- 1. Statistical results for migration distances measured for Park County.

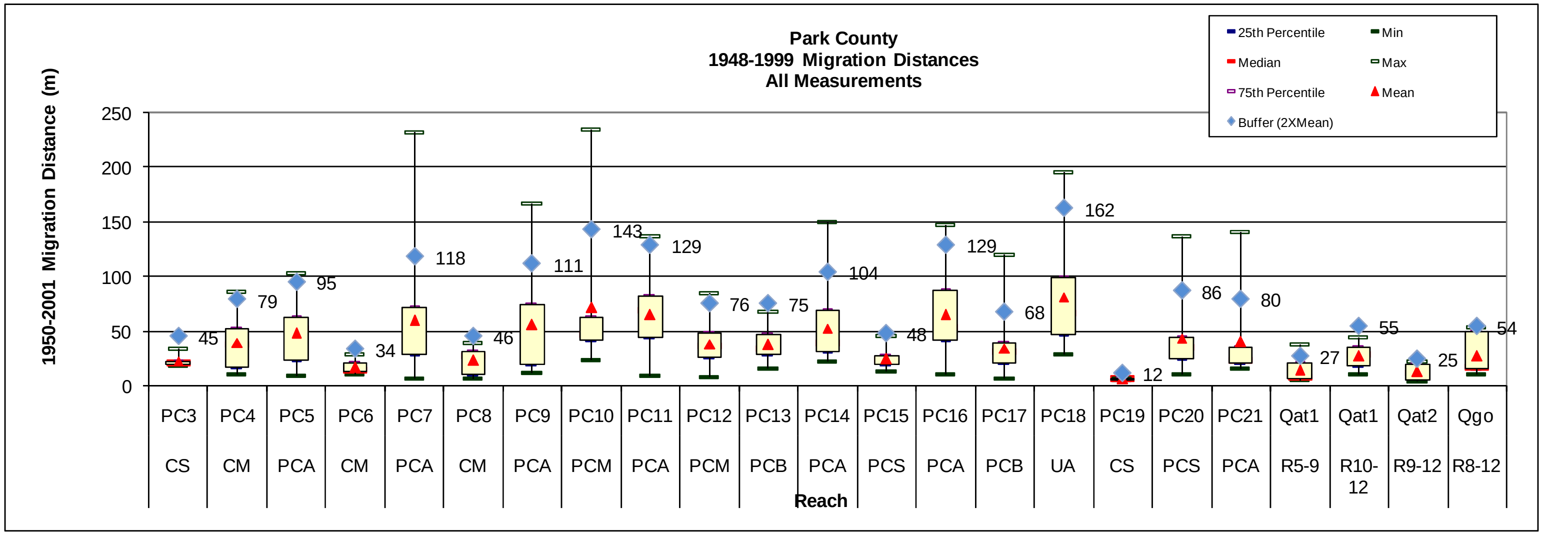


Figure C- 2. Statistical results for migration distances measured for Region A (Springdale to Clark Fork River Confluence).

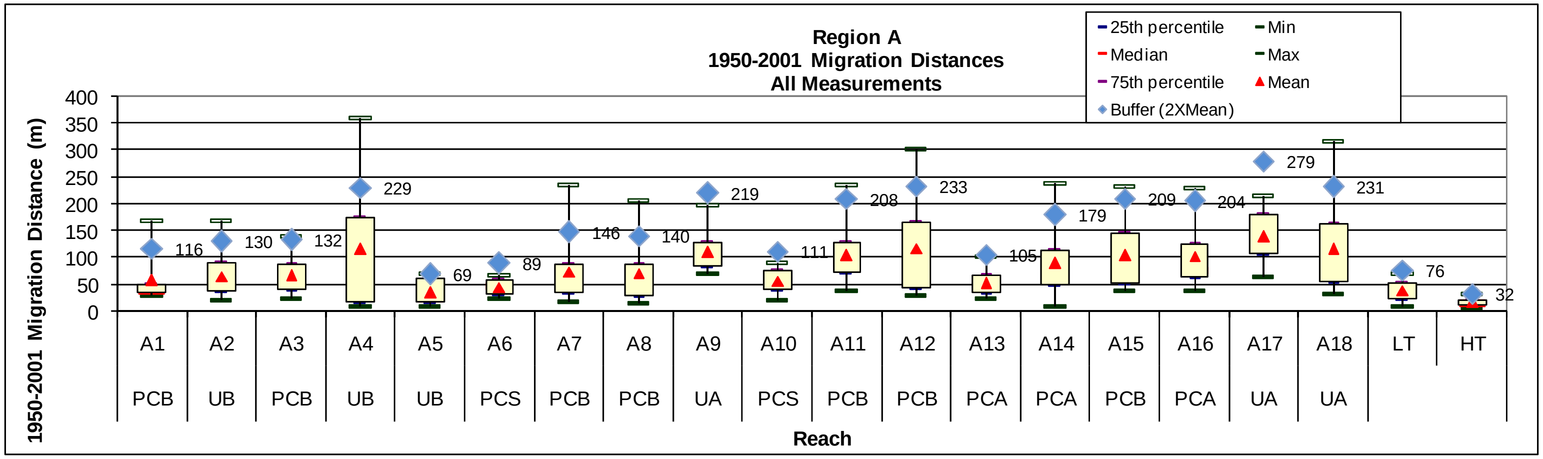


Figure C- 3. Statistical results for migration distances measured for Region B (Clark Fork River Confluence to Big Horn River Confluence).

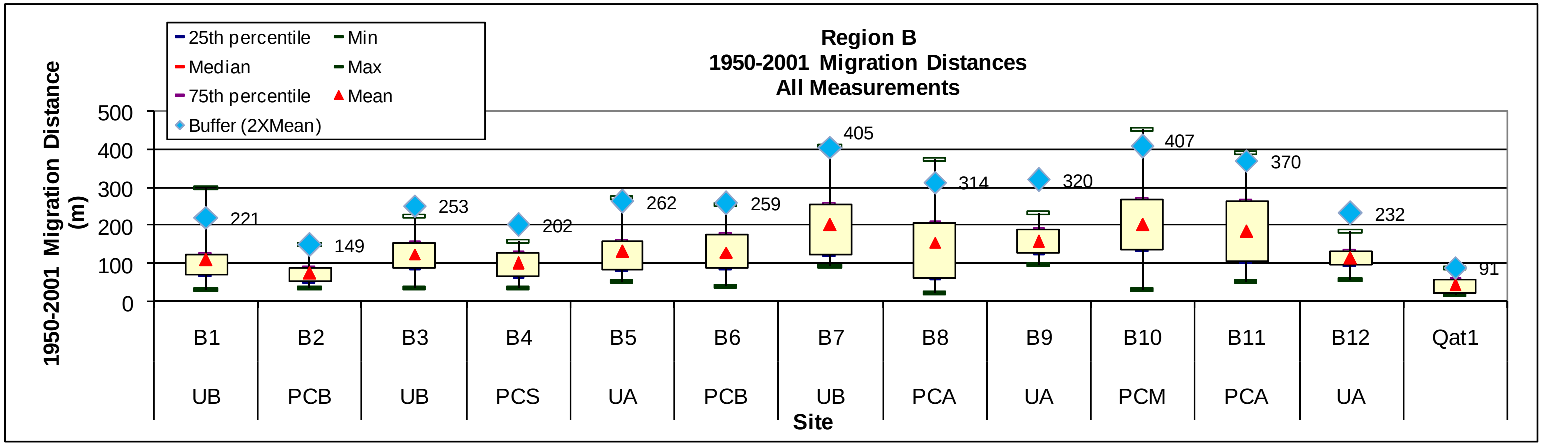


Figure C- 4. Statistical results for migration distances measured for Region C (Big Horn River Confluence to Tongue River Confluence).

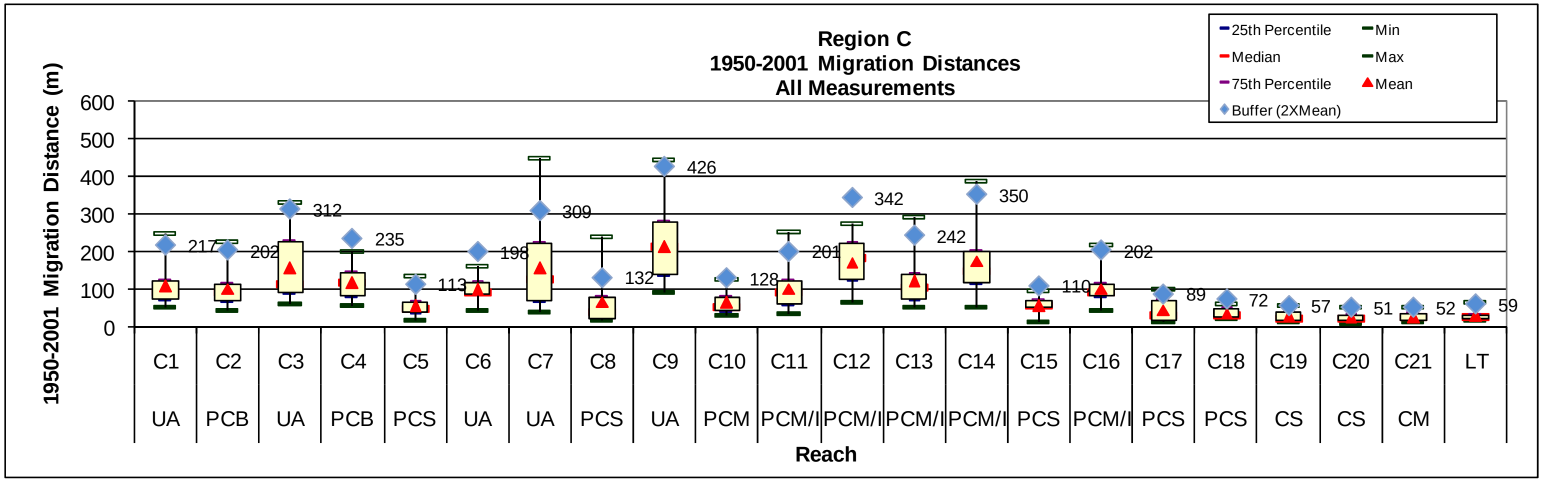
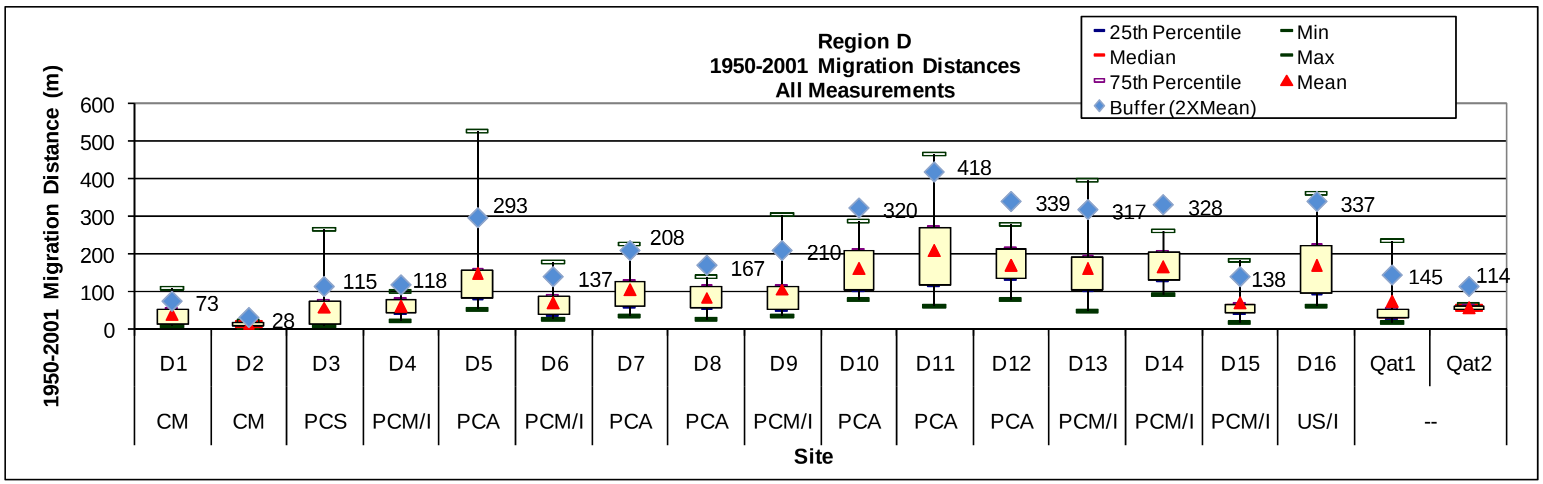


Figure C- 5. Statistical results for migration distances measured for Region D (Tongue River Confluence to Missouri River Confluence).



Appendix D. Erosion Buffer Values

Table D- 1. Erosion buffers applied to banklines

Reach	Mean Migration Distance: 50 year timeframe (meters)	Erosion Buffer (meters)	Erosion Buffer (ft)
Park County			
PC3	23	45	148
PC4	39	79	258
PC5	48	95	313
PC6	17	34	110
PC7	59	118	388
PC8	23	46	150
PC9	56	111	365
PC10	72	143	469
PC11	64	129	422
PC12	38	76	249
PC13	38	75	246
PC14	52	104	342
PC15	24	48	158
PC16	65	129	423
PC17	34	68	223
PC18	81	162	532
PC19	6	12	38
PC20	43	86	284
PC21	40	80	261
LT (PC5-PC9)	14	27	89
LT (PC10-PC12)	27	55	179
HT (PC9-PC12)	12	25	82
Qgo (PC8-PC12)	27	54	179
Region A: Springdale To Clark's Fork River			
A1	58	116	379
A2	65	130	425
A3	66	132	435
A4	115	229	753
A5	34	69	225
A6	45	89	292
A7	73	146	481
A8	70	140	458
A9	110	219	720
A10	56	111	365
A11	104	208	684
A12	116	233	763
A13	52	105	343
A14	89	179	587
A15	105	209	686
A16	102	204	671
A17	139	279	914

Reach	Mean Migration Distance: 50 year timeframe (meters)	Erosion Buffer (meters)	Erosion Buffer (ft)
A18	116	231	759
LT(A)*	38	76	250
HT(A)*	16	32	105
Region B: Clark's Fork River Confluence to Big Horn River Confluence			
B1	110	221	724
B2	75	149	490
B3	127	253	830
B4	101	202	663
B5	131	262	860
B6	130	259	850
B7	203	405	1330
B8	157	314	1031
B9	160	320	1049
B10	204	407	1336
B11	185	370	1214
B12	116	232	761
LT(B)*	45	91	298
Region C: Big Horn River Confluence to Powder River Confluence			
C1	108	217	711
C2	101	202	663
C3	156	312	1024
C4	118	235	772
C5	57	113	371
C6	99	198	651
C7	154	309	1012
C8	66	132	433
C9	213	426	1398
C10	64	128	420
C11	101	201	661
C12	171	342	1124
C13	121	242	793
C14	175	350	1150
C15	55	110	360
C16	101	202	663
C17	44	89	291
C18	36	72	236
C19	28	57	186
C20	25	51	166
C21	26	52	169
LT(C)*	29	59	193
Region D: Powder River Confluence to Mouth			
D1	37	73	241
D2	14	28	92
D3	57	115	376
D4	59	118	388
D5	147	293	962

Reach	Mean Migration Distance: 50 year timeframe (meters)	Erosion Buffer (meters)	Erosion Buffer (ft)
D6	69	137	451
D7	104	208	682
D8	84	167	549
D9	105	210	688
D10	160	320	1051
D11	209	418	1371
D12	170	339	1113
D13	159	317	1042
D14	164	328	1077
D15	69	138	452
D16	168	337	1106
LT(D)*	72	145	475
HT(D)*	57	114	373

* Erosion Buffers for the terraces were grouped for each region due to the low number of sites with terrace boundaries in each reach.