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Madison River
Channel Migration Mapping

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Abstract

This report contains the results of a Channel Migration Zone (CMZ) mapping effort for approximately 62 miles of the Madison River from Varney Bridge south of Ennis to its confluence with the Jefferson River near Three Forks, Montana. This is a part of a larger effort to map approximately 440 miles of rivers in the Missouri River headwaters watershed. In the upper project area, the river flows through the middle Madison Valley which contains extensive glacial terraces and local bedrock exposures in the bed and banks of the river. Between Varney Bridge and Ennis Lake the river is typically multi-thread, with numerous islands and active channel movement. The floodplain is broad and low, and relic channel features are common. Some avulsion risks have been identified where spring creeks parallel the main river; one historic avulsion into a spring creek was mapped south of Ennis. Mean migration rates are typically on the order of one foot per year where the river is reworking alluvial sediments. Ice jams are common, posing additional hazards. As the river approaches Ennis Lake it flows through a broad anastomosing channel pattern through a delta, where avulsions have been mapped and are likely to continue to occur. Leaving Ennis Lake, the river flows through several miles of crystalline basement rock of Bear Trap Canyon where migration rates are very low and limited to small areas where river deposits are stored in the canyon floor. Below Warm Springs Fishing Access, the river flows through fairly erosion resistant terraces before entering another dynamic reach that extends to Headwaters State Park and the confluence with the Jefferson River. The CMZ is typically broad in this lower section although it is confined by levees and bank armor along much of its length. Locally, the levees and transportation infrastructure create distinct CMZ pinch points, which has been associated with a higher density of bank armoring than more unconfined areas. There is little residential development within the CMZ on the Madison River, and in most reaches the extent of bank armor is currently fairly limited, indicating a strong allowance for natural river processes that have resulted in active bank migration, riparian recruitment, and habitat rejuvenation. Although physical features only locally impede channel movement, the flow regime has been altered at Hebgen Lake which has likely dampened migration rates throughout the whole system to some extent. Mean bankline migration rates range from less than one foot per year in confined reaches to over three feet per year upstream of Three Forks.

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Glossary and Abbreviations

Alluvial – Relating to unconsolidated sediments and other materials that have been transported, deposited, reworked, or modified by flowing water.

Avulsion – The rapid abandonment of a river channel and formation of a new channel. Avulsions typically occur when floodwaters flow across a floodplain surface at a steeper grade than the main channel, carving a new channel along that steeper, higher energy path. As such, avulsions typically occur during floods. Meander cutoffs are one form of avulsion, as are longer channel relocations that may be miles long.

Bankfull Discharge - The discharge corresponding to the stage at which flow is contained within the limits of the river channel, and does not spill out onto the floodplain. Bankfull discharge is typically between the 1.5- and 2-year flood event, and in the Northern Rockies it tends to occur during spring runoff.

CD – Conservation District.

Channel Migration – The process of a river or stream moving laterally (side to side) across its floodplain. Channel migration is a natural riverine process that is critical for floodplain turnover and regeneration of riparian vegetation on newly created bar deposits such as point bars. Migration rates can vary greatly though time and between different river systems; rates are driven by factors such as flows, bank materials, geology, riparian vegetation density, and channel slope.

Channel Migration Zone (CMZ) – A delineated river corridor that is anticipated to accommodate natural channel migration rates over a given period of time. The CMZ typically accommodates both channel migration and areas prone to avulsion. The result is a mapped "footprint" that defines the natural river corridor that would be active over some time frame, which is commonly 100 years.

DNRC – Department of Natural Resources and Conservation.

Erosion Buffer—The distance beyond an active streambank where a river is likely to erode based on historic rates of movement.

Erosion Hazard Area (EHA)– Area of the CMZ generated by applying the erosion buffer width to the active channel bankline.

Flood frequency – The statistical probability that a flood of a certain magnitude for a given river will occur in any given year. A 1% flood frequency event has a 1% chance of happening in any given year, and is commonly referred to as the 100-year flood.

Floodplain- An area of low-lying ground adjacent to a river, formed mainly of river sediments and subject to flooding.

Fluvial – Stream-related processes, from the Latin word fluvius = river.

Geomorphology - The study of landforms on the Earth's surface, and the processes that create those landforms. "Fluvial Geomorphology" refers more specifically to how river processes shape the Earth's surface.

GIS – Geographic Information System: A system of hardware and software used for storage, retrieval, mapping, and analysis of geographic data.

Historic Migration Zone (HMZ) – The historic channel footprint that forms the core of the Channel Migration Zone (CMZ). The HMZ is defined by mapped historic channel locations, typically using historic air photos and maps.

Hydrology – The study of properties, movement, distribution, and effects of water on the Earth's surface.

Hydraulics – The study of the physical and mechanical properties of flowing liquids (primarily water). This includes elements such as the depth, velocity, and erosive power of moving water.

Large Woody Debris (LWD) – Large pieces of wood that fall into streams, typically trees that are undermined on banks. LWD can influence the flow patterns and the shape of stream channels, and is an important component of fish habitat.

Management Corridor – A mapped stream corridor that integrates CMZ mapping and land use into a practical corridor for river management and outreach.

Meander - One of a series of regular freely developing sinuous curves, bends, loops, turns, or windings in the course of a stream.

Morphology - Of or pertaining to shape.

NAIP – National Agriculture Imagery Program – A United States Department of Agriculture program that acquires aerial imagery during the agricultural growing seasons in the continental U.S.

Planform - The configuration of a river channel system as viewed from above, such as on a map.

RDGP - Reclamation and Development Grants Program, DNRC.

Restricted Migration Area (RMA) – Those areas of the CMZ that are isolated from active river migration due to bank armor or other infrastructure.

Return Interval- The likely time interval between floods of a given magnitude. This can be misleading, however, as the flood with a 100-year return interval simply has a 1% chance of occurring in any given year.

Riparian – Of, relating to or situated on the banks of a river. Riparian zones are the interface between land and a river or stream. The word is derived from Latin ripa, meaning river bank. Plant habitats and communities along stream banks are called riparian vegetation, and these vegetation strips are important ecological zones due to their habitat biodiversity and influence on aquatic systems.

Riprap – A type of bank armor made up of rocks placed on a streambank to stop bank erosion. Riprap may be composed of quarried rock, river cobble, or manmade rubble such as concrete slabs.

Sinuosity - The length of a channel relative to its valley length. Sinuosity is calculated as the ratio of channel length to valley length; for example, a straight channel has a sinuosity of 1, whereas a highly tortuous channel may have a sinuosity of over 2.0. Sinuosity can change through time as rivers migrate laterally and occasionally avulse into new channels. Stream channelization results in a rapid reduction in sinuosity.

Stream competency - The ability of a stream to mobilize its sediment load which is proportional to flow velocity.

Terrace – On river systems, terraces form elongated surfaces that flank the sides of floodplains. They represent historic floodplain surfaces that have become perched due to stream downcutting. River terraces are typically elevated above the 100-year flood stage, which distinguishes them from active floodplain areas.

Wetland – Land areas that are either seasonally or permanently saturated with water, which gives them characteristics of a distinct ecosystem.

1 Introduction

The Madison River Channel Migration Zone (CMZ) mapping project developed approximately 62 miles of CMZ mapping for the Madison River from Varney Bridge, downstream to its confluence with the Jefferson River in Three Forks. It is part of a larger effort to map approximately 440 miles of river in the Upper Missouri River headwaters. Other rivers in the study include the Beaverhead, Jefferson, Gallatin and East Gallatin Rivers, revising the 2005 Big Hole River mapping (Wisdom to Twin Bridges), as well as updating mapping in the Ruby River Valley to include Clear Creek. The main stem of the Ruby River from Ruby Reservoir to Twin Bridges was mapped in 2010 and the Big Hole River in 2005. In total, approximately 493 miles of river in the Missouri River headwaters will have CMZ mapping. Other rivers in Montana that have CMZ significant areas of mapping include the Yellowstone River, sections of the Flathead, Clark Fork, and Bitterroot Rivers, Deep Creek (Broadwater County), and Prickly Pear and Tenmile Creeks (Lewis and Clark County).

The work is being funded through a 2013 Montana Department of Natural Resources and Conservation (DNRC) Reclamation and Development Grants Program (RDGP) titled *Upper Missouri Headwaters River/Flood Hazard Map Development*. The project is administered by the Ruby Valley Conservation District, but includes input and review from stakeholders associated with each of the mapped rivers.

1.1 The Project Team

This project work was performed Tony Thatcher of DTM Consulting and by Karin Boyd of Applied Geomorphology, with support from Chris Boyer of Kestrel Aerial Services (Kestrel). Over the past decade, we have been collaborating to develop CMZ maps for numerous rivers in Montana, in an attempt to provide rational and scientifically sound tools for river management. It is our overall goal to facilitate the understanding of rivers regarding the risks they pose to infrastructure, so that those risks can be managed and hopefully avoided. Furthermore, we hope to stress the economic and ecological benefits of managing rivers as dynamic, deformable systems that provide resilience to flooding and ecological sustainability, while reducing capital costs of poorly conceived engineered solutions.

1.2 What is Channel Migration Zone Mapping?

The goal of Channel Migration Zone (CMZ) mapping is to provide a cost-effective and scientifically-based tool to assist land managers, property owners, and other stakeholders in making sound land use decisions along river corridors. Typically, projects constructed in stream environments such as bank stabilization, homes and outbuildings, access roads, pivots, and diversion structures are built without a full consideration of site conditions related to river process and associated risk. As a result, projects commonly require unanticipated and costly maintenance or modification to accommodate river dynamics. CMZ mapping is therefore intended to identify those areas of risk, to reduce the risk of project failure while minimizing the impacts of development on natural river process and associated ecological function. The mapping is also intended to provide an educational tool to show historic stream channel locations and rates of movement in any given area.

CMZ mapping is based on the understanding that rivers are dynamic and move laterally across their floodplains through time. As such, over a given timeframe, rivers occupy a corridor area whose width is dependent on rates of channel shift. The processes associated with channel movement include lateral channel migration and more rapid channel avulsion (Figure 1).

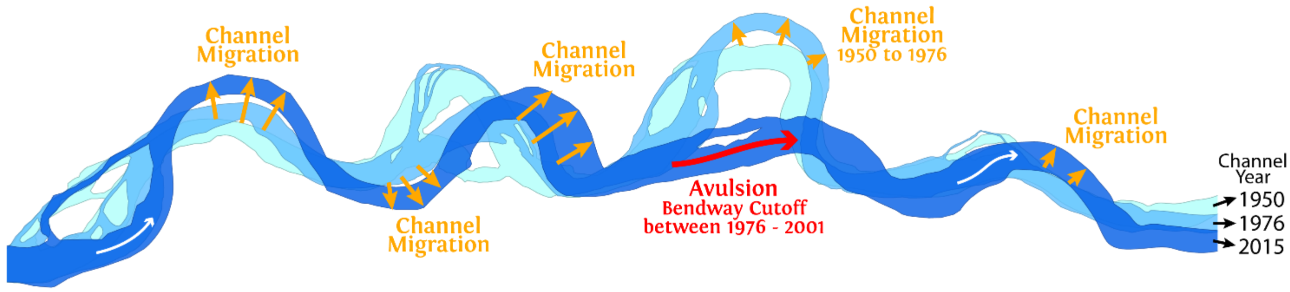

Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

The fundamental approach to CMZ mapping is to identify the corridor area that a stream channel or series of stream channels can be expected to occupy over a given timeframe – typically 100 years. This is defined by first mapping historic channel locations to define the Historic Migration Zone, or HMZ (Figure 1). Using those mapped banklines, migration distances are measured between suites of air photos, which allows the calculation of migration rate (feet per year) at any site. Average annual migration rates are calculated on a reach scale and extended to the life of the CMZ, which in this case is 100 years. This 100-year mean migration distance defines the Erosion Buffer, which is added to the modern bankline to define the Erosion Hazard Area, or EHA.

Channel migration rates are affected by local geomorphic conditions such as geology, channel type, stream size, flow patterns, slope, bank materials, and land use. For example, an unconfined meandering channel with high sediment loads would have higher migration rates than a geologically confined channel flowing through a bedrock canyon. To address this natural variability, the study area has been segmented into a series of reaches that are geomorphically similar and can be characterized by average migration rates. Reach breaks can be defined by changes in flow or sediment loads at tributary confluences, changes in geologic confinement, or changes in stream pattern. Reaches are typically on the order of five- to 10-miles-long. Within any given reach, dozens to hundreds of migration measurements may be collected.

Avulsion-prone areas are mapped where there is evidence of geomorphic conditions that are amenable to new channel formation on the floodplain. This would include meander cores prone to cutoff (Figure 1), historic side channels that may reactivate, and areas where the modern channel is perched above its floodplain.

The following map units collectively define a Channel Migration Zone (Rapp and Abbe, 2003):

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

The individual map units comprising the CMZ are as follows:

CMZ = HMZ + EHA + AHZ

The Restricted Migration Area (RMA) is commonly removed from the CMZ to show areas that are "no longer accessible" by the river (Rapp and Abbe, 2003). In our experience, the areas that have become restricted due to human activities provide insight as to the extent of encroachment into the CMZ, and highlight potential restoration sites. These areas may also actively erode in the event of common project failure such as bank armor flanking. For this reason, the areas of the natural CMZ that have become isolated are contained within the overall CMZ boundary and highlighted as "restricted" within the natural CMZ footprint.

Each map unit listed above is individually identified on the maps to show the basis for including any given area in the CMZ footprint (Figure 2).

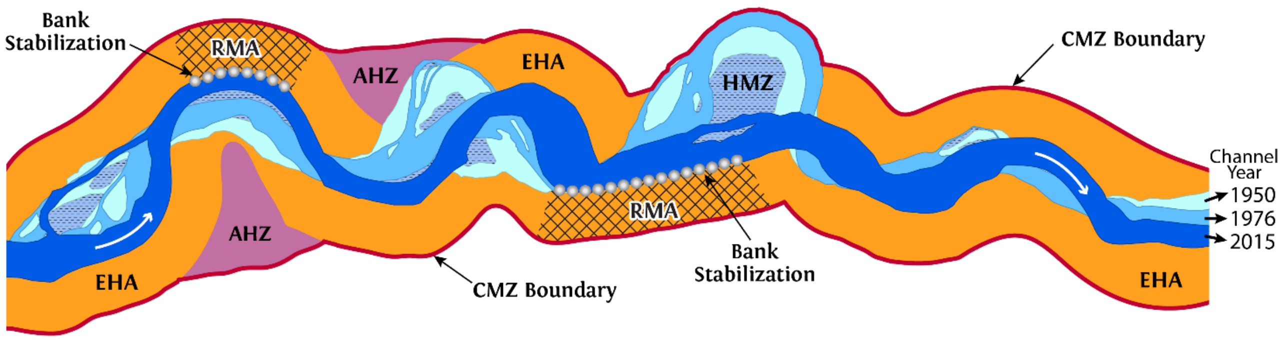

Figure 2. Channel Migration Zone mapping units.

1.3 CMZ Mapping on the Madison River

The Channel Migration Zone (CMZ) developed for Madison River extends 62 river miles from Varney Bridge approximately ten miles south of Ennis, MT to its confluence with the Jefferson River at Three Forks, MT. No CMZ mapping was developed for Ennis Lake.

Although the basic concept for Channel Migration Zone mapping efforts is largely the same throughout the country, different approaches to defining CMZ boundaries are used depending on specific needs and situations. These differences in assessment techniques can be driven by the channel type, different project scales, the type and quality of supporting information, the intended use of the mapping, etc. For this study, the CMZ is defined as a composite area made up of the existing channel, the collective footprint of mapped historic channel locations shown in the 1955, 1979, 2013, and 2015 imagery (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA), that is based on reach-scale average migration rates. Areas beyond the Erosion Buffer that pose risks of channel avulsion are identified as Avulsion Hazard Areas or AHZ. This approach generally falls into the minimum standards of practice for Reach Scale, Moderate to High Level of Effort mapping studies as defined by the Washington State Department of Ecology (www.ecy.wa.gov). This approach does not, however include a geotechnical setback on hillslopes; these areas would require a more site-specific analysis than that presented here.

1.4 Uncertainty

The adoption of a 100-year period to define the migration corridor on a dynamic stream channel requires the acceptance of a certain amount of uncertainty regarding those discrete corridor boundaries. FEMA (1999) noted the following with respect to predicting channel migration:

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

The upper Madison River shows historic patterns of lateral migration and avulsion, locally within a very broad floodplain surface that has dense networks of historic channels. Downstream of Ennis Lake, the river flows through a narrow bedrock canyon where migration is geologically impeded, before flowing into a dynamic corridor north of Greycliff and to Headwaters State Park. With potential contributing factors, such as woody debris jamming, sediment slugs, tectonic deformation, landslides, or ice jams, dramatic change could potentially occur virtually anywhere on the floodplain. As the goal of this mapping effort is to highlight those areas most prone to either migration or avulsion based on specific criteria, there is clearly the potential for changes in the river corridor that do not meet those criteria and thus are not predicted as high risk.

Uncertainty also stems from the general paradigm that "the past is the key to the future". As predicted future migration is based on an assessment of historic channel behavior, the drivers of channel migration over the past 50 years are assumed to be relatively consistent over the next century. If conditions change significantly, uncertainty regarding the proposed boundaries will increase. These conditions include system hydrology, sediment delivery rates, climate, valley morphology, riparian vegetation densities and extents, and channel stability. Bank armor and floodplain modifications, such as bridges, dikes, levees, or sand and gravel mining could also affect map boundaries.

1.5 Relative Levels of Risk

The natural processes of streambank migration and channel avulsion both create risk to properties within stream corridors. Although the site-specific probability of any area experiencing either migration or an avulsion during the next century has not been quantified, the characteristics of each type of channel movement allows some relative comparison of the type and magnitude of their risk. In general, the Erosion Hazard Area delineates areas that have a demonstrable risk of channel occupation due to channel migration over the next 100 years. Such bank erosion can occur across a wide range of flows, and the risk of erosion into this map unit is relatively high. In contrast, avulsions tend to be a flood-driven process; the Avulsion Hazard Area delineates areas where conditions may support an avulsion, although the likelihood of such an event is highly variable between sites and typically depends on floods. Large, long duration floods have the potential to drive extensive avulsions, even after decades of no such events. During the spring of 2011, for example, the Musselshell River flood drove 59 avulsions in three weeks, carving 9 miles of new channel while abandoning about 37 miles of old river channel (Boyd et al, 2012).

1.6 Other River Hazards

The CMZ maps identify areas where river erosion can be expected to occur over the next century. It is important to note that river erosion is only one of a series of hazards associated with river corridors.

1.6.1 Flooding

The CMZ maps do not delineate areas prone to flooding. The difference between mapped flood boundaries and CMZ boundaries can be substantial. In cases where the floodplain is broad and low, the CMZ tends to be narrower than the flood corridor (left schematic on Figure 3). In contrast, where erodible terrace units bound the river corridor, the CMZ is commonly wider than the floodplain, because the terraces may be high enough to prevent flooding, but not immune to erosion (right schematic on Figure 3). This is a common problem in Montana because of the extent of high glacial terraces that are above base flood elevations, but not erosion-resistant.

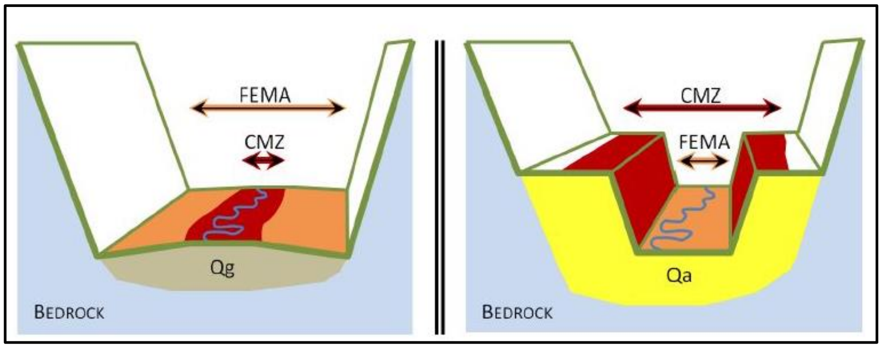

Figure 3. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

Figure 4 shows a property on the Yellowstone River in Park County that was progressively undermined during the 1996-1997 floods, prompting the owner to burn it down to prevent any liability associated with the structure falling into the river. This has been a chronic problem in river management, as landowners assume that if their home is beyond the mapped floodplain margin, it is removed from all river hazards. After experiencing massive 2005 flood damages in Saint George Utah (Figure 5), several property owners reflected on this issue (www.Utahfloodrelief.com):

> *"We knew the river was there. We were 3 feet above the 100-year flood plain and made sure we were well above the flood plain. It was surveyed and the engineers told us where we had to put it and no, we don't have flood insurance or any kind of insurance that is going to reimburse us for anything."*

> *"Our property was not located within the 500-year flood plain or was it adjacent to it. The river simply took a new route that went right through our property."*

> *"I knew we were in big trouble. The river was raging and making a sharp "S" turn right behind our home. Our property seemed to take the full force of the river turning against the bank. Large chunks of earth were being swallowed up into the river. We watched 20 feet erode in less than two hours. We knew if it continued at that pace, we'd lose our house. Our contractor contacted an excavation company early that morning, but they said there was nothing they could do for us. We were also informed that our contractor's insurance was not covered for floods."*

Figure 4. Yellowstone River home on high glacial terrace that was burned down in 1997 to prevent its undermining by the river.

Figure 5. Photos from a 2005 in Saint George Utah, where homes several feet above the mapped floodplain were destroyed by channel migration (www.Utahfloodrelief.com).

1.6.2 Ice Jams

Another serious river hazard, especially in Montana, is ice jamming. Over 1,470 ice jams have been recorded in Montana, which is the most of any of the lower 48 states (http://dphhs.mt.gov/). The ice jams are most common in February and March. The National Weather Service has identified the Madison River as having 17 reported ice jams (Figure 6). Ice jamming and gorging plays an important role on the river, especially from Ennis to Ennis Lake (Figure 7) and at Three Forks. Gorging refers to the formation of huge ice jams that can cause serious flooding. It happens when ice forms, and large chunks break loose, growing into larger slabs with more freezing. The slabs accumulate to form dams which cause flooding upstream. On rivers like the Madison, ice gorging can be especially problematic due to the low bank heights and shallow river conditions. According to the Bureau of Land Management (BLM 2009):

> *The Madison River is subject to ice gorging which causes flooding by raising the water level. Ice gorging typically occurs during the coldest part of the winter where streams are too turbulent to form crystalline ice. Instead, frazil ice, a slushy ice composed of loose ice crystals, and anchor ice, form. The gorging scours the vegetation along the banks, moves soil and rocks, and changes the character of the stream banks along these areas. Hebgen Reservoir has mitigated ice gorging…*

Ice jams can cause avulsions by entirely blocking channels and forcing flows onto the floodplain.

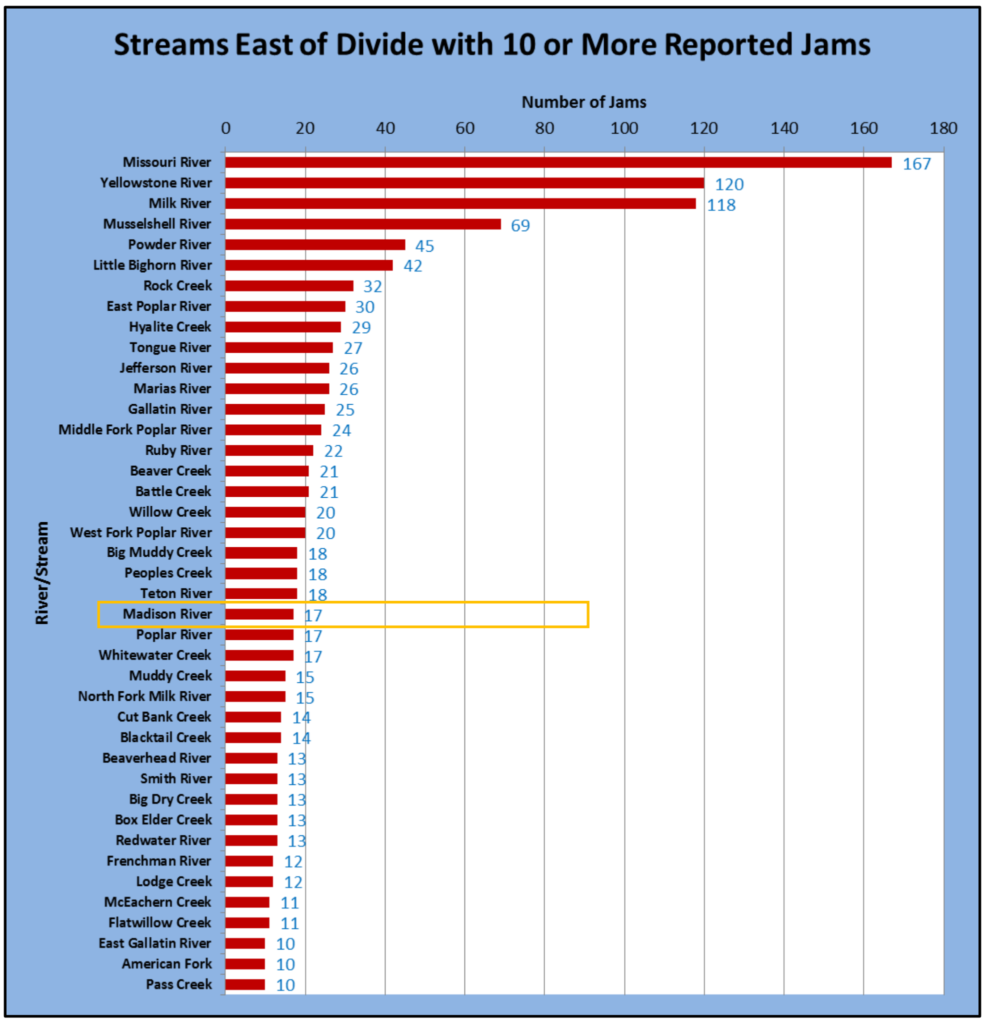

Figure 6. Montana rivers east of the continental divide with 10 or more reported ice jams.

Figure 7. Ice gorging in Ennis on January 28, 2007 (T. Thatcher).

1.6.3 Landslides

There are no mapped landslides on the valley walls of the Madison River in the project area. Upstream, however, the Quake Lake Slide formed a Landslide Dam on the Madison which still exists (Section 2.2.1). The 1959 Quake Lake slide created a lake that is 6 miles long and 190 feet deep. Landslides have the potential to create river hazards by blocking the channel and potentially diverting or impounding flow. Figure 8 shows an example of a relatively small landslide that occurred in February 2014 on the south wall of the Nooksack River Valley near Bellingham, Washington. The landslide originally blocked the channel, and the effect was seen at a gaging station downstream where river flows rapidly dropped from over 2,000 cubic feet per second to about 400 cubic feet per second in the early morning hours of February 21 (Figure 9). The river breached the landslide and flows returned to normal, however in some cases impacts have been much worse. Probably the most recently renown landslide into a river system was the 2014 Oso Slide into the North Fork of the Stillaguamish River, which dammed the river causing extensive flooding upstream (Figure 10).

Figure 8. Hillslope failure on Nooksack River near Bellingham Washington on February 21, 2014 (K. Boyd).

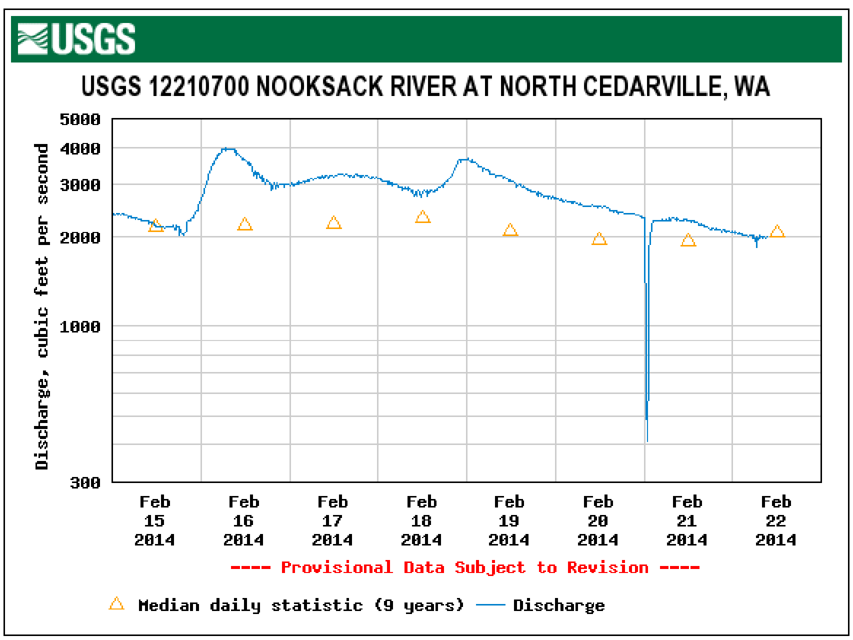

Figure 9. USGS gage data showing rapid drop in river flow following upstream hillslope failure.

Figure 10. Massive mudslide in Oso Washington on March 22, 2014, deflecting the North Fork of the Stilliguamish River (AP Photo/Ted Warren).

1.7 Potential Applications of the CMZ Maps

The CMZ mapping developed for the Madison River is intended to support a myriad of applications and was not developed with the explicit intent of either providing regulatory boundaries or overriding site-specific assessments. Any use of the maps as a regulatory tool should include a careful review of the mapping criteria to ensure that the approach used is appropriate for that application.

Potential applications for the CMZ maps include the following:

- Identify specific problem areas where migration rates are notably high and/or infrastructure is threatened;
- Strategically place new infrastructure to avoid costly maintenance or loss of capital;
- Strategically place new infrastructure to minimize impacts on channel process and associated ecological function;
- Assist in the development of river corridor best management practices;
- Improve stakeholder understanding of the risks and benefits of channel movement;
- Identify areas where channel migration easements may be appropriate;
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor;
- Help communities and developers integrate dynamic river corridors into land use planning; and,
- Assist long-term residents in conveying their experiences of river process and associated risk to newcomers.

1.8 Disclaimer and Limitations

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

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

1.9 Image Licensing and Use Restrictions

Many of the oblique color photographs taken by plane presented in this document and included on the associated project DVD were taken by Kestrel Aerial Services (Kestrel) and are subject to use restrictions. Kestrel grants that these photos can be used as follows:

For use as river and floodplain documentary imagery in efforts related to this study by project partners.

For uses outside these stated rights, contact Kestrel Aerial Services, Inc. (406) 580-1946.

1.10 Acknowledgements.

We would like to extend our gratitude to Rebecca Ramsey of Ruby Watershed Council and Shirley Galovic of Ruby Conservation District for their assistance in contract management and scheduling. The following individuals provided input and review while developing the mapping and report: Sunni Heikes-Knapton (Madison Watershed Coordinator), Charity Fechter (Madison County Planning Director), Liz Davis (Madison River Foundation), Ethan Kunard (Madison CD Water Programs Manager), and Tiffany Lyden (DNRC Floodplain

Program). We also acknowledge the professionalism and talent of Chris Boyer of Kestrel Aerial Services (Kestrel), in obtaining oblique aerial photography that provides a perspective of the river that can't be made with conventional air photos. We look forward to receiving comments on this draft report, and those contributors will be acknowledged accordingly.

2 Physical Setting

The following section contains a general description of the geographic, hydrologic, and geologic influences on the Madison River, to characterize the general setting and highlight how that setting may affect river process.

2.1 Geography

The Madison River in southwest Montana is one of three tributary rivers that form the Missouri River, along with the Gallatin and Jefferson Rivers (Figure 11). It is approximately 183 miles long with a watershed area of 2,556 square miles, or 18% of the total area of the Missouri Headwaters watershed. The Madison River forms as the confluence of the Gibbon and Firehole Rivers in Yellowstone National Park, Wyoming. The river was named in for the then U.S. Secretary of State James Madison by Meriwether Lewis in July 1805. The geography of the watershed is highly varied, with elevations ranging from over 11,000 feet in the Madison Range to approximately 4,400 feet at Three Forks. Similarly, the precipitation is highly varied with over 40 inches of annual precipitation in the high elevations, to just 12 inches in the lower reaches (BLM, 2009).

In Montana, the Madison River flows through Gallatin and Madison Counties. West Yellowstone, Ennis, and Three Forks are the largest communities, located on the upper, middle and lower river, respectively. According to a 2009 BLM Watershed Assessment (BLM 2009):

> *The MW [Madison Watershed] was explored by fur trappers as early as 1810 when Andrew Henry, of the Missouri Fur Company, traveled up the Madison River from the Three Forks area into the headwaters of the Snake River (Chittenden, 1902). Originally, the Madison Valley was settled in 1863 when William Ennis built a cabin while resting his cattle after hauling freight into Virginia City from Colorado. As settlers moved west, they quickly discovered the economic benefits that the Madison Valley offered, specifically in that of cattle, sheep, and horse ranching (Madison County History Association, 1976).*

The watershed’s diverse geographies support a variety of land uses, including: ranching, farming, recreational, and mining.

The Madison River is commonly broken up into Upper, Middle, and Lower segments. The upper section runs from the headwaters to Quake Lake. This section includes the manmade Hebgen Lake and Quake Lake, which was formed by a large landslide triggered during the 1959 earthquake. This landslide forms a natural dam at the mouth of the Madison River Canyon. The two lakes occupy a majority of the upper river valley. The middle section begins at the outlet of Quake Lake and runs downstream through the Madison Valley to Ennis Lake. This Blue Ribbon fishery is known as the “Fifty Mile Riffle.” The only significant tributaries entering the middle section of the Madison River are the West Fork of the Madison River entering near Lyons and Jack Creek near Ennis. The lower section of the river begins at the Madison Dam at the head of Bear Trap Canyon. Cherry Creek is the only significant tributary to the Madison in the lower section of the river, entering the river from the East near the Damselfly Fishing Access site. Below the Blacks Ford fishing access site, the river enters the Lower Madison Valley where it generally follows a bluff line that confines the river on the western side. Also, almost two thirds of the river in this section is confined on its eastern side by an 11-mile-long levee.

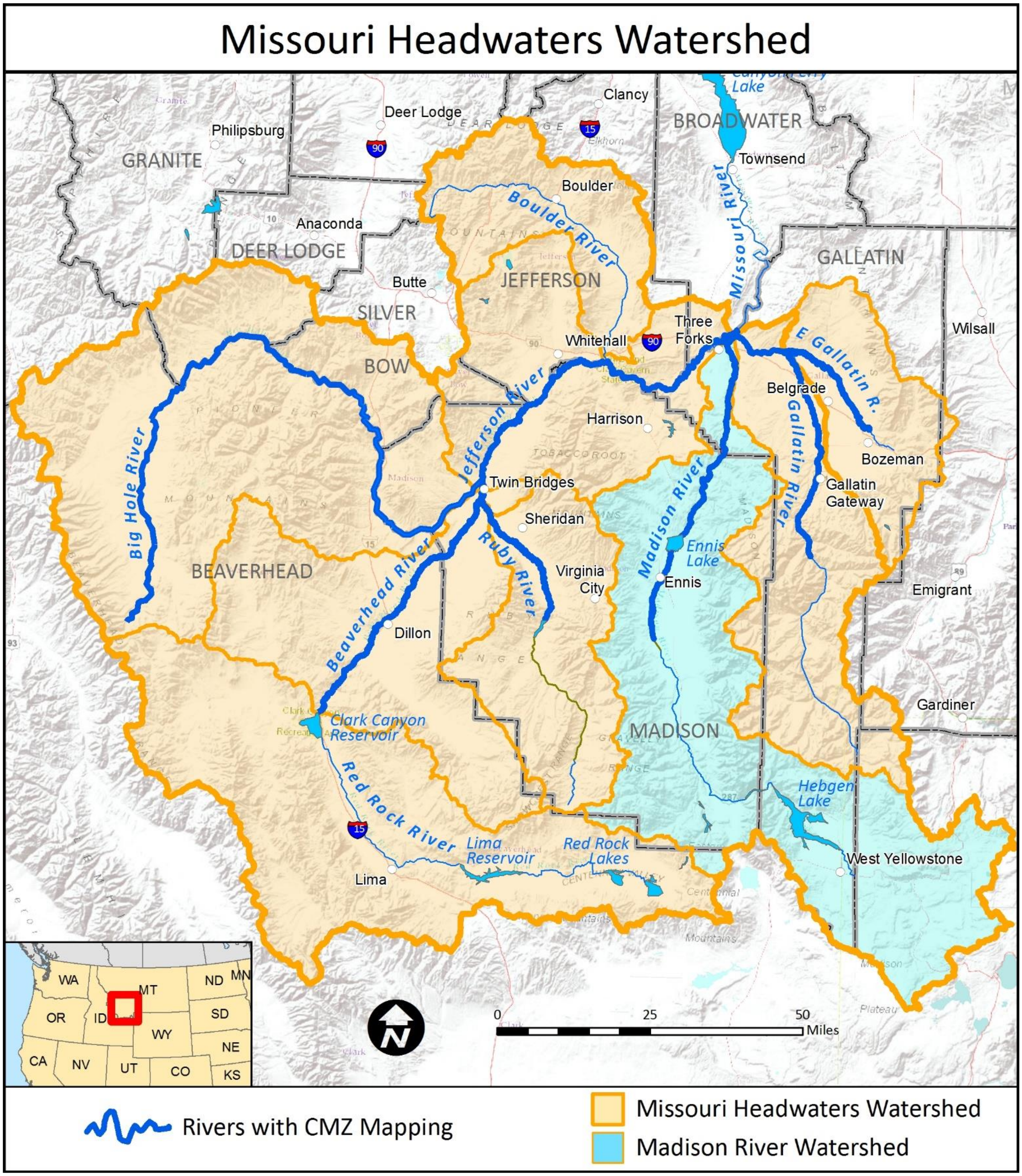

Figure 11. Madison River Watershed.

2.2 Geology and Glacial History

The following summary of the geological setting of the project reach is intended to provide some context as to how the physical setting influences river process. The geomorphology of the Madison River has been strongly impacted by tectonism and glaciation, both of which have affected channel slope, stream power, and bankline erodibility.

In general, the river valley transitions from narrow, forested headwaters river valleys that have been affected by intense natural disturbance, to a broad valley bounded by glacial outwash terraces and steep mountain fronts south of Ennis. The wide valley with alluvial fills and well developed floodplain terraces is typical of a Rosgen Valley Type VIII channel type (Rosgen, 1996). North of Ennis Lake the river enters a deep canyon comprised of extremely old (Archean) gneisses, which control base level for the river valley upstream. Over these 11 miles in Bear Trap Canyon the river shows only limited movement through the period of record. Below Bear Trap Canyon, the river emerges into a lower alluvial valley bottom once it flows out of the crystalline basement rocks. Between the mouth of Bear Trap Canyon and Three Forks, the river flows along bluffs of the Dunbar Creek Member of the Renova Formation (Vuke et al, 2014) onto a broad floodplain where it joins the Jefferson and Gallatin Rivers, forming the Missouri River.

The most recent glaciation of the Madison Range was during Pinedale glaciation about 15,000 to 12,000 years ago. Subsequent deglaciation drove downcutting and the most recent terrace formation along the river and its tributaries such as Jack Creek (Bearzi, 1987). The terraces of the Madison River Valley are glacial in origin, but their history is also related to uplift of the Norris Hills throughout Quaternary time which resulted in intermittent damming and repeated cycles of infilling and downcutting.

2.2.1 Upper Madison Valley (above Quake Lake)

Although the Upper Madison River is not part of the CMZ mapping effort, its geologic history is very active and worthy of note.

Probably the most spectacular geologic event to have occurred in Montana over the last century occurred in the upper Madison Valley on August 17, 1959. At 11:37 pm on that summer night, a magnitude 7.3 earthquake struck near Hebgen Lake under a full moon. The earthquake resulted in 28 fatalities and approximately $11 million in damages. The most dramatic impact was due to a massive landslide (Figure 12) coming off the slopes on the south side of the river approximately 7 miles below Hebgen dam. The Madison Slide impounded the Madison River, forming Quake Lake. Fault scarps as high as 20 feet developed along existing fault lines, while land movement and subsidence resulted in extensive damage to roads, structures, and timber (USGS, http://earthquake.usgs.gov).

The landslide was made up of about 37 million cubic yards of material that was up to 430 feet deep, blocking the Madison River to form Quake Lake. To prevent catastrophic flooding downstream, the Corps of Engineers (COE) excavated a spillway into the landslide deposits. Water first passed over the spillway on September 10, 1959, and the river immediately started downcutting into the spillway channel. The eroded material was transported down the Madison River. The erosion of the spillway caused much concern. Boulders as large as 100 tons (approximately 30-foot diameter) were placed in the channel as armor by the COE (Turner, 1995). Because of these concerns, in late September of 1959 the COE decided to lower the spillway by about 50 feet to reduce the storage in Quake Lake and associated threat of slide failure. The spillway lowering was completed in late October of 1959.

Turner (1995) suggested that aggradation downstream from the Madison Slide extended as far as Cameron. Fine sediment deposition in Ennis Lake has also been attributed to the slide.

In subsequent years, sediment reworking downstream of Quake lake resulted in erosion and property damage; in 1972, the COE performed a study recommending that the Hebgen Lake outflow upstream of Quake Lake be managed for a 3,500 cubic feet per second (cfs) threshold flow to prevent downcutting through the outlet. There have been recent evaluations as to whether that flow can be increased to benefit the fishery (Chase, 2012). The potential impacts of increased flows on sediment delivery to the project reach is unknown.

Figure 12. Massive landslide resulting from the August 17, 1959 earthquake. The slide dammed the Madison River below several miles below the Hebgen Dam, creating Quake Lake (USGS).

A study of the impacts of the Quake Lake Landslide on Madison River geomorphology was undertaken by Turner (1995) as a MS Thesis at Montana State University. The relevance of this study to Madison River CMZ mapping is that, in the event that accelerated sediment loads were delivered to the project reach, migration rates would be expected to increase. Turner concluded that the river has incised over 60 feet into the slide debris, and currently lies about 120 feet above its pre-slide level at the top of the slide. Downstream, the main locus of bedload deposition extends a couple of miles below the outlet of the lake, and the future limit of recognizable aggradation will continue for about 4 miles below the slide, which is well upstream of the project reach (Turner, 1995).

2.2.2 Middle Madison Valley (Quake Lake to of Ennis Lake)

The project reach starts at Varney Bridge which is in the Middle Madison Valley, about 36 miles downstream from Quake Lake. In this river section stretching from Quake Lake to Ennis Reservoir, the Middle Madison Valley is well-known for spectacular river terraces, pediments, and other erosional surfaces that reflect old valley floor elevations that are now perched above the river. Twelve terrace surfaces have been identified in the valley south of Ennis (Kellogg and Williams, 2000). Some of these terraces lie well above the modern river corridor; the Cameron Bench, for example, is about 250 feet above the modern Madison River floodplain. Alluvial fans also extend into the valley on the flanks of the Madison Range; the Cedar Creek alluvial fan has been described as one of the best examples of an alluvial fan in the world.

Whereas the Cameron Bench has been assigned a minimum age of about 75,000 years (Bearzi, 1987), the series of lower terraces of the middle Madison Valley have been assigned a Pinedale age by Lundstrom (1986), indicating the most recent glacial period, which ended about 11,700 years ago. The Pinedale glaciation represents the final episode of Pleistocene glaciation in North America; and deglaciation of the Madison Range was probably synchronous with much of the Rocky Mountains (Bearzi, 1987). The terraces formed when the Madison River had enough stream power to downcut into its old floodplain; this downcutting is likely due to a combination of increase flow due to glacial retreat and climate fluctuations, and a lowering of base level in Bear Trap Canyon due to tectonic activity (Bearzi, 1987).

2.2.3 Lower Madison Valley (Ennis Lake to Headwaters State Park)

Just below Ennis Lake, the Madison River flows into a deep bedrock canyon made up of Precambrian gneisses and schists that are 2.5 to 4 billion years old. This bedrock controls the base level for the Middle Madison River Valley, and its exposure was caused by uplift of the Norris Hills along the Spanish Peaks fault. Bearzi (1987) indicated that base level elevations for the Madison River have shifted with deformation on the Spanish Peaks Fault, and that a 4.5 earthquake in the area in 1987 indicates recent fault activity. Below Bear Trap Canyon, the river flows within older minimally erodible alluvial terraces before running against bluffs of Tertiary Dunbar Creek Formation, which consists of light gray tuffaceous siltstone and fine grained sandstone, for which the Greycliff fishing access is named. The bluffs form the west valley wall of the river corridor. About five miles south of Three Forks the river valley widens considerably, with an extensive swale network visible across the floodplain. The highway infrastructure tapers the river dramatically at the I-90 crossing before it broadens again, entering a mosaic of channels as the Jefferson River and Madison River floodplain coalesce at Headwaters State Park.

2.3 Hydrology and Flow Management

Although there are both constructed and natural impoundments on the Madison River, the hydrologic regime has a fair amount of variability and anticipated frequency for the 2- to 10- year flood discharges. That reflects a relatively minor influence of Hebgen dam, Quake Lake, and Madison Dam on those events. That said, there has not been any flow on the Madison equal to or exceeding a 25-year event since 1970, suggesting that larger floods may be more affected by the impoundments.

2.3.1 Hebgen Dam

Hebgen dam is located in the upper Madison River watershed approximately 16 miles north west of West Yellowstone, MT. It was built between 1914 and 1918 with the purpose of storing and regulating water for hydroelectric power and other downstream reservoirs. The dam is a concrete-core earthen structure, 85 feet tall and 721 feet long. It is currently owned and managed by NorthWestern Corporation. The dam creates Hebgen Lake, with a surface area of 21 square miles and of volume of 325,000 acre feet (Wikipedia).

In 1960 the reservoir was lowered to allow repairs after the earthquake. Damage included cracking of the core wall and the downstream embankment, which required extensive grouting and repairs. The spillway was completely replaced.

On Labor Day of 2008, several stoplogs at the intake structure failed, resulting in an uncontrolled flow release that lasted for a month. Over 3,000 cubic feet per second were released that fall when typical releases are about 1,000 cubic feet per second, but the release was ultimately controlled, and additional repairs became a priority. That release created an approximate 10-year flood event. In 2014 Hebgen Dam underwent a major rehabilitation project to upgrade the intake to meet modern seismic design standards.

As part of their Federal Energy Regulatory Commission (FERC) relicensing, proposed flow releases were not to exceed 3,500 cfs at Kirby Ranch to minimize erosion at the Quake Lake Outlet (FERC, 1997). According to FERC (1997), Hebgen Dam operations have minimally impacted the 2- and 5- year floods. Higher peak floods have been impacted more, but not enough to avoid the exceedance of 3,500 cfs at Quake Lake.

Figure 13. Hebgen Dam, Montana. (Google Earth).

2.3.2 Madison Dam

Madison Dam is a timber-crib structure constructed in 1906, replacing the original dam that was constructed in 1901. It is a run-of-the-river dam located at the head of Bear Trap Canyon, just north of Ennis, Montana. It is 35 feet high and 257 feet long, and the associated power plant has a generating capacity of nine megawatts. The dam and power plant are currently owned by NorthWestern Corporation. The dam creates Ennis Lake, a 27,200 acre-foot reservoir that covers 3,900 acres. As Madison Dam is a run-of-the-river structure, it does not appreciably impact the hydrology below the dam, though the shallow Ennis Lake does trap sediment and increase water temperatures (FERC, 1997). Several fish kills have occurred in the lower Madison coincidental with either a rapid increase in water temperature or long-term high temperatures. High arsenic concentrations in water and sediments in Ennis Lake have been identified as a water quality issue (FERC, 1997).

Figure 14. Madison Dam (Bozeman Daily Chronicle).

2.3.3 Major Diversion Structures

While there are no diversions into major canals on the Madison River, the Montana Department of Natural Resources and Conservation Water Rights data show 104 headgate points of diversion listed for the Madison River from Varney Bridge to the mouth. Above Ennis, a diversion that spans the Blain Spring Creek channel feeds the West Madison Canal (Figure 16). This is the only diversion structure in the Madison study area that spans a channel. The lower river, below the Madison Dam, has a number of local diversions that feed ditch systems including the Sloan, Hutchinson, Dell, Crowley and Darlington Ditches. Aerial photographs of these ditches are compiled in Appendix C. None of these structures appear to greatly impact the river processes.

Figure 15. Madison Dam on July 21, 2016 at the head of Bear Trap Canyon. (Kestrel)

Figure 16. The West Madison Canal diversion on the Blaine Spring Creek channel. (Kestrel)

2.3.4 Madison River Flood History

According to the Montana Fish Wildlife and Parks (No Date):

> *Flows in the Madison River are regulated by the two reservoirs. Hebgen Reservoir built in 1915 by the Montana Power Company, stores water for downstream power generation. Water storage usually occurs during the snow runoff period of mid-May through early June. Stored water is released to downstream reservoirs during the fall (October-December). Fall releases usually range from 1,500 to 2,200 cfs at Hebgen Dam. Ennis Reservoir, built in 1908 by a predecessor of the Montana Power Company, has a rather stable water level with little storage capacity of its own. Its primary function is to create a head for the power generating facility immediately below Ennis (Madison) Dam. Outflows from Ennis Reservoir are mainly regulated at Hebgen Dam.*

Figure 17 and Figure 18 show the annual peak flow records for the Madison River just below Hebgen Lake and below Ennis Lake, respectively. At the Hebgen Reservoir outlet, average peak flow from 1950-2015 is 2,603 cubic feet per second (cfs). The plot shown in Figure 17 shows each point labeled by the month in which it occurred. Releases from the dam cluster around the May-July timeframe to coincide with spring runoff, but a large percentage of the annual peaks were released during the month of November between 1960 and 1994. No annual peak has occurred in late fall since 1994, likely reflecting a change in management strategy at the reservoir (Figure 19). Peaks have occasionally exceeded the 3,500 cubic feet per second maximum recommendation for managing erosion at the Quake Lake outlet, most recently in 2008 and 2011. The high 2008 flow coincides with a month-long period of uncontrolled releases caused by stoplog failure at the dam intake (Section 2.3.1).

Overall the peak flow records show that although two dams affect the Madison River, it still has a fairly wide range in frequently occurring peak flow magnitudes, and 2-year discharges are commonly met or exceeded. The largest flood of record was in 1970, and this flood severely eroded the spillway at Quake Lake and damaged the roadway embankment downstream along Highway 287 (Chase and McCarthy, 2012).

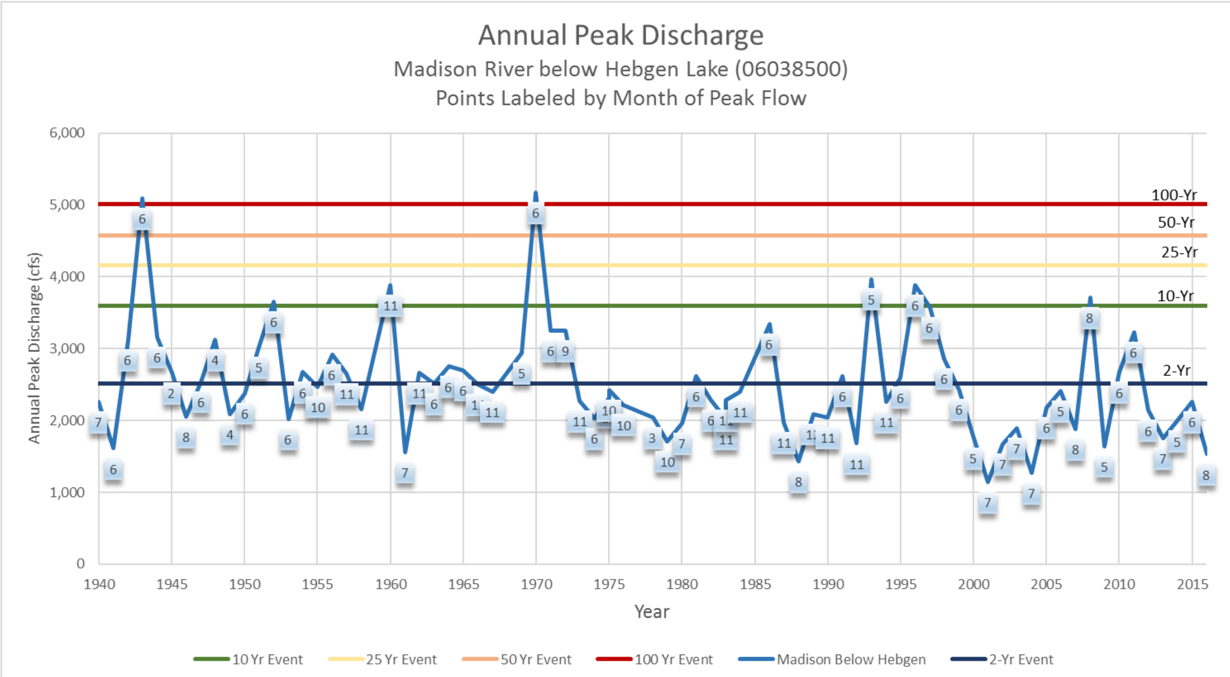

Figure 17. Peak flow record for Madison River below Hebgen Reservoir.

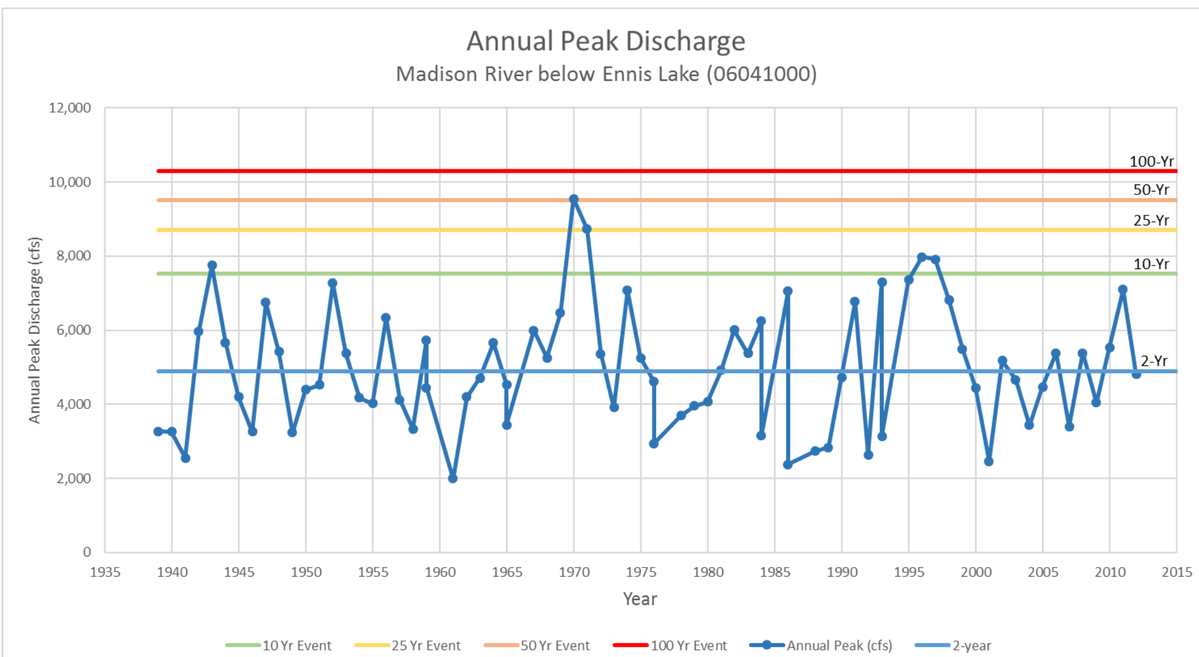

Figure 18. Annual peak flow record for Madison River below Ennis Lake.

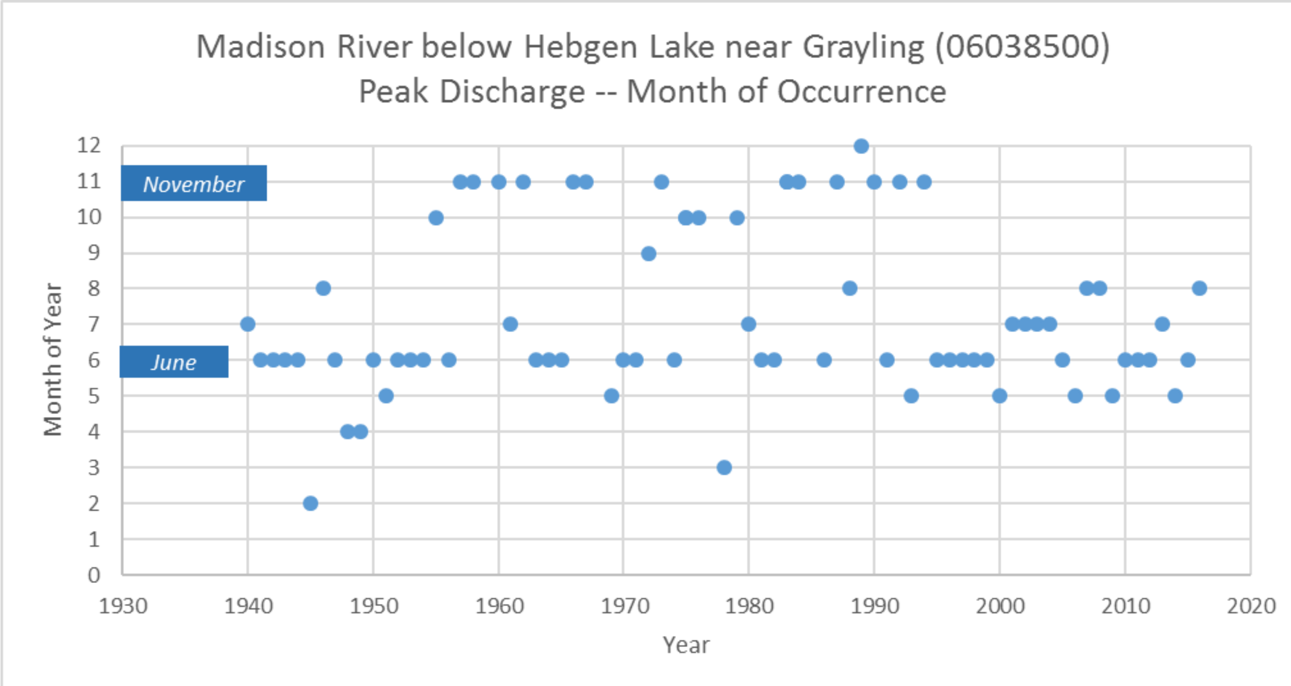

Figure 19. Month of peak discharge below Hebgen Lake, showing concentration of peaks in June and November.

2.4 Dikes and Levees

In the town of Ennis, approximately 0.9 miles of levees protect the town, city park, and sewage treatment lagoons from flooding (Figure 69), though flooding associated with ice gorging is known to overtop the levees below the bridge (Figure 7, Figure 20).

Figure 20. Ice related flooding in Ennis Lions Club Park on January 28, 2007. (Thatcher)

The 13.6-mile-long Lower Madison Levee system is the largest and most influential floodplain feature in the Madison study area in terms of size and impact to the river. Assuming equal bankline length on the left and right sides of the river, the levees collectively restrict natural channel processes on approximately 43 percent of the lowest sixteen miles of river.

The primary levee (Figure 21) It is approximately 10.6 miles long, starting in Three Forks (RM 2.1) and extending along the eastern bank of the river up to the Darlington Ditch Diversion (RM 15.8). This levee was reportedly built in the early 1950s to benefit a few large ranches who were experiencing ice jam related flooding (S. Gillilan, Personal Communication, 2016). The levee is now managed by the Madison Dike & Drain District with a board representing all the adjacent landowners who are taxed for ongoing maintenance needs. The river has locally migrated into the levee in several locations, prompting ongoing maintenance. As the levee is not certified, landowners on the landward side are required to apply for floodplain permits as if the levee did not exist. Additionally, recent ice jamming events have reportedly approached the top of the levee above Three Forks. There is also a 1.6-mile long levee on the west side of the river between river miles 5.7 to 7.7. We have no information on the installation date or purpose of this levee, but assume it serves the same purpose as the major levee on the east side of the river. It was in place by 1965. Below the Interstate-90 bridge complex there are a total of 1.4 miles of levee on both banks, all of which were in place by 1965.

While the levees appear to be performing their intended purpose of providing protection from ice jam flooding events, they also effectively narrow the available channel migration zone for the Madison throughout most of the Lower Madison River Valley.

Figure 21. The Madison River south of Three Forks on July 21, 2016, showing the 10.6 mile long Madison River Levee. Darlington Ditch follows the landward side of the levee. (Kestrel)

2.5 Bank Armor

Bank armor was mapped where visible on air photos, Google Earth, or oblique photographs. Since there was no ground inventory, the mapping probably captures a conservative estimate of the extent of bank armor on current and historic channels. Between Varney Bridge and Three Forks we mapped 4.9 miles of bank armor, which covers approximately 4% of the total bankline. About 1.6 miles of armor is protecting levee/berm features, 3.1 miles are associated with transportation features (bridges, bridge approaches, and roads), with the remaining 0.2 miles of armor associated with agricultural land or residential structures.

2.6 Transportation Infrastructure

Mapped transportation infrastructure in the Madison River corridor includes highways and smaller roads that parallel and cross the river. Transportation infrastructure running down-valley typically constricts the river corridor and channel migration footprint, whereas bridges commonly cause the Channel Migration Zone (CMZ) to “hourglass” through a pinch point created by the bridge approaches and footings.

Road encroachment into the Madison River corridor is minimal. Between Varney Bridge and Ennis, Varney Road closely follows the top left bank, but this area is geologically controlled and out of the CMZ. The same situation occurs in Bear Trap Canyon, where Ennis Lake Road follows the canyon bottom. Towards the lowermost canyon area, a BLM road does encroach into the narrow Erosion Hazard Area of the Madison River, although migration rates are low and difficult to measure in this area. The same is true with Highway 84 as it follows the river between the Warm Springs and Black’s Ford Fishing Access Sites. In general, levees and bridges have had a much stronger impact on the footprint of the CMZ than parallel road embankments.

Nine bridges span the entire channel within the project area. While these bridges and their associated approaches locally constrict the CMZ, they appear well-located and sufficiently sized such that and their overall impacts to the corridor are low. The exception to this is the grouping of bridges at Three Forks. A series of photos of the bridges on the river are compiled in Appendix B, and discussed on a reach scale in Section 4.7.

3 Methods

The development of the Madison River Channel Migration Zone (CMZ) mapping is based on established methods used by the Washington State Department of Ecology, as well as closely following similar efforts on a variety of Montana's rivers.

3.1 Aerial Photography

CMZ development from historic imagery is dependent on the availability of appropriate imagery that covers the required time frame (50+ years), the spatial coverage of that imagery, and the quality of the photos. It is important to use imagery with the best possible quality, scale, extent, and dates so that historic and modern features can be mapped in sufficient detail.

Several imagery sources are available for the Madison River study area. The most recent sources, starting around 1995 with the black-and-white Digital Orthophoto Quad imagery (DOQ) and continuing through the current NAIP (National Agriculture Imagery Program) imagery, are freely available in GIS-compatible format. The quality of these images, both spatially and resolution, ranges from good to excellent and they cover the entire project area.

Imagery older than 1995 must be acquired from various archival services as digital scans, and then mosaiced into a single spatially-referenced image for use in the GIS. For this project, the historic imagery scans were ordered from the United States Department of Agriculture (USDA) Air Photo Field Office (APFO) in Salt Lake City, Utah. Approximately 104 individual images were ordered from the APFO to cover two time periods for the Madison River. The area around Three Forks is shared by both the Jefferson and Gallatin Rivers, so there is some common imagery between the three rivers. The 1955 data set only extends downstream to approximately Black's Ford, with the remaining lower river to Three Forks covered by 1965 imagery. Collectively, these images make up the earliest data sets, and are often referred to as the 1955/65 imagery.

The scans were delivered as high-resolution (12.5 micron) TIFF images, each approximately 330 MB in size. They were then orthorecitified by Aerial Services, Inc. (ASI) in Cedar Falls, Iowa, using 2013 NAIP imagery as the spatial reference, providing identifiable ground control points. The resulting mosaics were assessed for spatial accuracy using National Spatial Data Accuracy standards, along with assessing the image quality. In some areas, the project team requested adjustments to the spatial fit to provide a higher degree of spatial accuracy.

Table 1 lists imagery used for this project from the USDA and archives of current GIS data sets. Examples of the imagery used in the analysis are shown in Figure 22 through Figure 25.

Table 1. Aerial photography used for the Madison River Channel Migration mapping study.

Date	Source	Scale	Notes
1955	USDA APFO	1:20,000	High-resolution Scans, used from Varney Bridge through Bear Trap Canyon (black-and-white)
1965	USDA	1:20,000	High-resolution Scans, used from Bear Trap Canyon to Three Forks (black-and-white)
1979	USDA APFO	1:40,000	High-resolution Scans (black-and-white)
2013 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)
2015 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)

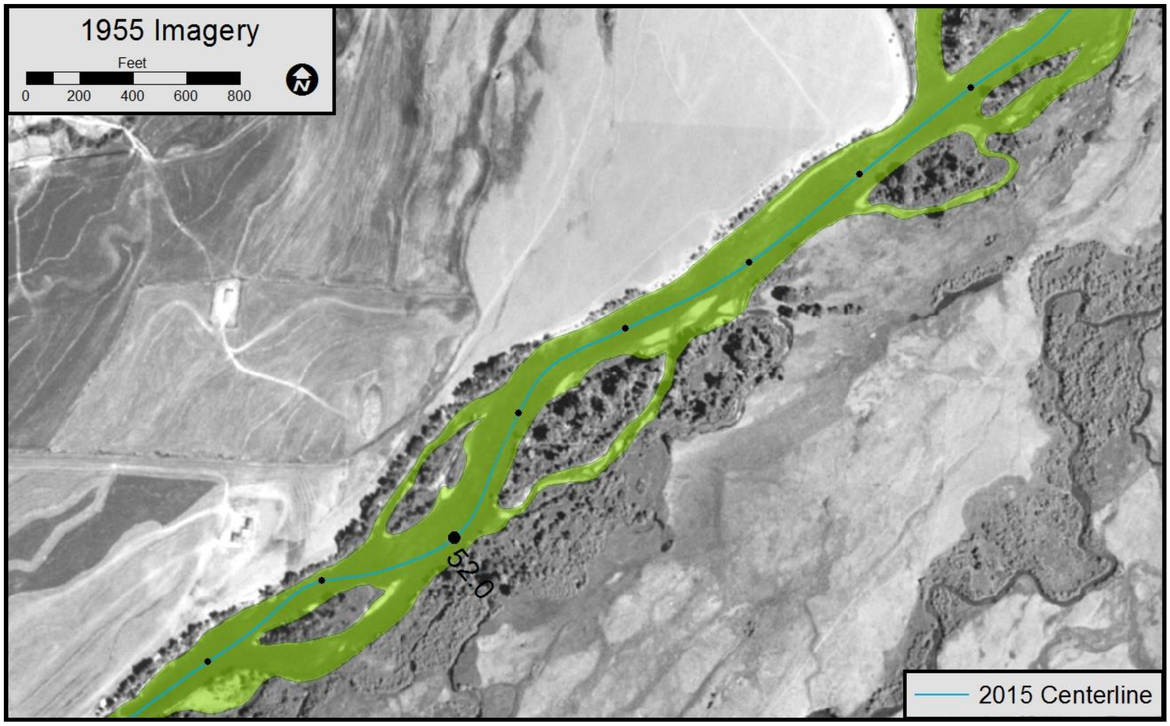

Figure 22. Example 1955 imagery, Madison River CMZ development (Ennis, Reach 8).

Figure 23. Example 1979 imagery, Madison River CMZ development (Ennis, Reach 8).

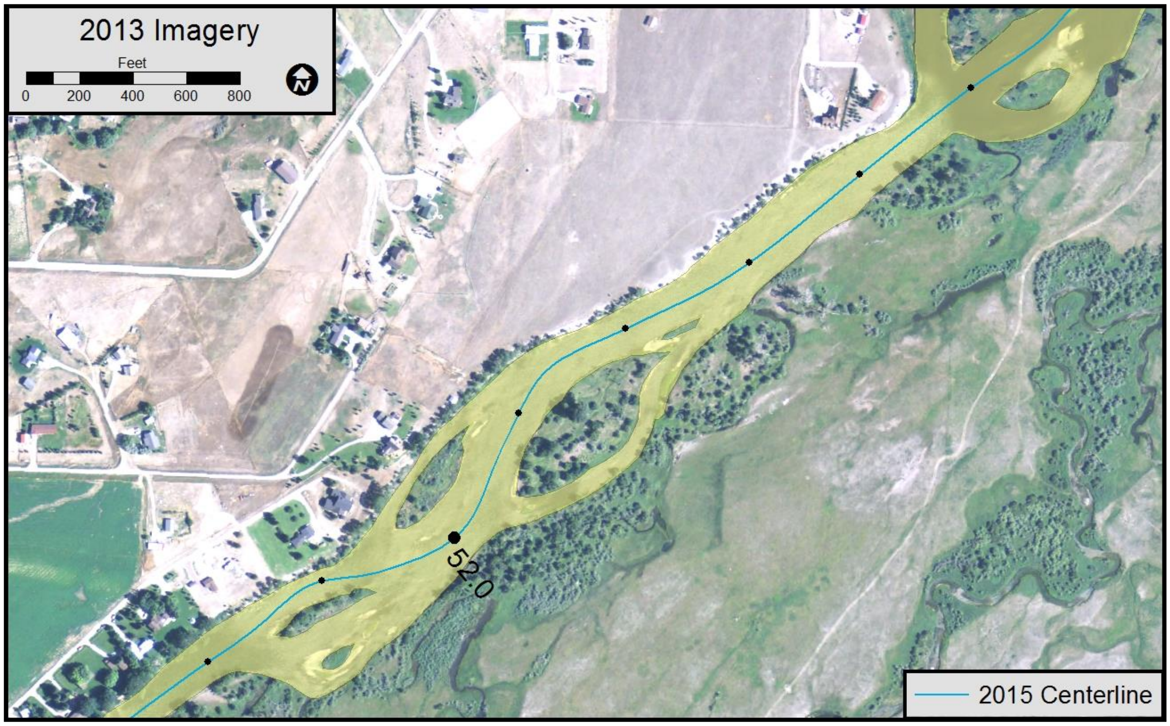

Figure 24. Example 2013 imagery, Madison River CMZ development (Ennis, Reach 8).

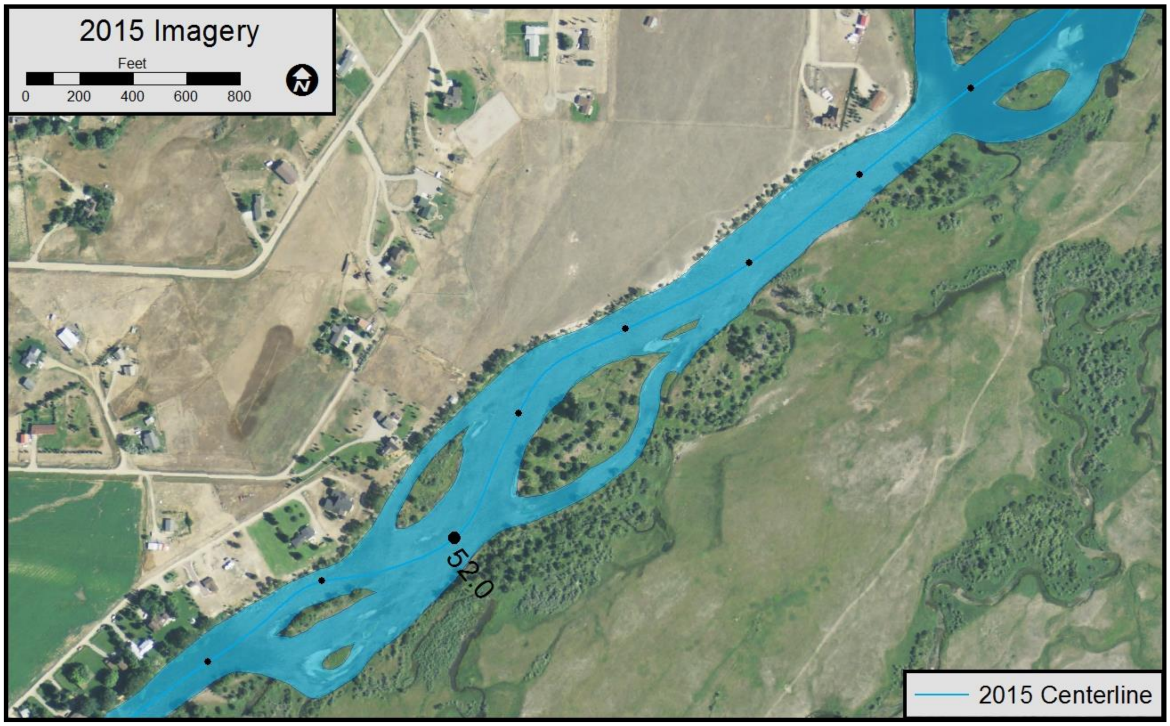

Figure 25. Example 2015 imagery, Madison River CMZ development (Ennis, Reach 8).

3.2 GIS Project Development

All project data was compiled using ESRI's ArcMap Geographic Information System (GIS) utilizing a common coordinate system - Montana State Plane NAD83 Feet (HARN). The 2010 Ruby River CMZ Study (AGI/DTM, 2010) utilized this coordinate system as it was the recommended best practice at the time. To be consistent with that study, the Madison mapping utilizes this reference system. The orthorectified air photos provide the basis for CMZ mapping. In addition to the specific project data created for this study, other data included roads, stream courses as depicted in the National Hydrography Dataset, scanned General Land Office Survey Maps obtained from Bureau of Land Management, and geologic maps produced by the United States Geological Survey.

3.3 Bankline Mapping

Banklines representing bankfull margins were digitized for each year of imagery at a scale of 1:2,000. A tablet computer running ArcGIS and using a pen stylus was used to trace the banklines using stream mode digitizing. This methodology allowed us to capture a much more detailed bankline than using a mouse. Bankfull is defined as the stage above which flow starts to spread onto the floodplain. Although that boundary can be identified using approaches such as field indicators or modeling (Riley, 1972), digitizing banklines for CMZ development requires the interpretation of historic imagery. Therefore, we typically rely on the extent of the lower limit of perennial, woody vegetation to define channel banks (Mount & Louis, 2005). This is based on the generally accepted concept that bankfull channels are inhospitable to woody vegetation establishment. Fortunately, shrubs, trees, terraces, and bedrock generally show distinct signatures on both older black-and-white as well as newer color photography. These signatures, coupled with an understanding of riparian processes, allow for consistent bankline mapping through time and across different types of imagery.

3.4 Migration Rate Measurements

Once the banklines were digitized, they were evaluated in terms of discernable channel migration since 1955 between Varney Bridge and Black's Ford below the mouth of Bear Trap Canyon, and since 1965 from Black's Ford to Headwaters State Park. Where migration was clear, vectors (arrows with orientation and length) were drawn in the GIS to record that change. At each site of bankline migration, measurements were collected at approximately 30 foot intervals (Figure 26). A total of 921 migration vectors were generated for the Madison River. These measurements were then summarized by reach. The results were then used to define a reach-scale erosion buffer width to allow for likely future erosion. Results of this analysis are summarized in Section 4.3.

Each location of channel migration was assigned a Migration Site ID based on the river mile location of the site. Each site may have anywhere from 1 to 11 migration vectors, depending on the length of the site. A total of 245 migration sites were identified throughout the study area. An accounting of the reach and site based statistics can be found in Appendix A.

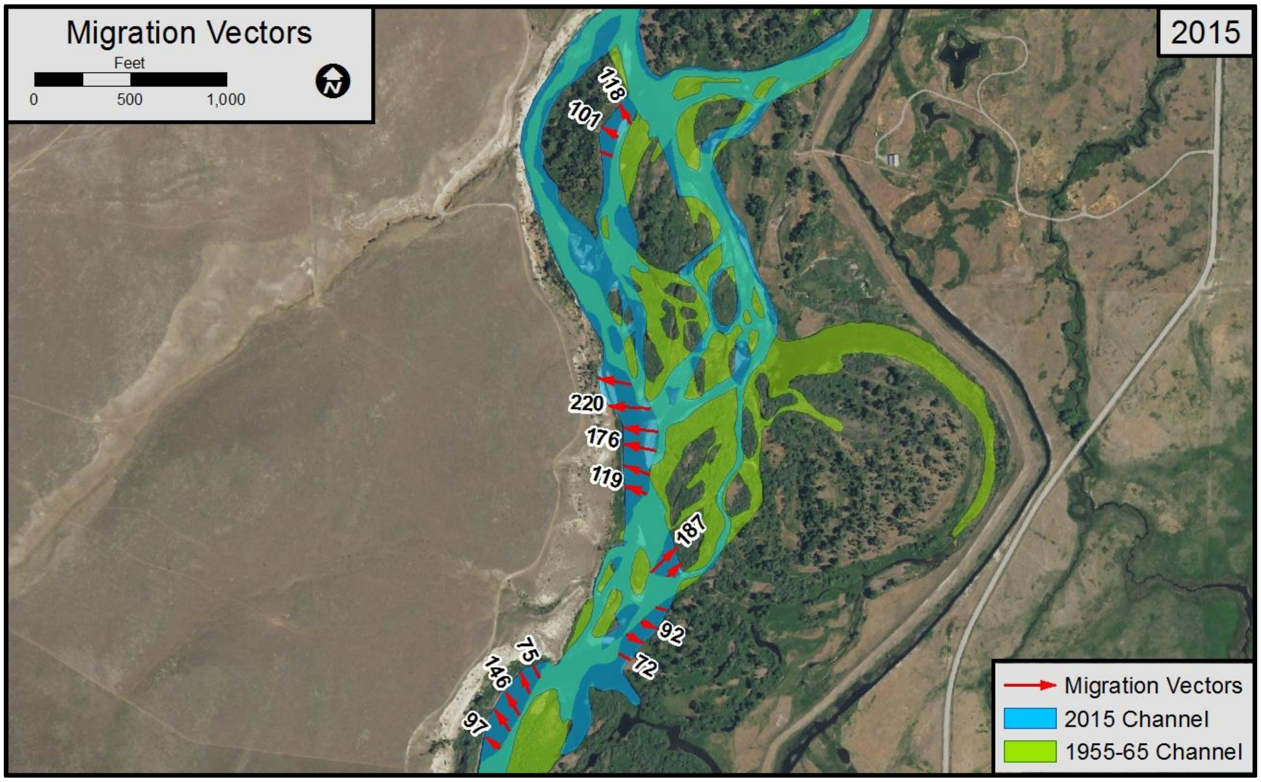

Figure 26. Example of migration measurements (migration distance in feet).

3.5 Inundation Modeling

Inundation Modeling, also known as Relative Elevation Modeling (REM), is an effective way to visually compare floodplain elevations to channel elevations, and is useful in identifying floodplain features such as historic channels that are prone to frequent flooding and/or avulsion.

Inundation modeling is a static model of relative elevations based upon Digital Elevation Model (DEM) data. The goal of the modeling is to identify areas that may be prone to flooding as the water surface of the stream is raised. The general technique involves using cross sections to create a water surface profile down the stream corridor. This profile is then transformed into a series of ramped planes down the stream corridor that match the down-valley slope of the water surface. The ground surface is then subtracted from this planar water surface, so that a relative depth can be assigned at each elevation data point. The resulting surface coarsely represents relative inundation potential based on relative elevation. This can be used to approximate flood prone areas, but it also is a useful tool for identifying low topographic features or channels that may pose an avulsion risk.

It is important to note that this modeling does not consider flood water routing or backwater effects, but only elevation. As such, low areas may not be flood prone if the overflow paths are blocked by physical features such as dikes or road prisms.

Additionally, the accuracy of an inundation model is directly related to the quality of the elevation data. While high-resolution LiDAR data provides the best results, modeling using 10-meter USGS National Elevation Dataset

(NED) still provides sufficient resolution to model broad trends in the floodplain. For the Madison River study area, inundation modeling was generated using the NED dataset (Figure 27).

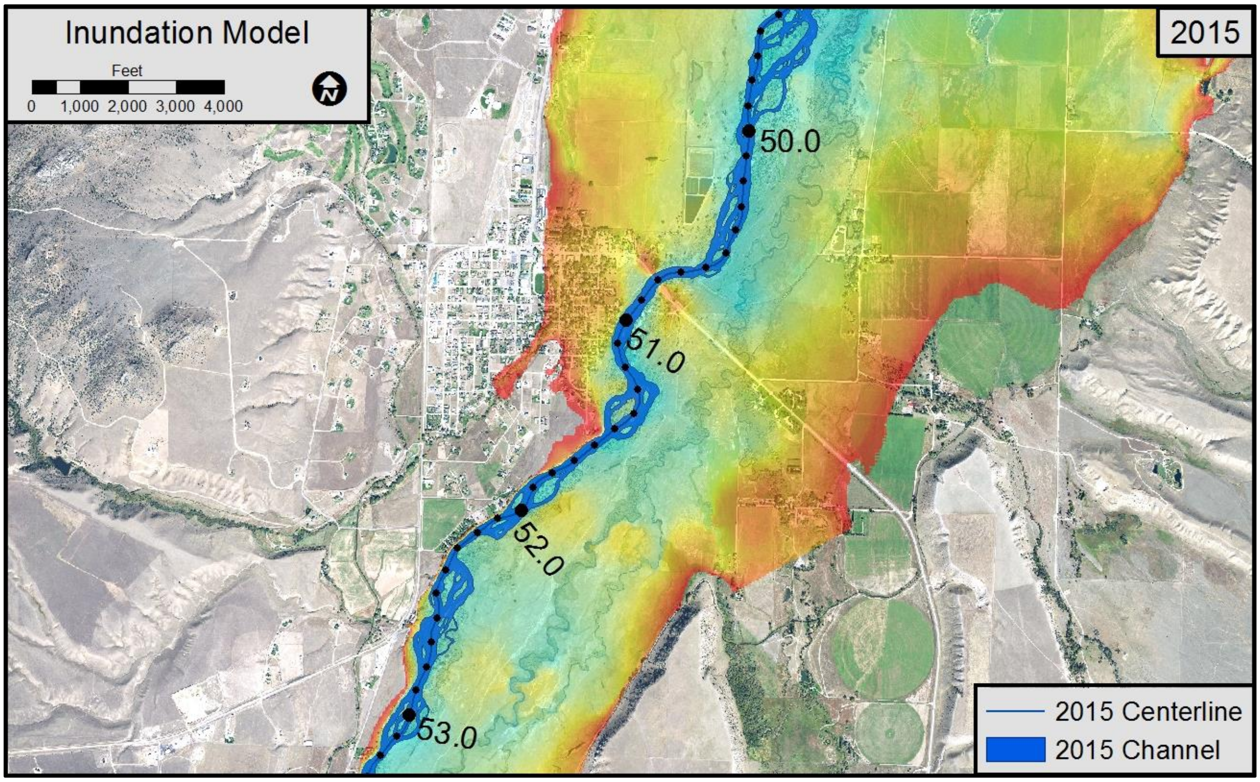

Figure 27. Example Inundation Modeling results. Colors represent elevations relative to the elevation of the main channel. Dark blue areas are equal to or lower than the channel. Yellows and reds are significantly higher than the adjacent main channel.

3.6 Avulsion Hazard Mapping

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

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

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

Where available, the GIS-based inundation model discussed in Section 3.5 was used to help identify potential avulsion pathways. These pathways were identified as low continuous swales with connectivity to the river (Figure 28). Additional information used in mapping avulsion paths included oblique photos from Kestrel Aerial Services and air photos.

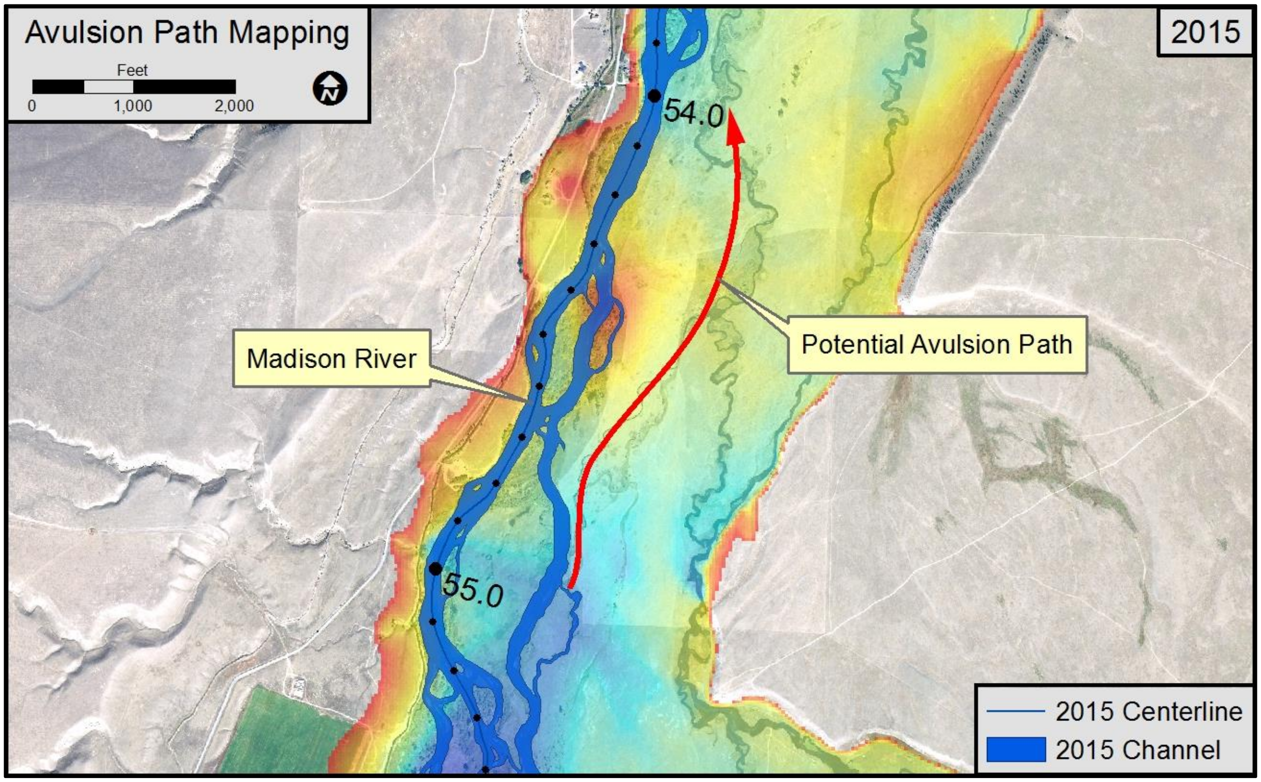

Figure 28. Example use of mapping avulsion pathways.

4 Results

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

4.1 Project Reaches

The approach to CMZ mapping used here includes a reach-scale evaluation of channel migration rates. For the 59 miles of project length, the river was broken into nine reaches based on geomorphic character such as river pattern, rates of change, geologic controls, etc. (Figure 30). The reaches range in length from 2.8 to 12.7 miles (Table 2).

Table 2. Madison River reaches.

Reach	General Location	Upstream RM	Downstream RM	Length (mi)
Reach 1	I-90 to Jefferson River confluence	3.7	0.0	3.7
Reach 2	Cobblestone to I-90 bridge	11.8	3.7	8.1
Reach 3	Below Grey Cliff to below Cobblestone	18.7	11.8	6.9
Reach 4	Warm Springs Fishing Access to below Greycliff	31.4	18.7	12.7
Reach 5	Bear Trap Canyon	40.6	31.4	9.2
Reach 6	Above Ennis Lake to Jack Creek	48.0	40.6	7.5
Reach 7	Ennis to just above Jack Creek	50.8	48.0	2.8
Reach 8	Upstream of Ennis	55.2	50.8	4.4
Reach 9	Downstream of Varney Bridge	59.8	55.2	4.6

4.2 The Historic Migration Zone (HMZ)

The Historic Migration Zone (HMZ) is created by combining the bankfull polygons for each time series into a single HMZ polygon. The bankfull channel boundaries are the boundary between open channel and off-stream areas, including woody vegetation stands, vegetated floodplains, terrace margins, or bedrock valley walls. Thus, the HMZ contains all unvegetated channel threads that are interpreted to have conveyed water under bankfull conditions (typical spring runoff), and as such, the zone has split flow segments and islands. Many of the larger islands have not had any active river channels since 1955, yet are included in the historic footprint of the HMZ. This inclusion of islands reflects the fact that the HMZ incorporates the entire river corridor area occupied by the Madison River from 1955/1965-2013. In some settings where island areas are non-erodible, it may be appropriate to exclude these features from the CMZ. In the case of the Madison River, these areas have been retained in the CMZ since they are made up of young alluvial deposits that are prone to reworking or avulsion.

Any side channels that have not shown unrestricted connectivity to the main channel since 1955/1965 were not mapped as active channels and are not included in the HMZ.

For this study, the Historic Migration Zone is comprised of the total area occupied by Madison River channel locations in 1955/1965, 1979, 2013 and 2015 (Figure 29). The resulting area reflects 60 years of channel occupation upstream of Black's Ford (RM 24), and 50 years below.

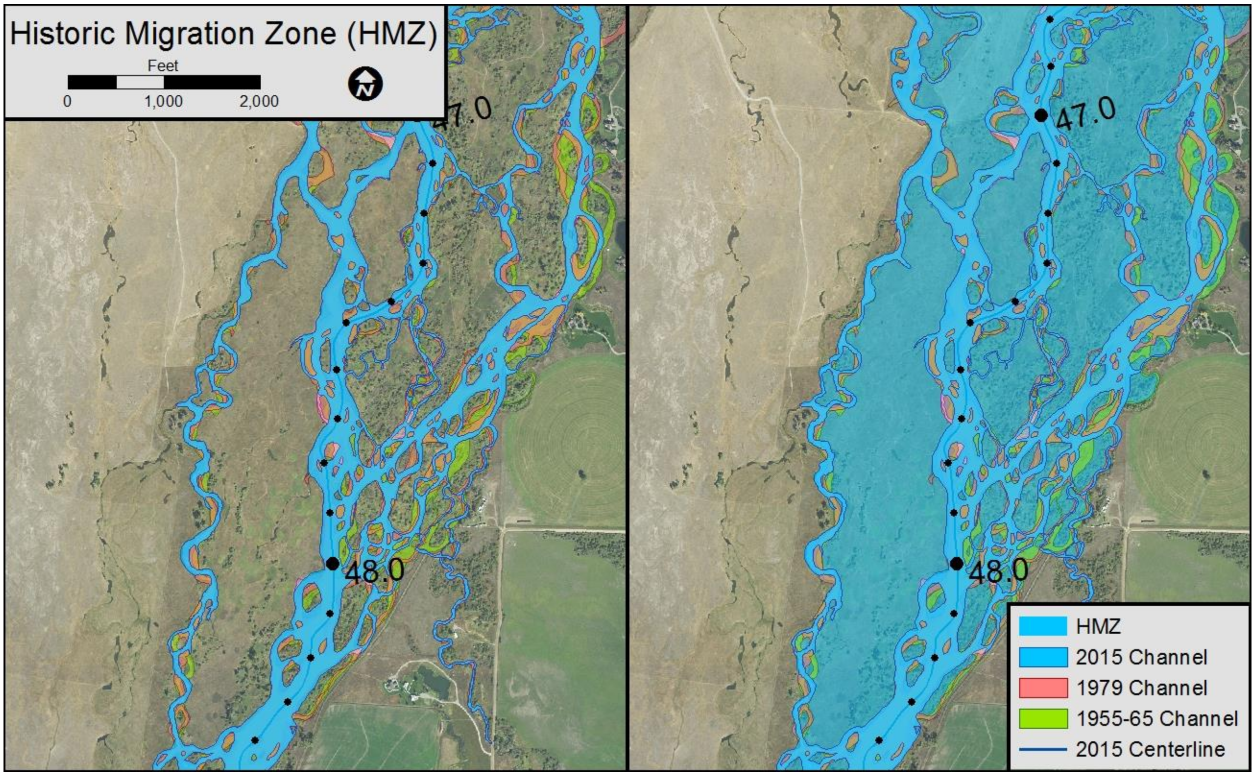

Figure 29. The Historic Migration Zone (HMZ) is the combined footprint of all mapped channel banklines.

4.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on measured migration rates, which are derived from historic migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement versus an avulsion. A total of 921 measurements were made through the project length where a bank had migrated at least 20 feet since 1955/1965. The 20-foot minimum was selected as an easily measurable distance that was not compromised by the resolution or spatial accuracy of the data. The migration distances vary substantially both within and between reaches, with several reaches showing over 100 feet of bank migration since 1956 (Figure 31).

The mean migration distances were used to generate a mean annual migration rate for each reach (Table 3). This in turn defined the erosion buffer width, which allows for 100 years of continual bank movement at the mean annual rate. The erosion buffer widths assigned to each reach are shown in Figure 32, and range from 46 feet in Bear Trap Canyon to 309 feet upstream of the I-90 Bridge. The erosion buffer width, when applied to the 2015 bankline, defines the Erosion Hazard Area (EHA). This area is considered prone to channel occupation over the life of the CMZ (100 years).

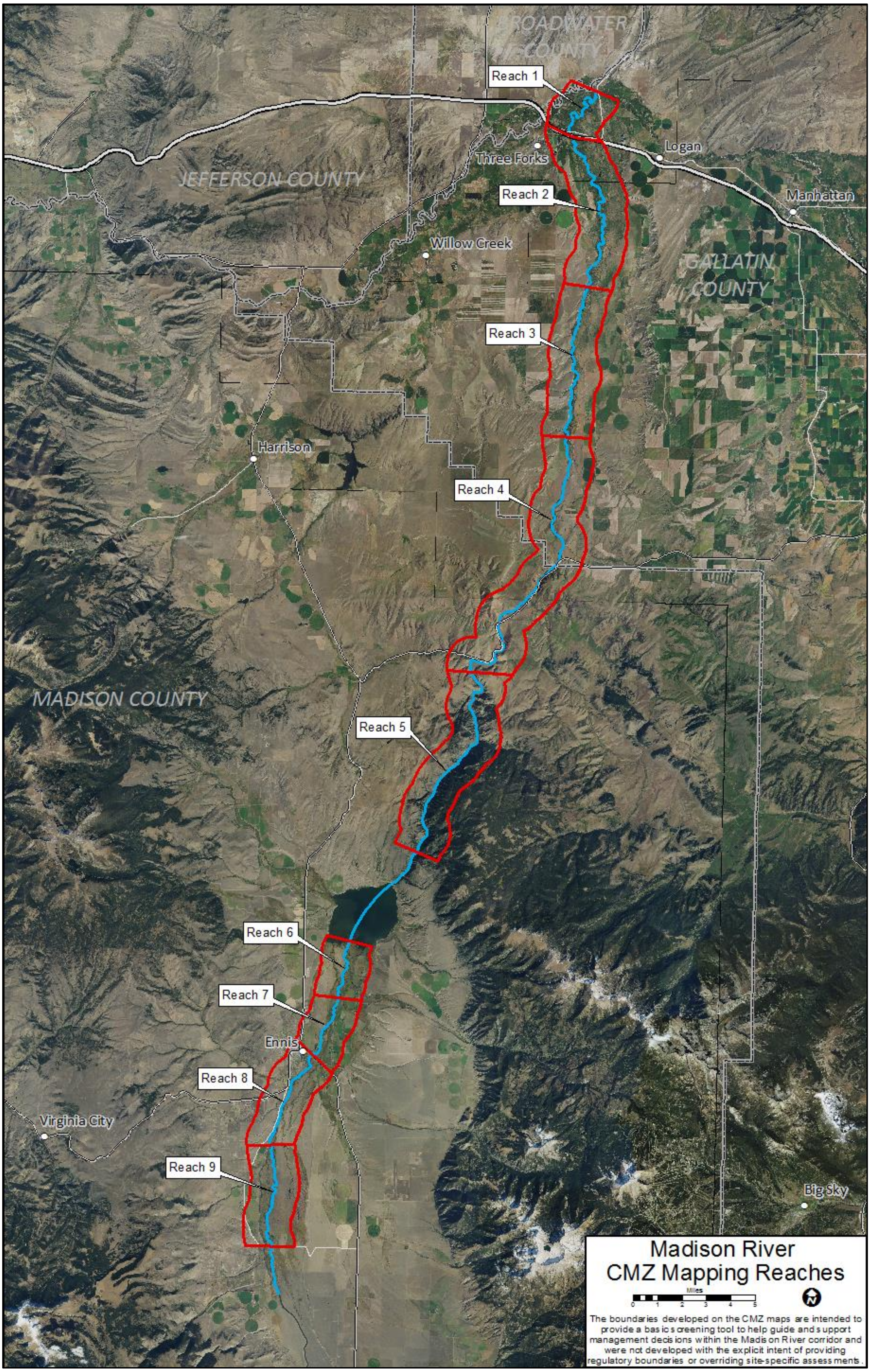

Figure 30. Reaches

This reach-scale assessment acknowledges that predicting movement at single sites over the next century is, at best, difficult due to the non-linear nature of channel migration. As such, the erosion buffer is assigned to all banks, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington State Department of Ecology (WSDE, 2010). The general approach to determining the Erosion Buffer (using the annual migration rate to do define a 100-year migration distance) 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).

An example of EHA mapping is shown in Figure 33. If the EHA extends into the Historic Migration Zone, it is masked by the HMZ so that areas of historic channel locations are prioritized in the mapping hierarchy. As a result, the EHA is typically discontinuous along the river.

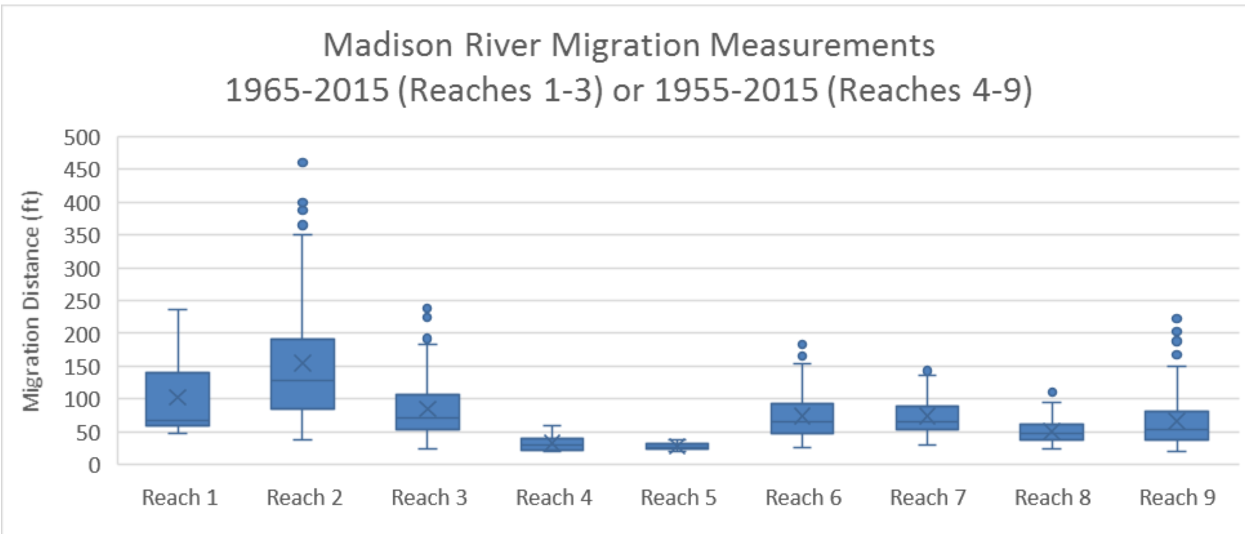

Figure 31. Distribution of migration measurements by reach.

Table 3. Reach-based summary of migration measurements.

Reach	Number of Measurements	Average Length (ft)	Maximum Length (ft)	Number of Years	Average Annual Migration Rate (ft/yr)	100- Year Buffer Width (ft)
Reach 1	18	103	236	50	2.1	206
Reach 2	150	154	460	50	3.1	309
Reach 3	93	85	238	50	1.7	170
Reach 4	44	33	59	60	0.5	55
Reach 5	12	28	37	60	0.5	46
Reach 6	186	74	183	60	1.2	123
Reach 7	89	74	147	60	1.2	123
Reach 8	108	50	110	60	0.8	84
Reach 9	221	67	228	60	1.1	111

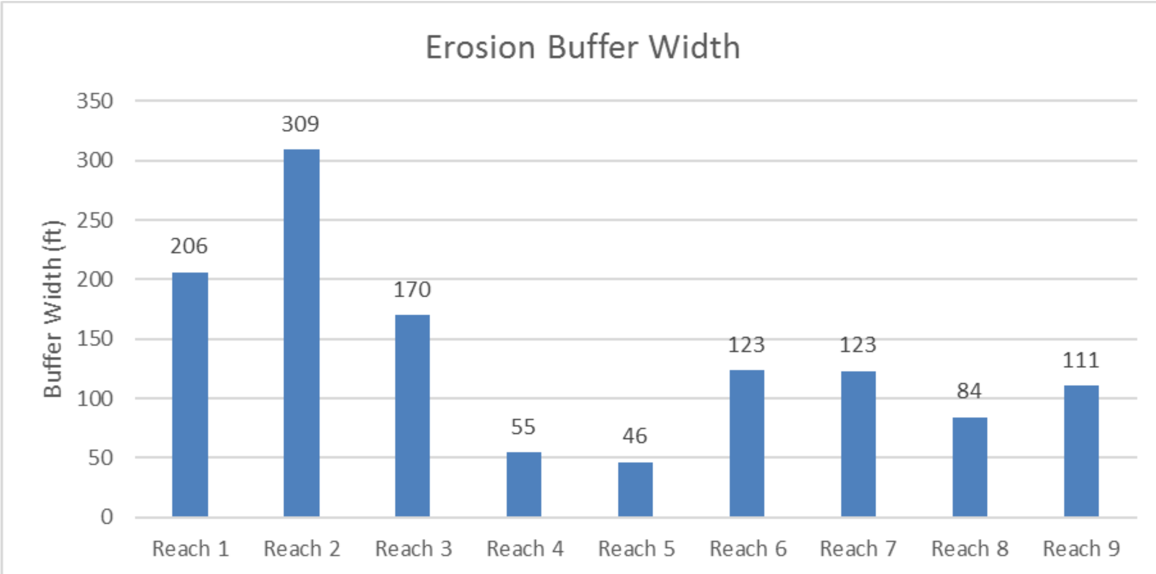

Figure 32. Erosion buffer widths assigned to 2015 banklines to define Erosion Hazard Area (EHA).

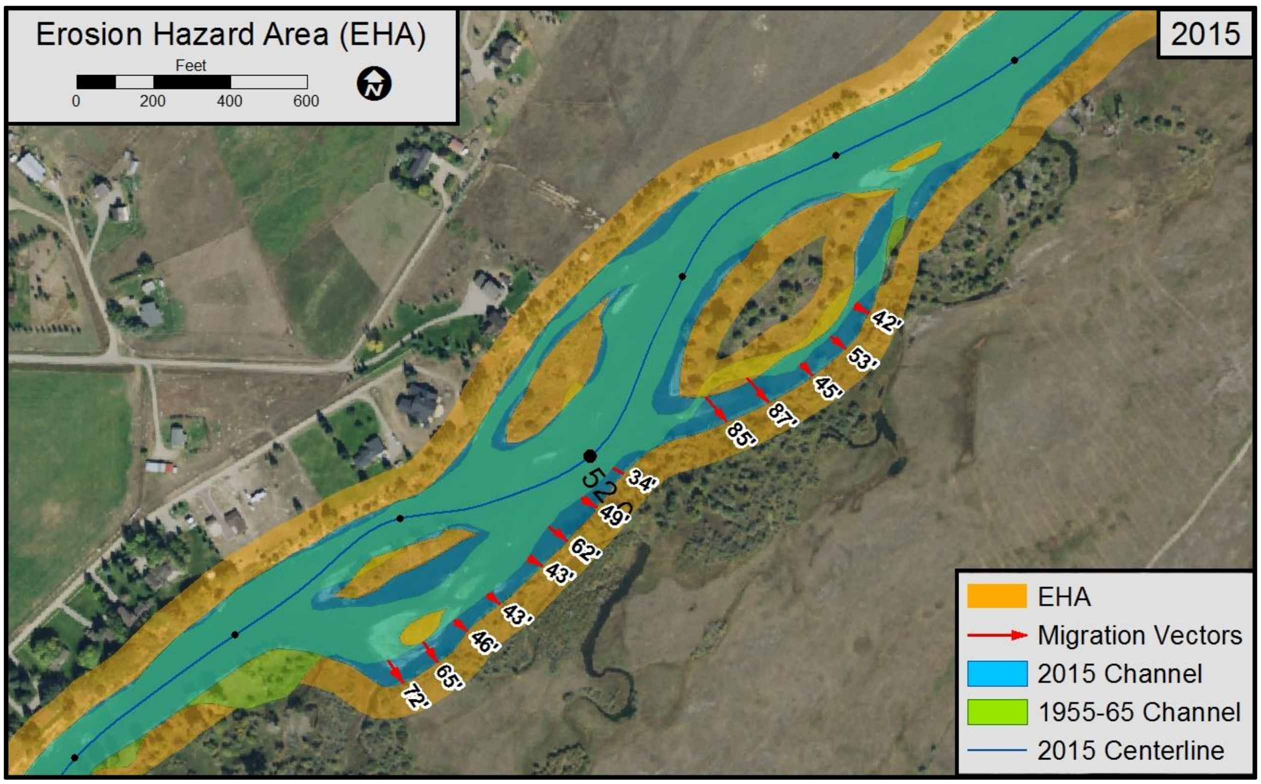

Figure 33. The Erosion Hazard Area (EHA) is a buffer placed on the 2015 banklines based on 100 years of channel migration for the reach.

The 100-year buffer distance was calculated as 100 times the annual mean migration rate for each entire reach (Table 3). Table 3 shows that in several reaches, the 100-year erosion buffer is less than the maximum measured migration distance. This shows that there are areas where very rapid bank migration has occurred, and that the Erosion Hazard Area 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. In a broader sense, it shows that the Erosion Hazard Area is a relatively conservative estimate of erosion risk.

4.4 The Avulsion Hazard Area (AHZ)

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

Avulsions have occurred on the Madison River since the mid-1950s. For example, several avulsions have occurred in the deltaic area upstream of Ennis Lake (Figure 34), and a spring creek was captured via avulsion across from the West Madison Canal between 1955 and 1979 (Figure 35). The avulsions have included bendway cutoffs, spring creek capture, or reactivation of former channels. The scale of avulsions can range from tens of feet to thousands of feet. The 1955-2015 avulsions are clearly captured by the bankline mapping, and are an important component of the Historic Migration Zone. The patterns of historic avulsions were also used to help identify areas where future avulsions are most likely.

The results of the avulsion hazard mapping can be seen on individual map sheets. In many locations, the AHZ creates a relatively smooth belt width corridor for the CMZ, and in others it extends out well beyond the core of the active meander belt.

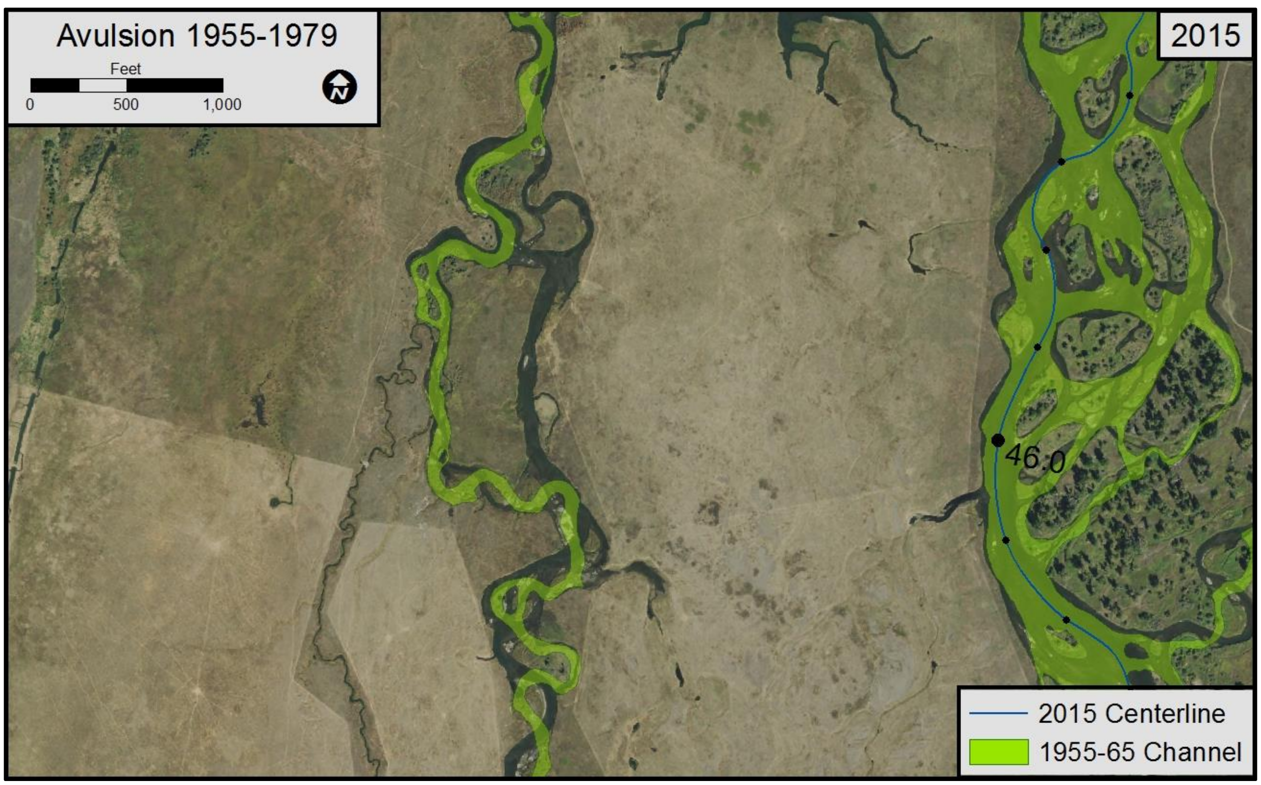

Figure 34. A long avulsion occurring between 1955 and 1979 in the Ennis Lake Delta.

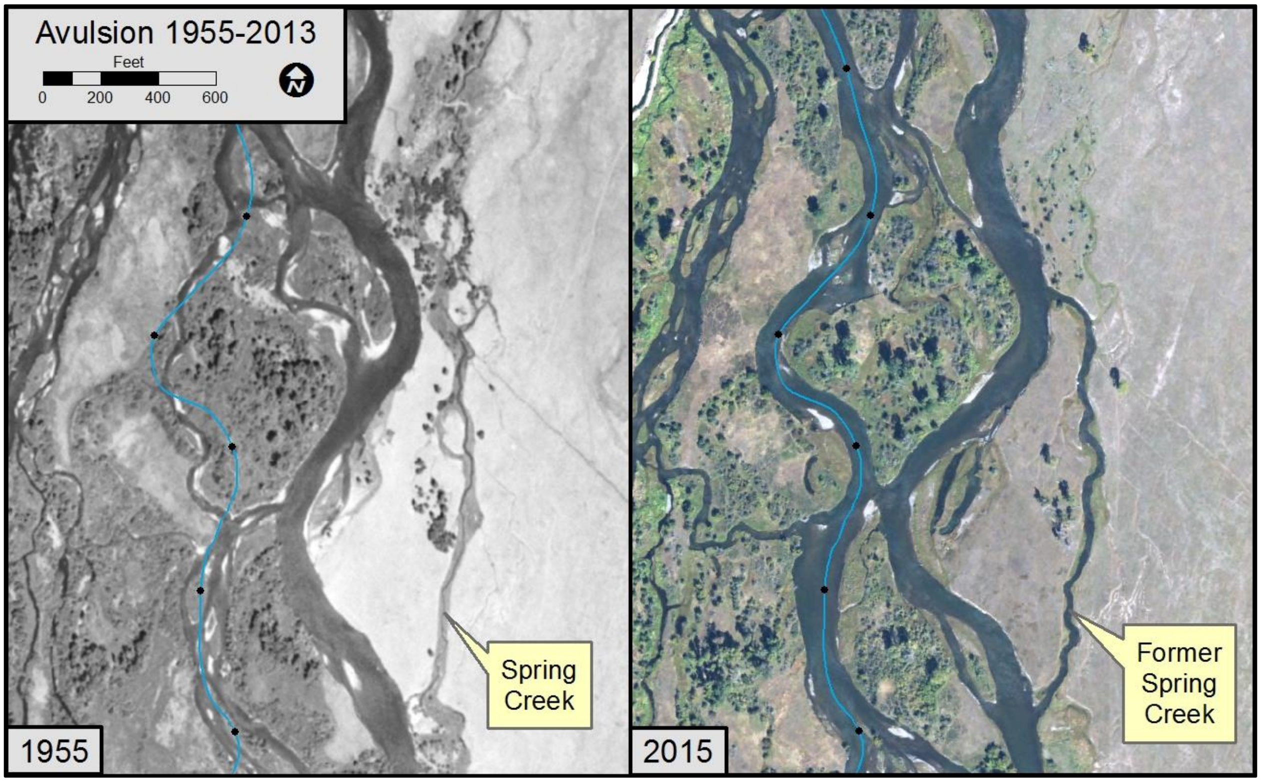

Figure 35. Capture of a spring creek upstream from Ennis; also note side channel enlargement to left.

4.5 The Restricted Migration Area (RMA)

The extent of migration area that is restricted by physical features is largely dependent on the proximity of transportation infrastructure to the channel and by the Lower Madison Levee. The highway and railroad embankments locally encroach well into the CMZ near Three Forks (Figure 36). By comparison, the river upstream of Ennis Lake is relatively unimpacted by infrastructure (Figure 37).

Figure 38 shows that the extent of banks that were mapped as armored ranges from 0% to 12% of the total bankline in any given reach (discounting islands). Four reaches contained no visible armor. The densest armor is in Reach 2 in Three Forks, where about 12% of the total bankline is armored to largely protect transportation infrastructure. Berms and levees play a larger influence on the Madison River (Figure 39). The Lower Madison Levee system (Section 2.4) forms an artificial barrier between the river corridor and its historic floodplain for almost 14 miles, affecting all of Reach 2 and much of Reaches 1 and 3. Reach 7, between Ennis and Jack Creek, has a series of levees protecting the sewage treatment ponds, and an approximately 1-mile-long levee on the east bank upstream from the Jack Creek confluence.

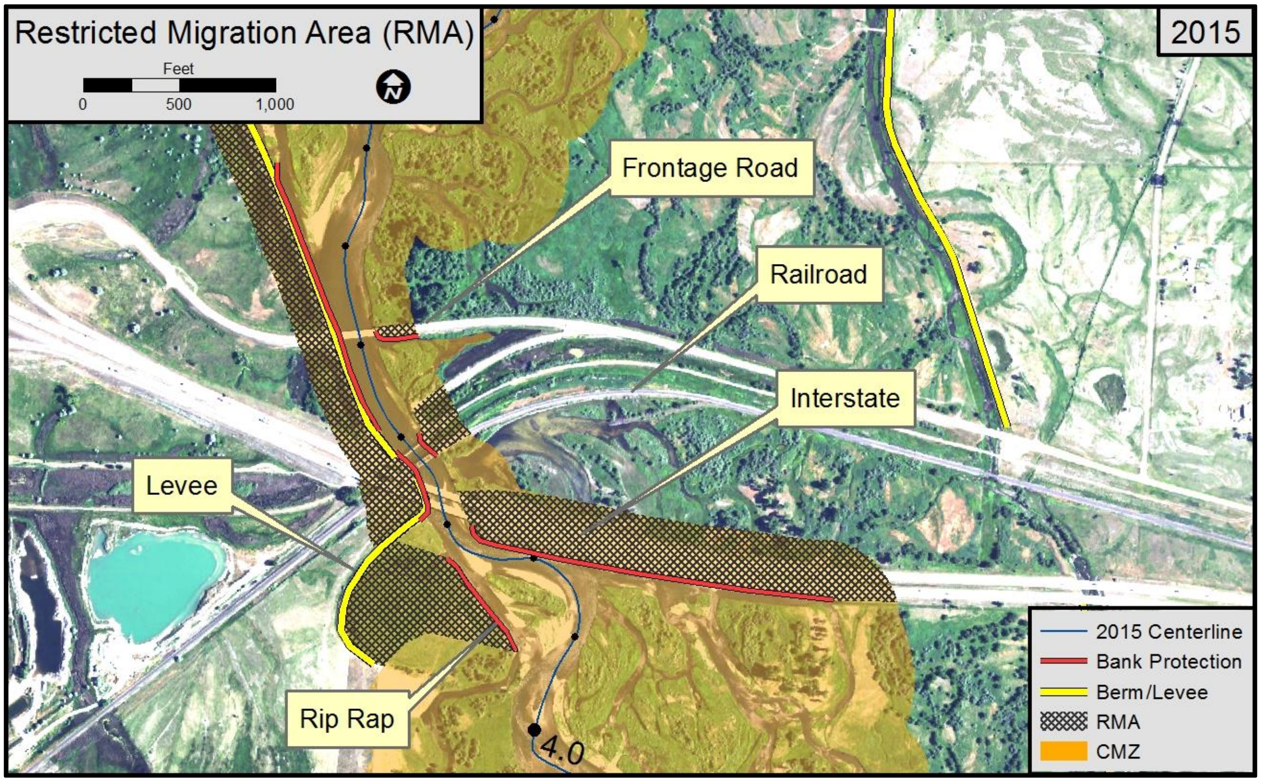

Figure 36. Restricted Migration Areas in Thee Forks.

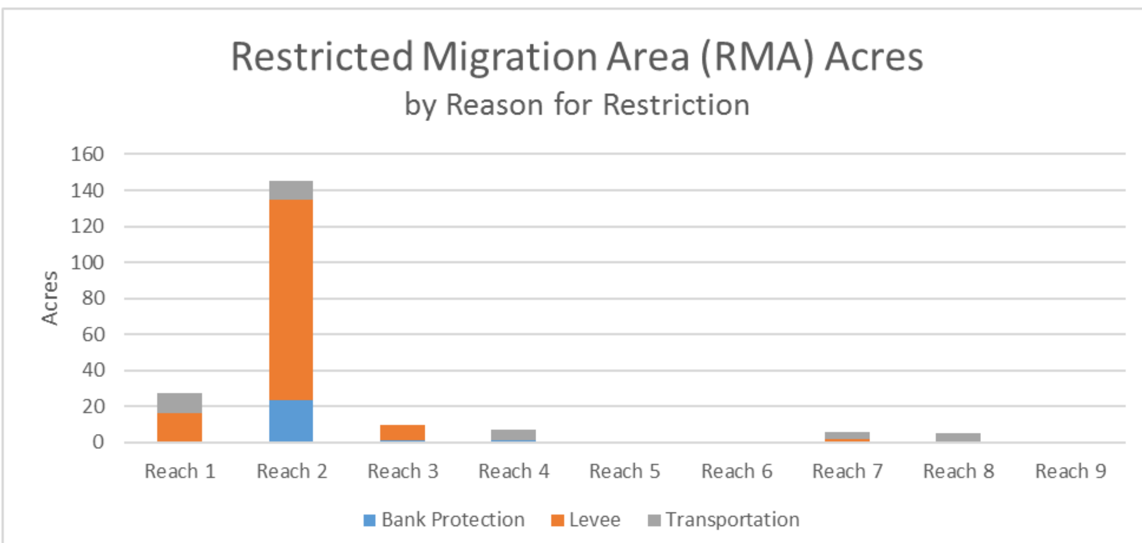

Figure 37. Acres of the CMZ mapped as restricted by reach.

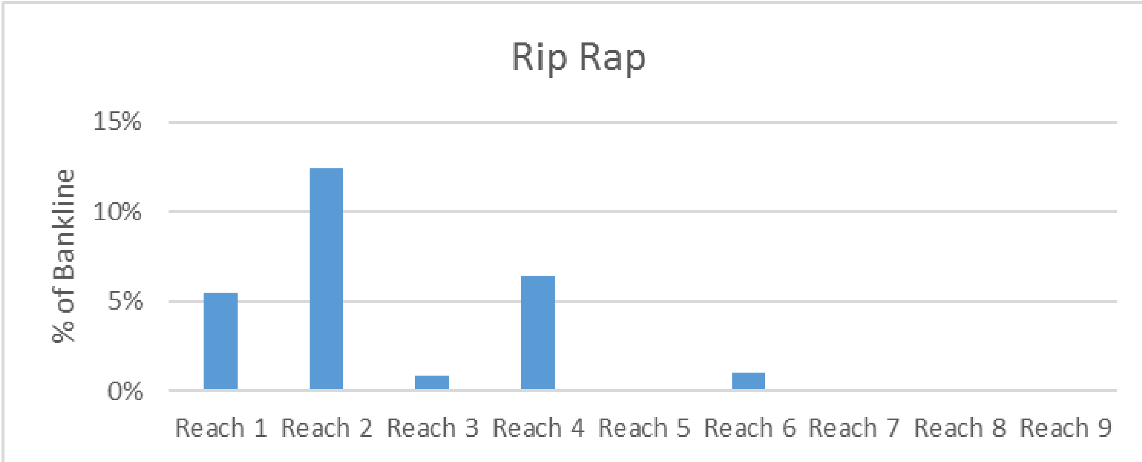

Figure 38. Percentage of bankline protected by armor by reach.

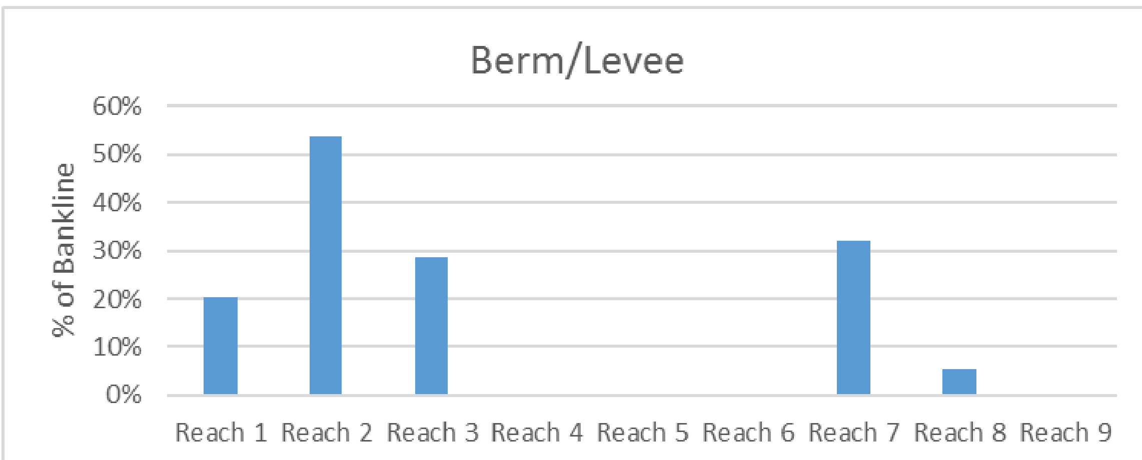

Figure 39. Percentage of bankline protected by berms or levees by reach

4.6 Composite Map

An example portion of a composite CMZ map for a section of the Madison River project area is shown in Figure 40. Each individual mapping unit developed for the CMZ has its own symbology, so that any area within the overall boundary can be identified in terms of its basis for inclusion.

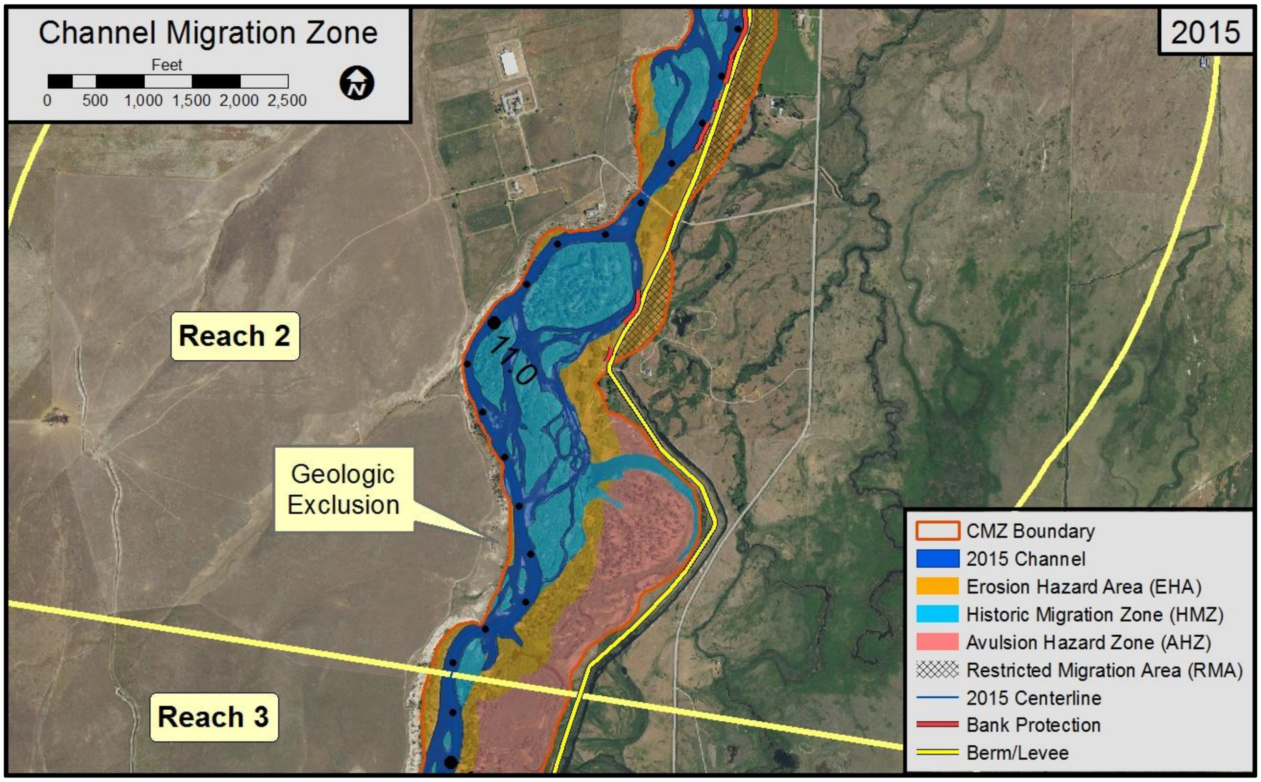

Figure 40. Composite Channel Migration Zone map.

4.7 Geologic Controls on Migration Rate

Many CMZ mapping efforts incorporate a Geotechnical Setback on valley walls, which is an area of expanded Erosion Hazard Area (EHA) against geologic units that may be prone to geotechnical failure such as landslides, slumps, or rockslides. Between Varney Bridge and Three Forks, there are no mapped active landslides against the river, which suggests indicate that the CMZ will not likely be altered by hillslope failure. Even so, Bear Trap Canyon could still be prone to rockslides or debris delivery via avalanches that may impact the river's course. Defining an appropriate setback for these processes is difficult at best and may reflect more stochastic processes than have been used to develop the CMZ. As a result, Geotechnical Setbacks have not been incorporated into the EHA, and incorporating the potential for mass failure on hillslopes was considered beyond the scope of this effort.

5 CMZ Mapping Results by Reach

The following sections summarize the mapping results for each reach of the Madison River. The reaches are numbered sequentially from downstream to upstream to allow the potential extension of the mapping above Varney Bridge in the future. To best describe the downstream trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach 9 at Varney Bridge, and ending with Reach 1 at Headwaters State Park. The maps can be found in Appendix D.

Note: Many of the reach descriptions, below, reference River Miles (RMs), which refer to the distance upstream from Three Forks along the 2015 channel centerline. River Miles are labeled on the maps in Appendix D.

5.1 Reach 9

Reach 9	
Upstream/Downstream RM	59.8/55.2
Length (miles)	4.6
General Location	Downstream of Varney Bridge
Mean 60-year Migration Distance (ft)	67
Max 60-year Migration Distance (ft)	228
100-year Buffer (ft)	111

Reach 9 extends from Varney Bridge downstream for almost five miles. Within this reach, the Madison River is bordered by a broad floodplain with numerous spring creeks and extensive irrigated terraces. The river corridor is typically about a half mile wide, with numerous swales dissecting the low floodplain surface. The geologic mapping of this area includes "Holocene Paludal Deposits," which are sand, silt, and organic matter described as having formed in a "swamp environment", possibly indicating high historic concentrations of beaver dams. General Land Office (GLO) maps show that the system has been multi-channeled at least since the late 1800s.

In Reach 9, the river shows relatively unimpeded migration into both riparian areas and agricultural lands, with a complex planform and riparian colonization on open bars (Figure 41). The floodplain is broad and characterized by fairly dense woody riparian corridors along channels, interspersed with broad grassed areas that are completely devoid of woody vegetation. These grassed floodplain surfaces were present in the 1950s as well, suggesting that disturbance in the active stream corridor is an important aspect of riparian regeneration and succession. The 100-year buffer width in Reach 9 is 111 feet.

In addition to active stream migration, avulsion processes are active in Reach 9. Blaine Spring Creek, which follows the valley bluff line west of the main river channel near Varney Bridge, creates a classic type of avulsion risk - that of a tributary running parallel to a main thread with a low intervening floodplain (Figure 42). Between Varney Bridge and Ennis, several spring creeks run parallel to the river. They are most concentrated east of the river, originating from the toes of glacial terraces that discharge groundwater from the Madison Range to the east. At RM 59.7, the river captured one of these spring creeks between 1955 and 1979, creating a new active side channel of the Madison (Figure 43). Historically these natural wetland areas east of the river were channelized to drain the floodplain and improve agricultural lands, but in recent years restoration has been underway. For example, O'Dell Spring Creek, which was excavated as a drain ditch in the 1950s, has been restored along about 9 miles of its length (www.riverdesigngroup.com).

Figure 41. View downstream of meander bend at RM 57.2 showing chute cutoffs and riparian succession in left foreground. (Kestrel)

Figure 42. View downstream from near Varney Bridge showing Blaine Spring Creek avulsion risk area; main channel is to right. (Kestrel)

Figure 43. View downstream showing spring creek on right captured by the Madison River between 1955 and 1979. (Kestrel)

5.2 Reach 8

Reach 8	
Upstream/Downstream RM	55.2/50.8
Length (miles)	4.4
General Location	Upstream of Ennis
Mean 60-year Migration Distance (ft)	50
Max 60-year Migration Distance (ft)	110
100-year Buffer (ft)	84

Reach 8 begins at RM 55.2, where a high glacial terrace to the east juts out into the Madison River corridor creating a pinch point. The spring creeks on the east side of the river are forced closer to the Madison as a result, increasing their risk of capture. The Madison River itself shifts over to the west side of the floodplain, flowing along bluffs of Miocene-age sedimentary rocks (Figure 44). The river tends to be very wide and shallow, with some sandstone exposures in the riverbed, and a propensity for ice formation within the shallow cross section (Figure 45). The Eight Mile Ford Fishing Access site shown in Figure 45 was reportedly the upper extent of ice gorging on the river in February of 2011. Downstream at RM 53.9, the river is within about 100 feet of one branch of O'Dell Spring Creek. There is a real risk of avulsion into this channel, that runs for over four valley miles downstream before joining the Madison below Ennis (Figure 46). Approaching Ennis, there is increasing development on the left bluff line; however, this area is out of the Channel Migration Zone due to its geology (Figure 47).

Figure 44. View downstream from lower Reach 9 showing West Madison Canal diversion and bluff line on west side of river; note spring creeks in upper right corner of photo. (Kestrel)

Figure 45. View downstream of Eight Mile Ford Fishing Access showing sandstone bluff line and wide, shallow river cross section. (Kestrel)

Figure 46. View downstream showing avulsion risk into spring creek, RM 53.9. (Kestrel)

Figure 47. View downstream showing development along bluff line on the outskirts of Ennis. (Kestrel)

5.3 Reach 7

Reach 7	
Upstream/Downstream RM	50.8/48.0
Length (miles)	2.8
General Location	Ennis to just above Jack Creek
Mean 60-year Migration Distance (ft)	74
Max 60-year Migration Distance (ft)	147
100-year Buffer (ft)	123

Reach 7 extends for a few miles below Ennis to near the mouth of Jack Creek. For approximately the upper two miles of the reach, O'Dell Spring Creek parallels the river and has been mapped as an avulsion hazard area. Just downstream of the highway bridge at Ennis the river is migrating towards the water treatment plant lagoons, however as there is still an approximately 225-foot-wide buffer between the lagoons and the channel, and they appear to be under no immediate threat of erosion. Ice gorging in this area, though, has resulted in water overtopping the levee and flowing through the park adjacent to the water treatment lagoons (Section 1.6.2, Figure 7). Towards the mouth of Jack Creek there are several mapped exposures of Holocene swamp deposits (Kellogg et al, 2000), which may be reflective of historic natural marsh and deltaic conditions that extended several miles upstream of the modern lakeshore. The density of small, relatively stable islands increases as well, and these islands support fairly dense cottonwood stands, although historic imagery indicates that the cottonwood density in 1995 was much greater than today (Figure 48 and Figure 49).

Figure 48. View downstream showing high density of small wooded islands at Valley Garden Fishing Access, Reach 7. (Kestrel)

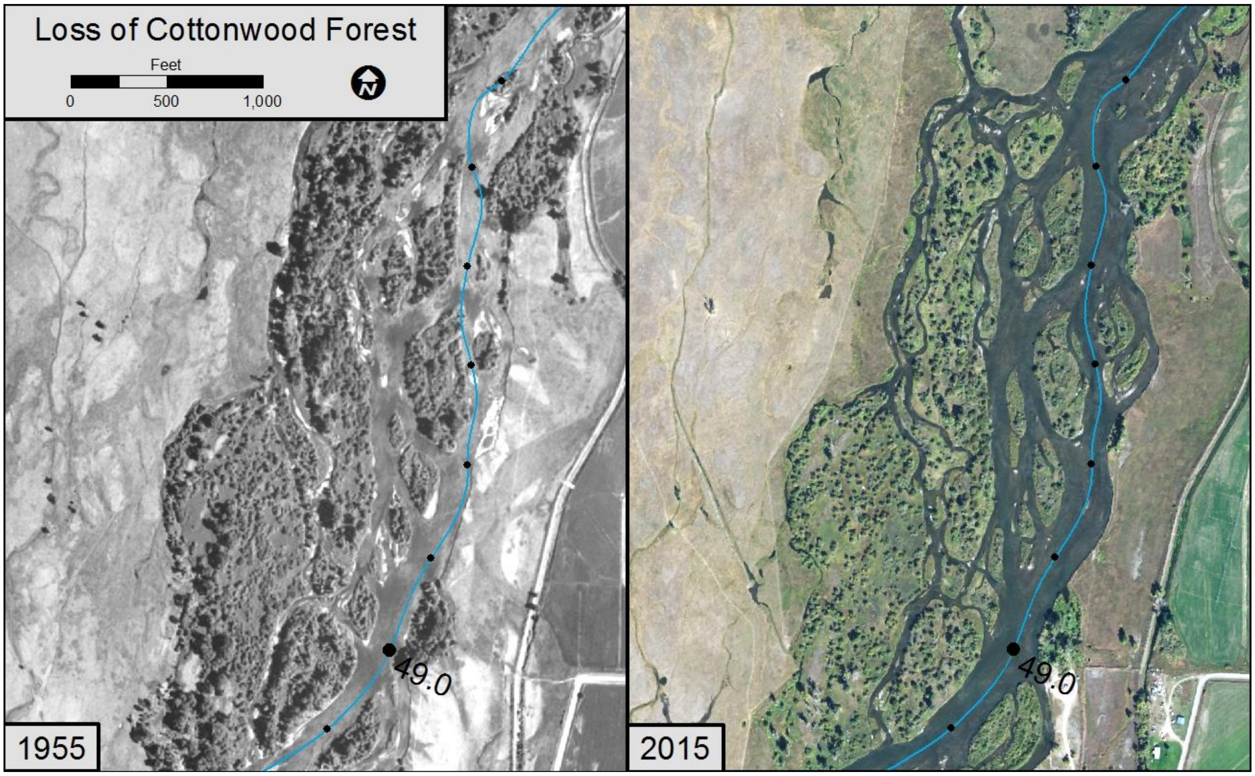

Figure 49. Madison River above Ennis Lake showing loss of cottonwood forest density from 1955 (left) to 2015 (right).

5.4 Reach 6

Reach 6 extends from near the Jack Creek confluence to Ennis Lake. It consists of an increasingly more complex anastomosing channel form, referring to multiple channels that diverge and rejoin, separated by persistent islands rather than open bars (Figure 50). The CMZ becomes over a mile wide across the delta (Figure 51). At RM 46.8, a large avulsion occurred in the delta on the east floodplain, it was subsequently blocked by a channel plug (Figure 52).

Reach 6	
Upstream/Downstream RM	48.0/40.6
Length (miles)	7.5
General Location	Above Ennis Lake
Mean 60-year Migration Distance (ft)	74
Max 60-year Migration Distance (ft)	183
100-year Buffer (ft)	123

The 1869 General Land Office Survey maps show that prior to the construction of Madison Dam, the river had multiple threads both in Reach 6 and downstream under what is now the lake. This indicates that this area was likely a low gradient, swampy system that had grade dictated by the elevation of the bedrock at the head of Bear Trap Canyon, and that the impoundment took advantage of a natural storage area (Figure 53).

Figure 50. View downstream towards Ennis lake showing anastomosing channel form of Madison River. (Kestrel)

Figure 51. View downstream towards Ennis lake showing Madison River delta at Ennis Lake. (Kestrel)

Figure 52. View downstream showing 1955-1979 avulsion blocked by channel plug in foreground. (Kestrel)

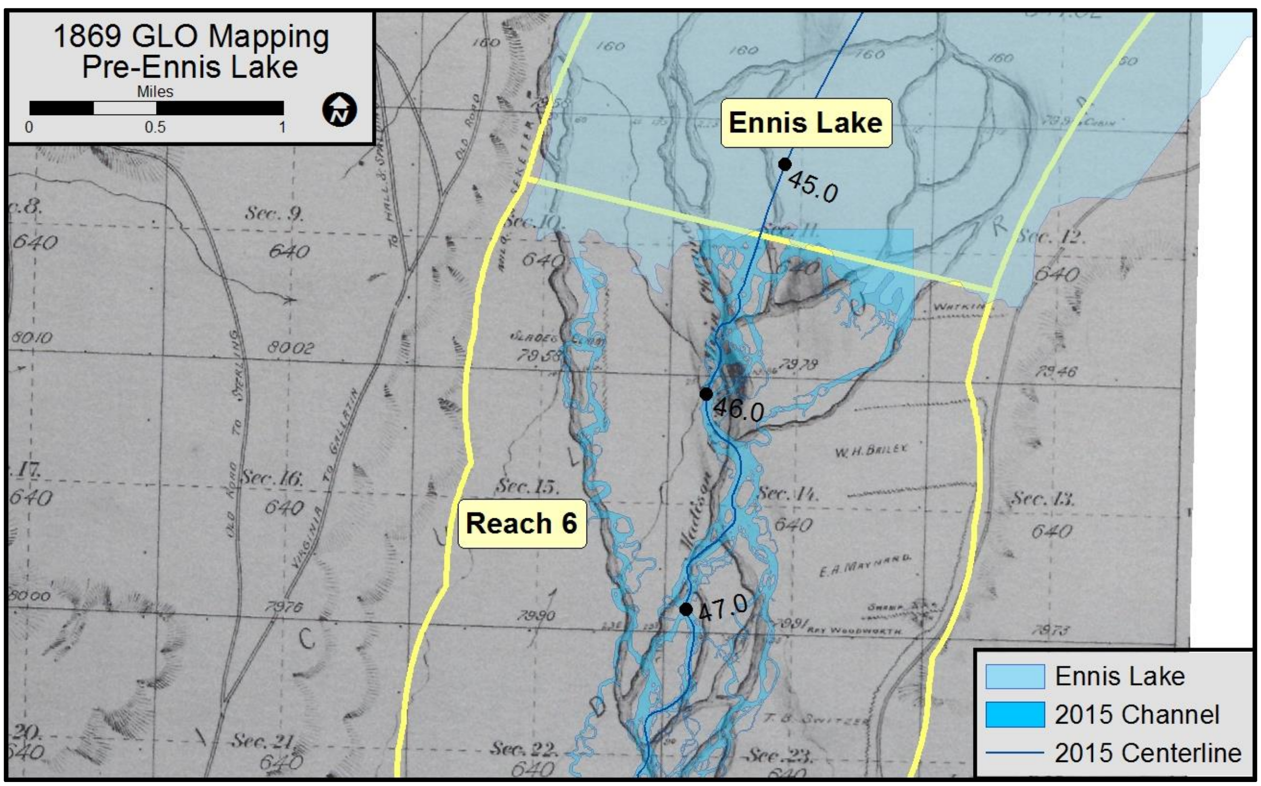

Figure 53. 1869 General Land Office Survey map overlain on 2015 imagery showing complex channel pattern prior to Madison Dam.

5.5 Reach 5

Reach 5	
Upstream/Downstream RM	40.6/31.4
Length (miles)	9.2
General Location	Bear Trap Canyon
Mean 60-year Migration Distance (ft)	28
Max 60-year Migration Distance (ft)	37
100-year Buffer (ft)	46

The Madison River flows through Bear Trap Canyon in Reach 5. The canyon is a major geologic feature, with an approximately 1,300 foot-deep canyon cut into crystalline basement rocks (Archean-age gneiss and schist). At the head of the canyon just below the dam, the channel bed is stripped of sediment indicating that Madison River bedload is trapped upstream in the lake (Figure 54). In the canyon, coarse sediment delivery is primarily related to hillslope processes and alluvial fan deposits at the mouths of tributaries. Rapids are common where bedrock is exposed or rockfalls have entered the channel (Figure 55 and Figure 56).

Figure 54. Sediment-starved channel form below Madison Dam. (Kestrel)

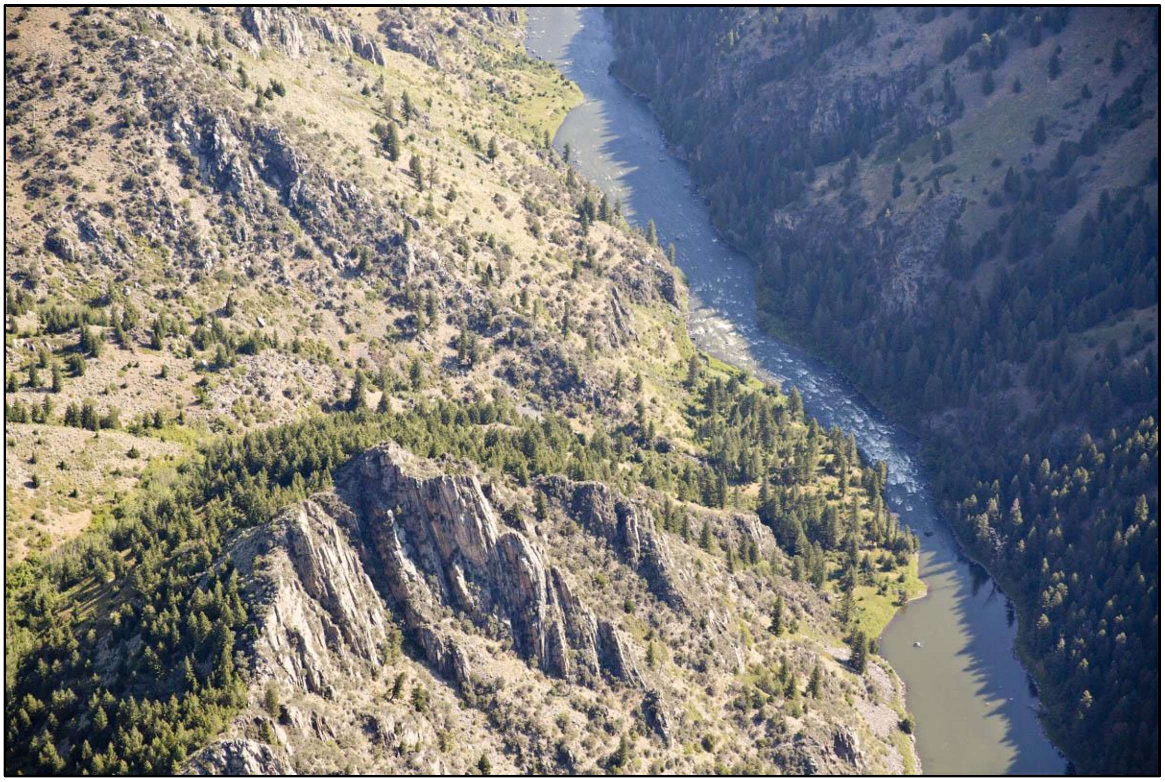

Figure 55. Formation of rapid at tributary mouth/alluvial fan, Bear Trap Canyon. (Kestrel)

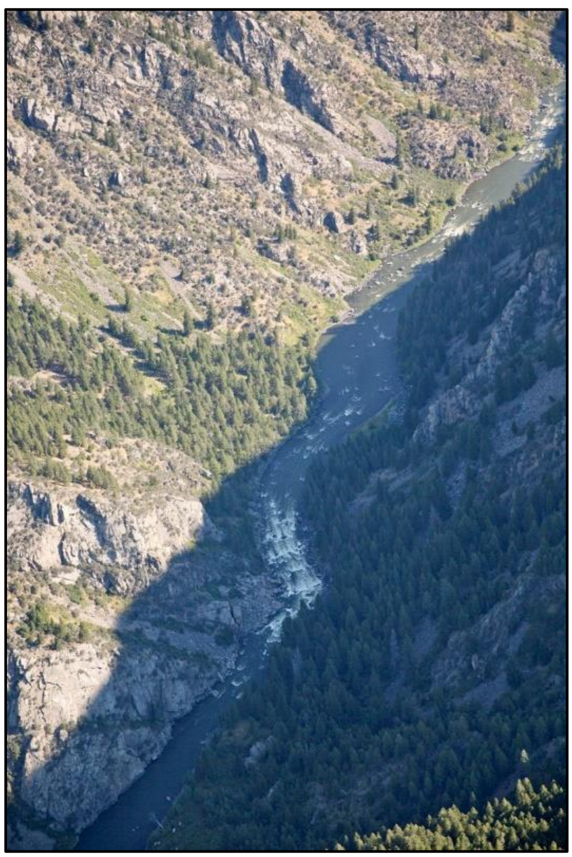

Figure 56. Formation of rapid at bedrock constriction, Bear Trap Canyon. (Kestrel)

5.6 Reach 4

Reach 4	
Upstream/Downstream RM	31.4/18.7
Length (miles)	12.7
General Location	Warm Springs Fishing Access to below Grey Cliff
Mean 60-year Migration Distance (ft)	33
Max 60-year Migration Distance (ft)	59
100-year Buffer (ft)	55

After the Madison River emerges from Bear Trap Canyon, it enters a geomorphic transition zone between the non-deformable canyon section and highly dynamic reaches near Three Forks. For almost 20 river miles, the channel flows between bedrock controls as well as glacial terraces that tend to be coarse grained and show very little erosion since the 1950s (Figure 57 and Figure 58). Although the valley bottom is alluvial, the Channel Migration Zone is relatively narrow with little planform complexity, avulsion risk, or side channel activity. The channel is wide and shallow, and migration rates are similar to those measured in Bear Trap Canyon. The woody riparian corridor is sparse to non-existent. Highway 84 and other access roads follow the corridor closely, but do not substantially encroach into the CMZ because of the geologic constraints on river movement.

Reach 4 appears to be essentially “underfit,” in that upstream sediment trapping and flow controls have reduced the ability for the channel to erode banks and migrate laterally. This, in turn, has resulted in the aging of floodplain cottonwoods with minimal regeneration (Figure 59).

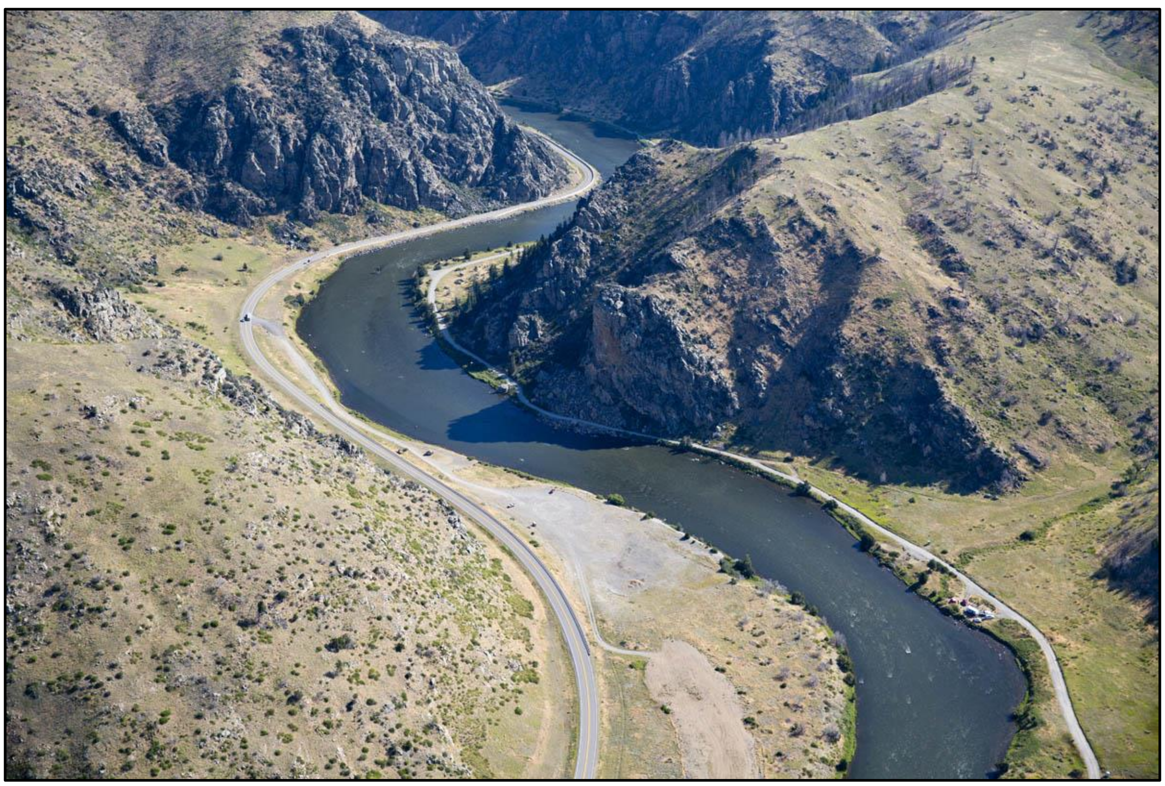

Figure 57. View downstream showing bedrock controls with some inset alluvial terraces. (Kestrel)

Figure 58. View downstream at mouth of Cherry Creek showing expanding terrace areas and minimal woody riparian fringe. (Kestrel)

Figure 59. Lowermost Reach 4 showing expanded floodplain with historic channel remnants and cottonwood swaths. (Kestrel)

5.7 Reach 3

Reach 3	
Upstream/Downstream RM	18.7/11.8
Length (miles)	6.9
General Location	Below Grey Cliff to below Cobblestone
Mean 60-year Migration Distance (ft)	85
Max 60-year Migration Distance (ft)	238
100-year Buffer (ft)	170

Reach 3 extends from about one mile below Greycliff Fishing Access Site to an area of side channel expansion just below Cobblestone Fishing Access Site. This most dominant characteristic is Reach 3 is the striking bluff line on the west side of the channel that is made up of Tertiary-age sandstones and siltstones (Figure 60). The other major feature is the Lower Madison Levee on the east river bank, separating Darlington Ditch from the river corridor (Figure 61). The levee has markedly narrowed the river corridor, and according to the 1969 GLO mapping, it was evidently built on top of the river channel (Figure 62). As the river flows along the bluff line, the river shows a classic anastomosing channel form with numerous islands and moderately dense vegetation. The mean migration rate in Reach 3 is more than triple that of Reach 4 upstream.

Figure 60. View downstream into Reach 3 showing west bank sandstone bluff (Kestrel).

Figure 61. View downstream showing Lower Madison Levee confinement on east bank, with Darlington Ditch flowing on the right (landward) side of the levee. (Kestrel)

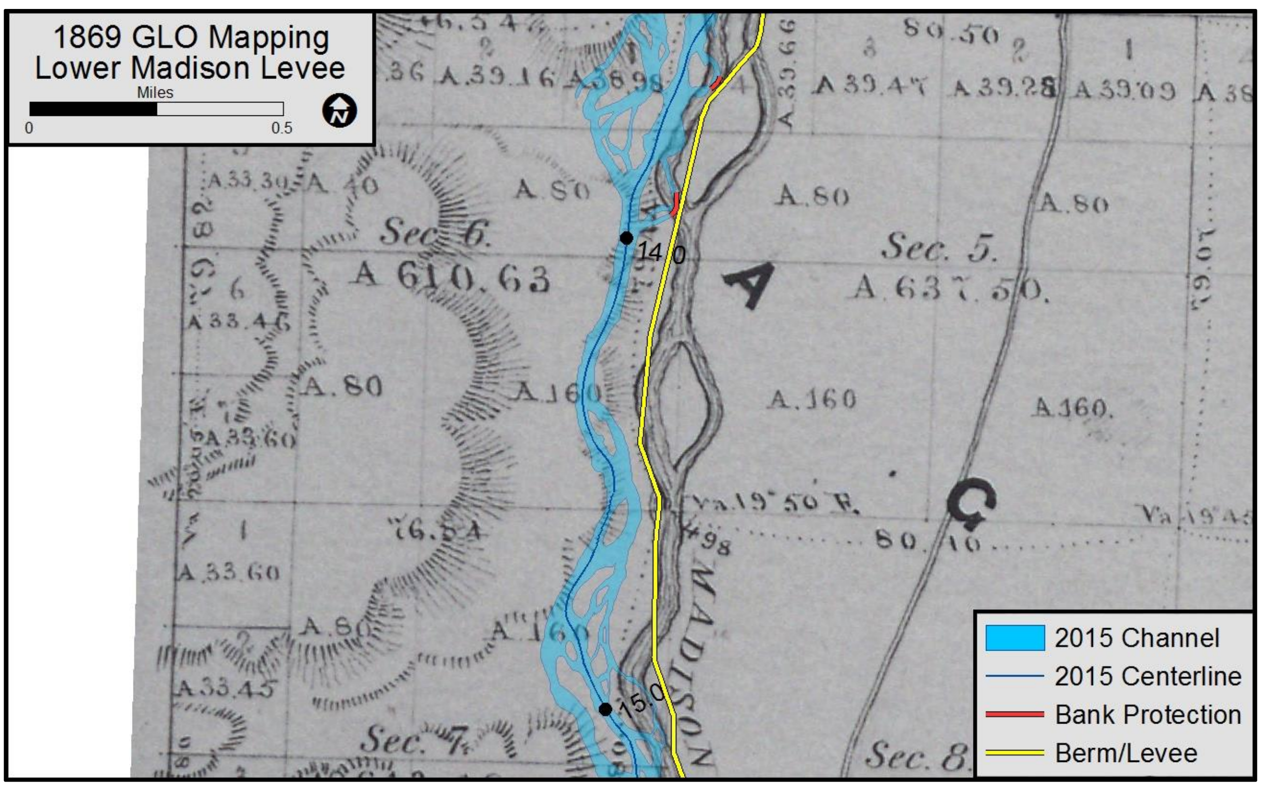

Figure 62. GLO map shown with 2015 banklines showing the 1869 Madison River course shifted westward and displaced by Lower Madison Levee.

5.8 Reach 2

Reach 2	
Upstream/Downstream RM	11.8/3.7
Length (miles)	8.1
General Location	Cobblestone to I-90
Mean 60-year Migration Distance (ft)	154
Max 60-year Migration Distance (ft)	460
100-year Buffer (ft)	309

Reach 2 extends from below Cobblestone to the I-90 bridge at Three Forks. The river still intermittently follows the sandstone bluff on the west side of the valley in this section, and there is an increase in residential development on that bluff line as the river approaches Three Forks. The extent of irrigated land also increases in the downstream direction. Between RM 6.0 and RM 7.5, levees follow both sides of the river, separating irrigated lands from the channel. The greatest impact from levees is on the east side of the river, as the Lower Madison Levee narrows the available corridor and creates distinct pinch points. At Climbing Arrow Road, for example (RM 10.0), the channel network hourglasses down to less than one third of its typical width. The levees in these constricted areas tend to be riprapped due to bank erosion (Figure 65). Even more dramatic is the constriction at the bottom end of Reach 2 at the I-90 bridge (and associated crossings), where the CMZ is abruptly narrowed from about 1,800 feet to 250 feet (Figure 64). The bridge approach and crossings are extensively armored.

Where the stream corridor is wide and channel migration is unimpeded, the combined effects of good floodplain connectivity, common disturbance, and good soils have promoted the development of a dynamic channel planform and a vibrant woody riparian corridor (Figure 65). Reach 2 has the highest migration rates in the project area, resulting in an erosion buffer width of over 300 feet.

Figure 63. View downstream showing armored levee on right bank at pinch point (foreground). (Kestrel)

Figure 64. View downstream showing corridor constriction at I-90 bridge on right. (Kestrel)

Figure 65. View downstream showing wide stream corridor, riparian forest, lower Madison Levee, and restored Darlington Ditch. (Kestrel)

5.9 Reach 1

Reach 1	
Upstream/Downstream RM	3.7/0
Length (miles)	3.7
General Location	I-90 to Jefferson Confluence
Mean 60-year Migration Distance (ft)	103
Max 60-year Migration Distance (ft)	236
100-year Buffer (ft)	206

Reach 1 is the downstream-most reach in the project area, extending from the I-90 bridge near Three Forks to the Jefferson River confluence in Headwaters State Park. It is about four miles long, consisting of a complex multi-thread system that has had historic intermingling with Jefferson River channels. Numerous old dikes are present on the floodplain, some of which have been breached (Figure 66). Avulsions are common in this area of coalescing floodplains. At its confluence with the Jefferson River, it is clear that the sediment load on the Madison River is relatively low, evidenced by lower turbidity, as well as less expansive open bar and riparian colonization areas relative to the Jefferson (Figure 67).

Figure 66. Lower Madison (foreground) showing breached dike. (Kestrel)

Figure 67. Relative turbidity and bar formation from Jefferson River (left) and Madison River (right), Headwaters State Park. (Kestrel)

6 References

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Appendix A: Site Migration Statistics

The Channel Migration Zone Mapping for the Madison River resulted in 934 individual measurements of channel movement between 1955 and 2015. These measurements were taken at approximately 30 foot intervals where notable movement has occurred. Each grouping of migration measurements, such as a bendway, was assigned a Migration Site ID (MSID) that includes the river mile as part of the ID. The statistics for each site are presented in the table below.

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MR01				
MSID-MR-1.43	4	56	48	64
MSID-MR-1.67	2	92	74	110
MSID-MR-1.72	3	66	56	75
MSID-MR-2.94	3	139	66	199
MSID-MR-3.02	3	61	58	67
MSID-MR-3.23	3	216	188	236
MR02				
MSID-MR-10	4	113	88	134
MSID-MR-10.28	2	78	60	95
MSID-MR-10.64	3	62	39	79
MSID-MR-11.41	6	171	119	220
MSID-MR-11.5	3	96	70	118
MSID-MR-11.54	2	144	101	187
MSID-MR-11.61	4	83	64	104
MSID-MR-11.77	5	115	75	146
MSID-MR-4.9	4	275	183	350
MSID-MR-5.4	3	345	286	410
MSID-MR-5.89	4	303	214	400
MSID-MR-6.34	6	284	112	388
MSID-MR-6.53	8	162	89	293
MSID-MR-7.04	3	108	93	129
MSID-MR-7.2	4	78	58	102
MSID-MR-7.31	3	79	52	113
MSID-MR-7.49	5	214	122	254
MSID-MR-7.61	3	133	90	162
MSID-MR-7.68	1	77	77	77
MSID-MR-7.77	2	155	141	168
MSID-MR-7.84	2	129	124	134
MSID-MR-7.92	2	156	120	191
MSID-MR-8.04	2	242	167	317
MSID-MR-8.21	4	306	181	460
MSID-MR-8.51	2	130	125	134
MSID-MR-8.63	7	172	124	262
MSID-MR-8.77	4	152	83	218
MSID-MR-8.82	2	195	135	254
MSID-MR-9.04	5	153	88	223
MSID-MR-9.08	5	150	125	183
MSID-MR-9.25	7	111	48	203
MSID-MR-9.32	6	53	45	59
MSID-MR-9.33	3	61	51	76
MSID-MR-9.34	5	309	199	401
MSID-MR-9.66	5	102	79	130
MSID-MR-9.69	4	155	96	230
MSID-MR-9.81	3	51	41	66
MSID-MR-9.85	3	77	69	83
MSID-MR-9.94	4	48	37	54
MR03				
MSID-MR-11.97	6	119	64	143
MSID-MR-12.16	2	160	136	184
MSID-MR-12.31	3	55	50	60

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-MR-12.48	4	142	94	192
MSID-MR-12.58	5	125	61	224
MSID-MR-13.2	3	48	32	59
MSID-MR-13.32	4	66	31	112
MSID-MR-13.38	1	82	82	82
MSID-MR-13.41	3	57	45	63
MSID-MR-13.48	3	106	60	150
MSID-MR-13.55	4	105	63	135
MSID-MR-13.62	1	45	45	45
MSID-MR-13.64	3	55	44	69
MSID-MR-13.68	3	68	41	91
MSID-MR-13.77	3	34	24	42
MSID-MR-13.82	2	25	24	25
MSID-MR-14.35	3	44	34	51
MSID-MR-14.36	4	53	40	65
MSID-MR-14.48	2	138	110	165
MSID-MR-14.53	4	50	36	58
MSID-MR-14.64	2	92	87	96
MSID-MR-14.79	2	66	57	75
MSID-MR-14.83	3	70	61	80
MSID-MR-14.86	3	78	37	107
MSID-MR-15.09	3	70	47	91
MSID-MR-16.67	2	85	58	111
MSID-MR-16.68	3	78	76	79
MSID-MR-17.19	3	81	61	103
MSID-MR-17.97	2	92	60	124
MSID-MR-18.35	2	167	96	238
MSID-MR-18.51	5	118	97	148
MR04				
MSID-MR-19.81	2	35	34	35
MSID-MR-20.2	2	57	55	59
MSID-MR-22.31	4	29	18	41
MSID-MR-23.1	3	32	25	38
MSID-MR-23.73	2	22	22	22
MSID-MR-24.83	5	29	27	32
MSID-MR-25.03	4	36	29	44
MSID-MR-25.92	2	23	23	23
MSID-MR-26.02	3	22	21	23
MSID-MR-28.26	2	48	46	50
MSID-MR-28.7	5	48	41	55
MSID-MR-29.23	4	21	18	23
MSID-MR-29.94	3	30	27	32
MSID-MR-30.09	5	19	15	23
MSID-MR-30.43	3	28	26	31
MR05				
MSID-MR-34.08	2	20	19	21
MSID-MR-35.02	2	23	16	29
MSID-MR-35.15	3	31	25	37
MSID-MR-38.45	2	28	22	34
MSID-MR-38.97	3	30	25	34
MSID-MR-39.45	3	22	20	25

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MR06				
MSID-MR-45.4	3	40	35	46
MSID-MR-45.54	2	45	39	50
MSID-MR-45.55	2	32	29	34
MSID-MR-45.6	3	44	37	56
MSID-MR-45.65	2	54	46	61
MSID-MR-45.7	4	44	29	57
MSID-MR-45.73	8	64	47	81
MSID-MR-45.8	5	58	45	73
MSID-MR-45.83	2	52	47	57
MSID-MR-45.85	3	102	76	127
MSID-MR-45.87	3	69	58	86
MSID-MR-45.9	3	52	41	65
MSID-MR-45.95	2	99	80	118
MSID-MR-46.03	3	89	75	99
MSID-MR-46.1	4	116	70	148
MSID-MR-46.15	7	64	30	147
MSID-MR-46.17	3	50	37	59
MSID-MR-46.26	7	68	30	107
MSID-MR-46.28	3	143	95	183
MSID-MR-46.35	5	108	52	153
MSID-MR-46.4	6	66	29	102
MSID-MR-46.44	4	43	37	46
MSID-MR-46.45	6	93	64	129
MSID-MR-46.5	7	47	39	60
MSID-MR-46.64	3	88	78	105
MSID-MR-46.65	3	84	69	108
MSID-MR-46.8	4	110	72	149
MSID-MR-46.81	12	50	26	91
MSID-MR-46.83	4	62	59	68
MSID-MR-46.84	3	100	58	122
MSID-MR-46.9	3	56	50	65
MSID-MR-46.96	3	87	55	105
MSID-MR-47.14	3	51	36	68
MSID-MR-47.27	3	52	32	74
MSID-MR-47.29	4	146	112	174
MSID-MR-47.32	5	68	54	77
MSID-MR-47.5	10	78	26	140
MSID-MR-47.52	3	38	26	45
MSID-MR-47.55	2	45	37	53
MSID-MR-47.76	3	82	57	98
MSID-MR-47.77	4	72	41	94
MSID-MR-47.78	2	66	54	78
MSID-MR-47.79	4	92	68	128
MSID-MR-47.8	5	124	90	177
MSID-MR-47.9	6	112	63	166
MR07				
MSID-MR-48	4	78	66	88
MSID-MR-48.04	4	126	99	147
MSID-MR-48.17	3	79	58	108
MSID-MR-48.37	5	90	50	143
MSID-MR-48.42	5	64	49	85
MSID-MR-48.43	2	97	83	111
MSID-MR-48.44	3	77	64	92
MSID-MR-48.45	2	49	43	54
MSID-MR-48.46	4	48	30	66
MSID-MR-48.53	3	52	42	58
MSID-MR-48.69	6	104	82	136
MSID-MR-48.84	5	103	70	123
MSID-MR-48.93	3	75	62	83
MSID-MR-49.05	8	76	49	105
MSID-MR-49.22	5	63	50	81

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-MR-49.39	3	63	51	76
MSID-MR-49.4	2	64	63	65
MSID-MR-49.7	3	59	43	69
MSID-MR-50.01	4	41	30	59
MSID-MR-50.17	7	57	37	96
MSID-MR-50.55	8	66	46	95
MR08				
MSID-MR-50.92	3	32	27	39
MSID-MR-51.17	2	39	38	39
MSID-MR-51.29	2	35	32	38
MSID-MR-51.36	3	34	28	43
MSID-MR-51.4	4	27	24	29
MSID-MR-51.46	4	70	51	88
MSID-MR-51.5	2	38	31	45
MSID-MR-51.92	5	62	42	87
MSID-MR-52.06	8	52	34	72
MSID-MR-52.36	6	59	44	69
MSID-MR-52.61	4	82	48	110
MSID-MR-52.68	2	53	45	60
MSID-MR-52.94	5	61	48	83
MSID-MR-53.05	4	47	37	60
MSID-MR-53.38	5	51	41	59
MSID-MR-53.54	2	28	28	28
MSID-MR-53.69	2	57	43	71
MSID-MR-54.33	5	54	40	79
MSID-MR-54.37	3	65	33	94
MSID-MR-54.43	3	60	47	73
MSID-MR-54.73	3	60	50	68
MSID-MR-54.8	11	38	28	56
MSID-MR-54.84	3	58	52	68
MSID-MR-55.2	8	48	37	66
MSID-MR-55.21	9	46	26	71
MR09				
MSID-MR-55.3	5	40	28	59
MSID-MR-55.31	3	39	36	42
MSID-MR-55.35	3	38	31	45
MSID-MR-55.39	4	47	37	56
MSID-MR-55.44	3	98	30	148
MSID-MR-55.51	2	49	43	54
MSID-MR-55.52	3	116	102	138
MSID-MR-55.59	5	121	54	180
MSID-MR-55.61	4	57	41	65
MSID-MR-55.71	9	54	28	129
MSID-MR-55.8	4	48	40	57
MSID-MR-55.82	11	66	22	117
MSID-MR-55.85	2	24	23	25
MSID-MR-55.87	2	27	21	33
MSID-MR-55.88	5	69	51	106
MSID-MR-56.01	4	56	45	70
MSID-MR-56.16	7	114	56	179
MSID-MR-56.25	2	53	53	53
MSID-MR-56.38	2	57	56	58
MSID-MR-56.39	8	44	28	68
MSID-MR-56.49	2	36	32	39
MSID-MR-56.5	1	35	35	35
MSID-MR-56.6	3	25	21	30
MSID-MR-56.66	11	75	41	96
MSID-MR-56.67	3	72	49	89
MSID-MR-56.82	2	49	43	54
MSID-MR-56.9	10	126	42	212
MSID-MR-57.18	9	87	74	118
MSID-MR-57.23	2	25	23	27

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-MR-57.41	6	178	99	228
MSID-MR-57.56	3	41	30	48
MSID-MR-57.63	10	106	35	148
MSID-MR-57.7	2	29	27	30
MSID-MR-57.89	4	56	40	67
MSID-MR-57.9	3	28	23	36
MSID-MR-57.93	2	55	47	62
MSID-MR-58.06	1	29	29	29
MSID-MR-58.14	5	59	38	93
MSID-MR-58.2	3	21	15	29
MSID-MR-58.25	1	31	31	31
MSID-MR-58.31	2	58	55	61
MSID-MR-58.4	2	41	38	43
MSID-MR-58.45	6	31	21	40

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-MR-58.52	3	21	19	24
MSID-MR-58.53	3	63	49	74
MSID-MR-58.56	2	39	35	43
MSID-MR-58.57	4	88	49	115
MSID-MR-58.61	2	25	19	31
MSID-MR-58.68	3	52	46	63
MSID-MR-59.02	4	46	32	64
MSID-MR-59.3	6	55	28	74
MSID-MR-59.43	3	46	45	47
MSID-MR-59.52	3	47	40	55
MSID-MR-59.65	4	64	30	94
MSID-MR-59.75	2	47	46	47
MSID-MR-59.76	2	42	35	49
MSID-MR-59.8	4	30	27	33

Appendix B: Bridge Photos

Varney Bridge

Varney Bridge marks the upstream limit of the project area. According to the U.S. Department of Interior (No Date), the bridge was originally built in 1897 and is "one of the oldest surviving steel truss bridges in Montana." The original construction costs were $4,999. It is a two span bridge with a total length of 191.2 feet. The bridge is owned and maintained by Madison County and in 1985 was determined eligible for the National Register of Historic Places, though the application was never submitted to the National Park Service. It is currently due for replacement with a similar structure. Of note, the Blaine Spring Creek Bridge, a single span steel truss bridge over a spring creek just to the west of Varney Bridge, is currently being replaced with a historically similar bridge (Madison County, 2011).

Figure 68. Varney Bridge on July 21, 2016. (Kestrel)

Highway 287 (Ennis)

The current Madison River bridge for Highway 287 in Ennis is an approximately 320 foot, concrete structure, with two supporting piers. It was constructed in 2001; replacing a 294 foot, two span, through truss bridge that was originally constructed in 1935 (bridgehunter.com) that was located slightly downstream.

Figure 69. Highway 287 Bridge on July 21, 2016. (Kestrel)

North Ennis Lake Road

The North Ennis Lake Road bridge crosses the outlet channel for the Madison River at the north end of Ennis Lake. It is a five span, concrete structure that is approximately 300 feet long. This bridge is not on an actively flowing section of the Madison River and thus does not influence river processes. The Madison Dam that forms Ennis Lake is approximately 1.5 miles north of the bridge.

Figure 70. North Ennis Lake Road bridge on July 21, 2016. (Kestrel)

Norris Road (Highway 84)

The Norris Road bridge is an approximately 430-foot-long, four span concrete bridge. It is the third bridge in this general location, and the fourth for this section of river. The second bridge was located approximately 1.5 miles upstream (south) in a narrow section of the canyon. The central pier from this bridge remains in the river. The third was located just upstream of the current location and was completely removed when the current bridge was constructed. The channel shows very little movement in the area of the current bridge.

Figure 71. Norris Road (Highway 84) bridge on July 21, 2016. (Kestrel)

Climbing Arrow Road

The Climbing Arrow Road Bridge is a typical Pratt through truss design, approximately 130 feet long. The road is private, accessing ranch and farm land on the west side of the river. It is anchored on a bedrock outcrop on the west side, while the eastern approach has approximately 300 feet of available floodplain width before passing over the Madison River levee.

Figure 72. Climbing Arrow Road bridge (private) on July 21, 2016. (Kestrel)

Three Forks Bridges

Five bridges make up a dense set of river crossings at Three Forks: Interstate 90 (2 bridges), railroad, pedestrian, and Frontage Road. All bridges are located within 1,000 feet of each other. A series of levees on the left bank above and below the bridges effectively armors the west bank.

Figure 73. Bridge grouping at Three Forks on July 21, 2016. (Kestrel)

Appendix C: Irrigation Infrastructure Photos

Figure 74. Sloan Ditch, July 21, 2016 (Kestrel).

Figure 75. Sloan Ditch, July 21, 2016 (Kestrel).

Figure 76. Hutchison Ditch, July 21, 2016 (Kestrel).

Figure 77. Dell Ditch, July 21, 2016 (Kestrel).

Figure 78. Unnamed ditch at Greycliff Campground and fishing access site, July 21, 2016 (Kestrel).

Figure 79. Crowley Ditch, July 21, 2016 (Kestrel).

Figure 80. Darlington Ditch, July 21, 2016 (Kestrel).

Figure 81. Two unnamed ditches, July 21, 2016 (Kestrel).

Appendix D: CMZ Maps