December 31, 2017

Upper Missouri Headwaters River Channel Migration Mapping Summary Report

Prepared by:

Tony Thatcher
DTM Consulting, Inc.
211 N Grand Ave, Suite J
Bozeman, MT 59715

DTMCONSULTING
MAPPING SPECIALISTS

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

<u>Prepared for:</u>

Ruby Valley Conservation District
P.O. Box 295
Sheridan, MT 59749

Ruby Valley Conservation District

Abstract

This report contains a summary overview of a Channel Migration Mapping effort on streams of the Upper Missouri River Watershed. The study collectively extends over almost 500 miles of the Beaverhead, Big Hole, Jefferson, Madison, Gallatin, and East Gallatin Rivers. Each river has a separate detailed report describing the physical setting, flood history, mapping process and results for that system. This summary report provides an overview of the mapping process, as well as a brief description of each river's character and geomorphic variability. This report also contains a comparison of results between rivers to help discern the relative rates of change within each system. Some common management issues associated with river corridor development that were observed in the mapping process are also described. The overall intent is to provide a brief synopsis of the CMZ mapping process, and to discuss each system in terms of geomorphic process, management challenges, and risk.

Contents

List of Figures

List of Tables

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

This report summarizes Channel Migration Zone (CMZ) mapping work created for six primary river courses in the Missouri River Headwaters watershed. These rivers include: Beaverhead River (Clark Canyon Reservoir to Twin Bridges), Madison River (Varney Bridge to Three Forks), Jefferson River (Twin Bridges to Three Forks), Gallatin River (Gallatin Canyon mouth to Three Forks), East Gallatin River (Bridger Creek confluence to confluence with the Gallatin River), and Big Hole River (Wisdom to Twin Bridges). Additionally, Clear Creek was added to 2010 Ruby River mapping (Ruby Reservoir to Twin Bridges). The Big Hole River mapping represents an update to the original mapping from 2005. In total, this mapping accounts for approximately 493 miles of river in the Upper Missouri River headwaters, with 440 miles mapped as part of this study. These river collectively basins drain approximately 79% of the Upper Missouri Watershed area.

The six rivers mapped for this effort are all unique systems that show a high amount of variability with respect to physical setting, hydrology, land use, and geomorphology. The CMZ mapping identify areas of the river corridor that show demonstrable risk of erosion, and to provide additional context as to reach-scale river behavior.

The challenges of channel movement in areas where land use pressures extend to streambanks can be persistent, ever-changing, and costly. From an ecologic perspective, lateral channel migration, avulsion, change, and disturbance are all critical processes that maintain the resilience, vibrancy, and health of our stream systems. Resiliency is maintained through physical deformability of the stream corridor, as that deformability can accommodate floods or other alterations in sediment or flow inputs. Vibrancy and health are maintained though the creation and rejuvenation of both riparian and aquatic habitats, which is what sustains our riparian corridors and fisheries.

Channel movement also poses challenges to stream corridor development, which commonly includes transportation infrastructure, irrigation systems, farming and ranching, and residential development. In many cases landowners understand the risks of capital investing adjacent to rivers, however in many other situations landowners are entirely unaware of the risk they are assuming. To that end, it is our intent to provide mapping and map interpretations that help stakeholders understand, anticipate, and mitigate those risks, to minimize unnecessary costs, and to optimize long-term river function in this series of spectacular river corridors.

1.1 Overview

This report provides a general overview of the mapping process and results. It draws from a series of river-specific reports that contain a much more detailed summary of the data, methodology, and results for each river. Supporting data, maps, and the report are available from the Ruby Valley Conservation District (RVCD) and the Montana State Library CMZ website (http://geoinfo.msl.mt.gov/data/montana_channel_migration_zones/data_maps_and_reports.aspx). Additionally, the Montana State Library CMZ website contains an interactive web map that can be used to view the mapping results and many of the of the project data sets.

The work was primarily 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*. Additional funding was provided by Madison County, Madison Conservation District (DNRC 223 Grant), and Ruby Valley Conservation District (DNRC 223 Grant). The project was administered by the Ruby Valley Conservation District, but includes input and review from stakeholders associated with each of the mapped rivers.

Other rivers in Montana that have significant areas of CMZ mapping include the Yellowstone River, sections of the Flathead, Clark Fork, and Bitterroot Rivers, Deep Creek (Broadwater County), Prickly Pear and Tenmile Creeks (Lewis and Clark County), and Musselshell River (Roundup area).

1.2 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 with the goal of providing 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.

1.3 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).

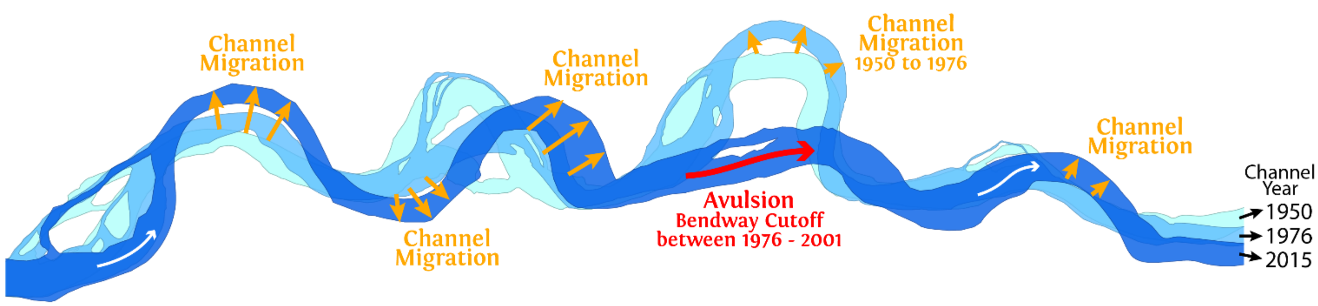

Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

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 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, allowing the calculation of a 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, each river 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 ten 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).

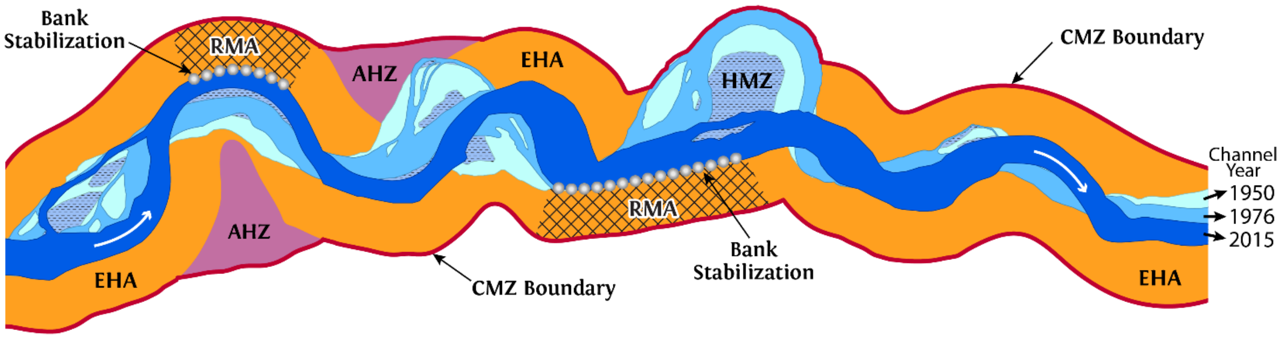

Figure 2. Channel Migration Zone mapping units.

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 channel locations shown in historic 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 Education and Outreach

Education and outreach efforts formed a key component to this study. A total of 14 meetings were held throughout the term of the study to discuss CMZ mapping, river process, mapping results, and CMZ applications. During the CMZ map development process, a meeting was held to discuss draft results for each river. For these meetings, efforts were made to assemble a cross section of stakeholders, including public officials, land use managers, and private citizens in order to gain input on areas of concern, educate stakeholders on river process, and answer questions regarding the mapping.

Towards the end of the study, project summary meetings were held in major communities throughout the study area. The primary goal of these meetings was to ensure that key decision makers (commissioners, planners, conservation district administrators, etc.) attended each meeting and were aware of the study. While these final outreach meetings focused on the mapping in that community, examples from throughout the study area, Montana, and regionally were presented with the goal of educating the stakeholders on ways that CMZ mapping can be used to help make informed decisions that influence the river. Table 1 lists the public outreach and education meetings held as part of this study.

Table 1. Public outreach and education meetings.

Date	Location	Notes
March 8, 2016	Ennis, MT	Project Kickoff, Madison River
September 29, 2016	Dillon, MT	Beaverhead River Preliminary
December 8, 2016	Dillon, MT	Beaverhead River Draft Report
December 14, 2016	Ennis, MT	Madison River Draft Report
February 23, 2017	Whitehall, MT	Jefferson River Draft Report
March 30, 2017	Manhattan, MT	Gallatin and East Gallatin River Draft
March 31, 2017	Bozeman, MT	Gallatin Local Water Quality District
September 13, 2017	Sheridan, MT	Clear Creek Mapping Draft
September 26, 2017	Miles City, MT	Montana Association of Planners, Project overview and CMZ applications
November 8, 2017	Bozeman, MT	Upper Missouri Headwaters Basin Task Force Meeting, CMZ Overview and Project Summary Report
November 15, 2017	Divide, MT	Big Hole River Draft Report
December 5, 2017	Virginia City, MT	Project Summary Report
January 18, 2018	Bozeman, MT	Project Summary Report
January 31, 2018	Dillon, MT	Project Summary Report

1.5 Other River Hazards

While the name of this study is *Upper Missouri Headwaters River/Flood Hazard Map Development*, the study focused primarily on hazards associated with channel migration over the next century. It is important to note that river erosion is only one of a series of hazards associated with river corridors. Flooding, ice jams, and landslides also pose significant hazards, that together with channel migration, define a suite of common hazards associated with rivers. This study included a separate effort that created Discovery Reports for the Madison, Jefferson, and Beaverhead Rivers. Discovery Reports are often the first step gathering and evaluating available floodplain related data and information on community needs and priorities to help guide future flood study and flood mitigation projects. Ice jam and landslide hazards are discussed for each river, though there is limited data to support modeling and mapping of these specific hazards.

1.5.1 Flooding

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.

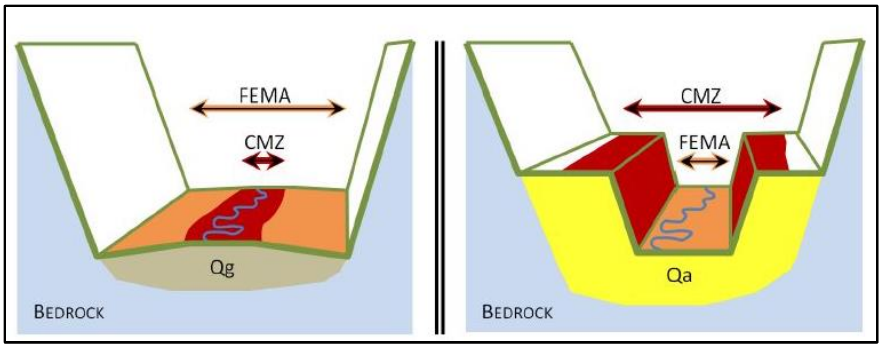

Figure 3. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

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.

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

1.5.2 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 lists five of the six rivers in this study as having 10 or more reported ice jams, with the Big Hole River being the only one absent from the list (Figure 5). Ice jamming and gorging plays an important role on the rivers. 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 (Figure 6). According to the Bureau of Land Management (BLM 2009):

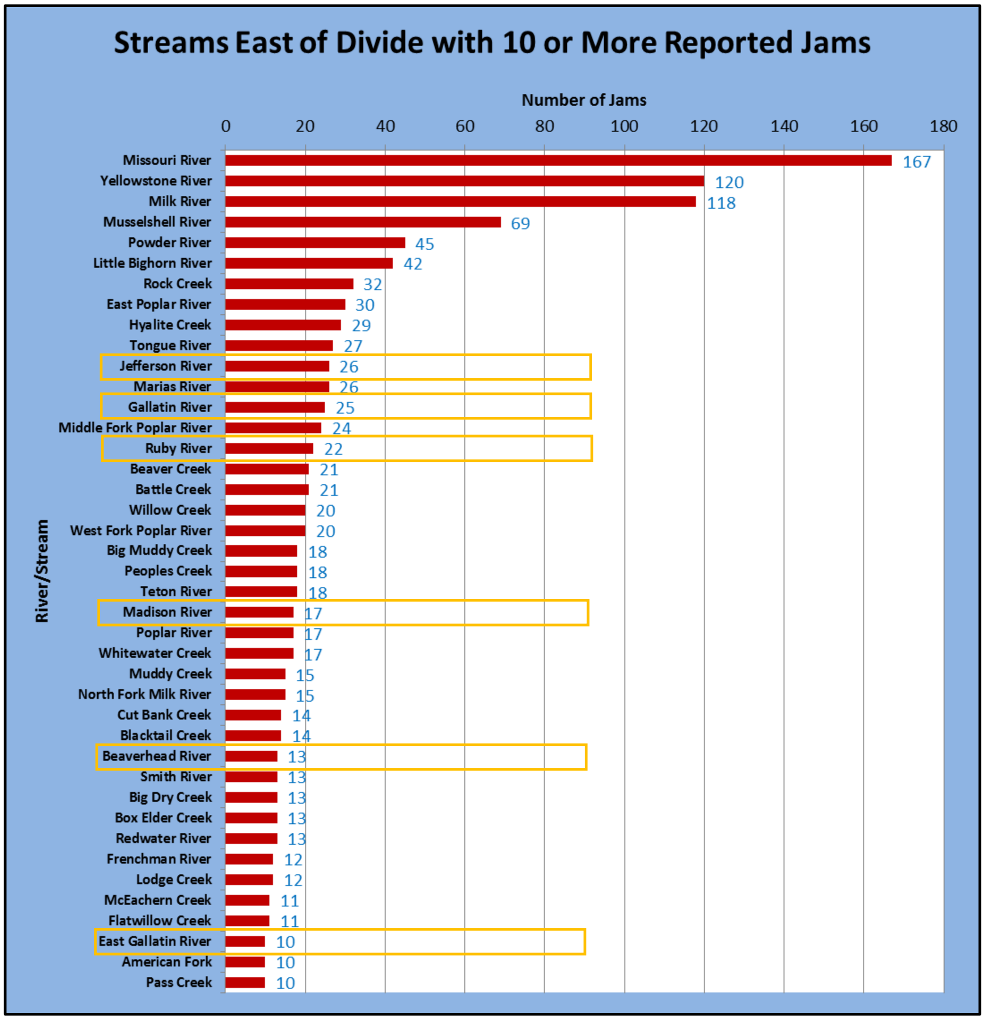

Figure 5. Montana rivers east of the Continental Divide with 10 or more reported ice jams.

Figure 6. Ice gorging in Ennis on January 28, 2007 (T. Thatcher).

1.5.3 Landslides

Landslides and other types of hillslope failures can dramatically affect river process and CMZ boundaries. When large quantities of hillslope debris are delivered to a stream corridor, the material can force streams into new channels by deflection or damming the river. In some cases, the effects of such an event can extend well downstream as the river reworks the material. Several of the rivers mapped for this effort have canyon sections where steep valley walls have the potential to contribute rockslides, debris flows, or landslides. This includes Beartrap Canyon on the Madison River, Clark Canyon on the Beaverhead River, Jefferson Canyon on the Jefferson River, and multiple short canyon sections on the Big Hole River (Divide, Maiden Rock, and Notch Bottom). The largest and most renowned landslide in these stream systems is the Quake Lake Slide on the Upper Madison River, where a massive earthquake-induced landslide blocked the river in August 1959, forming a landslide dam that is 6 miles long and 190 feet deep. This slide is upstream of the CMZ mapping area on the Madison River, yet still influences system hydrology and sediment delivery

Because of the inherent complexities and uncertainties in predicting hillslope processes, the potential for future hillslope failure has not been integrated into the CMZ mapping. However, geologic maps were reviewed for each river to see where active landslides have been mapped, and these sites are discussed in narrative form. Canyon areas that are prone to rock slides and debris flows are also pointed out where visible. In general, however, hillslope failures are considered a site-specific hazard that is beyond the level of analysis presented here.

1.6 Potential Applications of the CMZ Maps

The CMZ mapping is intended to support a myriad of applications (Figure 7), but the mapping should be primarily viewed as a tool to support informed management decisions throughout a river corridor. 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.

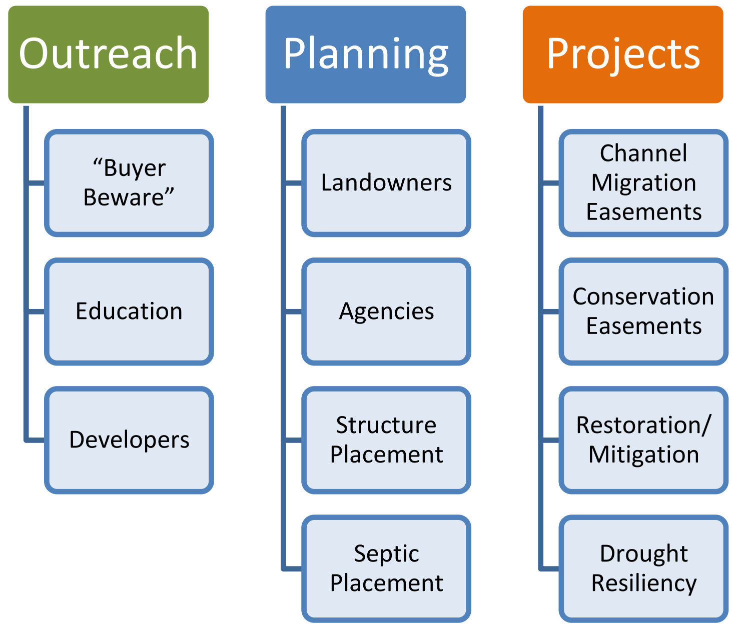

Figure 7. Potential applications.

Note:

The CMZ mapping developed in this study 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.

1.7 Acknowledgements

We would like to extend our gratitude to Rebecca Ramsey of Ruby Watershed Council, Shirley Galovic and David Stout of Ruby Conservation District for their assistance in contract management and scheduling. Ann Schwend (DNRC Water Resource Planner) provided critical project oversight and review throughout the development and implementation of the grant and study. The following individuals provided input and review while developing the mapping and report, and help plan the public outreach meetings. This study would not have been possible without their assistance. We apologize for anyone we have forgotten to include in this list.

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), Mary Hendrix (Gallatin CD Administrator), : Jennifer Downing (Big Hole Watershed Committee Executive Director), Sean O'Callaghan (Gallatin County Planning Director), Steve Story (DNRC Water Operations Bureau Chief), Jamie Cottom (Beaverhead CD Administrator), Ron Spoon (Montana Fish Wildlife and Parks), Ted Dodge, and Rick Hartz (Madison County Planner).

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 Methods

The CMZ mapping approach 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. While the mapping methods for all the rivers in the Missouri Headwaters are largely the same, there are some details such as imagery dates that are specific to each river. Detailed information for each river is included in the river's individual CMZ report. The following section summarizes the CMZ mapping methodology that was applied to all rivers. For more detailed information regarding the mapping methodology, please refer to the individual reports.

2.1 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 rest of the Upper Missouri CMZ Mapping utilizes this reference system. 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. All data, along with a web map application, will be archived at the Montana State Library Channel Migration Zone Mapping web site (http://geoinfo.msl.mt.gov/data/montana_channel_migration_zones).

2.2 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.

In general, three key imagery data sets were used for the mapping. The earliest was 1:20,000 scale imagery from 1955 (1965 was used for the lower Madison, Gallatin and East Gallatin Rivers) acquired from the USDA. All rivers used 1:40,000 scale imagery from the USDA for 1979. NAIP imagery was used for the most recent data set for all rivers. The exact NAIP year depended on when the mapping was completed. As the Ruby River was mapped in 2010, it relied on 2009 NAIP imagery. Both 2013 and 2015 NAIP imagery were used for the Beaverhead, Clear Creek, East Gallatin, Gallatin, and Madison Rivers. The Big Hole mapping used the only 2015 NAIP imagery.

The USDA imagery were delivered as high-resolution (12.5 micron) TIFF images. They were then orthorecitified by Aerial Services, Inc. (ASI) in Cedar Falls, Iowa, using 2015 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. Figure 8 through Figure 10 show examples of imagery, along with mapped banklines.

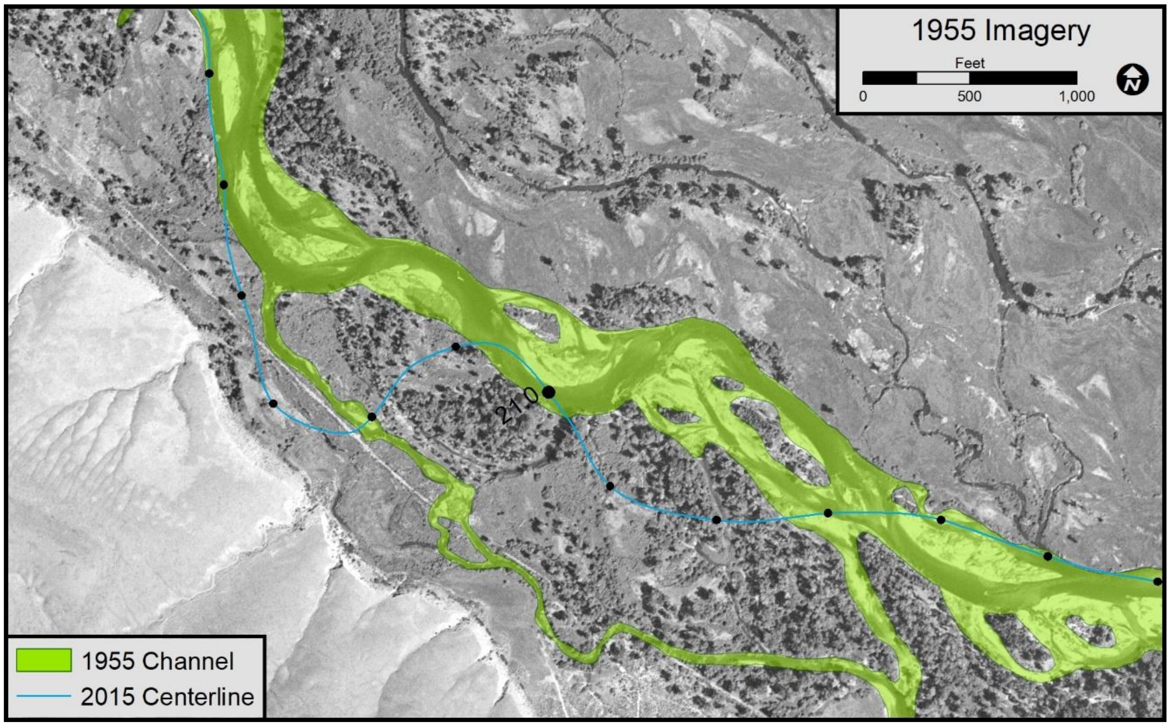

Figure 8. Example 1955 imagery, Big Hole River CMZ development.

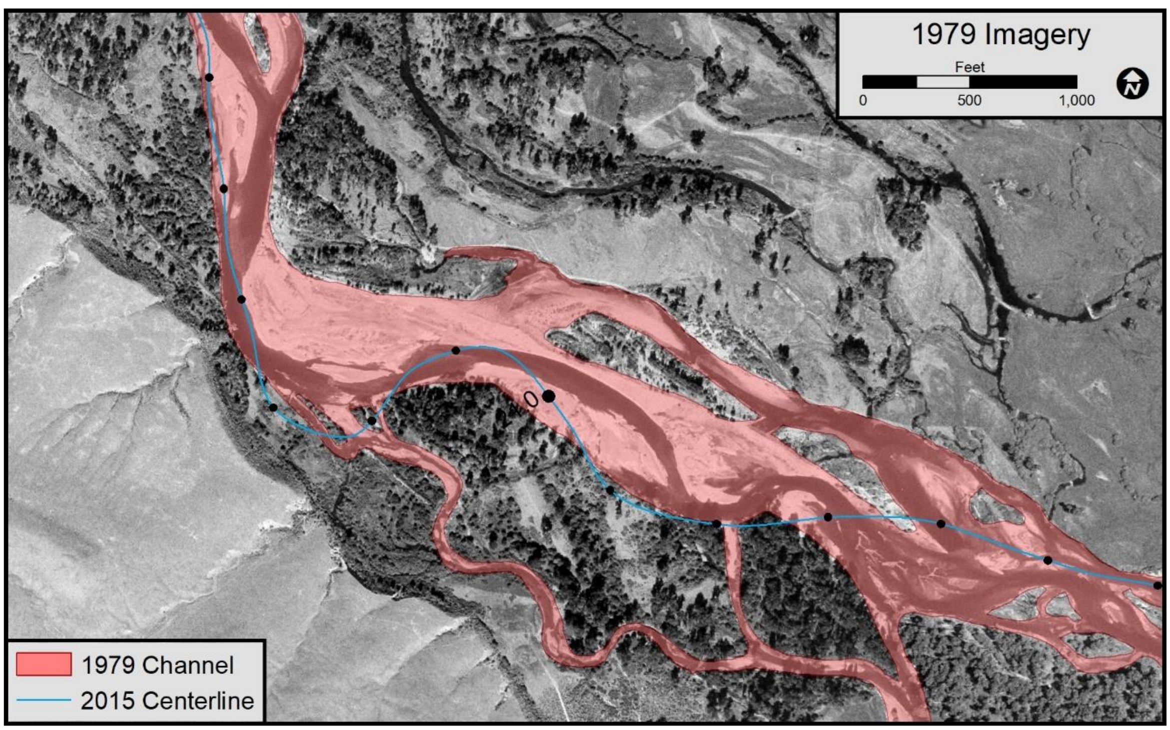

Figure 9. Example 1979 imagery, Big Hole River CMZ development.

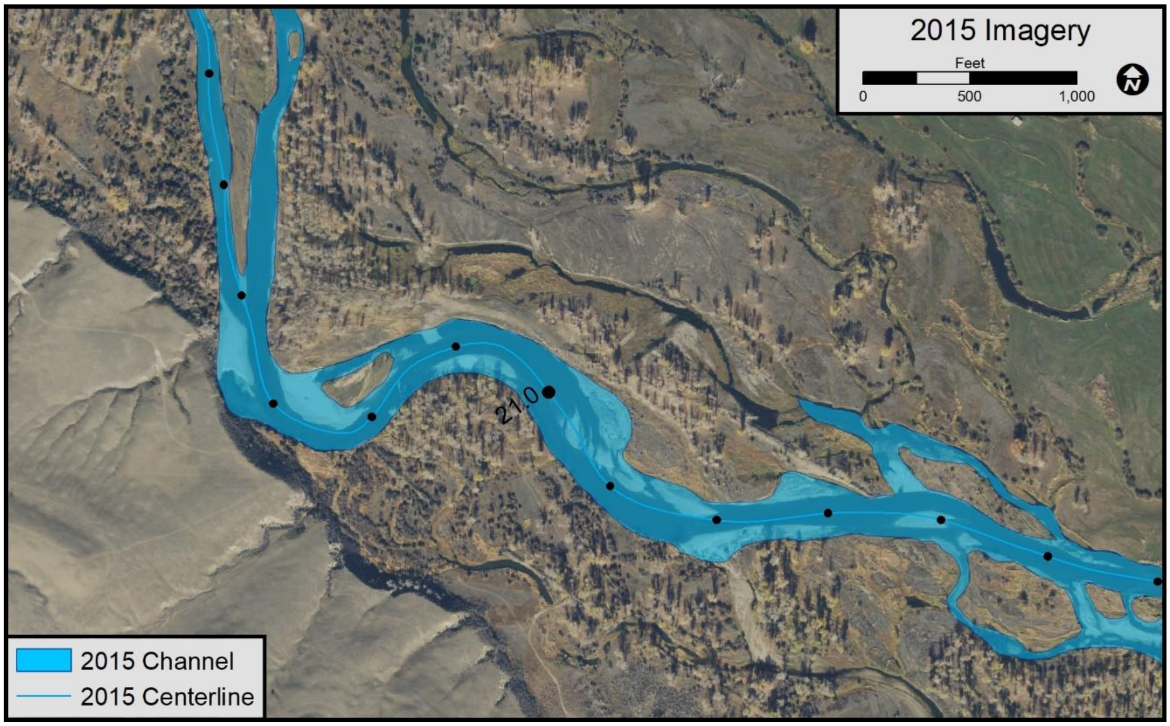

Figure 10. Example 2015 imagery, Big Hole River CMZ development.

2.3 Bankline Mapping

Banklines representing bankfull margins were digitized for each year of imagery at a scale of approximately 1:2,000. 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. Examples of bankline mapping are shown in Figure 8 through Figure 10.

2.4 Migration Rate Measurements

Once the banklines were developed, they were evaluated in terms of discernable channel migration since the earliest bankline mapping. 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 regular intervals of approximately one half the average channel width (Figure 11). A total of 7,818 migration vectors at 1,980 sites (e.g. a bendway) were generated for the all rivers in the study. These measurements were then summarized by reach for each river. The results were then used to define a reach-scale erosion buffer width to allow for likely future bankline erosion.

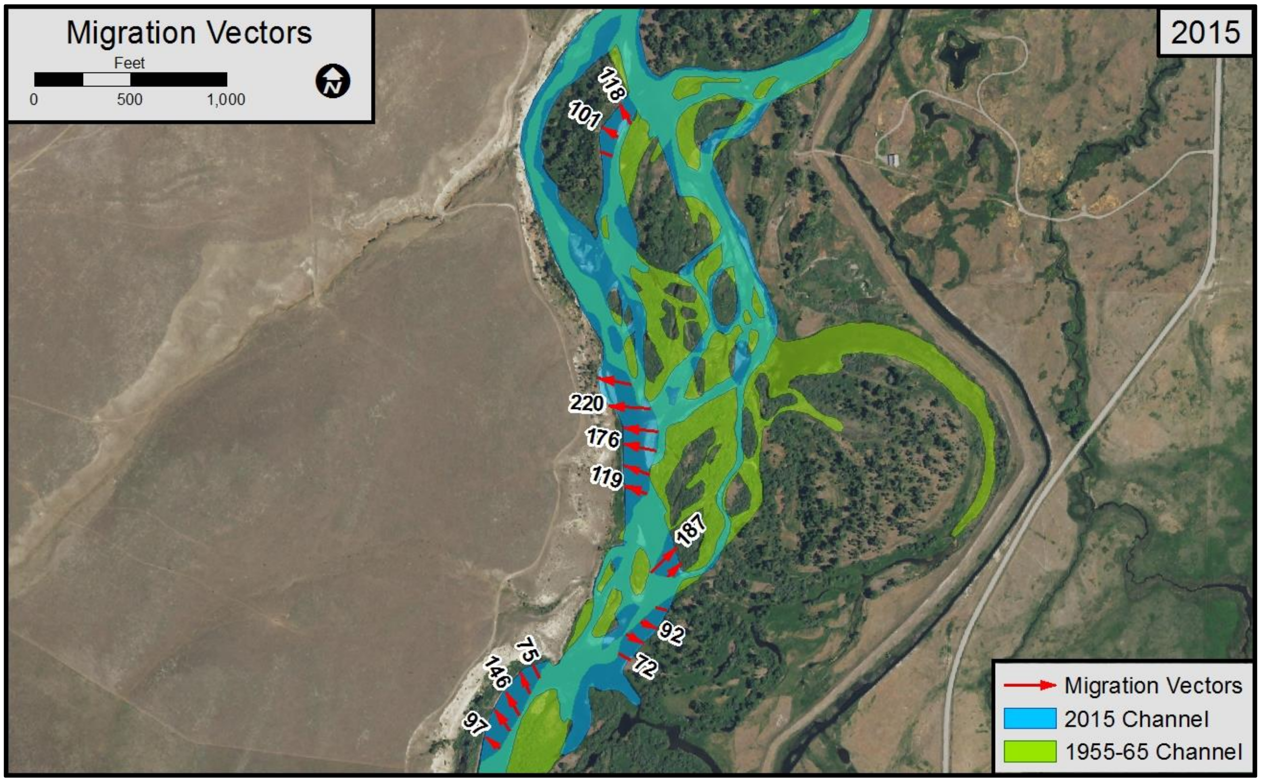

Figure 11. Example of migration measurements (migration distance in feet).

2.5 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 using aerial photos, topographic data, and inundation modeling results.

3 CMZ Mapping Results by River

CMZ mapping is a unique type of geomorphic assessment in that it is based on a broad empirical evaluation of historic and projected changes in river location. The assessment is based largely on historic mapping, and the results provide insight as to the reach-scale geomorphic character of each river. Since the rates and patterns of planform change reflect the combined influences of geology, hydrology, ice jams, land use, and riparian condition on fluvial geomorphology, it is therefore valuable to consider how these factors come into play, and how future changes in these influences may alter stream behavior and mapping results. To that end, each river has been described with some attention paid to the context of those geomorphic influences, which include physical setting, flood history, flow management, land use, and infrastructure controls.

The results show that each river system has unique characteristics that affect rates of change and risks associated with corridor development. The following section describes those characteristics to capture the overall "personality" of each river as observed in the CMZ mapping process.

3.1 Geography

With the conclusion of this study, CMZ mapping is available for the primary rivers that drain 79% of the Upper Missouri Headwaters watershed area (Table 2). Almost 500 miles of river were mapped, and each river was flown by Kestrel Aerial Services to collect oblique air photos to assist with site interpretation and outreach. The drainages not included in the study are the Red Rock River above Clark Canyon Reservoir and the Boulder River north of Whitehall (Figure 12).

Table 2. Rivers with CMZ mapping in the Missouri River Headwaters Watershed.

River	Total Length (mi)	Mapped Length (mi)	Unmapped Length (mi)	Area (mi^2)	% of Upper Missouri
Beaverhead River	83.2	83.2	0	1502	11%
Big Hole River	153	111	42	2789	20%
East Gallatin	41.4	41.4	0	642	5%
Gallatin River	120	55	65	1204	9%
Jefferson River	76	76	0	1299	9%
Madison River	183	62	121	2556	18%
Ruby River	76	53.7	22.3	966	7%
-Clear Creek	11.1	11.1	0	NA	NA
Totals	**744**	**493**	**250**	**10,958**	**79%**

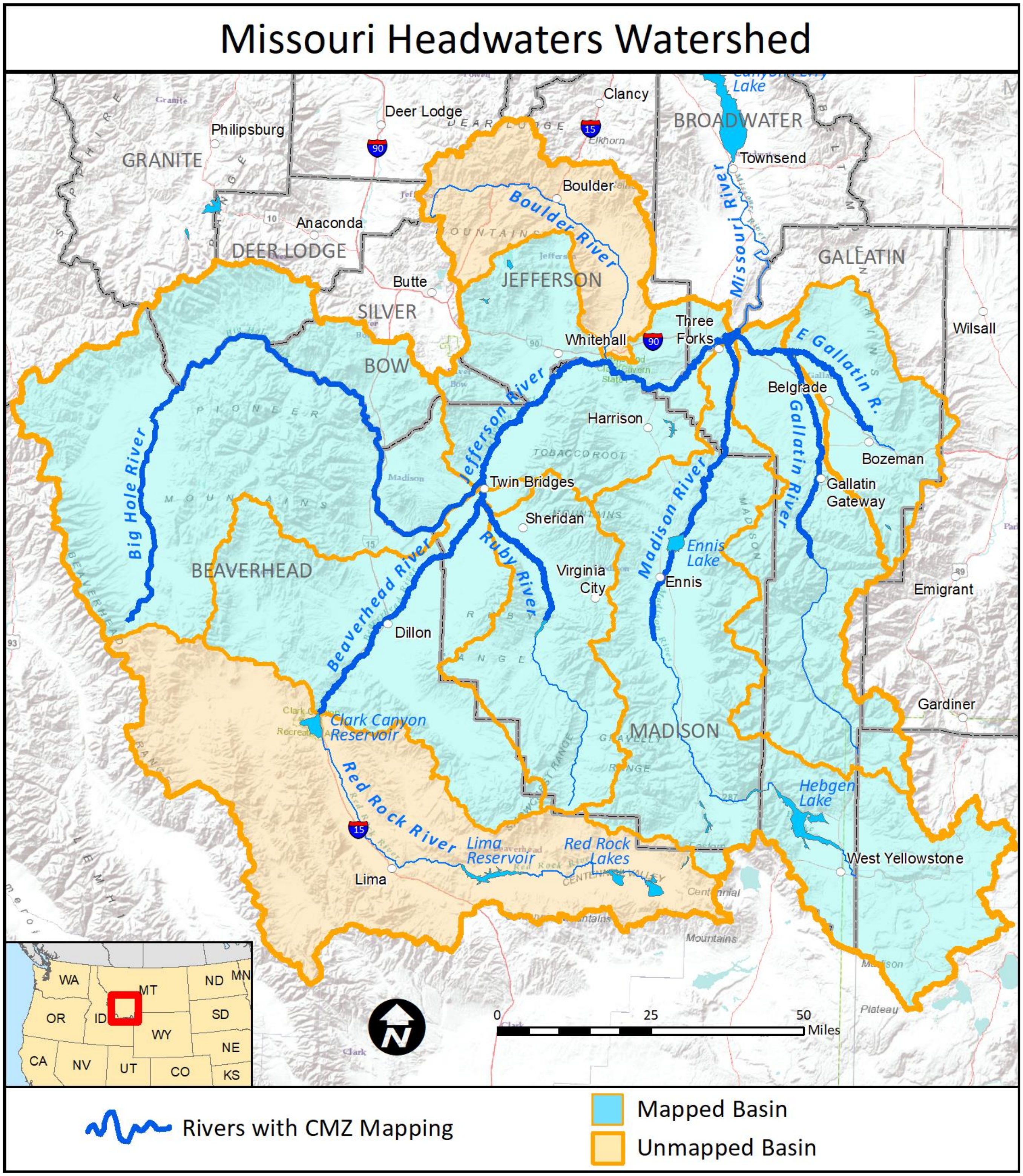

Figure 12. Missouri Headwaters Watershed.

3.2 Beaverhead River

The 83-mile long project reach of the Beaverhead River flows from the outlet of Clark Canyon Dam through Clark Canyon, where it turns northward to traverse the Beaverhead River Valley between Dillon and Twin Bridges (Figure 16). For the first 15 miles below Clark Canyon Dam, the river flows through a narrow canyon that is constricted by both volcanic rocks and transportation infrastructure (Figure 13 and Figure 14). The combined effects of Interstate 15, a rail line, and frontage road severely confine the naturally narrow stream corridor, in places isolating broad swaths of historic floodplain area. The river exits the canyon at a narrow constriction at Barretts, entering a broad valley for the remainder of its course to Twin Bridges. Some sections in the Beaverhead Valley show severe riparian degradation adjacent to the river since the 1950s, which can reduce floodplain and streambank resiliency. Many of these areas of riparian clearing have avulsion pathways that follow old floodplain channels (Figure 15). A few miles downstream of Dillon, the modern river is perched about 6 feet above a series of channel remnants to the west, including Selway Slough, Murray Gilbert Slough, and Albers Slough (Figure 17). This perching of the river over its ancestral floodplain creates a long-term flood and avulsion risk that is several miles wide. Because of the large scale of the perched segment, however, it was not included in the CMZ maps as a high risk avulsion hazard. That designation would require a more detailed investigation of floodplain connectivity and erodibility between the Beaverhead River and adjacent sloughs. Downstream of Beaverhead Rock, the Beaverhead River is very sinuous, with active channel meandering and cutoff; in some cases, future cutoffs will abandon irrigation points of diversion (Figure 18).

Figure 13. View downstream over Clark Canyon Dam, Montana (Kestrel).

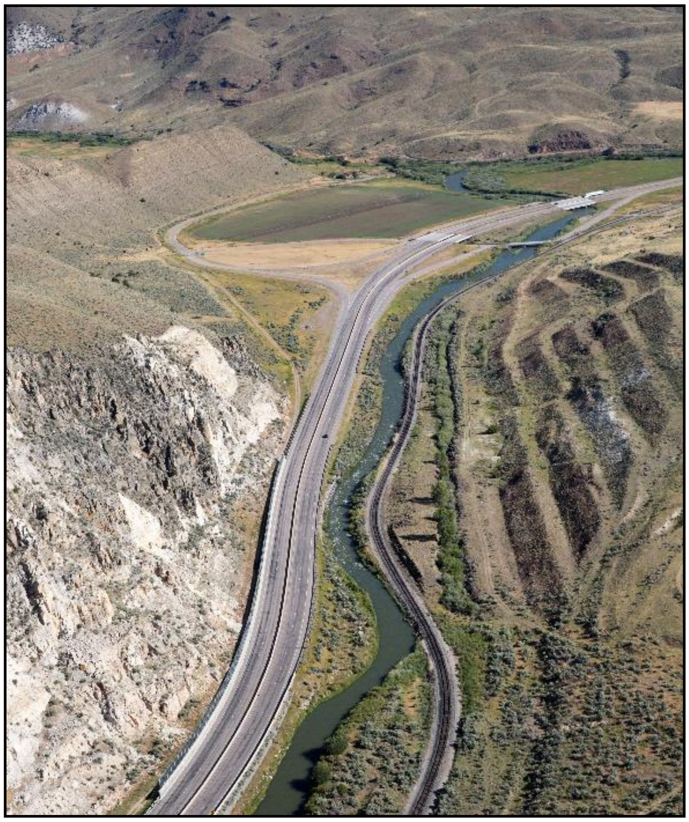

Figure 14. View downstream towards Grasshopper Creek showing Paleozoic-age sandstones on left valley wall, terraced right valley wall; an active landslide can be seen in distance at mouth of Grasshopper Creek (hummock ground surface) (Kestrel).

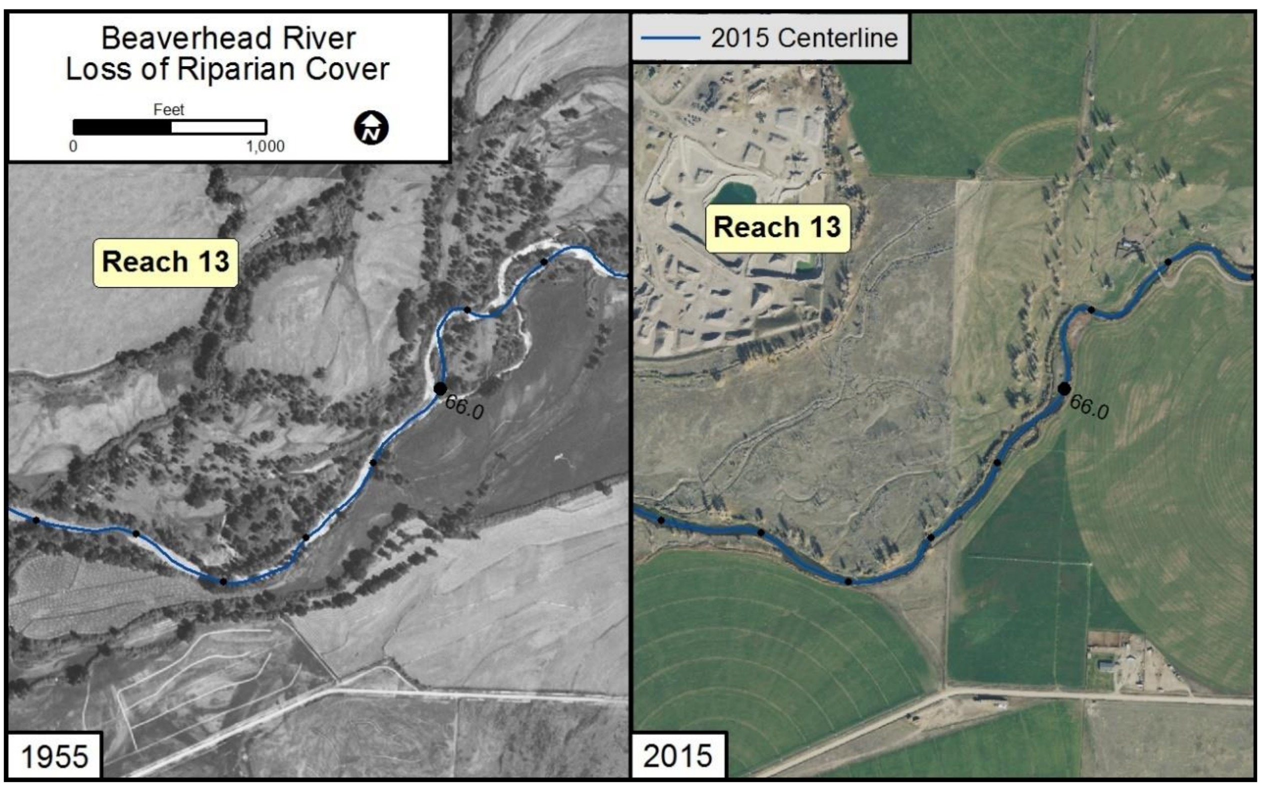

Figure 15. Loss of riparian cover downstream of Barrets from 1955 (left) to 2015 (right).

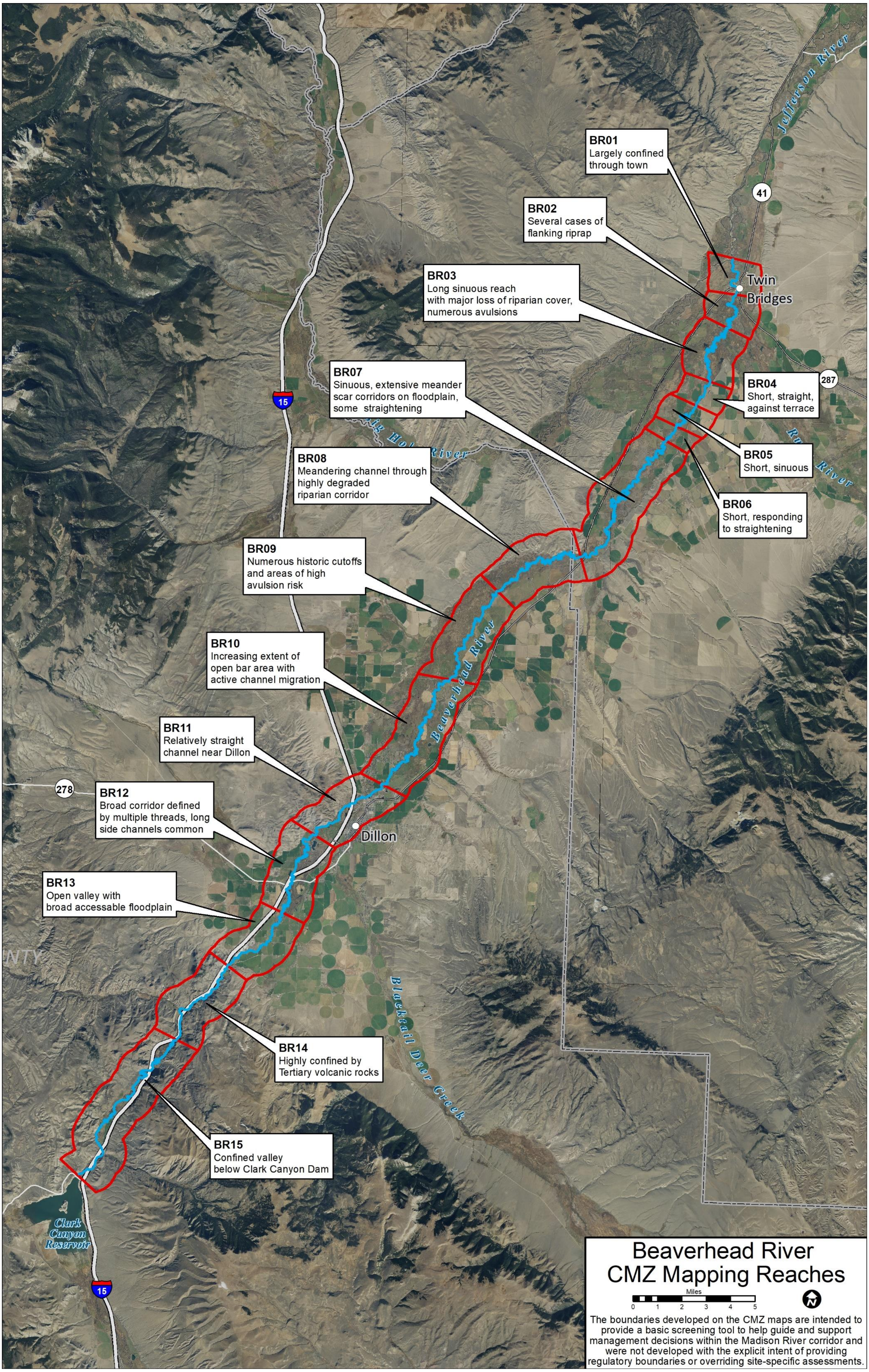

Figure 16. Beaverhead River CMZ mapping reaches.

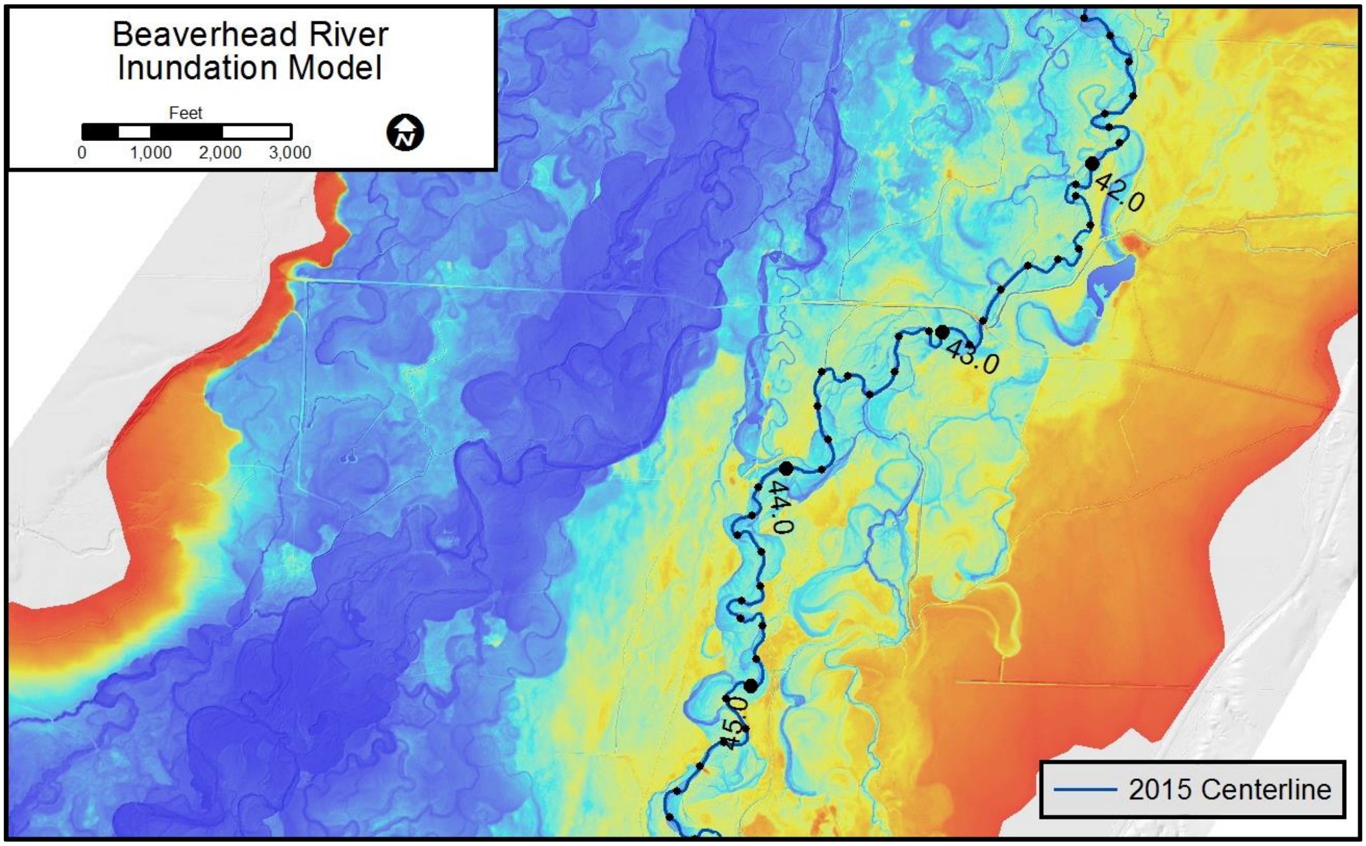

Figure 17. Inundation Modeling results showing perched section of Beaverhead River; lowest elevations are in dark blue.

Figure 18. View downstream near Dillon showing diversion structure at risk of abandonment by bendway cutoff (Kestrel).

Clark Canyon reservoir was built between 1961 and 1964 for irrigation and flood control. Before the dam was built, the flood peaks on the Beaverhead River were highly variable, with multiple events exceeding a 100-year flood since 1907. The relatively quiet post-dam flooding pattern consists of one enormous flood in 1984 and persistently low annual peaks since the late 1980s. From a geomorphic perspective, one of the most striking patterns in the flow record is the lack of channel forming flows over recent decades. For example, the 2-year flow, which tends to strongly influence channel form, has been exceeded only twice since the late 1980s at the Barretts gaging station south of Dillon.

The flow history on the Beaverhead River indicates that major floods can still occur with Clark Canyon Reservoir in place. The 1984 flood was caused by a long, wet spring that culminated with June flooding; the Beaverhead and Ruby Rivers have been identified as experiencing especially severe flows (USACE, 1984). One of the biggest problems in the area during the 1984 flood was flooding on Blacktail Creek in Dillon, where flows were routed using hay bales and railroad ties. Extensive damage to bridges and roads was recorded in the Beaverhead and Ruby River basins during that event (USACE, 1984).

Mean migration rates on the Beaverhead River range from 0.6 feet per year in geologically confined reaches to 1.6 feet per year in more dynamic areas below Dillon. Relative to other rivers in the Upper Missouri Watershed, these rates are notably low, which is to be expected with the marked absence of channel forming flows in recent decades. It should be noted, however, that floodplain development, riparian clearing, and a recent lack of channel-forming flows have probably made the system less resilient to floods such as that of 1984.

3.3 Big Hole River

The mapping segment of the Big Hole River extends from Wisdom to Twin Bridges, a distance of 111 river miles (Figure 21). Over this project reach, the river character ranges from highly dynamic multi-thread channels in unconfined river bottoms to confined and steep bedrock canyons that show very little change on the scale of decades.

One interesting aspect of the Big Hole River is its geologic history and resulting tortuous path through and around the Pioneer Mountains. According to Vuke (2004), the Big Hole River has changed course dramatically over the past 25 million years. Initially, the ancestral Big Hole River flowed northward through what is now the Divide Valley towards the Deer Lodge Basin. Geologic deposits between Divide and Butte record this northerly flow path, and mark an unusual location on the Continental Divide, where relatively low elevation alluvial deposits form the divide as it crosses from the Highland Mountains south of Butte towards Fleecer Ridge in the north Pioneers. Faulting then diverted the river to the west, where it flowed into what is now the Big Hole Valley. As the valley filled and continued tectonism occurred, the river switched course again and flowed back to the east, downcutting into older rocks west of Divide, and following the ancestral river valley south of Divide. Downcutting south of Divide also created the canyon section near Maiden Rock, which is west of its original valley location (Vuke, 2004).

From Wisdom to Pintlar Creek, the upper Big Hole River flows through a wide, willow-dominated, relatively low-gradient valley floor that hosts a complex mosaic of active and historic channels (Figure 19). Mapped channel changes in this upper segment since 1955 include lateral channel migration, rapid channel relocation into old swales, and wholesale creation of new channels on the floodplain (Figure 20). Channel blockages due to sediment loading, debris accumulations, and/or ice jamming has likely played a role in driving channel changes in the reach. The 1950s imagery of the upper Big Hole shows a dense riparian corridor supported by beaver dam impoundments and a shallow water table, which, coupled with little evidence of in-stream sediment storage, indicates a resilient floodplain that probably displayed low rates of channel movement and floodplain reworking (Figure 22). By the late 1970s, the system shifted to a much lower density of riparian shrubs on the floodplain, less evidence of emergent wetlands, and extensive open bar features in the channel, indicating more rapid bank migration in recent decades. Mean migration rates since the 1950s average 1.2 to 1.6 feet per year.

From Pintlar Creek to Melrose, the river flows through a series of geologic controls including bedrock valley walls, alluvial fans, and older river terraces that confine the river corridor (Figure 23 and Figure 24). Migration rates are generally low, although where the alluvial valley locally widens, channel movement tends to be discernable and measurable. Whereas the CMZ boundaries in the bedrock canyon sections are very narrow, less confined areas are more complex due to both bank erosion and channel avulsion.

Figure 19. View downstream of Reach BH13 showing broad valley bottom and willow-dominated riparian corridor (Kestrel).

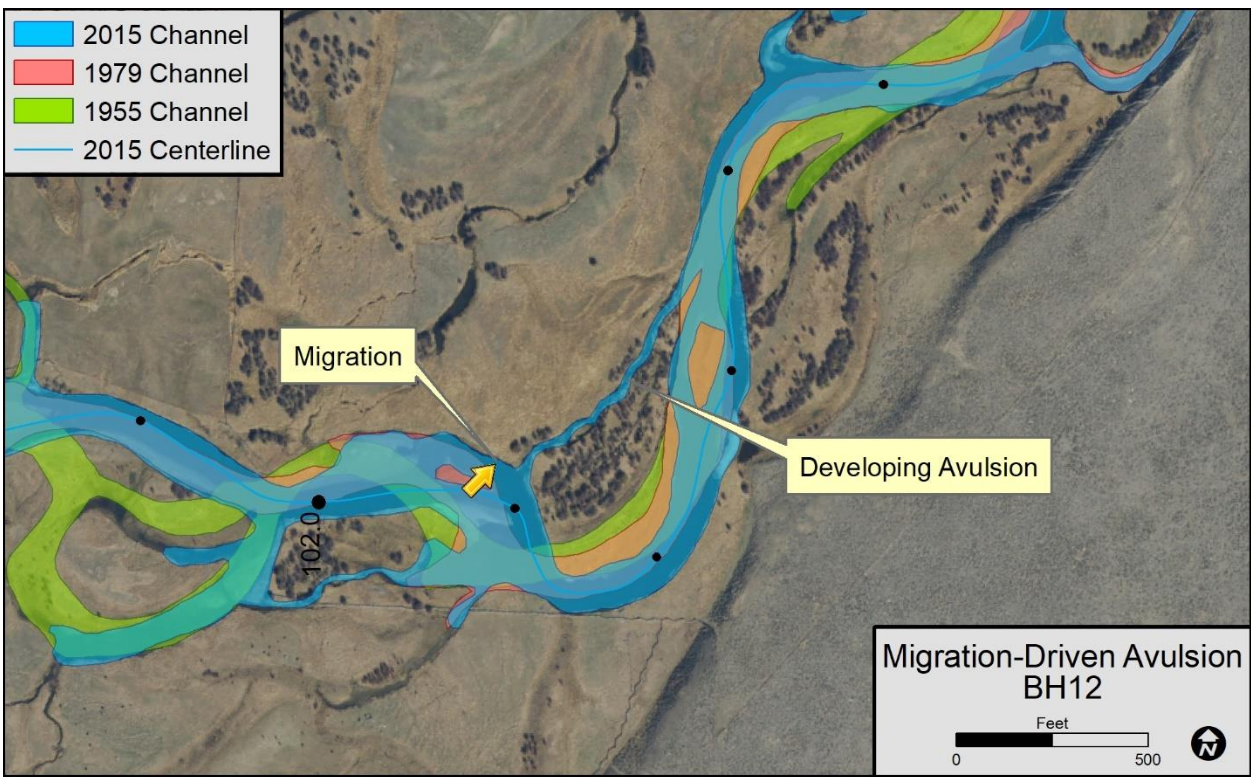

Figure 20. Big Hole River at RM 102 showing northeastward migration into floodplain swale driving bendway cutoff/avulsion.

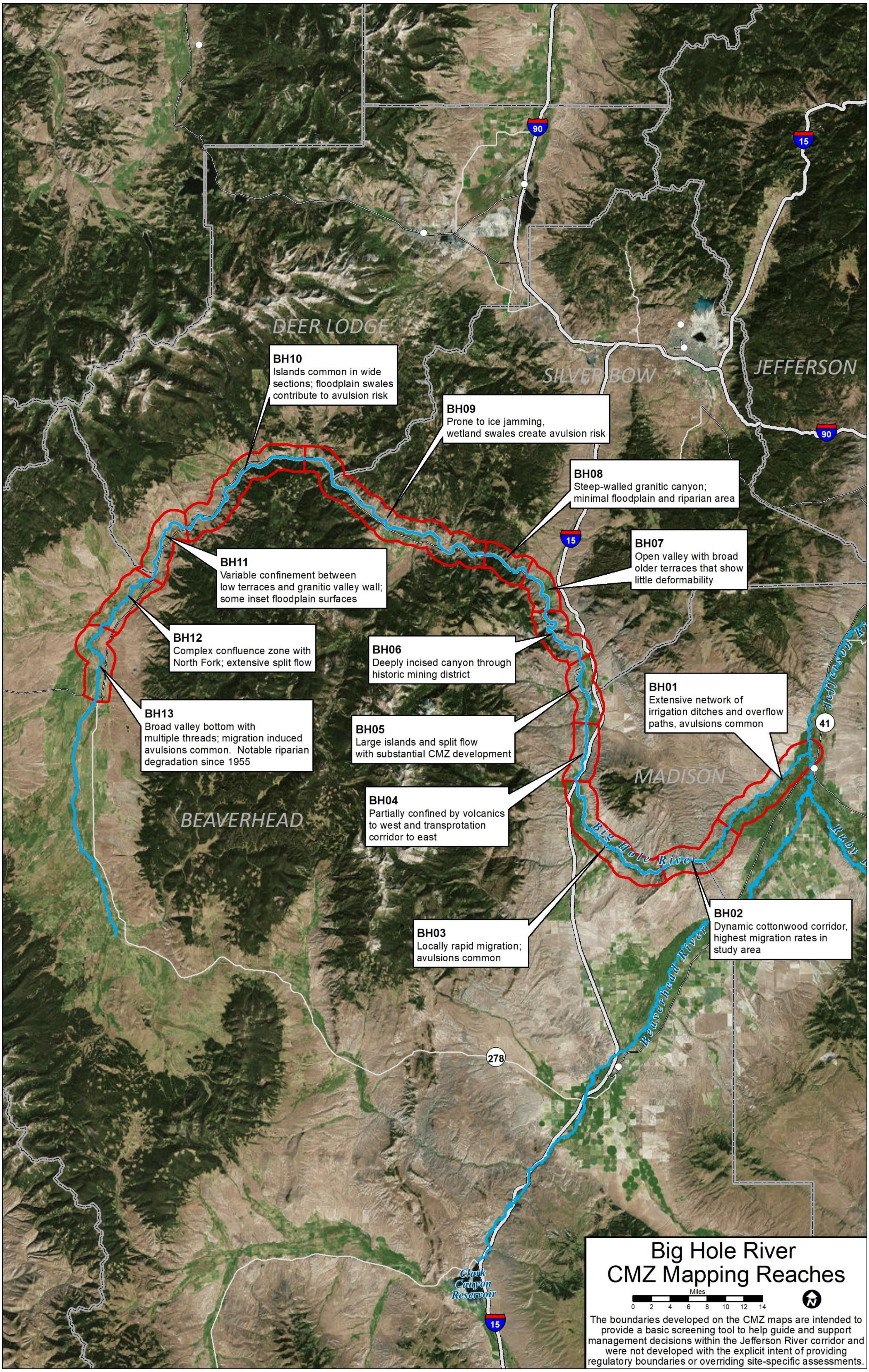

Figure 21. Big Hole River CMZ mapping reaches.

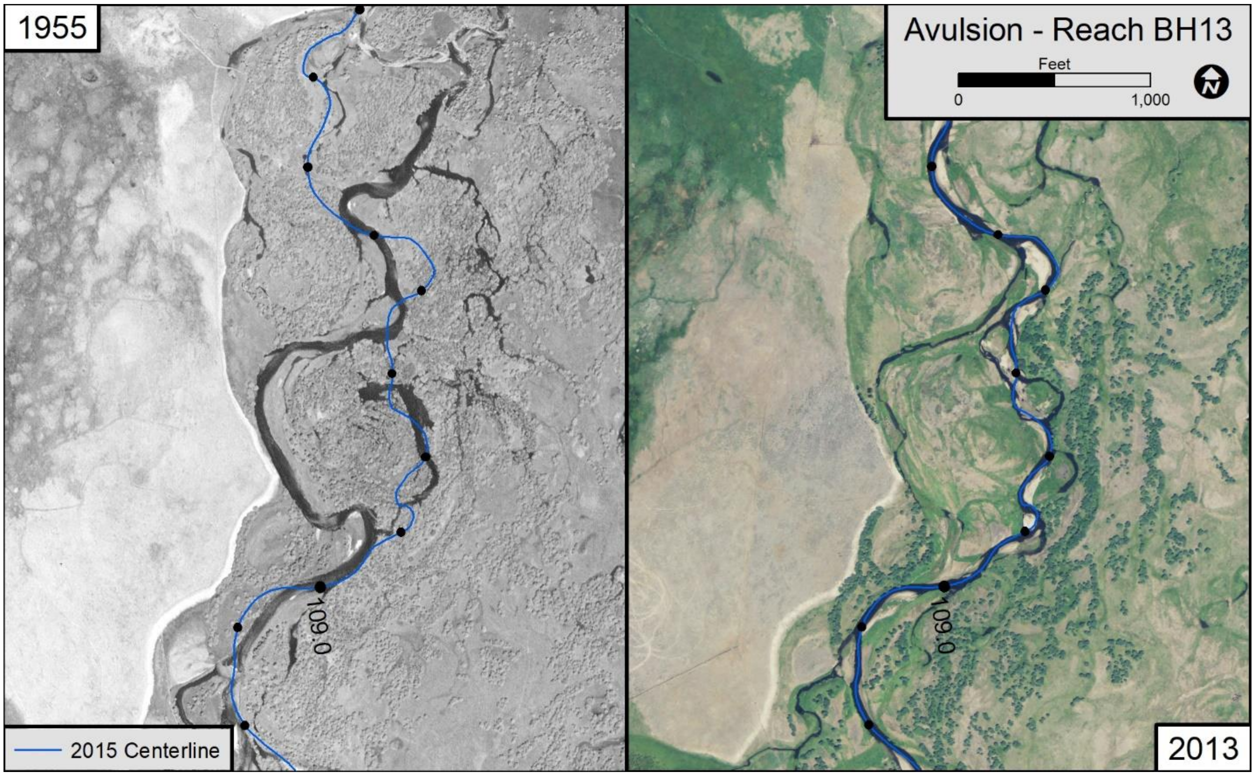

Figure 22. Reach BH13 showing 1,700 foot long avulsion since 1955; note loss of open water and riparian vegetation density.

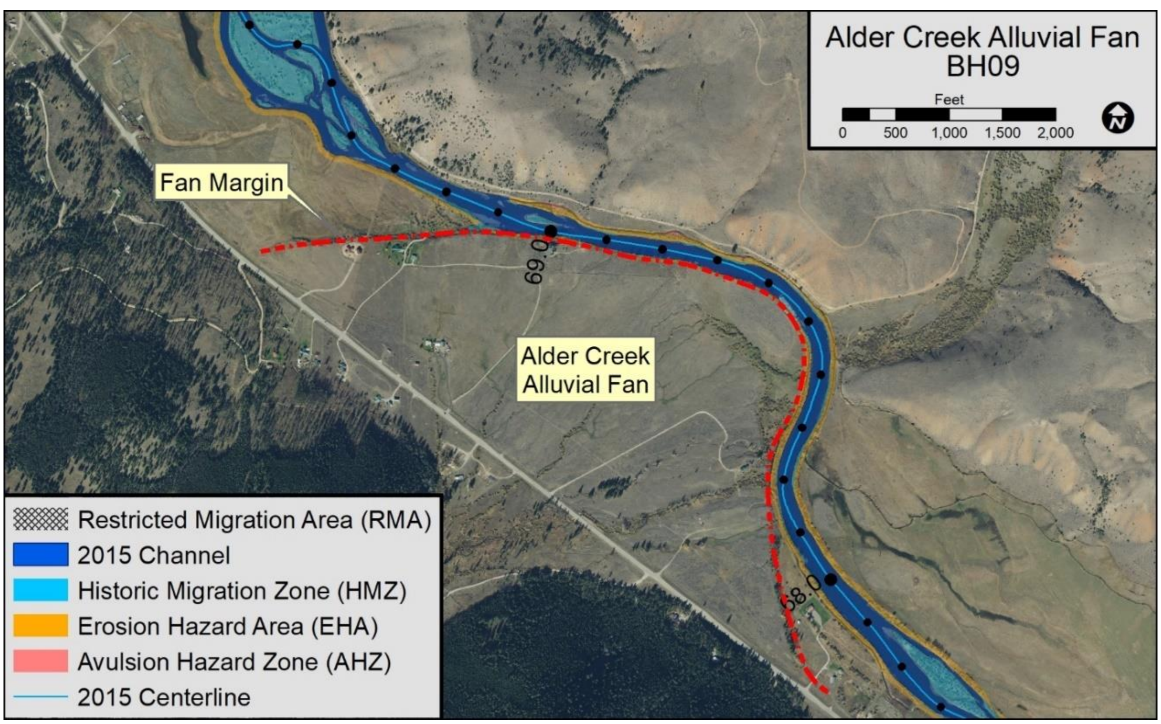

Figure 23. Reach BH9 showing Big Hole River confinement and CMZ narrowing caused by Alder Creek alluvial fan near Wise River, RM 69.0.

A propensity for ice jamming between Pintlar Creek and Melrose contributes to avulsion potential on low floodplain surfaces that are commonly dissected by swale-shaped depressions that form linear wetland features. In March 2017, an ice-jam related flood surrounded a house near Wise River (Big Hole River Watershed Committee; Figure 25). During this event Flood Warnings were issued from below Fishtrap to Divide. Ice-jam related flooding is an important potential mechanism for channel avulsion in this area, as the jams can entirely block the river and force overflows into floodplain swales for long periods of time.

Below Melrose, the Big Hole River dramatically changes character to a highly dynamic, coarse-grained, anabranching river system that, due to high migration rates and a broad corridor area, supports a vibrant cottonwood corridor (Figure 26). Meander cutoffs and floodplain avulsions are common. One avulsion above Pennington Bridge relocated about 1.6 miles of the Big Hole River about 1,000 feet westward (Figure 27). Shifting channel paths and local grade adjustments have created challenges to irrigation infrastructure operations, protection of residences, and bridge management (Figure 28 and Figure 29). These lowermost reaches have the highest mean migration rates in the project area, ranging from 2.0 feet per year just below Melrose to 3.3 feet per year near Notch Bottom.

Figure 24. View upstream of Reach BH8 showing narrow canyon segment (Kestrel).

Figure 25. Big Hole River flooding due to ice jamming upstream of Wise River, March 2017 (Big Hole Watershed Committee).

Figure 26. View upstream of Reach BH3 showing anabranching channel form (Kestrel).

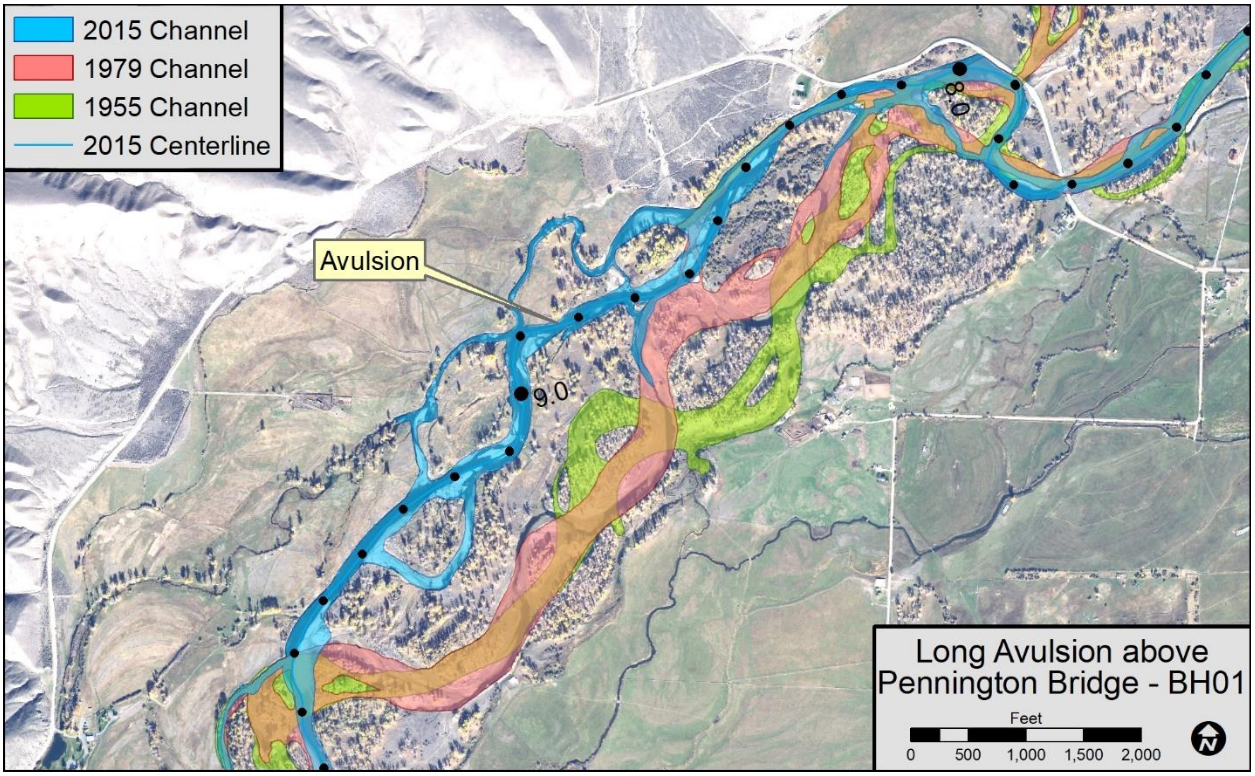

Figure 27. 2015 image of Reach BH1 above Pennington Bridge showing 1.6 mile long avulsion site.

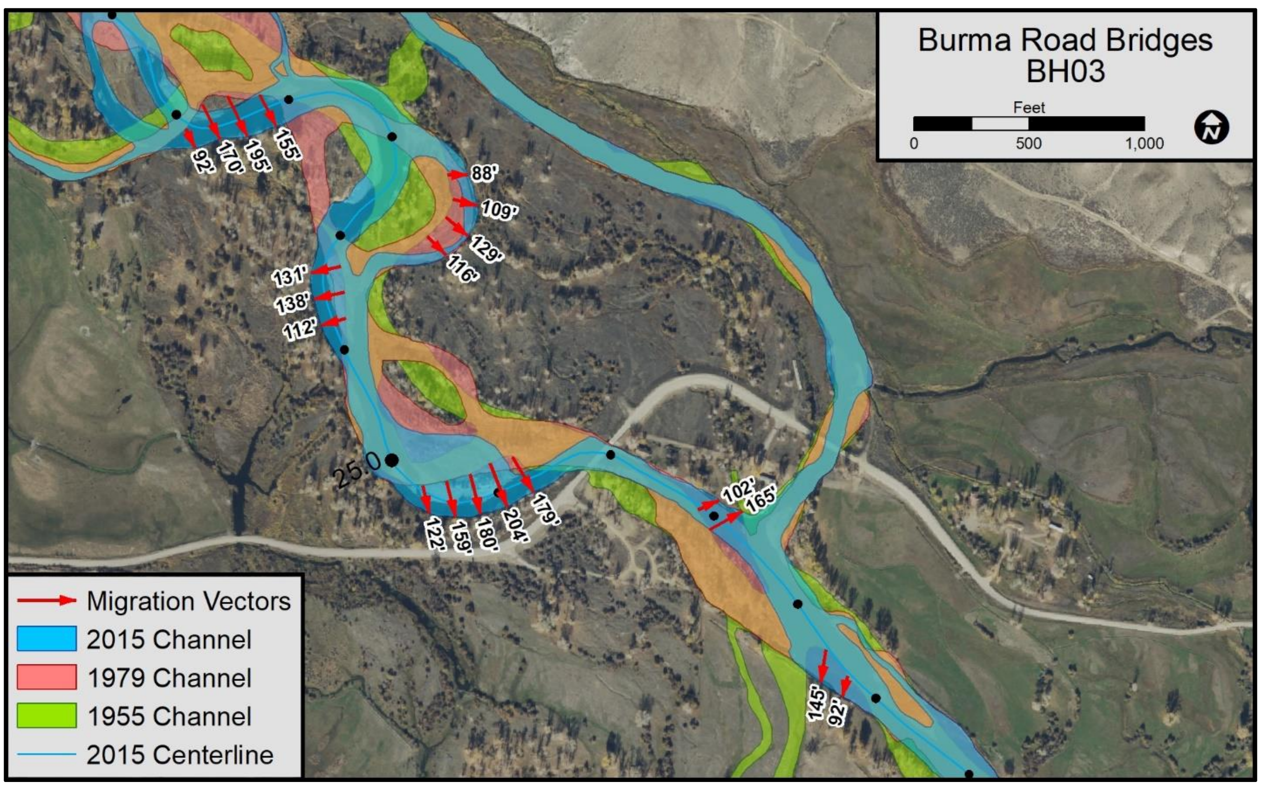

Figure 28. Big Hole River at Burma Road Bridge crossing showing progressive decay of river approach to west bridge structure.

Figure 29. View upstream showing river corridor development, Reach BH3 (Kestrel).

The most complete flood record on the Big Hole is from the USGS Melrose Gaging Station, which has been active since May of 1924 (USGS 06025500). The gage was installed just three years before recording the biggest flood to date, when in 1927 a dam failed on Pattengail Creek, a tributary to the Wise River. The dam was constructed to support irrigation in the area. But the dam failed in 1927 after a season of heavy snows and spring rain, creating a twenty-five foot wall of water that wiped out structures in Dewey and Wise River, killing four people in the process. The flood produced a flood of 23,000 cfs at Melrose. This site has since been reconsidered for new dam construction and storage (Davis, 2015).

In contrast to many of the rivers included in the study, the Big Hole has experienced numerous floods that were substantial enough to impart major geomorphic work on the channel. Since the dam failure of 1927, the largest flood on record occurred in 1972, when the Melrose gage recorded a peak discharge of 14,300 cfs. Since 1939, there have been 17 events that have exceeded a 5-year flood.

3.4 Ruby River and Clear Creek

In 2010, Channel Migration Zone mapping was developed for 53.7 miles of the Ruby River from the Ruby Dam to its confluence with the Beaverhead River in Twin Bridges (AGI/DTM, 2010). This mapping focused on the main stem of the Ruby River and did not include Clear Creek, other than to acknowledge it as a potential avulsion risk. Clear Creek is a major side channel that flows parallel to the Ruby below Alder for 11 miles, and because of its prominence in the Ruby River corridor, it was included in the Upper Missouri mapping project (Figure 30). The following summary reflects both the Ruby River and Clear Creek CMZ results.

The outlet of Ruby Reservoir discharges water into a narrow bedrock canyon carved through the eastern edge of the Ruby Range; this canyon section comprises the uppermost portion of the 2010 Ruby River CMZ mapping project reach (Figure 31 and Figure 32). Below the canyon, the river flows onto a largely unconfined floodplain where the channel is relatively flat and sinuous. Multiple channel threads and meander scrolls are common, recording historic channel changes, and creating a patchy riparian zone on a topographically subtle floodplain. Clear Creek is a major side channel that has been present since at least 1870, when it was identified on General Land Office Survey maps. Flows into Clear Creek are currently controlled by a diversion structure and road culvert on the Ruby River just above Judy Lane. Planform changes on the Ruby River at the head of Clear Creek will likely cause a meander cutoff in the near future which would cause the Ruby River to totally bypass the Clear Creek entrance (Figure 33).

The Ruby River was originally mapped in 2010, and those maps remain valid. The mapping was reviewed to determine if the river migrated beyond the CMZ boundaries during the 2011 flood, which caused extensive bank erosion and numerous avulsions on the Ruby (Figure 34). During that event a total of 14 meander cutoffs shortened the river by almost two miles between the reservoir and the mouth, however the CMZ boundary was not breached. Virtually all of the major geomorphic response to the 2011 flood occurred on segments of the Ruby that were above or below Clear Creek, indicating that the multi-thread section created by Clear Creek effectively dissipates flood energy and reduces rates of geomorphic change.

Where Clear Creek flows close to the Ruby River, the core CMZ boundaries intersect, thus defining areas prone to complex interactions between the two stream systems (Figure 35). The extent of riparian degradation on both streams is also visible in Figure 35; a striking lack of woody vegetation characterizes major segments of the stream corridor on both systems. However, the persistence a robust riparian corridor in some areas suggests a high potential for riparian recovery (Figure 34).

The hydrology of the project reach largely reflects the managed flow releases out of Ruby Reservoir, a state-owned impoundment managed primarily for irrigation water storage and flood control. Since 1962, the 100-year event has been exceeded once, on May 16, 1984, when the exceeded a 200-year flow. The 10-year flood has been exceeded only twice since 1962; the 1984 flood and in 1995, when the river peaked at 1820 cfs. The peak flow record on the Ruby generally shows that there have been few major floods below the reservoir since the mid-20th century. The 2011 event peaked at 1,720 cfs, which is just under a 10-year event.

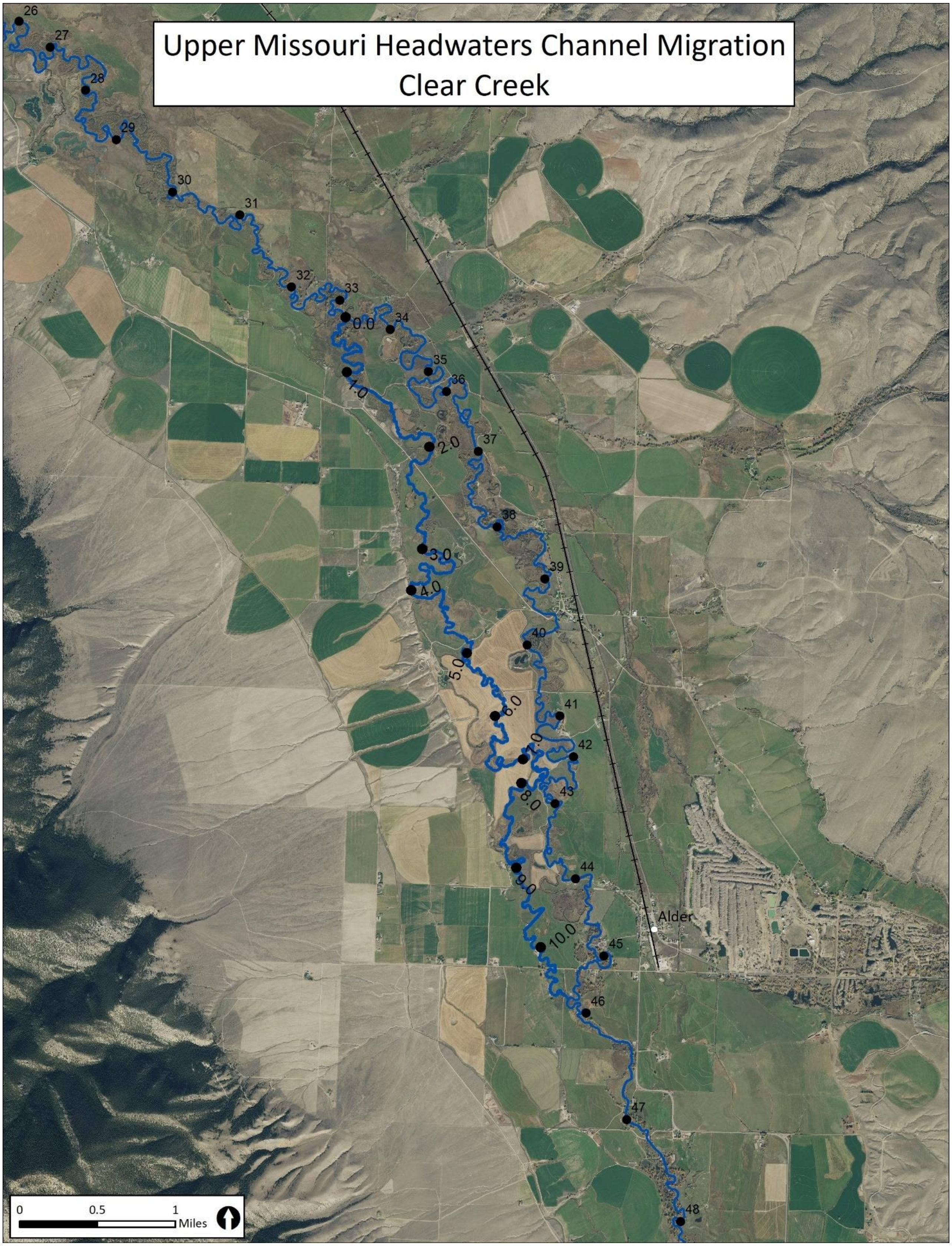

Figure 30. Clear Creek section of the Ruby River.

Figure 31. View upstream showing Ruby Reservoir outlet (Kestrel).

Figure 32. View upstream showing canyon section below Ruby Reservoir (Kestrel).

Figure 33. View west showing Clear Creek Diversion through culvert under road; note meander cutoff potential in center of photo (Kestrel).

Figure 34. View west showing 2011 avulsion on Ruby River (upper right corner of photo) (Kestrel)

Figure 35. View west showing common floodplains of Ruby River (foreground) and Clear Creek; note lack of woody riparian corridor (Kestrel).

3.5 Jefferson River

The Jefferson River begins at the confluence of the Big Hole and Beaverhead Rivers a few miles north of Twin Bridges Montana. Just upstream of Twin Bridges, the Ruby joins the Beaverhead as well, making the upper Jefferson River a system that is responding to the water and sediment delivered from three different watersheds. The Beaverhead and Ruby Rivers both have reservoirs affecting flows, and they are both fairly low energy systems with disproportionately small sediment inputs to the upper Jefferson. Most of the flow and energy affecting the Jefferson River is driven by the dynamics of the Big Hole, which, although it has a smaller drainage area than the Red Rock/Beaverhead system, it carries about three times the mean annual discharge and significantly more coarse sediment. As a result, the upper Jefferson shows an immediate response to the Big Hole influence, with a very dynamic confluence area (Figure 36).

Figure 36. View downstream of open gravel bars, riparian colonization and active side channels, RM 74 (Kestrel).

The Jefferson River can be divided into three segments: the Jefferson Valley, Jefferson Canyon, and the Lower Jefferson River. CMZ mapping on the Jefferson River has captured its geomorphic variability on a reach scale, with the CMZ ranging in width from essentially the active channel in Jefferson Canyon to over a mile wide in more dynamic reaches.

The Jefferson Valley section runs from the headwaters at Twin Bridges, northward to Whitehall, and ending at the Boulder River confluence near Cardwell. Land uses are predominantly agricultural, however there has been some residential development in the CMZ within this reach (Figure 37). Bank armoring is common, and some of that armor has been flanked (Figure 38). Side channels in the Jefferson Valley are commonly used as ditches, however in many cases such as at the Parrot Canal, progressive sedimentation in the side channel has made mid-channel berming necessary for its operation (Figure 40).

Figure 37. View downstream of bank armor protecting home and field, RM 72.1, Reach JR11 (Kestrel).

Figure 38. Flanked left bank riprap in channel, RM 71.8L (Kestrel).

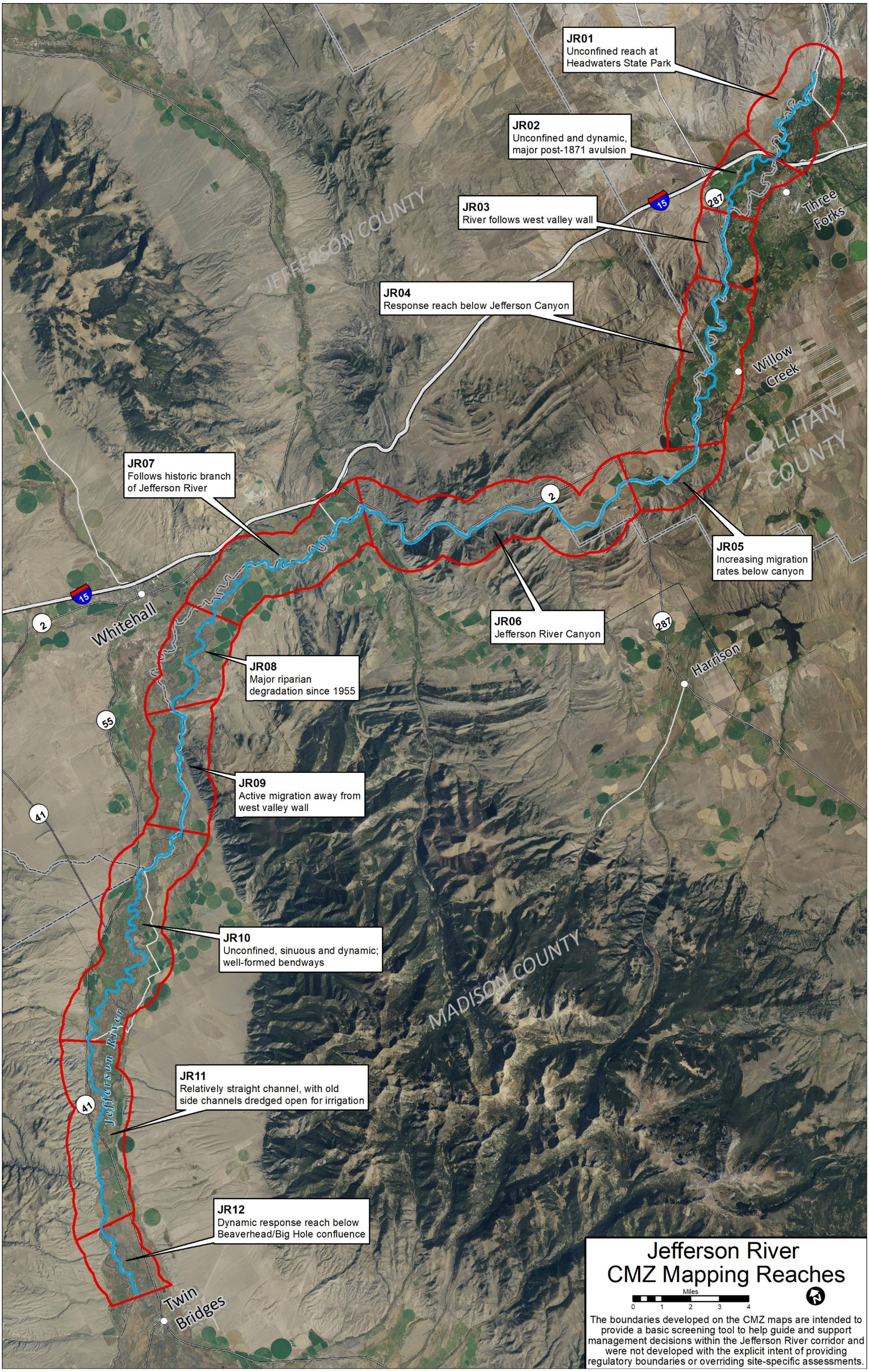

Figure 39. Jefferson River CMZ mapping reaches.

Figure 40. In-channel berming and side work at head of Parrot Canal, RM 68.54 (Kestrel).

Below the Renova Diversion in the Whitehall Valley, the late 1800s GLO maps show the main river channel was located in what is now Jefferson Slough and Slaughterhouse Slough, forming two distinct forks. The river now occupies a new channel south of the GLO-mapped river course where virtually no channel was mapped (Figure 41). This marks a major avulsion that left the historic channels as sloughs that are, without intervention, progressively infilling.

At LaHood, the river enters Jefferson Canyon, which is a deep, 12 mile long bedrock canyon that records over a billion years of geologic time. Channel migration is limited in the canyon due to both the erosion resistant geology and encroaching transportation infrastructure (Figure 42). As a result, the CMZ in the canyon is notably narrow.

Below Jefferson Canyon the river re-enters a very broad floodplain, flowing west of Three Forks and down to Headwaters State Park, where the Jefferson River floodplain coalesces with that of the Madison River, forming the beginning of the Missouri River north of I-90. In these reaches, active channel migration and avulsion have caused challenges with transportation infrastructure and residential developments where they encroach into the natural Channel Migration Zone (Figure 43 and Figure 44).

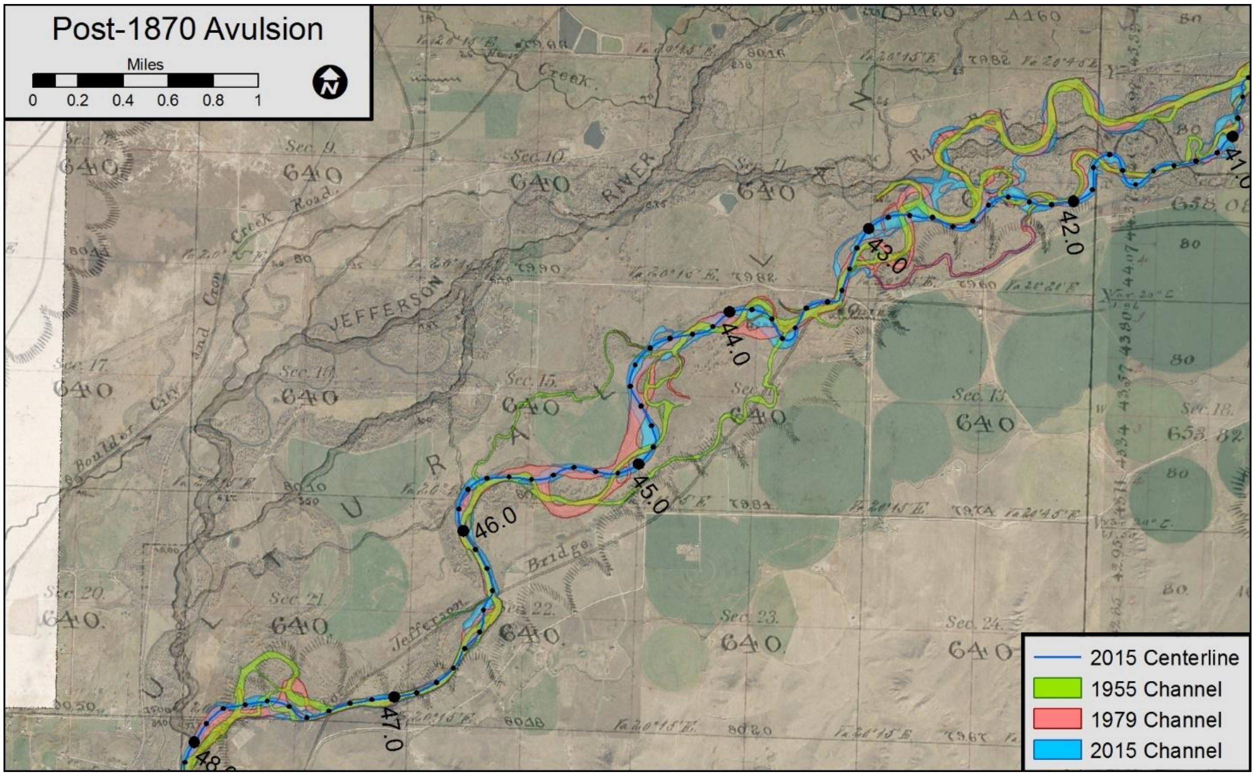

Figure 41. 1870 GLO map showing major 1870-1955 avulsion that relocated the over a mile south.

Figure 42. View downstream of Jefferson Canyon (Kestrel).

Figure 43. View downstream showing left bank barbs with erosion between structures (Kestrel).

Figure 44. View downstream showing poor river alignment and bank armoring at Old Town Road Bridge over Jefferson River (Kestrel)..

A total of 25 avulsions occurred on the Jefferson River between 1955 and 2015, with 14 occurring prior to 1979 and 11 occurring after. Figure 45 shows an example of a major 1955-1979 avulsion just downstream of Twin Bridges. The imagery shows a small 1955 floodplain swale that effectively captured the entire river by 1979.

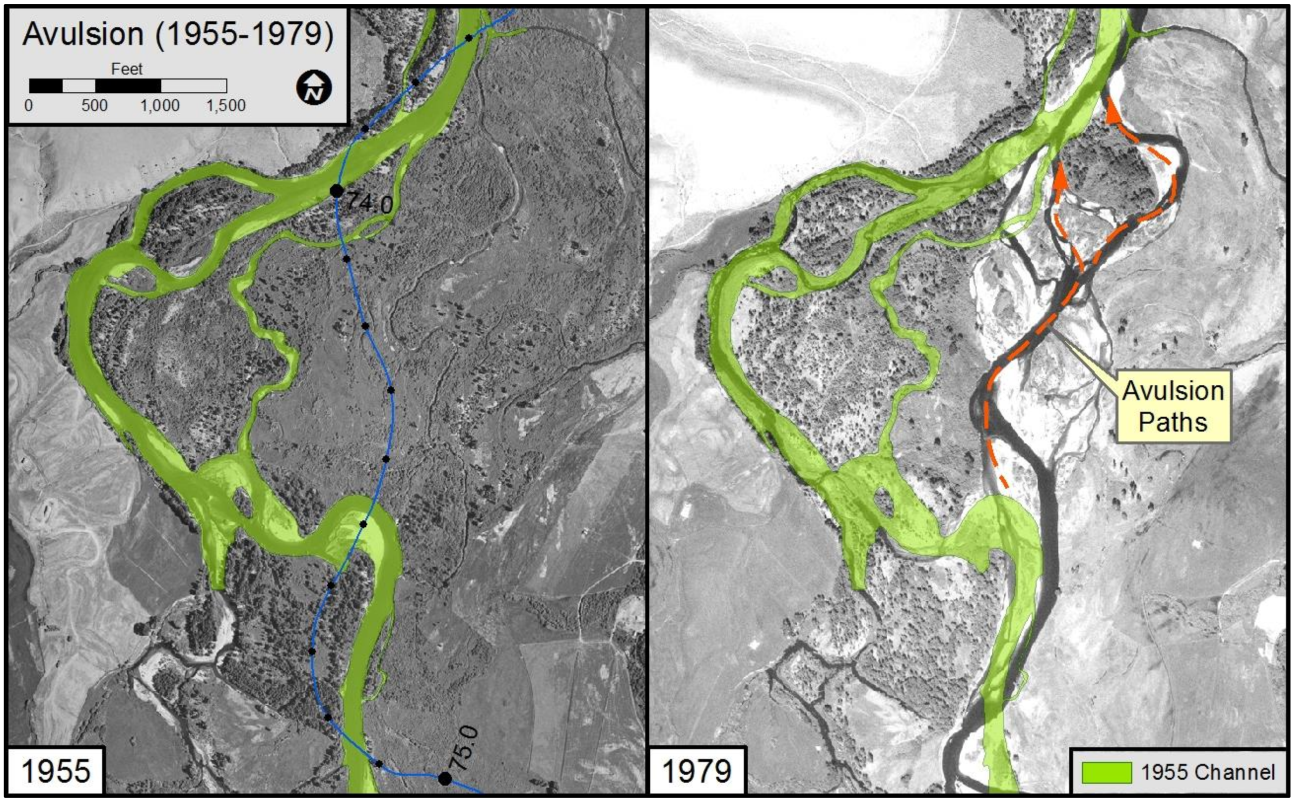

Figure 45. Imagery from 1955 (left) and 1979 (right) showing a major avulsion about 2.5 miles downstream of Twin Bridges.

The hydrology of the Jefferson River reflects combined inputs from contributing watersheds of the Big Hole, Beaverhead, and Ruby Rivers. While there are no constructed or natural impoundments on the Jefferson River, flows on the Beaverhead and Ruby Rivers are affected by reservoir operations.

Flow records on the Jefferson River are relatively short, with 36 years of record from the longest running gage at Three Forks (USGS #06036650). That record indicates that over those 36 years, the Jefferson River has had four floods exceeding a 10-year event and none exceeding a 25-year event. The largest flood recorded on the Jefferson at Three Forks peaked at 17,400 cfs on June 12, 2011. Floods on the Big Hole River have a much larger influence on Jefferson River flooding than the Beaverhead River does, even though the Beaverhead has a larger drainage area. In 1984 for example, the Beaverhead River experienced a major flood that exceeded a 100-year event, which was less than a 10-year event on the Jefferson at Three Forks.

3.6 Madison River

The Madison River was mapped over 62 miles of its length from Varney Bridge south of Ennis to its confluence with the Jefferson River near Three Forks, Montana. 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 (Figure 46). 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 such historic avulsion into a spring creek was mapped south of Ennis (Figure 47). 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. The National Weather Service has 17 ice jam entries reported on the Madison River. Ice jamming and gorging plays an important role on the river, especially from Ennis to Ennis Lake and at Three Forks.

Figure 46. View downstream of meander bend at RM 57.2 showing chute cutoffs and riparian succession in left foreground (Kestrel).

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. The CMZ becomes over a mile wide across the delta (Figure 48). 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 a low gradient, swampy system above the entrance to Bear Trap Canyon, and that the dam at Ennis Lake was constructed to take advantage of a natural storage area (Figure 50).

Figure 47. View downstream showing spring creek on right captured by the Madison River between 1955 and 1979 (Kestrel).

Figure 48. View downstream towards Ennis lake showing anastomosing channel form of Madison River (Kestrel).

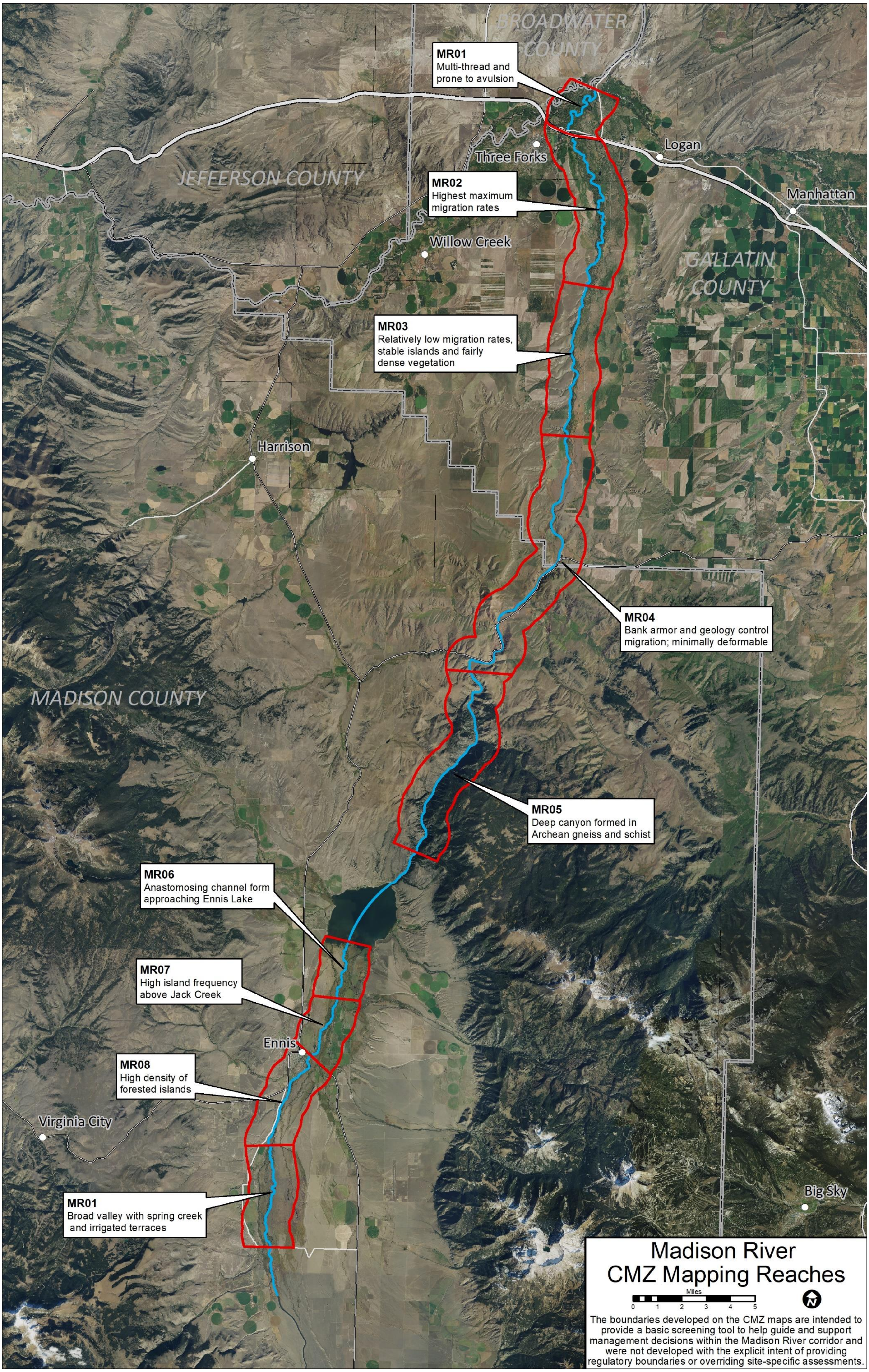

Figure 49. Madison River CMZ mapping reaches.

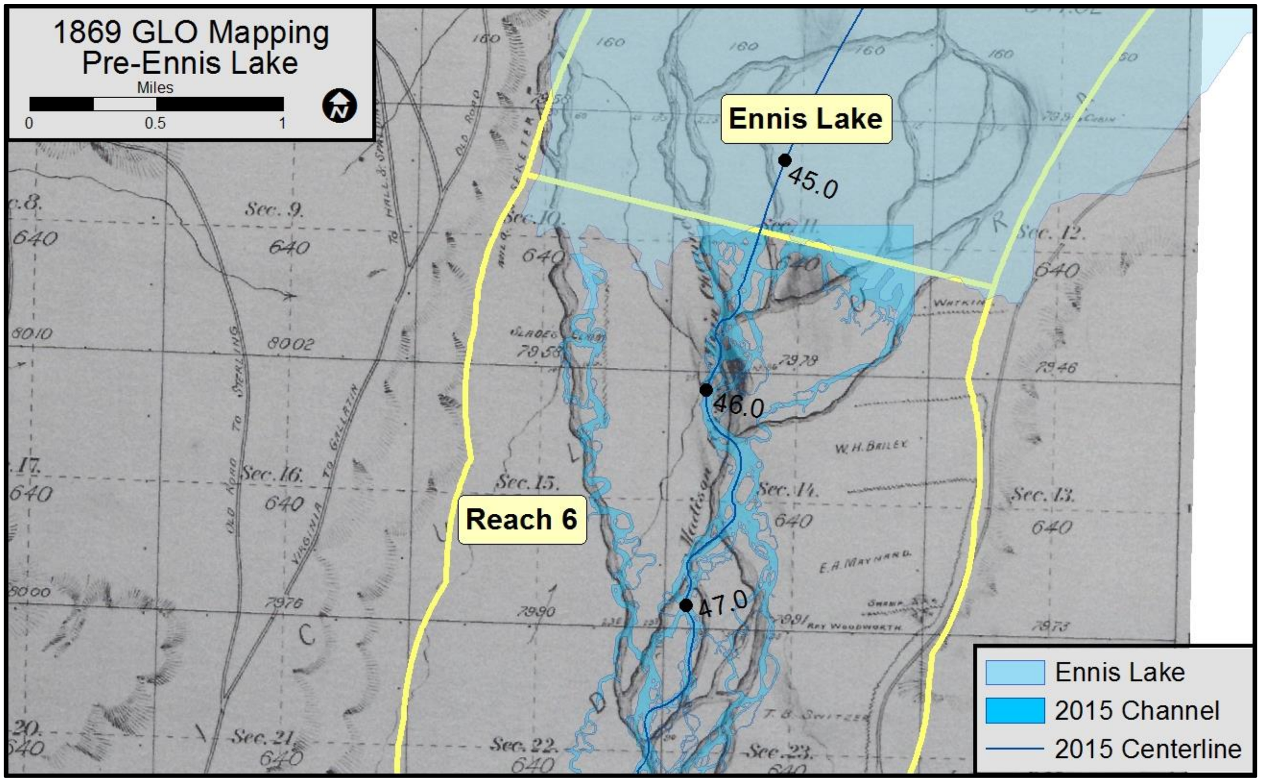

Figure 50. 1869 General Land Office Survey map overlain on 2015 imagery showing complex channel pattern prior to Madison Dam.

Leaving Ennis Lake, the Madison River flows through several miles of crystalline basement rock in Bear Trap Canyon where migration rates are very low and limited to small areas where river deposits are stored in the canyon floor. The canyon is a major geologic feature, where the river eroded approximately 1,300 feet through 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. 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 51).

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 sediment storage or erosion since the 1950s (Figure 52). Although the valley bottom is alluvial, the Channel Migration Zone is relatively narrow with little planform complexity, avulsion risk, or side channel activity. The woody riparian corridor is sparse to non-existent.

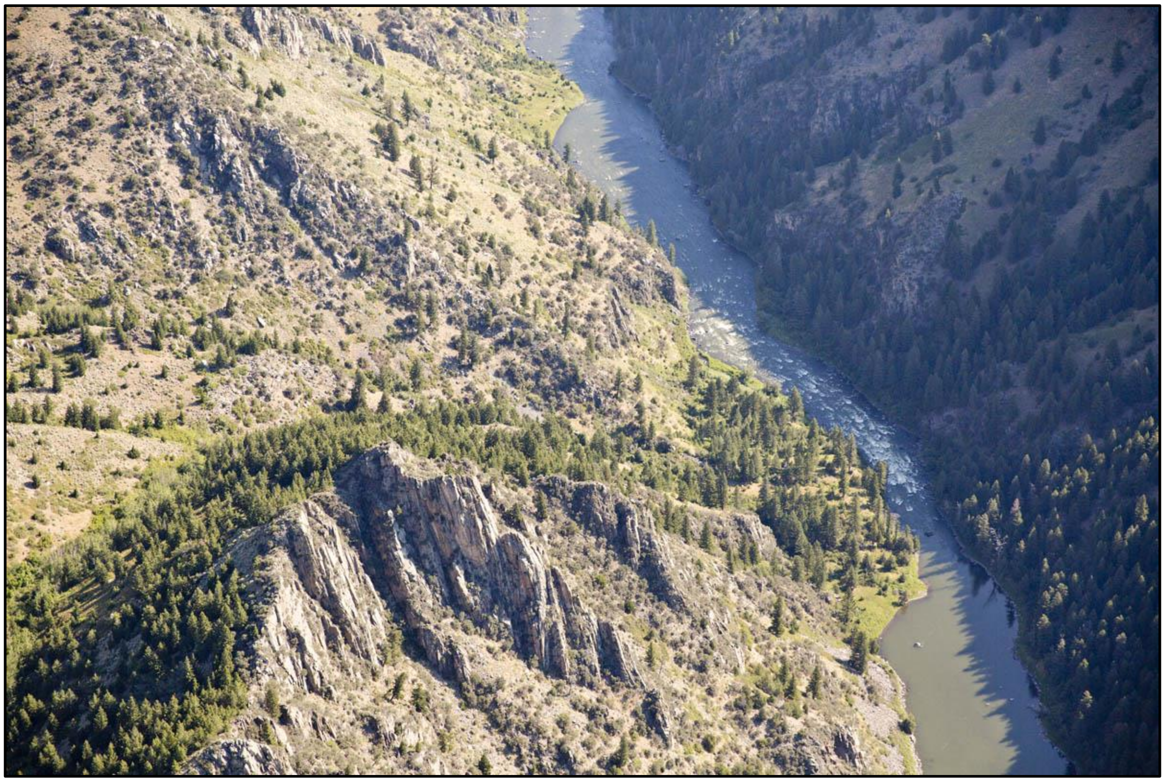

Figure 51. Formation of rapid at tributary mouth/alluvial fan, Bear Trap Canyon (Kestrel).

Figure 52. View downstream at mouth of Cherry Creek showing expanding terrace areas and minimal woody riparian fringe (Kestrel).

From Greycliff to the Cobblestone Fishing Access Site, the river flows along a dominant bluff line on the west side of the corridor that is made up of Tertiary-age sandstones and siltstones (Figure 53). The other major feature is the Lower Madison Levee on the east river bank, separating Darlington Ditch from the river corridor (Figure 54). The levee has markedly narrowed the river corridor, and according to the 1969 GLO mapping, it was evidently built on top of the historic river channel. As the river flows along the bluff line, it shows a classic anastomosing channel form with numerous islands and moderately dense vegetation. 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 53. View downstream into Reach 3 showing west bank sandstone bluff (Kestrel).

The hydrology of the Madison River is largely defined by Hebgen Dam releases. Hebgen dam is located in the upper watershed approximately 16 miles northwest 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. 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.

On Labor Day of 2008, several stoplogs at the Hebgen Dam 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.

Figure 54. View downstream showing Lower Madison Levee confinement on east bank, with Darlington Ditch flowing on the right (landward) side of the levee (Kestrel).

Figure 55. 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).

3.7 Gallatin River

The Gallatin River CMZ mapping covers approximately 42 miles of the river from the Highway 191 Bridge downstream to its confluence with the Jefferson and Madison Rivers in Three Forks. As the river emerges into the Gallatin Valley from Gallatin Canyon, it is strongly influenced by both sediment supply and slope. Steeper upstream reaches have relatively high sediment transport capacities, but as slope drops in the downstream direction, sediment deposition drives channel migration and avulsion. Maximum migration distances since 1965 exceed 600 feet in some areas, with average migration distances for that time frame typically exceeding 200 feet.

As the river flows north out of Gallatin Canyon, it is relatively steep, efficient, and non-deformable, as evidenced by low migration rates, minimal sediment storage, and a narrow strip of mature riparian vegetation on both banks (Figure 56). Further downstream as the river approaches Gallatin Gateway, split flow becomes more common, and avulsions are a dominant geomorphic process (Figure 57). This increased level of lateral change on the river supports a much broader and more complex riparian corridor relative to upstream.

Migration rates continue to increase in the Four Corners area as channel slope and sediment transport competency continue to drop. Numerous residences are within the CMZ boundaries near Four Corners, and bank armoring is common. Below Norris Road, the maximum migration distance measured was 616 feet, and avulsions were mapped at a frequency of two avulsions per river mile since 1965. The corridor continues to widen and support an increasingly diverse riparian corridor (Figure 59). As the river continues northward towards the I-90 bridge, it flows through a seven mile segment that has experienced numerous large avulsions since 1965. One avulsion was over a mile long and has created challenges at the head of a major diversion structure (Creamery Ditch; Figure 60 and Figure 61). Active channel movement threatens structures in this area, as a result, bank armor is relatively common (Figure 62).

North of I-90, the slope of the Gallatin River drops markedly by about 20%, creating a “response” reach that is especially prone to sediment loading, channel migration, and avulsion. It appears that the 1974 flood delivered massive quantities of sediment to this section of river. Downstream, the river joins the East Gallatin River near Manhattan, continuing down through a narrow geologic notch at Logan. Below Logan, the river emerges from the enters a 3,000 foot wide swath of active channels before joining the Missouri River at Headwaters State Park (Figure 63).

The National Weather Service database has 25 ice jam entries for the Gallatin River. These jams appear most common where the river corridor is constricted by bedrock and transportation infrastructure near Logan.

The geomorphic nature of the Gallatin River makes it especially prone to the delivery of coarse sediment pulses during floods that drive rapid river response. The air photo record indicates that the floods of 1974 and 1997 drove major changes, however, these events were only 25-year floods. This suggests that large, long-duration flooding in this system has the potential to drive massive change that will result in property damage as the system is undergoing substantial development pressure. Irrigation water management will also continue to be a challenge in this wide and dynamic river corridor.

Figure 56. View downstream of channel confinement and narrow riparian zone, Reach GR08 (Kestrel).

Figure 57. View downstream above Gallatin Gateway showing two channels on right formed since 1979, RM 42.2 (Kestrel).

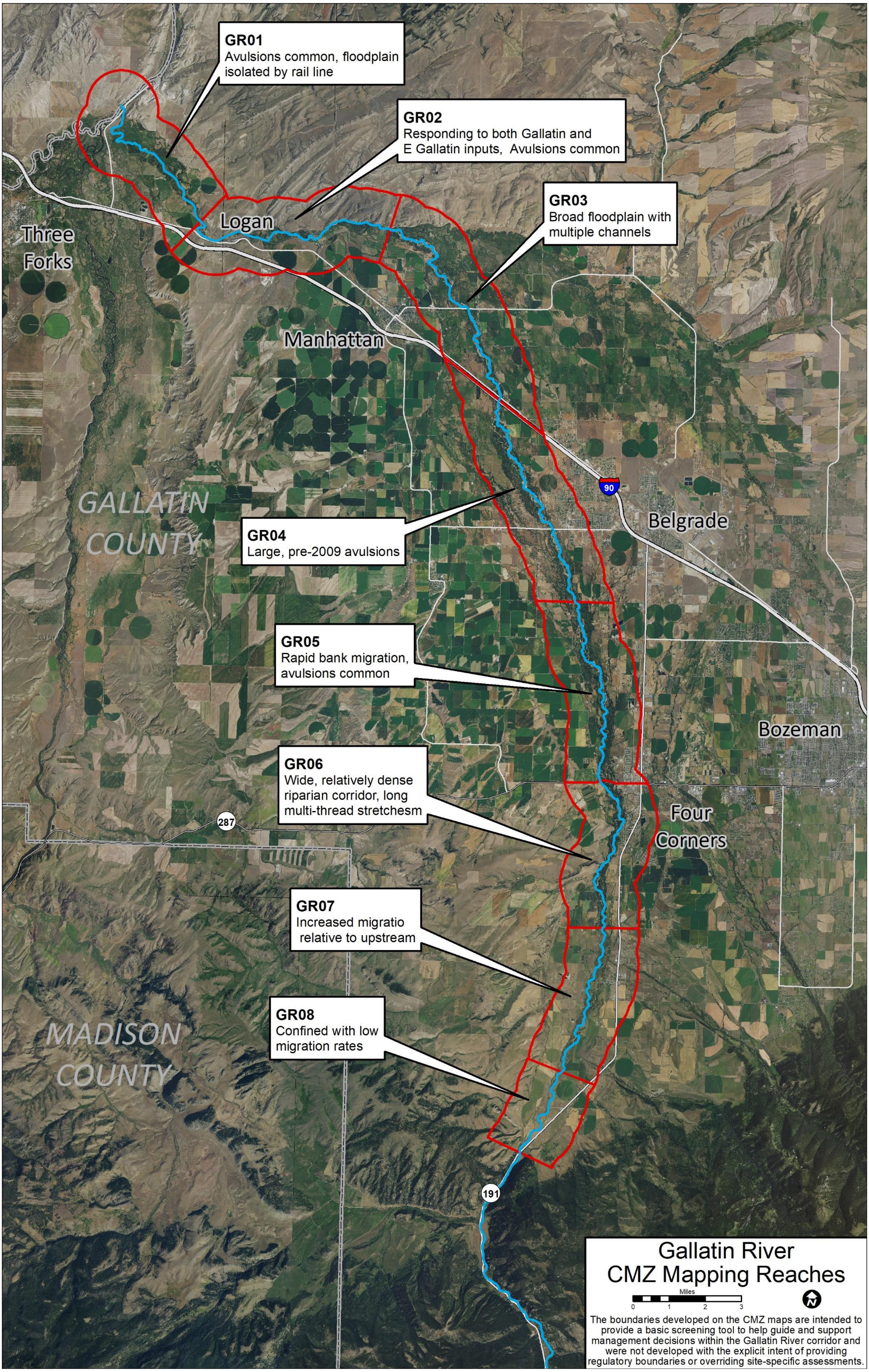

Figure 58. Gallatin River CMZ mapping reaches.

Figure 59. View downstream below Norris Road; bendway in left foreground has migrated 392 feet since 1965 (Kestrel).

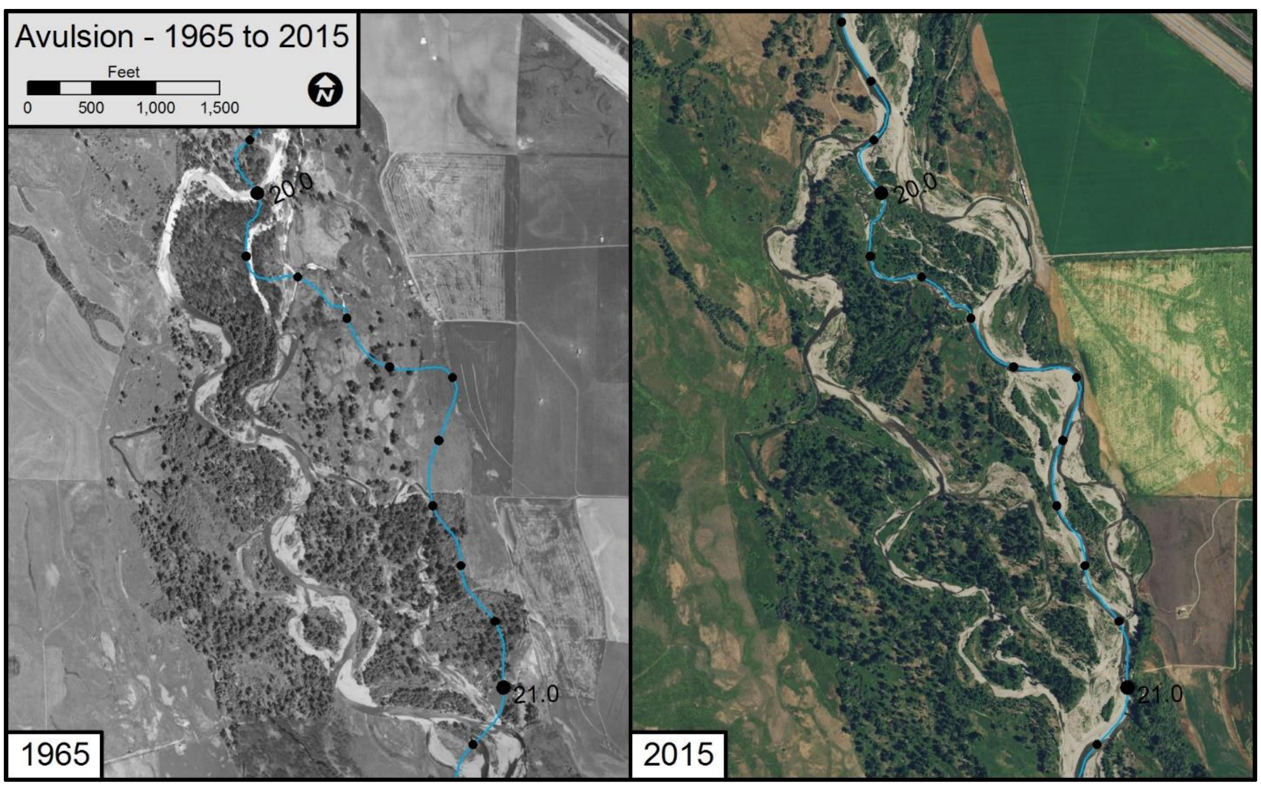

Figure 60. Major avulsion at RM 20.4 between 1965 (left) and 2015 (right).

Figure 61. View downstream of ~1.1 mile long avulsion shown in Figure 60; I-90 Bridge crossing is in distance (Kestrel).

Figure 62. Barn on right bank where river has migrated 216 feet since 1965, RM 23.2 (Kestrel).

Figure 63. View downstream showing wide floodplain and active avulsions, Reach GR01 (Kestrel).

3.8 East Gallatin River

Channel Migration Zone mapping on the East Gallatin River covers 41.4 river miles from Bozeman to Manhattan. The project reach has extensive agricultural and residential development within the river corridor that has created problems for numerous landowners and irrigators. About 4.5 miles of bank armor have been mapped between Bridger Creek and the mouth, and that is probably a conservative estimate due to the long history of manipulation on the river. By 1965 much of the riparian corridor had been cleared and substantial sections of river had been channelized (straightened). Although the CMZ has been encroached into by various land uses, segments of the river remain very dynamic, with channel migration and avulsions common. Migration distances measured for the 50 years from 1965-2015 are typically between 50-100 feet, but in some areas migration measurements between 250 and 400 feet are common. Some of the areas of more rapid migration were historically channelized, reflecting the tendency for a straightened stream to regain length and re-establish an equilibrium slope (Figure 65). A total of 33 avulsions were mapped between 1965 and 2015, with another nine sites that appear to be highly susceptible to such an event in the coming decades (Figure 66).

Rapid channel migration and avulsions in upper portions of the project area have generated sediment pulses that have affected downstream channel dynamics. For example, large avulsions have excavated new channels and conveyed that material downstream, increasing migration rates in turn. Channelized sections have similarly generated sediment by re-forming meanders. The downstream response is observable on a local scale, however similar patterns may be occurring on a larger scale.

Near Dry Creek Road and Thompson Creek, the river abruptly transitions to a highly sinuous and fairly stable condition that is characterized by a low gradient, low migration rates, and a relatively narrow erosion hazard area. However, riparian clearing has been extensive in this section of river, reducing bankline and floodplain resiliency (Figure 67). The river has widened since the mid-1950s, which may be in part due to riparian clearing. In the event that upstream processes increase sediment loading to this lower gradient section of river, an increase in migration rates and avulsion frequencies should be expected. Riparian restoration in lower gradient sections of the East Gallatin River would be an appropriate means of adding natural resiliency to a system that may experience increased sediment loading and accelerated rates of geomorphic change in the future.

The flood history for the East Gallatin River indicates that since 1970 there have potentially been five flood events exceeding a 10-year flood below Bridger Creek. According to flood frequency statistics, however, the system is capable of much higher flows.

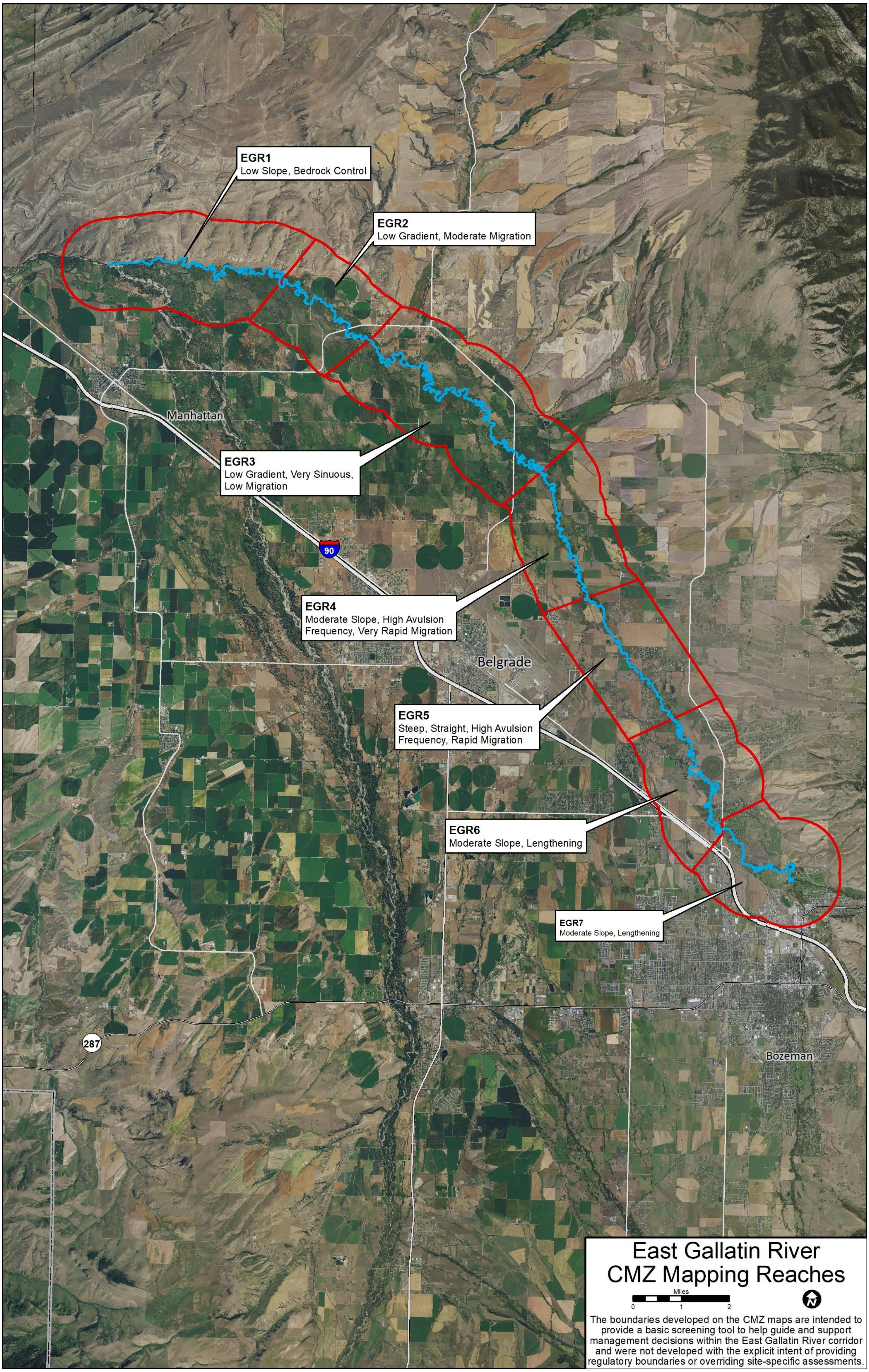

Figure 64. East Gallatin River CMZ mapping reaches.

Figure 65. East Gallatin River below Springhill Road, showing channelized segment in 1965 and lengthened channel in 2015.

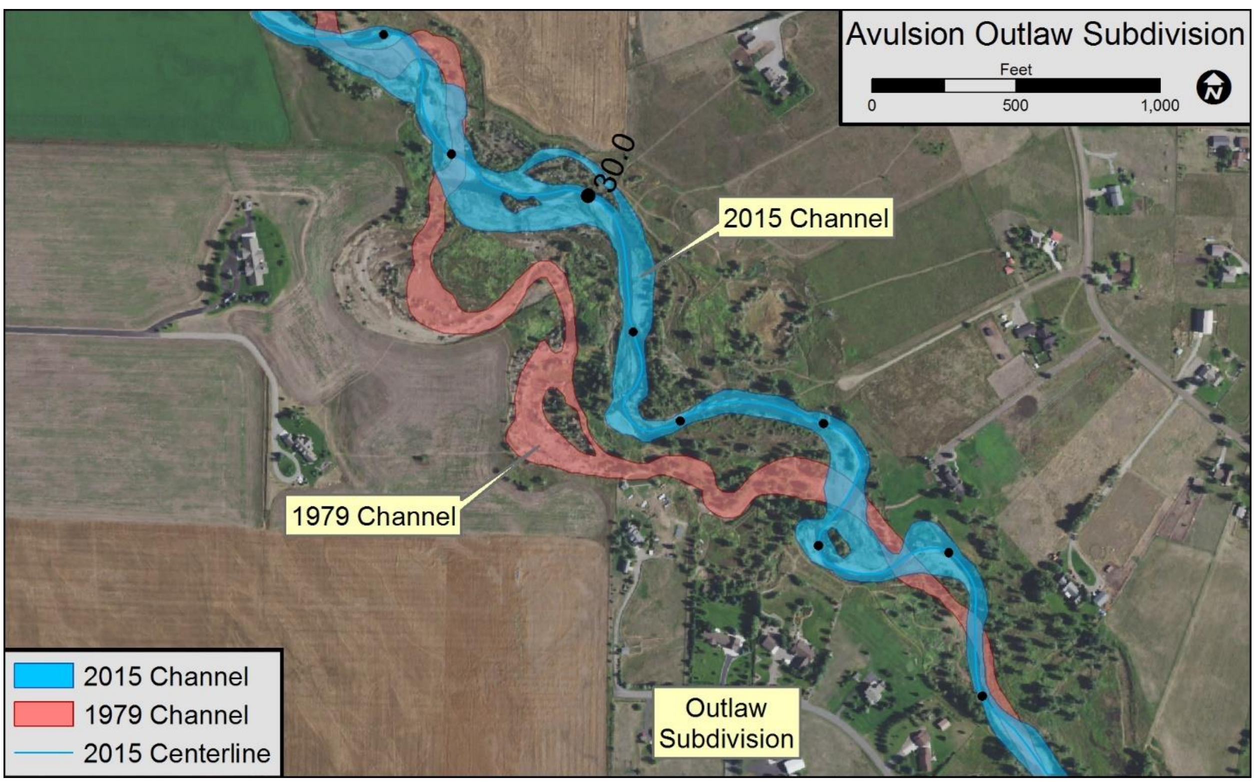

Figure 66. 1979-1995 avulsion site near Outlaw Subdivision.

Figure 67. View downstream showing lack of woody vegetation on banklines and floodplain (Kestrel).

4 Watershed Scale Patterns

The following section compares results between river systems to provide some perspective on the relative rates of channel migration in the Upper Missouri Watershed. The comparison focuses on Erosion Hazard Area Buffer widths, which are a direct reflection of the mean reach-scale migration rate. The buffer width is the calculated distance the river would migrate at the mean migration rate over 100 years. As such, a 400-foot buffer width would reflect a mean migration rate of 4.0 feet per year in that reach. The general trends show that migration rates tend to increase in the downstream direction as rivers coalesce and enlarge, although that trend is by no means linear due to local variability. The strongest local controls are bedrock canyons. Other local scale controls include slope, sediment regime, and bank erodibility. Land use and riparian conditions probably have a strong influence on migration rates, however these influences were not quantified in this effort. On the Yellowstone River, for example, erosion rates were associated with land which showed that average migration rates are higher in both hay ground and irrigated lands relative to wooded riparian areas. Over a 25-year period, banks on the Yellowstone eroded into hay ground and irrigated ground an average 40 to 50 feet further than through riparian areas (USACE and YRCDC, 2016).

4.1 Jefferson River Watershed

The Jefferson River watershed is the largest sub-watershed of the Missouri headwaters and is made up of the Jefferson, Boulder, Big Hole, Ruby, Beaverhead, and Red Rock Rivers. Figure 68 provides some insight as to the rates of channel movement in each river, plotted as a function of distance upstream from the mouth of the Jefferson River at Three Forks. The Jefferson River itself shows a high level of variability in Erosion Hazard Area (EHA) buffer widths. For example, just above RM20 the Jefferson Canyon reach has low migration rates and a narrow buffer width. In general, however, the plot shows that the contributing drainages of the Beaverhead and Ruby Rivers, both of which have reservoirs, are relatively low. The Big Hole, which is unregulated, has markedly higher migration rates especially as it approaches the Jefferson River below its canyon sections.

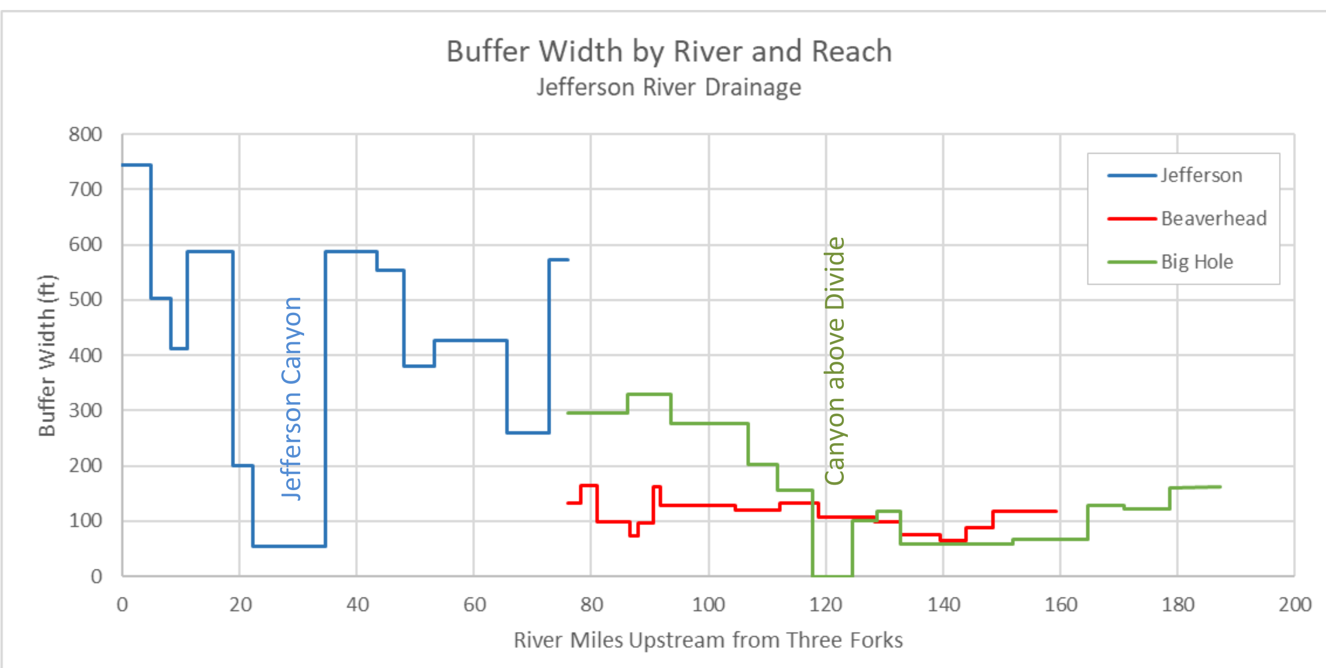

Figure 68. EHA Buffer Width (based on mean migration rates) for Jefferson River Watershed project reaches.

4.2 Madison River Watershed

The Madison River watershed is the second largest sub-watershed of the Missouri headwaters and no major tributaries. The watershed accounts for 18% of the total Missouri headwaters watershed area. Buffer widths on the Madison widen substantially over its lower ~20 miles, below Greycliff (Figure 69).

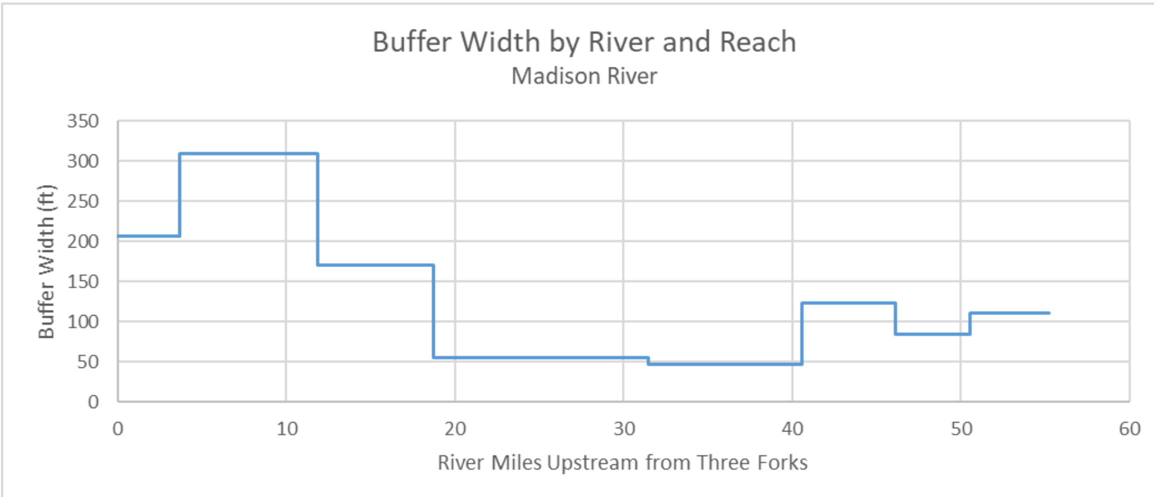

Figure 69. EHA Buffer Width (based on mean migration rates) for Madison River Watershed project reaches.

4.3 Gallatin River Watershed

The Gallatin River watershed is the third largest sub-watershed of the Missouri headwaters and is made up of the Gallatin and East Gallatin Rivers. In total, the Gallatin watershed accounts for 14% of the total Missouri Headwaters watershed area. Not surprisingly, the Gallatin River has Erosion Buffer Widths that are several times larger than those of the East Gallatin (Figure 70). Whereas Gallatin River buffer widths tend to increase in the downstream direction, the East Gallatin shows the opposite trend, with higher migration rates in middle and upstream reaches near Bozeman.

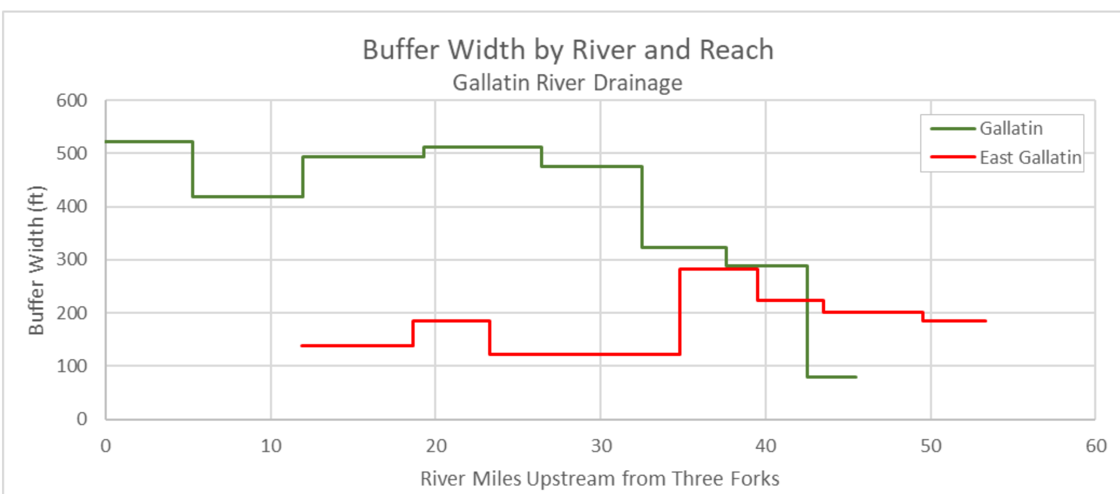

Figure 70. EHA Buffer Width (based on mean migration rates) for Gallatin River Watershed project reaches.

4.4 Upper Missouri Watershed

Migration rates have also been compared between all of the mapped rivers to consider the relative capacities of each system to perform geomorphic work that is manifested as channel movement. This in turn provides a broad scale depiction of stream dynamics and associated levels of development risk. A general characterization of relative stream power was made by calculating mean annual discharge at primary gages on each river. The mean annual flows range from a low of 121 cfs on the East Gallatin River near Bozeman to a high of 1,903 cfs on the Jefferson River near Three Forks (Table 3 and Figure 71). All of the results were then sorted by river system in terms of this mean annual flow. The results show that migration distances and erosion buffer widths tend to increase with mean annual flow, with some deviations from that trend (Figure 71Figure 72). For example, the Beaverhead and Ruby Rivers both have relatively low rates of change, and both are impacted by upstream reservoirs. The Madison River also has dampened rates and flow controls. Conversely, the Gallatin River has strikingly high rates of change in relation to its typical flow, which emphases the unique geomorphic environment on the Gallatin, which approaches that of an alluvial fan. It also emphasizes that stream power is a function of both stream discharge and slope, so that a disproportionate amount of geomorphic work will be done on a steeper alluvial river such as the Gallatin.

Table 3. Gaging stations used to estimate mean annual discharge.

River	Period of Record	Gage	Mean Annual Q (cfs)
East Gallatin	2001-2014	**USGS 06048700 East Gallatin R below Bridger Creek near Bozeman MT**	121
Ruby	1962-2016	**USGS 06020600 Ruby River below reservoir near Alder, MT**	204
Beaverhead	1936-2016	**USGS 06018500 Beaverhead River near Twin Bridges MT**	372
Gallatin	1931-2016	**USGS 06043500 Gallatin River near Gallatin Gateway, MT**	807
Big Hole	1924-2016	**USGS 06025500 Big Hole River near Melrose MT**	891
Madison	1939-2016	**USGS 06041000 Madison River below Ennis Lake near McAllister MT**	1724
Jefferson	1979-2016	**USGS 06036650 Jefferson River near Three Forks MT**	1903

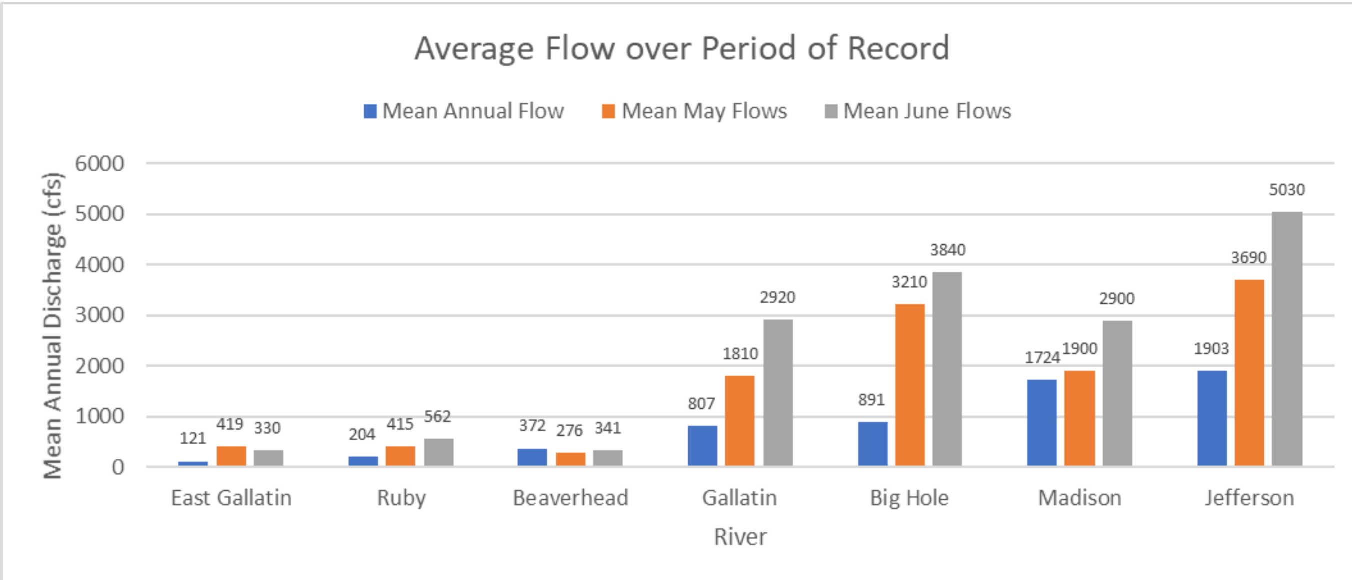

Figure 71. Mean annual discharge for gages listed in Table 3.

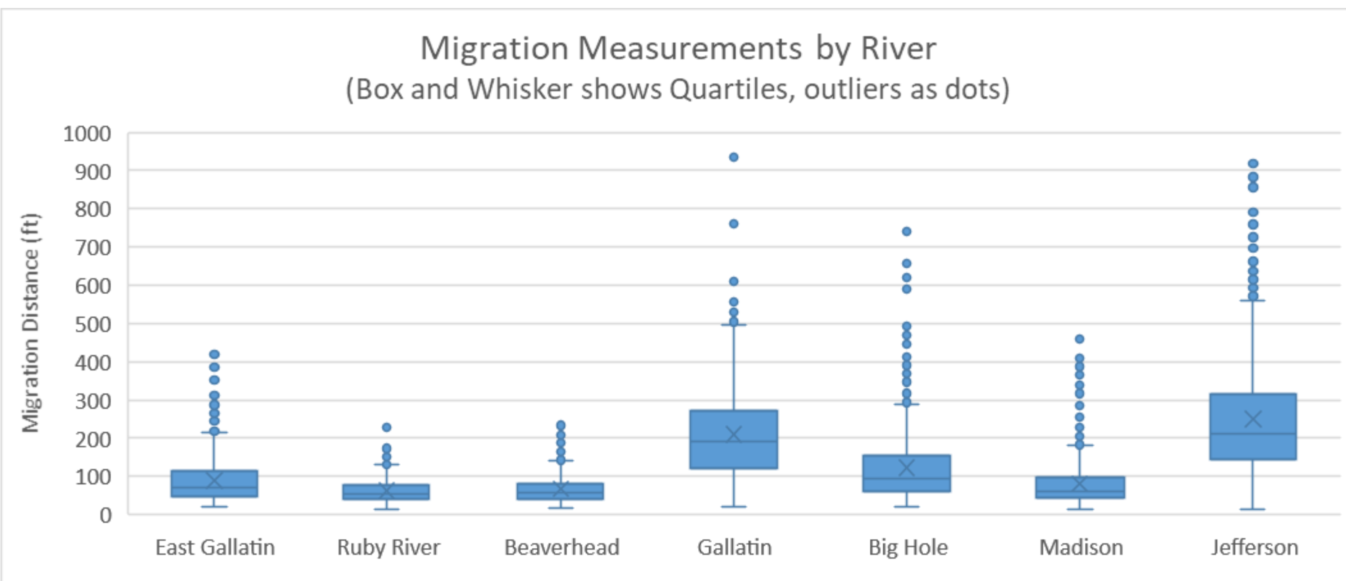

Figure 72. All migration distance measurements by river.

Figure 73 and Figure 74 summarize the variability in buffer widths between each reach and each river. The Gallatin and Jefferson Rivers both show high variability. On the Gallatin, this is primarily driven by geomorphic setting, which includes a rapid loss of slope in the downstream direction coupled by high sediment loads. On the Jefferson, the variability reflects a large river with both unconfined alluvial reaches and bedrock canyon sections.

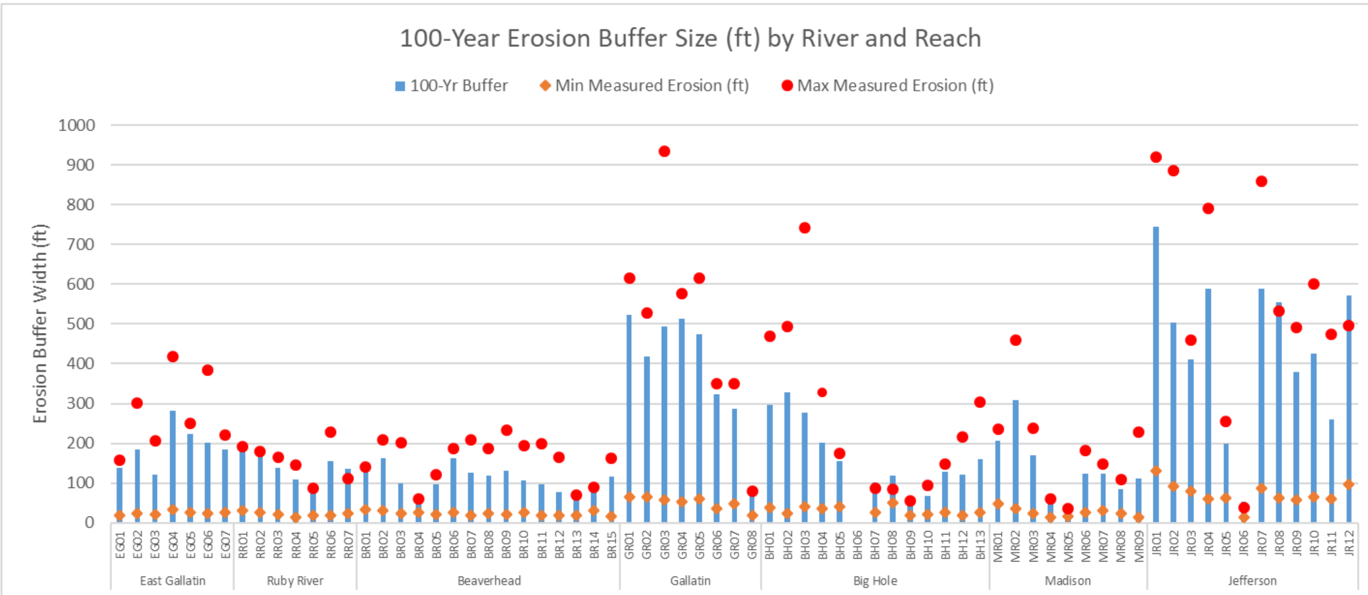

Figure 73. Erosion buffer widths for all reaches, all rivers.

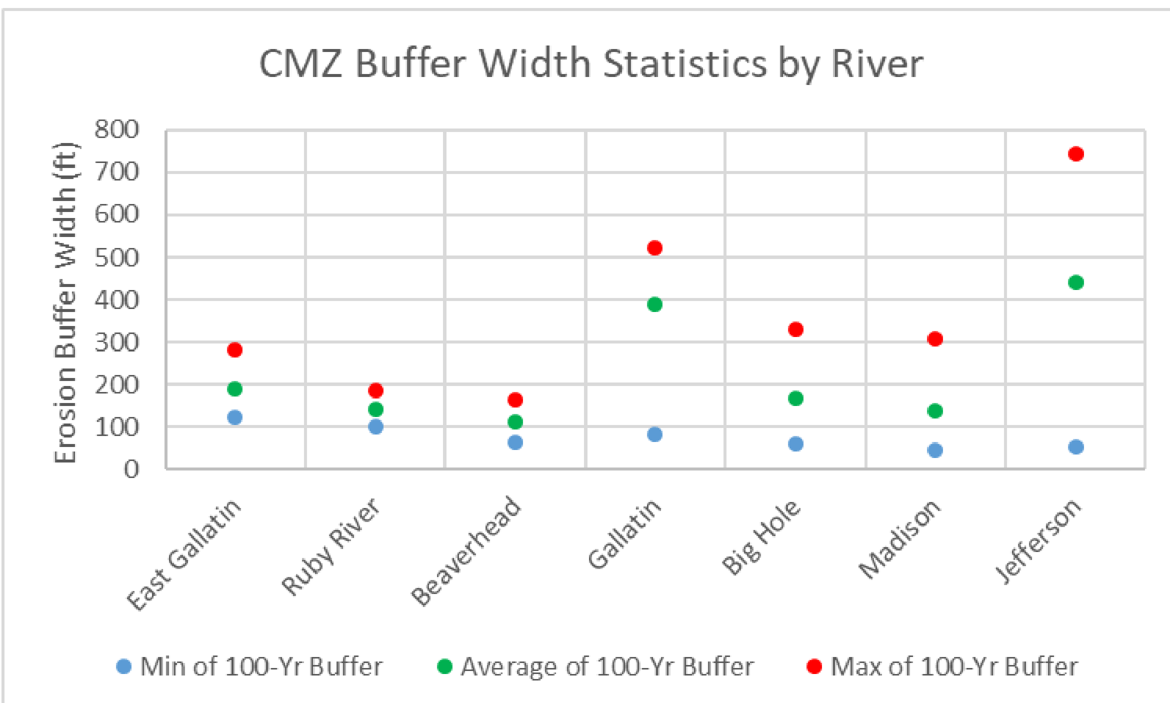

Figure 74. Variability in buffer widths for all reaches, all rivers.

In terms of the overall CMZ footprint, this effort mapped about 50,000 acres or 78 square miles as within the Channel Migration Zone of the Upper Missouri watershed. About 16% of that total acreage (8,000 acres) was

Avulsion Hazard Area whereas the rest is the combined footprint of the Historic Migration Zone and Erosion Hazard Area. On a river-wide scale, the Gallatin, Big Hole, Madison, and Jefferson Rivers have the largest overall CMZ footprint per river mile (Figure 75).

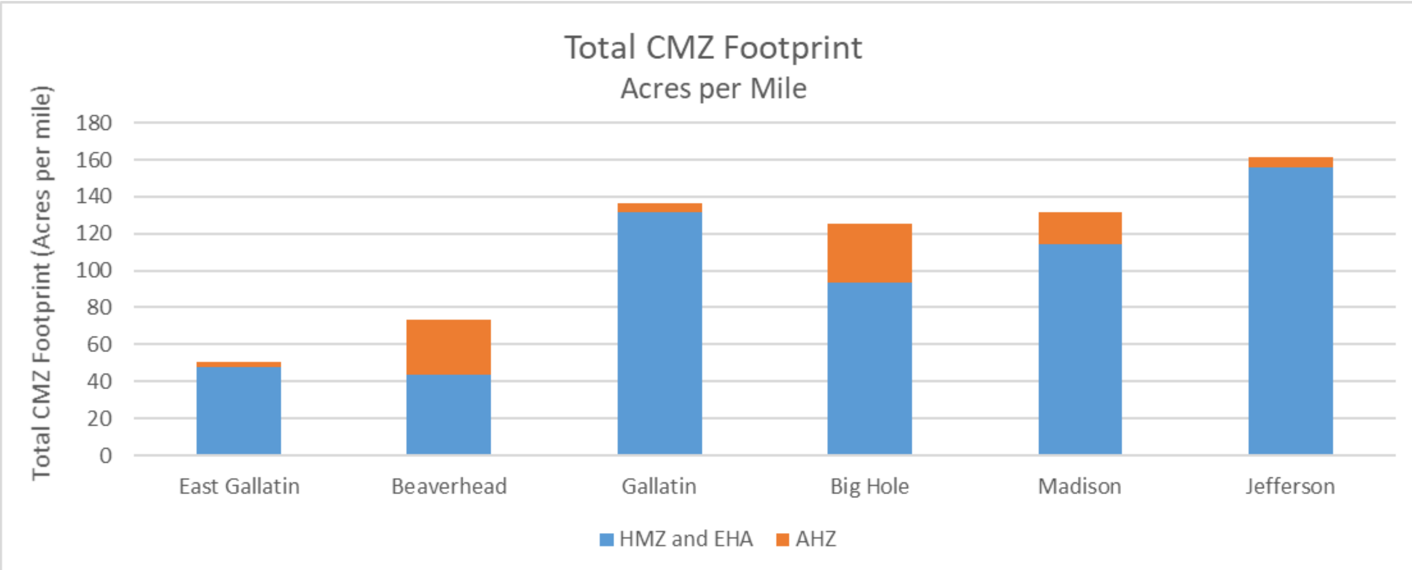

Figure 75. Acres of CMZ footprint per river mile, all rivers.

5 Common Issues Observed in CMZ Map Development

This section summarizes some CMZ-related management issues that became evident in the mapping process. These issues should be considered in future development on these rivers, as it is clear that channel migration has been costly in areas where development pressures have clashed with natural channel dynamics.

5.1 Roads and Bridges

The CMZ mapping area includes dozens of bridges and transportation features that encroach into the CMZ footprint. The main issues with bridges are twofold: 1) alignment of the river to the bridge crossing; and 2) consolidation of stream channels at a bridge crossing. Bridges are typically designed at a right angle to stream flow, so that the bridge is perpendicular to flow paths. As the channels migrate laterally, this alignment can decay, such as at Pennington Bridge on the Big Hole River (Figure 76). It is not uncommon for poor alignments to cause problems at bridges through accelerated scour which can damage bridge piers and embankments. To that end, it is important to consider stream corridor alignment and tolerance for change in both bridge design and management. In general, managing channel alignments at bridges should be considered with CMZ concepts taken into account rather than treated as a late-stage emergency when streams dog-leg through bridges, causing scour or deposition problems. The maps can help identify optimal bridge locations, and also define anticipated future alignment issues so support cost-effective risk mitigation.

Figure 76. View west of main channel at Pennington Bridge; flow direction is to the left.

Figure 77 shows another common management issue at bridge crossings, which is the need to "hourglass" multiple river channels through a bridge opening that is much narrower than the natural CMZ. This can create problems upstream of the bridge as channels run parallel to the road embankment, creating erosion problems. It is another example of how CMZ mapping can be used in transportation infrastructure design and management. For example, at Three Forks (Figure 77), it may be cost effective in the long run to construct bridges to accommodate a higher proportion of the CMZ through additional bridge spans or culverts.

Some bridges in the project area that have a poor CMZ configuration include the following:

1. East Gallatin River
   a. At Swamp Road: The river runs parallel to Swamp Road before dog-legging through the bridge, putting erosion pressure on the road embankment and left bridge pier.
   b. At West Dry Creek Road: A sharp, tight bendway just upstream of the bridge will continue to evolve and change the approach angle to the bridge, which is actively deteriorating.
2. Gallatin River
   a. Gateway South Road: The right (east) channel has been recently riprapped due to a sharp approach angle. This armor will likely need to be extended upstream with time.
   b. Norris Road: A CMZ constriction at Norris Road appears to have created some deposition upstream of the bridge and high velocities downstream.
   c. Cameron Bridge Road: Right bank migration upstream of the bridge is approaching the road and will threaten its stability without action in coming years.
   d. Amsterdam Road: The Amsterdam Road Bridge marks a major narrowing in the CMZ, in an area of extensive sediment deposition and channel movement. This site will likely have lateral erosion problems upstream, near the Irwin Bridge Fishing Access Site.
   e. I-90: Major corridor constriction.
   f. Dry Creek Road: The river is perched above channels to the west, so floodwaters my preferentially flow through secondary channels that could enlarge with time.
3. Madison River
   a. I-90 Bridge: Requires major channel consolidation.
4. Big Hole River
   a. Burma Road (Glen Fishing Access): Right bank erosion above bridge into road approach will require treatment and continues to degrade channel alignment through the structure.
   b. Pennington Bridge: Active erosion, complex split flows and a major avulsion upstream of the bridge have degraded the channel alignment, and continued maintenance will be necessary.
5. Jefferson River
   a. Meridian Road: Bendway compression immediately upstream of the bridge will result in a cutoff that will rapidly change the orientation of the river to the bridge opening.
   b. Drouillard Fishing Access: Deposition upstream of the bridge (likely driven by the CMZ constriction) is driving rapid right bank erosion that will cause problems as the river approaches the road embankment.
   c. Old Town Road: Poor alignment caused by a severe dogleg at the bridge has threatened the road.

d. Headwaters State Park: The active rail line runs semi-parallel to the Jefferson River, and at RM 1.7, northward river migration will continue to affect an already poor alignment at the structure.
6. Ruby River/Clear Creek: No readily apparent issues.
7. Beaverhead River: No readily apparent issues.

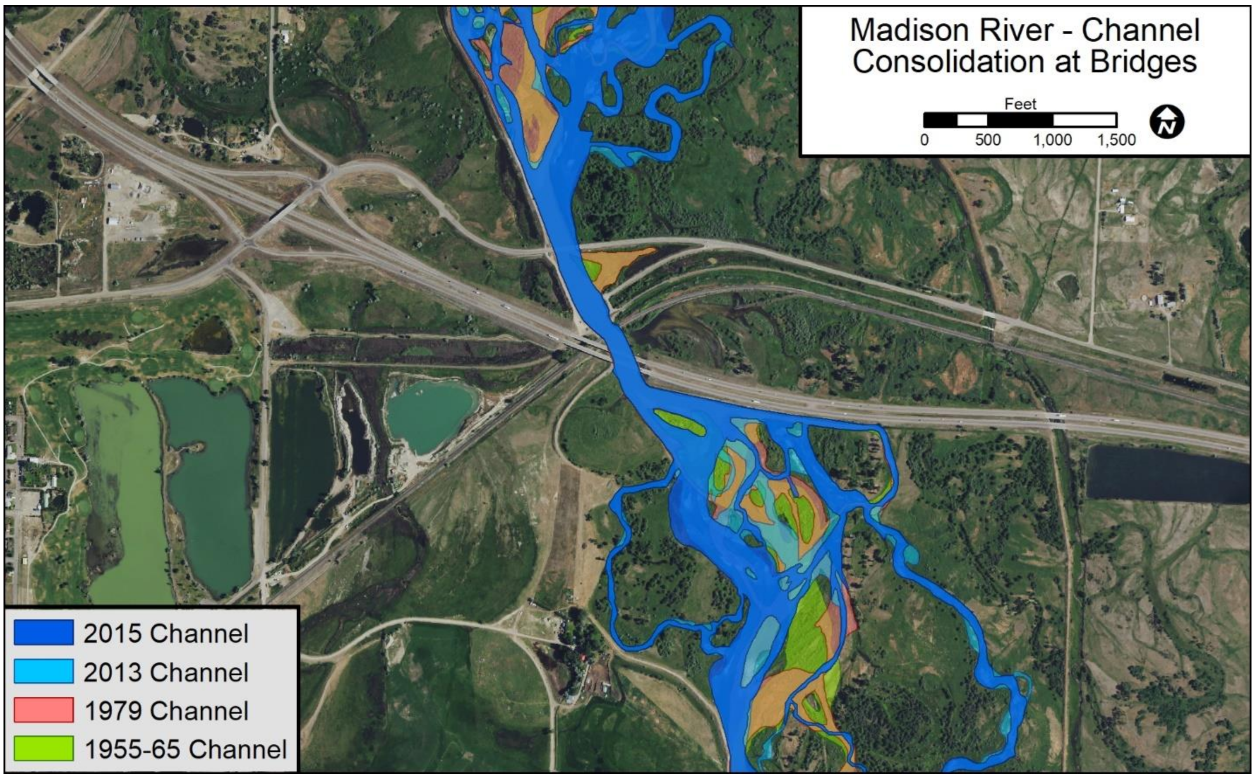

Figure 77. Madison River channel consolidation at I-90 Bridge crossing near Three Forks; flow direction is from bottom to top.

5.2 Floodplain Dikes and Levees

Floodplain dikes and levees can strongly influence CMZ boundaries, and where they are unmaintained, can alter erosion patterns and rates. In the Gallatin Valley, for example, an abandoned railroad grade behaves as a floodplain dike that confines the CMZ and affects floodplain connectivity. And below Dry Creek Road the rail line embankment crosses the river corridor at a high angle; since 1965 about 700 feet of this dike has been eroded out, expanding the CMZ through the crossing. Further downstream towards Logan the embankment has been breached, destroying an access road on the dike. Fortunately, the dike was not rebuilt, and the road was re-rerouted, providing a wider corridor for channel migration.

Another old rail embankment that is causing local problems is on the Jefferson River at the Cardwell Bridge Fishing access site, where an avulsion upstream delivered a sediment pulse to the old railroad bridge area, driving rapid migration immediately upstream of the crossing. The changing alignment angle of the river has in turn driven severe left bank erosion between barbs just upstream of the crossing.

Figure 78. View downstream of Gallatin River near Logan showing breached rail line embankment (left) and re-routed road (Kestrel).

5.3 Irrigation Infrastructure

Managing irrigation infrastructure on dynamic rivers is challenging in several ways. First, channels can migrate away from headgates and major diversions, effectively abandoning them. At the Renova Diversion on the Jefferson River near Whitehall, for example, there is concern that island formation, bank erosion, and a possible avulsion will cause the Jefferson River to bypass the structure. On the Musselshell River, several diversion structures were flanked during a major flood in 2011 and few of them have been rebuilt to date because of exorbitant costs. That flood also resulted in over 50 avulsions that abandoned dozens of points of diversions.

Another common problem with irrigation infrastructure stems from vertical changes in bed elevations, which may affect hydraulic head at diversion points and require grade controls to maintain diversion capacity (Figure 81). As stream channels move laterally or avulse into new pathways, bed elevations can change substantially on a local scale. Lastly, aggradation at headgates that are placed in passive areas in the CMZ can result in expensive, long-term maintenance needs (Figure 82).

Figure 79. View downstream towards Renova Diversion (upper left) showing channel migration away from right valley wall (Kestrel).

Figure 80. Flanking and abandonment of a diversion dam on the Musselshell River during the 2011 flood (Kestrel).

Figure 81. View upstream of rock grade controls at diversion structure just below Pennington Bridge (Kestrel).

Figure 82. View downstream of dredging at head of side channel that supplies irrigation water, Jefferson River (Kestrel).

5.4 Development Pressures

In developing the CMZ maps, it has been striking to see how many structures are at risk of damage due to bank erosion (Figure 83). In our public outreach meetings, both for this study and throughout Montana, we have heard numerous testimonies in which landowners have described their anxiety over river movement and financial stresses of property protection. Bank armoring typically costs on the order of $90-$120 per linear foot of bank, so protection of structures on these rivers can easily cost over $100,000. Yet structures are still constructed close to actively migrating channels.

Figure 83. View downstream of upper Jefferson River bendway where eastward migration of 440 feet since 1955 threatens a home site (Kestrel).

5.5 Riparian Clearing

This mapping has revealed a vast extent of riparian degradation in Upper Missouri River stream corridors. Some of the most striking areas are on the Beaverhead and Ruby Rivers, where dense willow corridors have been largely decimated. The causes of this degradation probably include active clearing, beaver trapping, grazing, and passive losses due to changes in channel form and/or hydrology. However, the continued persistence of robust riparian corridors on segments of each of these rivers indicates that riparian restoration could be an effective means of improving floodplain/bankline resilience, and possibly reducing bank migration rates.

5.6 Hydrologic Uncertainties

An important issue to consider with respect to CMZ mapping is the flood history of each river. Figure 84 shows the number of major flood events recorded on each river since 1955 (the Jefferson, Ruby, and East Gallatin records are incomplete, such that the results for those rivers are conservative). Since the start of the mapping timeframe, 100-year floods have been recorded on the Beaverhead, East Gallatin, and Ruby Rivers. The Madison and East Gallatin Rivers have also had 50-100 year floods. In general, however, major flooding has been relatively rare in the Upper Missouri Headwaters since the mid-1950s. This is an important consideration in CMZ applications, in that major floods of long duration could drive channel migration and avulsion rates and extents that are substantially more severe than what is currently documented in the air photo record.

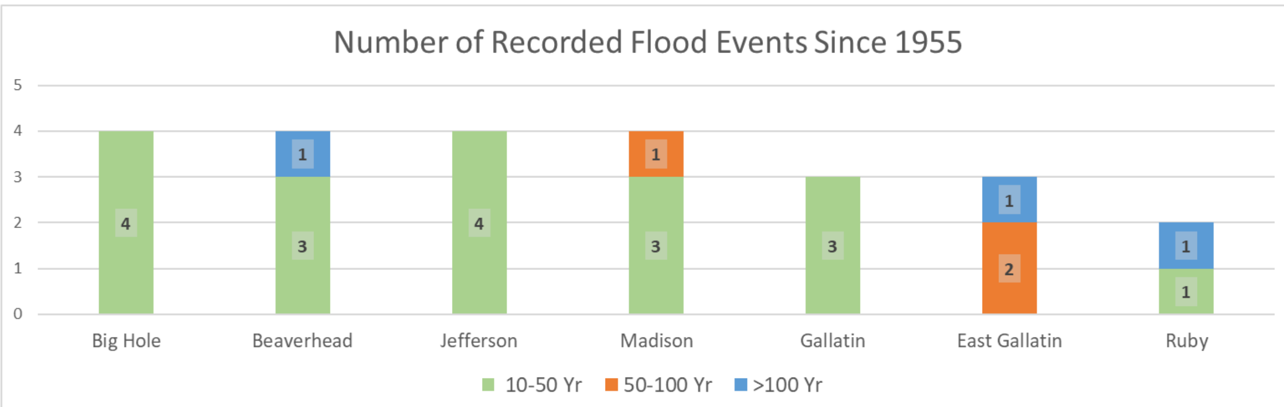

Figure 84. Number of flood events recorded on each river of the Upper Missouri Headwaters mapping area since 1955; Jefferson, Ruby, and East Gallatin Rivers have incomplete records.

5.7 Ice Jam Effects

The historic impacts of ice jams are inherently captured in the CMZ mapping if the jam caused measurable channel change that has persisted through time. That said, it is difficult to predict future long-term changes caused by ice jams, as the jams can occur with varying severity almost anywhere on these stream corridors. As a total of 113 ice jams have been recorded in the project area (Figure 85 and Figure 86), future jamming and flooding should be anticipated, and the geomorphic changes associated with this event may not be captured in the current maps.

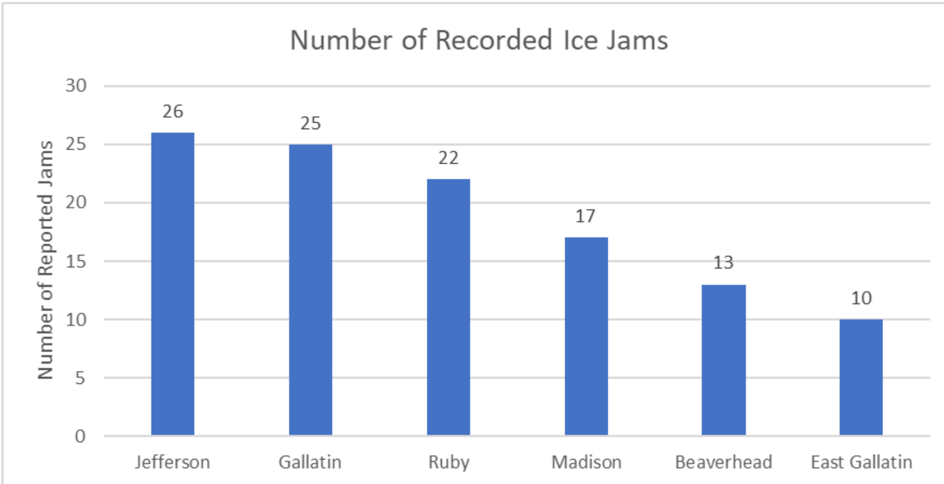

Figure 85. Number of ice jams reported on project rivers.

Figure 86. Ice jam and flooding at Twin Bridges, MT, January 4, 2011. (Madison County, MT Office of Emergency Management).

5.8 Geomorphic Stability and Ecological Function

Whereas the CMZ mapping is commonly used to identify development risks, it is also important to recognize the role that channel migration plays in maintaining geomorphic stability and optimizing the ecological function of these rivers. Whereas the major rivers of the Missouri Headwaters have been impacted by development pressures of transportation, irrigation water delivery, and residential expansion, their inherent dynamism has limited human encroachment into the CMZ footprint. As a result, there are sections on each of these systems that show largely unimpeded channel movement and resulting complex channel forms, both spatially and temporally. In places, the unrestricted CMZ corridors are over a mile wide, and commonly support broad riparian forests of diverse age classes. The continual turnover of floodplain forest supports long term riparian health as the woody vegetation is constantly regenerating (Figure 87). Wood recruitment in more dynamic reaches is common, and entrainment of both wood and sediment through bank erosion supports to aquatic habitat development and sustenance. These conditions clearly contribute to the long-term viability of our willow/cottonwood corridors, and provide geomorphically deformable river channels that can adjust to changing inputs in the future.

Figure 87. View upstream of lower Big Hole River showing multiple channel threads and riparian complexity.

6 References

AGI/DTM, 2010. Ruby River Channel Migration Zone Mapping, November 30, 2010, 75p.

BLM, 2009. Madison Watershed Assessment Report Dillon Field Office, December 2009, 75p.

Davis, Benjamin, 2015. Endangered Waters: Interdependency on Montana's Big Hole River: Montana State University Masters Thesis, April 2015, 74p.

Federal Energy Regulatory Commission (FERC), Office of Hydropower Licensing, 1997. Draft Environmental Impact Statement, Missouri-Madison Hydroelectric Project, Montana, FERC No. 2188.

Mount, N., & Louis, J. (2005). Estimation and Propagation of Error in Measurements of River Channel Movement from Aerial Imagery. Earth Surface Processes and Landforms , v.30, p. 635-643.

Rapp, C., and T. Abbe, 2003. A Framework for Delineating Channel Migration Zones: Washington State Department of Ecology and Washington State Department of Transportation. Ecology Final Draft Publication #03-06-027.

Riley, S. (1972). A Comparison of Morphometric Measures of Bankfull. Journal of Hydrology , v.17, p. 23-31.

U.S. Army Corps of Engineers (USACE), 1984. Post-flood report, Missouri River and tributaries—Spring Floods 1984, Omaha District COE.

U.S. Army Corps of Engineers (USACE) and Yellowstone River Conservation District Council (YRCDC), 2016. Yellowstone River Cumulative Effects Analysis, Final Report, U.S. Army Corps of Engineers Omaha District. Omaha NE.

Vuke, S.M., 2004. Geologic Map of the Divide Area, Southwestern Montana: Montana Bureau of Mines and Geology Open File Report MBMG 502.