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Gallatin River
Channel Migration Mapping

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Abstract

This report contains the results of a Channel Migration Zone (CMZ) mapping effort for the Gallatin River from the Highway 191 bridge at the mouth of Gallatin Canyon its confluence with the Missouri River at Missouri River Headwaters State Park in Three Forks, Montana. The Gallatin River is a coarse grained, dynamic river system that shows active channel migration and avulsion processes. Maximum migration distances since 1965 exceed 600 feet in some areas, with average migration distances for that time frame typically exceeding 200 feet. As a result, 100-year erosion hazard area buffer widths range from 80 feet just below the mouth of Gallatin Canyon where the channel is geologically confined to about 500 feet from Norris Road to Headwaters State Park. The river tends to support multiple channels that are also dynamic, with new channels forming and older channels becoming frequently abandoned. Those changes were measured as a total of 63 avulsion events between 1965 and 2015. The avulsions formed within the woody riparian corridor, through ditches, and in grassy floodplain areas. The new channels range in length from hundreds of feet to over a mile long, and once they form they commonly rapidly enlarge and migrate laterally. Upstream of the I-90 bridge, mile-long avulsions have relocated the river over a thousand feet laterally across its floodplain.

The 100-year flood mapping for the Gallatin River shows a complex network of channel threads that are prone to flooding during a major flood event. The CMZ mapping presented here indicates that lateral channel migration is also a demonstrable threat to capital investment and human safety on the river, and that rapid changes in erosion rate and location should be expected virtually anywhere on the river, especially during floods. Although the Gallatin River experienced major geomorphic change during the floods of 1974 and 1997, these floods have been estimated as approximately 25-year events, indicating that the river should be expected to persistently occupy a wide, multi-channeled stream corridor that is capable of rapid short-term change.

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Glossary and Abbreviations

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

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

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

CD – Conservation District.

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

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

DNRC – Department of Natural Resources and Conservation.

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

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

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

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

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

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

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

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

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

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

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

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

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

Morphology - Of or pertaining to shape.

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

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

RDGP - Reclamation and Development Grants Program, DNRC.

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

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

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

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

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

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

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

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

1 Introduction

The Gallatin River Channel Migration Zone (CMZ) mapping project developed approximately 42 miles of CMZ mapping for the Gallatin River from the Highway 191 Bridge, downstream to its confluence with the Jefferson and Madison Rivers in Three Forks. It is part of a larger effort to map approximately 440 miles of river in the Upper Missouri River headwaters. Other rivers in the study include the Beaverhead, Jefferson, Madison, and East Gallatin Rivers, revising the 2005 Big Hole River mapping (Wisdom to Twin Bridges), as well as updating mapping in the Ruby River Valley to include Clear Creek. The main stem of the Ruby River from Ruby Reservoir to Twin Bridges was mapped in 2010 and the Big Hole River in 2005. In total, approximately 493 miles of river in the Missouri River headwaters will have CMZ mapping. Other rivers in Montana that have CMZ significant areas of mapping include the Yellowstone River, sections of the Flathead, Clark Fork, and Bitterroot Rivers, Deep Creek (Broadwater County), and Prickly Pear and Tenmile Creeks (Lewis and Clark County).

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

1.1 The Project Team

This project work was performed by Karin Boyd of Applied Geomorphology and Tony Thatcher of DTM Consulting, 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, to provide rational and scientifically-sound tools for river management. It is our 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 believe the mapping supports the premise that managing rivers as dynamic, deformable systems contributes to ecological and geomorphic resilience while supporting sustainable, cost-effective development.

1.2 What is Channel Migration Zone Mapping?

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

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

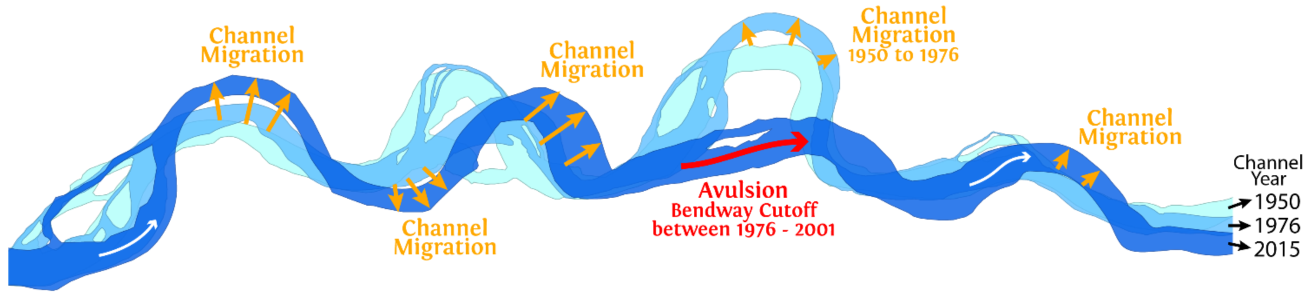

Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

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

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

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

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

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

The individual map units comprising the CMZ are as follows:

CMZ = HMZ + EHA + AHZ

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

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

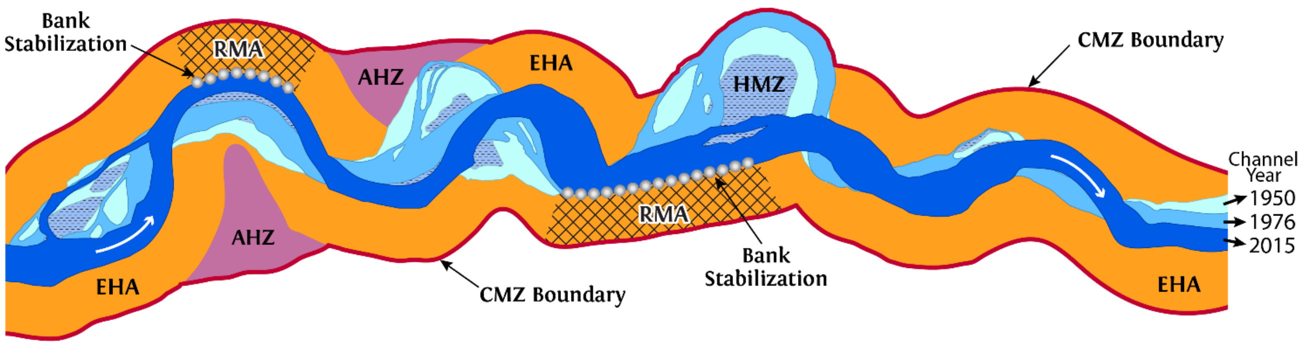

Figure 2. Channel Migration Zone mapping units.

1.3 CMZ Mapping on the Gallatin River

The Channel Migration Zone (CMZ) developed for Gallatin River extends 45.5 river miles from the mouth of Gallatin Canyon south of Gallatin Gateway to its confluence with the Missouri River at Three Forks, MT, The Gallatin River, Madison River, and Jefferson Rivers join at Three Forks to form the Missouri River.

Although the basic concept for Channel Migration Zone mapping efforts is largely the same throughout the country, different approaches to defining CMZ boundaries are used depending on specific needs and situations. These differences in assessment techniques can be driven by the channel type, different project scales, the type and quality of supporting information, the intended use of the mapping, etc. For this study, the CMZ is defined as a composite area made up of the existing channel, the collective footprint of mapped historic channel locations shown in the 1965, 1979, 2013, and 2015 imagery (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA), that is based on reach-scale average migration rates. Areas beyond the Erosion Buffer that pose risks of channel avulsion are identified as Avulsion Hazard Areas or AHZ. This approach generally falls into the minimum standards of practice for Reach Scale, Moderate to High Level of Effort mapping studies as defined by the Washington Department of Ecology (www.ecy.wa.gov). This approach does not, however include a geotechnical setback on hillslopes; these areas would require a more site-specific analysis than that presented here.

1.4 Uncertainty

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

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

From the mouth of Gallatin Canyon to Headwaters State Park, the Gallatin River shows historic patterns of lateral migration and avulsion, locally within a very broad floodplain surface that has dense networks of historic channels. With potential contributing factors, such as woody debris jamming, sediment slugs, tectonic deformation, landslides, or ice jams, dramatic change could potentially occur virtually anywhere in the stream corridor or adjacent floodplain. As the goal of this mapping effort is to highlight those areas most prone to either migration or avulsion based on specific criteria, there is clearly the potential for changes in the river corridor that do not meet those criteria and thus are not predicted as high risk.

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

1.5 Relative Levels of Risk

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

1.6 Other River Hazards

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

1.6.1 Flooding

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

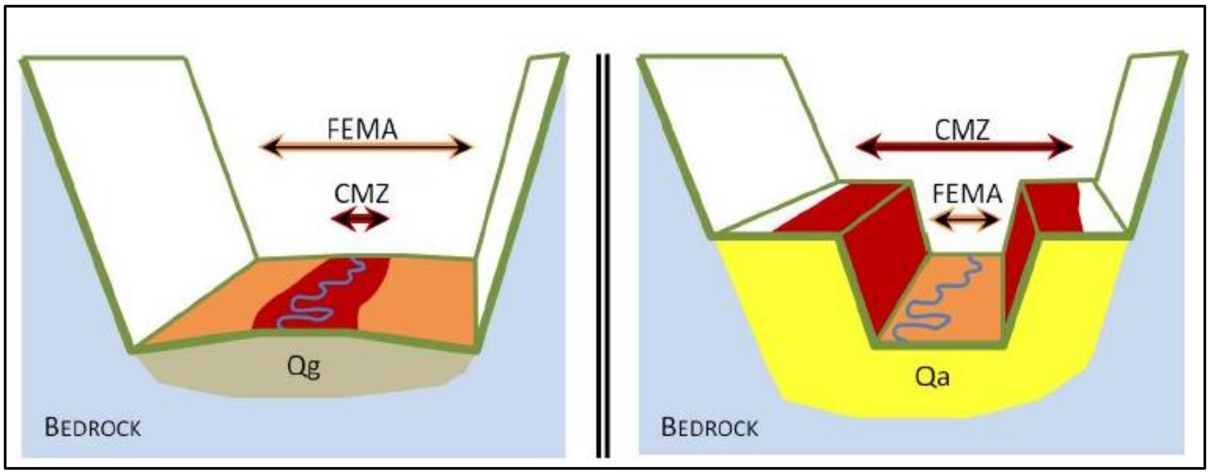

Figure 3. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

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

> *We knew the river was there. We were 3 feet above the 100-year flood plain and made sure we were well above the flood plain. It was surveyed and the engineers told us where we had to put it and no, we don't have flood insurance or any kind of insurance that is going to reimburse us for anything.*
>
> *Our property was not located within the 500-year flood plain or was it adjacent to it. The river simply took a new route that went right through our property.*
>
> *I knew we were in big trouble. The river was raging and making a sharp "S" turn right behind our home. Our property seemed to take the full force of the river turning against the bank. Large chunks of earth were being swallowed up into the river. We watched 20 feet*

erode in less than two hours. We knew if it continued at that pace, we'd lose our house. Our contractor contacted an excavation company early that morning, but they said there was nothing they could do for us. We were also informed that our contractor's insurance was not covered for floods.

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

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

An example floodplain map for the Gallatin River at the I-90 bridge is shown in Figure 6. The floodplain boundaries depict a complex series of active channels and floodplain areas, and recent proposed revisions include substantial changes to the older mapped boundary. This shows the difficulty in mapping flood boundaries on a dynamic, complex river such as the Gallatin. The combined risks of flooding and channel migration on the Gallatin River create a broad swath of hazards along the river, and both should be considered as threats to human health and safety.

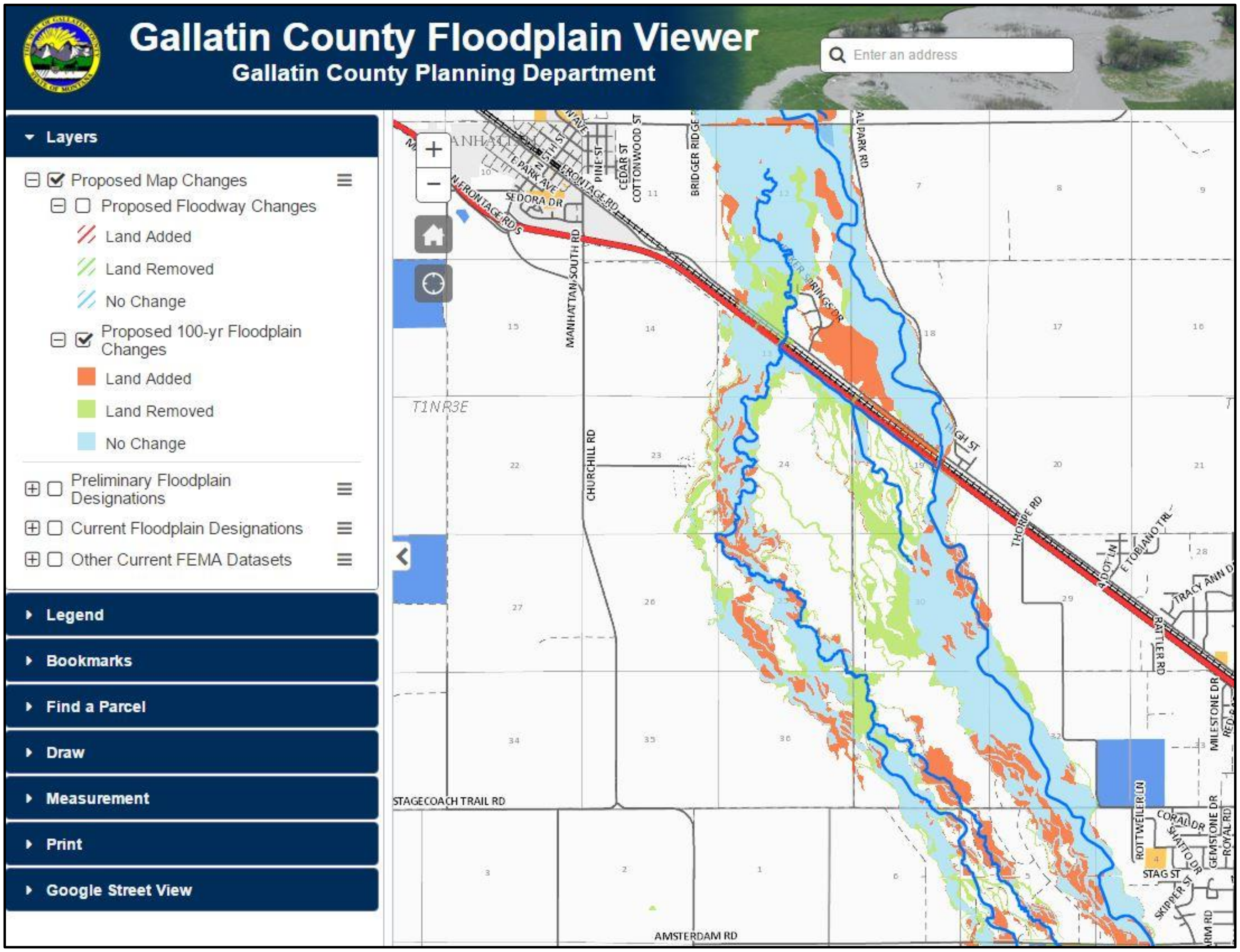

Figure 6. Example floodplain mapping for Gallatin River at I-90 (gis.gallatin.mt.gov).

1.6.2 Ice Jams

Another serious river hazard, especially in Montana, is ice jamming. Over 1,470 ice jams have been recorded in Montana, which is the most of any of the lower 48 states (http://dphhs.mt.gov/). Ice jams are most common in Montana during February and March. Dams can cause flooding upstream due to backwatering, and downstream of the jam ice chunks mobilized by breakups can cause damage. Breakups can occur rapidly, and it generally takes water that is almost two to three times the thickness of the ice to mobilize the jammed ice. Ice jams can also cause avulsions by entirely blocking channels and forcing flows onto the floodplain.

The National Weather Service has identified the Gallatin River as having 25 reported ice jams (Figure 7), and these jams appear most common where the river is relatively constricted by bedrock and transportation infrastructure near Logan (Figure 8). In January of 2013, National Weather Service personnel saw the river stage rapidly rising near Logan, nearing the flood stage of 9 feet. This area has been described as prone to jamming due to a bridge crossing just downstream of a bend that slows water. Concerns regarding ice jamming in this area includes flooding upstream near Manhattan, and in December 2009, ice jamming sent the river out of its banks west of Belgrade, flooding pastures and threatening homes. In 2014, the river jammed near Gallatin Gateway causing flooding (www.nbcmontana.com), closing the Axtell Gateway Road.

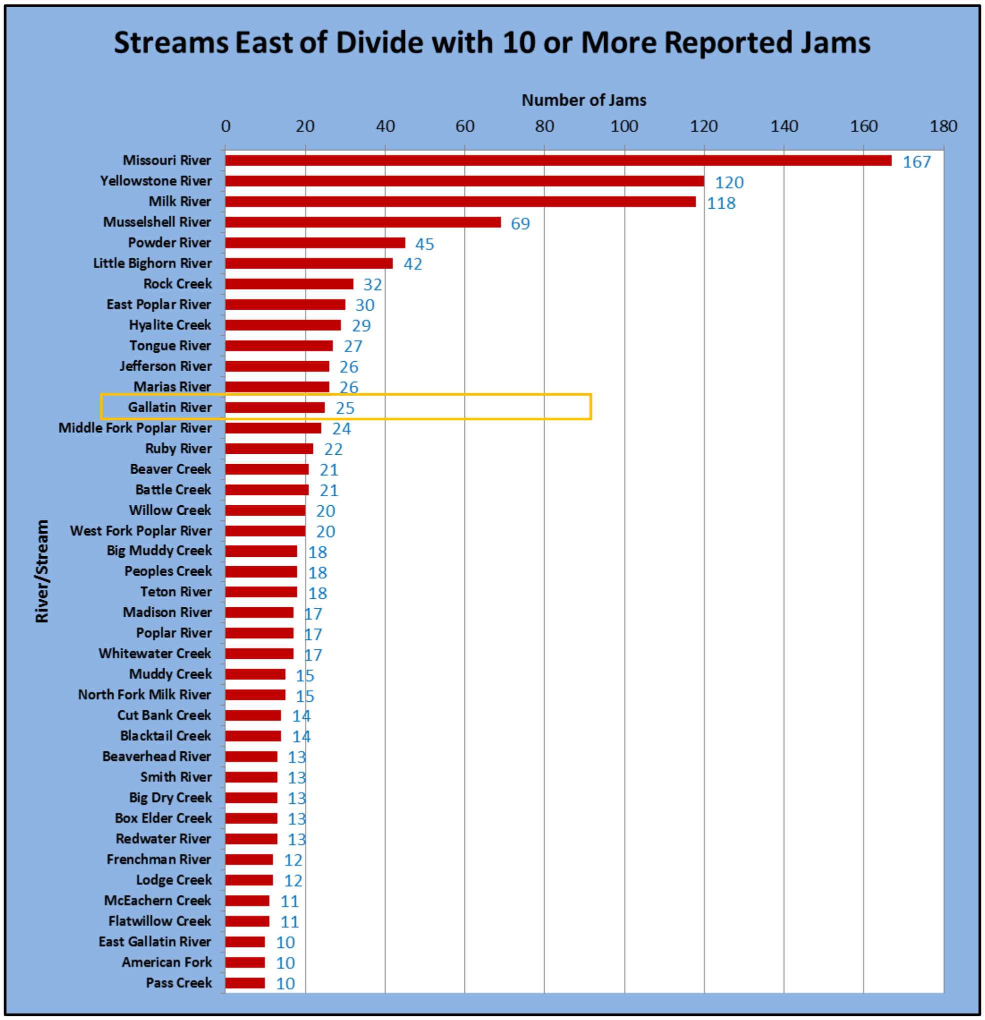

Figure 7. Montana rivers east of the continental divide with 10 or more reported ice jams.

Figure 8. Bridge damage caused by 1963 Ice jam on Gallatin River near Logan (billingsgazette.com).

1.6.3 Landslides

There are no mapped landslides adjacent to the Gallatin River in the project area. Upstream, however, landsliding in the Gallatin River watershed could impact stream process in the project reach by impounding and then releasing massive volumes of water and sediment. In 1997, for example, the Bozeman Daily Chronicle reported that Dave Lageson, an MSU geology professor, found huge cracks near the summit of Mount Jumbo near Lava lake. After making some measurements Lageson concluded that a strong earthquake could trigger a massive landslide that would be about equivalent to the 1959 Quake Lake Slide (bozemandailychronicle.com).

Figure 9 shows an example of a relatively small landslide that occurred in February 2014 on the south wall of the Nooksack River Valley near Bellingham, Washington. The landslide originally blocked the channel, and the effect was seen at a gaging station downstream where river flows rapidly dropped from over 2,000 cubic feet per second to about 400 cubic feet per second in the early morning hours of February 21 (Figure 10). The river breached the landslide and flows returned to normal, however the river was shifted hundreds of feet. Probably the most recently renown landslide into a river system was the 2014 Oso Slide into the North Fork of the Stillaguamish River, which dammed and relocated the river causing extensive flooding upstream (Figure 11).

Figure 9. Hillslope failure on Nooksack River near Bellingham Washington on February 21, 2014 (K. Boyd).

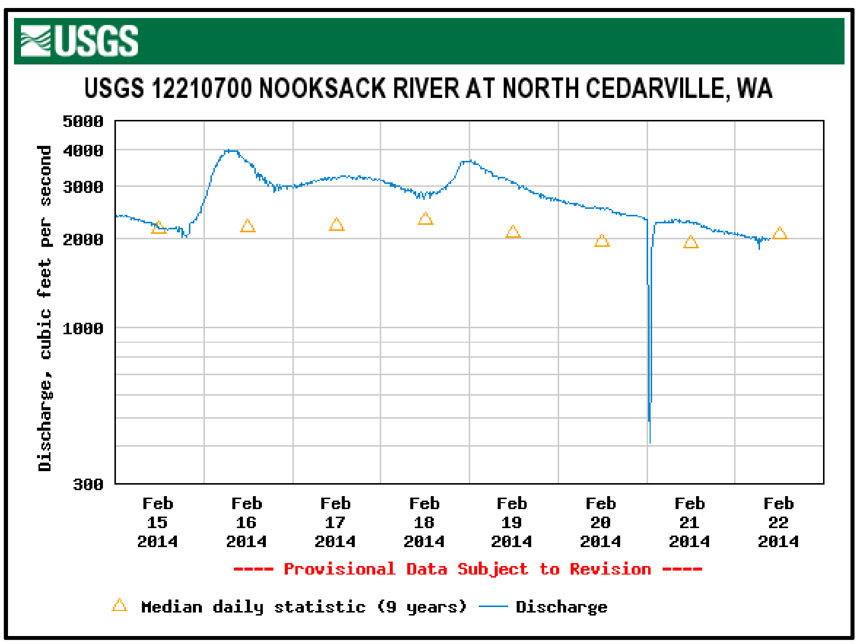

Figure 10. USGS gage data showing rapid drop in river flow following upstream hillslope failure.

Figure 11. Massive mudslide in Oso Washington on March 22, 2014, deflecting the North Fork of the Stilliguamish River (AP Photo/Ted Warren).

1.7 Potential Applications of the CMZ Maps

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

Potential applications for the CMZ maps include the following:

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

1.8 Disclaimer and Limitations

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

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

1.9 Image Licensing and Use Restrictions

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

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

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

1.10 Acknowledgements

We would like to extend our gratitude to Rebecca Ramsey of Ruby Watershed Council and Shirley Galovic of Ruby Conservation District for their assistance in contract management and scheduling. Additionally, Sean O'Callaghan, Gallatin County Planning Director and Floodplain Administrator, provided valuable input and helped coordinate review efforts in Gallatin County. We also acknowledge the professionalism and talent of Chris Boyer of Kestrel Aerial Services (Kestrel), in obtaining oblique aerial photography that provides a perspective of the river that can't be made with conventional air photos. We look forward to receiving comments on this draft report, and those contributors will be acknowledged accordingly.

2 Physical Setting

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

2.1 Geography

The Gallatin River in southwest Montana is one of three tributary rivers that form the Missouri River, along with the Jefferson and Madison Rivers (Figure 12). The Gallatin River begins at Gallatin Lake in Yellowstone National Park and flows for about 115 miles to Headwaters State Park near Three Forks, Montana, where it joins the Jefferson and Madison Rivers to form the Missouri River. The watershed is about 1,200 square miles, or 9% of the Upper Missouri Watershed. The entire drainage area is above 4,000 feet in elevation, and whereas most of the land above 5,000 feet is forested terrain, most below 5,000 feet is within the Gallatin Valley, a rich agricultural area experiencing rapid residential growth. The contributing watershed area above the project reach is mostly public land, and the land surrounding the river between the mouth of Gallatin Canyon and Three Forks is largely private.

Gallatin Canyon and the Gallatin Valley were first explored by Native American hunters and then gold prospectors and trappers. The Gallatin River was named by Meriwether Lewis in July 1805 as the Lewis and Clark Expedition reached what is now Headwaters State Park. It was named for Albert Gallatin, the U.S. Treasury Secretary from 1801-1814.

2.2 Geology and Glacial History

The following summary of the geological setting of the project reach is intended to provide some context as to how the physical setting influences river process. Upstream of the project reach, Upper Gallatin Canyon is bound by the Madison Range west of the river and the Gallatin Range to the east. The Madison Range consists of an actively uplifting basement block that is still covered by folded Paleozoic and Mesozoic sedimentary formations (Alt and Hyndman, 1986). The Gallatin Range to the east is also actively rising, with greater exposures of basement rock, much of which has been covered by volcanic rocks erupted from the Absaroka volcano during Eocene time about 50 million years ago. In the northern part of Gallatin Canyon, the river flows along the eastern margin of the Spanish Peaks, where Precambrian basement rocks that have been uplifted about 13,500 feet are exposed.

Glaciation on the high Yellowstone Plateau during the ice ages spilled into the Gallatin River drainage, although the western edge of the Yellowstone Ice Cap only reached into the upper Gallatin where the river flows through Yellowstone National Park.

As the Gallatin River emerges from Gallatin Canyon and into the Gallatin Valley, it leaves the confining bedrock canyon and enters a much more fluvially dynamic stretch, with extensive alluvial deposits exposed along stream corridors and alluvial fans that have developed on tributaries such as South Cottonwood Creek. The valley floor is largely mapped as “braid plain alluvium” (Vuke et al, 2014), which consists of coarse recent deposits that are underlain by thousands of feet of relatively young sedimentary units. The Gallatin River follows a thread of modern river alluvium inset within that older braid plain alluvial deposit. This thread of alluvium widens markedly where the river encounters alluvial fan deposits of Little Bear and South Cottonwood Creeks (Figure 13).

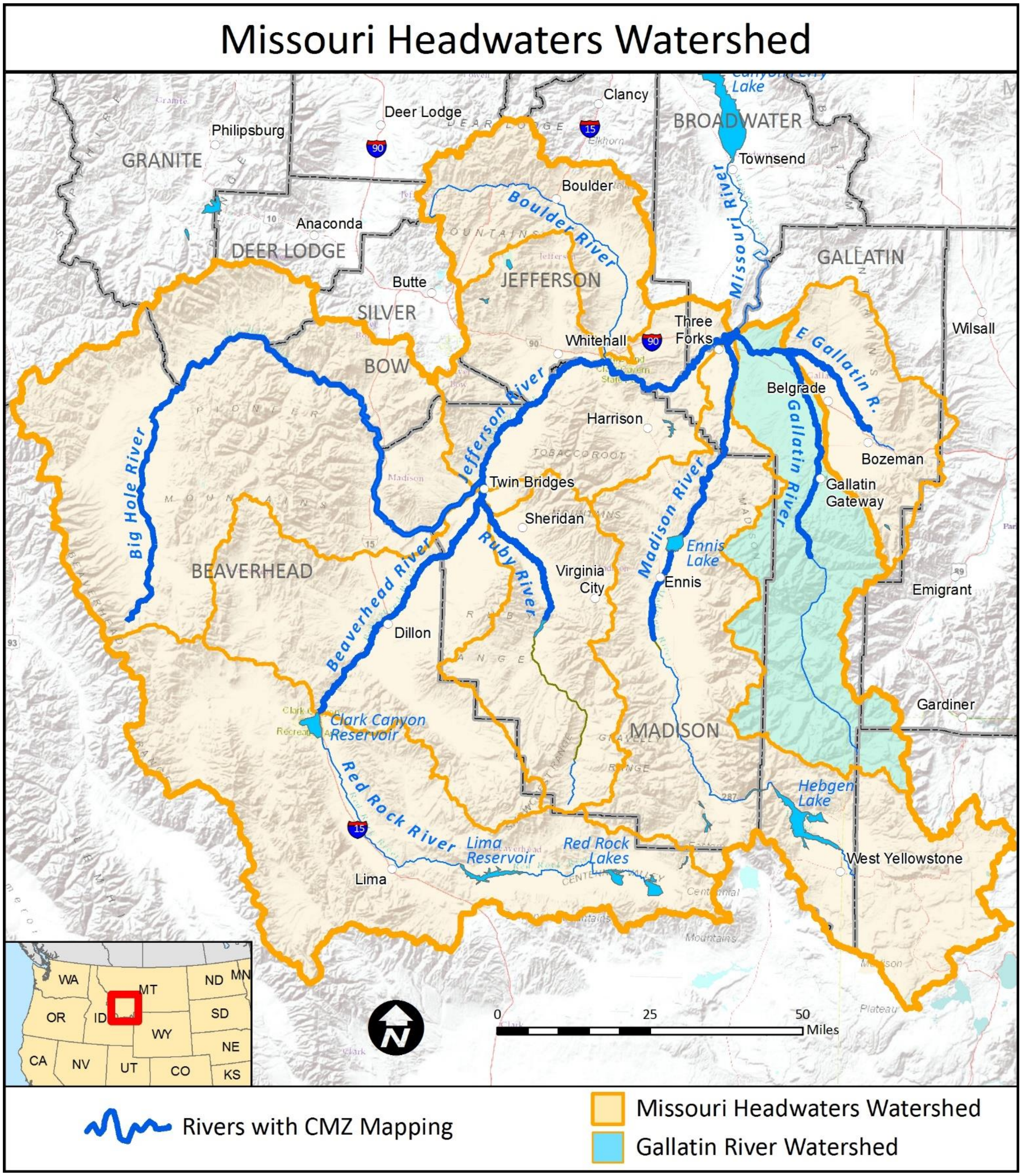

Figure 12. Gallatin River Watershed.

The emergence of the Gallatin River from Gallatin Canyon marks an abrupt change in stream morphology and associated dynamics. As the canyon is formed in largely non-erodible bedrock, the Gallatin River CMZ in through the canyon is very narrow and in many places, does not extend beyond the modern streambank. Downstream in the project reach, however, the combination of a decreasing channel slope, increased lateral sediment inputs from tributaries, and an erodible channel margin result in a highly dynamic stream corridor that has experienced extensive bankline migration and numerous avulsions since 1965. In some locations, low alluvial terraces border the stream corridor, and these surfaces are commonly developed in areas such as Four Corners. Although the river has eroded into these deposits, measured migration rates are slower than that of modern alluvium of the main river corridor, and this geologic variability has been taken into account in the CMZ mapping. Near Logan the river flows through a short bedrock-controlled segment where a notch has formed, with highly deformed Mesozoic sedimentary rocks exposed on the north side of the river in the Rattlesnake Hills, and younger Tertiary sediments (Sixmile Creek Formation) to the south. The river flows through the geologic notch at Logan directly through the contact zone of these units (Figure 14).

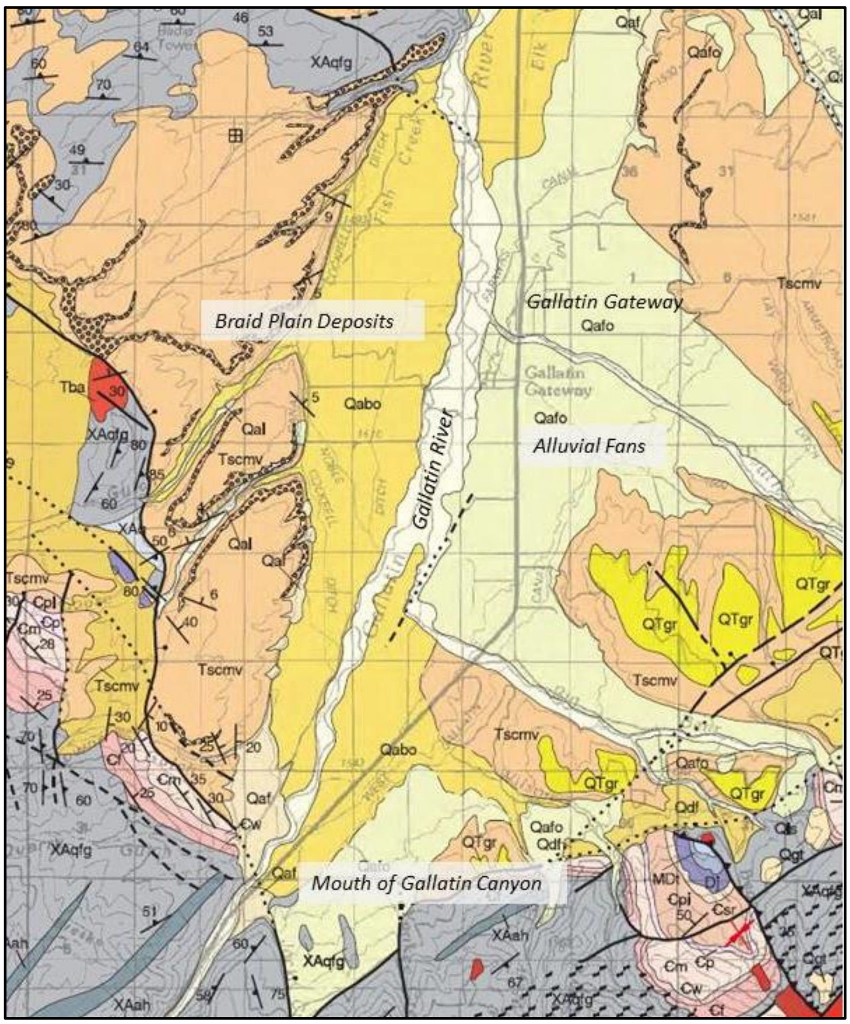

Figure 13. Geologic map of upper project reach area (Vuke et al, 2014).

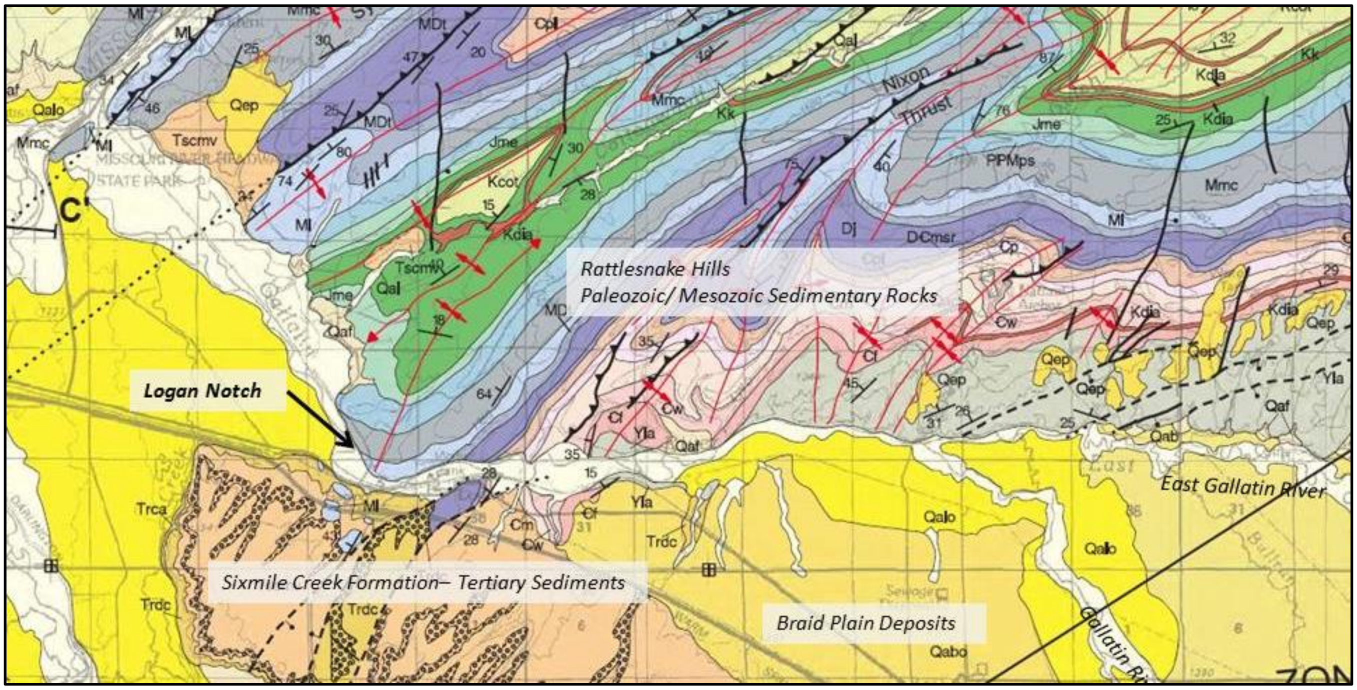

Figure 14. Geologic map of Logan Area (Vuke et al, 2014).

2.3 Hydrology and Flow Management

The hydrology of the Gallatin River reflects a typical snowmelt system, with peak flows occurring between late May and early July.

2.3.1 Major Diversion Structures

Although numerous diversions feed an extensive network of canals on the Gallatin River, there are no diversion structures in the study area that span the entire river. The Montana Department of Natural Resources and Conservation Water Rights data show 504 headgate points of diversion listed for the Gallatin River within the study area. Oblique aerial photographs of selected major diversions are compiled in Appendix C.

Some diversions in more dynamic sections of river require annual site work such as the construction of in-stream gravel berms to secure water delivery to ditches; other diversions in more geologically controlled reaches appear to function well with minimal maintenance.

2.3.2 Gallatin River Flood History

Over the past 75 years, the largest flood events on the Gallatin River occurred in 1974 and 1997, and both events slightly exceeded the 25-year discharge of 9,080cfs (Figure 15). The June 30, 2011 flood of 8,410 cfs was just over a 10-year event. Some older datasets record major floods in the late 1800's, including one 1899 flood described by Morrison Maierle (2014) as having exceeded a 50-year event (Table 1). In general, however, major flooding has been notably rare on the Gallatin River at least since the 1930s.

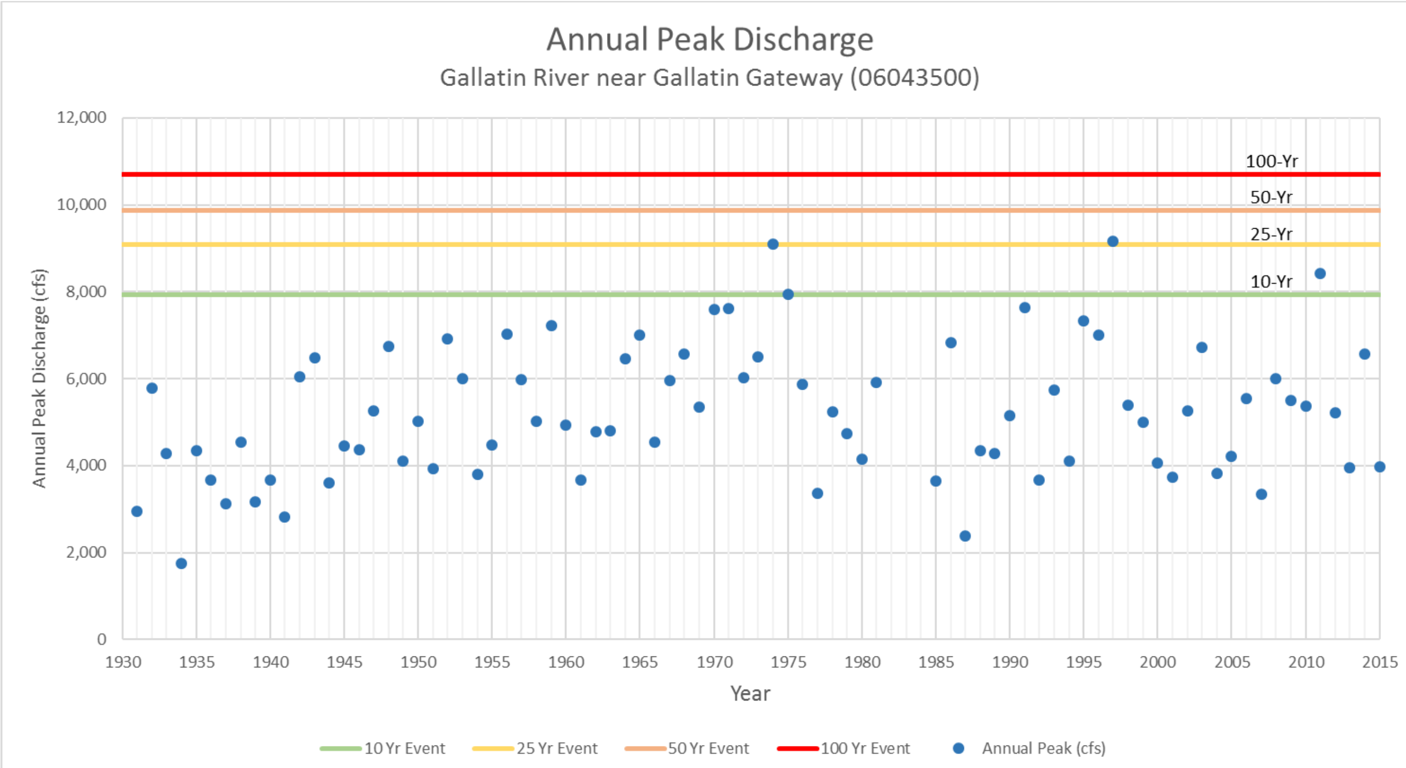

Figure 15. Annual peak flow record, Gallatin River near Gallatin Gateway (USGS 06043500).

Table 1. Five largest peak floods recorded on the Gallatin River (Morrison Maierle, 2014).

Ranking	06043500 Gallatin River near Gallatin Gateway		06052500 Gallatin River at Logan, MT	
	Date	Peak Discharge (cfs)	Date	Peak Discharge (cfs)
1	June 20, 1899	10,000(1)	June 21, 1899	9,840
2	June 2, 1997	9,160	June 8, 1997	9,400
3	June 17, 1974	9,100	June 10, 1970	9,390
4	June 18, 1896	8,700(1)	June 18, 1974	9,170
5	June 30, 2011	8,410	June 28, 1971	8,480

(1) Note: Peak flow from 06044000 Gallatin River near Salesville, MT

2.4 Dikes and Levees

Embankments constructed on the floodplain to keep areas dry are called dikes or levees. For the purposes of this study, levees are defined as embankments that are integrated to form coherent flood control systems. In contrast, dikes tend to be shorter, more informal flood protection features that are typically discontinuous. Within the study area, the Gallatin River has no levee system, although we mapped approximately 2.3 miles of discontinuous dikes within the Channel Migration Zone, which reflects about 2.5% of the total bank length. Some of the dikes follow the active bankline and others are older and set back from the active corridor. An example of dikes on the channel margin is shown in (Figure 16). The impact of dikes on the CMZ is described in more detail in Section 4.5.

Figure 16. A 0.6-mile dike on left (west) bank of the Gallatin River below West Dry Creek Road. (Kestrel)

2.5 Bank Armor

Bank armor was mapped where visible on air photos, Google Earth, or oblique photographs. Since there was no ground inventory, the mapping probably captures a conservative estimate of the extent of bank armor on current and historic channels. Additionally, the bank armor inventory has not assessment of condition or functionality. Along the length of the Gallatin River, we mapped 7.3 miles of bank armor which covers about 8% of the total bankline. The bank armor consists of rock riprap, barbs, and other revetments such as wood structures, and potentially concrete rubble.

The extent and impact of bank armoring on the CMZ is described in more detail in Section 4.5.

2.6 Transportation Infrastructure

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

Road encroachment into the Gallatin River CMZ is fairly moderate, with the exception of the river segment between Logan and Three Forks, where the rail line isolates hundreds of acres of historic migration area.

Seventeen bridges span the entire primary channel or major side channels within the project area. The bridges are dispersed along the river's length. These bridges and their associated approaches locally constrict the CMZ, and they are commonly armored and/or leveed to manage alignment of the river through the structure (Figure 17).

Figure 17. Extensive armor associated with the Norris Road bridge approach. (Kestrel)

3 Methods

The development of the Gallatin River Channel Migration Zone (CMZ) mapping is based on established methods used by the Washington State Department of Ecology (Rapp and Abbe, 2003), and closely follows methodologies used on other rivers in Montana.

3.1 Aerial Photography

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

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

Imagery older than 1995 must be acquired from various archival services as digital scans, and then mosaiced into a single spatially-referenced image for use in the GIS. For this project, the historic imagery scans were ordered from the United States Department of Agriculture (USDA) Air Photo Field Office (APFO) in Salt Lake City, Utah. Approximately 67 individual images were ordered from the APFO to cover two time periods for the Gallatin River. The area around Three Forks is shared by both the Madison and Jefferson Rivers, so there is some common imagery between the three rivers.

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

Table 2 lists imagery used for this project from the USDA and archives of current GIS data sets. Examples of the imagery used in the analysis are shown in Figure 18 through Figure 21.

Table 2. Aerial photography used for the Gallatin River Channel Migration mapping study.

Date	Source	Scale	Notes
1965	USDA APFO	1:20,000	High-resolution Scans (black-and-white)
1979/80	USDA APFO	1:40,000	High-resolution Scans (black-and-white)
2013 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)
2015 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)

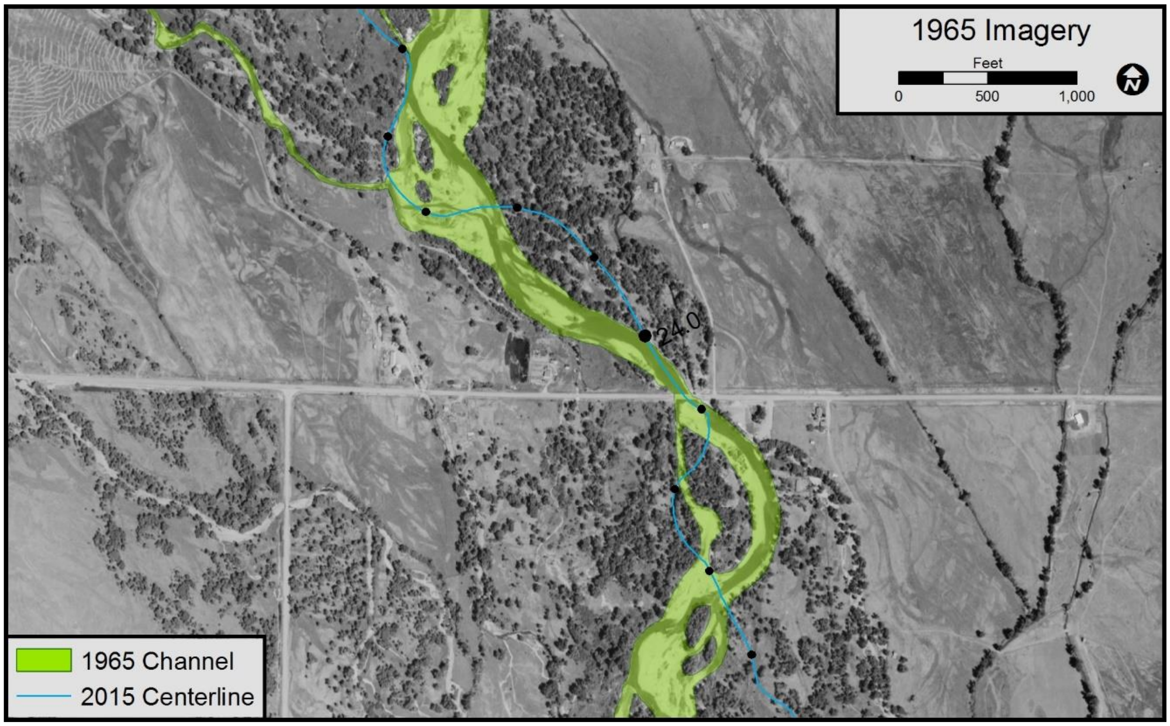

Figure 18. Example 1965 imagery at Amsterdam Road, Gallatin River CMZ development.

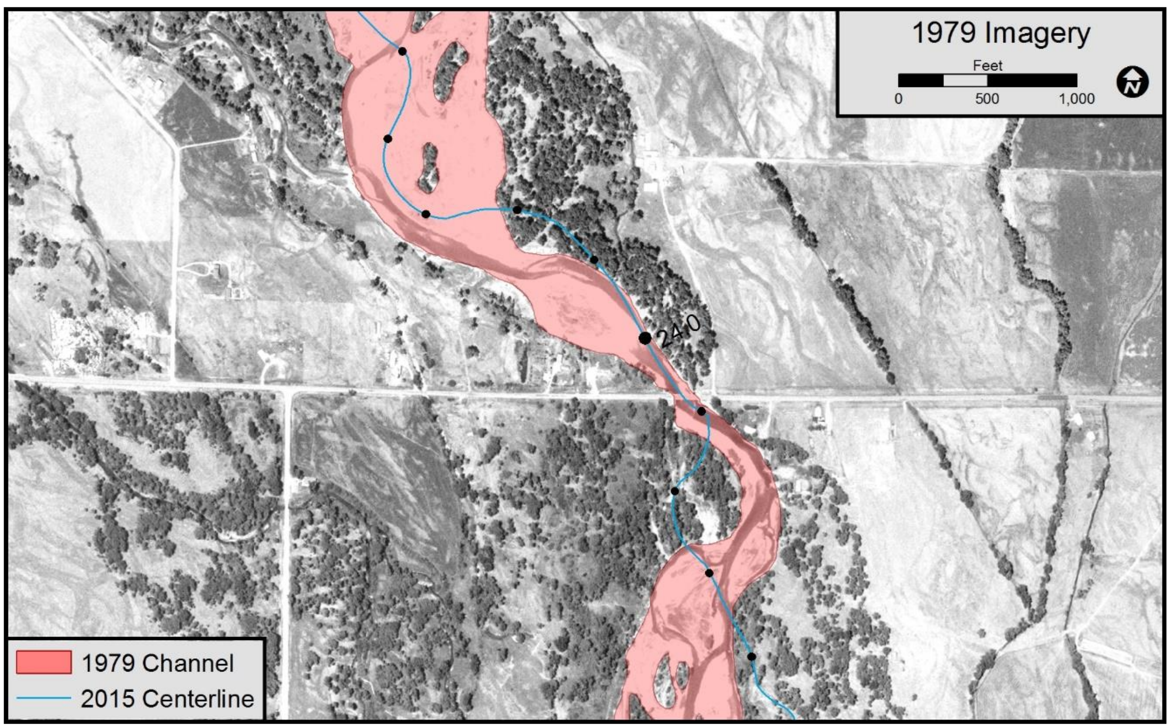

Figure 19. Example 1979 imagery at Amsterdam Road, Gallatin River CMZ development.

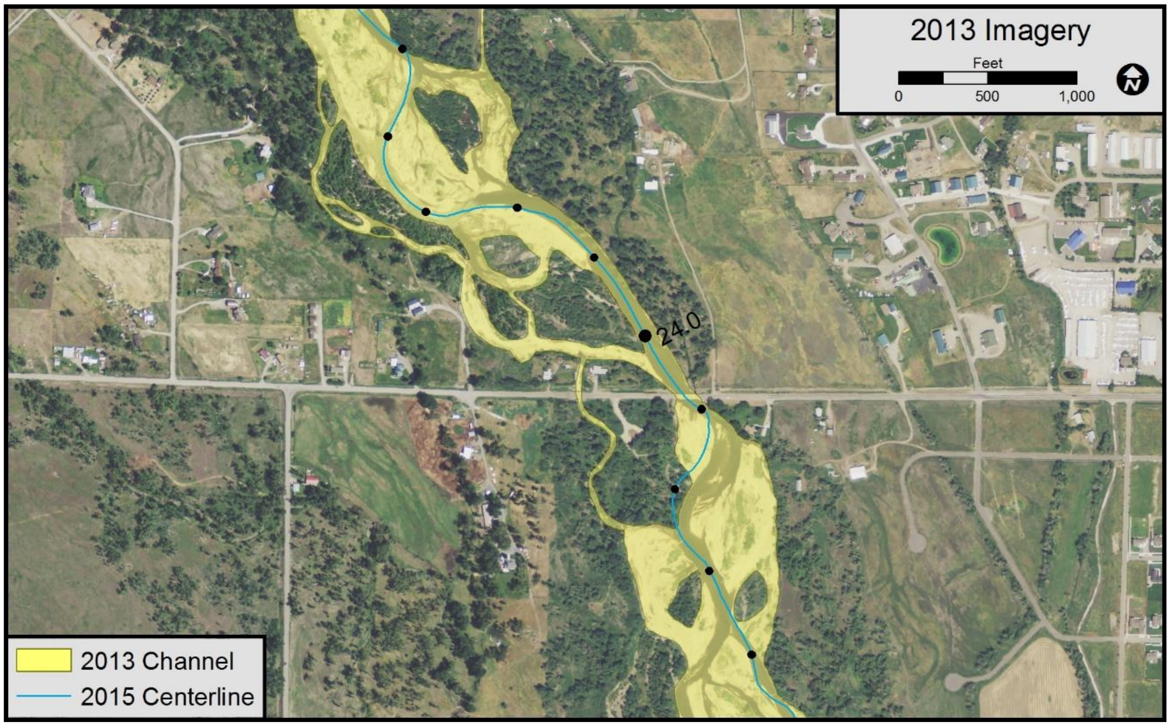

Figure 20. Example 2013 NAIP imagery at Amsterdam Road, Gallatin River CMZ development.

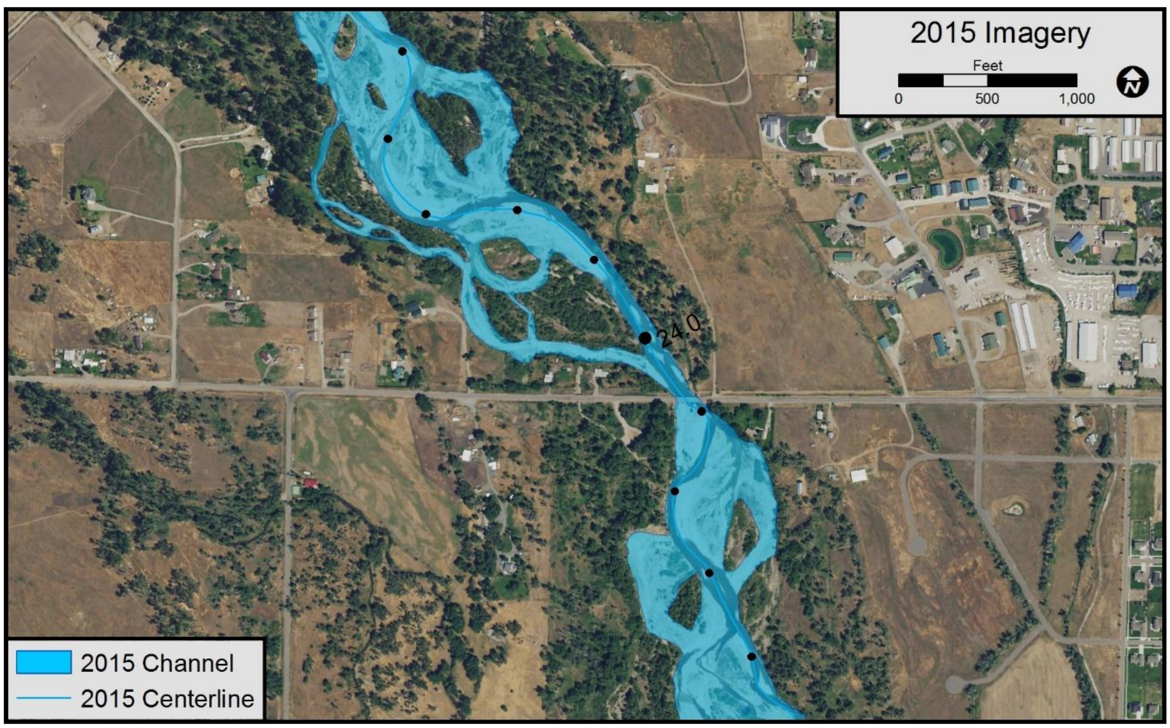

Figure 21. Example 2015 NAIP imagery at Amsterdam Road, Gallatin River CMZ development.

3.2 GIS Project Development

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

3.3 Bankline Mapping

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

3.4 Migration Rate Measurements

Once the banklines were digitized, they were evaluated in terms of discernable channel migration since 1965. 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 approximately every 30 feet (Figure 22). A total of 841 migration vectors were generated for the Gallatin River at a scale of 1:2,000. These measurements were then summarized by reach. The results were then used to define a reach-scale erosion buffer width to allow for likely future erosion. Results of this analysis are summarized in Section 4.3.

Each location of channel migration was assigned a Migration Site ID based on the river mile location of the site. Each site may have anywhere from 1 to 12 migration vectors, depending on the length of the site. A total of 169 migration sites were identified throughout the study area. An accounting of the reach and site based statistics can be found in Appendix A.

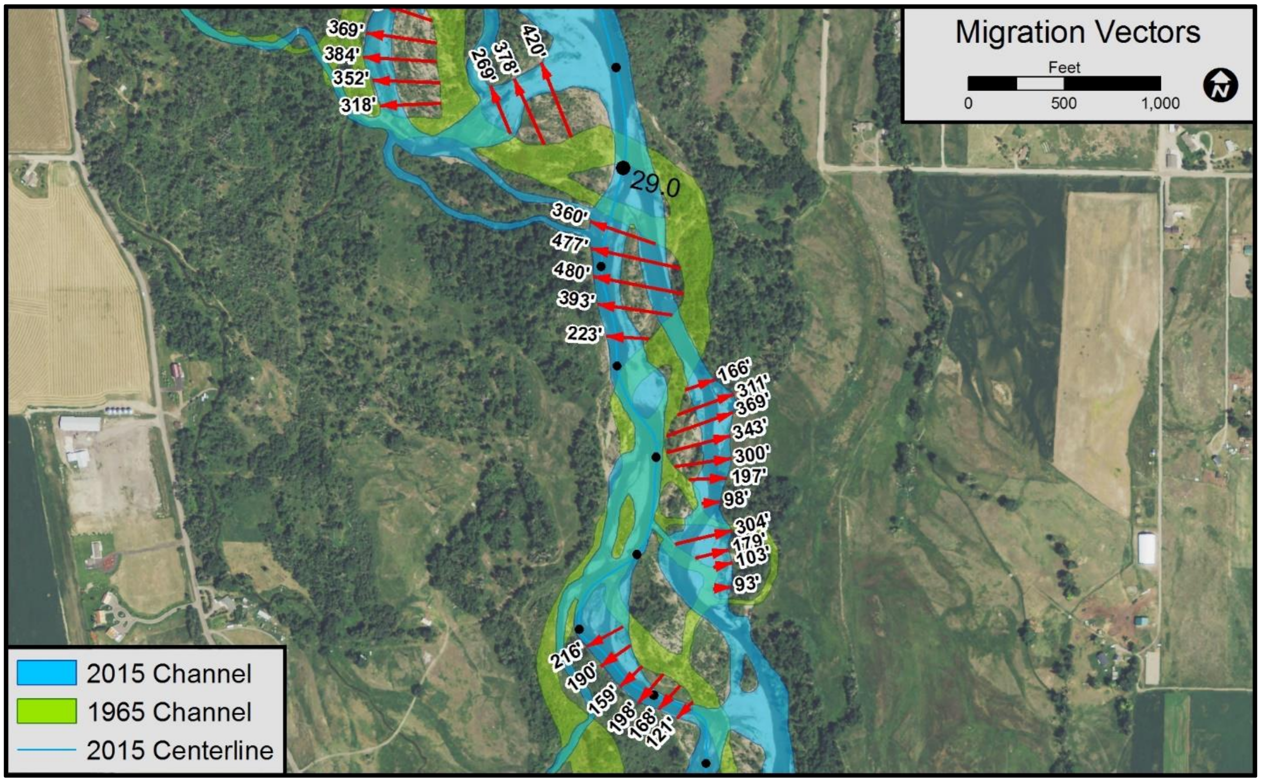

Figure 22. Example of migration measurements between 1965 and 2015 (migration distance in feet).

3.5 Inundation Modeling

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

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

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

The accuracy of an inundation model is directly related to the quality of the elevation data. High-resolution LiDAR data provides the best results. LiDAR data was collected for the Gallatin River from the mouth of Gallatin Canyon, to just below the confluence with the East Gallatin River in 2013. These data were used to generate an inundation model (Figure 23). No modeling was performed below the confluence of the East Gallatin River.

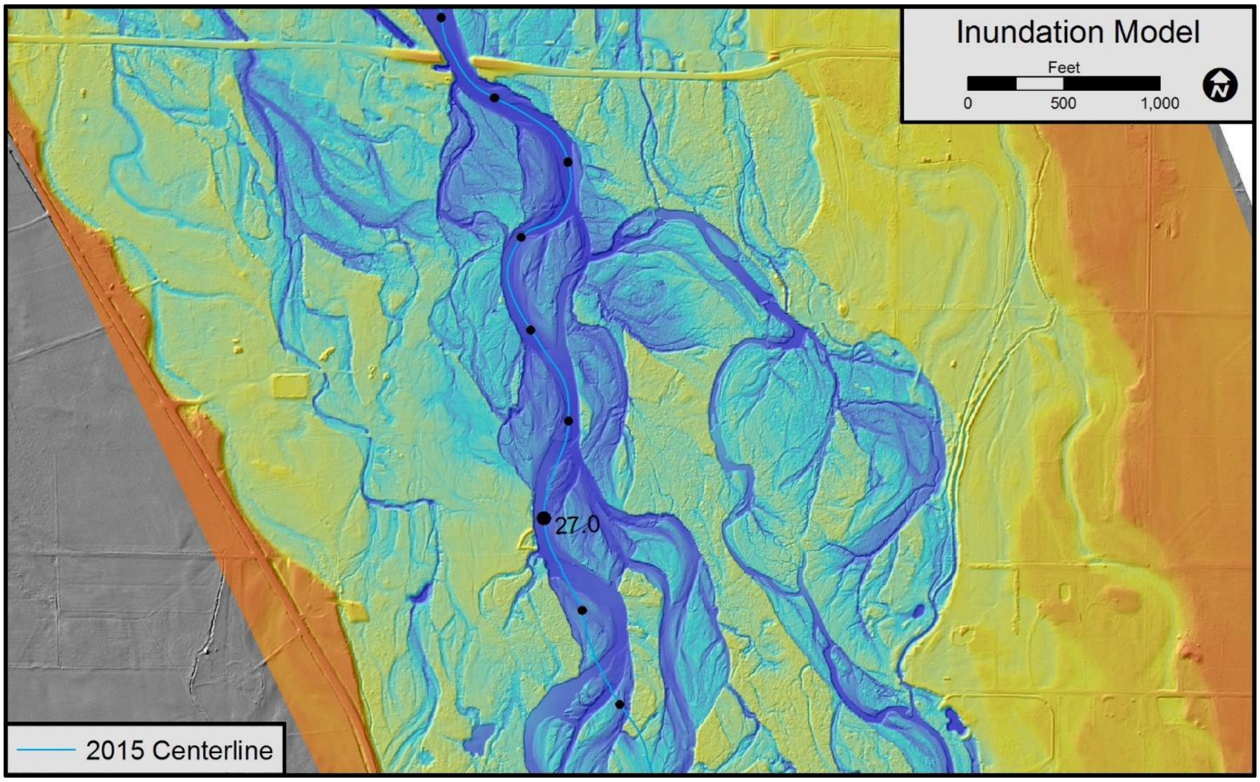

Figure 23. Example Inundation Modeling results above Cameron Bridge. Colors represent elevations relative to the water surface elevation of the main channel. Dark blue areas are equal to or lower than the channel. Yellows and reds are significantly higher than the adjacent main channel.

3.6 Avulsion Hazard Mapping

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

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

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

Where available, the LiDAR data and GIS-based inundation modeling were used to help identify potential avulsion pathways. These pathways were identified as low continuous swales with connectivity to the river (Figure 24). Additional information used in mapping avulsion paths included oblique photos from Kestrel Aerial Services and air photos.

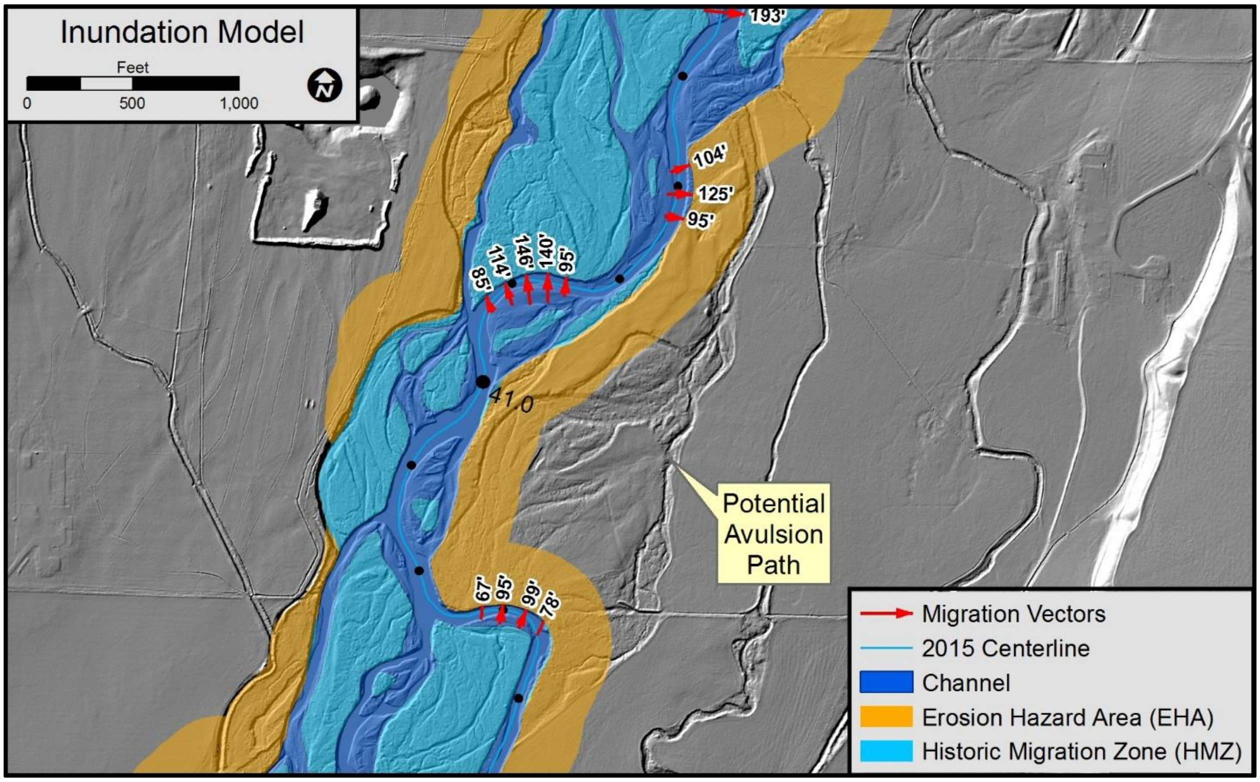

Figure 24. Example floodplain channel indicating an avulsion pathway.

4 Results

The Channel Migration Zone (CMZ) developed for the Gallatin River is defined as a composite area made up of the existing channel, the historic channel since 1965 (Historic Migration Zone, or HMZ), and an Erosion Hazard Area (EHA) that encompasses areas prone to channel erosion over the next 100 years. Areas beyond the EHA that pose risks of channel avulsion comprise the Avulsion Hazard Zone (AHZ). Lastly, those areas where migration has been restricted are highlighted as Restricted Migration Area (RMA).

4.1 Project Reaches

The approach to CMZ mapping used here includes a reach-scale evaluation of channel migration rates. For the 45.5 miles of project length, the river was broken into eight reaches based on geomorphic character such as river pattern, rates of change, geologic controls, and channel slope (Figure 27). The reaches range in length from 5.0 to 7.3 miles (Table 3). Figure 25 shows a continual drop in channel slope between the mouth of Gallatin Canyon, with a notable reduction between Logan and the I-90 Bridges (Reaches GR02 and GR03).

Table 3. Gallatin River reaches.

Reach	General Location	Upstream RM	Downstream RM	Length (mi)
GR01	Logan to Mouth	5.3	0.0	5.3
GR02	East Gallatin To Logan	12.0	5.3	6.7
GR03	I-90 to East Gallatin River Confluence	19.3	12.0	7.3
GR04	Cameron Bridge to I-90	26.5	19.3	7.2
GR05	Below Four Corners: Norris Road to Cameron Bridge	32.5	26.5	6.0
GR06	Four Corners: McReynolds Road to Norris Road	37.5	32.5	5.0
GR07	Gallatin Gateway: From below W. Williams Road to McReynolds Rd	42.6	37.5	5.1
GR08	Mouth of canyon to below W. Williams Rd	45.5	42.6	2.9

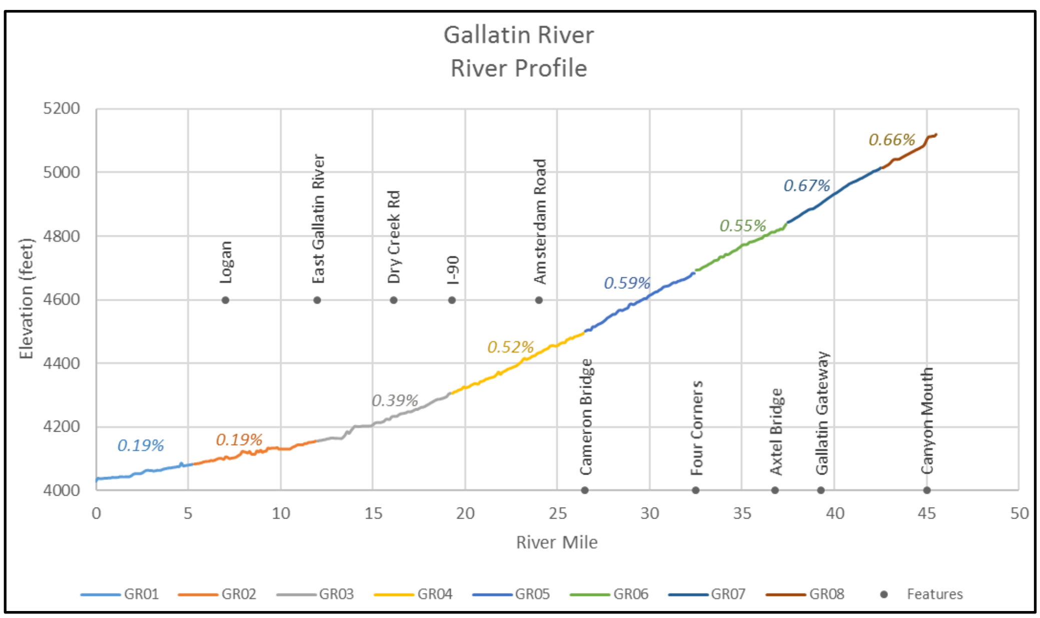

Figure 25. Average channel slope by reach, Gallatin Canyon.

4.2 The Historic Migration Zone (HMZ)

The Historic Migration Zone (HMZ) is created by combining the bankfull channel polygons into a single HMZ polygon. The bankfull channels commonly split and rejoin, creating a mosaic of channel courses with intervening islands, some of which are seasonal. The HMZ footprint includes all channels as well as any area between split flow channels. By including islands, the HMZ captures the entire footprint of the active river corridor from 1965-2015. In some settings where island areas are non-erodible, it may be appropriate to exclude these features from the CMZ. In the case of the Gallatin River, however, these areas have been retained in the CMZ since they are made up of young alluvial deposits that are prone to reworking or avulsion, and are thus part of the active meander corridor.

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

For this study, the Historic Migration Zone is comprised of the total area occupied by Gallatin River channel locations in 1965, 1979, 2013 and 2015 (Figure 26). The resulting area reflects 50 years of channel occupation for the length of the Gallatin River.

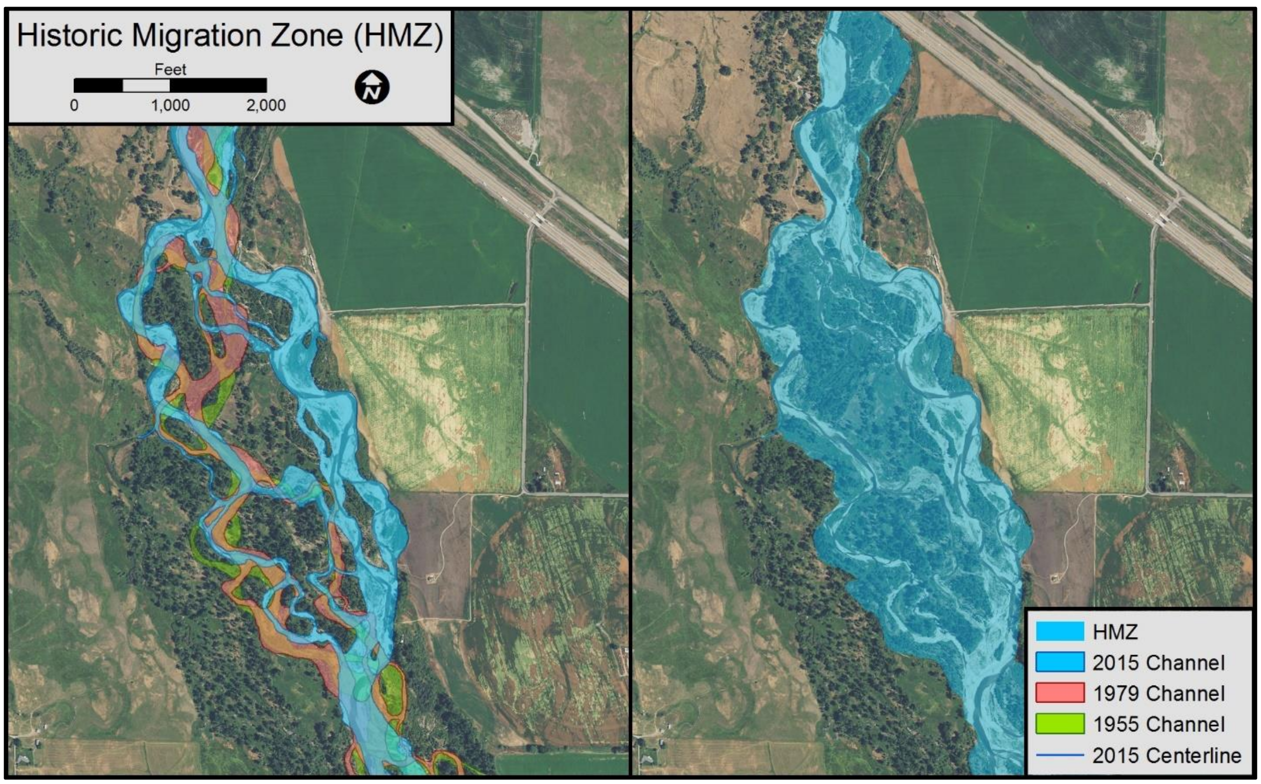

Figure 26. The Historic Migration Zone (HMZ) is the combined footprint of all mapped channel banklines.

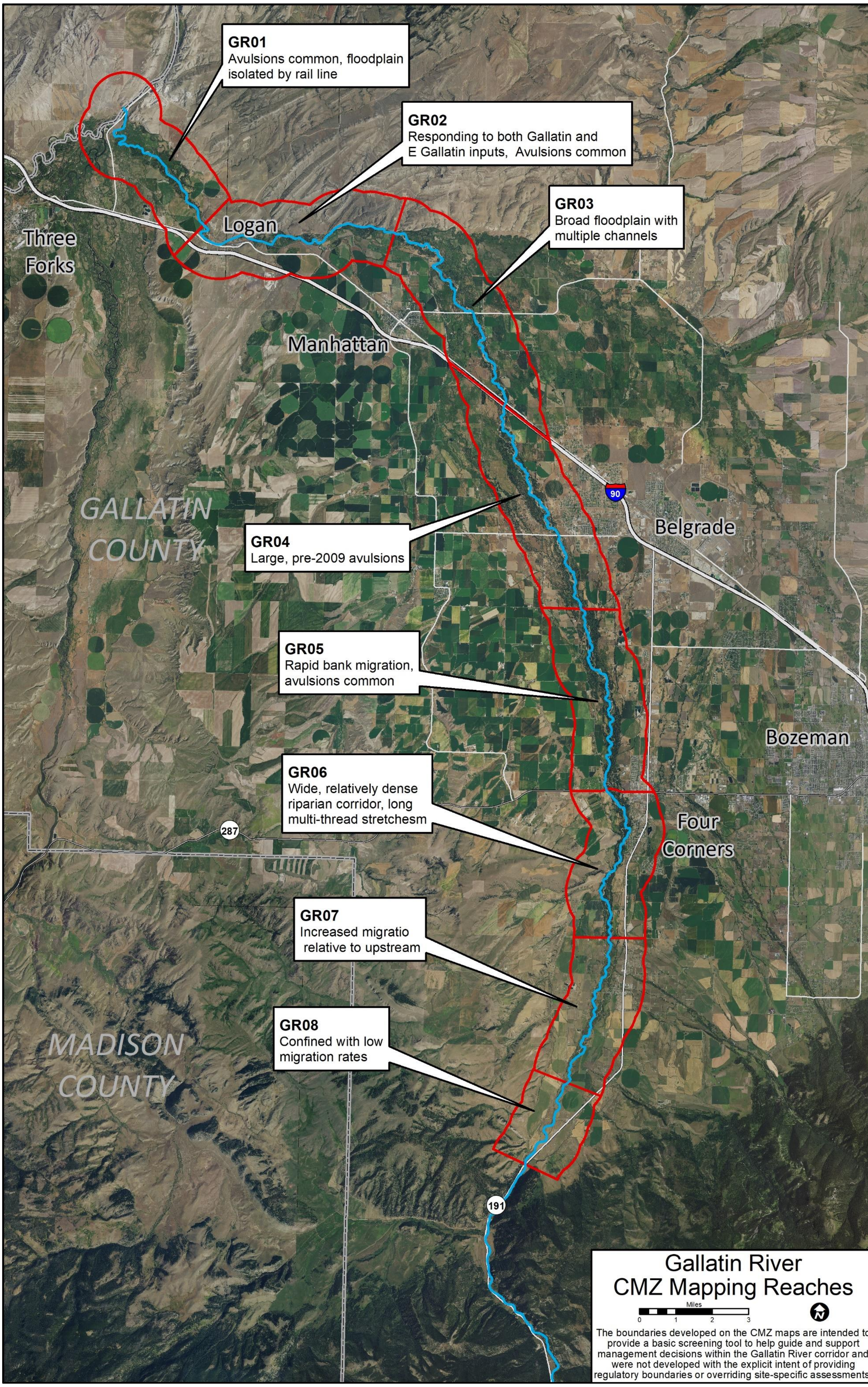

Figure 27. Gallatin River Channel Migration Zone reaches.

4.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on measured migration rates, which are derived from measured migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement and not an avulsion. A total of 841 measurements were collected on the Gallatin River. The minimum distance measured is 20 feet, which proved to be an easily measurable distance that is not compromised by the resolution or spatial accuracy of the data. The measurements all capture the complete imagery timeframe (1965-2015). Although shorter time frame measurements (e.g. 1965-1979) could have been collected to calculate interim migration rates, the 1979 imagery captures 1974 flood impacts that obscure bankfull margins. The 1965-2015 measured migration distances are summarized in Figure 28. Migration into the terrace bankline was summarized separately, to allow the application of an erosion hazard buffer specifically to that geologic unit. Although erosion into the terrace is rare, it has occurred since 1965 hence is included as a CMZ unit. Mean migration rates and EHA buffer widths are shown in Table 4 and Figure 29. The buffer width is calculated as that distance the river would move over a century's time at the mean annual rate.

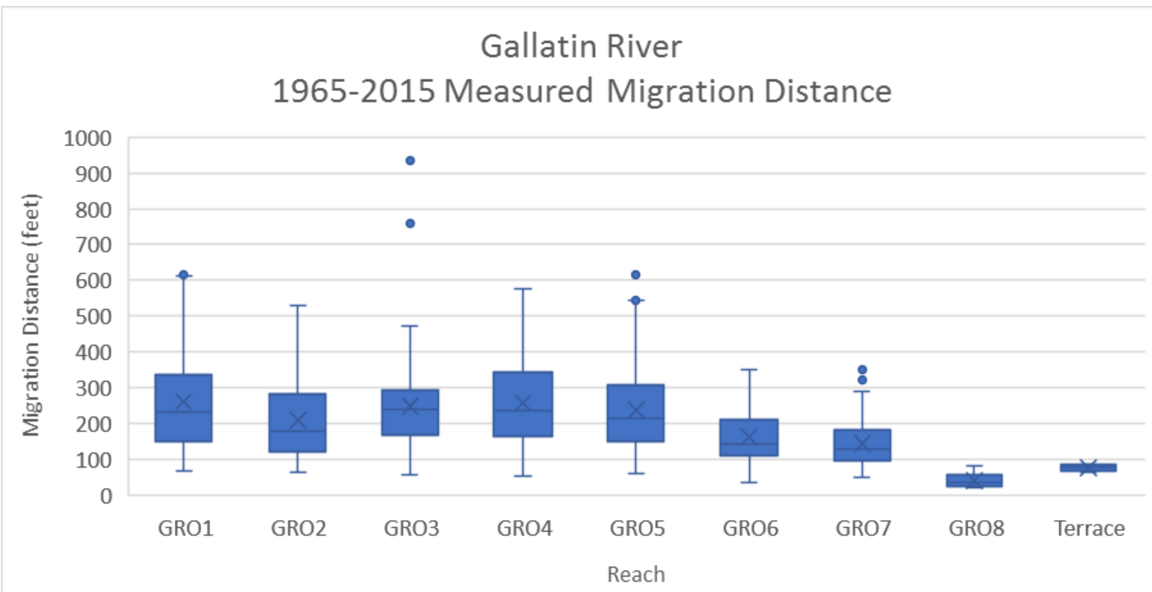

Figure 28. Box and whisker plot showing measured 1965-2015 migration distances by reach.

As the *mean* migration rate is the statistic used to define the EHA buffer, the results are inherently conservative. Thus, some localized channel migration through and beyond the EHA buffer should be anticipated over the next century. Table 4 shows that in almost every reach, the 100-year erosion buffer is less than the maximum measured migration distance. Typically, however, these areas of rapid bankline movement are within the Historic Migration Zone, and thereby captured in the CMZ.

Table 4. Average migration rate and 100-year EHA buffer by reach.

Reach	Number of Measurements	Maximum Migration Distance (ft)	Average Annual Migration Rate (ft/yr)	100- Year Buffer Width (ft)
GRO1	43	615	5.2	522
GRO2	68	529	4.2	419
GRO3	140	935	4.9	494
GRO4	173	576	5.1	513
GRO5	146	616	4.8	475
GRO6	110	349	3.2	322
GRO7	135	349	2.9	288
GRO8	26	80	0.8	80
Terrace	4	84	1.5	153

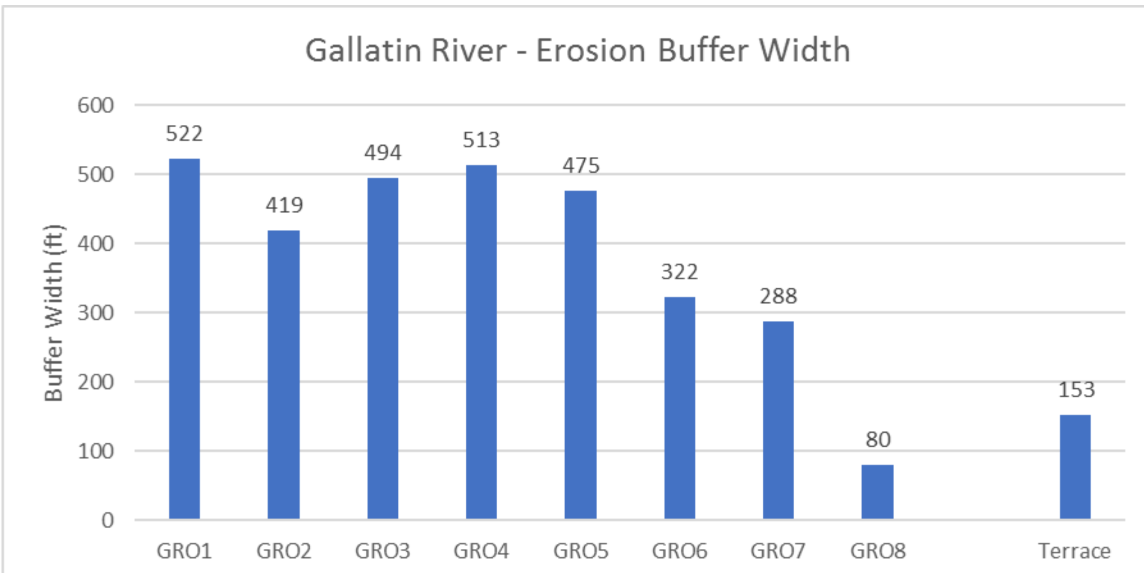

Figure 29. Mean migration rate-based EHA buffer width, Gallatin River.

The location and intensity of rapid streambank erosion shifts with time. Over a century, areas that currently show no erosion may become more active. Predicting these shifts is difficult due to the number of drivers that can cause these shifts (ice, woody debris, floods, cutoffs, etc.). As such, the erosion buffer is assigned to all banks, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington State Department of Ecology (WSDE, 2010). The general approach to determining the Erosion Buffer (using the annual migration rate to define a 100-year migration distance) is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004).

An example of EHA mapping is shown in Figure 30. If the EHA extends into the Historic Migration Zone, it is masked by the HMZ so that areas of historic channel locations are prioritized in the mapping hierarchy. As a result, the EHA is typically discontinuous along the river.

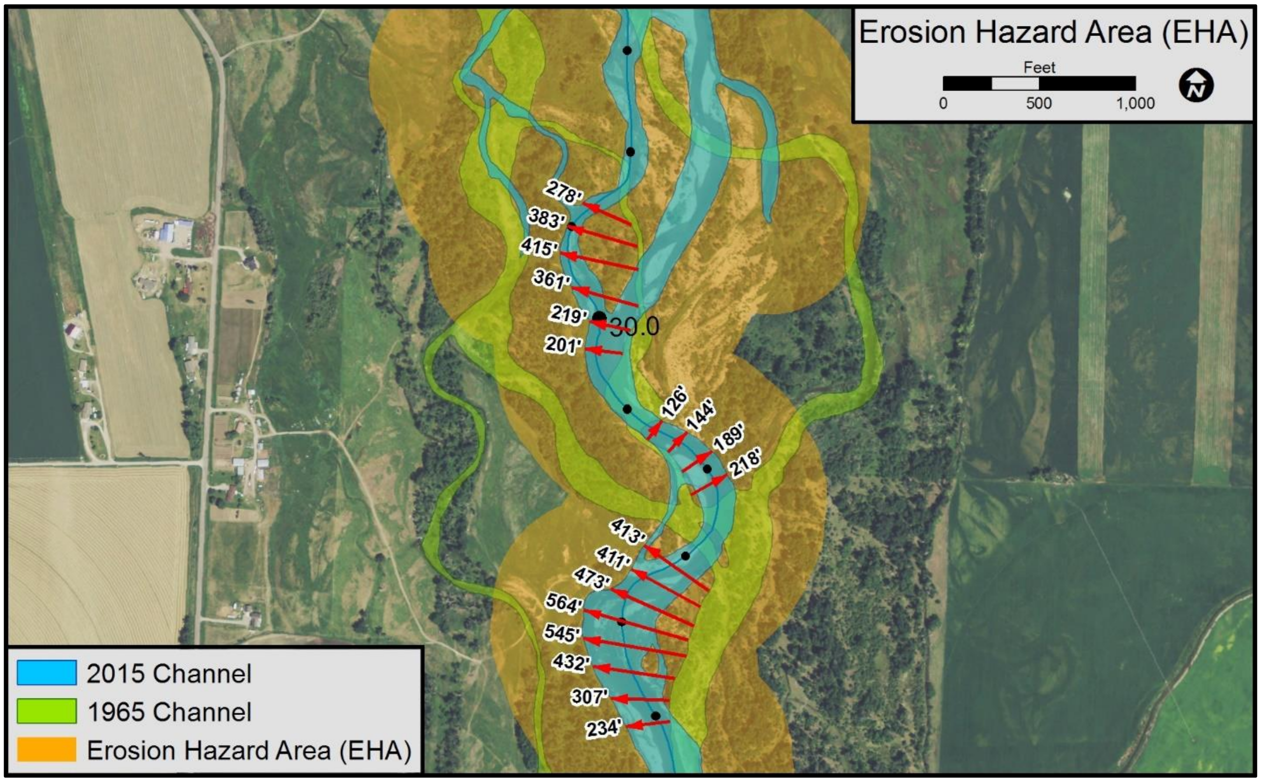

Figure 30. The Erosion Hazard Area (EHA) is a buffer placed on the 2015 banklines based on 100 years of channel migration for the reach.

4.4 The Avulsion Hazard Area (AHZ)

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

Relative to the other rivers of the Upper Missouri Watershed, the Gallatin River is exceedingly prone to avulsions. A total of 63 avulsions occurred on the Gallatin River between 1965 and 2015, with occurrences in every reach and during every timeframe except for Reach GR08, which is a minimally deformable channel segment located just downstream of the mouth of Gallatin Canyon (Figure 31). The highest concentration of avulsions occurred in reaches GR04 to GR07, which extends from a few miles below the mouth of Gallatin Canyon to the I-90 bridge (Figure 32). This downstream trend in avulsion frequency is consistent with a downstream reduction in channel slope; between Reach G07 and GRO4, the channel slope drops from about 0.7% to 0.5% (Figure 25).

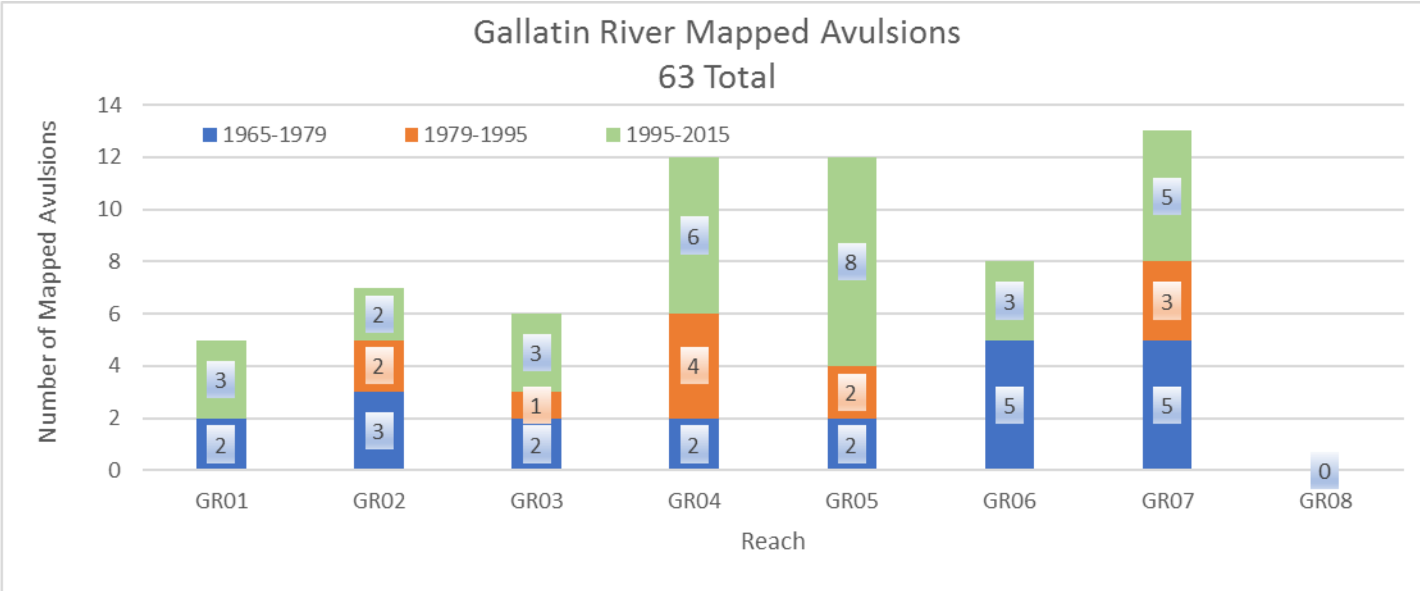

Figure 31. Number of mapped avulsions by Reach, Gallatin River.

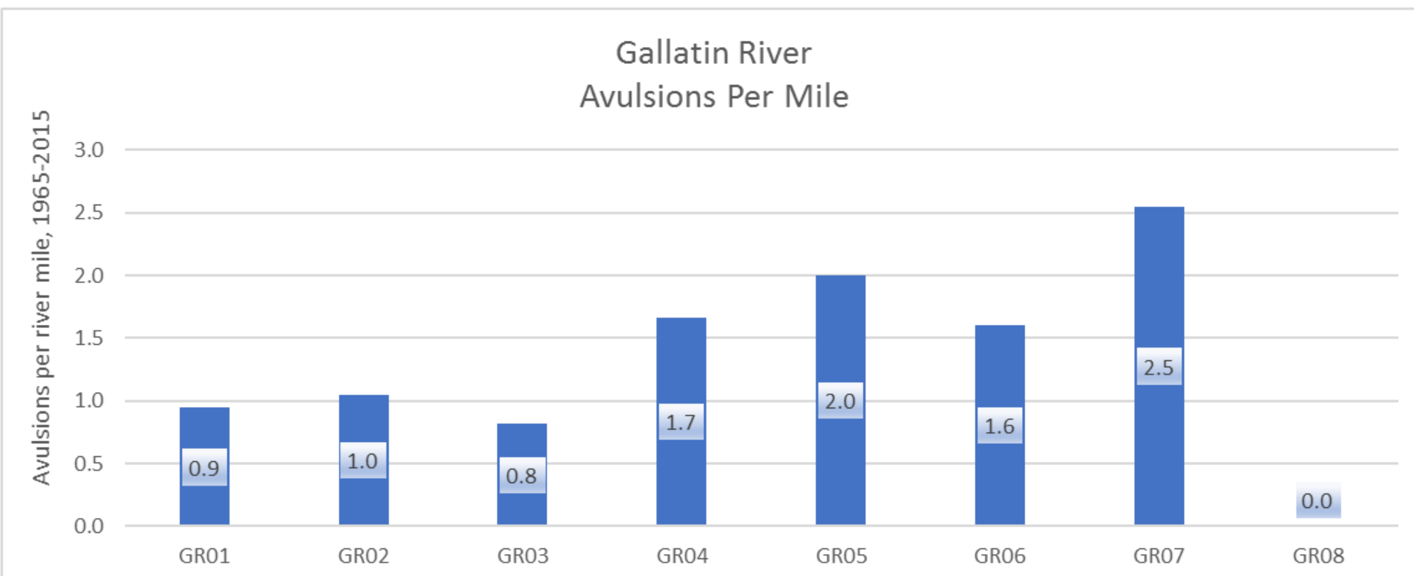

Figure 32. Number of mapped avulsions per river mile by reach.

Figure 33 shows an example of a major 1965-1979 avulsion in Reach GR04 about a half mile upstream of the I-90 Bridge. The avulsion created a new approximately mile-long channel in an area that had only a few subtle channel traces in 1965. The lower end of the avulsion consisted of two major channel relocations. This avulsion resulted in the relocation of the main channel approximately 1,800 feet eastward of its 1965 position, dramatically expanding the footprint of the river corridor in a relatively short period of time. The second avulsion, which relocated the main channel back westward, caused the main river channel to bypass the Creamery Ditch diversion, which now requires channel berming to function at relatively high water (Figure 34). At RM 20.2, the lower avulsion has perched the channel that diverts flow into the Creamery Ditch above the main thread, indicating that diversions will become more difficult with time at this location.

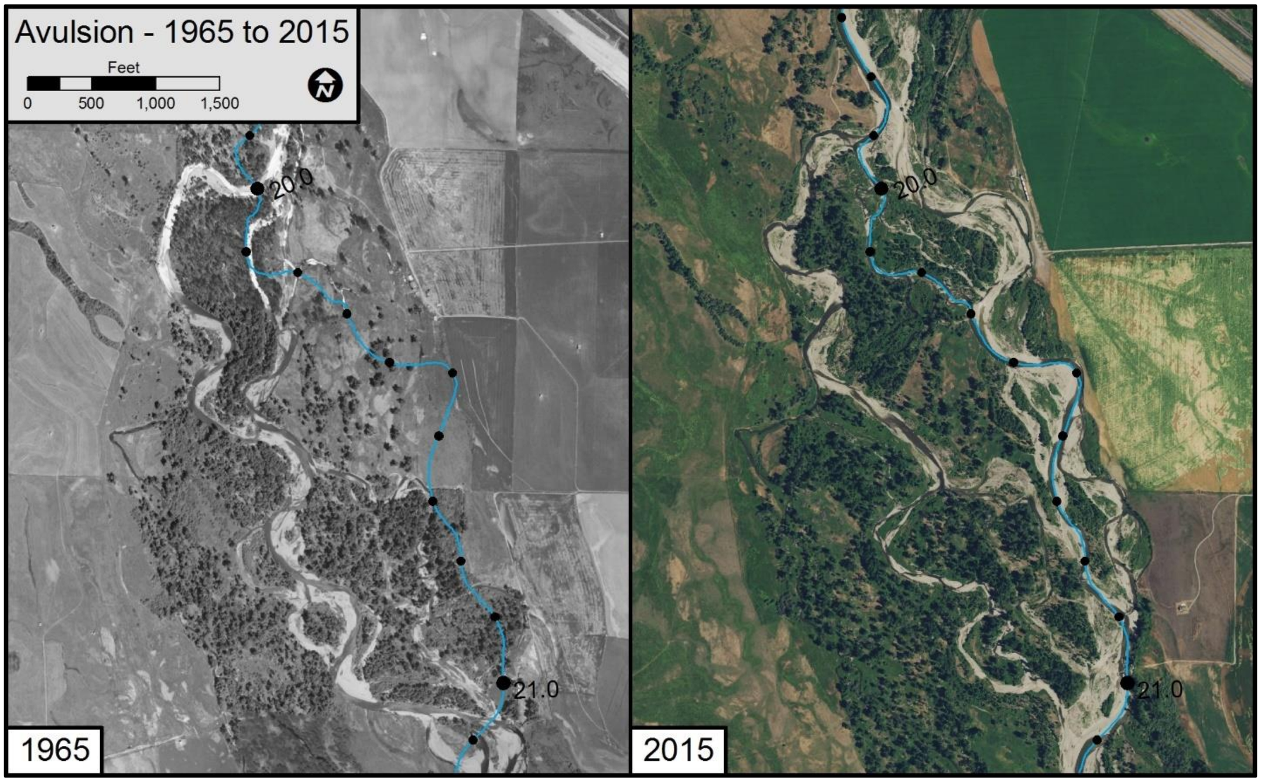

Figure 33. Imagery from 1965 (left) and 2015 (right) showing major avulsion in reach GR04 upstream of I-90.

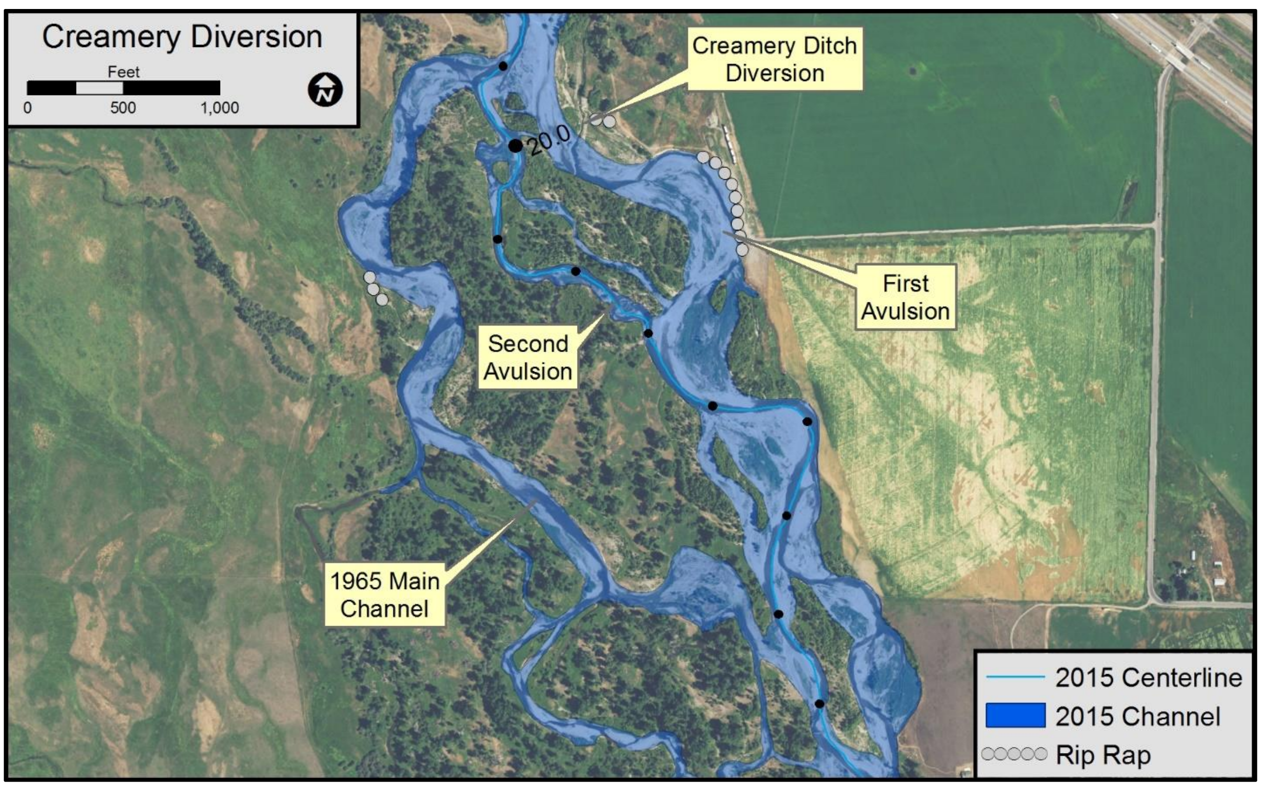

Figure 34. 2015 imagery showing low flow conditions at Creamery Ditch Diversion following avulsion, Reach GR04.

Figure 35 shows that a relatively high number of avulsions occurred during the timeframes that bracket the large floods of 1974 and 1997. These events both reached a 25-year flood event. Downstream of I-90, the 1974 flood appears to have driven widespread deposition and channel expansion, which was likely due to sediment loading caused from upstream avulsions.

In general, the avulsion mapping on the Gallatin River indicates that these events are most common between the mouth of Gallatin Canyon and the I-90 Bridge, where the river emerges from the confinement of the canyon and begins to lose channel slope and associated sediment transport energy. This reflects the typical geomorphic characteristics of an alluvial fan, where reduced slopes coupled with floodplain expansion cause inherently aggradational conditions (continued coarse sediment deposition) due to a loss of sediment transport energy. The historic patterns of avulsions suggest that this section of river will remain prone to rapid channel relocations in the future, especially during floods.

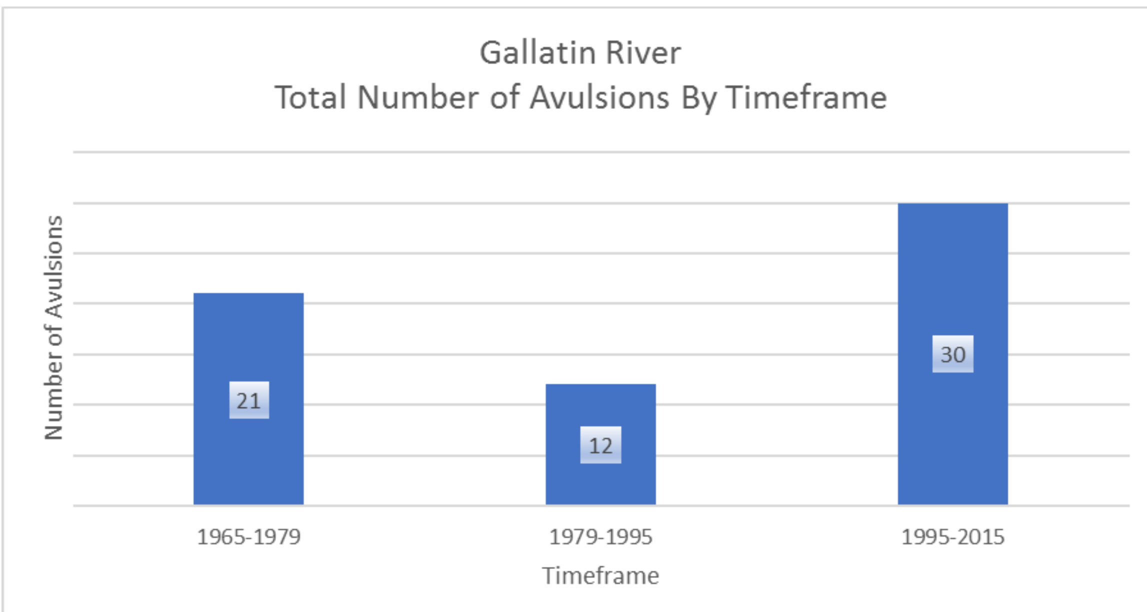

Figure 35. Total number of avulsions mapped as occurring during each evaluated timeframe, Gallatin River.

Considering historic patterns of avulsions, the CMZ boundaries were extended to capture areas that show demonstrable potential for avulsions over the next century. These mapped units capture floodplain areas that are beyond the HMZ or EHA but have side channels prone to re-occupation or meander cores prone to cutoff (Figure 37). The LiDAR data is very useful in defining these features. It is important to recognize, however, that some historic avulsions occurred in floodplain areas that showed no strong indicators for such an event, reinforcing the concept that these events could realistically happen anywhere on the river's floodplain, and the CMZ mapping captures only the most demonstrable avulsion-prone areas.

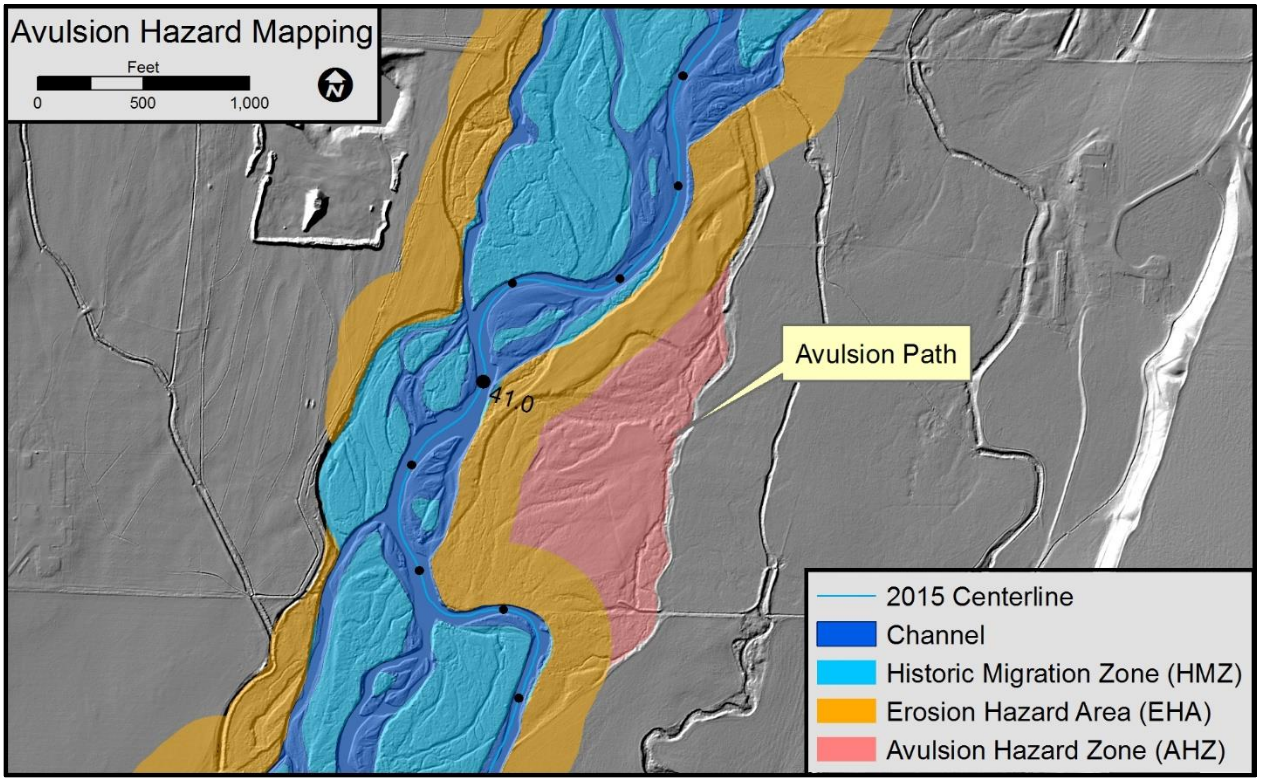

Figure 36. Gallatin River Avulsion Hazard Area mapping, RM 41.

4.5 The Restricted Migration Area (RMA)

The extent of migration area that is restricted by physical features is largely dependent on the extent and locations of mapped bank armor, with some additional restrictions by transportation infrastructure.

A total of 7.3 miles of bank armor were mapped on the river. Figure 37 shows that the extent of armored banks ranges from 2.3% to 18.8% of the total bankline in any given reach (discounting islands). The densest armor is in Reach GR01, where about 10,600 feet or almost 19% of the total bankline is armored to largely protect the railroad. Floodplain dikes play a lesser role on the Gallatin River (Figure 38), with the total dike length of 2.3 miles representing about 2.5% of the bank length river-wide. Reaches GR03 and GR04 which extend from Cameron Bridge to the East Gallatin confluence have the most extensive diking, with over two miles of mapped dikes.

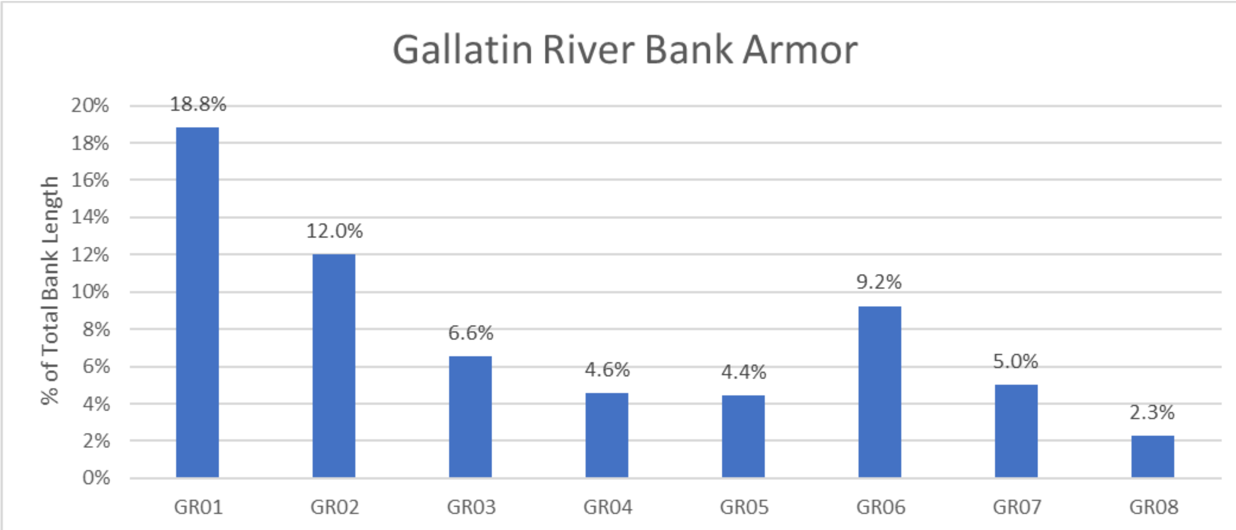

Figure 37. Percentage of bankline protected by armor by reach.

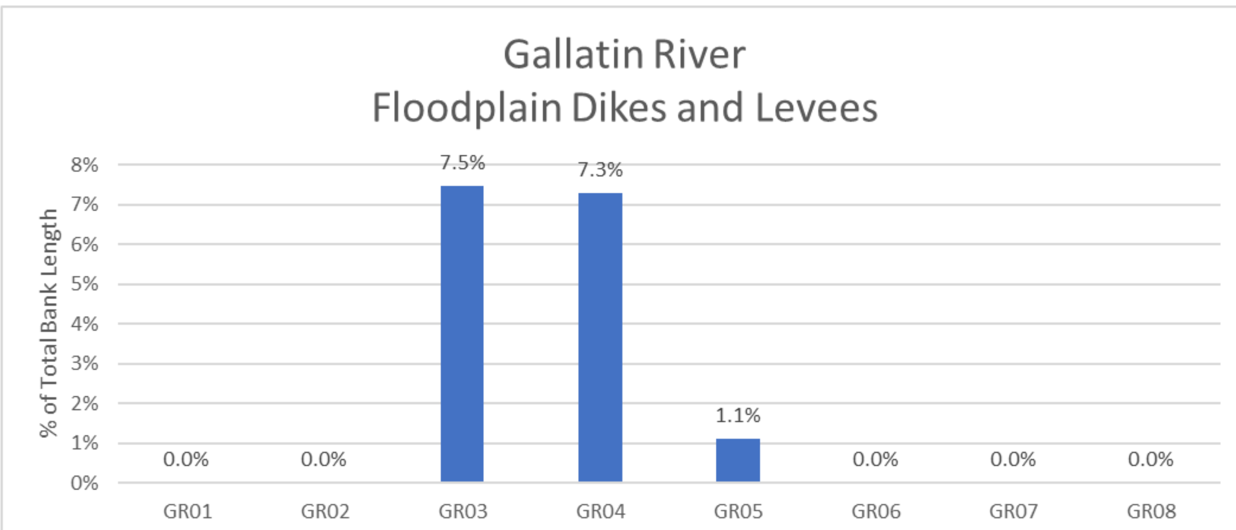

Figure 38. Percentage of bankline affected by dikes by reach.

Figure 39 shows an example of Restricted Migration Areas at the Dry Creek Road bridge. In total, 492 acres of the CMZ are mapped as Restricted, with 224 acres attributed to bank protection and 268 acres to transportation (Figure 40).

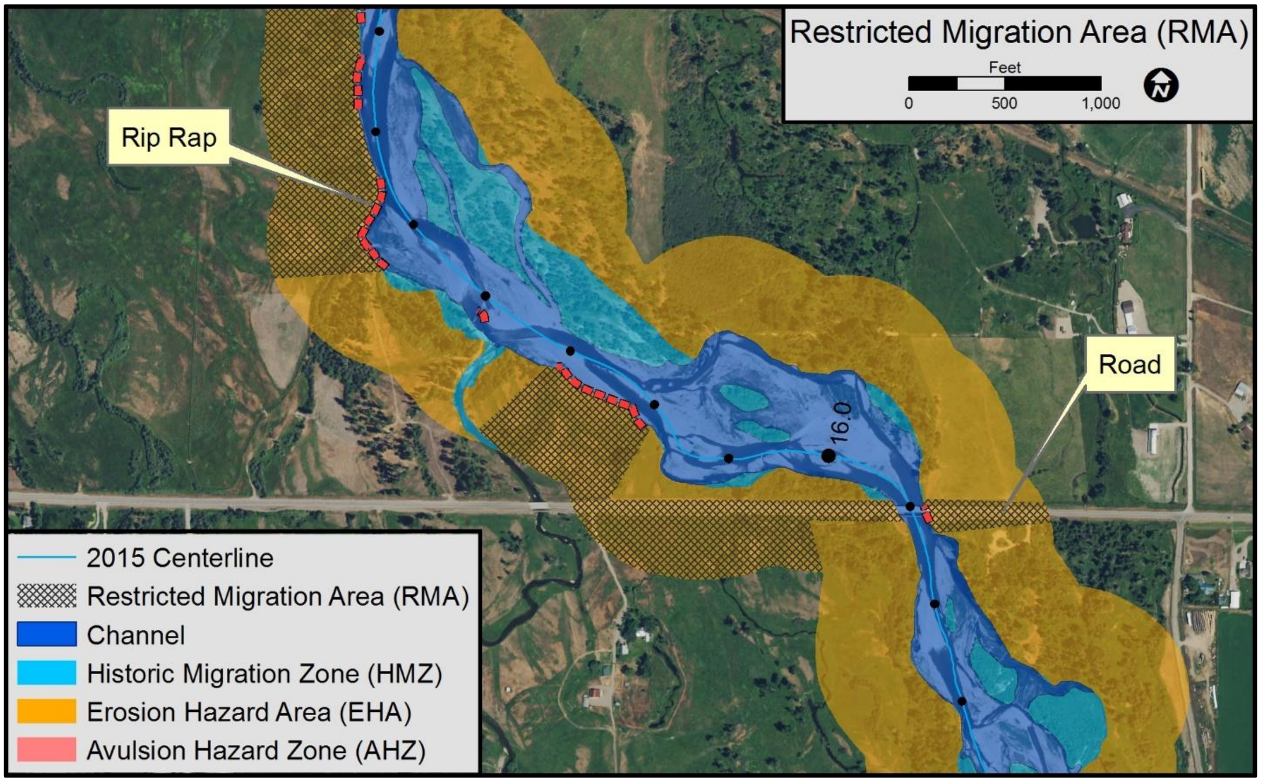

Figure 39. Restricted Migration Areas at Dry Creek Road bridge.

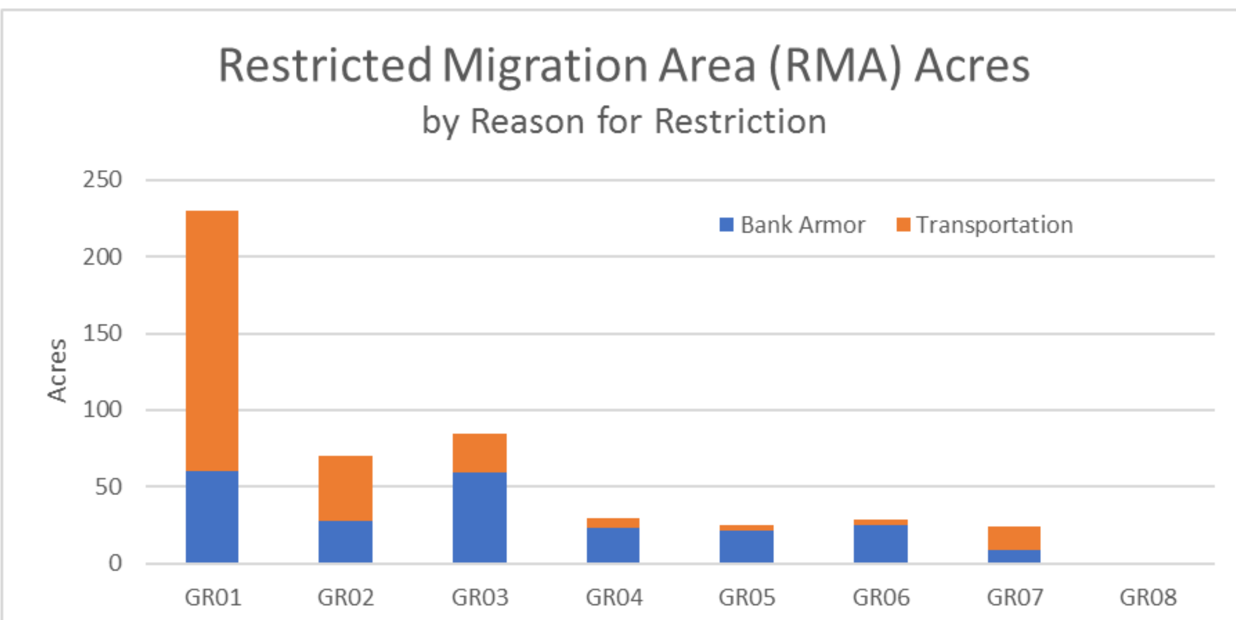

Figure 40. Acres of the CMZ mapped as restricted by reach.

4.6 Composite Map

An example portion of a composite CMZ map for a section of the Gallatin River project area is shown in Figure 41. Each individual mapping unit developed for the CMZ has its own symbology, so that any area within the overall boundary can be identified in terms of its basis for inclusion.

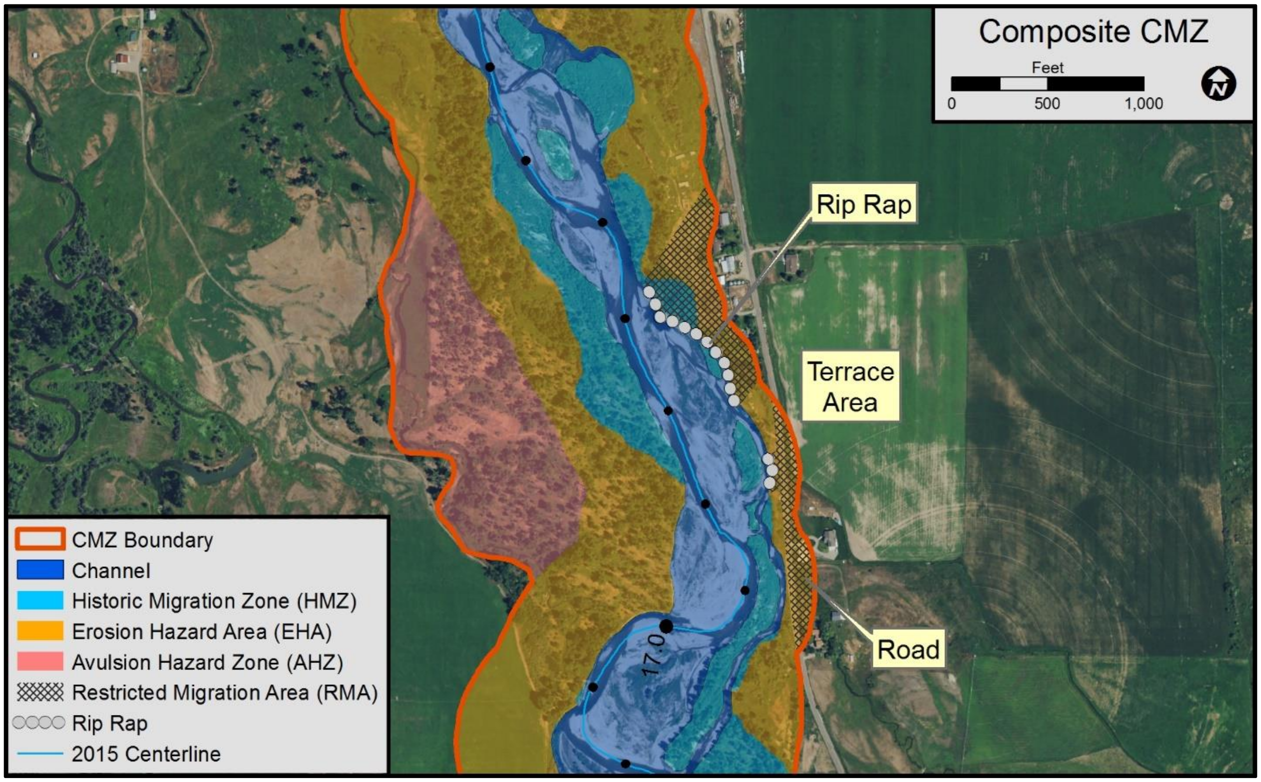

Figure 41. Composite Channel Migration Zone map.

4.7 Geologic Controls on Migration Rate

Between Gallatin Canyon and Logan, the margins of the Gallatin River corridor are largely made up of alluvial deposits that form the mapped braid plain and alluvial fans of the Gallatin Valley. Whereas in most locations the banks of the river are a few feet tall, in some locations the river margin is formed by a higher, older alluvial terrace. These units were shown to have lower migration rates than that of the more recent alluvium, and as a result the erosion buffer assigned to these units was narrower than those of more recent alluvial deposits (Figure 41).

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

5 Gallatin River Reach Descriptions

The following sections describe each reach of the Gallatin River. The reaches are numbered sequentially from the downstream end of the project. To best describe the trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach GR08 just below the mouth of the canyon, and ending with Reach GR01 at Headwaters State Park. The maps can be found in Appendix D.

Note: All references to River Miles (RMs) reflect the distance upstream from Three Forks along the 2015 channel centerline. River Miles are labeled on the maps in Appendix D. Wherever streambanks or floodplain areas are described as “right” or “left”, that refers to the side of the river as viewed in the downstream direction. For example, “RM 6.4R” refers to the right streambank located 6.4 miles upstream of the river’s mouth.

5.1 Reach GR08

Reach GR08		
Upstream/Downstream RM	45.5	42.6
Length (miles)	2.9	
General Location	Confined reach below mouth of canyon to below W. Williams Rd	
Mean Migration Rate (ft/yr)	0.8	
Max 60-year Migration Distance (ft)	80	
100-year Buffer (ft)	80	

Reach GR08 is about 3 miles long, extending from the mouth of Gallatin Canyon to about a mile downstream of the West Williams Road Bridge. Within this reach the river is tightly confined between alluvial fan deposits on the west and braid plain deposits to the east. Although these units are not particularly old, they are relatively erosion-resistant, probably due to their coarse gravel component and relative height above the river. The results of Inundation/Relative Elevation Modeling demonstrate the river confinement, a very narrow corridor at the mouth of the canyon and increasing floodplain expansion in the downstream direction (Figure 42). The riparian corridor is a narrow strip along the streambanks, indicating little channel migration or floodplain connectivity. The reach is relatively steep at 0.66%, and sediment storage is minimal, which also supports low rates of lateral channel movement. One of the benefits of the lack of channel migration in this reach is the stability of points of diversion, as is evident at RM 43.2L (Figure 44).

The geologic confinement in Reach GR08 has resulted in a narrow CMZ with erosion buffer width of 80 feet. This buffer was developed based on measurable lateral migration mostly in the lower end of the reach near and below the West Williams Road Bridge, where sediment storage, channel migration, and riparian corridor width all begin to increase (Figure 45).

Reach GR08 has just over 700 feet of bank armor which isolates about 0.2 acres of the CMZ. No floodplain dikes were mapped in the reach.

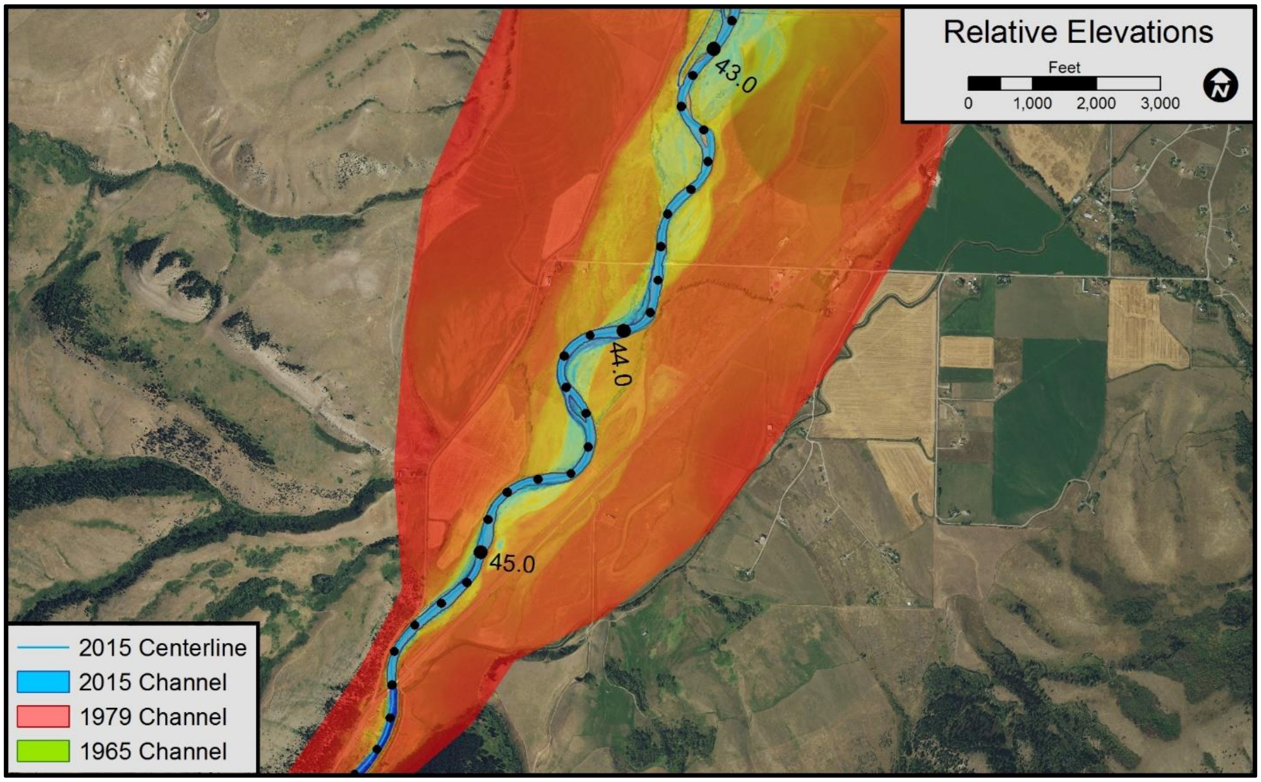

Figure 42. Relative Elevation Model (REM) of Reach GR08 showing relatively high elevations (reds) surrounding the narrow river corridor.

Figure 43. View downstream of channel confinement and narrow riparian zone, Reach GR08 (Kestrel).

Figure 44. View downstream of diversion structure in area of minimal channel migration, RM 43.2L, Reach GR08 (Kestrel).

Figure 45. Increasing sediment storage and channel migration near West Williams Road Bridge, Reach GR08 (Kestrel).

5.2 Reach GR07

Reach GR07		
Upstream/Downstream RM	**42.6**	**37.5**
Length (miles)	**5.1**	
General Location	**Gallatin Gateway: From below W. Williams Road to McReynolds Rd**	
Mean Migration Rate (ft/yr)	**2.9**	
Max 60-year Migration Distance (ft)	**349**	
100-year Buffer (ft)	**288**	

Reach GR07 is just over five miles long, extending from below West Williams Road Bridge down to McReynolds Road at RM 37.5. Within this reach, channel migration rates increase rapidly relative to upstream, with the erosion buffer width expanding from 80 feet in Reach GR07 to 288 feet in Reach GR07. As the channel slope is similar to that upstream, this rapid increase in migration rates is likely due to the intersection of the Gallatin River stream corridor with the alluvial fans of Little Bear Creek and South Cottonwood Creek (Figure 13). Avulsions become relative common, and rapid channel widening post-avulsion is common. Figure 46 shows an area at RM 42.2 in the upper portion of Reach GR07 where two avulsions occurred between 1979 and 2009, creating three active channels where there was only one in 1965. A total of 13 avulsions were identified in Reach GR07 between the 1965 and 2015 suites of imagery. This translates to 2.5 avulsions per river mile, which is the highest avulsion density mapped in the project area.

As migration rates and avulsion frequencies increase, the riparian corridor similarly widens in Reach GR07. Figure 47 shows this corridor widening as the river approaches Gateway South Road in two distinct channels. This road crossing essentially forms a dike across the river corridor that impounded water during the 2011 flood event (Figure 48). Figure 48 also shows an avulsion just above the bridge on the right (east) channel, where the river captured a ditch. Downstream at RM 38.7R, the channel is actively migrating eastward towards a ditch (Figure 49); since 1965 the channel has migrated about 170 feet eastward and is now about 150 feet away from the ditch. Fortunately for water users, however, that meander has formed a chute channel and will likely cut off before the ditch is intercepted by the river.

About a half mile of bank armor was mapped in Reach GR07, protecting 5% of the total bankline. This armor restricts about 8.3 acres of the CMZ, and transportation infrastructure restricts another 15.7 acres. The majority of bank armor is located near Gateway South Road.

Figure 46. Reach GR07 showing two channels on right formed since 1979, RM 42.2 (Kestrel).

Figure 47. View downstream of Reach GR07 showing split flow approach to Gateway South Road bridge crossings (Kestrel).

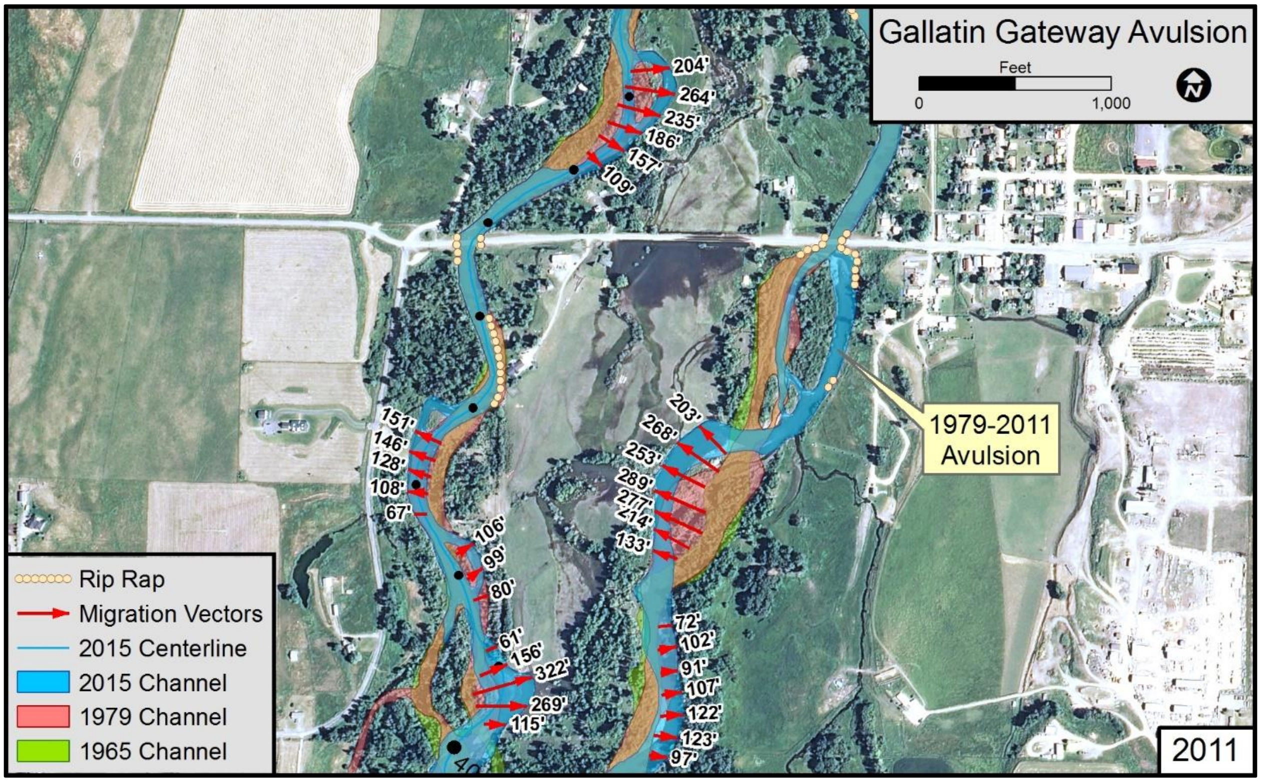

Figure 48. 2011 image of Gallatin River at Gateway South Road showing channel migration and flow impoundment above road embankment.

Figure 49. View downstream of Reach GR07 active meander migration towards a ditch at RM38.7R (Kestrel).

5.3 Reach GR06

Reach GR06 is in the Four Corners area, extending from McReynolds Road at RM 37.5 downstream to Norris Road at Four Corners. Migration rates continue to increase relative to upstream reaches, demonstrated by an erosion buffer width of 322 feet. The maximum migration distance measured in Reach GR06 was 349 feet, indicating that, over the next century, local migration beyond the CMZ boundaries is likely. A total of eight avulsions were mapped in Reach GR06, which reflects an average of 1.6 avulsions per river mile since 1965.

Reach GR06		
Upstream/Downstream RM	37.5	32.5
Length (miles)	5.0	
General Location	Four Corners: McReynolds Road to Norris Road	
Mean Migration Rate (ft/yr)	3.2	
Max 60-year Migration Distance (ft)	349	
100-year Buffer (ft)	322	

The 1979 imagery shows broad open bars in Reach GR06. From 1965 to 1979 the bankfull channel area increased by 34%, suggesting major channel expansion during the 1974 flood. At least three avulsions appear to have occurred during the 1997 flood. The combination of rapid channel migration and avulsion processes combine to create a broad CMZ that is typically on the order of 1,500 feet wide. The reach also shows increasing road and residential development relative to upstream. Numerous structures are located within the CMZ, especially on the right bank at Four Corners. With the rates and patterns of channel shift documented in this reach, it is clear that channel locations and erosion sites should be expected to shift rapidly, especially during floods.

Downstream of Axtell Bridge, south of Four Corners, the river corridor is constricted by braid plan deposits to the east and an outcrop of very old Archean-age gneiss to the west. Upstream of this constriction there is a high density of floodplain channels that appear to be in part maintained by groundwater upwelling, as evidenced by the fact that they become more pronounced in the down-valley direction with no apparent low-flow connectivity to the main river channel (Figure 50). These channels pose avulsion risks, and may be in part formed and maintained due to groundwater upwelling above the constriction. This approximately 0.7-mile long section of channel experienced at least three avulsions since 1965 (Figure 51).

Almost a mile of bank armor was mapped in Reach GR06, protecting 9.2% of the total bankline. This armor restricts about 25 acres of the CMZ, and transportation infrastructure restricts another 4 acres. The increased bank armor is associated with increased residential development towards Four Corners, where the corridor is severely constricted at the Norris Road Bridge (Figure 52).

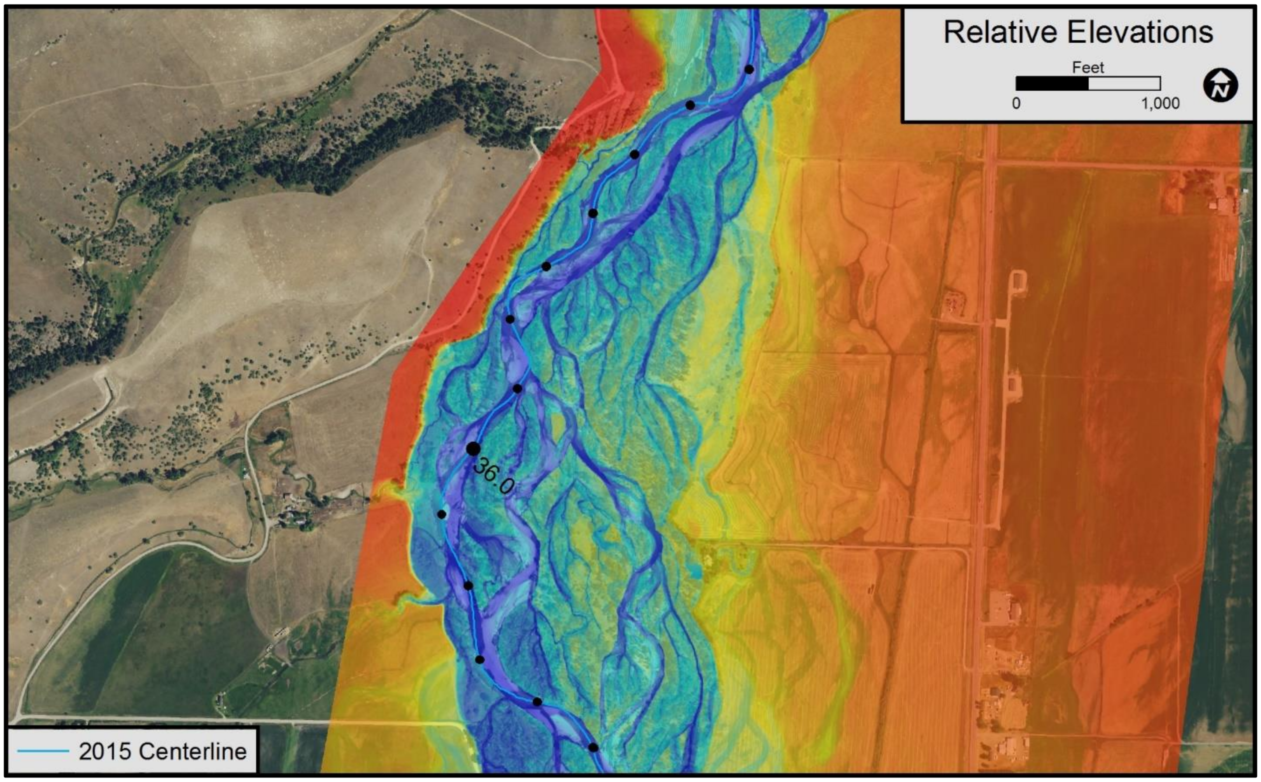

Figure 50. Relative Elevation Model output for Reach GRO6 showing dense network of floodplain channels and likely groundwater influences on channel form upstream of valley constriction.

Figure 51. View downstream at RM 36.1 showing area with frequent avulsions; channel in foreground avulsed since 1995 (Kestrel).

Figure 52. View downstream of Lower Reach GR06 at Norris Road showing corridor constriction and residential development (Kestrel).

5.4 Reach GR05

Reach GR05		
Upstream/Downstream RM	32.5	26.5
Length (miles)	6.0	
General Location	Below Four Corners: Norris Road to Cameron Bridge	
Mean Migration Rate (ft/yr)	4.8	
Max 60-year Migration Distance (ft)	616	
100-year Buffer (ft)	475	

Reach GRO5 extends for 6 miles from Norris Bridge at Four Corners to Cameron Bridge. Migration rates in Reach GRO5 continue to increase relative to upstream, with an erosion buffer width of 475 feet. The maximum migration distance measured in this reach was 616 feet, indicating that the CMZ boundaries represent a fairly conservative estimate of channel location over the next century. There are numerous locations in Reach GRO5 where hundreds of feet of movement was measured since 1965 (Figure 53). Avulsions have also been relatively common; a total of 12 avulsions were mapped, reflecting an average of 2.0 avulsions per river mile since 1965. Most of these avulsions (eight) occurred since 1995; an example is shown in Figure 54.

About 3.5 miles downstream of Norris Road, there is a broad, low floodplain area west of the river that hosts numerous channels, some of which pose avulsion risks and have been mapped as such (Figure 55 and Figure 56).

Just over a half mile (2,846 ft) of bank armor was mapped in Reach GR05, protecting 5% of the total bankline. This armor restricts about 21 acres of the CMZ, and transportation infrastructure restricts another 3.5 acres.

Figure 53. Reach GR05 channel complexity at RM 31; bendway in left foreground has migrated 392 feet since 1965 (Kestrel).

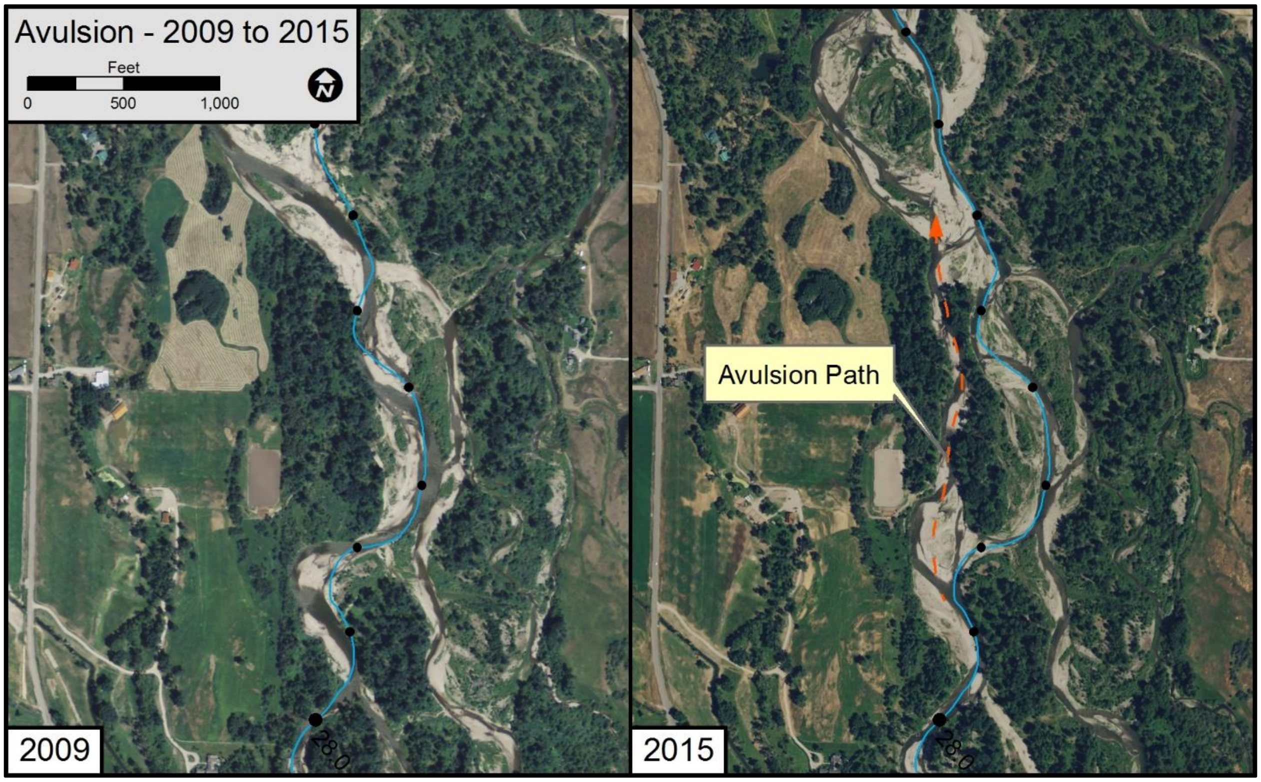

Figure 54. 2009-2015 Avulsion, RM 27.7.

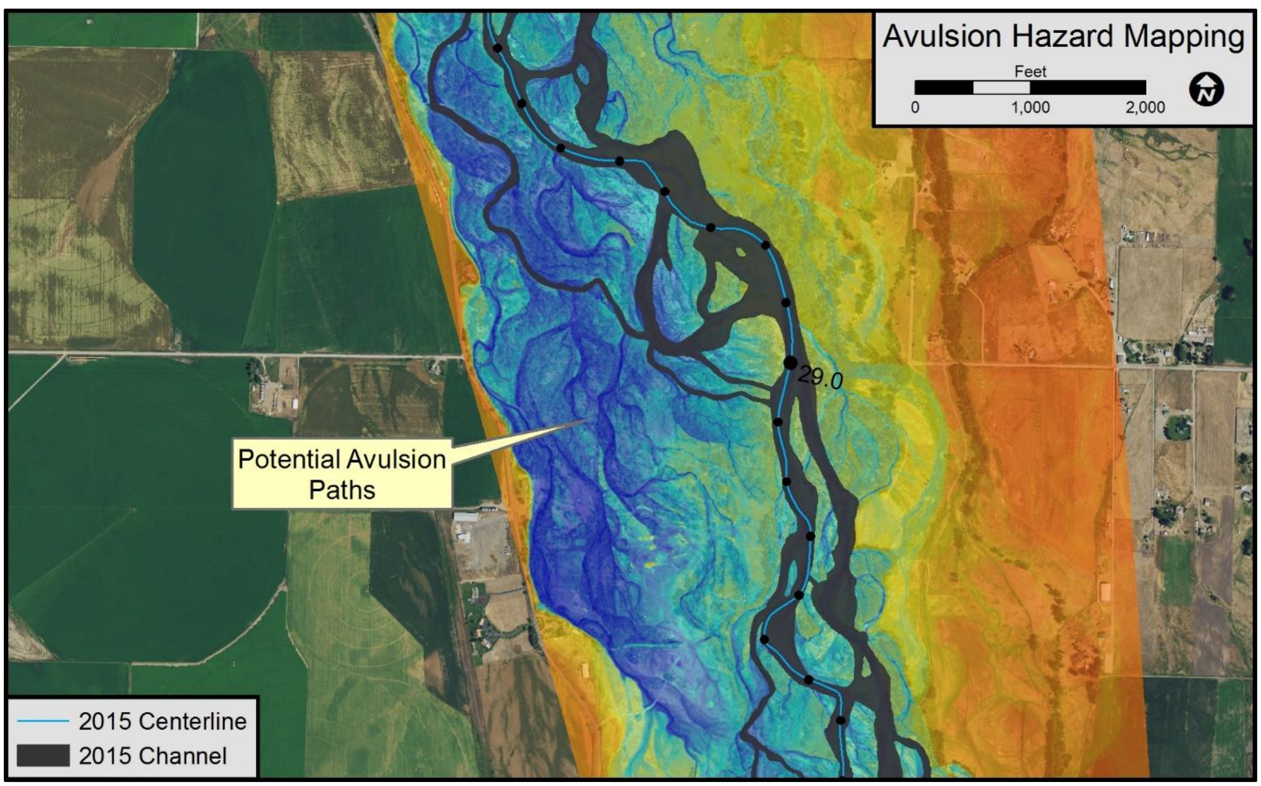

Figure 55. Broad avulsion hazard area west of Gallatin River, Reach GR05, RM 29.

Figure 56. View downstream of Reach GR05 showing broad avulsion hazard area to left (Kestrel).

5.5 Reach GR04

Reach GR04		
Upstream/Downstream RM	26.5	19.3
Length (miles)	7.2	
General Location	Cameron Bridge to I-90	
Mean Migration Rate (ft/yr)	5.1	
Max 60-year Migration Distance (ft)	576	
100-year Buffer (ft)	513	

Reach GR04 is just over seven miles long, extending from Cameron Bridge to I-90. Similar to upstream reaches, this channel segment is characterized by rapid bank migration and numerous avulsions. The erosion buffer for this reach is 513 feet, which is based on a mean measured migration rate of 5.1 feet per year. A total of 12 avulsions were mapped in Reach GR04, half of which occurred since 1995. This reflects an average density of 1.7 avulsions per river mile since 1965. What is most notable about the avulsions in Reach GR04 is their length. One avulsion at RM 20.4 was over a mile long and has created challenges for continued operations of the Creamery Ditch Diversion (Figure 34 and Figure 57). This area also shows very diverse riparian age classes, which contributes to the long-term sustainability of the riparian forest on the Gallatin River (Figure 58). Another major avulsion that carved about a mile of new channel occurred at RM 25.

Figure 59 shows an example of structures located within the Erosion Hazard Area that have come under threat only in recent decades. Since 1965 the river has migrated 260 feet eastward to its current location. Barbs have been built to protect the structure, but the river is now attacking the bank at a high angle to the barbs which will result in erosion between the rock structures. The current river configuration at this site appears to be caused by large quantities of bedload deposition during the 2011 flood.

Just below Cameron Bridge, Baker Creek exits the Gallatin River towards the northwest in Reach GR04. Baker Creek extends as continuous mapped floodplain to and beyond the I-90 crossing, indicating it is a viable distributary channel of the Gallatin (Figure 60 and Figure 61). Several avulsion routes from the Gallatin River into Baker Creek have been blocked by a dike about a mile below Cameron Bridge, indicating substantial geomorphic connectivity between the two. The Baker Creek system was not included in the Gallatin CMZ.

Approximately 3,450 feet of bank armor were mapped in Reach GR04, protecting 5% of the total bankline. Just over a mile of floodplain dikes were mapped in the reach. The bank armor restricts about 23 acres of the CMZ, and transportation infrastructure restricts another 6 acres.

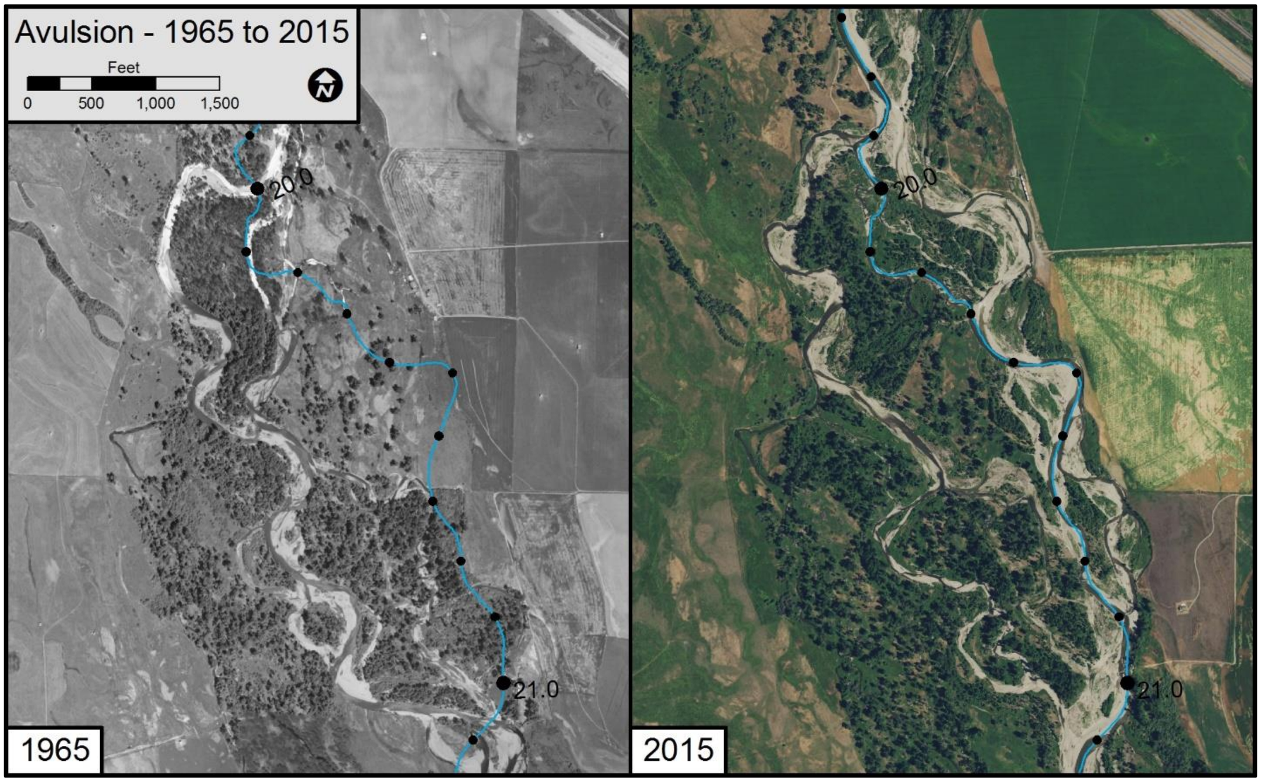

Figure 57. Major avulsion at RM 20.4 between 1965 (left) and 2015 (right).

Figure 58. View downstream of ~1.1 mile long avulsion shown in Figure 57; I-90 Bridge crossing is in distance (Kestrel).

Figure 59. Barn on right bank where river has migrated 216 feet since 1965, RM 23.2 (Kestrel).

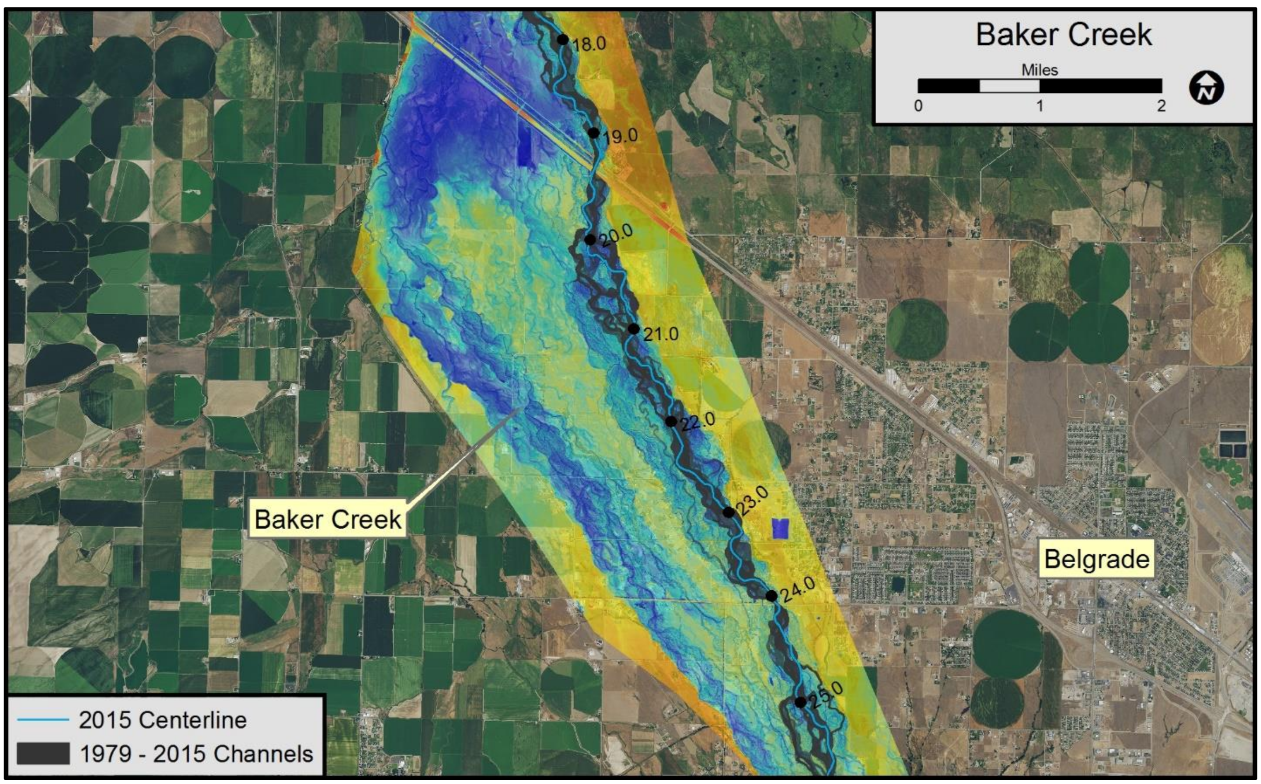

Figure 60. Relative Elevation Modeling results showing main Gallatin River course in black and Baker Creek trending to northwest.

Figure 61. View downstream showing Baker Creek trend splitting to the left from Gallatin River; note development in between (Kestrel).

5.6 Reach GR03

Reach GR03		
Upstream/Downstream RM	19.3	12.0
Length (miles)	7.3	
General Location	I-90 to East Gallatin River Confluence	
Mean Migration Rate (ft/yr)	4.9	
Max 60-year Migration Distance (ft)	935	
100-year Buffer (ft)	494	

Downstream of the I-90 Bridge, Reach GR03 marks an abrupt reduction in the slope of the Gallatin River (Figure 25). Although a flattening in channel slope is a fairly continuous trend downstream from Gallatin Canyon, this area marks an especially notable approximately 20% drop in grade. As a result, this reach appears to function in many ways as a "response reach" to upstream processes. Flood impacts upstream have generated sediment loads that have accumulated in Reach GRO3, causing major channel relocations since 1965. The maximum migration distance measured in this reach was 934 feet, and this was in an area of extensive sediment storage following the 1974 flood. The erosion hazard area is almost 500 feet wide. A total of six avulsions were mapped in Reach GR03, half of which occurred since 1995. This reflects an average density of 0.8 avulsions per river mile since 1965.

The Inundation/Relative Elevation Modeling results of Reach GRO3 show the broad floodplain connectivity in Reach GRO3, with extensive channel networks on both sides of the river.

At RM 15, the Gallatin River flows through an abandoned rail grade that has been breached, causing an avulsion between 1979 and 2015 (Figure 64). There are several other small breaches in the grade, and additional breaches could expand floodplain channels that currently flow north to the East Gallatin River.

The lowermost portion of Reach GRO3 consists of the coalescing floodplains of the Gallatin and East Gallatin Rivers. The LiDAR data show that where Gallatin swings to the west and starts to parallel the East Gallatin (RM ~13.3) it is actually perched about 12 feet above the East Gallatin, and furthermore, the drainage divide between the two systems is essentially the right (north) bank of the Gallatin (Figure 65). This means that over bank flows from the Gallatin River in this area will flow down gradient to the north, entering the East Gallatin River about a mile upstream of the modern confluence. Any further migration of the Gallatin to the north in this area will continue to lower that drainage divide, causing water to flow more frequently and for a longer duration to the north. This will, in turn, increase the risk of an avulsion on the Gallatin which would effectively move the confluence between the rivers up to a mile upstream. That process is currently active at RM 12.25, where only an approximately 40 foot wide sliver of ground separates the two rivers; breaching of that sliver will move the confluence about a quarter mile westward (Figure 66).

A total of 5,088 feet of bank armor were mapped in Reach GR03, protecting 7% of the total bankline. Just over a mile of floodplain dikes were mapped in the reach. The bank armor restricts about 59 acres of the CMZ, and transportation infrastructure restricts another 26 acres.

Figure 62. View downstream showing large open bar areas in Reach GR03 (Kestrel).

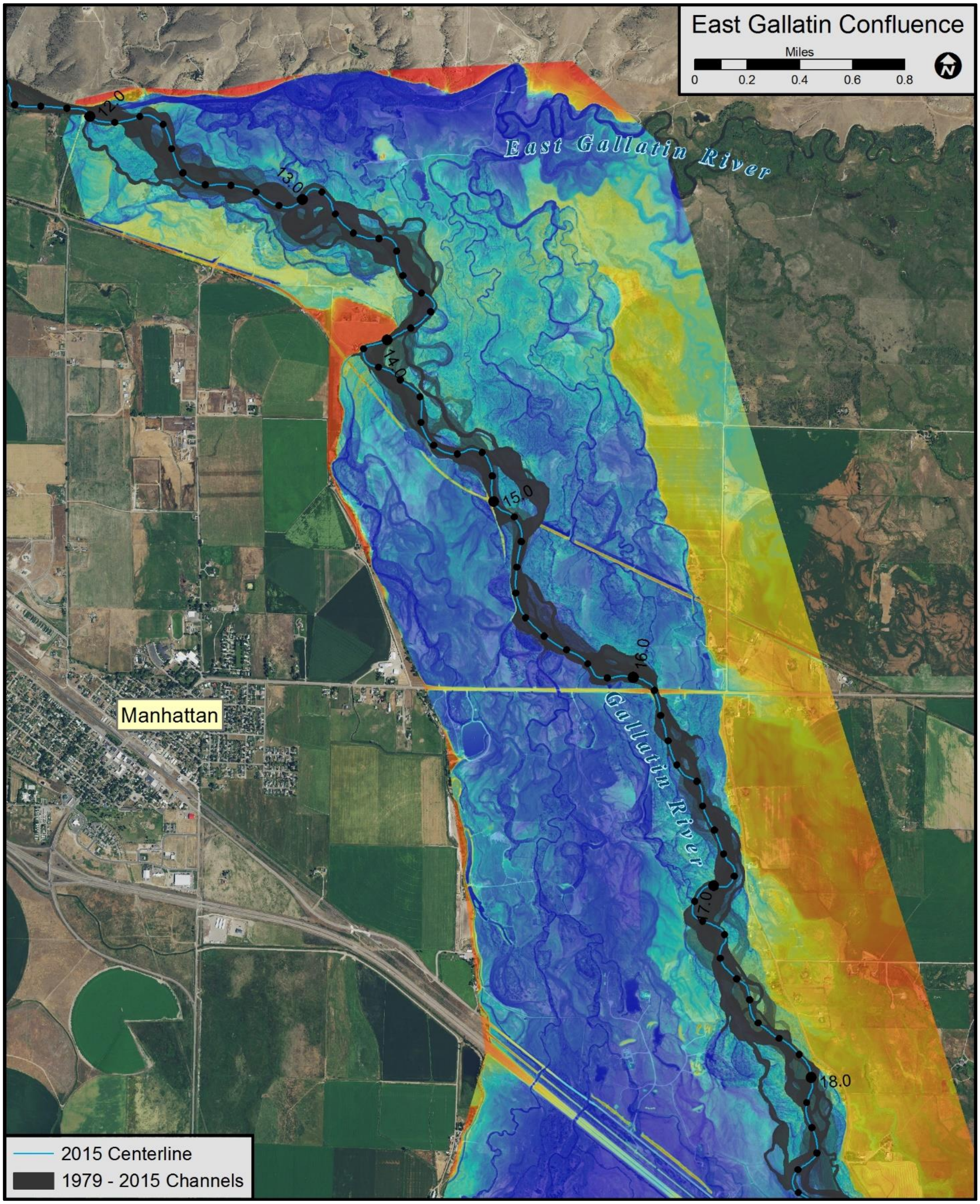

Figure 63. Reach GRO3 channel network depicted by REM output; blue areas are similar in elevation to modern channel (black).

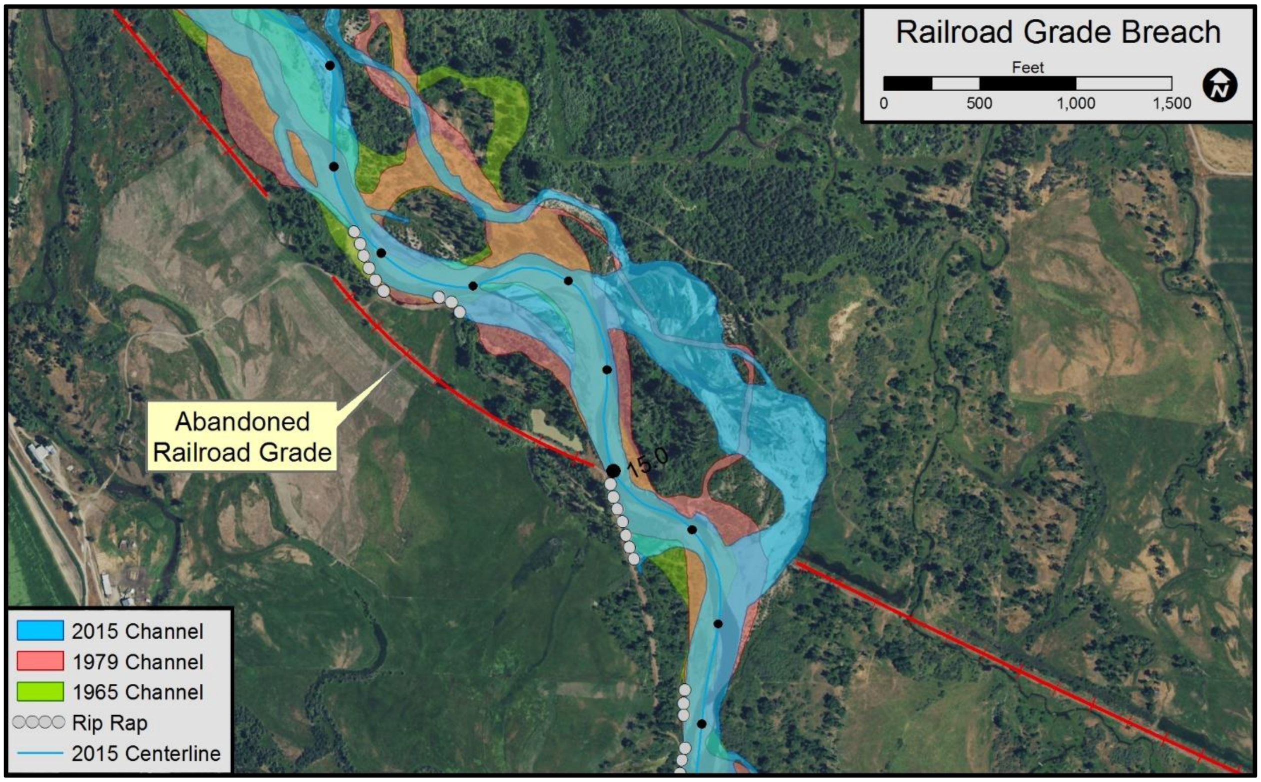

Figure 64. Progressive breach through abandoned rail grade, RM 15.

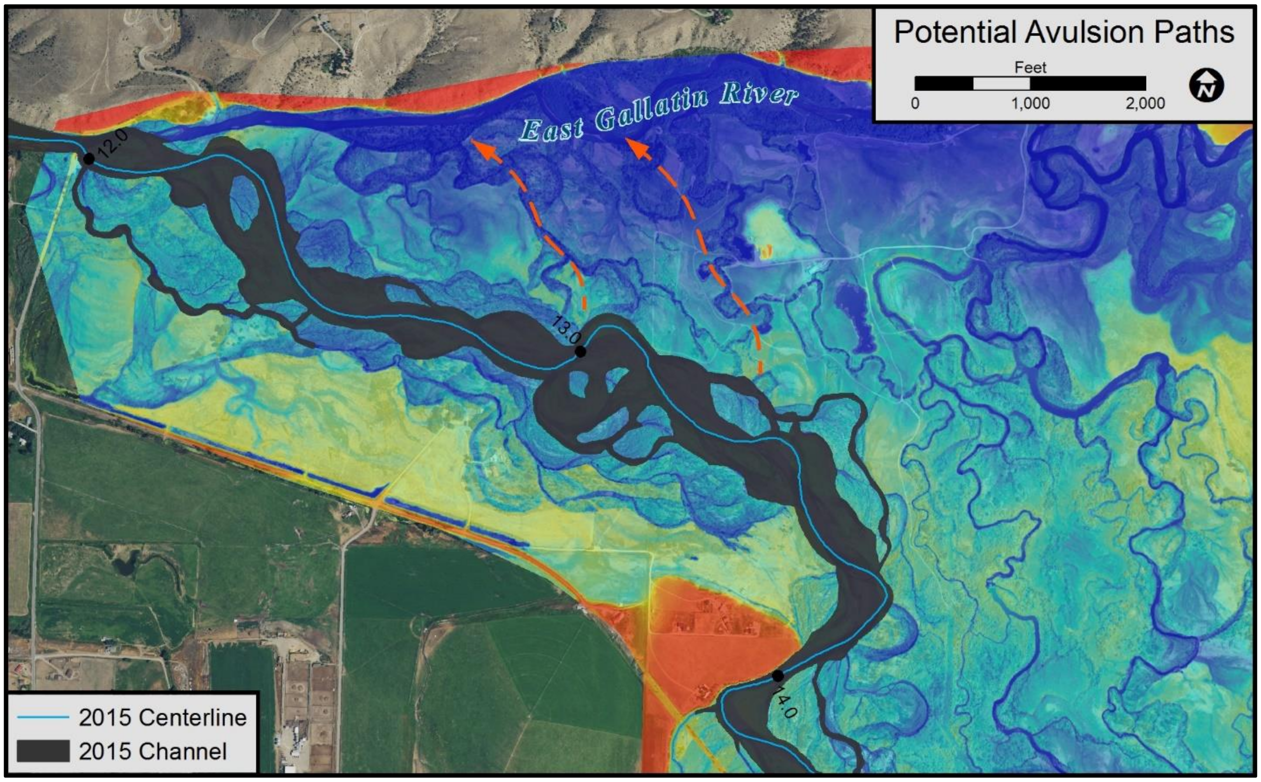

Figure 65. Relative Elevation Model output for Gallatin/East Gallatin River confluence (far left) showing relatively low East Gallatin elevations (dark blue) and potential avulsion area (orange arrows).

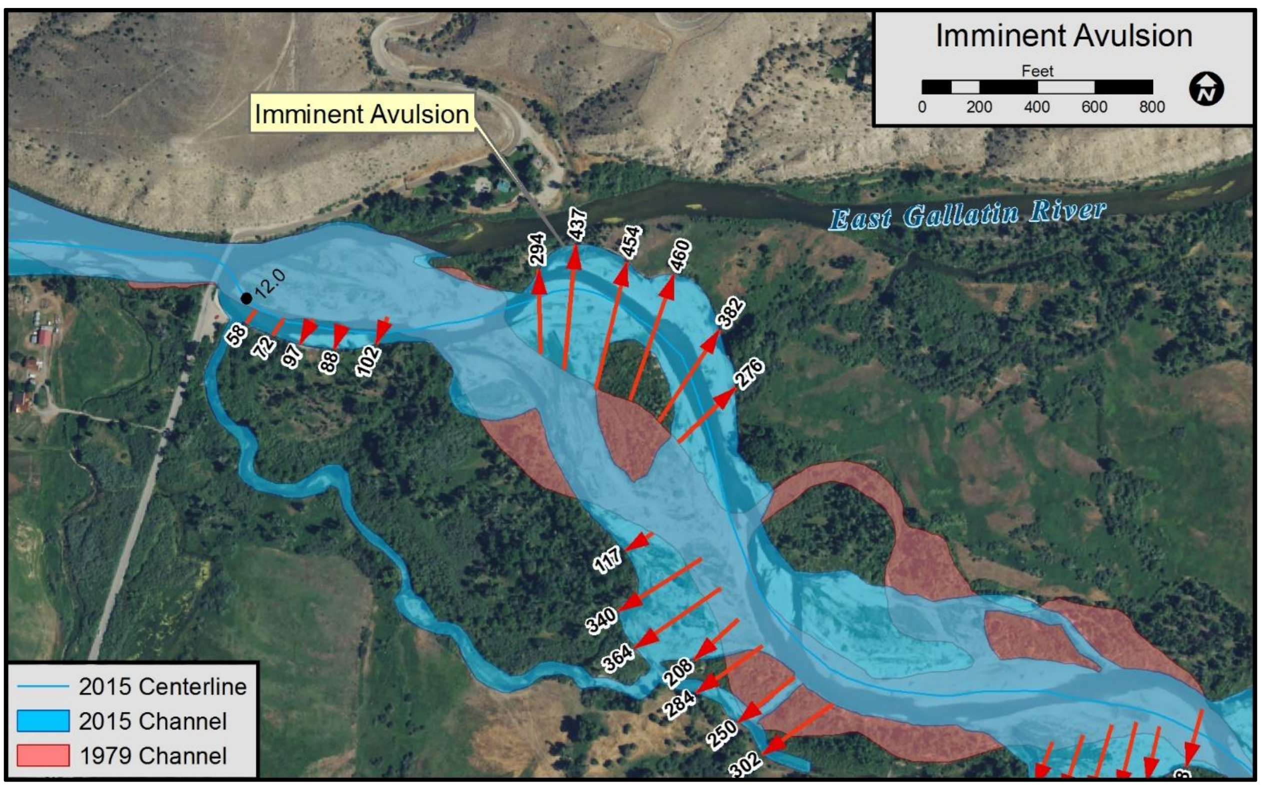

Figure 66. Gallatin River northward migration and likely avulsion site that will relocate confluence with East Gallatin ~0.25 miles upstream.

5.7 Reach GR02

GR02		
Upstream/Downstream RM	12.0	5.3
Length (miles)	6.7	
General Location	East Gallatin Confluence to Logan	
Mean Migration Rate (ft/yr)	4.2	
Max 60-year Migration Distance (ft)	529	
100-year Buffer (ft)	419	

Reach GR02 extends from the mouth of the East Gallatin River at Nixon Bridge to Logan. It is 7.6 miles long. The erosion buffer width in reach GR02 is 419 feet, based on a mean migration rate for actively eroding banks of 4.2 feet per year. Within this reach the Gallatin River is responding to inputs from both the East Gallatin and Gallatin River system. Avulsions are common as the river corridor tapers towards a bedrock notch at Logan. The corridor is also highly influenced by both active and abandoned rail lines. The irregular trend of the north bedrock valley wall creates a highly variable bottom width.

A total of seven avulsions were mapped in Reach GR02. This reflects an average density of 1.0 avulsions per river mile since 1965. On avulsion at RM 9.5 completely eroded out about 1,200 feet of the abandoned rail line sometime between 1979 and 2009 (Figure 67); the rail grade had been used as an access road and has since been relocated away from the river. The river continues to send water behind the breach, and the site will likely remain unstable for some time (Figure 68). Just downstream, there have been several avulsions at RM 8.0, with a large approximately 0.5 mile long avulsion occurring between 1979 and 2015 (Figure 69). Currently the river closely follows the rail line for almost 4,000 feet below the avulsion site; the line has been armored along this stretch. At Logan, the river is tightly confined by limestone bluffs to the north and the community of Logan on the left floodplain area (Figure 71).

A total of 8,423 feet of bank armor were mapped in Reach GR02, protecting 12% of the total bankline. Although no floodplain dikes were mapped in the reach, much of the transportation infrastructure, which isolates 43 acres of the CMZ, behaves as a dike. Bank armor restricts another 28 acres of the CMZ.

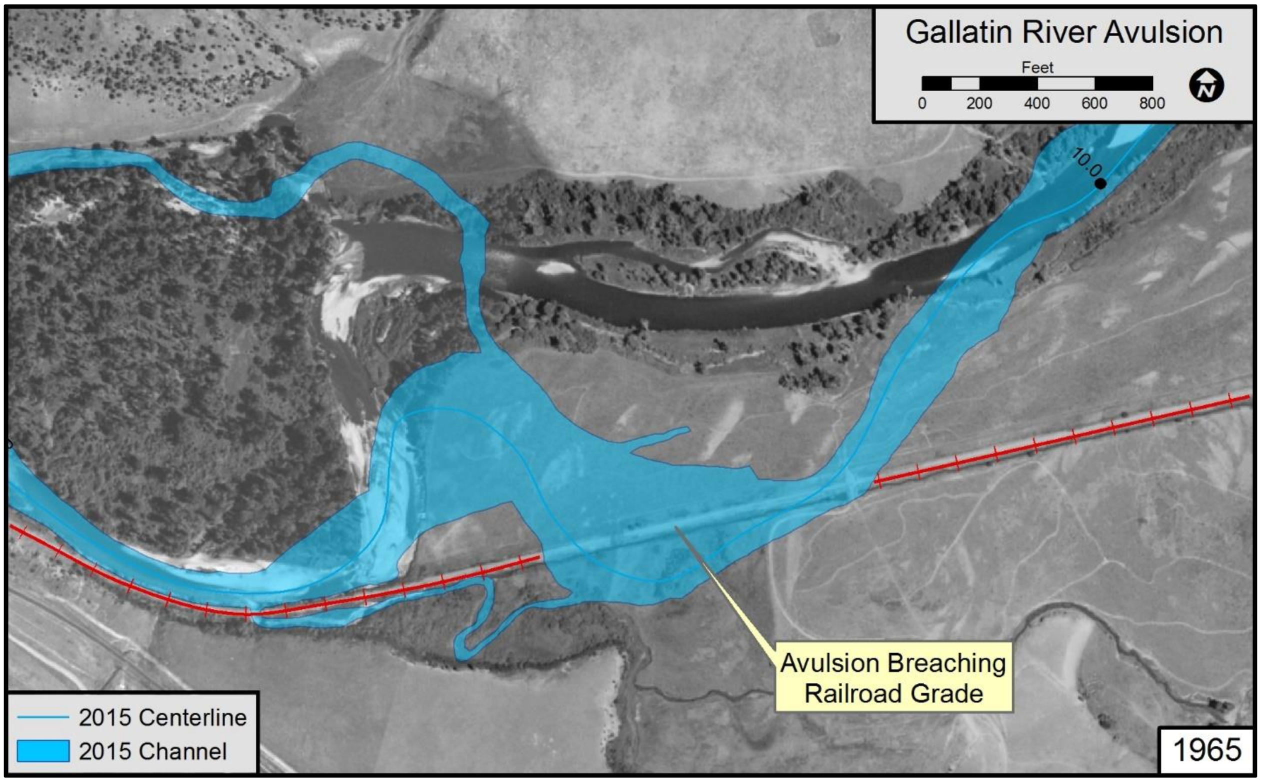

Figure 67. 1965 image showing avulsion site through old rail grade (2015 channel shown in blue).

Figure 68. View downstream breached railroad grade and relocated road, Reach GR02 (Kestrel).

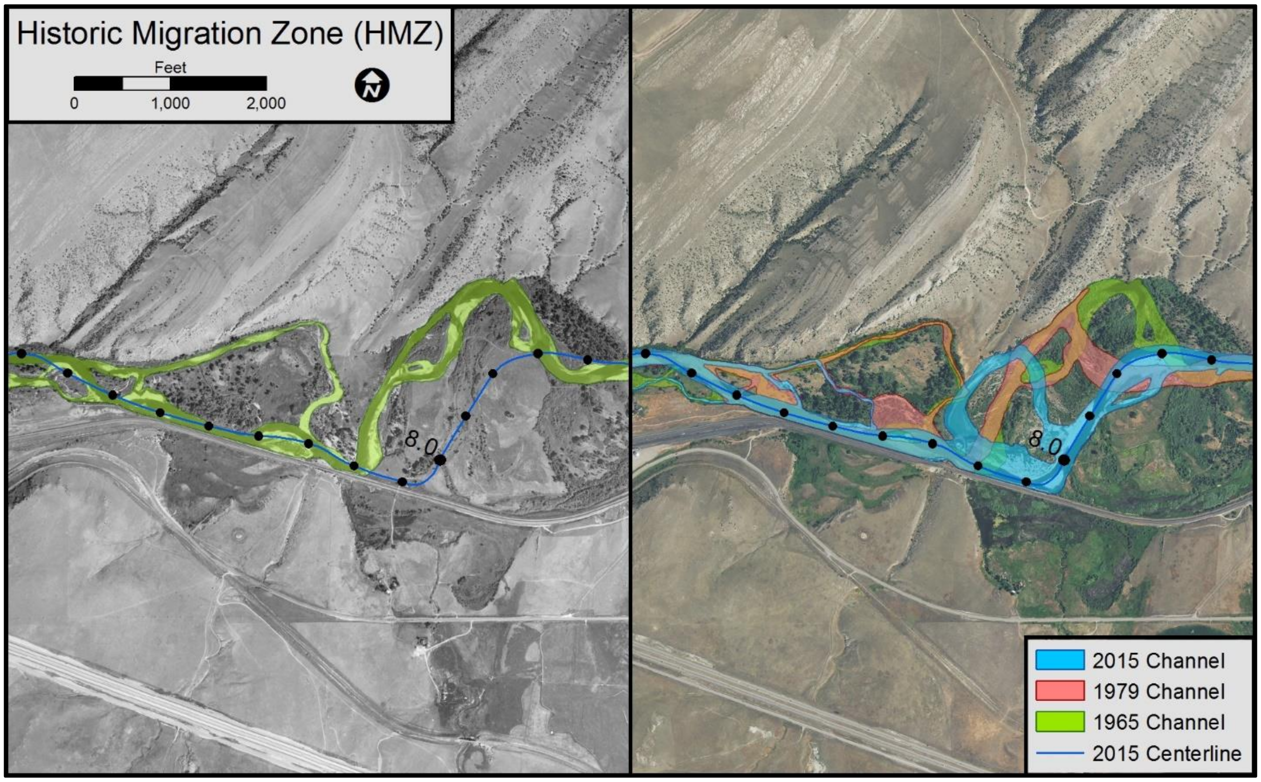

Figure 69. Major avulsion at RM 8.0 between 1965 (left) and 2015 (right).

Figure 70. View downstream showing avulsion site and rail line isolation of historic floodplain, Reach GRO2 (Kestrel).

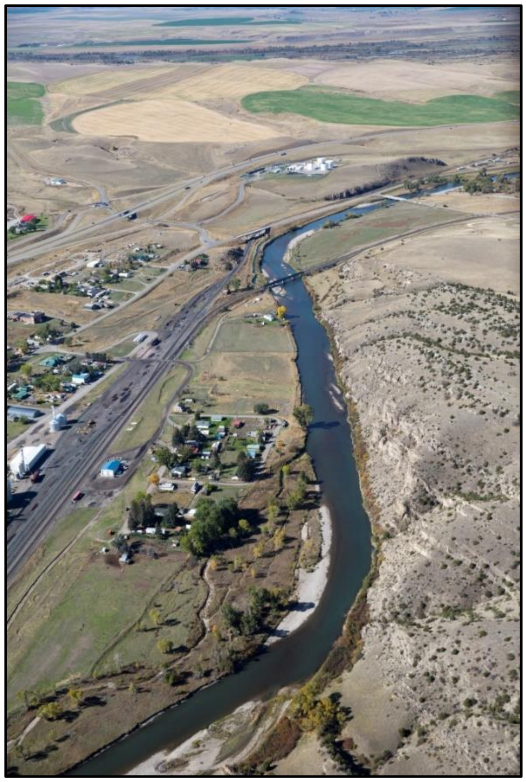

Figure 71. View downstream showing bedrock constriction at Logan, Reach GR02 (Kestrel).

5.8 Reach GR01

Reach GR01		
Upstream/Downstream RM	5.3	0.0
Length (miles)	5.3	
General Location	Logan to Headwaters State Park	
Mean Migration Rate (ft/yr)	5.2	
Max 60-year Migration Distance (ft)	615	
100-year Buffer (ft)	522	

Reach GR01 is 5.3 miles long and extends from Logan to the mouth of the Gallatin River at Headwaters State Park. This reach has the largest erosion buffer of the project area at 522 feet, and the maximum distance measured for the 1965-2015 timeframe was 615 feet. Below Logan, the river flows into the broad open coalescing floodplain areas for the Gallatin, Madison, and Jefferson Rivers. The slope of the channel is 0.2%, which is less than one third of the slope upstream at Gallatin Gateway. Similar to Reach GR02 just upstream, the railroad isolates historic CMZ area in Reach GR01. In addition to the rail line impacts, there have been multiple pivot irrigation projects built since the late 1970s on the left floodplain just downstream of Logan. Between the rail line and the pivot infrastructure, the channel has become closely confined and densely armored for about three miles below the Logan Bridge (Figure 72). Most of the armor is on the right bank along the rail line, but actively eroding banks against the pivots have also been armored. As a result, the stream corridor has been artificially narrowed from approximately 2,000 feet to less than 800 feet. At RM 3.0, the river emerges from the artificial confinement, peels away from the railroad and enters a broad approximately 3,000 foot wide swath of active channels before joining the Missouri River at Headwaters State Park (Figure 73). There are several active avulsions in this lower portion of Reach GR01. A total of five avulsions were mapped in the reach, which reflects an average density of 0.9 avulsions per river mile since 1965 (Figure 74 and Figure 75).

A total of 10,589 feet of bank armor were mapped in Reach GR01, protecting 19% of the total bankline. No floodplain dikes were mapped in the reach, although the rail grade functionally forms a dike. The bank armor restricts about 60 acres of the CMZ, and transportation infrastructure restricts another 170 acres.

Figure 72. View downstream showing stream corridor narrowing between armored pivot field (left) and rail line (right) (Kestrel).

Figure 73. View downstream showing river flowing along the rail line towards Headwaters State Park (Kestrel).

Figure 74. View downstream showing wide floodplain and active avulsions, Reach GR01 (Kestrel).

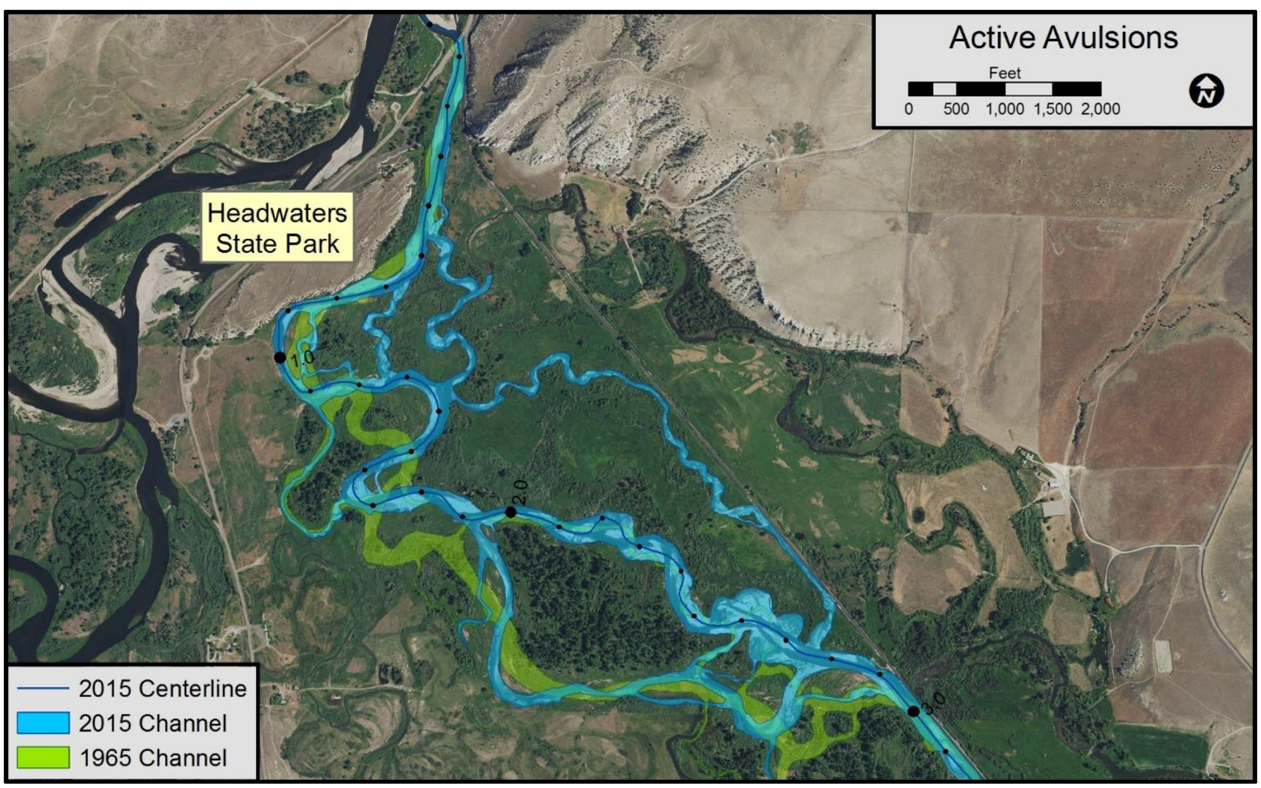

Figure 75. View downstream showing new channel formation since 1965, Reach GR01 (Kestrel).

6 References

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

Alt, D., and D.W Hyndman, 1986. Roadside Geology of Montana, Mountain Press Publishing Company, Missoula, 427p.

Boyd, K., W. Kellogg, T. Pick, M. Ruggles and S. Irvin, 2012. Musselshell River Flood Rehabilitation River Assessment Triage Team (RATT) Summary Report: Report prepared for Lower Musselshell Conservation District, Roundup, Montana, 111p.

Dalby, C, 2006. Comparison of channel migration zones in plane-bed, pool-riffle and anabranching channels of the upper Yellowstone River: Poster Session delivered at the Montana Section AWRA annual meeting, October 12-13, 2006.

FEMA, 1999. River Erosion Hazard Areas—Mapping Feasibility Study: Federal Emergency Management Agency, Technical Services Division, Hazards Study Branch, 154p.

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.

Morrison Maierle, 2014. Hydrology Design Report, Wests Gallatin River, Gallatin County, MT: Report prepared for Montana Department of Natural Resources and Conservation, 123p.

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.

Vuke, S.M., J.D. Lonn, R.B. Berg, and C.J. Schmidt, 2014. Geologic map of the Bozeman 30'X60' Quadrangle, Southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 648, 44p.

Washington Department of Natural Resources Forest Board Manual, 2004, Section 2: Standard Methods for Identifying Bankfull Channel Features and Channel Migration Zones, 69p.

Washington State Department of Ecology (WSDE), 2010. Channel Migration Assessment webpage. Accessed 11/1/2010. http://www.ecy.wa.gov/programs/sea/sma/cma/index.html.

Appendix A: Reach and Site Migration Statistics

The Channel Migration Zone Mapping for the Gallatin River resulted in 841 individual measurements of channel movement between 1965 and 2015. These measurements were taken at approximately 30 foot intervals where notable movement has occurred. Each grouping of migration measurements, such as a bendway, was assigned a Migration Site ID (MSID) that includes the river mile as part of the ID. The statistics for each site are presented in the table below.

Site ID	Count	Avg (ft	Min (ft)	Max (ft)
GRO1				
MSID-GR-0.65	4	136	89	177
MSID-GR-1.34	4	562	464	615
MSID-GR-1.61	3	307	264	330
MSID-GR-1.81	4	460	404	505
MSID-GR-1.93	4	286	177	354
MSID-GR-2.1	4	188	128	235
MSID-GR-2.16	4	154	125	182
MSID-GR-2.22	3	131	108	151
MSID-GR-2.34	3	218	184	269
MSID-GR-2.46	4	132	66	185
MSID-GR-2.57	3	213	125	264
MSID-GR-4.54	3	319	248	373
GRO2				
MSID-GR-5.69	7	346	176	529
MSID-GR-7.74	7	353	193	434
MSID-GR-8.39	4	165	118	217
MSID-GR-8.89	6	222	149	378
MSID-GR-10.01	7	210	118	325
MSID-GR-10.37	7	183	87	261
MSID-GR-10.65	5	130	98	149
MSID-GR-11.04	6	165	125	201
MSID-GR-11.28	3	86	78	92
MSID-GR-11.39	8	86	64	106
MSID-GR-11.73	8	251	122	438
GRO3				
MSID-GR-12.06	5	83	58	102
MSID-GR-12.28	6	384	276	460
MSID-GR-12.48	7	266	117	364
MSID-GR-12.75	6	225	172	273
MSID-GR-12.93	4	212	181	232
MSID-GR-13.35	5	618	377	935
MSID-GR-13.46	5	339	226	447
MSID-GR-13.62	5	242	172	264
MSID-GR-13.83	5	247	167	337
MSID-GR-14.13	5	232	157	279
MSID-GR-14.39	5	238	170	294
MSID-GR-15.18	3	164	117	245
MSID-GR-15.44	8	199	125	260
MSID-GR-15.96	8	220	134	306
MSID-GR-16.3	9	199	74	328
MSID-GR-16.47	3	92	76	103
MSID-GR-17.18	11	295	183	466
MSID-GR-17.51	6	264	224	301
MSID-GR-17.69	7	273	128	396

Site ID	Count	Avg (ft	Min (ft)	Max (ft)
MSID-GR-17.99	3	124	93	172
MSID-GR-18.07	5	141	57	236
MSID-GR-18.53	3	408	357	473
MSID-GR-18.67	8	220	112	393
MSID-GR-18.99	8	193	114	347
GRO4				
MSID-GR-19.52	6	205	122	303
MSID-GR-19.71	4	308	248	353
MSID-GR-19.89	2	223	177	268
MSID-GR-19.93	4	287	176	407
MSID-GR-20.09	3	145	110	164
MSID-GR-20.12	3	221	151	263
MSID-GR-20.13	3	251	139	318
MSID-GR-20.66	3	239	186	316
MSID-GR-21.18	3	260	164	327
MSID-GR-21.38	6	284	140	365
MSID-GR-21.47	3	194	162	215
MSID-GR-21.69	11	153	80	231
MSID-GR-21.9	5	359	163	434
MSID-GR-22.11	5	299	161	380
MSID-GR-22.31	12	320	113	454
MSID-GR-22.59	6	215	115	276
MSID-GR-22.67	6	132	85	195
MSID-GR-22.77	5	152	82	218
MSID-GR-22.89	6	422	277	512
MSID-GR-23.11	11	288	113	462
MSID-GR-23.48	16	363	78	538
MSID-GR-23.78	4	222	85	329
MSID-GR-23.87	7	276	141	355
MSID-GR-23.89	6	219	80	272
MSID-GR-24.26	6	240	104	381
MSID-GR-24.84	3	93	52	124
MSID-GR-25.19	4	416	256	576
MSID-GR-25.6	5	312	222	381
MSID-GR-25.76	3	128	78	172
MSID-GR-26.05	4	207	187	236
MSID-GR-26.13	4	187	126	266
MSID-GR-26.29	4	117	75	144
GRO5				
MSID-GR-26.54	5	286	196	345
MSID-GR-26.77	4	288	184	364
MSID-GR-27.56	4	136	111	171
MSID-GR-27.6	4	169	80	263
MSID-GR-27.75	3	235	182	274
MSID-GR-27.84	5	255	168	326

Site ID	Count	Avg (ft	Min (ft)	Max (ft)
MSID-GR-27.93	2	194	173	214
MSID-GR-28.31	5	186	108	265
MSID-GR-28.45	10	162	105	242
MSID-GR-28.59	4	491	390	616
MSID-GR-28.67	5	342	286	384
MSID-GR-28.92	3	356	269	420
MSID-GR-29.12	5	387	223	480
MSID-GR-29.29	7	255	98	369
MSID-GR-29.38	4	170	93	304
MSID-GR-29.58	6	175	121	216
MSID-GR-29.97	6	310	201	415
MSID-GR-30.18	4	169	126	218
MSID-GR-30.42	8	422	234	564
MSID-GR-30.69	3	154	86	199
MSID-GR-30.88	5	210	138	285
MSID-GR-31.12	8	302	148	392
MSID-GR-31.25	6	218	94	300
MSID-GR-31.4	3	186	165	202
MSID-GR-31.54	7	200	154	240
MSID-GR-31.71	3	142	110	158
MSID-GR-31.86	3	219	127	285
MSID-GR-31.98	4	111	60	163
MSID-GR-32.02	5	136	107	176
MSID-GR-32.43	5	98	76	134
GRO6				
MSID-GR-33.03	4	101	76	119
MSID-GR-33.32	7	214	113	349
MSID-GR-33.6	4	253	196	295
MSID-GR-33.83	5	235	132	308
MSID-GR-33.97	6	197	128	252
MSID-GR-34.13	5	152	99	189
MSID-GR-34.15	9	104	70	131
MSID-GR-34.96	8	210	96	304
MSID-GR-35.1	2	91	85	96
MSID-GR-35.11	3	73	40	90
MSID-GR-35.18	5	69	51	91
MSID-GR-35.19	3	47	35	56
MSID-GR-35.28	3	274	249	320
MSID-GR-35.44	4	142	78	191
MSID-GR-35.53	6	149	74	193
MSID-GR-35.73	5	200	120	315
MSID-GR-36.02	3	121	87	144
MSID-GR-36.05	3	97	56	125
MSID-GR-36.18	3	187	120	228

Site ID	Count	Avg (ft	Min (ft)	Max (ft)
MSID-GR-36.28	5	214	118	276
MSID-GR-36.42	3	108	84	125
MSID-GR-36.67	3	145	135	161
MSID-GR-37.09	4	211	157	266
MSID-GR-37.28	7	149	113	195
GRO7				
MSID-GR-37.74	6	150	82	217
MSID-GR-38.42	5	194	152	223
MSID-GR-38.6	4	212	105	349
MSID-GR-38.74	8	130	85	169
MSID-GR-38.81	4	79	49	121
MSID-GR-39	5	124	95	155
MSID-GR-39.22	6	193	109	264
MSID-GR-39.5	7	234	133	289
MSID-GR-39.69	5	120	67	151
MSID-GR-39.8	3	95	80	106
MSID-GR-39.92	7	102	72	123
MSID-GR-39.93	5	185	61	322
MSID-GR-40.06	4	128	102	143
MSID-GR-40.14	2	172	147	196
MSID-GR-40.15	4	183	126	243
MSID-GR-40.29	6	157	76	224
MSID-GR-40.34	3	119	84	146
MSID-GR-40.52	2	175	157	193
MSID-GR-40.71	3	108	95	125
MSID-GR-40.88	5	116	85	146
MSID-GR-41.31	4	85	67	99
MSID-GR-41.62	4	131	99	145
MSID-GR-41.69	4	110	53	159
MSID-GR-41.74	5	118	70	152
MSID-GR-41.82	3	99	96	104
MSID-GR-41.88	4	76	65	84
MSID-GR-41.91	3	184	117	237
MSID-GR-42.03	3	186	114	227
MSID-GR-42.24	3	190	146	219
MSID-GR-42.35	3	74	58	86
MSID-GR-42.44	5	178	78	290
GRO8				
MSID-GR-42.66	8	55	36	76
MSID-GR-43.06	5	27	24	32
MSID-GR-43.31	4	57	34	80
MSID-GR-43.8	4	24	19	32
MSID-GR-43.96	5	28	21	41

Appendix B: Bridge Photos

Figure 76. Hwy 191 bridge on September 26, 2016. (Kestrel)

Figure 77. W Williams Road bridge on September 26, 2016. (Kestrel)

Figure 78. Gateway South Road (east span) bridge on September 26, 2016. (Kestrel)

Figure 79. Axtell Anceny Road bridge on September 26, 2016. (Kestrel)

Figure 80. Norris Road bridge on September 26, 2016. (Kestrel)

Figure 81. W Cameron Road bridge on September 26, 2016. (Kestrel)

Figure 82. Amsterdam Road bridge on September 26, 2016. (Kestrel)

Figure 83. Bridge complex at I-90 on September 26, 2016. (Kestrel)

Figure 84. Dry Creek Road bridge on September 26, 2016. (Kestrel)

Figure 85. Nixon Gulch Road bridge on September 26, 2016. (Kestrel)

Figure 86. Railroad bridge at Logan on September 26, 2016. (Kestrel)

Figure 87. Logan Trident Road bridge on September 26, 2016. (Kestrel)

Appendix C: Selected Irrigation Infrastructure Photos

Figure 88. Diversion at RM 43.1 Highline Canal, September 26, 2016 (Kestrel).

Figure 89. Diversion at RM 28.3 Lewis Ditch, September 26, 2016 (Kestrel).

Figure 90. Diversion at RM 25.6, September 26, 2016 (Kestrel).

Figure 91. Diversion at RM 25.4, September 26, 2016 (Kestrel).

Appendix D: Reach Maps