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

From the upper end of the project reach to near Dry Creek Road north of Belgrade, the river corridor is naturally dynamic and responding to historic channelization by reestablishing channel length. Continued shifts in the channel have the potential to alter overflow paths and flooding patterns seen in the 2008 flood, especially upstream of Manley Road where a major overflow carries floodwater to Churn Creek.

Rapid channel migration and avulsions in upper portions of the project area river have generated sediment pulses that have affected downstream channel dynamics. For example, large avulsions have excavated new channels and conveyed that material downstream, increasing migration rates in turn. Channelized sections have similarly generated sediment by re-forming meanders. The downstream response is observable on a local scale, however similar patterns may be occurring on a larger scale. Near Dry Creek Road and Thompson Creek, the river abruptly transitions to a highly sinuous and fairly stable condition that is characterized by a low gradient, low migration rates, and a relatively narrow erosion hazard area. However, riparian clearing has been extensive in this section of river, reducing bankline and floodplain resiliency. The river has widened since the mid-1950s, which may be in part due to riparian clearing. In the event that upstream processes increase sediment loading to this lower gradient section of river, an increase in migration rates and avulsion frequencies should be expected. Riparian restoration in lower gradient sections of the East Gallatin River would be an appropriate means of adding natural resiliency to a system that may experience increased sediment loading and accelerated rates of geomorphic change in the future.

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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 East Gallatin River Channel Migration Zone (CMZ) mapping project developed approximately 41 miles of CMZ mapping for the East Gallatin River from the Highway the Bridger Creek/Rocky Creek confluence, downstream to its confluence with the Gallatin River. 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 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 Tony Thatcher of DTM Consulting and Karin Boyd of Applied Geomorphology, with support from Chris Boyer of Kestrel Aerial Services (Kestrel). Over the past decade, we have been collaborating to develop CMZ maps for numerous rivers in Montana, 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).

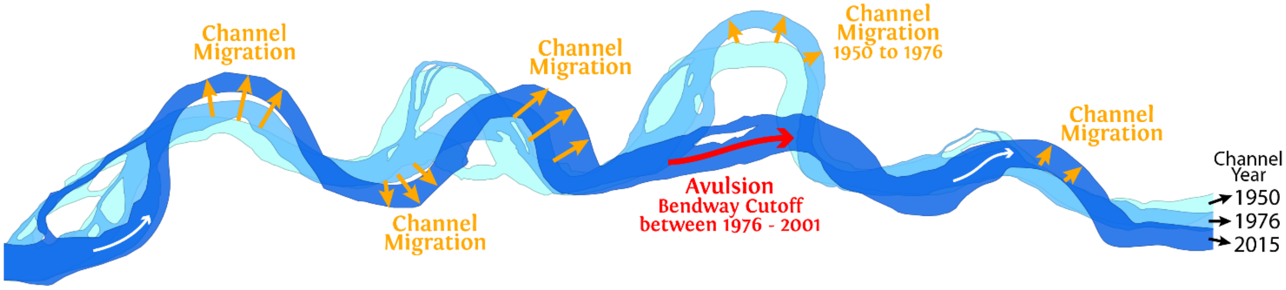


Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

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).

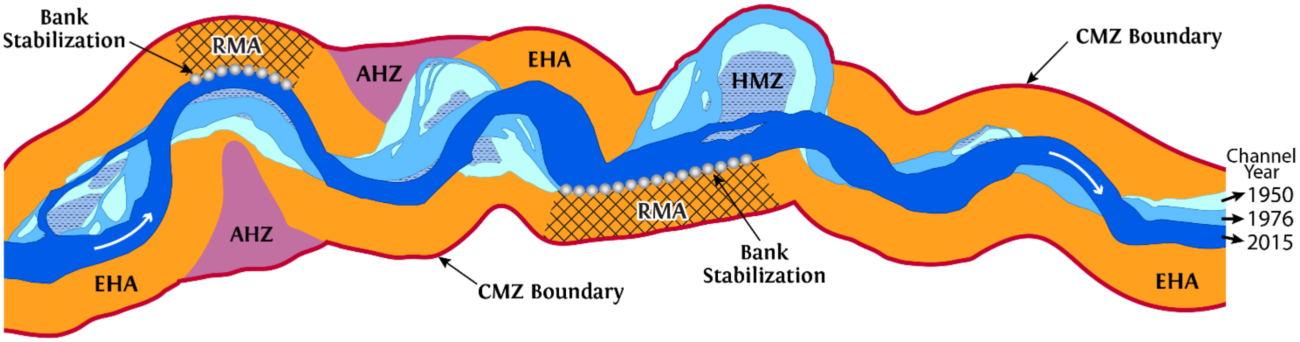


Figure 2. Channel Migration Zone mapping units.

1.3 CMZ Mapping on the East Gallatin River

The Channel Migration Zone (CMZ) developed for East Gallatin River extends 41.4 river miles from Bridger Creek to its confluence with the Gallatin River north of Manhattan, MT.

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, 1979/80, 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 Bridger Creek to its confluence with the Gallatin River, the East Gallatin River shows historic patterns of lateral migration and avulsion, typically within a broad valley that is prone to flooding such as occurred in 2008. 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. With the current development rate in the Gallatin Valley, for example, there may be significant alterations in system hydrology due changing rainfall/runoff patterns on impervious surfaces. This urbanization of the river’s hydrology could potential increase migration rates and avulsion frequency by creating higher peak flows. If, however, the riparian corridor is restored along the channel, the consequences of increased flow energy could be somewhat mitigated. These types of changes could affect future rates of channel movement and should be considered as development and/or restoration projects proceed.

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.

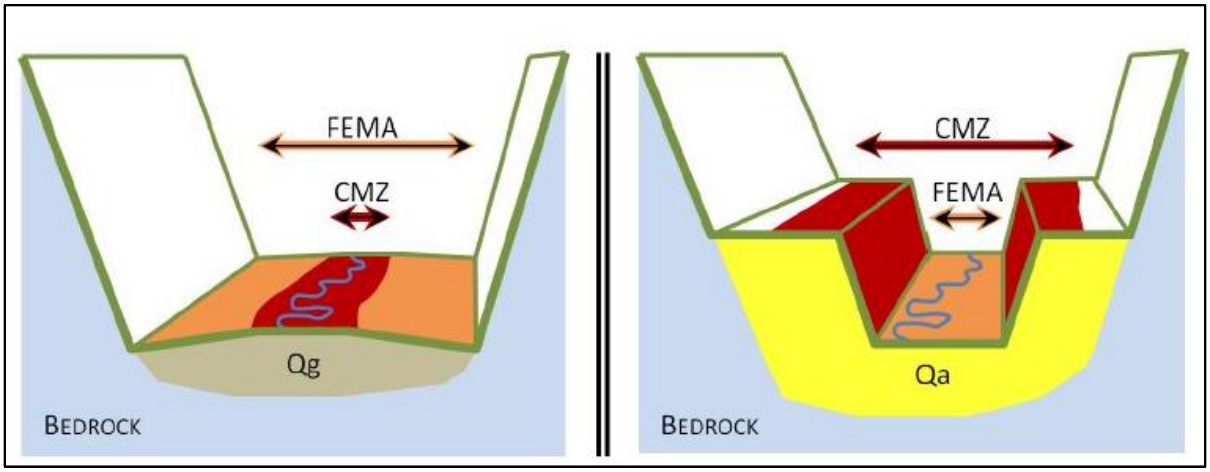


Figure 3. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

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.

Utahfloodrelief.com

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 East Gallatin River east of Belgrade is shown in Figure 6, and an older map from 1972 is shown in (Figure 7). On the East Gallatin River, there are few terraces and the CMZ tends to be narrower than the mapped floodplain. As a result, most development within the CMZ is also prone to flood hazards.

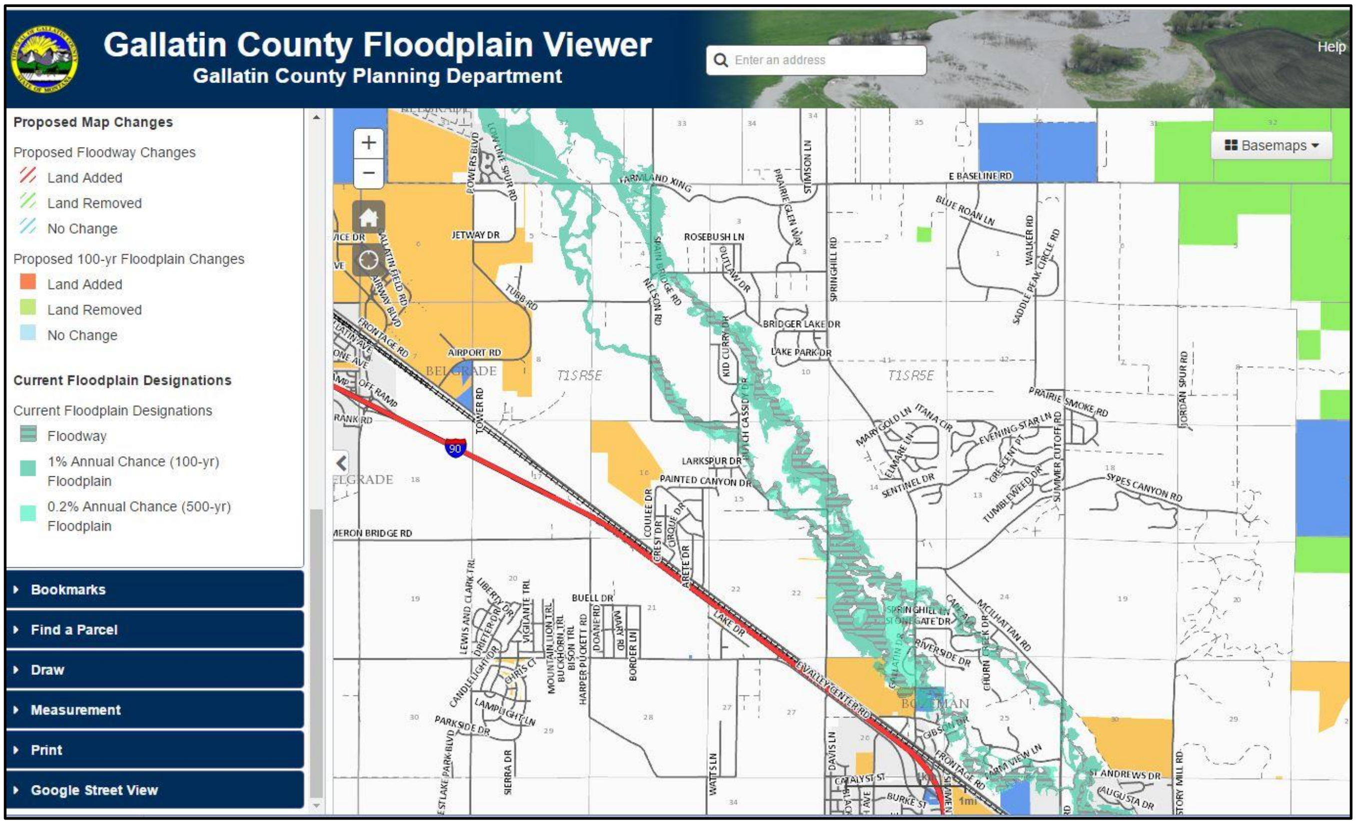


Figure 6. Example floodplain mapping for East Gallatin River between Bozeman and Belgrade (gis.gallatin.mt.gov).

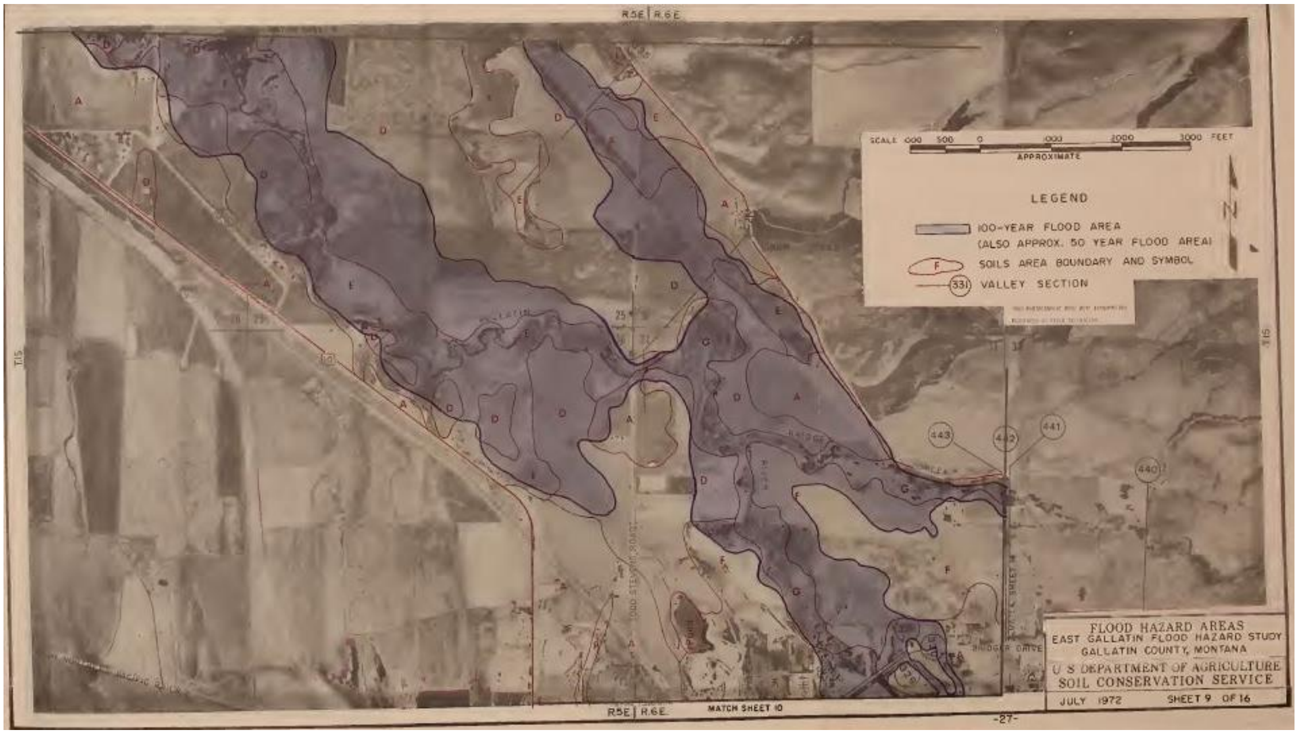


Figure 7. 1972 Floodplain mapping of East Gallatin river north of Bozeman --Manley Road is in center of map (SCS, 1972).

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/). Historically, 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 East Gallatin River as having 10 reported ice jams (Figure 8). No additional information was available regarding the timing, location, or severity of these jams.

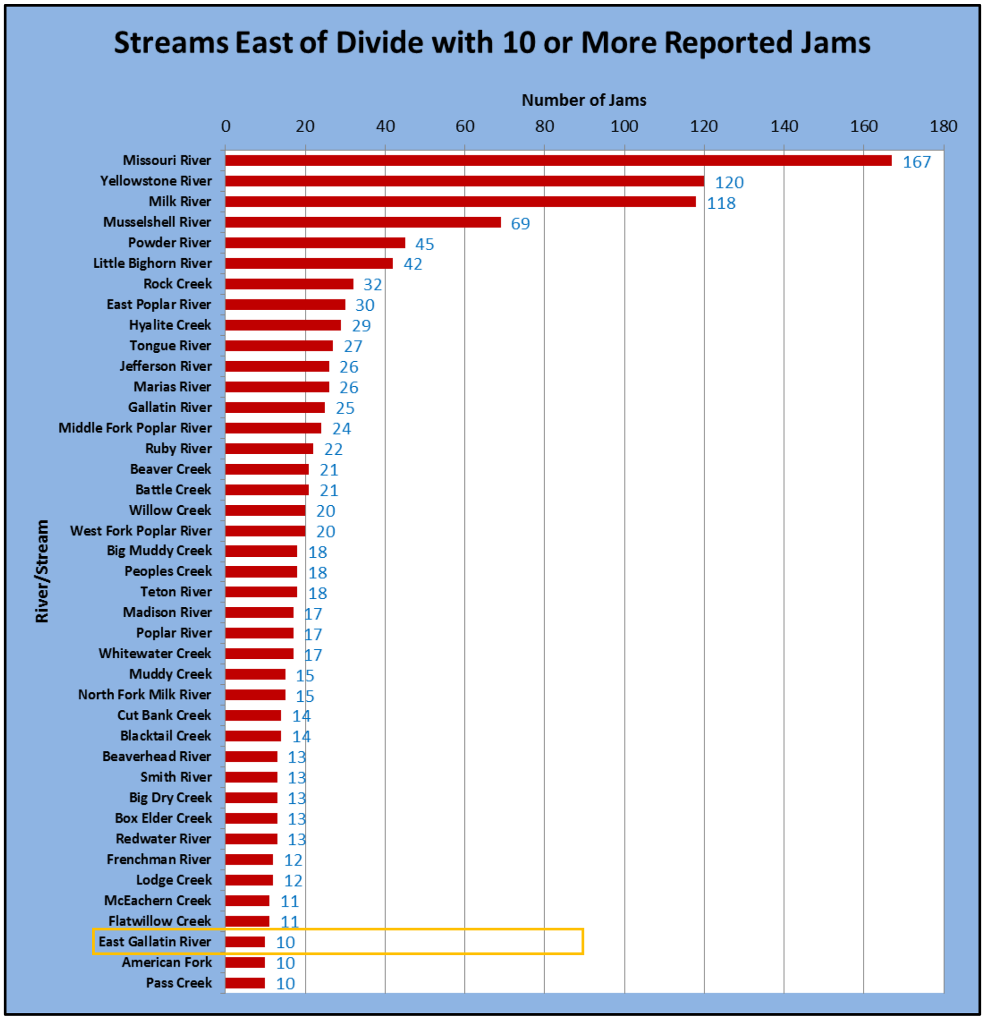


Figure 8. Montana rivers east of the continental divide with 10 or more reported ice jams.

1.6.3 Landslides

Although there are no mapped landslides adjacent to the East Gallatin River in the project area, landsliding in the upper watershed could impact stream process in the project reach by impounding and then releasing massive volumes of water and sediment.

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).

A similar risk occurred in the East Gallatin watershed when Mystic Lake Dam was constructed in 1903-1904 on the site of an approximately 100-year old landslide near Mount Ellis southeast of Bozeman. The dam leaked excessively during its lifetime and generated stability and safety concerns. In 1984 the approximately 40-foot tall earthfill water supply dam for the City of Bozeman was breached in response to the U.S. Dam Safety Program (Schuster, 2006).

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

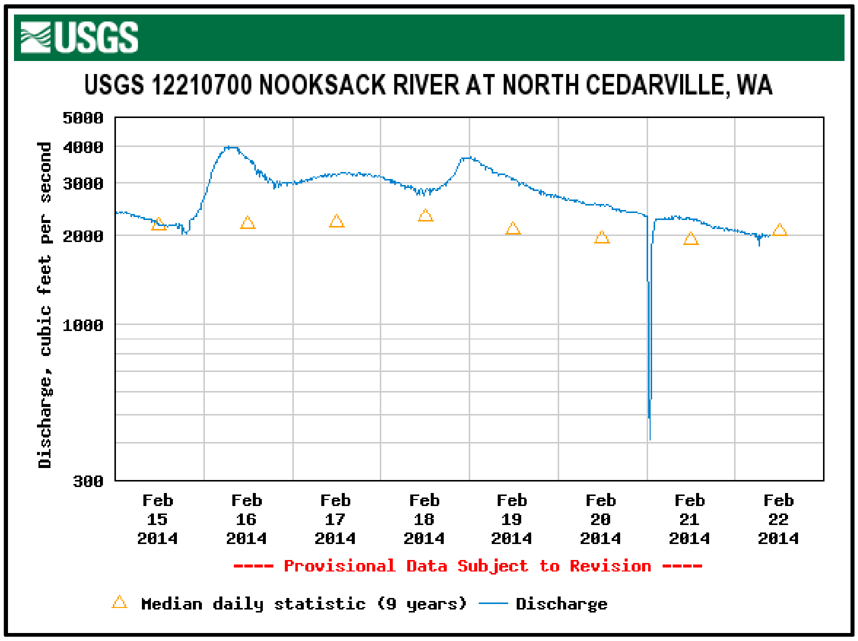


Figure 10. USGS gage data showing rapid drop in river flow following upstream hillslope failure.

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 East 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 East Gallatin River, to characterize the general setting and highlight how that setting may affect river process.

2.1 Geography

The East Gallatin River in southwest Montana is the only major tributary of the Gallatin River (Figure 12). The East Gallatin River begins about a mile north of downtown Bozeman, Montana, where the tributaries of Bridger Creek, Rocky Creek, and Bozeman Creek join. From the Bridger Creek/Rocky Creek confluence, the river flows 41.5 miles westward to its confluence with the Gallatin River north of Manhattan. In 1965, the river length over the same valley distance was about 2.5 miles less, as several sections of stream that were channelized prior to 1965 have since regained length. The watershed is about 642 square miles (including the contributing areas of Bridger, Bozeman, and Rocky Creeks), or 5% 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 a mixture of public and private land, while the land surrounding the river is largely private.

The East Gallatin is a popular trout fishery. Starting with Thompson Spring Creek at Dry Creek Road north of Belgrade numerous spring creeks flow parallel to and join the river. Between Dry Creek Road and the Gallatin River confluence, numerous other spring creeks supply flow to the main channel, including Ben Hart Creek, Bull Run Creek, and Smith Creek. Numerous landowners have completed fisheries enhancement projects on the East Gallatin River and its tributaries. The river gained national interest in 2009 when President Barak Obama fished the river with local guide Dan Vermillion (Figure 13).

The East Gallatin has been described as a “small meadow river” due to its passage through agricultural lands and relatively small size that typically won’t support a drift boat. Land ownership along the stream corridor is almost entirely private, although there are two public fishing access sites.

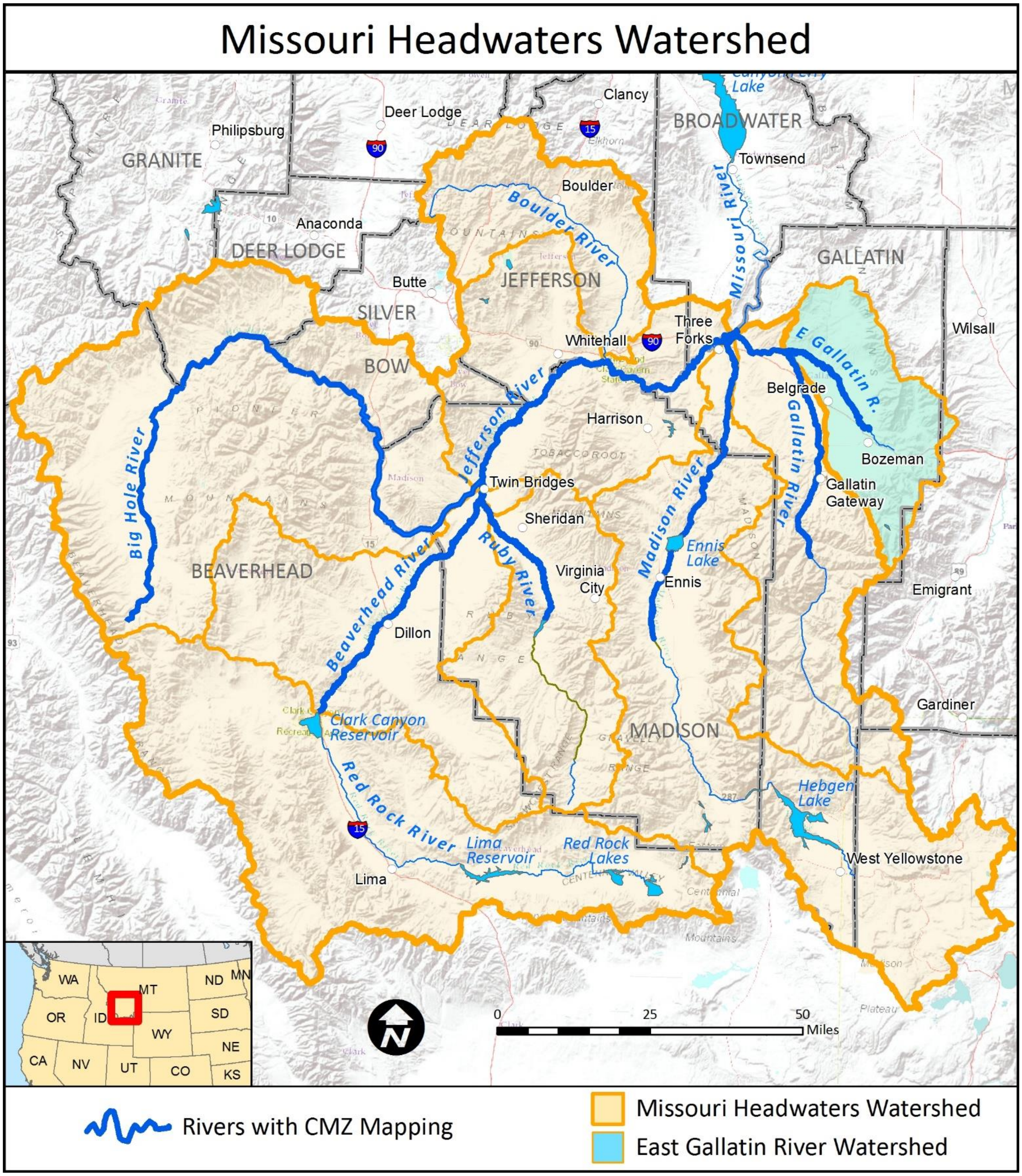


Figure 12. East Gallatin River Watershed.

Figure 13. Barak Obama fishing the East Gallatin in August 2009 (Pete Souza photo).

William Clark described the East Gallatin River in July of 1806 as he came up the river from Three Forks, on his way east over Bozeman Pass and to the Yellowstone. He repeatedly describes a multi-thread system with vast beaver complexes that impeded his travels. His journal from July 14, 1806 includes the following description of his journey up the Gallatin and East Gallatin River from Three Forks (University of Nebraska):

> *At 6 miles I Struck the river and crossed a part of it and attemptd to proceed on through the river bottoms which was Several Miles wide at this place, I crossed Several chanels of the river running through the bottom in defferent directions. I proceeded on about two miles crossing those defferent chanels all of which was damed with beaver in Such a manner as to render the passage impracticable and after Swamped as I may Say in this bottom of beaver.*

Later in this journal entry Clark describes the East Gallatin River as having "emence quantities of beaver".

2.2 Geology

The following summary of the geological setting of the project reach is intended to provide some context as to how the physical setting influences river process.

The Gallatin Valley is bounded on the north, east, southeast, and southwest by uplifted mountain ranges. The western margin is formed by the Madison Plateau. The thickness of the valley fill deposits is reportedly up to 6,000 feet in some areas, although on the MSU campus, bedrock has been encountered ad a depth of about 25 feet (English, 2007). For the majority of the project reach, the river flows within a broad, low elevation floodplain made up of recent stream deposits. This thread of active river deposits flows with in valley floor deposits 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. Near the Cherry River Fishing Access Site and Bozeman Water Treatment Plant, the river abuts an older braid plain terrace that is higher and more erosion resistant than the younger deposits. Similarly, downstream of the Dry Creek confluence the river flows against the toe of the Horseshoe Hills, encountering both alluvial fan deposits and the very old Proterozoic rocks of the LaHood Formation, which is a conglomerate that has been described as having clasts (embedded pieces of rock) that are up to 12 feet in diameter (Vuke et al, 2014).

2.3 Hydrology and Flow Management

The hydrology of the East Gallatin River reflects a typical snowmelt system, with peak flows occurring in late May or early June. At the USGS Gaging station below Bridger Creek (USGS 06048700), the highest average daily flow between 2001 and 2014 was 572cfs on May 20 (Figure 14). The runoff season tends to extend from April through June, with consistent flows of about 50 cfs for the remainder of the year.

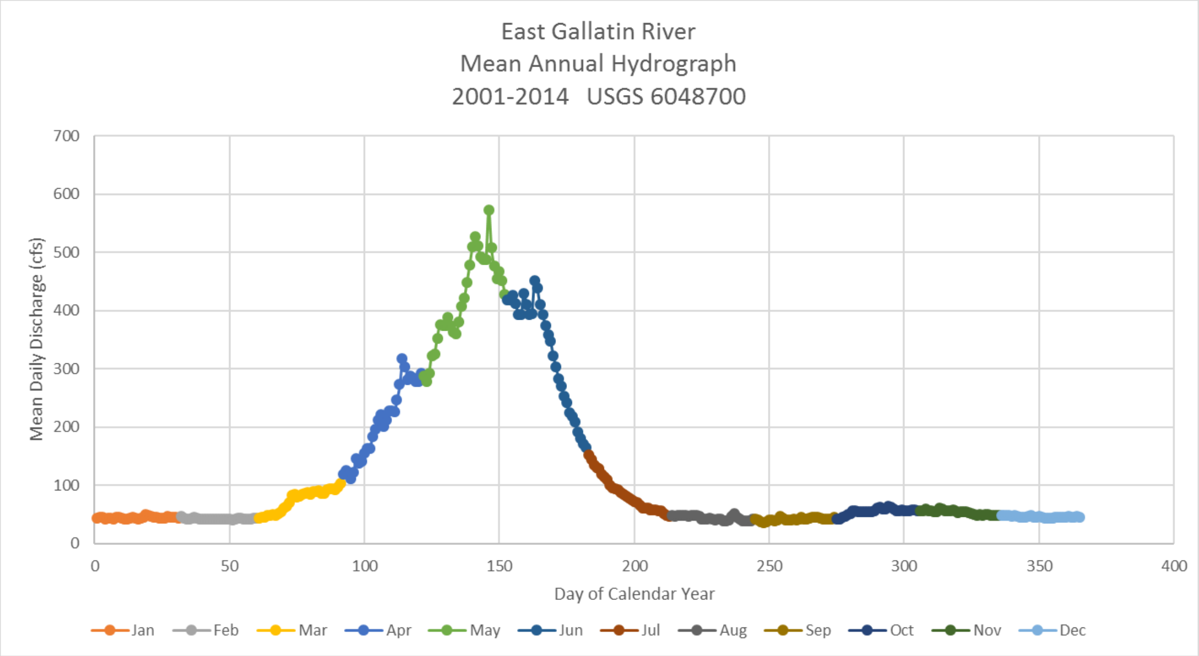


Figure 14. Mean annual hydrograph for East Gallatin River above the Water Treatment Plant (USGS 6048700).

2.3.1 Major Diversion Structures

The Montana Department of Natural Resources and Conservation Water Rights data show 52 headgate points of diversion listed for the East Gallatin River within the study area. None of these structures are major or span the entire river channel. As such, there is not an extensive network of ditches or canals being fed from the East Gallatin River.

Between Bridger Creek and Middle (Hyalite) Creek, six ditches that divert streamflow from the main Gallatin River contribute recharge to the East Gallatin. Concern has been raised that alterations in water use from the main Gallatin River could affect East Gallatin streamflows and aquifer recharge; these east side diversions from the mainstem Gallatin River have a combined water right of 802 cubic feet per second (cfs) (RESPEC, 2014).

2.3.2 East Gallatin River Flood History

Flooding on the East Gallatin River is typically caused by snowmelt that is accelerated by rainfall. The USGS flood record for the East Gallatin River is discontinuous, with some measurements prior to 1960, a single historic peak in 1981, and another 12 years of measurements from 2002-2014. The pre-1960 flows are from an old gage upstream of Bridger Creek, so that record does not capture all flows in the East Gallatin. Other sources have reported additional floods. Available flood information from various sources is shown in Figure 15 and a summary of major floods is summarized in Table 1. The flood frequencies shown are from a FEMA flood study (FEMA, 2011) that summarized flood frequencies for the East Gallatin River at Airport Road. There is some discrepancy between FEMA flood frequencies curves and flood narratives, so results should be considered approximate.

The documented flood of record occurred May 22, 1981, when the East Gallatin peaked at 2,460 cfs, probably reaching about a 30 year event. Gallatin County was one of nine counties declared a flooding disaster area that year (Bozeman Daily Chronicle, 1997). According to FEMA, the second largest flood on the East Gallatin River probably occurred in 1997, although the peak flow was not recorded for that event. The next largest recorded peak flood was the “Mother’s Day Flood” of May 28 2008, when the gage at the Water Treatment Plant north of Bozeman recorded 1,900 cfs. The current flood frequency curves indicate that this was just over a 10-year flood, although the DNRC describes it as a 21-25 year event (DNRC.gov). DNRC collected numerous photos from a helicopter during that event, which shows extensive flooding around residences north of Bozeman (Figure 16).

A 1972 Flood Hazard Analysis performed by the Soil Conservation Service (SCS, 1972) documents two other major floods not captured in the USGS gage record. They occurred in 1970 (1,900 cfs) and 1971 (2,100 cfs), and each exceeded a 10-year event. These floods evidently occurred “back-to back” (SCS, 1972). Photos of these two events, with the data and estimated frequency of occurrence as reported by the SCS are shown in Figure 17 and Figure 18.

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

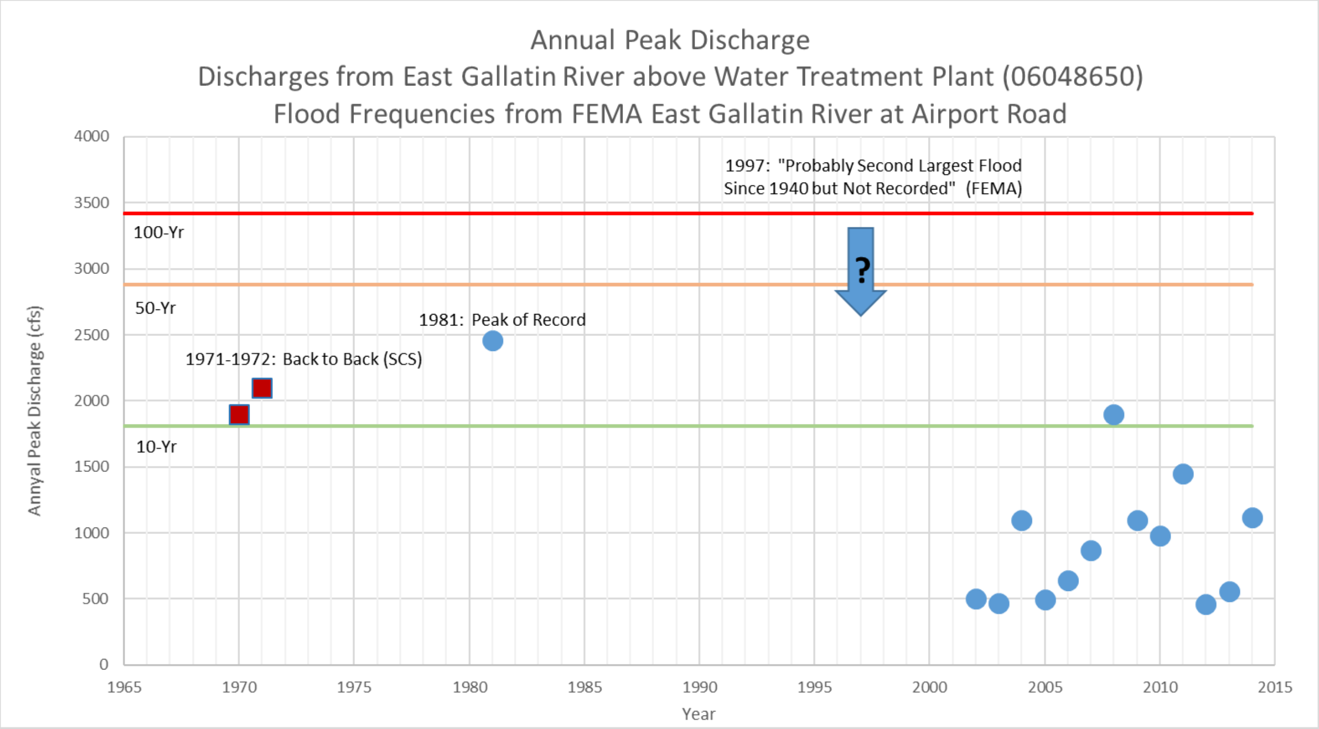


Figure 15. Annual peak flow record, East Gallatin River above Water Treatment Plant (USGS 06048650) showing flood frequencies for East Gallatin River at Airport Road (FEMA, 2011).

Table 1. East Gallatin River flood history.

Major Floods	Discharge	Flood Frequency Based on USGS	Notes
1981	2,460	>30 year	Measured as Historic Flood
1997	?	?	Unmeasured-- "probably second largest since 1940 but not recorded" (FEMA, 2011)
1971	2,100	>10 year	SCS Report—Described as “35 year frequency”
2008	1,900	>10 Year	Mother's Day Flood—DNRC Described as “21-25 Year Event”
1970	1,900	>10 Year	SCS Report—Described as “10-year frequency”

Figure 16. East Gallatin River Flooding, May 2008 (MT DNRC).

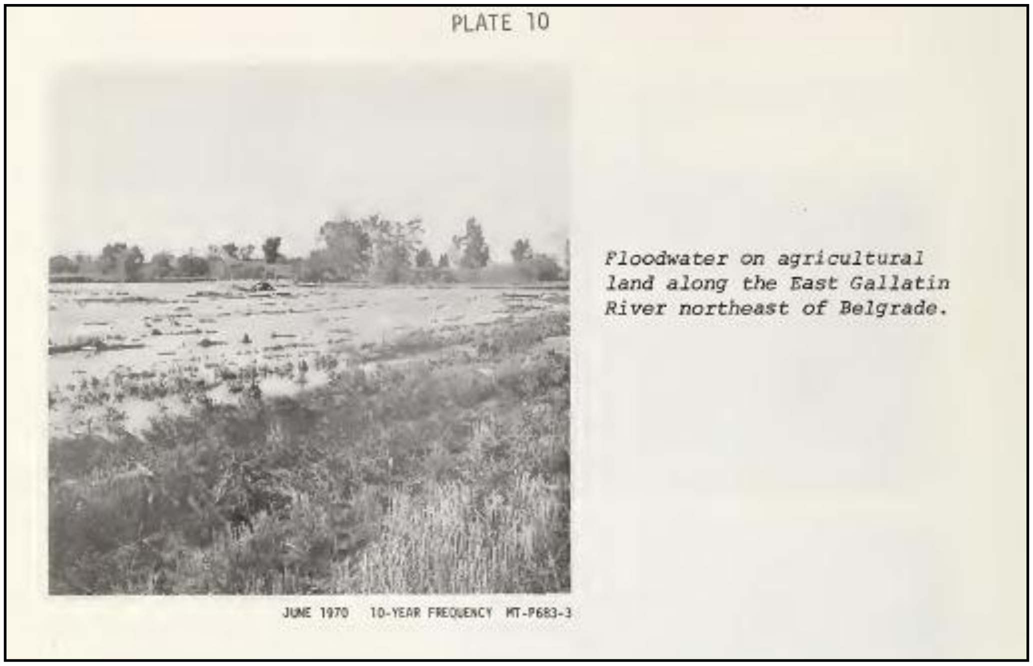


PLATE 10

Floodwater on agricultural land along the East Gallatin River northeast of Belgrade.

JUNE 1970 10-YEAR FREQUENCY MT-P683-3

Figure 17. June 1970 flood, East Gallatin River (SCS, 1972).

APRIL 1971 35-YEAR FREQUENCY SCS PHOTO

Area flooded by a record event. Lesser floods also inundate portions of this area.

Figure 18. April 1971 flood, East Gallatin River (SCS, 1972).

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. No dikes or levees were mapped in the East Gallatin Stream corridor. FEMA (2011) describes a minor flood control structure adjacent to the East Gallatin River at Riverside Country Club north of Bozeman, but note that “the structure does not provide flood protection against the 1-percent [100-year flood] annual chance flood event.”

2.5 Bank Armor

Bank armor was mapped where visible on air photos, Google Earth, or oblique photographs. This mapping was supplemented with a 2005 ground inventory of the East Gallatin River from the East Gallatin Recreation Area, downstream to approximately Airport Road (Sagari, 2005). 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 East Gallatin River, we mapped 4.5 miles of bank armor which covers about 8% of the total bankline. The bank armor consists of rock riprap, barbs, car bodies, concrete rubble, and other revetments such as bioengineered wood structures.

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

2.6 Transportation Infrastructure

Seventeen bridges span the entire primary channel within the project area. These include 14 road bridges and three small bridges associated with the Riverside Country Club golf course. The bridges are dispersed along the river's length. These bridges and their associated approaches locally constrict the CMZ, and they are commonly armored to manage alignment of the river through the structure (Figure 19).

Figure 19. Right bank armor associated with the Dry Creek School Road bridge approach. (Kestrel)

2.7 Channelization

One fairly unique aspect of the East Gallatin River relative to other rivers of the Upper Missouri system is the extent to which it was historically straightened in support of floodplain agriculture and development. Channelization is essentially the process of shortening a meandering stream by excavating a straight channel through the core of the meanderbelt, or along some other shorter route. Channelization is well-known for creating unintended consequences of stream destabilization due to channel oversteepening and flow concentration, both of which greatly increase in-stream energy and erosion potential. Figure 20 shows examples of two channelization on the East Gallatin River. The 1965 image on the left captures recent channelization at what is now the Outlaw Subdivision east of Belgrade, and the image on the right documents post-channelization erosion and lengthening a short distance below the Bozeman Water Treatment Plant.

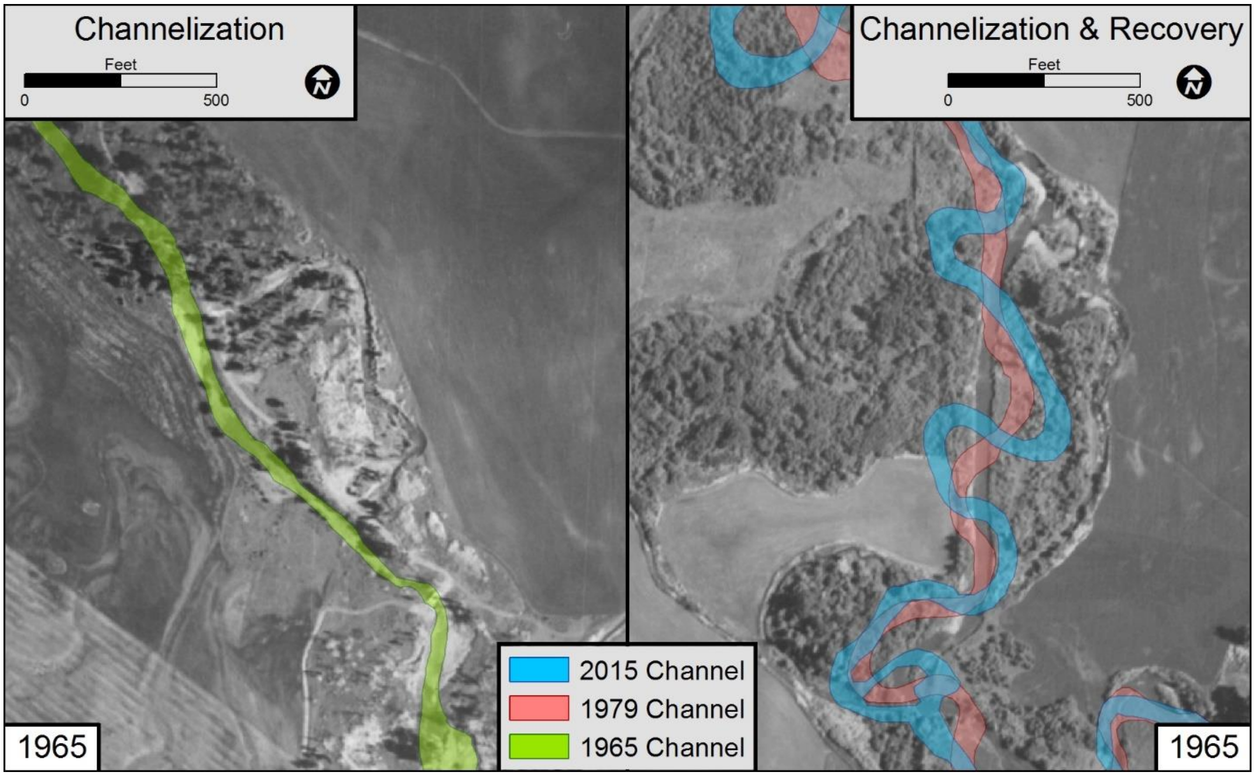


Figure 20. Channelization on East Gallatin River, showing active channelization (left) and post-channelization lengthening (right).

3 Methods

The development of the East 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 East 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 47 individual images were ordered from the APFO to cover two time periods for the Gallatin River. There is some common imagery between the Gallatin and East Gallatin Rivers where they join at north of Manhattan.

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 21 through Figure 24.

Table 2. Aerial photography used for the East 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). 1980 images between ~Swamp Rd and Spaulding Bridge Rd.
2013 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)
2015 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)

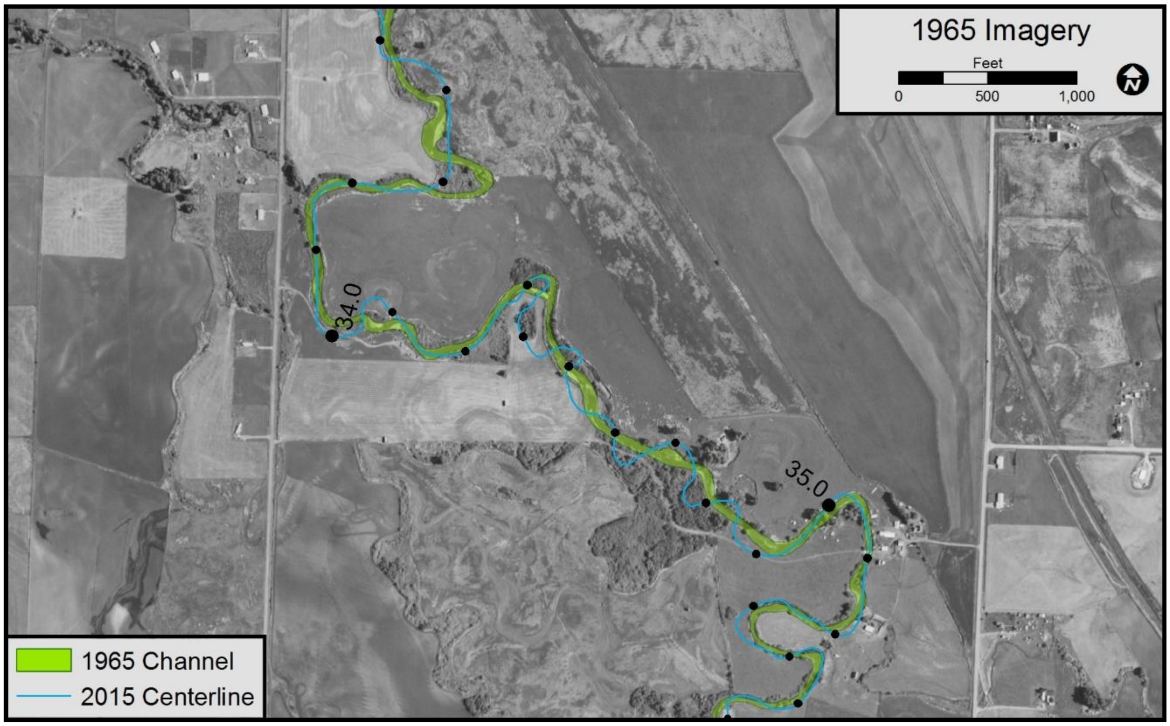


Figure 21. Example 1965 imagery between Springhill and Nelson Roads, East Gallatin River CMZ development.

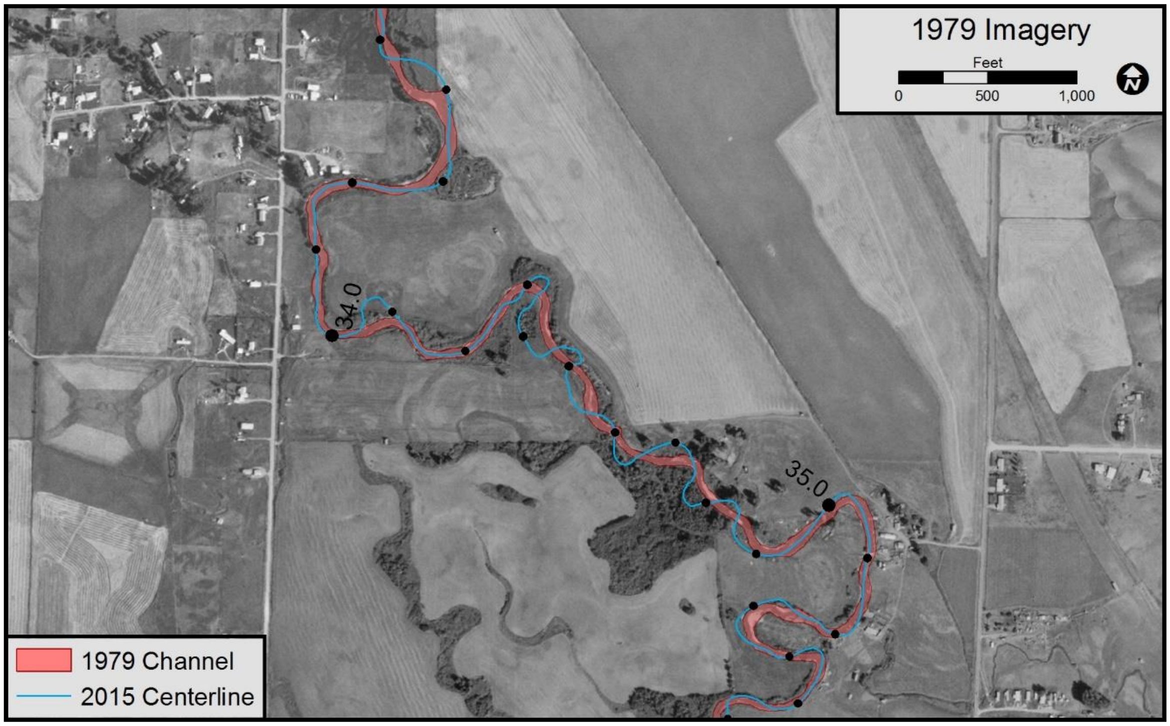


Figure 22. Example 1979 imagery between Springhill and Nelson Roads, East Gallatin River CMZ development.

Figure 23. Example 2013 NAIP imagery between Springhill and Nelson Roads, East Gallatin River CMZ development.

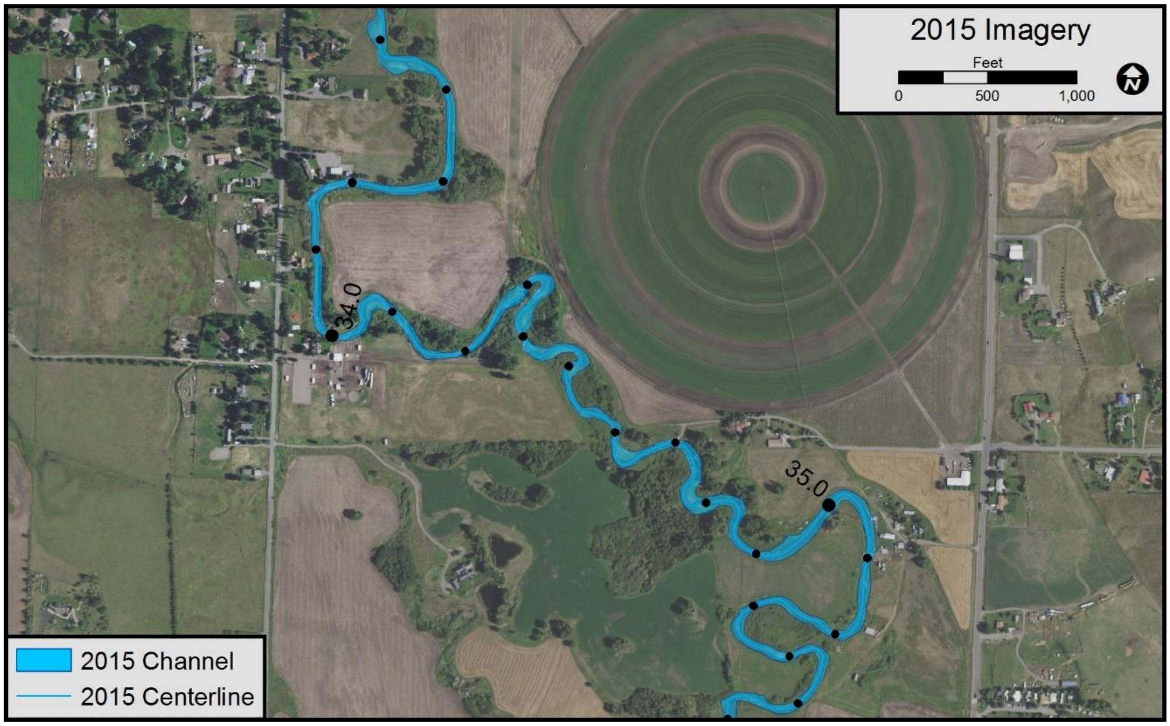


Figure 24. Example 2015 NAIP imagery between Springhill and Nelson Roads, East Gallatin River CMZ development.

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 East 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 60 feet (Figure 25). A total of 1,105 migration vectors were generated for the East 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 14 migration vectors, depending on the length of the site. A total of 288 migration sites were identified throughout the study area. An accounting of the reach and site based statistics can be found in Appendix A.

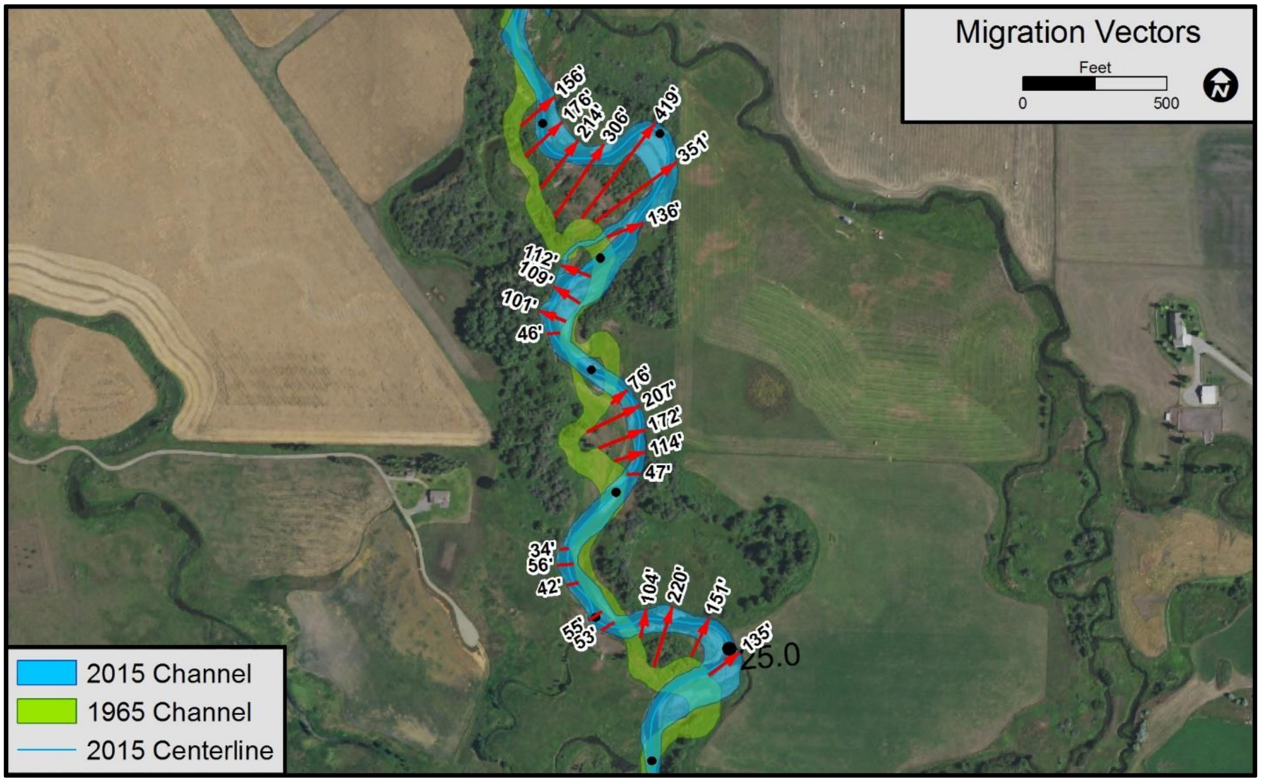


Figure 25. Example of migration measurements between 1965 and 2015 (migration distance in feet).

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 inundation potential based on relative elevation. This can be used to approximate flood prone areas, but it also is a useful tool for identifying low topographic features or channels that may pose an avulsion risk.

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

Additionally, the accuracy of an inundation model is directly related to the quality of the elevation data. While high-resolution LiDAR data provides the best results, modeling using 10-meter USGS National Elevation Dataset (NED) still provides sufficient resolution to identify broad trends in the floodplain. For the East Gallatin River study area, inundation modeling was generated using the NED dataset (Figure 26), except in the confluence area with the Gallatin River, where LiDAR elevation data were available (Figure 27).

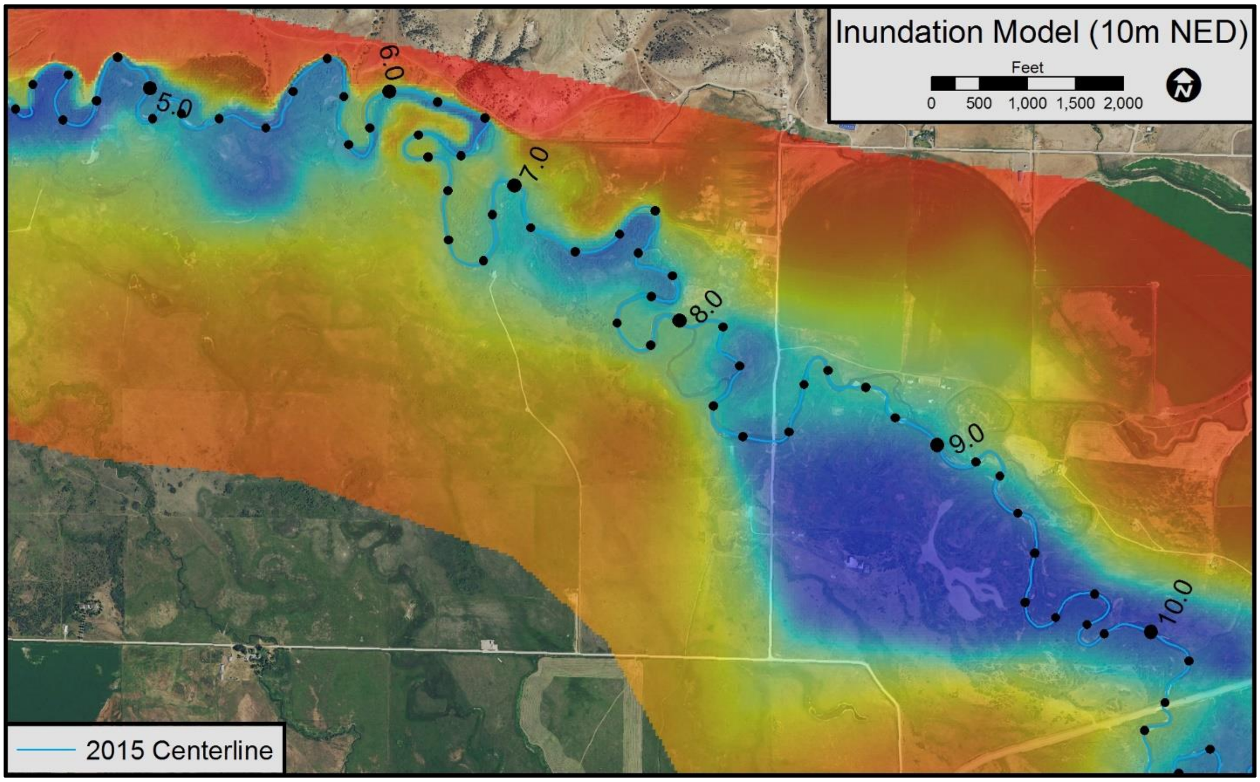


Figure 26. Example Inundation Modeling results using 10m DEM at Spaulding Bridge Road. Colors represent elevations relative to the water surface elevation of the main channel. Dark blue areas are equal to or lower than the channel. Yellows and reds are significantly higher than the adjacent main channel.

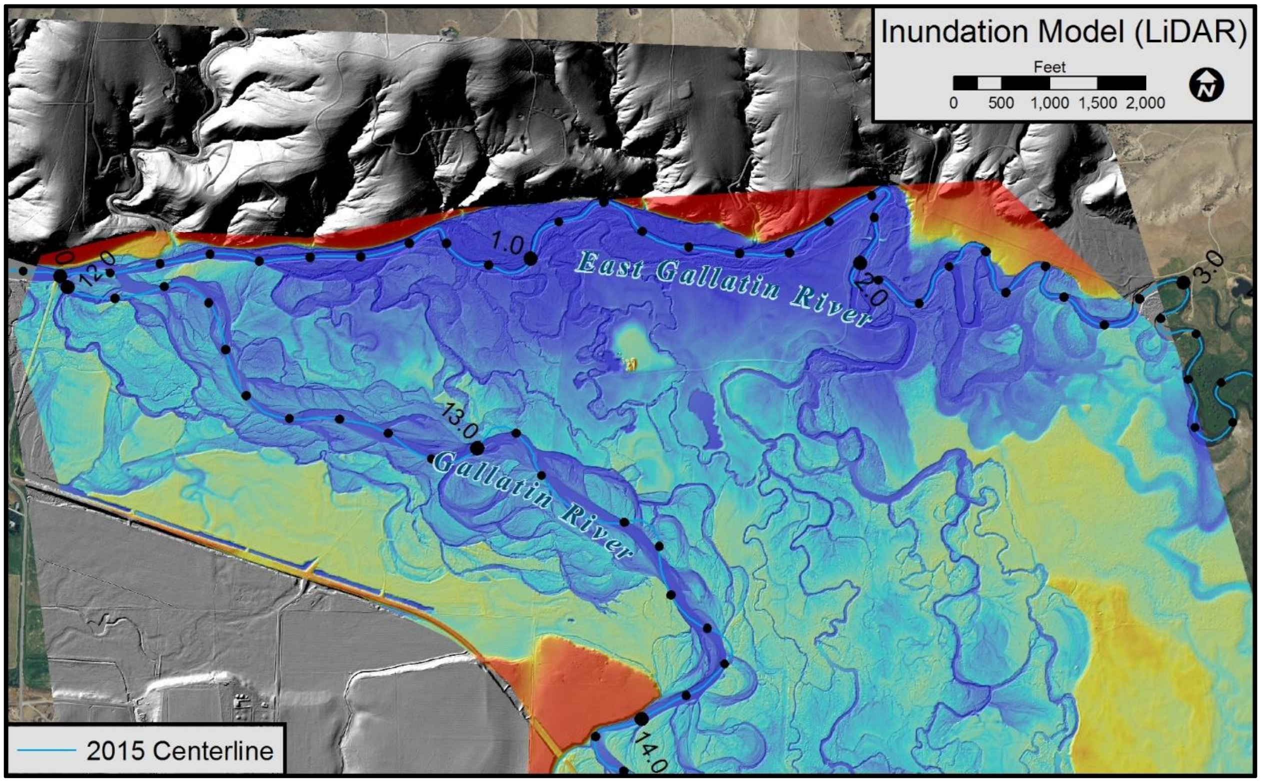


Figure 27. Example Inundation Modeling results using LiDAR elevation data at the Gallatin River confluence. Colors represent elevations relative to the water surface elevation of the main channel. Dark blue areas are equal to or lower than the channel. Yellows and reds are significantly higher than the 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 East 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.

The East Gallatin River is a highly sinuous stream that has experienced dozens of avulsions since 1965. Most of those avulsions were in areas where sinuous channel segments cut off one or several bendways, straightening the channel onto a steeper flow path. Using that pattern of recorded avulsions, additional potential avulsion pathways were identified and incorporated into the CMZ (Figure 28). Additional information used in mapping avulsion paths included oblique photos from Kestrel Aerial Services.

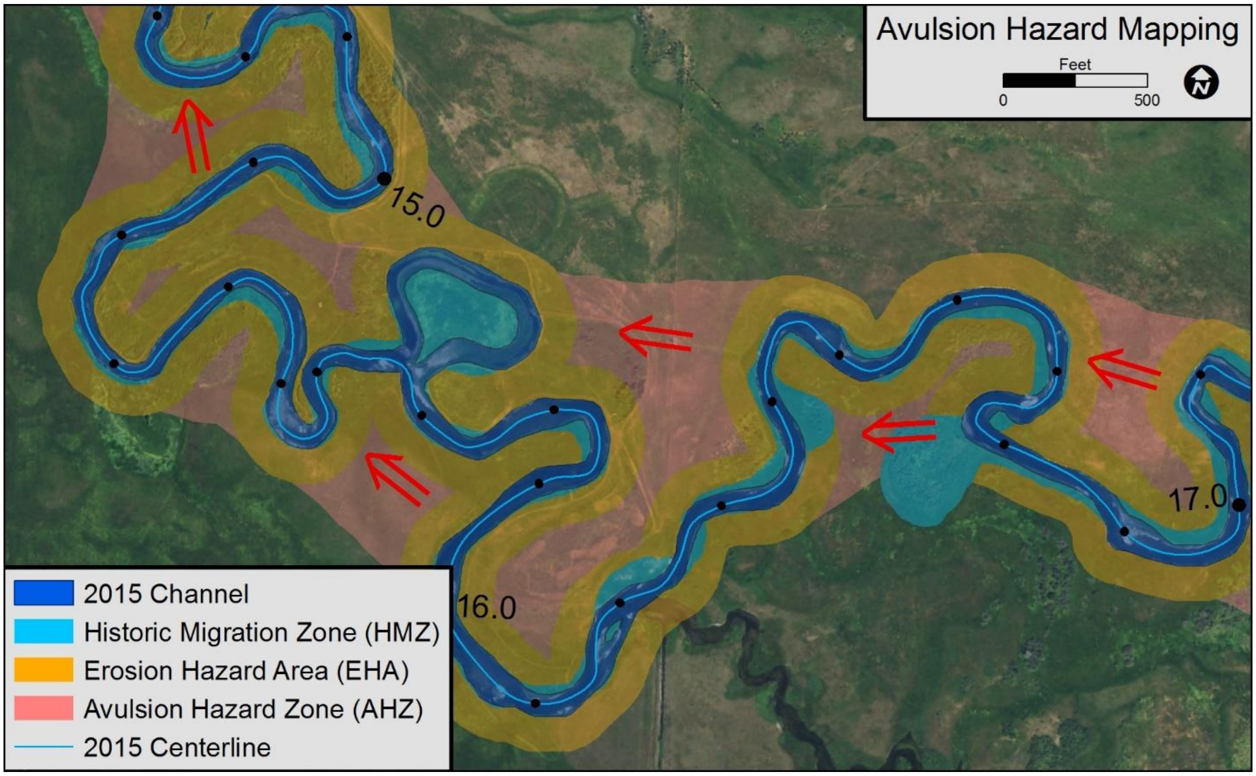


Figure 28. Example sinuous channel with multiple avulsion pathways.

4 Results

The Channel Migration Zone (CMZ) developed for the East 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 41.4 miles of project length, the river was broken into seven reaches based on geomorphic character such as river pattern, rates of change, geologic controls, and channel slope (Figure 34)(Figure 29). The reaches range in length from 4.0 to 11.6 miles (Table 3). Major geographic features are identified by River Mile in

Table 4.

Table 3. East Gallatin River reaches.

Reach	General Location	Upstream RM	Downstream RM	Length (mi)
EGR1	Bluff Line to Mouth	6.7	0.0	6.7
EGR2	Dry Creek School Road to Bluff Line	11.3	6.7	4.6
EGR3	Above Thompson Spring Creek to Dry Creek School Road	22.9	11.3	11.6
EGR4	Middle Creek to just above Thompson Spring Creek	27.6	22.9	4.7
EGR5	Outlaw Subdivision to Middle Creek	31.6	27.6	4.0
EGR6	Springhill Road to Outlaw Subdivision	37.6	31.6	6.0
EGR7	Bridger Creek/Rocky Creek to Springhill Road	41.4	37.6	3.8

Table 4. River Mile locations of major geographic features.

RM	Feature
40.2	Manley Road
37.6	Springhill Road
33.8	Buster Gulch
29.5	Airport Road
29	Spain Bridge Road
27.6	Middle Creek
26.2	Penwell Bridge Road
24.1	Hamilton Road
20.8	Dry Creek Road
13.7	Swamp Road
11.3	Dry Creek School Road
10.2	West Dry Creek Road
8.5	Spaulding Bridge Road
0	Gallatin River

A large component of the reach delineation is channel slope. Figure 29 shows an abrupt steepening in channel slope starting about two miles upstream of Airport Road above the Outlaw Subdivision. The steep slope continues downstream to about Middle Creek. This anomalously steep channel segment defines Reach EGR5. Downstream, starting two miles above Dry Creek Road, there is a rapid reduction in channel slope as the channel gradient drops by about one half between Reach EGR4, continuing for the rest of the lower river. Slopes are plotted by reach in Figure 30. The reduction in channel slope above Dry Creek Road (EGR3/EGR4 boundary) is also associated by an increase in channel sinuosity (Figure 30), as the river transitions from a relatively steep and straight channel to a low gradient, highly sinuous, low-energy stream.

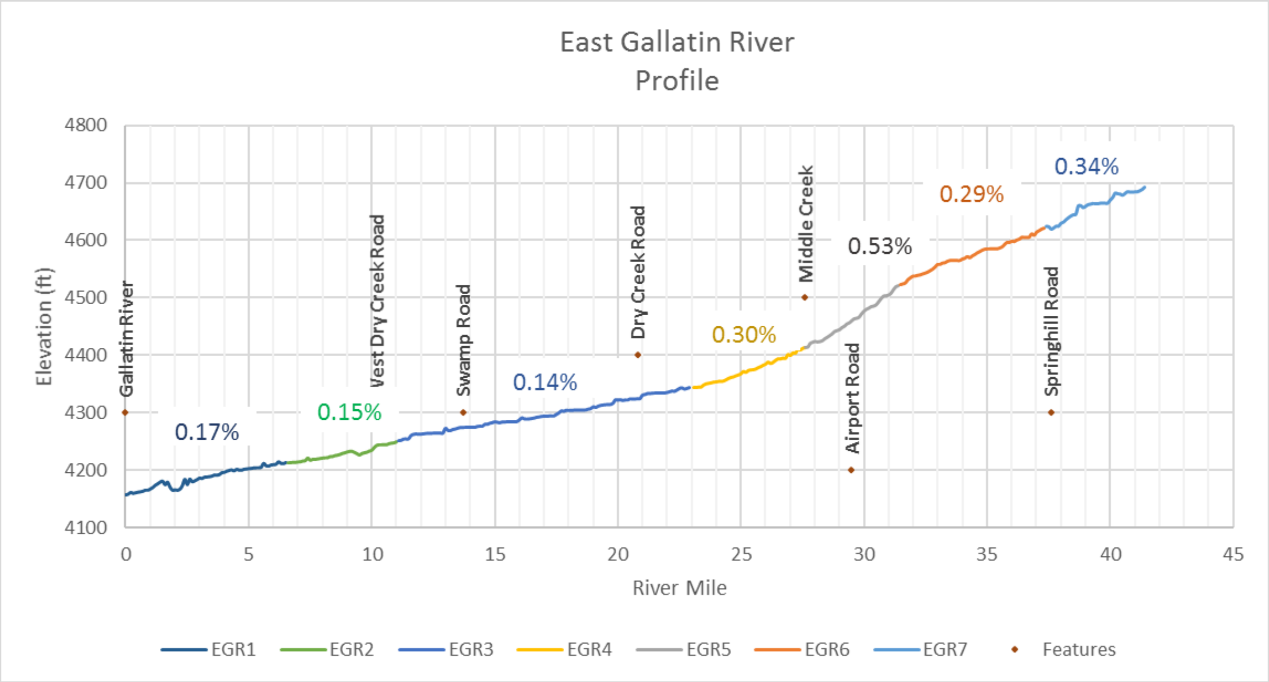


Figure 29. Plotted river profile showing average slope by reach.

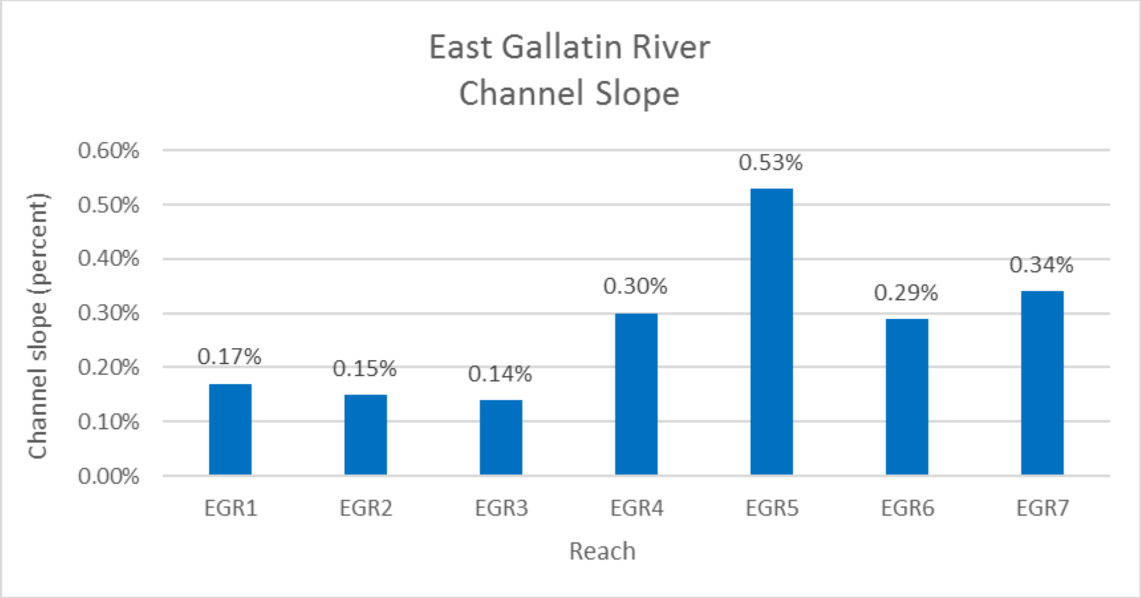


Figure 30. Average channel slopes by reach.

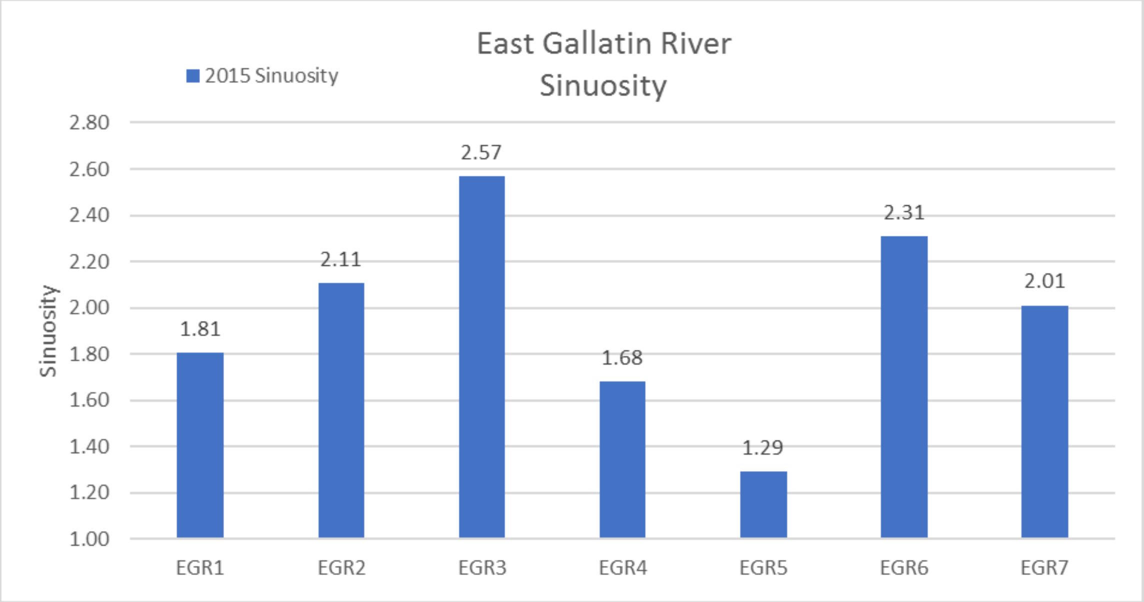


Figure 31. Reach-scale sinuosity (channel length/valley distance).

As described in Section 2.7, several sections of the East Gallatin River were channelized prior to 1965, and many of these channelized sections have since regained channel length through active migration (Figure 20). The extent of post-1965 channel lengthening is summarized by reach in Figure 32. Since 1965, the river has gained 2.5 miles in total channel length, which is about a 7% increase. The only reach to lose length in that time was Reach EGR5, which is the anomalously steep reach through and below the Outlaw Subdivision. This is also the straightest reach in the project area (Figure 31). The steep and straight condition in this section of river above Middle (Hyalite) Creek makes it especially prone to high energy conditions that can drive rapid erosion and avulsions.

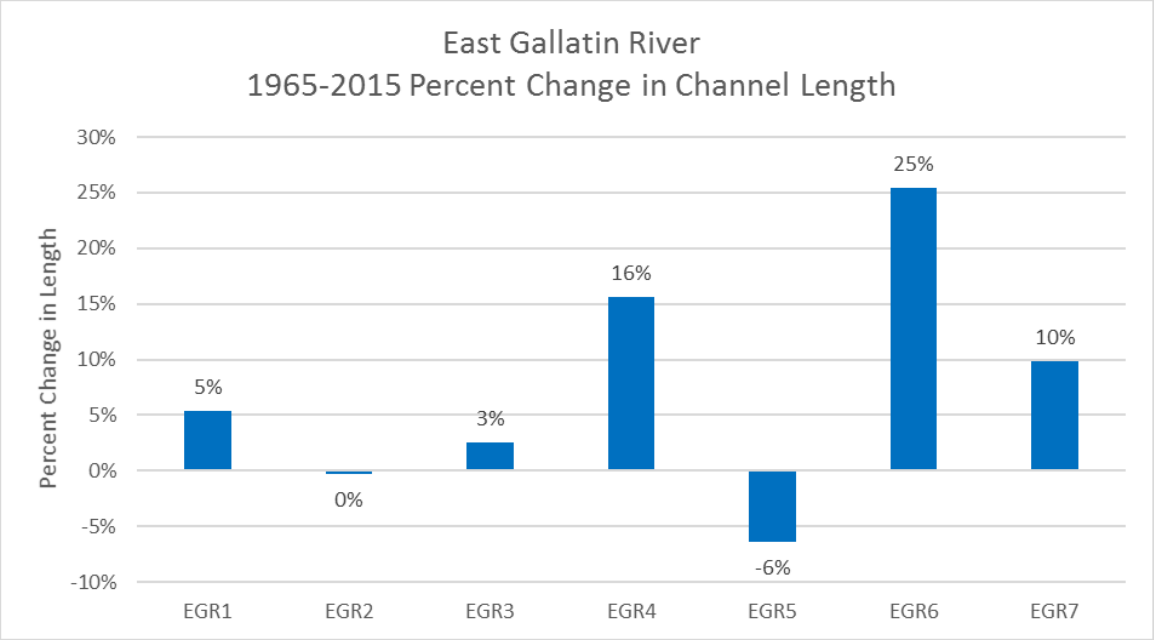


Figure 32. Percent change in total channel length showing extent of lengthening since 1965.

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 East 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 East Gallatin River channel locations in 1965, 1979, 2013 and 2015 (Figure 33). The resulting area reflects 50 years of channel occupation for the length of the East Gallatin River.

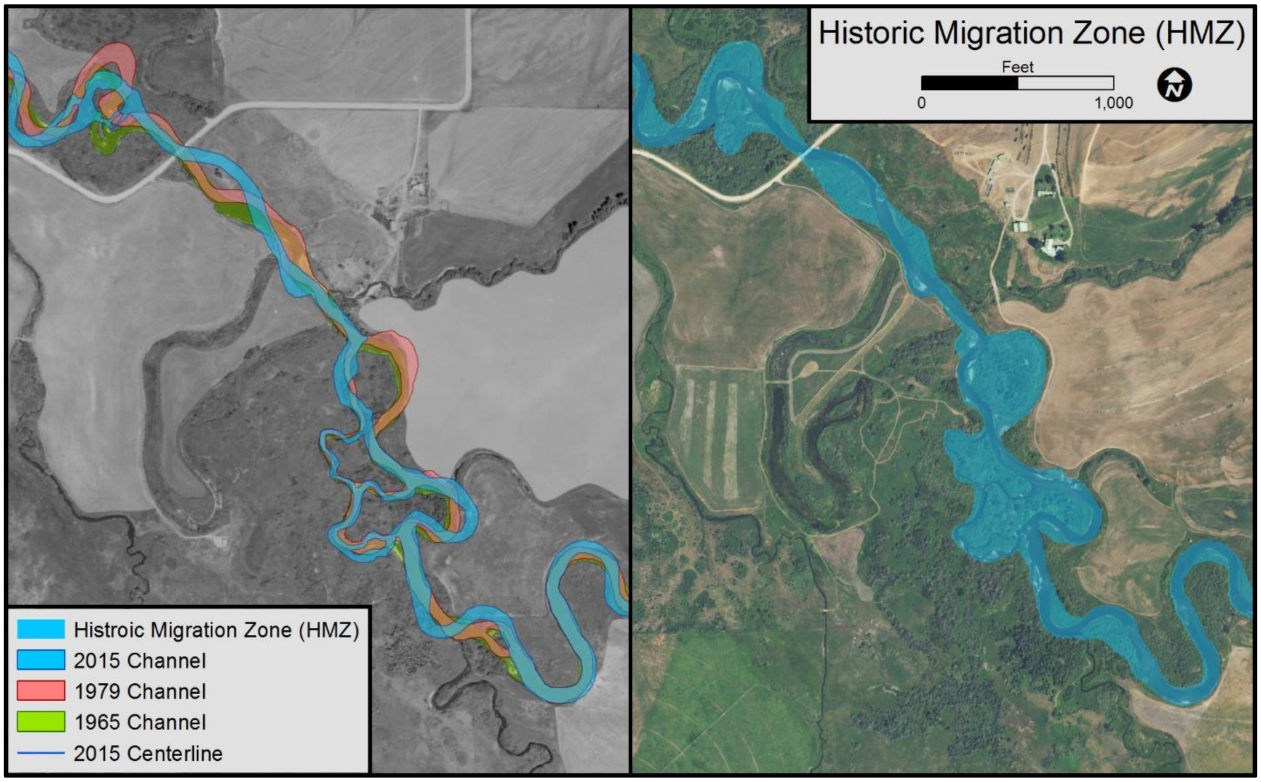
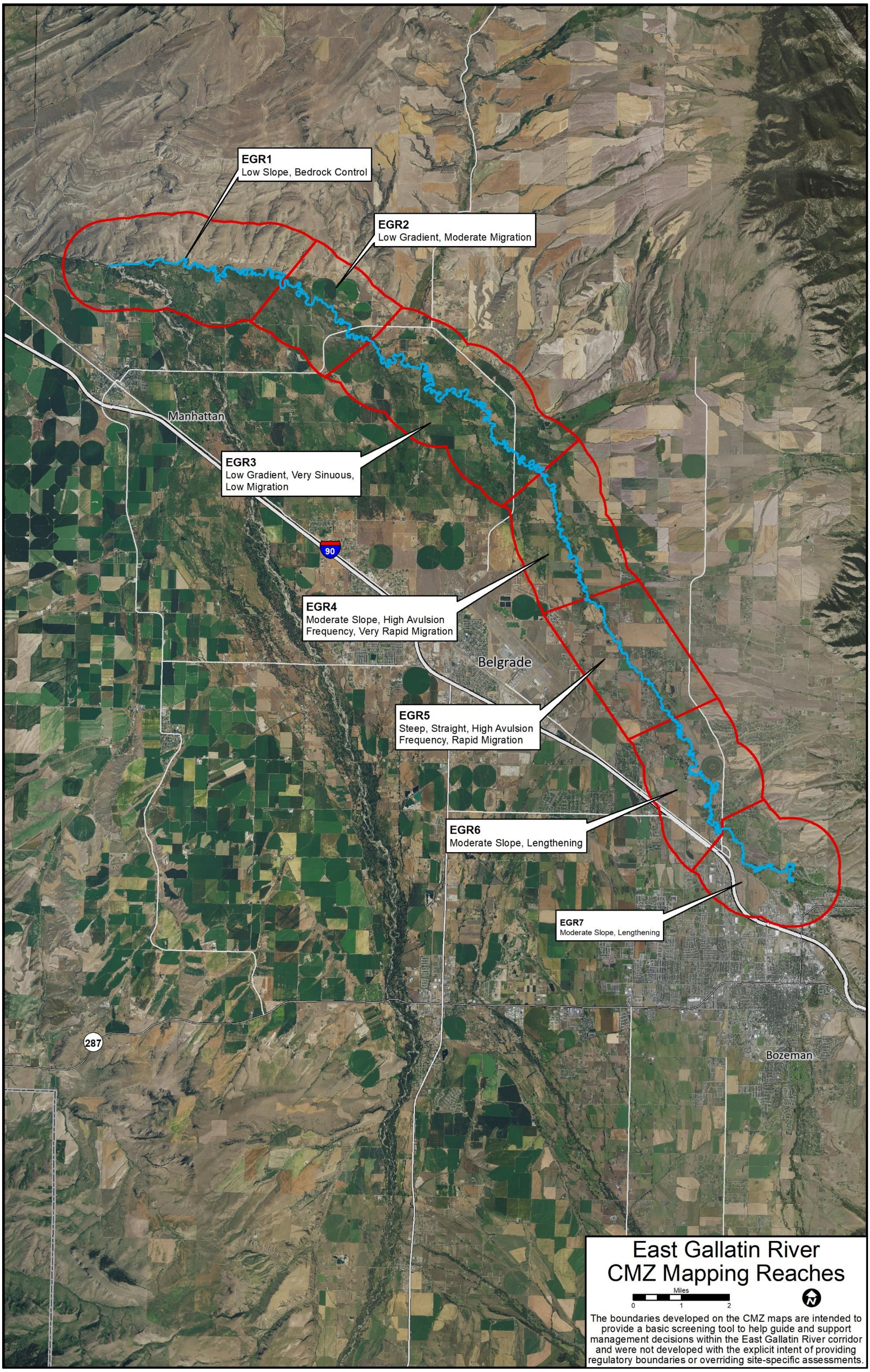


Figure 33. The Historic Migration Zone (HMZ) as shown at the mouth of Dry Creek is the combined footprint of all mapped channel banklines.



East Gallatin River
CMZ Mapping Reaches

The boundaries developed on the CMZ maps are intended to provide a basic screening tool to help guide and support management decisions within the East Gallatin River corridor and were not developed with the explicit intent of providing regulatory boundaries or overriding site-specific assessments.

Figure 34. East 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 1,072 measurements were collected on the East 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). The 1965-2015 measured migration distances are summarized in Figure 35. 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 5 and Figure 36. The buffer width is calculated as that distance the river would move over a century's time at the mean annual rate. The highest average migration rate is in Reach EGR4 below Middle Creek. Just downstream in Reach EGR3 rates drop significantly as the channel slope drops and the river becomes much more sinuous.

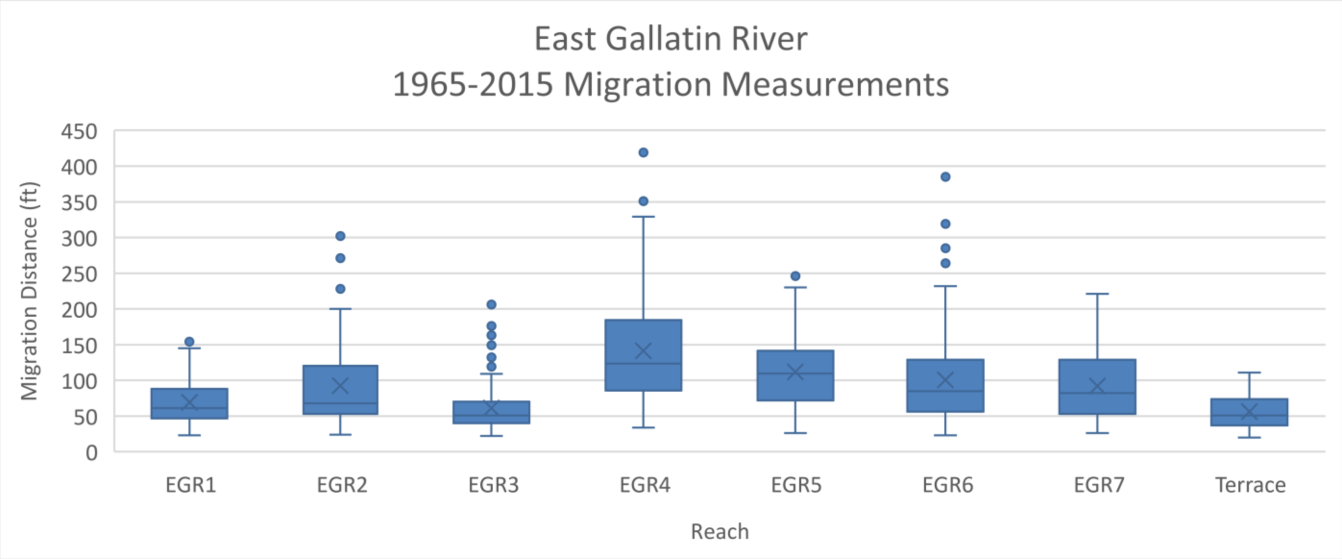


Figure 35. Box and whisker plot showing measured 1965-2015 migration distances by reach.

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 5 shows that in 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 5. Average migration rate and 100-year EHA buffer by reach, East Gallatin River.

Reach	Number of Measurements	Maximum Migration Distance (ft)	Average Migration Distance (ft)	Average Migration Rate (ft/yr)	Erosion Buffer Width (ft)
EG01	143	158	69	1.4	138
EG02	109	302	92	1.8	185
EG03	270	206	61	1.2	122
EG04	128	419	141	2.8	283
EG05	114	250	112	2.2	224
EG06	204	385	101	2.0	201
EG07	96	221	92	1.8	184
Terrace	8	141	91	1.8	112

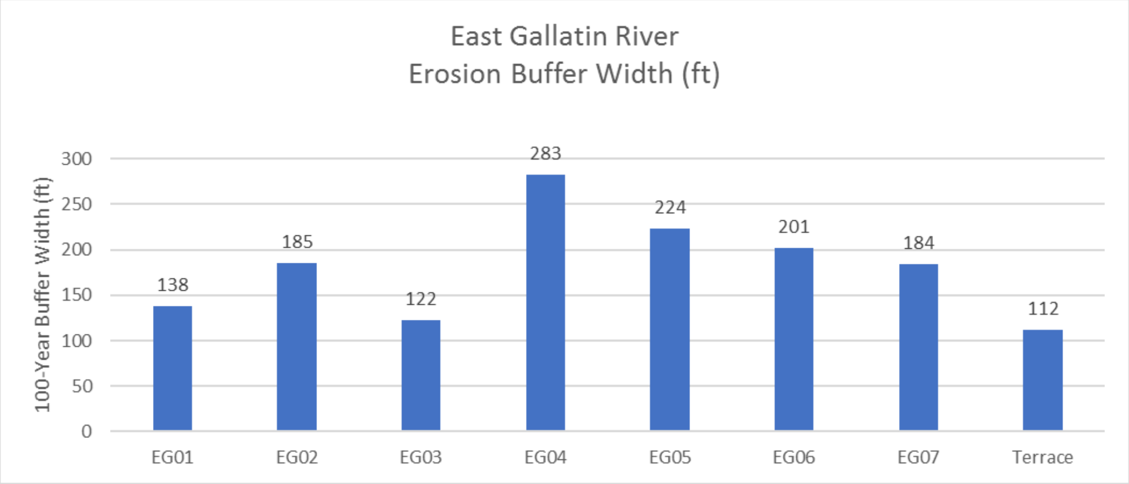


Figure 36. Mean migration rate-based EHA buffer width, East Gallatin River.

As the location and intensity of streambank erosion shifts with time, many streambanks that are currently stable will become erosion sites over the next century. Shifts in erosion patterns can sometimes be predicted in the short-term, however over decades the entire bankline becomes a potential erosion site. 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 37. 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.

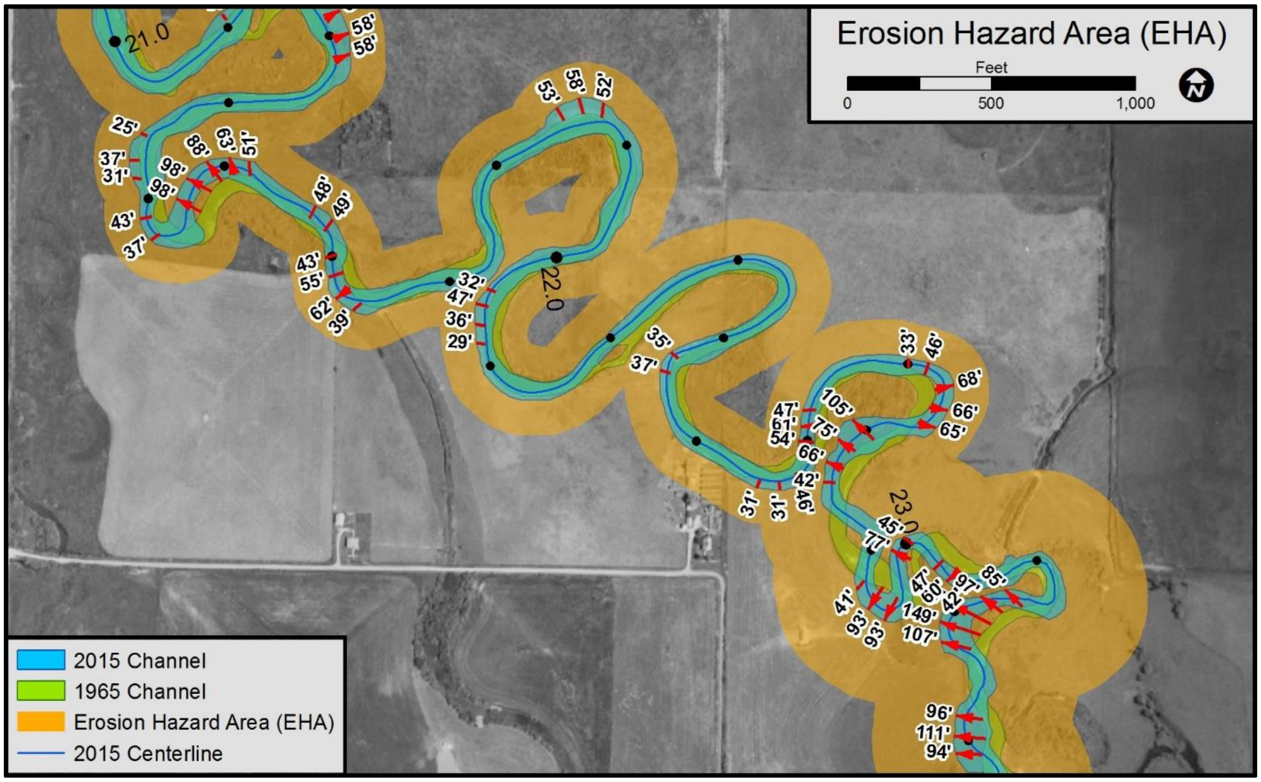


Figure 37. The Erosion Hazard Area (EHA) is a buffer placed on the 2015 banklines based on 100 years of channel migration for the reach.

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 East Gallatin River is moderately prone to avulsions. A total of 33 avulsions occurred on the East Gallatin River between 1965 and 2015, with occurrences in every reach (Figure 38). The highest concentration of avulsions occurred in reaches EGR4 and EGR5, which extends from the Outlaw Subdivision off of Nelson Road to Thompson Creek at Dry Creek Road (Figure 39). This downstream trend in avulsion frequency is consistent with a downstream reduction in channel slope; between Reach EGR5 and EGR3, the channel slope drops from about 0.5% to 0.1% (Figure 29). In addition to the historic mapped avulsions, there are at least nine river bends that are highly prone to an avulsion in coming years. When normalized by river mile, the results show an even stronger density of avulsions in Reaches EGR4 and EGR5.

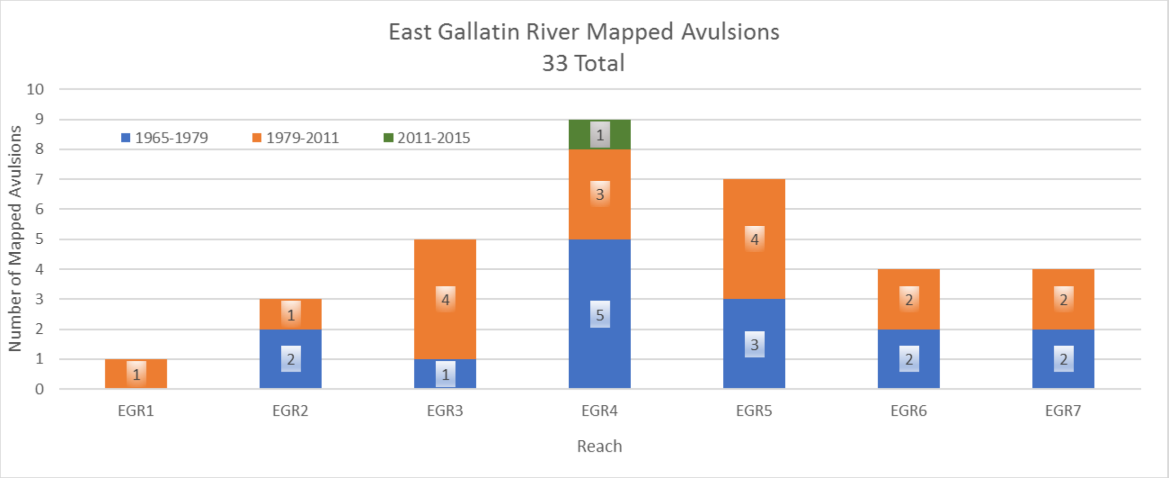


Figure 38. Number of mapped avulsions by Reach, Gallatin River.

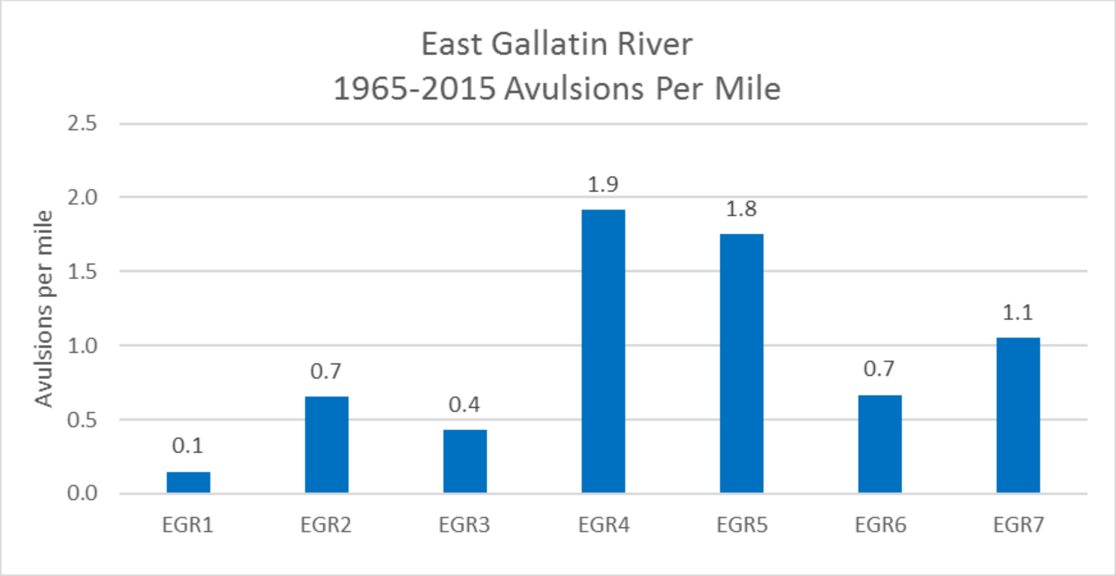


Figure 39. Number of mapped avulsions per river mile by reach.

Figure 40 shows an example of a major 1965-2011 avulsion in Reach EGR4 just downstream of Penwell Bridge. The avulsion created a new channel that is about 1,000 feet long. The site also shows a good example of meander migration upstream of the avulsion, where the channel migrated southwestward about 400 feet between 1979 and 2015. Sometimes migration and avulsion sites can be linked; migrating banklines can induce avulsions as the river intercepts swales or overlengthens, and conversely avulsions can drive downstream migration by creating a sediment pulse that accelerates channel movement.

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 28). It is important to recognize 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.

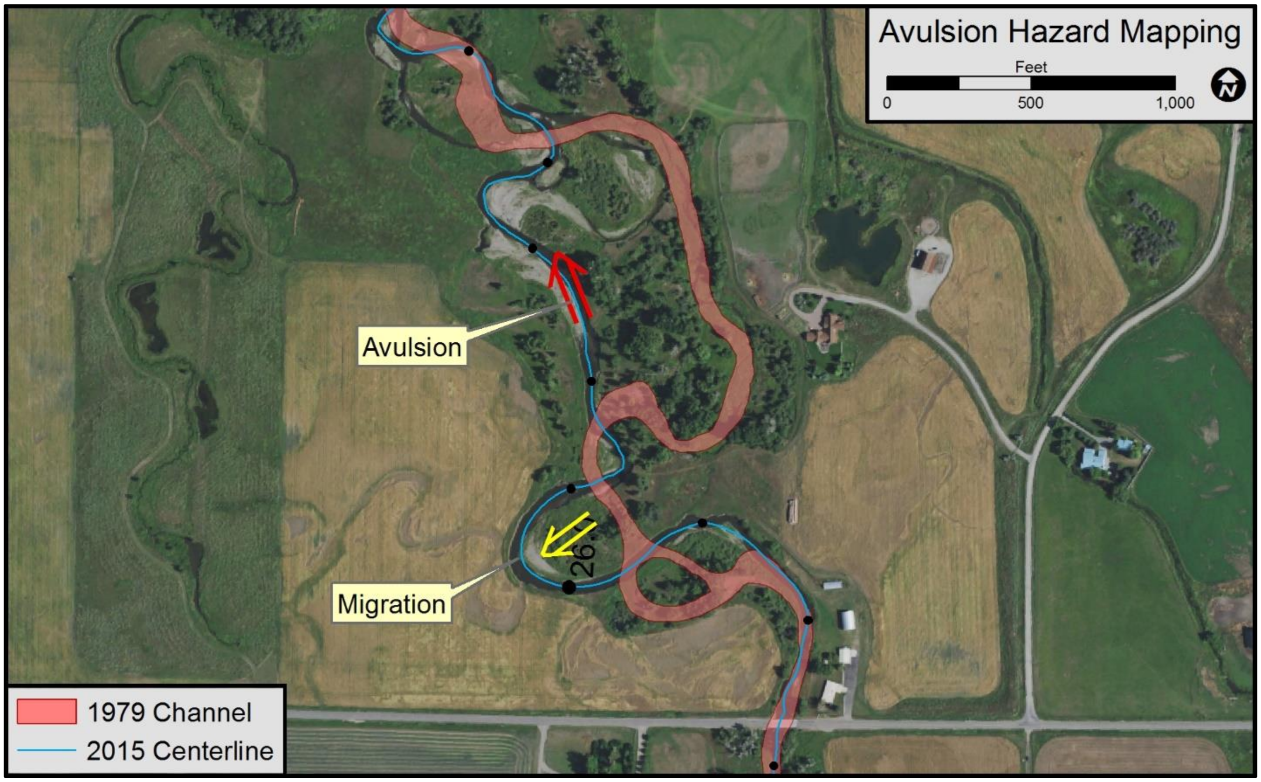


Figure 40. East Gallatin River Avulsion Hazard mapping, RM 26 below Penwell Bridge Road.

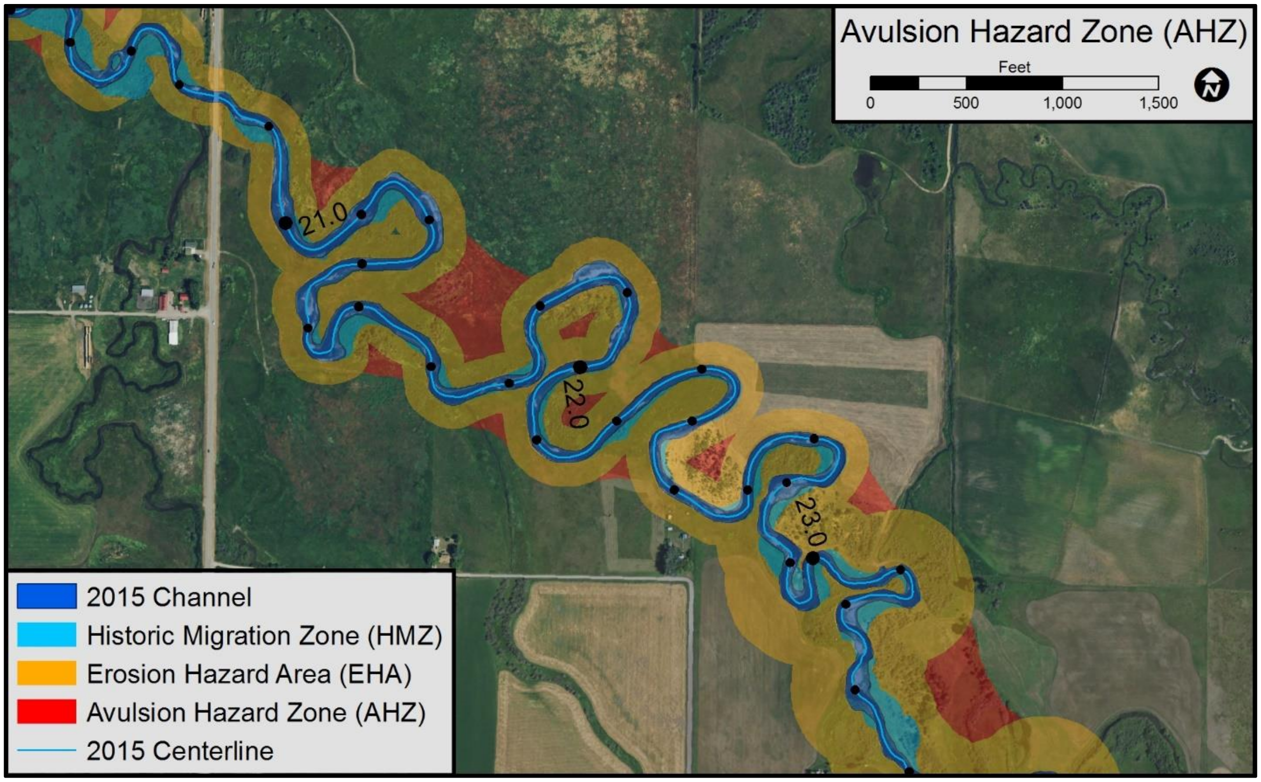


Figure 41. East Gallatin River Avulsion Hazard Zone mapping, Dry Creek Road.

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 4.5 miles of armor were mapped on the East Gallatin River, although this value is probably conservative as much of the armor is old and difficult to see on air photos. A 2005 inventory performed by Toshi Sagari (Sagari, 2005) and provided by the Gallatin Local Water Quality District was used to verify and compliment the mapping, however this field inventory did not extend below Dry Creek Road north of Belgrade. The 4.5 miles of armor cover just over 5% of the total bankline, although on a reach scale up to 10% of the banks are armored (Figure 42). Most of the mapped armor is concentrated in the upper three reaches, which extend from Bozeman to Middle Creek north of the airport. Downstream of Belgrade, both the density of CMZ development and the extent of bank armor continually drop.

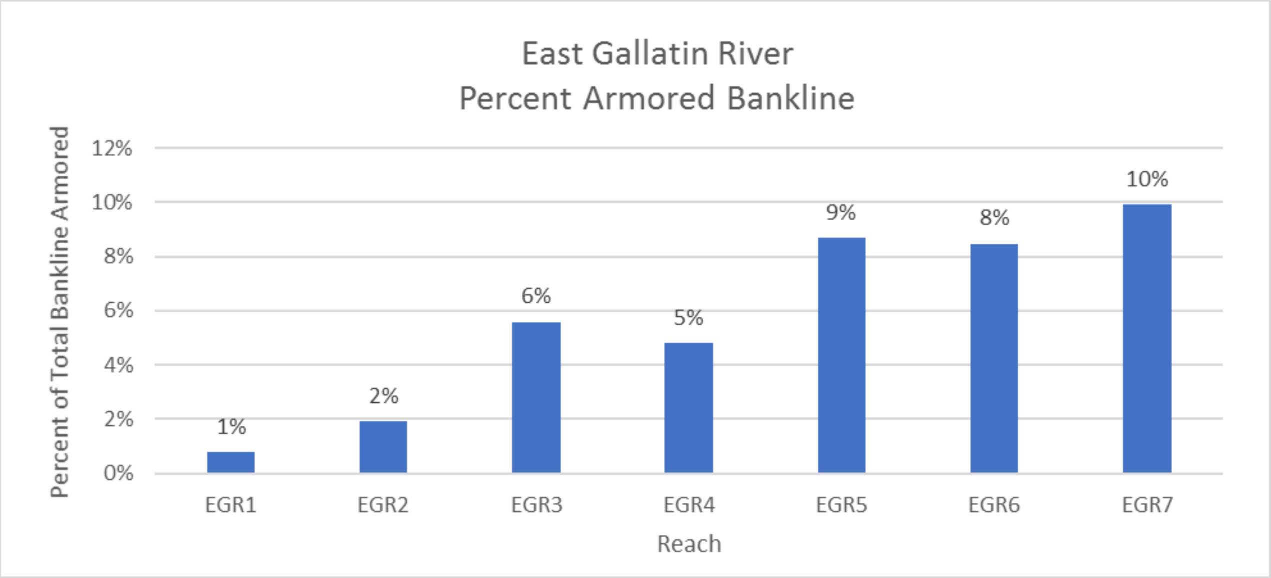


Figure 42. Percentage of bankline protected by armor by reach.

Figure 43 shows an example of Restricted Migration Areas at the Swamp Road bridge. In total, 123 acres of the CMZ are mapped as Restricted, with 104 acres attributed to bank protection and 18 acres to transportation (Figure 44).

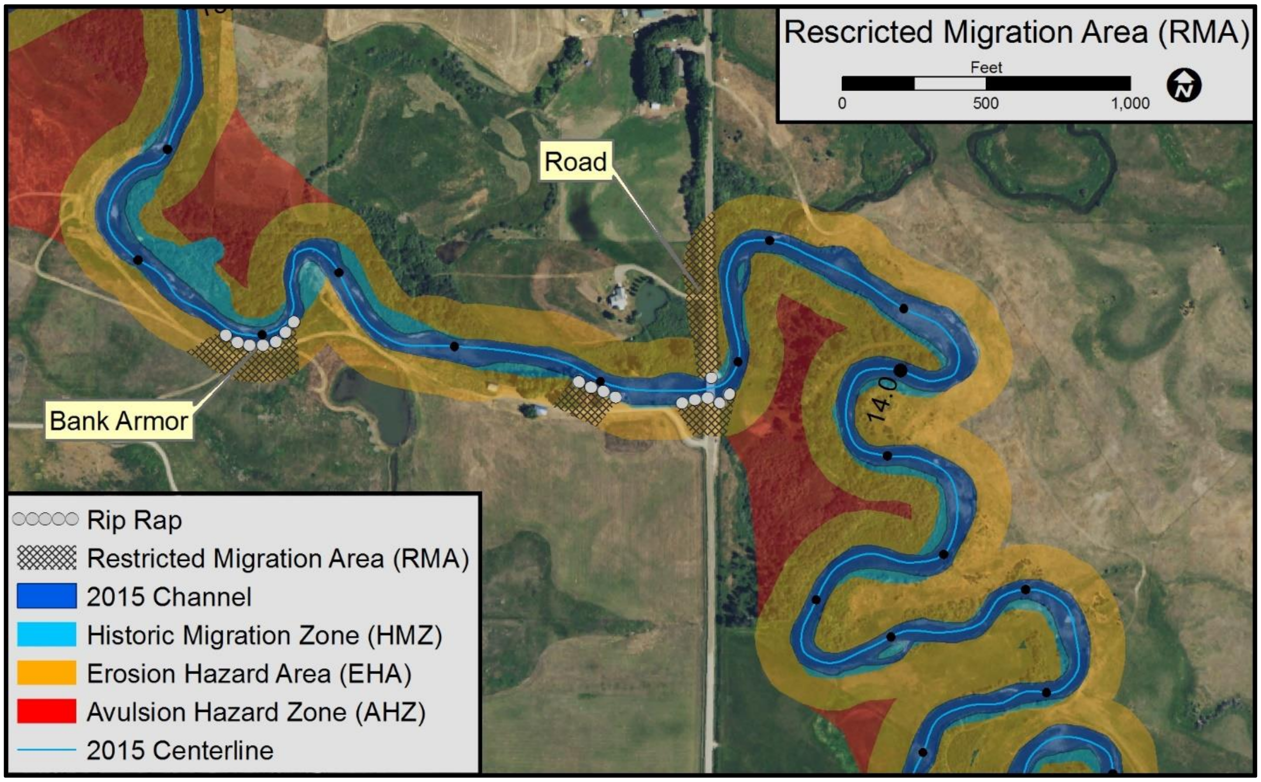


Figure 43. Restricted Migration Areas at Swamp Road bridge.

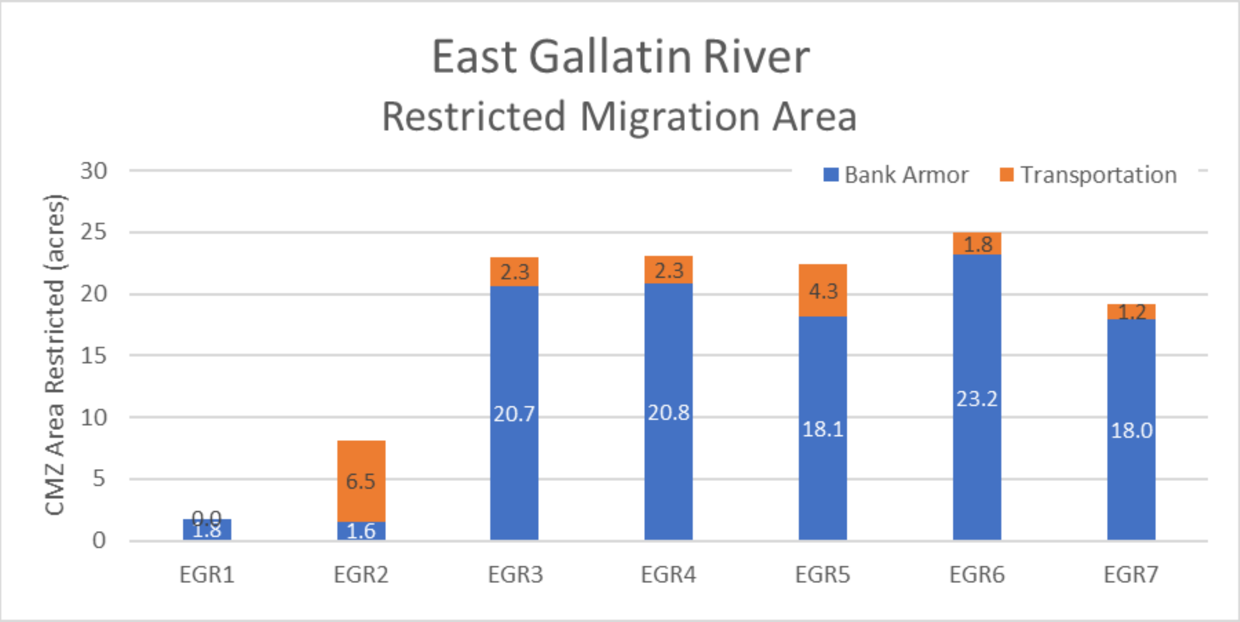


Figure 44. Acres of the CMZ mapped as restricted by reach.

4.6 Composite Map

An example portion of a composite CMZ map for a section of the East Gallatin River project area is shown in Figure 45. 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.

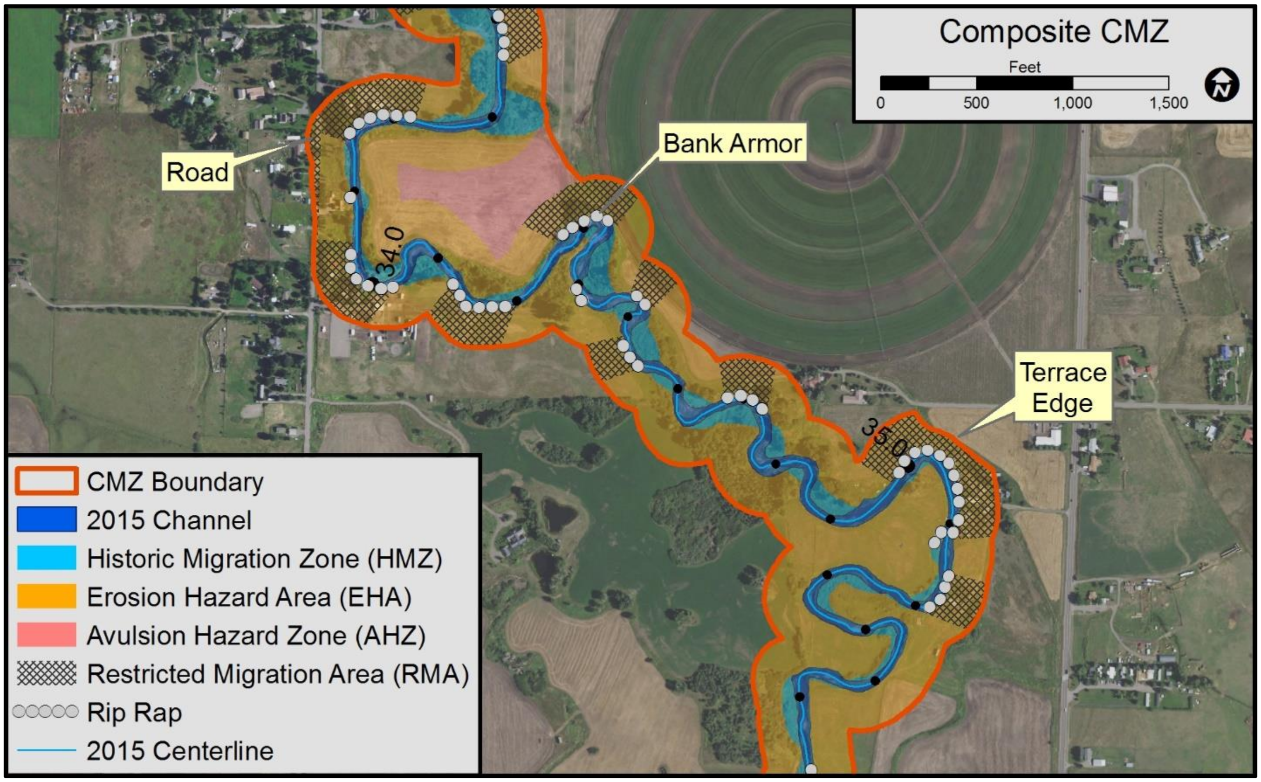


Figure 45. Composite Channel Migration Zone map.

4.7 Geologic Controls on Migration Rate

The banks of the East Gallatin River are largely made up of erodible materials deposited by the stream itself. In two locations near Bozeman and on the north channel edge north of Manhattan, however, the river runs against higher terraces and alluvial fan deposits. The rate of river erosion into these units is slower than the active channel deposits, so that the erosion buffer assigned to these units is relatively narrow (Figure 45). Between Manhattan and Logan, bedrock exposures on the north valley wall (Rattlesnake Hills) are designated as non-erodible and clipped from the CMZ.

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. There are no mapped active landslides against the river, which suggests that the CMZ will not likely be altered by hillslope failure. Even so, the steep hillslopes that reach the river against the Rattlesnake Hills could experience rockslides and 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 East Gallatin River Reach Descriptions

The following sections describe the channel dynamics of each reach of the East Gallatin River, highlighting specific points of interest. The reaches are numbered sequentially from the downstream end of the project (EGR1 to EGR7). To best describe the trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach EGR7 near Bozeman and ending with Reach EGR1 at the confluence with the Gallatin River north of Manhattan. The CMZ maps can be found in Appendix C.

Note: All references to River Miles (RMs) reflect the distance upstream from the Gallatin River confluence along the 2015 channel centerline. River Miles are labeled on the maps in Appendix C. 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 EGR7

Reach EGR7		
Upstream/Downstream RM	41.4	37.6
Length (miles)	3.8	
General Location	Bridger Creek/Rocky Creek to Springhill Road	
Mean Migration Rate (ft/yr)	1.8	
Max 60-year Migration Distance (ft)	221	
100-year Buffer (ft)	184	

Reach EGR7 is almost four miles long and extends from the upstream end of the project reach at Bridger Creek Golf Course downstream to Springhill Road. This section the river flows through rural high-end subdivisions, and several of these areas were isolated by floodwaters during the May 2008 event (Figure 46). The isolation and flooding of these homes occurred due to the activation of floodplain channels north of the river that create discreet flood paths. Figure 47 shows the floodplain mapping for this area; the channels that visible in Figure 46 can be seen just south of Old Farm Road.

Further upstream, above Manley Road, a larger floodplain "breakout point" on the right bank of the East Gallatin River carries floodwaters along a major flow split to a parallel drainage to the north called Churn Creek. This breakout point is labeled as "overflow" in Figure 47. From a channel migration perspective, this is an interesting site as the location of the river affects the nature of this major flood breakout point.

The overflow point labeled on Figure 47 is located on the apex of a large north-trending bendway just upstream of Manley Road. A comparison of 1965 and 2011 imagery shows that the channel has lengthened with time through the bend, which has reduced its slope (Figure 48). There has also been active deposition in the upstream limb of the bend, and the 2011 image shows recent sediment deposition across an avulsion path through the core of the bend. This is not uncommon; when bendways lengthen, they sometimes lose the gradient necessary to effectively transport its sediment load, resulting in deposition where the channel flattens, channel infilling, and overflows across the core of the bend. Figure 48 also shows an armored headcut on the downstream limb of the bend suggesting that overflows have started to develop an avulsion channel. The importance of this is with respect to river management and flooding. An avulsion may be the natural trajectory for the East Gallatin River at this site, as the channel lengthening is affecting sediment transport capacity. In the event of an avulsion, the Churn Creek overflow will be largely abandoned, which would substantially alter flood paths through residential areas to the northwest.

There are numerous residential structures within the CMZ in Reach EGR7, although most of them are in areas designed as RMA due to bank armoring. Reach EGR7 has almost 4,000 feet of bank armor that covers 10% of the bankline and restricts 18 acres of the CMZ. The bank armor includes vehicle bodies, rock riprap, and cement blocks.

The Erosion Buffer in Reach EGR7 is 184 feet, which is less than the maximum measured migration distance of 221 feet. This indicates that substantial bank movement should be expected in this reach, and that over the next century there will likely be local areas that erode beyond the CMZ margin.

Reach EGR7 contains the very popular Cherry River Fishing Access Site, which protects a dense willow corridor and highly sinuous channel segment from development (Figure 49).

Figure 46. View upstream (east) showing floodplain channel activation south of Old Farm Road during 2008 flood; East Gallatin River is to right of homes in willow corridor (MT DNRC).

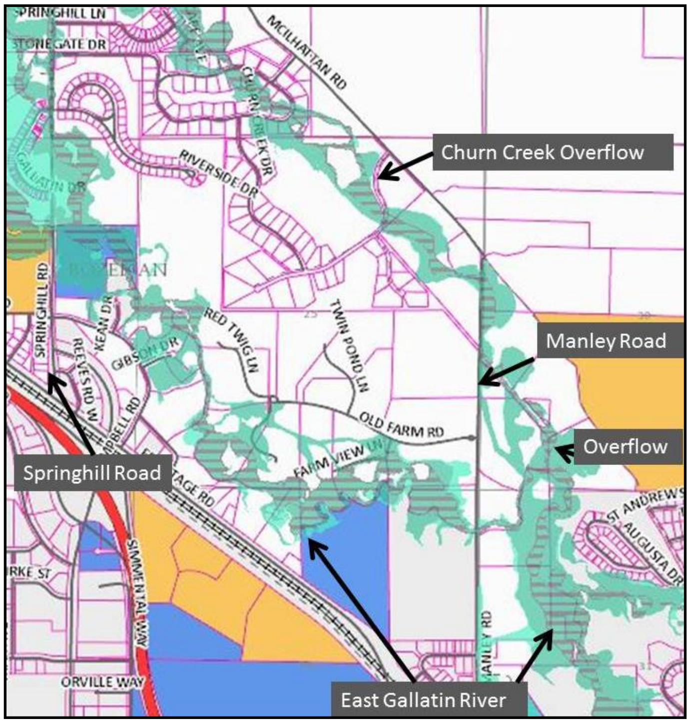


Figure 47. East Gallatin River floodplain mapping (green) showing overflow from point upstream of Manley Road.

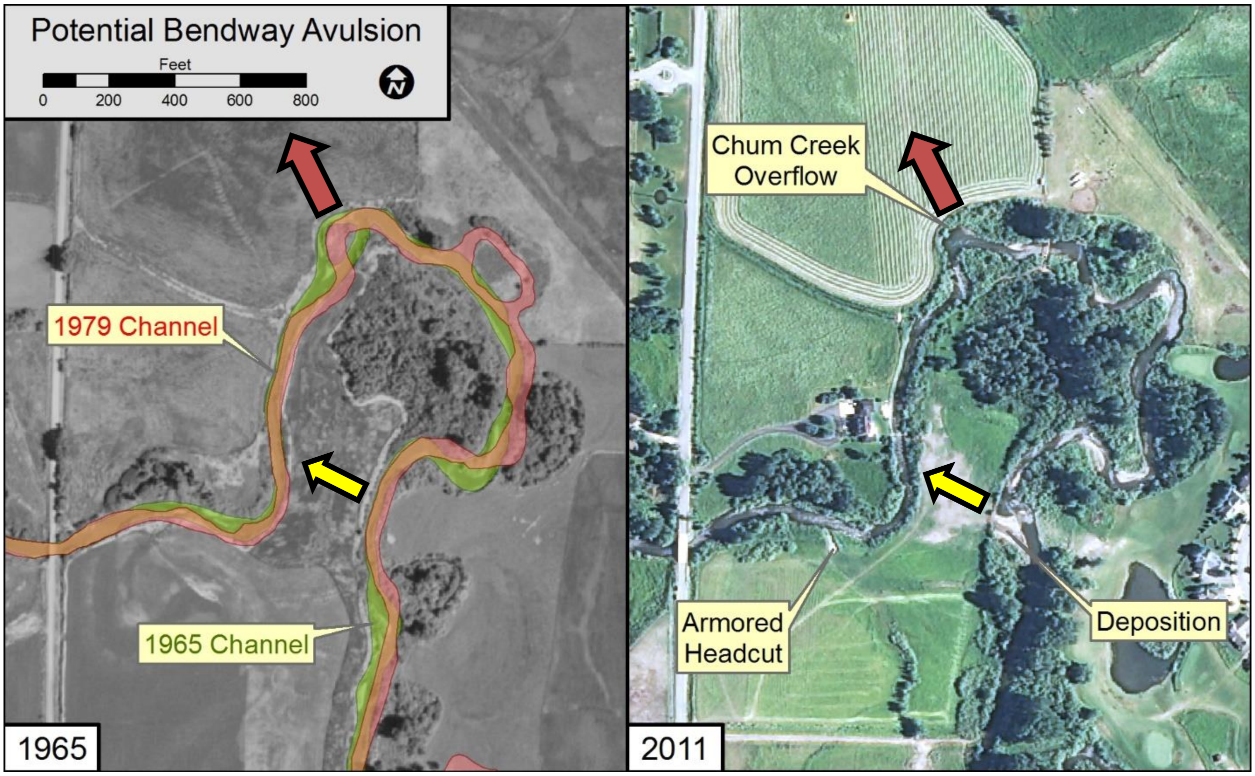


Figure 48. East Gallatin River above Manley Road, showing overflow pint (red arrow) and potential avulsion path (yellow arrow) upstream of Manley Road in 1965 (left) and 2011 (right).

Figure 49. View downstream of Reach EGR7 below Manley Road; Cherry River Fishing Access site is on left (Kestrel).

5.2 Reach EGR6

EGR6		
Upstream/Downstream RM	37.6	31.6
Length (miles)	6.0	
General Location	Springhill Road to Outlaw Subdivision	
Mean Migration Rate (ft/yr)	2.0	
Max 60-year Migration Distance (ft)	385	
100-year Buffer (ft)	201	

Reach GR07 is six miles long, extending from Springhill Road to the Outlaw Subdivision upstream of Airport Road. Similar to Reach EGR7 upstream, this channel segment experienced substantial overbank flooding into floodplain channels in 2008, highlighting the potential extent of avulsion paths in the reach that are difficult to see on imagery alone (Figure 50).

The reach has experienced several avulsions, including a major 1979-1995 avulsion just below the Bozeman Water Treatment Plant Figure 51 and Figure 52. There have been attempts to block this avulsion at its upper end, so it has not yet become the main channel. However, as the avulsion path is 1,600 feet shorter than the main channel, it will eventually capture the main thread without continued management.

A high risk avulsion site at RM 35.2 demonstrates the cutoff potential of a very long bendway with a short avulsion path; there is a headcut formed through the avulsion path that has been armored with rock similar to the site described upstream in Reach EGR7 (Figure 53).

This reach is notable in that it has experienced a 25% increase in total channel length since 1965, indicating historic channelization and subsequent lengthening to better dissipate energy. There is strong evidence of channelization in the upper two miles of this reach, from below Springhill Road to Nelson Road. Comparisons of imagery from 1965 and 2015 show the re-meandering of channelized segments with time (Figure 54). There was apparently extensive riparian clearing in this reach prior to 1965 as well, and there has been some riparian recovery since that time.

At RM 33.7L Buster Gulch leaves the East Gallatin River and flows through a rural subdivision along Nelson Road. This channel was mapped as an active East Gallatin distributary on the 1868 General Land Office survey maps.

The erosion buffer width in Reach EGR6 is 201 feet, although the maximum migration distance measured is almost twice that at 385 feet. This area of maximum migration is located at RM 36, which is just downstream of the channelized section shown in Figure 54. This exemplifies the longitudinal impacts of channelization, as the re-gaining of length in a channelized reach transports high sediment loads downstream, which can drive rapid bar formation and bankline migration.

About a 5,400 feet of bank armor was mapped in Reach EGR6, protecting 8% of the total bankline. This armor restricts about 23 acres of the CMZ, and transportation infrastructure restricts another two acres.

Figure 50. View upstream showing 2008 flooding highlighting floodplain channels, RM 35.3.

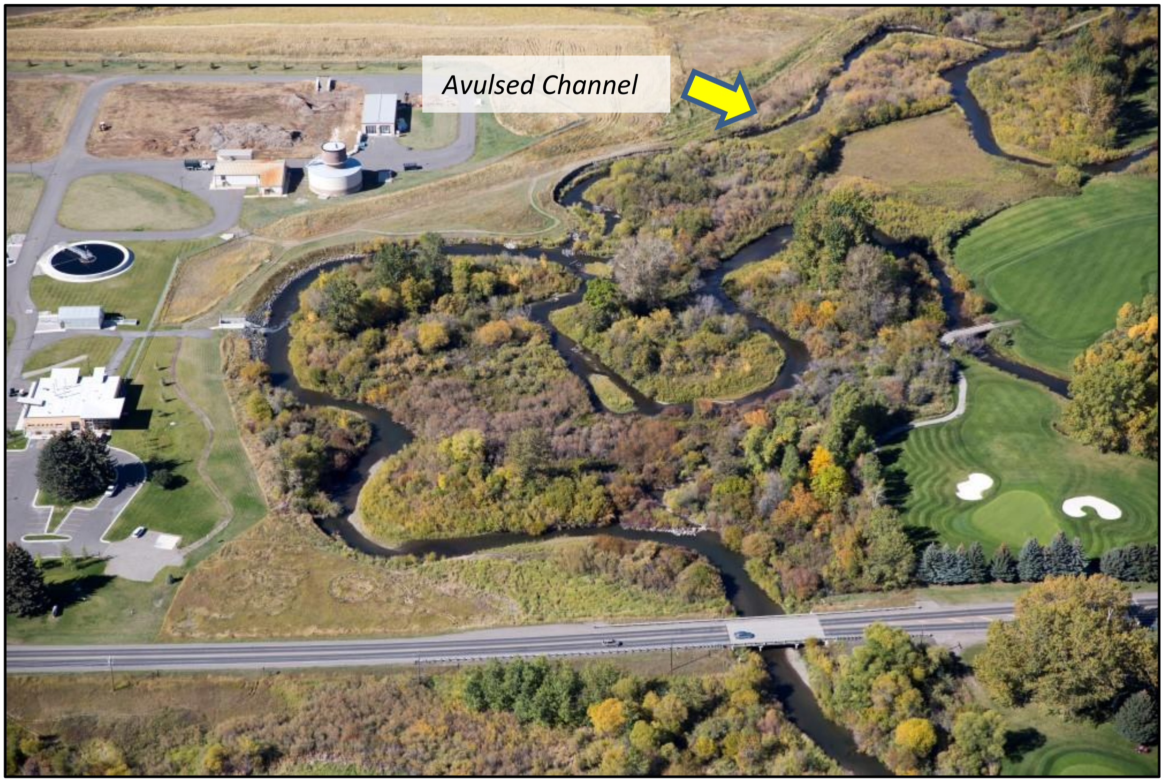


Figure 51. Reach EGR 6 showing avulsion site at Bozeman Water Treatment Plant (Kestrel).

Figure 52. East Gallatin River at Bozeman Water Treatment Plant showing avulsion between 1979 (left) and 1995 (right).

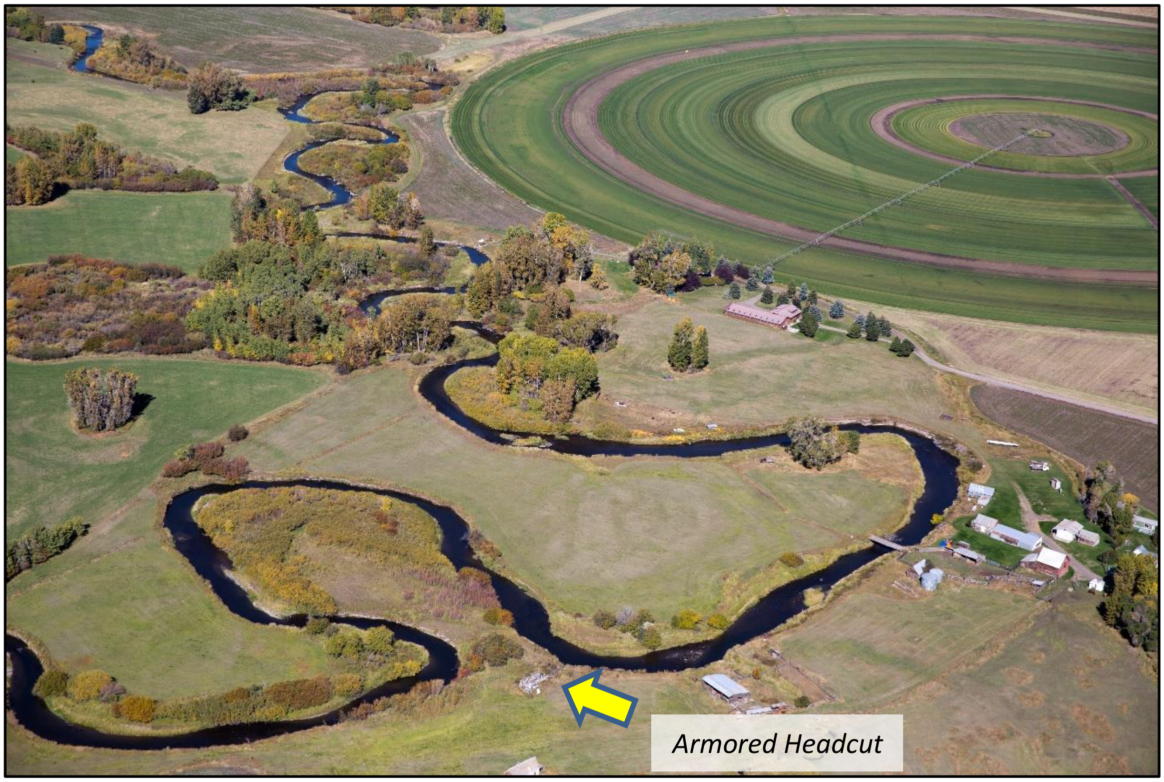


Figure 53. View downstream of Reach EGR6 showing armored headcut on meander core, RM 35.2 (Kestrel).

Figure 54. East Gallatin River below Springhill Road, showing channelized segment in 1965 and lengthened channel in 2015.

5.3 Reach EGR5

EGR5		
Upstream/Downstream RM	31.6	27.6
Length (miles)	4.0	
General Location	Outlaw Subdivision to Middle Creek	
Mean Migration Rate (ft/yr)	2.2	
Max 60-year Migration Distance (ft)	250	
100-year Buffer (ft)	224	

Reach EGR5 is east of the airport, extending from the Outlaw Subdivison to the mouth of Middle (Hyalite) Creek. Reach EGR5 is probably most notable for its anomalously steep channel slope of 0.5%, which marks a distinct inflection in the river profile (Section 4.1). The reach has lost 6% of its length since 1965 (0.3 miles), and it is the least sinuous reach in the project area. The 1965 channelization shown in Figure 20 is in Reach EGR5. As a result of being steep and straight, this reach has the potential to rapidly develop bendways, cutoffs, and avulsions. Recent imagery captures a relatively large extent of open bar area in this river segment. This active sediment movement and channel scour may be in part due to nine mapped avulsions, which tend to create sediment pulses as a new channel is eroded. The erosion buffer width is 224 feet, which is only second to Reach EG04 immediately downstream. In addition to Reach EGR5 hosting a high-energy channel environment, there has been a substantial amount of rural residential development within the CMZ (Figure 55).

One of the avulsions in Reach EGR5 was about a half mile long, creating a wide historic migration corridor on the CMZ maps. This avulsion abruptly relocated the channel about 300 feet eastward between 1979 and 1995 (Figure 56 and Figure 57). Several avulsions were also mapped at the mouth of Middle Creek (Figure 58). At RM 35.4, the river avulsed into about 400 feet of ditch between 1965 and 1979.

About 3,700 feet of bank armor was mapped in Reach EGR5, protecting 9.2% of the total bankline. This armor restricts about 18 acres of the CMZ, and transportation infrastructure restricts another 4 acres.

Figure 55. View downstream of Reach EGR5 showing rural residential subdivision (Outlaw Subdivision) adjacent to the river corridor.

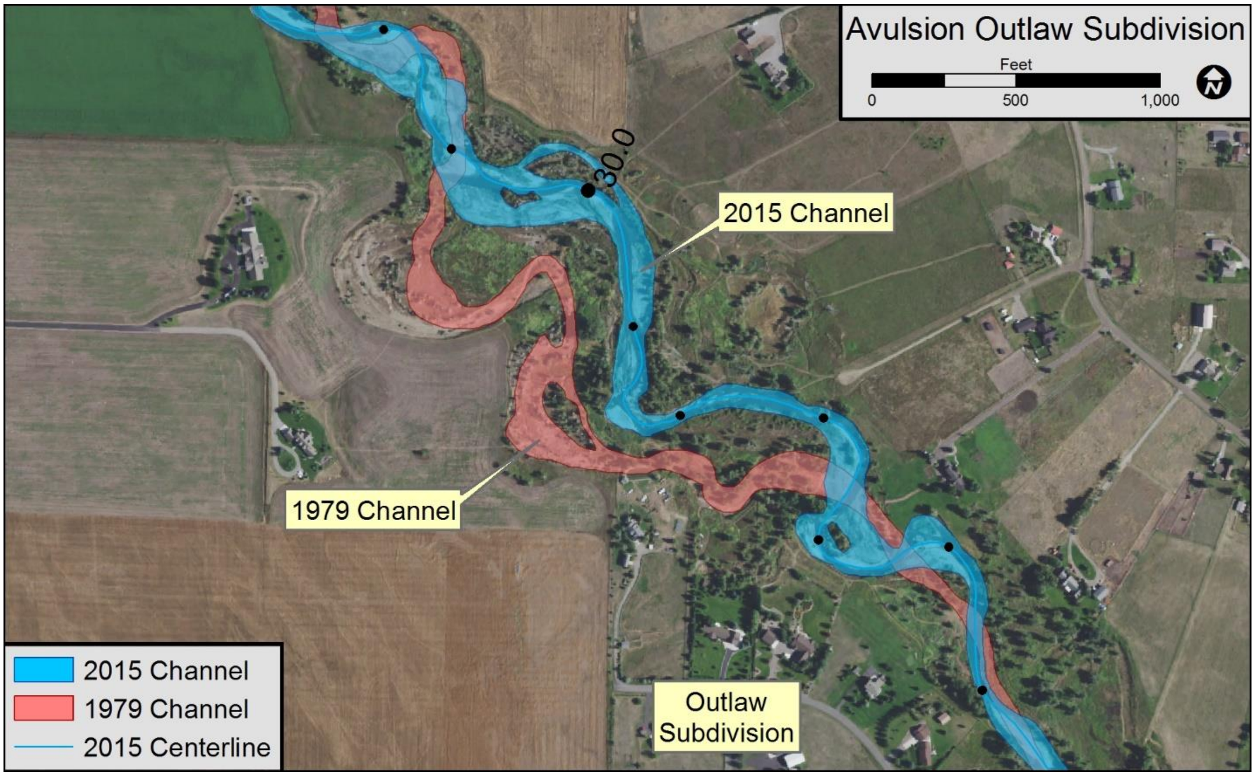


Figure 56. 1979-1995 avulsion site, Reach EGR5.

Figure 57. View downstream of Reach EGR5 towards Airport Road Bridge showing avulsion site corridor (Kestrel).

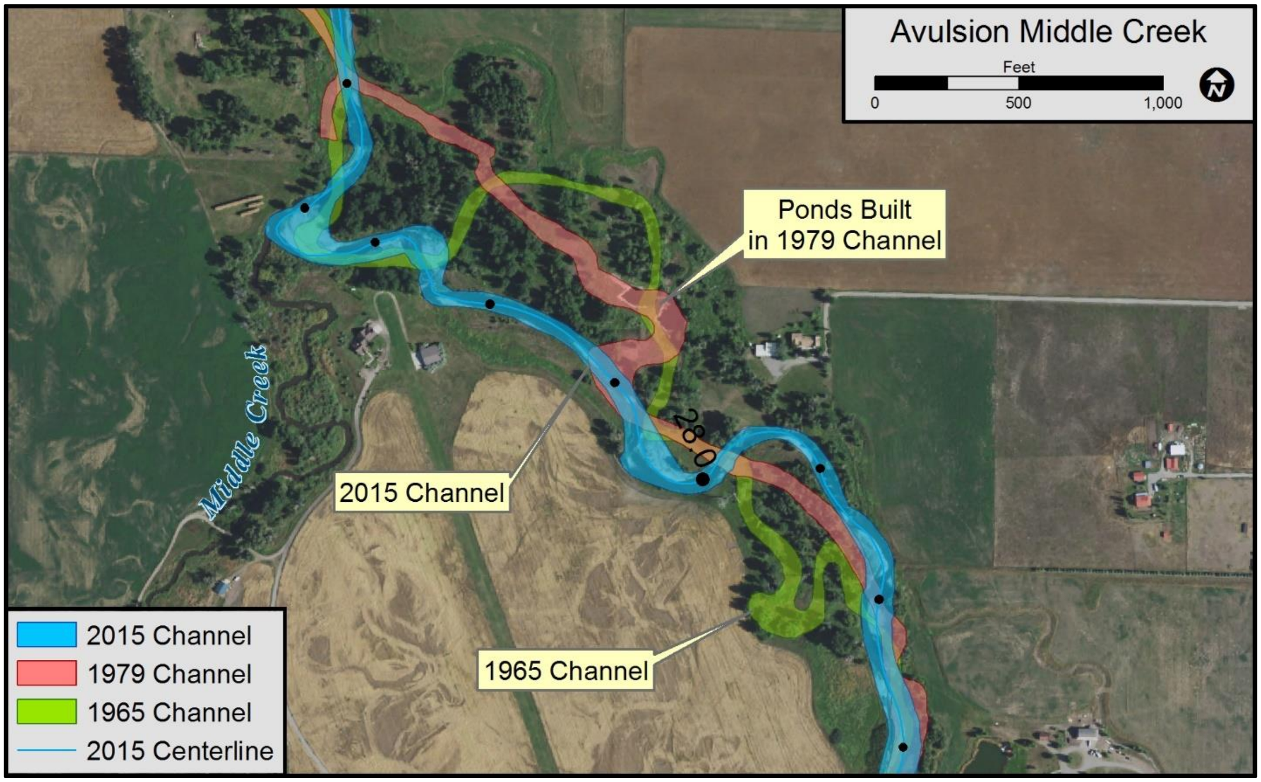


Figure 58. Multiple avulsions at the mouth of Middle (Hyalite) Creek (Kestrel).

5.4 Reach EGR4

EGR4		
Upstream/Downstream RM	27.6	22.9
Length (miles)	4.7	
General Location	Middle Creek to just above Thompson Spring Creek	
Mean Migration Rate (ft/yr)	2.8	
Max 60-year Migration Distance (ft)	419	
100-year Buffer (ft)	283	

Reach EGR4 is almost 5 miles long extending from the mouth of Middle Creek, past Penwell Bridge and down to just above Thompson Spring Creek and Dry Creek Road. This reach has the highest mean migration rate in the project area, with a 100-year erosion buffer width of 283 feet. The largest migration distance measured is 419 feet. Reach EGR4 also has the highest avulsion density in the project reach. These processes can be clearly seen just downstream of Hamilton Road, where within about 1,500 feet of stream corridor a 700-foot long avulsion channel formed since 1976, and two bendways immediately downstream have migrated at least 250 feet in opposite directions across the floodplain. This rapid migration is probably in response to the sediment pulse delivered by the avulsion (Figure 59).

The length of the river in Reach EGR4 has increased by 0.6 miles or 16% since 1965. Similar to Reach EGR5 upstream, the channel has a low sinuosity relative to other reaches. Although the sinuosity is low compared to other reaches, it still maintains a sinuosity value of over 1.6, and cutoffs through highly sinuous meander cores are common (Figure 60).

General Land Office (GLO) survey maps show that in 1868 the river was about a half mile east of its current location between Penwell Bridge and Hamilton Road (Figure 61).

About a half mile (2,382 ft) of bank armor was mapped in Reach EGR4, protecting 5% of the total bankline. Some of that armor is actively flanking (Figure 62). Bank armor restricts about 21 acres of the CMZ, and transportation infrastructure restricts another 2.3 acres.

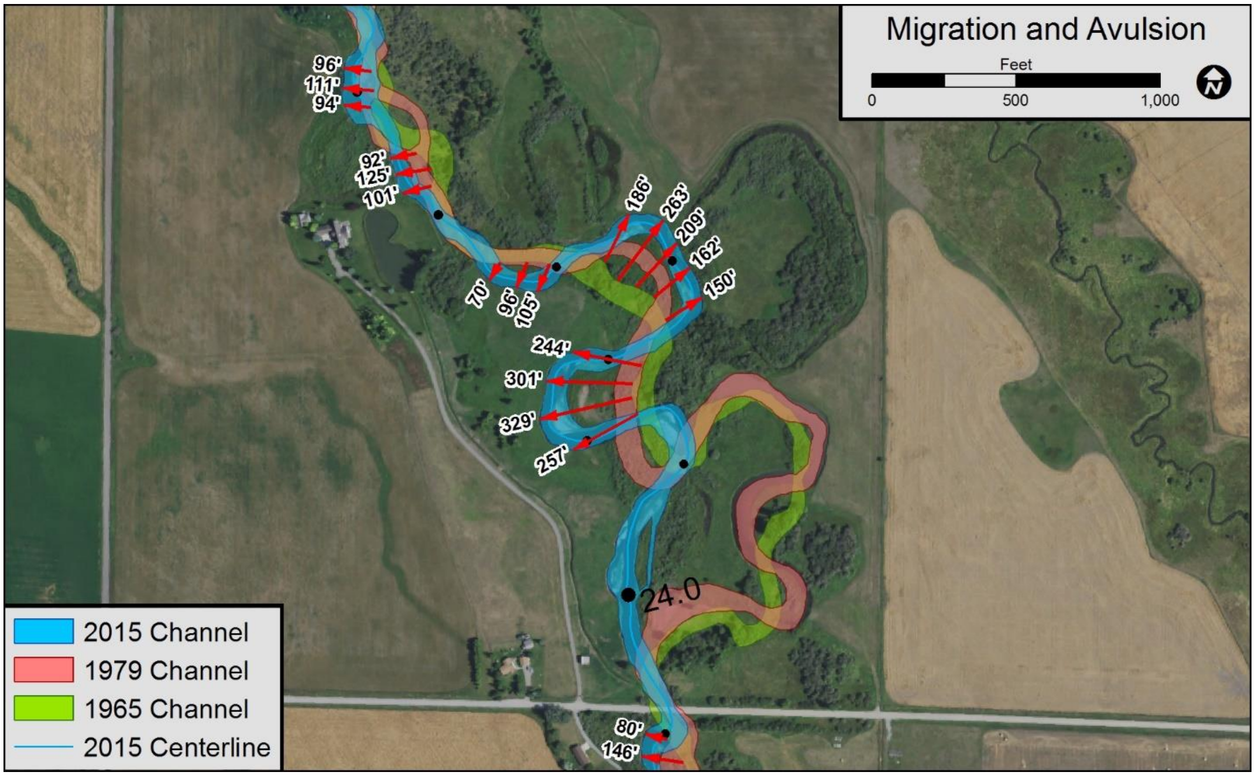


Figure 59. 2015 imagery and historic banklines showing avulsion and migration processes just downstream of Hamilton Road.

Figure 60. Active meander cutoff, RM 23.

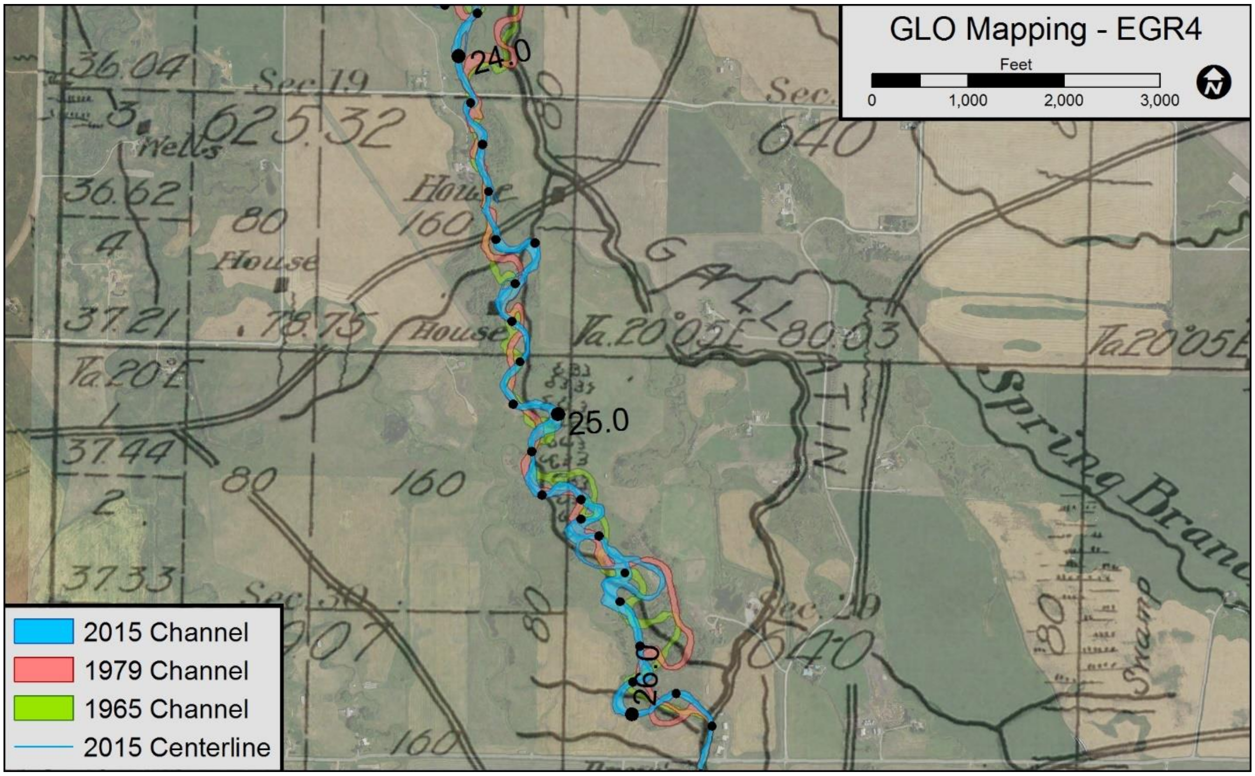


Figure 61. 1869 GLO map showing westward shift of East Gallatin River below Penwell Bridge.

Figure 62. Flanking rock riprap on left bank, Reach EGR4 (Kestrel).

5.5 Reach EGR3

EGR3		
Upstream/Downstream RM	22.9	11.3
Length (miles)	11.6	
General Location	Above Thompson Spring Creek to Dry Creek School Road	
Mean Migration Rate (ft/yr)	1.2	
Max 60-year Migration Distance (ft)	206	
100-year Buffer (ft)	122	

Reach EGR3 starts at a distinct break in channel slope at RM 22.9, which is located about 0.75 miles upstream of the Dry Creek Road Bridge at Thompson Spring Creek north of Belgrade. The downstream end of the reach is at Dry Creek School Road Bridge, which is almost 12 miles downstream.

The plotted channel profile shows a distinct reduction in slope from 0.30% upstream in Reach EGR4 to 0.14% in Reach EGR3 (Figure 29). From the upstream end of Reach EGR3 to the Gallatin River over 20 miles downstream, the gradient remains consistently low. Along with an abrupt reduction in slope, there is a dramatic increase in channel sinuosity from 1.7 to 2.6 between Reach EGR4 upstream and Reach EGR3. This change is highly apparent on the imagery as the river transitions into a series of very high amplitude relatively stable bendways. Migration rates drop due to the low energy system. This area and reaches below are very likely in the area that William Clark described as “dammed with beaver in such as manner as to render the passage impracticable”. Beaver dam complexes tend to create low gradient fine grained river systems in which banks have marked erosion resistance supported by cohesive silts and clays accumulated in beaver ponds. Reach EGR3 has the lowest mean migration rate in the project reach, with a 100-year erosion buffer width of 122 feet (Figure 63).

Although migration rates are low, the high sinuosity of Reach EGR3 makes in especially prone to avulsions, especially neck cutoffs where the limbs of a bendway gradually migrate towards one another and eventually “pinch” the meander tab causing a cutoff (Figure 64). This reach has five mapped historic avulsions, with another four areas mapped as “imminent”.

Between Dry Creek and Swamp Creek roads, the floodplain in Reach EGR3 has experienced extensive riparian clearing which may contribute to avulsion risk (Figure 65).

The lateral stability of the river in Reach EGR3 is a striking difference from upstream, where there are extensive open bars, sediment pulses derived from avulsions, and more dramatic changes in channel location. Reach EGR3 exhibits bank cohesion, low gradients, and low transport energy. These conditions tend to provide a fairly stable geomorphic state even with flooding, unless there is a substantial change in inputs (water or sediment), loss of bankline/floodplain resilience, or loss of sediment transport competency. The riparian clearing in this reach has reduced bankline resilience, and it is apparent from the imagery that the channel has widened, even though migration rates remain relatively slow. Floodplain resilience to flooding has been dampened by loss of woody vegetation. Additionally, upstream channelization projects and avulsion processes have the potential to eventually increase the sediment delivery to this reach. In 1965 there were few in-stream open bar deposits below Hamilton Road (RM 24.1). Since then open bar deposits have become more common in the widened channel. If substantially larger sediment loads do reach this portion of the river, it is highly likely that coarse sediment will deposit in the channel, bank migration rates will increase, and avulsions will become more frequent.

Riparian restoration would be a very appropriate means of improving resilience in this section of river.

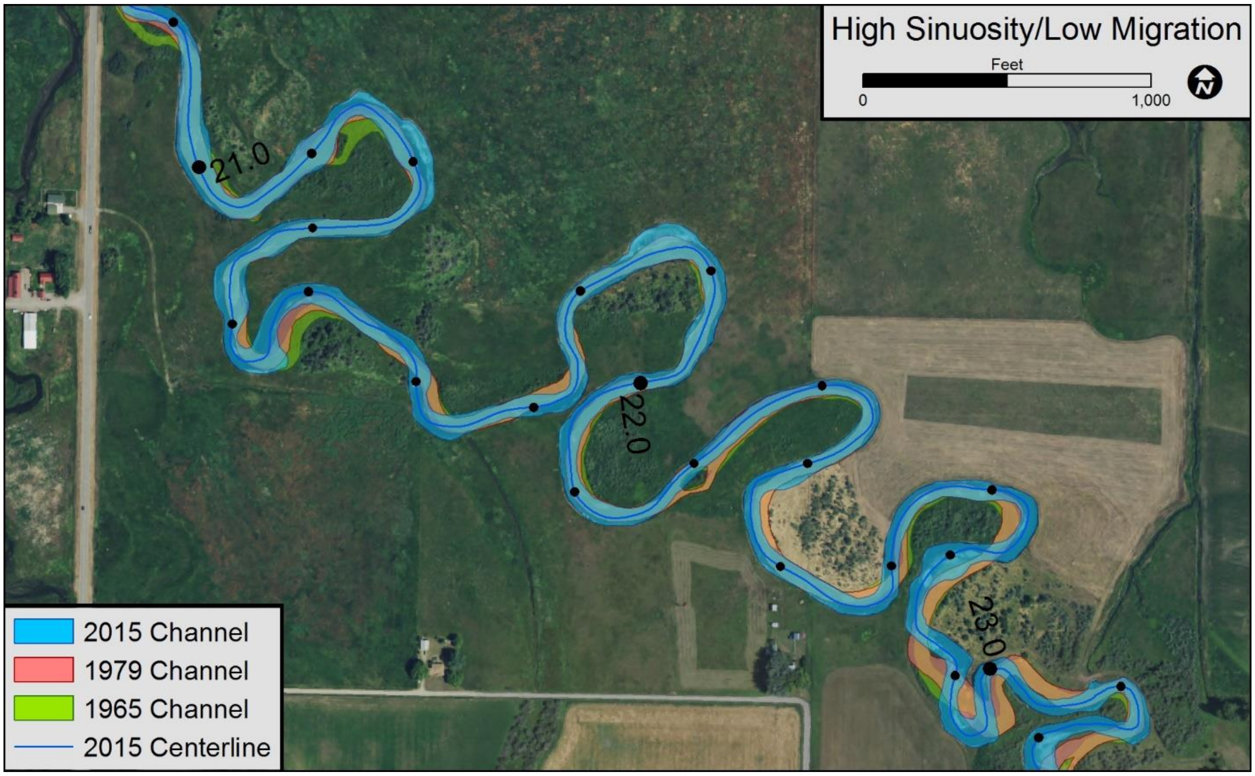


Figure 63. 2015 imagery and historic banklines showing high sinuosity and low migration rates in upper Reach EGR3.

Figure 64. View downstream avulsion prone bendways above Dry Creek Road; Thompson Creek is in distance (Kestrel).

Figure 65. View downstream showing lack of woody vegetation on banklines and floodplain, Reach EGR3 (Kestrel).

5.6 Reach EGR2

EGR2		
Upstream/Downstream RM	11.3	6.7
Length (miles)	4.6	
General Location	Dry Creek School Road to Bluff Line	
Mean Migration Rate (ft/yr)	1.8	
Max 60-year Migration Distance (ft)	302	
100-year Buffer (ft)	185	

From the Dry Creek School Road Bridge at RM 11.3, the East Gallatin River continues to flow within a broad floodplain as it approaches the northern flank of the Rattlesnake Hills. The reach is almost five miles long, with a 100-year buffer distance of 185 feet. The upper end of Reach EGR2 marks a moderate increase in woody riparian vegetation density, with a higher number of dense willow stands evident both on the floodplain and bankline. In some areas the riparian corridor density provides a reference for the overall riparian potential of the lower East Gallatin River (Figure 66).

Migration rates are somewhat higher in Reach EGR2 relative to upstream, which may reflect additional sediment inputs from Dry Creek (Figure 67). Three avulsions were mapped in the reach.

As the river approaches the bluff line of the Horseshoe Hills, riparian vegetation becomes discontinuous patches within a highly sinuous corridor, creating substantial avulsion risk (Figure 68).

A total of 934 feet of bank armor were mapped in Reach EGR3, protecting 2% of the total bankline. The bank armor restricts less than two acres of the CMZ.

Figure 66. View downstream from Dry Creek School Road Bridge showing healthy riparian corridor (Kestrel).

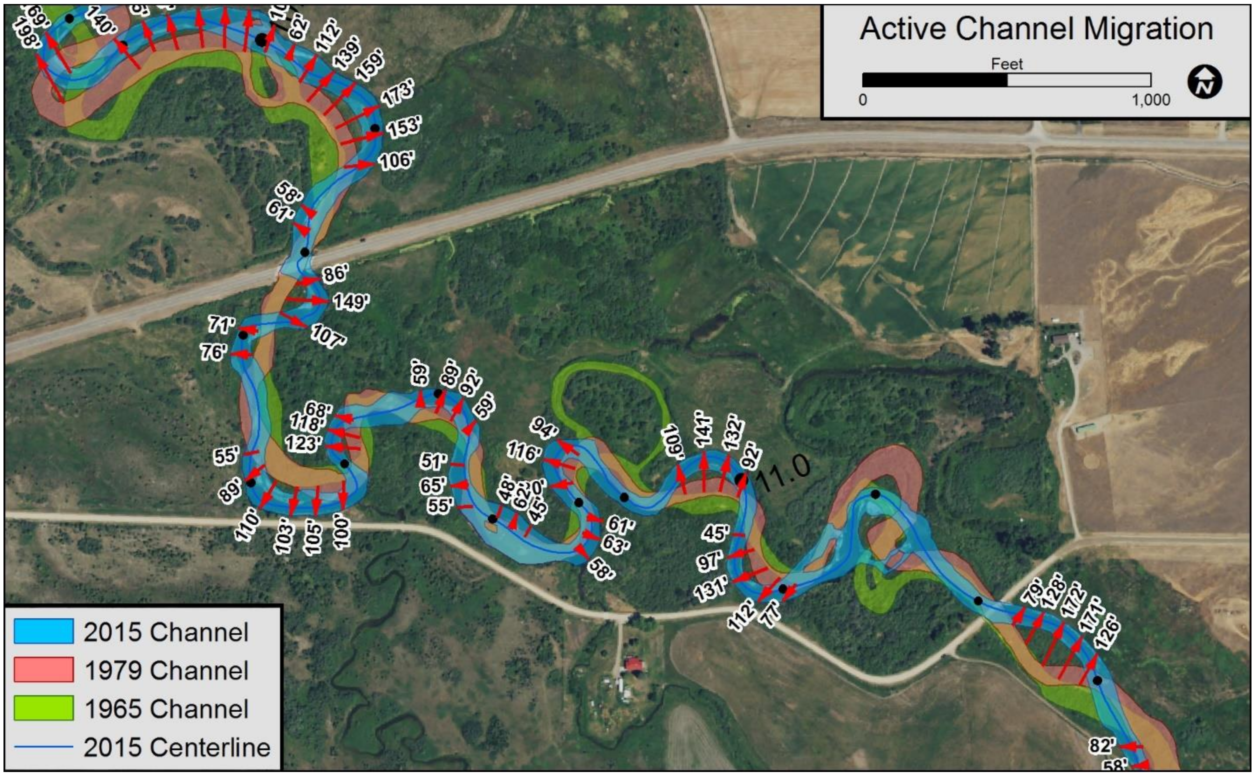


Figure 67. Active channel migration between Dry Creek School Road and Dry Creek Road, Reach EGR3.

Figure 68. View downstream of lower reach EGR2 approaching Horseshoe Hills bluff line (Kestrel).

5.7 Reach EGR1

EGR1		
Upstream/Downstream RM	6.7	0.0
Length (miles)	6.7	
General Location	Bluff Line to Mouth	
Mean Migration Rate (ft/yr)	1.4	
Max 60-year Migration Distance (ft)	158	
100-year Buffer (ft)	138	

Reach EGR01 flows almost seven miles along the north flank of the Horseshoe Hills to the confluence of the East Gallatin and Gallatin Rivers. As the river flows along the bluff line, it runs against both alluvial fan deposits and Proterozoic rocks that are over a billion years old. Whereas the river has locally migrated into the alluvial fan deposits, the bedrock shows no river erosion and has been clipped out of the CMZ (Figure 69). The bedrock consists of the LaHood Formation, which is a conglomerate that has been described as having clasts (embedded pieces of other rock) that are up to 12 feet in diameter (Vuke, 2014).

At RM 0.2 the East Gallatin flows into a complex channel complex formed by the coalescence of the East Gallatin and Gallatin River floodplains (Figure 70). The main Gallatin River is somewhat perched above the East Gallatin near the mouth, creating a risk of the Gallatin River capturing the lower East Gallatin through avulsion. This is most imminent about 1,200 feet upstream from the current confluence, where about 40 feet of floodplain area separates the two rivers (Figure 71). Figure 70 captures the striking difference in sediment loading between the two rivers; whereas the East Gallatin is a fairly fine grained low bedload system in this area, the Gallatin is a high bedload gravel bed river.

One avulsion was mapped in reach EGR1, and migration rates are moderate with an erosion buffer width of 138 feet.

A total of 560 feet of bank armor were mapped in Reach EGR1, protecting 1% of the total bankline. Bank armor restricts less than two acres of the CMZ.

Figure 69. View downstream showing right bank erosion of alluvial fans and terraces (Kestrel).

Figure 70. View downstream showing confluence of Gallatin River (left) and East Gallatin River (right) (Kestrel).

Figure 71. View downstream showing narrow floodplain remnant between Gallatin River (left) and East Gallatin River (right) (Kestrel) .

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Appendix A: Reach and Site Migration Statistics

The Channel Migration Zone Mapping for the East Gallatin River resulted in 1,105 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)
EG01				
MSID-EG-0.81	5	91	62	107
MSID-EG-0.96	3	53	50	59
MSID-EG-1.04	3	53	46	58
MSID-EG-1.19	3	58	50	66
MSID-EG-1.3	4	83	54	102
MSID-EG-1.56	3	59	57	60
MSID-EG-1.88	4	63	57	65
MSID-EG-1.99	2	40	38	41
MSID-EG-2.06	4	38	30	47
MSID-EG-2.26	4	30	23	34
MSID-EG-2.37	6	58	30	84
MSID-EG-2.48	4	108	85	130
MSID-EG-2.5	4	87	51	125
MSID-EG-2.58	5	74	36	99
MSID-EG-2.64	4	93	66	129
MSID-EG-2.71	2	47	43	51
MSID-EG-2.75	3	66	50	82
MSID-EG-2.99	7	72	40	111
MSID-EG-3.11	4	46	41	50
MSID-EG-3.2	4	57	50	63
MSID-EG-3.26	2	46	38	54
MSID-EG-3.44	6	44	29	56
MSID-EG-3.57	4	52	33	64
MSID-EG-3.65	3	55	35	70
MSID-EG-3.73	11	61	34	103
MSID-EG-3.9	5	70	48	89
MSID-EG-4.08	9	46	30	64
MSID-EG-4.21	3	58	40	69
MSID-EG-4.28	5	29	20	42
MSID-EG-4.43	4	109	79	140
MSID-EG-4.49	3	93	72	117
MSID-EG-4.97	4	93	72	119
MSID-EG-5.05	4	122	80	154
MSID-EG-5.15	3	108	96	118
MSID-EG-5.23	3	137	120	158
MSID-EG-5.31	2	101	75	127
MSID-EG-5.38	5	74	70	81
MSID-EG-5.61	6	37	29	43
MSID-EG-5.83	5	89	56	115
MSID-EG-5.93	5	49	43	55
MSID-EG-6.52	2	28	27	28
EG02				
MSID-EG-6.73	2	25	24	26
MSID-EG-6.99	7	55	44	66
MSID-EG-7.38	4	50	36	58
MSID-EG-7.51	2	32	28	35
MSID-EG-7.69	3	39	36	43
MSID-EG-7.77	3	36	32	39
MSID-EG-7.95	6	48	40	63
MSID-EG-8.05	4	60	50	70
MSID-EG-8.31	4	54	35	68
MSID-EG-8.66	3	51	42	58
MSID-EG-8.71	2	59	53	65
MSID-EG-8.9	3	79	57	112
MSID-EG-9.16	3	167	137	189
MSID-EG-9.51	6	185	58	271
MSID-EG-9.72	4	198	97	302
MSID-EG-9.84	2	184	169	198
MSID-EG-10.07	14	130	62	173
MSID-EG-10.18	2	60	58	61
MSID-EG-10.25	3	114	86	149
MSID-EG-10.3	2	74	71	76
MSID-EG-10.43	6	94	55	110
MSID-EG-10.53	3	103	68	123
MSID-EG-10.61	4	75	59	92
MSID-EG-10.67	3	57	51	65
MSID-EG-10.71	3	52	45	62
MSID-EG-10.77	3	61	58	63
MSID-EG-10.83	3	97	80	116
MSID-EG-10.98	4	119	92	141
MSID-EG-11.07	5	92	45	131
EG03				
MSID-EG-11.36	5	135	79	172
MSID-EG-11.47	4	63	51	82
MSID-EG-11.62	3	61	52	71
MSID-EG-11.81	5	84	55	125
MSID-EG-12.01	3	68	53	78
MSID-EG-12.09	4	90	65	128
MSID-EG-12.4	3	49	44	59
MSID-EG-12.45	3	39	29	44
MSID-EG-12.69	5	39	34	44
MSID-EG-12.94	4	48	41	52
MSID-EG-13.16	4	82	56	98
MSID-EG-13.24	2	62	55	68
MSID-EG-13.37	3	62	50	72
MSID-EG-13.43	5	53	47	61
MSID-EG-13.94	4	43	35	49
MSID-EG-14.15	1	30	30	30
MSID-EG-14.24	1	34	34	34

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-EG-14.54	3	25	22	27
MSID-EG-14.86	7	35	29	39
MSID-EG-14.98	4	34	28	39
MSID-EG-15.07	2	31	31	31
MSID-EG-15.44	5	44	40	48
MSID-EG-15.67	1	45	45	45
MSID-EG-15.79	4	52	41	59
MSID-EG-15.82	4	56	42	74
MSID-EG-16.27	1	41	41	41
MSID-EG-16.34	3	63	47	73
MSID-EG-16.51	5	54	47	59
MSID-EG-17	9	47	35	73
MSID-EG-17.15	3	56	46	67
MSID-EG-17.3	2	41	37	45
MSID-EG-17.38	2	40	38	42
MSID-EG-17.45	4	54	44	64
MSID-EG-17.72	4	105	66	125
MSID-EG-17.89	4	97	58	121
MSID-EG-17.97	2	43	37	48
MSID-EG-18.21	2	38	35	40
MSID-EG-18.28	5	74	67	86
MSID-EG-18.35	3	51	39	57
MSID-EG-18.4	2	50	47	53
MSID-EG-18.43	2	55	52	58
MSID-EG-18.6	4	37	33	46
MSID-EG-18.68	5	41	33	49
MSID-EG-18.78	7	40	37	44
MSID-EG-19.07	5	45	41	50
MSID-EG-19.28	9	44	32	64
MSID-EG-19.4	5	55	43	70
MSID-EG-19.55	3	45	34	56
MSID-EG-19.69	4	134	105	176
MSID-EG-19.89	4	153	78	206
MSID-EG-20.18	6	54	35	77
MSID-EG-20.25	5	54	43	71
MSID-EG-20.36	4	90	76	107
MSID-EG-20.47	6	81	47	106
MSID-EG-20.55	4	137	109	158
MSID-EG-20.62	2	71	62	80
MSID-EG-20.71	6	102	62	132
MSID-EG-20.89	3	84	60	105
MSID-EG-21.15	10	52	26	80
MSID-EG-21.37	3	31	25	37
MSID-EG-21.42	2	40	37	43
MSID-EG-21.49	5	80	51	98
MSID-EG-21.57	2	49	48	49
MSID-EG-21.62	4	50	39	62
MSID-EG-21.86	3	54	52	58
MSID-EG-22.07	4	36	29	47
MSID-EG-22.44	2	36	35	37
MSID-EG-22.56	3	36	31	46
MSID-EG-22.61	3	54	47	61
MSID-EG-22.74	5	56	33	68
MSID-EG-22.82	4	72	42	105

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
EG04				
MSID-EG-22.94	3	76	41	93
MSID-EG-23	2	61	45	77
MSID-EG-23.04	3	50	42	60
MSID-EG-23.19	5	119	85	157
MSID-EG-23.3	3	100	94	111
MSID-EG-23.37	3	106	92	125
MSID-EG-23.47	3	90	70	105
MSID-EG-23.6	5	194	150	263
MSID-EG-23.81	4	283	244	329
MSID-EG-24.12	3	93	54	146
MSID-EG-24.2	5	86	79	99
MSID-EG-24.3	3	55	47	71
MSID-EG-24.45	7	251	136	419
MSID-EG-24.64	4	92	46	112
MSID-EG-24.76	5	123	47	207
MSID-EG-24.86	3	44	34	56
MSID-EG-24.91	2	54	53	55
MSID-EG-24.97	4	153	104	220
MSID-EG-25.17	4	143	100	186
MSID-EG-25.47	5	146	97	213
MSID-EG-25.85	4	179	121	236
MSID-EG-25.99	4	213	142	278
MSID-EG-26.34	3	42	41	43
MSID-EG-26.41	5	90	43	129
MSID-EG-26.53	3	290	227	324
MSID-EG-26.61	4	217	173	262
MSID-EG-26.71	3	138	106	154
MSID-EG-26.8	3	210	125	287
MSID-EG-26.91	3	179	142	215
MSID-EG-27.08	4	122	62	169
MSID-EG-27.12	3	178	146	210
MSID-EG-27.19	5	190	128	311
MSID-EG-27.32	3	118	95	130
MSID-EG-27.37	2	88	81	94
MSID-EG-27.44	3	92	64	122
EG05				
MSID-EG-27.9	3	218	174	250
MSID-EG-27.97	4	150	119	169
MSID-EG-28.08	5	123	83	145
MSID-EG-28.16	4	75	57	84
MSID-EG-28.24	4	59	45	73
MSID-EG-28.32	3	67	50	79
MSID-EG-28.47	3	117	90	143
MSID-EG-28.58	4	92	65	106
MSID-EG-28.62	2	68	67	69
MSID-EG-28.65	2	34	33	35
MSID-EG-28.69	6	123	74	161
MSID-EG-28.82	5	95	68	117
MSID-EG-28.91	5	101	60	129
MSID-EG-29.08	3	69	39	91
MSID-EG-29.12	2	48	44	51
MSID-EG-29.16	3	51	26	73
MSID-EG-29.21	2	84	63	104
MSID-EG-29.25	4	135	117	147

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-EG-29.34	2	72	61	82
MSID-EG-29.41	6	144	57	183
MSID-EG-29.61	4	87	59	104
MSID-EG-29.7	4	137	69	209
MSID-EG-29.86	3	118	92	135
MSID-EG-30.42	4	197	139	246
MSID-EG-30.5	5	128	83	156
MSID-EG-30.66	4	65	50	78
MSID-EG-30.78	9	157	75	229
MSID-EG-31.1	3	115	111	119
MSID-EG-31.16	4	137	110	162
MSID-EG-31.22	2	52	46	57
EG06				
MSID-EG-31.61	4	69	35	97
MSID-EG-31.66	3	61	45	75
MSID-EG-31.71	4	113	68	138
MSID-EG-31.88	3	143	108	167
MSID-EG-32.02	8	231	122	328
MSID-EG-32.15	2	139	136	142
MSID-EG-32.22	5	118	41	199
MSID-EG-32.39	9	47	32	59
MSID-EG-32.5	3	46	43	48
MSID-EG-32.55	3	67	49	88
MSID-EG-32.6	3	95	68	130
MSID-EG-32.94	11	170	72	285
MSID-EG-33.1	2	60	49	71
MSID-EG-33.23	5	100	73	132
MSID-EG-33.34	7	89	56	117
MSID-EG-33.48	3	68	63	76
MSID-EG-33.52	2	60	52	68
MSID-EG-33.57	3	141	124	157
MSID-EG-33.64	4	72	54	108
MSID-EG-33.74	2	49	47	51
MSID-EG-34	4	72	41	99
MSID-EG-34.09	4	110	61	162
MSID-EG-34.4	5	145	110	176
MSID-EG-34.48	3	75	65	86
MSID-EG-34.53	3	76	64	88
MSID-EG-34.59	2	45	39	51
MSID-EG-34.64	3	82	55	112
MSID-EG-34.71	4	63	37	85
MSID-EG-34.79	4	116	92	143
MSID-EG-34.83	3	62	43	74
MSID-EG-34.89	5	69	43	95
MSID-EG-35.01	3	45	37	53
MSID-EG-35.17	4	50	23	66
MSID-EG-35.31	6	67	42	104
MSID-EG-35.43	2	41	34	47

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-EG-35.48	6	37	26	44
MSID-EG-35.55	2	36	36	36
MSID-EG-35.61	4	96	88	105
MSID-EG-35.75	4	61	45	76
MSID-EG-35.8	1	58	58	58
MSID-EG-35.88	3	141	120	164
MSID-EG-36.02	3	335	291	385
MSID-EG-36.11	2	97	74	119
MSID-EG-36.17	2	46	42	49
MSID-EG-36.24	4	149	79	203
MSID-EG-36.34	3	100	53	142
MSID-EG-36.41	2	199	172	226
MSID-EG-36.47	4	112	95	134
MSID-EG-36.55	3	58	51	71
MSID-EG-36.64	5	143	125	159
MSID-EG-36.73	3	102	93	108
MSID-EG-36.82	4	107	73	137
MSID-EG-37.23	4	104	91	119
MSID-EG-37.37	4	79	64	92
MSID-EG-37.51	4	103	64	141
EG07				
MSID-EG-37.83	4	56	44	65
MSID-EG-38.01	4	133	67	179
MSID-EG-38.13	7	153	111	185
MSID-EG-38.24	3	106	77	130
MSID-EG-38.36	2	39	36	42
MSID-EG-38.42	2	36	34	38
MSID-EG-38.47	2	58	55	60
MSID-EG-38.51	4	122	79	162
MSID-EG-38.56	4	90	75	113
MSID-EG-38.62	4	69	51	89
MSID-EG-39.09	2	179	137	221
MSID-EG-39.16	4	95	70	109
MSID-EG-39.34	5	47	32	70
MSID-EG-39.51	3	74	48	116
MSID-EG-39.56	3	108	55	143
MSID-EG-39.65	2	33	31	35
MSID-EG-39.69	4	37	26	45
MSID-EG-39.77	4	62	38	82
MSID-EG-39.99	5	116	72	164
MSID-EG-40.1	4	132	76	174
MSID-EG-40.7	3	156	135	198
MSID-EG-40.79	4	76	39	103
MSID-EG-40.86	2	97	94	99
MSID-EG-40.96	4	121	96	131
MSID-EG-41.19	4	97	53	130
MSID-EG-41.29	4	75	61	85
MSID-EG-41.35	3	33	30	38

Appendix B: Bridge Photos

Figure 72. Manley Road bridge on September 26, 2016. (Kestrel)

Figure 73. Springhill Road bridge on September 26, 2016. (Kestrel)

Figure 74. Airport Road bridge on September 26, 2016. (Kestrel)

Figure 75. Spain Bridge Road bridge on September 26, 2016. (Kestrel)

Figure 76. Norris Road bridge on September 26, 2016. (Kestrel)

Figure 78. Hamilton Road bridge on September 26, 2016. (Kestrel)

Figure 77. Penwell Bridge Road bridge on September 26, 2016. (Kestrel)

Figure 79. Dry Creek Road (Thompson Spring Creek enters on left) on September 26, 2016. (Kestrel)

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

Figure 81. Dry Creek School Road bridge on September 26, 2016. (Kestrel)

Figure 82. W Dry Creek Road bridge on September 26, 2016. (Kestrel)

Figure 83. Spaulding Bridge Road bridge on September 26, 2016. (Kestrel)

Figure 84. Private bridge at RM 2 on September 26, 2016. (Kestrel)

Appendix C: Reach Maps