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Big Hole River
Channel Migration Mapping

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Abstract

This report contains the results of a Channel Migration Zone (CMZ) mapping effort for approximately 111 miles of the Big Hole River from the town of Wisdom in the Big Hole Valley to its confluence with the Beaverhead River at Twin Bridges, Montana. This is a part of a larger effort to map approximately 425 miles of rivers in the Missouri River Headwaters watershed.

The Big Hole River shows highly variable conditions with respect to rates and magnitudes of change through time. The 111-mile long mapping segment has been subdivided into 13 reaches to capture this variability, which ranges from dynamic multi-thread channels in unconfined river bottoms to highly confined and steep bedrock canyons that show very little change on the scale of decades.

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

From Pintler Creek to Melrose, the river flows through a series of geologic controls including bedrock valley walls, alluvial fans, and older river terraces that confine the river corridor. Migration rates are generally low, however where the alluvial valley locally widens, channel movement tends to be discernable and measurable. Whereas the CMZ boundaries in the bedrock canyon sections are very narrow, less confined areas are more complex due to both bank erosion and channel avulsion. A propensity for ice jamming in these areas contributes to avulsion potential through mappable floodplain swales/wetland complexes.

Below Melrose, the Big Hole River dramatically changes character to a highly dynamic, coarse-grained, anabranching river system that, due to high migration rates, supports a vibrant cottonwood corridor. Meander cutoffs and floodplain avulsions are common. Shifting channel paths and local grade adjustments have created challenges to irrigation infrastructure operations, protection of residences, and bridge management. These lowermost reaches have the highest mean migration rates in the project area, ranging from 2.0 feet per year just below Melrose to 3.3 feet per year near Notch Bottom.

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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 Big Hole River Channel Migration Zone (CMZ) mapping 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, Madison, Jefferson, Gallatin, and East Gallatin Rivers, as well as updating mapping in the Ruby River Valley to include Clear Creek. The Big Hole was originally mapped in 2005 as part of a watershed characterization study (AGI/DTM, 2010). That effort included the first large scale CMZ mapping effort in Montana. Since that study, CMZ mapping methods and the availability of quality data has both improved greatly, prompting the current remapping effort. The main stem of the Ruby River from Ruby Reservoir to Twin Bridges was mapped in 2010. 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 funded through a 2013 Montana Department of Natural Resources and Conservation (DNRC) Reclamation and Development Grants Program (RDGP) titled *Upper Missouri Headwaters River/Flood Hazard Map Development*. The project is administered by the Ruby Valley Conservation District, but includes input and review from stakeholders associated with each of the mapped rivers.

1.1 The Project Team

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

1.2 What is Channel Migration Zone Mapping?

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

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

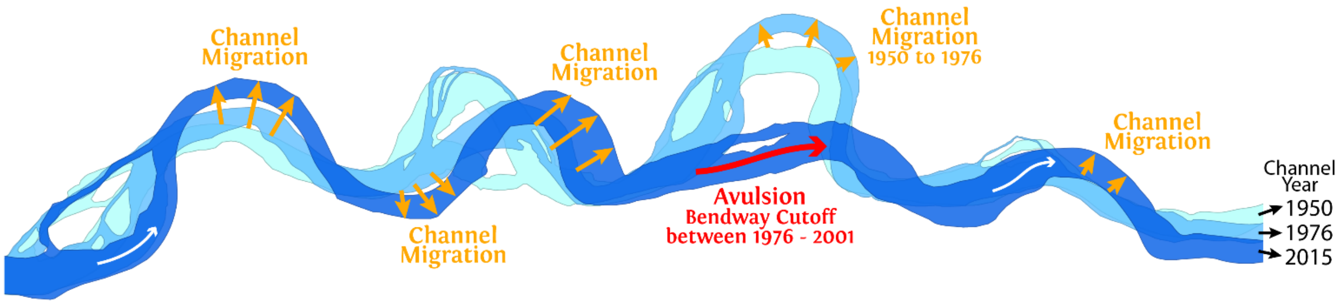

Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

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

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

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

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

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

The individual map units comprising the CMZ are as follows:

CMZ = HMZ + EHA + AHZ

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

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

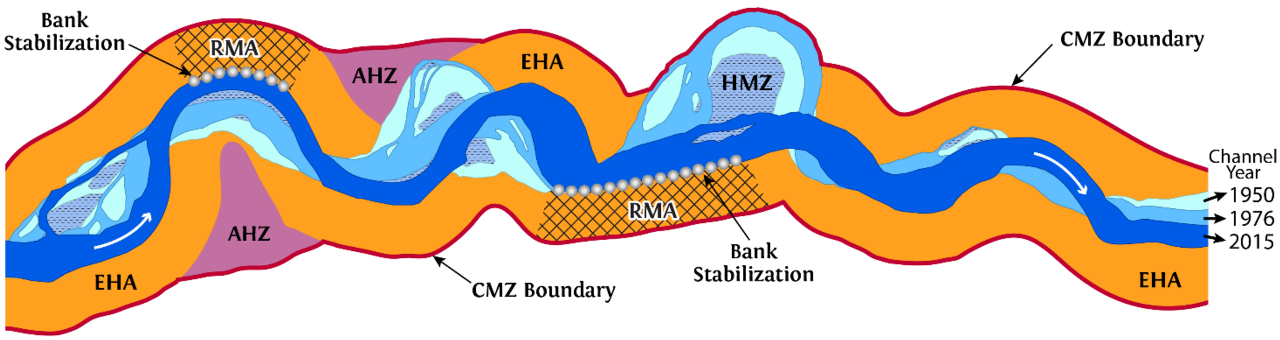

Figure 2. Channel Migration Zone mapping units.

1.3 CMZ Mapping on the Big Hole River

The Channel Migration Zone (CMZ) developed for Big Hole River extends 111 river miles from the town of Wisdom, MT in the Big Hole Valley to its confluence with the Beaverhead River at Twin Bridges, MT. No mapping was performed for the river upstream from the Hwy 41 bridge in Wisdom.

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

1.4 Uncertainty

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

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

The Big Hole River shows historic patterns of lateral migration and avulsion, locally within a very broad floodplain surface that has dense networks of historic channels. Between Dickie Bridge and Glen, the river flows through several narrow bedrock canyons where migration is geologically impeded, before flowing into a dynamic corridor downstream of the I-15 Bridge near Glen. With potential contributing factors, such as woody debris jamming, sediment slugs, tectonic deformation, landslides, or ice jams, dramatic change could potentially occur virtually anywhere on the floodplain. As the goal of this mapping effort is to highlight those areas most prone to either migration or avulsion based on specific criteria, there is clearly the potential for changes in the river corridor that do not meet those criteria and thus are not predicted as high risk.

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

1.5 Relative Levels of Risk

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

1.6 Other River Hazards

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

1.6.1 Flooding

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

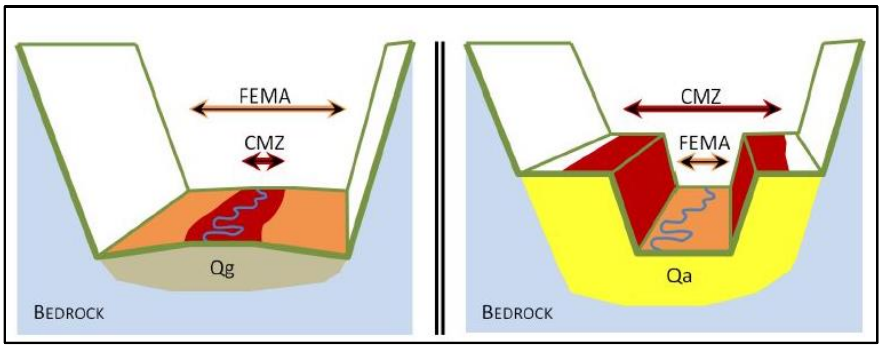

Figure 3. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

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

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

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

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

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

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

1.6.2 Ice Jams

Another serious river hazard, especially in Montana, is ice jamming. Over 1,470 ice jams have been recorded in Montana, which is the most of any of the lower 48 states (http://dphhs.mt.gov/). The ice jams are most common in February and March. Ice jams on the Big Hole River appear to form most frequently in the fairly confined river segments near and upstream of Wise River. In March 2017, ice-jam related flooding backed water up to surround a house and approach Highway 43 near Wise River (Big Hole River Watershed Committee; Figure 6). During this event Flood Warnings were issued from below Fishtrap to Divide (krtv.com). Ice-jam related flooding is an important potential mechanism for channel avulsion in this area, as the jams can by entirely blocking the river and force overflows into floodplain swales for long periods of time. This reach of river also experienced substantial jamming in 2009 and 2011 (Figure 7).

Figure 6. Big Hole River flooding due to ice jamming upstream of Wise River, March 2017 (Big Hole Watershed Committee).

Figure 7. April 2009 ice jamming near Sportsmans Park, Big Hole River (DivideMT).

1.6.3 Landslides

There are several mapped landslides that abut the Big Hole River Valley, however the potential for active movement on these slides is unknown. The geologic mapping of the landslide units indicates that "Many landslides are marked by torn sod, tilted trees, and steep unvegetated slopes that indicate continuing movement" (Rappel and others, 1993). One is located on the north side of the river just downstream of Lamarche Creek; it has a 550-acre mapped footprint and about a thousand feet away from the river. Just downstream of Wise River, there are a series of landslides mapped on the south side of the river across from the Jerry Creek alluvial fan. These landslide deposits form the active valley wall although their current level of activity is unknown. In the event that this slide is active, it has the potential to impact the course of the Big Hole River due to its location at a distinct constriction point in the river valley (Figure 8).

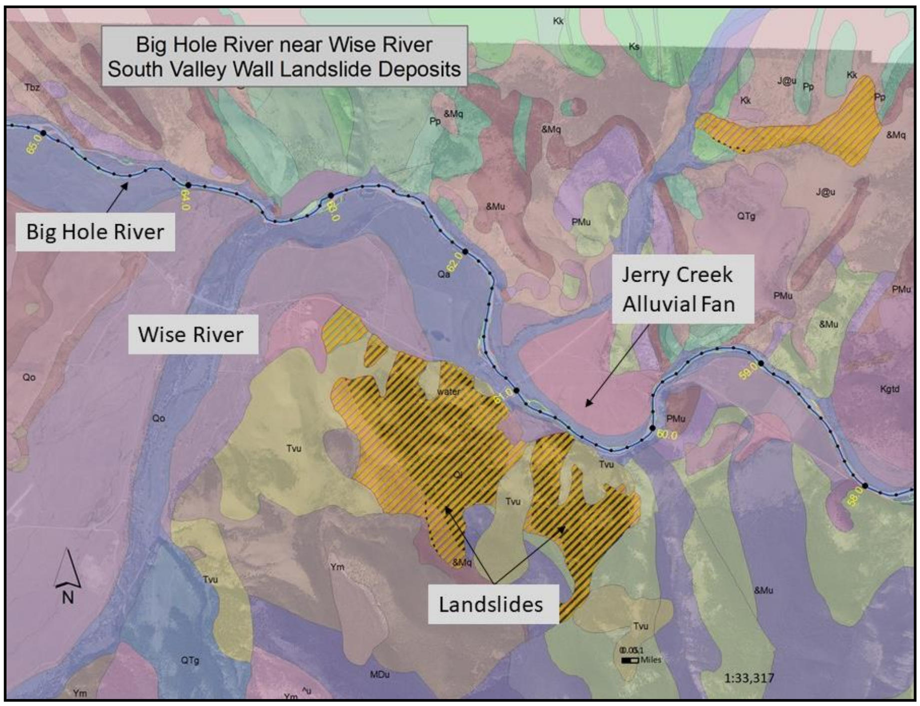

Figure 8. Mapped landslides on south valley across from Jerry Creek alluvial fan near Wise River (Ruppel and others, 1993).

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 in some cases impacts have been much worse. Probably the most recently renown landslide into a river system was the 2014 Oso Slide into the North Fork of the Stillaguamish River, which dammed the river causing extensive flooding upstream (Figure 11).

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

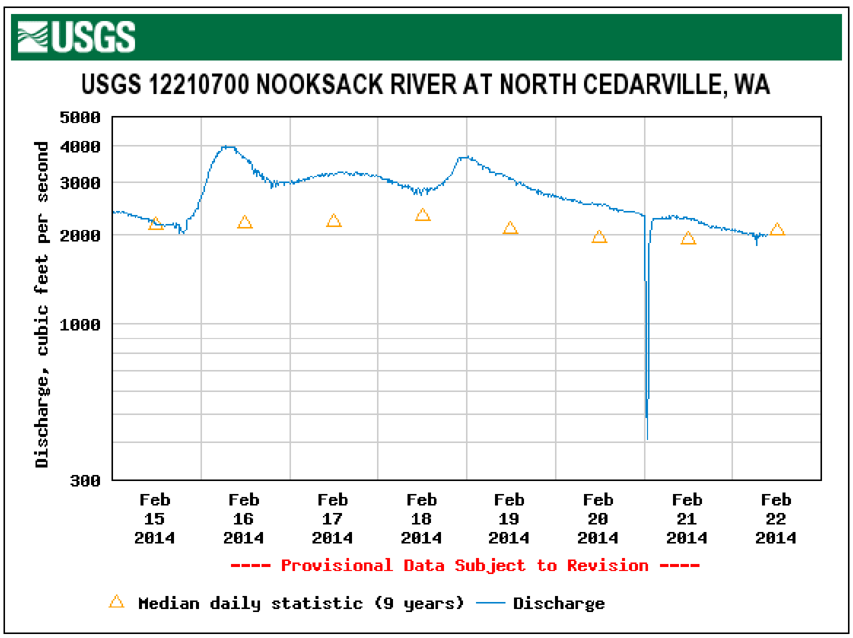

Figure 10. USGS gage data showing rapid drop in river flow following upstream hillslope failure.

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

1.7 Potential Applications of the CMZ Maps

The CMZ mapping developed for the Big Hole 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 streambank 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 David Stout and Shirley Galovic of Ruby Conservation District for their assistance in contract management and scheduling, and Jennifer Downing (Big Hole Watershed Committee Executive Director) for her detailed review. 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 General Project Setting

The following section contains a general description of the overall setting of the project reach, to provide some context as to how various natural and human influences may affect river process.

2.1 Geography

The Big Hole River in southwest Montana is one of two tributary rivers that form the Jefferson River, along with the Beaverhead and Ruby Rivers (Figure 12). It is approximately 153 miles long, with a watershed area of 2,789 square miles, or 20% of the total area of the Missouri Headwaters watershed. The Big Hole River headwaters are at Skinner Lake in the Beaverhead Mountains along the Montana/Idaho border. The geography of the watershed is highly varied, with elevations ranging from over 10,000 feet in the Beaverhead Mountains Range to approximately 4,600 feet at Twin Bridges.

The river takes its current name from the Big Hole Valley, a name used by early ranchers in the area. According to the Montana Standard (2005):

> *Captain William Clark, who in 1806 stopped at present-day Jackson Hot Springs in the Big Hole Valley of southwest Montana, noting that meat could be cooked in the steaming water in less than six minutes, named the area Hot Springs Valley. ….And the captains of the Corps of Discovery named the Big Hole River "Wisdom River" for the astuteness of "the author of our enterprise, President Thomas Jefferson." The town of Wisdom in the Big Hole Valley has kept the name alive, but the river lost that moniker and took on the name of the valley where it headwaters.*

The Big Hole River is commonly broken up into Upper, Middle, and Lower segments. The upper section runs from the headwaters to the Pintler Creek. This section consists of a wide, high-elevation floodplain with multiple channel threads, and a broad willow-dominated riparian corridor. This section of river hosts fluvial arctic grayling. The upper Big Hole Valley was originally named by the Flatheads as *La-im-tse-la-lik*, or "the place of the ground squirrel (Davis, 2015). It supported extensive stands of the camas plant, which was a staple and trading good for Native Americans tribes. Camas is a bulb-producing lily that was one of the most widely utilized plant foods of the Nez Perce people. The Battle at Big Hole occurred at a traditional Nez Perce camas harvesting campsite (National Park Service).

Between Pintler Creek and Melrose, the river flows through the "Canyon Section", which is a series of canyon segments separated by short alluvial reaches. The canyons are bound by steep bedrock valley walls which contribute coarse sediment to the bed and banks of the river. This reach includes the communities of Wise River, Dewey, and Divide. Between Divide and Melrose, the river flows through Maiden Rock Canyon which is a notable historic mining area. Below Melrose, the lower Big Hole River is a dynamic, cottonwood-dominated alluvial bottom that has braided channel segments. Floodplain irrigation is extensive, the channel is dynamic, and numerous bridges cross the corridor that create challenges in planform management. Brown trout are dominant in the lower river.

The Big Hole River flows through or forms the border for four counties. The upper river flows through Beaverhead County throughout the Big Hole Valley. At Pintler Creek (RM 94.5) the river forms the boundary between Beaverhead and Deer Lodge Counties. Just below Bear Creek (RM 72.6) the river forms the boundary between Beaverhead and Silver Bow Counties. Finally, at the town of Melrose, the river forms the boundary between Beaverhead and Madison Counties.

2.2 Historic Land Use

Major historic influences on the geomorphology of the Big Hole River begin with the fur trade of the 1800s and continue today with agriculture, transportation, and residential development in the river corridor. Lewis and Clark originally described the Big Hole as containing "emence numbers of beaver", and active trapping was recorded by 1829 (Davis, 2015). The extensive trapping of beaver had a profound impact on stream geomorphology throughout the Northern Rockies, with flow consolidation into fewer channels, increased flow velocities, lowered groundwater tables, loss of wetlands, and loss of woody riparian extent and vigor. According to Davis (2015), "In the case of the Big Hole, the absence of beaver is a major contributor to the desertification of valley floors". By the 1840s fur trapping was on the decline because of falling prices and low beaver numbers.

The next stage of human impacts on the Big Hole River was associated with the discovery of gold near Bannack in 1862. This rapid development drove increased summer grazing in the upper Big Hole Valley to support miners. As mining declined, cattle ranching and livestock became a staple of the local economy. The natural grasses of the Big Hole Valley became renowned, described in 1900 as "the best to be found any place. It will fatten without grain, any animal that can be fattened" (Davis, 2015). By that time Big Hole cattle were shipped as far as Chicago, Seattle, and Dawson City. The impacts of intensive livestock grazing on river corridors has been well-studied, and includes loss of riparian vegetation and associated change in stream morphology, lowering of groundwater elevations, and increasing water temperatures and icing. The livestock industry is still dominant in the upper Big Hole Valley, which is often called the "Valley of 10,000 Haystacks".

The Maiden Rock Phosphate Mining District is located upstream of Melrose. Phosphate was discovered in the canyon around 1910, and mined as early as 1921. Ore was shipped to Silver Bow for processing. The mine was closed in 1963 and has since undergone substantial reclamation (Gableman, 2012). According to the USGS, the Maiden Rock and nearby Canyon Creek mine may have produced several million dollars in phosphate through the mid-1960s (Lowen and Pearson, 1983).

River corridor land uses today are still dominantly agricultural, with extensive diversions, ditch networks and floodplain irrigation in both the upper and lower river segments. Residential development along streambanks is becoming increasingly common, and transportation infrastructure commonly dissects the valley bottom and intersects the stream corridor.

2.3 Ongoing Conservation Efforts

Significant conservation effort in the Big Hole River valley has occurred since the early 1990's. Early efforts focused on drought, specifically low flows in the river late into the summer and its impact on fish. The Upper Big Hole River is home to native Arctic grayling that suffered decline as a result of poor river conditions leading up to the early 1990's and thus helped spur conservation. As conservation progressed, work expanded to improve water quality, specifically addressing high water temperatures in summers, high sediment loads due to changes in streamside habitats, and high nutrient loads in limited locations either naturally occurring or from livestock, or metals from past mining practices. In the last decade, work expanded further into floodplain health, specifically floodplain development tools to help guide new river development in congruence with the river as well as incentivize healthy floodplain function. Using easements to limit or omit floodplain disturbance has also been an effective tool in the valley. Many millions of dollars have been invested across the watershed to restore natural stream, river, and floodplain function to benefit fish as well as the river's natural course to improve conditions for fish, support sustainable ranching and thereby open lands, integrate progressive development standards, coordinate response to drought conditions, and improve water quality and drought resiliency. The work has been and continues to be completed by many agencies, conservation groups, individuals, funders, and conservation-minded landowners, most notably by Montana Fish, Wildlife and Parks (also operator of the Conservation Candidate Agreement with Assurances for the Arctic grayling), Big Hole Watershed Committee (Land Use efforts in partnership with Future West), and The Nature Conservancy.

2.4 Geology and Geomorphology

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

2.4.1 Upper Big Hole River (Above Pintler Creek)

The headwater areas of the Big Hole River consist of relatively steep, historically glaciated drainages that flow through timbered uplands of the Beaverhead-Deerlodge National Forest. The western edge of the valley is formed by the Beaverhead Mountains, which are comprised primarily of extremely old Proterozoic-age metamorphic and sedimentary rocks (542 million to 2.5 billion years old). To the east, the Pioneer Mountains are made up of considerably younger Cretaceous-age granitic rocks (79 million to 145 million years). Even younger granitic rocks are exposed in the Anaconda Range to the north. These rocks are Tertiary in age (65 million to 2.4 million years old), and overlap in age with the upper Big Hole Valley basin fill deposits, which are Tertiary in age and almost 14,000 feet thick (Alt and Hyndman, 1986). The Continental Divide follows the crest of the Beaverhead mountains to the west and the Anaconda Range to the north.

Approximately 10 miles south of Jackson, the river emerges into the upper Big Hole River Valley, which has been described is the "highest and widest of the broad mountain valleys of western Montana" (Alt and Hyndman 1986). Wisdom lies at an elevation of 6,050 feet. The valley is known for having an exceptionally short growing season, with an average of 45 frost-free days per year. Several major tributaries join the river in this valley, including Governor Creek, Warm Springs Creek, the North Fork Big Hole River, and Pintler Creek. Through this broad, high elevation valley, the river flows through a sinuous willow corridor, commonly within a complex network of multiple low gradient channels. Numerous abandoned channel remnants are present on the floodplain, and some of these old channels have been converted to ditches. In many areas, such as just north of Wisdom, relic channels become more prominent in the downstream direction due to flow gains from tributaries, groundwater, and irrigation returns.

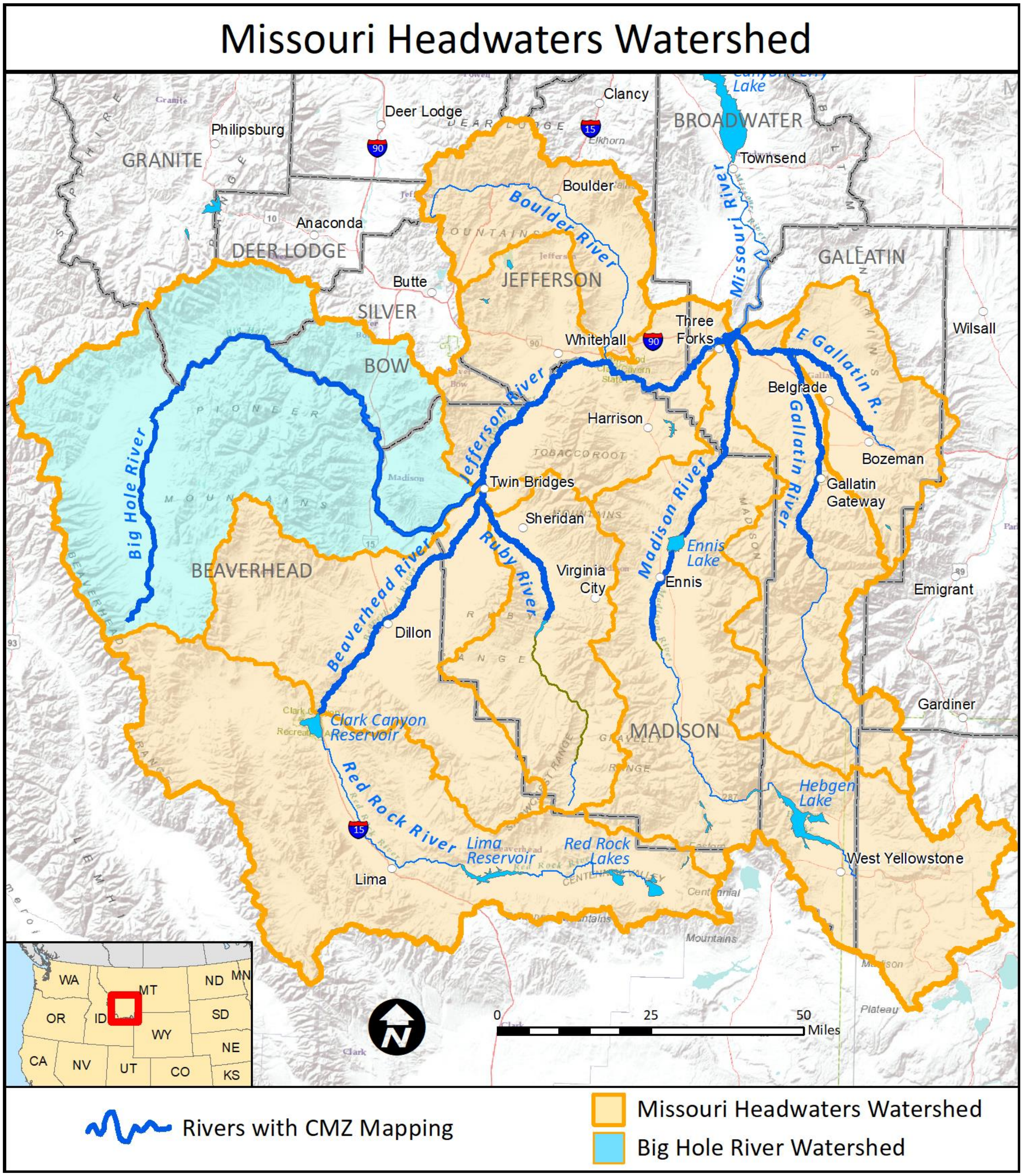

Figure 12. Big Hole River Watershed.

2.4.2 Middle Big Hole (Pintler Creek to Melrose)

Just upstream of the Pintler Creek confluence, the Big Hole River enters an increasingly confined valley, with granites of the Pioneer Batholith forming the south valley wall and Bozeman Formation sediments on the more topographically-subtle north wall. The river confinement between Pintler Creek and Melrose is highly variable, with some sections narrowed to essentially the channel width and others supporting relatively broad swaths of river floodplain and low terraces. From Pintler Creek to Dewey, inset terrace/floodplain surfaces are common, although channel migration rates are low, bed and bank substrate is coarse, and the riparian corridor is notably narrow. That said, the terrace and floodplain surfaces support distinct swales indicative of historic fluvial disturbance, either through flood scour driven by spring runoff or ice jamming. Wetlands are commonly established in these low swales. Numerous tributaries enter the river in this reach, including Fishtrap Creek, LaMarche Creek, Deep Creek, and the Wise River. In some areas Highway 43 has isolated historic floodplain area from the river.

At Dewey the river enters an approximately 4-mile long canyon segment that flows through Cretaceous-age granites to the water intake near Divide. This canyon is closely followed by Highway 43 and has very little floodplain area or riparian fringe. From Divide to Maiden Rock Canyon, the river is mildly sinuous but minimally deformable, flowing thorough low older terraces that show little susceptibility to fluvial erosion. One mapped landslide at RM 50.0 on the west side of the river extends from a small tributary drainage to the edge of the stream corridor, but there is no evidence that it has affected river process. The river flows into Maiden Rock Canyon at RM 49.0. For the next seven miles it flows through a deep and narrow canyon that hosts a multitude of abandoned mines. The Maiden Rock Quarry is an old limestone mine, and other mines have produced phosphorite, uranium, fluorine, chromium, and nickel.

2.4.3 Lower Big Hole River (Melrose to Mouth)

Through Melrose, the Big Hole River flows through an open, heavily irrigated valley bottom that contains long sections of split flow through two main river channels. Just downstream of Melrose, the river flows through a moderately confined reach that is bound by volcanic rocks to the west and transportation infrastructure to the east. From the interstate crossing to a prominent hogback ridge southeast of Glen, the river bottom is wide and multiple channel threads are common. This hogback ridge constitutes a major north/south geologic control that abruptly constricts the valley bottom. Upstream of this constriction, the Big Hole River corridor contains a network of channel threads and apparent groundwater sourced channels. This complex channel pattern potentially reflects the narrowing and shallowing of river alluvium at the constriction, and consequent upwelling of groundwater in the reach. Downstream of the geologic control, the river flows through two broad valleys separated by similar, but less prominent geologic constrictions.

From the lowermost geologic control, past Pennington Bridge to the High Road Fishing Access, the lower Big Hole River flows through a wide active meander belt with numerous floodplain channels and scars that reflect dynamic channel conditions. A network of sloughs parallels the channel as it approaches the Beaverhead River confluence. Below the High Road Fishing Access, the Big Hole River is braided along its course to the Beaverhead River. Extensive split flows and unvegetated bars are present, and these conditions continue beyond the confluence, along the Jefferson River. Historic air photos indicate that the confluence with the Beaverhead was located several miles to the north of its current position in the early 1940s. Sloughs visible on topographic maps (e.g., Schoolhouse Slough and Owsley Slough) suggest that sometime prior to 1940, the Big Hole/Beaverhead confluence was located south of Twin Bridges. The complex channel patterns and recorded avulsions associated with the mouth of the Big Hole River indicate that the open, flat convergent zone between the Beaverhead and Big Hole River valleys has created a highly dynamic river environment.

2.5 Hydrology

There are currently no major impoundments that affect streamflows on the Big Hole River, although a myriad of smaller diversions collectively influence system hydrology, especially low flows. With regard to CMZ mapping, the flood history is an important aspect of physical context, because flooding can be a major driver of channel movement. To that end, the following is a very brief summary of the flood history on the Big Hole River.

2.5.1 Major Diversion Structures

Although there are no diversions into major canals on the Big Hole River, the Montana Department of Natural Resources and Conservation Water Rights data show 237 headgate and 15 diversion dams listed as active points of diversion for the Big Hole River from Wisdom to the mouth. Although these structures do not substantially impact river processes, the headgates and ditches commonly require site management that may include bank armoring, in-stream berm construction and/or grade controls. Ditches that run parallel to the river can also create avulsion risks. Some example photos of irrigation infrastructure are compiled in Appendix B.

2.5.2 Big Hole River Flood History

Flooding patterns on the Big Hole River are typical in Southwestern Montana in that they reflect rapid, high-elevation snowmelt in spring. As is also common on Montana's rivers, the Big Hole typically shows two spring snowmelt peaks: one in early spring when the lowland melt occurs in the valley bottom, and another later when the high elevation melt occurs in late spring (Atkins, 2013). The north-south trending upper Big Hole Valley shows more complexity; with the Pioneer Mountains on the east side of the valley experiencing snowmelt earlier than the east and south facing slopes on the Continental Divide to the west (Davis, 2015).

The most complete flood record on the Big Hole is from the USGS Melrose Gaging Station, which has been active since May of 1924 (USGS 06025500, Figure 14). The gage was installed just three years before recording the biggest flood to date, when in 1927 a dam failed on Pattengail Creek, a tributary to the Wise River. Pattengail Creek was named after a Civil War Veteran named George Pattengill, who was locally referred to as the "Wild Man of Montana"; Pattangail was a local character who lived in a wikiup and "regularly frightened Butte fisherman until his demise in 1895" (Davis, 2015). The dam was constructed to support irrigation in the area, but the dam failed in 1927 after a season of heavy snows and spring rain, creating a twenty-five foot wall of water that wiped out structures in Dewey and Wise River, killing four people in the process (Figure 13). The flood produced a flood of 23,000 cfs at Melrose. This site has since been reconsidered for new dam construction and storage (Davis, 2015).

The largest flood on record that was not related to a structural failure occurred in 1972, when the Melrose gage recorded a peak discharge of 14,300 cfs. Since that time, substantial floods occurred in 1975, 1995, 1996, 1997, and 2011 (Figure 14).

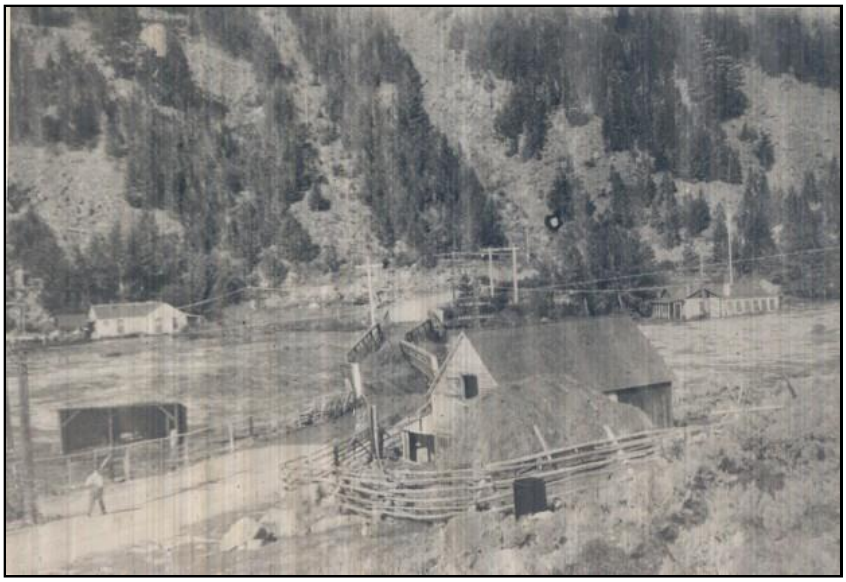

Figure 13. 1927 photo of Big Hole River Bridge washout following Pattengail Reservoir failure.

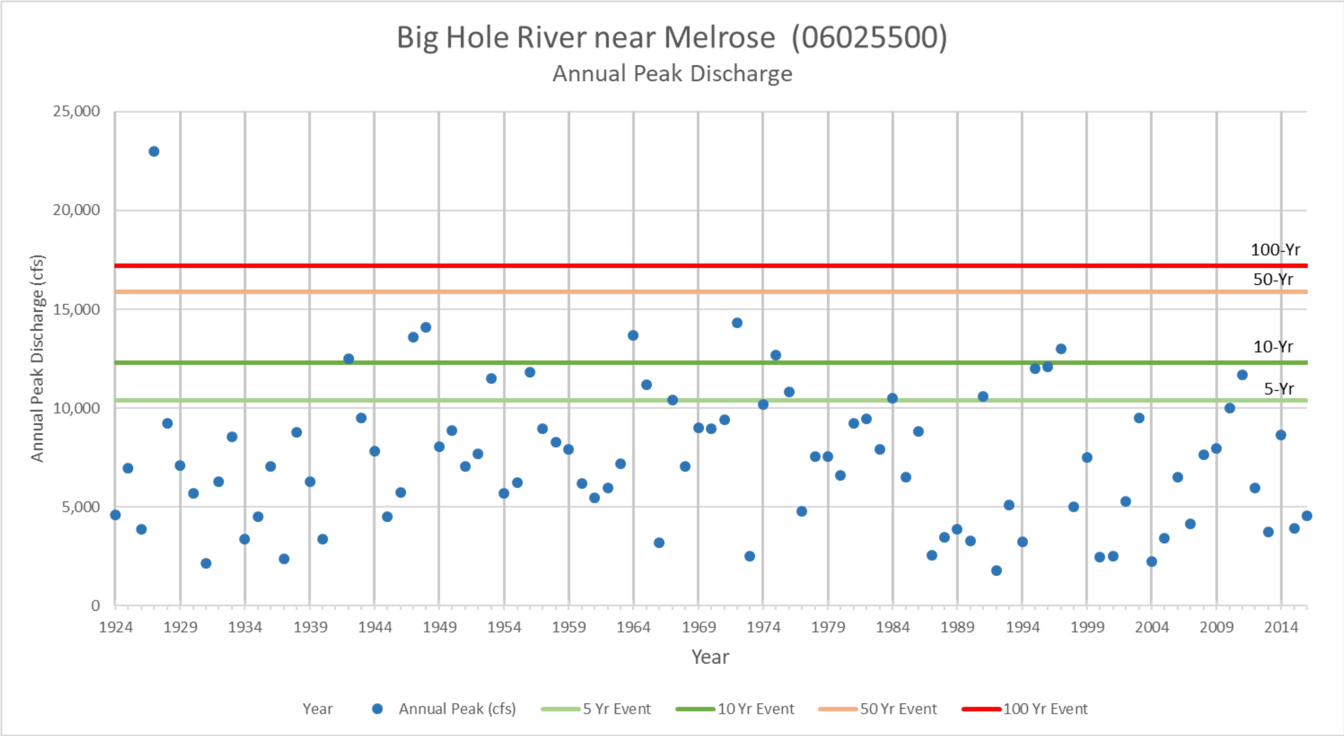

Figure 14. Annual peak flood record, Big Hole River near Melrose.

2.6 Dikes and Levees

The Big Hole River is largely devoid of dikes and levees. Only one short section, approximately 1,100 feet long, was mapped between Wisdom and Twin Bridges. This feature may have been longer at some point in time, though it is currently being flanked on the upstream end.

2.7 Bank Armor

The extent of bank armor on the Big Hole River is very limited, with only approximately 2% of the total bankline excluding islands being armored. Most of the armor is associated with roads and irrigation canals that parallel the river corridor, often where the river is already confined by valley walls. As such, the amount of bank armor on active channel sections that limits channel migration is very low. See Section 4.3 for a detailed review of bank armor and its impact on the river corridor.

2.8 Transportation Infrastructure

With the exception of bridges, transportation infrastructure does not have a large influence on the Big Hole River. Twenty-two bridges were identified between Wisdom and Twin Bridges. These bridges locally constrict the river corridor, presenting management challenges as the channel approach to a bridge is actively changing position. Local roads, and in one section the railroad, parallel the river corridor. This is often in canyon sections where the river is already constrained by valley walls, and thus has little impact on channel processes.

3 Methods

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

3.1 Aerial Photography

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

Several imagery sources are available for the Big Hole 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 163 individual images were ordered from the APFO to cover two time periods for the Big Hole River. The area around Twin Bridges is shared by the Jefferson, Beaverhead, and Ruby Rivers, so there is some common imagery between the four rivers.

The scans were delivered as high-resolution (12.5 micron) TIFF images, each approximately 350 MB in size. They were then orthorecitified by Aerial Services, Inc. (ASI) in Cedar Falls, Iowa, using 2015 NAIP imagery as the spatial reference, providing identifiable ground control points. The resulting mosaics were assessed for spatial accuracy using National Spatial Data Accuracy standards, along with assessing the image quality. In some areas, the project team requested adjustments to the spatial fit to provide a higher degree of spatial accuracy.

Table 1 lists imagery used for this project from the USDA and archives of current GIS data sets. Examples of the imagery used in the analysis are shown in Figure 15 through Figure 17.

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

Date	Source	Scale	Notes
1955	USDA APFO	1:20,000	High-resolution Scans (black-and-white)
1979	USDA APFO	1:40,000	High-resolution Scans (black-and-white)
2015 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)

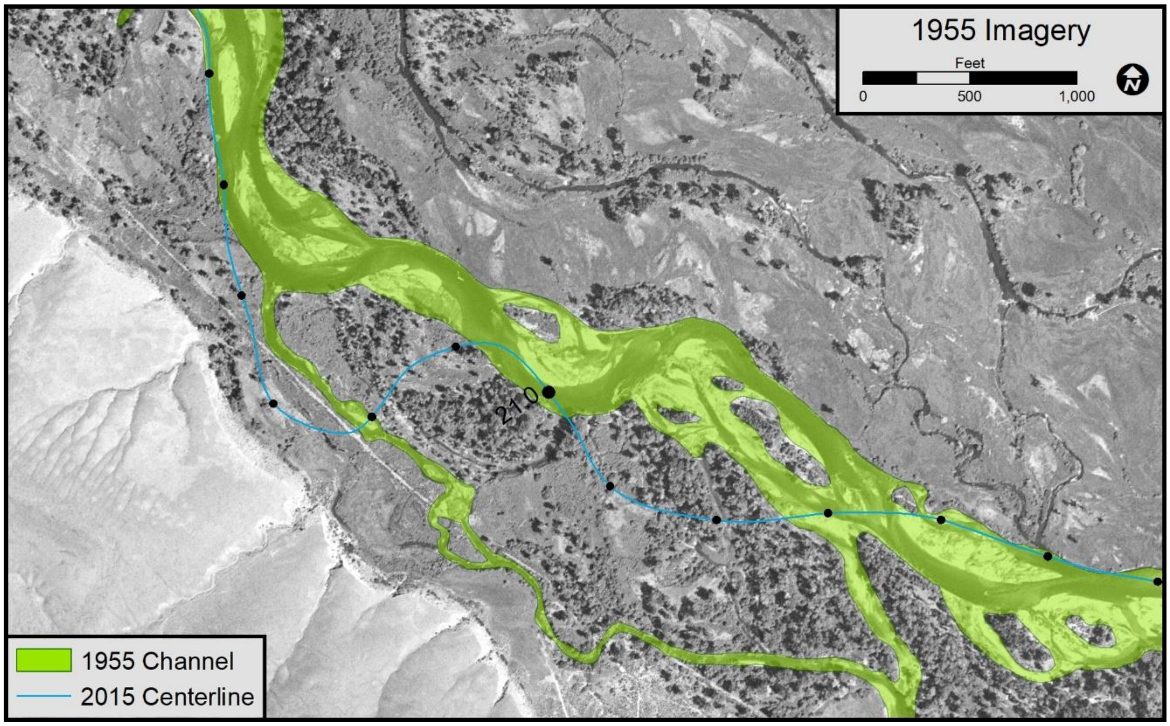

Figure 15. Example 1955 imagery, Big Hole River CMZ development (above Notch Bottom, Reach 3).

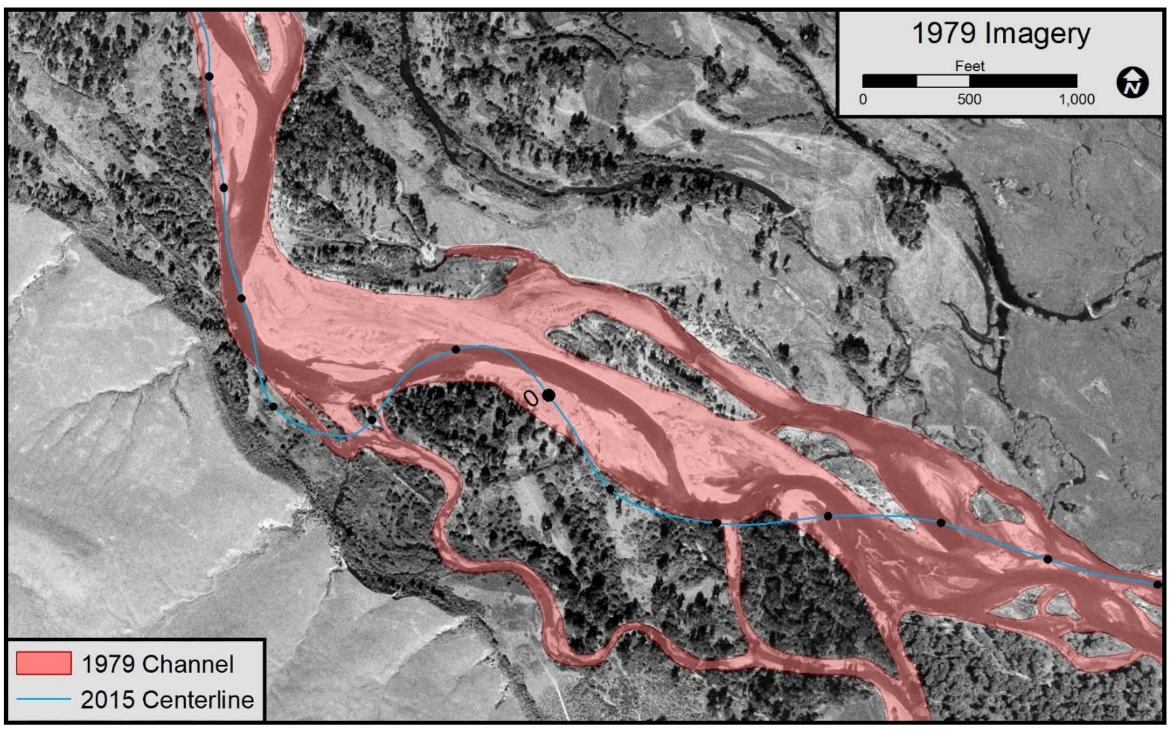

Figure 16. Example 1979 imagery, Big Hole River CMZ development (above Notch Bottom, Reach 3).

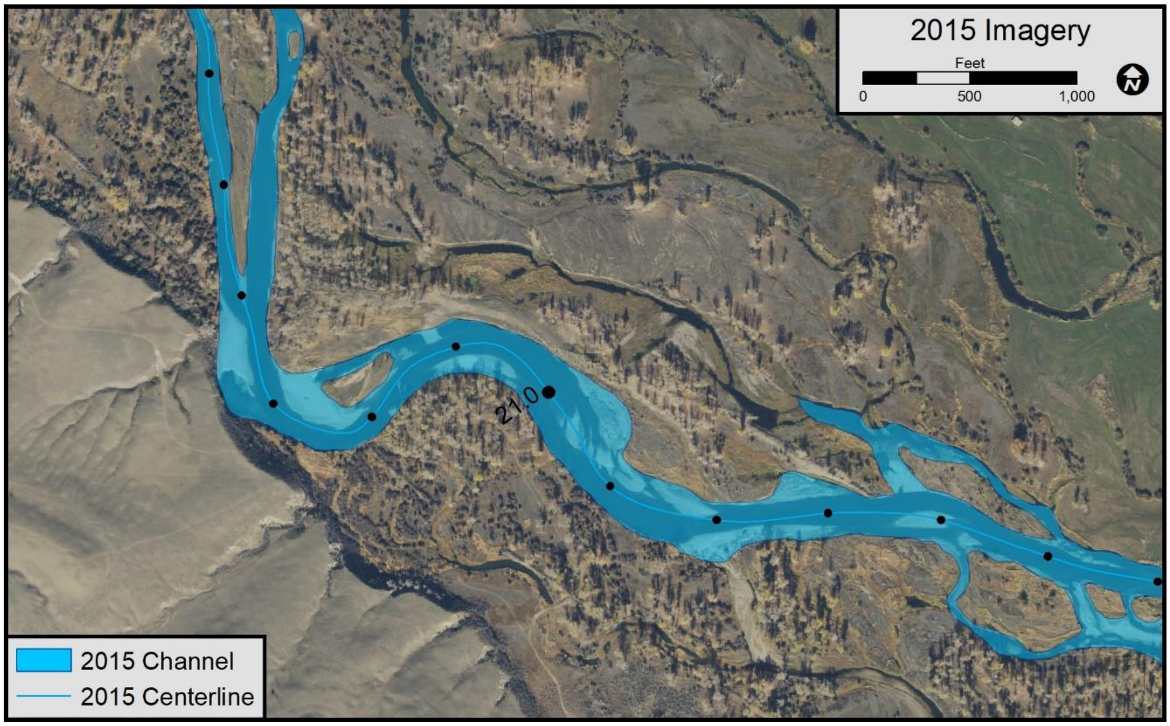

Figure 17. Example 2015 imagery, Big Hole River CMZ development (above Notch Bottom, Reach 3).

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 Big Hole mapping utilizes this reference system. The orthorectified air photos provide the basis for CMZ mapping. In addition to the specific project data created for this study, other data included roads, stream courses as depicted in the National Hydrography Dataset, scanned General Land Office Survey Maps obtained from Bureau of Land Management, and geologic maps produced by the United States Geological Survey (Harrison et al., 2000).

3.3 Bankline Mapping

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

3.4 Migration Rate Measurements

Once the banklines were developed, they were evaluated in terms of discernable channel migration since 1955. Where migration was clear, vectors (arrows with orientation and length) were drawn in the GIS to record that change. At each site of bankline migration, measurements were collected at approximately 80 foot intervals (Figure 18). A total of 1,165 migration vectors were generated for the Big Hole River. These measurements were then summarized by reach. The results were then used to define a reach-scale erosion buffer width to allow for likely future erosion. Results of this analysis are summarized in Section 4.3.

Each location of channel migration was assigned a Migration Site ID based on the river mile location of the site. Each site may have anywhere from 1 to 11 migration vectors, depending on the length of the site. A total of 236 migration sites were identified throughout the study area. An accounting of the reach and site based statistics can be found in Appendix A.

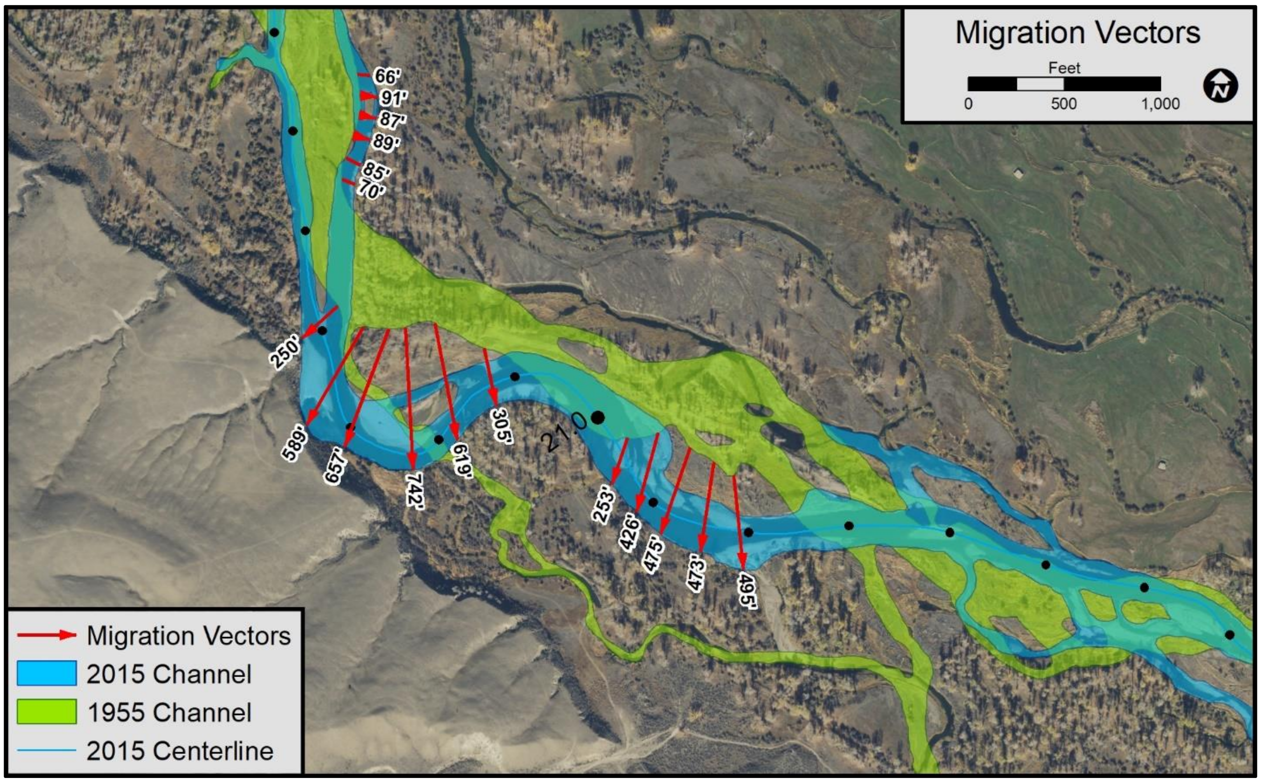

Figure 18. Example of migration measurements (migration distance in feet).

3.5 Inundation Modeling

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

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

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

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 alternate data sets such as 5-meter radar can still provide excellent results. The 2014 Big Hole River Approximate Level Floodplain Study (RESPEC, 2014) utilized a 2008 5-meter IFSAR elevation data for to floodplain mapping of the Big Hole River. While this data set would be ideal for inundation modeling, licensing restrictions prohibited its use for the current CMZ study. Thus, we relied on the inundation model generated as part of the 2005 *Big Hole River CMZ and Inundation Potential Mapping Study* that used 30-meter USGS DEM. This model still provides sufficient resolution to identify broad trends in the floodplain. When combined with the 2014 flood mapping (RESPEC, 2014), these data sets can help identify potential overflow and avulsion pathways (Figure 19).

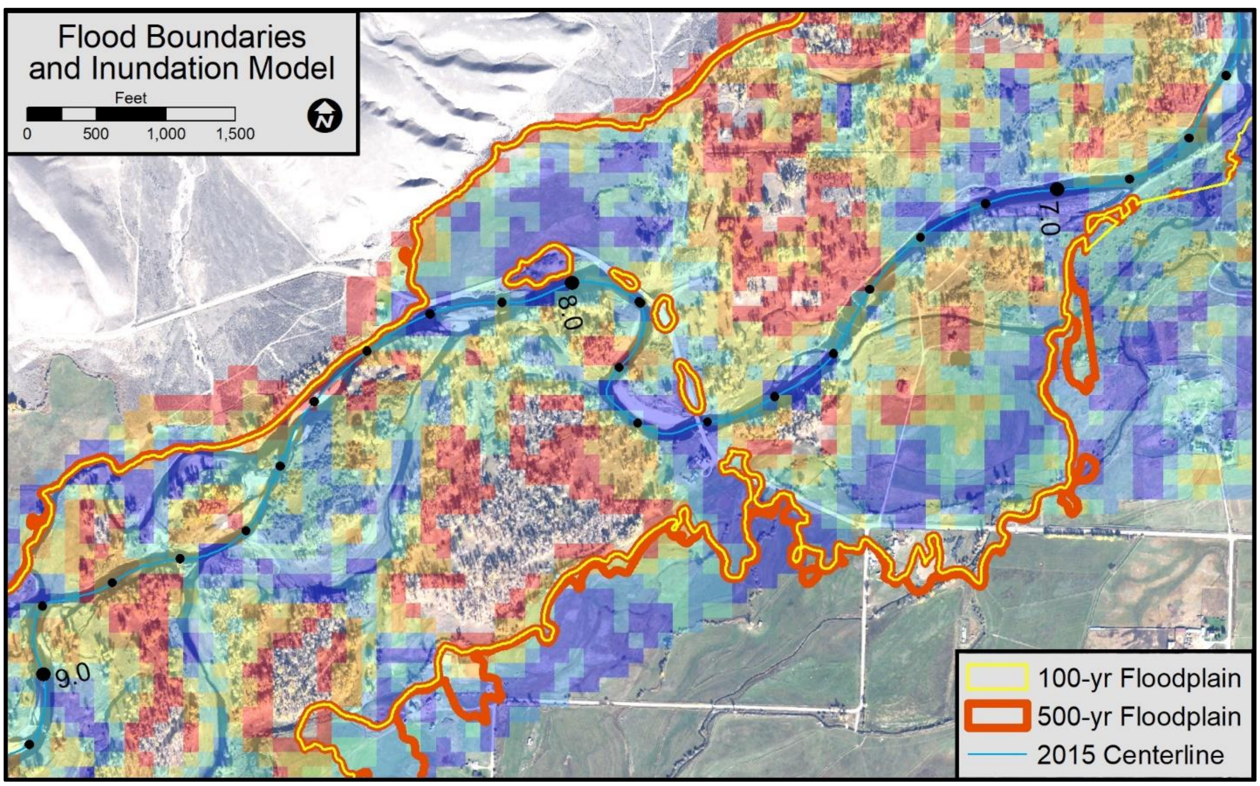

Figure 19. Example Inundation Modeling results with floodplain modeling. Colors represent elevations relative to the elevation of the main channel. Dark blue areas are equal to or lower than the channel. Yellows and reds are significantly higher than the adjacent main channel.

3.6 Avulsion Hazard Mapping

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

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

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

Where available, the GIS-based inundation model and floodplain modeling discussed in Section 3.5 were used to help identify potential avulsion pathways. These pathways were identified as low continuous swales with connectivity to the river (Figure 20). Additional information used in mapping avulsion paths included oblique photos from Kestrel Aerial Services and air photos.

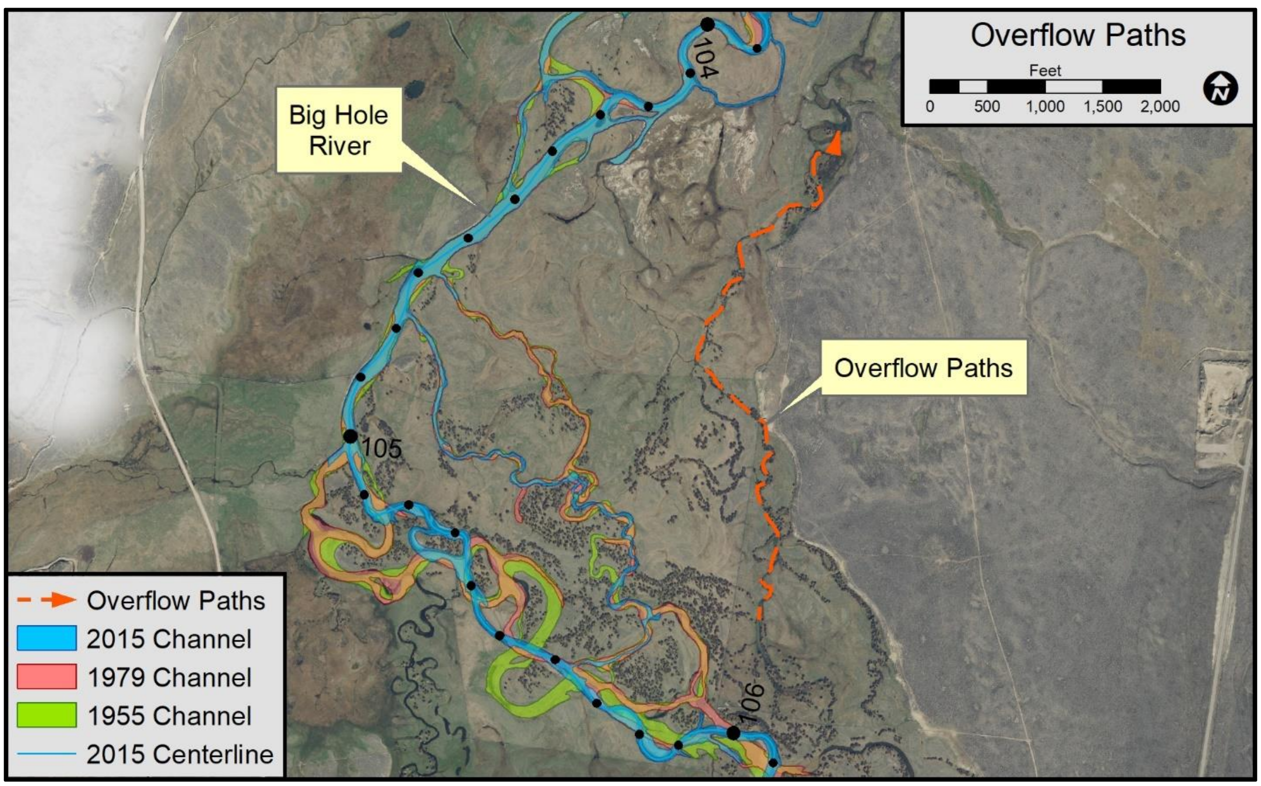

Figure 20. A long overflow path and potential avulsion pathway.

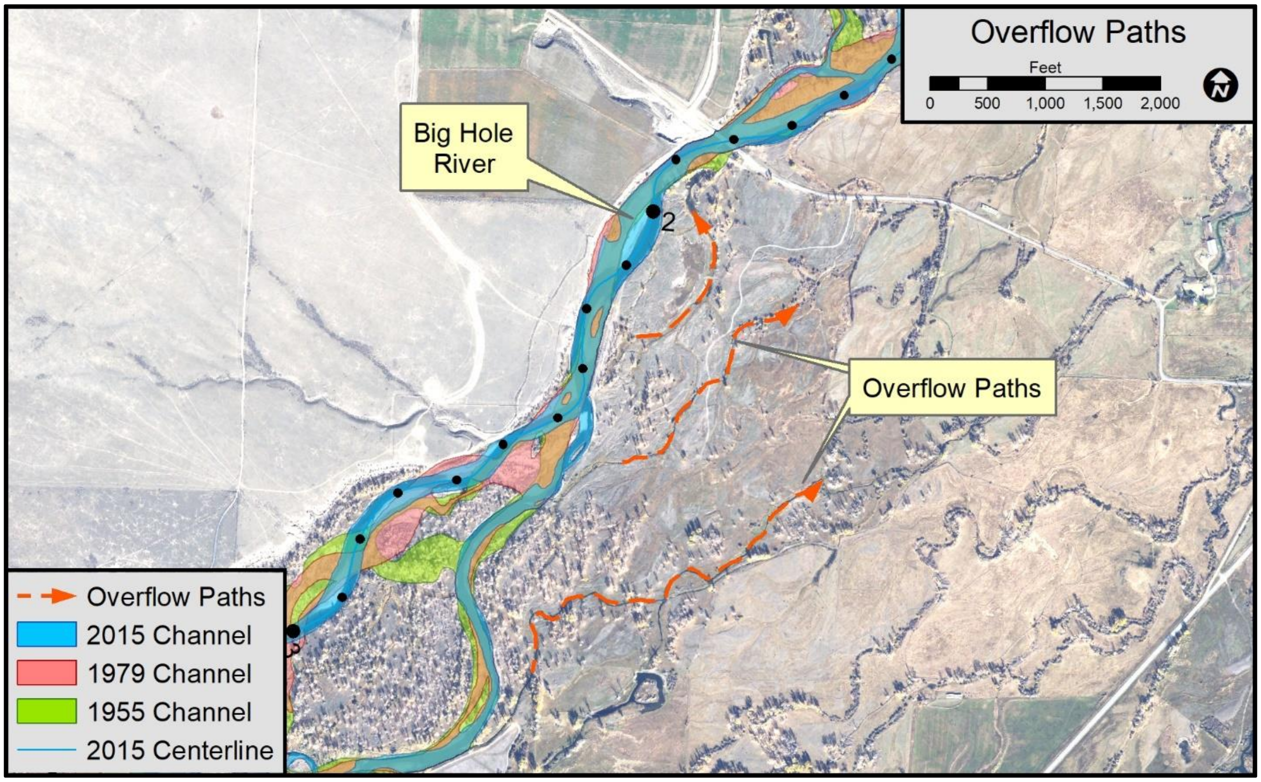

Figure 21. Extensive overflow paths in the lower river.

4 Results

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

4.1 Project Reaches

The approach to CMZ mapping used here includes a reach-scale evaluation of channel migration rates. For the 111 miles of project length, the river was broken into thirteen reaches based on geomorphic character such as river pattern, rates of change, geologic controls, etc. (Figure 25). The reaches range in length from 4.1 to 19.1 miles (Table 2). Figure 22 shows the estimated channel slopes for each reach. Reaches BH11 and BH12 have notably low gradients; this stretch of river extends from point where the North Fork Big Hole distributary channels begin to join the Big Hole River, downstream to the Highway 43 Bridge at North Fork Road.

Table 2. Big Hole River reaches.

Reach	General Location	Upstream RM	Downstream RM	Length (mi)
Reach 1	Beaverhead/Jefferson confluence to canyon mouth 2.4 miles above Pennington Bridge Road	10.1	0.0	10.1
Reach 2	Canyon mouth 2.4 miles above Pennington Bridge Road to Notch	17.7	10.1	7.6
Reach 3	Notch to I-15 Bridge upstream from Glen	30.8	17.7	13.1
Reach 4	I-15 Bridge upstream from Glen to below Cherry Creek, 2.8 miles below Melrose	35.7	30.8	4.9
Reach 5	Below Cherry Creek, 2.8 miles below Melrose, to Maiden Rock Canyon mouth	41.7	35.7	6.0
Reach 6	Maiden Rock Canyon	48.6	41.7	6.9
Reach 7	Maiden Rock Canyon to Hwy 43 Bridge	52.7	48.6	4.1
Reach 8	Hwy 43 Bridge to 0.5 miles downstream of Dewey	56.8	52.7	4.1
Reach 9	0.5 miles downstream of Dewey to 0.5 upstream of Deep Creek	75.9	56.8	19.1
Reach 10	0.5 miles upstream of Deep Creek to Hwy 43 Bridge at N. Fork Road	88.7	75.9	12.8
Reach 11	Hwy 43 Bridge at N. Fork Road to 0.5 miles upstream of Pintler Creek	95.0	88.7	6.3
Reach 12	0.5 miles upstream of Pintler Creek to upstream end of North Fork distributary channels	102.6	95.0	7.6
Reach 13	Upstream end of North Fork distributary channels to Wisdom Bridge	111.3	102.6	8.7

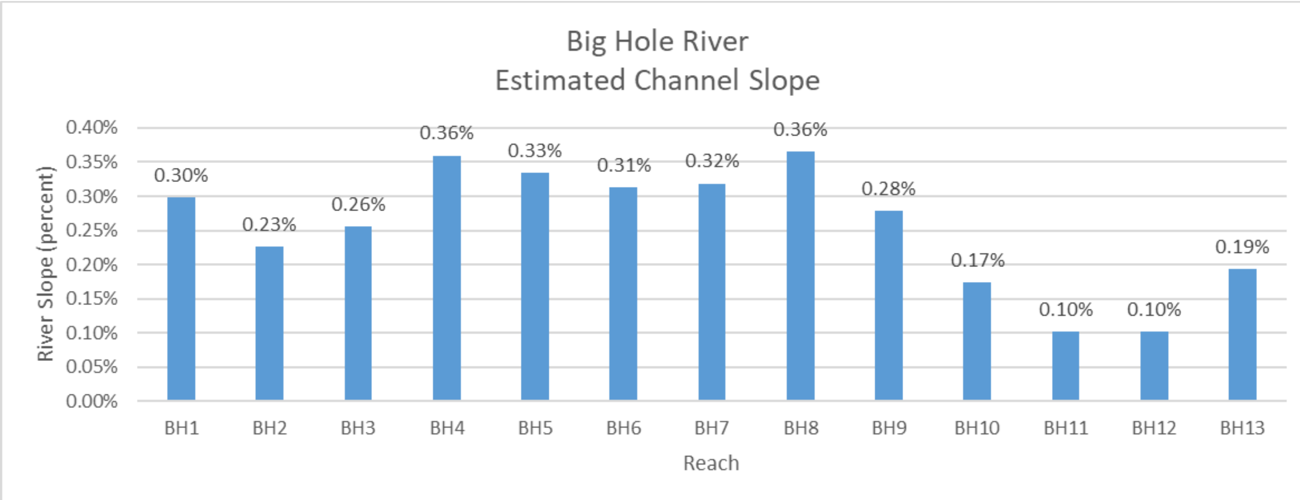

Figure 22. Estimated channel slope (in percent) for Big Hole project reaches.

4.2 The Historic Migration Zone (HMZ)

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

Any side channels that have not shown unrestricted connectivity to the main channel since 1955 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 Big Hole River channel locations in 1955, 1979, and 2015 (Figure 23). The resulting area reflects 60 years of channel occupation.

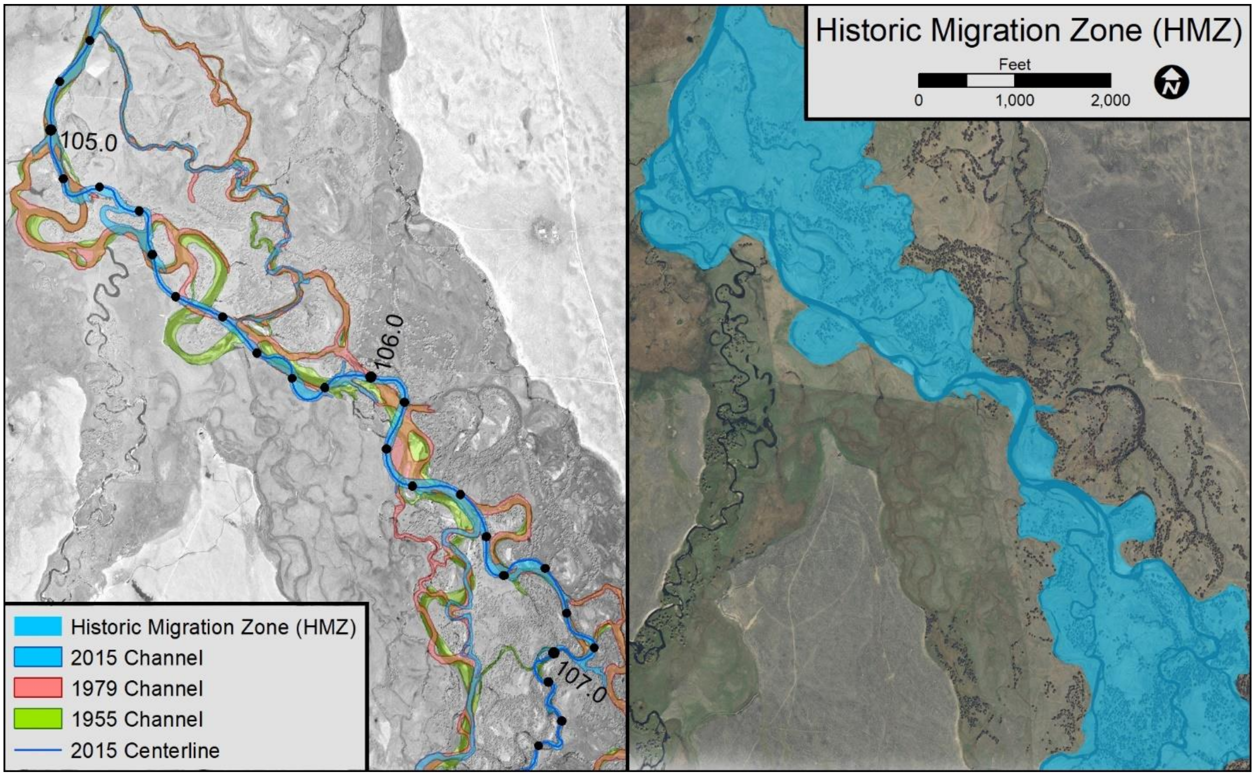

Figure 23. The Historic Migration Zone (HMZ) is the combined footprint of all mapped channel banklines.

4.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on measured migration rates, which are derived from historic migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement versus an avulsion. A total of 1,165 measurements were made through the project length where a bank had migrated at least 20 feet since 1955. The 20-foot minimum was selected as an easily measurable distance that was not compromised by the resolution or spatial accuracy of the data. The migration distances vary substantially both within and between reaches, with several reaches showing over 300 feet of bank migration since 1955, with a maximum migration distance of 742 feet near Glen (Figure 24).

The mean migration distances were used to generate a mean annual migration rate for each reach (Table 3). This in turn defined the erosion buffer width, which allows for 100 years of continual bank movement at the mean annual rate. The erosion buffer widths assigned to each reach are shown in, and range from 59 feet in Reach 10 between Deep Creek and the North Fork Road, and 329 feet in Reach 2 above Pennington Bridge. The erosion buffer width, when applied to the 2015 bankline, defines the Erosion Hazard Area (EHA). This area is considered prone to channel occupation over the life of the CMZ (100 years).

This reach-scale assessment acknowledges that predicting movement at single sites over the next century is, at best, difficult due to the non-linear nature of channel migration. As such, the erosion buffer is assigned to all banks, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington State Department of Ecology (WSDE, 2010). The general approach to determining the Erosion Buffer (using the annual migration rate to do define a 100-year migration distance) is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004).

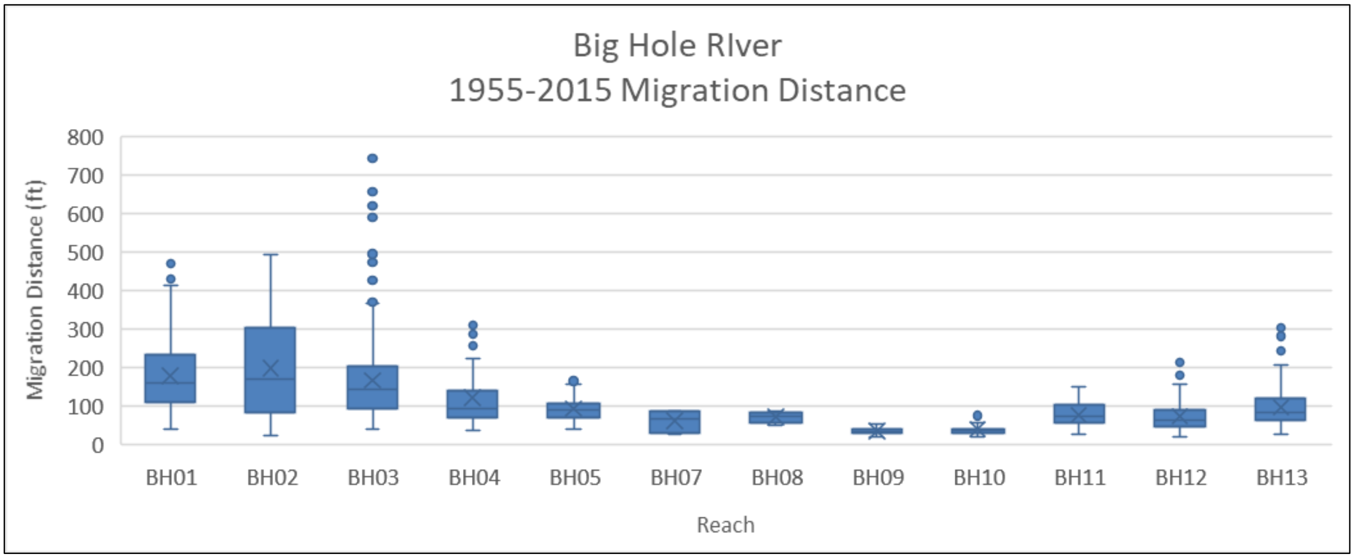

Figure 24. Distribution of migration measurements by reach.

Table 3. Reach-based summary of migration measurements.

Reach	Number of Measurements	Average Length (ft)	Maximum Length (ft)	Number of Years	Average Annual Migration Rate (ft/yr)	100- Year Buffer Width (ft)
Reach 1	188	178	470	60	3.0	296
Reach 2	104	197	494	60	3.3	329
Reach 3	204	166	742	60	2.8	277
Reach 4	66	121	327	60	2.0	201
Reach 5	74	93	174	60	1.5	155
Reach 6	0	No Measurable Channel Migration in Maiden Rock Canyon				
Reach 7	7	Minimal Measurements - Older Alluvial Terrace				
Reach 8	7	Minimal Measurements – Canyon Section				
Reach 9	38	35	55	60	0.6	59
Reach 10	21	40	94	60	0.7	66
Reach 11	40	76	148	60	1.3	127
Reach 12	236	72	216	60	1.2	121
Reach 13	180	96	303	60	1.6	161

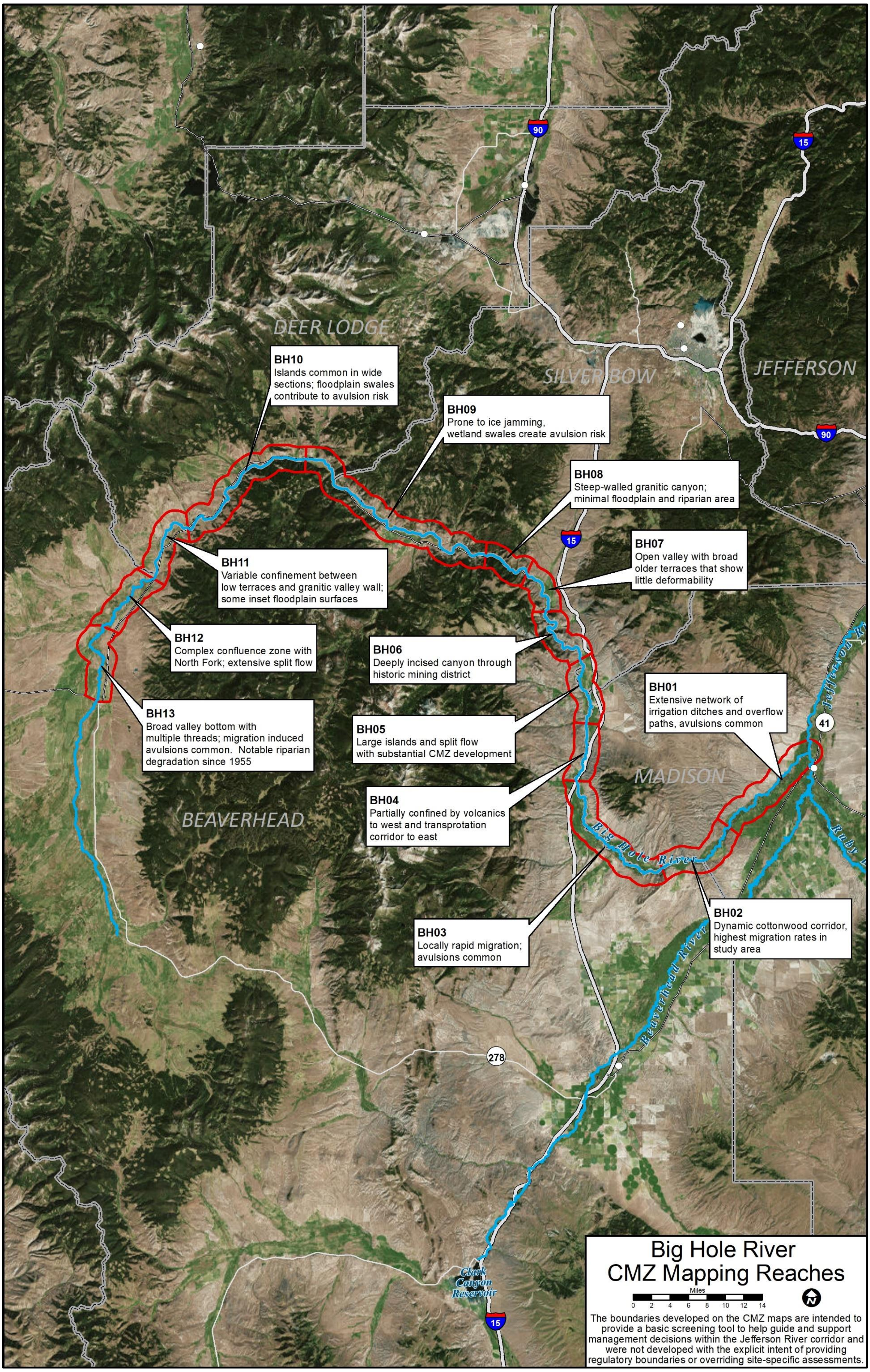

Figure 25. Reaches

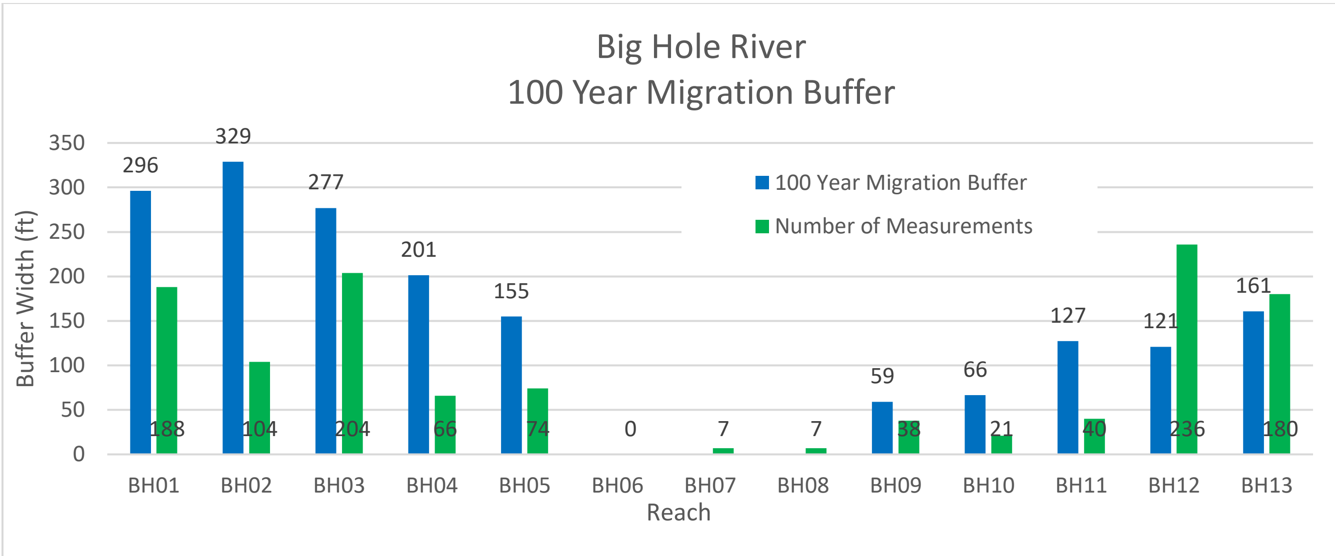

Figure 26. Erosion buffer widths assigned to 2015 banklines to define Erosion Hazard Area (EHA).

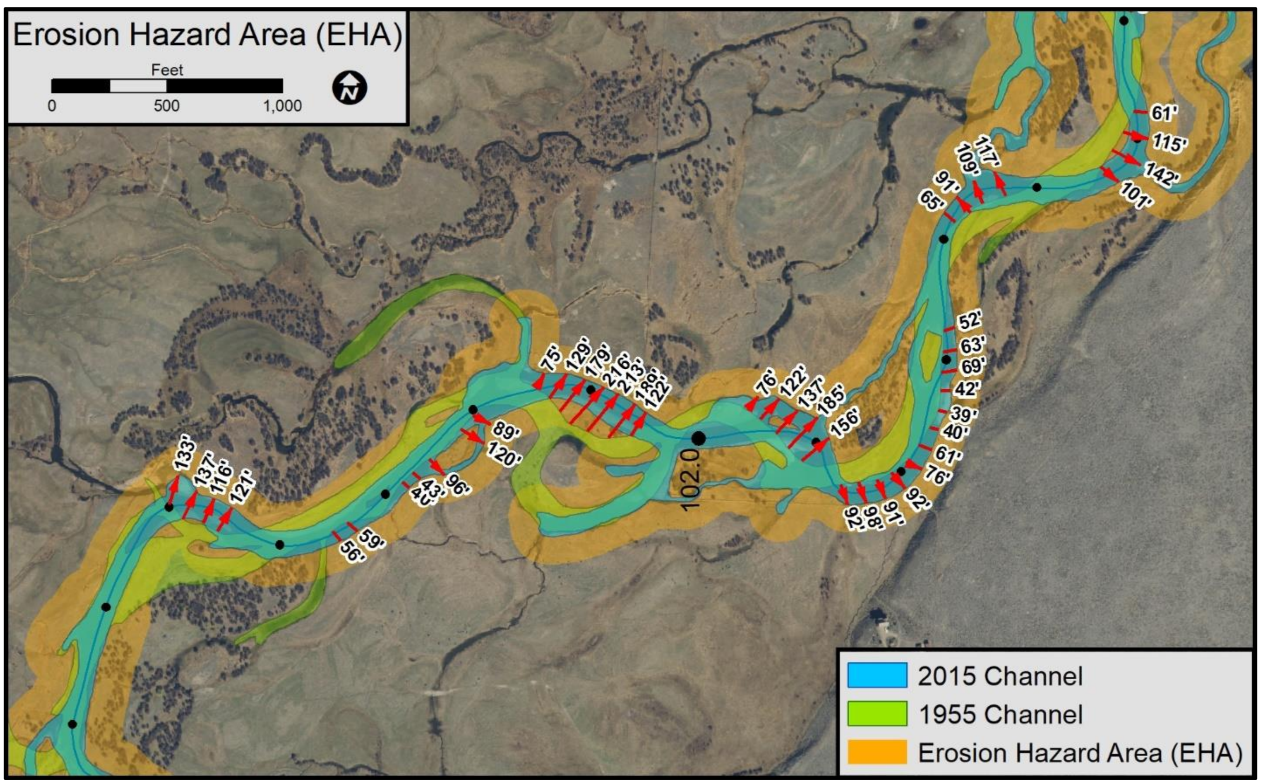

Figure 27. The Erosion Hazard Area (EHA) is a buffer placed on the 2015 banklines based on 100 years of channel migration for the reach.

The 100-year buffer distance was calculated as 100 times the annual mean migration rate for each entire reach (Table 3)(Figure 26). Table 3 shows that in several reaches, the 100-year erosion buffer is less than the maximum measured migration distance. This shows that there are areas where very rapid bank migration has occurred, and that the Erosion Hazard Area may be locally eroded through over the next 100 years. Typically, however, these areas of rapid bankline movement are within the Historic Migration Zone, and thereby captured in the CMZ. In a broader sense, it shows that the Erosion Hazard Area is a relatively conservative estimate of erosion risk.

An example of EHA mapping is shown in Figure 27. If the EHA extends into the Historic Migration Zone (HMZ), 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.

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 more dynamic reaches of the Big Hole River are highly prone to avulsions. A total of 57 avulsions were mapped on the Big Hole River between 1955 and 2015, with most concentrated above Pintler Creek and below Glen (Figure 28). When normalized by River Mile, Reach BH13 has the highest mapped spatial frequency of avulsions, with one occurrence per 3.2 miles of river (Figure 29 and Figure 30). The locations and patterns of historic avulsions were used to help identify where additional avulsions are most likely.

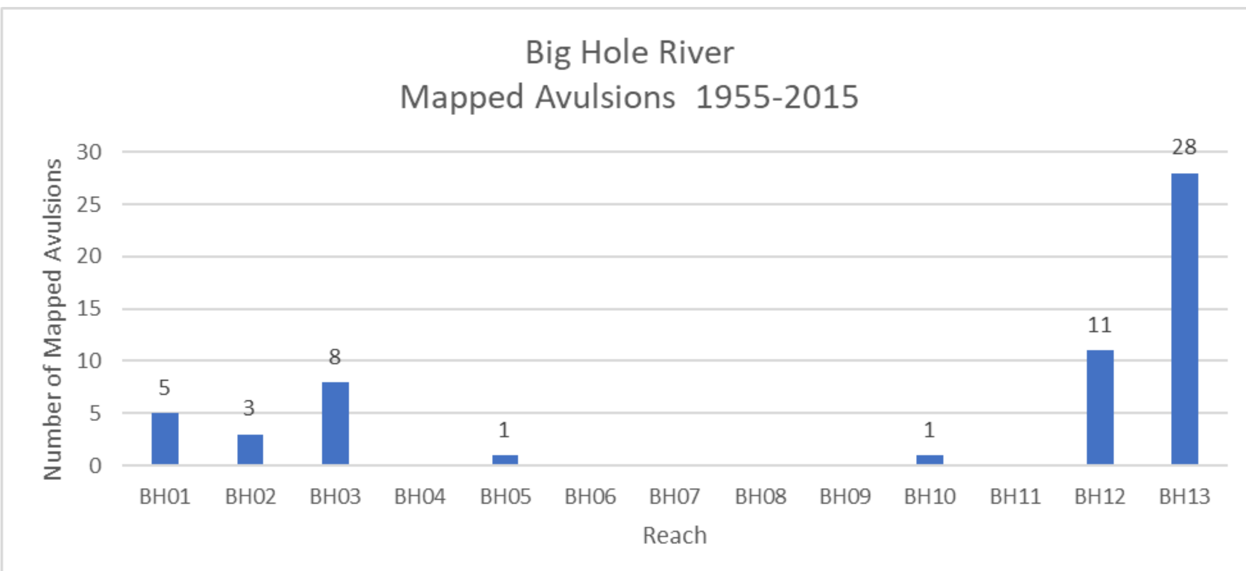

Figure 28. Number of avulsions mapped on Big Hole River between 1955 and 2015 by reach.

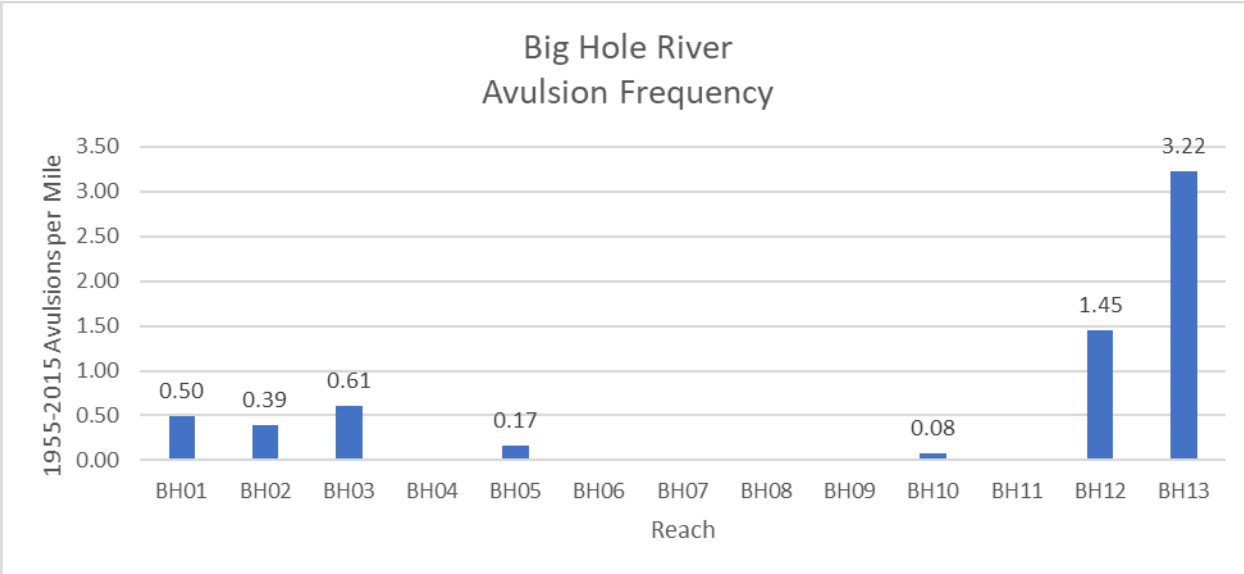

Figure 29. Number of 1955-2015 avulsions normalized by River Mile.

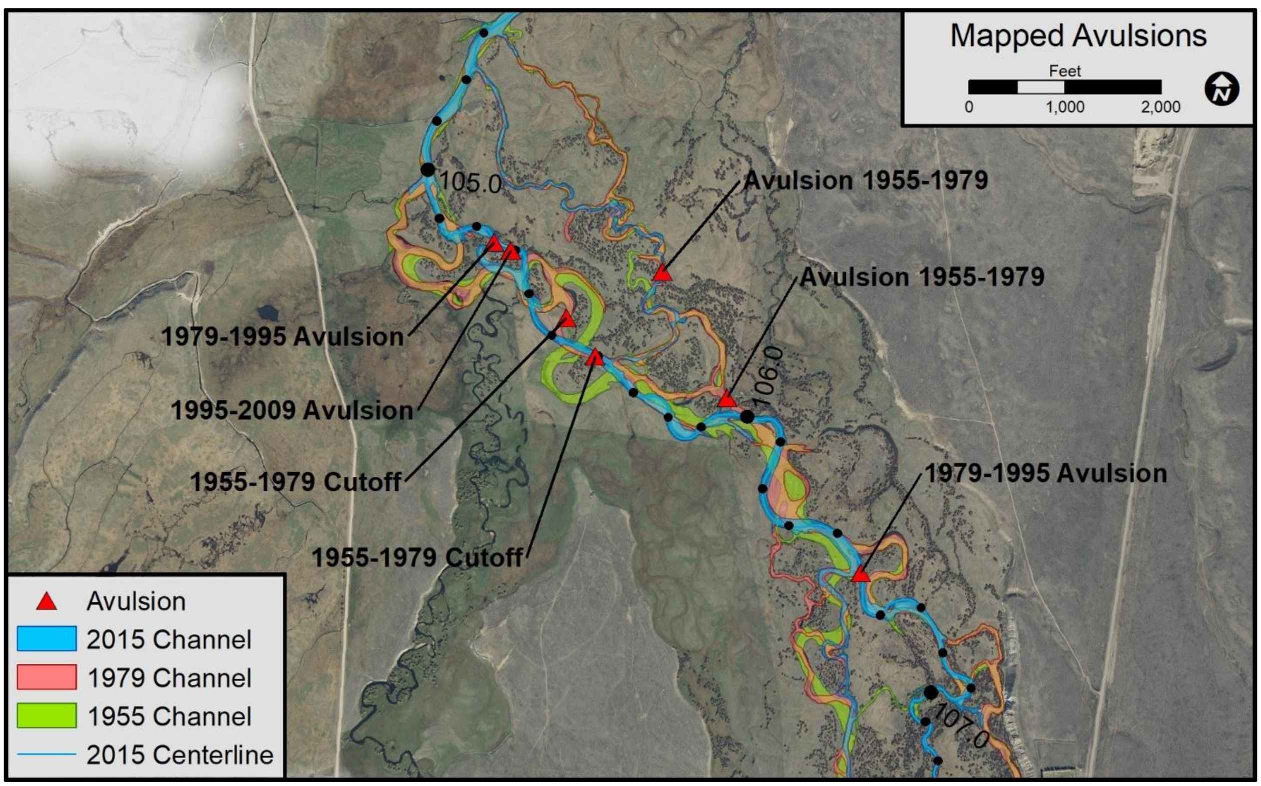

Figure 30. Numerous avulsions near mouth of Swamp Creek, Reach BH13.

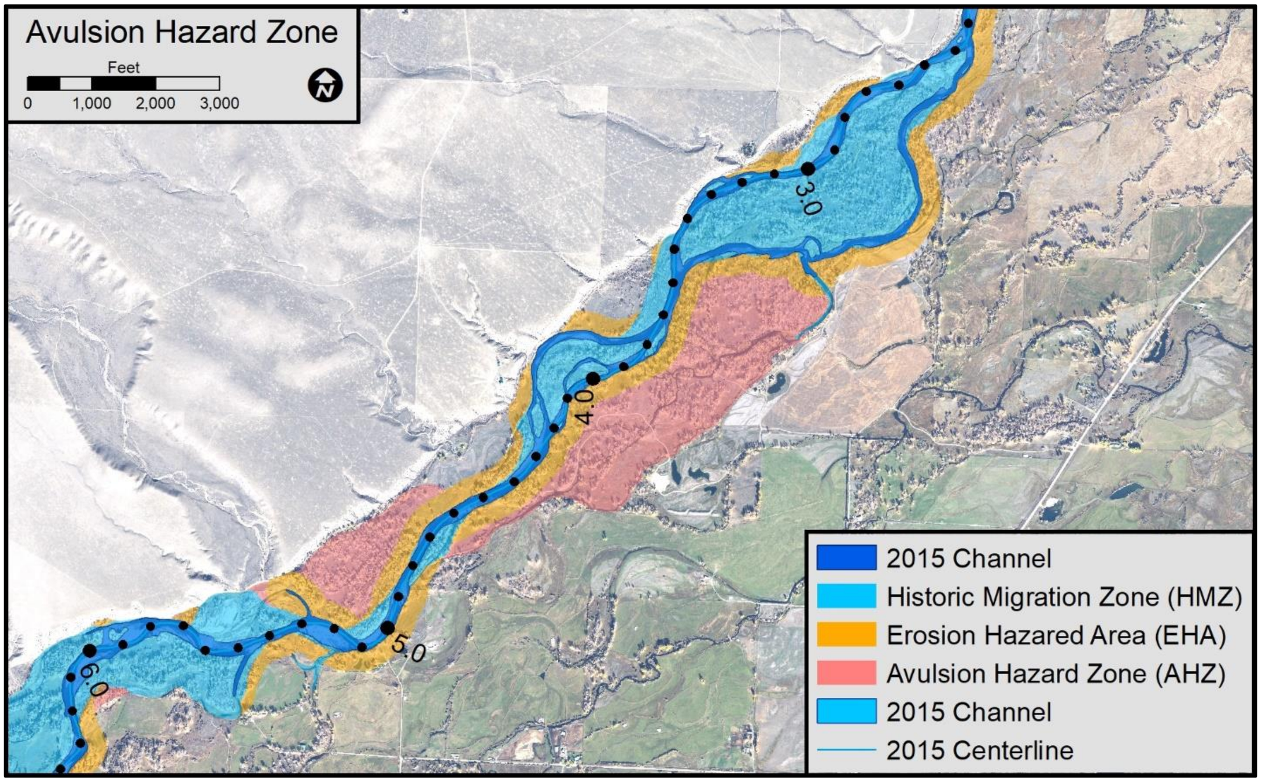

Figure 31. Avulsion hazards below Pennington Bridge.

4.5 The Restricted Migration Area (RMA)

The extent of migration area that is restricted by physical features is largely dependent on the proximity of transportation and irrigation infrastructure to the channel. The highway, local roads, and bridges locally encroach well into the CMZ throughout the length of the Big Hole River (Figure 32). Additionally, irrigation diversions and ditches that parallel the active channel are often protected with armor. This is most prominent in the lowest five reaches, from Melrose to the mouth, sections of bank armor are associated with irrigation diversions, ditches, and residential buildings (Figure 33). Figure 34 shows that the extent of banks that were mapped as armored ranges from 0% to 4% of the total bankline in any given reach (discounting islands). Three reaches contained little to no visible armor.

4.6 Composite Map

An example portion of a composite CMZ map for a section of the Big Hole River project area is shown in Figure 35. 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.

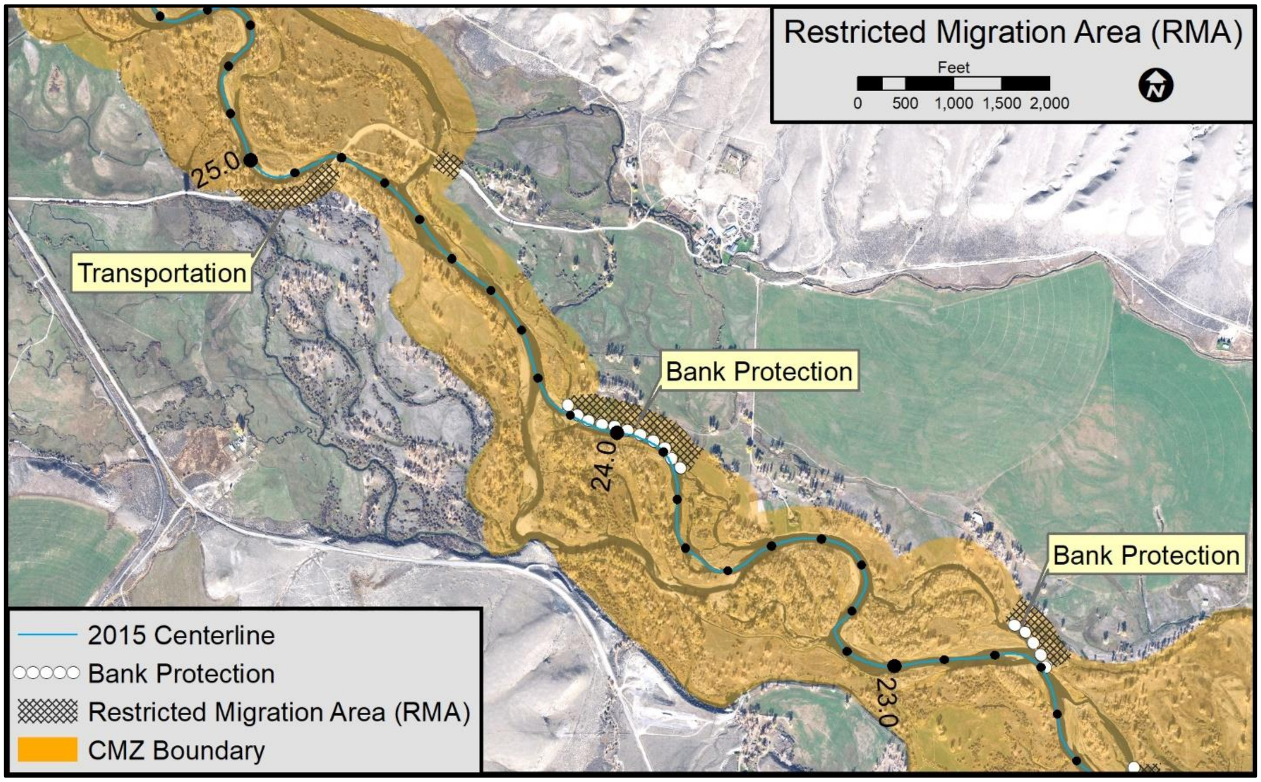

Figure 32. Restricted Migration Areas.

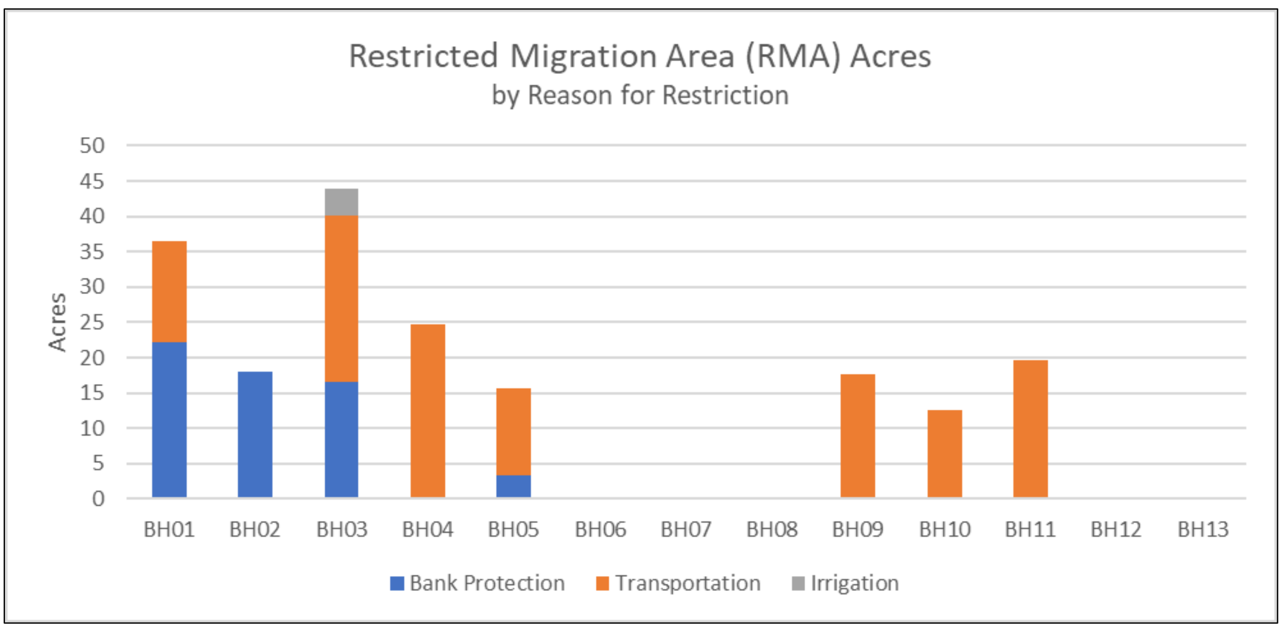

Figure 33. Acres of the CMZ mapped as restricted by reach.

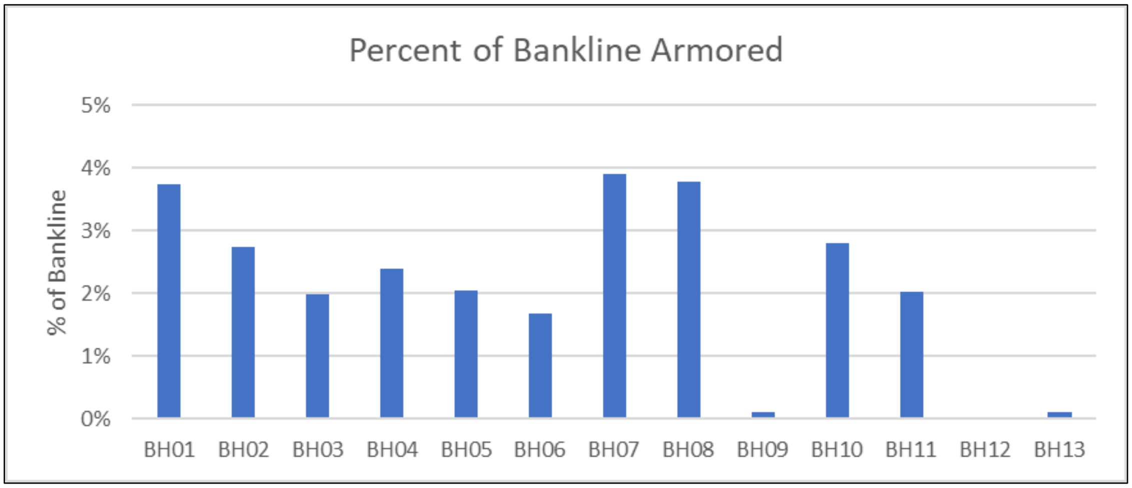

Figure 34. Percentage of bankline protected by armor by reach.

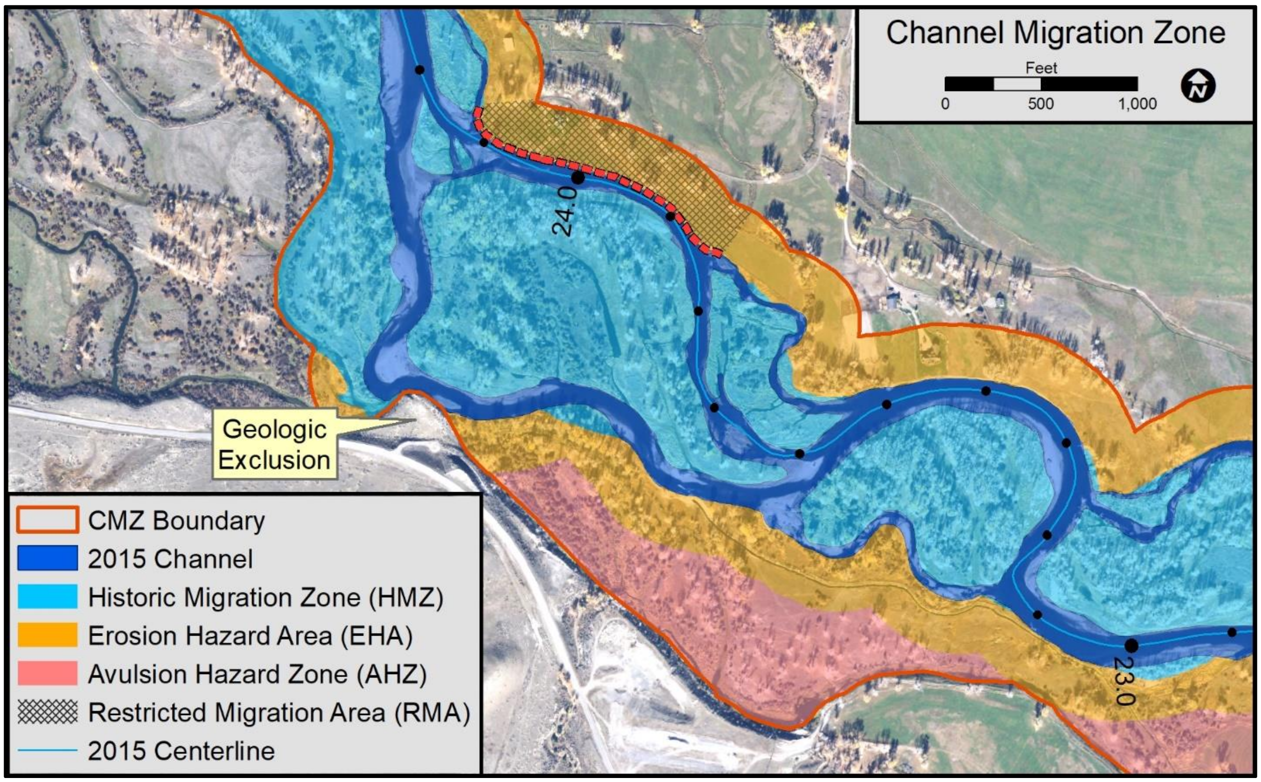

Figure 35. Composite Channel Migration Zone map.

4.7 Geologic Controls on Migration Rate

Many CMZ mapping efforts incorporate a Geotechnical Setback on valley walls, which is an area of expanded Erosion Hazard Area (EHA) against geologic units that may be prone to geotechnical failure such as landslides, slumps, or rockslides. Defining an appropriate setback for these processes is difficult at best and may reflect more stochastic processes than have been used to develop the CMZ. As a result, Geotechnical Setbacks have not been incorporated into the EHA, and incorporating the potential for mass failure on hillslopes was considered beyond the scope of this effort.

5 CMZ Mapping Results by Reach

The following sections summarize the mapping results for each reach of the Big Hole River. The reaches are numbered sequentially from downstream to upstream to allow the potential extension of the mapping above Wisdom in the future. To best describe the downstream trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach BH13 at Wisdom, and ending with Reach BH1 at Twin Bridges. The maps can be found in Appendix C.

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

5.1 Reach BH13

BH13	
Upstream/Downstream RM	111.3/102.6
Length (miles)	8.7
General Location	Wisdom to North Fork
Mean Migration Rate (ft/yr)	1.6
Max 60-year Migration Distance (ft)	303
100-year Buffer (ft)	161

Reach BH13 is located in the upstream-most portion of the study reach, flowing almost nine miles from Wisdom to where it intersects the distributary channel network and floodplain of the North Fork. Within this segment, the river flows through a broad open river valley that sits at about 6,000 feet in elevation. The riparian corridor is dominated by herbaceous plants and variably dense willows (Figure 36). Split flow is common. A total of nine bendway cutoffs and 18 avulsions were mapped in the reach since 1955. The largest migration measurement made in this section is 303 feet, and the mean migration rate is 1.6 feet per year. The 100-year buffer width in Reach BH13 is 161 feet.

Figure 37 shows an example avulsion in Reach BH13 that created 1,700 feet of new channel about two miles north of Wisdom. The imagery also shows a marked loss in open water area and willow density through time. The distribution and shape of the open water ponds are indicative of beaver activity and associated shallow water tables. In contrast the 2013 floodplain is notably dryer with less shrub cover. Intermediate imagery from 1979 shows that the riparian and open water losses had largely occurred by that time. This indicates that, even though beaver trapping had largely ceased in the mid-1800s, substantial beaver activity and associated geomorphic processes were active through at least the mid part of the 20th century. The 2013 image also shows more extensive open bar area than the earlier photos. This is not uncommon with active avulsions as the carving of a new floodplain channel creates sediment slugs that progressively work downstream. The expansion of open bar area is ubiquitous throughout the reach and demonstrates how riparian degradation has resulted in increased bank erosion rates and sediment recruitment through time.

Figure 36. View downstream of Reach BH13 showing broad valley bottom and willow-dominated riparian corridor.

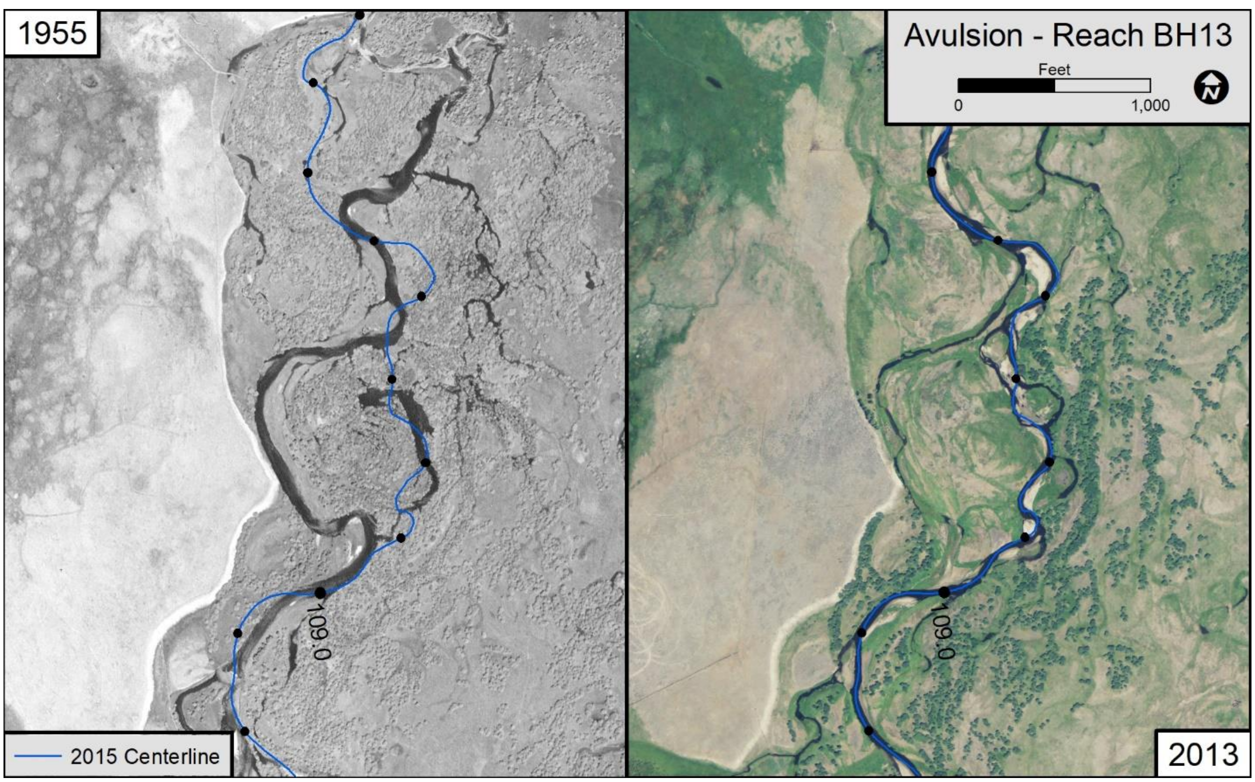

Figure 37. Reach BH13 showing 1,700 foot long avulsion since 1955; note loss of open water and riparian vegetation density.

5.2 Reach BH12

BH12	
Upstream/Downstream RM	102.6/95.0
Length (miles)	7.6
General Location	To just above Pintler Creek
Mean Migration Rate (ft/yr)	1.2
Max 60-year Migration Distance (ft)	216
100-year Buffer (ft)	121

Reach BH12 begins at RM 102.6, where the floodplain of the North Fork Big Hole River coalesces with that of the main stem and continues downstream to just above the Pintler Creek confluence at RM 95.0. Within this reach the Big Hole River floodplain is up to a mile wide, with multiple channel threads flowing through a somewhat degraded riparian corridor (Figure 38). The broad floodplain coupled with a complex swale system creates a wide stream corridor footprint in Reach BH12; in several locations the CMZ is about a half-mile wide. The southern margin of the corridor is formed by a low terrace that has arcuate margins indicating historic erosion of its edges by the river and a long history of lateral channel movement. Although the CMZ in Reach BH12 is relatively wide, the mean measured migration rate is somewhat lower than Reach BH13 upstream, which is somewhat surprising considering the additional stream power contributed by the North Fork. There are areas in Reach BH12, however where saline soils appear to contribute to a relatively static planform and low migration rates. The low rates of migration are also likely due to the unusually low gradient in this reach (0.10%), which may be in part related to those saline soils (Figure 22). Although there are no Pleistocene-age lacustrine deposits mapped in the area, Alden (1953) describes exposures of older lake bed deposits in the area that may also affect the modern slope of the Big Hole Valley in reaches BH12 and BH11. With glacial moraines mapped on upper reaches of Fishtrap and Lamarche Creek, it is possible that the Big Hole Valley was intermittently dammed with glacial activity in this area.

A total of 11 avulsions were mapped in Reach BH12, and five of those were bendway cutoffs. A common cause of avulsion in the reach is channel migration into old floodplain swales which then enlarge and establish as secondary channels. Figure 39 shows an example of the very early stages of that process. Whereas the cutoff in Figure 39 is relatively short, migration-induced avulsions can be over a thousand feet long.

There is only minor development on the floodplain near the mouth of Doolittle Creek, however no infrastructure has been identified as encroaching into the CMZ.

Figure 38. View of Reach BH13 showing broad floodplain with low willow density and persistent split flow; note discrete terrace surface to right. (Kestrel)

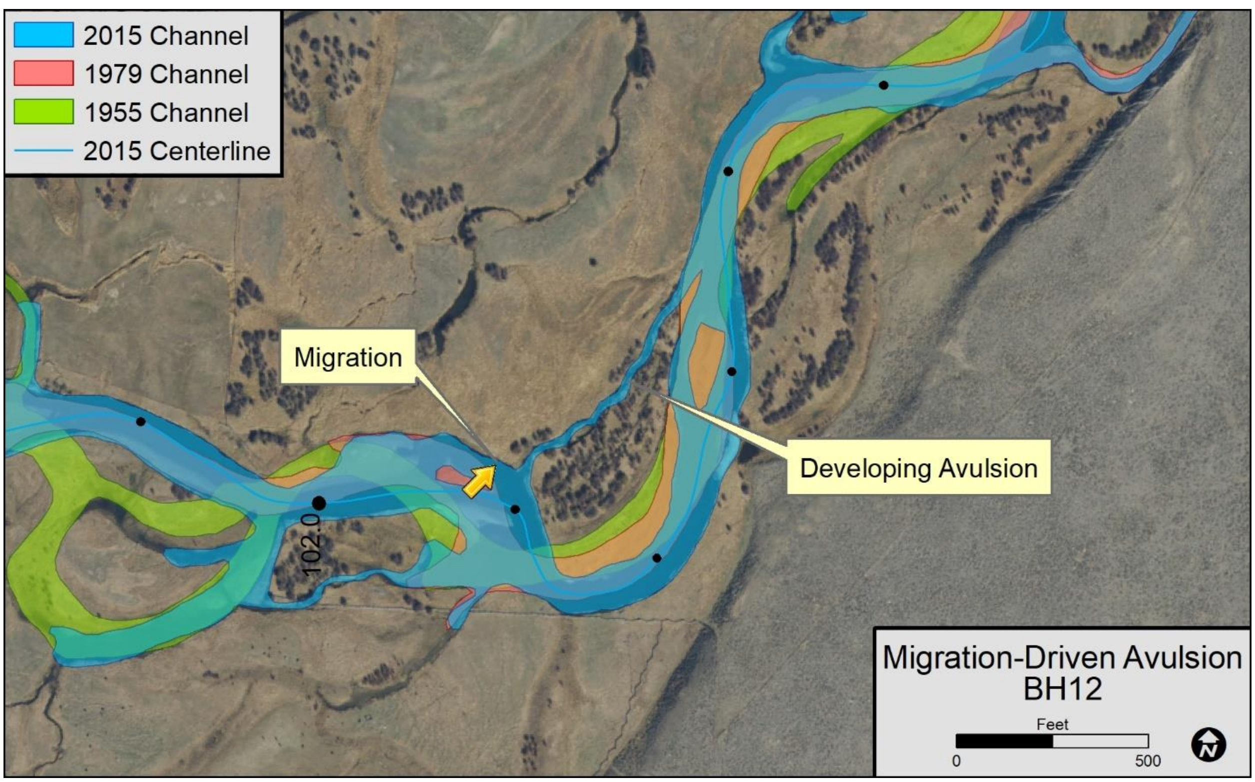

Figure 39. Big Hole River at RM 102 showing northeastward migration into floodplain swale driving bendway cutoff/avulsion.

5.3 Reach BH11

BH11	
Upstream/Downstream RM	95/88.7
Length (miles)	6.3
General Location	Pintler Creek to bridge below Mudd Creek
Mean Migration Rate (ft/yr)	1.3
Max 60-year Migration Distance (ft)	148
100-year Buffer (ft)	127

Reach BH11 is 6.3 miles long, extending from near the Pintler Creek confluence to the Hwy 43 Bridge at North Fork Road. This reach has a relatively high mean migration rate (1.3 feet per year), and that rate is derived from 40 measurements in the 6.3 mile long river segment. The maximum migration distance measured is 148 feet, and the 100-year CMZ buffer width is 127 feet. Although migration rates in the reach are fairly rapid, Reach BH11 has a simple single thread planform that has shown little change since the 1950s; as a result, the HMZ is quite narrow through the reach. In the lower portion of the reach, however, long floodplain swales create broad Avulsion Hazard areas that expand the CMZ footprint.

At RM 93.2, outbuildings at a farmstead extend into the Erosion Hazard Area, although no active migration has been measured at the site (Figure 40).

Figure 40. View downstream showing single thread channel in Reach BH11. (Kestrel)

5.4 Reach BH10

BH10	
Upstream/Downstream RM	88.7/76.0
Length (miles)	12.7
General Location	Mudd Creek to Deep Creek
Mean Migration Rate (ft/yr)	0.7
Max 60-year Migration Distance (ft)	94
100-year Buffer (ft)	66

Reach BH10 extends from the Highway 43 Bridge downstream to near Deep Creek. It is 12.7 miles long, and has a relatively narrow EHA buffer width of 66 feet.

Reach BH10 is highly confined between a steep, forested valley wall on the south and lower gradient sedimentary rocks to the north. Fishtrap Creek and Lamarche Creek both flow into BH10 from the north. Both tributaries were glaciated and host moraine deposits in their respective valleys 2-3 miles upstream from their confluences with the Big Hole (Figure 42). Reach B11 reach has experienced substantial ice jamming and ice jam-induced flooding. One of these areas prone to ice-jam flooding is Sportsman's Park at RM 77.8, which extends into the mapped CMZ footprint.

In general, Reach BH10 hosts a minimally deformable channel that is highly influenced by coarse sediment inputs from tributaries and valley walls. The greatest geomorphic diversity in the reach comes from island complexes that show a higher degree of reworking than the surrounding floodplain (Figure 43).

Figure 41. View downstream of reach BH10 showing steep, forested south valley wall (right). (Kestrel)

Figure 42. View northward up Lamarche Creek showing moraine deposits (forested) and dense willow corridor below. (Kestrel)

Figure 43. View downstream of Reach BH11 showing geomorphic diversity at islands. (Kestrel)

5.5 Reach BH9

BH9	
Upstream/Downstream RM	76/56.8
Length (miles)	19.2
General Location	Deep Creek to Canyon Entrance at Dewey
Mean Migration Rate (ft/yr)	0.6
Max 60-year Migration Distance (ft)	55
100-year Buffer (ft)	59

In Reach BH9, the Big Hole River flows through a 19.2-mile long section of semi-confined valley bottom between Deep Creek and Dewey. Confinement is created by both valley wall geology as well as terrace and alluvial fan surfaces that can control channel planform and the width of the CMZ. A good example of alluvial fan influences on the CMZ is at the mouth of Alder Creek, where a northeast-trending fan has pinned the river against the north valley wall and inhibited channel movement (Figure 44). Another good example is at the mouth of Jerry Creek near Dewey (RM 61.0). The largest tributary in the reach is the Wise River, which flows northward from the core of the Pioneer Mountains onto a large Holocene/Pleistocene fan that intersects the Big Hole River valley as a major topographic feature that is 1.8 miles wide at its mouth. As this fan pins the Big Hole to the north side of the valley, the Big Hole CMZ is confined and narrowed. The Wise River itself is incised into this fan, forming an inset stream corridor that is about 0.3 miles wide. Reach BH9 marks an increase in slope relative to upstream; this reach has almost triple the stream gradient than Reach BH11 above Mudd Creek (Figure 22).

Reach BH9 is an interesting section of river with respect to CMZ mapping, because although the mean migration rate is relatively low (0.6 ft/yr), there are complex floodplain features surfaces that show evidence of fluvial scour and potential channel occupation (Figure 45). As a result, Reach BH9 has numerous mapped Avulsion Hazard Areas as well as overflow paths. The Avulsion Hazard Areas were mapped where available data indicate continuous low swales that show evidence of a high level of fluvial connectivity, such as linear wetlands. Overflow paths were added to show other areas where historic swales are mappable such that they appear to provide continuous flow paths, however their level of connectivity is more uncertain.

Another interesting aspect of Reach BH9 is the level of residential development adjacent to the river. Several homes have been constructed in recent years on low geomorphic surfaces adjacent to the channel, and in many locations there are avulsion pathways or overflow paths landward of the homes (Figure 47). At least one of these homes was flooded by ice jamming in 2017 (RM 72.0, Figure 6). This house is located on the landward edge of the mapped CMZ.

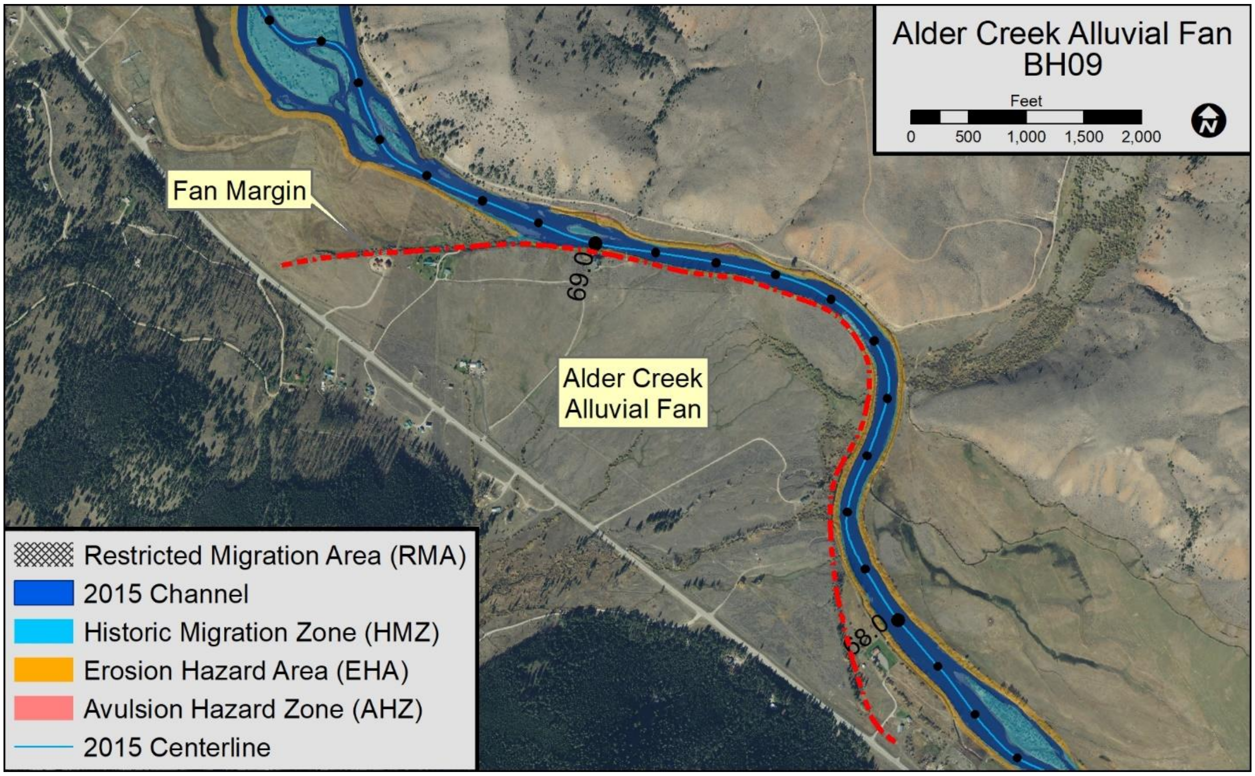

Figure 44. Reach BH9 showing Big Hole River confinement and CMZ narrowing caused by Alder Creek alluvial fan, RM 69.0.

Figure 45. View downstream of Reach BH9 showing floodplain swales on left that form avulsion hazards. Wise River is just off photo in distance. (Kestrel)

Figure 46. View downstream of Reach BH9 showing overflow paths on 100-year floodplain, RM 65.0. (Kestrel)

Figure 47. View downstream of Reach BH9 past mouth of Wise River showing avulsion path that extends behind residence. (Kestrel)

5.6 Reach BH8

BH8	
Upstream/Downstream RM	56.8/52.7
Length (miles)	4.1
General Location	Dewey to Divide
Mean Migration Rate (ft/yr)	NA
Max 60-year Migration Distance (ft)	NA
100-year Buffer (ft)	NA

Approximately ½ mile downstream of Dewey, the Big Hole River flows into a granitic canyon that is four miles long. The canyon is steep walled, and Highway 43 follows the south valley wall (Figure 48). Although a mean migration rate of 1.2 feet per year was developed for the reach, this rate is based on only seven measurements at one site where alluvium was reworked in the canyon. As a result, no erosion buffer was calculated for this reach. Additionally, because of the narrow valley bottom, the entirety of the channel margin would be clipped out of the CMZ as non-erodible bedrock, making an Erosion Hazard Area unnecessary. Numerous rock slides/debris fan encroach into the stream corridor off of the canyon walls suggesting that the most change in this reach is driven by hillslope processes rather than floodplain development and reworking.

Figure 48. View upstream of Reach BH8 showing narrow canyon segment. (Kestrel)

5.7 Reach BH7

BH7	
Upstream/Downstream RM	52.7/48.6
Length (miles)	4.1
General Location	Divide to Canyon Entrance
Mean Migration Rate (ft/yr)	NA
Max 60-year Migration Distance (ft)	NA
100-year Buffer (ft)	NA

Reach BH7 begins at Divide and extends downstream to the mouth of Maiden Rock Canyon. Although migration was observed in the reach, it was measureable at only one site with seven vectors, indicating a notably low level of channel deformability. The seven migration measurements are all located in the downstream portion of the reach where the railroad line channelized 0.3 miles of river, making that section especially prone to adjustment. As a result, the majority of the floodplain area would be clipped from the CMZ boundary due to a lack of empirical evidence of channel movement since 1955, and no erosion buffer was calculated. The rural residential development along the bankline in Reach BH7 is all outside of the CMZ boundary (Figure 49).

Figure 49. View downstream into Reach BH7 showing left bank development (Kestrel).

5.8 Reach BH6

BH6	
Upstream/Downstream RM	48.6/41.7
Length (miles)	6.9
General Location	Canyon Entrance to Maiden Rock Fishing Access Site
Mean Migration Rate (ft/yr)	N/A
Max 60-year Migration Distance (ft)	N/A
100-year Buffer (ft)	N/A

Reach BH6 extends though Maiden Rock Canyon, a unique stretch of the Big Hole River as it is evidently geologically young relative to the rest of the river. As described in Section 2.4, the flow direction and course of the Big Hole has changed several times over the past 25 million years, with its most recent shift including downcutting into Maiden Rock Canyon (Vuke, 2004). Geologic evidence indicates that the ancestral path of the Big Hole, which first flowed north into the Clark Fork basin and later flowed east into the Big Hole Valley, lies east of Maiden Rock Canyon, generally following the trend of I-15.

The rail line closely follows the river through the canyon, and the bounding hillslopes have numerous abandoned mines that have collectively produced limestone, phosphate, uranium, fluoride, chromium and nickel. The mines followed steeply dipping bedding planes, such that their scars are distinctive linear excavation trenches on hillslopes, in addition to numerous exploration pits and a large quarry. Mine reclamation has been ongoing on the canyon walls.

There was no measurable migration in this 7-mile-long river segment, so the CMZ is limited to the historic footprint of the river.

Figure 50. View west of Maiden Rock Canyon; flow direction is right to left. (Kestrel)

5.9 Reach BH5

BH5	
Upstream/Downstream RM	41.7/35.7
Length (miles)	6.0
General Location	Maiden Rock to Cherry Creek
Mean Migration Rate (ft/yr)	1.5
Max 60-year Migration Distance (ft)	174
100-year Buffer (ft)	155

At the mouth of Maiden Rock Canyon, the Big Hole River intersects its ancestral valley. As a result, the width of the river corridor abruptly expands from about 250 feet in Reach BH6 to a mile in Reach BH5. With this abrupt shift in valley type, the river becomes much more laterally dynamic, supporting floodplain reworking, side channel formation, and an established cottonwood corridor. About 1.5 miles downstream of the mouth of the canyon, the Historic Migration Zone widens abruptly to encompass a series of islands that persist through the entirety of Reach BH5 (Figure 51). The two primary channels that create these islands are both laterally active, and in some locations they intersect, longitudinally separating the islands into individual features and creating complex, dynamic flow paths that create some uncertainty with respect to flow distributions through time (Figure 52). Other channel remnants have been converted to ditches that are within the CMZ, such as at RM 37.0.

The rail line follows parallel to the stream corridor, bisecting the ancestral river valley and forming an artificial margin on the east side of the CMZ. At several locations in Reach BH5, the river has migrated into the transportation embankment; at RM 37.3, for example, the riverbank is less than 30 feet from the railroad tracks (Figure 53).

Reach BH5 has seen substantial river corridor development, some of which has been on islands. Large islands at Meriwether Ranch (RM 40.5), and near Melrose (RM 38.5) have bridge access to residences (Figure 54). All of these structures are within the Big Hole River Channel Migration Zone. Numerous other structures adjacent to the river are within the CMZ as well, most of which are in the 155-ft wide Erosion Hazard Area. An example structure in the Erosion Hazard Area (EHA) can be seen in Figure 53.

Figure 51. View northwest of island with constructed wetlands, Reach BH5. (Kestrel)

Figure 52. View of channel intersection at RM 39.0. (Kestrel)

Figure 53. View upstream showing channel migration towards the railroad grade near Melrose, RM 37.3.

Figure 54. Meriwether Ranch housing development on Big Hole River island, Reach BH5. (Kestrel)

5.10 Reach BH4

BH4	
Upstream/Downstream RM	35.7/31.8
Length (miles)	3.9
General Location	Cherry Creek to I-15 Bridge
Mean Migration Rate (ft/yr)	2.0
Max 60-year Migration Distance (ft)	327
100-year Buffer (ft)	201

Reach BH4 begins where the multi-thread planform tapers to a single channel about 3.5 miles south of Melrose near the mouth of Cherry Creek. At this point the stream corridor becomes increasingly confined by the valley wall to the west and railroad/interstate lines to the east. Migration rates are relatively high in this reach with a mean rate of 2.0 feet per year and a 100-year buffer width of 201 feet. In several locations the river is flowing along a bedrock bluff on the west side of the valley, and that bluffline has been clipped from the CMZ (Figure 55). Most of the migration in the reach has been eastward away from the bluffline and at RM 33.0, the river has eroded to within 200 feet of the railroad tracks. Much of the left bank in Reach BH4 has been armored where it approaches the railroad (Figure 56). Channel migration in Reach BH4, although laterally constrained, has been active enough to promote cottonwood succession on channel margins and islands, with recent deposits supporting young age classes relative to older geomorphic features (Figure 55).

Figure 55. View upstream of Reach BH4 showing volcanic bluffline on western edge of CMZ and cottonwood succession on enlarging island in center of photo. (Kestrel)

Figure 56. View upstream of Reach BH4 showing proximity of river to rail line, which is riverward of Frontage Road. (Kestrel)

5.11 Reach BH3

BH3	
Upstream/Downstream RM	31.8/17.7
Length (miles)	14.1
General Location	I-15 Bridge to Notch Bottom
Mean Migration Rate (ft/yr)	2.8
Max 60-year Migration Distance (ft)	742
100-year Buffer (ft)	277

Reach BH3 is just over 14 miles long, extending from the I-15 Bridge crossing to Notch Bottom. Within this reach the river displays relatively rapid migration rates, with a maximum 1955-2015 migration distance of 742 feet. The mean rate, which is based on 204 measurements, is 2.8 feet per year, and the 100-year Erosion Hazard Area buffer width is 277 feet. Within this reach the Big Hole River takes on an anabranching form, meaning it supports multiple active channel threads that are separated by forested islands (Figure 57). One of the most recently dynamic sections is at Glen, where the river is progressively abandoning a historic meander near town that cut off prior to 1979 when the river avulsed (Figure 58 and Figure 59). Six avulsions occurred in the reach between 1955 and 2015, and in the lower end of the reach just above Notch Bottom, the CMZ is almost a mile wide.

Burma Road crosses the Big Hole River at RM 24.8, and as it crosses an island, the road requires two bridges (Figure 60 and Figure 61). Although the east bridge has had a relatively stable planform and channel approach angle to the bridge structure since the 1950s, the west bridge has experienced over 200 feet of migration that has progressively impacted the approach angle, creating a “dogleg” pattern of approach that will eventually require substantial maintenance to protect the integrity of both the road and the bridge. In addition to bridges, Reach BH3 supports some residential development within the Channel Migration Zone (Figure 62). Most of the armor mapped in Reach BH3 is protecting residential structures, many of which have little to no riparian buffer on adjacent streambanks.

Figure 57. View upstream of Reach BH3 showing anabranching channel form. (Kestrel)

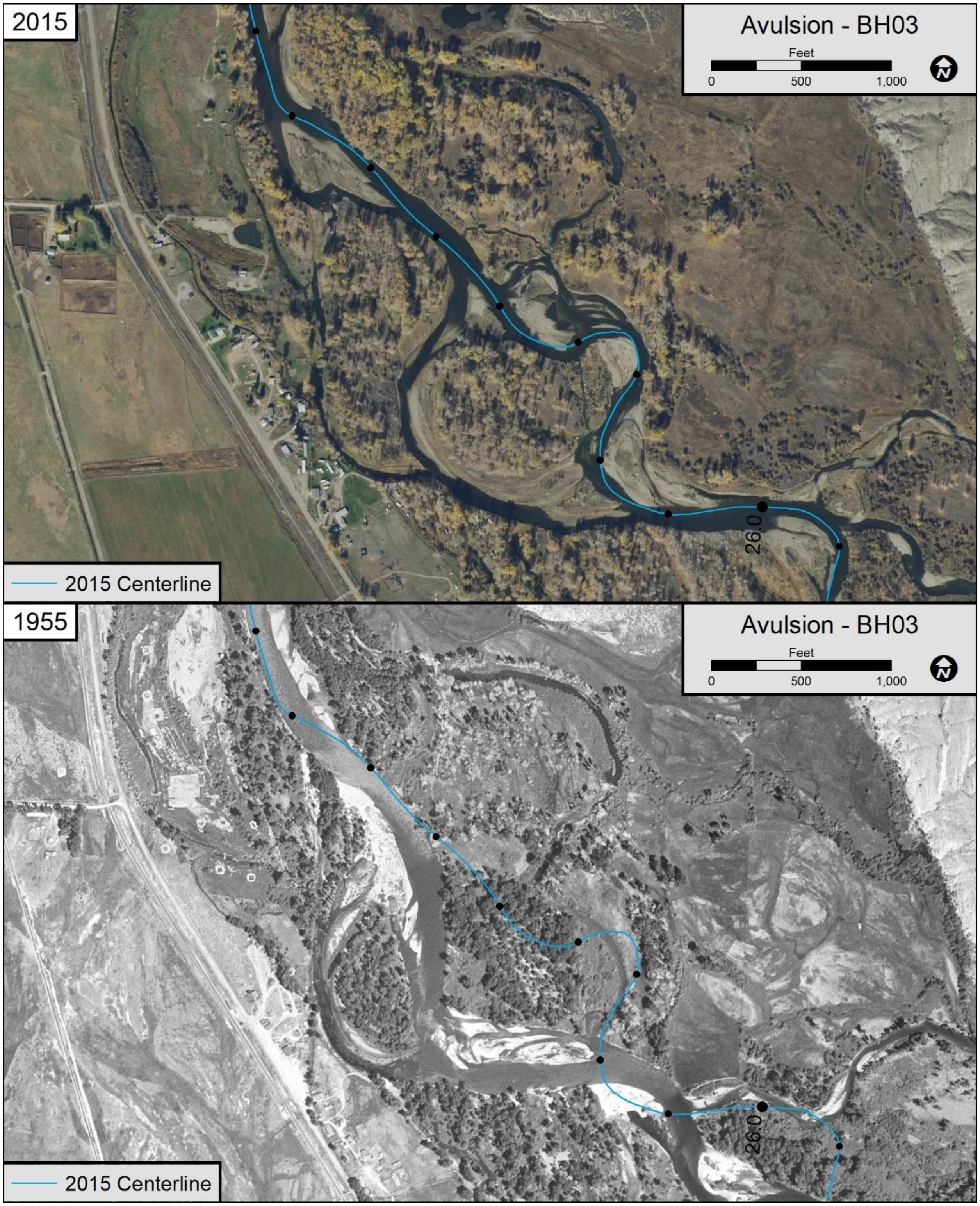

Figure 58. 1955-2015 Avulsion near Glen, BH3; flow direction is top to bottom.

Figure 59. View west of Reach BH3 towards Glen showing avulsed channel in foreground. (Kestrel)

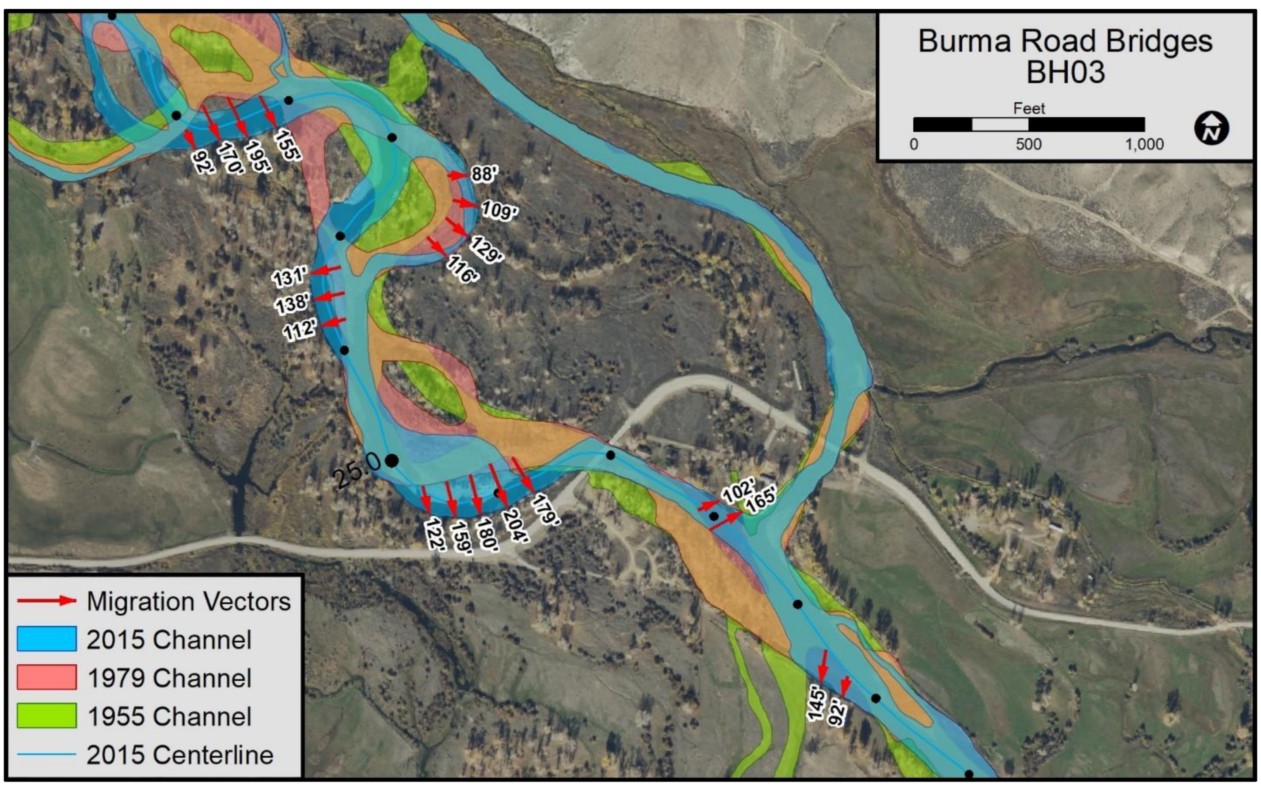

Figure 60. Big Hole River at Burma Road Bridge crossing showing progressive decay of river approach to west bridge structure.

Figure 61. View west showing two Burma Road Bridges; far bridge approach angle has decayed with time and road is increasingly threatened. (Kestrel)

Figure 62. View upstream showing river corridor development, Reach BH3. (Kestrel)

5.12 Reach BH2

BH2	
Upstream/Downstream RM	17.7/10.1
Length (miles)	7.6
General Location	Notch Bottom to Lowest Constriction
Mean Migration Rate (ft/yr)	3.3
Max 60-year Migration Distance (ft)	494
100-year Buffer (ft)	329

Reach BH2 extends from Notch Bottom 7.6 miles downstream. Notch Bottom is also known as "The Hogback", which is a "conspicuous dark ridge that extends several miles south from McCartney Mountain (Alt and Hyndman, 1986). The Hogback is a tight anticlinal fold formed in quartzite that creates a north-south trending ridge that crosses the Big Hole River at RM 18.0 (Figure 63). The Hogback creates a narrow corridor constriction that marks a distinct reach break. For several miles downstream of Notch Bottom, the width of the river valley hourglasses into narrow constrictions two more times, once at RM 15.0 and again at RM 10.5 (Figure 64). These constrictions create similar geologic controls on valley form and, although less severely confining than the Hogback, still affect channel dynamics and the form of the CMZ. Between these constrictions, the river valley widens out and migration rates increase along with overall geomorphic complexity Figure 65.

Reach BH2 has a mean migration rate of 3.3 feet per year based on 104 measurements, and the EHA buffer width BH2 is 329 feet. As the maximum migration distance measured in the reach is almost 500 feet, localized future migration beyond the Erosion Hazard Area (EHA) is likely, which again highlights the conservative approach to the buffer calculation.

Figure 63. View upstream showing entrance to Reach BH2, with dark quartzite constriction at Notch Bottom. (Kestrel)

Figure 64. View downstream of Reach BH2 showing three geologic constrictions; Notch Bottom is in foreground (Google Earth).

Figure 65. View upstream of Reach BH2 showing geomorphic complexity at RM 13.5.

5.13 Reach BH1

BH1	
Upstream/Downstream RM	10.1/00
Length (miles)	10.1
General Location	Constriction to Mouth
Mean Migration Rate (ft/yr)	3.0
Max 60-year Migration Distance (ft)	470
100-year Buffer (ft)	296

Reach BH1 encompasses the lowermost 10 miles of the Big Hole River. Through this reach the valley bottom continues to expand as the floodplain of the Big Hole begins to coalesce with those of the Beaverhead and Ruby Rivers. The valley bottom is wide, flat, and dissected with a myriad of overflow channels, many of which have been converted to ditches.

Migration rates are relatively high in Reach BH1 with a mean rate of 3.0 feet per year and a resulting EHA buffer width of 296 feet. The maximum migration distance measured in the reach is 470 feet.

Reach BH1 has one of the largest avulsions identified in the project reach; just above Pennington Bridge the river flanked left bank armor at RM 9.6 and subsequently carved a new channel several hundred feet to the west of its 1979 location (Figure 66 and Figure 67). The upper mile of the avulsion is entirely new channel and the lower 0.6 miles is a captured side channel. The avulsion has been followed by progressive abandonment of the 1979 channel and progressive morphologic evolution of the new thread. This evolution is evident in the 2011 imagery; high flows that year caused expansive flooding along the avulsion route due to the lack of floodwater capacity in the new channel at that time (Figure 68).

Pennington Bridge is similar to the Burma Road bridge in that it consists of two bridge spans over an island. This site has caused concern with regard to channel migration due to active erosion and poor channel alignments towards the bridge (Figure 69 and Figure 70).

In several locations on the river, constant changes in river conditions have created challenges in maintaining access to water at irrigation diversions. These challenges are commonly caused by a change in river location, as lateral channel movement can completely abandon a diversion structure. On the Big Hole River, however, diversion structures appear to be well-placed with respect to lateral channel movement, such that they remain functional with minimal intervention. However, it is also important to note that the dynamics of channel migration cause vertical changes in bed elevation. The bed profile of the lower Big Hole River is in constant flux with continual change in channel length though both migration and avulsion. Figure 71 shows an example of a series of grade controls designed to maintain bed elevations at a diversion just below Pennington Bridge.

Further downstream near High Bridge the river flows against a high terrace of outwash gravels (Figure 72). Although this unit appears to mark the boundary of the CMZ, it is clearly erodible as evidenced by arcuate erosional scars in the terrace margin. At one location at RM 2.6 which is about 0.7 miles upstream of the High Bridge, the river eroded out an 80-ft wide section of the high terrace that protruded into the stream corridor in 1955. This high terrace erosion highlights the fact that high surfaces that are well above the floodplain are not necessarily immune to river erosion.

Figure 66. View upstream of avulsion site in Reach BH1; the decaying 1979 channel is to left.

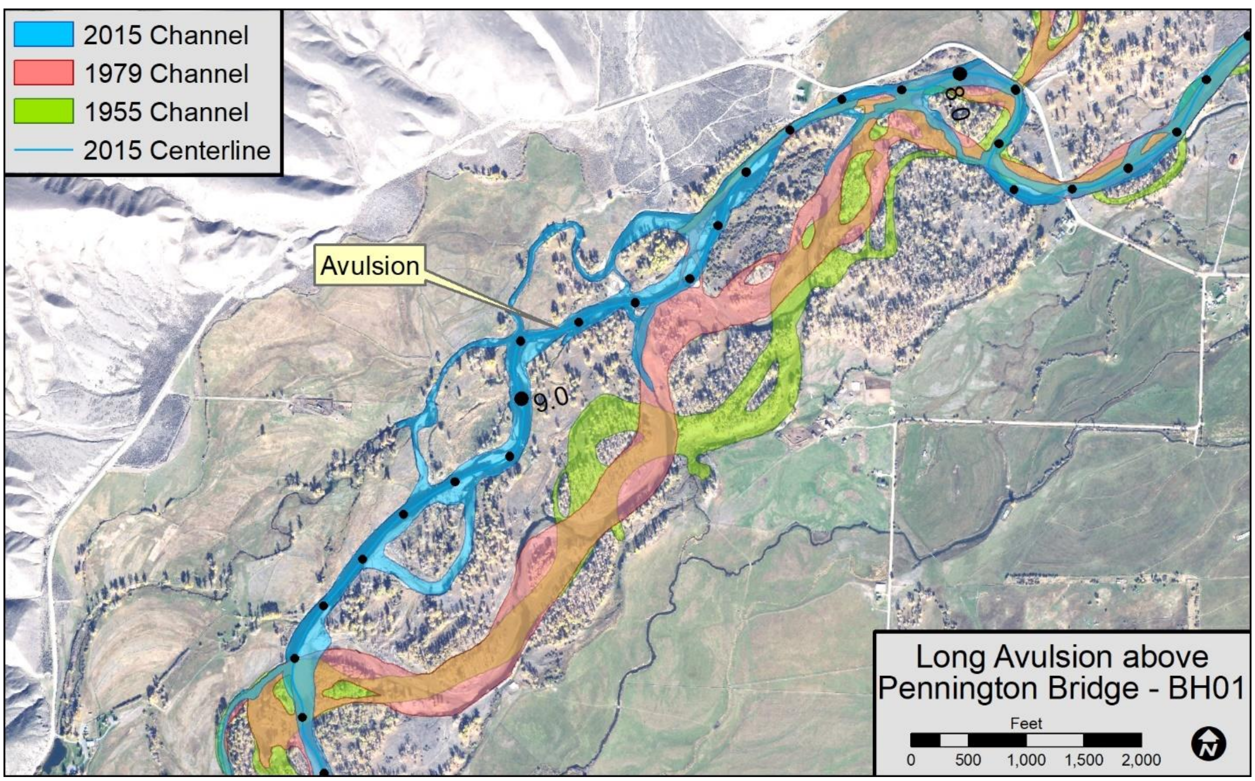

Figure 67. 2015 image of Reach BH1 above Pennington Bridge showing 1.6 mile long avulsion site.

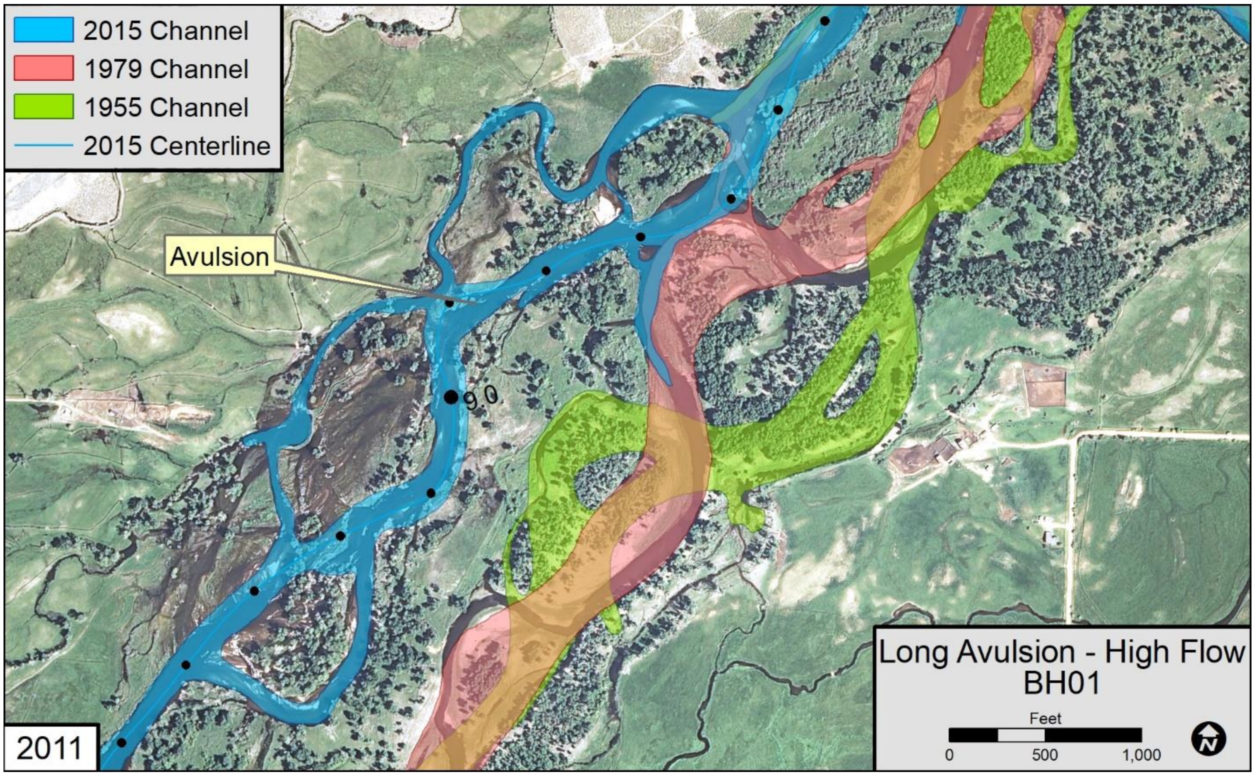

Figure 68. 2011 high flow image of avulsion site showing flooding on poorly evolved channel course.

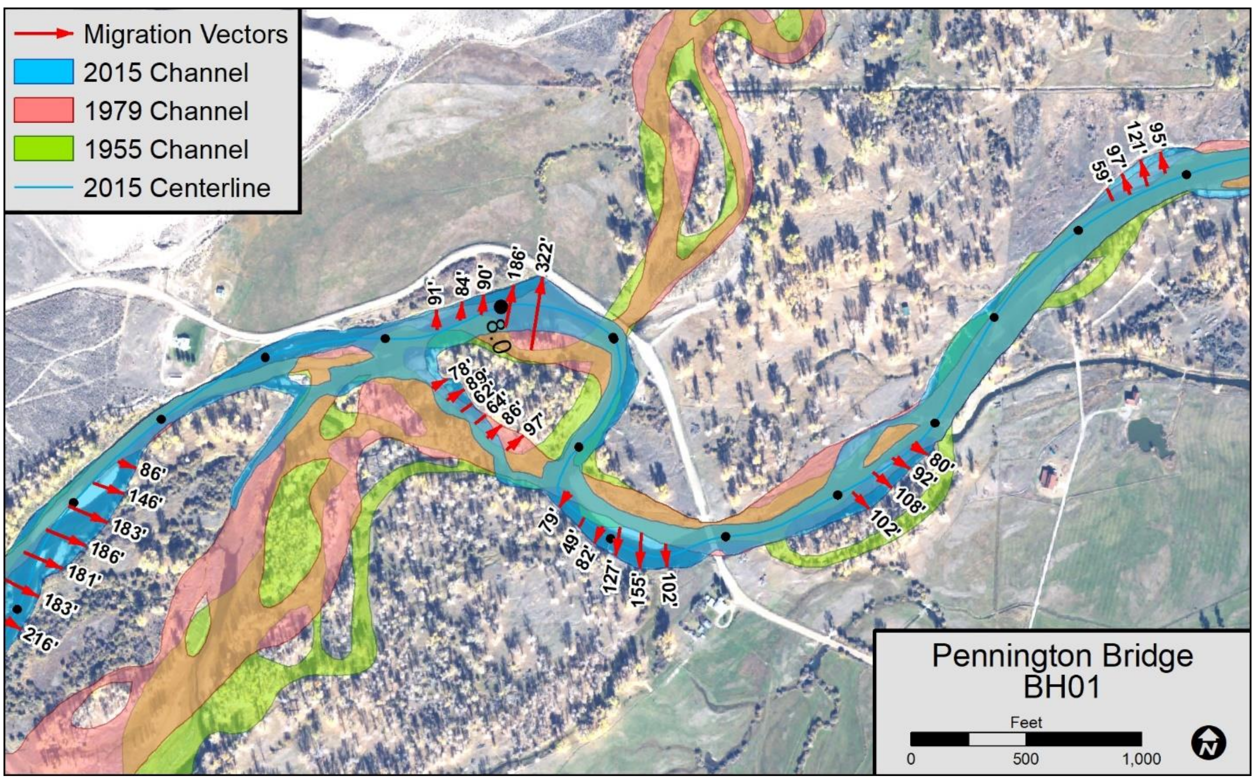

Figure 69. 2015 imagery showing historic and modern channel alignments to Pennington Bridge; flow is left to right.

Figure 70. View west of main channel at Pennington Bridge; flow direction is to the left.

Figure 71. View upstream of rock grade controls at diversion structure just below Pennington Bridge.

Figure 72. View upstream of high left bank terrace above High Bridge; note breached dike remnant on right bank.

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Appendix A: Site Migration Statistics

The Channel Migration Zone Mapping for the Big Hole River resulted in 1,165 individual measurements of channel movement between 1955 and 2015. These measurements were taken at approximately 30-foot intervals where notable movement has occurred. Each grouping of migration measurements, such as a bendway, was assigned a Migration Site ID (MSID) that includes the river mile as part of the ID. The statistics for each site are presented in the table below.

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
BH01				
MSID-BH-0.29	5	216	105	271
MSID-BH-0.56	8	141	102	179
MSID-BH-0.78	5	107	88	128
MSID-BH-0.82	2	184	119	249
MSID-BH-1	4	179	120	242
MSID-BH-1.21	17	294	153	470
MSID-BH-1.36	7	185	122	243
MSID-BH-2.05	7	181	90	244
MSID-BH-2.38	5	154	111	183
MSID-BH-2.42	3	111	83	133
MSID-BH-2.65	9	198	117	324
MSID-BH-2.93	4	162	145	178
MSID-BH-3.02	7	71	38	115
MSID-BH-3.33	6	155	120	197
MSID-BH-3.66	6	209	69	300
MSID-BH-4.04	11	251	94	391
MSID-BH-4.2	8	299	116	433
MSID-BH-4.6	7	60	43	78
MSID-BH-5.24	4	147	114	176
MSID-BH-5.37	2	54	51	56
MSID-BH-5.72	3	173	167	179
MSID-BH-6.08	7	239	117	333
MSID-BH-6.31	6	236	148	323
MSID-BH-6.45	5	154	120	177
MSID-BH-7.14	4	93	59	121
MSID-BH-7.46	4	96	80	108
MSID-BH-7.7	6	99	49	155
MSID-BH-8.01	5	155	84	322
MSID-BH-8.05	6	79	62	97
MSID-BH-8.44	7	169	86	216
MSID-BH-9.8	7	187	146	244
BH02				
MSID-BH-10.2	10	55	24	82
MSID-BH-10.53	7	355	301	452
MSID-BH-11.26	6	396	230	494
MSID-BH-11.61	7	87	66	137
MSID-BH-12.12	7	84	50	113
MSID-BH-12.35	4	278	187	336
MSID-BH-12.48	3	405	383	445
MSID-BH-12.79	7	334	172	471
MSID-BH-13.43	9	84	56	117
MSID-BH-13.65	9	269	157	329
MSID-BH-14.01	15	160	40	317
MSID-BH-14.7	6	123	102	151
MSID-BH-14.96	8	204	164	250

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-BH-15.55	7	196	137	245
BH03				
MSID-BH-18.16	4	79	70	84
MSID-BH-18.47	3	86	78	94
MSID-BH-18.67	10	150	70	236
MSID-BH-19.95	3	244	191	281
MSID-BH-20.88	5	424	253	495
MSID-BH-21.33	6	527	250	742
MSID-BH-21.6	6	81	66	91
MSID-BH-22.02	10	249	102	370
MSID-BH-22.51	11	174	84	254
MSID-BH-23.35	11	208	68	294
MSID-BH-23.64	9	208	123	313
MSID-BH-24	12	116	49	196
MSID-BH-24.18	11	125	72	182
MSID-BH-24.54	2	119	92	145
MSID-BH-24.7	2	134	102	165
MSID-BH-24.91	5	169	122	204
MSID-BH-25.15	3	127	112	138
MSID-BH-25.26	4	111	88	129
MSID-BH-25.45	4	153	92	195
MSID-BH-26.18	6	177	91	253
MSID-BH-26.8	8	109	56	170
MSID-BH-27	6	111	75	130
MSID-BH-27.1	4	61	49	69
MSID-BH-27.28	5	62	50	70
MSID-BH-27.77	12	115	40	166
MSID-BH-28.04	5	84	74	94
MSID-BH-28.31	4	215	185	241
MSID-BH-28.78	11	174	89	234
MSID-BH-29.03	8	162	76	230
MSID-BH-29.18	5	122	57	180
MSID-BH-29.44	9	179	88	233
BH04				
MSID-BH-31.22	2	129	88	170
MSID-BH-31.44	3	86	62	102
MSID-BH-31.54	3	99	59	126
MSID-BH-31.65	5	49	36	62
MSID-BH-32.54	6	94	76	117
MSID-BH-32.94	12	235	103	327
MSID-BH-33.37	8	176	58	288
MSID-BH-33.94	6	58	43	73
MSID-BH-34.02	7	78	61	93
MSID-BH-34.09	4	84	66	105
MSID-BH-34.51	2	92	73	111
MSID-BH-34.61	3	66	55	73

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-BH-34.67	2	111	111	111
MSID-BH-34.89	3	98	89	109
BH05				
MSID-BH-36.35	5	123	96	143
MSID-BH-36.87	5	125	71	168
MSID-BH-37.01	4	74	61	90
MSID-BH-37.04	3	85	73	96
MSID-BH-37.05	3	48	41	53
MSID-BH-37.13	3	104	99	110
MSID-BH-37.38	4	81	53	101
MSID-BH-37.52	2	87	82	92
MSID-BH-37.53	3	82	62	110
MSID-BH-37.95	6	130	91	174
MSID-BH-37.96	3	56	47	61
MSID-BH-38.31	4	63	56	78
MSID-BH-38.92	3	66	60	69
MSID-BH-38.93	4	84	69	103
MSID-BH-39.21	3	101	91	110
MSID-BH-39.54	3	96	84	105
MSID-BH-40.02	5	103	89	116
MSID-BH-40.48	4	108	90	127
MSID-BH-40.82	3	88	83	98
MSID-BH-41.55	4	87	61	110
BH07				
MSID-BH-48.97	4	79	65	86
MSID-BH-49.22	3	37	26	56
BH08				
MSID-BH-54.41	7	71	51	85
BH09				
MSID-BH-61.3	4	33	25	38
MSID-BH-62.57	5	41	35	46
MSID-BH-66.99	3	31	30	32
MSID-BH-67.62	3	29	24	33
MSID-BH-69.61	2	25	20	29
MSID-BH-69.73	4	35	33	36
MSID-BH-73.01	1	27	27	27
MSID-BH-73.57	3	45	29	55
MSID-BH-73.67	5	37	26	52
MSID-BH-73.78	2	39	29	48
MSID-BH-73.88	2	43	39	46
MSID-BH-73.92	2	35	34	36
MSID-BH-73.94	2	33	32	33
BH10				
MSID-BH-81	3	30	25	36
MSID-BH-81.32	3	33	27	37
MSID-BH-81.47	4	68	44	94
MSID-BH-81.6	1	21	21	21
MSID-BH-81.61	2	32	31	32
MSID-BH-82.09	3	33	28	37
MSID-BH-85.27	2	45	39	51
MSID-BH-87.25	3	35	32	38
BH11				
MSID-BH-89.46	3	28	25	31
MSID-BH-89.97	2	30	28	31
MSID-BH-90.13	2	34	31	36
MSID-BH-90.37	13	97	78	123

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-BH-90.9	9	106	62	148
MSID-BH-91.1	6	57	51	61
MSID-BH-91.36	2	50	42	58
MSID-BH-91.43	3	62	60	63
BH12				
MSID-BH-100.04	8	47	32	54
MSID-BH-100.19	5	54	40	72
MSID-BH-100.29	6	68	50	88
MSID-BH-100.38	5	68	52	80
MSID-BH-100.47	4	68	45	84
MSID-BH-100.58	5	83	38	114
MSID-BH-100.59	3	42	36	46
MSID-BH-100.64	4	71	49	87
MSID-BH-100.86	4	51	38	57
MSID-BH-100.98	4	28	20	39
MSID-BH-101	3	81	71	91
MSID-BH-101.01	4	37	25	44
MSID-BH-101.12	7	113	70	141
MSID-BH-101.25	6	99	59	124
MSID-BH-101.41	4	105	61	142
MSID-BH-101.55	4	96	65	117
MSID-BH-101.8	12	68	39	98
MSID-BH-101.93	5	135	76	185
MSID-BH-102.09	7	160	75	216
MSID-BH-102.21	2	105	89	120
MSID-BH-102.27	3	60	40	96
MSID-BH-102.34	2	58	56	59
MSID-BH-102.48	4	127	116	137
MSID-BH-95.07	7	105	80	125
MSID-BH-95.23	4	100	79	120
MSID-BH-95.34	6	108	81	126
MSID-BH-95.46	3	44	32	50
MSID-BH-95.51	2	44	43	45
MSID-BH-95.54	3	54	49	59
MSID-BH-95.55	3	26	24	29
MSID-BH-95.77	2	27	24	30
MSID-BH-96.15	5	40	27	53
MSID-BH-96.34	6	80	54	98
MSID-BH-96.48	3	77	68	86
MSID-BH-96.63	4	83	79	87
MSID-BH-96.79	6	72	59	82
MSID-BH-97.24	5	78	51	98
MSID-BH-97.45	5	64	56	73
MSID-BH-97.68	2	67	64	69
MSID-BH-97.69	3	55	49	59
MSID-BH-97.8	2	49	48	50
MSID-BH-98.03	3	57	50	62
MSID-BH-98.12	2	55	48	61
MSID-BH-98.18	2	49	40	57
MSID-BH-98.62	4	52	43	59
MSID-BH-98.67	3	38	33	44
MSID-BH-99.17	5	49	42	58
MSID-BH-99.25	3	30	23	36
MSID-BH-99.57	6	60	44	71
MSID-BH-99.66	3	56	49	65
MSID-BH-99.73	4	81	52	101

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-BH-99.74	3	46	36	54
MSID-BH-99.75	6	38	25	45
MSID-BH-99.95	6	85	46	116
MSID-BH-99.96	4	72	42	94
BH13				
MSID-BH-102.72	9	68	32	102
MSID-BH-102.87	5	54	25	78
MSID-BH-102.98	6	101	64	139
MSID-BH-103.1	7	88	35	126
MSID-BH-103.25	5	39	29	46
MSID-BH-103.32	5	60	56	65
MSID-BH-103.58	5	70	31	96
MSID-BH-103.71	12	89	47	162
MSID-BH-103.87	7	121	73	143
MSID-BH-103.95	4	46	39	50
MSID-BH-104.1	3	47	45	51
MSID-BH-104.26	7	69	49	90
MSID-BH-104.72	4	44	30	65
MSID-BH-105.69	2	97	73	121
MSID-BH-105.84	4	128	69	176
MSID-BH-106.06	3	114	91	140
MSID-BH-106.21	4	174	137	215

Site ID	Count	Avg (ft)	Min (ft)	Max (ft)
MSID-BH-106.38	3	76	39	106
MSID-BH-106.55	6	89	67	123
MSID-BH-106.58	3	76	50	99
MSID-BH-106.67	5	92	67	106
MSID-BH-107.05	4	78	55	92
MSID-BH-107.38	4	58	41	80
MSID-BH-107.39	5	69	53	88
MSID-BH-107.47	3	68	63	76
MSID-BH-107.6	4	90	68	112
MSID-BH-107.7	5	123	94	163
MSID-BH-108.15	6	88	59	108
MSID-BH-108.56	5	157	75	224
MSID-BH-109.08	4	73	53	81
MSID-BH-109.53	5	103	75	135
MSID-BH-109.67	3	107	94	127
MSID-BH-109.75	4	127	91	154
MSID-BH-109.87	2	91	81	100
MSID-BH-110.05	2	95	76	114
MSID-BH-110.14	5	260	186	303
MSID-BH-110.36	2	94	86	101
MSID-BH-110.43	4	166	77	209
MSID-BH-110.74	4	199	136	259

Appendix B: Select Infrastructure Photos

Figure 73. High Bridge, September 30, 2017 (Kestrel).

Figure 74. Grade control, September 30, 2017 (Kestrel).

Figure 75. Pennington Bridge, September 30, 2017 (Kestrel).

Figure 76. Local access bridge (RM 16.9), September 30, 2017 (Kestrel).

Figure 77. Burma Road bridges, September 30, 2017 (Kestrel).

Figure 79. Hwy 91, railroad, and I-15 bridges, September 30, 2017 (Kestrel).

Figure 78. Burma Road bridges, September 30, 2017 (Kestrel).

Figure 80. I-15 bridges, September 30, 2017 (Kestrel).

Figure 81. Brownes Bridge Road, September 30, 2017 (Kestrel).

Figure 83. Meriwether Ranch bridge, September 30, 2017 (Kestrel).

Figure 82. Trapper Creek Road west bridge, September 30, 2017 (Kestrel).

Figure 84. Maiden Rock Road bridge, October 6, 2017 (Kestrel).

Figure 85. Hwy 43 bridge at Divide, October 6, 2017 (Kestrel).

Figure 86. Pump house diversion, October 6, 2017 (Kestrel).

Figure 87. Jerry Creek Road bridge, October 6, 2017 (Kestrel).

Figure 88. Jerry Creek Road bridge, October 6, 2017 (Kestrel).

Figure 89. Dickie bridge, October 6, 2017 (Kestrel).

Figure 90. Hwy 43 bridge at N Fork Road, October 6, 2017 (Kestrel).

Figure 91. Hwy 43 bridge at Wisdom, October 6, 2017 (Kestrel).

Appendix C: CMZ Maps