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FINAL

Bighorn River
Channel Migration Zone Mapping

PREPARED FOR

BIG HORN RIVER ALLIANCE

THE RESEARCH INITIATIVE

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Executive Summary

This report contains the results of a Channel Migration Zone (CMZ) mapping effort for 86 miles of the Bighorn extending from just below the Yellowtail Afterbay Dam near Fort Smith to its confluence with the Yellowstone River near Bighorn MT. Along this stretch, the river transitions from having relatively low rates of channel movement between Yellowtail Dam and the Little Bighorn River confluence to a much more dynamic system downstream. The river commonly flows along high bluff lines that are relatively erosion resistant, but the finer grained units are prone to both some erosion as well as landslides. Within the stream corridor itself, the river shows highly variable rates of movement. Avulsions (the creation or re-activation of channels on the floodplain) have occurred historically and will continue to pose risk of rapid channel shift. Migration rates generally increase in the downstream direction as the channel slope flattens, the valley widens, the river becomes bigger, and large rapidly migrating meanders traverse the floodplain. Old floodplain swales, meander cores, and tributary channels running parallel to the river create high flow paths and avulsion routes.

Historic imagery beginning in the mid-1950s was used to measure migration rates through the project reach; hundreds of measurements were collected and statistically analyzed to determine mean rates of movement for each reach. Maximum migration distances measured for the mid-1950s-2019 timeframe range from about 90 feet below afterbay dam to 1,020 feet in the lower river.

The impacts of Yellowtail Dam completed in 1966 have included reduced flooding and sediment delivery through the project reach. As flooding and sediment are two large drivers of bank movement, it was important to discern the historic versus modern rates of movement. As a result, the migration measurements were segmented to capture mid-1950s-1979/80 conditions (pre- and early post-dam) and 1979/80-2019 (post-dam). The post dam statistics were used to develop the CMZ units that incorporate anticipated rates of future movement.

Our objective with the mapping and interpretations provided in this document is to assist river corridor landowners and other stakeholders in understanding the nature of Bighorn River lateral migration, focusing not only on the challenges that channel migration creates but also the critical contributions that these processes make to stream heath, resilience, and ecological vibrancy.

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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.

Avulsion Node– The location where a river splits or relocates from an existing channel into an avulsion path.

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 riverbank. 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 Bighorn River Channel Migration Zone (CMZ) mapping project extends 84 river miles from Afterbay Dam near Fort Smith down to the confluence of the Bighorn and Yellowstone Rivers near Bighorn, MT (Figure 1). River corridor communities located within or adjacent to the Bighorn River corridor include Fort Smith, Hardin, and Bighorn.

This work was funded by the Bighorn River Alliance (BHRA) as part of the BHRA Research Initiative. The Research Initiative has completed several projects to date focused on understanding the physical, biological, and management issues on the river. Reports and summary documents can be found online at https://www.bighornriveralliance.org/.

The goal of the Channel Migration Zone mapping is to evaluate historic rates of channel movement, and to use that data to develop a mapped corridor with a supporting narrative that describes erosion patterns, erosion risks, and corridor boundaries that will demonstrably accommodate a century of unimpeded channel movement. The ultimate product of the effort is a series of Channel Migration Zone maps that extend from Afterbay Dam to the Yellowstone River, accompanied by this report that describes methods and results. The project also has a public outreach component focusing on the agricultural, tribal, and recreational sectors along the river, although that task has yet to be completed due to Covid-19.

The mapping can be used to assess patterns of bank erosion in areas of concern, locate old channel paths and restoration opportunities, and identify areas with spawning gravel recruitment, riparian expansion, and cost-effective land use management opportunities.

1.1 Other Relevant Studies

Over the past few years, the Bighorn River Alliance has funded several investigations through the Research Initiative that may be useful to those interested in the evolution and current condition of the Bighorn River as they relate to channel dynamics.

1.1.1 Characterization of Bighorn River Hydrologic Alterations Below Yellowtail Dam (Boyd, 2019)

This report may be useful to those interested in understanding how flow control has changed the hydrology of the river below Yellowtail Dam. Long-term trends show that dam construction has reduced spring flooding while increasing flows in fall and winter. Boysen Dam, which was built between 1947 and 1952, had a major impact on river flows prior to Yellowtail Dam completion in 1965. Once Yellowtail Dam was closed, flows became increasingly simplified downstream, with a lower range in flows resulting in less variability, less flooding, and fewer low flow periods. This effectively created the tailwater fishery we see today. Since then, there have been periods of drought coupled with changes in operating criteria that affected flow patterns. The drought years prior to 2009 occurred prior to the establishment of modern operating criteria, and have a distinct hydrologic signature, including persistently low flows and a dominance of flow releases through the dam powerhouse. Since 2009 flows have been consistently higher, resulting in an increased use of the dam spillway supplemental to the powerhouse. Occasional use of the lowermost river outlet appears to have a distinct temperature signature on the river.

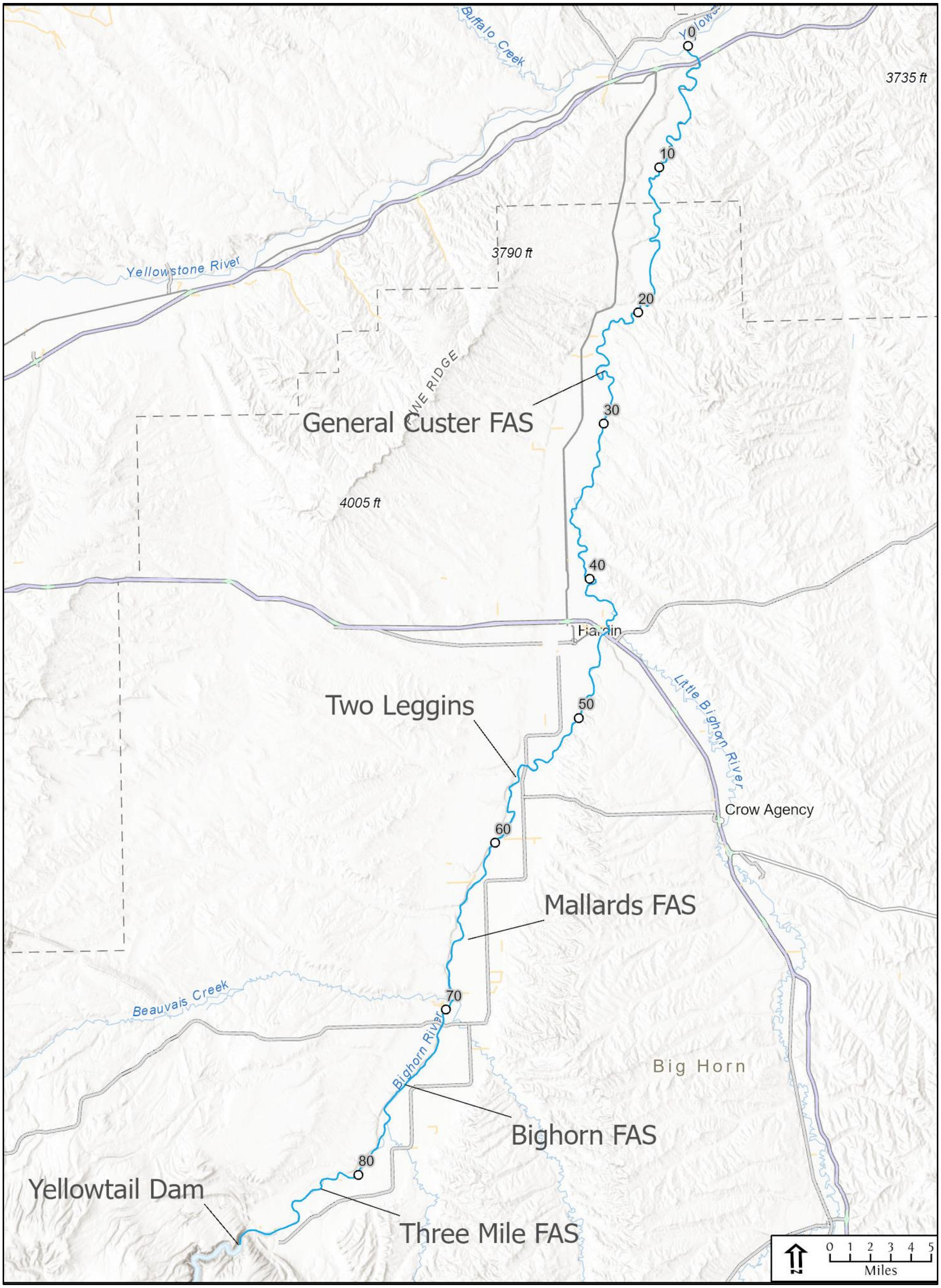


Figure 1. General project location map.

1.1.2 Spatial Imagery Consolidation and Channel Feature Delineation (Thatcher, 2019)

This report details the key spatial data sets that were compiled or created to support the Research Initiative. The imagery, bankline mapping, physical feature, and LiDAR data sets are the core information for this Channel Migration study.

1.1.3 Preliminary Assessment of Bighorn River Side Channel Restoration Potential (Boyd, 2020)

Many historic side channels on the Bighorn River have become increasingly disconnected from the mainstem due to sediment infilling and vegetation encroachment at their entrances. In this effort, channels with limited connectivity were evaluated and ranked in terms of restoration potentials. A total of 29 channels were evaluated in terms of current and potential connectivity. Of these 29 channels evaluated, 13 were considered "top tier". These highest priority opportunities were identified as such because substantial reconnection can be achieved with minimal to moderate excavation. Each top tier channel is described in terms of the approximate amount of excavation necessary, the flows at which activation will occur, and the length of channel restored.

1.1.4 Bighorn River Alliance Research Initiative - Inundation Risk Maps (Thatcher/Boyd, 2020)

There has been a strong desire to assess flood risk along the Bighorn River corridor. Creating flood maps that are regulatory in nature is a costly process that relies on both elevation data and a calibrated hydraulic model. That said, the elevation data itself can be used to estimate extents of anticipated inundation based on river stage. The results help landowners understand the elevation of their properties relative to water surface elevations on the river and better understand risk.

This report details a series of Inundation Risk Maps generated for the river corridor from Yellowtail Dam to the Interstate 94 river crossing near the Yellowstone River confluence. This builds on work completed in 2019 (Thatcher and Boyd) to develop baseline data sets and assessments of conditions in the corridor. The primary goal was to develop a series of maps depicting relative levels of inundation risk posed by river flooding. These maps should not be confused with flood mapping that relies on calibrated hydraulic modeling. They are intended to act as a tool to help river and land use managers, both public and private, better understand potential risks from overbank flow. These maps can be used in conjunction with the Channel Migration Zone Mapping to make informed management decisions.

1.2 The Project Team

This project work was performed by Karin Boyd of Applied Geomorphology and Tony Thatcher of DTM Consulting. Over the past decade, we have been collaborating to develop CMZ maps for numerous rivers in Montana, to provide rational and scientifically-sound tools for river management. It is our goal to facilitate the understanding of rivers regarding the risks they pose to infrastructure, so that those risks can be managed and hopefully avoided. Furthermore, we believe the mapping supports the premise that managing rivers as dynamic, deformable systems contributes to ecological and geomorphic resilience while supporting sustainable, cost-effective development.

1.3 What is Channel Migration Zone Mapping?

The goal of Channel Migration Zone (CMZ) mapping is to provide a cost-effective and scientifically-based tool to assist land managers, property owners, agency personnel, 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 2).

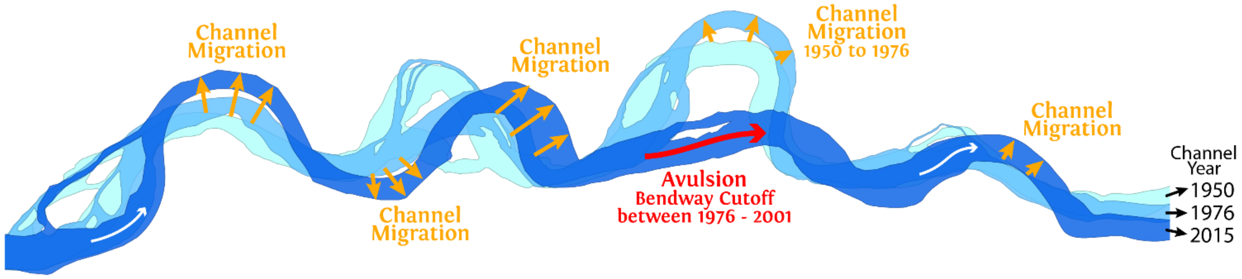


Figure 2. Typical patterns of channel migration and avulsion evaluated in CMZ development; these polygons collectively make up the Historic Migration Zone (HMZ).

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 2). 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 geomorphic influences such as geology, channel type, stream size, sediment volume, sediment 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.

Changes in geomorphic drivers can also be imposed on a river system, and on the lower Bighorn River, the construction of numerous dams in the upper watershed has altered flow patterns and sediment delivery to the project reach. As such, the migration rate measurements have been evaluated with those impacts considered.

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 2), 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 current and 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 formation or re-occupation.
- ***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 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 3).

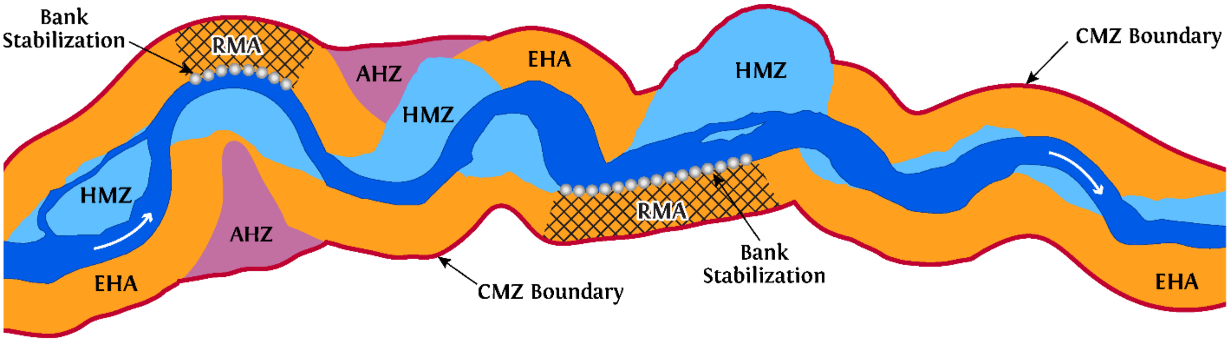


Figure 3. Channel Migration Zone mapping units.

Although the basic concept for Channel Migration Zone mapping efforts is similar 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 including the Historic Migration Zone (HMZ), Erosion Hazard Zone (EHA), and Avulsion Hazard Zone (AHZ). The HMZ consists of the collective footprint of mapped channel locations using air photos from the mid-1950s, late 1970s, 1996, 2005, and 2019. The EHA is created as a "buffer" that extends landward from the 2019 channel margins. The width of the buffer is based on reach-scale average migration rates and is intended to show areas that are at demonstrable risk of channel migration over the next century. Areas beyond the erosion buffer that pose risks of channel avulsion, which is a different process than gradual migration, are identified as Avulsion Hazard Areas or AHZ. This approach generally falls into the standards of practice for Reach Scale, Moderate to High Level of Effort mapping studies as defined by the Washington Department of Ecology (www.ecy.wa.gov). As the Bighorn River commonly flows along and migrates into high valley walls that are erodible, specific EHA buffers have been developed based on measurements as well as geology. Geotechnical setbacks that would capture the risk of hillslope failures in the uplands have ***not*** been created for the valley margins since they are so site specific, but landslides are common and should always be considered as another risk factor.

1.4 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. 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 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).

1.5 Uncertainty

There is always uncertainty in predicting river behavior, in part due to the range of stochastic events that can occur. On the Bighorn River, site-specific events such as woody debris jams, sediment slug delivery, landslides, or ice jams could drive responses that may not be captured in the mapping in terms of spatially explicit risks. We believe that the CMZ mapping effectively envelops likely river locations projected over the next century, but occasional channel movement beyond the CMZ boundaries is plausible and should be expected.

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 since Yellowtail Dam was built 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. If substantial changes are made to the flow release patterns from Yellowtail Dam, for example, rates of bank erosion could change. In addition, bank armor and floodplain modifications such as bridges, dikes, levees, or sand and gravel mining could also affect map boundaries.

1.6 Potential CMZ Map Applications

The CMZ mapping is intended to support a range of applications, but the mapping should be primarily viewed as a tool to support informed management decisions throughout a river corridor. Potential applications for the CMZ maps include the following:

- Identify specific problem areas where migration rates are notably high and/or infrastructure is threatened.
- Identify restoration opportunities, especially in the Historic Migration Zone.
- Improve stakeholder understanding of the risks and benefits of channel movement.
- Help stakeholders avoid unnecessary risk to investment.
- Optimize long-term ecological function through allowed channel movement.
- Develop project priorities, timelines, and funding mechanisms.
- Develop river corridor best management practices.
- Facilitate productive discussion between regulatory, planning, and development interests active within the river corridor.

Note:

The CMZ mapping developed in this study was developed without any explicit intent of either providing regulatory boundaries or overriding site-specific assessments. Any future use of the maps as a regulatory tool should include a careful review of the mapping criteria to ensure that the approach used is appropriate for that application.

1.7 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.

1.7.1 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 4). In contrast, where erodible materials form high valley walls, the CMZ is commonly wider than the floodplain, because the valley wall may be high enough to escape flooding, but not resistant enough to avoid erosion (right schematic on Figure 4). On the Bighorn, for example, high valley margins composed of fine grained silts have been assigned an EHA buffer, even though the high surfaces are well out of the floodplain.

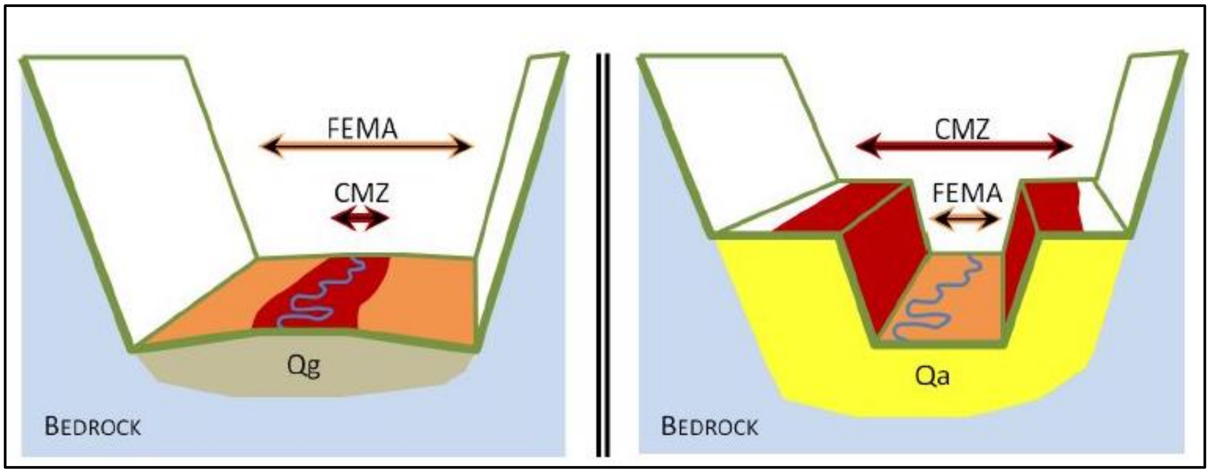


Figure 4. Schematic comparisons between CMZ and flood mapping boundaries (Washington Department of Ecology).

Figure 5 shows a property on the Yellowstone River in Park County that was progressively undermined during the 1996-1997 floods, prompting the owner to burn it down to prevent any liability associated with the structure falling into the river. This has been a chronic problem in river management, as landowners assume that if their home is beyond the mapped floodplain margin, it is removed from all river hazards.

Figure 5. Yellowstone River home on high glacial terrace that was burned down in 1997 to prevent its undermining by the river.

FEMA flood mapping from 1978 is available for the Bighorn River, and it shows only Approximate Zone A (approximate 100-year flood) boundaries (www.fema.gov). This information is quite old and does not include any detailed hydraulic analyses that would have provided Base Flood Elevations or flood depths. In order to further our understanding of flood risks on the Bighorn River, we recently completed a relative elevation analysis of the Bighorn River floodplain (Thatcher and Boyd, 2020). This mapping shows relative flood risks as a function of height above river (Figure 6). These Relative Elevation maps can be used in combination with the Channel Migration Zone maps to consider spatial risks to human health and safety associated with channel movement and flooding.

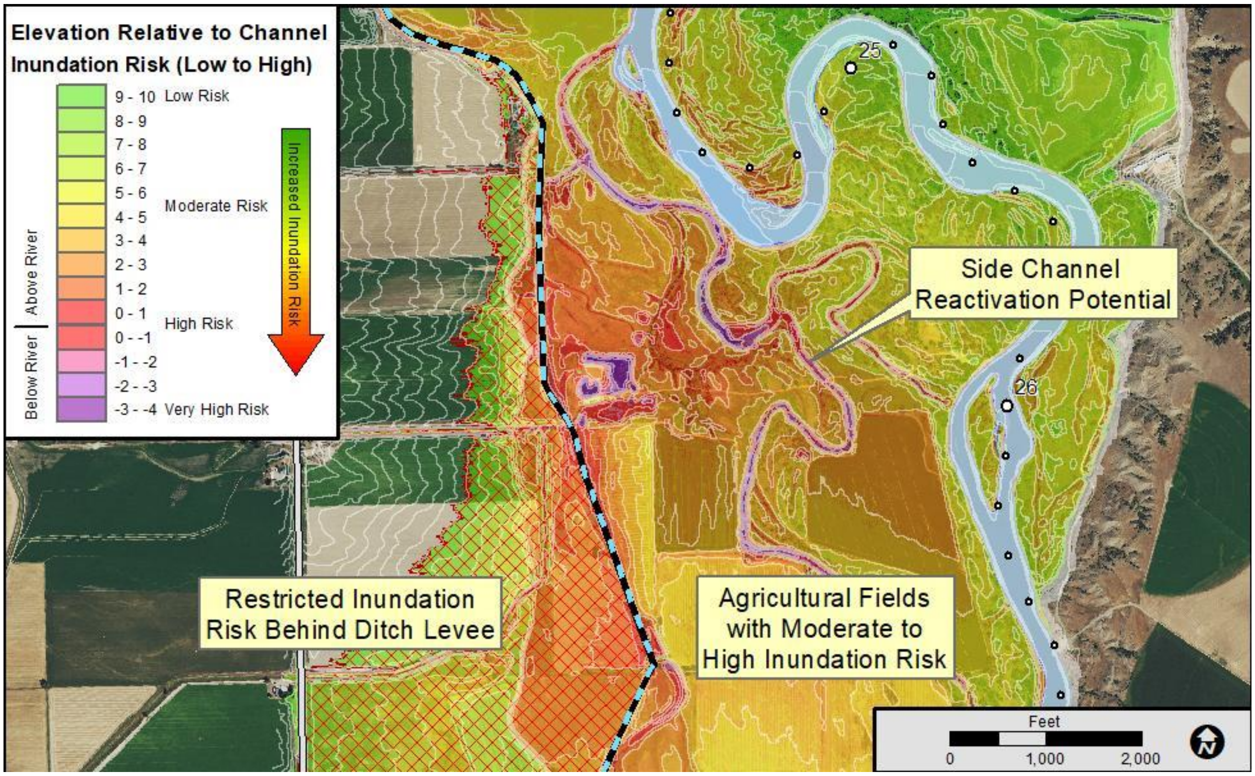


Figure 6. Inundation Risk Mapping on the Bighorn River, showing elevation-based risk assessment results (Thatcher, 2020).

1.7.2 Ice Jams

Another serious river hazard, especially in Montana, is ice jamming. The Corps of Engineers Ice Jam Database (www.icejam.sec.usace.army.mil) shows that, between 1894 and 2017, a total of 4,514 ice jams have been documented in Montana, and 380 rivers in Montana have at least one recorded jam (Figure 7). Montana has the most ice jam events recorded in the US.

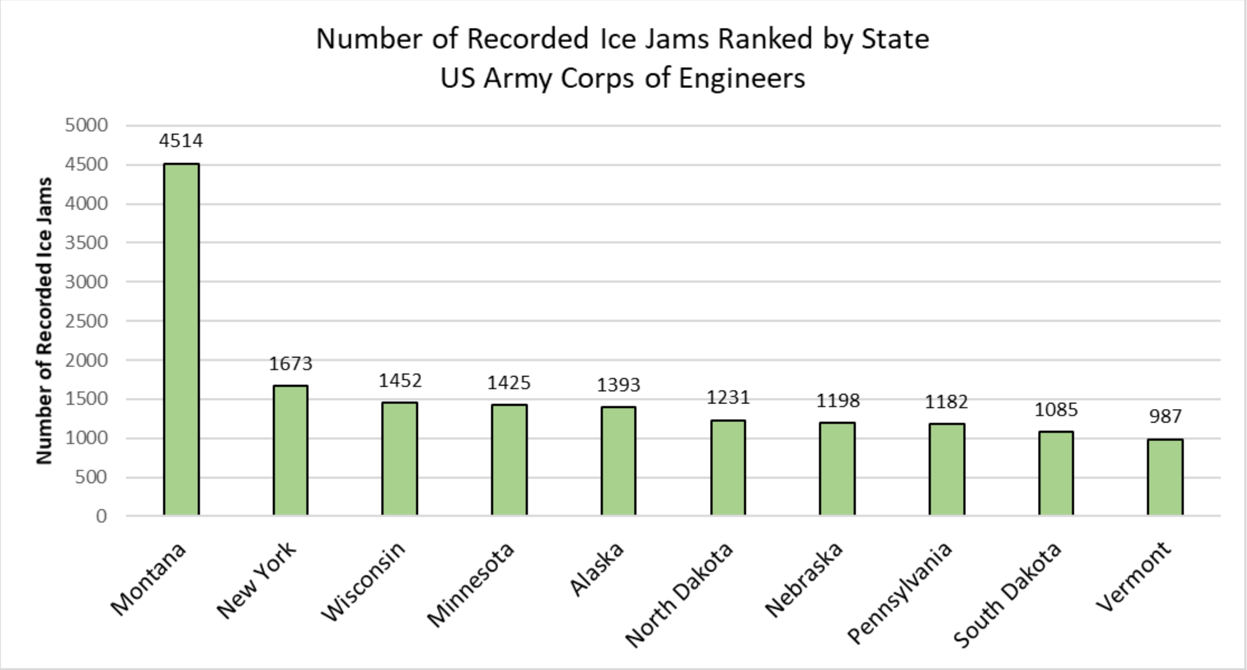


Figure 7. State ranking of ice jam frequency; Montana ranks first with over twice as many jams as the second ranked state.

Ice jams are most common in Montana during February and March. Dams can cause flooding upstream due to backwatering, and downstream of the jam where ice chunks mobilized by breakups can cause damage. Breakups can occur rapidly, and it generally takes water that is almost two to three times the thickness of the ice to mobilize the jammed ice. Ice jams can also cause avulsions by entirely blocking channels and forcing flows onto the floodplain.

The Bighorn River below Yellowtail Dam does not appear to be particularly prone to ice jamming, which is likely due to relatively warm water releases from Yellowtail Dam in winter months. However, the river is highly prone to ice jamming upstream of Bighorn Lake in Wyoming—for example Bighorn River ice jams have caused substantial damages in Worland and Greybull. A 2014 ice jam in Worland (Figure 8) resulted in the flooding of 60 homes and evacuation of 80 people (www.icejam.sec.usace.army.mil). Below Yellowtail Dam, numerous ice jams have been recorded on Big Horn River tributaries, including Soap Creek, Beauvais Creek, Rotten Grass Creek, the Little Bighorn, and Tullock Creek. Only two ice jams are recorded on the mainstem Bighorn, and both are at the lowermost end of the river near its confluence with the Yellowstone; one on March 7, 1956 and another on January 14, 1983.

Figure 8. Bighorn River flood fight in Greybull Wyoming, March 2014 (army.mil).

1.7.3 Landslides

The valley wall along the Bighorn River is prone to landslides, especially in the upper reaches of this study where they are composed primarily of fine grained shales. Figure 9 shows an example of a landslide blocking a side channel on the Bighorn. Although a geotechnical setback has not been quantified to incorporate landslide risks, an erosion buffer has been applied to the erodible valley walls to capture risk of channel migration into those units.

Figure 9. Google Earth (2016) image showing side channel blocked by landslide at RM 56.7.

1.8 Disclaimer and Limitations

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

Primary limitations of this reach-scale mapping approach include a potential underestimation of migration rates in discrete areas that are eroding especially rapidly, which could result in migration beyond the mapped CMZ boundary. Additionally, site-specific variability in alluvial deposits may affect rates of channel movement. Mapping errors introduced by the horizontal accuracy of

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

1.9 Acknowledgements

We would like to extend our gratitude to Jim Chalmers and Anne Marie Emery of the Bighorn River Alliance for their assistance in project scoping, contract management, scheduling, and draft document review. Both Jim and Anne Marie have been wonderful to work with over the last few years, and we are grateful for the opportunity to support the BHRA's mission to protect, preserve, and enhance the long-term health and viability of the Bighorn River. Over the course of our work, conversations with Dennis Fischer and Doug Haacke have helped us gain a better understanding of the system; we appreciate their generosity and insights. Dennis Fischer's willingness to pilot a boat and share his knowledge in the field has been tremendously helpful. And Mike Ruggles and Shannon Blackburn from Montana Fish Wildlife and Parks have been generous with their input regarding issues at Fishing Access Sites as well as relationships between the fishery and river geomorphology.

2 Physical Setting

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

2.1 Watershed Geography

The Bighorn River watershed is about 23,000 square miles in total area, about 83% of which is upstream of Yellowtail Dam. Above Bighorn Reservoir, the river drains portions of the Wind River Range, Absaroka Plateau, and Bighorn Mountains. The project area is in the lower river below the dam, which receives additional runoff from the northern flank of the Bighorn Mountains.

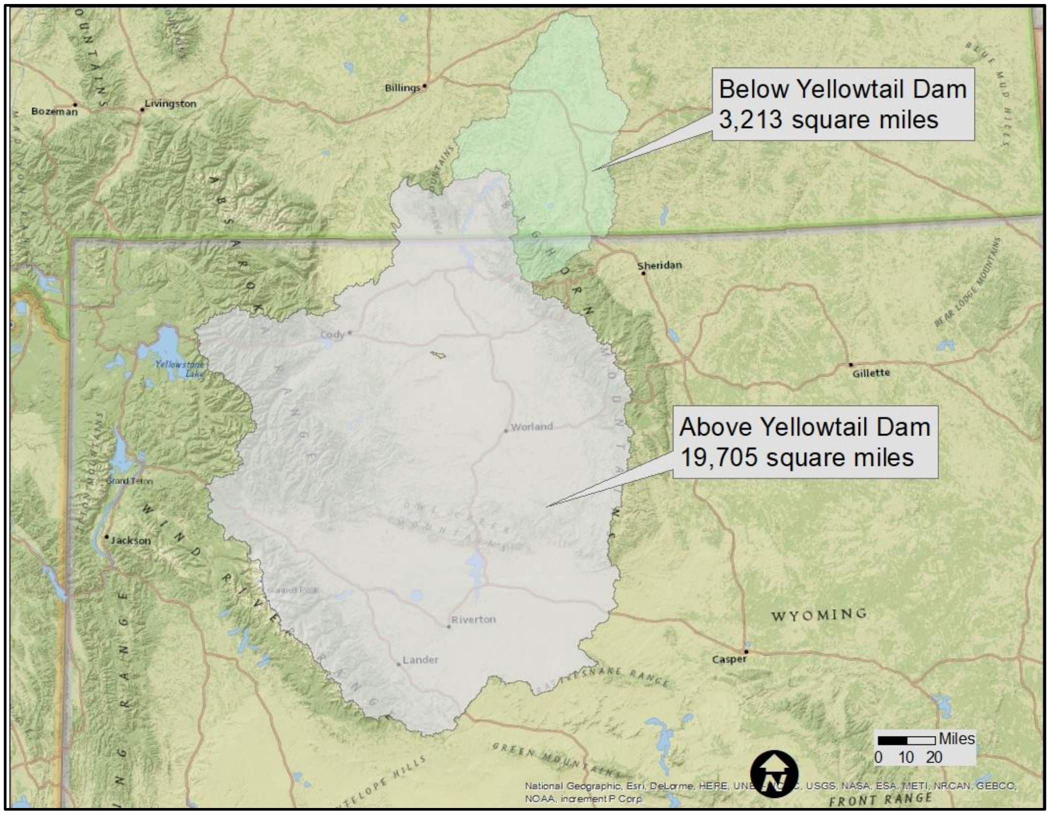


Figure 10. Bighorn River Watershed.

2.2 Geology

The Bighorn River valley is a well-defined geologic feature, with a broad floodplain and steep valley margins. The valley walls consist of primarily fine grained shales from Fort Smith to below Hardin, transitioning to primarily sandstones in the lower project area. These Cretaceous-age units are typically capped by young alluvial gravels that form high terraces on the valley margins.

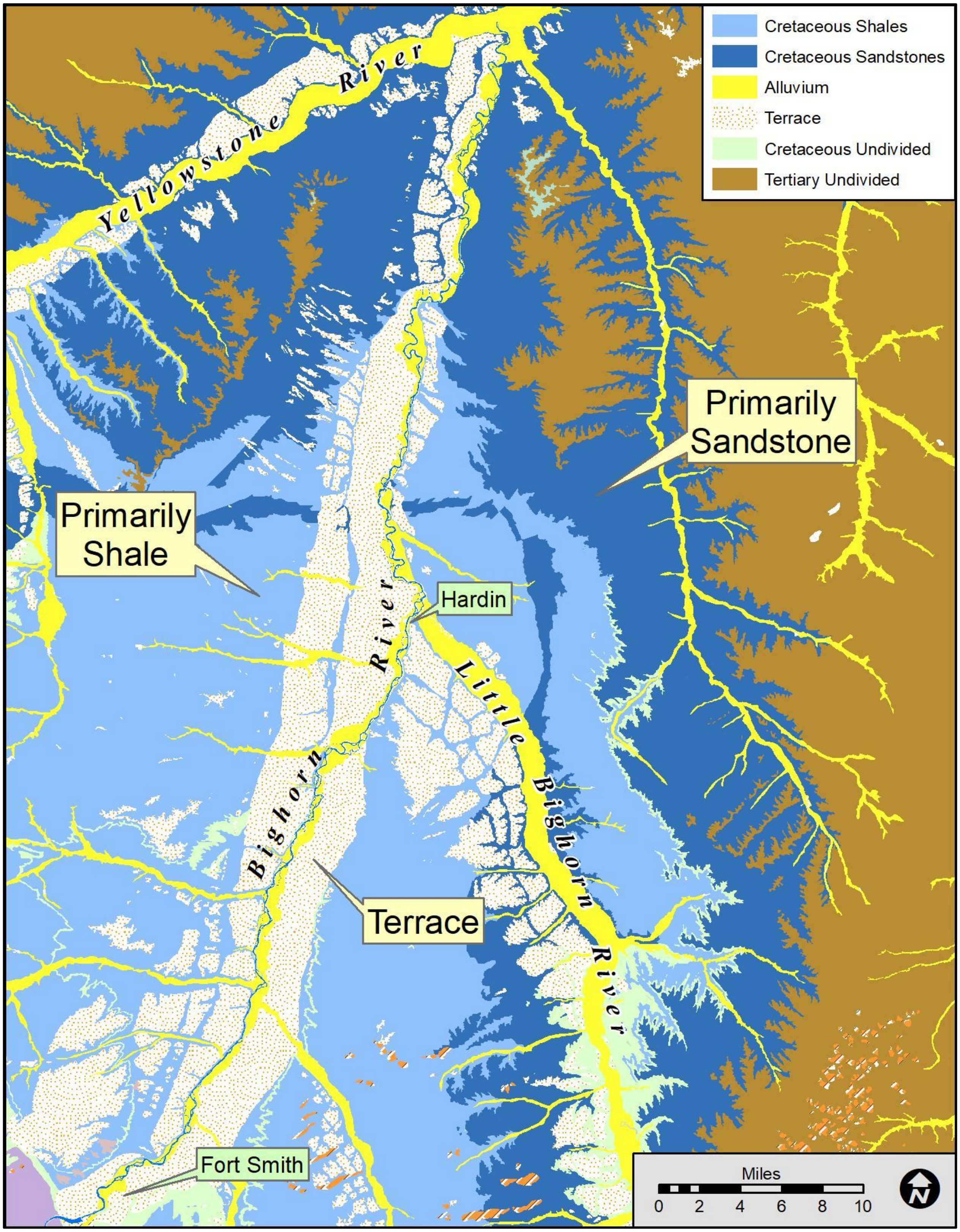


Figure 11. Simplified geologic map of the lower Bighorn river showing terraces capping the valley walls underlain predominantly by shale from Fort Smith to below Harding, and sandstones downstream.

2.3 Hydrology and Flow Management

In mapping Channel Migration Zones, it is important to consider whether the time frames used to evaluate channel movement are representative. The “representativeness” of the historic data with respect to current and anticipated future channel migration rates can be affected by changes in flow management as well as natural flow patterns. Our goal is to use the longest representative timeframe possible. Longer timeframes will provide better results in terms of calculating average annual rates of movement, as longer timeframes are more likely to capture natural variability in flows, including low water years and high water years. That said, if major changes have been made in flow management, timeframes for the analysis may have to be shortened.

The hydrologic history of the Bighorn River has proven a major consideration in our analytical approach to CMZ mapping. Currently, river flows are governed by the volume of water entering Bighorn Lake and released through Yellowtail Dam, one of several reservoirs in the basin. The progressive hydrologic alterations imparted by flow management since the 1920s in the Bighorn River watershed were summarized in a Bighorn River Alliance Research Initiative report (Boyd, 2019). Some major conclusions of that investigation that are relevant to this analysis include the following:

- Boysen Dam, which was built on the Wind River near Thermopolis between 1947 and 1952, had a major impact on Bighorn River flows prior to Yellowtail Dam completion in 1966.
- Once Yellowtail Dam was completed in 1966, flows became increasingly simplified downstream, with a lower range in flows resulting in less variability, less flooding, and fewer periods of low flow. This flow management has created the tailwater fishery that is so renowned on the Bighorn River.
- High inflows since 2009 created a new recent hydrologic pattern relative to the drought years prior, with higher peak flows of longer duration.

Figure 12 shows the trend of decreasing annual peak flows over three management timeframes. On these plots, the “box” includes the 2nd and 3rd quartiles (25th to 75th percentiles, or 50% of the data points surrounding the median). The whiskers are the 1st and 4th quartiles. The median value is a horizontal line in the box and statistical outliers are shown as individual points. This gaging station is located at Afterbay Dam near Fort Smith, and thus captures Yellowtail Dam releases. The results of this assessment suggest that conditions prior to 1966 are probably not reflective of current rates of channel change. This helps put boundaries on migration rate measurements and analyses, to ensure that the CMZ mapping captures modern hydrologic conditions. The influence of flow alterations on data collection and analysis is further described in Section 3.4.

Another important consideration in the analysis is the more recent flood history, to see if there has been a fair representation of events that would provide confidence in calculating average rates of channel movement. Figure 13 and Figure 14 show annual peak flows measured from 1980-2020 at Afterbay Dam and above Tullock Creek (near the confluence with the Yellowstone River), respectively. Flood frequencies are plotted as horizontal lines on the charts. These plots show that no floods in excess of a

25-year event have been recorded at Afterbay Dam since at least 1980 (Figure 12), although there have been five ~10 year floods since 2009.

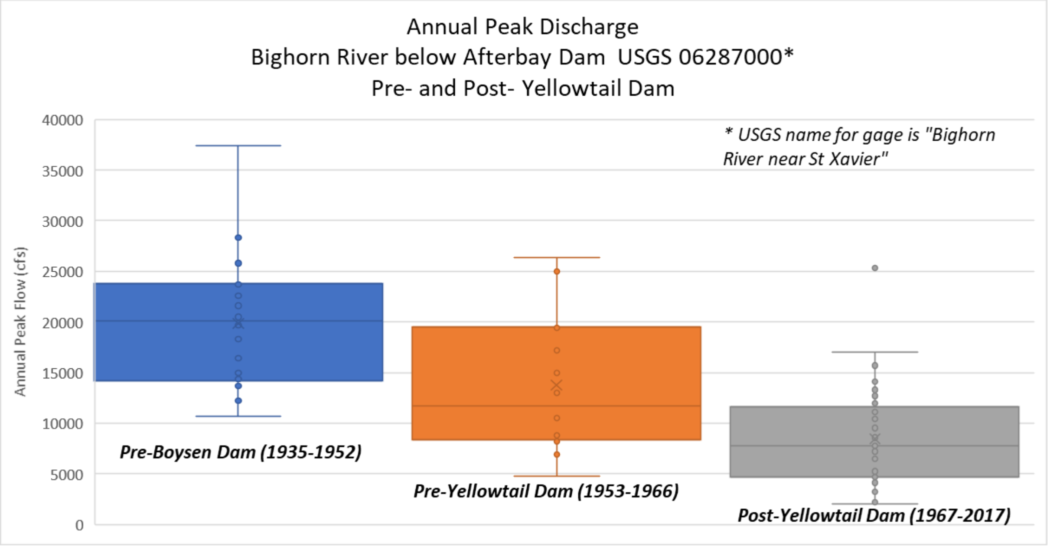


Figure 12. Range of annual peak flows for timeframes prior to Boysen Dam completion, between Boysen and Yellowtail completion, and post-Yellowtail dam showing continued drop in annual peak flows.

The gage above Tullock Creek is located near the confluence of the Bighorn and Yellowstone Rivers, so it captures the lowermost part of the watershed. Flows at this gage are still strongly affected by Yellowtail Dam operations, but additional tributary inputs below the dam create more flow variability in the lower river. Figure 13 shows that there has been very little flooding on the lower river with the exception of a large flood in 2011 that was about a 50-year flood event.

The lack of repetitive flooding below Hardin suggests that migration rate measurements collected below the mouth of the Little Bighorn River may underestimate overall potential rates of movement and thus should be considered conservative.

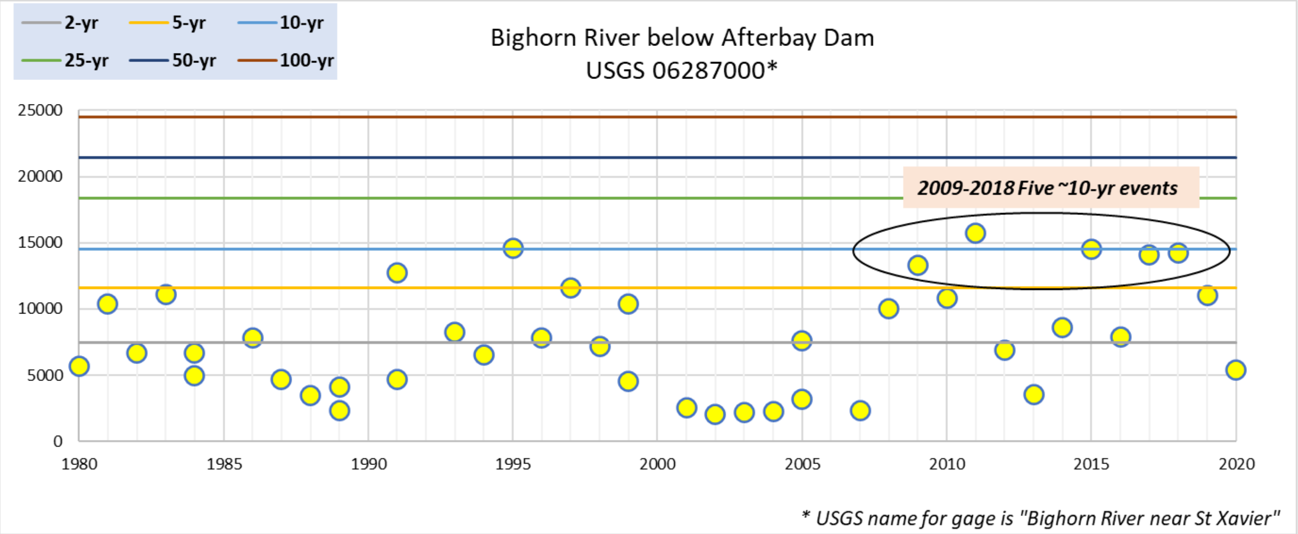


Figure 13. Annual peak flows for the Bighorn River at Afterbay Dam, 1980-2020; recent high flow events are circled.

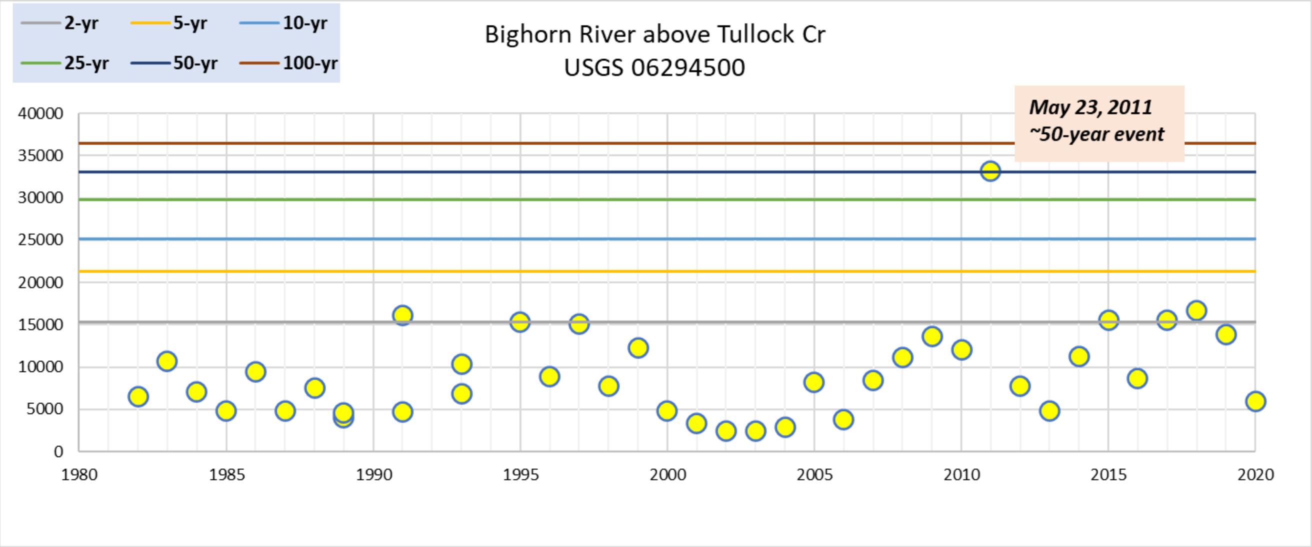


Figure 14. Annual peak flows for the Bighorn River above Tullock Creek (near the Yellowstone River confluence), 1980-2020.

Annual peak discharges plotted for both gaging stations (Figure 15) show how large the 2011 flood was on the lower river relative to upstream, which reflects tributary inputs below Yellowtail Dam. For example, the 2011 flood was intense on the Little Bighorn River, where I-90 had to be closed due to complete inundation on May 22 (Figure 16). St Xavier was also badly flooded, but images of the flood patters indicate much of that was due to swollen Rotten Grass Creek rather than the Bighorn itself (Figure 17).

The 1979/80-2019 timeframe as defined by the 1979/1980 imagery was ultimately used to calculate rates of movement, as this imagery was available for the entire study area for post-Yellowtail Dam conditions, and 2019 fall imagery to capture recent high water years. As discussed later in this document, earlier imagery from the 1950s was used to help characterize pre-Yellowtail channel morphology and dynamics, although the mapping is based on post-Yellowtail Dam migration rates.

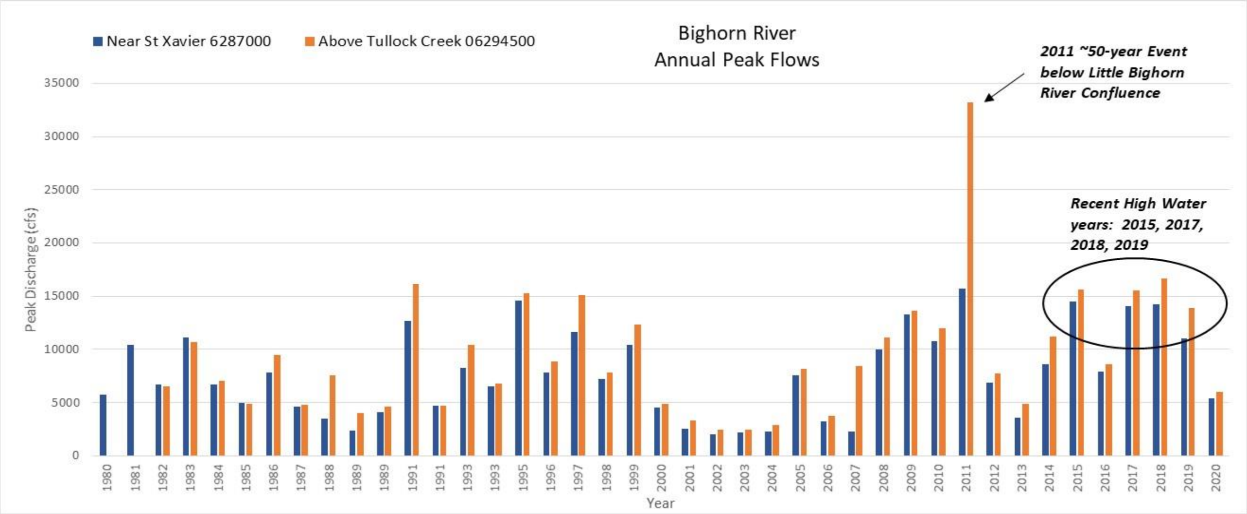


Figure 15. Recorded annual peak floods for gaging stations near Afterbay Dam (6287000) and near the Yellowstone River confluence (06294500).

Figure 16. May 22, 2011 Little Bighorn River flooding prompting closure of I-90 near Crow Agency (Billings Gazette).

Figure 17. View northwest showing St Xavier flooded by Rotten Grass Creek in 2011; Bighorn River flows from left to right in distance.

2.4 Bank Armor

Bank armor was mapped where visible on air photos, Google Earth, or oblique photographs. Since there was no ground inventory, the mapping probably captures a conservative estimate of the extent of bank armor on current and historic channels. Additionally, the bank armor inventory has no assessment of condition or functionality. Along the length of the Bighorn River, we mapped 3.5 miles of bank armor which covers about 2.1% of the total bankline. The bank armor consists mainly of rock riprap. 58 barbs were also mapped, of which 31 were flanked in the 2019 imagery. As a result, these areas are not included in the bank armor totals.

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

2.5 Transportation Infrastructure

Transportation infrastructure, including roads, bridges, and railroads are high-value features that often have extensive bank armoring associated with them. This is especially true where the feature parallels the channel. Armoring will restrict the ability for a stream to migrate laterally in an effort to protect the feature from damage. With the exception of local impacts at 12 bridge crossings, the Bighorn River within the study area is generally unaffected by transportation infrastructure. In the case of the Interstate 90 crossing in Hardin, four bridges (I90 East and West, railroad and frontage road) are clustered together creating a single constriction. Similarly, the Interstate 94 crossing near the Yellowstone confluence is a grouping of four bridges within a mile of the confluence.

3 Methods

The development of the Bighorn Channel Migration Zone (CMZ) mapping is based on established methods used by the Washington State Department of Ecology (Rapp and Abbe, 2003), and closely follows methodologies used on over 1,200 miles of rivers in Montana.

3.1 Aerial Photography

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

As discussed in the BHRA Research Initiative Spatial Information report (Thatcher and Boyd, 2019), five primary imagery data sets were selected: 1954/56, 1979/80, 1996 DOQ, 2005 NAIP, and 2017 NAIP. These imagery sources are discussed in depth in that report and summarized in Table 1. The 2019 NAIP imagery was added as a primary data set for the CMZ analysis to include changes that occurred during the 2018 and 2019 floods. Additional US Army Corps of Engineers imagery from 1939, 1961, 1970, and 1990 for the area upstream of Mallard's Landing was used as additional references when needed.

Table 1. Aerial photography used for the Bighorn River Channel Migration mapping study. Bold text represents time frames with mapped banklines.

Year	Source	Image Date	Digitized Banklines	Flow (CFS)	Notes
1939	USACOE	NA	No	NA	Dam to Mallards Landing
1954	**USACOE**	**NA**	**Yes**	**2,000 to 4,000**	**Dam to Mallards Landing**
1956	**USDA APFO**	**8/9/56**	**Yes**	**2,060**	**Mallards Landing to Yellowstone**
1961	USACOE	NA	No	NA	Dam to Mallards Landing
1970	USACOE	NA	No	NA	Dam to Mallards Landing
1979	**USDA APFO**	**8/9/79**	**Yes**	**3,610**	**Lower 13 miles**
1980	**USDA APFO**	**9/26/80**	**Yes**	**3,980**	**Big Horn County**
1980	**USACOE**	**NA**	**Yes**	**3,000 to 4,000**	**Dam to Mallards Landing**
1990	USACOE	NA	No	NA	Dam to Mallards Landing
1996 DOQ	**USDA**	**8/8-26/1996**	**Yes**	**2,440 to 2,900**	**Entire river**
2005 NAIP	**USDA**	**7/13/05**	**Yes**	**4,410**	**Entire river**
2017 NAIP	**USDA**	**8/10 and 8/18/17**	**Yes**	**3,990 / 3,140**	**Entire river**
2019 NAIP	**USDA**	**7/22, 8/12 and 8/31/20**	**Yes**	**8730 / 3400 / 3150**	**Entire river**

*Note: imagery in bold boxes define a single time period for analysis.

The 1939 imagery is only available for river segments upstream of Mallards landing, but it captures conditions several decades before the completion of Yellowtail Dam. Similarly, the mid-1950s imagery was taken before dam completion; both suites capture more dynamic river conditions relative to post-dam photos (Figure 18). The 1970/80 imagery (Figure 19) represents the earliest post-Yellowtail Dam conditions. The 2019 NAIP imagery captures the impacts of recent floods.

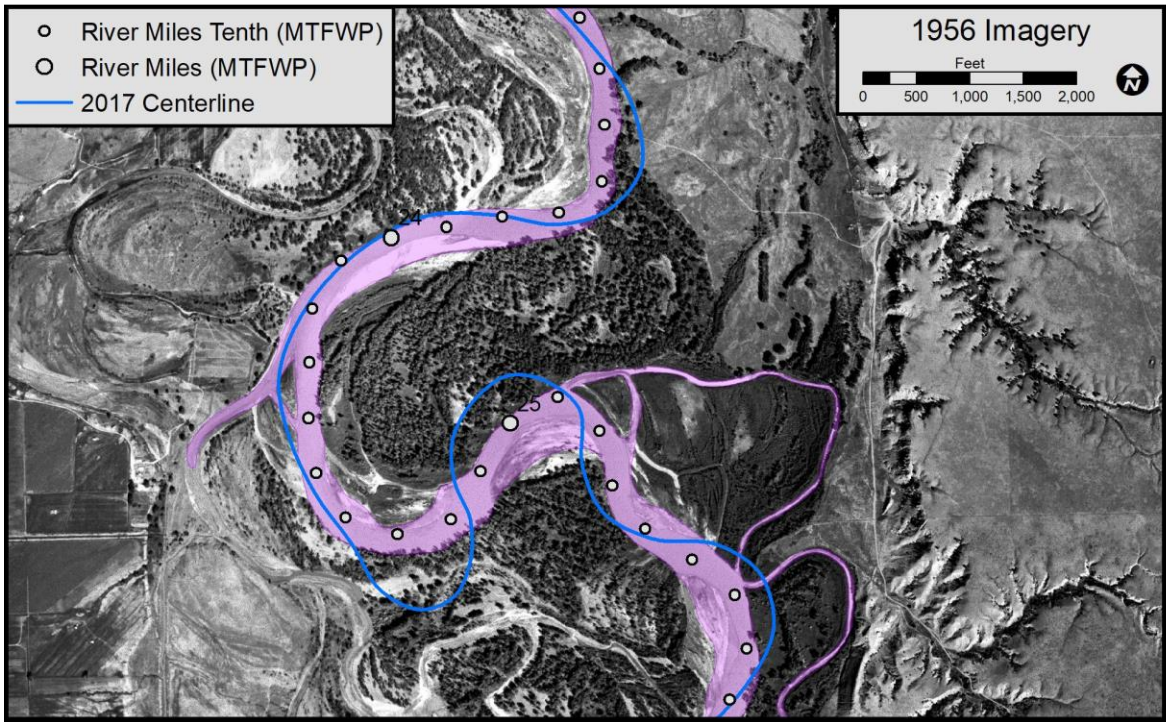


Figure 18. Example 1956 USDA orthorectified imagery.

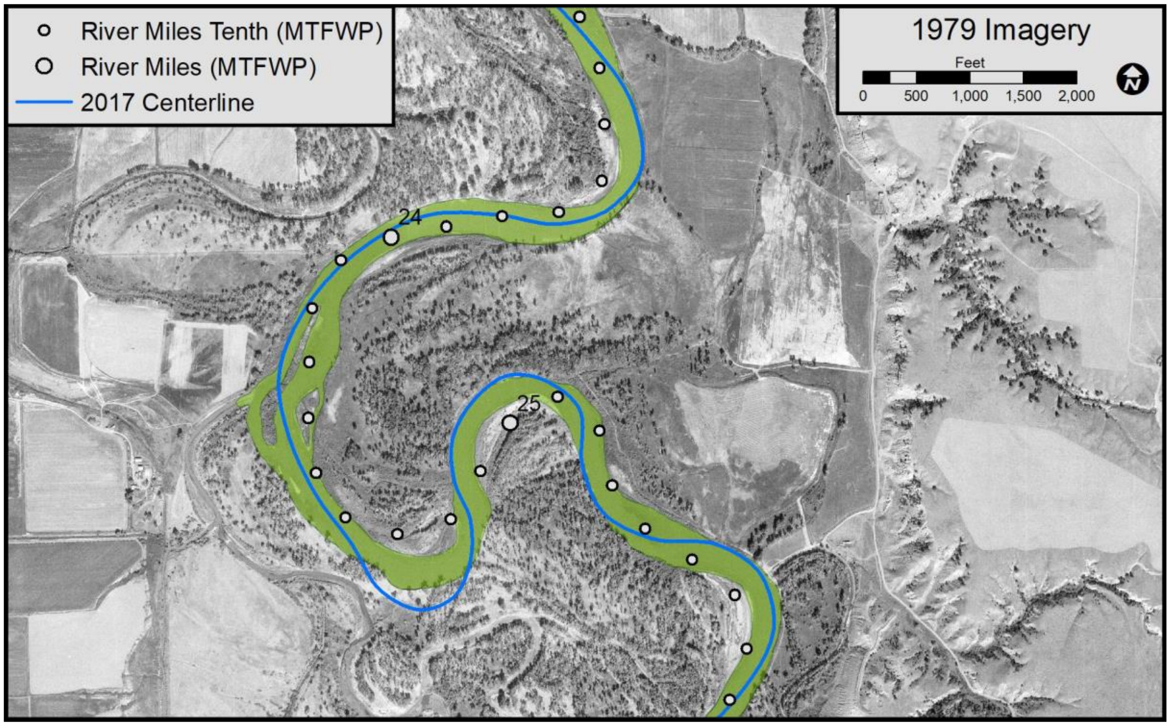


Figure 19. Example of 1979 USDA orthorectified imagery.

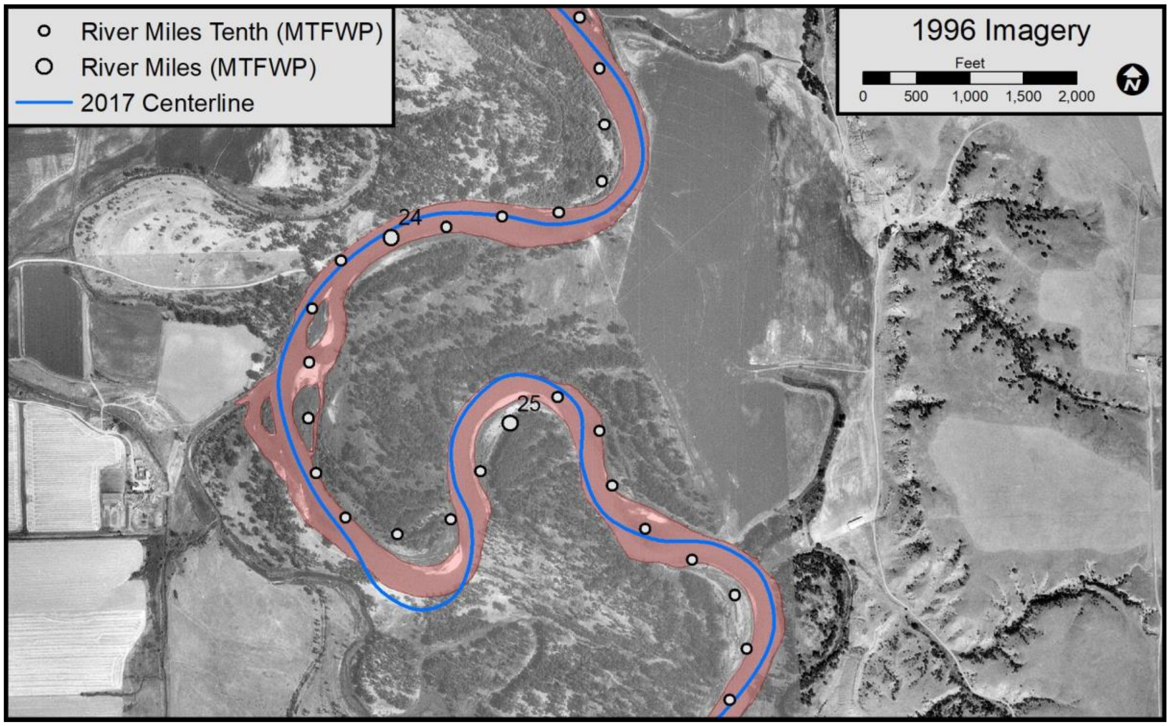


Figure 20. Example 1996 DOQ imagery.

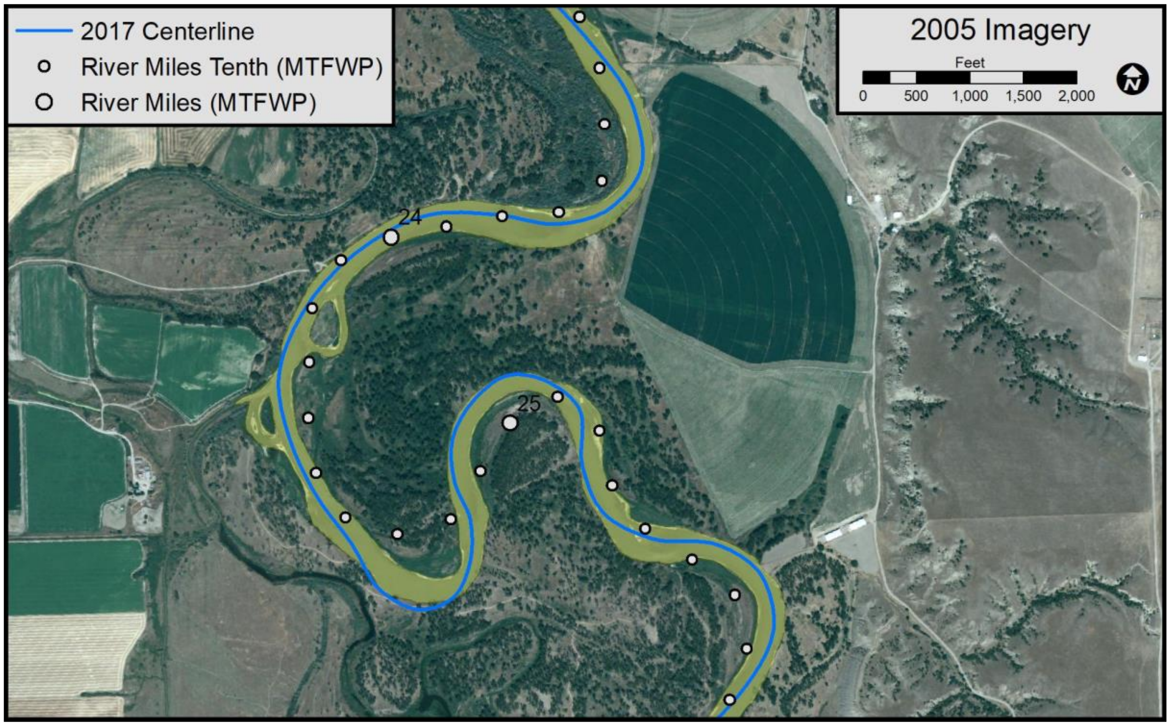


Figure 21. Example 2005 NAIP imagery.

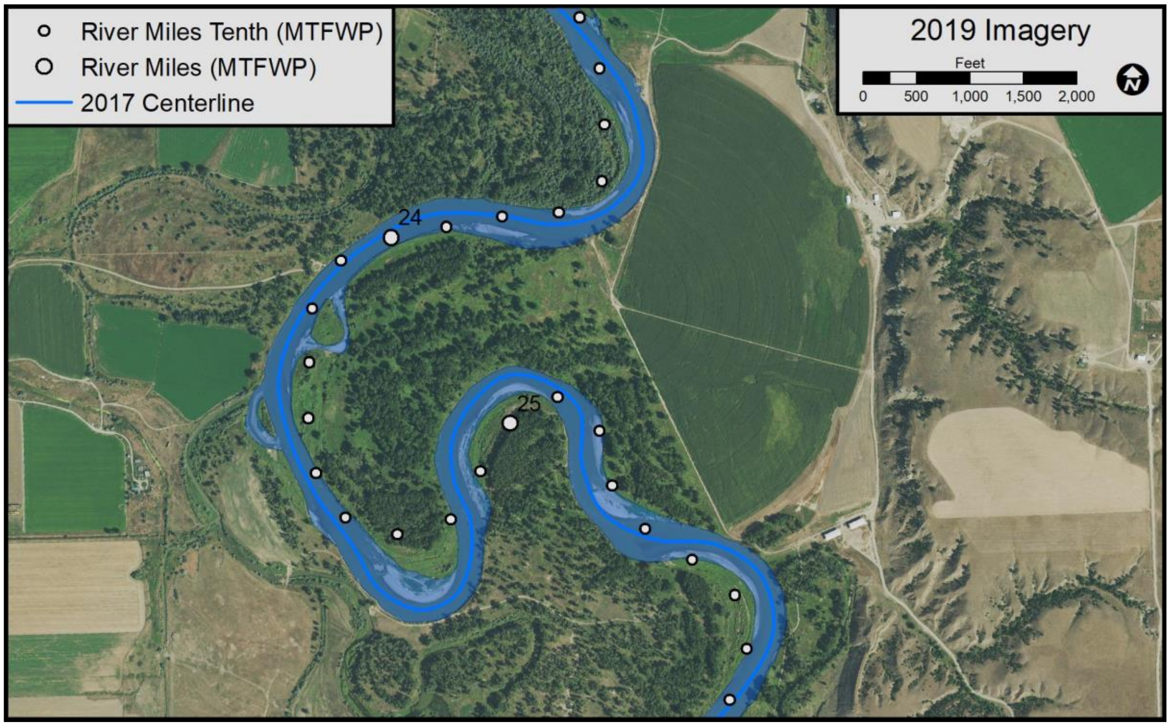


Figure 22. Example 2019 NAIP imagery.

3.2 GIS Project Development

GIS project data for the Bighorn River has been developed over the past two years to support several BHRA studies. All data is compiled using ESRI's ArcMap Geographic Information System (GIS) utilizing a common coordinate system - Montana State Plane NAD83 Meters. While the orthorectified air photos provide the basis for CMZ mapping; other existing datasets included roads, MT Fish Wildlife and Parks stream stationing, scanned General Land Office Survey Maps obtained from Bureau of Land Management, and geologic maps produced by the United States Geological Survey. Additionally, 2018 LiDAR data collected by the Natural Resources Conservation Service (NRCS) and developed for the BHRA Inundation Risk Study (Thatcher/Boyd, 2020) provides a key dataset for understanding the river's floodplain connectivity.

3.3 Bankline Mapping

Banklines representing bankfull margins were digitized for each year of imagery at a scale of ~1:3,000. A tablet computer running ArcGIS and using a pen stylus was used to trace the banklines using stream mode digitizing. This methodology allowed us to capture a much more detailed bankline than using a mouse. Bankfull is defined as the stage above which flow starts to spread onto the floodplain. Although that boundary can be identified using field indicators or modeling results (Riley, 1972), digitizing banklines for CMZ development requires the interpretation of historic imagery. Therefore, we typically rely on the extent of the lower limit of perennial, woody vegetation to define channel banks (Mount & Louis, 2005). This is based on the generally accepted concept that bankfull channels are inhospitable to woody vegetation establishment. Fortunately, shrubs, trees, terraces, and bedrock generally show distinct signatures on both older black-and-white as well as newer color photography. These signatures, coupled with an understanding of riparian processes, allow for consistent bankline mapping through time and across different types of imagery.

3.4 Migration Rate Measurements

Once the banklines were digitized, they were evaluated in terms of discernable channel migration since the mid-1950s. Where migration was clear, vectors (arrows with orientation and length) were drawn in the GIS to record that change. At each site of bankline migration, measurements were collected approximately every 150-200 feet (Figure 23). A total of 1181 migration vectors were generated for the Bighorn at a scale of ~1:2,000. These measurements were then segmented by timeframe (1955-1979 and 1979/80-2019) to capture pre- and post-Yellowtail Dam conditions and summarized by reach (Figure 23). The post-Yellowtail Dam results were then used to define a reach-scale erosion buffer width to accommodate anticipated future erosion. Results of this analysis are summarized in Section 4.3.

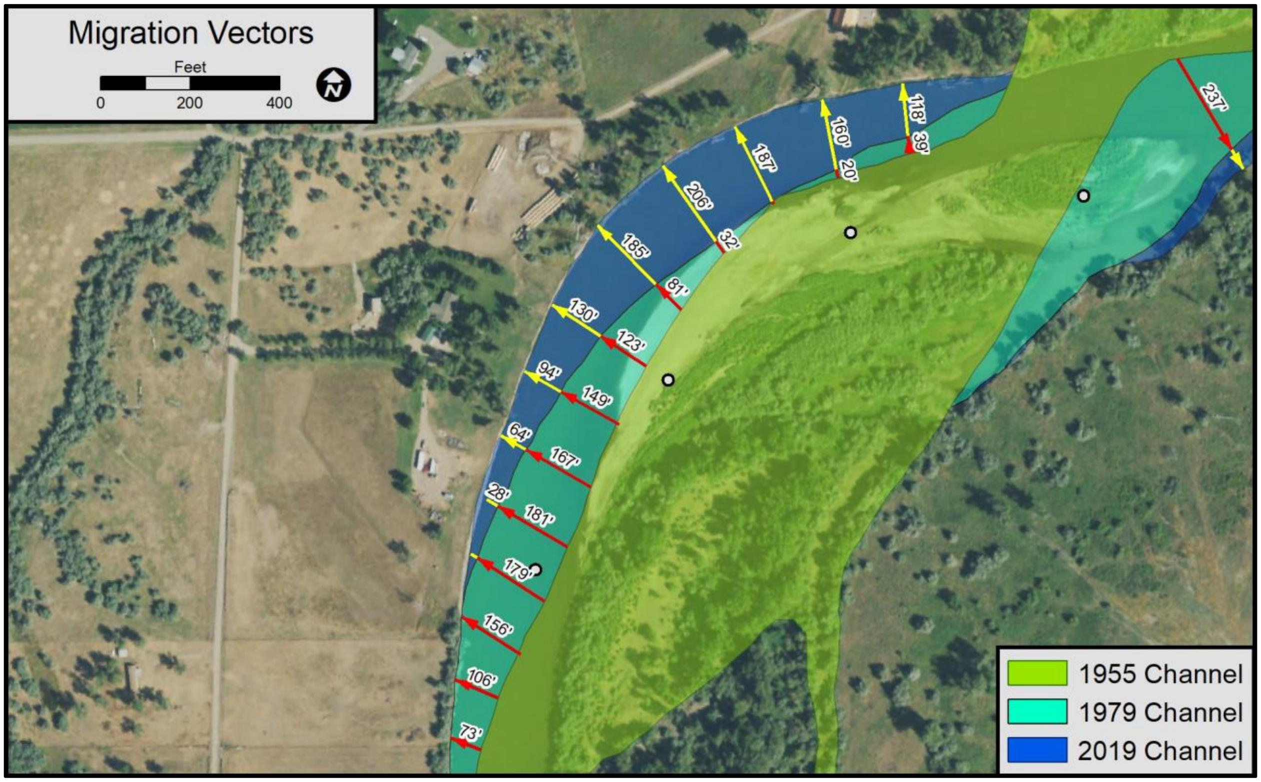


Figure 23. Example of migration measurements between 1955 and 2019 (migration distance in feet).

3.5 Avulsion Hazard Mapping

Avulsion hazards can be difficult to identify on broad floodplains because an avulsion could occur virtually anywhere on the entire floodplain if the right conditions were to occur. As such, avulsion pathways were identified and mapped using criteria that identify a relatively high propensity for such an event. These criteria usually include the identification of high slope ratios between the floodplain and channel (shortcuts across the floodplain), tributary channels at risk of capture, and the presence of relic channels that concentrate flow during floods. Figure 24 shows several potential avulsion paths that follow remnant channels, several of which were active prior to dam closure.

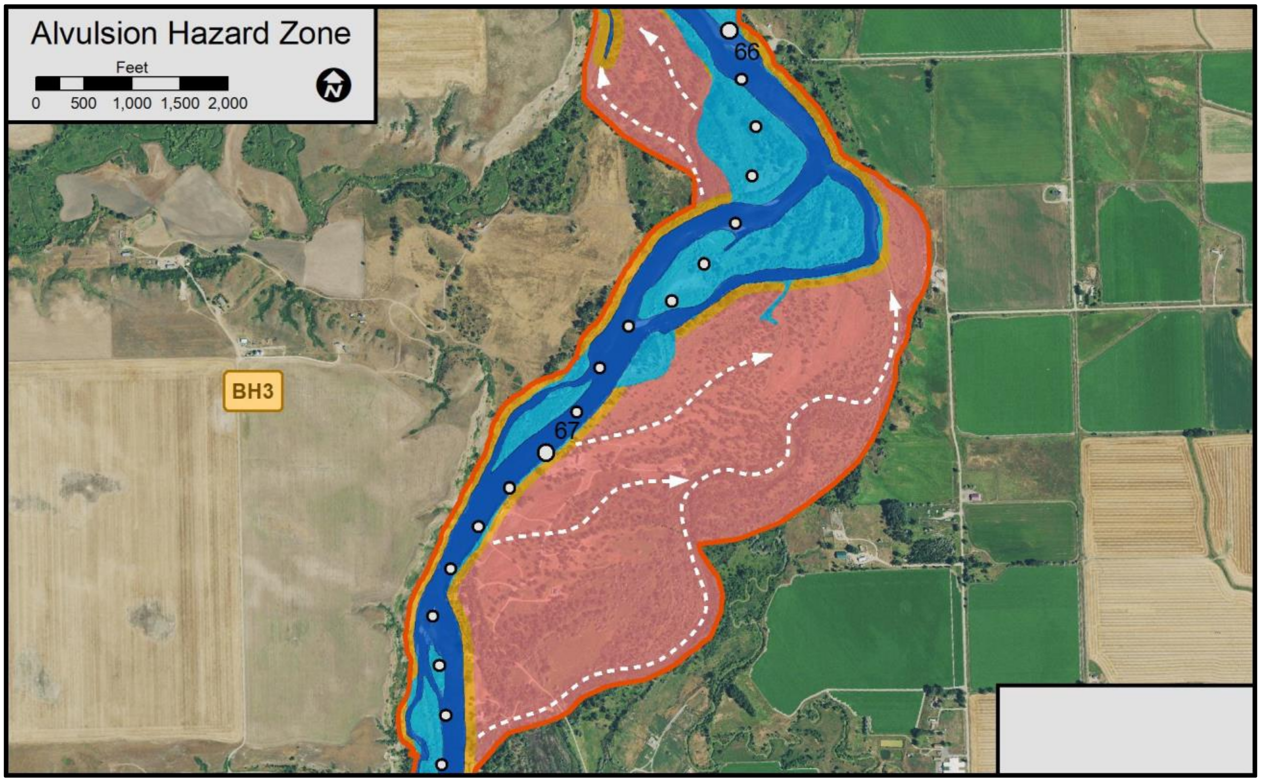


Figure 24. Example avulsion paths on Bighorn River floodplain.

4 Results

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

4.1 Project Reaches

The study area includes approximately 84 miles of river from the Afterbay Dam to the Yellowstone River (Figure 25). The river flows primarily through Big Horn County, with the lower 13 miles flowing along the Yellowstone/Treasure County boundary. Imagery datasets cover the active river corridor and adjacent uplands, while feature digitizing focuses on the historic active river corridor.

The approach to CMZ mapping used here includes a reach-scale evaluation of channel migration rates. For the 84 miles of project length, the river was broken into seven reaches based on geomorphic character such as river pattern, rates of change, and geologic controls (Figure 25). The reaches range in length from 3.7 to 25.3 miles (Table 2). Average channel slope for each reach flattens in the downstream direction, with a clear drop in slope below Reach BR3 which ends at Mallard's Landing (Figure 26). These are the same reaches used in the BRI Spatial Data Report (Thatcher and Boyd, 2019).

Table 2. Bighorn River reach summary.

Reach	Location	Upstream RM	Downstream RM	Length (mi)	Description
BH1	Afterbay Dam to Three Mile	83.7	80	3.7	First few miles below Afterbay Dam; geomorphically simple and relatively stable/static
BH2	Three Mile to Bighorn FAS	80	71.6	8.4	Increasing complexity via side channels, wetlands, and sloughs, increased sediment transport and disturbance.
BH3	Bighorn FAS to Mallard's Landing FAS	71.6	63	8.6	River closely follows west bluff line. Loss of several miles of side channel at St Xavier since 1939
BH4	Mallard's Landing FAS to Two Leggins FAS	63	52	11	Continues to follow bluff line. Several complex island segments.
BH5	Two Leggins FAS to Little Bighorn River	52	42	10	River crosses valley to east bluff line; some persistent split flow segments.
BH6	Little Bighorn River to General Custer FAS	42	26.2	15.8	Increased meander development and channel migration below Little Bighorn River confluence. Increased armoring relative to upstream.
BH7	General Custer FAS to Yellowstone River Confluence	26.2	0.9	25.3	Some rapidly migrating bendways and threats to infrastructure/agricultural land.

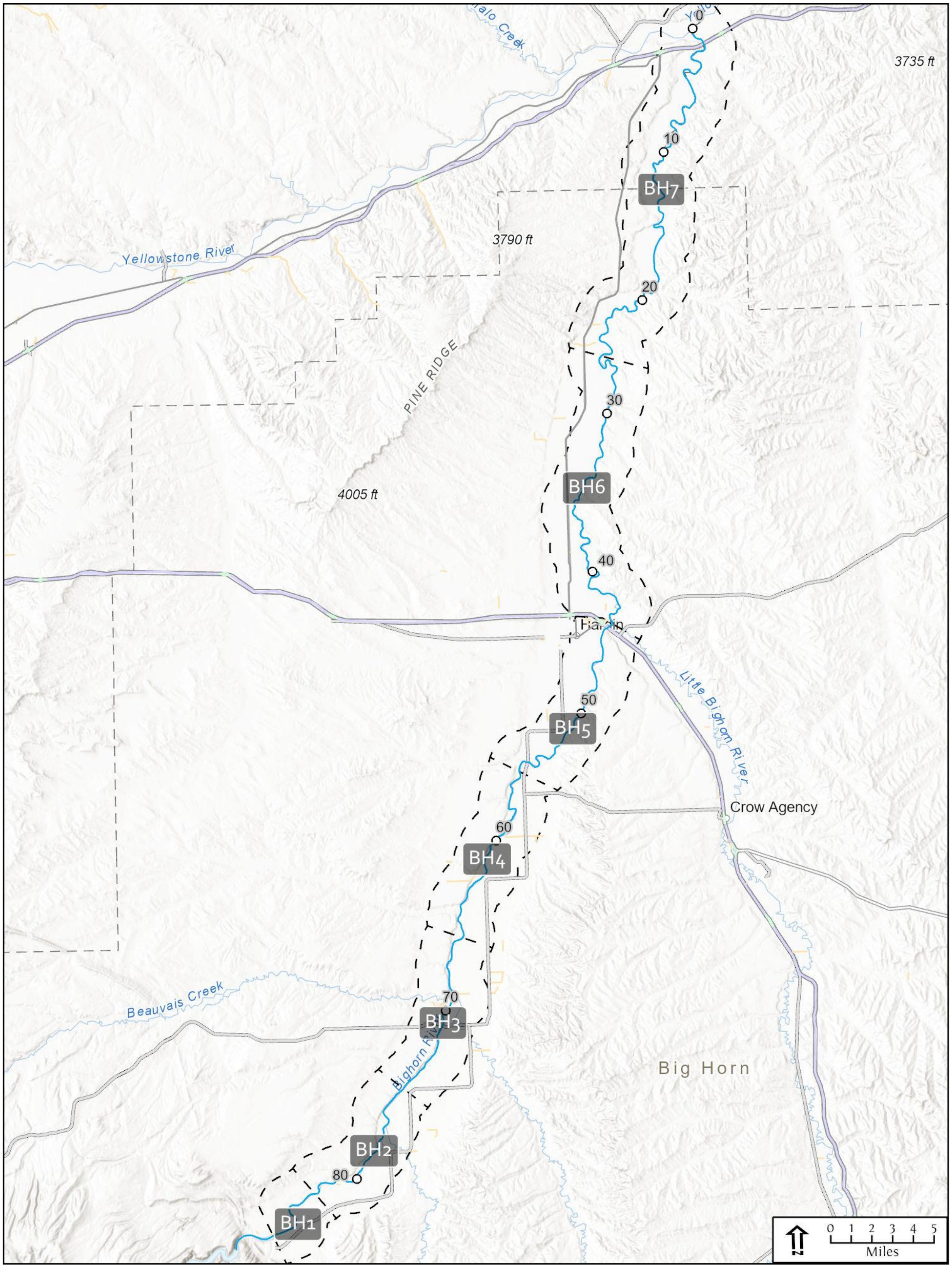


Figure 25. Study area boundaries and reaches.

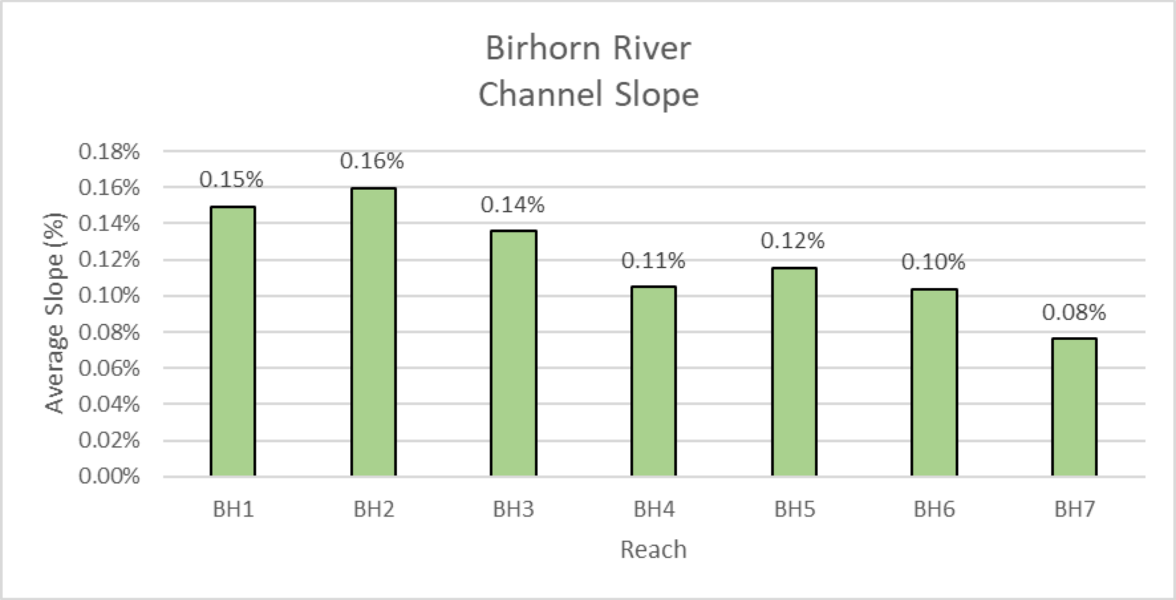


Figure 26. Average water surface slope for project reaches plotted from upstream (BH1) to downstream (BH7) showing progressive loss of gradient.

4.2 The Historic Migration Zone (HMZ)

The Historic Migration Zone (HMZ) is created by combining the bankfull channel polygons into a single HMZ polygon. The bankfull channels commonly split and rejoin, creating a mosaic of channel courses with intervening islands, some of which are seasonal. The HMZ footprint includes all channels as well as any area between split flow channels. By including islands, the HMZ captures the entire footprint of the active river corridor from 1950s to 2019. 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 Bighorn River, however, these areas have been retained in the CMZ since they are made up of young alluvial deposits that are prone to reworking or avulsion and are thus part of the active meander corridor.

Any side channels that have not shown perennial connectivity to the main channel since the mid-1950s 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 Bighorn River channel locations in 1954/56, 1979/80, 1996, 2005, 2017 and 2019 (Figure 27). The resulting area reflects 65 years of channel occupation for the length of the Bighorn River study area.

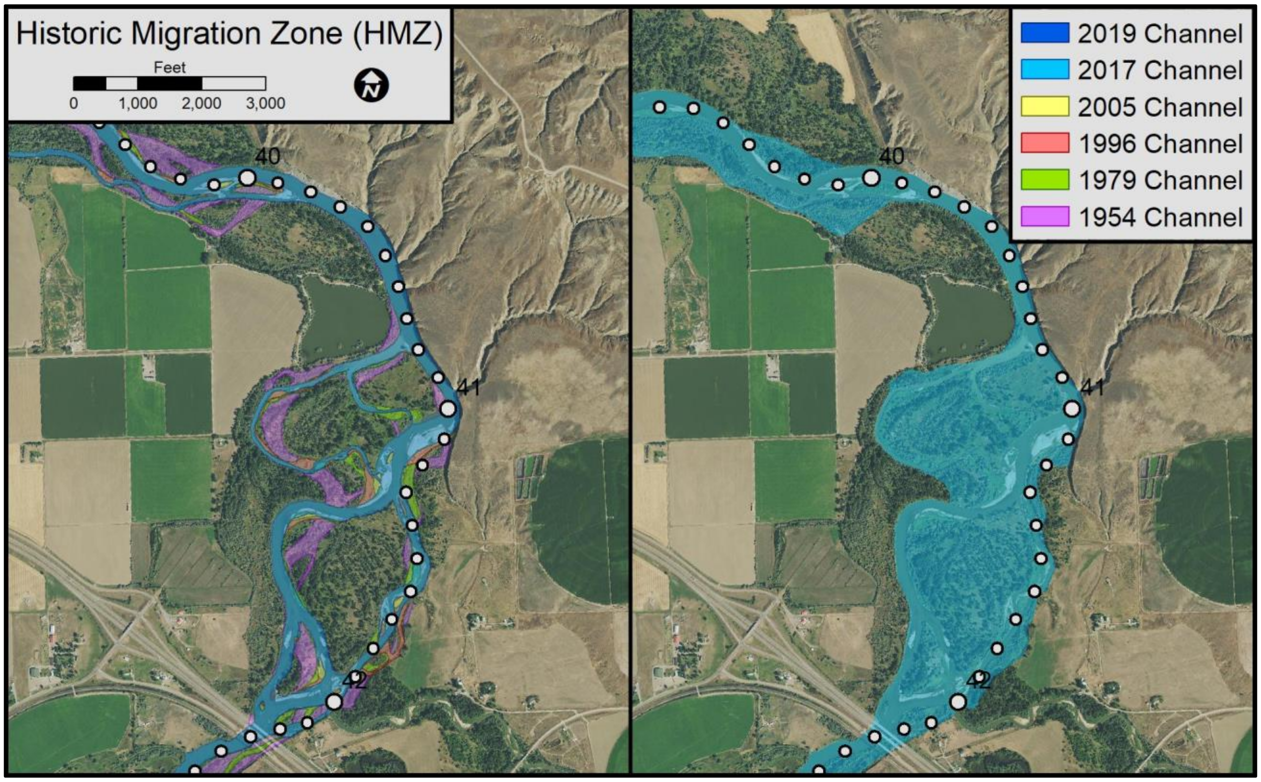


Figure 27. The Historic Migration Zone (HMZ) is the combined footprint of all mapped channel banklines.

4.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on measured migration rates, which are derived from measured migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement and not an avulsion. In order to characterize longer term rates of movement (not just post-dam), a total of 1205 measurements were collected on the Bighorn River to capture movement from the 1950s imagery (either 1954 or 1956) to 2019. The minimum distance measured is 20 feet, which proved to be an easily measurable distance that is not compromised by the resolution or spatial accuracy of the data. The measured migration distances are summarized in Figure 28, and migration rates are shown in Figure 29. Migration into the bluffs along the valley wall was summarized separately. The results show that migration rates generally increase in the downstream direction, with the most rapid bank movement in reaches BH6 and BH7, which are located downstream of the mouth of the Little Bighorn River. Below the mouth of the Little Bighorn, the mean migration distance measured for the 1950s-2019 timeframe was about 250 feet. The maximum migration distance measured was 1,017 feet, on a rapidly migrating bendway at RM 18.7, where the river has eroded into the base tower of a 500KV power line that runs west from Colstrip. That bendway has migrated towards the power line at an average rate of 16.1 feet per year since 1956. This site is discussed in more detail in Section 0.

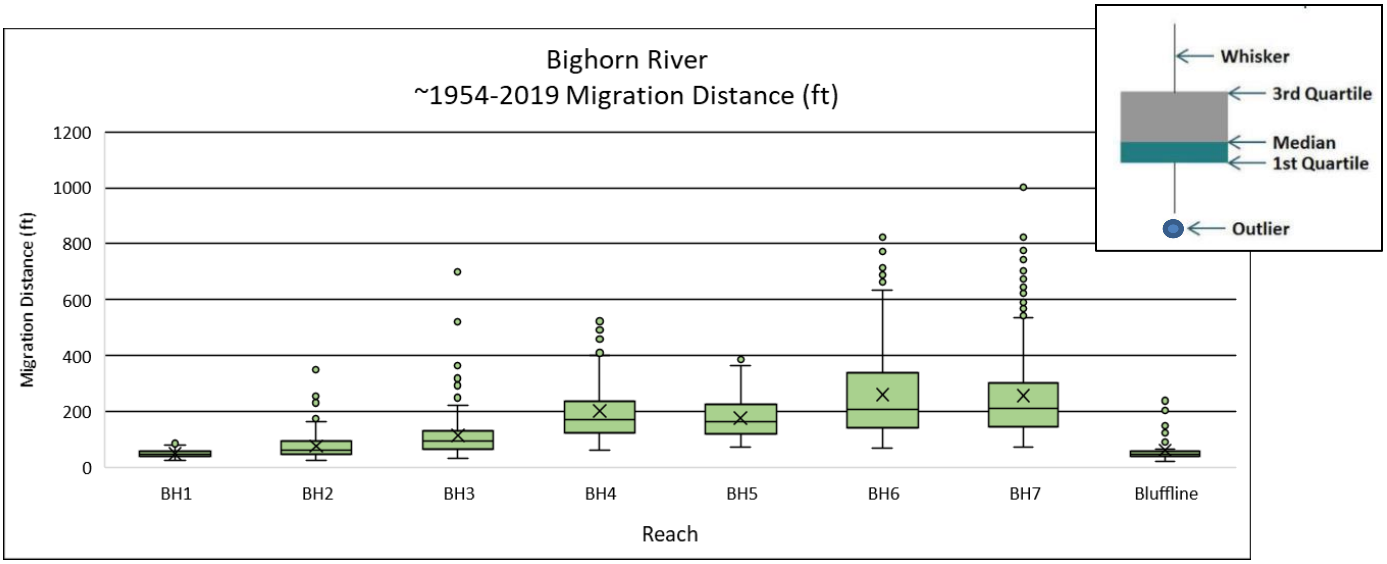


Figure 28. Box and whisker plot showing measured 1957-2019 migration distances by reach and for the bluff line-- reaches are plotted from upstream (left) to downstream (right). Mean values are denoted by "X".

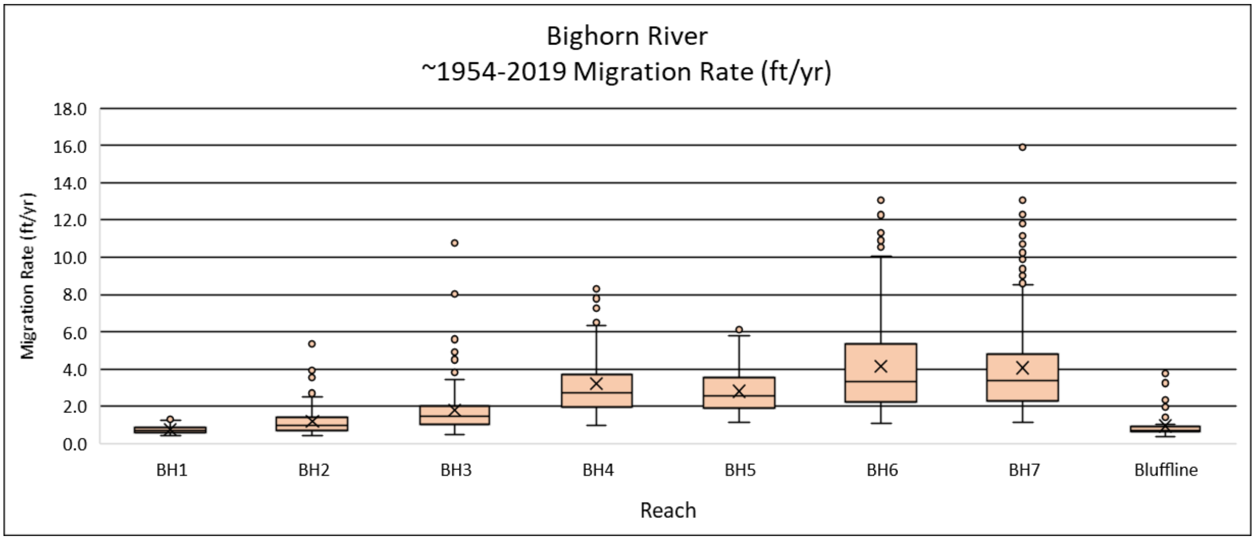


Figure 29. Box and whisker plot showing measured 1957-2019 migration rates by reach and for the bluffline -- reaches are plotted from upstream (left) to downstream (right). Mean values are denoted by "X".

One major consideration with the migration rate analysis and EHA development on the Bighorn River is capturing erosion hazards under the current hydrologic regime. Yellowtail Dam was completed in 1966 and the flood regime on the river below the dam has been dampened substantially since then (Figure 12). As a result, using pre-dam measurements of channel movement will potentially inflate estimates of current rates of change. To capture the effects of flow management on migration rates, the migration vectors were segmented using the 1979/80 banklines, providing two datasets: 1950s to 1979/80; and 1979/80-2019. The earlier dataset summarized in Figure 28 and Figure 29 above includes 16 years of pre-dam conditions and 13 years of post-dam conditions. The second dataset is entirely post-dam. When plotted as segmented migration measurements, results show that migration rates were markedly higher in the earlier dataset (Figure 30 and Figure 31).

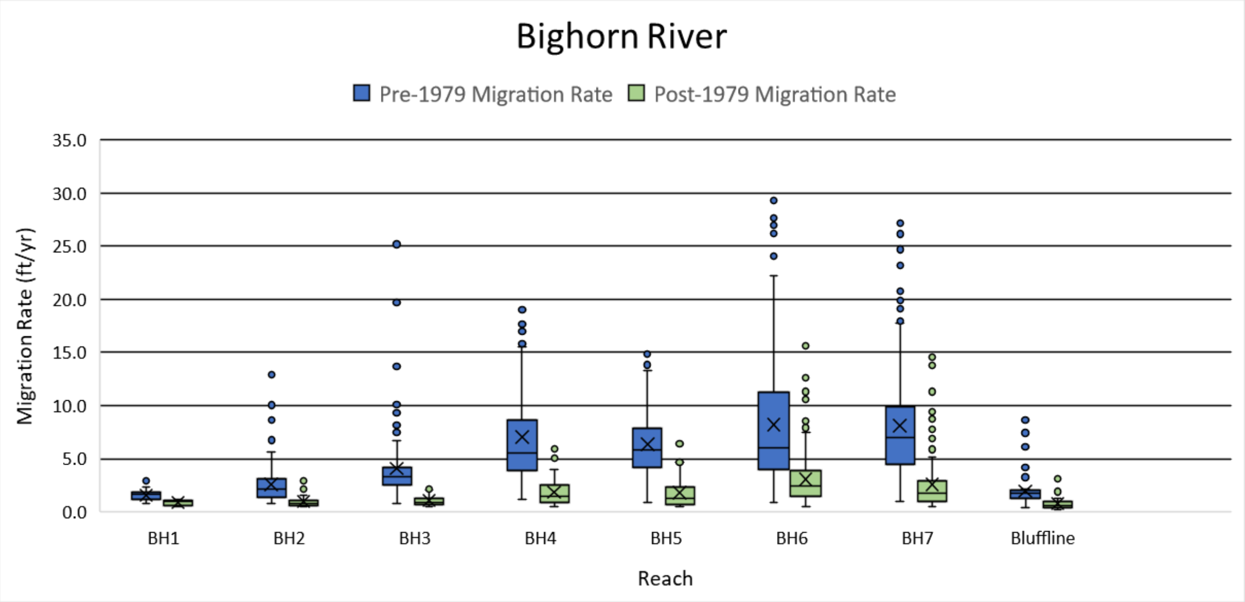


Figure 30. Migration rate measurements for data including pre-Yellowtail Dam conditions ("pre-1979/80"), and for those data capturing only post-dam conditions ("Post-1979/80").

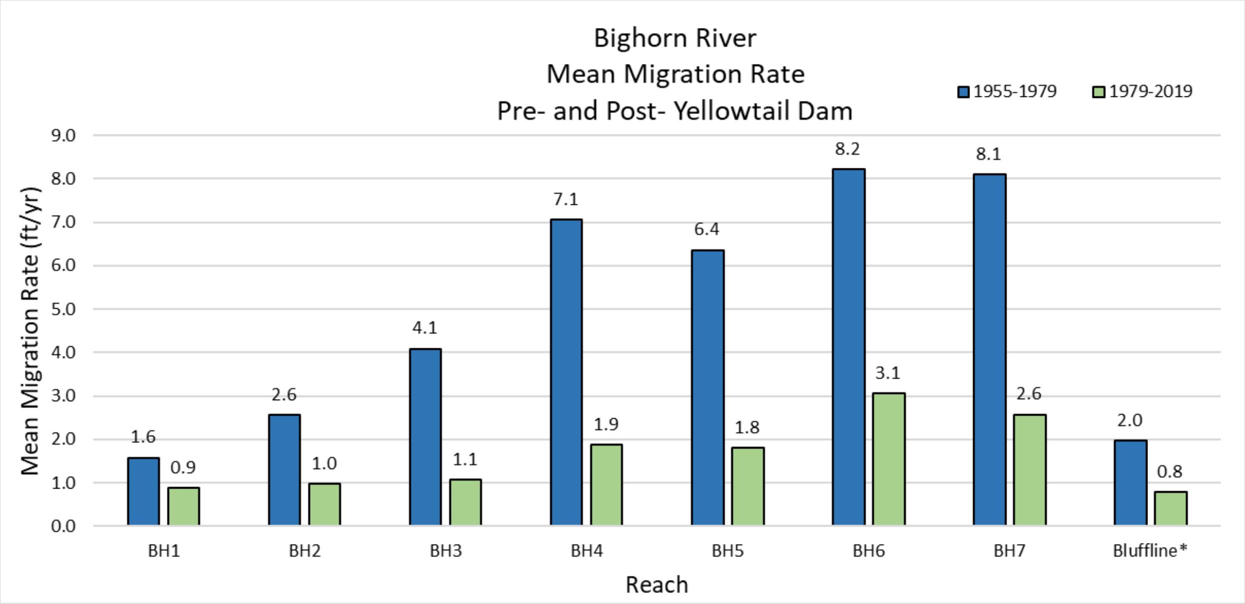


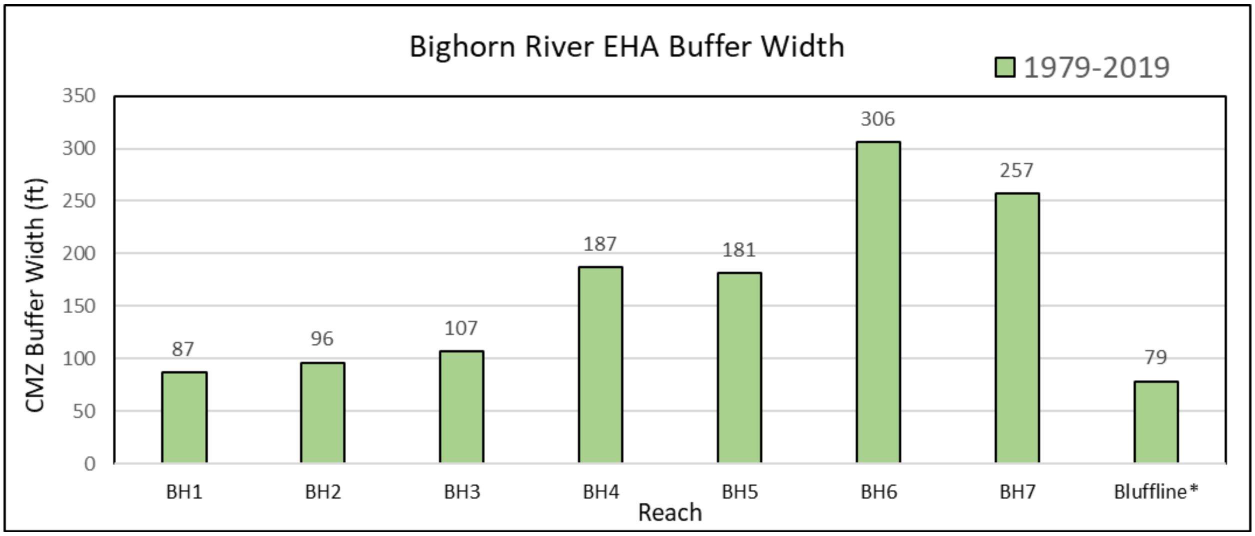
Figure 31. Mean migration rates for ~1955-1979/80 and 1979/80-2019 conditions, Bighorn River.

Since flow alterations imposed by Yellowtail Dam appear to have reduced rates of channel migration, only post-dam migration were used to calculate the EHA buffer widths. This is done by taking the average annual rate of movement in each reach and multiplying it by 100, giving an estimate of how far the river may be expected to move, under current water management conditions, over the next century. These widths range from 87 feet in Reach BH1 just below Afterbay Dam to 206 feet in Reach BH6 below Hardin (Table 3 and Figure 32).

As the *mean* migration rate is the statistic used to calculate the EHA buffer, the results are inherently conservative. Thus, some localized channel migration through and beyond the EHA buffer should be anticipated over the next century. Table 3 shows that in almost every reach, the 100-year erosion buffer is less than the maximum measured migration distance. Typically, however, these areas of rapid bankline movement are within the Historic Migration Zone, and thereby captured in the CMZ.

Table 3. EHA buffer widths used for Bighorn River CMZ mapping.

Bighorn River Erosion Hazard Area Buffer Widths 1979/80-2019 Data				
Reach	**Number of Measurements**	**Maximum Migration Distance (ft)**	**Mean Migration Rate (ft/yr)**	**CMZ Buffer Distance (ft)**
BH1	14	45	0.9	87
BH2	42	131	1.0	96
BH3	62	101	1.1	107
BH4	57	238	1.9	187
BH5	58	272	1.8	181
BH6	172	626	3.1	306
BH7	196	582	2.6	257
Bluffline	36	125	0.8	79
	637			



*Bluffline buffers only added to erodible (shale-rich) geologic units.

Figure 32. Erosion Hazard Area (EHA) buffer widths by Reach, Bighorn River.

The location and intensity of rapid streambank erosion shifts with time. Over a century, areas that currently show no erosion may become more active. Predicting these shifts is difficult due to the number of drivers that can cause these shifts (ice, woody debris, floods, cutoffs, etc.). As such, the erosion buffer is assigned to all banks defined by the most recent (2019) bankline mapping dataset, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington State Department of Ecology (WSDE, 2010). The general approach to determining the Erosion Buffer (using the annual migration rate to define a 100-year migration distance) is similar to that used in Park County (Dalby, 2006), on the Tolt River and Raging River in King County, Washington (FEMA, 1999), and as part of the Forestry Practices of Washington State (Washington DNR, 2004).

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

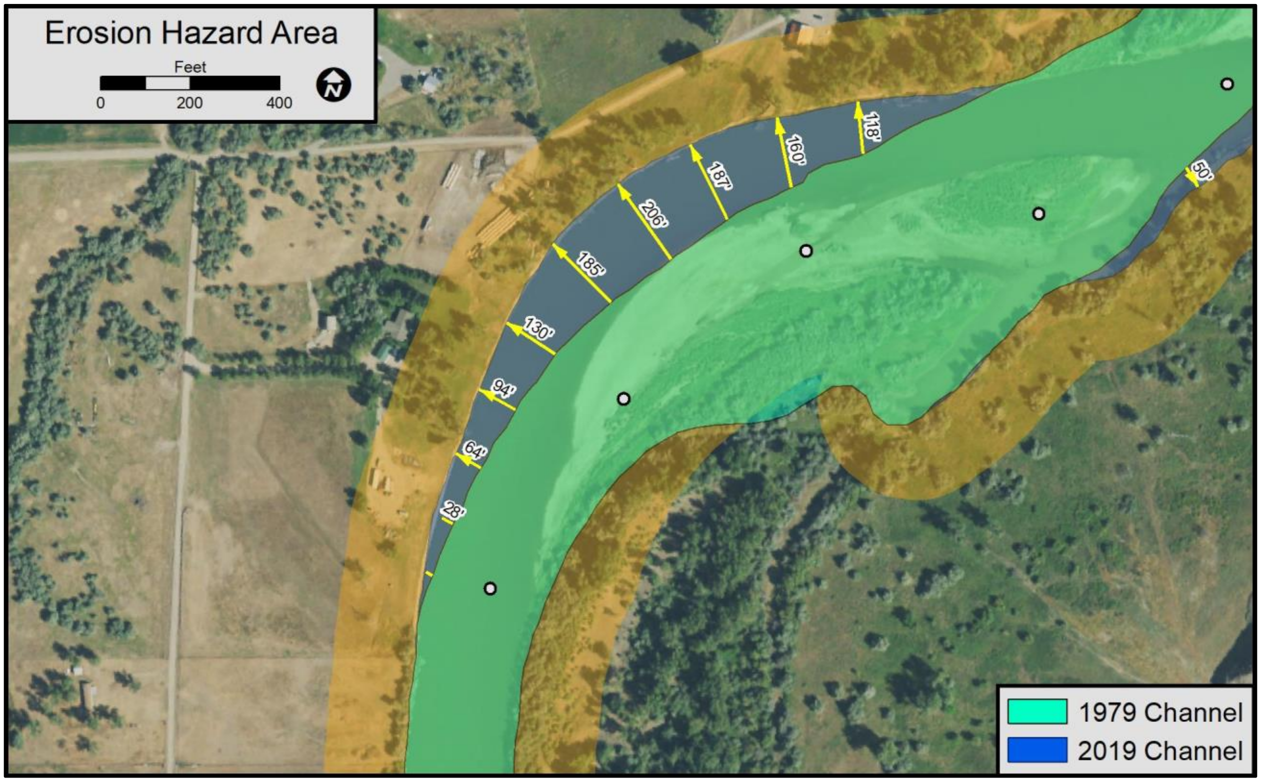


Figure 33. The Erosion Hazard Area (EHA) is a buffer placed on the 2019 banklines based on 100 years of channel migration for the reach.

4.4 The Avulsion Hazard Area (AHZ)

The Avulsion Hazard Zone (AHZ) includes the areas of the river landscape, such as secondary channels, relic channels, and swales that are at risk of channel occupation outside of the Historic Migration Zone (HMZ)(Figure 34).

A total of four historic avulsions were mapped on the Bighorn River. All of them occurred between 1954 and 1978. The two major types of avulsion processes on the Bighorn River are meander cutoffs and capture of old channels/floodplain swales. Considering historic patterns of avulsions, the CMZ boundaries were extended to capture similar areas that show demonstrable potential for avulsions over the next century. These mapped units capture floodplain areas that are beyond the HMZ or EHA but have side channels prone to re-occupation or meander cores prone to cutoff. It is important to recognize, however, that these events could realistically happen anywhere on the river's floodplain, and the CMZ mapping captures only the most demonstrable avulsion-prone areas.

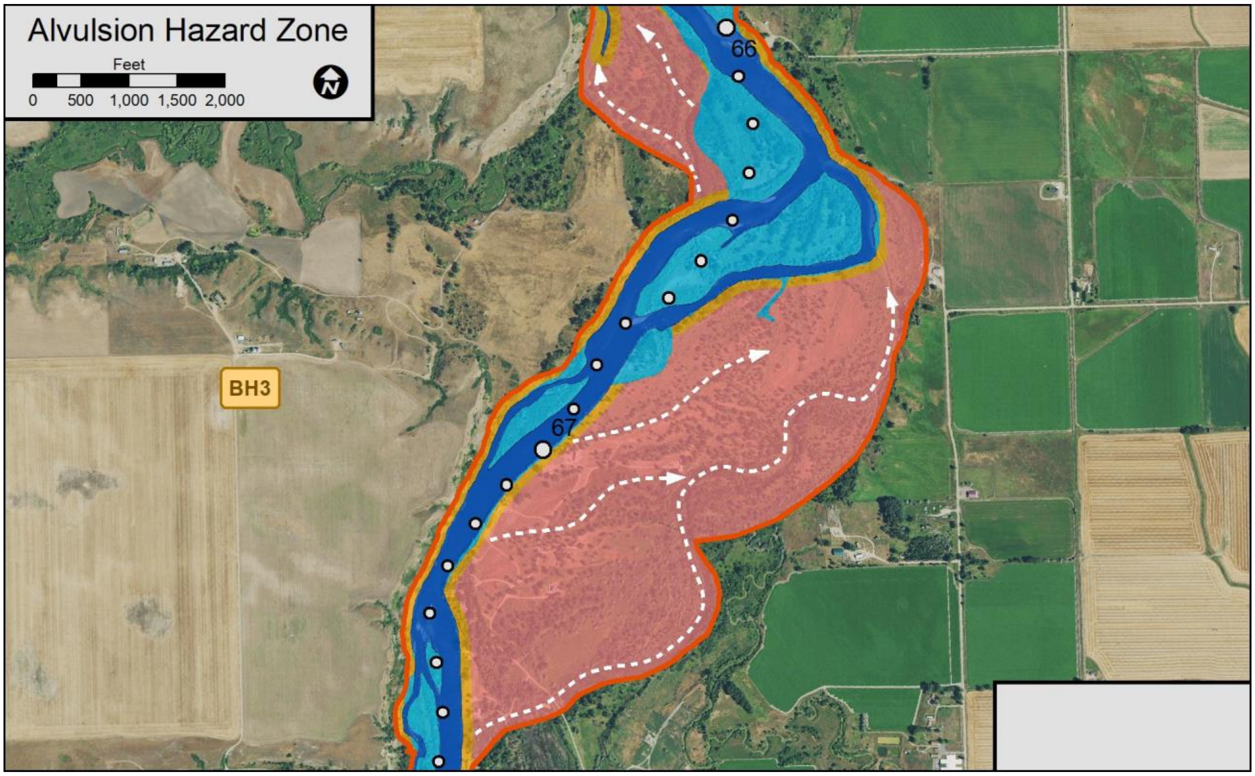


Figure 34. The Avulsion Hazard Zone (AHZ) captures areas beyond the EHA at risk of channel occupation due to avulsion.

4.5 The Restricted Migration Area (RMA)

The restricted migration area largely reflects bank protection associated with major diversions and bridges.

A total of 3.5 miles of bank armor were mapped on the 84 miles of project length. Barbs are also present although they do not appear to be very effective at stopping bank erosion; most of the mapped barbs have either been flanked or are at imminent risk of flanking. Figure 35 shows that the extent of armored banks ranges from 2% to 12% of the main channel length. Because they perform so poorly, the length of rock barbs is not included in the armor totals.

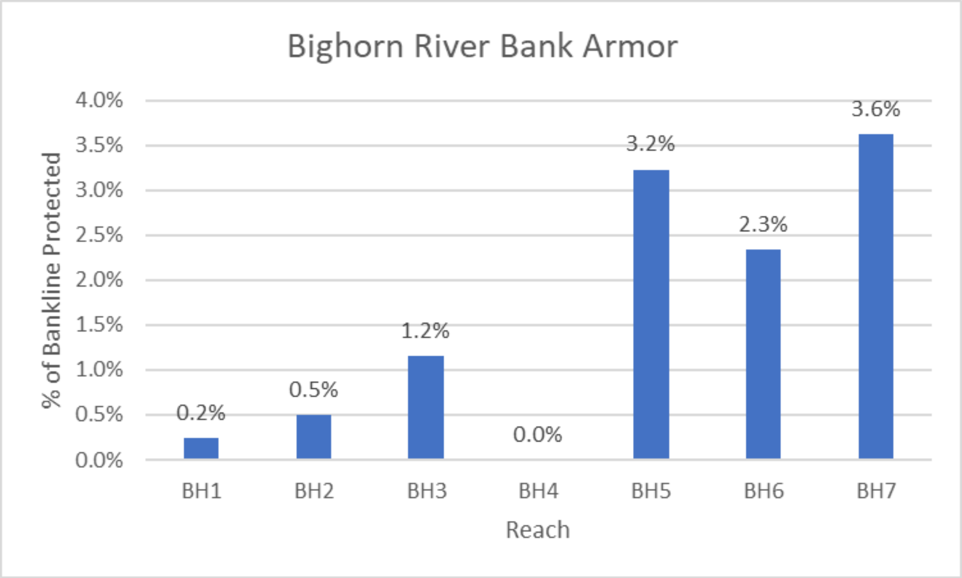


Figure 35. Percentage of bankline protected by armor by reach.

Figure 36 shows an example of Restricted Migration Areas around the Two Leggins Canal.

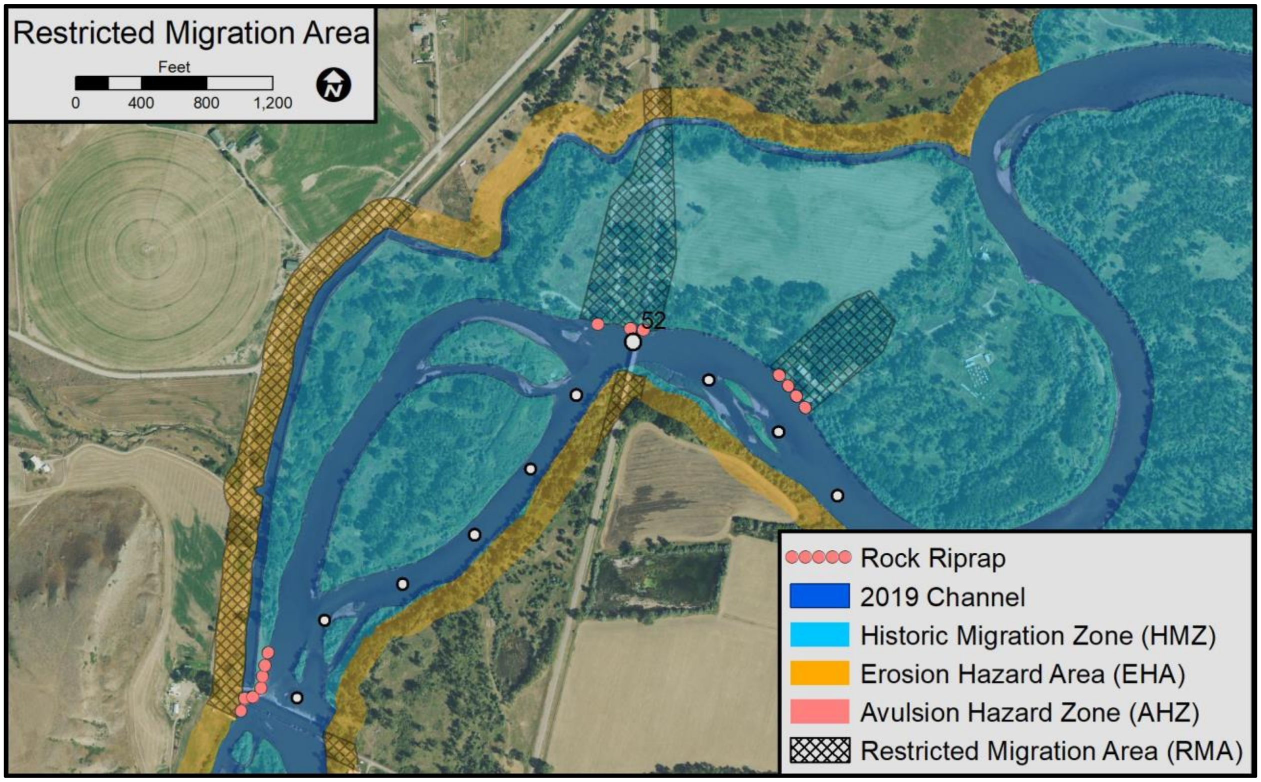


Figure 36. Restricted Migration Areas Two Leggins Canal.

Bank armoring currently restricts access to approximately 342 acres of the Channel Migration Zone. The armor is protecting a mix of transportation, municipal (water treatment), and agricultural (irrigation and fields) assets.

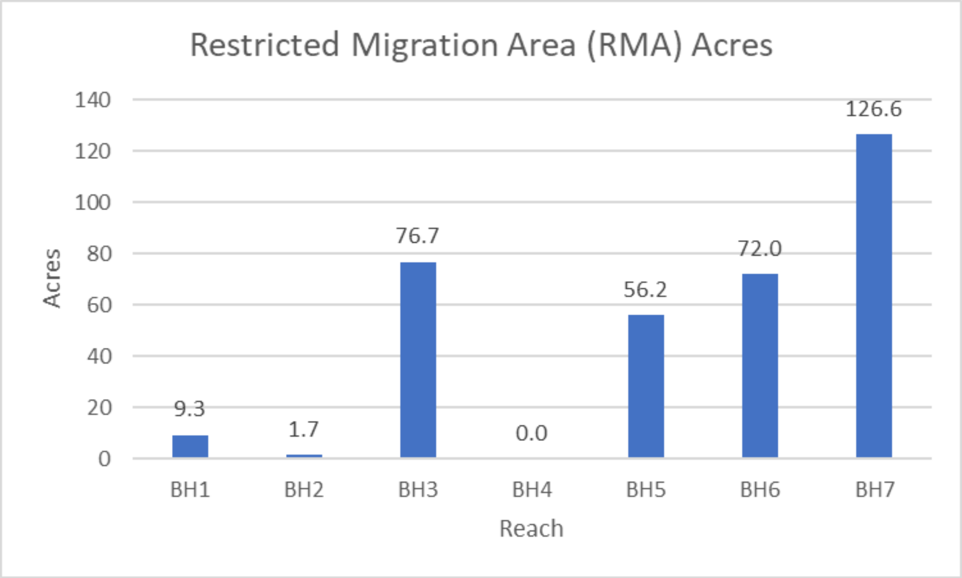


Figure 37. Acres of the CMZ mapped as restricted by reach.

4.6 Valley Wall Erosion

Between Afterbay Dam and the Yellowstone River, the margins of the active Bighorn River floodplain consist of both erodible and non-erodible valley walls. The non-erodible margins are generally comprised of Cretaceous-age sandstone overlain by a younger alluvial cap. The erodible terraces are more consistently shales or young terraces that were shown to erode, but typically at a lower rate than the floodplain alluvium. An erosion buffer was added to the erodible valley margins (shales and alluvial terraces), and sandstone bluffs that show no evidence of erosion were entirely clipped from the CMZ.

Many CMZ mapping efforts incorporate a Geotechnical Setback on valley walls, which is an area of expanded Erosion Hazard Area (EHA) against geologic units that may be prone to geotechnical failure such as landslides, slumps, or rockslides. Landslides are not uncommon along the Bighorn. 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.

4.7 Composite Map (Appendix A)

An example portion of a composite CMZ map for a section of the Bighorn River project area is shown Figure 38. 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. Over the 84 mile project reach, a total of 17,483 acres of land comprise the CMZ, or about 208 acres per mile.

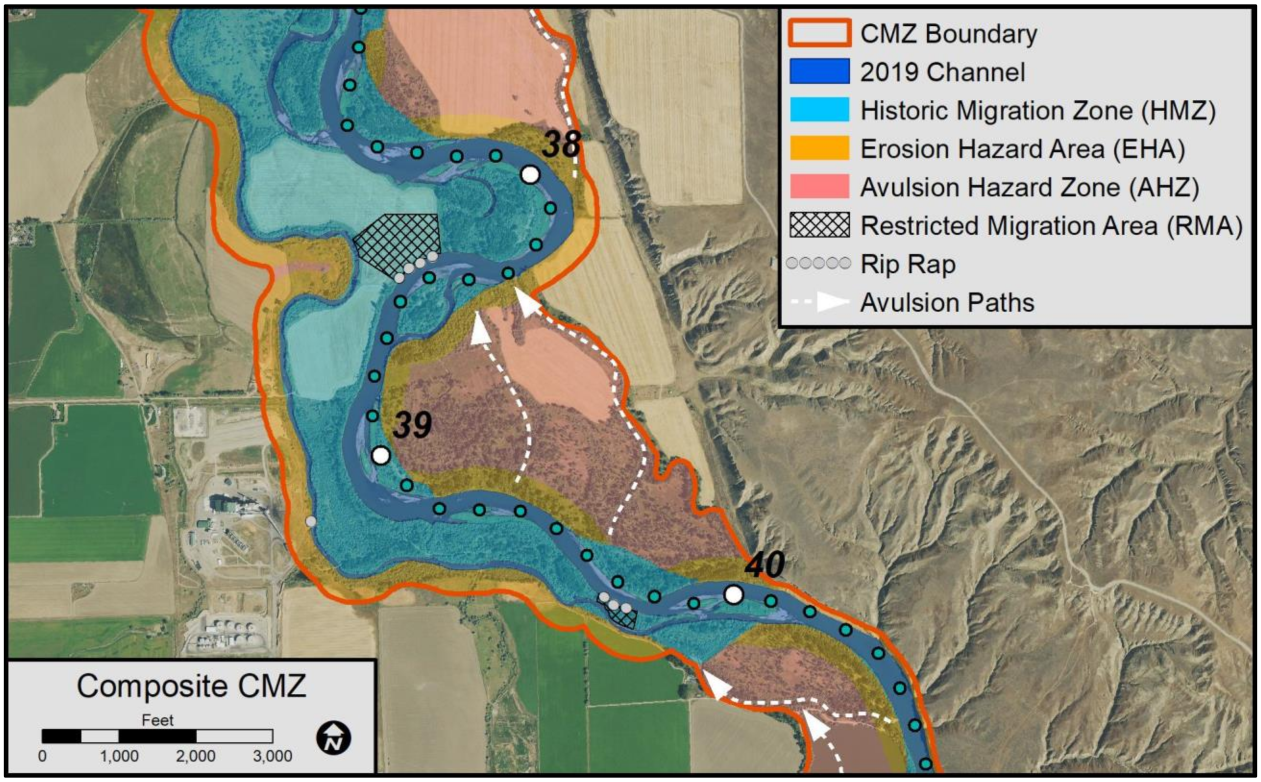


Figure 38. Composite Channel Migration Zone map.

5 Bighorn River Reach Descriptions

The following section describes each reach in terms of general aspects of the CMZ that demonstrate fundamental aspects of channel migration on the river, and highlights areas of special concern.

General observations of the project area are dominated by a marked change in river conditions between the earliest available imagery (mid-1950s) and current conditions. The 1939 photos capture a much less controlled and wild river, with broad open sand bars and extensive split flow. As flows have become more managed, the sediment load has dropped and flow variability has waned, resulting in vegetation encroachment and landform stabilization. Another trend is from upstream to downstream; reaches below the Little Bighorn River confluence are inherently more dynamic than those above. More discussion of the impacts of dam construction on river flows and reach conditions can be found in the Bighorn River Alliance Hydrology Report (Boyd, 2019).

The CMZ maps for each reach are compiled in Appendix A.

5.1 Reach BH1: Afterbay Dam to Three Mile

Reach BH1 extends 3.7 miles below Afterbay Dam to Three Mile Fishing Access (Figure 39). This section of river immediately below the Afterbay Dam shows little in the way of geomorphic change in recent decades.

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), Reach BH1 has an average migration rate of 0.9 feet per year as measured at 14 sites. The maximum migration distance is 45 feet. These rates of movement are substantially lower than those measured for the 1954-1979/80 timeframe, which average 1.6 feet per year at 44 sites. This is the same pattern we see system-wide, and based on the geomorphic character of the river, dampened rates of movement clearly stem from the reduction in both flooding and sediment delivery following the completion of Yellowtail Dam in the 1960s. The erosion hazard buffer width in Reach BH1 is 87 feet, with a buffer of 79 feet along the high erodible bluffs. This is the narrowest erosion buffer on the river.

Although Yellowtail Dam has blocked most sediment delivery to Reach BH1, there is still some gravel delivered through bank erosion and from tributaries. The most significant gravel source appears to be from the Red Cliffs (RM 81.4), where gullying of the terrace has delivered coarse sediment to the river (Figure 40), which has downcut through the terrace, enters the Bighorn along the Red Cliffs and similarly delivers gravels which could prove to be important for spawning habitat sustainability in this sediment-starved reach.

Reach BH1 currently has no active side channels, although remnants are visible on the floodplain.

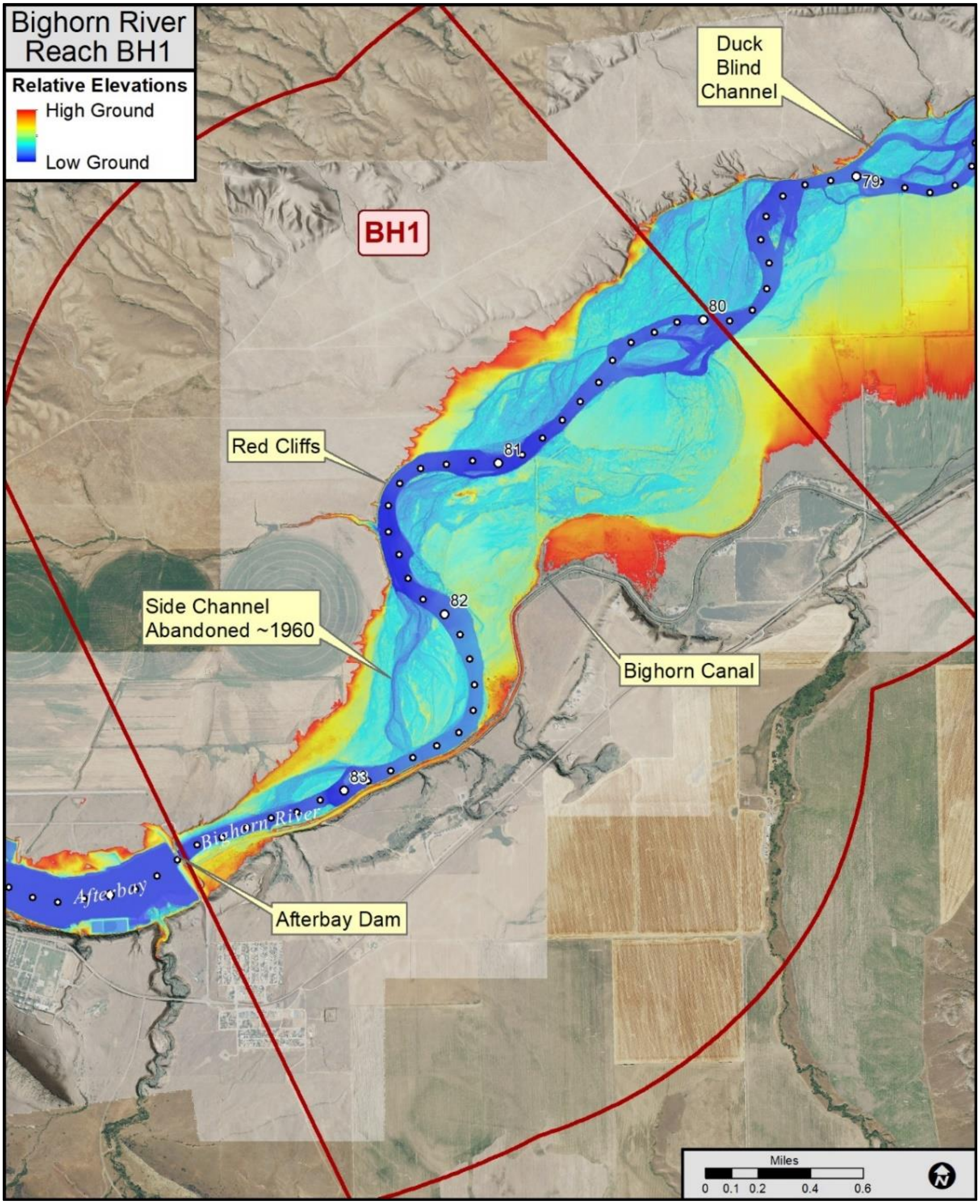


Figure 39. Relative elevation map of BH1.

Figure 40.Coarse sediment delivered via terrace gullying below Grapevine Creek, RM 81.4.

Most of CMZ in Reach BH1 is mapped as avulsion hazard area, where floodplain swales are continuous and un-perched, indicating their potential for reactivation during floods. Several avulsion risk areas capture channels that were active prior to dam completion (Figure 41). One avulsion event was mapped in this reach; it occurred between 1954 and 1979 when a new channel cut through an island just upstream of the Three Mile Access (Figure 42).

Areas of discernable erosion in Reach BH1 include the following:

- RM 82.4: Severe local erosion adjacent to the Bighorn Canal (Figure 43).
- RM 82.2: Right bank at Bonefish Flats
- RM 82.1: Both banks have eroding as Second Island and Third Island have established and expanded
- RM 81.8: Substantial left bank erosion (~50 feet) at Bacon Hole prior to 1979

One concern with the lack of geomorphic disturbance in Reach BH1 is the total lack of riparian recruitment on the floodplain; most cottonwoods are mature and becoming increasingly decadent, with few young trees to take their place (Figure 44). Russian olive is common and commonly forms thick stands on the streambanks. One positive observation in the CMZ mapping is the local recruitment of gravels from terraces, floodplain surfaces, and via tributaries; this will contribute at least some spawning gravels to the reach, helping to mitigate future inevitable gravel depletions due to the upstream trapping of sediment in Bighorn Lake (Figure 45).

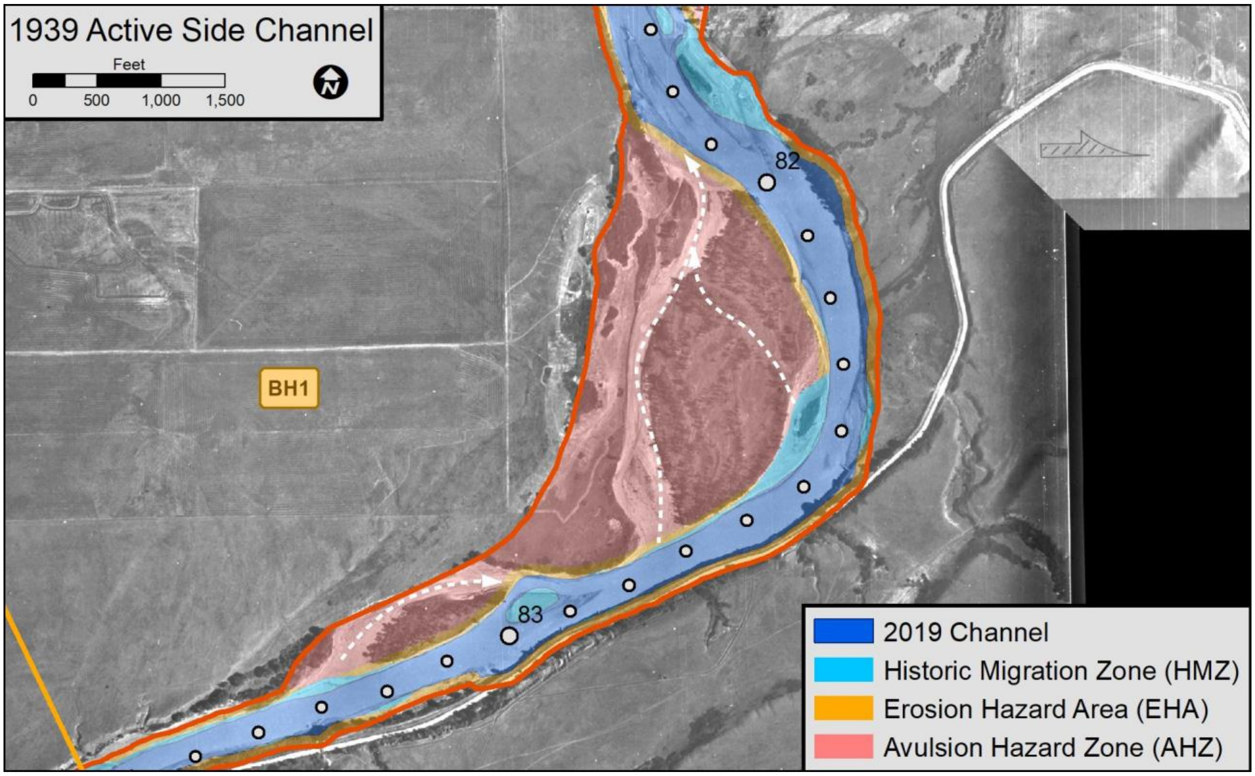


Figure 41. 1939 aerial image showing active side channel that is now abandoned but remains in the CMZ due to its potential for reactivation.

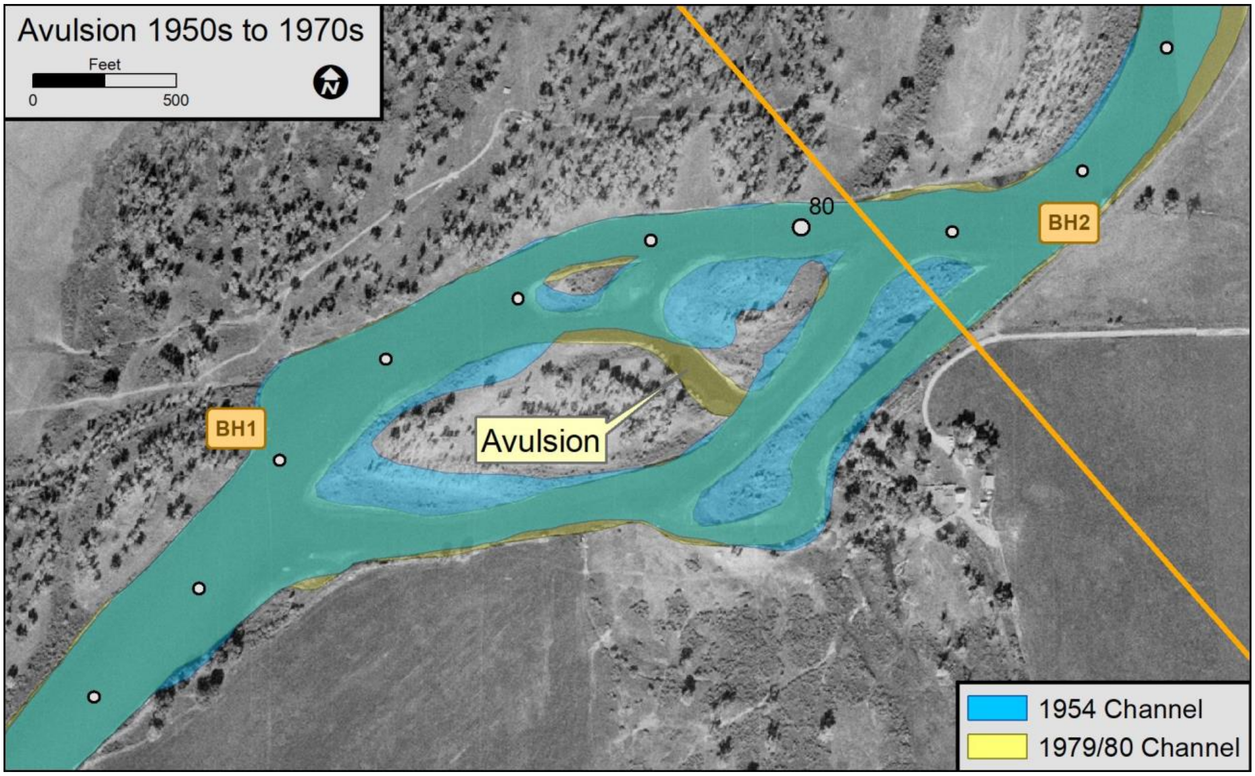


Figure 42. Avulsion upstream of Three mile access.

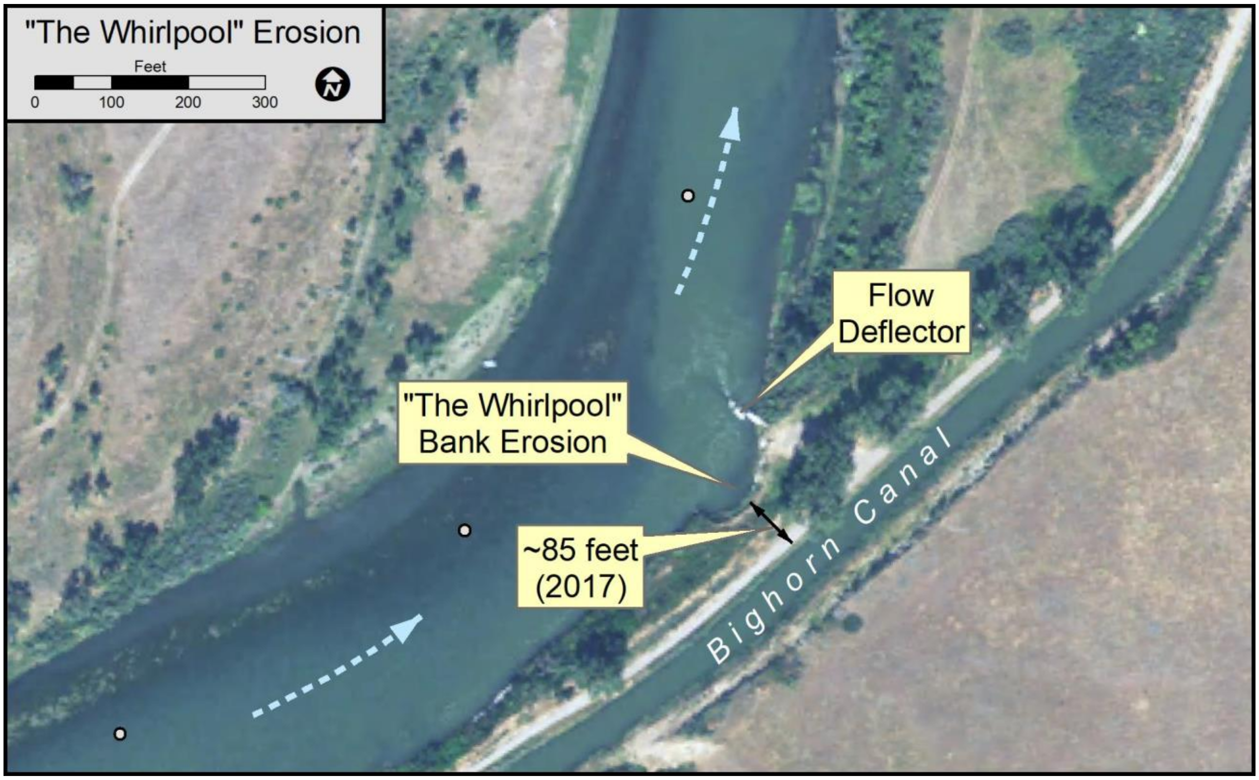


Figure 43. 2017 air photo showing scour upstream of flow deflector; back eddy has eroded the bank towards Bighorn Canal.

Figure 44. Aging cottonwood forest, Reach BH1.

Figure 45. Gravel/cobble alluvium in historic floodplain that provides good spawning substrate to river.

5.2 Reach BH2: Three Mile to Bighorn FAS

Reach BH2 extends from the 3-Mile to Bighorn Fishing Access sites, a channel distance of 8.3 miles (Figure 46). This reach is substantially more complex than Reach BH1 upstream, especially with respect to side channel density (Figure 46). That said, there are numerous other side channels that have become progressively abandoned since the 1950s (Figure 47). This has prompted several side channel reactivation projects in this reach, including Clines Channel, Juniper Channel and Rattlesnake Channel (Figure 48; Boyd, 2020).

In Reach BH2 the river tends to follow the west margin of the floodplain which is comprised of Cretaceous-aged Mowry shale in the upper portion of the reach and Belle Fouche Shale below RM 71 (Figure 50; Vuke et. al, 2007).

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), Reach BH2 has an average migration rate of 1.0 feet per year as measured at 42 sites. The maximum 1979/80-2019 migration distance measured is 131 feet near Snag Hole at RM 79.4 (Figure 49). The erosion hazard buffer width in Reach BH2 is 96 feet, with a buffer of 79 feet along the high erodible bluffs.

Reach BH2 shows evidence of more disturbance relative to Reach BH1 upstream. Although large wood is still relatively rare in the channel, it does locally affect geomorphology by promoting flow splits at the heads of islands (Figure 51). One positive aspect of the bedload movement and associated geomorphic disturbance in this reach is the presence of a few cottonwood seedlings (Figure 52). Although these cottonwoods will be prone to scour by high flows or ice, the survival of any seedlings will help sustain the Bighorn River cottonwood forest. Both Russian olive and Tamarisk (salt cedar) are common in the reach and may eventually replace cottonwoods without successful cottonwood recruitment.

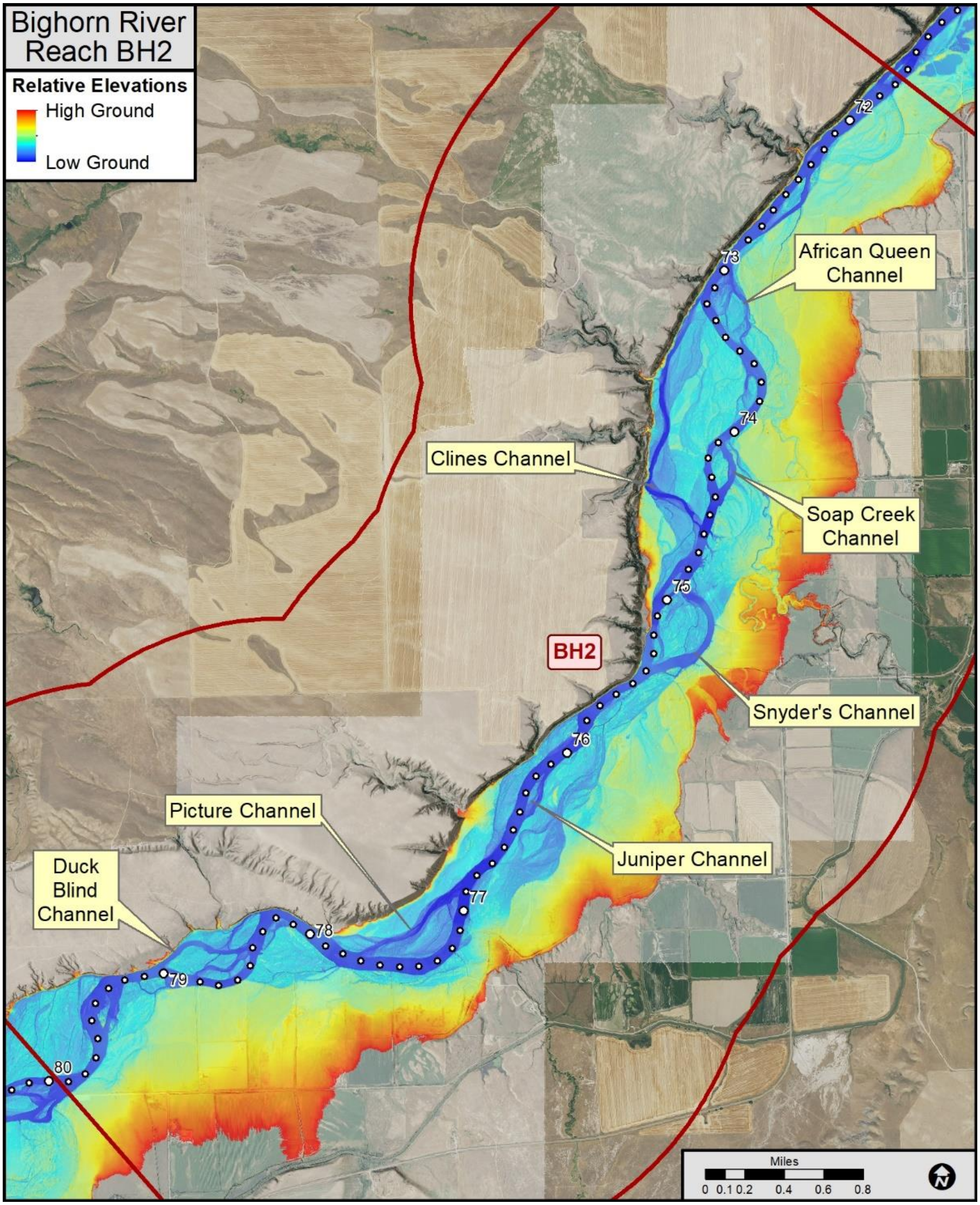


Figure 46. Relative Elevation Model (REM) map showing major side channels in Reach BH2.

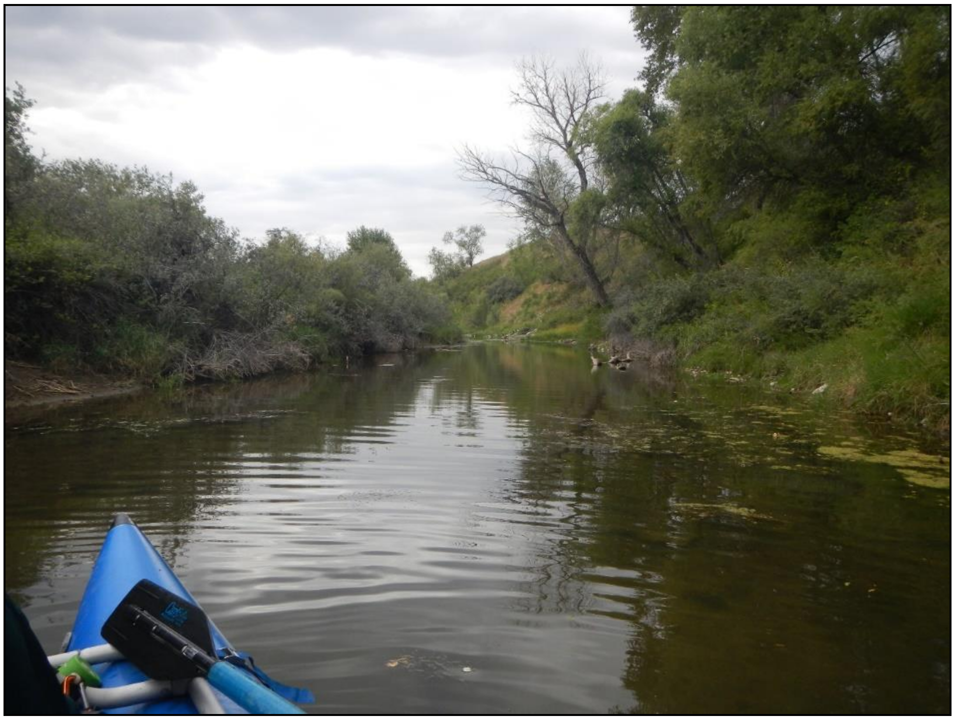


Figure 47. View upstream of remnant 1950s channel below Carol's Run, Rm 78.2.

Figure 48. View downstream of the entrance into Juniper Channel, slated for reactivation.

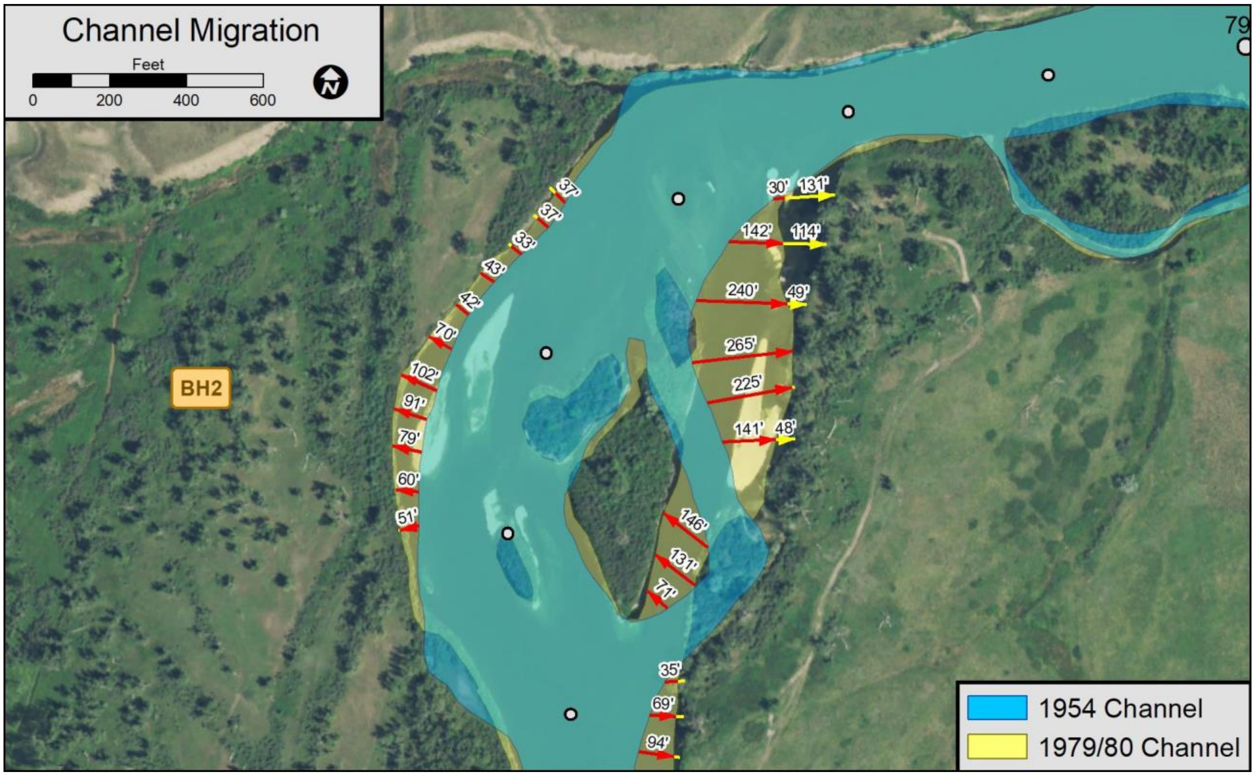


Figure 49. Eastward channel movement near Snag Hole showing banklines from 1954 and 1979 on 2019 imagery.

Figure 50. Gray cliffs of the Cretaceous age Mowry Shale, a source of largely fine sediment.

Figure 51. Large wood accumulation at head of Picture Side Channel, Reach BH2.

Figure 52. Cottonwood seedling, Reach BH2.

5.3 Reach BH3: Bighorn FAS to Mallard's Landing FAS

Between Bighorn and Mallard's Landing Fishing Access Sites, the Bighorn River continues to follow the western bluff line, which consists of Upper Cretaceous Belle Fourche Shale overlain by young alluvial terrace deposits (Figure 54). The shale is described as dark grey with numerous bentonite beds (Vuke, et. al, 2007).

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), 62 measurements were collected, indicating an average migration rate of 1.1 feet per year along actively eroding banklines in reach BH3. The maximum 1979/80-2019 migration distance of 101 feet was measured about a mile downstream of Beauvais Creek, where an island has established and widened, driving right bank erosion.

One eroding bankline that has received much attention in recent years is just below the St Xavier Bridge, where channel migration eastward has threatened several houses and prompted extensive bank armoring (Figure 53).

The erosion hazard buffer width in Reach BH3 is 107 feet, with a buffer of 79 feet along the high erodible bluffs.

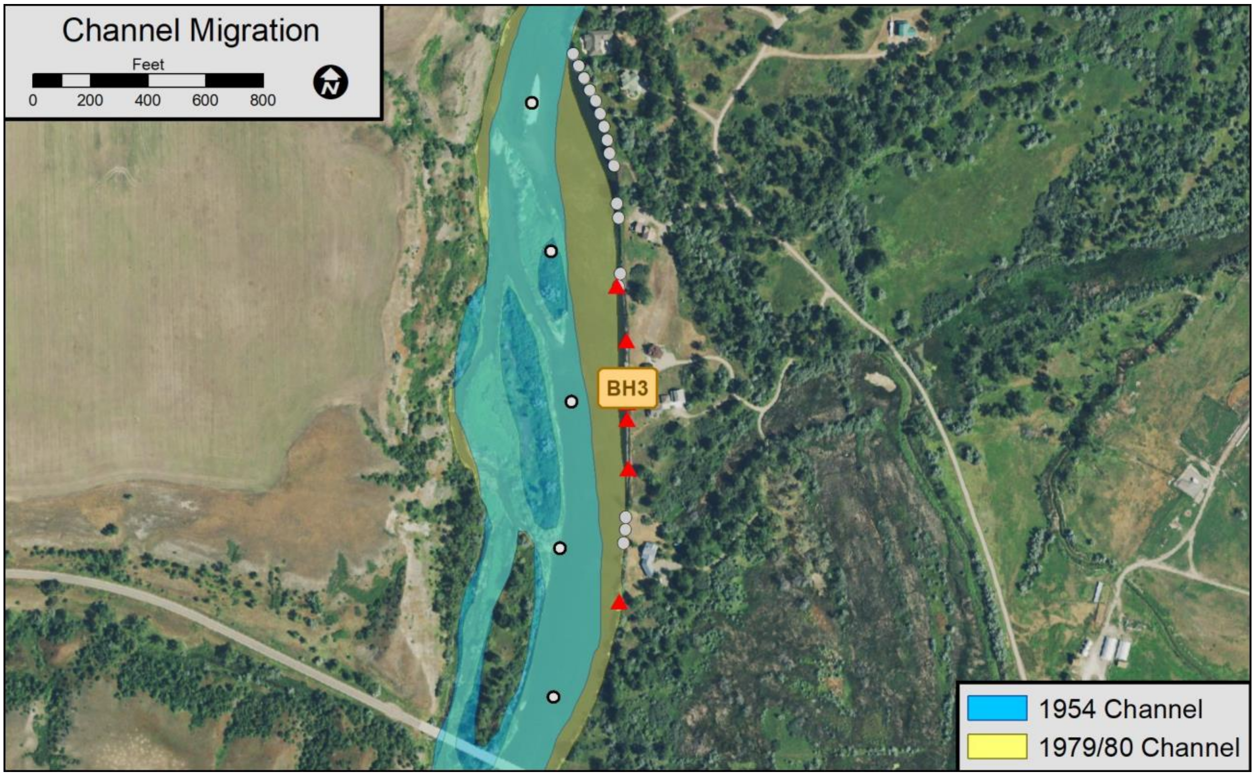


Figure 53. Right bank erosion threatening homes below St. Xavier Bridge.

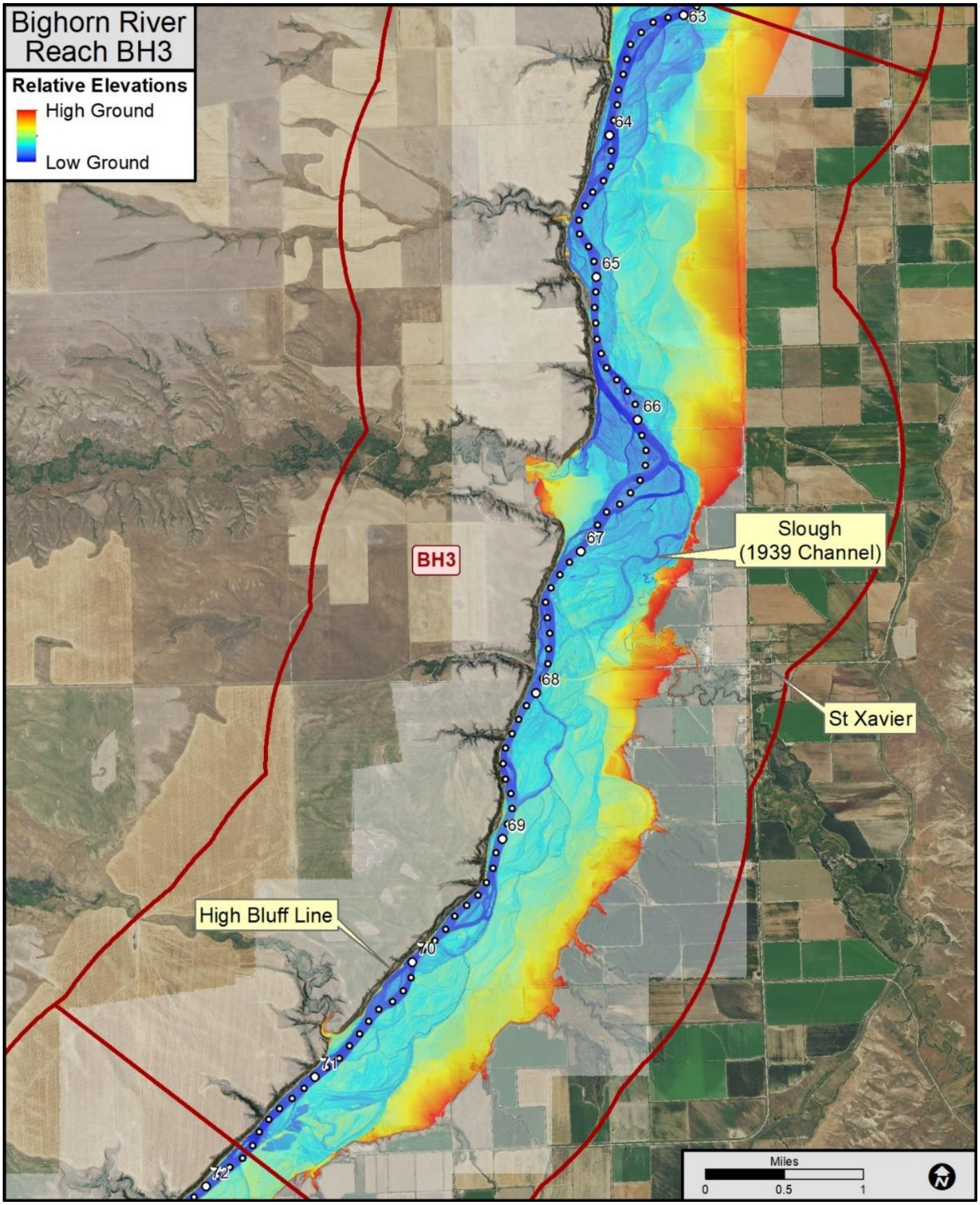


Figure 54. Relative elevation map of Reach BH3.

5.4 Reach BH4: Mallard’s Landing FAS to Two Leggins FAS

Reach BH4 extends from Mallard’s Landing to Two Leggins Fishing Access and is 10 miles long, flowing primarily against the western bluff line (Figure 56). The bluff consists of Carlisle shale, described as a very dark shale with bentonite beds (Vuke, et. al, 2007). It is capped by younger alluvium.

This reach has several complex island segments, creating a relatively wide Historic Migration Zone (Figure 55).

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), 57 measurements were collected, indicating an average migration rate of 1.9 feet per year along actively eroding banklines in reach BH4. The maximum 1979/80-2019 migration distance of 238 feet was measured at RM 58.9. Much of the erosion in this reach is occurring along hayfields that do not support any woody vegetation to help resist that erosion (Figure 57).

The erosion hazard buffer width in Reach BH4 is 187 feet, with a buffer of 79 feet along the high erodible bluffs. The bluffs are prone to mass failure (landslides) as well as incremental erosion; one major hillslope failure just downstream of the mouth of Woody Creek occurred in the last few years, narrowing the mainstem river channel (Figure 58).

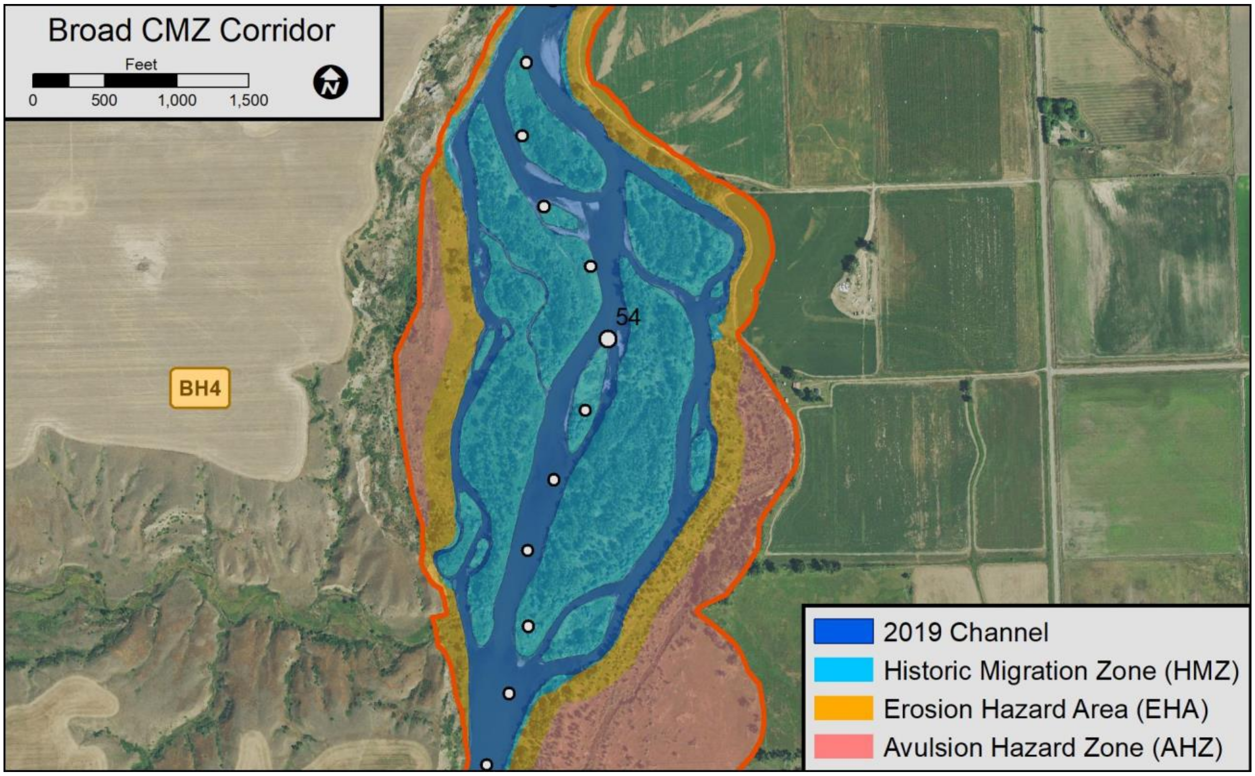


Figure 55. Example of a broad HMZ in area of split flow that supports complex geomorphology and dense riparian forest.

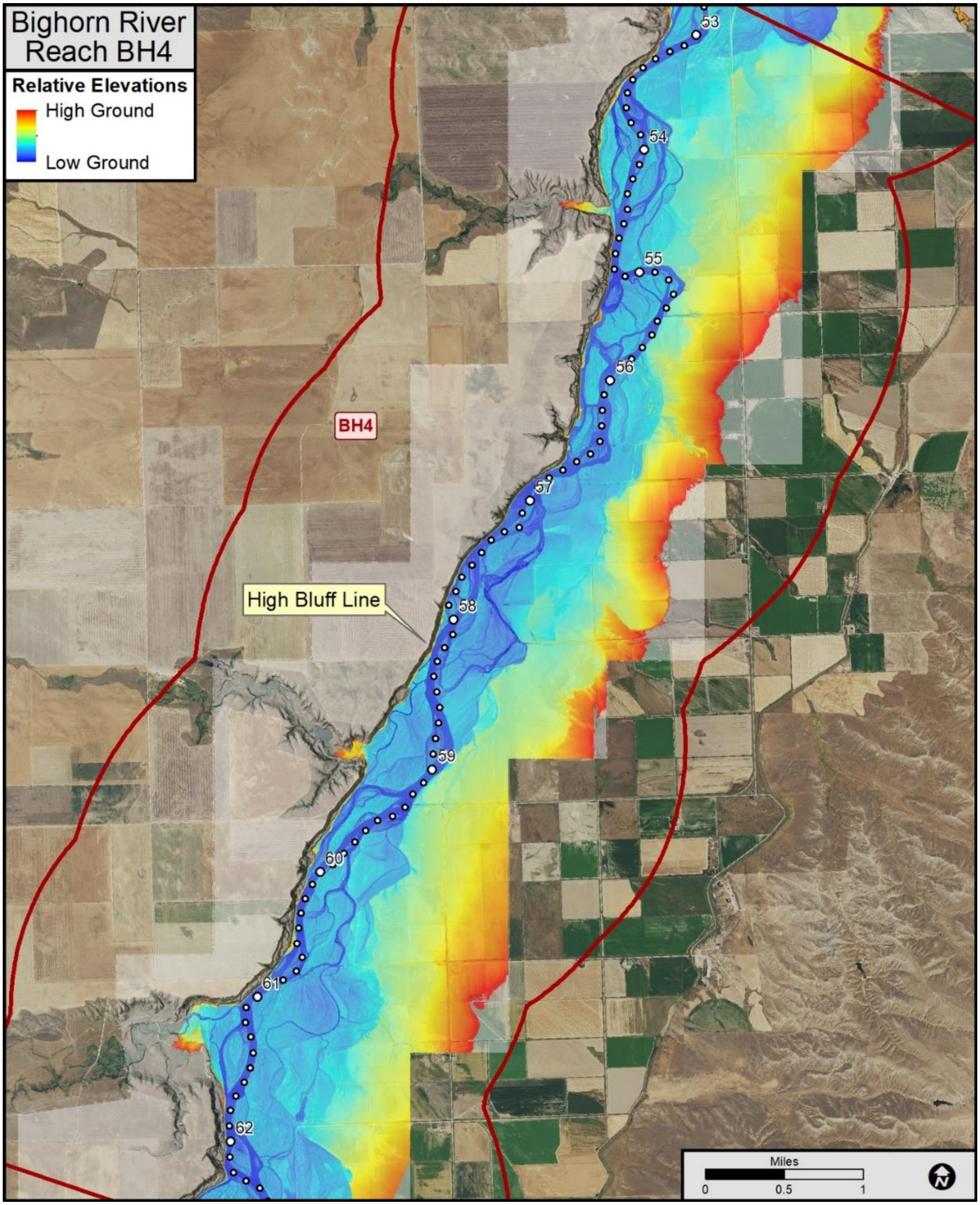


Figure 56. Relative elevation map of Reach BH4.

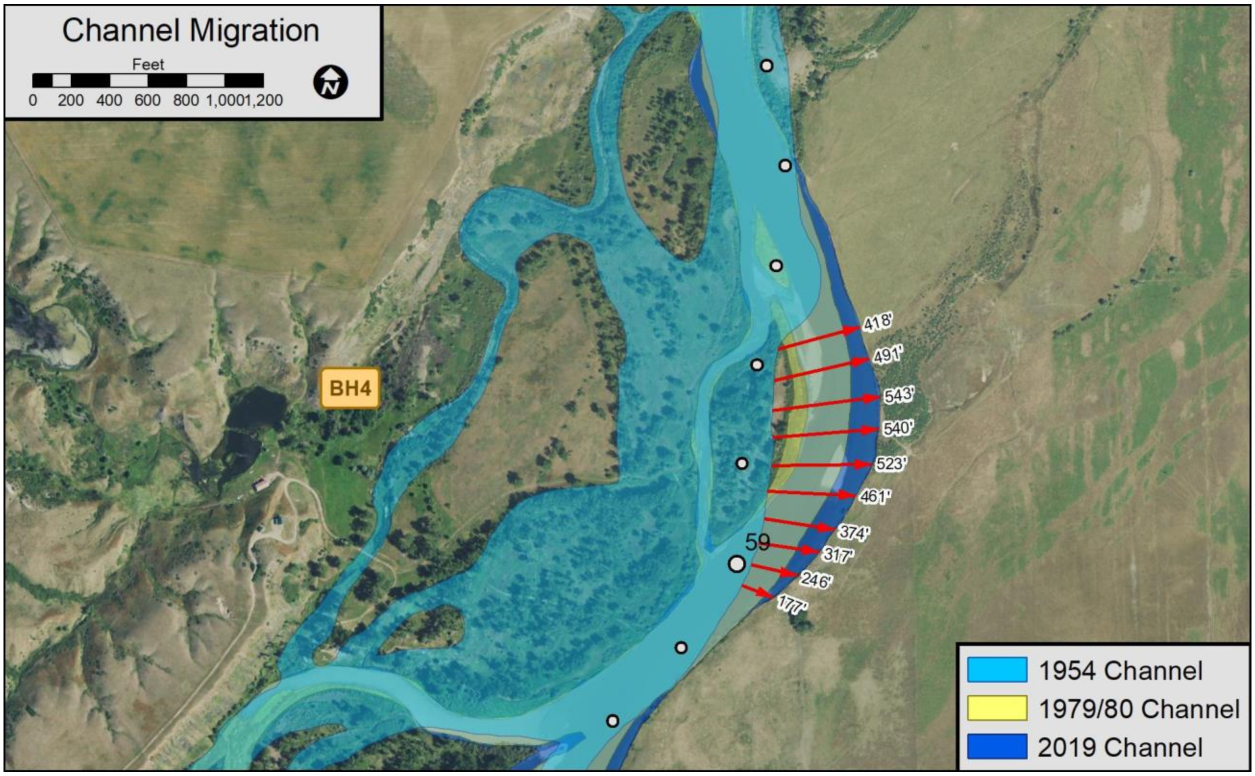


Figure 57. Right bank meander migration into unvegetated bankline, RM 58.9.

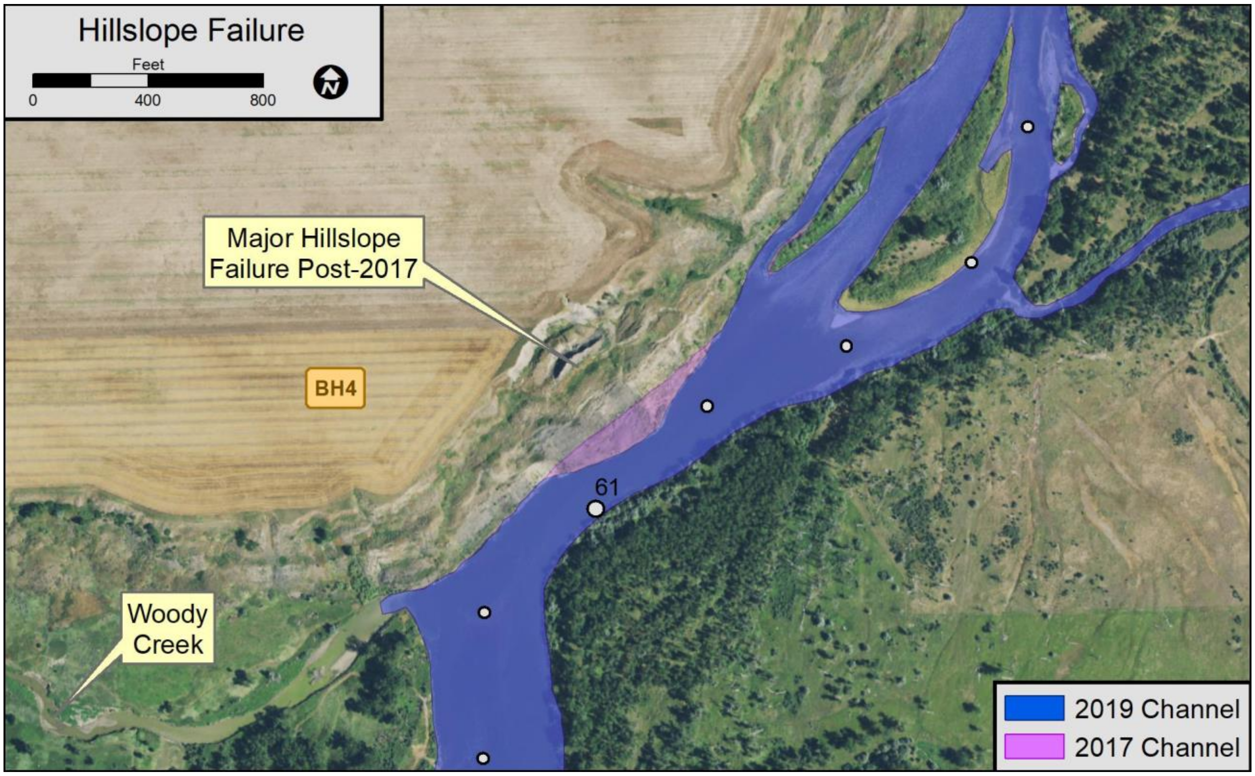


Figure 58. Recent landslide just below Woody Creek RM 61.

5.5 Reach BH5: Two Leggins FAS to Little Bighorn River near Hardin

At the Reach BH4/BH5 boundary, the Bighorn River crosses the valley to follow the eastern bluff line, which consists of Cretaceous-age Niobrara Shale (Figure 60). Although the primary thread tends to hug the valley wall, in several locations, islands have formed that support persistent split flow. This is most apparent at the Two Leggins Fishing Access Site at RM 52, where migration eroded out the original access road to the site.

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), 58 measurements were collected, providing an average migration rate of 1.8 feet per year along actively eroding banklines in reach BH5. The maximum 1979/80-2019 migration distance of 272 feet at RM 62.2. The erosion hazard buffer width in Reach BH5 is 181 feet, with a buffer of 79 feet along the high erodible bluffs. The bluffs are prone to erosion by the river as well as gullying (Figure 59).

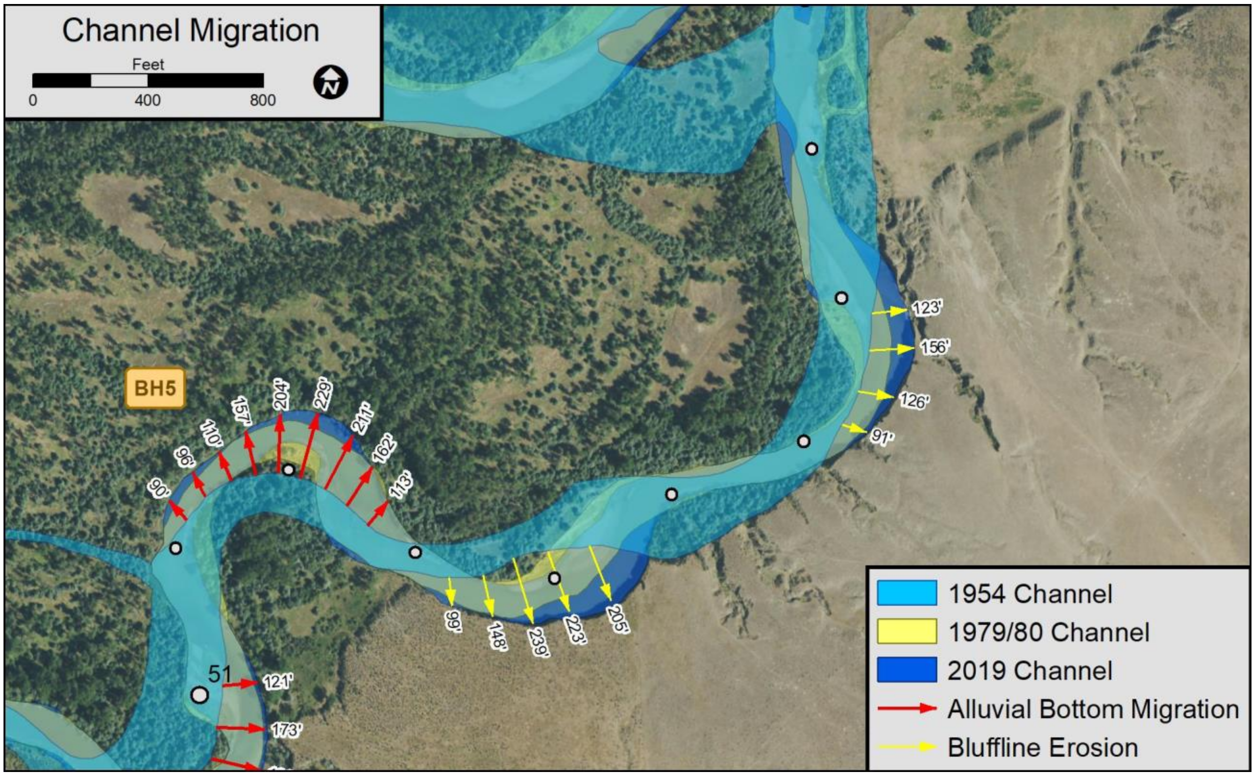


Figure 59. Terrace erosion at RM 50.6.

About a mile upstream of the interstate bridge at RM 42.3, a large avulsion abandoned almost 3,000 feet of channel, the old swale has reclaimed for a small garden plot (Figure 61).

Channel migration above the interstate bridge at Hardin could become problematic in coming years, active left bank erosion just upstream of the bridge has flanked some rock and the river alignment to the bridge is decaying as a result (Figure 62 and Figure 63).

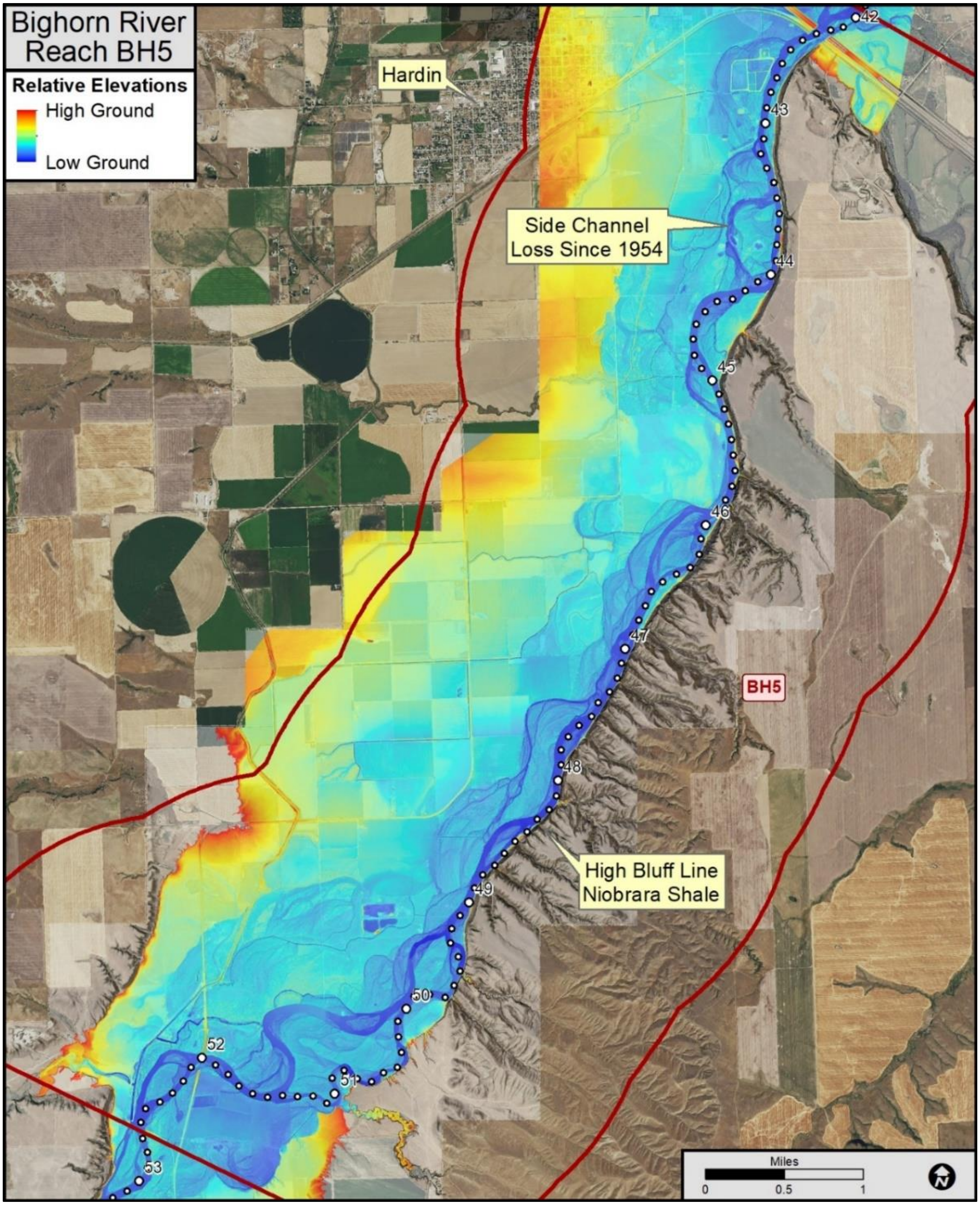


Figure 60. Relative elevation map of Reach BH5.

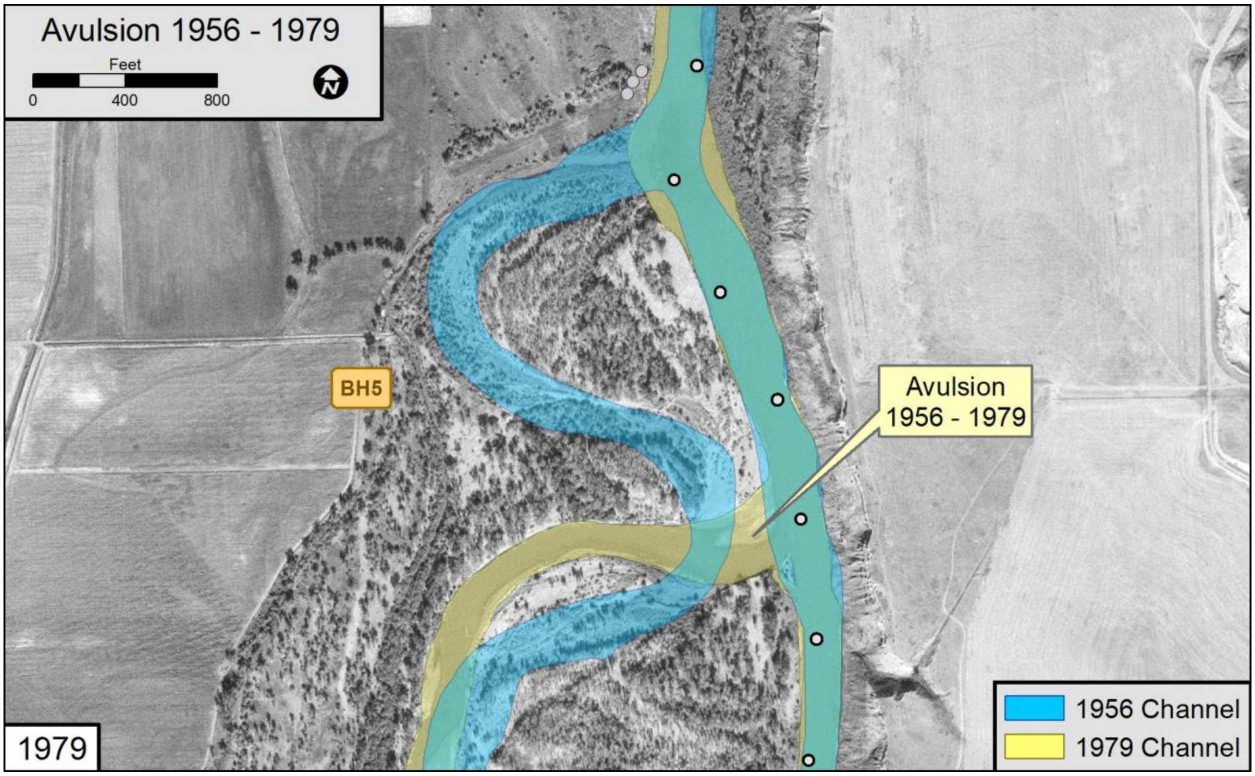


Figure 61. Avulsion at RM 43.5 that abandoned almost 3,000 feet of channel.

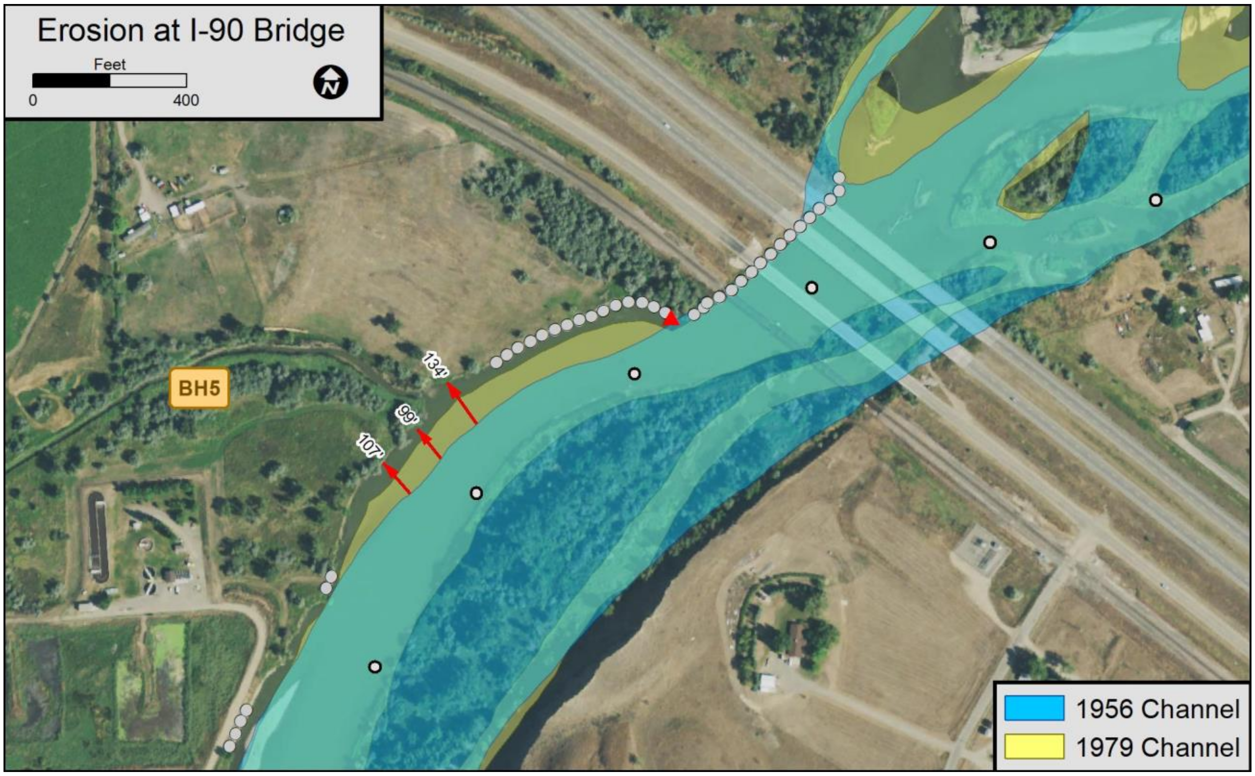


Figure 62. Left bank erosion above interstate bridge that appears to be flanking bank armor.

Figure 63. Google Earth image showing flanking of left bank armor above Interstate Bridge.

5.6 Reach BH6: Little Bighorn River near Hardin to General Custer FAS

Reach BH6 (Figure 64) is the first channel segment below the mouth of the Little Bighorn River. It is 17 miles long. Similar to most other reaches, long segments of the river closely follow the valley wall, which in this area consists of Cretaceous-age Bearpaw Shale (Vuke, et. al, 2007). This unit consists of dark interbedded siltstone and fine sandstone, reaching thicknesses of 860 feet. This is the first reach below Yellowtail Dam that shows meander development and associated channel migration, which likely reflects the sediment and flow inputs from the Little Bighorn River.

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), 172 measurements were collected, providing an average migration rate of 3.1 feet per year along actively eroding banklines in reach BH6. The maximum 1979/80-2019 migration distance of 626 feet at RM 34.5.

The erosion hazard buffer width in Reach BH6 is 306 feet. Only those blufflines that are comprised of demonstrably erodible geology were given an erosion buffer of 79 feet, the other sandstone-dominated units that show no evidence of erosion were clipped entirely from the CMZ.

In general, this reach is characterized by large sweeping meanders, many of which have shown hundreds of feet of movement since 1979. Figure 65 shows a series of three meanders progressively developing since 1950, with several hundred feet of migration occurring on each (Figure 65). One area where meander migration has caused specific problems is Grant Marsh Fishing Access, where recent bank movement has taken out the primary access road to the boat ramp (Figure 66).

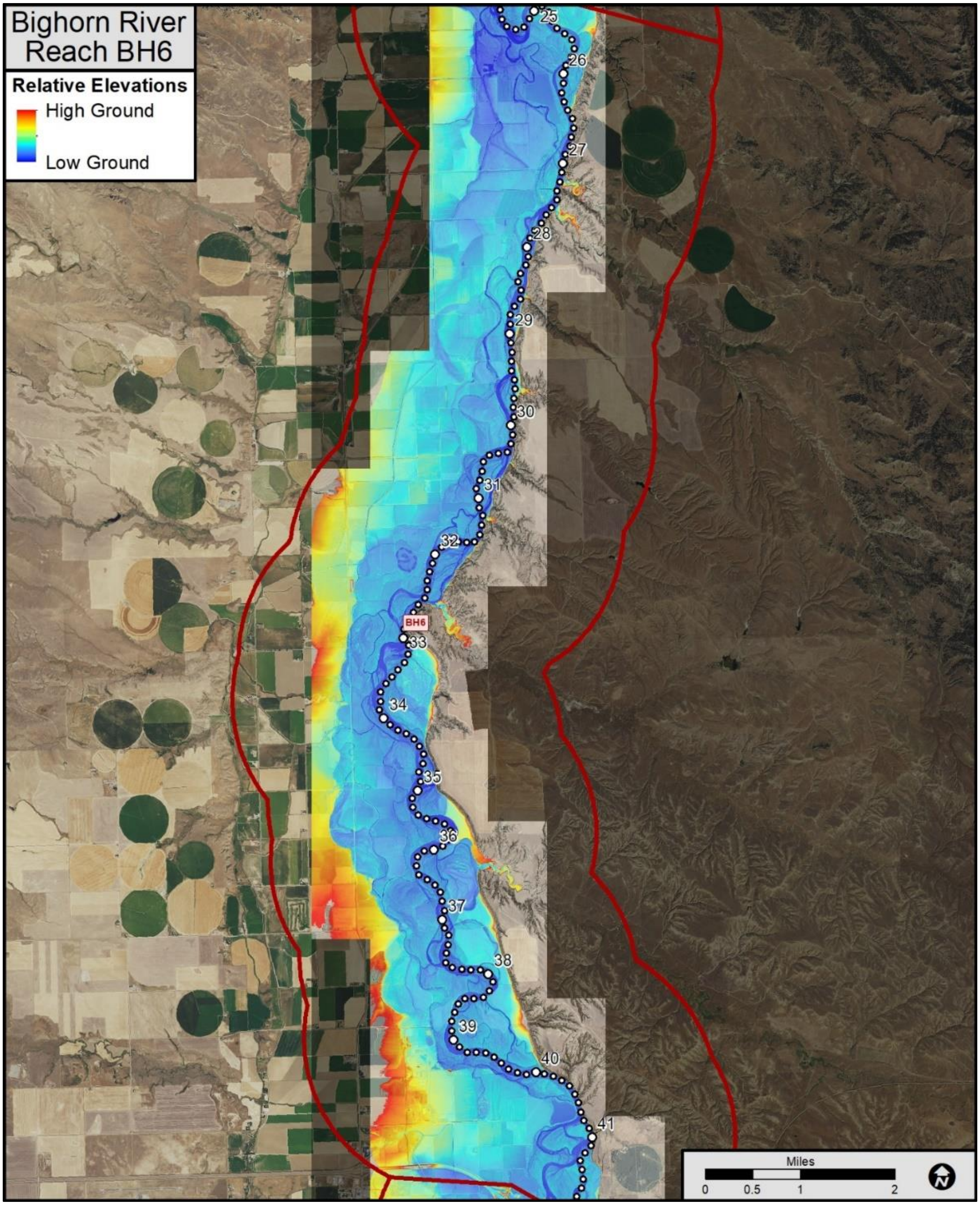


Figure 64. Relative elevation map of Reach BH7.

The George Custer FAS at the lower end of Reach BH6 is on a large, lengthening bendway that is prone to cutoff incoming decades. Depending on how a cutoff manifests, the changes could result in the Bighorn River abandoning the access site (Figure 67).

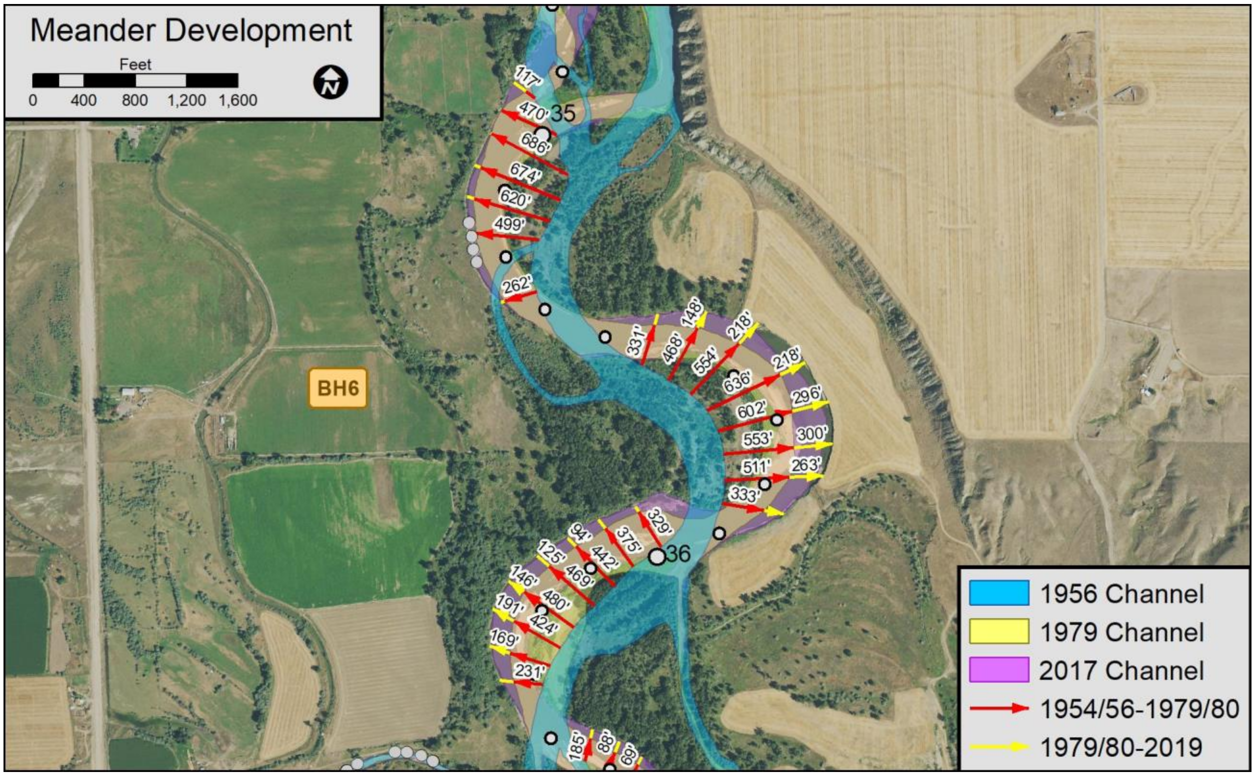


Figure 65. Large meander migration across floodplain causing field erosion, RM 35.7.

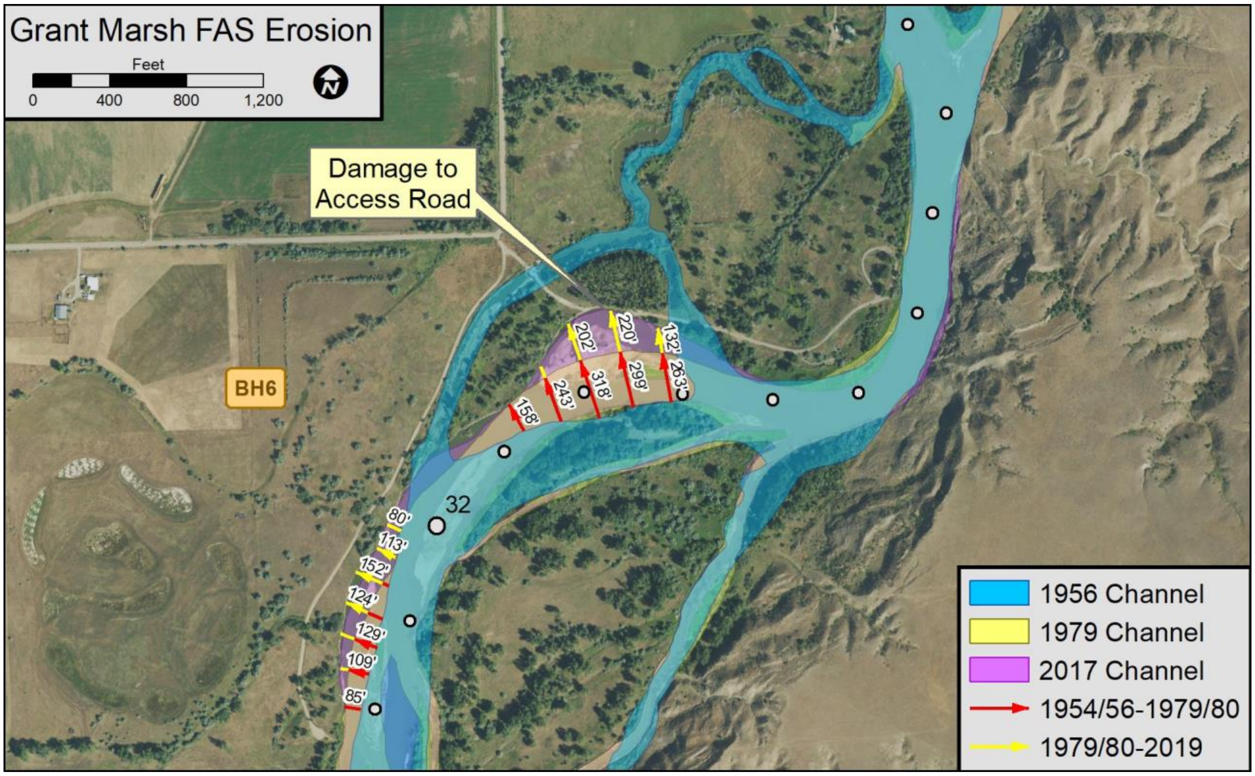


Figure 66. Northward channel migration into Grand Marsh FAS.

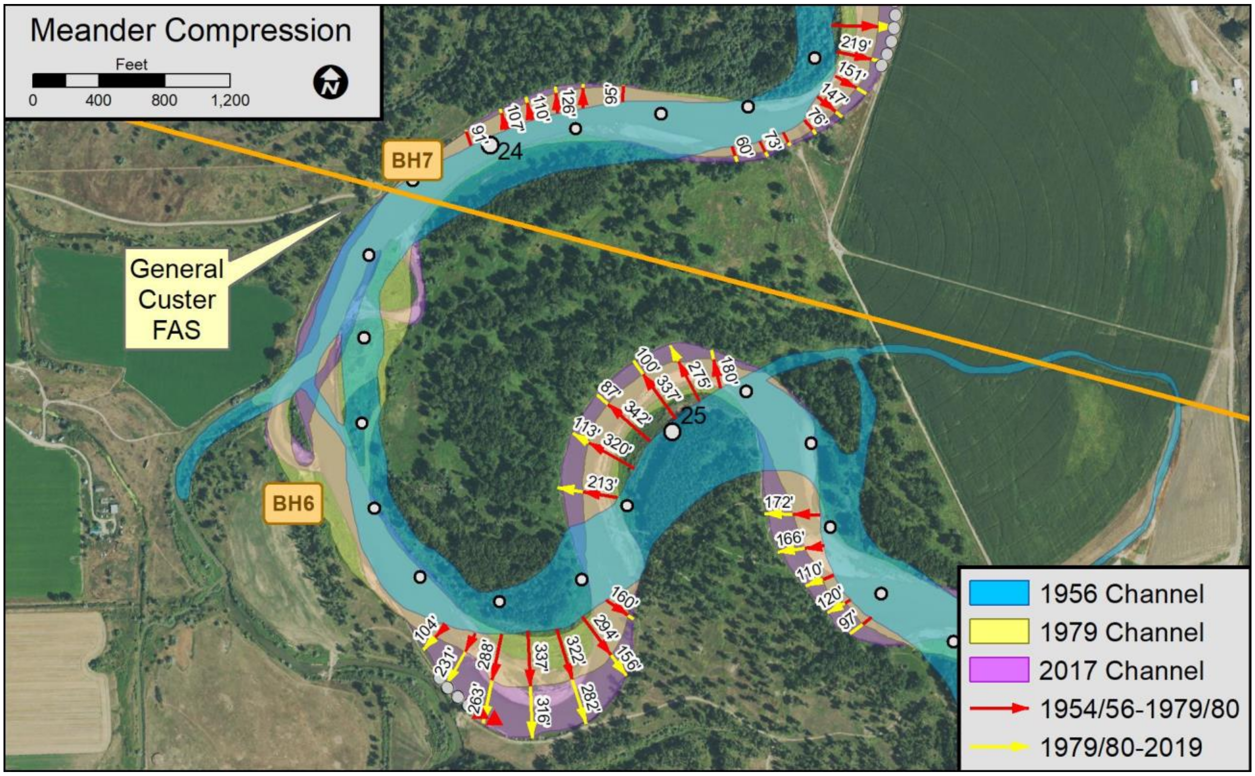


Figure 67. Meander compression at General Custer FAS; an avulsion across the meander core would abandon the site.

5.7 Reach BH7: General Custer FAS to Yellowstone River Confluence

Reach BH7 is about 24 miles long and extends to the mouth of the Bighorn River (Figure 68). Within this reach the river intermittently flows against sandstone rather than shale with the Lance Formation forming the valley wall for much of the reach. This unit also contains some conglomerate (Vuke, et al, 2008).

For the Post-Yellowtail Dam timeframe captured in the imagery (1979/80-2019), 196 measurements were collected, providing an average migration rate of 2.6 feet per year along actively eroding banklines in reach BH6. The maximum 1979/80-2019 migration distance of 582 feet at RM 18.7 where a large power line tower is being undermined.

The erosion hazard buffer width in Reach BH6 is 257 feet. In this section of the river, most of the bluff line is non-erodible sandstone hence was clipped from the CMZ (Figure 69).

Where the river follows the valley wall, migration rates tend to be low, however there are several areas where large, rapidly migrating bendways have formed away from the valley margin. One area of special concern is at RM 18.7, where a northward-migrating bendway has encroached into an irrigated field that has a massive power line tower currently sitting on the edge of the stream bank (Figure 70). This bend has migrated over a thousand feet in the last 70 years, averaging over 14 feet of movement per year for 7 decades.

Although several bendways are armored in Reach BH7, bankline erosion control is still relatively rare. There are several sites where barbs have been flanked or completely eroded out, showing how difficult it may be to stop channel movement on this large system. As a result of continued movement, the cottonwood forest appears much more robust and inherently sustainable relative to upstream reaches.

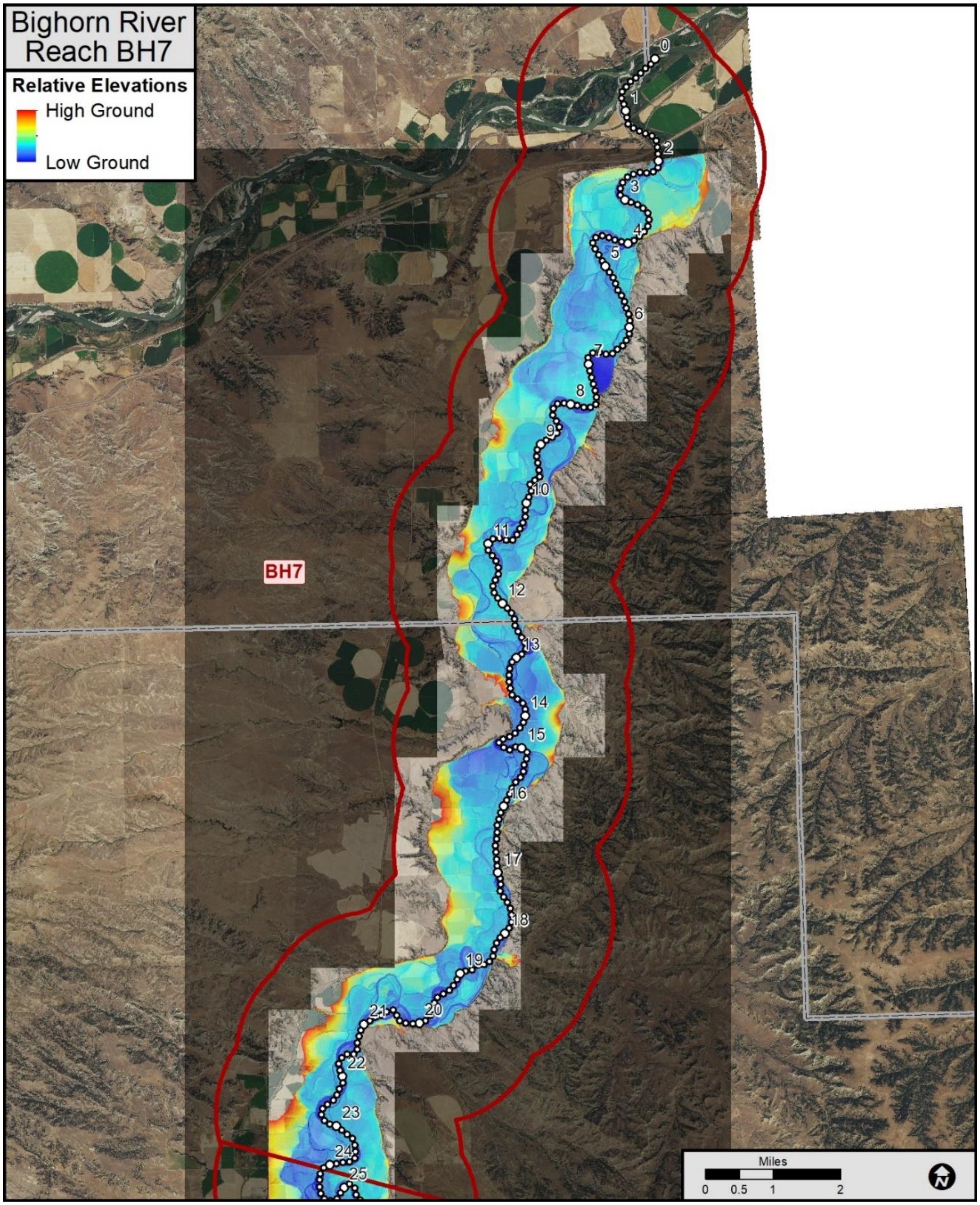


Figure 68. Relative elevation map of Reach BH7.

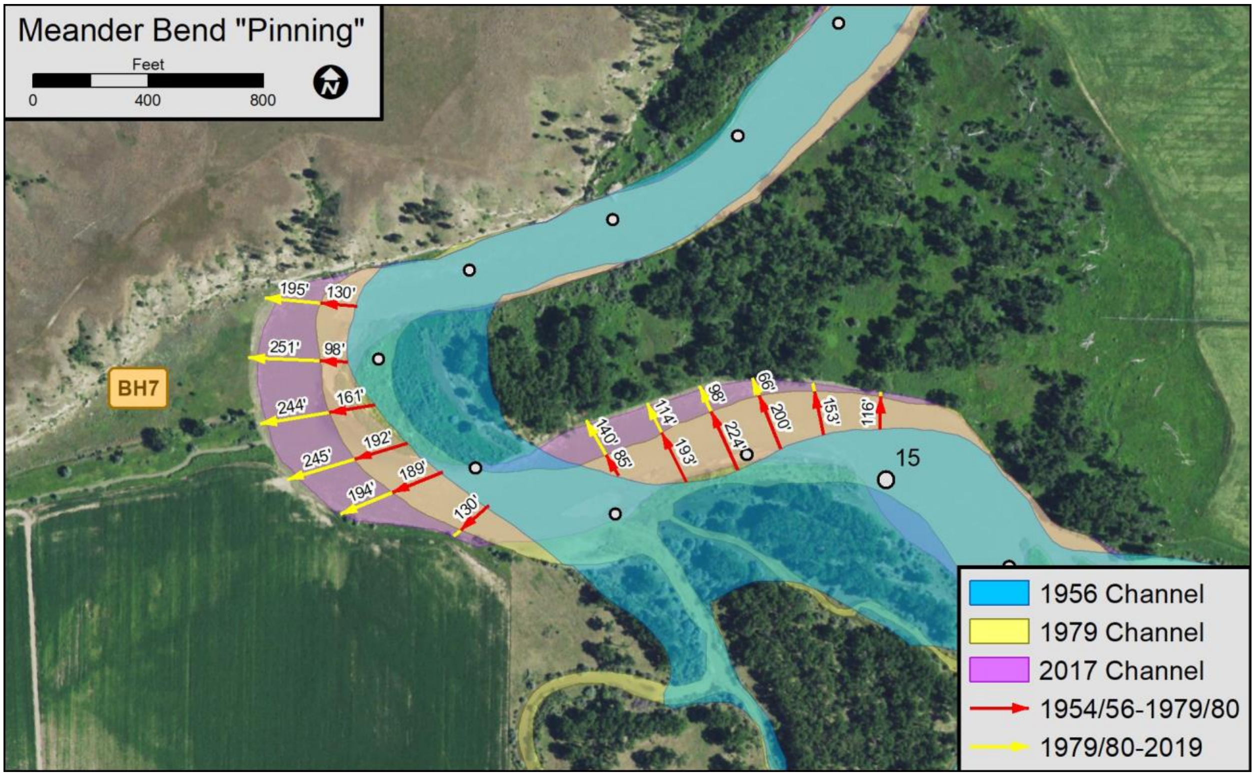


Figure 69. Meander bend "pinning" against a non-erodible sandstone valley wall.

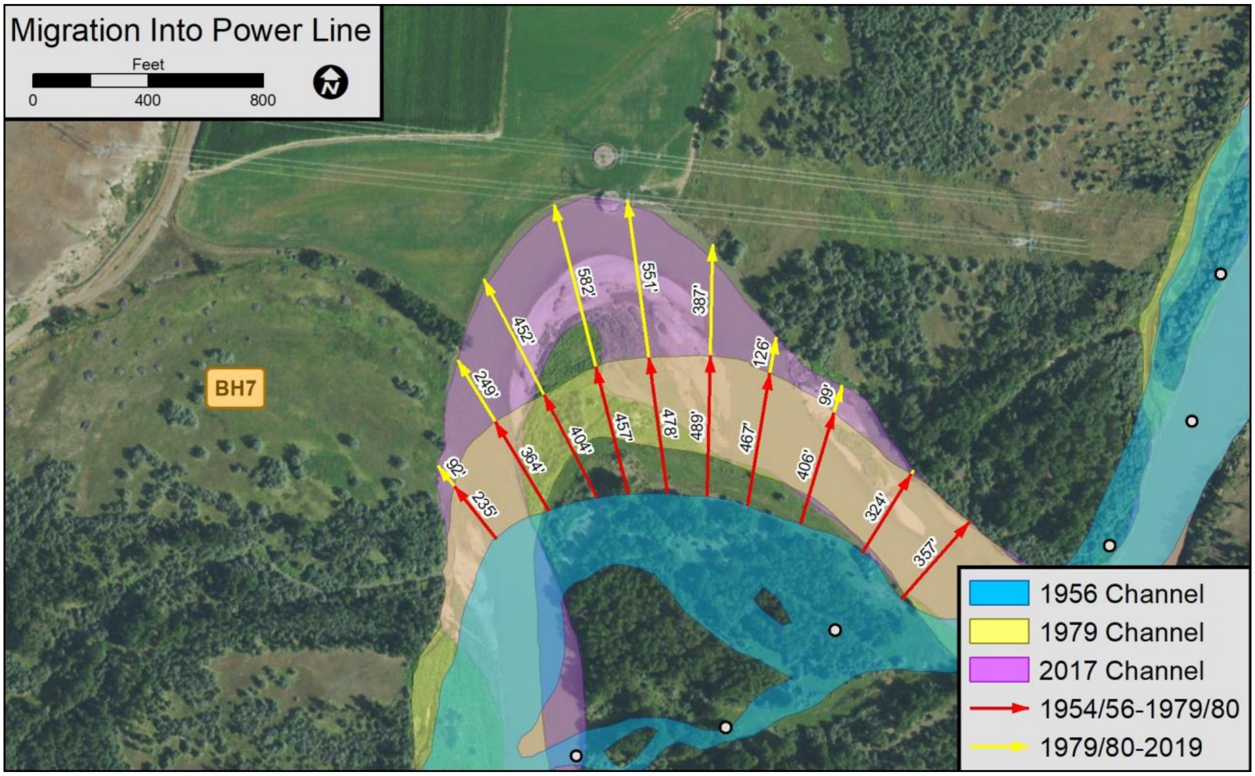


Figure 70. Migration into power line tower at RM 18.7.

Another issue with the large rates of migration is the increased potential for an avulsion where the river is migrating into old side channels (Figure 71).

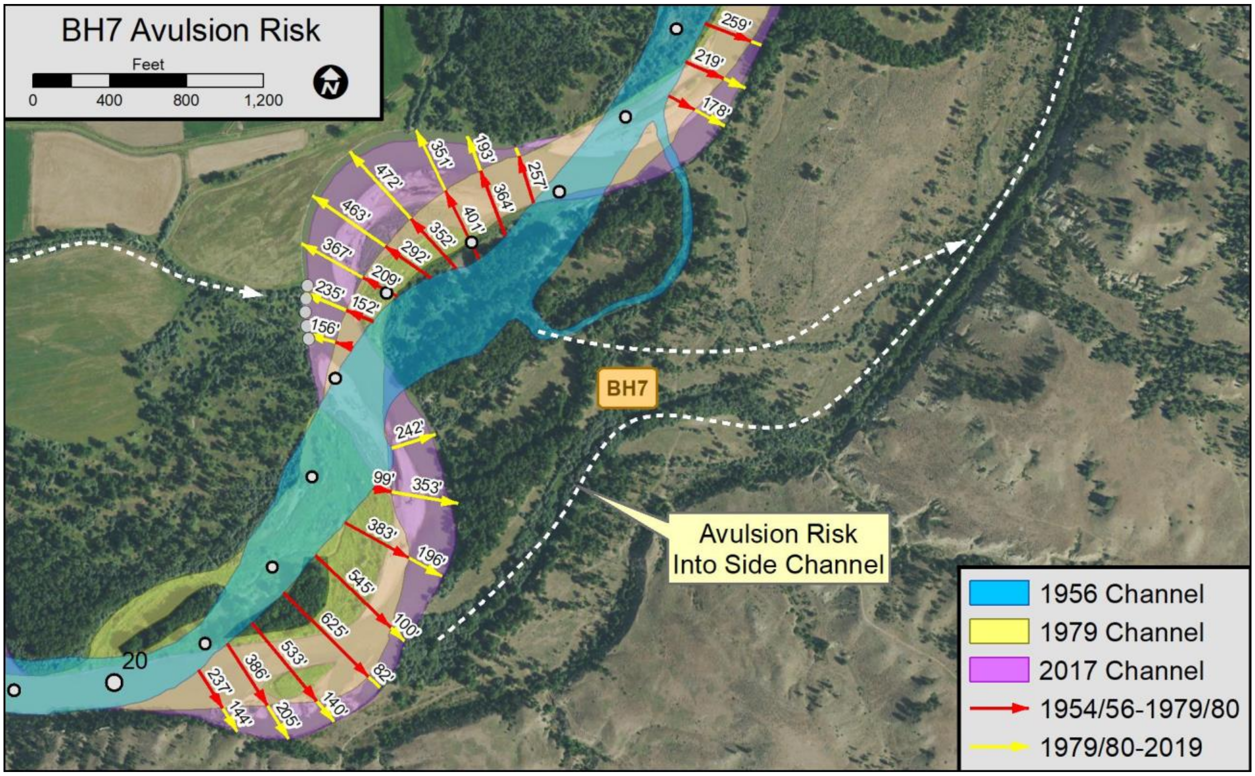


Figure 71. Migration into a long side channel at RM 20.8 creating a heightened risk of avulsion.

6 Considerations in CMZ Application

The following section contains a brief discussion of some ways to integrate the CMZ mapping into river management strategies.

6.1 CMZ Management and Stream Corridor Resiliency

The management of the river as a “corridor” is an important first application of CMZ mapping. Minimizing economic losses due to land loss, infrastructure failure, or bank armor loss should consider the following:

- Consolidate infrastructure where possible. For example, diversion headgates tend to function well below bridges, which taper the CMZ to the width of the bridge opening.
- Promote woody riparian growth in the corridor, to increase the resiliency of the floodplain during long floods that have the potential to scour floodplain channels and drive cutoffs.
- Place infrastructure such as pivot towers beyond the margins of the Erosion Hazard Area to reduce the need for near-term bank armoring.
- Carefully taper the CMZ to bridge openings using bank armor approaches that gradually narrow the stream corridor to the bridge opening.
- As possible, minimize bank armoring projects that run perpendicular to the axis of the CMZ. Any channel segments that trend across the CMZ (typically north/south) will have increased erosive pressure on the down-valley (east) side, as the armor is disrupting normal down-valley translation of bends. As such, these projects typically fail or require a higher level of maintenance than projects that trend on the edge of the CMZ in a direction parallel to the stream corridor axis.

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

6.2 Roads and Bridges

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

6.3 Development Pressures

In developing CMZ maps across Montana, it is always striking to see how many structures are at risk of damage due to bank erosion. In CMZ related public outreach meetings that we have held across the state for other projects, we have heard numerous testimonies in which landowners have described their anxiety over river movement and financial stresses of property protection. Bank armoring typically costs on the order of $90-$120 per linear foot of bank, so protection of structures on these rivers can easily cost over $100,000. Yet structures are still constructed close to actively migrating channels. We sincerely hope that this analysis will help landowners make cost-effective decisions in siting homes or irrigation structures. On the Big Hole River, for example, one landowner moved his house site 100 feet back from the top of a terrace edge based on the mapping; subsequent erosion of that terrace has proven that decision to be a major cost saving move.

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8 Appendix A: 11x17” CMZ Maps (Separate Document)