Karin Boyd, P.G.
Applied Geomorphology, Inc.
Specializing in Fluvial Geomorphology

211 N. Grand Ave.
Bozeman,MT 59715
(406) 587-6352

TECHNICAL MEMORANDUM

To: Mike Ruggles and Zach Shattuck, Montana Fish Wildlife and Parks

From: Applied Geomorphology and DTM Consulting, Inc.

Date: April 10, 2017

In Regards To: Musselshell River CMZ Pilot

1 Introduction

This technical memorandum describes the development of a draft Channel Migration Zone (CMZ) map for the portion of the Musselshell River through Roundup, MT, extending from above Naderman Diversion to near Kilby Butte, a distance of 34.4 river miles. The work was authorized under FWP Contract P17035.

Primary findings of this project include the following:

- Within the project reach the Musselshell River has been affected by early 20th century straightening with construction of the Milwaukee Road rail line, followed by the construction of cutoff trenches several decades later, and transportation corridor confinement.
- Major floods have driven channel response to these impacts, including rapid bank erosion and channel lengthening.
- Mean migration rates from 1953-2015 range from 2.1 feet per year to 3.7 feet per year on a reach scale.
- 100-year erosion buffer widths that define an Erosion Hazard Area range from 205 feet to 368 feet.
- Avulsions have occurred both due to floods and channel manipulation; 18 avulsions have occurred in the project reach since 1953 and numerous additional sites are currently avulsion-prone.
- Reach 2, which is located between Newton-Pedrazzi Dam and Kilby Butte appears the most geomorphically stable and resilient to flooding. It could potentially be used as a reference condition for other less stable channel segments.

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.

This effort reflects a limited pilot study for CMZ mapping on the Musselshell River. As the available resources focused on the mapping itself, the interpretations provided in this memo are necessarily brief, focusing on the mapping process and results. In the event the mapping and associated scope of effort are expanded, we would anticipate that resources would allow us to provide a more comprehensive interpretation of Musselshell River dynamics and associated management implications. If the reader is interested in additional relevant information about the Musselshell River, we recommend you review the final report by the River Assessment Triage Team (RATT), which describes the 2011 flood in detail (Boyd and others, 2012). A series of best management practices developed by RATT team members may also be of interest, and these practices can be obtained by the Musselshell Watershed Coalition.

1.1 Channel Migration Zone Mapping

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

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

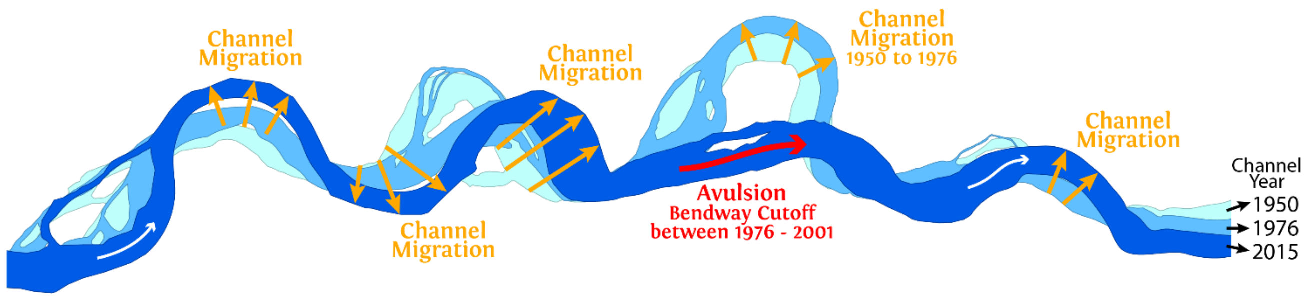

Figure 1. Typical patterns of channel migration and avulsion evaluated in CMZ development.

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

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

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

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

- Historic Migration Zone (HMZ) – the area of historic channel occupation, usually defined by the available photographic record.
- Erosion Hazard Area (EHA) – the area outside the HMZ susceptible to channel occupation due to channel migration.
- Avulsion Hazard Zone (AHZ) – floodplain areas geomorphically susceptible to abrupt channel relocation.

- Restricted Migration Area (RMA)-- areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features. The RMA has been referred to in other studies as the DMA- Disconnected Migration Area.

The individual map units comprising the CMZ are as follows:

CMZ = HMZ + EHA + AHZ

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

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

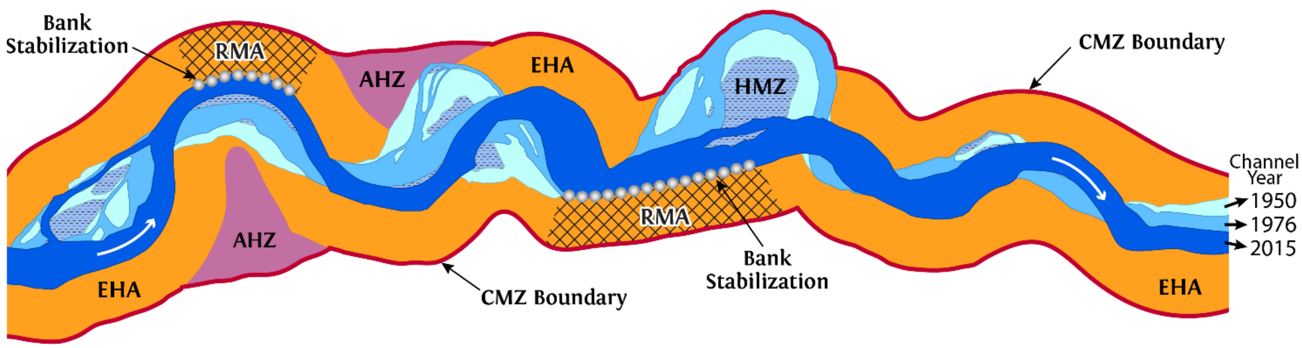

Figure 2. Channel Migration Zone mapping units.

2 Methods

The following sections describe the methods used in developing the pilot study CMZ maps.

2.1 Aerial Photography

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

Several imagery sources are available for the Musselshell River in the Roundup study area. The most recent sources, starting in the 1990s with the black-and-white Digital Orthophoto Quad imagery (DOQ) and continuing through the current NAIP (National Agriculture Imagery Program) imagery, are freely available in GIS-compatible format. The quality of these images, both spatially and resolution, ranges from good to excellent and they cover the entire project area.

Imagery older than 1995 must be acquired from various archival services as digital scans, and then mosaiced into a single spatially-referenced image for use in the GIS. For this project, the historic imagery scans were either downloaded from the United States Geological Survey (USGS) Earth Explorer archives or ordered from the United States Department of Agriculture (USDA) Air Photo Field Office (APFO) in Salt Lake City, Utah. The earliest readily available imagery is the 1953 USGS data set. This included eight images that provided the required stereo coverage. A 1979 photo series was available from the USDA archives, consisting of eleven images providing stereo coverage.

The high-resolution scans were then orthorecitified by Aerial Services, Inc. (ASI) in Cedar Falls, Iowa, using 2015 NAIP imagery as the spatial reference, providing identifiable ground control points. The resulting mosaics were assessed for spatial accuracy using National Spatial Data Accuracy standards, and reviewed for image quality.

Table 1 lists imagery used for this project from the USGS, USDA, and archives of current GIS data sets.

Table 1. Aerial photography used for the Musselshell River Roundup study area CMZ mapping study.

Date	Source	Scale	Notes
1953	USGS	~1:40,000	High-resolution Scans (black-and-white)
1979	USDA	~1:20,000	High-resolution Scans (black-and-white).
1996	DOQ	~3 meter resolution	GIS Image Service provided by the Montana State Library
2011 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)
2015 NAIP	NRIS	~ 1 meter resolution	Digital Download, Compressed County Mosaics (color)

2.2 GIS Project Development

All project data was compiled using ESRI's ArcMap Geographic Information System (GIS) utilizing a common coordinate system - Montana State Plane NAD83 Meters. The orthorectified air photos provide the basis for CMZ mapping. Other existing datasets that were compiled for the Musselshell River Watershed Plan (Boyd & Thatcher, 2015). New data sets were generated for the CMZ mapping and are described in further sections.

2.3 Bankline Mapping

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

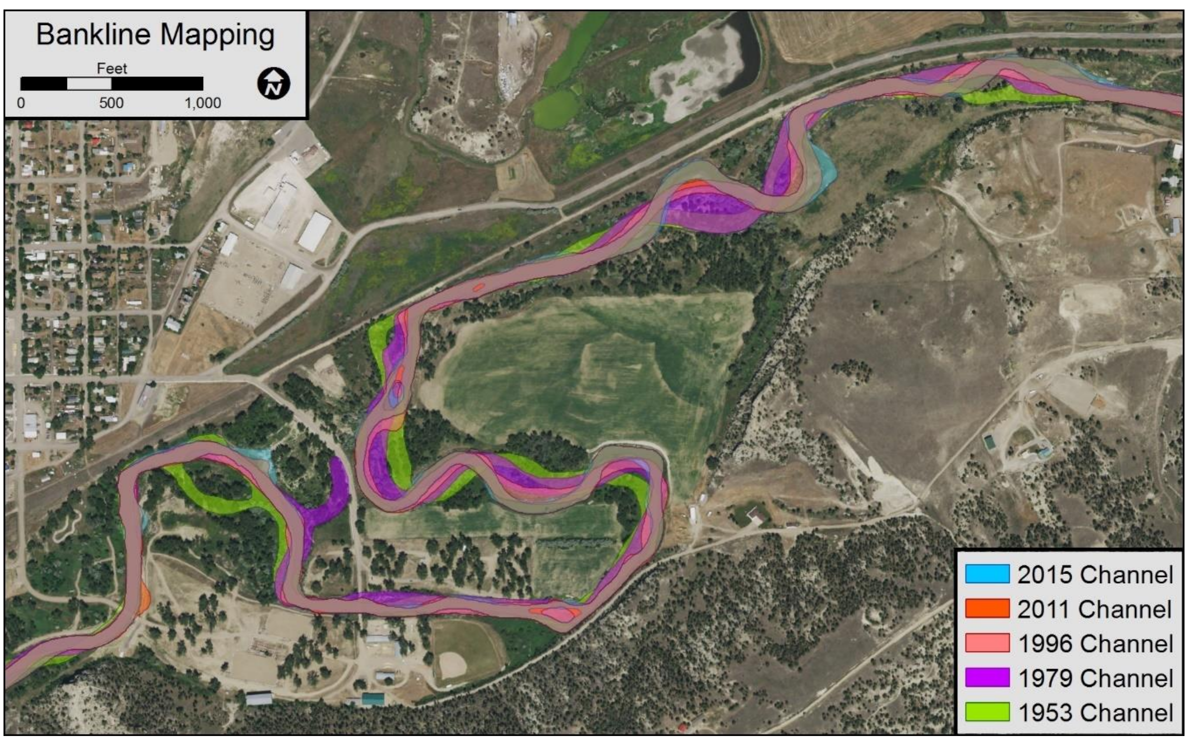

Figure 3. Historic bankline mapping.

2.4 Migration Rate Measurements

Once the historic banklines were completed, the banklines were evaluated in terms of discernable channel migration since 1953. 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 100 feet. A total of 634 migration vectors were generated for the Musselshell River at a scale of 1:2,000. These measurements were then summarized by reach. The results were then used to define a reach-scale erosion buffer width to allow for likely future erosion.

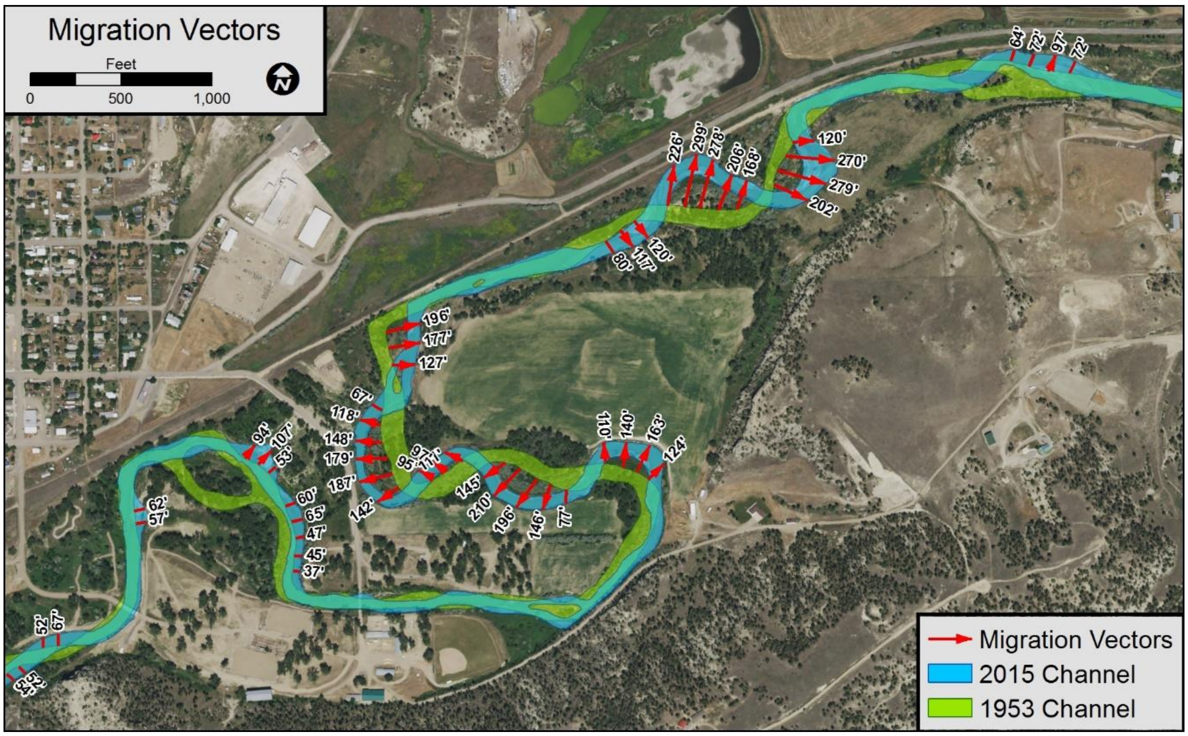

Figure 4. Migration rate measurements.

2.5 Avulsion Hazard Mapping

Avulsion hazards can be difficult to identify on broad floodplains, because an avulsion could occur virtually anywhere on the entire floodplain if the right conditions were to occur. As such, avulsion pathways were identified and mapped using criteria that identify a relatively high propensity for such an event. These criteria usually include the identification of high slope ratios between the floodplain and channel, perched channel segments, and the presence of relic channels that concentrate flow during floods. These features were identified for the Musselshell River project reach using aerial photos and LiDAR data Figure 5.

Features that can help determine avulsion hazard areas include:

- Low, frequently flooded floodplain areas with relic channels
- Compressed meander-bends

- Main channel aggradation in the upstream limb of a bend
- Lower elevation of relict channel than active channel bed
- Creeks that run somewhat parallel to main channel.

Potential avulsion pathways were identified and incorporated into the CMZ.

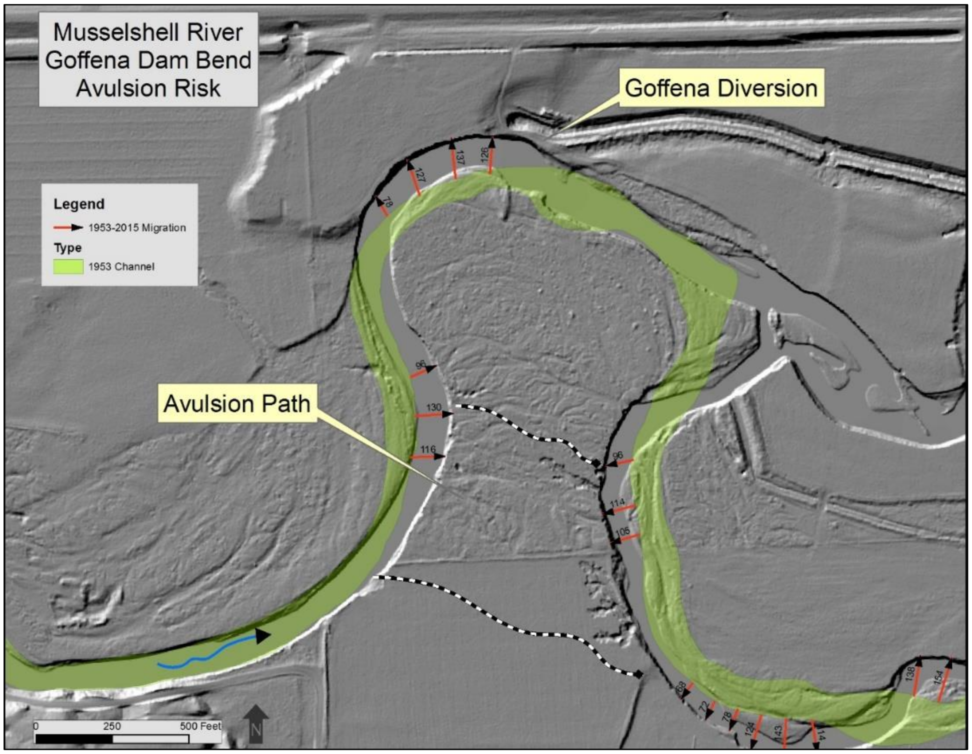

Figure 5. Example avulsion path through bendway core at Goffena Diversion.

3 Results

The following section describes the primary results of the mapping process. The maps are contained in Appendix A.

3.1 Project Reaches

The project was divided into six reaches based on overall geomorphic character (Table 2 and Figure 6). The reaches are largely defined by degree of confinement due to the bedrock valley wall and/or transportation lines, and the overall planform of the river. Figure 7 shows that reaches lose gradient in the downstream direction, and much of this is due to an increase in channel sinuosity (Figure 8).

Table 2. Musselshell River Project Reaches.

Reach	Start RM	End RM	Length (miles)	Location	Comments
Roundup 06	197.1	193	4.1	Two miles above Kinsey Diversion to one mile below Naderman Diversion	Locally tightly confined by old rail line. Several old meanders isolated north of the rail line. Post-2011 armor common.
Roundup 05	193	189.3	3.7	Below Naderman Diversion to Goulding Creek Road	Valley bottom widens as railroad grade shifts to north side of valley. Migration rates increase with river pulling migrating off south valley wall into large meanders. Bank armoring common. Numerous avulsions 1953-1979. Two 2011 avulsions.
Roundup 04	189.3	183.1	6.2	Goulding Creek Road to just below Highway 87 Bridge	Anomalously straight channel follows south valley wall for ~2 miles to Eliason Dam, then shifts to north side of valley to closely follow old railroad grade/highway.
Roundup 03	183.1	176.3	6.8	Below Highway 87 bridge to bedrock constriction about one mile below Newton-Pedrazzi Dam	Main roundup reach. Two high amplitude bendways prone to cutoff. Extensive armor and infrastructure. Two major constrictions formed between bedrock and transportation infrastructure.
Roundup 02	176.3	170.2	6.1	Below Newton-Pedrazzi Dam to constriction at RM 170.2	Low confinement in wide meanderbelt; low migration rates.
Roundup 01	170.2	162.5	7.7	To Kilby Butte	Low confinement; relatively high migration rates in open bendways. Several avulsions post-1953.

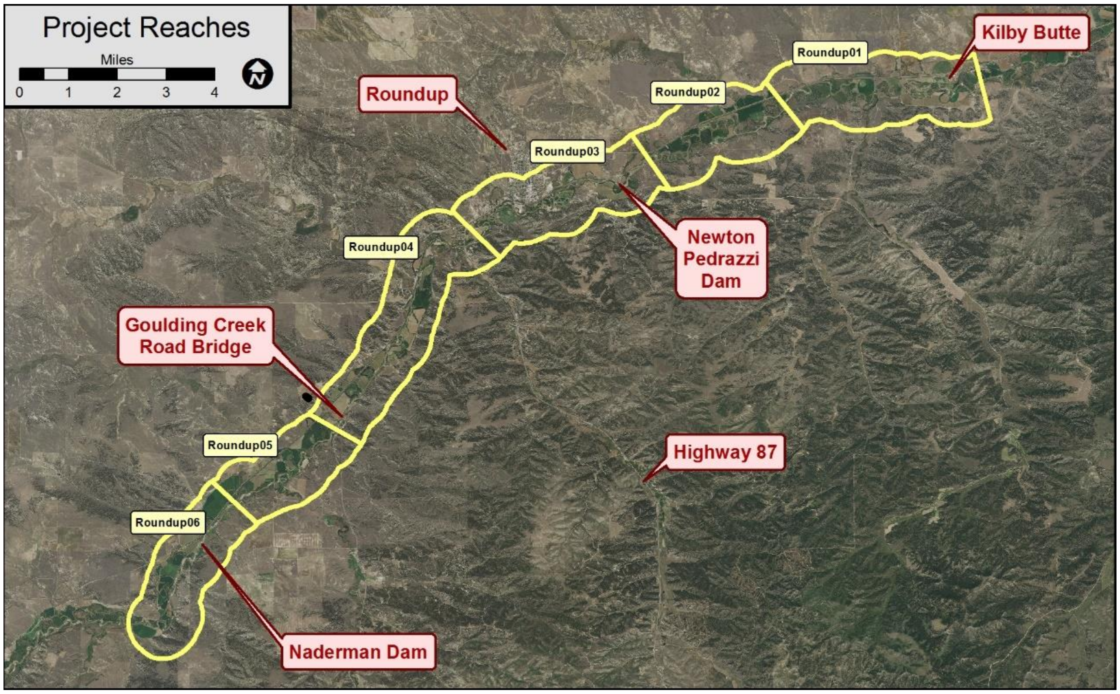

Figure 6. Musselshell River project reaches for pilot CMZ assessment.

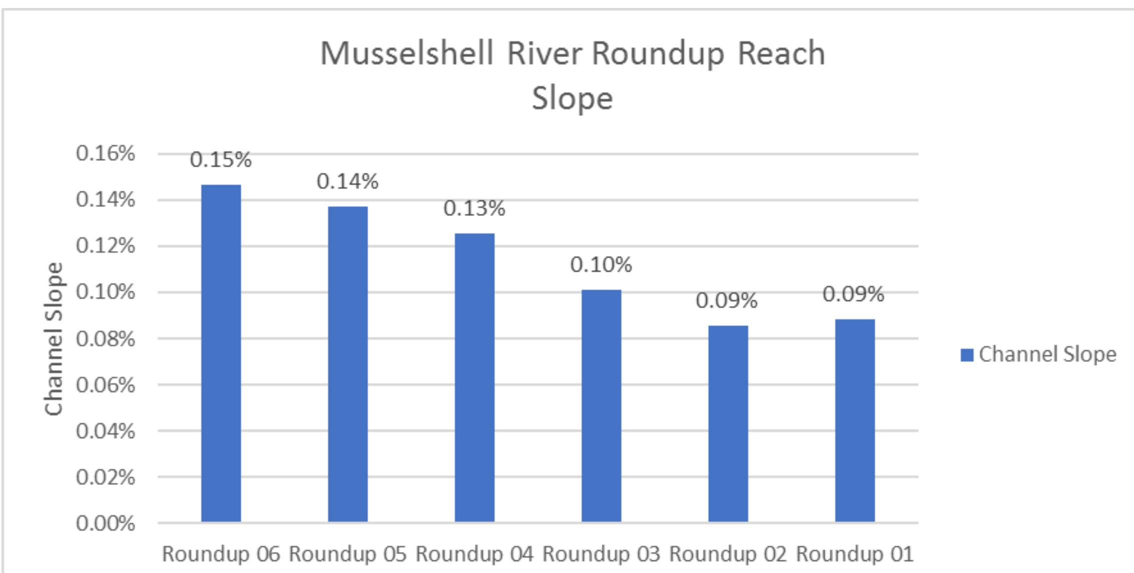

Figure 7. Average channel slope for each reach plotted upstream (left) to downstream (right).

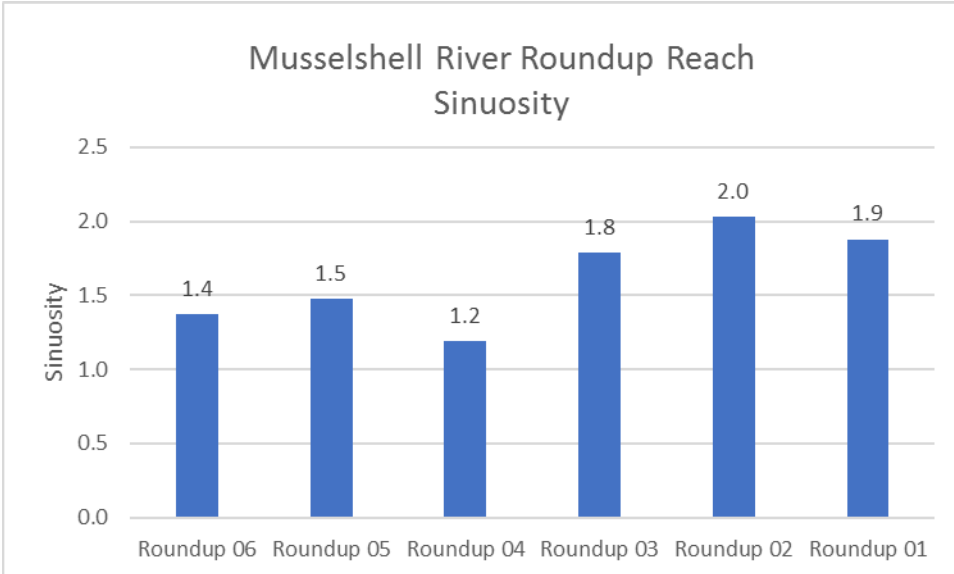

Figure 8. Project reach channel sinuosity plotted upstream (left) to downstream (right).

3.2 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 1953-2015. In some settings where island areas are non-erodible, it may be appropriate to exclude these features from the CMZ. In the case of the Musselshell 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 1953 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 Musselshell River channel locations in 1953, 1979, 1996, 2011 and 2015 (Figure 9). The resulting area reflects 62 years of channel occupation for the Roundup study area of the Musselshell River (Figure 10).

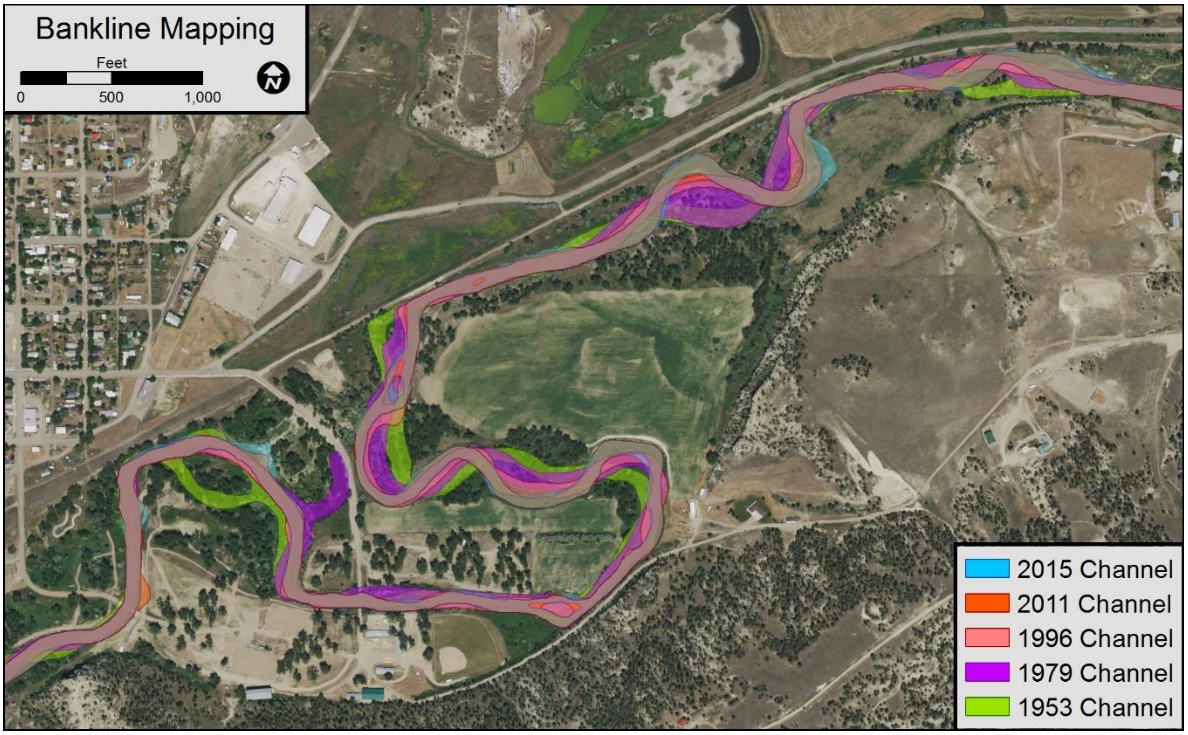

Figure 9. All mapped channel locations.

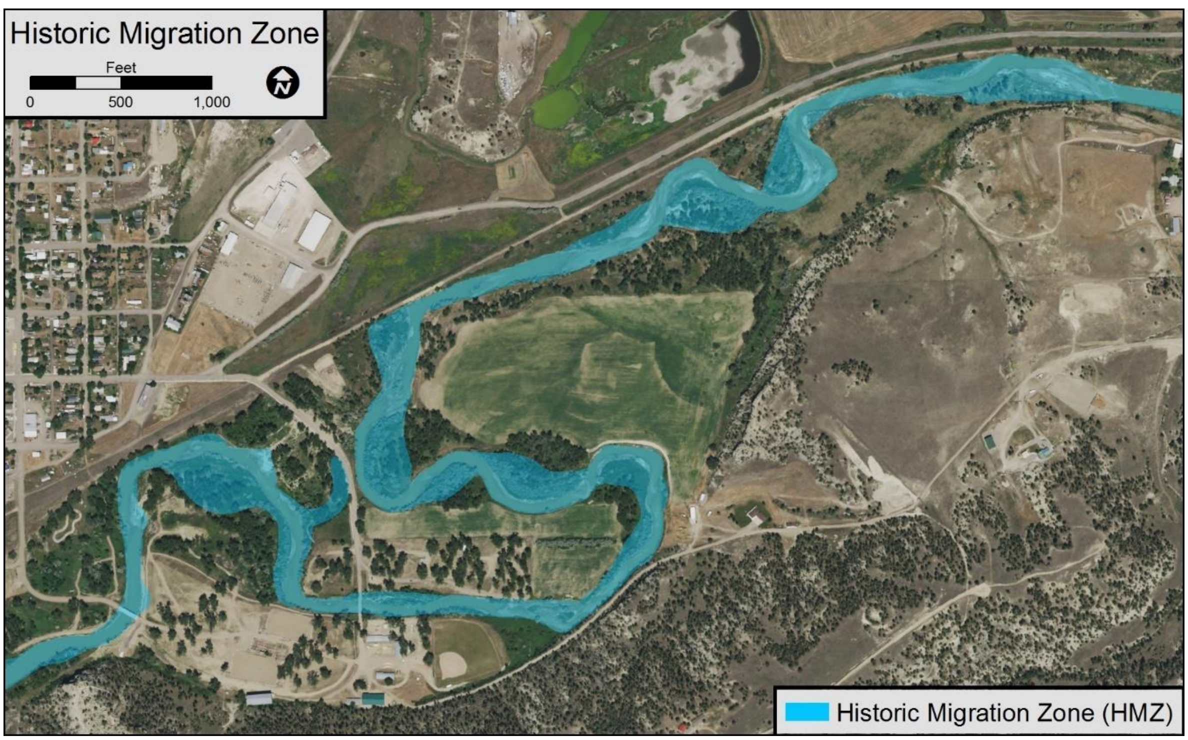

Figure 10. Historic Migration Zone.

3.3 The Erosion Hazard Area (EHA)

The Erosion Hazard Area (EHA) is based on mean migration rates, which are derived from measured migration distances. Migration distances were measured where it was clear that the channel movement was progressive lateral movement and not an avulsion. A total of 634 measurements were collected in the Roundup study area. The minimum distance measured is 37 feet. These measurements are summarized by reach to define mean migration rates specific to a given section of river. That rate is then extrapolated to 100-years to define the width of the Erosion Buffer, which is attached to the 2015 banklines, defining the Erosion Hazard Area (EHA). The Erosion Buffer width values range from just over 200 feet in Reach 2 below Newton-Pedrazzi Diversion Dam to 368 feet upstream in Reach 5 above Goulding Creek Road Bridge (Figure 12).

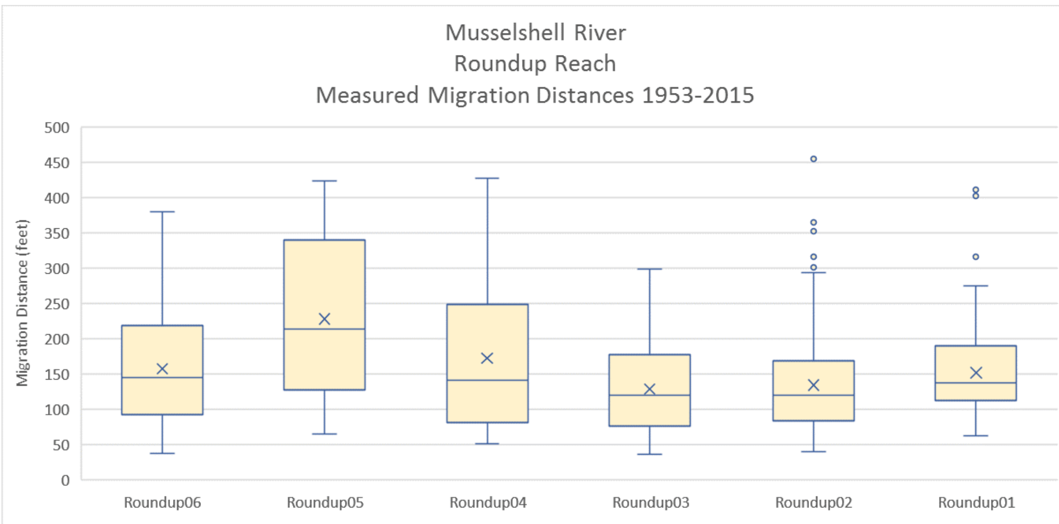

Figure 11. Measured migration distances by reach.

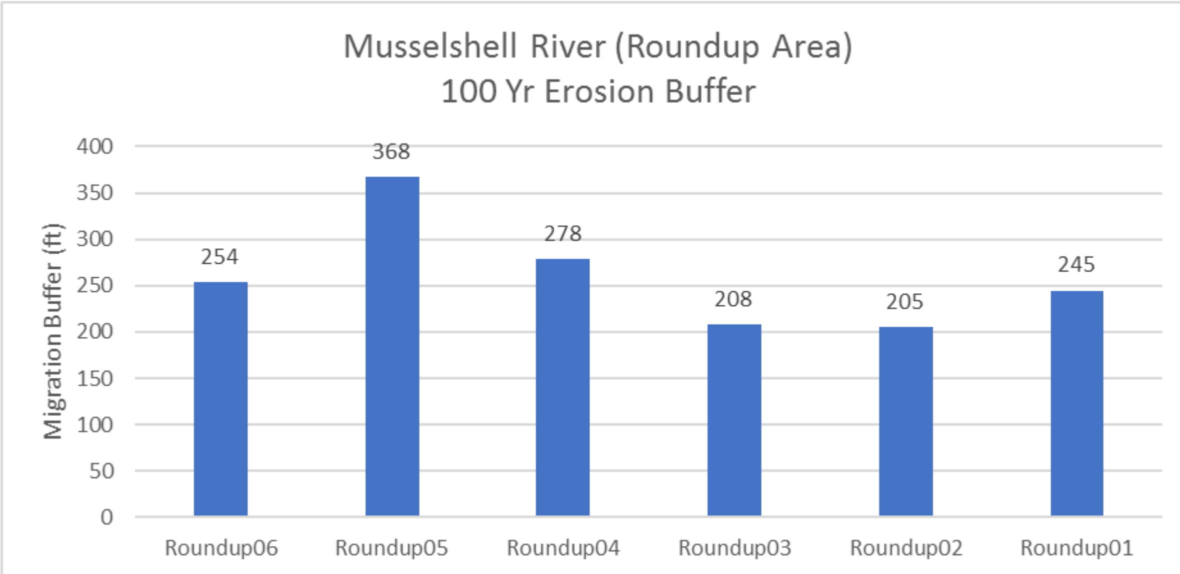

Figure 12. Erosion Hazard Area buffer widths by reach.

As the location and intensity of streambank erosion shifts with time, many streambanks that are currently stable will become erosion sites over the next century. Shifts in erosion patterns can sometimes be predicted in the short-term, however over decades the entire bankline becomes a potential erosion site. As such, the erosion buffer is assigned to all banks, even those not currently eroding, to allow future bank movement at any given location. This is consistent with the Reach Scale approach outlined by the Washington Department of Ecology(www.ecy.wa.gov). 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 13. 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.

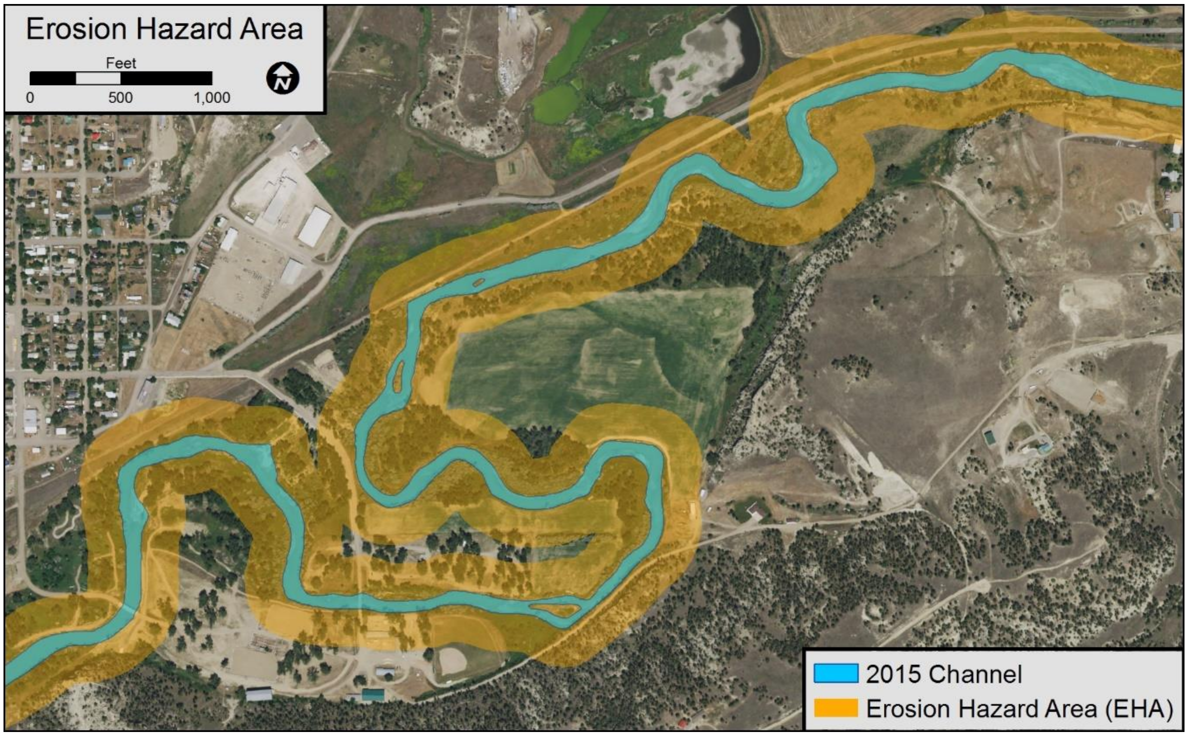

Figure 13. Erosion Hazard Area.

3.4 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). Avulsions are not uncommon on the Musselshell River, and avulsions were one of the most dramatic impacts of the 2011 flood. During that event, a total of 59 avulsions occurred over a three week period along the entire river, abandoning almost 40 miles of channel. The abandoned channels ranged in length from a few hundred feet to several miles.

Figure 14 shows that a total of 18 avulsions were mapped in the project reach between 1953 and the 2011 flood. Reach 5 and Reach 1 had the highest concentration of avulsions, and those avulsions are reflected in the total change in channel length in the reach. Since 1953, Reach 5 has shortened by 20% and Reach 1 shortened by 12% (below). Over the entire project the river lost about 2.14 miles of channel length since 1953, or about 6% of the total length.

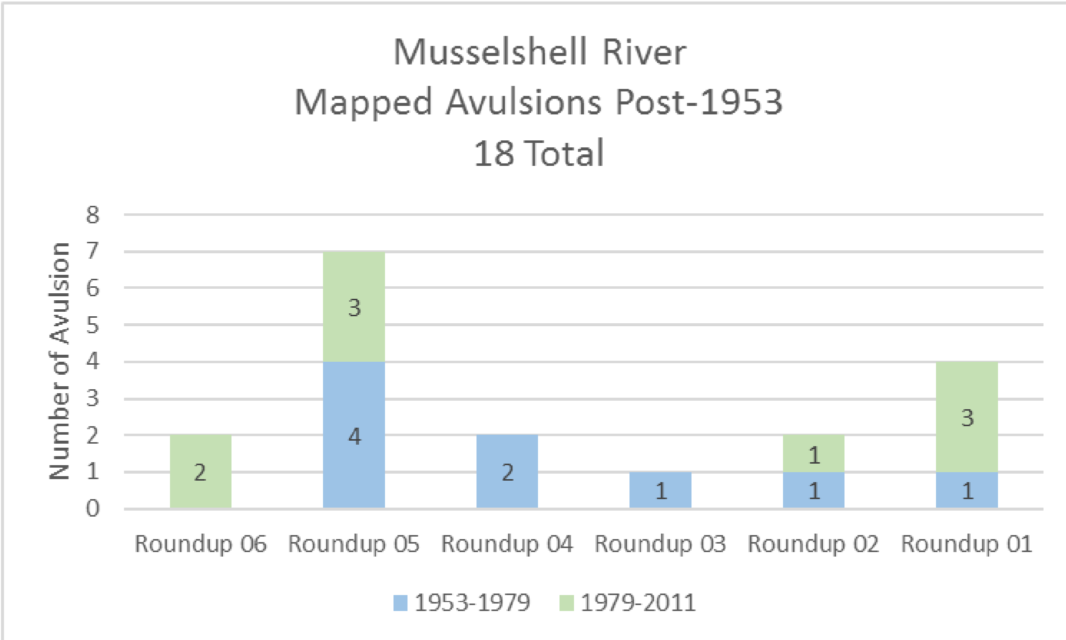

Figure 14. Number of mapped avulsions by reach.

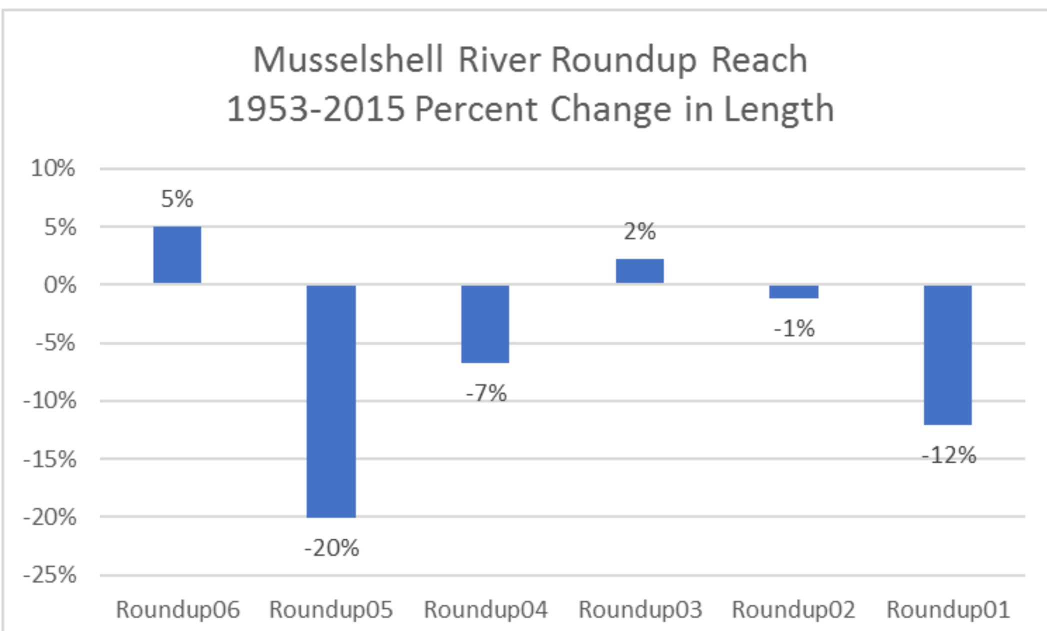

Figure 15. Percent change in channel length 1953-2015.

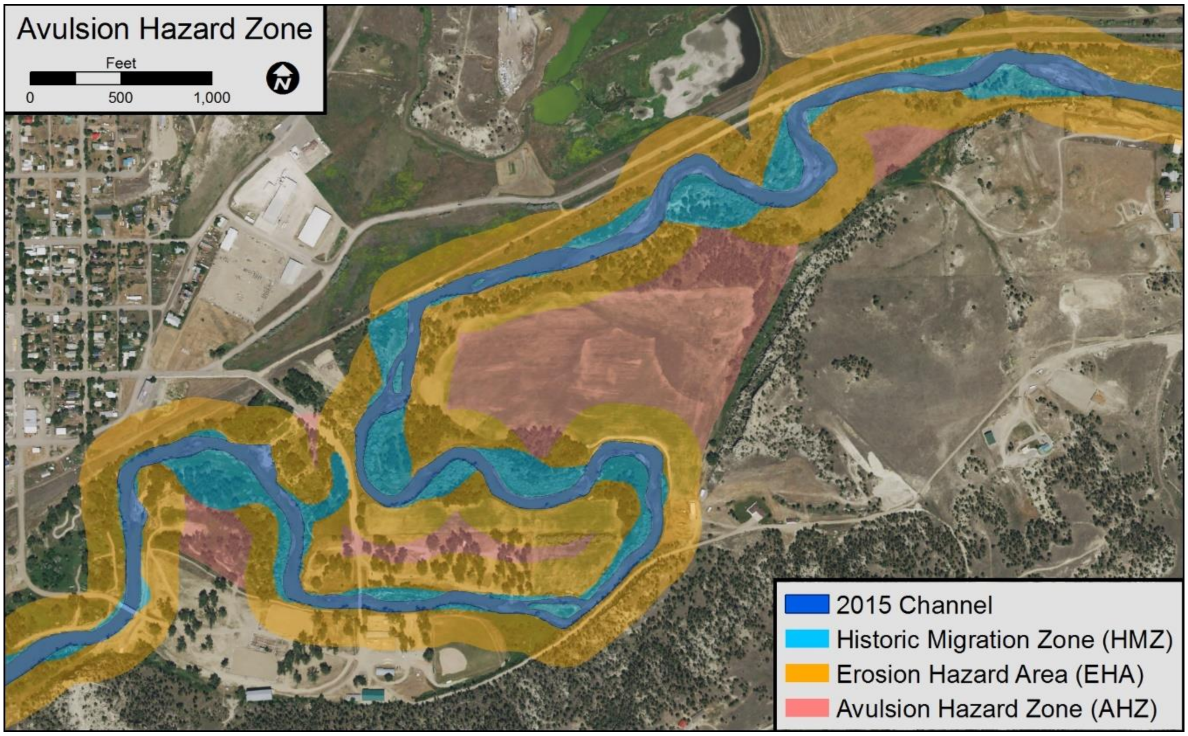

Figure 16. Avulsion hazard mapping.

3.5 The Restricted Migration Area (RMA)

The extent of migration area that is restricted by physical features is largely dependent on the extent and locations of mapped bank armor and transportation infrastructure. For this project armor was mapped using available imagery and other sources such as Google Earth. The mapped extents are probably conservative as older armor tends to be difficult to see on air photos. Transportation was also identified as a major cause of CMZ restriction and these areas were mapped and specifically attributed as railroad or road prism.

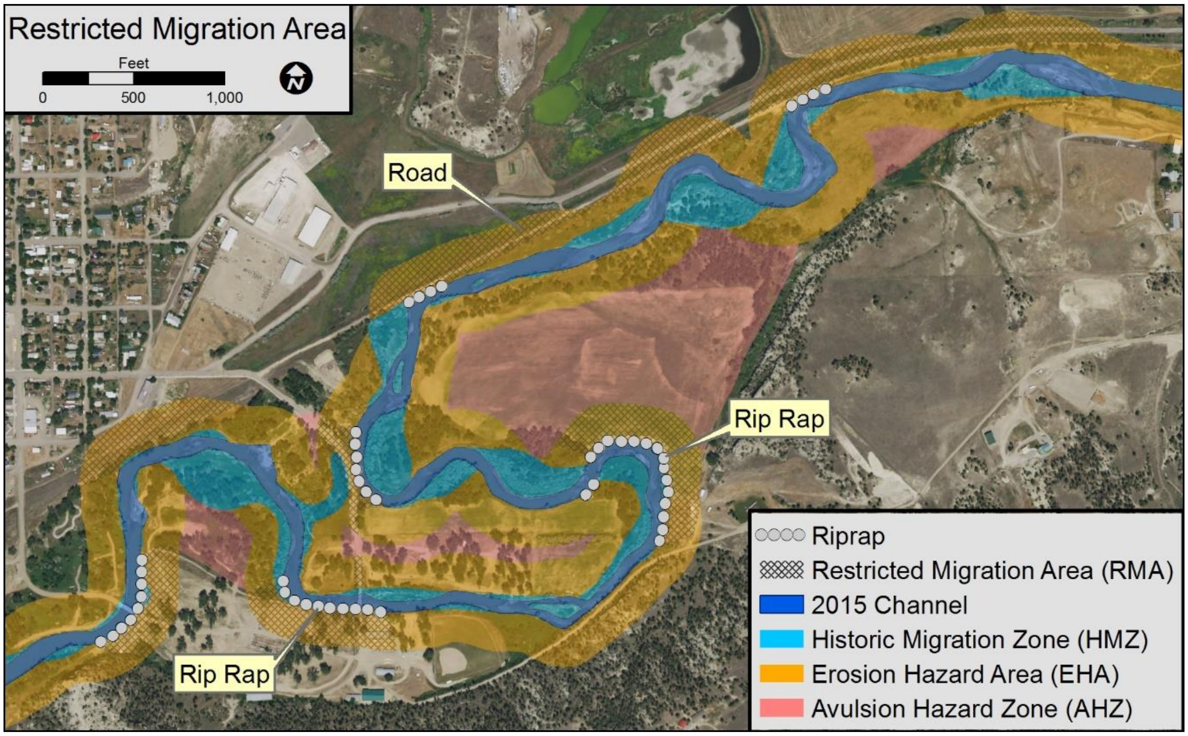

Figure 17. Restricted Migration Area mapping.

3.6 Composite Map

An example portion of a composite CMZ map for a section of the Musselshell River project area is shown in Figure 18. Each individual mapping unit developed for the CMZ has its own symbology, so that any area within the overall boundary can be identified in terms of its basis for inclusion.

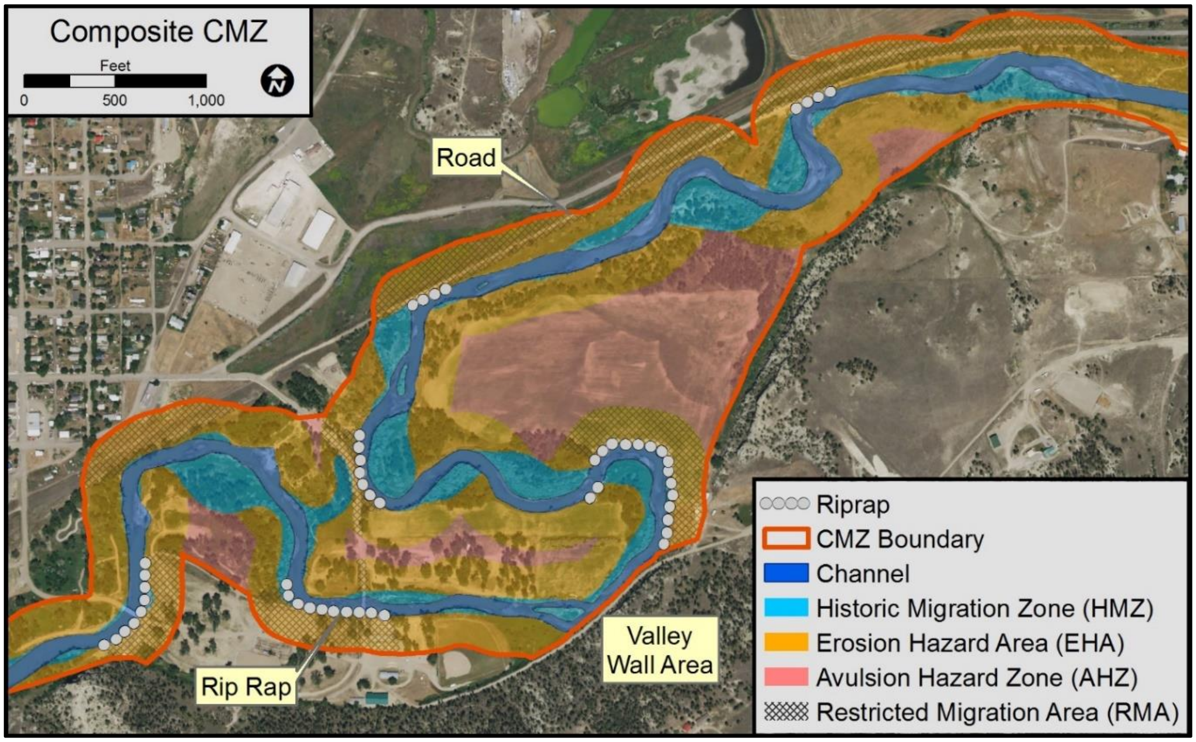

Figure 18. Composite Channel Migration Zone map.

3.7 Geologic Controls on Migration Rate

The banks of the Musselshell River are in many locations composed of erodible materials deposited by the stream itself. On the south side of valley, however, the river commonly flows against a high valley wall that is formed by the Tongue River Member of the Fort Union Formation. This 65 million year old unit is made up of sandstone, shale, and coal. Sandstones are most commonly exposed, although coal seams are not uncommon. As many as 32 coal seams have been mapped in the unit across Wyoming and Montana.

Many CMZ mapping efforts incorporate a Geotechnical Setback on valley walls, which is an area of expanded Erosion Hazard Area (EHA) against geologic units that may be prone to geotechnical failure such as landslides, slumps, or rockslides. There are no mapped active landslides against the river, which suggests that the CMZ will not likely be altered by hillslope failure. 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 Reach Descriptions

The following sections describe each reach of the Musselshell River. The reaches are numbered sequentially from the downstream end of the project. To best describe the trends in geomorphology and mapping results, they are described below in the opposite order, starting with Reach 6 at Naderman Diversion and ending with Reach 1 at Kilby Butte. The maps can be found in Appendix A.

Note: All references to River Miles (RMs) reflect the distance upstream from the river mouth along the post-flood 2011 channel centerline. River Miles are labeled on the maps in Appendix A. Wherever streambanks or floodplain areas are described as "right" or "left", that refers to the side of the river as viewed in the downstream direction. For example, "RM 6.4R" refers to the right streambank located 6.4 miles upstream of the river's mouth.

4.1 Reach Roundup 06

Roundup06		
Two miles above Kinsey Diversion to one mile below Naderman Diversion		
Upstream/Downstream RM	170.2	162.5
Length (miles)	7.7	
Mean Migration Rate (ft/yr)	2.5	
Max 60-year Migration Distance (ft)	380	
100-year Buffer (ft)	253.9	

Reach 6 extends almost eight miles from above Kinsey Diversion to below Naderman Dam, which was flanked by an avulsion during the 2011 flood. The maximum migration distance measured between 1953 and 2015 is 380 feet, and the 100-year buffer width is 254 feet.
Reach 6 is the steepest channel in the project area with a mean channel slope of 0.15%. The river is confined between the historic Milwaukee Rail line to the west and the right valley wall sandstones to the east. About a half mile upstream of Naderman Diversion Dam is a good example of a Milwaukee Road cutoff project, which has active channel lengthening back towards the abandoned meander. About 0.8 miles of channel was cut off by the rail line in the early 20th century, and since that time the river has migrated almost 280 feet northward back towards the abandoned meander, breaching the rail grade over about 800 feet of its length (Figure 18 and Figure 19). Most of that migration occurred during the 2011 flood, and the breach has since been armored.

The lower mile of Reach 6, below the flanked Naderman Diversion Dam at Elso, is tightly confined between the rail line/highway and the sandstone bluffs. In this area the channel has migrated northward hundreds of feet since 1953, and this movement will continue to threaten the rail grade and highway into the future.

Two avulsions were mapped in the Reach 6, one of which flanked and abandoned the Naderman Diversion Dam (Figure 21). There are two bendways in the upper part of Reach 6 that appear prone to cutoff in coming decades.

The three large meanders that were cut off by the Milwaukee Road are not included in the Historic Migration Zone because the change occurred prior to 1953.

Figure 19. View upstream of northward migration through Milwaukee Road, RM 194.8. Photo taken on Sept 20, 1012 (Kestrel).

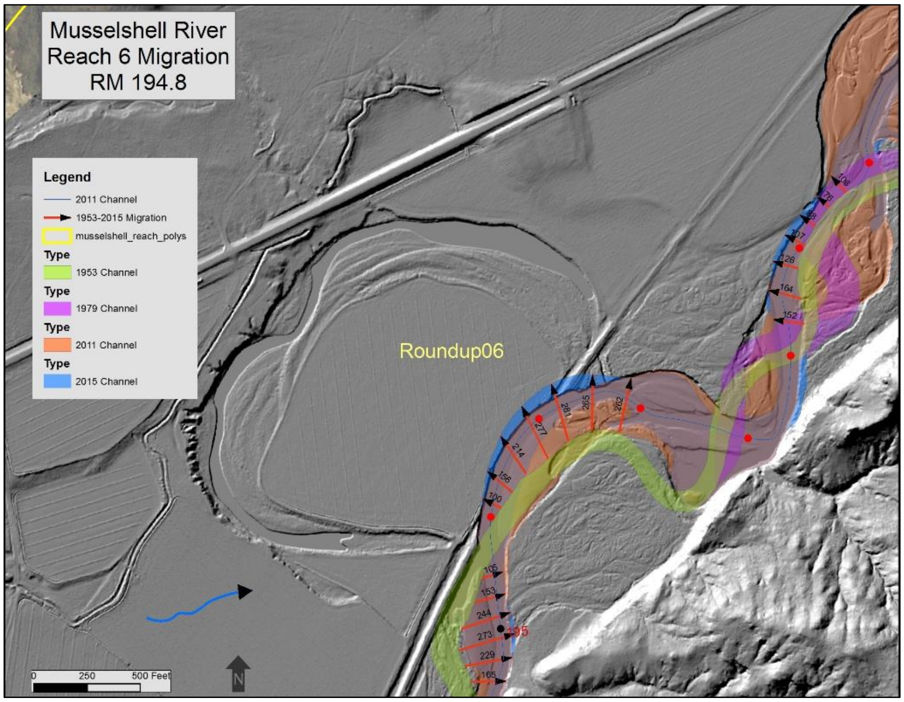

Figure 20. Northwest channel migration towards historic railroad cutoff showing 2011 rail grade breach.

Figure 21. Naderman Dam 2011 avulsion, RM 194.2 (Sept 20, 2012—Kestrel).

4.2 Reach Roundup 05

Roundup05		
Below Naderman Diversion to Goulding Creek Road		
Upstream/Downstream RM	176.3	170.2
Length (miles)	6.1	
Mean Migration Rate (ft/yr)	3.7	
Max 60-year Migration Distance (ft)	423	
100-year Buffer (ft)	368	

Reach 5 extends from below the Naderman Dam to near the Goulding Creek Road Bridge. The reach is about 6 miles long, and the maximum migration distance measured between 1953 and 2015 is 423 feet. The 100-year EHA buffer width is 367 feet.

Reach 5 is much less confined than Reach 6 upstream, mainly because the rail line and highway both cross the river valley and expand the corridor (Figure 22). Reach 5 has the highest mean migration rate in the project reach, and the 368 foot-wide erosion hazard buffer is the largest as a result.

Reach 5 has had seven avulsions since 1954, with four occurring prior to 1979 and another three since. Reach 5 has lost almost a mile of channel length since 1953, or 20% of its total length. It is clearly a dynamic river segment with active meander formation and cutoff. There is no evidence that these cutoffs were engineered.

Figure 22. View downstream showing Musselshell River following south valley wall (Sept 20, 2012—Kestrel).

4.3 Reach Roundup 04

Reach 4 extends from below Goulding Creek Road to just below the Highway 89 Bridge. The reach is almost 7 miles long, and the maximum migration distance measured between 1953 and 2015 is 427 feet. The 100-year EHA buffer width is 278 feet.

Roundup04		
Goulding Creek Road to just below Highway 87 Bridge		
Upstream/Downstream RM	183.1	176.3
Length (miles)	6.8	
Mean Migration Rate (ft/yr)	2.8	
Max 60-year Migration Distance (ft)	427	
100-year Buffer (ft)	278	

Reach 4 is the straightest reach in the project area, with a sinuosity of 1.2 (the channel length is 1.2 times the straight valley distance). Numerous floodplain meander scars record a much longer channel length, on both sides of the highway/rail line (Figure 23).

At RM 188.4 there is a good example of a deliberate bendway cutoff between 1953 and 1979 that was achieved by excavating a pilot trench through the bendway core that eventually captured the main river channel (Figure 24 and Figure 25). This resulted in the loss of almost a mile of channel length. The bankline upstream of this man-made cutoff is now intensively armored (Figure 26).

Figure 23. View upstream of Eliason Diversion Dam on June 16, 2011 showing historic channel remnants both within active corridor and beyond highway (Kestrel).

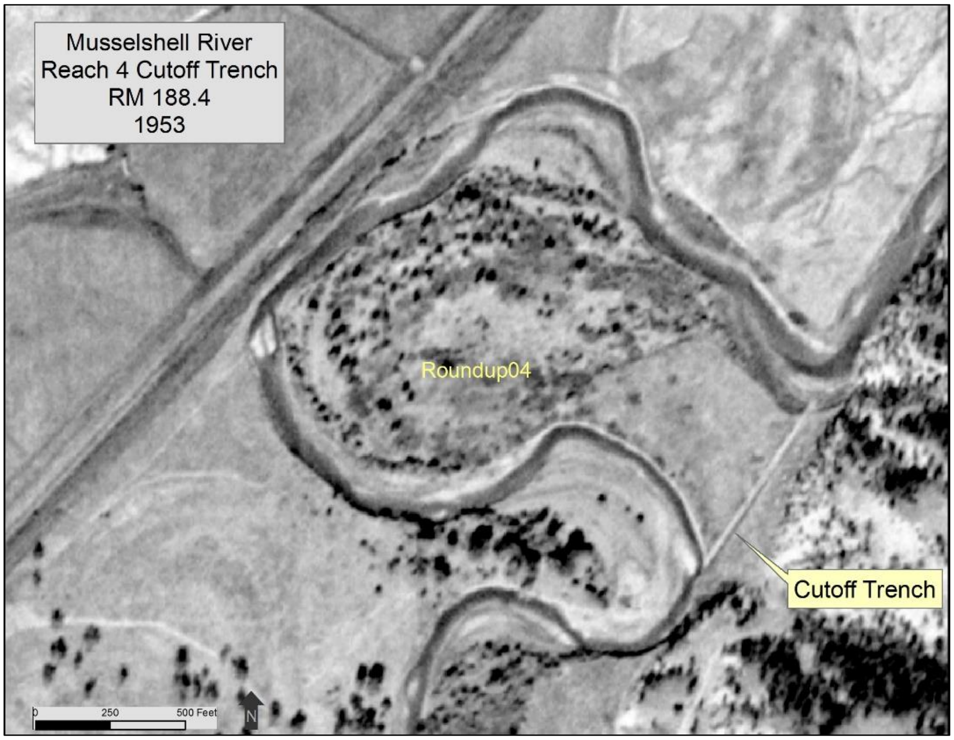

Figure 24. 1953 image at RM 188.4 showing cutoff trench excavated through meander core.

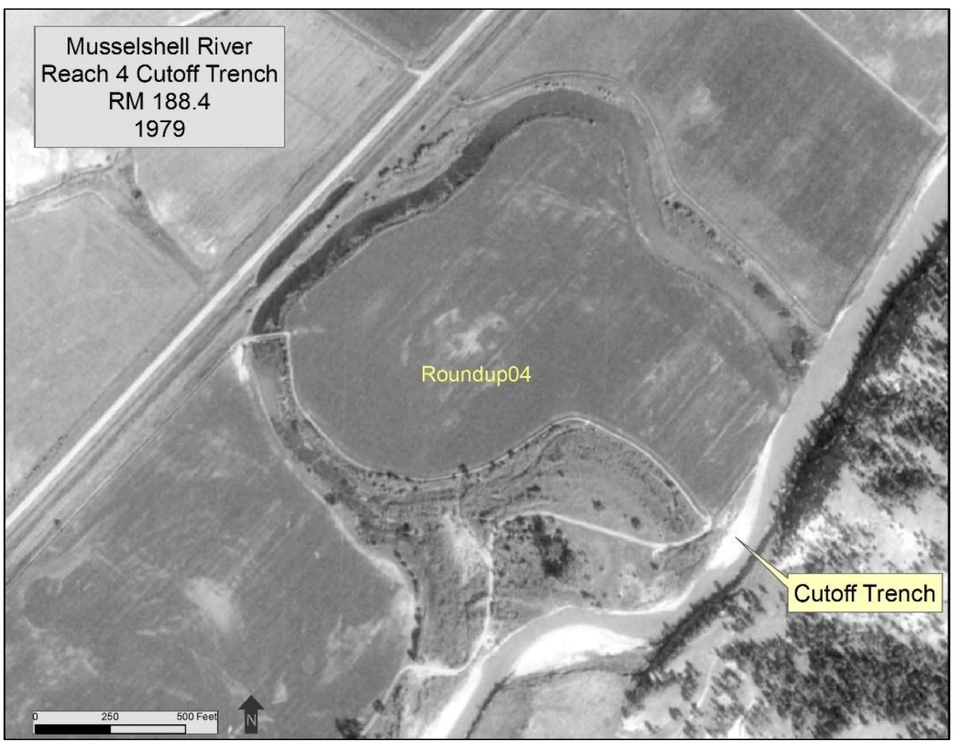

Figure 25. 1979 image at RM 188.4 showing trench capture of main river channel.

Figure 26. View downstream showing left bank armoring just below Goulding Creek Road Bridge (Sept 20, 2012, Kestrel).

4.4 Reach Roundup 03

Roundup03		
Below Highway 87 bridge to bedrock constriction about one mile below Newton-Pedrazzi Dam		
Upstream/Downstream RM	189.3	183.1
Length (miles)	6.2	
Mean Migration Rate (ft/yr)	2.1	
Max 60-year Migration Distance (ft)	299	
100-year Buffer (ft)	208	

Reach 4 extends from below the Highway 89 Bridge through Roundup to a bedrock constriction downstream of the Newton-Pedrazzi Dam. The reach is just over 6 miles long, and the maximum migration distance measured between 1953 and 2015 is 299 feet. The 100-year EHA buffer width is 208 feet.

Migration rates in Reach 3 are relatively low as compared to the remaining project area. One area with fairly high rates of movement is in the upstream portion of the reach near Timberline Drive, where a bendway is rapidly compressing towards cutoff (Figure 27). A cross section through the avulsion path shows that the slope through a cutoff is over 1%, whereas the existing channel slope is approximately 0.07%. This indicates that relative to the rest of the river, the channel is overlengthened through this bend and a cutoff in the near future is likely.

Another tight bendway at the fairgrounds actually did cut off between 1953 and 1979; the access road to the fairgrounds was rebuilt through the cutoff and several of the banks in this section of river have been armored to maintain overall planform (Figure 29 through Figure 31). The slope discrepancy between the avulsion path and existing channel course is very similar to the bend at Timberline Drive.

Also notable in Reach 3 are two constrictions formed by bedrock and transportation infrastructure, one of which is just upstream of Roundup, where a high bedrock shelf juts into the stream corridor. Historically, the river flowed north of this bedrock in an area now isolated by development (Figure 32 and Figure 33). The second constriction is located downstream just above Number Four Road.

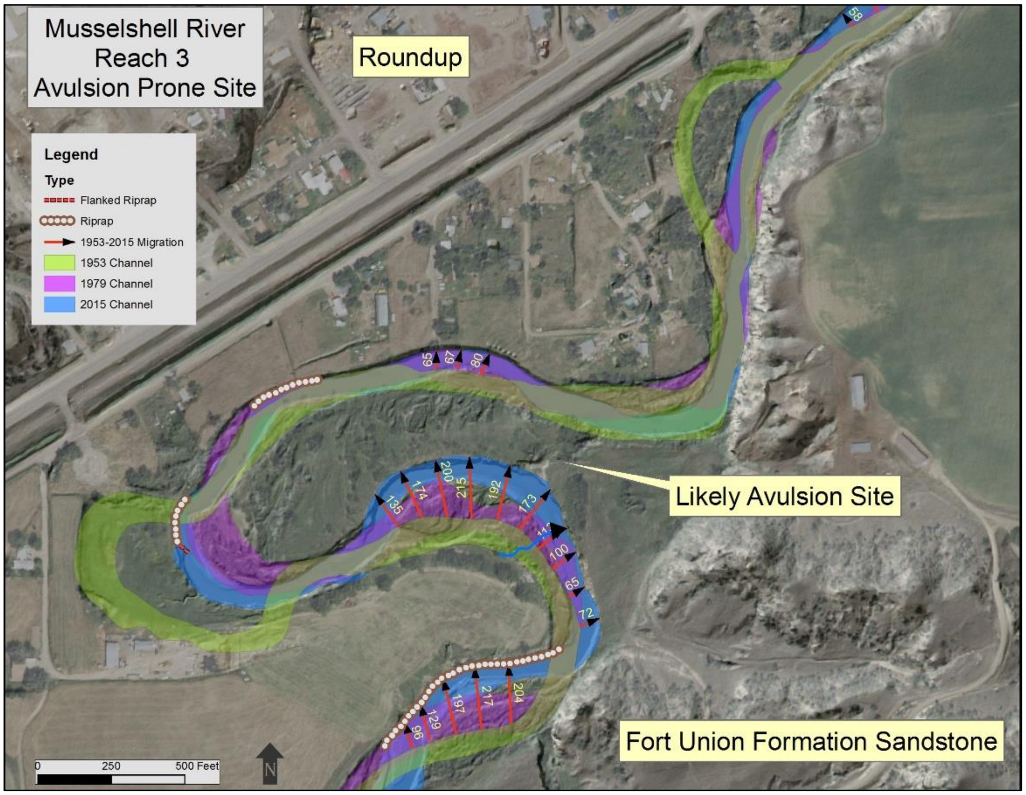

Figure 27. LiDAR overlain on 2015 imagery showing likely avulsion site near Roundup.

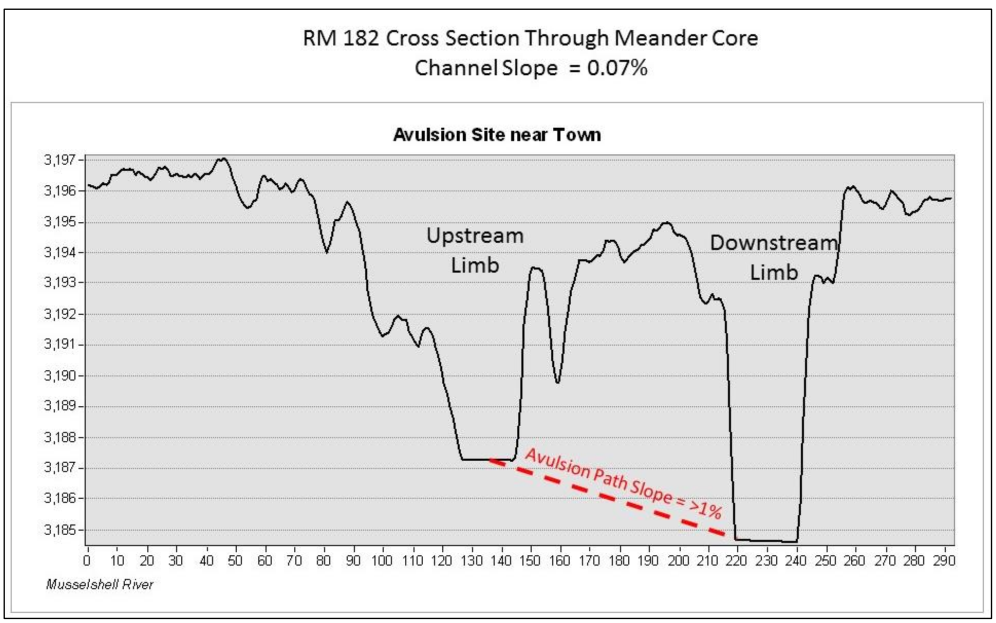

Figure 28. Cross section through avulsion path showing avulsion route slope is about 14 times that of channel slope.

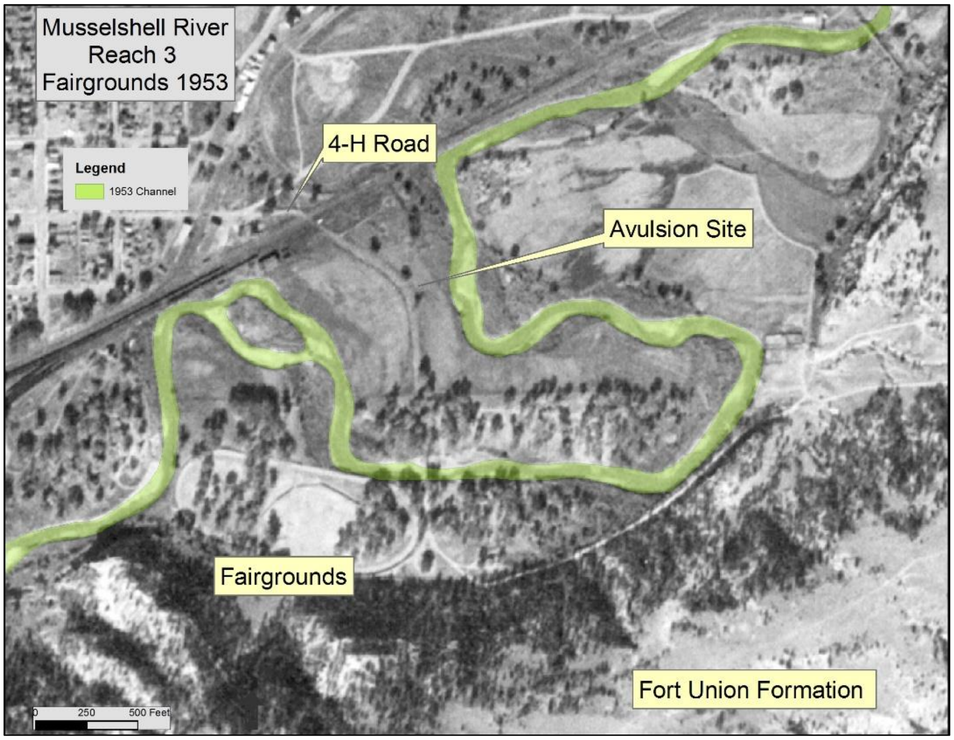

Figure 29. 1953 image of Fairgrounds showing large meander.

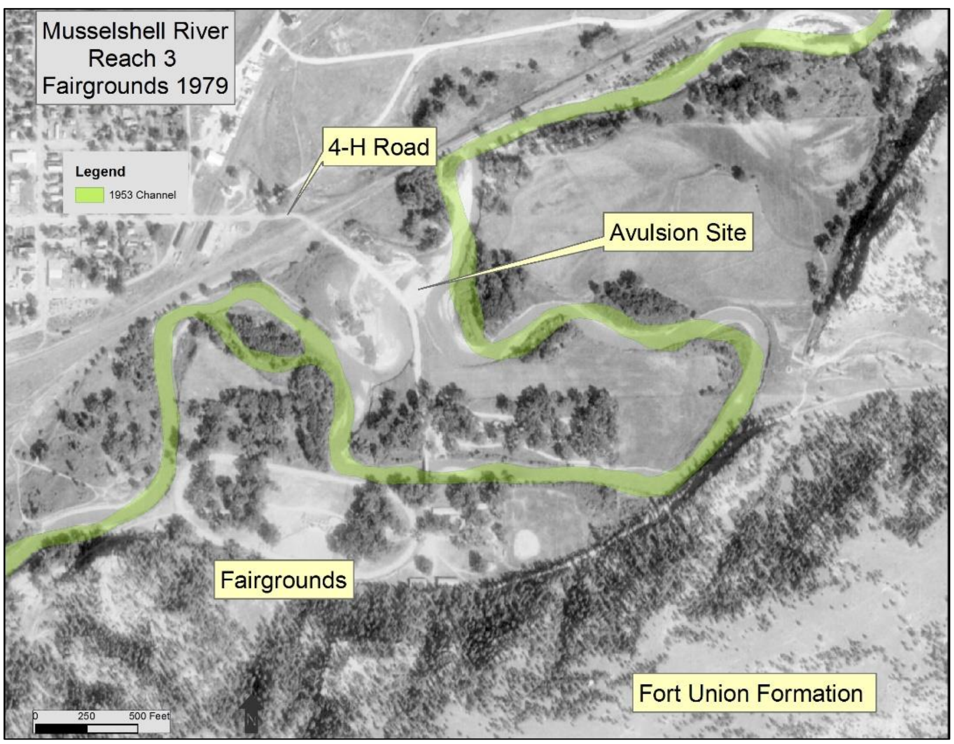

Figure 30. 1979 image of Fairgrounds meander cutoff.

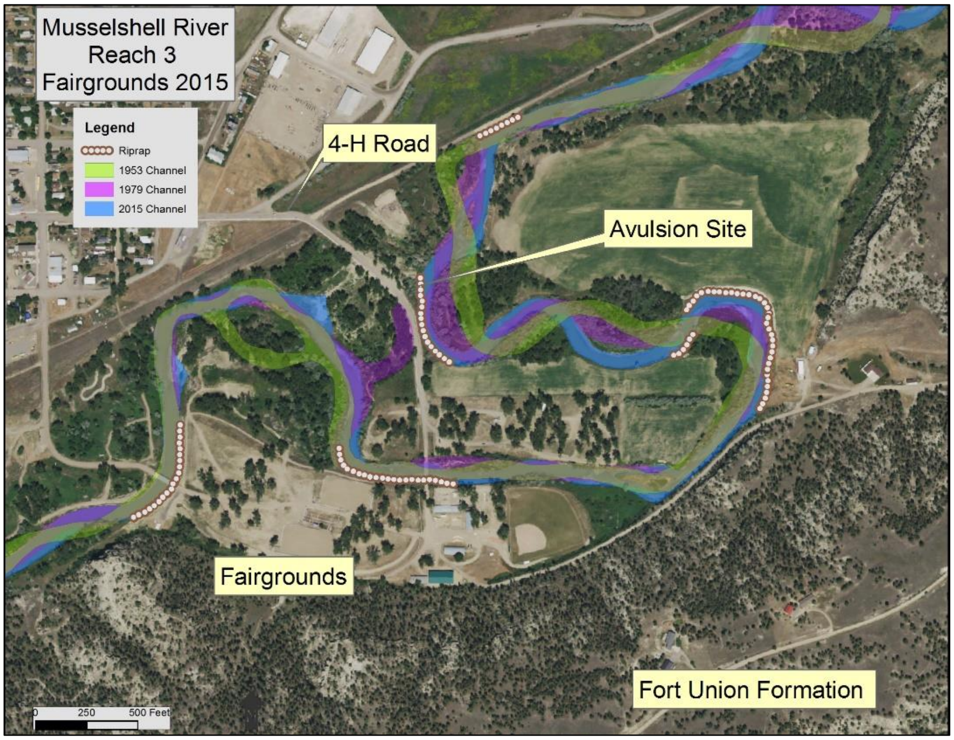

Figure 31. 2015 image of Fairgrounds planform management and bank armor.

Figure 32. View downstream of bedrock constriction (arrow) at Roundup during 2011 flood (May 26, 2011—Kestrel).

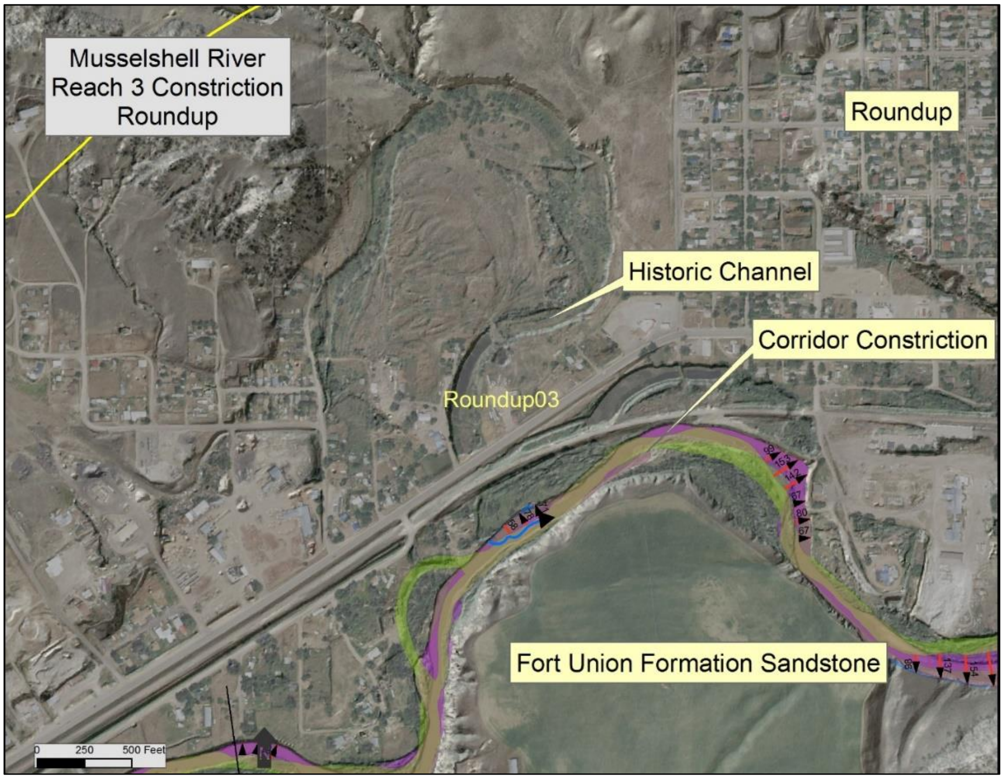

Figure 33. River corridor constriction between bedrock shelf and transportation infrastructure just upstream of Roundup.

4.5 Reach Roundup 02

Roundup02		
Below Newton-Pedrazzi Dam to constriction at RM 170.2		
Upstream/Downstream RM	193.0	189.3
Length (miles)	3.7	
Mean Migration Rate (ft/yr)	2.1	
Max 60-year Migration Distance (ft)	457	
100-year Buffer (ft)	205.4	

Reach 2 is located below Newton-Pedrazzi Dam and is almost 4 miles long. The maximum migration distance measured between 1953 and 2015 is 427 feet. The 100-year EHA buffer width is 205 feet.

Reach 2 has the lowest mean migration rate in the project area. This reach appears to be the most geomorphically stable of any reach sections, and could provide a reference condition for other areas. The mean channel slope is 0.09% and channel sinuosity, which is a ratio of channel length to valley length, is 2.0. The channel confinement is minimal, and the river flows through a series of broad bendways, occupying an approximately 1,000-foot wide meanderbelt.

Although there have been two major cutoffs in the reach since 1953, neither of those avulsions occurred during the 2011 flood. One of those cutoffs was precipitated by the excavation of a cutoff trench through a meander core sometime prior to 1953 (Figure 34 and Figure 35). It is interesting to note that both this cutoff and another immediately downstream were blocked by dikes by 1979, limiting high water flow into the oxbows (Figure 36). With regard to natural storage of spring runoff, removal of these blockages could provide restoration opportunity.

One bendway at RM 193 appears prone to cutoff in the near future.

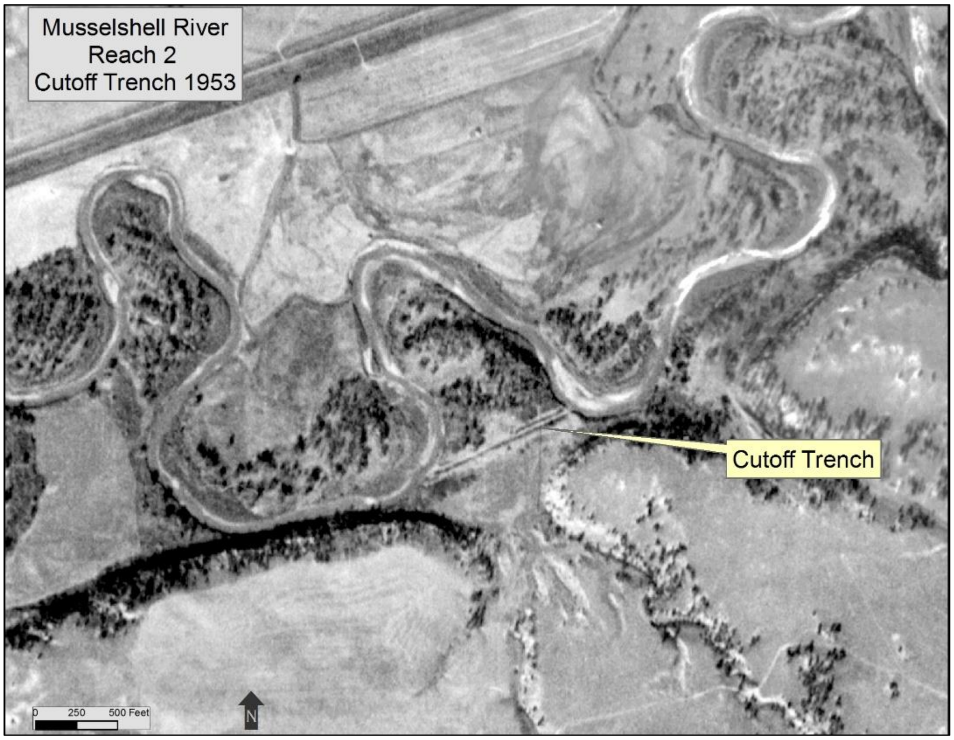

Figure 34. 1953 image of Reach 2 meander cutoff trench.

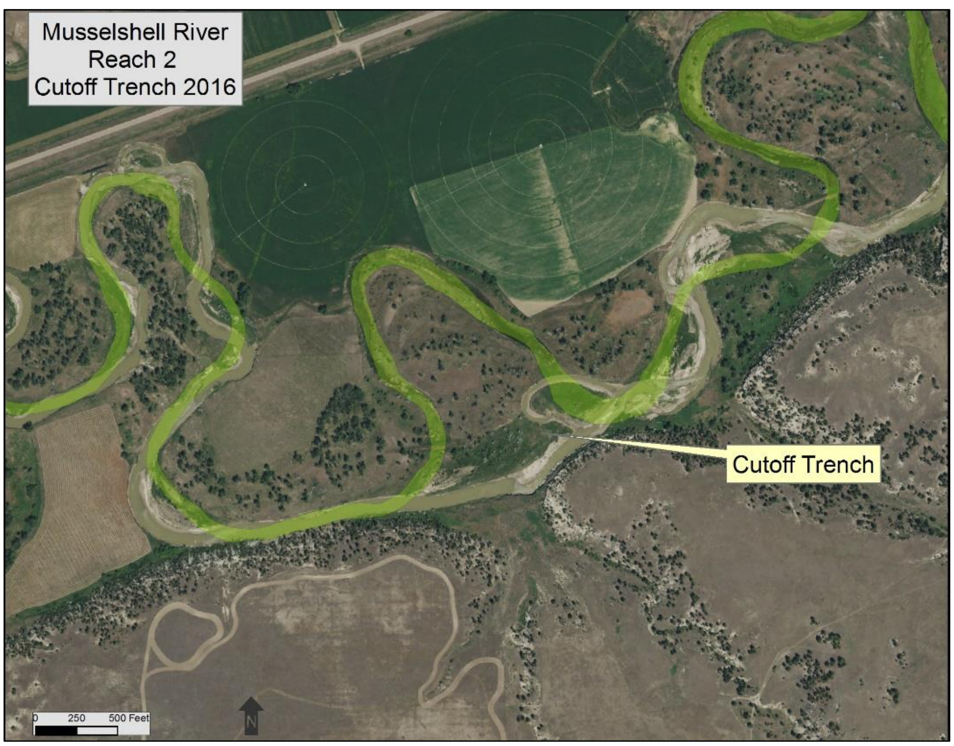

Figure 35. 2015 image of Reach 2 meander cutoff through trench.

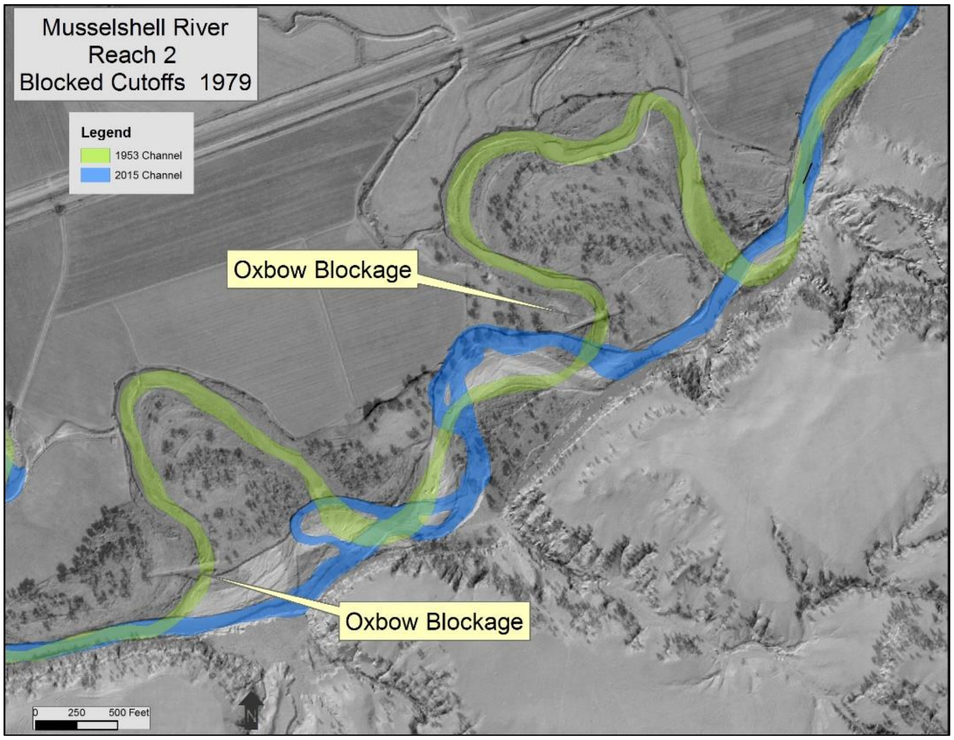

Figure 36. 1979 image of Reach 2 meander cutoff blockages.

4.6 Reach Roundup01

Roundup01		
To Kilby Butte		
Upstream/Downstream RM	197.1	193.0
Length (miles)	4.1	
Mean Migration Rate (ft/yr)	2.4	
Max 60-year Migration Distance (ft)	411	
100-year Buffer (ft)	245	

Reach 1 extends through the Kilby Butte Colony. The reach is just over four miles long, and the maximum migration distance measured between 1953 and 2015 is 411 feet. The 100-year EHA buffer width is 245 feet. Four major avulsions occurred in Reach 1 since 1953, one of which occurred during the 2011 flood (Figure 37). This avulsion path is crossed by an old oxbow channel plug which resisted erosion and prevented a wholesale cutoff at the site.

The other, older avulsions appear to be both natural and forced. The 1953 imagery shows no clear cutoff trench excavation in Reach 1, however by 1979 a major trench had been excavated through a bend just downstream of the main colony housing site at RM 163.4 (Figure 38). This bend cut off sometime before 1995 (Figure 39), and the oxbow has since been blocked similar to those in Reach 2 (Figure 40). The blockages were constructed since the 2011 flood. Just upstream at RM 164.5, a large bendway still hosts a cutoff trench that was dug sometime prior to1979 (Figure 41). This trench is clearly visible on LiDAR and is likely to eventually precipitate a large bendway cutoff.

One concern in Reach 1 is the increasing potential for large cutoff around the Goffena Diversion structure (Figure 42). This site is located just upstream of the Kilby Butte 2011 avulsion site. In 2011 the avulsion path was eroded to some extent such that new channels have begun to form across the meander core which will become increasingly active during future floods (Figure 43).

Figure 37. View downstream showing Kilby Butte avulsion (arrow) and Goffena Diversion in foreground - Sept 20, 2012, Kestrel.

Figure 38. 1979 image showing newly excavated cutoff trench at RM 163.4.

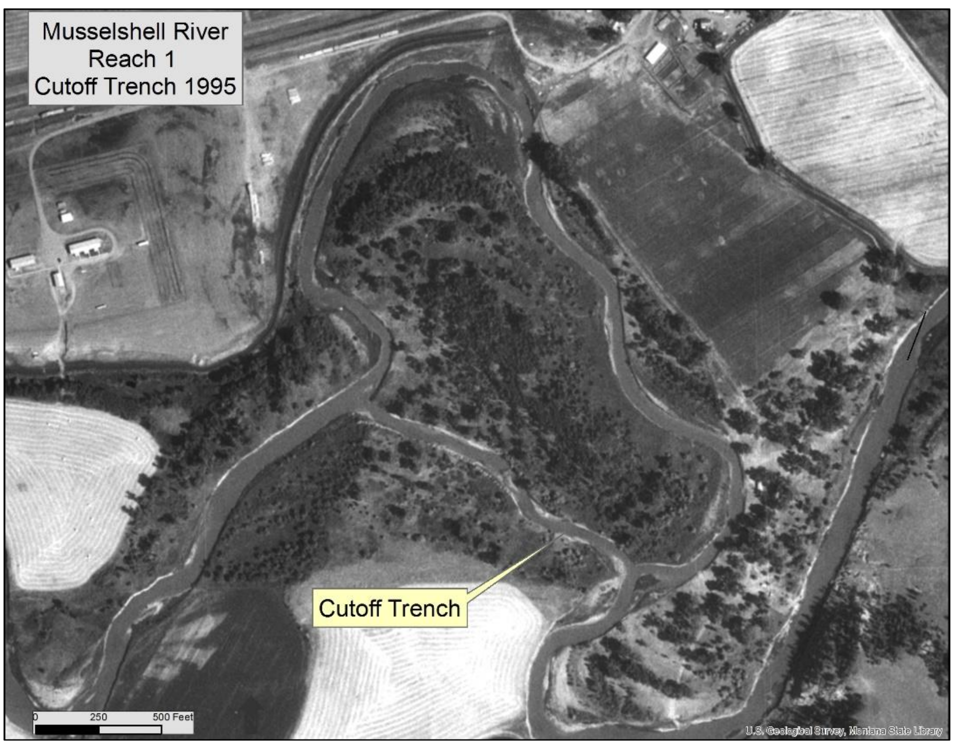

Figure 39. 1995 image showing captured cutoff trench at RM 163.4.

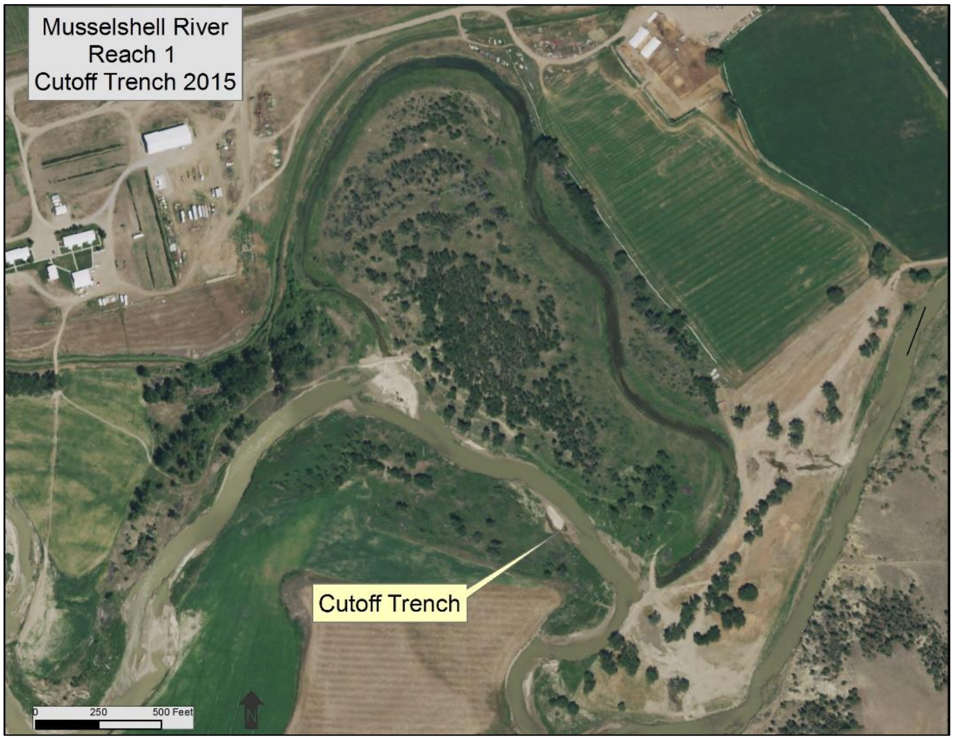

Figure 40. 1979 image showing cutoff through trench and oxbow blockages at RM 163.4.

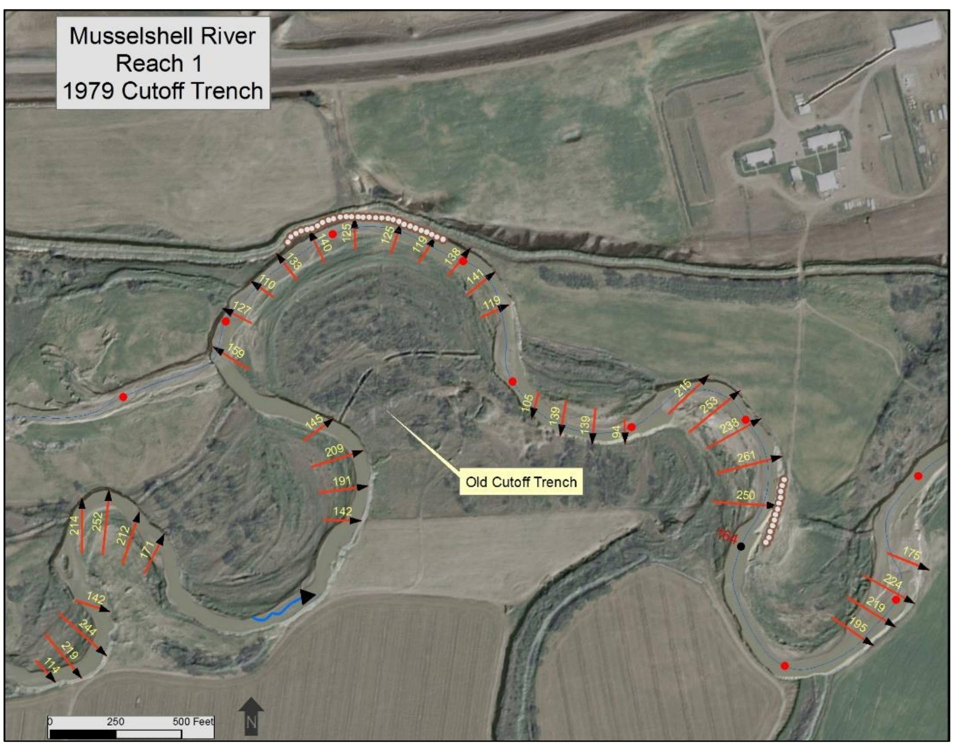

Figure 41. 2015 image showing old cutoff trench still visible at RM 163.4.

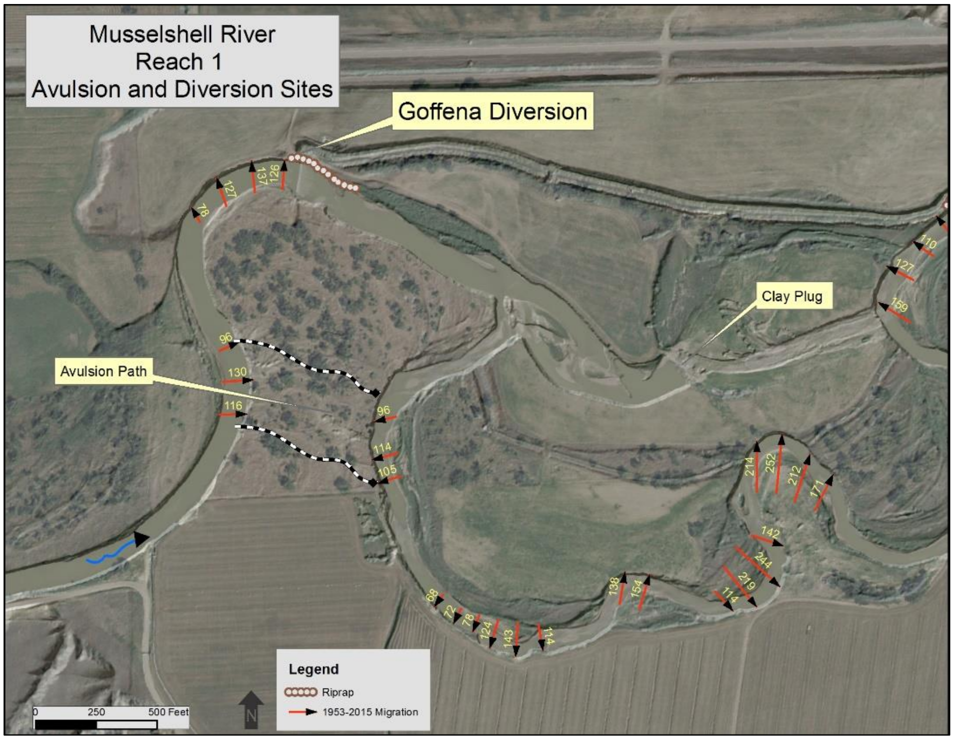

Figure 42. Avulsion hazard at Goffena Diversion.

Figure 43. View downstream of 2011 flood showing Kilby Butte avulsion in formation as well as overflows across upstream meander bend bypassing Goffena Dam (arrow).

5 Summary and Recommendations

The pilot CMZ mapping of the project reach records the complex history of this section of the Musselshell River, with combined influences of human interference with river process and extreme flood events. The following section provides some interpretation as to the overall stability of the river, as well as some recommendations for future steps.

5.1 Channel Stability

The main issue with channel stability on the Musselshell River stems from impediments toward developing a stable planform/slope configuration on a broad scale. Any natural trend towards an equilibrium condition has been hindered by the original railroad construction that straightened portions of the river, the construction of cutoff trenches since the 1950s, and major flooding that has driven, channel widening, migration, and avulsion. The recent flooding on the river has been extreme, with the flood of record in 2011 exceeding a 200-year event and another March 2014 ice event approaching a 100-year flood (Figure 44). The result is a myriad of slope/planform configurations that make it very difficult to assess overall channel stability. In performing the CMZ mapping it appears that Reach 2, which begins about a mile downstream of Newton-Pedrazzi Dam, shows the highest level of geomorphic stability, with low overall migration rates and a largely stable planform. Migration does occur, but it occurs at a moderate pace and is rarely impeded by riprap, which allows bendways to deform naturally. It is also notable that this reach showed the least damage during the 2011 flood, suggesting that its planform/slope configuration provides a relatively resilient condition. Only two avulsions occurred in this reach since 1953, and one of these was human-caused. The notable attributes of this reach are a high channel sinuosity (2.0) relatively low slope (0.09%), and naturally formed bendways that occupy a ~1,000 ft wide meanderbelt.

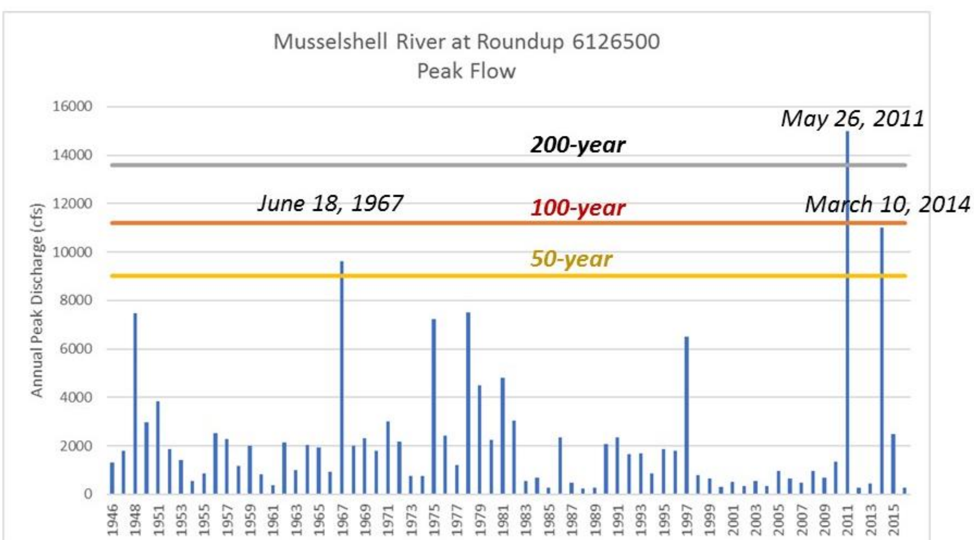

Figure 44. Peak floods and flood frequency for Musselshell River at Roundup (USGS 6126500).

The river is currently in a phase of re-lengthening in many areas, although some meanders are still prone to cutoff due to their unsustainable shape. As such the river has yet to reach a system-wide state of equilibrium. This creates somewhat of a dilemma with regard to river management, because the long-term solution would be to allow system-wide lengthening, localized cutoffs, and natural re-equilibration, however that will result in erosion of agricultural lands. In the event that a corridor-based management approach is taken on the Musselshell River, it is our intent that the CMZ mapping can provide some guidance as to an optimal deformable footprint for the river.

5.2 Recommendations

Based on the results and interpretations presented here, we would recommend that MWC consider the following additional steps to further understand the geomorphic trajectory of this highly impacted river.

1. ***Physical Features Inventory:*** The bank armor mapping shown on the CMZ maps is based on a remote evaluation of imagery. A field inventory of the extent, type, and condition of bank armor would help further interpret channel dynamics in the reach and provide baseline information regarding armor function in given settings.

2. ***Channel Stability Analysis:*** The recent development of a hydraulic model (HECRAS) for the Roundup Reach allows for the quantitative assessment of channel stability by looking at cross-section based sediment transport energy conditions as compared to incoming sediment loads. In conjunction with geomorphic indicators such as channel migration rates, in-stream bar formation etc., areas specifically prone to either downcutting or channel infilling can be identified, and management strategies can then be developed for problem segments.

3. ***Inundation Modeling (Relative Elevation Modeling):*** The LiDAR data can be used to develop Relative Elevation maps that effectively capture floodplain avulsion risks and other channel features. This assessment can be performed cost-effectively with LiDAR in hand and we would recommend that MWC include it as a task item in future mapping.

4. ***Migration Vector Analysis for Flood Impacts:*** Because the river experienced major flooding in recent years, the migration rates reflect those flood-driven changes that may be atypical. It may therefore be helpful to segment the migration measurements into shorter timeframes to help decipher typical background rates of channel movement versus flood-driven channel movement.

5. ***Migration Vector Analysis for Land Use:*** Commonly the rates of channel movement can be statistically correlated to land uses. On the Yellowstone River, for example, mean migration rates were higher through agricultural fields than woody riparian areas. An

evaluation of the relationship between land use and migration rate can help determine whether woody riparian buffers should be employed as a BMP to help mitigate accelerated channel movement.

6 References

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Appendix A – Rach Maps