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Musselshell River Flood Rehabilitation River Assessment Triage Team (RATT II) 2018 Summary Report

Prepared for:

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Roundup MT

Petroleum Conservation District
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Contents

Contents i
List of Figures iii
List of Tables vii
Executive Summary 1
1 Introduction 3
1.1 Previous Efforts Related to RATT Work 4
1.1.1 Summary of the 2011 RATT Findings (2012) 4
1.1.2 LiDAR Data Collection (2012) 5
1.1.3 Best Management Practices (2013) 5
1.1.4 Watershed Planning (2014) 7
1.1.5 Musselshell River Hydrologic Analysis (2015) 8
1.1.6 Roundup Reach Flood Mitigation: Engineering Evaluation and Cost Analysis (2016) 8
1.1.7 Channel Migration Zone Mapping Pilot (2017) 9
1.2 Methods 10
1.3 Acknowledgements 10
2 Project Location and General Conditions 13
3 Major Human Influences on River Function 15
3.1.1 The Milwaukee Railroad 15
3.1.2 Channelization/Straightening 16
3.1.3 Bank Armoring 16
3.1.4 Diversion Structures 17
3.1.5 Floodplain Clearing 19
3.1.6 Summary 20
4 Flood History 21
4.1 Flood Measurements at Roundup 21
4.2 Flood Measurements at Mosby 22
4.3 Duration of Bankfull Flows 24
5 The RATT II 2018 Site Visits—Observations 27
5.1.1 Bank Erosion 28
5.1.2 Avulsions 34
5.1.3 Channel Widening 39
5.1.4 Downcutting 39
5.1.5 Future Avulsion or Meander Cutoff Risk 42
5.1.6 Pump Site Damage 45
5.1.7 Bank Armor Damage/Failure 48
5.1.8 Diversion Dam Flanking 49
5.1.9 Railroad Berm Breaches 51
5.1.10 Salt Cedar 53

6 Geomorphic Evolution of the Musselshell River 55
6.1 Pre-1980s: Initial Corridor Development and River Response 55
6.2 1980-2011: Channel Contraction, Dewatering during Dry Years 57
6.3 2011-2018: Flood-Driven Geomorphic Reset 58
6.3.1 The 2011 Flood 58
6.3.2 Flooding Since 2011 64
6.4 Channel Stability Concepts 64
7 Restoration Alternatives and Long-Term Opportunities 69
7.1 Reducing Channel Slope 70
7.1.1 Passive Lengthening of the Musselshell River 70
7.1.2 Active Lengthening of the Musselshell River (Meander Reactivation) 71
7.1.3 Minimizing Future Shortening of Musselshell River 74
7.2 Dissipating Flood Energy 75
7.3 Bank Integrity 75
7.4 Floodplain Integrity 76
7.5 Landowner Adaptability 77
8 Summary and Discussion 79
9 References 81
Appendix A: Bank Armor Supplement 83
9.1 Introduction 83
9.2 Infrastructure Protection—No Tolerance for Bank Movement 86
9.2.1 Full Bank Rock Riprap 86
9.2.2 Toe Rock with Fabric Lifts and Planting Bench 91
9.2.3 Flow Deflectors 94
9.3 Non-Rock Treatments—Allowance for Some Bank Movement 97
9.3.1 Brush Matrix 97
Appendix B: Glossary of Terms 101

List of Figures

Figure 1. River Assessment Triage Team (RATT) observing a damaged pump site below Roundup. 10
Figure 2. Musselshell Watershed in Montana, with assessment reach (black line) and counties labeled. 13
Figure 3. River Assessment Triage Team (RATT) Project Area; 2011 river miles are shown on digitized river centerline. 14
Figure 4. 2011 Air photo showing mapped meander segments isolated by rail berm above Musselshell. 15
Figure 5. Example of a cutoff trench dug by 1979 that drove an avulsion by 1995; trench is about 1,200 feet long. 16
Figure 6. Example flow deflector (left) and rock riprap (right) placed to protect infrastructure. 16
Figure 7. View upstream of Egge Dam after its flanking and prior to its removal following the 2011 flood. 18
Figure 8. Example portable pump on lower river (2011). 18
Figure 9. Developed floodplain, Musselshell River (Musselshell Conservation District, 2004). 19
Figure 10. Air photo comparison from 1953 (left) and 1979 (right) showing clearing of woody riparian vegetation as part of field development. 19
Figure 11. Flood history for Musselshell River near Roundup (flood frequencies from Pioneer, 2015). .. 21
Figure 12. Mean daily flow hydrographs for 2011 and 2018 floods at Roundup. 22
Figure 13. Flood history for Musselshell River at Mosby (flood frequencies from Pioneer, 2015). 23
Figure 14. Mean daily flow hydrographs for recent floods at Mosby. 23
Figure 15. Photos from the 2014 flood showing March ice-jam flooding in Ryegate and August flooding at Mosby (Missoula.com and Kestrel Aerial Services). 24
Figure 16. Number of days the 2-year flood was exceeded at Mosby and Roundup in 2011, 2014, and 2018. 25
Figure 17. RATT sites visited in 2011 (green) and 2018 (red); yellow points mark 2011 avulsions. 27
Figure 18. View upstream towards pump site showing electrical line in middle of river above Roundup. 28
Figure 19. Digitized banklines for site shown in Figure 18. 29
Figure 20. View upstream of erosion through fenceline above Roundup. 29
Figure 21. View upstream of high bank erosion into road below Mosby. 30
Figure 22. View upstream showing 2018 erosion just below rocked siphon crossing. 30
Figure 23. Mapped banklines below Roundup showing four acres of field erosion in 2018. 31
Figure 24. View downstream showing storage tank on right bank and large point bar on opposite side driving erosion. 32
Figure 25. Channel migration through time below Mosby; note lengthening following 2011 cutoffs. The black star marks a pump site that was eroded out during 2018 flood. 32
Figure 26. View downstream showing pond, headcutting spillway, and cabin at risk. 33
Figure 27. View upstream showing tension cracks in bluff between river and pond. 33
Figure 28. 2011 flood photo of avulsion in process (upstream migrating headcuts) below the Musselshell River Road Bridge (Kestrel Aerial). 34

Figure 29. Abandoned channel below Mosby resulting from 2011 avulsion/chute cutoff (Kestrel Aerial). 35
Figure 30. View downstream showing 2018 avulsion (red) that abandoned about 1,500 feet of channel (blue). 36
Figure 31. Wheatland County site showing conditions in 2012 (top) and 2018 (bottom). 36
Figure 32. View downstream through avulsion path showing large wood in channel. 37
Figure 33. 2011 air photo showing avulsion channel/meander cutoff. 37
Figure 34. Northward oblique view of avulsion sites on south channel (flow is left to right). 38
Figure 35. Profile pulled through avulsion paths in Figure 34 showing vertical drops at avulsion points. Dashed line shows potential long-term steepened profile which includes several feet of downcutting above avulsion pints. 38
Figure 36. Cumulative impacts of floods on channel process, including widening, point bar formation, bank erosion, and riparian succession (young cottonwood establishment). 39
Figure 37. 2012 LiDAR hillshade showing two 2011 avulsions that shortened the river by over 15 miles. 40
Figure 38. View downstream of headcut in channel bed, caught on a shale reef. 40
Figure 39. Drone image from September 2018 showing rocked sill holding graded on new channel; note much smaller width of old channel in background. 41
Figure 40. View across river of steep drop across reinforced rock sill. 41
Figure 41. Relative elevation model (from 2012 LiDAR data) showing floodplain headcuts (blue fingers) in formed by 2011 flood waters below Mosby. Flow direction is to north. 42
Figure 42. Google Earth image showing 2011 floodplain headcuts creating avulsion path; this bend cut off in 2018. 43
Figure 43. 2012 LiDAR hillshade showing prominent channel forming an avulsion path. 44
Figure 44. Schematic drawings of neck and chute cutoffs (modified from Depret, 2017). 45
Figure 45. View downstream of bendway showing old pump site and likely cutoff path that will abandon meander. 45
Figure 46. View down pump site access ramp that washed out during the 2018 flood. 46
Figure 47. View upstream of pump site with buried irrigation pipe exposed in streambank (2018 drone flight). 47
Figure 48. Lost pump site foundation behind and below metal plates. 47
Figure 49. Images from Google Earth (top) and drone flight (bottom) showing buried pump site due to 2018 flood event; the recommended pump site relocation would be along the riprapped left bank shown in lower image. 48
Figure 50. View downstream from damaged pump site—note flanked rock riprap in channel. 49
Figure 51. 2012 air photo showing Musselshell River path in 2009 and 2018, capturing flanking of dam to south (flow direction is left to right). 50
Figure 52. 2018 drone image of flanked diversion dam and channel widening. 50
Figure 53. View upstream (west) of long railroad grade breach that occurred in 2011 east of Shawmut (Kestrel Aerial). 51
Figure 54. Digitized banklines showing railroad breach about two miles below Painted Robe Creek. 52

Figure 55. View upstream of railroad berm breach below Painted Robe Creek -- photo taken on September 20, 2012. 52
Figure 56. View downstream showing overflow paths and one potential return flow point through an old swale. 53
Figure 57. Cottonwood and salt cedar seedlings on 2018 flood deposits. 54
Figure 58. American Forests publication from 1935 promoting stream channelization. 55
Figure 59. View upstream of a downcut channel located upstream of channelized reach; channel incision stops where headcuts get stopped by road culverts (USACE). 56
Figure 60. Floodplain clearing and channel downcutting on the Musselshell River by the early 2000s (LMCD, 2004). 57
Figure 61. Change in Musselshell River below Roundup from 1979 (left) to 2009 (right) showing narrowing of channel, loss of open bars and expansion of Russian olive, which can be seen as sage-colored vegetation in the 2009 image. 57
Figure 62. Musselshell River Photo from Montana River Action (date unknown). 58
Figure 63. Floodplain inundation and erosion during the 2011 event dramatically changed the face of the Musselshell River. 59
Figure 64. View downstream of point bar formation, bank erosion, and channel lengthening near Shawmut (kestralaerial). 60
Figure 65. Cottonwood seedling colonization following 2011 flood. 60
Figure 66. Comparison of bank movement in relatively low slope area below Newton Dam (top) and steep reach above Naderman Dam (bottom). Values are reach-averages. 62
Figure 67. Reaches evaluated in CMZ Pilot Project (AGI and DTM, 2017). 63
Figure 68. Average migration rates for CMZ pilot reaches plotted against slope (left) and sinuosity (right) showing more active migration on steeper and straighter river segments above Roundup (R4-R6). 63
Figure 69. Lane's balance provides a useful conceptual framework for considering probable channel response to changes sediment delivery, slope, and flow (North Carolina State University). 65
Figure 70. Raw gravel bedload deposit on point bar. 66
Figure 71. Straightened section of the Walla Walla River actively regaining length during a 1964 flood. 66
Figure 72. Schematic drawing showing the direction of Musselshell River changes between 2009 and 2019 (www.slideshare.net). 67
Figure 73. General Land Office (GLO) survey map from 1883 showing sinuous and well vegetated channel downstream of Musselshell; blue line is 2011 channel course, and 1908 railroad grade is in black. 68
Figure 74. Conceptual schematic of optimal Musselshell River trajectory (image from www.slideshare.net). 69
Figure 75. Relative Elevation Model (REM) showing old swales (blue arcs on floodplain, that could be areas of allowable channel movement. 70
Figure 76. Closeup imagery of avulsion path in 2017 (top right) and 2018 (bottom right) showing potential reactivation site; pump site is marked by star. 71
Figure 77. View downstream of abandoned channel following avulsion shown in Figure 76, 2018. 72
Figure 78. Example meanders that could be evaluated for reactivation; meander on right is clearly lower and would be more cost-effective to reconnect. 73

Figure 79. General concept for meander reactivation. 73
Figure 80. Potential meander reactivations (dashed white lines) below Mosby that could recover almost 2 miles of channel length and recover a pump. 74
Figure 81. Example cutoff trench through meander core. 75
Figure 82. Decision pathway for bank armoring (Appendix A). 76
Figure 83. Decision matrix for a range of Musselshell River Bank Protection Alternatives. 85
Figure 84. Cross Section of typical full-bank rock revetment. 87
Figure 85. Full bank rock riprap against floodplain surface (left) and higher terrace (right), Musselshell River. 88
Figure 86. Example of rock riprap that covers most of the bank but will allow for some vegetation growth on upper most bank -Yellowstone River, Riverside Park at Laurel (billingsgazette.com). 88
Figure 87. NRCS Cross Section of rock riprap that stops at the elevation of the "stream forming flow" transitioning to planting systems above. 89
Figure 88. View upstream of flanked bank armor, Musselshell River. 90
Figure 89. Limited application of full bank rock riprap at bridge crossing, Prickly Pear Creek at East Helena. 91
Figure 90. Example schematic drawing for vegetated soil lift design. 92
Figure 91. Soil lift project with planting bench behind on Musselshell River above Roundup. 92
Figure 92. Willow growth in soil lifts on Clark Fork River (top) and Prickly Pear Creek (bottom). 93
Figure 93. Bankfull bench construction on Clark River just after construction (left) and ~4 years later (right). 94
Figure 94. Bankfull bench construction on Boulder River near Drummond (George Austiguy). 94
Figure 95. Erosion control barbs on Musselshell River (left) and Yellowstone River (right) showing orientation to flow, and erosion between structures. 96
Figure 96. View downstream showing recently constructed (left) and older (right) barbs showing erosion between structures in older projects. 96
Figure 97. Barb treatment converted to full bank riprap. 97
Figure 98. Example design drawing for a brush matrix treatment; this can be constructed over a rock toe in areas of higher energy (CDM Smith, 2016). 98
Figure 99. Recently constructed brush matrix treatments, Clark Fork River near Deer Lodge. 98
Figure 100. Brush matrix construction creating low bench (left), willow growth four months after installation- Ruby River near Sheridan MT (note—steep scarp on photo on left will be graded back to 3H:1V. 99
Figure 101. Robust willow growth ~3 years after installation, Clark Fork River near Deer Lodge. 99

List of Tables

Table 1. 2011 River Mile locations of major features, Musselshell River Valley 14
Table 2. Diversion structures mapped below Two Dot, with 2017 status listed. 17
Table 3. Summary of treatment cost, performance, and considerations.. 86

Executive Summary

In the fall of 2018, the Musselshell River Assessment Triage Team ("RATT") was reconvened after major flooding the previous spring to evaluate a series of sites between Two Dot and Fort Peck Reservoir. This followed the RATT's initial work following the 2011 flood. In each effort, the team visited landowners on their properties to evaluate specific issues and discuss potential options for post-flood rehabilitation measures. Each landowner was provided a site report that summarized site-specific issues and recommended treatments while providing some context as to broader flood-related processes on the river.

During the 2018 site visits, a common theme was severe bank erosion that impacted pump sites, road crossings, field acreages, canals etc. This trend of rapid channel movement is a direct response to the 2011 flood, as the river is essentially regaining the length lost during that period of tremendous change. In 2011, 59 avulsions (channel relocations) abandoned 36.9 miles of river, shortening the river by about 10%. These avulsions ranged from 280 feet to 2.6 miles long, and were well-distributed from Harlowton to Fort Peck, with the longest occurring below Mosby. As the river shortened, it became over-steepened, which resulted in extensive bank erosion, downcutting, and re-lengthening in 2018. The sediment added to the river added erosion pressure as point bars grew. In 2018, there were some additional avulsions, so the flood was characterized by both lengthening through bank erosion but also some shortening.

The 2011, 2014, and 2018 floods have collectively exerted the strongest cumulative geomorphic force on the river since recordkeeping began at Mosby in 1929. Historic channel straightening, and riparian clearing compounded the rivers' response to these floods. As a result, this river has experienced a shift in overall morphology, and is currently in a period of continued change and long-term recovery.

This poses unique challenges to the Musselshell Watershed community in that channel lengthening and associated energy dissipation (slower water) are important aspects of 2011 flood recovery. Lengthening should be allowed or encouraged where possible, otherwise armoring projects on the steep channel will become costlier and more prone to failure or damage, and severe bank erosion will continue on unarmored banks for decades. Financial and ecological consequences would be high. As a result, our approach has focused on avoiding locking the channel into place where possible while recognizing that strategic armor placement is an important tool in maintaining infrastructure such as roads, pump sites, residences, and diversion dams. As an alternative to bank armoring, opportunities to promote natural recovery and reduce in-stream power are described.

1 Introduction

This report is intended to build upon the original RATT report completed in 2012 (Boyd, et al., 2012). The first report was completed after an evaluation of 2011 flood impacts and included relatively detailed summaries of Musselshell River geomorphology, riparian vegetation, fisheries, 2011 flood impacts, and restoration opportunities. The 2012 report also describes project monitoring strategies, water rights considerations, and specific programs to assist with flood recovery. For that level of detail, we refer the reader to the 2012 document.

This document focuses on how more recent floods have continued to affect the river, and how the changes observed in recent years fit in with the long-term trajectory of the Musselshell. The report is divided into the following eight chapters and two Appendices:

Chapter 1: Introduction

Chapter 2: General Location and Setting

Chapter 3: Human Influences on Stream Function

Chapter 4: Flood History

Chapter 5: Observations from the 2018 RATT site visits

Chapter 6: Geomorphic Evolution of the Musselshell River

Chapter 7: Restoration Opportunities and Recommendations

Chapter 8: Summary and Discussion

Appendix A: Bank Armor Supplement

Appendix B: Glossary of Terms

1.1 Previous Efforts Related to RATT Work

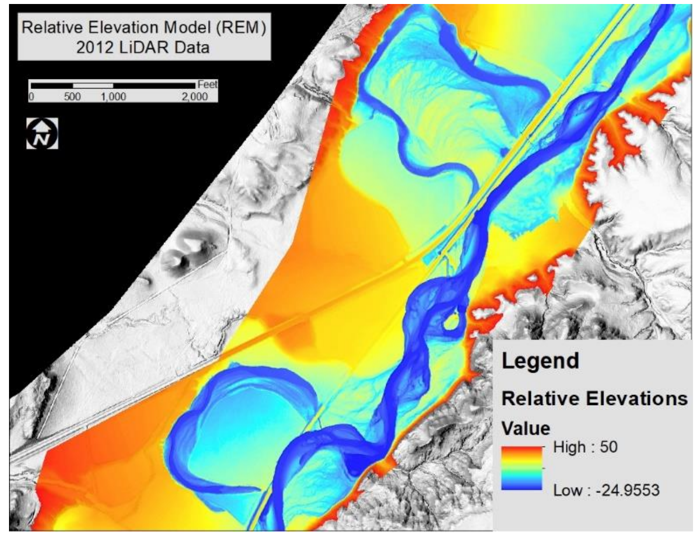
Since the initial 2012 RATT report was completed, several additional projects have supported and expanded upon our work. A brief summary of the projects that are most relevant to the RATT work is provided below.

1.1.1 Summary of the 2011 RATT Findings (2012)

In the fall of 2011, the RATT visited 43 flood impacted sites and provided individual site reports to each landowner that requested our input. This was followed by a summary report that broadly describes system-wide impacts of the 2011 flood (Boyd, et al., 2012). Major points from that document include the following:

- The 2011 Musselshell River flood was record-breaking in terms of both the magnitude of the event, and the length of time that flood stage was exceeded;
- The flood caused 59 avulsions, which abandoned almost 37 miles of channel;
- Avulsions created just over nine miles of new channel;
- The river was shortened by 8% between Fort Peck Reservoir and Martinsdale;
- The most severe shortening was in the lowermost 89 miles of river, below Flatwillow Creek;
- In places, the river migrated several hundreds of feet during the flood, causing massive erosion, and sediment deposition/delivery downstream;
- A total of 31 breaches through the railroad graded were mapped on post-flood air photos;
- Several cross-channel diversion structures were flanked or abandoned;
- Dozens of irrigation pumps were abandoned;
- Floodplain deposition was several feet thick in some areas, commonly in agricultural fields;
- Vast carpets of cottonwood and willow seedlings were established on newly deposited sediment by the flood; and,
- Effective rehabilitation strategies can address both short-term needs as well as the longer-term processes of system recovery.

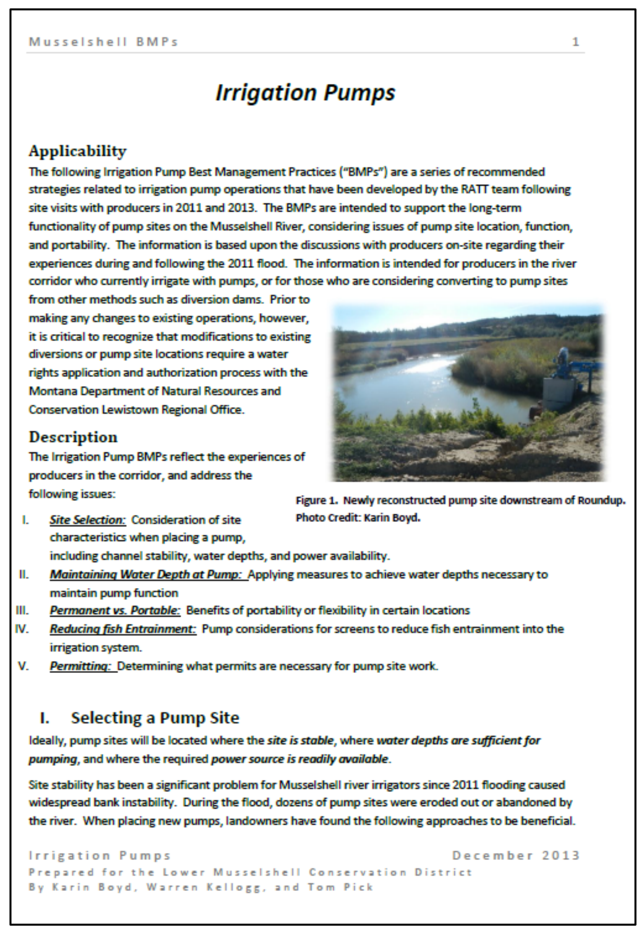
1.1.2 LiDAR Data Collection (2012)



In 2012 the Natural Resource Conservation Service contracted out the collection of LiDAR data for the Musselshell River corridor. The deliverable for this work included 1-meter bare earth grids of the entire river corridor. These data have been used extensively in this assessment to evaluate topographic conditions at RATT sites in 2012. Longitudinal profiles were pulled to evaluate topographic discontinuities across avulsion paths. Hillshade representations of the data provide a means of visualizing topographic subtleties, and the creation of a Relative Elevation Model (REM) allows the representation of relative elevations as a color ramp, with blue colors reflecting elevations approximating that of the river and progressively warmer elevations depicting higher ground.

1.1.3 Best Management Practices (2013)

In the fall of 2013, members of the RATT created a series of Best Management Practices related to flood damages and conservation opportunities on the river (Boyd, Kellogg, and Pick, 2013). These BMPs can be accessed through the Lower Musselshell Conservation District.



Musselshell BMPs 1

Irrigation Pumps

Applicability

The following Irrigation Pump Best Management Practices ("BMPs") are a series of recommended strategies related to irrigation pump operations that have been developed by the RATT team following site visits with producers in 2011 and 2013. The BMPs are intended to support the long-term functionality of pump sites on the Musselshell River, considering issues of pump site location, function, and portability. The information is based upon the discussions with producers on-site regarding their experiences during and following the 2011 flood. The information is intended for producers in the river corridor who currently irrigate with pumps, or for those who are considering converting to pump sites from other methods such as diversion dams. Prior to making any changes to existing operations, however, it is critical to recognize that modifications to existing diversions or pump site locations require a water rights application and authorization process with the Montana Department of Natural Resources and Conservation Lewistown Regional Office.

Description

The Irrigation Pump BMPs reflect the experiences of producers in the corridor, and address the following issues:

Figure 1. Newly reconstructed pump site downstream of Roundup. Photo Credit: Karin Boyd.

I. ***Site Selection:*** Consideration of site characteristics when placing a pump, including channel stability, water depths, and power availability.
II. ***Maintaining Water Depth at Pump:*** Applying measures to achieve water depths necessary to maintain pump function
III. ***Permanent vs. Portable:*** Benefits of portability or flexibility in certain locations
IV. ***Reducing fish Entrainment:*** Pump considerations for screens to reduce fish entrainment into the irrigation system.
V. ***Permitting:*** Determining what permits are necessary for pump site work.

I. Selecting a Pump Site

Ideally, pump sites will be located where the ***site is stable***, where ***water depths are sufficient for pumping***, and where the required ***power source is readily available***.

Site stability has been a significant problem for Musselshell river irrigators since 2011 flooding caused widespread bank instability. During the flood, dozens of pump sites were eroded out or abandoned by the river. When placing new pumps, landowners have found the following approaches to be beneficial.

Irrigation Pumps December 2013
Prepared for the Lower Musselshell Conservation District
By Karin Boyd, Warren Kellogg, and Tom Pick

BMPs were created for the following issues on the river:

1. ***Avulsions:*** this BMP summarizes recommended approaches to managing abandoned channels within the Musselshell River stream corridor. The information is based upon the on-site evaluation of floodplain features and discussions with producers. This BMP is intended for producers and residents who are living or farming in areas where abandoned channel segments exist.
2. ***Channel Maintenance:*** this BMP offers recommended strategies for activities that include debris and sediment removal and placing fill within the active river channel. The BMP was developed following visits with producers in 2011 and 2013. Practical and regulatory considerations are provided, as well. The information is for use by producers who anticipate or are considering channel maintenance work and for

Conservation Districts responsible for issuing 310 permits.

3. ***Agricultural Field Recovery:*** Many fields were buried by sediment during the spring of 2011. A BMP was thus developed to restore the sustained productivity of crop fields on the Musselshell River, considering issues of sediment deposition by floodwater, the depth and texture of such deposits, the magnitude and location of field erosion features, weed control, and restoration costs. The information presented is based on the field evaluation of multiple flood affected sites and discussions with producers. The information is intended for use by land managers in the river corridor who have experienced field damage from deposition of sediment, scour, and/or soil erosion.
4. ***Floodplain Dikes:*** As described previously, the 2011 flood damaged floodplain dikes. This BMP provides recommendations for placing, repairing, or removing floodplain dikes to support the long-term functionality of the Musselshell River floodplain while protecting infrastructure as necessary. The recommendations are based upon field site reviews and discussions with local stakeholders and are intended for producers and residents who currently farm or maintain infrastructure in areas prone to flooding. In general, however, further isolation of the Musselshell River floodplain was strongly discouraged due to the role of the floodplain in dissipating flood energy, storing water in the shallow aquifer, and contributing to river stability.
5. ***Irrigation Diversions:*** The diversion structure BMP reviews the major types of irrigation diversion structures found on the Musselshell River and similar rivers in Montana. On-site observations of irrigation diversion structures and discussions with Musselshell River water users are the basis for BMP recommendations.
6. ***Irrigation Pumps:*** a series of recommended strategies related to irrigation pump operations were developed by the RATT team following site visits with producers in 2011 and 2013. The BMPs are intended to support the long-term functionality of pump sites on the Musselshell River, considering issues of pump site location, function, and portability. The information is based upon the discussions with producers on-site regarding their experiences during and following the 2011 flood. The information is intended for producers in the river corridor who currently irrigate with pumps, or for those who are considering converting to pump sites from other water withdrawal methods such as diversion dams.
7. ***Noxious Weed Control:*** The BMP for weed control considers issues of noxious weed species adaptation, the role of disturbance, and environmental and regulatory restrictions. This information is intended for producers in the river corridor where disturbance (flooding or human-caused) has altered channel vegetation or distributed fresh sediment in the floodplain. Canada thistle (*Cirsium arvense*), field bindweed (*Convolvulus arvensis),* leafy spurge (*Euphorbia esula*), spotted knapweed (*Centaurea spp.)*, saltcedar (*Tamarix chinensis*) and Russian olive (*Elaeagnus angustifolia*) are noxious weeds commonly associated with disturbance in the floodplain. Producers affected by flooding are encouraged to develop a site-specific weed management plan.
8. ***Pipeline Crossings:*** This BMP focuses primarily on irrigation water pipelines and siphons but does include some criteria on permitting oil/gas pipeline crossings. On-site observations of irrigation pipeline/siphon crossings and discussions with Musselshell River water users are the basis for much of the information.

9. ***Riparian Protections:*** The overall objective of the Riparian Protection recommendations is to capitalize on the remarkable riparian response to the 2011 flooding, because in systems like the Musselshell, these events are exceedingly rare. The information is based upon the evaluation of riparian trends and discussions with producers on-site and is intended for producers and residents who manage properties where the flood resulted in colonization of native woody riparian vegetation, primarily willows and cottonwoods.
10. ***River Crossings:*** This Best Management Practice (BMP) reviews the primary types of river crossings found on the Musselshell River. On-site observations of river crossings and discussions with Musselshell River water users are the basis for the information that follows.

A list of project permitting contacts was provided with the BMPs.

1.1.4 Watershed Planning (2014)

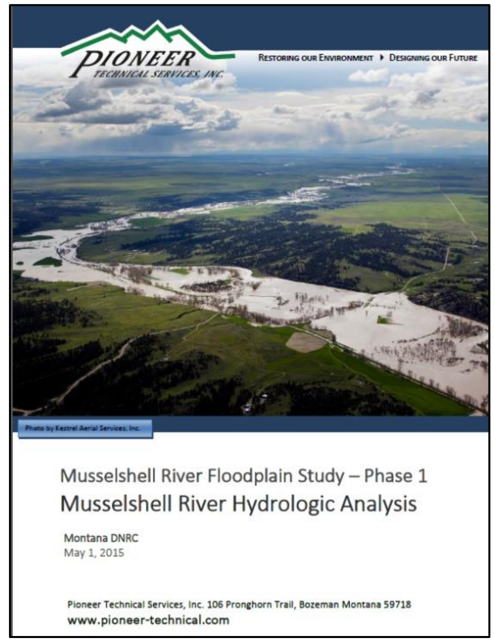
During the fall of 2014, a series of public stakeholder meetings were held throughout the Musselshell River corridor to solicit input from local producers, agency representatives, government officials, water user associations and others regarding water resource management-related project needs and opportunities within the basin (Boyd, Thatcher, and Kellogg, 2015). Preparation for those meetings included the creation of maps showing available data plotted, project forms designed to feed into a project planning database, and presentation materials to engage stakeholders and describe the planning process. Approximately 100 people attended the six meetings which were held over a two-day period.

The result of the meetings was a list of 58 project concepts with varying amounts of supporting information. Projects concepts were submitted by a wide range of attendees, including local producers as well as other stakeholders affiliated with various organizations and agencies. Once the projects were submitted as general concepts, they were further developed for input into the database.

In December of 2014, the projects were presented one-by-one to a Project Ranking Team, which was assembled by the Musselshell Watershed Coalition to refine and rank proposed projects. The team was comprised of local water managers, Conservation District administrators and supervisors, partners from Federal and State Agencies, and local landowners. There were a total of 13 members on the ranking committee, two of which provided advisory capacity but did not vote on decisions. The ranking process consisted of the evaluation of individual projects with regard to specific resource benefit. These benefits were then converted to scores and the overall project ranked. The ranking process also consisted of the consolidation and trimming of projects from 58 original project concepts to 27, including 19 engineering projects and 8 studies/outreach projects.

Following the ranking process, another meeting was held in June of 2015 with members of the Project Ranking Team and representatives from funding entities to develop an implementation strategy for the 27 projects. The implementation strategy includes individual project characterization in terms of timeline, sponsor, and potential funding sources.

This is intended to be a living document that will assist the Musselshell Watershed Coalition in its continued development and implementation of stakeholder-driven water management efforts in the basin.

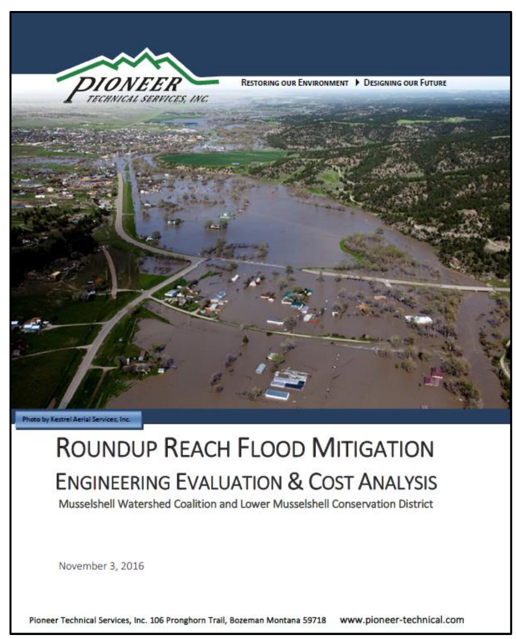


1.1.5 Musselshell River Hydrologic Analysis (2015)

Pioneer Technical Services was contracted by DNRC to develop flow frequency calculations for a 325-mile reach of the Musselshell River (Pioneer, 2015). Flow frequency analyses were conducted to develop peak flow estimates for the 2-year, 10-year, 25-year, 50-year, 100-year, and 500- year flood events. Estimates were calculated at 49 mainstream locations. The results showed that in the middle and lower reaches of the river, the flood frequency discharge estimates are much higher than developed in early studies, due to the inclusion of the 2011 and 2014 floods in the data analysis. Since those floods were less consequential in the upper basin, the flood discharge estimates high in the watershed did not significantly change previous estimates.

1.1.6 Roundup Reach Flood Mitigation: Engineering Evaluation and Cost Analysis (2016)

One of the outcomes of the 2015 Watershed Plan was a recommendation to bundle several proposed projects in the Roundup area, to assess their value and feasibility in a more holistic manner. This report evaluates several different projects to mitigate flooding through the Roundup Reach and includes a full reach hydraulic model, preliminary project engineering plans, and preliminary engineer cost estimates (Pioneer, 2016). The projects included realignment and installation of culverts at the Number 4 Road, improvements to the Fairgrounds Area, Meathouse Road Area improvements, a low water crossing on the 4-H Road, and removal of the Jeffries Tipple embankment below town.

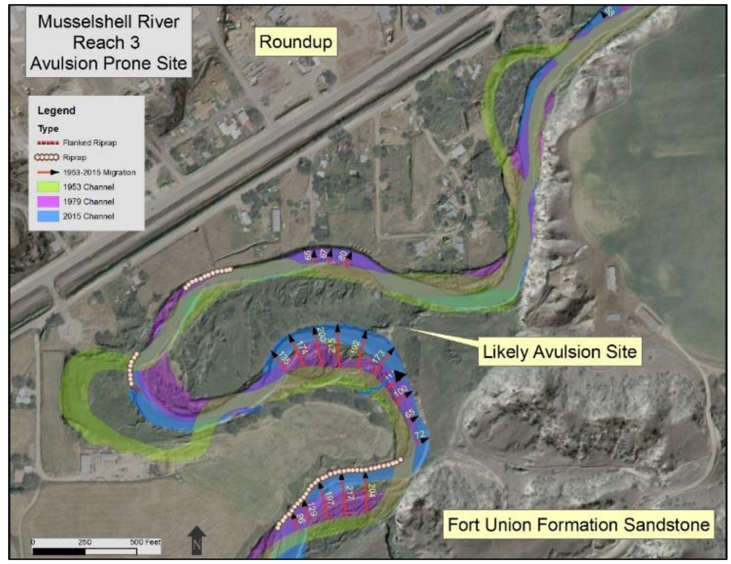


The results showed that the Fairgrounds Area Improvements and Meathouse Road Area Improvements would most strongly reduce flooding in the Roundup Reach. If implemented, the Fairgrounds project would also reduce the potential maintenance costs which reached hundreds of thousands of dollars after the 2011 flood. The Number 4 Road Realignment and Bridge Culverts project improves access and safety and reduces road maintenance. Road maintenance would also be reduced by the 4-H Road Low Water Crossing, and removal of the Tipple Embankment removes a floodplain flow impediment.

Since this report was written, the Tipple Embankment has been largely eroded out.

1.1.7 Channel Migration Zone Mapping Pilot (2017)

In 2017, Applied Geomorphology (AGI) and DTM Consulting were contracted by Montana Fish Wildlife and parks to develop a Channel Migration Zone Map of the Musselshell River from Naderman Diversion Dam downstream to near Kilby Butte, a distance of 34.4 river miles (Boyd and Thatcher, 2017). The Channel Migration Zone (CMZ) includes the mapped 1953-2015 historic river footprint as well as erosion hazard areas that extend beyond that historic channel footprint based on typical migration rates. Avulsion hazard areas are also identified in the mapping. The primary findings of this mapping effort 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.

As this mapping was completed prior to the recent floods, future mapping should re-evaluate channel locations and migration rates to update areas of erosion risk.

1.2 Methods

This report is intended to build on to the first RATT report by describing flood impacts that have occurred since then, and to evaluate a longer history of river behavior in light of additional flooding. The approach was similar to that of 2011, as we again visited a series of flood-impacted sites accompanied by local agency personnel and landowners to discuss site conditions and concerns (Figure 1). In total we visited with 27 landowners to review a total of 50 issues that were addressed in landowner-specific writeups. Those site writeups were sent to each landowner via email and surface mail, along with an addendum describing bank armoring considerations.

The site reports were also provided to the local Conservation Districts. The intent here is not to describe each site individually, but to look at river responses since 2011 as more of a pattern that can help stakeholders look at longer-term evolution of the river, and thereby develop rehabilitation, restoration, and management strategies that are thoughtful and cost-effective in this highly altered river corridor.

Figure 1. River Assessment Triage Team (RATT) observing a damaged pump site below Roundup.

1.3 Acknowledgements

The RATT team is comprised of Karin Boyd (Applied Geomorphology, Inc.) Warren Kellogg (Stream and Watershed Planning), and Mike Ruggles (Montana Fish, Wildlife, and Parks). We extend our sincere thanks to Laura Nowlin and Bill Milton of MWC for their vision and persistence in the promotion of collaborative approaches to water management in the Musselshell River basin. MWC was instrumental in providing background information and scheduling site visits. Carie Hess of Petroleum County

Conservation District held a portion of the contract and we thank the CD for their willingness to assist this project with funding and contract management. The US Army Corps of Engineers provided recent imagery from several sites and we appreciate their help. We would also like to thank all of the producers of the Musselshell River Valley who requested our assistance, provided access to their lands, and shared their experiences regarding the nature of the flooding, its impacts, and associated challenges they currently face. Many of their quotes are in callout boxes in this report; their observations of river process were keen. While out walking the river, we were often reminded of our 2011 RATT colleague and friend Tom Pick, whose wisdom and humor was greatly missed this time around; we are forever grateful to Tom for his dedicated contributions to our work.

2 Project Location and General Conditions

For a more detailed summary of background conditions, please refer to the 2011 RATT Report (Boyd, et al., 2012). This section will briefly summarize those conditions for general context.

The Musselshell River drainage consists of approximately 8,000 square miles of central Montana (Figure 2). Elevations range from about 9,000 feet on the northern slopes of the Crazy Mountains in southern Meagher County to approximately 2,000 feet at the river mouth in northern Petroleum/Garfield Counties. The general terrain includes expansive grass and shrub lands, broken and rolling foothills, and a low density drainage network. The largest town in the area is Roundup, which is located near the middle of the watershed in west-central Musselshell County and has a population of about 2,000 people.

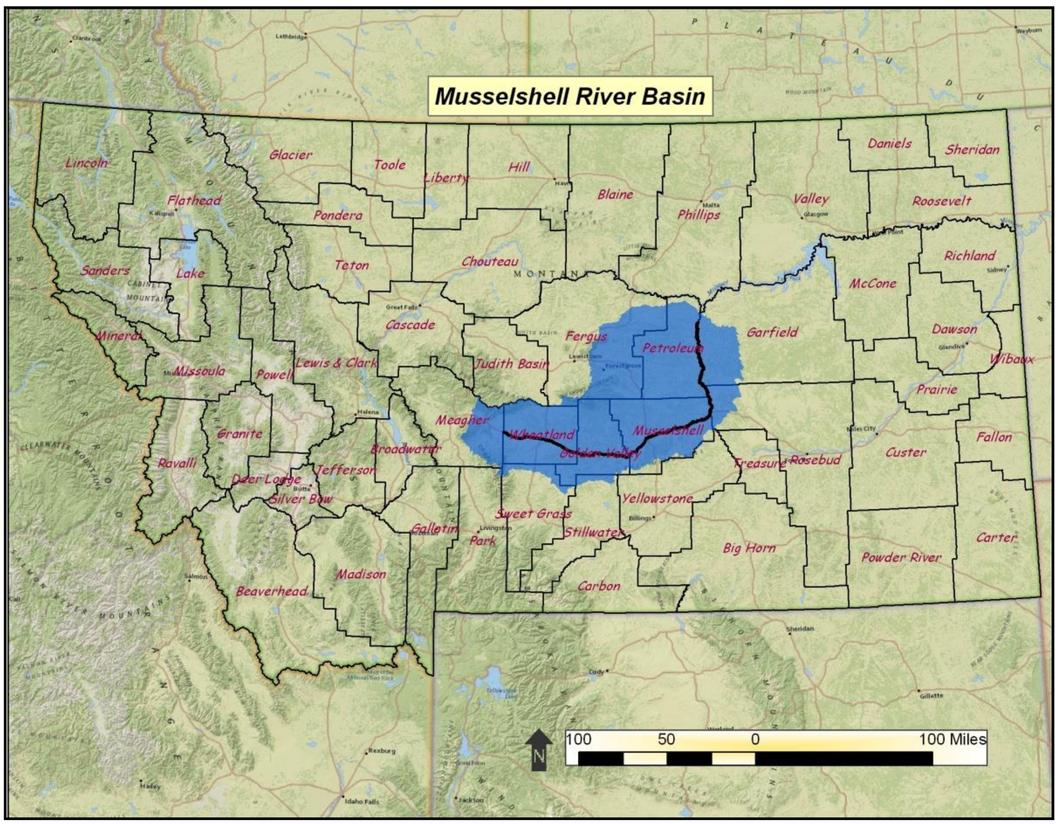


Figure 2. Musselshell Watershed in Montana, with assessment reach (black line) and counties labeled.

The main stem of the Musselshell River flows from the confluence of the North and South Forks near Martinsdale for nearly 340 miles to Fort Peck Reservoir. The River Assessment Triage Team (RATT) covered this entire extent of river, with field sites ranging from west of Harlowton to north of Mosby. Tributaries to the Musselshell River were not included in the project area.

Figure 3 shows a map of the overall project area and River Mile references for major points of interest are listed in Table 1.

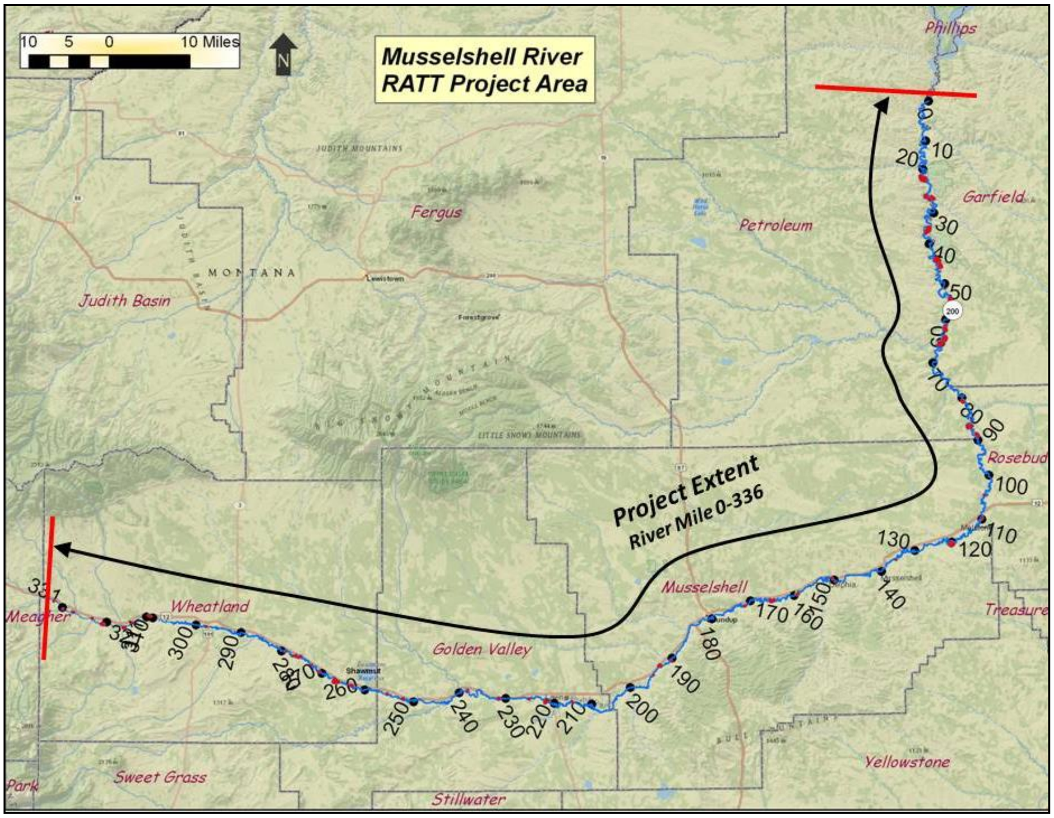


Figure 3. River Assessment Triage Team (RATT) Project Area; 2011 river miles are shown on digitized river centerline.

Table 1. 2011 River Mile locations of major features, Musselshell River Valley

Location	2011 River Mile (RM)	Location	2011 River Mile (RM)
Mouth (CMR Wildlife Refuge)	0	Delphia	150.5
Lodgepole Creek	8	Roundup	181
Dovetail Creek	14	Bundy	204
Blood Creek	19.7	Lavina	219.5
Calf Creek	27.3	Careless Creek	239.2
Hwy 200 (Mosby)	56.8	Ryegate	246.2
Flatwillow Creek	65	Barber	256
Garfield/Rosebud County Line	76.5	Shawmut	268
North Willow Creek	76.6	Harlowton	298
Melstone	115	South Fork Musselshell	335.9
Musselshell	140.5		

3 Major Human Influences on River Function

The history of human development in the Musselshell River corridor plays directly into its flood response, current condition, and anticipated trajectory. These major influences include floodplain development in support of transportation and agriculture, water development including diversion structures and pumps, and erosion control measures such as riprap. As discussed in subsequent sections, these activities have contributed to the instabilities generated in recent years.

3.1.1 The Milwaukee Railroad

When the Milwaukee Road was constructed in the early 20th Century, the Musselshell River was dramatically altered to accommodate the railroad right-of-way. To minimize both the length of track and the need for bridges, the river was extensively straightened and shortened between Melstone and Two Dot. According to an article in the Billings Gazette (Graetz, 2003), "In building the route [through the Musselshell River Valley], workers moved the river's channel more than 100 times". In the GIS project for the 2011 RATT study, a total of 82 meanders were mapped that are currently isolated behind the abandoned rail line. Figure 4 shows an example of several isolated channel segments a few miles upstream (west) of Musselshell. The Musselshell River Assessment Report (Lower Musselshell Conservation District, 2004) describes 140 meanders as shortened or cut off from the river, indicating that our mapping results are conservative.

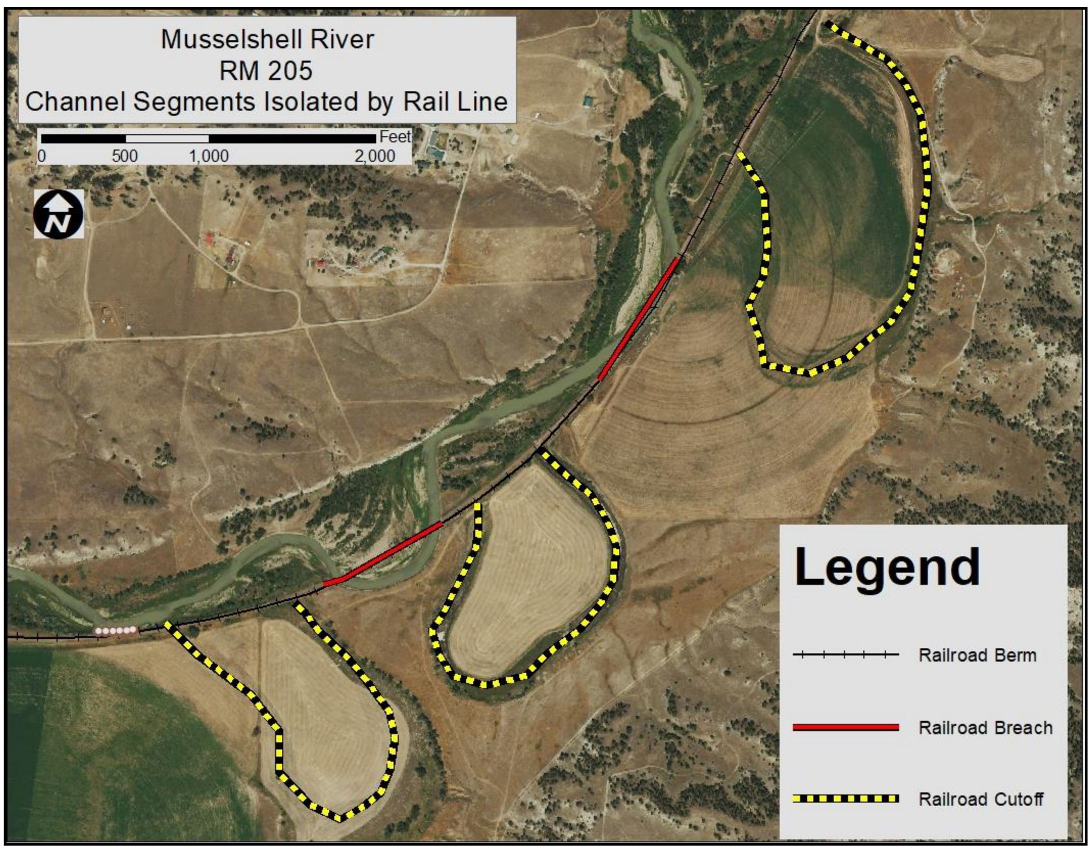


Figure 4. 2011 Air photo showing mapped meander segments isolated by rail berm above Musselshell.

3.1.2 Channelization/Straightening

In addition to the straightening by the railroad in the early 20th Century, the river has been shortened as part of agricultural development as well. In looking at LiDAR data and older imagery it is clear that excavation of "cutoff trenches" was a pervasive practice, presumably intended to relocate the river away from fields (Figure 5).

Figure 5. Example of a cutoff trench dug by 1979 that drove an avulsion by 1995; trench is about 1,200 feet long.

3.1.3 Bank Armoring

Bank armoring is common on the river, especially where fixed infrastructure (bridges, pumps, canals) or productive fields have been threatened by bank erosion. Most armor consists of either flow deflectors or rock riprap (Figure 6). This armoring has locally arrested channel migration and hardened the location of the river, sometimes in locations where the river has been intentionally straightened.

Figure 6. Example flow deflector (left) and rock riprap (right) placed to protect infrastructure.

3.1.4 Diversion Structures

Irrigation is the lifeblood of most agricultural operations in the Musselshell River valley. We mapped 23 channel spanning diversions on the river (Table 1). In 2011, four of those diversions (Newton/Pedrazzi, Naderman, Anderson, and Egge) were visited by the RATT team as they were completely breached by the flood. None of these structures have been rebuilt to date. Figure 7 shows an example flanked dam (Egge); the structure has since been removed and the adjacent streambank area restored with bioengineered bank treatments (see Section 9.2.2 for more details). In addition to diversions, irrigation pumps are very common on the river with portable pumps becoming increasingly popular (Figure 8).

Table 2. Diversion structures mapped below Two Dot, with 2017 status listed.

Diversion Name	River Mile	Status 2017	Comment
Korenco	137.4	Intact	Downstream of Delphia Melstone Siphon
Musselshell	140.2	Intact	At Musselshell
Delphia	155.3	Intact	
Davis	147.2	Intact	
Goffena/Kruger	157.7	Intact	Feeds Kruger Spendiff Ditch
Kilby Butte	165.2	Intact	Bank Erosion upstream in 2018
Newton Pedrazzi	177.5	FLANKED	Flanked in 2011; shifted to pumps
Clements	187.5	Intact	Rodeghiero
Naderman	194.3	FLANKED	Flanked in 2011; shifted to pumps
Parrott	202.7	Intact	
Anderson	205.5	FLANKED	Flanked in 2011
Egge	209.8	FLANKED	Flanked in 2011; shifted to pumps
Lavina	227	Intact	
Name?	228.9	Intact	Above Cushman Bridge
Deadmans	278.5	Intact/Repaired	Fish passsage added post-2011
Agriservices	280	Intact	
Clements Ranch	285	Intact	
Springwater Colony 2	287.8	Intact	Just downstream of American Fork
Springwater Colony 1	290.7	Intact	
Name?	295.3	Intact	Aboer Red Bridge Road near Harlowton
Name?	301	Appears Intact	Below Milton Creek
Harlowton East Arden	303.1	Intact	Avulsion in process around structure
Two Dot	325	Intact	

Figure 7. View upstream of Egge Dam after its flanking and prior to its removal following the 2011 flood.

Figure 8. Example portable pump on lower river (2011).

3.1.5 Floodplain Clearing

Floodplain development over the last century has included the conversion of riparian forest to irrigated fields. Hundreds of acres of riparian floodplain have been cleared, most of which occurred prior to the 1950s. Figure 9 shows a photo of the floodplain condition in the early 2000s, with a farmed high bench next to the active channel, and a relatively low poorly vegetated inset surface on the other. Figure 10 shows riparian clearing and field development that occurred sometime between 1953 and 1979; also note the constructed trench in this photo sequence that captured and moved the river to accommodate the newly developed field.

Figure 9. Developed floodplain, Musselshell River (Musselshell Conservation District, 2004).

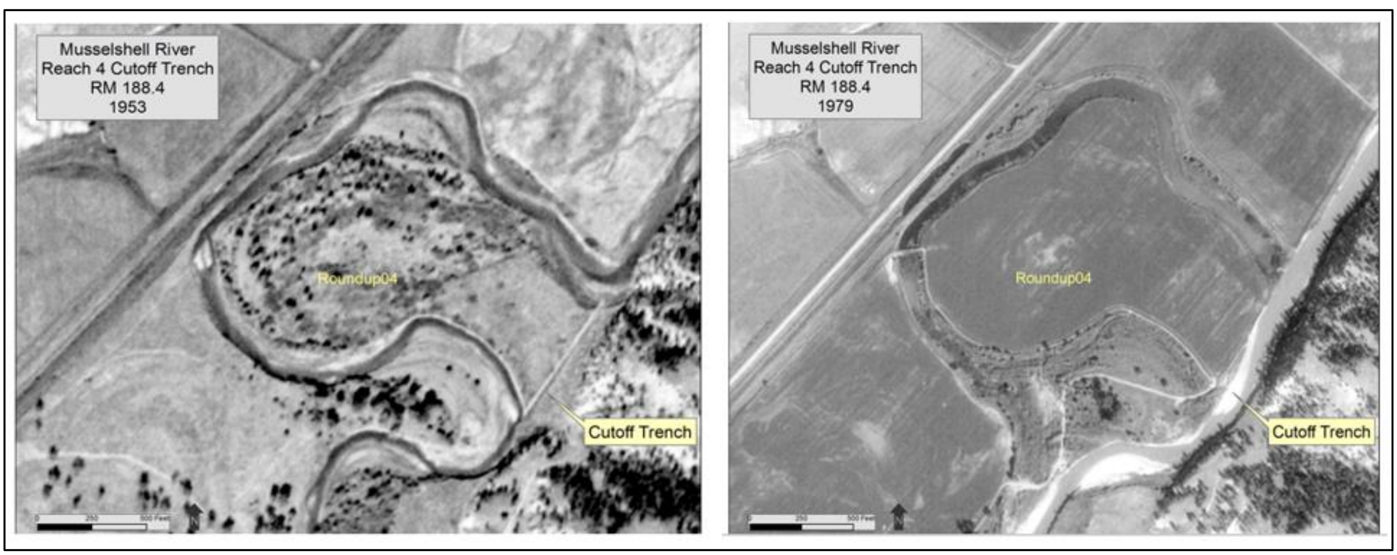


Figure 10. Air photo comparison from 1953 (left) and 1979 (right) showing clearing of woody riparian vegetation as part of field development.

3.1.6 Summary

The collective impact of human influences in the valley bottom since the early 20th Century created a river corridor that had limited ability to emerge from a major flood unscathed. Major contributing factors to this lack of resiliency include the following:

- An over-steepened channel that had been purposefully shortened by the railroad and subsequent development of the floodplain.
- High streambanks due to channel downcutting in response to the straightening. This also caused a drop in the water table and perching of adjacent floodplain.
- Floodplain restrictions due to the railroad grade, perched irrigation laterals, roads, etc. that diminished the ability of the floodplain to dissipate energy during high water events.
- A floodplain cleared of riparian forest that once provided more roughness and erosion resistance. The altered floodplain no longer has the same ability to dissipate high-energy flows, capture nutrient-rich sediment, or promote shallow aquifer infiltration that augments late summer flow.
- Ever-expanding bank armor designed to stop channel movement, precluding natural recovery from straightening.

As discussed in the next section, the flood history of the river has also played a role in its evolution.

4 Flood History

The Musselshell River is a predominantly snowmelt-fed system that typically floods in the spring until about mid-June, when flows typically reach on the order of 800 cfs at Roundup. Flows may drop to a trickle in late summer and early fall unless off-stream storage is supporting the system.

4.1 Flood Measurements at Roundup

The USGS stream gage for the Musselshell River at Roundup has been operation since 1946. Figure 11 shows the highest flow (peak) measured each year since then. The plot shows that floods have generally clustered from about 1975 to 1982 and from 2011 to present. Another important aspect of the plot is the long period of low peak flows from about 1983-2010. As discussed in later sections of this report, this low flow period set up a vulnerable pre-flood condition prior to the 2011 event.

The two largest floods ever recorded at Roundup happened in the last eight years; in the spring of 2011 and late winter of 2014. The 2011 event is the flood of record, having peaked at 15,000 cfs at Roundup (Figure 11). The recent hydrologic analysis by Pioneer Technical Services (Pioneer, 2015) indicate that, at Roundup, the 2011 event was just under a 100-year event, and the 2014 event was about a 50-year flood. The 2011 flood crested in late May and was driven by spring rains on a late heavy snowpack. In contrast, the 2014 event occurred in early March and was driven by ice-related flooding.

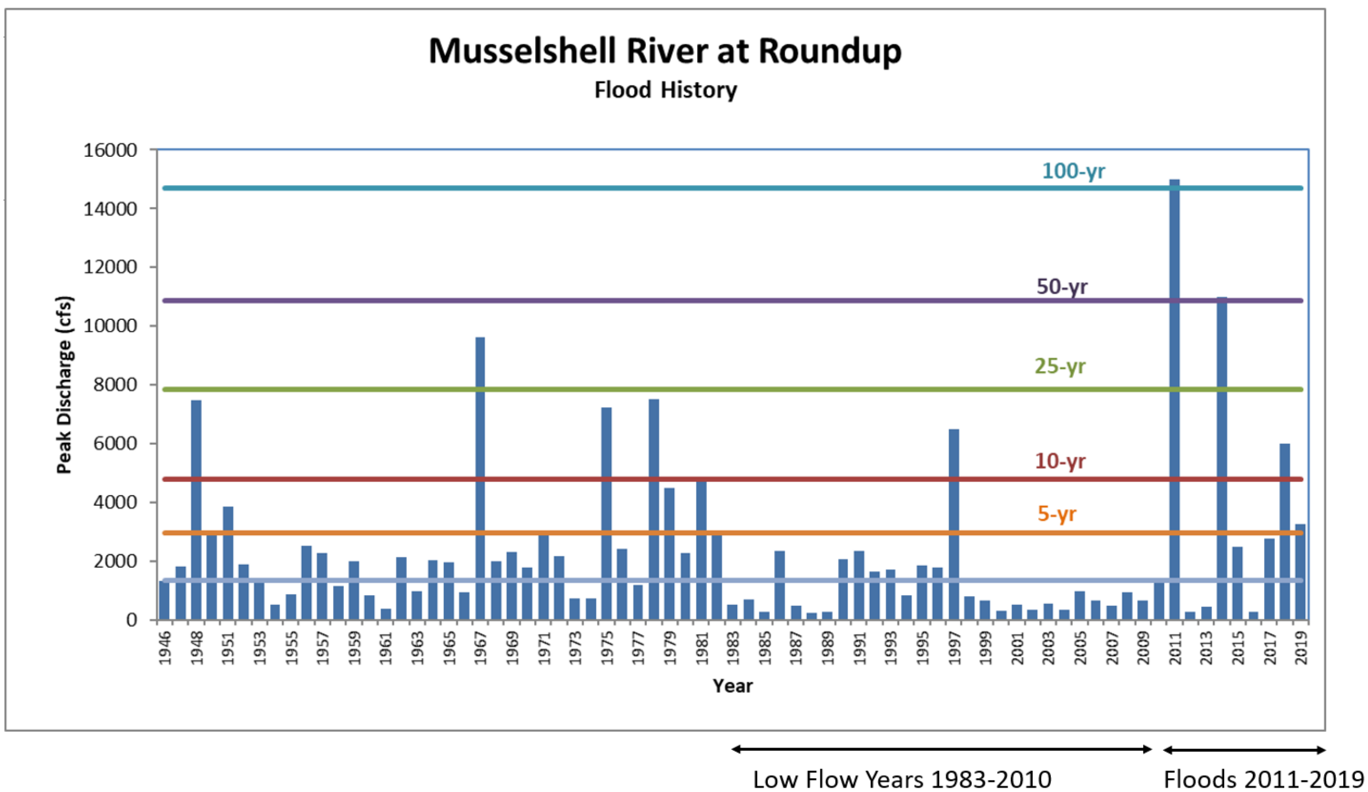


Figure 11. Flood history for Musselshell River near Roundup (flood frequencies from Pioneer, 2015).

Another important flood occurred on the upper river in 2018. Although this flood had a much smaller peak than 2011, it still reached a 10-year flood. Figure 12 shows hydrographs for the 2011 and 2018 events. Both has two distinct peaks, making them especially difficult to cope with in early summer.

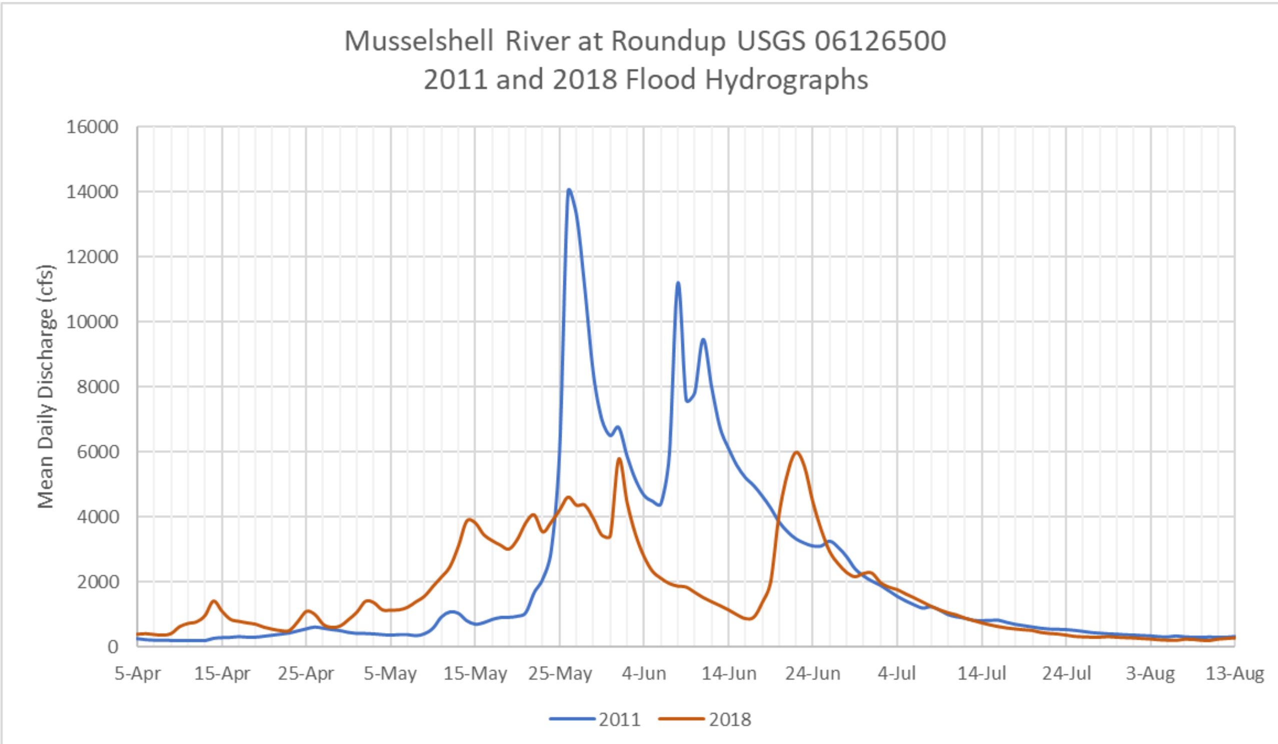


Figure 12. Mean daily flow hydrographs for 2011 and 2018 floods at Roundup.

4.2 Flood Measurements at Mosby

The gage at Mosby has been active since 1929. At this site, the 2011 event was about a 50-year flood and the 2014 flood was over a 25-year (Figure 13). The 2018 flood was also important at Mosby, because it lasted for weeks (Figure 14). Whereas the 2014 flood in Roundup was driven by ice in March, down in Mosby the 2014 flood happened in August and was driven by flooding on Flatwillow Creek (Figure 15).

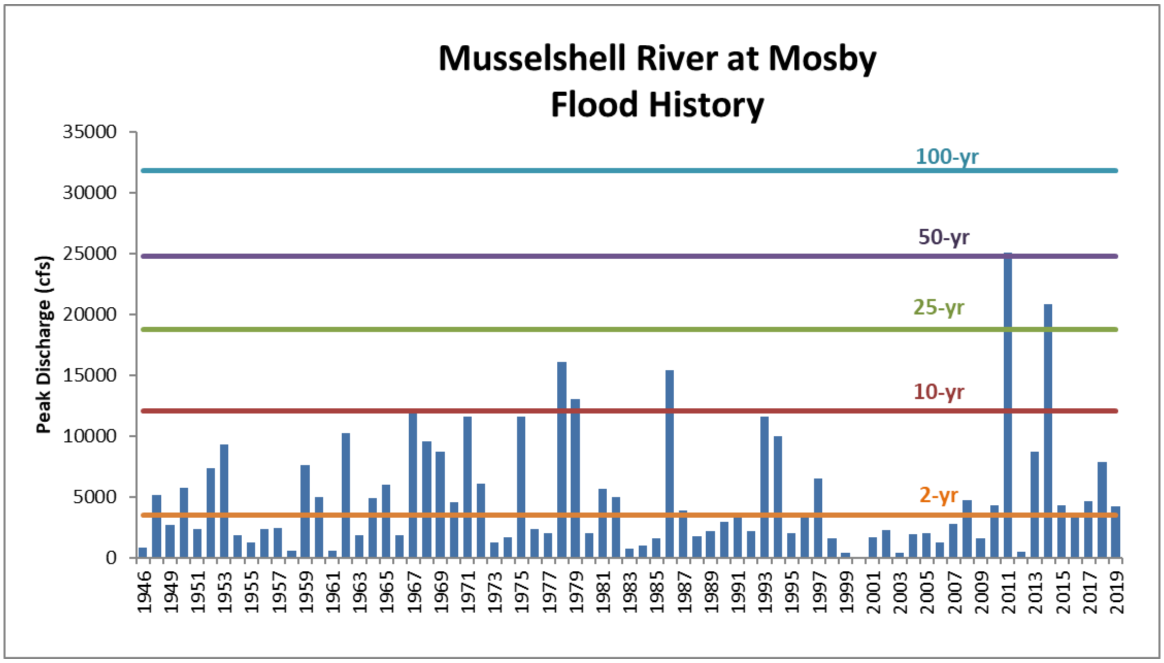


Figure 13. Flood history for Musselshell River at Mosby (flood frequencies from Pioneer, 2015).

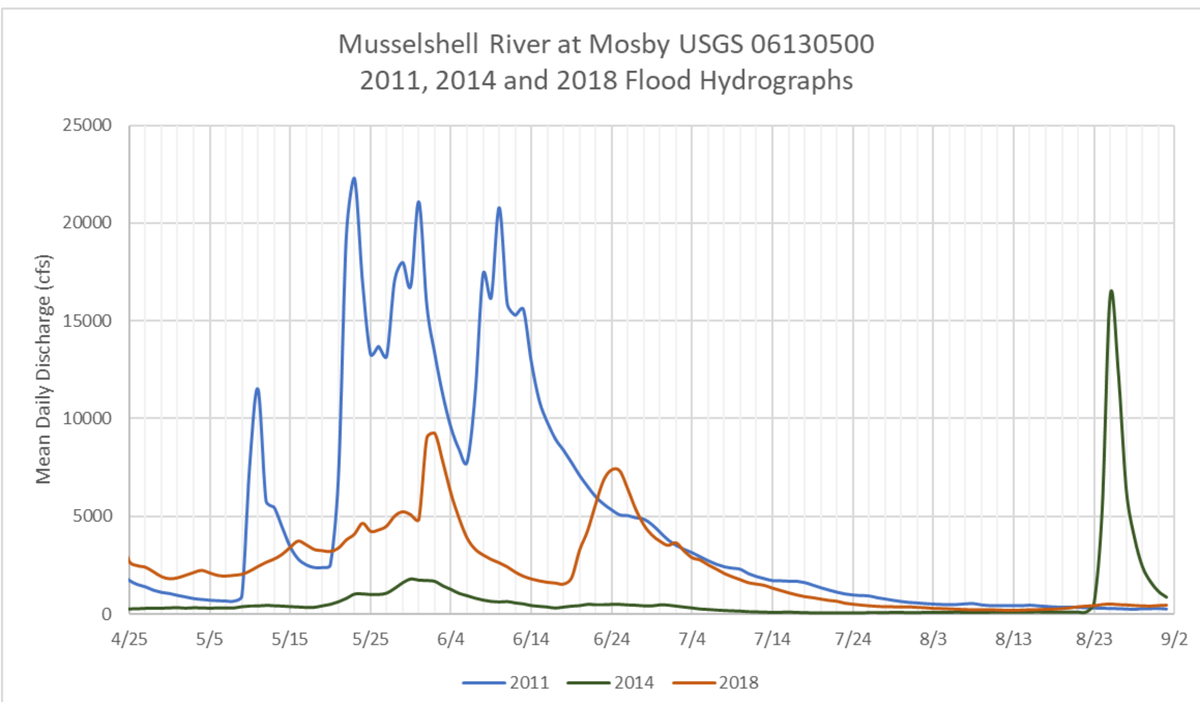


Figure 14. Mean daily flow hydrographs for recent floods at Mosby.

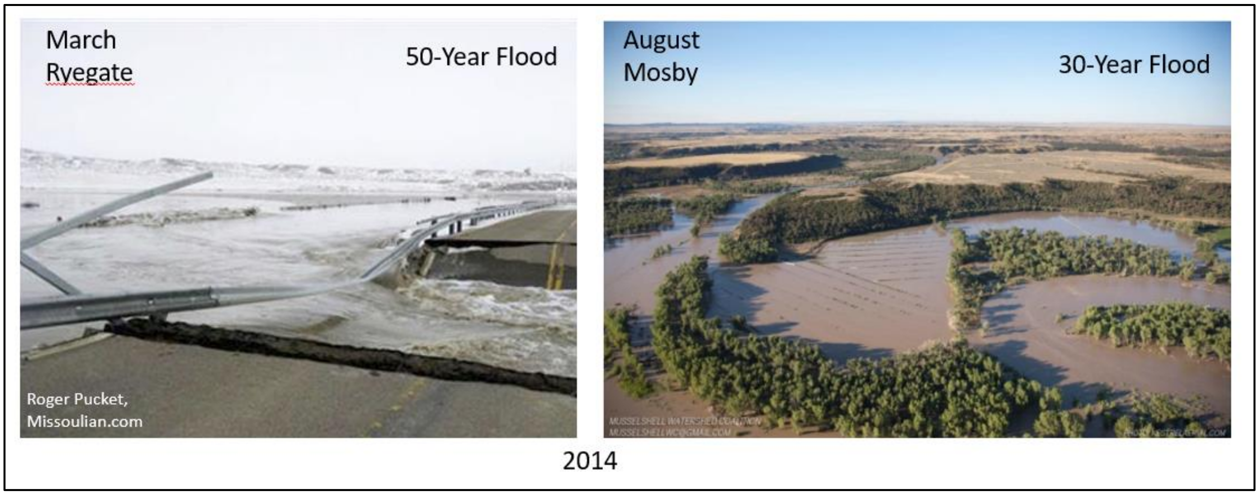


Figure 15. Photos from the 2014 flood showing March ice-jam flooding in Ryegate and August flooding at Mosby (Missoula.com and Kestrel Aerial Services).

4.3 Duration of Bankfull Flows

The duration of the floods is more important than the peak discharge when considering how much work is done on a stream channel. To that end, the 2-year flood ("Q2") is commonly used as an estimate of the "channel forming flow", or that flow that is responsible for developing and maintaining the size of the river. The Q2 is about equal to the flow that fills the stream channel, and in snowmelt systems it is typically exceeded for about 11 days on average.

Figure 16 shows the number of days that Q2 was exceeded for the major floods described above. Although the 2011 event dwarfed the 2018 flood in terms of peak discharge, they were quite similar in terms of how long the channel saw bankfull flows, with the 2018 event being especially long in Roundup (almost two months over bankfull). And as far as the 2014 events go, they were clearly short-lived pulse floods.

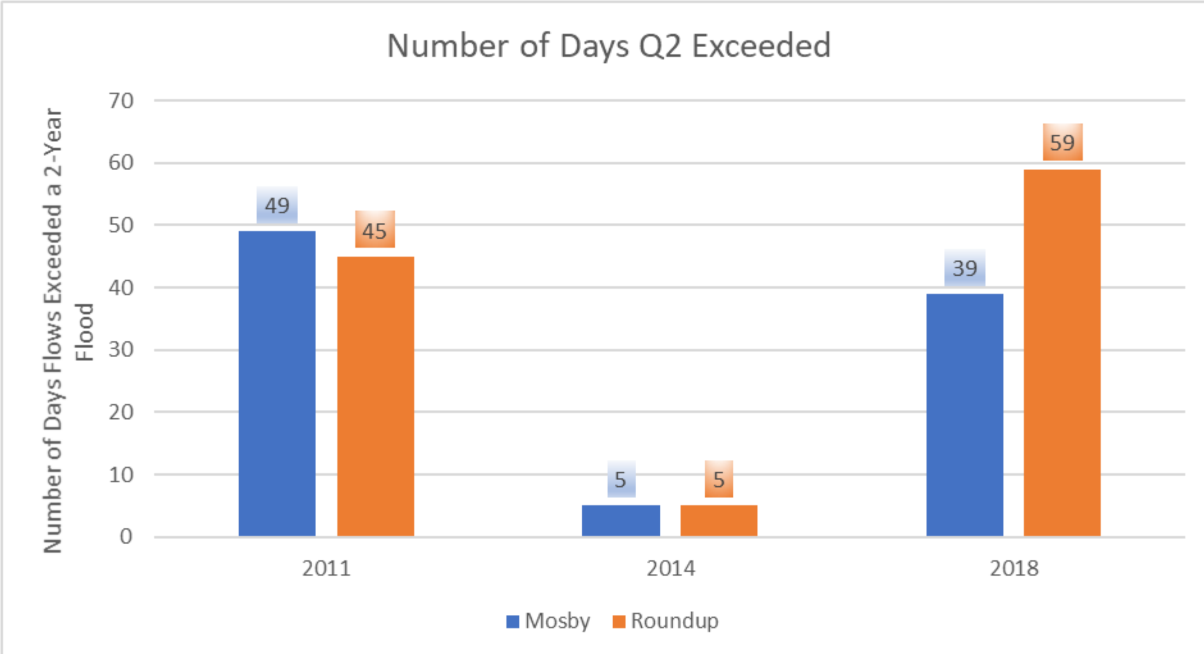


Figure 16. Number of days the 2-year flood was exceeded at Mosby and Roundup in 2011, 2014, and 2018.

The last decade has been unprecedented in terms of flooding on the Musselshell River. In addition to the floods described above, the 2-year flow was well-exceeded in 2015, 2017, and 2019. Over the past nine years, the annual peak flow was less than the 2-year flood only once, in 2012.

5 The RATT II 2018 Site Visits—Observations

During the fall of 2018, the RATT team visited 29 landowners between Two Dot and Fort Peck Reservoir (Figure 17). We wrote 27 individual site reports for landowners that covered about 50 specific issues. In each of the reports we summarized site characteristics and provided recommendations to landowners. Unfortunately, we did not have system-wide air photos that could capture the overall impacts of the 2018 flood, although NAIP (National Agriculture Imagery Program) imagery should be flown in the fall of 2019 and become available sometime the following year. We did request more recent site-specific air photos from the Corps of Engineers and were able to use them to show localized channel changes at several sites. The following section summarizes the primary themes of our visits. The general recurring issues were rapid channel migration and bank erosion, channel widening, slope instability, avulsions and loss of bank armor.

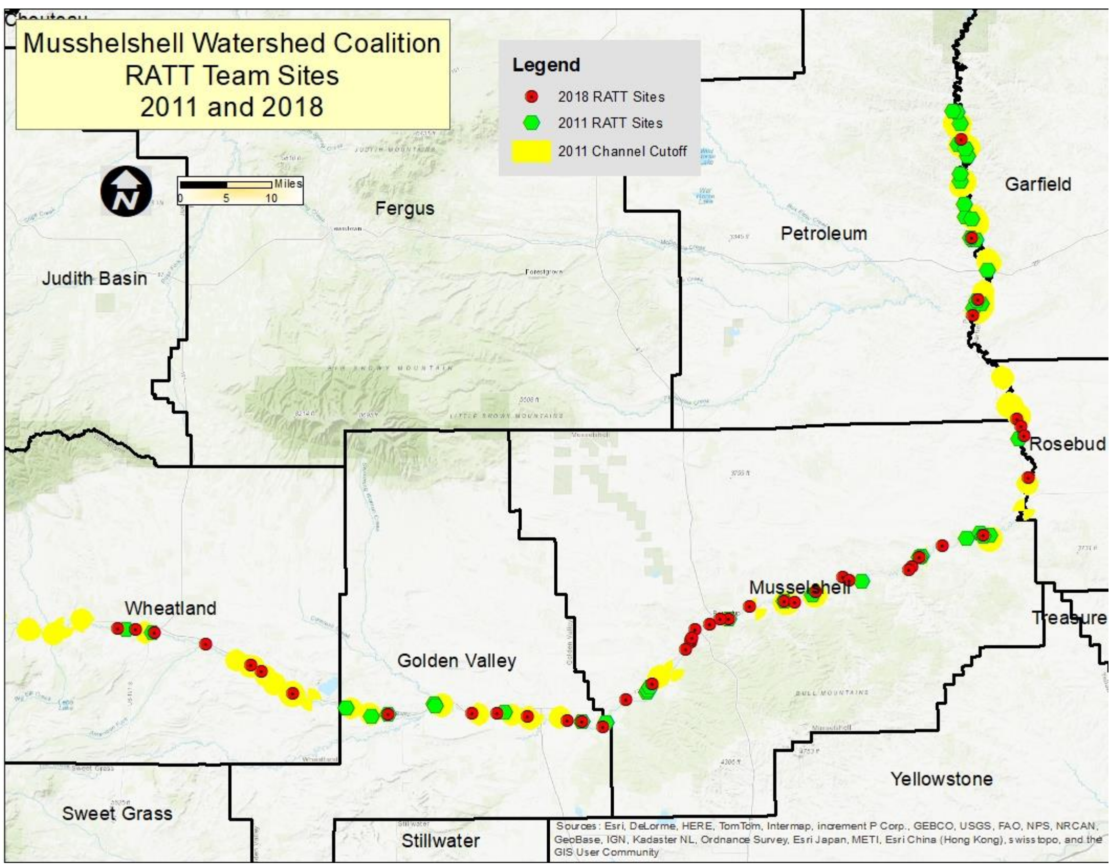


Figure 17. RATT sites visited in 2011 (green) and 2018 (red); yellow points mark 2011 avulsions.

5.1.1 Bank Erosion

Bank erosion was the most common problem we were shown on the river. In many cases this erosion took out pump sites (Figure 18 and Figure 19) or fences (Figure 20). In places outside bend erosion during the 2018 flood exceeded 100 feet. Typically, the biggest problems were where the erosion was threatening infrastructure or roads. Figure 21 shows high bank erosion into a field road and Figure 22 shows erosion into an access road (old railroad grade) just downstream of the Delphia-Melstone siphon.

Where we had post-2018 flood air photos, we mapped banklines to determine the rates and extents of bank movement for landowners. At one site above the Number 4 Road, for example, bank movement during the 2018 event eroded about four acres of a hayfield within one river bend (Figure 23).

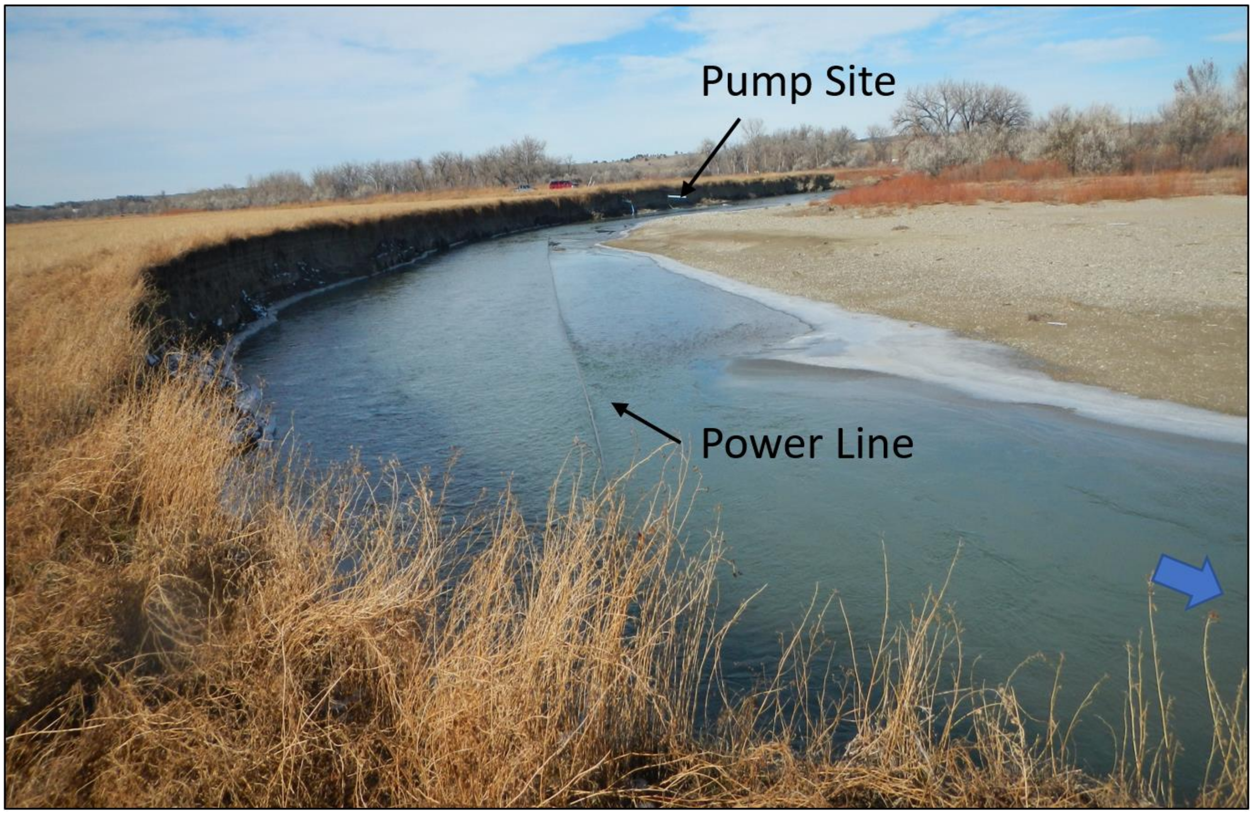


Figure 18. View upstream towards pump site showing electrical line in middle of river above Roundup.

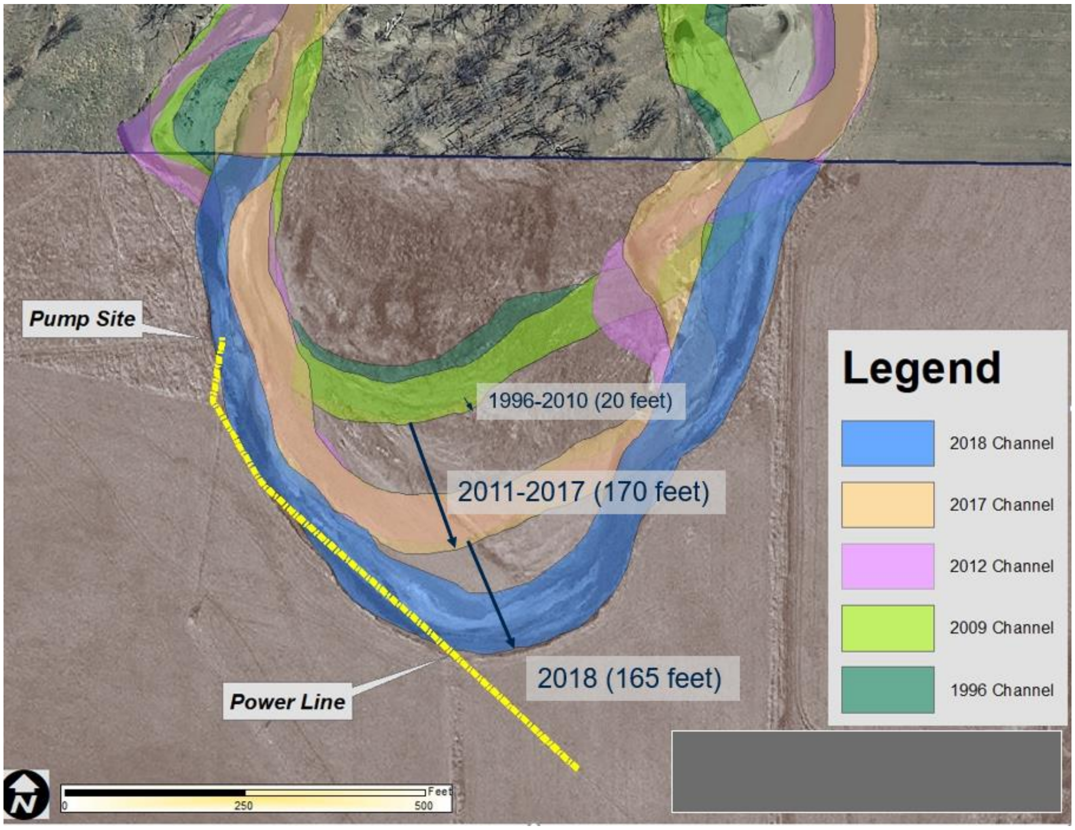


Figure 19. Digitized banklines for site shown in Figure 18.

Figure 20. View upstream of erosion through fenceline above Roundup.

Figure 21. View upstream of high bank erosion into road below Mosby.

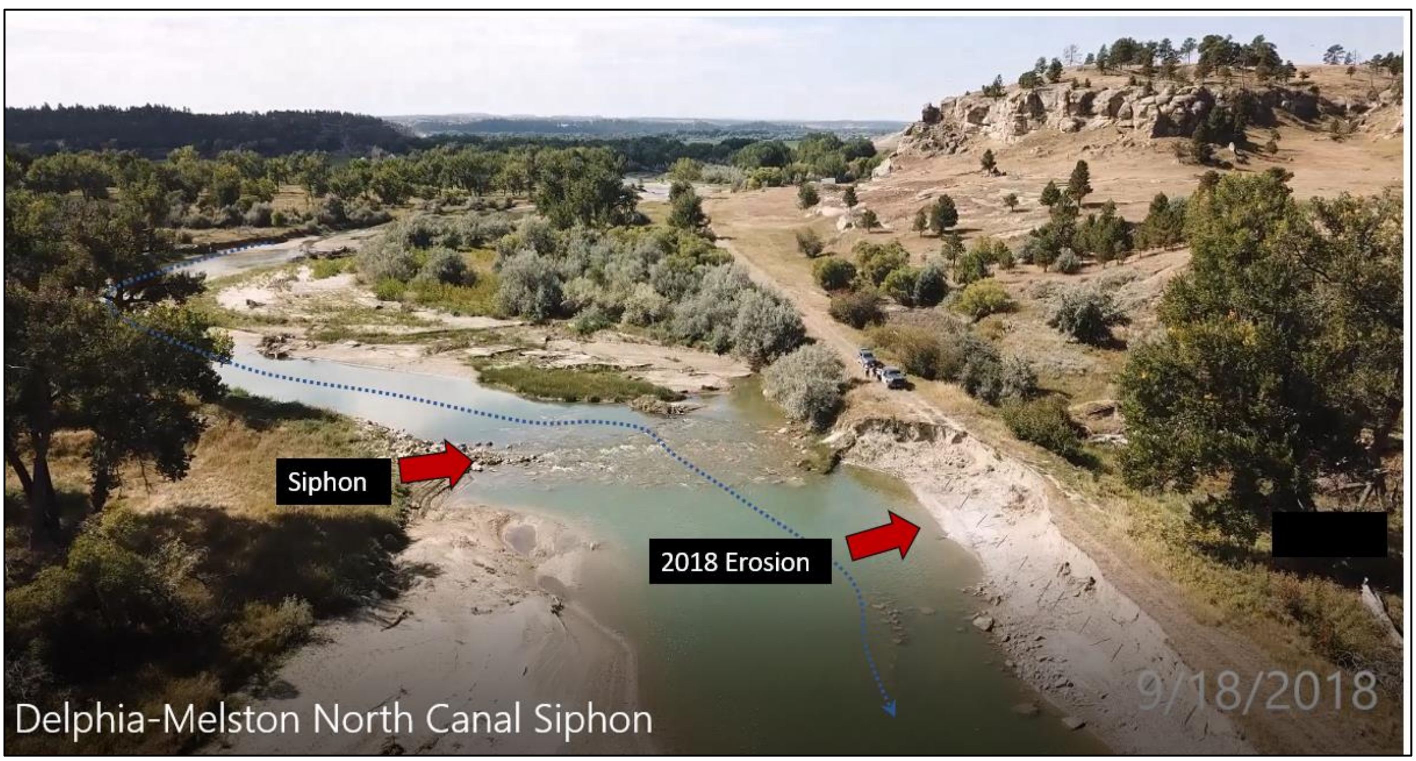


Figure 22. View upstream showing 2018 erosion just below rocked siphon crossing.

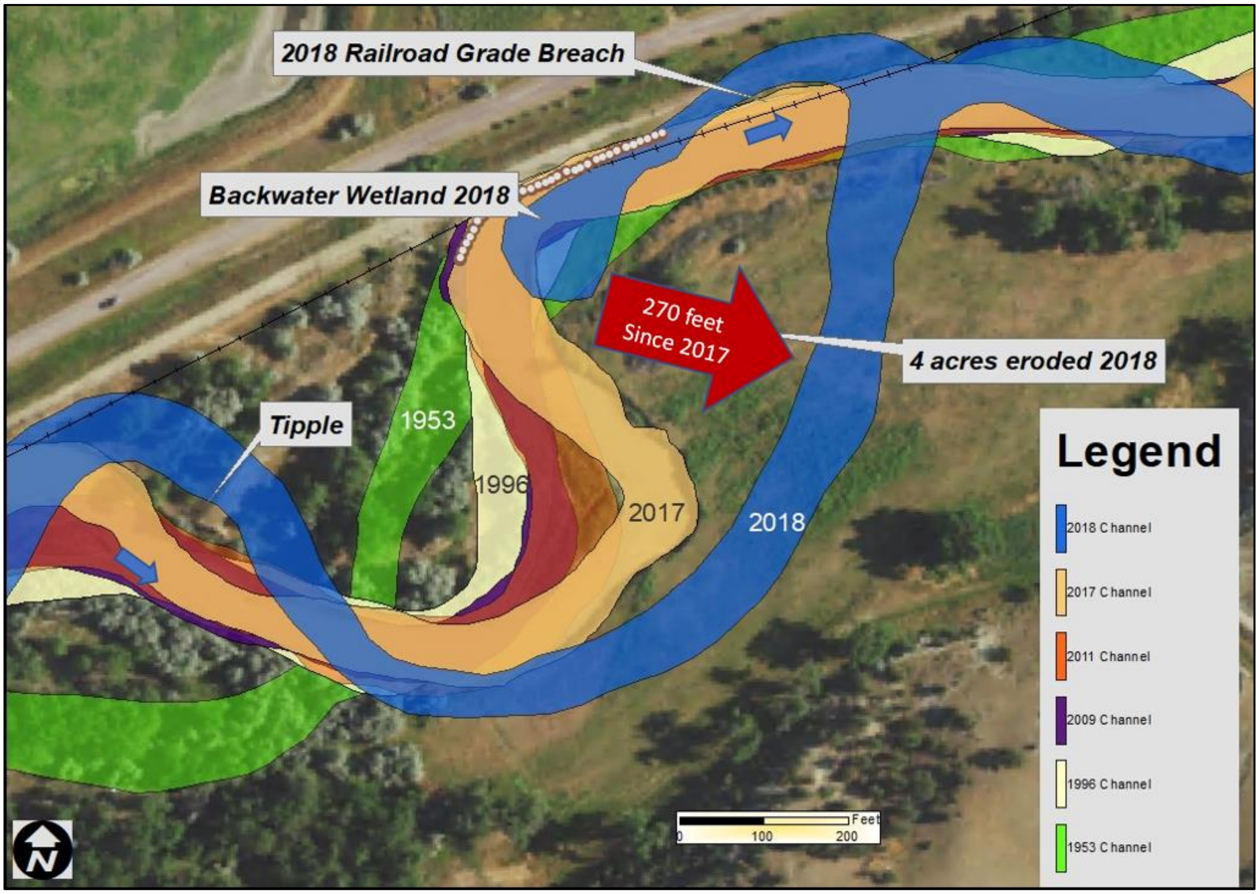


Figure 23. Mapped banklines below Roundup showing four acres of field erosion in 2018.

The severe bank erosion seen since 2011 can be attributed to long high flow periods that transported massive sediment loads, building point bars that put additional pressure on cutbanks, driving the channel migration process (Figure 24). The process is somewhat self-perpetuating during long duration floods, as the erosion incorporates sediment into the channel that builds a point bar downstream, driving more erosion and incorporating more sediment. The underlying driver for this is the “regaining” of length on a river that has been straightened by both intentional projects and the 2011 flood. Figure 25 shows an example area below Mosby where a large 2011 cutoff was followed by channel re-lengthening. This process is an important aspect of the geomorphic evolution of the river and is discussed in more detail in Chapter 6.

Figure 24. View downstream showing storage tank on right bank and large point bar on opposite side driving erosion.

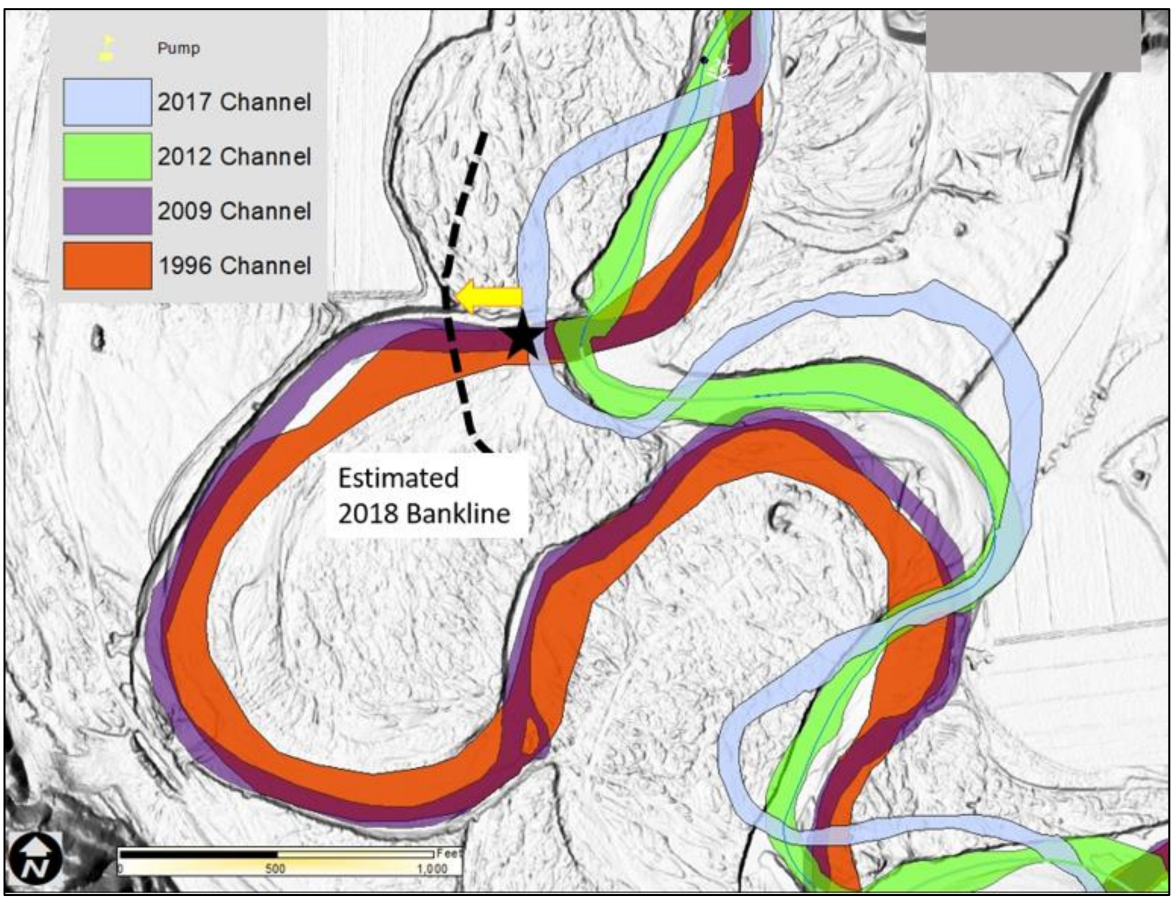


Figure 25. Channel migration through time below Mosby; note lengthening following 2011 cutoffs. The black star marks a pump site that was eroded out during 2018 flood.

In many cases, the erosion has geotechnically destabilized banks that will continue to change, even with moderate river flows. Figure 26 and Figure 27 show a site below Mosby where erosion of a high bankline against a pond has caused the development of deep tension cracks on the topbank that will continue to destabilize the bank.

Figure 26. View downstream showing pond, headcutting spillway, and cabin at risk.

Figure 27. View upstream showing tension cracks in bluff between river and pond.

Our recommendations for managing bank erosion depended on the risk it created. As discussed later in this document, the ability for the river to lengthen through erosion is an important aspect of its geomorphic stabilization. To that end, we tried to limit hard armor recommendations to areas where there was essentially no tolerance for bank movement. In other areas, it may be possible to use softer armor techniques that will help recover vegetation on the banklines and slow the rate of bank movement without stopping it entirely. When we provided landowners site reports, we included a bank protection supplement to help them consider options for addressing erosion. That document is included in this report as Appendix A.

5.1.2 Avulsions

An ***avulsion*** is the rapid carving of a new channel through a floodplain surface that captures the flow of the main channel thread. Avulsions typically form by headcutting, where a new channel erodes in an up-valley direction, starting from a headcut formed where overbank flows re-enter the main channel over a steep bank (Figure 28). We mapped a total of 59 avulsions as having occurred during the 2011 flood, abandoning about 37 miles of channel. The most shortening in 2011 was below Flatwillow Creek, where the river lost over 20% of its total length (Figure 29). Most of these avulsions cut through the cores of long meander bends, cutting off the bend and leaving a large oxbow on the floodplain. These features are also referred to as "chute cutoffs".

Figure 28. 2011 flood photo of avulsion in process (upstream migrating headcuts) below the Musselshell River Road Bridge (Kestrel Aerial).

Figure 29. Abandoned channel below Mosby resulting from 2011 avulsion/chute cutoff (Kestrel Aerial).

Our site visits in 2018 suggest that avulsions were a less common flood impact compared to 2011, although we won't be able to fully capture how many avulsions happened until 2019 air photos are available. We did evaluate some new avulsions, however, which shortened the river even more since 2011, further steepening the channel slope. Figure 30 shows one example below Roundup, where a new channel cut through a meander core. In these locations we anticipate some downcutting upstream, as well as future bank erosion as the river recovers length. In most cases the avulsions were relatively small and did not appear to significantly threaten agricultural operations, although the new channel routes typically create islands that can be difficult to access during high water. Figure 31 shows an area with two 2018 avulsions that created islands in riparian bottom land. In many cases these avulsions through riparian bottoms can create good fish habitat because the carving of new channels recruits trees to the river that create good habitat elements (cover, scour holes) for fish (Figure 32).

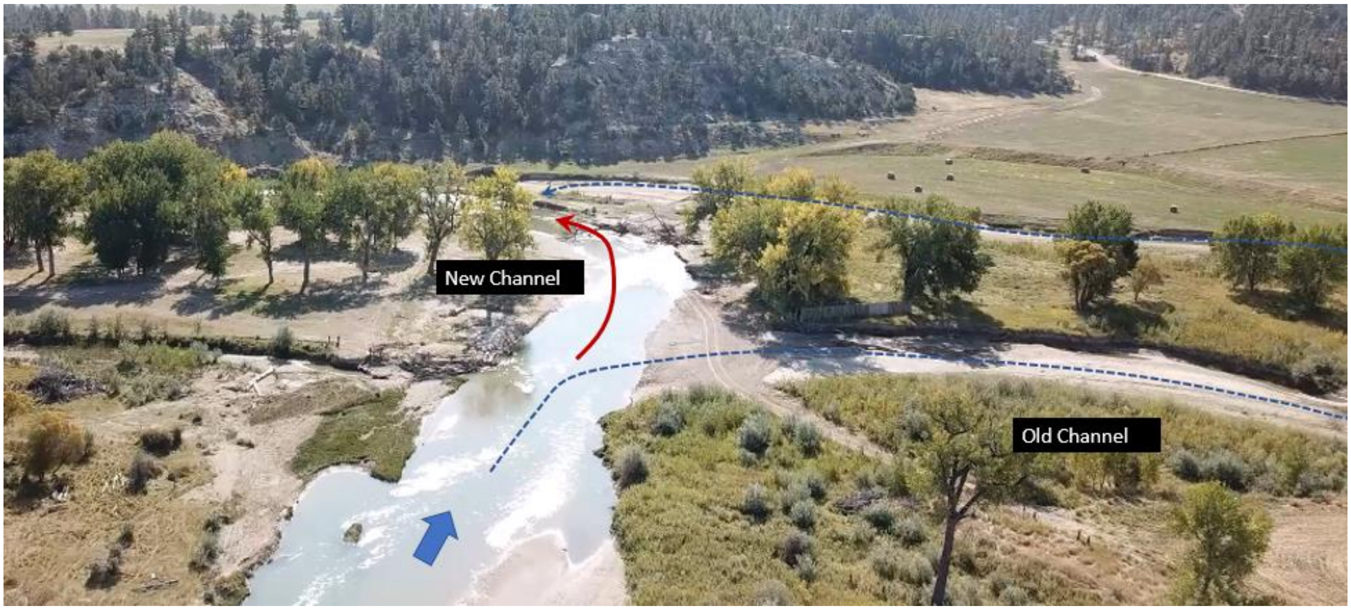


Figure 30. View downstream showing 2018 avulsion (red) that abandoned about 1,500 feet of channel (blue).

Figure 31. Wheatland County site showing conditions in 2012 (top) and 2018 (bottom).

Figure 32. View downstream through avulsion path showing large wood in channel.

The biggest risk to operations with an avulsion tends to be the isolation of pump sites or diversions from the river, as well as the secondary effects of channel steepening and accelerated bank erosion. Avulsions can also isolate fields. Upstream of Harlowton for example, a developing avulsion threatens to bypass a diversion structure (Figure 33). In cases like this it may be most cost-effective to relocate the diversion or consider the conversion to portable pumps.

Figure 33. 2011 air photo showing avulsion channel/meander cutoff.

In understanding the evolution of the Musselshell River, it is important to consider the effect of avulsions on channel slope. Figure 34 and Figure 35 show a site near Shawmut, where a long meander loop cut off in 2018 ("2018 avulsion" labeled in Figure 34). Downstream there is another bend that is highly compressed and at risk of cutting off. The 2012 LiDAR data can be used to draw a topographic profile along the post-avulsion channel path, to show how much the river would steepen through the avulsion path. In Figure 35, for example, the 2018 avulsion created a drop of over 5 feet in the river, with another potential 4-foot drop on the bendway downstream. Because of these drops, floodwaters that flow over the neck of a meander will create a waterfall that will downcut, carving a series of headcuts that migrate up through the avulsion path. Once the avulsion has occurred, this headcutting will continue upstream potentially resulting in channel downcutting well upstream of the avulsion itself.

Figure 34. Northward oblique view of avulsion sites on south channel (flow is left to right).

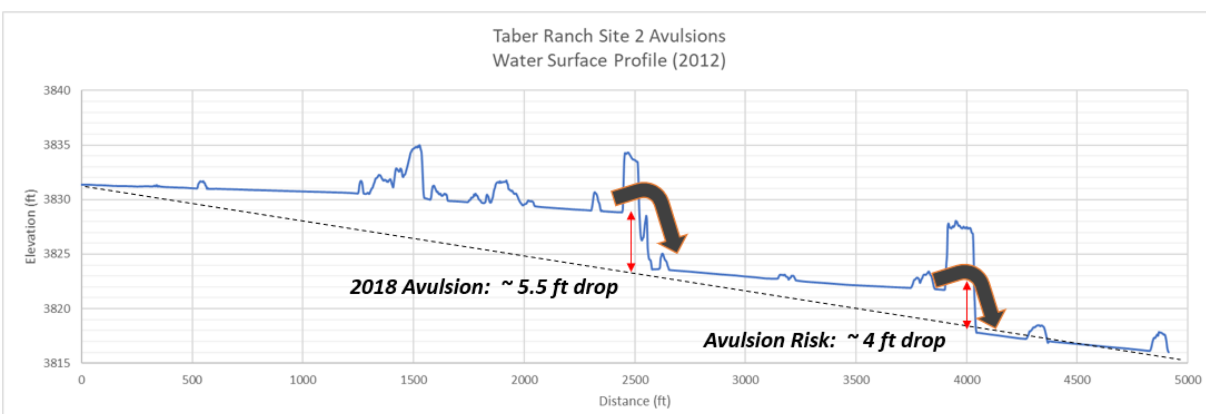


Figure 35. Profile pulled through avulsion paths in Figure 34 showing vertical drops at avulsion points. Dashed line shows potential long-term steepened profile which includes several feet of downcutting above avulsion pints.

Our recommendations regarding avulsions depended entirely on local site conditions. In many cases, no action was warranted because there was no real risk associated with the change, and any restoration would be costly. In a few locations, we recommended re-activating meanders where it appeared economically and geomorphically feasible to recover channel length and reduce the impacts of over-steepening or lost access to infrastructure. These recommendations are discussed further in Chapter 7.

5.1.3 Channel Widening

Another common flood response on the river was channel widening. On the lower river, for example, the channel width has tripled in some areas since 2009 (Figure 36). This widening has been accompanied by large gravel bar formation, bank erosion, and riparian expansion on developing gravel bars.

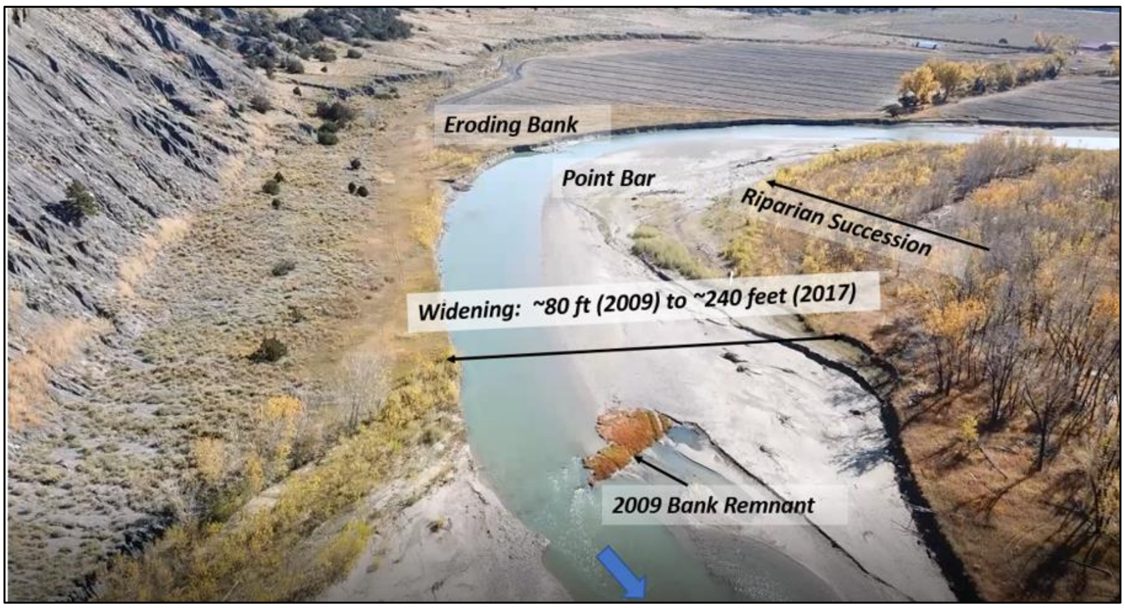


Figure 36. Cumulative impacts of floods on channel process, including widening, point bar formation, bank erosion, and riparian succession (young cottonwood establishment).

5.1.4 Downcutting

One common channel response to straightening is downcutting because as a channel straightens, it steepens and then has more energy to erode its bed. Vertical downcutting may also occur where there is a high density of bank armoring that prevents the river from gaining length by moving laterally. Figure 37 shows an area above Flatwillow Creek where two avulsions shortened the river by over a mile and a half in 2011. In between the two cutoffs, a pump site was damaged by subsequent bank erosion. There was also clear evidence of downcutting at the pump site, where downcutting was intercepted by a natural grade control formed by a shale reef that crossed the river (Figure 38).

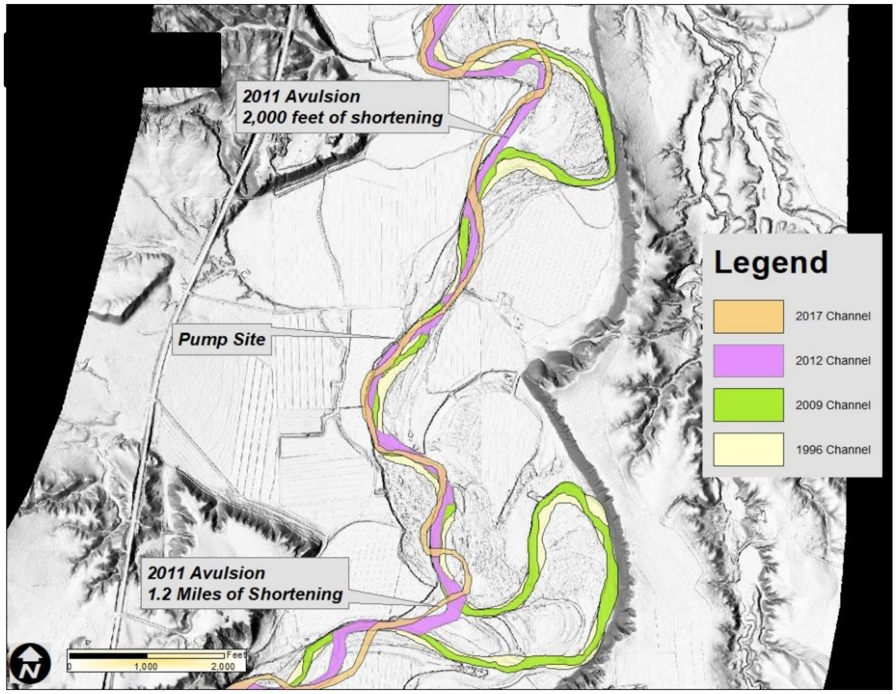


Figure 37. 2012 LiDAR hillshade showing two 2011 avulsions that shortened the river by over 15 miles.

Figure 38. View downstream of headcut in channel bed, caught on a shale reef.

Downcutting was also evident on avulsion paths that were shorter than the pre-2011 channel. Figure 39 and Figure 40 show a steep grade break at a rocked sill that was reinforced through an avulsion path. The “old channel” shown in Figure 39 is the pre-2011 channel. It is clearly longer and much narrower than the modern river. At this location the avulsion shortened the river by 4,200 feet and more than doubled its slope from 0.09% to 0.2%.

Figure 39. Drone image from September 2018 showing rocked sill holding graded on new channel; note much smaller width of old channel in background.

Figure 40. View across river of steep drop across reinforced rock sill.

5.1.5 Future Avulsion or Meander Cutoff Risk

Some sites did not experience avulsions but clearly show high risk for such an event in coming decades. In many cases these risks first developed as "failed avulsions" in 2011, that is, avulsions that did not capture the main channel but carved headcuts into the floodplain. On example of these remnant 2011 headcuts is shown in Figure 41. This Relative Elevation Model shows low elevations in blue and higher elevations in yellow and red. The 2011 headcuts can be seen on the floodplain as fingers that migrated up the valley as the flood progressed (see Figure 28 to see the development of these features). In this case, the fingers never reached the upstream channel so an avulsion did not occur. On the bend shown in Figure 42, however, the 2011 headcuts created a defined avulsion path that was further excavated in 2018, causing an avulsion/cutoff (photo is pre-cutoff).

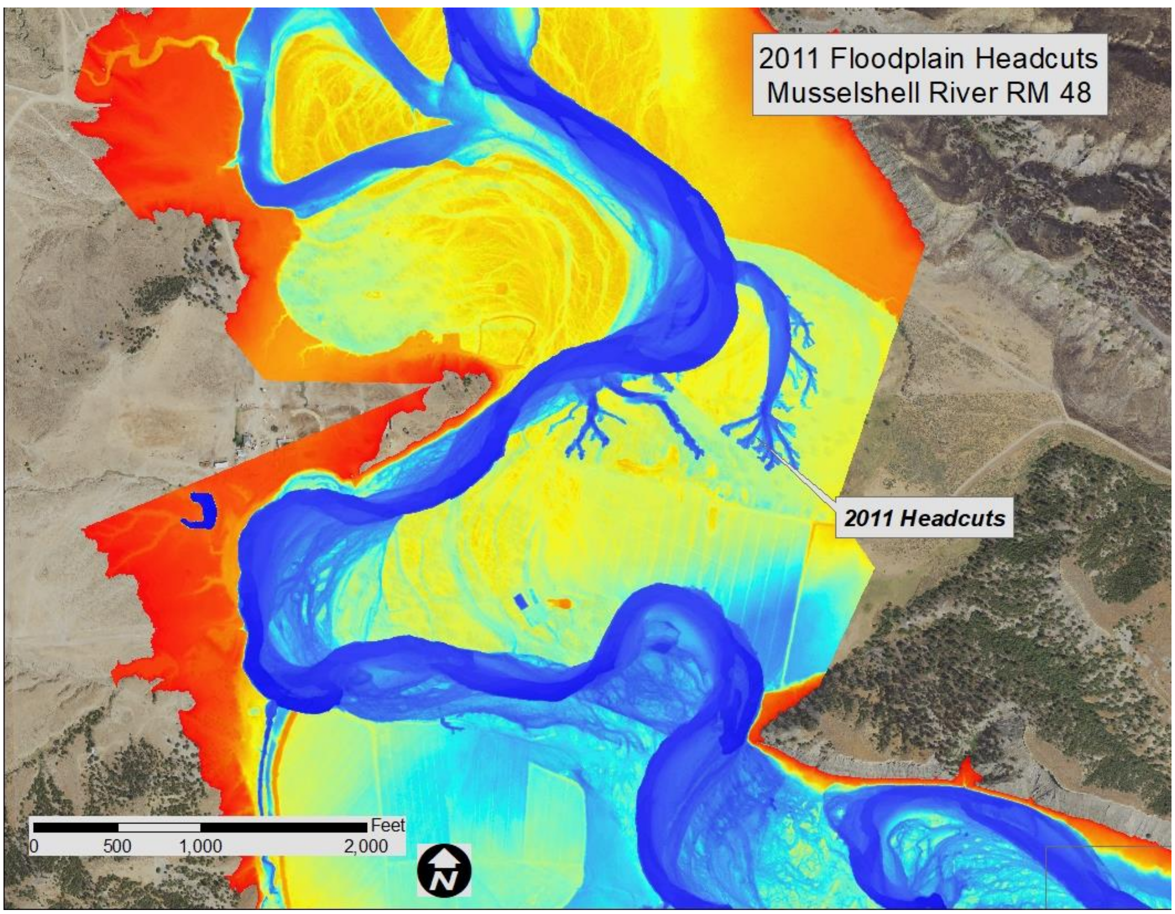


Figure 41. Relative elevation model (from 2012 LiDAR data) showing floodplain headcuts (blue fingers) in formed by 2011 flood waters below Mosby. Flow direction is to north.

Figure 42. Google Earth image showing 2011 floodplain headcuts creating avulsion path; this bend cut off in 2018.

As shown in Figure 41, the LIDAR data can capture potential avulsion paths that are difficult to see on air photos. Another example is shown in Figure 43, where a bendway that has a large pump site is clearly at risk of experiencing an avulsion through its core, where a ~6-foot deep channel has formed. If the bend cuts off due to an avulsion, the pump site will be about 700 feet from the main channel.

Our recommendations for these areas generally depended on the level of risk, which includes the likelihood of an avulsion as well as its consequences. At the site shown in Figure 43, where loss of the bend would isolate a major pump site, the avulsion route should be carefully monitored as a minimum. More proactive approaches to lower the risk of a cutoff include grading out the avulsion path or adding roughness elements such as large wood to slow down flows and reduce the potential for the path to enlarge. In many cases, locating an alternative pump site in the event of an avulsion is a good way to integrate avulsion risk into operations.

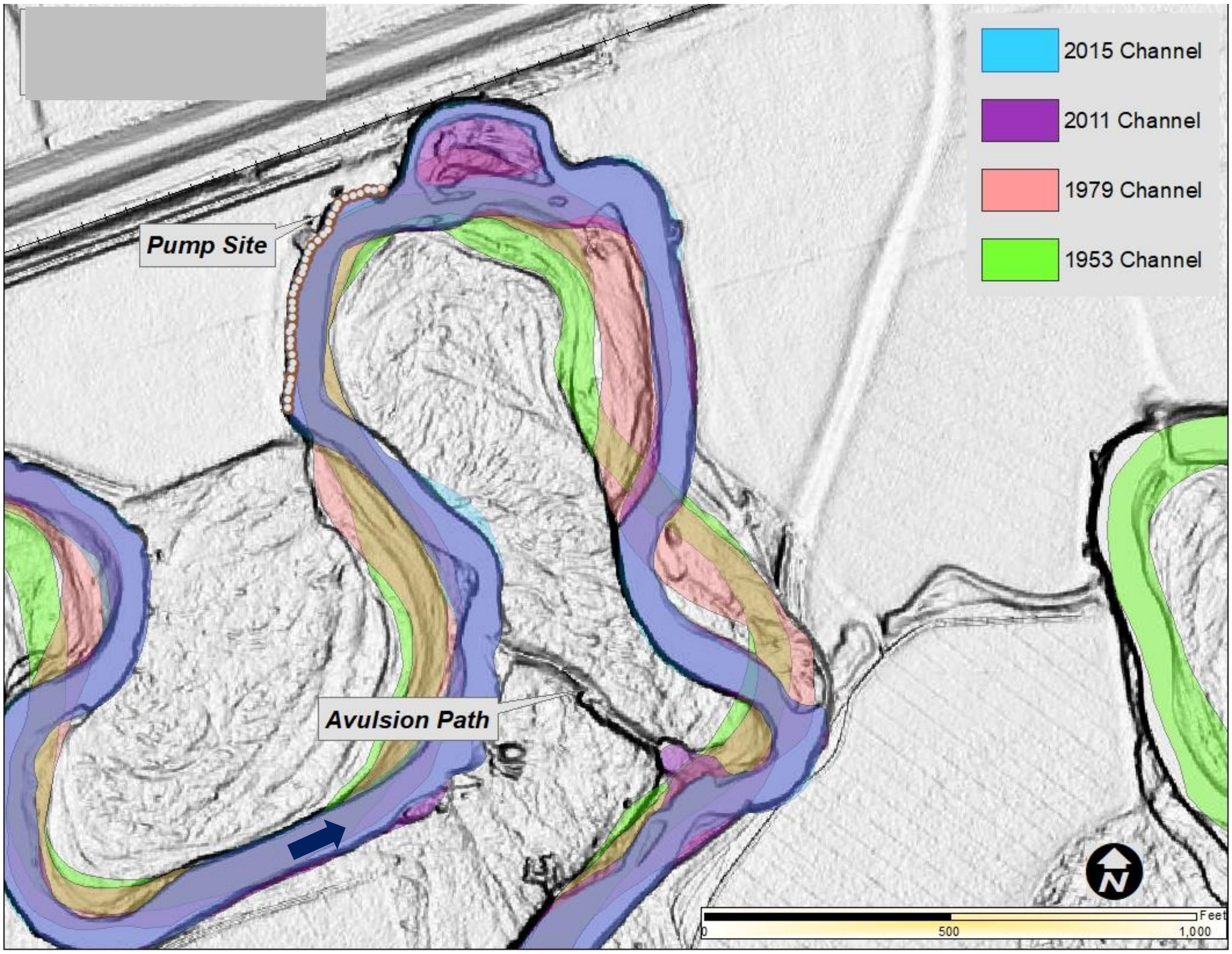


Figure 43. 2012 LiDAR hillshade showing prominent channel forming an avulsion path.

As described previously, another term for an avulsion that cuts through a meander bend is a "chute cutoff". Another way that meander bends can cut off on the Musselshell River is by "neck cutoff" (Figure 44). Whereas a chute cutoff is a true avulsion caused by excavation of a new channel across the floodplain, a neck cutoff is caused by the more gradual meeting of bendway limbs as a meander compresses through time. Figure 45 shows an example of an area where a neck cutoff is likely as bank erosion continues through a narrow meander neck. This is a process that should be anticipated in coming years, even without large floods, as the river continues to evolve following major point bar growth in 2018. This risk should be considered when locating pump sites, and with all of the changes anticipated on the river, keeping infrastructure portable should be a high priority where possible.

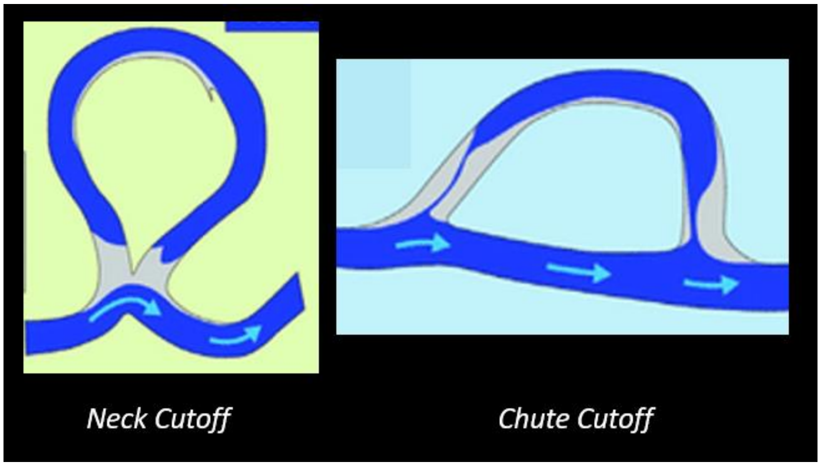


Figure 44. Schematic drawings of neck and chute cutoffs (modified from Depret, 2017).

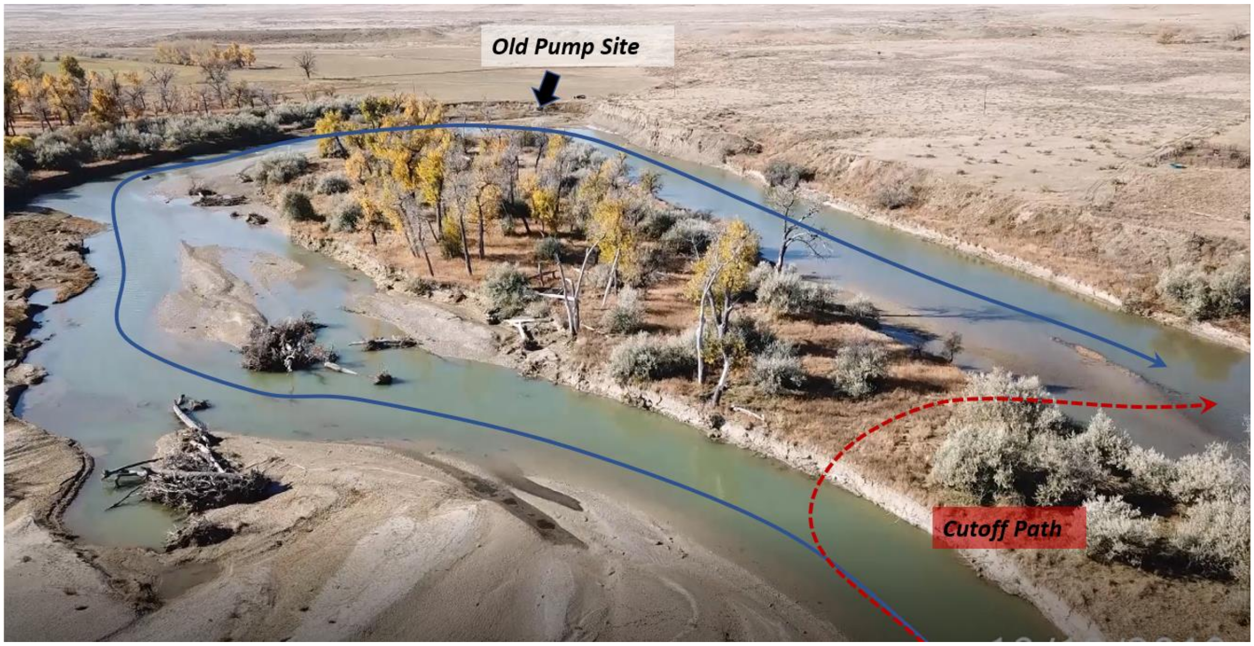


Figure 45. View downstream of bendway showing old pump site and likely cutoff path that will abandon meander.

5.1.6 Pump Site Damage

The 2014 and 2018 floods caused substantial erosion at pump sites. In many cases the sites consisted of access ramps that can be re-graded (Figure 46), but in other cases the erosion extended into fixed infrastructure such as field pipes (Figure 47). Pump site erosion was also localized at several sites, with flood and ice damage to site foundations and/or bank armor (Figure 48). And because of the massive transport of sediment during these floods, some sites suffered from more passive deposition. Figure 49 shows a pump site that fully silted in during the 2018 flood as a meander bend migrated down-valley and away from the pump. This site is currently accessed by a trench that conveys water from the river to the pump.

Our recommendations at pump sites were very site-specific and included site relocations and bank protection. The most consistent recommendation, however, was to keep pump sites portable as possible, to allow water users to adapt to inevitable future post-flood adjustments throughout the river corridor.

Figure 46. View down pump site access ramp that washed out during the 2018 flood.

Figure 47. View upstream of pump site with buried irrigation pipe exposed in streambank (2018 drone flight).

Figure 48. Lost pump site foundation behind and below metal plates.

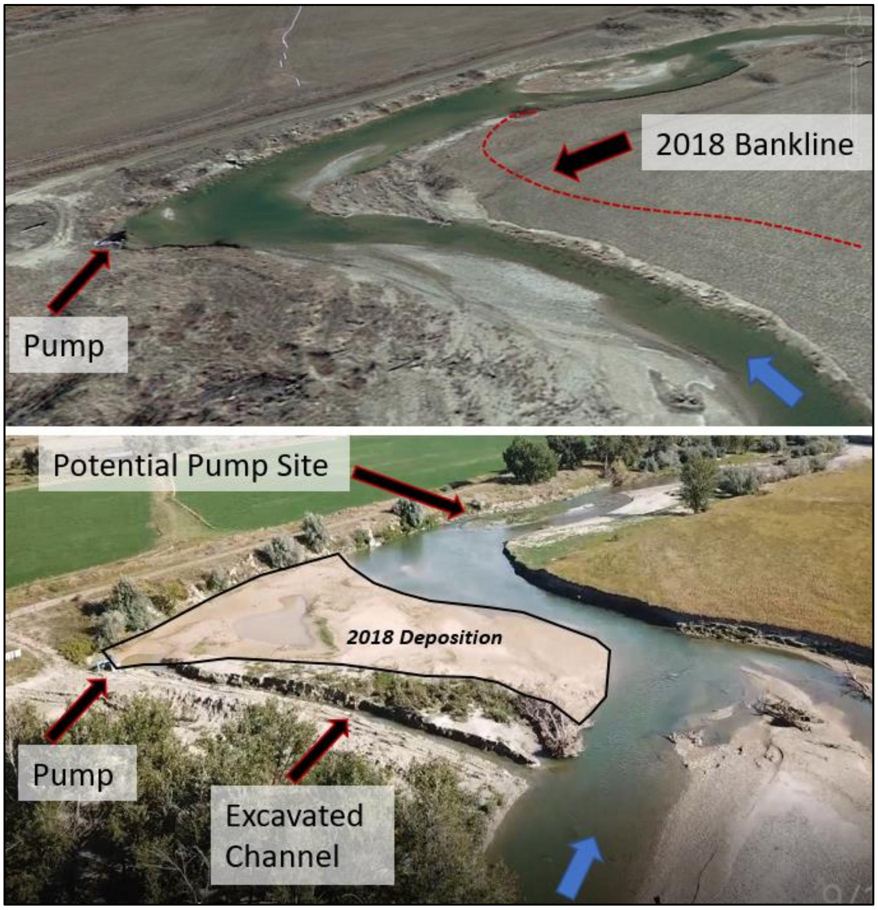


Figure 49. Images from Google Earth (top) and drone flight (bottom) showing buried pump site due to 2018 flood event; the recommended pump site relocation would be along the riprapped left bank shown in lower image.

5.1.7 Bank Armor Damage/Failure

Bank armor is always prone to failure, especially during floods that cause toe failure or flanking of the rock structures. On the Musselshell River, most bank armor consists of either riprap (rock or concrete) and/or flow deflectors (barbs or jetties). Both types of armor were damaged in 2018. Figure 50 shows a common cause of bank armor failure which is flanking on the upstream end of the treatment. If the river gets behind the rock, it can rapidly erode the bank and leave the rock out in the channel. When this occurs, the flanked riprap will often accelerate bank erosion that it was originally intended to prevent. At another site upstream from Roundup, at least seven flow deflectors were flanked in 2018 along an especially straight section of river.

Our recommendations for damaged armor generally consisted of repairs and upgrades. We provided a Bank Protection Supplement (Appendix A) to discuss construction and treatment approaches. In many cases, remnants left in the channel will make erosion problems worse and should be removed.

Figure 50. View downstream from damaged pump site—note flanked rock riprap in channel.

5.1.8 Diversion Dam Flanking

In 2011 we visited wholesale structure flanking at the Naderman, Anderson, and Egge Diversion Dams. These dams have not been rebuilt, and producers have shifted to pumps. In 2018, one more dam flanked to our knowledge, the Newton/Pedrazzi Dam a few miles downstream of Roundup. The dam flanked on its south side accompanied by a tripling of channel width (Figure 51 and Figure 52). This structure had been slated for removal after it was abandoned after the 2011 flood. The upper ditch also eroded out, and the producers shifted to pumps. Currently, the dam is largely buried and does not appear to impact channel function (Figure 52).

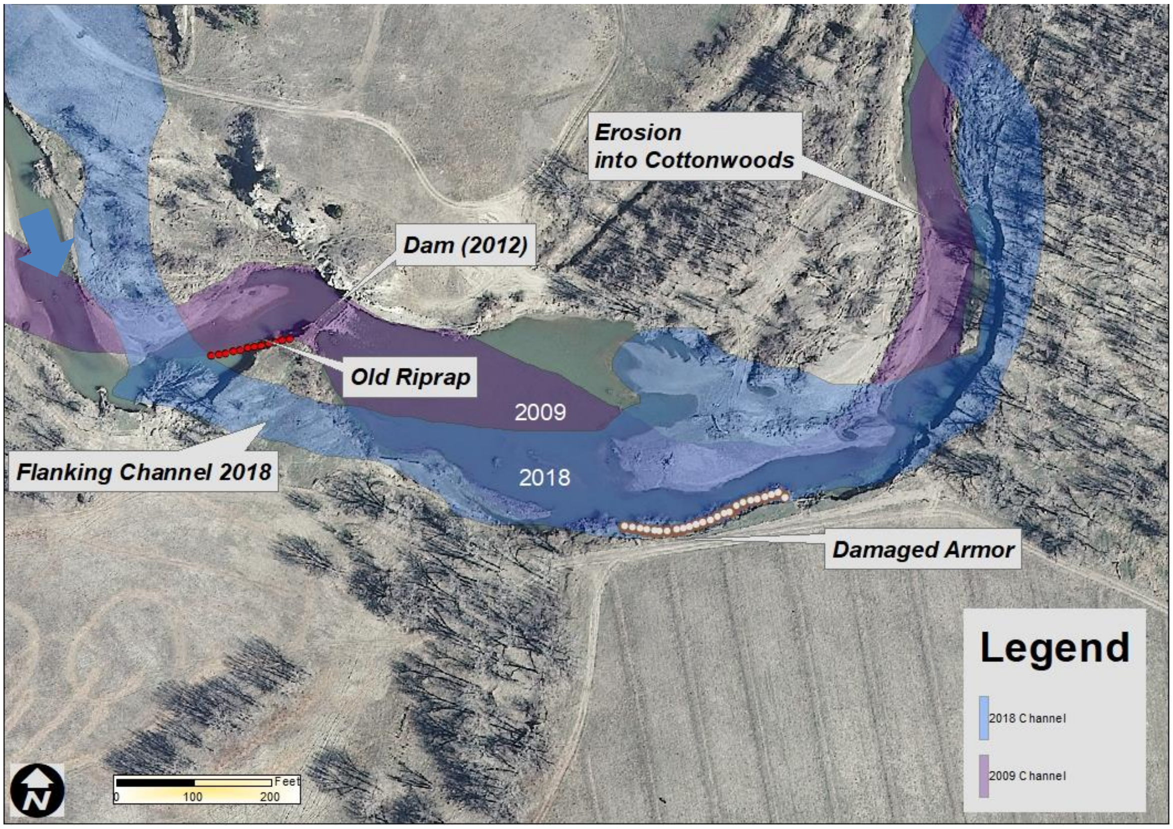


Figure 51. 2012 air photo showing Musselshell River path in 2009 and 2018, capturing flanking of dam to south (flow direction is left to right).

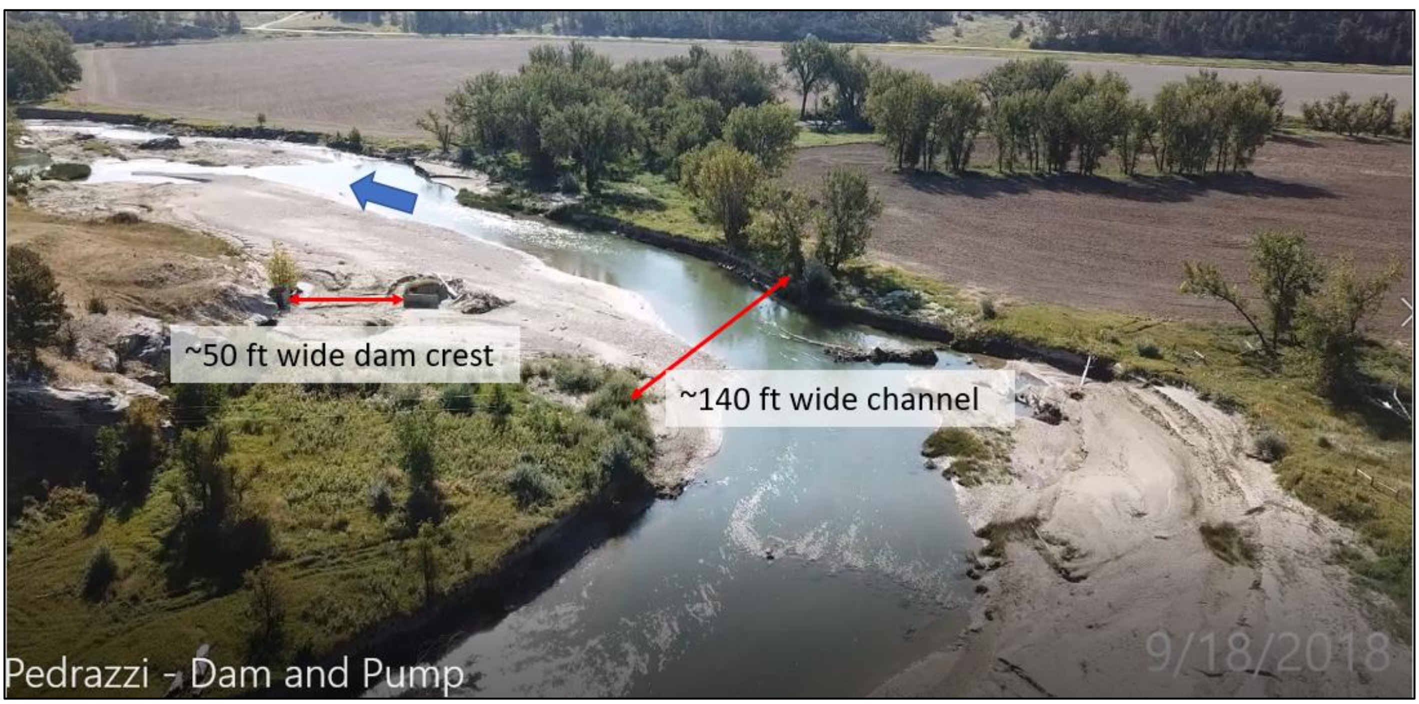


Figure 52. 2018 drone image of flanked diversion dam and channel widening.

5.1.9 Railroad Berm Breaches

As described previously, the Milwaukee Line railroad berm closely follows the river between Melstone and Two Dot. During the 2011 flood this berm breached completely in 31 places. In one location near Shawmut the river relocated to the opposite side of the berm (Figure 53). Railroad berm breaches are recognized as somewhat of a "double edged sword" on the Musselshell, in that the breaches dissipate high-energy flows and improve floodwater storage which potentially mitigates flooding downstream, but in some cases the water gets behind the berm without a clear path back to the river. Because the isolation of historic floodplain area by the berm has been extensive, reconnecting the river to the historic floodplain area is a clear opportunity for improved ecological function on the floodplain as well as flood mitigation. To that end, our approach regarding the breaches is to identify means of allowing floodplain access behind the berm (not patching breaches) but providing improved drainage back to the river down-valley from the breach.

Figure 54 shows an example of a breach that first occurred in 2011 and has been expanding since. The river is confined between the berm and the valley wall to the north, and the south floodplain has numerous old swales that show the extent of the historic floodplain. The channel is migrating south towards an old swale, which is currently an emergent wetland (Figure 55). Allowing the river to intercept the old meander and reconnecting the lower end of the oxbow to the river would both lengthen the river and reduce its stream power while greatly improving floodplain connectivity and storage potential. Figure 56 shows another area where the grade breached in 2018 above Harlowton where strategic reconnection of the floodplain to the river would help manage flooding, especially since more breaches are inevitable (the figure is pre-breach).

Figure 53. View upstream (west) of long railroad grade breach that occurred in 2011 east of Shawmut (Kestrel Aerial).

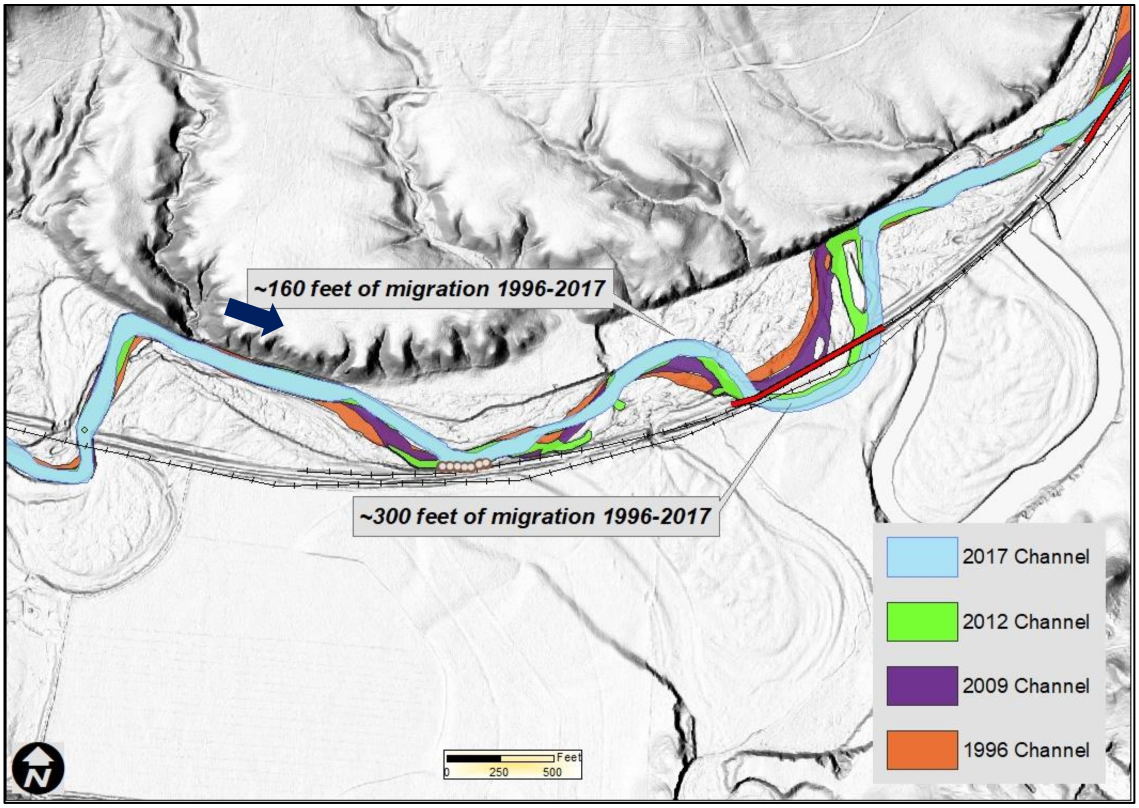


Figure 54. Digitized banklines showing railroad breach about two miles below Painted Robe Creek.

Figure 55. View upstream of railroad berm breach below Painted Robe Creek -- photo taken on September 20, 2012.

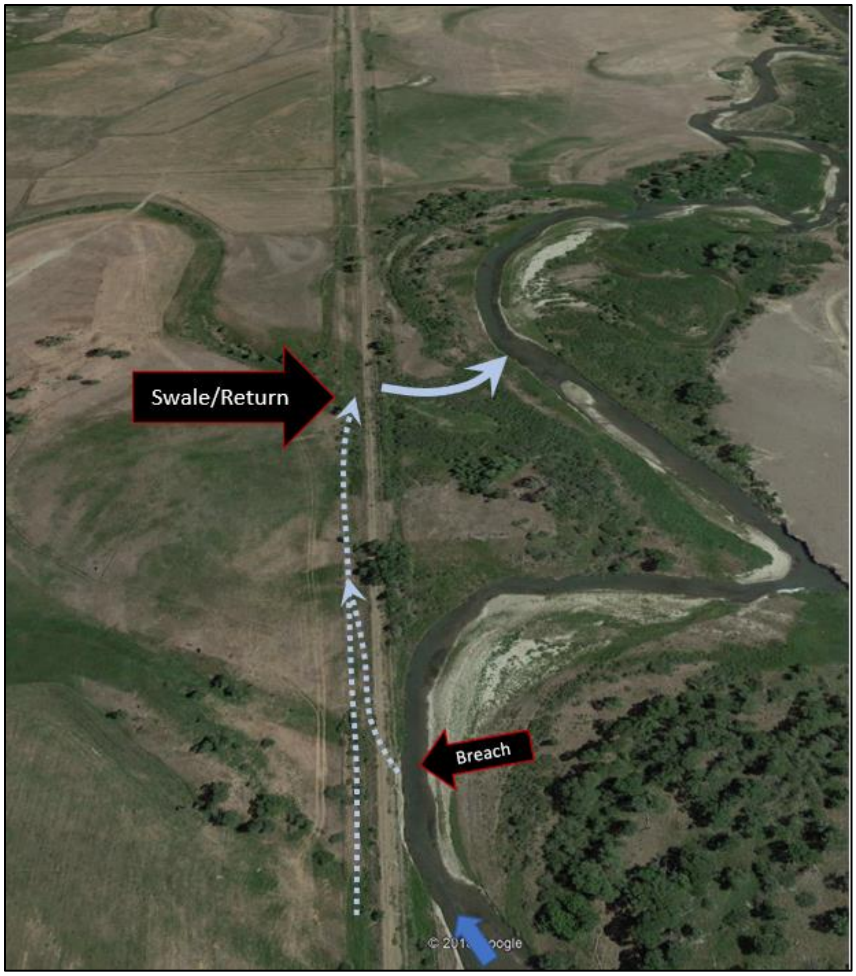


Figure 56. View downstream showing overflow paths and one potential return flow point through an old swale.

5.1.10 Salt Cedar

The expansion of salt cedar onto open sand and gravel bars in 2011 and 2018 was striking. Figure 57 shows 2018 flood deposits colonized by both cottonwood and salt cedar seedlings. In some locations the salt cedar densities dwarfed that of the cottonwoods. Weed management will continue to be a constant battle in the Musselshell River corridor for years. Where cottonwoods are establishing, promoting their survival through grazing management and salt cedar controls will greatly help with natural flood recovery on streambanks, gravel bars, and floodplain areas.

Figure 57. Cottonwood and salt cedar seedlings on 2018 flood deposits.

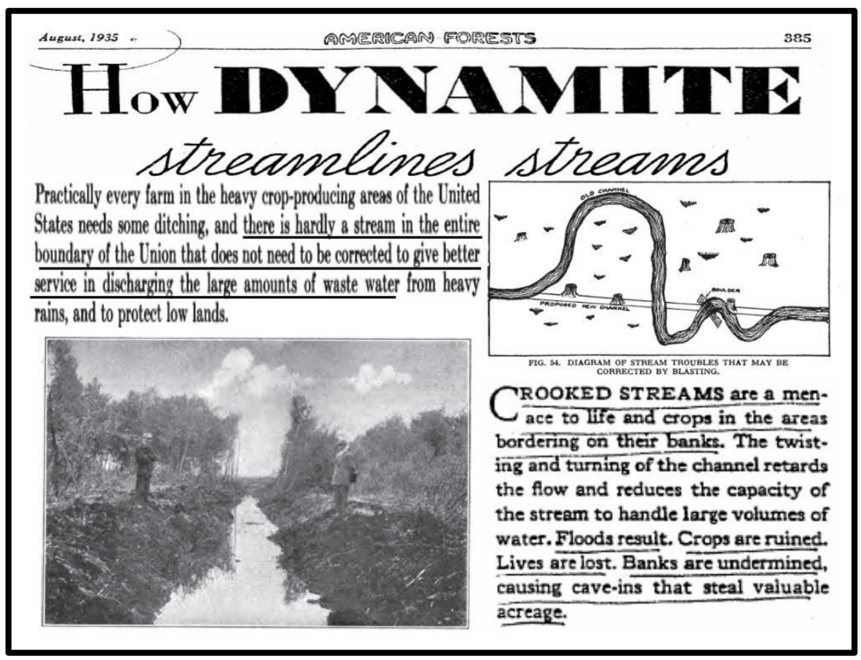
6 Geomorphic Evolution of the Musselshell River

The history of the Musselshell River has included over a century of development and manipulation, a long period of low flows in the late 20th century, and an unprecedented series of flood events in the last decade. These three major influences have collectively driven the river to its condition today and will continue to influence its recovery for decades to come. The processes that we see at work are quite explainable when the changes observed are considered in light of all three influences. This section is intended to provide discussion of the geomorphic processes at work and to provide a foundation for developing management strategies that will most cost-effectively help the river recover and regain natural resiliency against future floods and/or droughts.

6.1 Pre-1980s: Initial Corridor Development and River Response

As described in Chapter 3, the river has been intentionally shortened, due to both the railroad development as well as agriculture-related meander cutoffs. This is a common situation on stream systems in Montana and throughout the US, as stream straightening was a common technique used to move rivers out of the way of infrastructure, make them "more efficient", and to allow floodplain development (Figure 58). Between 1960 and 1971, the Soil Conservation Service (SCS) designed and cost-shared the channelization of 16,500 miles of waterways in the US, and Aldo Leopold described the post-WWII SCS as "an army of stream straighteners" (Brown, 1974). On the Musselshell, the channelization impacts by the railroad work include both the physical shortening of the river and the concentration of high-energy flows into the channel by isolating floodplain areas behind the berms. Subsequent work by landowners to induce meander cutoffs further shortened the river and created river instability.

Beginning in the 1970s, as straightened stream systems across the country began to destabilize, a series of "unintended consequences" of channelization became clear. Streams that were straightened were effectively steepened, which increased stream velocities and erosive energy. The result was extensive channel downcutting in shortened river systems, and that downcutting commonly migrated upstream from channelized reaches (Figure 59).


August, 1935 AMERICAN FORESTS 385

How DYNAMITE *streamlines streams*

Practically every farm in the heavy crop-producing areas of the United States needs some ditching, and there is hardly a stream in the entire boundary of the Union that does not need to be corrected to give better service in discharging the large amounts of waste water from heavy rains, and to protect low lands.

FIG. 54. DIAGRAM OF STREAM TROUBLES THAT MAY BE CORRECTED BY BLASTING.

CROOKED STREAMS are a menace to life and crops in the areas bordering on their banks. The twisting and turning of the channel retards the flow and reduces the capacity of the stream to handle large volumes of water. Floods result. Crops are ruined. Lives are lost. Banks are undermined, causing cave-ins that steal valuable acreage.

Figure 58. American Forests publication from 1935 promoting stream channelization.

Figure 59. View upstream of a downcut channel located upstream of channelized reach; channel incision stops where headcuts get stopped by road culverts (USACE).

These processes were active to some extent on the Musselshell. By the mid-1950s, the impacts of the railroad work, which reportedly included 117 cases of either bridge crossings or channel relocations was a concern. The April 17, 1958 edition of the Roundup Record-Tribune included the following account (Pedersen, 1980):

> "While the Musselshell River gave good water and the valley's Cottonwood trees furnished fuel, the channel changes made in the Musselshell to save bridging entailed not only large amounts of riprapping, but brought about serious complications in irrigation systems, in many cases requiring the construction of inverted siphons to carry irrigation ditches across the roadbed and of entirely new systems of dams, head gates and ditches to satisfy the demands of the owners and, as an aftermath, required the company's right-of-way agents to spend months of time and thousands of dollars in the work of settling claims for damages."

Figure 60 shows photos of the Musselshell River taken as part of an assessment by the Lower Musselshell Conservation District in 2004 (LMCD, 2004). By that time, the river was downcut, the floodplain cleared, and the water table was reportedly 6-10 feet deep on the perched floodplain. These conditions created concerns regarding sediment production, as bank erosion was active. A physical features inventory completed decades earlier in 1980 by the Montana Water Quality Bureau (Pederson, 1980), reported that between Shawmut and Melstone (~160 miles), there was a total of 34,680 feet of rock riprap, 3,320 feet of log riprap, 45 rock jetties, 158 car bodies, and half a million feet of eroding banks. Sixty-nine of those banks were considered “critical” sediment sources. Pederson concluded that “channel alterations and realignments by the Milwaukee Railroad dominate man’s impact to the river although streambank erosion has been aggravated severely by farming and grazing to the river’s edge.”

Figure 60. Floodplain clearing and channel downcutting on the Musselshell River by the early 2000s (LMCD, 2004).

6.2 1980-2011: Channel Contraction, Dewatering during Dry Years

As described in Chapter 3, there were very few floods on the Musselshell River between 1983 and 2010. A comparison of air photos that bracket this nearly three decade long period shows that during that time the river contracted and lost most of its open gravel bars to encroaching vegetation, indicating little in the way of stream power, geomorphic work, and overall change (Figure 61). Landowners frequently describe this timeframe as forming their major memory of the river; that is, quiet and non-damaging.

Figure 61. Change in Musselshell River below Roundup from 1979 (left) to 2009 (right) showing narrowing of channel, loss of open bars and expansion of Russian olive, which can be seen as sage-colored vegetation in the 2009 image.

6.3 2011-2018: Flood-Driven Geomorphic Reset

The air photo comparison shown in Figure 61 shows that, by 2009, the Musselshell River had "atrophied" following decades of low flow. Dewatering had become a chronic problem, and the diversion of all flows for irrigation purposes was a much bigger concern than flooding. We do not have first-hand experience of the river's condition in 2009, but reports indicate that, at least locally, streambanks were fine grained and high, the floodplain was cleared, and the channel was relatively small. Figure 62 shows a photo of the Musselshell River from Montana River Action. The date of the photo is unknown, but it is probably fairly reflective of the stream prior to 2011. The photo shows a high cutbank on the left and a small inset floodplain developed on the right, which indicates downcutting. There is no woody riparian vegetation on the inset floodplain surface (grassed platform on the right side of the channel) and the river is dewatered.

Figure 62. Musselshell River Photo from Montana River Action (date unknown).

6.3.1 The 2011 Flood

> *"Definitely catastrophic, but I gotta say it was impressive too".*
>
> *--Musselshell County Producer*

Just prior to the 2011 flood, that channel was narrow, locally entrenched below its historic floodplain, and dewatered. Riparian vegetation was locally sparse, and the historic floodplain was largely cleared and irrigated. When the 2011 flood happened, flows were out of bank for weeks (Figure 63). The floodplain became saturated, and major channel changes were apparent when the waters finally dropped. Bendways had cut off, bank erosion was rampant, and fixed pump sites were abandoned. This was what is commonly described as a "resetting event". This event was described in detail in the previous RATT report (Boyd et. al., 2012).

Figure 63. Floodplain inundation and erosion during the 2011 event dramatically changed the face of the Musselshell River.

Some of the river response to the 2011 flood actually drove geomorphic recovery from previous impacts. The river eroded into cultivated fields, lengthening in some areas and creating new lower floodplain surfaces on open gravel bars (Figure 64). Cottonwood seedling recruitment was described as both unprecedented and spectacular (Figure 65); some transects estimated the establishment of 129,000 cottonwood and 17,000 willow seedlings per acre during the summer of 2012 (NRCS, 2012).

Unfortunately, however, the 2011 flood, now estimated as a 100-year event, was just too big to promote any sort of gradual recovery. Although some areas gained length, there was much more additional shortening due to the long-duration flows and poorly vegetated floodplain. The net result of the 2011 event was additional instability.

Figure 64. View downstream of point bar formation, bank erosion, and channel lengthening near Shawmut (kestralaerial).

Figure 65. Cottonwood seedling colonization following 2011 flood.

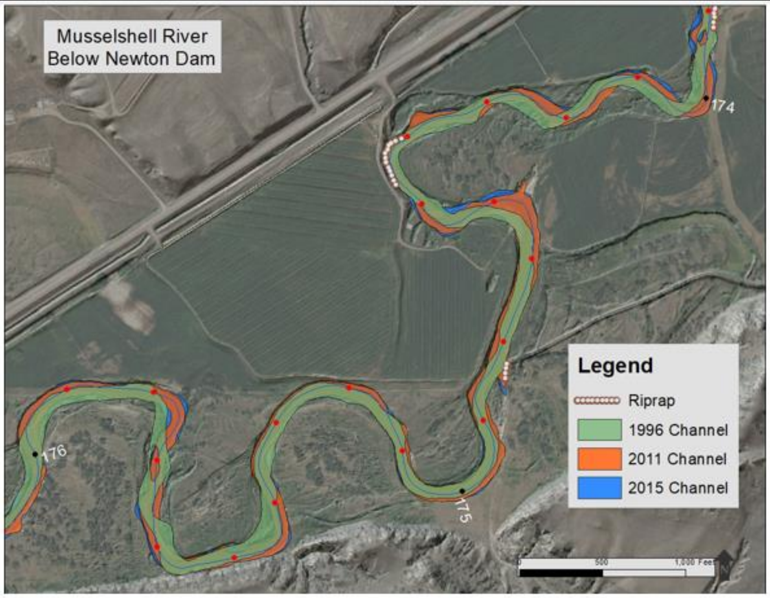
Although the 2011 flood damage was system-wide, the CMZ Pilot mapping effort (Boyd and Thatcher, 2017) showed that some areas withstood that flood event rather well. Figure 66 shows two areas above and below Roundup that responded very differently during the flood. The top of the figure shows a river segment below Newton Dam that showed only minor changes after the 2011 flood. This reach has an average slope of 0.09% (4.8 feet per mile), and an average migration rate of 2.1 feet per year. Upstream above Naderman Dam, the river has been more extensively straightened such that the average slope is almost double at 0.14% (7.4 feet per mile). The average migration rate in this reach is 3.7 feet per year. The image shows that whereas the lower slope reach showed some migration, it retained its meander planform through the flood without major channel adjustments. In contrast, the relatively straight and steep river segment above Naderman Dam experienced much more extensive bank erosion and channel widening.

When all six reaches evaluated for the CMZ pilot are considered, the results show that steeper and straighter sections of river tend to have higher migration rates, and those higher rates are more predominant upstream of Roundup where the confinement by the railroad berm is most severe (Figure 67 and Figure 68).

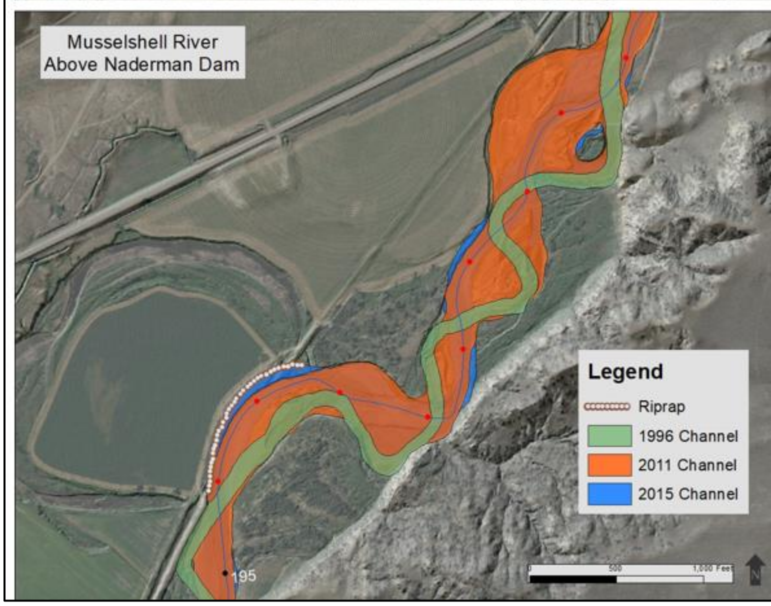
"Seems like the straighter this river gets, the more problems we have".

--Petroleum County Producer

It is interesting in that the work performed by Pioneer Technical on the Roundup Reach (Pioneer, 2016) identified an "equilibrium slope" value of 0.09% for the Musselshell River above Newton Dam, which is consistent with the slope captured in the top image of Figure 66. This suggests that this reach could potentially provide a rough reference condition for channel slope and sinuosity that should be considered for restoration project designs on other portions of the river.



Average Slope: 0.09%
Average Migration Rate: 2.1 ft/yr
1953-2011 Avulsions: 2



Average Slope: 0.14%
Average Migration Rate: 3.7 ft/yr
1953-2011 Avulsions: 7

Figure 66. Comparison of bank movement in relatively low slope area below Newton Dam (top) and steep reach above Naderman Dam (bottom). Values are reach-averages.

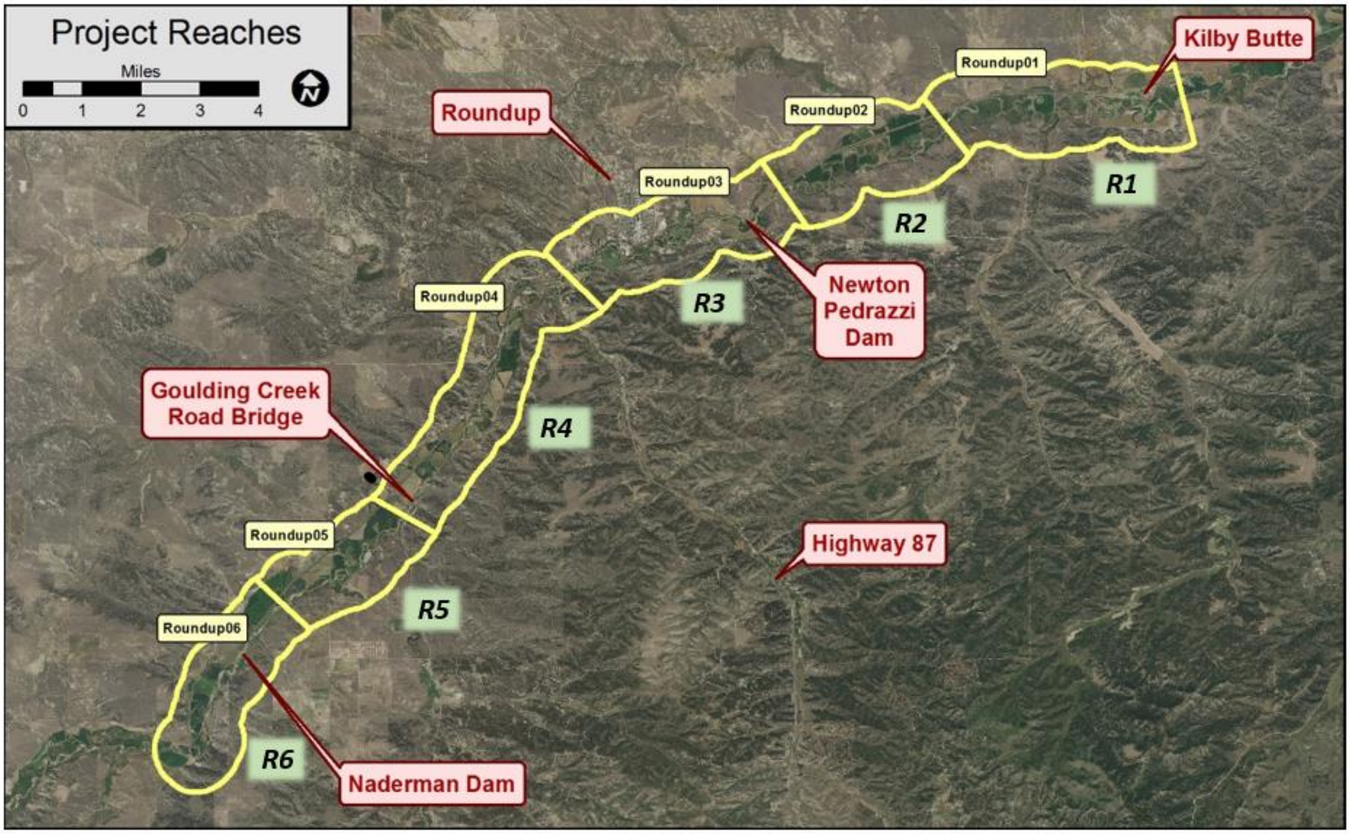


Figure 67. Reaches evaluated in CMZ Pilot Project (AGI and DTM, 2017).

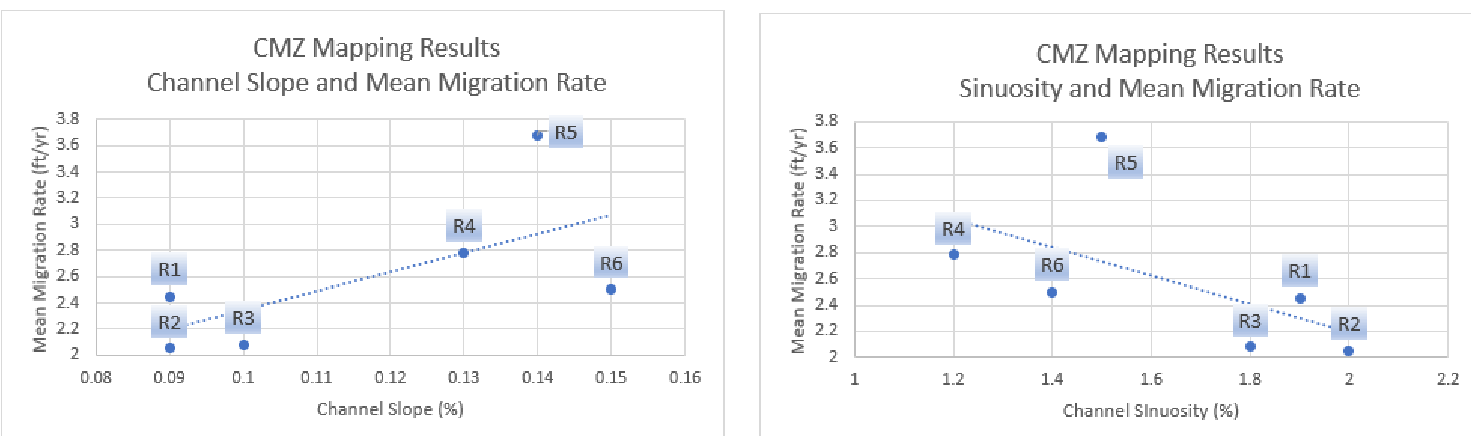


Figure 68. Average migration rates for CMZ pilot reaches plotted against slope (left) and sinuosity (right) showing more active migration on steeper and straighter river segments above Roundup (R4-R6).

6.3.2 Flooding Since 2011

As described in Chapter 4, large floods have been frequent throughout the basin since 2011. As we don't have post-2018 flood images for the whole river corridor so we currently can't quantify broad-scale changes on the river caused by that event. As described in Chapter 5, however, the river changes since 2011 flood have included substantial channel lengthening and widening. Large inset floodplain surfaces were built, and thousands of feet of channel length were gained. The geomorphic response in 2014 and 2018 reflect more of a trend towards geomorphic equilibrium than the 2011 flood, which some have described as an "unraveling" event. For more discussion on the impacts of the post-2011 floods, see Chapter 5.

"The first two times it wasn't funny… this last time it kinda made you laugh."

-- Producer near Roundup

"By the end of last spring, we felt like we were getting picked on."

--Wheatland County Producer

6.4 Channel Stability Concepts

The progressive changes on the Musselshell River can be explained using the concept of stream equilibrium. An equilibrium condition in a stream channel reflects a balance between the energy in the stream ("stream power") and the sediment load/size transported (Figure 69). A balanced condition between stream power and sediment transport generally means the size, shape, and slope of the stream creates hydraulic conditions that can effectively transport the quantity and size of sediment delivered without the channel either enlarging (excess stream power) or infilling (insufficient stream power). Equilibrium conditions do not mean there is no bank erosion or lateral channel movement, but that the movement is in balance so that the channel form is maintained. ***Stream Power,*** which is an important concept on the Musselshell, is the product of slope and discharge.

The balance shown in Figure 69 shows that if stream power is increased by either an increase in stream slope/discharge or reduction in sediment load, the stream will undergo "degradation" (downcutting). In contrast, if the stream power is reduced, or sediment load increased, "aggradation" (infilling) will occur. The response to this imbalance can also be influenced by other factors such as bank integrity, as woody riparian vegetation can dissipate energy and reduce stream power. Lost floodplain access will focus flows and increase stream power in the channel.

"The river's a lot faster—I'll bet it's twice as fast, no dead spots".

--Petroleum County Producer

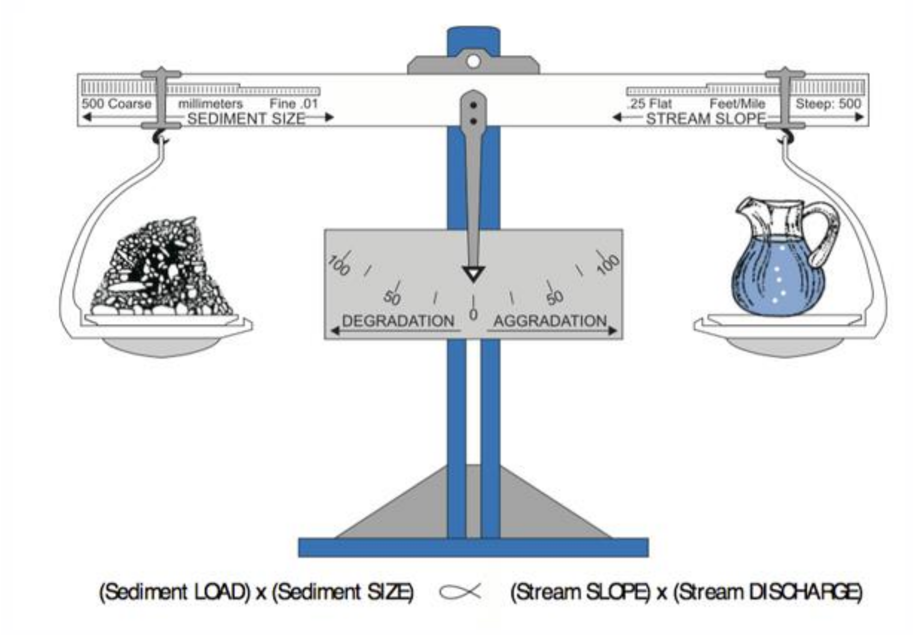


Figure 69. Lane's balance provides a useful conceptual framework for considering probable channel response to changes sediment delivery, slope, and flow (North Carolina State University).

> *"For twenty-four years I didn't think about a flood and then…. it's not my river".*
>
> *--Irrigator near Musselshell*

Figure 69 conceptually shows how an increase in stream slope due to straightening would drive channel downcutting during the 20th century. The low flow years that followed were probably characterized by low stream power and channel infilling, as the channel narrowed due to persistently low transport energy. Then, the 2011 flood overwhelmed this small channel, flows went out of bank onto a farmed, non-woody floodplain, and the system was not resilient enough to withstand the long duration flood, so the instability worsened as the river straightened and steepened. The subsequent floods in 2014 and 2018 also had high erosive energy, but since the river channel enlarged in 2011, much of the work was performed within the channel rather than on the floodplain. This resulted in massive bank cutting, sediment transport, point bar growth, and channel lengthening. Figure 70 shows an example of a large 2018 gravel deposit on a point bar. In some places this process did not threaten infrastructure or other resources, but in others this process consumed productive fields and damaged canals, siphons, and pump sites. Figure 71 shows an example of a straightened river recovering length during a flood event due to excess stream power.

> *"2011 came down and it was over fast; but this one, the banks were calving in July."*
>
> *--Musselshell County Producer*

Figure 70. Raw gravel bedload deposit on point bar.

"It's all good running east-west, it's the north-south that creates trouble".

--Irrigator along Rail Grade

Figure 71. Straightened section of the Walla Walla River actively regaining length during a 1964 flood.

Another way to conceptualize the changes on the Musselshell River is to look at stream pattern. Figure 72 shows how river pattern can be affected by slope, bank materials, flow patterns, and incoming sediment size and quantity. This model is appropriate for the Musselshell River and helps explain the transition from a flat, sinuous river to a steeper and meandering/braided channel over time (left to right on the graphic). Prior to the railroad work, the river was long and flat, accessed the full floodplain, and supported dense bank and floodplain vegetation (Figure 73). With time, it has transitioned to a braided pattern, with a steeper slope, a high sediment load, unstable banks, restricted floodplain, and a low density of woody vegetation.

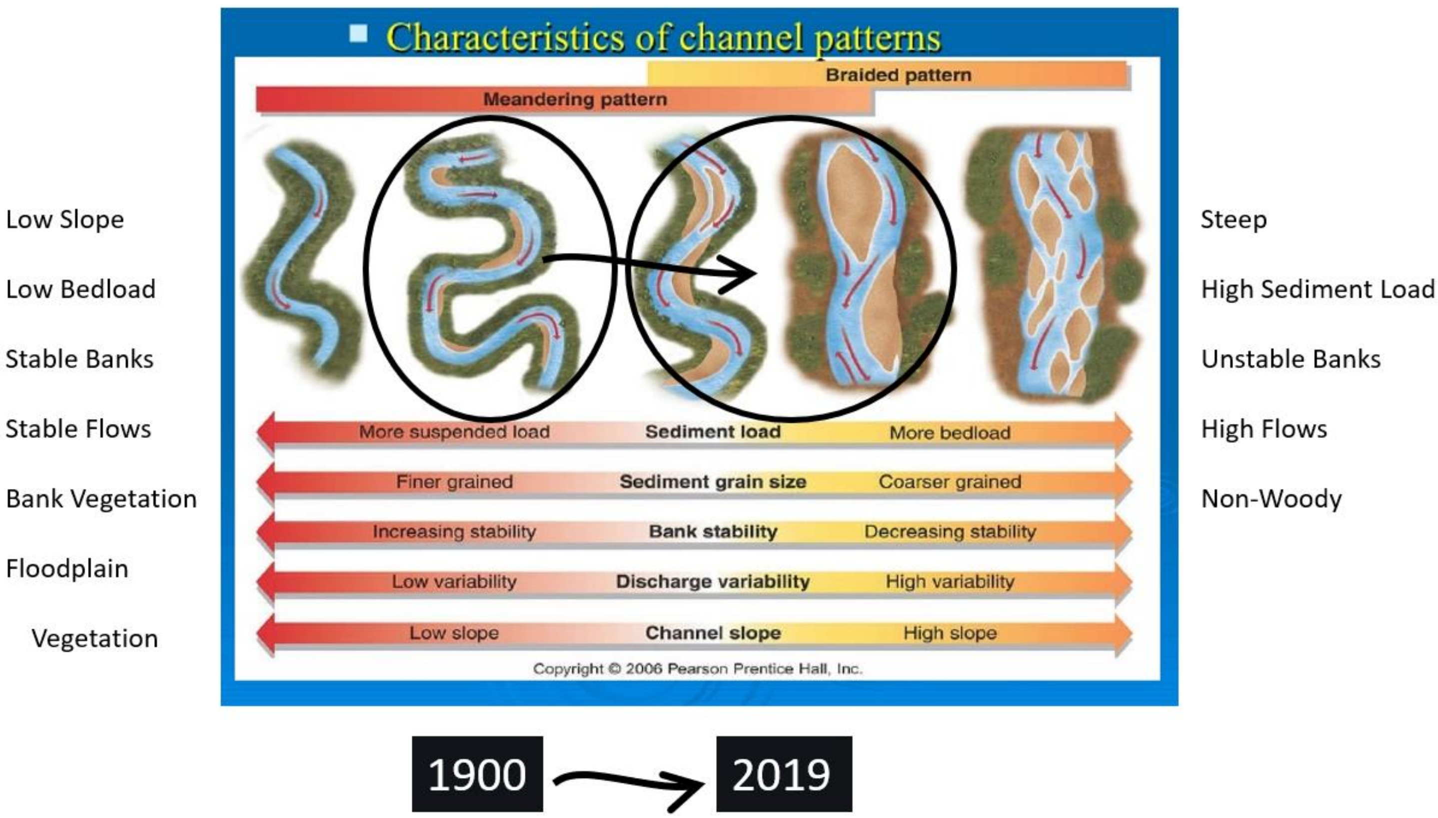


Figure 72. Schematic drawing showing the direction of Musselshell River changes between 2009 and 2019 (www.slideshare.net).

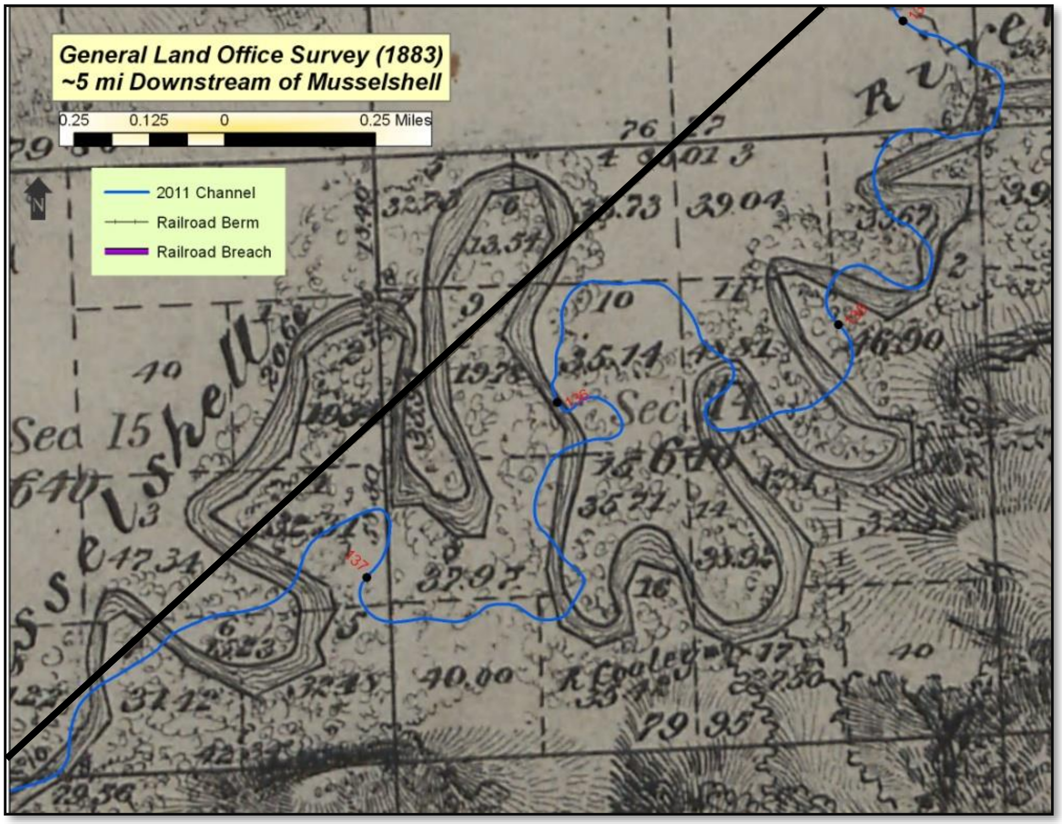


Figure 73. General Land Office (GLO) survey map from 1883 showing sinuous and well vegetated channel downstream of Musselshell; blue line is 2011 channel course, and 1908 railroad grade is in black.

7 Restoration Alternatives and Long-Term Opportunities

The following section contains some broad recommendations for managers and producers on the river. The intent is to apply our understanding of river process to the development of conceptual treatment options. Figure 74 shows the parameters that are important if stakeholders are interested in transitioning the destabilized river back to a more stable condition. Looking at the parameters on the left side of the graphic, the important issues to focus on are channel slope, floodwater dissipation (floodplain access), bank integrity, and floodplain vegetation.

> *"The river continues to revenge the actions of the past, and appears determined to re-build its floodplain. Not a pretty and certain process, especially if you live and work along the river".*
>
> *--Local Landowner*

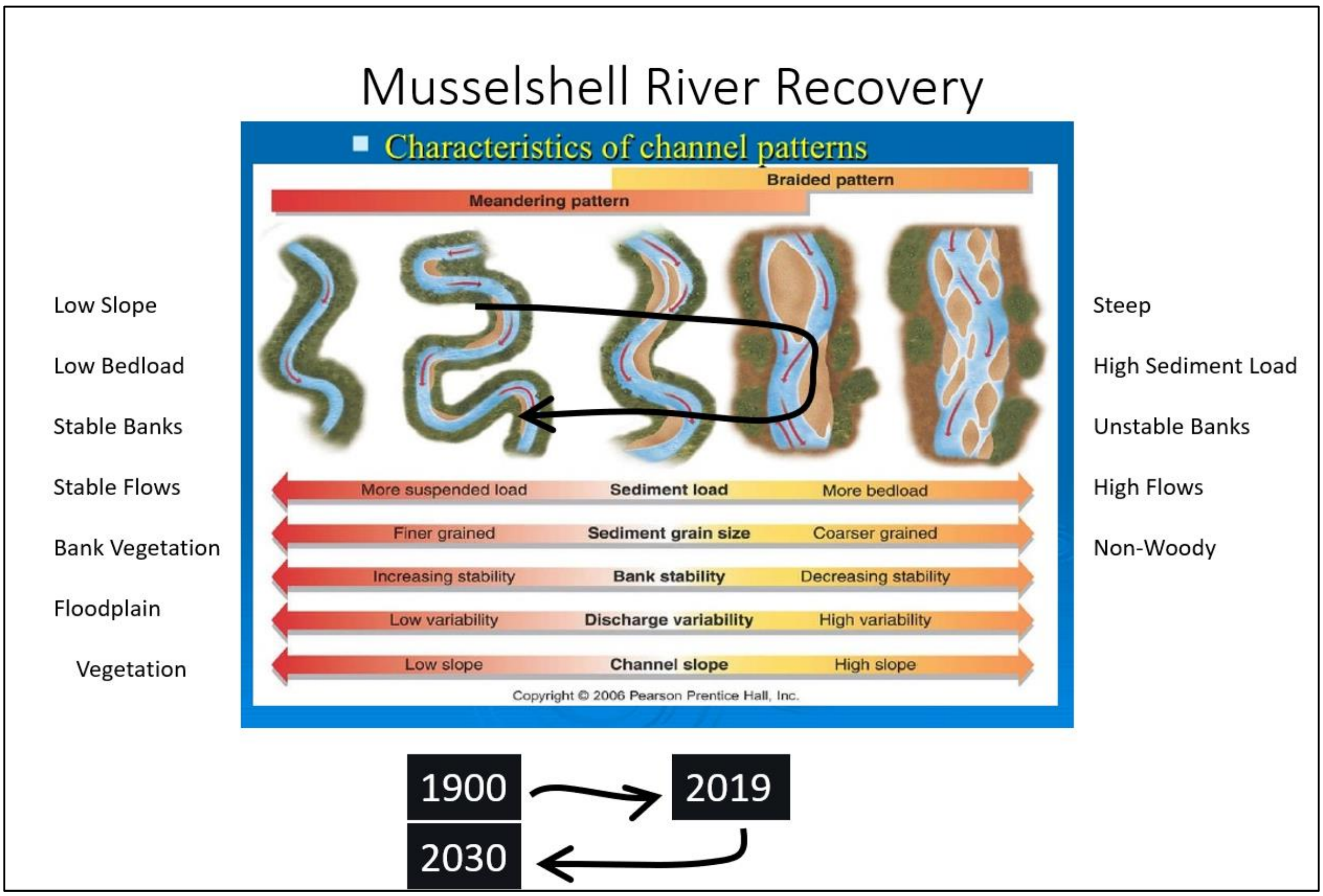


Figure 74. Conceptual schematic of optimal Musselshell River trajectory (image from [www.slideshare.net).](http://www.slideshare.net)

7.1 Reducing Channel Slope

There are essentially two ways to manage the slope of the river: passively and actively. Passive slope reduction essentially means ***allowing the river to migrate and lengthen where possible***. Most sections of the river appear to still be over-steepened such that more lengthening through bank erosion should be expected over a long period of time. Active reduction in channel slope can be achieved sooner by re-activating abandoned meanders.

7.1.1 Passive Lengthening of the Musselshell River

Figure 75 shows an example section of river that is relatively steep but shows active meander development. Many of these meanders are migrating into low elevation swale areas that typically contain riparian bottomland rather than improved fields. We recommend that landowners evaluate their tolerance for bank movement and consider allowing migration and lengthening into less productive lands to help reduce stream energy and longer-term erosive pressure. This would also include undeveloped high benches or terraces.

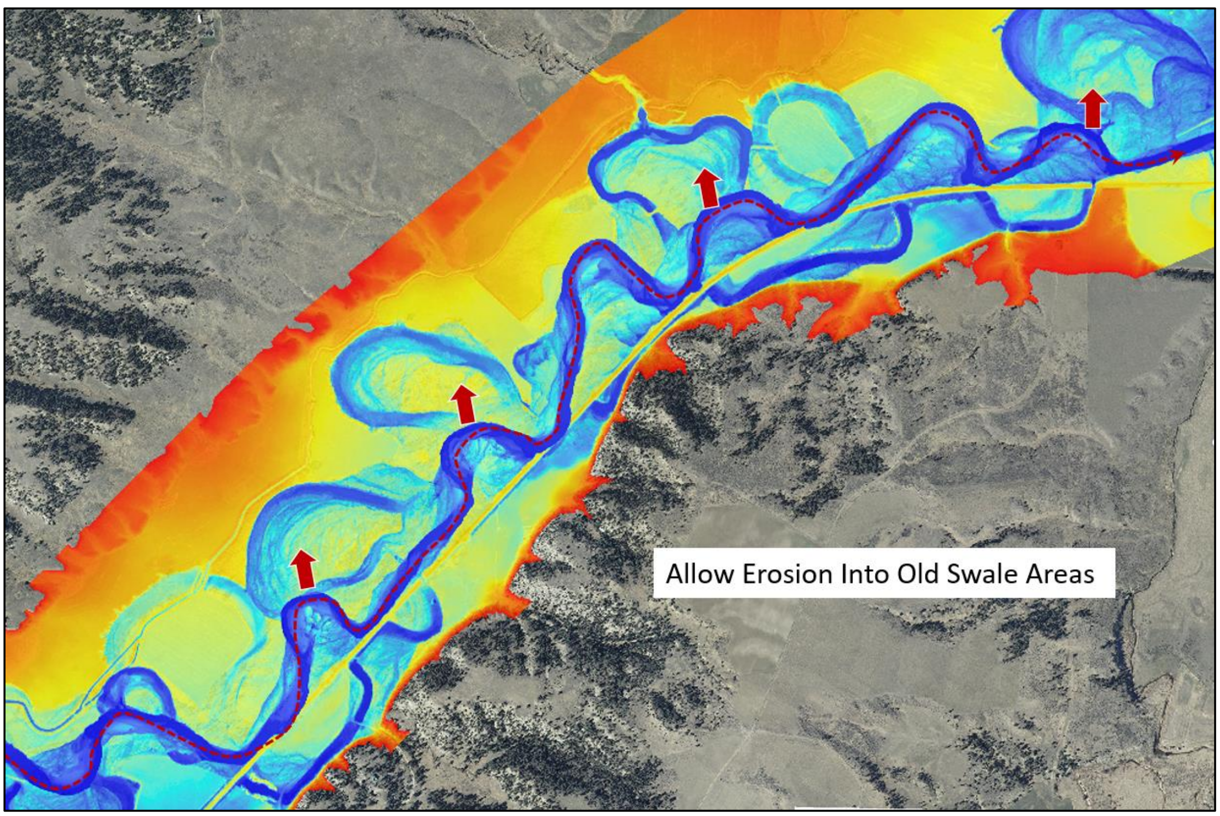


Figure 75. Relative Elevation Model (REM) showing old swales (blue arcs on floodplain, that could be areas of allowable channel movement.

7.1.2 Active Lengthening of the Musselshell River (Meander Reactivation)

Another means of reducing channel slope and stream energy on the river is to reactivate abandoned meanders. This is a common restoration action in systems that have seen excessive straightening due to past engineering projects or floods. Figure 76 shows an example meander that cut off in 2018 and abandoned a pump site. This meander is currently under consideration for reactivation, which would include plugging the avulsion path shown in the lower right of Figure 76 and rerouting flows back to the 2017 channel (Figure 77).

Figure 76. Closeup imagery of avulsion path in 2017 (top right) and 2018 (bottom right) showing potential reactivation site; pump site is marked by star.

Figure 77. View downstream of abandoned channel following avulsion shown in Figure 76, 2018.

The LiDAR data can be very helpful when considering a reactivation project, as many of the old meanders on the floodplain have become perched due to mainstem channel downcutting (Section 1.1.2). Perched meanders can be very expensive to reactivate as they require either extensive excavation or boosting of the river itself. Figure 78 shows two examples of floodplain meanders with different degrees of perching. The same site is shown in Figure 79 with the general reactivation/railroad berm removal concept shown.

In some areas of the lower river below Mosby, several miles of channel could potentially be reactivated, reducing channel slope and stream power while potentially allowing the recovery of previously abandoned pump sites (Figure 80). Reactivation of the two meanders shown in this figure would reduce the channel slope from 0.14% to 0.06%.

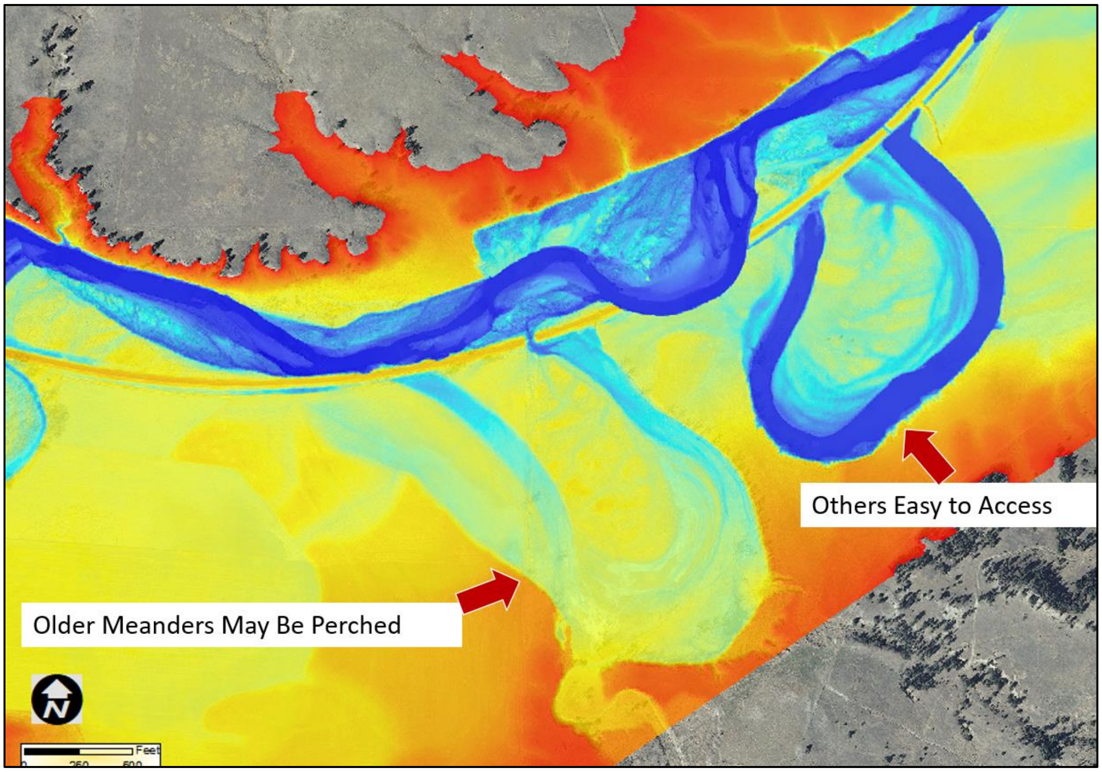


Figure 78. Example meanders that could be evaluated for reactivation; meander on right is clearly lower and would be more cost-effective to reconnect.

Figure 79. General concept for meander reactivation.

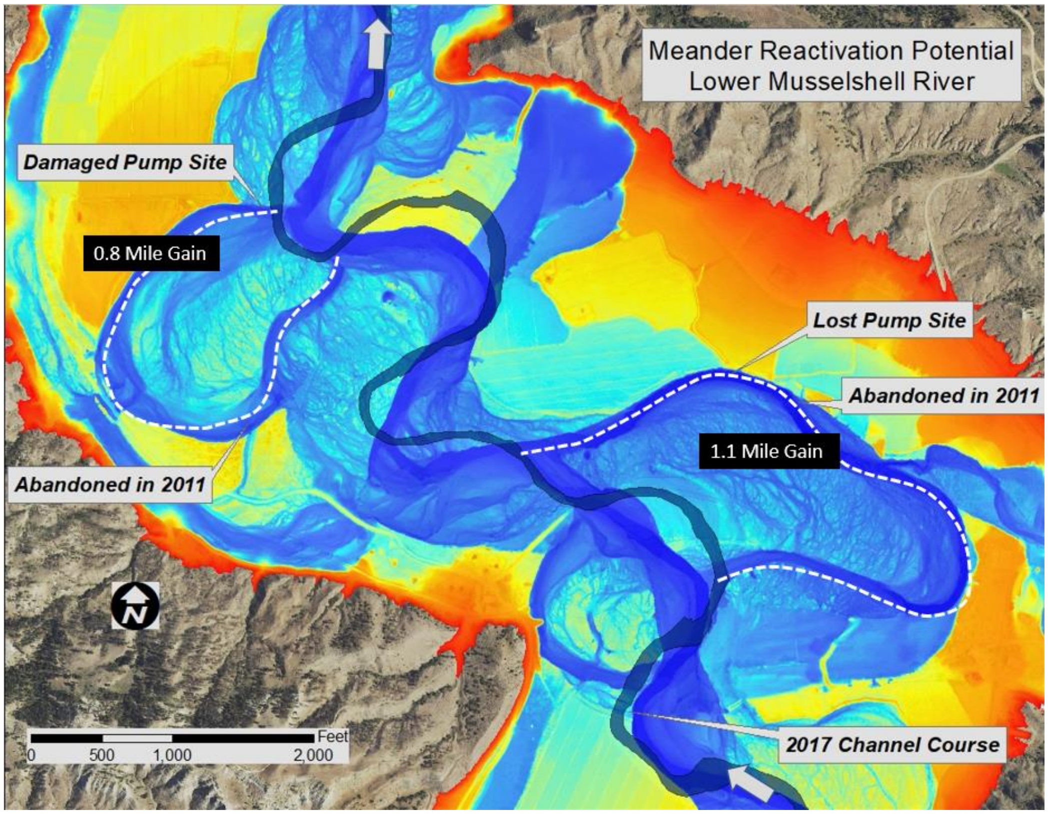


Figure 80. Potential meander reactivations (dashed white lines) below Mosby that could recover almost 2 miles of channel length and recover a pump.

7.1.3 Minimizing Future Shortening of Musselshell River

We strongly recommend against constructed cutoff trenches and intentional channel shortening. Figure 81 shows an example trench that, if captured, will create a four-foot drop in the river that will likely make erosion problems upstream much worse. We highly recommend the existing trenches be remediated and future channel shortening be stopped.

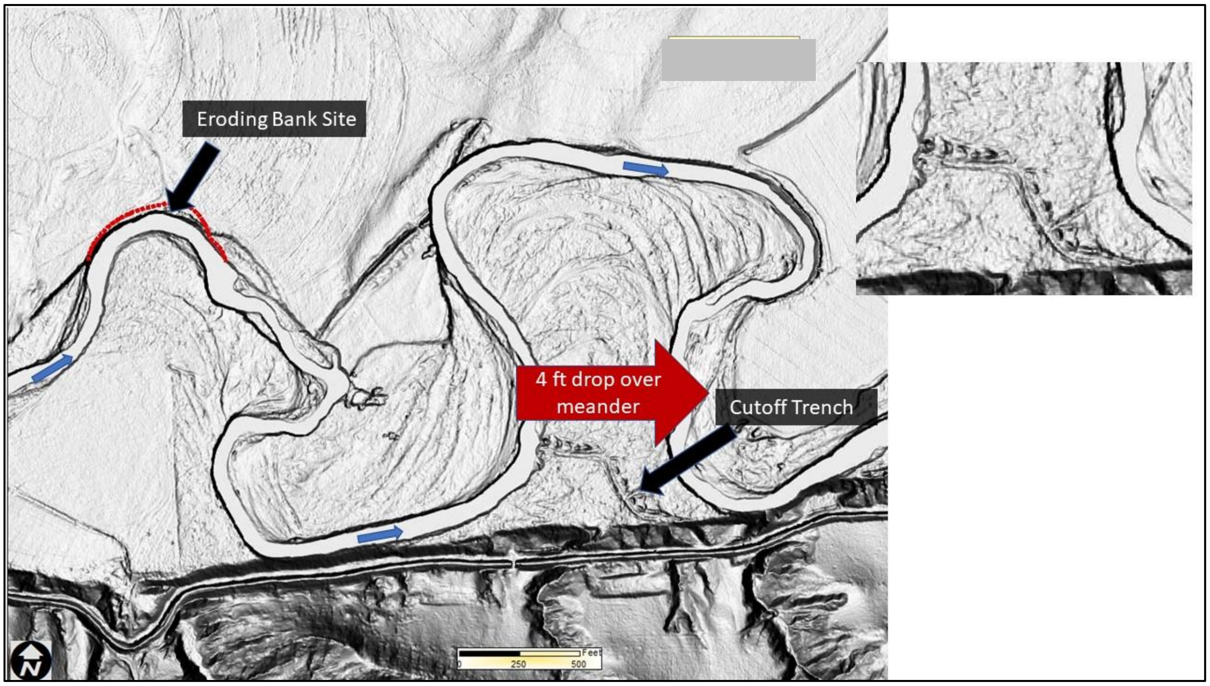


Figure 81. Example cutoff trench through meander core.

7.2 Dissipating Flood Energy

Another way to reduce stream power is to spread floodwaters away from the main channel. This can be achieved by reconnecting the river to the historic floodplain activation through the railroad berm breaches or by the installation of culverts through the berm (Figure 56).

7.3 Bank Integrity

Bank erosion on the river has understandably prompted landowners to consider aggressive bank protection to preserve ground. Our main recommendation with bank armoring is to "choose your battles", and consider the cost/benefit of armoring projects. The supplement in Appendix A provides alternatives to hard armor that will promote the recovery of bank integrity without locking the river into an unstable configuration perpetually.

> *"If a guy could outlast it until it stabilizes, that's what we're after"*
>
> *--Petroleum County Irrigator*

Our concern with excessive armoring is that it will end up being a perpetually expanding process that will be very costly and will stop natural recovery of the river. That said, we fully understand that it is sometimes appropriate and necessary (Figure 82) in certain situations.

> *My Dad told me "don't fight the river, only a fool would fight the river".*
>
> *--Irrigator below Roundup*

We would also recommend encouraging the recovery of riparian vegetation through grazing management or other riparian protections. Optimally, the vegetation would be dominated by species native to the Musselshell River corridor.

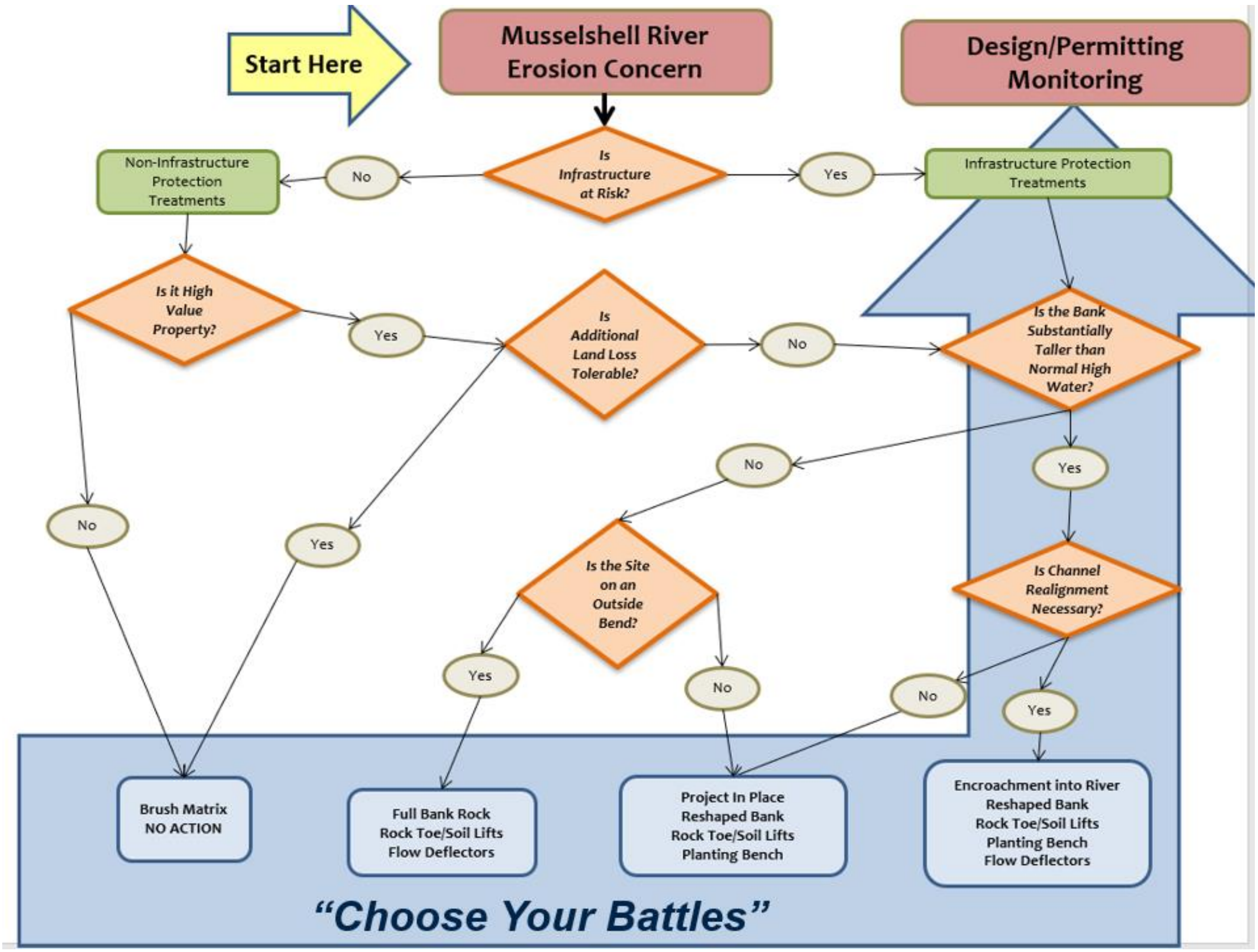


Figure 82. Decision pathway for bank armoring (Appendix A).

7.4 Floodplain Integrity

Floodplain integrity will continue to be an important component of flood resilience. Where possible, protecting the meandering stream as a complete riparian corridor or Channel Migration Zone (Section 1.1.7) that supports woody vegetation will contribute to long-term stability.

7.5 Landowner Adaptability

"Everything from now on will be a portable something or other…"

--Musselshell County Irrigator

Many of the recommendations we have made will require landowners to integrate the natural river processes that are driving the Musselshell River recovery into their planning and operations. Understanding how the river usually responds to high-flow, high-energy flood events will provide insight on how to manage the riparian and floodplain areas to minimize future damage and recovery costs.

River modifications over the last century provided the setup for massive destabilization of the Musselshell River in 2011. Since then, work performed by major flooding has set the river on a path to re-stabilization through re-lengthening and reduction of stream power. As the river continues to evolve towards an equilibrium condition (balance of stream power and sediment), additional change is inevitable. If flow patterns become more characteristic of pre-2011 patterns, this will include channel narrowing and vegetation encroachment onto open gravel bars. This will increase roughness and reduce stream energy, although the river will still be locally over-steepened and erosive. Additional flooding will drive continued lengthening, at least locally, which will reduce stream energy and speed up the recovery process (if allowed). However, this lengthening may be offset by additional avulsions, especially where there are cutoff trenches, cleared meander cores, or remnant floodplain headcuts that could be reactivated. As a result the path to recovery depends heavily on future flow patterns as well as management actions that may encourage, accommodate, or impede that recovery.

On a practical level, one of the most apparent ways to cost-effectively accommodate continued change in is to make pump sites portable. The conversion from permanently-placed pump sites to portable pump sites has been a positive change on the Musselshell and should continue to be encouraged.

Another tool is the Channel Migration Zone (CMZ) maps that show where existing and future development may be jeopardized by future channel movement and bank erosion. The proactive siting of infrastructure and development of irrigated fields outside the CMZ can proactively reduce the need to relocate infrastructure and/or investing in expensive bank stabilization measures. Post-2018 imagery should be used to map channel locations, calculate migration rates, and identify areas of risk.

Helping landowners adapt to near-term changes would also be facilitated by a geomorphic stability analysis of the river that identifies areas most dramatically shortened and prone to excessive stream power.

As described previously, another adaptive measure by landowners would be to allow and encourage the recovery of native woody riparian vegetation (cottonwoods and willows) within the meander corridor to improve floodplain resilience.

8 Summary and Discussion

Over the last decade, unprecedented flood patterns on the Musselshell River have caused systemic instability through the entire river corridor from Two Dot to Fort Peck Reservoir, a distance of over 300 miles. This instability was driven by the spring 2011 flood of record, when a late season snowpack was rapidly melted by several inches of rain (RATT, 2012). A 100-year flood event ensued, driving extensive change in both the channel and floodplain. This flood was large in magnitude and long in duration. High flows that overwhelmed the channel and spread onto the floodplain were sustained for weeks.

When considering the impacts of the 2011 flood, it is important to consider the condition of the Musselshell River prior to the event. A common concept in river management is ***resilience,*** which is the ability of a river corridor to absorb disturbances without major destabilization. In rivers, resilience is generally provided by bank integrity, floodplain integrity, a stable flow regime, and effective dissipation of flood energy. Prior to the construction of the railroad, the river corridor was densely vegetated, sinuous, and connected to its floodplain such that high flows could spread out and dissipate. Since then, the floodplain has been cleared, and the river straightened. Floodplain connectivity was reduced by berms and channel downcutting. But, as floods were rare during the final decades of the 20th century, the river changed very little. Over the last eight years, however, the flow regime on the Musselshell has shifted from decades of low flows to a distinct period of repetitive flooding. As the river wasn't set up to absorb the flood energy very well, the system had the potential to "unravel", which it did in 2011 (RATT, 2012). Floodplain clearing had reduced roughness and deep root reinforcement of that surface. Channel straightening by both the railroad and producers left the river over-steepened in areas and prone to bank erosion and meander cutoffs (avulsions) during high water. The flood caused extensive carving of new channels through the floodplain, additional channel shortening and steepening, and bank erosion. Diversion dams were flanked, pump sites were abandoned, bank erosion was severe and productive fields were damaged by overland flow erosion and/or burial from sediment deposition.

If we had seen minimal flooding over the last decade (post-2011), the changes on the river may have been fairly modest, even though the channel remained over-steepened by the loss of length prior to and during the 2011 flood. Bank erosion would have been localized, and vegetation would have slowly encroached into the enlarged channel, contributing to longer-term resiliency. The river would have slowly regained length. However, a series of additional floods in rapid succession drove dramatic change, driven by the high stream power (the product of channel slope and river discharge) imparted on the flood-impacted channel. Extensive bank erosion, downcutting, additional channel widening, and more avulsions occurred. Although we don't have post-2018 imagery to measure changes system-wide, the post-2011 floods appear to have driven more lengthening through bank erosion than shortening by avulsion. As a result, a major theme since 2011 has been the regaining of channel length, resulting in some reduction in channel slope, some reduction in stream power, and long-term contributions toward resiliency. A basic tenet in river process is that streams will naturally trend towards an equilibrium condition (balance of stream power and sediment delivery) if allowed. This often takes decades to happen and requires understanding and patience from landowners who live along the river.

Managing the re-establishment of equilibrium and resiliency on over 300 miles of river corridor can be extremely difficult, as the recovery process requires the accommodation and/or encouragement of continued change. Bank armor will be necessary in certain areas yet impedes long-term recovery as the river will remained over-steepened where locked in. We are concerned that excessive armoring will create challenges for landowners in that those who armor over-steepened sections will face risks of additional downcutting and continued maintenance/project extensions. We are also concerned that upstream and downstream neighbors will begin to have problems as those who aggressively armor may perpetuate downcutting and erosion in off-site areas.

Our primary recommendation for the Musselshell River community is to work collaboratively and systemically to improve the long-term resiliency of the Musselshell River to future flooding and/or wholesale changes in flow regime due to climate change. This requires accommodating or encouraging the river to regain an equilibrium configuration, which is the slope, size, and shape that creates a balance between sediment transport and stream energy (sediment in = sediment out). For decades prior to 2011, the river appeared to be in equilibrium, but the combination of a massive flood and poor resiliency disrupted that condition.

The re-establishment of resiliency on the river should include the following considerations:

- Allow bank erosion and meander formation/lengthening in areas of low economic productivity (riparian bottoms, undeveloped terraces, etc);
- Reconnect blocked meanders to dissipate flood energy (access by high flows);
- Locally reactivate meanders where feasible (access by all flows);
- Encourage riparian recovery within the meander corridor, including meander cores, potential avulsion paths, and field buffers;
- Use bank protection techniques that support woody riparian recovery;
- Minimize hard armor in over-steepened sections; and
- Incorporate portable infrastructure in agricultural operations (eg portable pumps).

Additionally, management of the river corridor should include aggressive noxious weed/invasive species control and the encouragement of long-term native woody species sustainability on the floodplain. It is important to note that all of these management strategies are compatible with the strategic management of fisheries and riparian areas to also recover an ecologically robust system.

We understand the desire to ”wind back the clock” on the river and restore the conditions of the late 1990s. To do that, landowners should consider the slope and length of the river, and brainstorm ways of recovering that slope and length. Native woody vegetation should be reestablished on streambanks and in the core of the meander belt. In the event that climate change will alter the flow regime in the long-term, we as the RAT Team concur that staying flexible and allowing the river to adjust to the “new normal” will serve as an economic and ecological advantage for Musselshell River corridor producers, residents, and stakeholders, as well as for future generations that will ultimately take on the management role.

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Appendix A: Bank Armor Supplement

Select Bank Protection Alternatives

Supplement to 2018 RATT Site Reports

9.1 Introduction

This Bank Stabilization Report Supplement describes a series of bank stabilization strategies that we feel are applicable to the Musselshell River. They include the following:

I. **Full Bank Rock Riprap**: The most aggressive option, most appropriate where you want to protect key infrastructure; in most cases this approach is not necessary. Finer material can be added to this treatment to create "dirty riprap".
II. **Toe Rock with Vegetated Soil Lifts**: A common approach consisting of toe rock overlain by fabric-wrapped soils with willow cuttings, which promotes willow establishment on the upper bank.
III. **Planting Bench with a Riprap Toe/Soil Lifts**: Useful where you would like to build out from a high, steep eroding bank to create a low bench that will support riparian vegetation, or excavate a low bench against the bank.
IV. **Flow Deflectors**: Flow deflectors can be useful but should be used where you feel confident that the angle of approach by the river won't change much.
V. **Alluvial Brush Matrix**: this treatment is gaining popularity in parts of the state, and can be used in areas of moderate energy, especially where you would like to build a new bench off of a bank to and re-establish vegetation.

Numerous other types of treatments have shown success in controlling bank erosion across the state, such as using coarse woody material in bank toes, simple bank grading/planting, etc. The alternatives presented here are intended to give landowners some ideas for different treatment types in different settings, and we encourage further exploration and pilot trials.

The selection of a treatment type is dependent on the site and project objectives. Figure 83 shows an example decision tree to help identify the types of treatments that may be most applicable in a given setting. This is based on a general desire to provide the level of protection needed while minimizing unnecessary cost and impacts to stream function. Table 3 summarizes estimated costs and design considerations for the suite of approaches described in this document.

Disclaimer: The example schematic drawings that are this document have not been specifically catered to any given site on the Musselshell River. As such, their application at any given site requires site specific assessment and design. We highly recommend that landowners consult with a streambank erosion control specialist to accommodate their goals and resources; furthermore, factors such impacts on upstream/downstream landowners, ability to permit, anticipated maintenance, and availability of materials must be addressed prior to treatment selection and implementation. In summary, we make no claim that any of the treatment concepts provided here are generically appropriate without further assessment.

For additional information regarding bank armor on the Musselshell River, please refer to the RATT BMP.

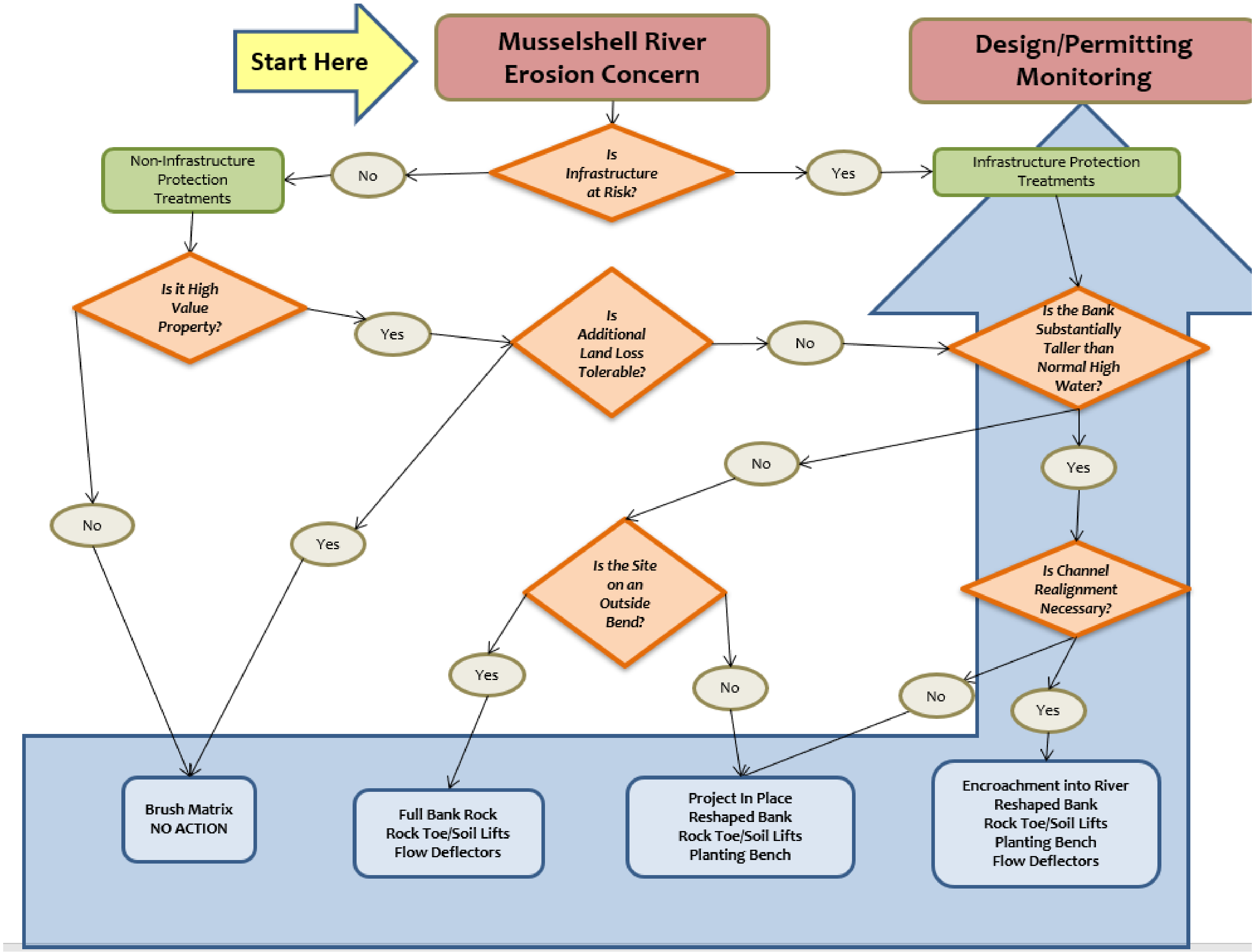

Figure 83. Decision matrix for a range of Musselshell River Bank Protection Alternatives.

Table 3. Summary of treatment cost, performance, and considerations.

Treatment	Estimated Cost*	Level of Erosion Control	Ecological Value	Key Design Considerations
Full Bank Riprap	$150/ft	High—Long Term	Low: Accelerates velocities, can cause downcutting	• Upstream and downstream extents • Rock sizing • Key toe and both ends of riprap
Toe Rock with Fabric Lifts and Planting Bench	$70/ft	High- Long Term	Moderate: Provides some shade and bank habitat	• Upstream and downstream extents • Toe Sizing • Key toe and both ends of riprap • Elevation of lifts • Viabillity of willow cuttings • Timing of construction
Flow Deflectors	~$7,000/ deflector	Moderate—function may degrade with time	May create scour holes off of barb, but will narrow channel and cause eddy erosion. Can affect adjacent properties	• Applicability at site • Length • Spacing • Orientation • Rock Sizing • Key into bank
Brush Matrix	$40/ft	Moderate- deformabillity can be designed at toe	High- Creates good cover, and enhances bankline vegetation	• Applicability at Site • Viability of willow cuttings • Alluvial source material

Costs have been estimated from other Montana projects and may vary.

9.2 Infrastructure Protection—No Tolerance for Bank Movement

Where there is no tolerance for additional bank movement, such as where infrastructure is at risk or where a landowner is determined to stop erosion into a field, and where the threat can't be removed by other means (such as moving a road), rock-based bank armor is likely appropriate. These treatments are based on a rock toe that extends to scour depth, with varying options for grading and upper bank treatments.

9.2.1 Full Bank Rock Riprap

Full bank rock riprap is a commonly expensive, susceptible to damage requiring maintenance, and prone to issues on the upstream and/or downstream end of the treatment that require project extensions. Full bank rock riprap is also commonly over-applied, as it extends to very high bank elevations where erosive energy is relatively low (Figure 84). As a result, the treatments commonly support little to no vegetation. The NRCS discourages practices that provided limited or minimally functional vegetation, or no re-vegetation (NRCS, 2011).

Figure 85 shows two examples of full-bank armor on the Musselshell. Both of these projects appear functional, with the photo on the left showing a relatively low riprapped bank, and the photo on the right showing a very high bank. With both of these projects, the most important part of the treatment is in the lowermost part of the bank, from a couple of feet above the water surface to the depth of scour below the streambed. This toe essentially provides the foundation over which the upper bank treatment is built. On the upper banks of both sites shown in Figure 85, there are means of bank shaping and incorporating or encouraging willow growth to improve aesthetics, add roughness to reduce erosive energy, and contribute some bank habitat (Figure 86). The NRCS (2011) indicates that the rock only needs to extend as high as the “stream forming flow”, which is typically an average runoff event or about a 2-year flood (Figure 87).

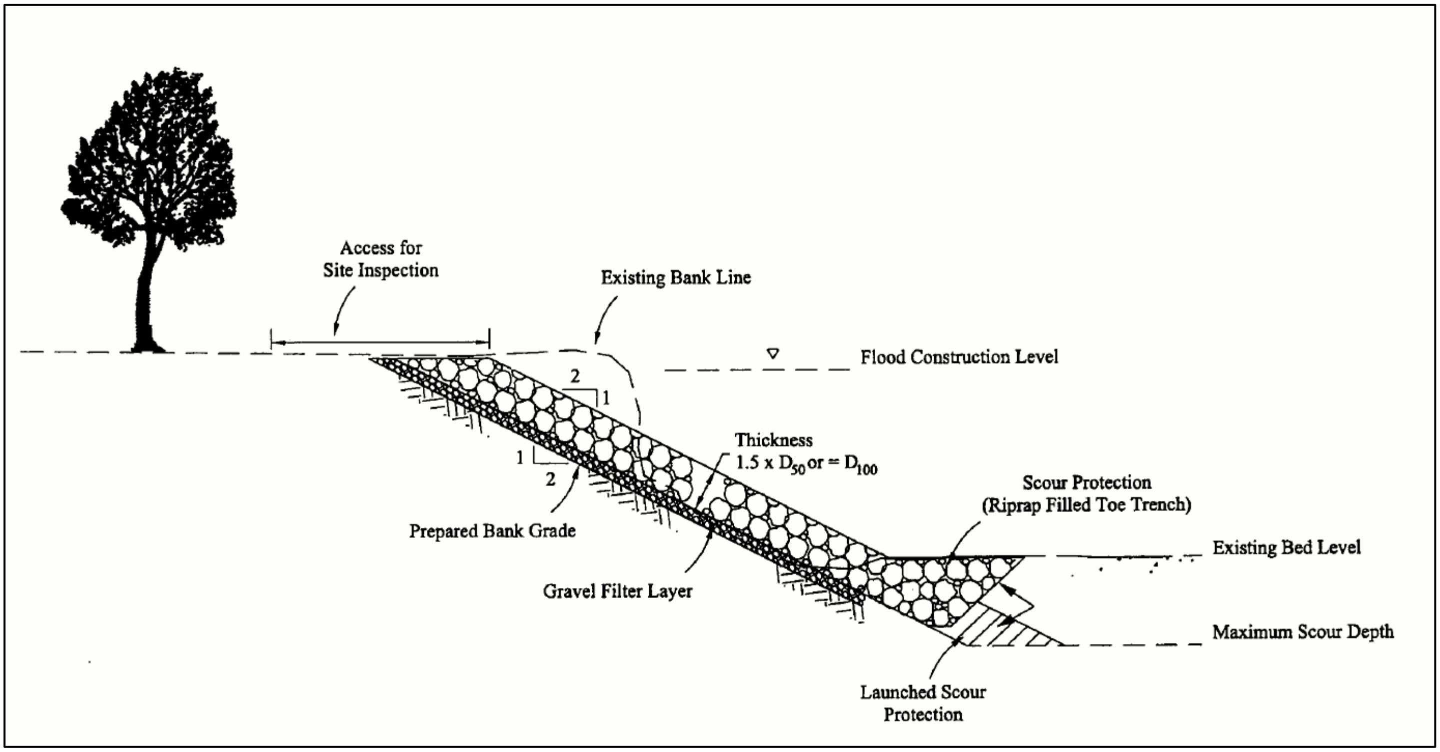

Figure 84. Cross Section of typical full-bank rock revetment.

Figure 85. Full bank rock riprap against floodplain surface (left) and higher terrace (right), Musselshell River.

Figure 86. Example of rock riprap that covers most of the bank but will allow for some vegetation growth on upper most bank -Yellowstone River, Riverside Park at Laurel (billingsgazette.com).

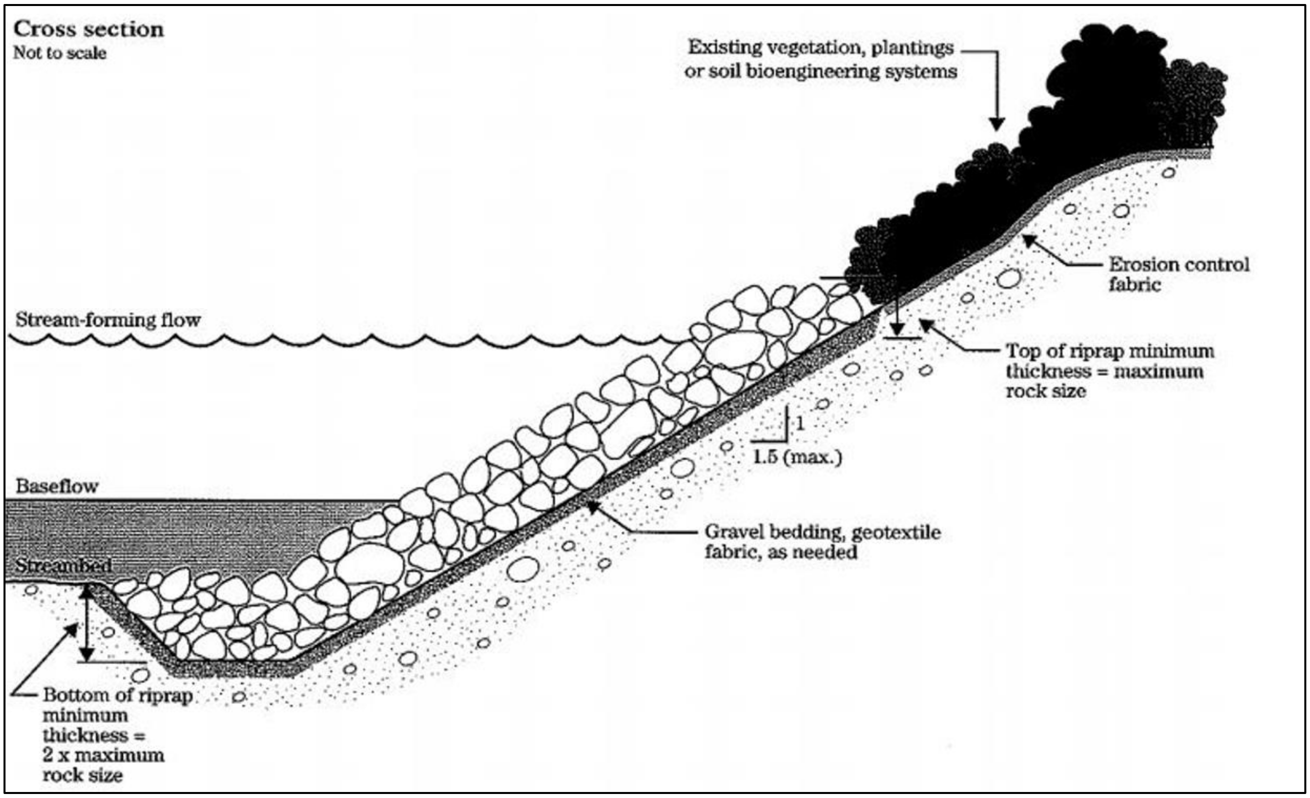

Figure 87. NRCS Cross Section of rock riprap that stops at the elevation of the "stream forming flow" transitioning to planting systems above.

Stakeholders who select full bank rock riprap as a treatment should consider the following:

- Excavate and 'key in' the base or 'toe' of the rock blanket below the elevation of anticipated bed scour as this is the zone of highest erosive stress from water, ice, and the weight of the rock above.
- Carefully consider the upstream and downstream limits of the armor to avoid project flanking or local scour failure (Figure 88).
- Utilize a gravel filter blanket beneath the rock in sites with sandy soil to retain soil fines.
- Use angular rock properly sized for the energy setting. Concrete and round rock is unsuitable as riprap.
- Avoid placing rock on slopes that are steeper than 2H:1V—although the slope in Figure 87 says a 1.5H:1V is acceptable, they note that a slope that steep should only be used if absolutely necessary and that 2H:1V is much more appropriate. If possible, a slope of 3H:1V is even better.
- Riprap projects should incorporate native vegetation into the design whenever possible and use 'dirty' rock or rock that has some soil incorporated into the rock matrix to encourage vegetation.
- Always have a qualified professional engineer and/or hydrologist evaluate, design, and oversee installation of rock riprap projects. This may help to avoid failure and treatments that simply 'band aid' a larger stream stability issue. Bank armor is notorious for being flanked, which can drive extremely fast erosion and result in costly reconstruction/repair (Figure 88).

In general, the use of full bank rock riprap without added incorporation of vegetation on the upper bank should be reserved for local infrastructure protection such as bridge crossings where floodplain restrictions create high velocities high on the channel banks (Figure 89).

Figure 88. View upstream of flanked bank armor, Musselshell River.

Figure 89. Limited application of full bank rock riprap at bridge crossing, Prickly Pear Creek at East Helena.

9.2.2 Toe Rock with Fabric Lifts and Planting Bench

As an alternative to full bank rock, biodegradable fabric lifts (commonly called “vegetated soil lifts”) are commonly used to provide upper bank structure that supports the growth of woody vegetation. The intent of the lifts is to provide bank structure, contribute soil material for growth, and hold moisture to allow the establishment of woody vegetation that eventually takes over the bank stabilization role as the fabric decays, typically over about five years. The lifts are built above a constructed toe, above the base flow elevation (Figure 90).

In many designs such as that shown below, the lifts are angled back into the bank to keep the willow cuttings between the lifts wet at their base. Soil lifts that incorporate a low planting bench behind have been successfully used on the Musselshell (Figure 91). Figure 92 shows other soil lift examples on the Clark Fork River and Prickly Pear Creek near Helena. Both of these projects used toe material that was rounded cobble rather than quarried rock. The cobble was sorted from local alluvium. The Clark Fork River examples show how a “sacrificial toe” extending into the river below the bottom lift can become colonized by woody vegetation (Figure 92). Also, the toe material can be sized to move if that is desirable. On the Clark Fork River, for example, the toe is designed to mobilize at a 10-year flood so the river won’t be perpetually locked in place, only until vegetation is reestablished.

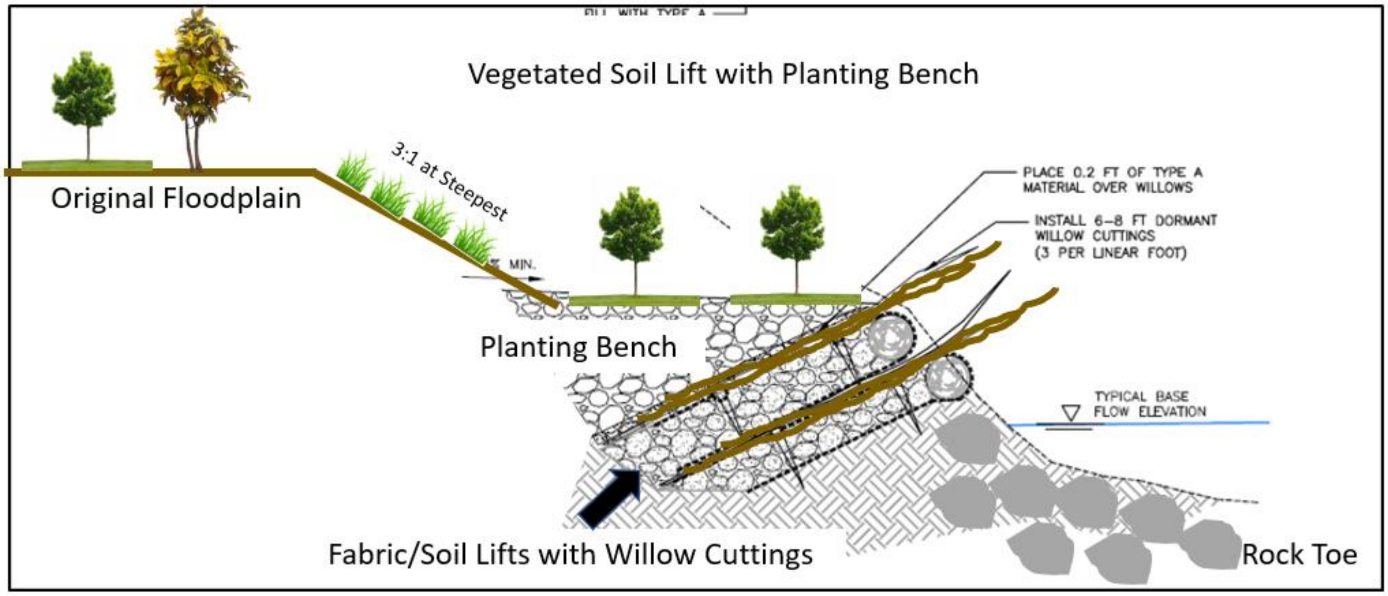

Figure 90. Example schematic drawing for vegetated soil lift design.

Figure 91. Soil lift project with planting bench behind on Musselshell River above Roundup.

Figure 92. Willow growth in soil lifts on Clark Fork River (top) and Prickly Pear Creek (bottom).

With regard to the "planting bench", this surface can either be left for natural colonization of willows and other woody species (Figure 93), or actively planted (Figure 94). This bench is also commonly called an "inset floodplain bench" or "bankfull bench". Many designs set this bench elevation at "Q2", which is the 2-year flood or the water surface elevation during common snowmelt runoff events. The goal is to have a surface that is in contact with groundwater and river processes so riparian vegetation can establish at the toe of the steeper bank. The width of the bench can vary, so it can be used to rebuild floodplain to reconfigure channel alignment, such as at diversion dams. On the Musselshell, this technique could be used to rebuild floodplain area lost in the 2018 flood for example.

Figure 93. Bankfull bench construction on Clark River just after construction (left) and ~4 years later (right).

Figure 94. Bankfull bench construction on Boulder River near Drummond (George Austiguy).

9.2.3 Flow Deflectors

Flow deflectors is s general term of techniques that include groins, spur dikes, barbs, vanes, bendway weirs, or any other low elevation structures that project into the channel from a bank to redirect flow away from the bank. They are often combined with other types of bank protection techniques, such as bank shaping and planting between the deflectors. The long-term function of these treatments is best on long, uniform bends where the upstream approach remains relatively constant through time. They are inappropriate in channels that are actively downcutting, aggrading, or notably steep (over 2%). If an avulsion is likely in an area, flow deflectors should be avoided. And in some cases, bendways can become too compressed for flow deflectors to function. The spacing of flow deflectors depends on the length, angle, and shape of the channel and requires careful design for optimal performance. They should be properly keyed into the bank.

Barbs Vanes, or Jetties are the most common type of deflector used on the Musselshell River to date. They are designed deflect water, ice, and debris away from the bank on gentle outside bends or straight reaches. They are usually constructed of a series of evenly spaced, large diameter stone or log structures (or a combination of both). They are typically aligned perpendicular to flow, but can also be pointed at an angle upstream or downstream. Upstream alignments are becoming more common to reduce erosion between the structures at high flow. Their length should not exceed about one-fourth of the channel width. Barbs that are pointed downstream often increase erosion on the opposite bank. If the river changes its approach direction, or if the barbs are poorly design or constructed, severe erosion between the structures can occur which can result in complete flanking (Figure 95 and Figure 96). When compared to traditional rock riprap, barbs have a lower impact on natural streambank and fisheries. To improve fish habitat, wood is sometimes used in barbs. The use of concrete rubble, concrete slabs, or metal debris is highly discouraged. When building them, they can be positioned to minimize their impacts on existing vegetation. They typically require less material and cost less than rock riprap, but they are riskier.

On the Yellowstone River, barbs are generally discouraged because most projects end up being converted to full bank riprap because of erosion problems between the structures (Figure 97).

For a summary of other types of flow deflectors, see the Musselshell River Bank Armor BMP.

Figure 95. Erosion control barbs on Musselshell River (left) and Yellowstone River (right) showing orientation to flow, and erosion between structures.

Figure 96. View downstream showing recently constructed (left) and older (right) barbs showing erosion between structures in older projects.

Figure 97. Barb treatment converted to full bank riprap.

9.3 Non-Rock Treatments—Allowance for Some Bank Movement

In some cases there are opportunities to use "softer" bank treatments that are intended to provide shorter-term protection while a channel adjusts to a more stable planform. These are referred to as bioengineering treatments or "engineered deformability". These treatments can be extremely cost effective where risk is low and the potential for recovering vegetation is high. The Musselshell River Bank Protection BMP document describes numerous types of bioengineered bank treatments. The soil lifts described above are a type of bioengineered bank, however the rock toe under the lifts makes them non-deformable. The treatments below are intended for use where some additional bank movement is tolerable.

9.3.1 Brush Matrix

One low cost, deformable treatment that is showing great promise on different rivers of Montana is referred to as a "brush matrix" which is a bank constructed of a mixture of alluvium (gravel and cobbles) mixed with wood fragments. The wood extends into the channel at all different angles, creating a rough edge that provides excellent fish habitat while reducing erosive energy. These treatments can also be built to form an inset bench that promotes woody vegetation growth (Figure 98 through Figure 101). This treatment can also be built on a larger rock toe if that is of interest; this approach was taken on the Ruby River to support fish habitat, however the toe was not riprap so some deformability is expected and desired (Figure 100).

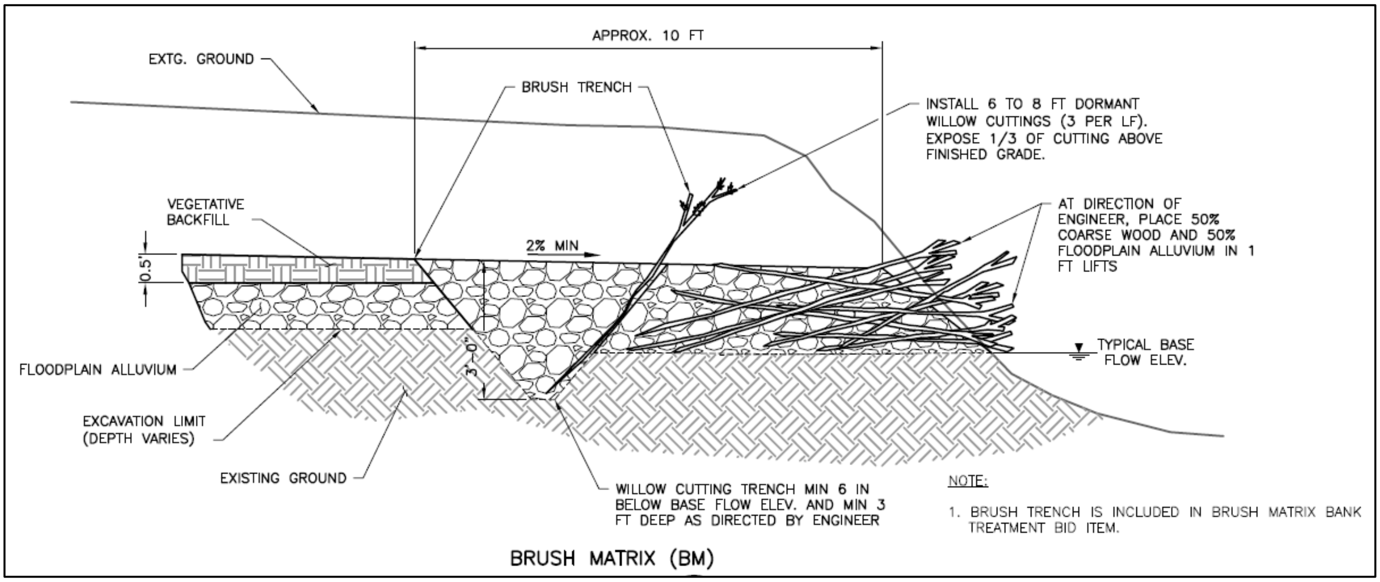

Figure 98. Example design drawing for a brush matrix treatment; this can be constructed over a rock toe in areas of higher energy (CDM Smith, 2016).

Figure 99. Recently constructed brush matrix treatments, Clark Fork River near Deer Lodge.

Figure 100. Brush matrix construction creating low bench (left), willow growth four months after installation- Ruby River near Sheridan MT (note—steep scarp on photo on left will be graded back to 3H:1V..

Figure 101. Robust willow growth ~3 years after installation, Clark Fork River near Deer Lodge.

Sources of Additional Information.

Montana Department of Natural Resources and Conservation – Guide to Permits. **http://dnrc.mt.gov/Permits/StreamPermitting/Guide.asp**

Montana Department of Natural Resources and Conservation – Montana Stream Permitting Handbook. http://dnrc.mt.gov/Permits/StreamPermitting/PermittingBook.asp

USDA Natural Resources Conservation Service Stream Corridor Restoration Handbook:
http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1043244

Integrated Streambank Protection Guidelines:
https://wdfw.wa.gov/publications/00046/

Appendix B: Glossary of Terms

Acre-foot – The volume of water that will cover one acre of surface area to a depth of one foot. One acre foot is equivalent to approximately 326,000 gallons.

Avulsion - A sudden cutting off or separation of land by a flood or by abrupt change in the course of a stream, as by a stream breaking through a meander or by a sudden change in current whereby the stream deserts its old channel for a new one. The result is often the formation of a straighter channel pattern characterized by an increase in channel bed slope and decrease in channel length.

Bankfull Depth - refers to the maximum depth of flow measured from the channel thalweg to the estimated bankfull elevation.

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. The stage just before over bank flow begins.

Belt width - the linear distance, perpendicular to the valley's axis, within the floodplain, and including the width of the channel(s), where channel shifting and/or lateral migration forms a bare or sparsely vegetated depositional or eroded surface that may be estimated from aerial photographs.

Bendway translation - a geomorphic process where a river channel bend migrates down-valley.

Flood frequency – The statistical probability that a flood of a certain magnitude for a given river will occur in a certain period of time.

Floodplain- a flat or nearly flat land adjacent a stream or river that stretches from the banks of its channel to the base of the enclosing valley walls and experiences flooding during periods of high discharge

Floodplain swales - depressions in the floodplain, which are often remnant channels that have partially filled in with sediment and/or vegetation.

Fluvial - formed or produced by the action of flowing water; of, pertaining to, or inhabiting a river or stream.

Geomorphic threshold - the threshold or sudden change of landform stability that is exceeded either by intrinsic change of the landform itself, or by a progressive change of an external variable. In this context, threshold refers to the point where episodic change in river course, form, or pattern occurs.

Geomorphology - the study of landscape evolution including shape, form and process through space and over time. It is the earth science that focuses on understanding the processes of erosion, weathering, transport, and deposition, with measuring the rates at which such processes operate, and with quantitative analysis of the forms of the ground surface and the materials of which they are composed (Goudie et. al. 1994).

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

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

Lacustrine - of or pertaining to lakes**.**

Large Woody Debris (LWD) - Functional wood in streams is called *large woody debris*. The definition of large woody debris has evolved in the scientific, regulatory and political arenas to include wood as small as four inches in diameter and six feet in length. However, the typical size of LWD are 18-36 inches in diameter and 12 – 32 feet in length.

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.

Prograding - the advancing or growth of a bar deposit**.**

Riparian: Relating to or inhabiting the banks of a natural course of water. Riparian zones are ecologically diverse and contribute to the health of other aquatic ecosystems by filtering out pollutants and preventing erosion.

Return Interval- The likely time interval between floods of a given magnitude.

Rosgen classification - a system of river channel classification developed by Rosgen (1994) that uses a letter and number system (i.e., B4, C3) as nomenclature to describe the geomorphic character of the stream channel, floodplain, and surrounding valley. Physical variables used in a morphological description Level II Rosgen classification include channel gradient, bed material type and size, channel pattern, and channel geometry.

Sediment continuity - where sediment input equals sediment output**.**

Seral-stage - of or pertaining to plant succession its relation to disturbance mechanisms such as floods or fires over time. A particular plant community type or dominant species may represent a *seral*-stage along a temporal scale; a *climax* stage represents the most mature and stable state prior to disturbance.

Sinuosity - the measurement of a channel's relative straightness or curving configuration. It is the ratio of channel length to downward valley length; for example, a value of one 1.0 is a straight channel pattern, whereas a sinuosity of 1.5 is considered meandering.

Stream competency - the ability of a stream to mobilize its sediment load; refers to the maximum size of particles of given specific gravity, which, at a given velocity, the stream will move.

Stream power - a concept that relates fluvial energy to sediment transport. To transport sediment, work (defined as the product of force and distance) must be performed. Power is the rate of doing that work, and stream power per unit length of stream. It is expressed as the product of the specific weight of water, discharge, and water surface slope.

Subaqueous return flow - existing or situated under water, as in the movement of shallow groundwater through riverbank materials to open channel flow.

Terrace - A step-like surface, bordering a valley floor or shoreline, that represents the former position of a flood plain, or lake or sea shore. The term is usually applied to both the relatively flat summit surface (tread), cut or built by stream or wave action, and the steeper descending slope (scarp, riser),graded to a lower base level of erosion. Compare - stream terrace, flood-plain step. HP. [soil survey] Practically, terraces are considered to be generally flat alluvial areas above the 100 yr. flood stage.