Geomorphology Study of the Fargo, ND & Moorhead, MN Flood Risk Management Project

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Table of Contents

1 Introduction 1-1
  1.1 Purpose and Authorization 1-1
  1.2 Scope 1-1
  1.3 Datums 1-6
  1.4 Acknowledgements 1-6

2 Background 2-1
  2.1 Prior Studies 2-1
  2.2 Basin Description 2-1

3 Study Reach Selection and Field Investigation 3-1
  3.1 Study Reach Selection 3-1
    3.1.1 General Study Reaches 3-1
    3.1.2 Detailed Study Reaches 3-1
  3.2 Field Investigations 3-6
  3.3 Cross Section Surveys 3-6
  3.4 Soil and Sediment Sample Analysis 3-7

4 Hydrology Assessment 4-1
  4.1 Flood History 4-1
  4.2 Channel-Forming Discharge for Current Conditions 4-2
    4.2.1 Bankfull Discharge Method 4-2
    4.2.2 Effective Discharge Method 4-4
    4.2.3 Recurrence Interval Method 4-47
    4.2.4 Channel-Forming Discharge for Current Conditions Summary 4-49
  4.3 Channel-Forming Discharge for Historic Conditions 4-50
  4.4 Discharge-Duration and Elevation-Duration Curves 4-51
    4.4.1 Discharge-Duration Curves 4-52
    4.4.2 Elevation-Duration Curves 4-62
  4.5 Specific Gage Analysis 4-69
    4.5.1 Specific Gage Record Development 4-69
    4.5.2 Specific Gage Record Analysis 4-71
  4.6 Hydrology Assessment Conclusions 4-77

5 Geomorphic Stream Classifications 5-1
  5.1 General 5-1
  5.2 Rosgen Stream Classification System 5-1
    5.2.1 General 5-1
    5.2.2 Rosgen System Classification 5-4
  5.3 Schumm and Brice Methods 5-45
    5.3.1 General 5-45
    5.3.2 Schumm Method 5-45
    5.3.3 Brice Method 5-45
    5.3.4 Selected Classification System 5-47
  5.4 Geomorphic Stream Classification Conclusions 5-49

6 Stability Analysis 6-1
- 6.1 Aerial Photography Analysis 6-1
  - 6.1.1 Sinuosity 6-3
  - 6.1.2 Meander Migration Rates 6-5
  - 6.1.3 Meander Amplitude and Frequency 6-8
  - 6.1.4 Meander Belt 6-12
  - 6.1.5 Trends in Sedimentation Features 6-15
  - 6.1.6 Changes in Channel Width 6-16
  - 6.1.7 Large Woody Debris 6-17
  - 6.1.8 Bank Erosion Rates 6-19
  - 6.1.9 Riparian Vegetation 6-28
- 6.2 Cross Section Geometry 6-30
  - 6.2.1 Current Geometric Comparison Baseline Data 6-30
  - 6.2.2 Historic Geometric Comparison Plots 6-33
  - 6.2.3 Regime Channel Geometry Methods 6-52
- 6.3 Stability Analysis Conclusions 6-53

7 Sediment Impact Analysis 7-1
- 7.1 Future Flow Conditions 7-1
  - 7.1.1 FCP Alignment 7-1
  - 7.1.2 LPP Alignment 7-1
- 7.2 Future Channel-Forming Discharge 7-2
- 7.3 Sediment Delivery Analysis 7-3
- 7.4 Low Flow Channel Design – LPP Diversion Alignment Alternative 7-7
- 7.5 Staging Area Deposition – LPP Diversion Alignment Alternative 7-8
- 7.6 Sediment Impact Analysis Conclusions 7-8

8 Monitoring Plan 8-1
- 8.1 Aerial Photography Evaluation 8-1
- 8.2 Field Reconnaissance 8-1
- 8.3 Cross Section Surveys 8-2
- 8.4 Communication with Local Agencies 8-3

9 Future Conditions Effects 9-1
- 9.1 Sedimentation/Erosion Potential 9-1
- 9.2 Changes in Sediment Transport Rates 9-4
- 9.3 Potential Morphologic Changes 9-6
- 9.4 Potential Effects on Riparian Vegetation 9-7
- 9.5 Conclusions for Future Conditions 9-9
  - 9.5.1 Buffalo River 9-9
  - 9.5.2 Lower Rush River 9-9
  - 9.5.3 Maple River 9-9
  - 9.5.4 Red River 9-10
  - 9.5.5 Rush River 9-11
  - 9.5.6 Sheyenne River 9-12
  - 9.5.7 Wild Rice River 9-12
  - 9.5.8 Wolverton Creek 9-13

9.5.9 FCP Channel 9-13
9.5.10 LPP Channel 9-14

10 Summary and Conclusions 10-1
10.1 Hydrology Assessment 10-1
10.2 Geomorphic Stream Classification 10-2
10.3 Stability Analysis 10-2
10.4 Sediment Impact Analysis 10-3
10.5 Monitoring Plan 10-4
10.6 Future Conditions 10-4

11 References 11-1

12 Quality Control 12-1

List of Figures

Figure 1-1. Locations of Diversion Channel Alternatives 1-5
Figure 2-1. Project Drainage Basin Extents 2-3
Figure 2-2. Sand Distribution in Study Area (USACE, 2011) 2-4
Figure 2-3. USGS Stream Gage Locations 2-5
Figure 3-1. General Study Reach Locations 3-3
Figure 3-2. Detailed Study Reach Locations 3-4
Figure 4-1. Natural Annual Maximum Mean Daily Flow – Red River at Fargo (David Ford Consulting Engineers, Inc., using USACE data) 4-1
Figure 4-2. Suspended Sediment Discharge Comparison for Red River Sites 4-7
Figure 4-3. Sediment Transport Histogram for Red River – 1 – 410.65 4-8
Figure 4-4. Sediment Transport Histogram for Red River – 2 – 419.14 4-9
Figure 4-5. Sediment Transport Histogram for Red River – 3 – 440.57 4-10
Figure 4-6. Sediment Transport Histogram for Red River – 4 – 452.52 4-11
Figure 4-7. Sediment Transport Histogram for Red River – 5 – 463.56 4-12
Figure 4-8. Sediment Transport Histogram for Red River – 6 – 470.23 4-13
Figure 4-9. Sediment Transport Histogram for Red River – 7 – 492.47 4-14
Figure 4-10. Sediment Transport Histogram for Red River – 8 – 521.18 4-15
Figure 4-11. Suspended Sediment Discharge Comparison for Sheyenne River Sites 4-17
Figure 4-12. Sediment Transport Histogram for Sheyenne River – 1 – 4.20 4-18
Figure 4-13. Sediment Transport Histogram for Sheyenne River – 2 – 11.56 4-19
Figure 4-14. Sediment Transport Histogram for Sheyenne River – 3 – 18.15 4-20
Figure 4-15. Sediment Transport Histogram for Sheyenne River – 4 – 22.27 4-21
Figure 4-16. Sediment Transport Histogram for Sheyenne River – 5 – 26.47 4-22
Figure 4-17. Sediment Transport Histogram for Sheyenne River – 6 – 35.82 4-23
Figure 4-18. Sediment Transport Histogram for Sheyenne River – 7 – 43.27 4-24
Figure 4-19. Sediment Transport Histogram for Sheyenne River – 8 – 55.75 4-25
Figure 4-20. Suspended Sediment Discharge for Maple River 4-27
Figure 4-21. Sediment Transport Histogram for Maple River – 1 – 0.78 4-28
Figure 4-22. Sediment Transport Histogram for Maple River – 2 – 11.39 4-29
Figure 4-23. Suspended Sediment Discharge for Wild Rice River 4-31

Figure 4-24. Sediment Transport Histogram for Wild Rice River – 1 – 3.01 4-32
Figure 4-25. Sediment Transport Histogram for Wild Rice River – 2 – 4.23 4-33
Figure 4-26. Sediment Transport Histogram for Wild Rice River – 3 – 17.52 4-34
Figure 4-27. Sediment Transport Histogram for Wild Rice River – 4 – 22.94 4-35
Figure 4-28. Sediment Transport Histogram for Wild Rice River – 5 – 38.49 4-36
Figure 4-29. Sediment Transport Histogram for Wild Rice River – 6 – 42.36 4-37
Figure 4-30. Suspended Sediment Discharge for Rush River 4-39
Figure 4-31. Sediment Transport Histogram for Rush River – 1 – 0.08 4-40
Figure 4-32. Sediment Transport Histogram for Rush River – 2 – 6.15 4-41
Figure 4-33. Suspended Sediment Discharge for Lower Rush River Site 4-43
Figure 4-34. Sediment Transport Histogram for Lower Rush River – 1 – 1.10 4-44
Figure 4-35. Sediment Transport Histogram for Lower Rush River – 2 – 6.03 4-45
Figure 4-36. Graphical Representation of Discharge-Duration Curve Interpolation Procedure 4-52
Figure 4-37. Relationship between Horace Diversion and Sheyenne River above Diversion Flows 4-53
Figure 4-38. Channel-Forming Discharge Duration and Drainage Area Relationship 4-56
Figure 4-39. Comparison of Discharge-Duration Curves for Red River – 4 – 452.52 4-59
Figure 4-40. Comparison of Discharge-Duration Curves for Wild Rice River – 6 – 42.36 4-60
Figure 4-41. Comparison of Discharge-Duration Curves for Sheyenne River – 5 – 26.47 4-61
Figure 4-42. Comparison of Elevation-Duration Curves for Red River – 4 – 452.52 4-66
Figure 4-43. Comparison of Elevation-Duration Curves for Wild Rice River – 6 – 42.36 4-67
Figure 4-44. Comparison of Elevation-Duration Curves for Wild Rice River – 3 – 17.52 4-68
Figure 4-45. Specific Gage Record for Red River at Fargo - 05054000 4-72
Figure 4-46. Specific Gage Record for Sheyenne River near Kindred - 05059000 4-73
Figure 4-47. Specific Gage Record for Red River at Halstad - 05064500 4-74
Figure 4-48. Specific Gage Record for Sheyenne River at West Fargo - 05059500 4-75
Figure 4-49. Specific Gage Record for Sheyenne River Diversion near Horace - 05059310 4-76
Figure 5-1. Rosgen Stream Classification Diagram (Rosgen, 2006) 5-7
Figure 5-2. Rosgen Level II Classification 5-8
Figure 5-3. Flow Regime Classification (Rosgen, 2006) 5-12
Figure 5-4. Stream Size Classification (Rosgen, 2006) 5-13
Figure 5-5. Meander Pattern Classification (Rosgen, 2006) 5-14
Figure 5-6. Depositional Pattern Classification (Rosgen, 2006) 5-15
Figure 5-7. Debris Blockage Classification (Rosgen, 2006) 5-16
Figure 5-8. Degree of Channel Incision Classification (Rosgen, 2006) 5-18
Figure 5-9. Modified Pfankuch Classification (Rosgen, 2006) 5-23
Figure 5-10. BEHI Calculation Worksheet (Rosgen, 2006) 5-26
Figure 5-11. BEHI Calculation Figures (Rosgen, 2006) 5-27
Figure 5-12. Near-Bank Stress Estimation Method (Rosgen, 2006) 5-28
Figure 5-13. Bank Erosion Rate Estimation Method (Rosgen, 2006) 5-29
Figure 5-14. Stage Shift Stability Rating Method (Rosgen, 2006) 5-31
Figure 5-15. Lateral Stability Prediction Worksheet (Rosgen, 2006) 5-34
Figure 5-16. Vertical Stability Prediction for Deposition Worksheet (Rosgen, 2006) 5-35
Figure 5-17. Vertical Stability Prediction for Incision Worksheet (Rosgen, 2006) 5-36

Figure 5-18. Channel Enlargement Prediction Worksheet (Rosgen, 2006) 5-37
Figure 5-19. Sediment Supply Rating Worksheet (Rosgen, 2006) 5-38
Figure 5-20. Rosgen Level III Classification – Lateral Stability 5-40
Figure 5-21. Rosgen Level III Classification – Vertical Stability for Aggradation 5-41
Figure 5-22. Rosgen Level III Classification – Vertical Stability for Degradation 5-42
Figure 5-23. Rosgen Level III Classification – Channel Enlargement Prediction 5-43
Figure 5-24. Rosgen Level III Classification – Sediment Supply Prediction 5-44
Figure 5-25. Brice Method of Stream Classification for Alluvial Channels (Brice, 1975) 5-47
Figure 6-1. Types of Meander Migration (NCHRP, 2004) 6-6
Figure 6-2. Sample of Meander Migration Calculation Methodology 6-7
Figure 6-3. Definitions of Amplitude and Frequency (Leopold et al., 1964) 6-9
Figure 6-4. Meander Amplitude and Wavelength Calculation Method 6-10
Figure 6-5. Example of a Specific Meander Defining the Meander Belt Width for a Reach (Parish Geomorphic, 2004) 6-13
Figure 6-6. Example of Meander Bend Digitizing Procedure 6-14
Figure 6-7. Sample Reach Showing ‘Slivers’ of Area Lost Due to Bank Erosion 6-20
Figure 6-8. Abandoned Meander, Sheyenne River - 8 (left – 1962, right – 2010) 6-25
Figure 6-9. Abandoned Meander, Sheyenne River - 8 (left – 1962, right – 2010) 6-25
Figure 6-10. Meander Cutoff, Red River - 8 (left – 1939, right – 2010) 6-26
Figure 6-11. Example of Bank Failure, Red River – 8 (left – 1997, right – 2010) 6-26
Figure 6-12. Bank Slumping along Sheyenne River - 1 6-26
Figure 6-13. Cycle of Overbank Depositions, Bank Slumping, and Toe Erosion 6-27
Figure 6-14. Example of No Notable Cross-Sectional Changes Occurring Between 2010 and 2011 on the Sheyenne River 6-31
Figure 6-15. Example of Notable Cross-Sectional Changes Occurring Between 2010 and 2011 on the Lower Rush River 6-32
Figure 6-16. Example Lower Rush River Cross-Section Comparison 6-36
Figure 6-17. Example Wild Rice River Cross-Section Comparison 6-37
Figure 6-18. Historic Cross Section Comparison for Location B2 6-39
Figure 6-19. Historic Cross Section Comparison for Location M1 6-40
Figure 6-20. Historic Cross Section Comparison for Location M3 6-41
Figure 6-21. Historic Cross Section Comparison for Location R1 6-42
Figure 6-22. Historic Cross Section Comparison for Location R2 6-43
Figure 6-23. Historic Cross Section Comparison for Location R3 6-44
Figure 6-24. Historic Cross Section Comparison for Location R6 6-45
Figure 6-25. Historic Cross Section Comparison for Location R7 6-46
Figure 6-26. Historic Cross Section Comparison for Location R8 6-47
Figure 6-27. Historic Cross Section Comparison for Location R9 6-48
Figure 6-28. Historic Cross Section Comparison for Location R10 6-49
Figure 6-29. Historic Cross Section Comparison for Location W1 6-50
Figure 6-30. Historic Cross Section Comparison for Location W2 6-51
Figure 9-1. Sheyenne River Overbank Sand Deposits Interbedded with Clays and Silts 9-2
Figure 9-2. Natural Levee Formed by Sand Deposition along the Sheyenne River 9-2
Figure 9-3. Silt and Clay Deposits in the Overbank Area of the Sheyenne River 9-3
Figure 9-4. Clay and Silt Overbank Sediment Deposits along Maple River - 2 9-4
Figure 9-5. Lanes Relationship (1955) 9-5

Figure 9-6. Riparian Vegetation Conditions along Sheyenne River - 5 9-7
Figure 9-7. Riparian Vegetation Conditions along Sheyenne River - 1 9-8

List of Tables

Table 2-1. Stream Gage Information 2-6
Table 3-1. Contributing Drainage Area Estimates 3-5
Table 3-2. Particle Size Distributions for Bed Material Samples 3-8
Table 3-3. Average Particle Size Distribution for Bank Material Samples 3-9
Table 3-4. Particle Size Distributions for the Sheyenne River Diversion Channels Samples 3-10
Table 4-1. Channel-Forming Discharges Using the Bankfull Discharge Method 4-3
Table 4-2. Suspended Sediment Data Collection Sites 4-5
Table 4-3. Channel-Forming Discharges Using the Effective Discharge Method 4-46
Table 4-4. Channel-Forming Discharge Method Comparison for Current Conditions 4-48
Table 4-5. Channel-Forming Discharges and Recurrence Intervals for Current Conditions 4-50
Table 4-6. Historic Stream Gage Information 4-51
Table 4-7. Comparison of Drainage Area versus Exceedence Percentages for Average Channel-Forming Discharges 4-55
Table 4-8. Comparison of Selected Points on Discharge-Duration Curves 4-58
Table 4-9. Comparison of Selected Points on Elevation-Duration Curves 4-64
Table 4-10. Discharges Used to Create Specific Gage Records 4-69
Table 4-11. Dates of High Discharge Events at Gage 05054000 – Red River at Fargo 4-70
Table 4-12. Control Structure Installations and Modifications 4-70
Table 4-13. Specific Gage Record Analysis Summary 4-77
Table 5-1. Level II Rosgen Classification for Detailed Study Reaches 5-6
Table 5-2. Rosgen Level III Riparian Vegetation Summary 5-10
Table 5-3. Rosgen Level III Stream Stability Indices Summaries 5-17
Table 5-4. Rosgen Level III Degree of Channel Incision Summary 5-19
Table 5-5. Rosgen Level III Meander Width Ratio 5-21
Table 5-6. Rosgen Level III Pfankuch Channel Stability Rating Summary 5-24
Table 5-7. Rosgen Level III Streambank Erosion Prediction Summaries 5-30
Table 5-8. Rosgen Level III Process-Based Channel Stability Summaries 5-39
Table 5-9. Schumm Method of Stream Classification for Alluvial Channels (Schumm, 1963) 5-46
Table 5-10. Schumm Classification for Detailed Study Reaches 5-49
Table 6-1. Aerial Imagery Source Dates 6-1
Table 6-2. Sinuosity Calculated from Orthophotos 6-4
Table 6-3. Meander Migration Rates for the Detailed Study Reaches 6-8
Table 6-4. Average Meander Amplitude for Detailed Study Reaches 6-11
Table 6-5. Average Meander Frequency for Detailed Study Reaches 6-12
Table 6-6. Average Meander Belt Widths 6-15
Table 6-7. Average Channel Top Widths 6-17
Table 6-8. 2010 Large Woody Debris Counts 6-19
Table 6-9. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 3 to Year 2 6-21
Table 6-10. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 2 to Year 1 6-22

Table 6-11. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 3 to Year 1.... 6-23
Table 6-12. Summary of Aerial Vegetation Survey 6-29
Table 6-13. Cross Sectional Geometry Source Dates 6-33
Table 6-14. Cross Sections Used to Compare Historic and Current Geometry........................ 6-34
Table 6-15. Cross Section Geometric Change Rates 6-38
Table 7-1. Reach Averaged Channel Velocity and Shear Stress for Bankfull Conditions......... 7-5
Table 7-2. Threshold Values for Shear and Velocity 7-6
Table 7-3. Comparison of SIAM Sediment Transport Potentials for the Sheyenne River......... 7-7
Table 8-1. Summary of Cross Sections for Monitoring... 8-2
Table 10-1. Predicted Geomorphology Impacts Resulting from LPP Diversion Alternative.. 10-6
Table 10-2. Predicted Geomorphology Impacts Resulting from FCP Diversion Alternative.. 10-7

List of Appendices

VOLUME 2

Appendix A.	Field Investigation Notes
Appendix B.	Field Investigation Results

VOLUME 3

Appendix C.	Current Conditions Discharge-Duration Curves
Appendix D.	Historic Conditions Discharge-Duration Curves
Appendix E.	Future Conditions Discharge-Duration Curves
Appendix F.	Current Conditions Elevation-Duration Curves
Appendix G.	Historic Conditions Elevation-Duration Curves
Appendix H.	Future Conditions Elevation-Duration Curves
Appendix I.	Specific Gage Records
Appendix J.	Level II Rosgen Worksheets
Appendix K.	Level III Rosgen Worksheets
Appendix L.	Historic Cross Section Comparisons
Appendix M.	Future Conditions Hydrology Curves (FCP Alignment)
Appendix N.	Future Conditions Hydrology Curves (LPP Alignment)
Appendix O.	Monitoring Cross Section Endpoints
Appendix P.	SIAM Analysis
Appendix Q.	Electronic Data
Appendix R.	Independent Review Comments and Comment Responses
Appendix S.	Incipient Bank Overtopping Analysis

Executive Summary

A feasibility study designed by the US Army Corps of Engineers, St. Paul District, to investigate flood issues in the Fargo, ND and Moorhead, MN metropolitan area began in September 2008. The objectives of the study are to manage flood risk and damages for the area; restore or improve degraded riverine and riparian habitat in and along the Red River of the North, Wild Rice River (North Dakota), Sheyenne River (North Dakota), and Buffalo River (Minnesota); provide additional wetland habitat in conjunction with other flood risk management features; and provide recreational opportunities in conjunction with other flood risk management features.

Two diversion channel alignment alternatives are proposed to achieve the study objectives. Both alignment alternatives will divert flood flows out of the Red River of the North (hereafter referred to as the Red River) and into the diversion alignments, thereby reducing the amount of flow entering the Fargo-Moorhead metropolitan area via the Red River. The alignment alternatives and major streams within the study area are shown in Figure 1.

The Locally Preferred Plan (LPP) – North Dakota Alignment alternative contains a 36-mile long diversion channel starting approximately four miles south of the Red River and Wild Rice River confluence and extending north and west around the cities of Horace, Fargo, West Fargo, and Harwood. It rejoins the Red River downstream of the Sheyenne River confluence. The alignment would incorporate the existing Horace to West Fargo Sheyenne River Diversion channel. Two hydraulic structures would control flow passing into the protected area during flood events; one on the Red River and the other on the Wild Rice River. At diversion channel crossings of the Sheyenne and Maple Rivers, aqueduct structures will be used to allow base flows to follow the natural channel. Flow in the Sheyenne and Maple Rivers in excess of the 50-percent annual chance event would be diverted. Flow from the Lower Rush River, Rush River and various other drainage ditches would be entirely intercepted by the diversion channel. Tie back levees and a storage area would be located at the southern end of the project to prevent floodwaters from flanking the diversion channel and to prevent an increase in peak discharges downstream of where the diversion ties back in to the Red River.

The Federally Comparable Plan (FCP) – Minnesota Alignment alternative contains a 25-mile long main diversion channel that starts immediately downstream of the Red River and Wild Rice River confluence and extends north and east around the cities of Moorhead and Dilworth. It rejoins the Red River downstream of the Sheyenne River confluence with the Red River. The main Minnesota Diversion channel would have a control structure located at its south (upstream) end of the channel, which would allow diversion of flows in excess of the Red River natural channel capacity. Two smaller diversion channels would be constructed along the Red and Wild Rice Rivers upstream of the Red River control structure would prevent stage increases upstream of the project along these rivers. The FCP also includes a tie back levee at the southern end of the project. The tie back levee connects the Red River control structure to high ground and prevents flood water from flowing overland to the north and west into the protected area.

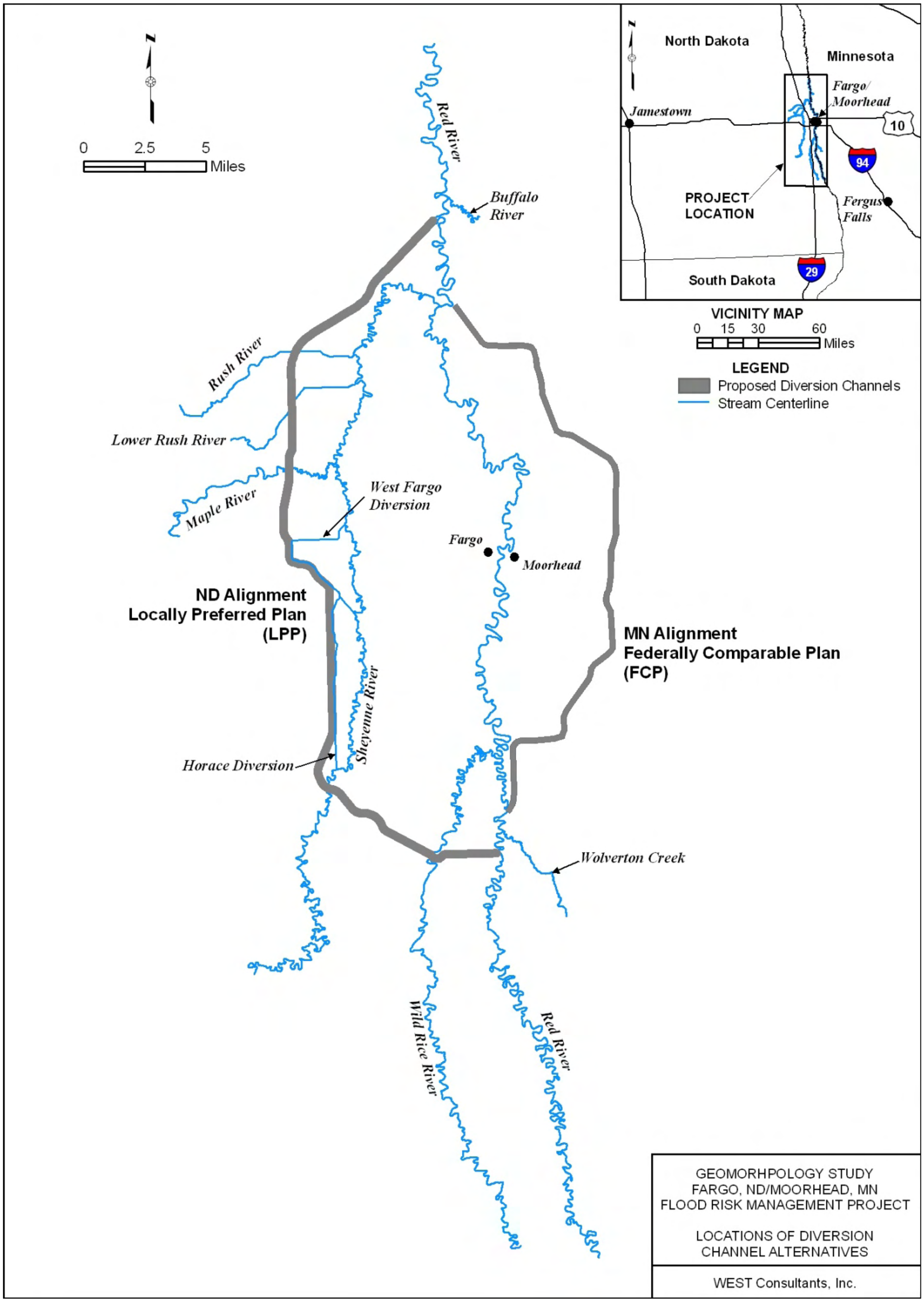


Figure 1. Locations of Diversion Channel Alternatives

Use of either diversion channel alignment alternative may interrupt or change on-going geomorphic processes in the Red River and involved tributaries. Similarly, impacts to geomorphic processes could potentially affect the function and effectiveness of proposed flood-risk management projects. Therefore, as a part of the feasibility study, potential geomorphic impacts associated with the diversion channel alignment alternatives are to be evaluated. The US Army Corps of Engineers, St. Paul District, contracted with WEST Consultants, Inc. to assess the current geomorphic conditions and potential impacts to the geomorphic conditions from each diversion alignment alternative.

Results of the geomorphic assessment indicate that the involved study reaches are not prone to significant change in morphology over short or even moderate periods of time. Channel migration rates are on the order of a few inches per year. The erosion resistant nature of the cohesive glacial lake bed soils and the very flat gradient of the channels prevent significant changes in channel cross section geometry and results in very low rates of lateral migration. Further, the sediment supply from upstream and the surrounding landscape is generally composed of silt- and clay-sized material with only minor amounts of sand-sized material. The study streams appear to have sufficient capacity to transport nearly all of the sediment supplied to them in suspension as wash load.

Although the Sheyenne River has a relatively greater proportion of sand-sized material compared to the other study streams, the underlying cohesive clay and silt bed still appears to control the overall channel geometry and rate of lateral migration within the study area. As previously mentioned, the greater abundance of sand within the Sheyenne River is the result of the river traversing the ancient beach deposits of glacial Lake Agassiz in the portion of the basin located upstream from the study area. As a result, a relatively larger amount of sand-sized material is supplied to the study reaches of the Sheyenne River. This material is transported as both suspended load and bed load. Again, alluvial channel features that are typically associated with sand bed rivers are not present along the project's study reaches. This suggests that the Sheyenne River generally has the capacity to transport the majority of the sand-sized material that is supplied to it from upstream sources.

Significant sediment deposition would not be expected within the FCP Diversion channel because the Red River does not have a significant supply of sand. The fine-grained sediments entering the FCP channel from the Red River are expected to stay in suspension within the diversion channel. The lower end of the FCP channel is generally steeper than the upstream reaches. Erosion of the channel bed would be expected at this location unless protected by armoring.

Localized deposits around hydraulic structures and along the inside of bends in the LPP Diversion channel alignment downstream of the Sheyenne River would be expected due to the significant supply of sand-sized sediment transported in suspension by the Sheyenne River. Some future maintenance should be expected in order to maintain the desired hydraulic capacity with the diversion channel. Additional sediment transport analysis is recommended to further understand the potential amounts and extents of sedimentation as well as probable maintenance requirements along the LPP Diversion channel.

The location of each general study reach is shown in Figure 2. The expected changes to the geomorphology of each of the study streams for the LPP and FCP diversion alternative are summarized in Table 1 and Table 2, respectively. As seen in the tables, bank stability and riparian vegetation density are expected to slightly increase in the reaches that are protected from high flows by the proposed LPP and FCP diversion alignments. Conversely, bank stability and riparian vegetation density are expected to slightly decrease in the staging areas upstream of the LPP diversion alignment as a result of more frequent overbank inundation and sedimentation. The only expected significant changes in channel geometry are for Reach 1 of the Rush River and Reach 1 of the Lower Rush River. Since all flow in the Rush and Lower Rush will be diverted by the LPP diversion alignment, local runoff and backwater from the Sheyenne River is expected to cause sedimentation in the portion of these streams located downstream from the diversion. Therefore, the channel size for these reaches would be expected to decrease over time.

Table 1. Predicted Geomorphology Impacts Resulting from LPP Diversion Alternative

General Study Reach	Bank Stability	Channel Migration Rate	Bankfull Depth	Bankfull Width	Riparian Vegetation Density	Predicted Discernible Changes to Geomorphology
Buffalo River 1	0	0	0	0	0	No
Lower Rush River 1	0	0	-	-	+	Yes
Lower Rush River 2	0	0	0	0	0	No
Maple River 1	+	0	0	0	+	Minor
Maple River 2	0	0	0	0	0	No
Red River 1	0	0	0	0	0	No
Red River 2	+	0	0	0	+	Minor
Red River 3	+	0	0	0	+	Minor
Red River 4	+	0	0	0	+	Minor
Red River 5	+	0	0	0	+	Minor
Red River 6 d/s of diversion	+	0	0	0	+	Minor
Red River 6 u/s of diversion	-	0	0	0	-	Minor
Red River 7	-	0	0	0	-	Minor
Red River 8	0	0	0	0	0	No
Rush River 1	0	0	-	-	+	Yes
Rush River 2	0	0	0	0	0	No
Sheyenne River 1	+	0	0	0	+	Minor
Sheyenne River 2	+	0	0	0	+	Minor
Sheyenne River 3	+	0	0	0	+	Minor
Sheyenne River 4	+	0	0	0	+	Minor
Sheyenne River 5	0	0	0	0	0	No
Sheyenne River 6	0	0	0	0	0	No
Sheyenne River 7	0	0	0	0	0	No
Sheyenne River 8	0	0	0	0	0	No
Wild Rice River 1	+	0	0	0	+	Minor
Wild Rice River 2	+	0	0	0	+	Minor
Wild Rice River 3	-	0	0	0	-	Minor
Wild Rice River 4	-	0	0	0	-	Minor
Wild Rice River 5	0	0	0	0	0	No
Wild Rice River 6	0	0	0	0	0	No
Wolverton Creek 1	+	0	0	0	+	Minor
Wolverton Creek 2	-	0	0	0	-	Minor

(0) No Change, (+) increasing, (-) decreasing

Table 2. Predicted Geomorphology Impacts Resulting from FCP Diversion Alternative

General Study Reach	Bank Stability	Channel Migration Rate	Bankfull Depth	Bankfull Width	Riparian Vegetation Density	Predicted Discernible Changes to Geomorphology
Buffalo River 1	0	0	0	0	0	No
Lower Rush River 1	0	0	0	0	0	No
Lower Rush River 2	0	0	0	0	0	No
Maple River 1	0	0	0	0	0	No
Maple River 2	0	0	0	0	0	No
Red River 1	0	0	0	0	0	No
Red River 2 d/s of diversion	+	0	0	0	0	Minor
Red River 2 u/s of diversion	0	0	-	0	0	Minor
Red River 3	+	0	0	0	+	Yes
Red River 4	+	0	0	0	+	Yes
Red River 5	+	0	0	0	+	Yes
Red River 6	+	0	0	0	+	Yes
Red River 7	0	0	0	0	0	No
Red River 8	0	0	0	0	0	No
Rush River 1	0	0	0	0	0	No
Rush River 2	0	0	0	0	0	No
Sheyenne River 1	+	0	0	0	+	Minor
Sheyenne River 2	0	0	0	0	0	No
Sheyenne River 3	0	0	0	0	0	No
Sheyenne River 4	0	0	0	0	0	No
Sheyenne River 5	0	0	0	0	0	No
Sheyenne River 6	0	0	0	0	0	No
Sheyenne River 7	0	0	0	0	0	No
Sheyenne River 8	0	0	0	0	0	No
Wild Rice River 1	0	0	0	0	0	No
Wild Rice River 2	0	0	0	0	0	No
Wild Rice River 3	0	0	0	0	0	No
Wild Rice River 4	0	0	0	0	0	No
Wild Rice River 5	0	0	0	0	0	No
Wild Rice River 6	0	0	0	0	0	No
Wolverton Creek 1	0	0	0	0	0	No

(0) No Change, (+) increasing, (-) decreasing

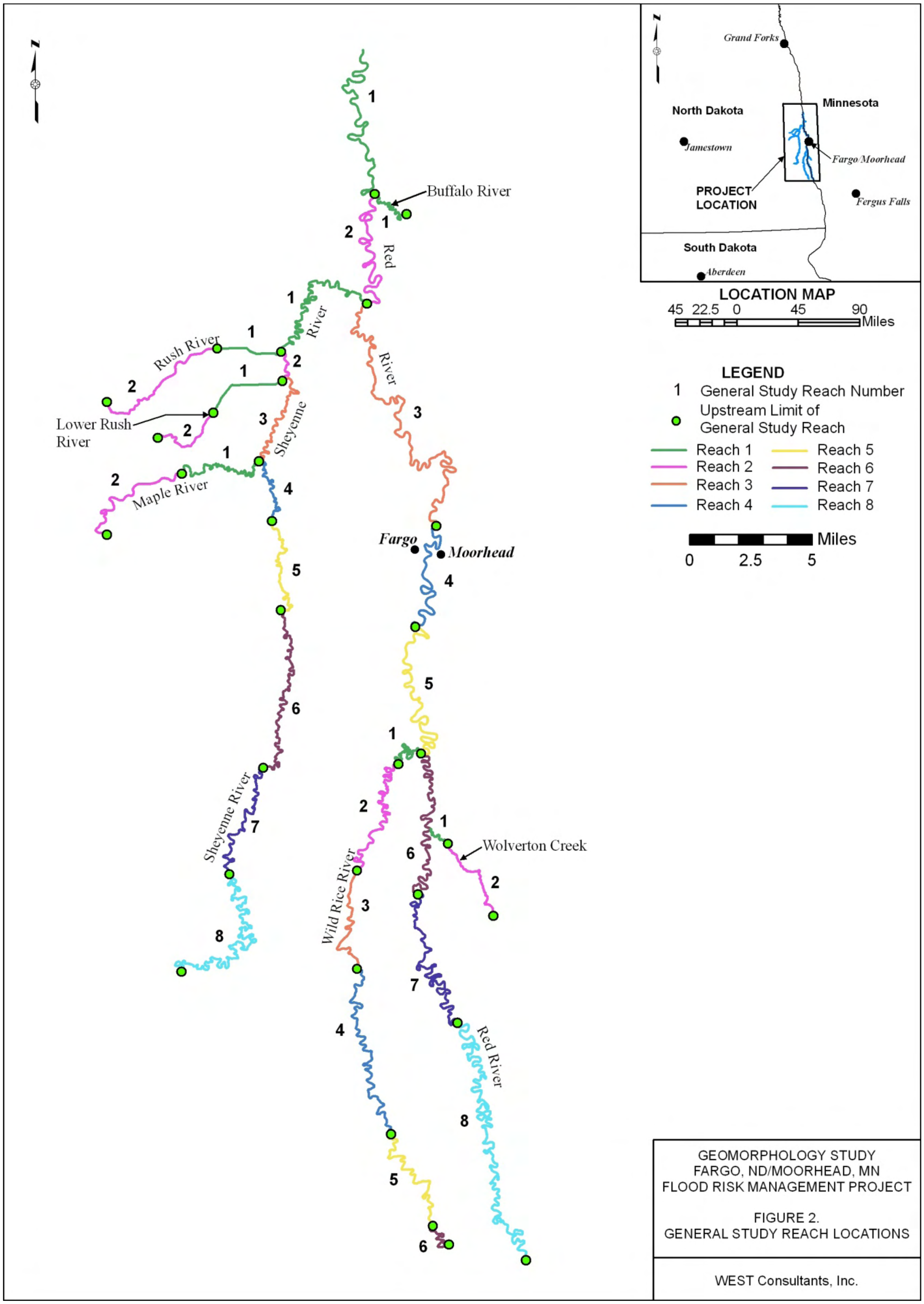


Figure 2. General Study Reach Locations

1 Introduction

1.1 Purpose and Authorization

The purpose of this study is to determine the potential geomorphic impacts associated with two alternative diversion channel alignments that are proposed to manage flood risk for Fargo, ND and Moorhead, MN. Use of the diversion channels may interrupt or change on-going geomorphic processes in the Red River of the North (hereafter referred to as the Red River) and involved tributaries. Similarly, impacts to geomorphic processes could potentially affect the function and effectiveness of proposed flood-risk management projects. The study is intended to characterize existing geomorphic conditions of involved watercourses, describe controlling geomorphic processes in the study area, evaluate proposed alternative conditions, and define expected impacts associated with each alternative. A combination of fluvial geomorphic, hydrologic, and hydraulic engineering analysis approaches were used to define the potential impacts associated with the alternative diversion channel alignments. The predicted impacts will be used by the U.S. Army Corps of Engineers, St. Paul District (the District) to determine project feasibility and costs, including required mitigation measures. The District authorized this study under contract W912P9-10-D-0516, task orders DD02 and DD03.

1.2 Scope

The study scope involved efforts to predict the potential geomorphic impacts associated with two alternative diversion alignments to minimize flood impacts to the communities of Fargo, ND and Moorhead, MN. Figure 1-1 shows the alternative diversion alignments. The two alternative diversion alignments are named the Federally Comparable Plan (FCP) - Minnesota Diversion and the Locally Preferred Plan (LPP) - North Dakota Diversion, based on their locations.

The proposed FCP diversion alignment contains a 25-mile long main diversion channel that starts immediately downstream of the Red River and Wild Rice River confluence and extends north and east around the cities of Moorhead and Dilworth. It rejoins the Red River downstream of the Sheyenne River confluence with the Red River. The main Minnesota Diversion channel would have a control structure located at its south (upstream) end of the channel, which would allow diversion of flows in excess of the Red River natural channel capacity. Two smaller diversion channels would be constructed along the Red and Wild Rice Rivers upstream of the Red River control structure would prevent stage increases upstream of the project along these rivers. The FCP also includes a tie back levee at the southern end of the project. The tie back levee connects the Red River control structure to high ground and prevents flood water from flowing overland to the north and west into the protected area.

The proposed LPP diversion alignment contains a 36-mile long diversion channel starting approximately four miles south of the Red River and Wild Rice River confluence and extending north and west around the cities of Horace, Fargo, West Fargo, and Harwood. It rejoins the Red River downstream of the Sheyenne River confluence. The alignment would incorporate the existing Horace to West Fargo Sheyenne River Diversion channel. Two hydraulic structures would control flow passing into the protected area during flood events; one on the Red River and the other on the Wild Rice River. Both structures would become operable when the forecasted peak discharge at the Red River at Fargo gage is greater than 9,600 cfs. At diversion channel crossings of the Sheyenne and Maple Rivers, aqueduct structures will be used to allow base flows to follow the natural channel. Flow in the Sheyenne and Maple Rivers in excess of the 50-percent annual chance event would be diverted. Flow from the Lower Rush River, Rush River and various other drainage ditches would be entirely intercepted by the diversion channel. Tie back levees and a storage area would be located at the southern end of the project to prevent floodwaters from flanking the diversion channel and to prevent an increase in peak discharges downstream of where the diversion ties back in to the Red River.

The specific tasks performed as a part of this study are outlined below.

Task 1 – Document and Data Review

- Compile existing technical and historical documents, photographs, and maps relevant to geomorphic conditions within the study area.

Task 2 – Hydrology Assessment

- Perform a specific gage analysis for each gage to analyze gage changes over time.
- Determine channel-forming discharge based on the following three methods: bankfull discharge, recurrence interval, and effective discharge.
- Determine historical channel-forming discharge for all study reaches except Rush River, Lower Rush River and Wolverton Creek, from old HEC-RAS cross section plots and other available information.
- Construct discharge-duration and elevation-duration curves from gage data and cross section geometry for historic and current conditions.

Task 3 – Field Investigations and Assessment

- Identify geomorphic reaches with similar characteristics.
- Within each geomorphic reach, define detailed study reaches.
- Determine where cross sections need to be surveyed on each reach and provide the endpoint coordinates along with locations to obtain longitudinal profiles to the Corps within 1 week of the Notice-to-Proceed so the contracted surveyor can survey these in November and December 2010. The expected total number of cross sections would be 250-350 cross sections. Consideration should be given to locating cross sections where historic cross sections are available.
- Within each erosion study reach define geo-referenced precision cross sections (at the same location of a historic cross section) to monitor over time.
- Obtain bank, bar and bed sediment samples (including sub-pavement and riffle pavement) for an approximate total of 100 sediment samples, delineate cross section and floodplain features, calculate slope, and document any erosion or deposition features and significant sources of sediment.
- Obtain additional field data needed for assessment of stability using Level III of the Rosgen system, including a Pfankuch evaluation, Bank Erosion Hazard Index and Near Bank Stress assessment.
- Perform discharge measurement or estimate discharge using nearby gages for the dates of measurement. Determine bankfull discharge.

- Perform a morphological classification using Level II of the Rosgen system, including documentation of any riffle / pool / run sequences.
- Perform a morphological classification using Brice or Schumm methods. Submit explanation of why the method was selected and how the selected method provides additional information compared to the Rosgen system.
- Maintain a digital photographic record of field investigations.
- Qualitative description of riparian vegetation types and how that would impact bank stability.

Task 4 – Stability Analysis

- Review available time-sequential aerial photographs, historic land surveys, historic topographic maps, and cross section data compared to current survey data to evaluate historic changes in river position and adjacent riparian conditions over time. The Corps will provide three sets of aerial photographs of the study area from different time periods in order to complete this task.
- Determine sinuosity, channel (meander) migration and erosion rates, and meander amplitude and frequency from historic to current conditions. More intensive measurements may include trends in sedimentary features (in-stream sediment bars), changes in plan form channel width, sand and gravel bar dynamics, changes in large woody debris, channel instability (bank erosion), and changes in riparian vegetation.
- Determine regime channel dimensions using two or more applicable methods.
- Evaluate changes in cross section geometry for historic and current conditions and estimate if channel geometry has been adjusting towards or away from regime channel geometry.
- Present data from Tasks 3 and 4 in a set of GIS-based maps of the study area showing existing channel conditions with morphological classification, the spatial distribution of channel morphology and geomorphic processes and the zones in which different sets of geomorphic processes dominate.

Task 5 – Sediment Impact Analysis

- Generate discharge-frequency, discharge-duration, and elevation-duration curves for the Minnesota and North Dakota Diversion alignments.
- Estimate new channel-forming discharge. Please provide channel geometry parameters for the low flow channel in the North Dakota diversion channel below the Lower Rush River that would increase long-term stability with respect to erosion and sedimentation of the North Dakota diversion channel.
- Develop an analysis of sediment delivery using the SIAM tool in HEC-RAS version 4.1. The sediment delivery analysis will incorporate existing data and data collected during the field investigations to characterize the nature of suspended sediment load and total sediment load by determining the sediment transport capacity.

Task 6 – Future Conditions Effects

- Evaluate effects of all future conditions (no action, North Dakota Diversion and Minnesota Diversion). Identify relative sedimentation / erosion potential for all relevant modeled reaches. Predict sediment transport rate changes for all future conditions (no action, Minnesota Diversion, and North Dakota Diversion). Predict morphological changes due to these future conditions including possible succession of the river channels according to the Rosgen System. A discussion of the relative results and the importance of the findings should be included in the final report.

- Predict impacts all future conditions (no action, Minnesota Diversion, and North Dakota Diversion) may have on the riparian vegetation and erosion from adjacent lands, and relate to changes in morphology.

Task 7 – Monitoring Plan

- Develop a monitoring plan for use after project completion to identify changes in river geomorphology. The plan should require the use of the geo-referenced precision cross sections that will be resurveyed and compared periodically.

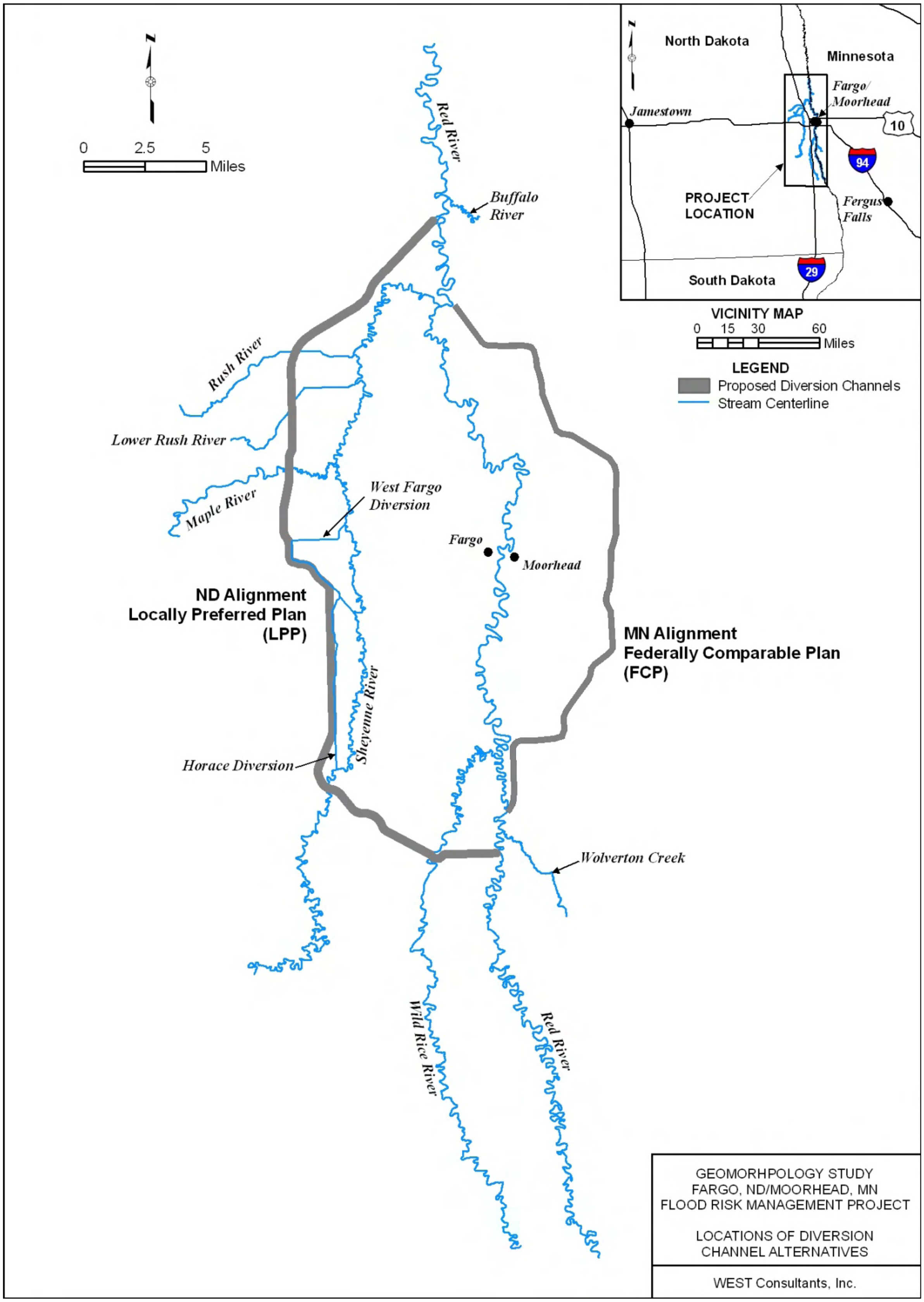


Figure 1-1. Locations of Diversion Channel Alternatives

1.3 Datums

Unless otherwise noted, all geographic and spatial data used in this study were adjusted to a horizontal datum of North American Datum (NAD) 1983 North Dakota State Plane South (FIPS 3302) and a vertical datum of NAVD 1988.

1.4 Acknowledgements

Professionals from the U.S. Army Corps of Engineers St. Paul District managed this study. Brett Coleman, P.E., served as the project manager. Michael Dahlquist, P.E., served as the contracting officer's representative. Michelle Larson, P.E., coordinated the study efforts. Aaron Buesing, P.E., and Daniel Reinartz, P.E., provided hydraulic and hydrologic information required for the study. Technical reviewers from the Omaha District were Mark Nelson, P.E., Richard Donovan, P.E., Roger Kay, P.E., and Dan Pridal, P.E. Miguel Wong, Ph.D., P.E., with Barr Engineering provided an independent external review of the project report.

Hans Hadley, P.E., CFM, was the WEST project manager for this study. Ken Puhn, CFM, and Kevin Denn conducted technical analyses and wrote the report. Tom Grindeland, P.E., D.WRE and Chris Goodell, P.E., D.WRE provided quality control review. Aaron Lee and Jeff Budnick assisted in the field data collection. Rebecca Yalcin and Bill Garcia developed many of the figures for the report.

2 Background

2.1 Prior Studies

An extensive literature search and review was conducted to assess the availability of data relevant to the project. Eighteen documents from a variety of sources were found to contain relevant information. A summary of the literature reviewed was compiled and submitted to the St. Paul District on December 21, 2010 (WEST, 2010).

2.2 Basin Description

The Red River drainage basin encompasses portions of eastern North Dakota, western Minnesota, northeastern South Dakota, and Manitoba, Canada. The northward flowing Red River drains into Lake Winnipeg in Manitoba, Canada. For the purposes of this study, the northern extent of the Red River study reach is located near Perley, MN. The drainage basin area at this point, shown in Figure 2-1, covers approximately 19,100 mi^2. The drainage basin shown in Figure 2-1 includes both contributing and noncontributing areas (i.e., the Devils Lake basin). This study is focused on the streams near the Fargo-Moorhead metropolitan area (see Figure 2-3) and includes:

- Red River of the North from Abercrombie, ND to Perley, MN
- Wild Rice River from Abercrombie, ND to its confluence with the Red River
- Sheyenne River from Kindred, ND to its confluence with the Red River
- Sheyenne River Diversion Channel from Horace, ND to West Fargo, ND
- Rush River from Prosper, ND to its confluence with the Sheyenne River
- Lower Rush River from 165th Ave SE in Cass County to its confluence with the Sheyenne River
- Maple River from Mapleton, ND to its confluence with the Sheyenne River
- Buffalo River from one mile upstream of Georgetown, MN to its confluence with the Red River
- Wolverton Creek from three miles upstream of its confluence with the Red River to the confluence with the Red River.

The surficial topography and geologic features of the Red River basin are primarily the result of deposition and erosion associated with continental glaciation. Glacial Lake Agassiz left clay-rich sediments in a flat lake plane along the Red River axis (Stoner et al., 1993). The Red River has a very gradual slope within the project area, ranging in elevation from 903 ft to 844 ft over 118.3 river miles (0.5 ft/mi).

The annual mean temperature for the Fargo-Moorhead area is about 42°F. The area experiences extreme variations in temperature. The normal mean monthly temperature varies from 71°F in July to 7°F in January. Normal annual precipitation for the Fargo-Moorhead area is about 21 inches. Normal monthly precipitation ranges from a maximum of 3.5 inches during the month of June to a minimum of 0.6 inches in December. Snowfall averages about 46 inches a year.

The streams within the study area flow through the extremely flat clay deposits of the glacial Lake Agassiz basin. These cohesive soils are up to 95 ft thick in some locations (Stoner et al., 1993). Lake Agassiz also deposited large quantities of sand along its shoreline. The distribution of the sand relative to the project area is shown in Figure 2-2. As seen in the Figure, the Sheyenne River flows through the sand deposits upstream of the project area, supplying sand to the downstream study reaches.

As described in later sections, streamflow gage data were used for this study. The locations of the USGS stream gages are shown in Figure 2-3. Table 2-1 summarizes the drainage area defined by the USGS for each stream gage.

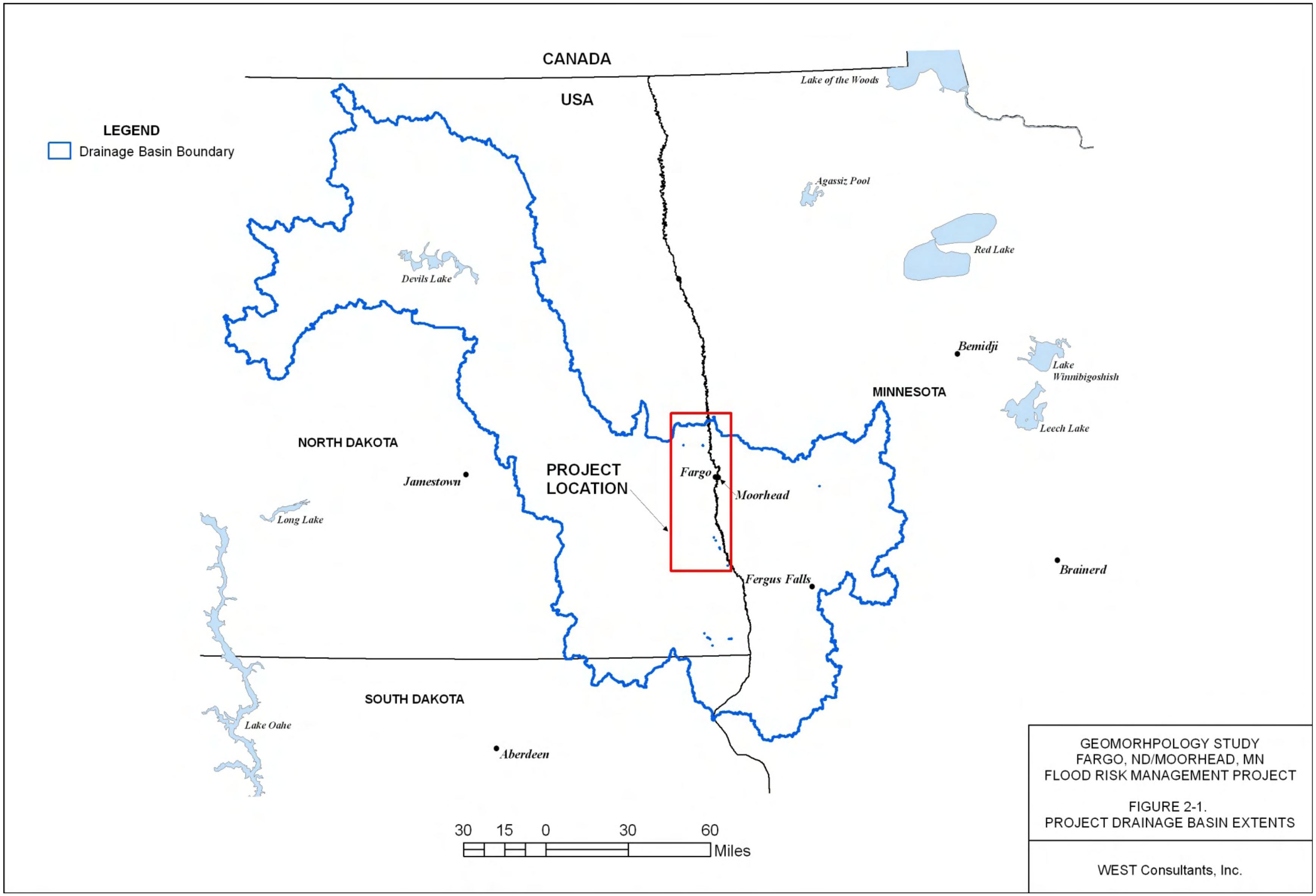


Figure 2-1. Project Drainage Basin Extents

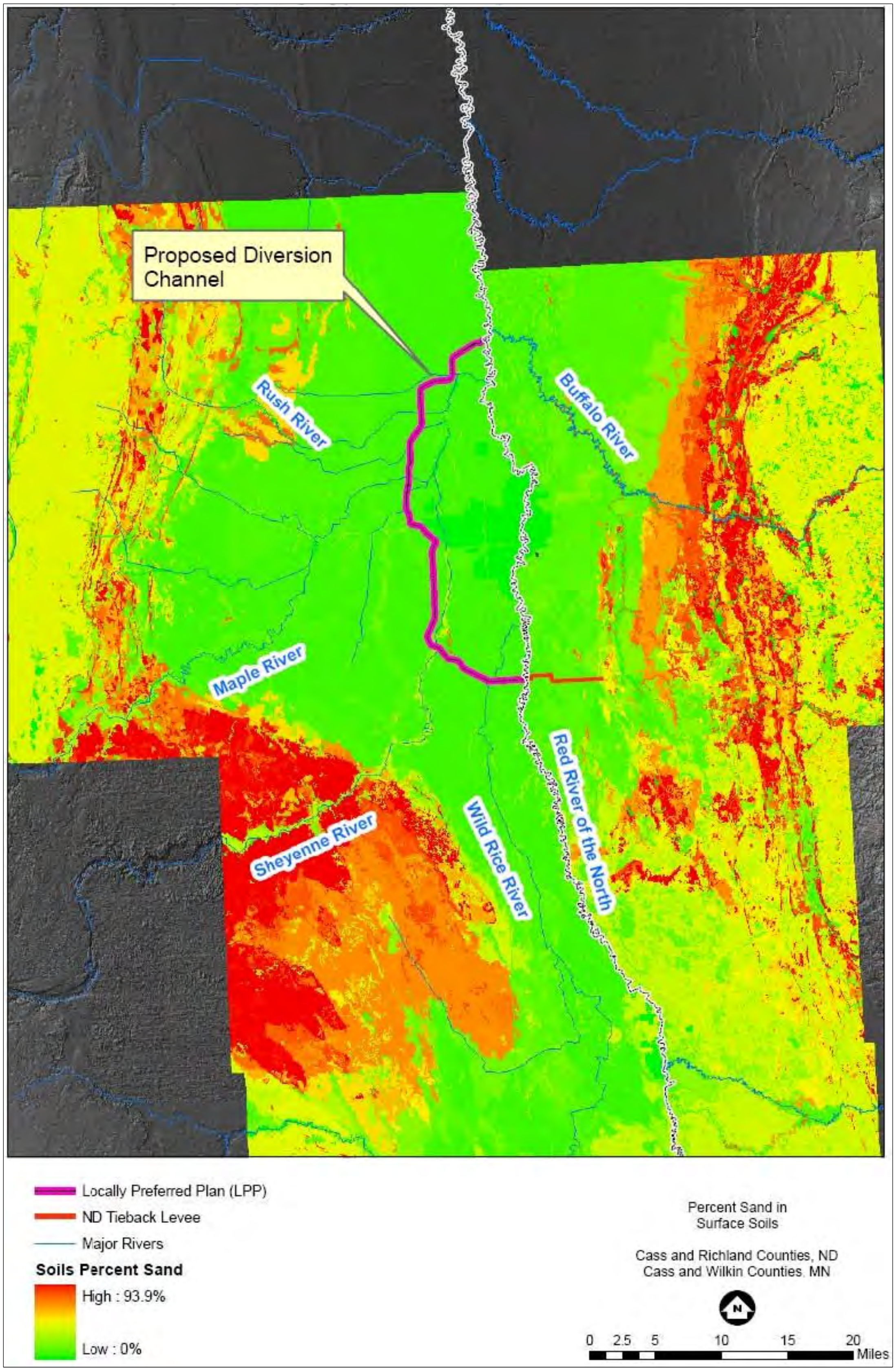


Figure 2-2. Sand Distribution in Study Area (USACE, 2011)

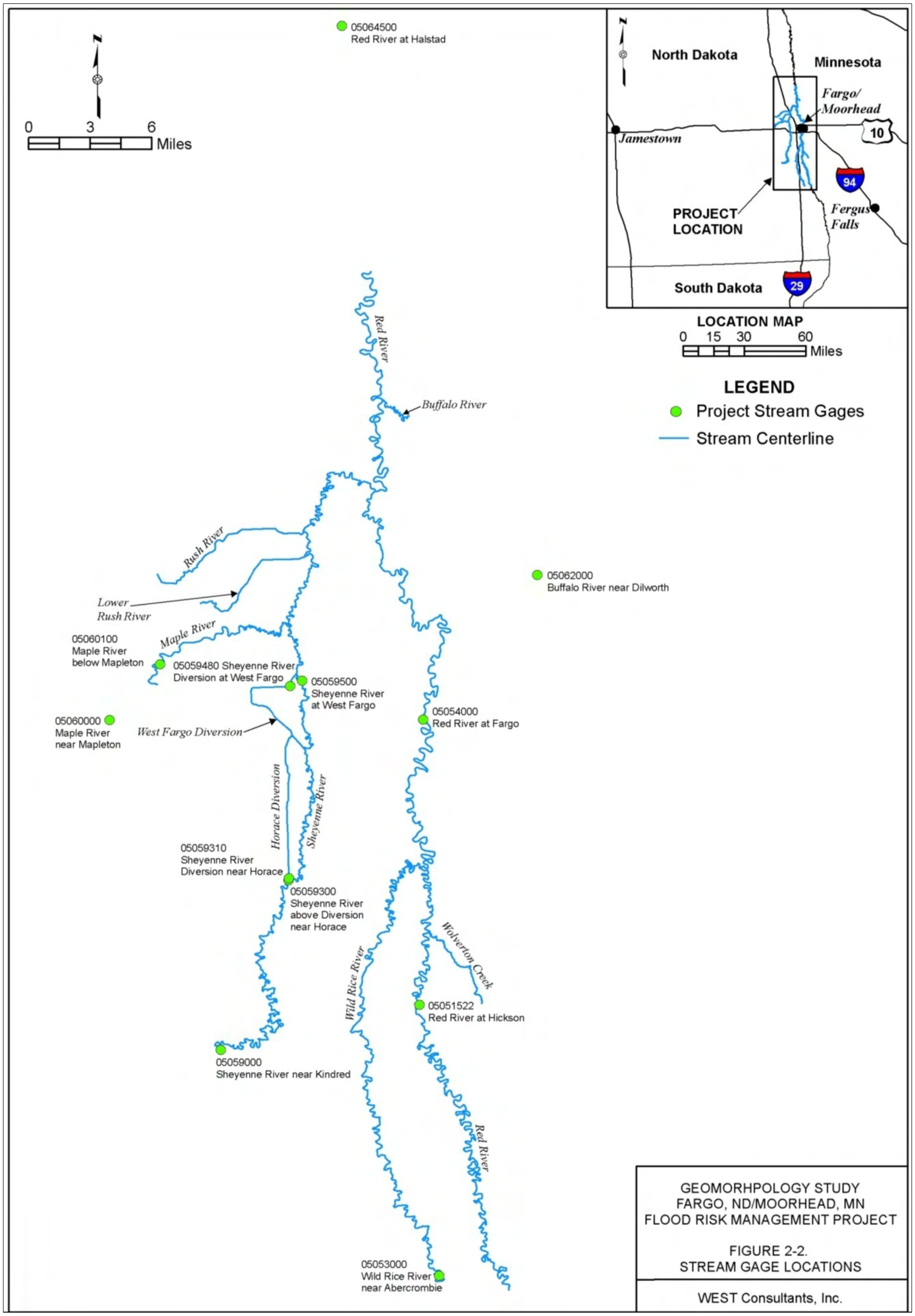


Figure 2-3. USGS Stream Gage Locations

Table 2-1. Stream Gage Information

Gage Number	Gage Name	USGS Drainage Area (mi^2)
05051522	Red River at Hickson	4,300
05053000	Wild Rice River near Abercrombie	1,490
05054000	Red River at Fargo	6,800
05059000	Sheyenne River near Kindred	3,020
05059300	Sheyenne River above Diversion near Horace	3,060
05059310	Sheyenne River Diversion near Horace	[1/]
05059480	Sheyenne River Diversion at West Fargo	[1/]
05059500	Sheyenne River at West Fargo	3,090
05060000	Maple River near Mapleton	1,380
05060100	Maple River below Mapleton	1,410
05062000	Buffalo River near Dilworth	975
05064500	Red River at Halstad	21,800

[1/] gage does not have a defined drainage area due to its location on a diversion structure

3 Study Reach Selection and Field Investigation

3.1 Study Reach Selection

3.1.1 General Study Reaches

The geomorphic characteristics of streams can vary with location. To define potential impacts, the geomorphic characteristics of the existing channels within the study area were evaluated. Extents of general study reaches (reaches having approximately the same geomorphic characteristics) were identified based on the location of hydraulic structures, meander characteristics, channel shape, channel slope, the location of major river confluences, and the alternative diversion channels alignments. Using this methodology, 31 general study reaches were defined. The general study reaches were named and numbered using the following nomenclature "Stream Name-Reach Number for Stream". The reach number for each stream is listed in increasing order from downstream to upstream (i.e., Maple River-1, Maple River-2, etc.). The extents of each general study reach and the location of the alternative channel alignments are shown in Figure 3-1.

3.1.2 Detailed Study Reaches

Within each general study reach, detailed study reaches were selected based physical conditions observed from aerial photography, road access, proximity to boat launch locations, and documented right of entry to private properties. A total of 31 detailed study reaches were defined. Each detailed study reach was typically between a few hundred to a few thousand feet in length, depending on the relative stream size and the distance between meander bends. The physical conditions within each detailed study reach were evaluated and documented. This information was used to define the existing morphologic characteristics of each study reach and to understand the physical processes involved in their formation. The field observations and data collected provided information for use in subsequent office-based evaluations. The results obtained from each detailed study reach are considered applicable to the entire general study reach in which it is located. Each detailed study reach is identified by the name and number of the general study reach in which the detailed study reach is located, followed by the river mile location for the downstream end of the detailed study reach. The locations of the detailed study reaches are shown in Figure 3-2.

Drainage basin boundaries were defined for each detailed study reach, USGS gage, and other selected locations, including the downstream and upstream extents of the study streams. Estimates of the discharge characteristics for each detailed study reach were then made by interpolation of available flow data using contributing drainage area relationships. The drainage area for each site was determined using the ArcHydro tool in ArcGIS (ESRI, 2009). The St. Paul District provided shapefiles of contributing drainage basins for the Red River tributaries and the Red River at the downstream extent of the study area. The drainage basin boundary shapefiles were subdivided to determine the contributing drainage area for each detailed study reach using available 30-meter by 30-meter Digital Elevation Models (DEMs) of North Dakota and Minnesota (USGS, 2011a). The contributing drainage area for each location of interest is provided in Table 3-1. There are a number of inconsistencies between the calculated drainage area for the USGS gage sites and the drainage area determined by the USGS, denoted by parentheses in the table. The inconsistencies are attributed to differences in how the USGS and St. Paul District define contributing drainage area (personal communication with Daniel Reinartz, St. Paul District, December 14, 2011). The St. Paul District defines contributing drainage area as that portion of the drainage basin that has the ability to contribute flow during the 100-year, 10-day storm event. Any portion of the basin that naturally stored all runoff during this event was considered to be non-contributing.

A consistent drainage area calculation methodology was necessary in order to develop hydrologic data for each detailed study reach using interpolation procedures. Therefore, the drainage areas calculated from the shapefiles provided by the St. Paul District, rather than the values provided by the USGS, were used to develop the discharge values at all sites, unless otherwise noted in Table 3-1

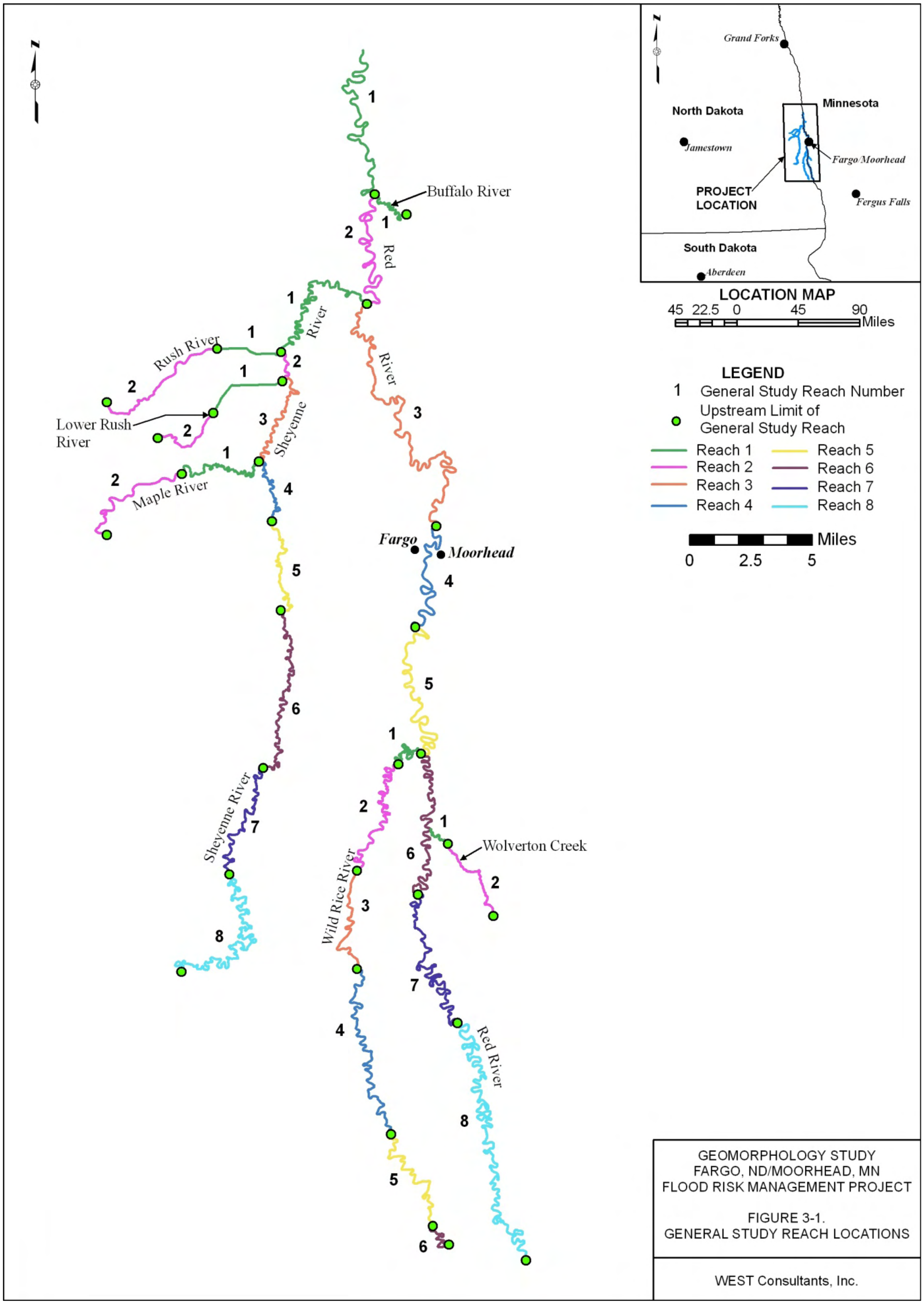


Figure 3-1. General Study Reach Locations

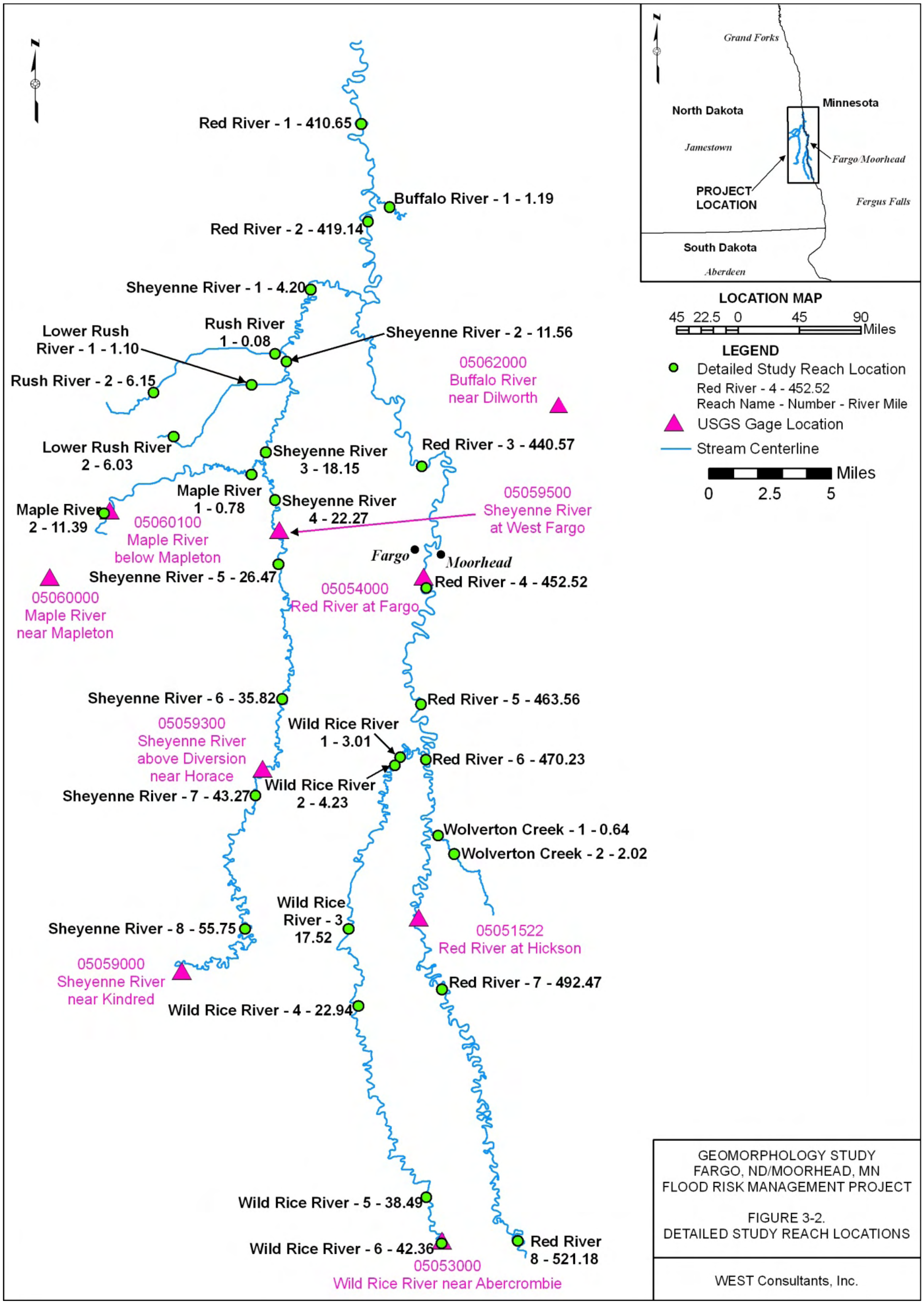


Figure 3-2. Detailed Study Reach Locations

Table 3-1. Contributing Drainage Area Estimates

Type	Identifier	Contributing Drainage Area (mi^2)
Mouth	Buffalo River at Mouth	994.6
Detailed Reach	Buffalo River-1-1.19	994.1
USGS Gage	05062000 - Buffalo River near Dilworth (RM 34.78)	836.0 (975.0)[1]
Mouth	Lower Rush River at Mouth	61.56
Detailed Reach	Lower Rush River-1-1.10	59.39
Detailed Reach	Lower Rush River-2-6.03	53.35
Upstream End	Lower Rush River at Upstream End	51.50
Mouth	Maple River at Mouth	1,483
Detailed Reach	Maple River-1-0.78	1,482
USGS Gage	05060100 - Maple River below Mapleton (RM 11.27)	1,460 (1,410)[1]
Detailed Reach	Maple River-2-11.39	1,460
USGS Gage	05060000 - Maple River near Mapleton (RM 20.14)	1,376 (1,380)[1]
USGS Gage	05064500 - Red River at Halstad (RM 375.30)	14,384 (21,800)[1]
Detailed Reach	Red River-1-410.65	12,267
Detailed Reach	Red River-2-419.14	11,044
Detailed Reach	Red River-3-440.57	5,763
USGS Gage	05054000 - Red River at Fargo (RM 452.29)	5,718 (6,800)[1]
Detailed Reach	Red River-4-452.52	5,718
Detailed Reach	Red River-5-463.56	5,603
Detailed Reach	Red River-6-470.23	3,591
USGS Gage	05051522 - Red River at Hickson (RM 485.37)	3,473 (4,300)[1]
Detailed Reach	Red River-7-492.47	3,461
Detailed Reach	Red River-8-521.18	3,421
Upstream End	Red River at Upstream End	3,420
Mouth	Rush River at Mouth	154.7
Detailed Reach	Rush River-1-0.08	154.6
Detailed Reach	Rush River-2-6.15	139.3
Upstream End	Rush River at Upstream End	124.4
Mouth	Sheyenne River at Mouth	5,252
Detailed Reach	Sheyenne River-1-4.20	5,249
Detailed Reach	Sheyenne River-2-11.56	5,086
Detailed Reach	Sheyenne River-3-18.15	4,968
Detailed Reach	Sheyenne River-4-22.27	3,483
USGS Gage	05059500 - Sheyenne River at West Fargo (RM 24.44)	3,481 (3,090)[1]
Detailed Reach	Sheyenne River-5-26.47	3,476
Detailed Reach	Sheyenne River-6-35.82	3,433
USGS Gage	05059300 - Sheyenne River above Diversion near Horace (RM 41.59)	3,424 (3,060)[1]
Detailed Reach	Sheyenne River-7-43.27	3,423
Detailed Reach	Sheyenne River-8-55.75	3,406
USGS Gage	05059000 - Sheyenne River near Kindred (RM 67.44)	3,401 (3,020)[1]
Mouth	Wild Rice River at Mouth	2,012
Detailed Reach	Wild Rice River-1-3.01	2,012
Detailed Reach	Wild Rice River-2-4.23	2,011
Detailed Reach	Wild Rice River-3-17.52	1,970
Detailed Reach	Wild Rice River-4-22.94	1,905
Detailed Reach	Wild Rice River-5-38.49	1,862
Detailed Reach	Wild Rice River-6-42.36	1,847
USGS Gage	05053000 - Wild Rice River near Abercrombie (RM 42.45)	1,847 (1,490)[1]
Mouth	Wolverton Creek at Mouth	103.2
Detailed Reach	Wolverton Creek-1-0.64	103.0
Detailed Reach	Wolverton Creek-2-2.02	99.13
Upstream End	Wolverton Creek at Upstream End	87.45

[1] Number in parentheses is the contributing drainage area as determined by the USGS.

3.2 Field Investigations

WEST personnel conducted field investigations to identify and document the geomorphic characteristics for each study reach. The field work began on 16 November 2010 and prematurely ended on 22 November 2010 due to considerable snowfall and iced over rivers. Field work recommenced on 22 September 2011, following a significant spring flood and continued high summer flows, and was completed on 6 October 2011. At each detailed study reach, the following tasks were conducted:

- Staking of top of bank, bankfull, and water surface elevations (at a minimum of five cross sections)
- Collection of bank, bed, and bar (if applicable) sediment samples
- Estimation of Manning's n roughness values
- Measurement of root depth
- Estimation of percent root density
- Estimation of percent ground surface cover
- Estimation of percent eroding bank length
- Identification of bank material stratifications
- Measurement of distance from bank toe to water surface
- Identification of vegetation coverage and characteristics
- Identification of depositional features
- Identification of channel blockages
- Measurement of flow velocity and discharge
- Collection of photographic records

The notes from the field investigations are included in Appendix A. The results of the field investigation are presented in Appendix B. Included in Appendix B are maps and figures that define the detailed study reach locations within each stream, the cross-sections within each detailed study reach, locations where sediment sample and field photos were taken within each detailed study reach, cross-sectional views of the surveyed data, modeled water surface elevations for both the day of the survey and the bankfull discharge, observed water surface elevation and bankfull elevation, field photos, and grain size distribution curves for the sediment samples.

3.3 Cross Section Surveys

A total of 340 cross sections were surveyed for the project by Anderson Engineering of Minnesota. Cross section data were collected on all streams and existing diversion channels within the project area, except for the majority of the Red River for which detailed bathymetric data was collected in 2010 (USACE, 2010a). Of the 340 cross sections, 123 were surveyed within the detailed study reaches at or near the locations where the top of bank, bankfull, and water surface stakes were placed during the field investigation efforts. The remaining 217 cross sections were surveyed in order to make comparisons with historic cross section data.

3.4 Soil and Sediment Sample Analysis

Bank and bed sediment samples were collected at each detailed study reach during the field investigations. A total of 109 samples were analyzed, of which 47 were bank samples and 43 were bed samples collected from within the detailed study reaches. The remaining 19 samples were collected from the existing Sheyenne River diversion channels. Each sample collected was analyzed by Midwest Testing Laboratory, Inc. The analysis completed on each sample classified the soil type (according to ASTM D2488 standards), noted the color, and described the grain size distribution (according to ASTM D422 standards). Detailed analysis results for each sample are included in Appendix B.

Sediment samples were collected by one of three methods. Bank samples were taken using a shovel. Bed samples were collected using either a clamshell sampler (AMS 25lb Stainless Steel Dredge) or a coring sampler (AMS Multi-Stage Sludge Sampler). In general, the clamshell sampler did not perform well due to the type of bed material encountered. Compacted clays could not be sampled with this device. Most of the samples were collected with the coring sampler. The coring device was hammered into the bed of the stream and cores were extracted from the sampler. The cores were approximately 2-inches in diameter and varied from 2- to 10-inches in length depending on the density and cohesiveness of the bed material encountered

In general, the bed material within the detailed study reaches was dominated by silt- and clay-sized particles (<0.0625 mm). The only notable exceptions were associated with the samples collected from the Sheyenne River. Sand-sized particles were much more prevalent within this stream compared to any of the other streams within the study area. A summary of the particle size distribution information for the bed material samples collected in the detailed study reaches is shown in Table 3-2. For any sample that had a median particle size smaller than the analysis method limits (0.001 mm), the value was noted as <0.001.

Table 3-2. Particle Size Distributions for Bed Material Samples

Detailed Reach	% Gravel	% Sand	% Silt	% Clay	D_{50}
Buffalo River-1-1.19	0	2	30	68	0.0015
Lower Rush River-1-1.10	0	1	10	89	<0.001
Lower Rush River-2-6.03	0	3	38	59	0.0019
Maple River-1-0.78	0	33	24	43	0.0091
Maple River-2-11.39	0	3	31	66	0.001
Red River-1-410.65	0	2	36	62	0.0018
Red River-2-419.14	0	1	10	89	<0.001
Red River-3-440.57	2	15	70	13	0.026
Red River-4-452.52	0	23	20	57	0.0027
Red River-5-463.56	0	0	16	84	0.001
Red River-6-470.23	0	5	22	73	0.00165
Red River-7-492.47	0	47	14	39	0.025
Red River-8-521.18	12	25	17	46	0.007
Rush River-1-0.08	0	1	15	84	<0.001
Rush River-2-6.15	0	2	2	96	<0.001
Sheyenne River-1-4.20	1	28	32	39	0.175
Sheyenne River-2-11.56	2	72	13	13	0.51
Sheyenne River-3-18.15	0	44	33	23	0.73
Sheyenne River-4-22.27	0	46	37	17	0.073
Sheyenne River-5-26.47	0	63	14	23	0.12
Sheyenne River-6-35.82	0	27	35	38	0.0175
Sheyenne River-7-43.27	0	34	45	21	0.0495
Sheyenne River-8-55.75	0	94	2	4	0.18
Wild Rice River-1-3.01	0	5	34	61	0.0031
Wild Rice River-2-4.23	0	11	28	61	0.0029
Wild Rice River-3-17.52	0	5	11	84	0.001
Wild Rice River-4-22.94	0	1	39	60	0.0032
Wild Rice River-5-38.49	0	6	25	69	0.0025
Wild Rice River-6-42.36	0	16	19	65	0.0027
Wolverton Creek-1-0.64	0	8	17	75	<0.001
Wolverton Creek-2-2.02	0	9	22	69	0.0016

The bank materials sampled within the detailed study reaches were also dominated by silt- and clay-sized particles, again with the only notable exception being the Sheyenne River. Sand-sized particles were more prevalent along the banks of the Sheyenne River than in the other streams. A summary of the particle size distributions for bank material samples collected in the detailed study reaches is shown in Table 3-3. For reaches where more than one bank sample was collected, the value shown in Table 3-3 is the average value of the collected samples. Again, for any sample that had a median particle size smaller than the analysis method limits (0.001 mm), the value was noted as <0.001.

Table 3-3. Average Particle Size Distribution for Bank Material Samples

Detailed Reach	% Gravel	% Sand	% Silt	% Clay	D_{50}
Buffalo River-1-1.19*	0	6	51	44	0.0098
Lower Rush River-1-1.10	0	2	17	81	<0.001
Lower Rush River-2-6.03*	0	6	31	64	<0.001
Maple River-1-0.78*	0	7	26	68	<0.001
Maple River-2-11.39	0	3	31	66	0.0014
Red River-1-410.65*	0	7	34	60	0.0021
Red River-2-419.14*	0	17	37	46	0.0074
Red River-3-440.57	0	4	31	65	0.0021
Red River-4-452.52*	0	5	33	63	0.0022
Red River-5-463.56*	0	3	33	64	0.0023
Red River-6-470.23*	0	4	36	61	0.0025
Red River-7-492.47	0	21	35	44	0.0082
Red River-8-521.18*	0	25	27	49	0.0361
Rush River-1-0.08	0	4	16	80	<0.001
Rush River-2-6.15*	0	1	19	81	<0.001
Sheyenne River-1-4.20*	0	38	42	21	0.0530
Sheyenne River-2-11.56	0	39	33	28	0.0500
Sheyenne River-3-18.15	0	26	33	41	0.0140
Sheyenne River-4-22.27	0	19	54	27	0.0250
Sheyenne River-5-26.47	0	33	41	26	0.0390
Sheyenne River-6-35.82	0	33	41	26	0.0370
Sheyenne River-7-43.27*	0	31	44	26	0.0385
Sheyenne River-8-55.75	0	45	39	16	0.0730
Wild Rice River-1-3.01	0	1	38	61	0.0027
Wild Rice River-2-4.23	0	1	38	61	0.0027
Wild Rice River-3-17.52*	0	2	27	71	0.0020
Wild Rice River-4-22.94*	0	4	39	58	0.0031
Wild Rice River-5-38.49	0	11	36	53	0.0042
Wild Rice River-6-42.36*	0	6	41	54	0.0041
Wolverton Creek-1-0.64	0	3	21	76	<0.001
Wolverton Creek-2-2.02	0	3	23	75	<0.001

*Based on an average derived from two samples

Sediment samples were also collected along the Sheyenne River diversion channels. Samples were extracted from the bed and side slopes of the diversion channel using a shovel. Where water was present in the channel, samples were taken from the side slopes near the edge of water. Samples were only collected at locations where deposition had recently occurred. No core samples were taken. Sediment deposits along the bed of the Sheyenne River Diversion Channel are dominated by sand-sized particles. Samples taken along the side slopes of the diversion channel tended to have a greater percentage of silt- and clay-sized particles. A summary of the general particle size distributions for bed and side slope material samples collected in the Sheyenne River Diversion Channel is shown in Table 3-4. Also shown is the median particle size (D_{50}) of the sample.

Table 3-4. Particle Size Distributions for the Sheyenne River Diversion Channels Samples

Location	% Gravel	% Sand	% Silt	% Clay	% Colloids	D_{50}
Horace to West Fargo Diversion						
200 ft U/S of Diversion Weir (right bank)	0	59	31	10	0	_/1
200 ft D/S of Diversion Weir (bed)	No analysis – similar to 44th Street SE					
45th Street SE (bed)	No analysis – similar to 44th Street SE					
44th Street SE (bed)	0	86	9	1	4	0.11
U/S of 64th Ave S (bed)	0	92	2	6	0	_/1
D/S of 64th Ave S (bed)	0	88	7	0	5	0.13
630 ft U/S of 52nd Ave W (bed)	No analysis – similar to D/S of 64th Ave S					
630 ft U/S of 52nd Ave W (right bank)	0	60	33	1	6	0.08
U/S of 40th Ave S (bed)	0	88	2	3	7	0.17
U/S of 40th Ave S (left bank)	No analysis – similar to 1,000 ft U/S of 32nd Ave W (left bank)					
1,000 ft U/S of 32nd Ave W (bed)	0	93	2	1	4	0.19
1,000 ft U/S of 32nd Ave W (left bank)	0	10	57	8	25	0.019
550 ft D/S of 21st Ave W (bed)	0	68	25	1	6	0.09
550 ft D/S of 21st Ave W (right bank)	0	7	57	12	24	0.016
West Fargo Diversion						
800 ft D/S of Diversion Weir (left bank)	0	46	34	5	15	0.073
670 ft U/S of Confluence with Horace Diversion (left bank)	0	19	61	5	15	0.048
Confluence of Horace and West Fargo Diversions	0	65	26	9	0	_/1
575 ft D/S of Confluence	0	51	34	3	12	0.075
Near 13th Ave W (left bank)	0	22	57	21	0	_/1
1,750 ft U/S of I-94 (right bank)	0	47	37	3	13	0.074
400 ft U/S of I-94 (left bank)	0	6	66	28	0	_/1
7,700 ft D/S of I-94 (right bank)	0	49	32	5	14	0.075
270 ft D/S of 12th Ave NW (right bank)	0	0	61	38	0	_/1
1,550 ft D/S of 12th Ave NW (right bank)	0	11	75	3	21	0.033
Confluence of Sheyenne River with Sheyenne Diversion (right overbank)	0	0	51	12	34	0.0074

_/1 Samples collected by St. Paul District did not include determination of D_{50}.

4 Hydrology Assessment

4.1 Flood History

The Red River basin has several characteristics that render it particularly susceptible to problematic flooding (FEMA, 2002). Significant flood events are typically the result of spring rain on snow during the months of March and April. The Red River and its tributaries regularly freeze during the winter months and because of its northerly flow direction the upstream reaches typically melt prior to the downstream reaches. Spring melting and subsequent runoff are often hindered from downstream flow by ice blockages in the lower reaches of the Red River which are located further north and melt later than the upstream reaches. This characteristic, combined with a particularly low basin gradient (~ 0.5ft/mi) and generally flat topography, result in significant and frequent floods.

An expert panel assembled to assess the impact of increasing flood flows on the Fargo-Moorhead flood risk management project determined that the basin hydrology is non-stationary, with flood discharges increasing in recent decades (Figure 4-1).

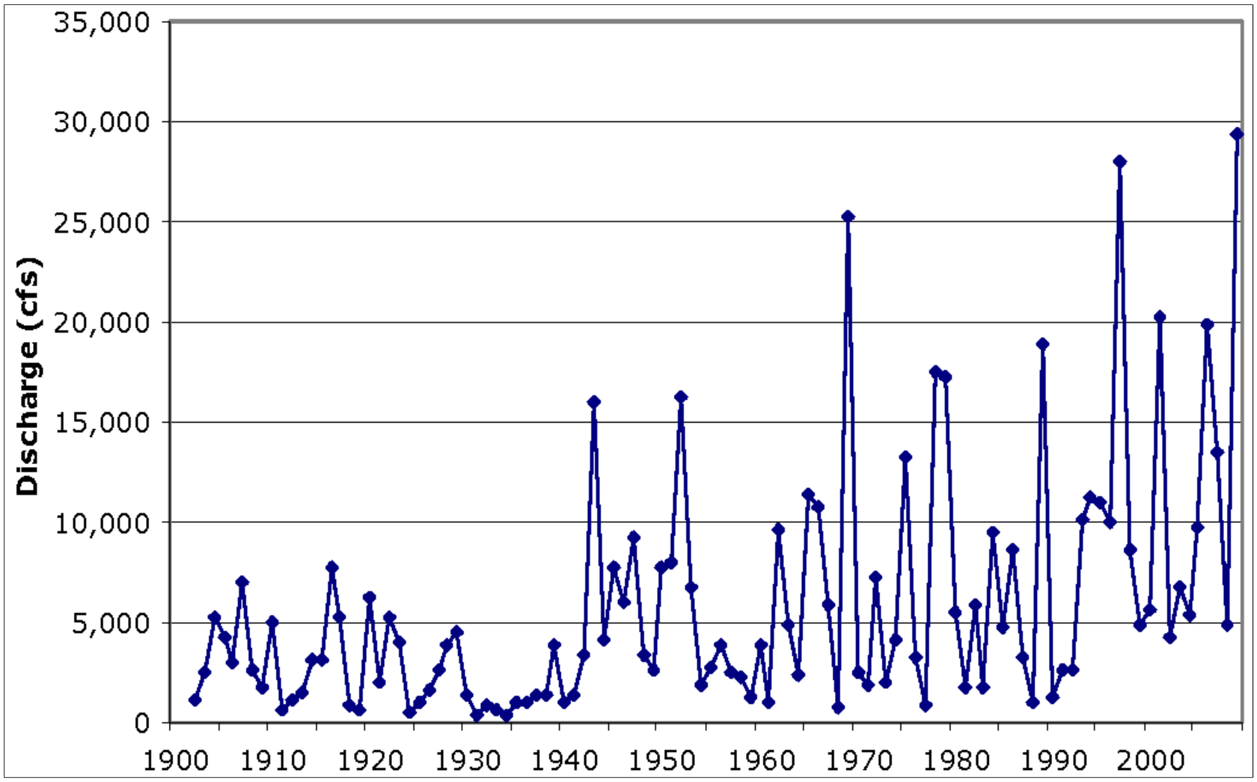


Figure 4-1. Natural Annual Maximum Mean Daily Flow – Red River at Fargo (David Ford Consulting Engineers, Inc., using USACE data)

The Red River has exceeded the National Weather Service flood stage of 18 ft during 48 of the past 109 years, and every year from 1993 to 2011 (USACE, 2011). The flood of record reached a stage of 40.8 feet at the Fargo gage in the spring of 2009.

4.2 Channel-Forming Discharge for Current Conditions

A channel-forming discharge is a single steady representative discharge that will theoretically produce (for rivers in equilibrium) the same bankfull channel dimensions as a natural sequence of discharge events. Unfortunately, identification of the channel-forming discharge is inherently uncertain. Therefore, two separate approaches (bankfull discharge and effective discharge) were used to estimate the channel-forming discharge for the detailed study reaches. A third method and one approach (recurrence interval) was used to evaluate the applicability of each approach. The results of the analysis were used to estimate the channel-forming discharge for each study reach.

4.2.1 Bankfull Discharge Method

The bankfull discharge is defined by geomorphologists as the discharge that barely overtops the channel banks in a non-incised channel. The bankfull discharge for each study reach was estimated using a two-step process. First, the bankfull elevation was estimated during site visits based on numerous physical indicators, such as presence of vegetation, breaks in slope, staining of rocks, gleyed soil layers, and exposure of roots. In addition, the water surface elevation at the time of the field work was staked and later surveyed, stream discharge was measured, and the Manning's n roughness value was estimated.

Second, the one-dimensional Corps of Engineers River Analysis System (HEC-RAS) standard-step backwater computer program (USACE, 2010b) was used to estimate the discharge corresponding to the field-estimated bankfull stage. Not to be confused with the HEC-RAS models developed by the USACE, all HEC-RAS models referred to in this study were developed by WEST, unless otherwise noted. The HEC-RAS models were developed from survey data collected during 2010 and 2011. Data for structures not surveyed during the field survey effort were taken from existing USACE hydraulic models. This approach was used because numerous hydraulic structures (bridges, weirs, culverts) located downstream of the detailed study reaches were found to create sufficient backwater to control the water surface elevations within the detailed study reaches.

The Manning's n values for the hydraulic models were initially set equal to field-estimated values. The downstream boundary condition for modeling was set to normal depth unless backwater from the main stem stream was likely to occur. The energy slope used to define normal depth was set equal to the water surface slope observed during the field visit. The discharge value, at the day and time the site was visited, used in the model was from either the measured discharge during the field investigation or the discharge recorded by a nearby USGS stream gage. The HEC-RAS model was then calibrated by adjusting the Manning's n values so that the water surface profile agreed with the surveyed water surface elevations. On average, the calculated water surface elevation was within +/- 0.1 feet of the observed water surface elevation. Once calibrated, the discharge in the HEC-RAS model was increased until the modeled bankfull water surface profile agreed with the field-determined bankfull elevations, resulting in the estimated bankfull discharge. The results of the bankfull discharge analysis are summarized in Table 4-1.

Table 4-1. Channel-Forming Discharges Using the Bankfull Discharge Method

Type	Location	Discharge (cfs)	Discharge Per Area (cfs/mi^2)
Detailed Reach	Buffalo River-1-1.19	420	0.4
Detailed Reach	Lower Rush River-1-1.10	65	1.1
Detailed Reach	Lower Rush River-2-6.03	60	1.1
Detailed Reach	Maple River-1-0.78	650	0.4
Detailed Reach	Maple River-2-11.39	650	0.4
Detailed Reach	Red River-1-410.65	4,700	0.4
Detailed Reach	Red River-2-419.14	4,280	0.4
Detailed Reach	Red River-3-440.57	2,380	0.4
Detailed Reach	Red River-4-452.52	2,380	0.4
Detailed Reach	Red River-5-463.56	2,380	0.4
Detailed Reach	Red River-6-470.23	1,780	0.5
Detailed Reach	Red River-7-492.47	1,650	0.5
Detailed Reach	Red River-8-521.18	1,650	0.5
Detailed Reach	Rush River-1-0.08	150	1.0
Detailed Reach	Rush River-2-6.15	150	1.1
Detailed Reach	Sheyenne River-1-4.20	1,900	0.4
Detailed Reach	Sheyenne River-2-11.56	1,750	0.3
Detailed Reach	Sheyenne River-3-18.15	1,680	0.3
Detailed Reach	Sheyenne River-4-22.27	1,030	0.3
Detailed Reach	Sheyenne River-5-26.47	[1/]	[1/]
Detailed Reach	Sheyenne River-6-35.82	860	0.3
Detailed Reach	Sheyenne River-7-43.27	1,200	0.4
Detailed Reach	Sheyenne River-8-55.75	1,000	0.3
Detailed Reach	Wild Rice River-1-3.01	600	0.3
Detailed Reach	Wild Rice River-2-4.23	600	0.3
Detailed Reach	Wild Rice River-3-17.52	517	0.3
Detailed Reach	Wild Rice River-4-22.94	517	0.3
Detailed Reach	Wild Rice River-5-38.49	517	0.3
Detailed Reach	Wild Rice River-6-42.36	517	0.3
Detailed Reach	Wolverton Creek-1-0.64	130	1.3
Detailed Reach	Wolverton Creek-2-2.02	130	1.3

[1/] Bankfull discharge could not be determined.

The bankfull discharge for detailed study reach Sheyenne River – 5 – 26.47 could not be determined. Operation of the gate control structure located at the downstream end of the West Fargo protected area significantly influences water surface elevations along Sheyenne River – 5 – 26.47. The bankfull stake elevations identified appear to be more reflective of the near static water surface elevation that is maintained in this protected reach, while the remainder of the Sheyenne River and Sheyenne Diversion is experiencing high flows. Additionally, the provided geometry data for two hydraulic structures located within the protected area were found to be incorrect. As a result, the bankfull discharge could not be determined for this reach.

In general, the ratios of the bankfull discharge to the contributing drainage area within each stream are consistent. Additionally, when grouping the streams based on channel-forming discharge where large streams have a discharge of greater than 400 cfs and small streams have a discharge of less than 400 cfs, the ratios are also consistent. The ratio for the larger streams lies within the range of 0.2 to 0.5 cfs per mi^2, while the ratio for the smaller streams lies within the range of 1.0 to 1.3 cfs per mi^2. The discrepancy between the two sets of values is likely due to channelization of the smaller streams that was completed in part to move floods quickly through the system, which increases the discharges and the corresponding ratios for the small streams over those of the larger, more natural channels.

4.2.2 Effective Discharge Method

The effective discharge is the discharge that transports the most sediment in a year based upon both its ability to transport sediment and the frequency of its occurrence. The procedures outlined in USACE Technical Report TR-00-15 (Biedenharn et al., 2000) were used to estimate the effective discharges for the study reaches. The procedure involves calculation of discharge-duration and sediment transport rating curves. From these curves, a sediment-transport histogram was generated, wherein the annual sediment load for various discharges was plotted.

Discharge-duration curves were generated for each of the detailed study reaches. A discharge-duration curve shows the percent of time a given discharge is equaled or exceeded under a certain hydrologic regime. Discharge-duration curves were developed by the USACE for selected locations within the study area. The discharge-duration curves generated for the selected locations were used to interpolate discharge-duration curves to each of the detailed study reaches. Additional information regarding the development of the discharge-duration curves is discussed in Section 4.4.1. The curves are also presented in Appendix C.

The total sediment load of a river is transported either suspended in the flow (“suspended load”) or rolling, sliding, or saltating along the channel bed (“bedload”). Fine-grained materials, such as silts and clays, are typically supplied to a watercourse from watershed areas and generally do not represent a significant fraction (greater than 10 percent by weight) of a channel bed sample. Such fine-grained materials are easily transported in suspension and are referred to as “washload”. The summation of the suspended load and bed load, excluding the wash load, is defined as the “bed-material load”.

The Red River and its tributaries in the study area are not, however, typical streams. Bed-material samples collected during this study demonstrated that the bed of the Red River and its tributaries, with the exception of the Sheyenne River, is predominantly composed of cohesive clays and silts. The clays and silts that form the bed of the streams originated from the buildup of successive layers of fine sediments that were deposited within glacial Lake Agassiz (Stoner, 1993). These layers of fine sediments have compacted over time, resulting in the formation of a “hardpan” channel bottom. The USGS noted the existence of the hardpan channel bottom during their bed-material sampling efforts that were conducted for this project (personal communication with J. Galloway, USGS, June 27, 2011). The relative erosion resistance of the hardpan bottom minimizes or prevents significant bed-material transport. Any bed-material sediments of this size that are transported would be transported in suspension and are indistinguishable from the wash load. Therefore, the suspended sediment load in the Red River and its tributaries is a combination of wash load and bed-material load particles, and a distinction between the two types of loads within the suspended sediment load cannot be made. As a result, the suspended sediment load was used as a surrogate for the bed-material load in the effective discharge calculations.

Suspended sediment transport rating curves can be confidently created using field measurements that have been collected over a wide range of discharges. An adequate number of suspended sediment transport field measurements have been collected at seven permanent and four temporary USGS gage sites within the project area. The gage characteristics are shown in Table 4-2.

Table 4-2. Suspended Sediment Data Collection Sites

Gage Number	Gage Name	Type	Period of Record
05051522	Red River at Hickson	Permanent	11/1975-9/1981, 5/1997-9/1999, 5/2003-9/2003, 3/2010-11/2011
05054000	Red River at Fargo	Permanent	7/1975, 5/2001-7/2001, 5/2003-11/2011
05058700	Sheyenne River at Lisbon	Permanent	8/1976-9/1979
05059000	Sheyenne River near Kindred	Permanent	8/1976-9/1980
05059300	Sheyenne River above Diversion near Horace	Permanent	3/2010-11/2011
05059330	Sheyenne River at Horace (below Diversion)	Permanent	3/2010-9/2011
05060100	Maple River below Mapleton	Permanent	3/2010-11/2011
05060550	Rush River near Prosper	Permanent	4/2011-11/2011
463421096451000	Red River near Christine	Temporary	3/2010-11/2011
465603096472900	Red River at County Road 20 near Fargo	Temporary	3/2010-11/2011
464243096495100	Wild Rice River near St Benedict	Temporary	3/2010-11/2011
465752096573000	Lower Branch Rush River east of Prosper	Temporary	4/2011

Suspended sediment transport relationships could not be defined for any location on the Buffalo River or Wolverton Creek; therefore, effective discharge calculations were not conducted for the detailed study reaches on those streams.

Sediment-transport histograms were created using a three-step process. The histogram is created by first separating the discharge points from the discharge-duration curve into discharge ‘bins’ that encompass a range of discharges. Yevjevich (1972) recommended that the bin size should be no larger than the standard deviation of the flow record divided by four. For this study a bin size of 100 cfs meets Yevjevich’s criteria for all sites. For example, the first bin encompasses discharges from 0 to 100 cfs, the second bin encompasses discharges from 100 to 200 cfs, etc. The number of bins required was based on the highest discharge of the discharge-duration curve divided by the 100 cfs bin size. The second step in the sediment-transport histogram creation process is to determine the percentage of days through the flow record that the average daily discharge falls within each bin. The bin interval duration is simply the percent time the discharge is equaled or exceeded at the low end of the discharge bin minus the percent time the discharge is equaled or exceeded at the high end of the discharge bin. The final step in the sediment-transport histogram creation process is to calculate the sediment transported by the discharges within each bin. The geometric average of bin end points for each bin interval is input to the suspended sediment curve relationship, yielding a sediment transport rate ($Q_{sediment}$). The $Q_{sediment}$ for each bin was then multiplied by the bin interval duration for each bin to determine the average bin sediment transport rate for the gage record. Plotting each bin sediment transport rate yielded a sediment transport histogram.

4.2.2.1 Red River Effective Discharge Calculations

Suspended sediment measurements have been recorded at four different sites on the Red River: 1) 05051522 – Red River at Hickson, 2) 05054000 – Red River at Fargo, 3) 463421096451000 – Red River near Christine [site 1 in USGS (2011b) sediment sampling report], and 4) 465603096472900 – Red River at County Road 20 near Fargo [site 2 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for each of the four sites were plotted against the average daily discharge as shown in Figure 4-2. Figure 4-2 shows that the suspended sediment discharges at the four sites followed a consistent relationship regardless of their location. Therefore, it was assumed that the suspended sediment transport rating curve developed in Figure 4-2 was applicable to all of the Red River detailed study reaches. The equation for the suspended sediment transport rating curve developed for the Red River is:

$$Q_{sediment} = 0.030788(Q\ )^{1.2531}\ (R^2 = 0.85)$$

The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Red River detailed study reaches are shown in Figure 4-3 through Figure 4-10. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Red River detailed study reaches.

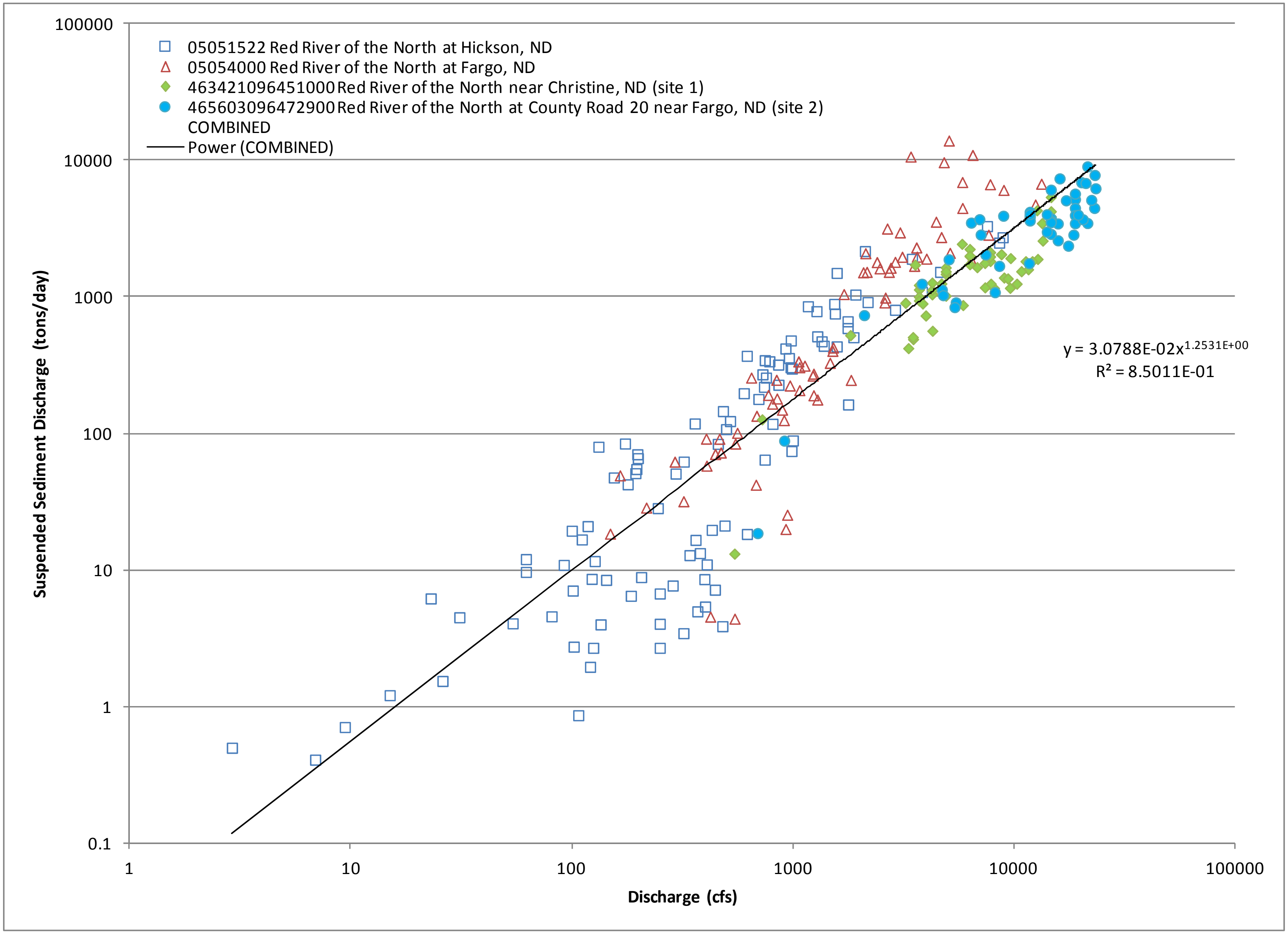


Figure 4-2. Suspended Sediment Discharge Comparison for Red River Sites

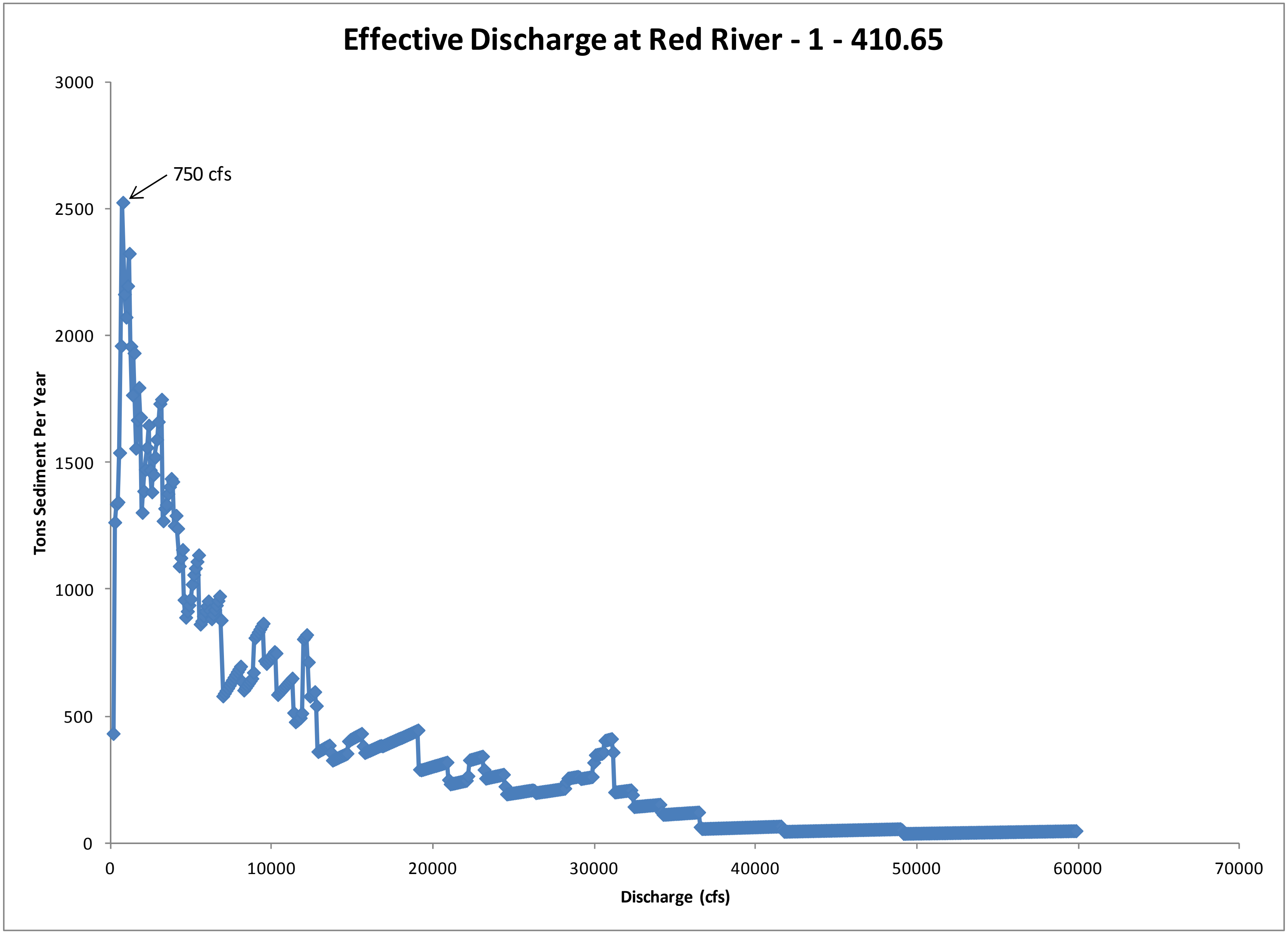


Figure 4-3. Sediment Transport Histogram for Red River – 1 – 410.65

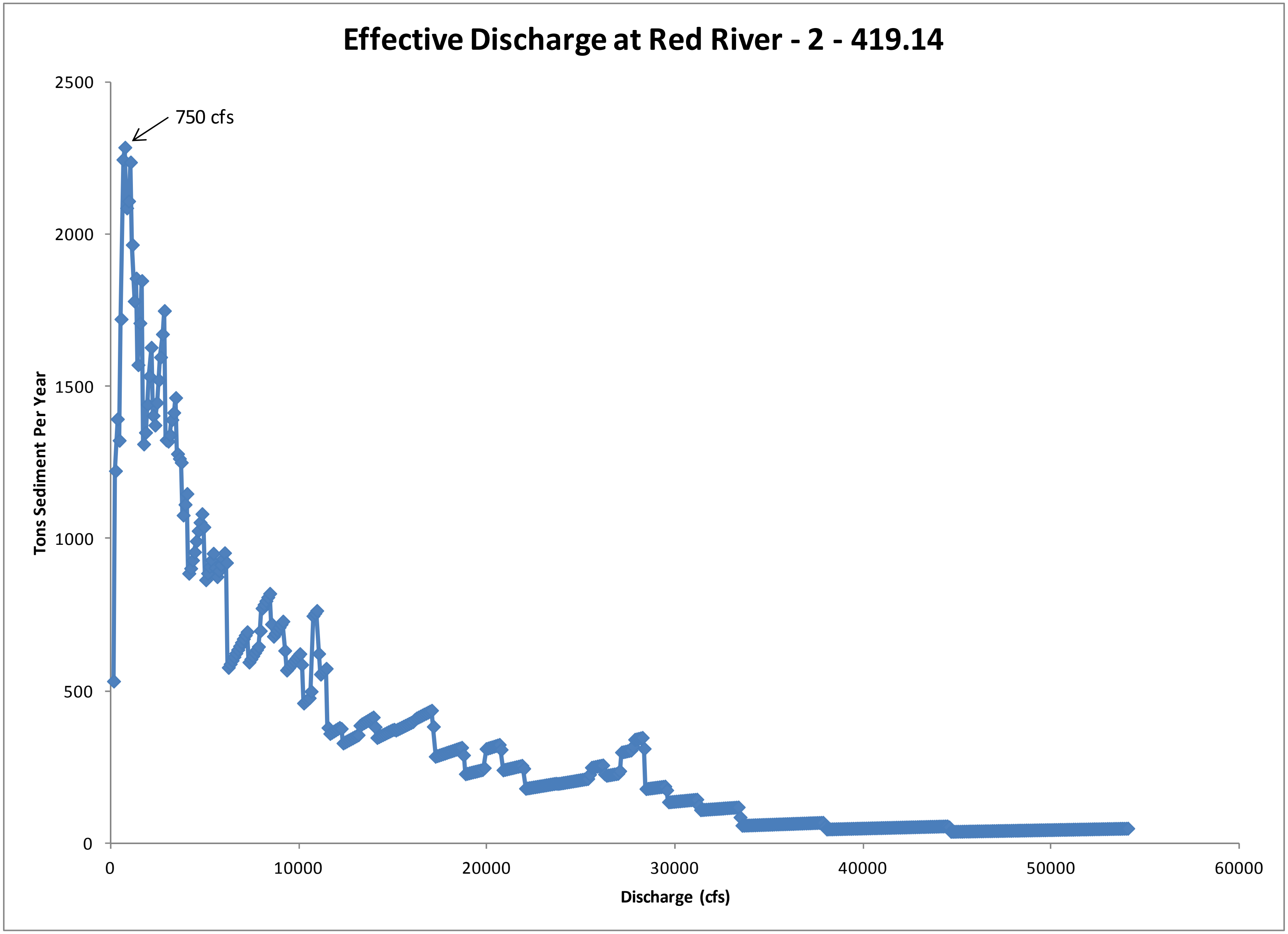


Figure 4-4. Sediment Transport Histogram for Red River – 2 – 419.14

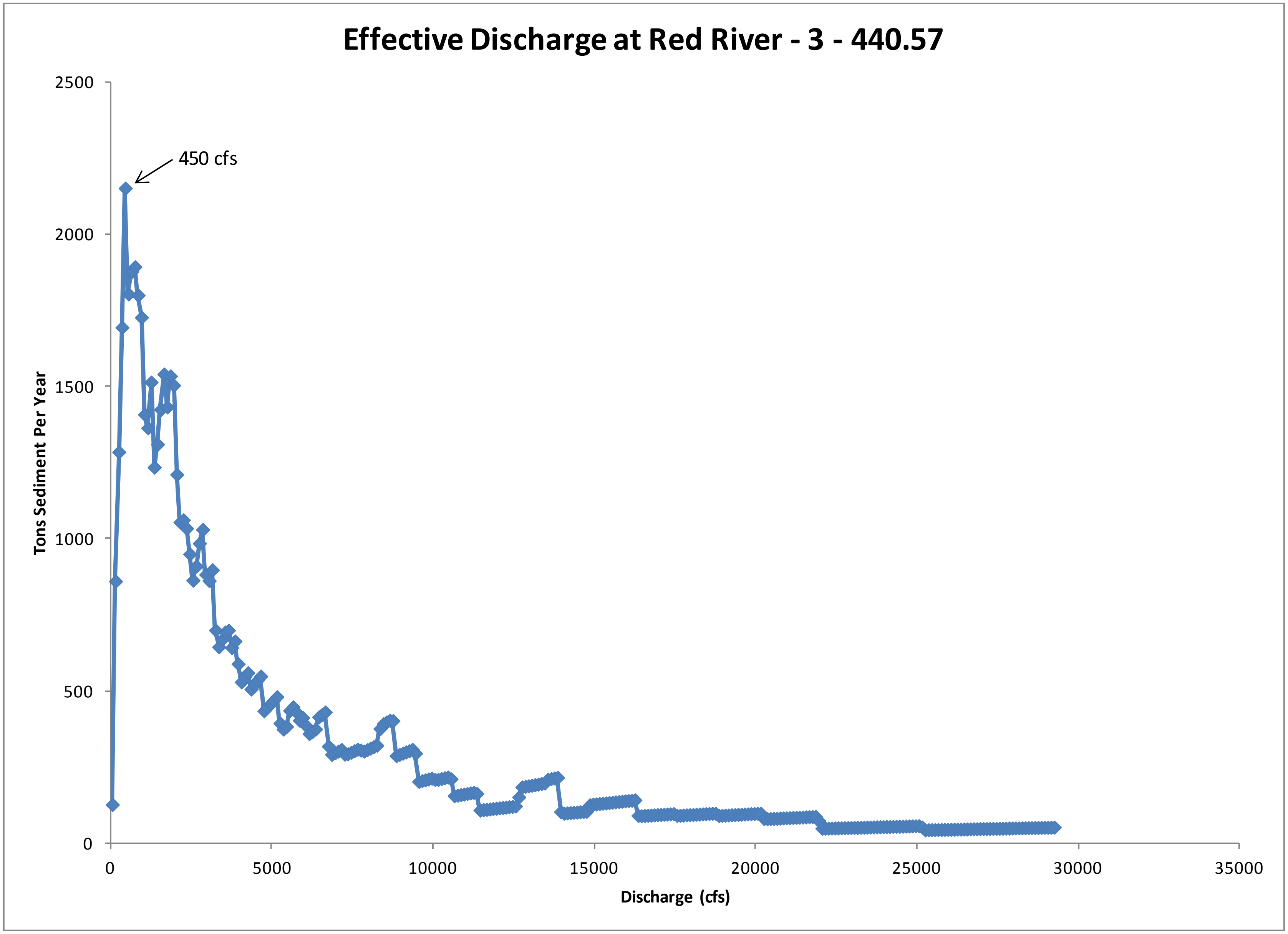


Figure 4-5. Sediment Transport Histogram for Red River – 3 – 440.57

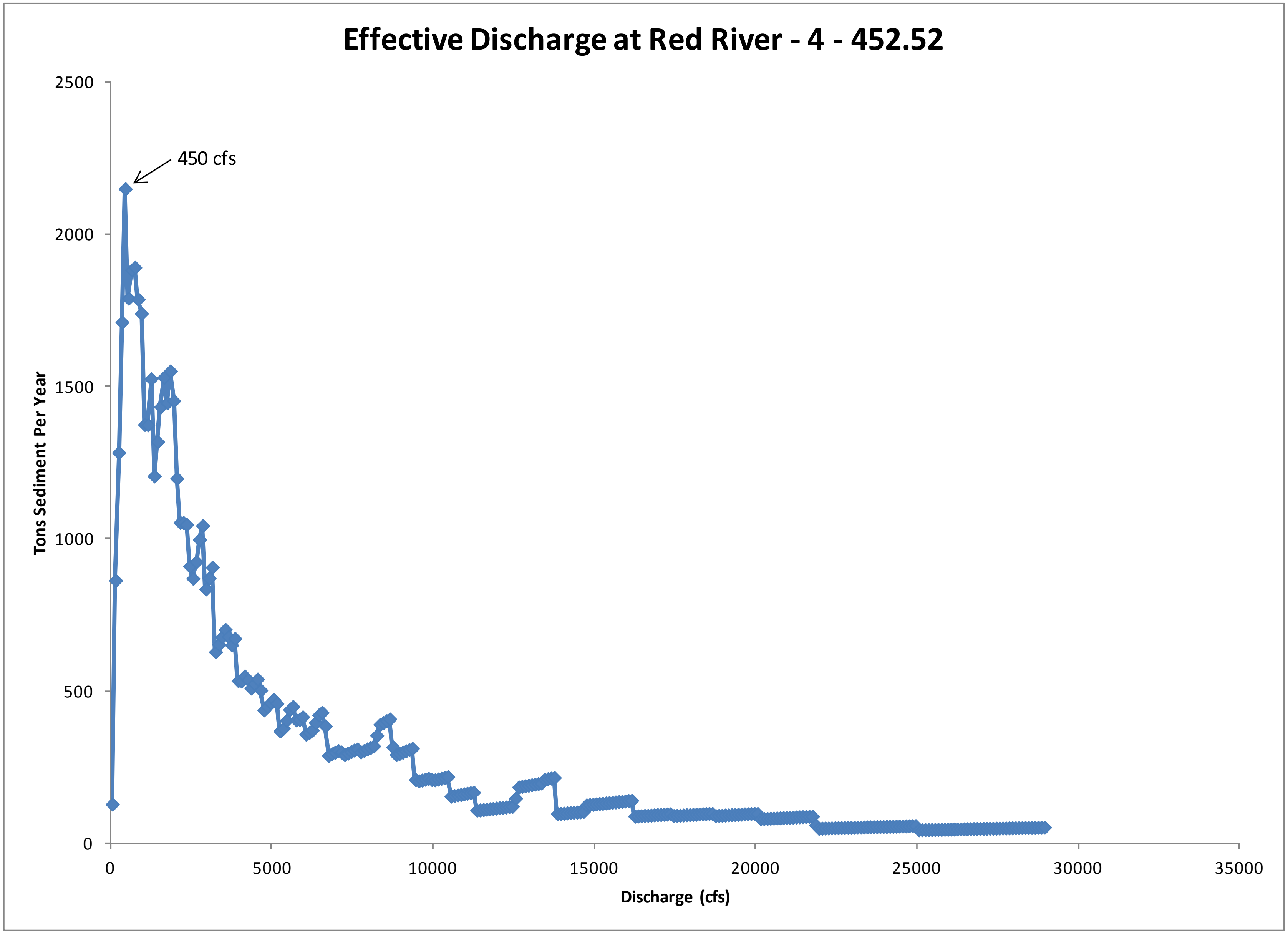


Figure 4-6. Sediment Transport Histogram for Red River – 4 – 452.52

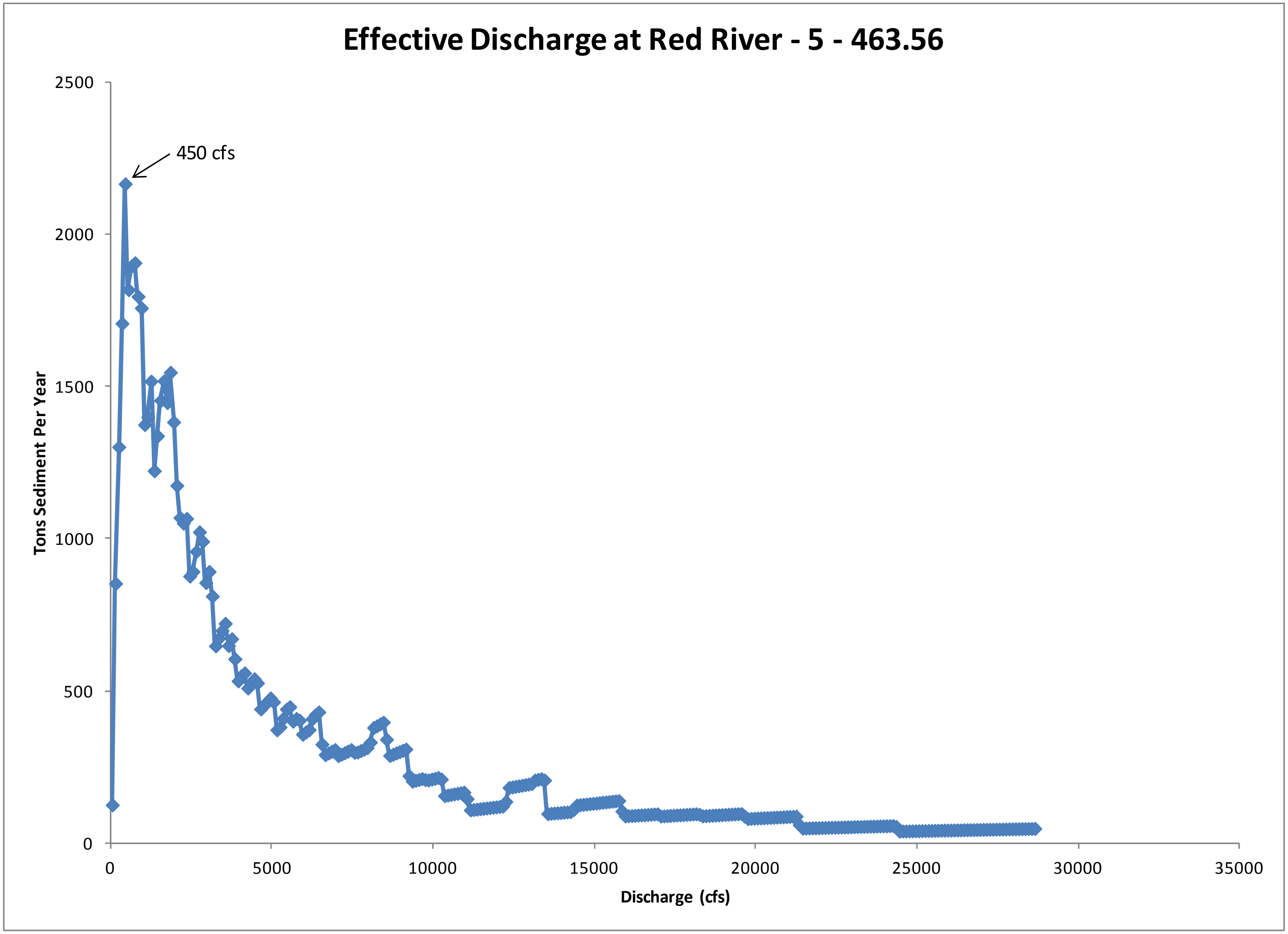


Figure 4-7. Sediment Transport Histogram for Red River – 5 – 463.56

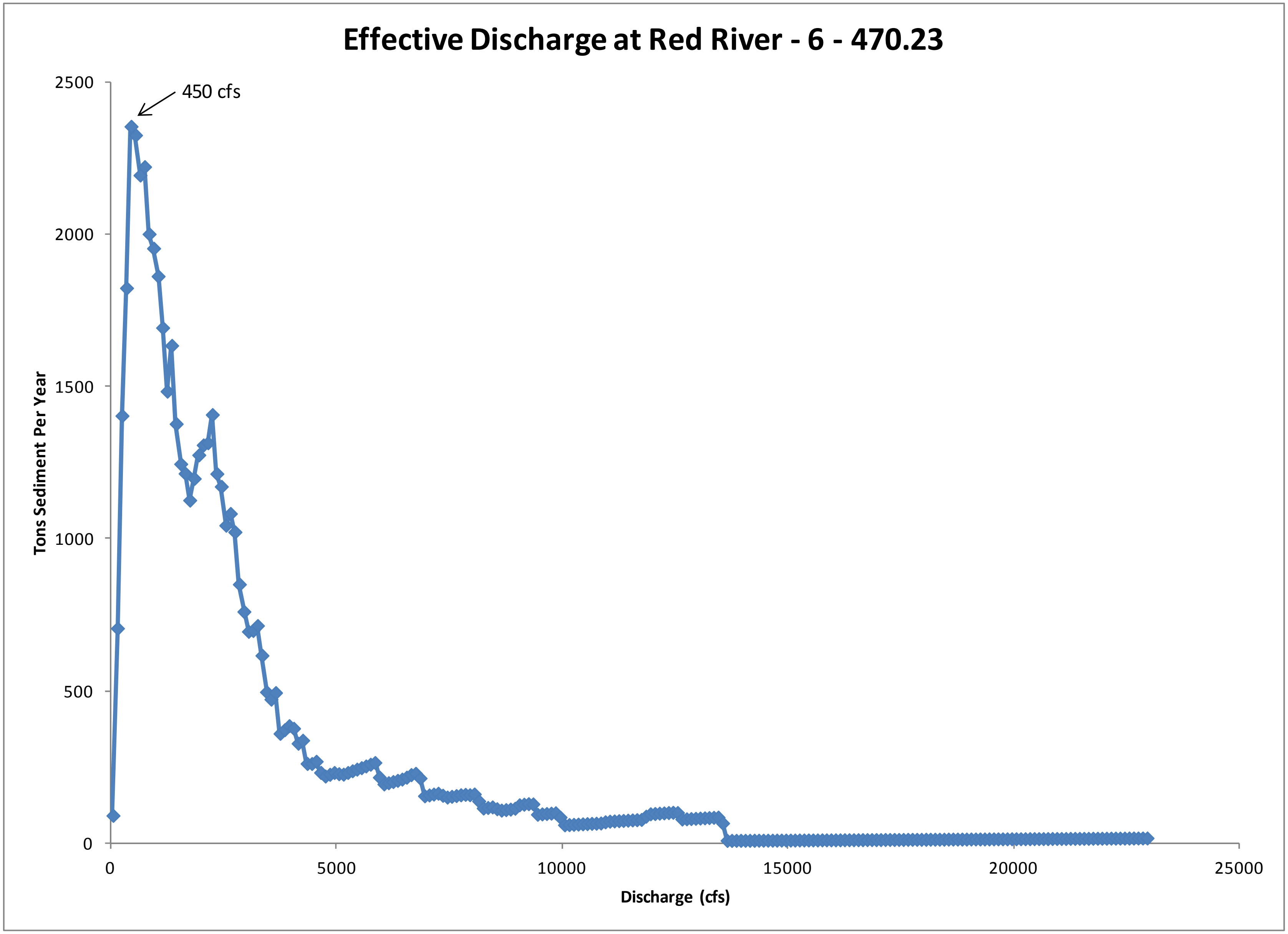


Figure 4-8. Sediment Transport Histogram for Red River – 6 – 470.23

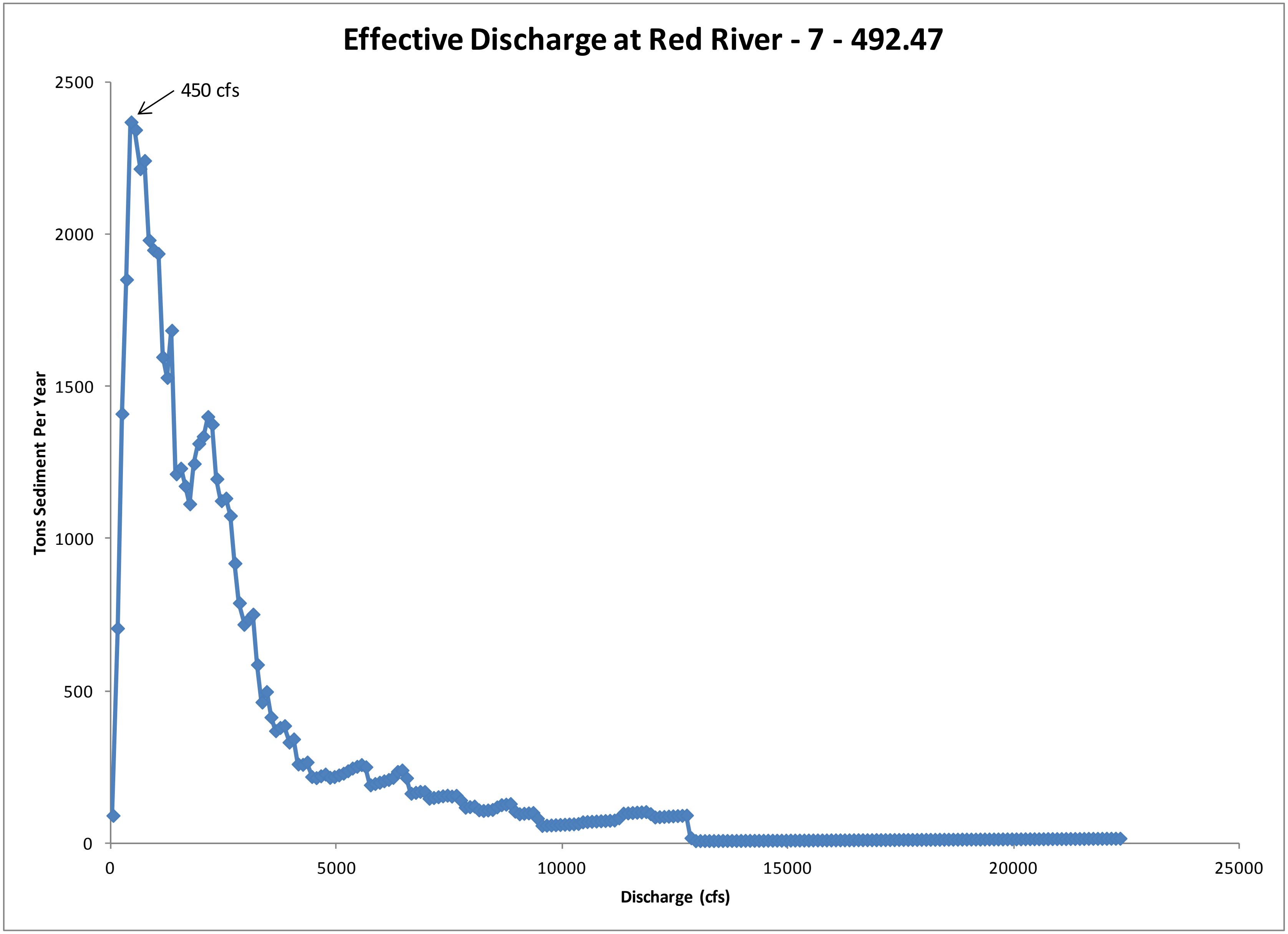


Figure 4-9. Sediment Transport Histogram for Red River – 7 – 492.47

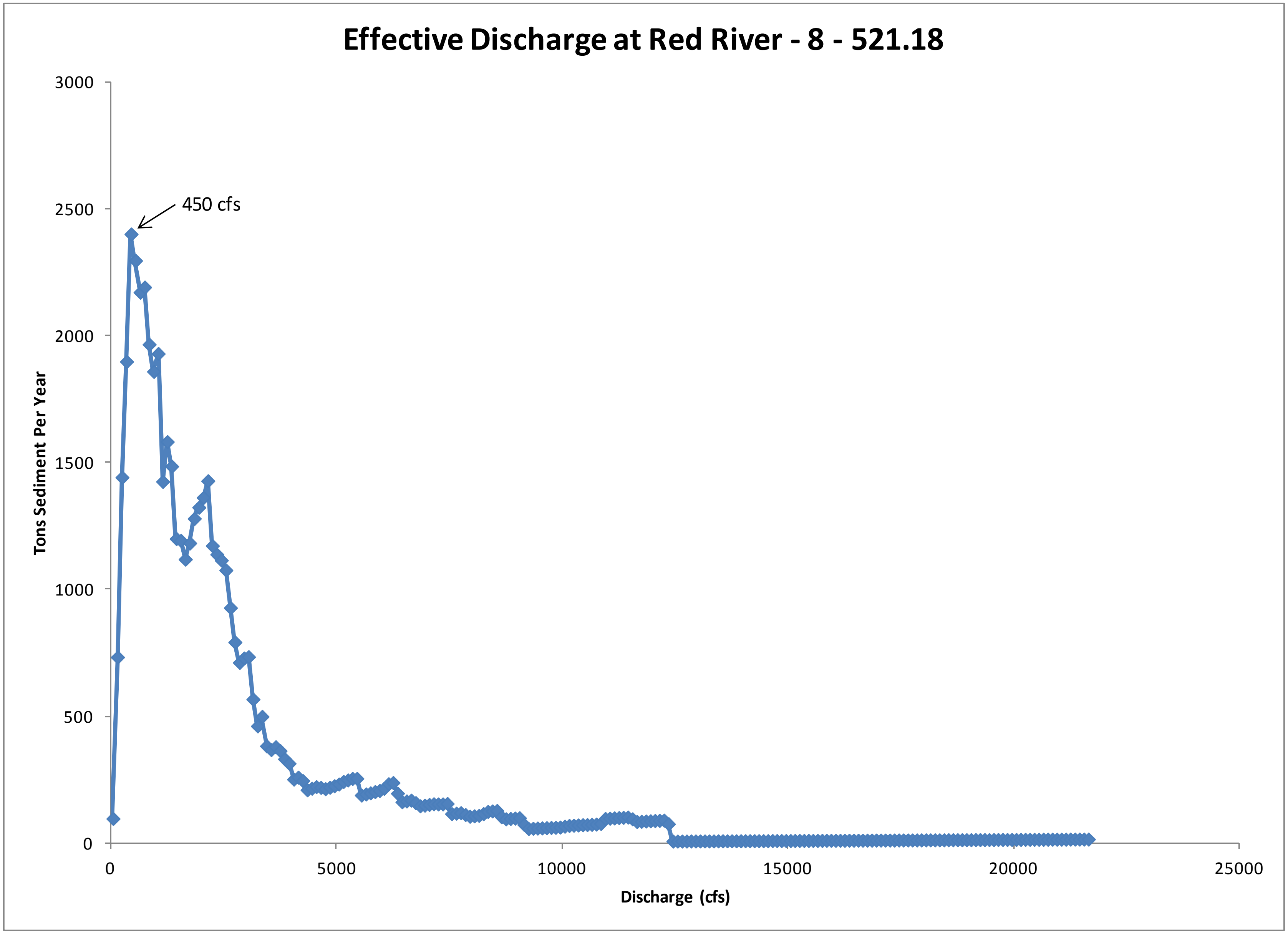


Figure 4-10. Sediment Transport Histogram for Red River – 8 – 521.18

4.2.2.2 Sheyenne River Effective Discharge Calculations

Suspended sediment measurements were recorded at four different sites on the Sheyenne River: 1) USGS gage 05058700 – Sheyenne River at Lisbon; 2) USGS gage 05059000 – Sheyenne River near Kindred; 3) Sheyenne River above Sheyenne River Diversion near Horace [site 3 in USGS (2011b) sediment sampling report]; and 4) Sheyenne River at Horace [site 4 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for each of the four sites were plotted against the average daily discharge as shown in Figure 4-11. Similar to the Red River sites, Figure 4-11 shows that the suspended sediment discharges at the four Sheyenne River sites followed a consistent relationship regardless of their location. Therefore, it was assumed that the suspended sediment transport rating curve developed in Figure 4-11 was applicable to all of the Sheyenne River detailed study reaches. The equation for the suspended sediment transport rating curve developed for the Sheyenne River is:

$$Q_{\text{sediment}} = 0.008634(Q\ )^{1.5603}\ (R^2 = 0.89)$$

The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Sheyenne River detailed study reaches are presented in Figure 4-12 through Figure 4-19. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge, except for detailed study reaches Sheyenne River – 6 – 35.82, Sheyenne River – 7 – 43.27, and Sheyenne River – 8 – 55.75. The effective discharge calculation for those three detailed study reaches are functions of the discharge-duration curve developed by the USACE for USGS gage 05059300 - Sheyenne River above Diversion near Horace. This curve exhibits a slight decrease in discharges between the 1.6 percent and 1.0 percent time equaled or exceeded values, which is counter to the usual manner in which discharge values increase as percent time equaled or exceeded values decrease. This decrease in discharge is propagated into the discharge-duration curves for Sheyenne River detailed study reaches 6-8 because the curves are based on an interpolation between the discharge-duration curve for the Horace gage and USGS gage 05059000 – Sheyenne River at Kindred. The decrease in discharges causes extraordinarily high peaks in the sediment transport histogram corresponding to the point at which the discharge decrease has propagated into the discharge-duration curve. As this peak is likely the result of incorrect data, it was disregarded and the next highest peak was used to determine the effective discharge for Sheyenne River detailed study reaches 6-8. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Sheyenne River detailed study reaches.

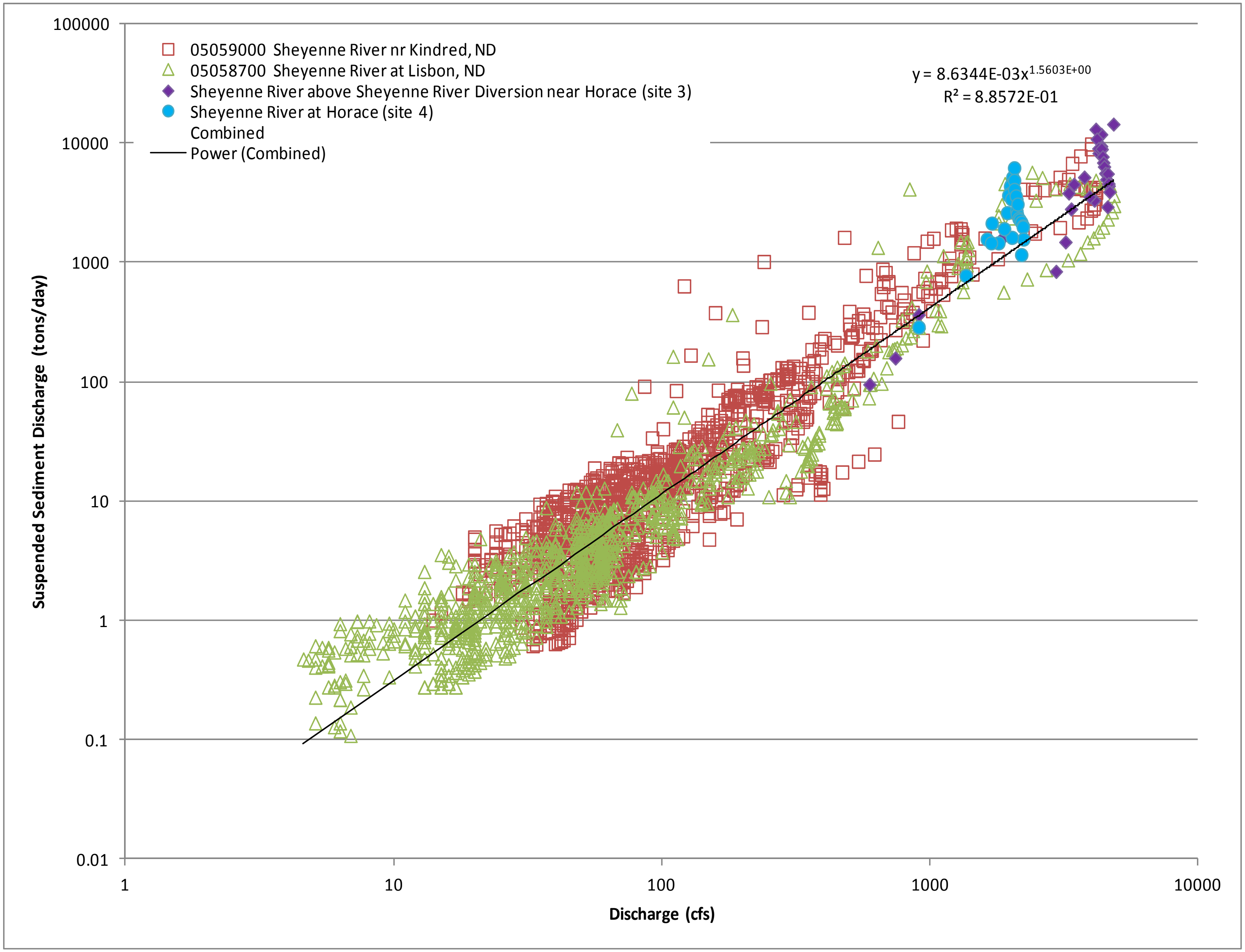


Figure 4-11. Suspended Sediment Discharge Comparison for Sheyenne River Sites

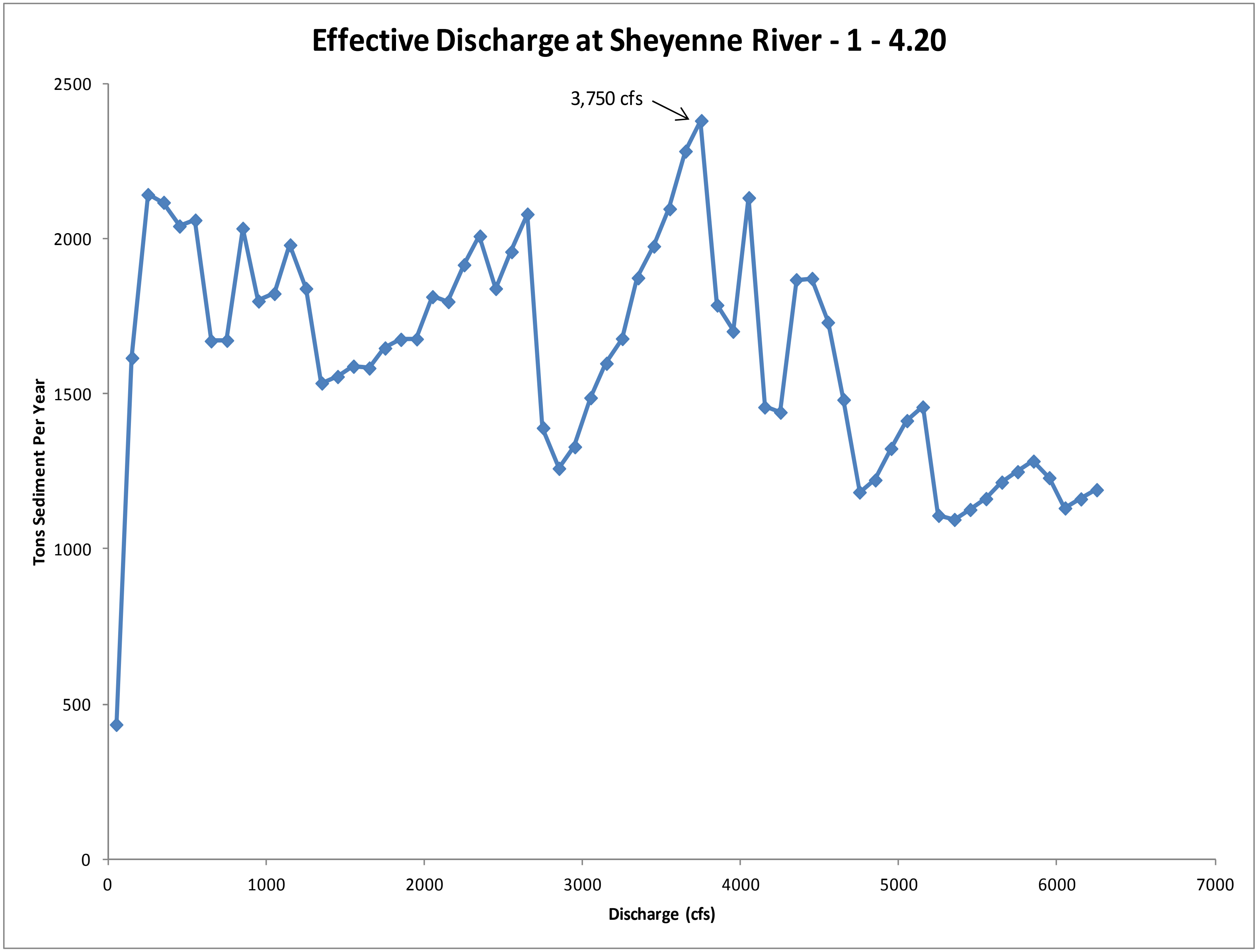


Figure 4-12. Sediment Transport Histogram for Sheyenne River – 1 – 4.20

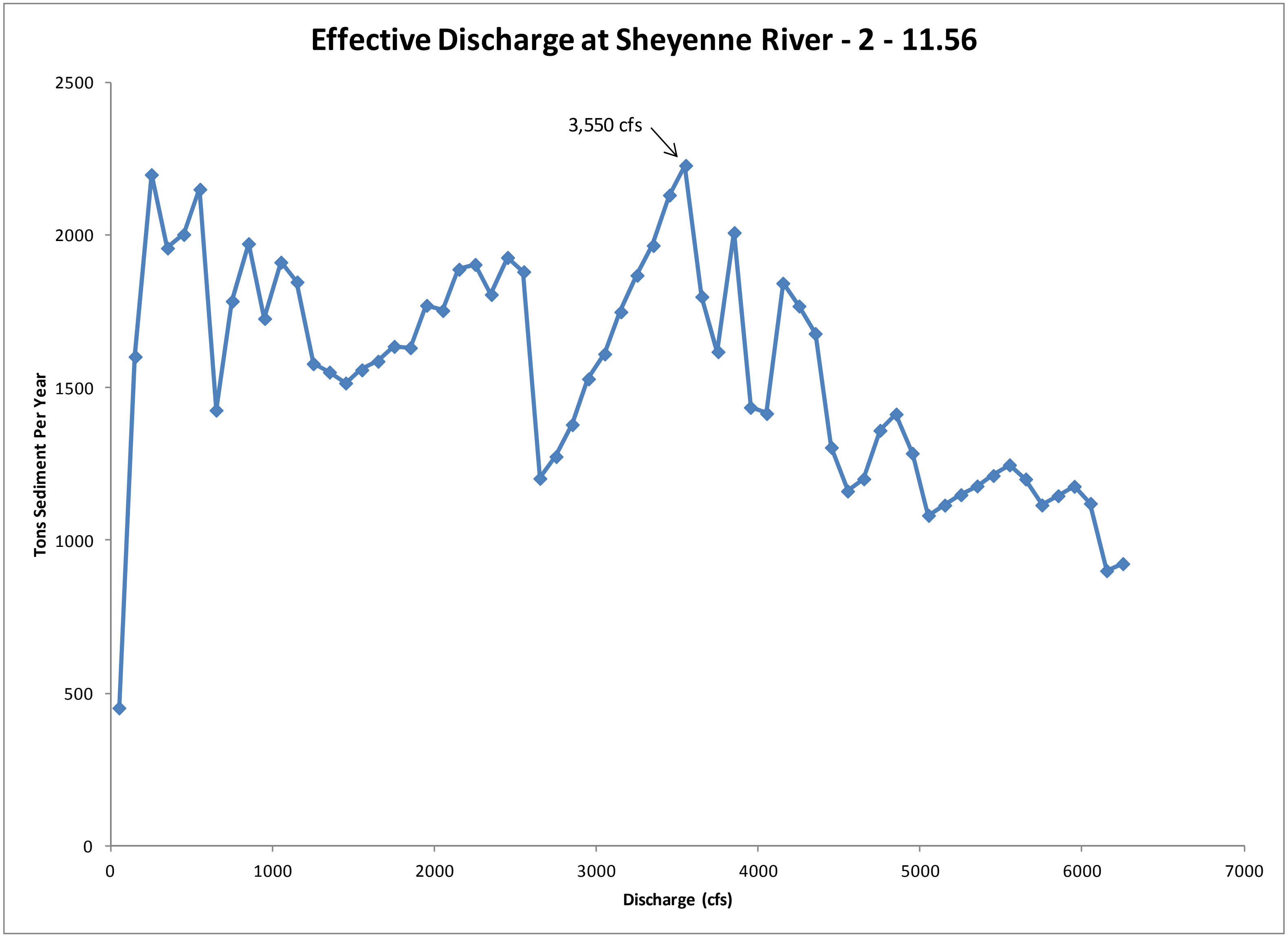


Figure 4-13. Sediment Transport Histogram for Sheyenne River – 2 – 11.56

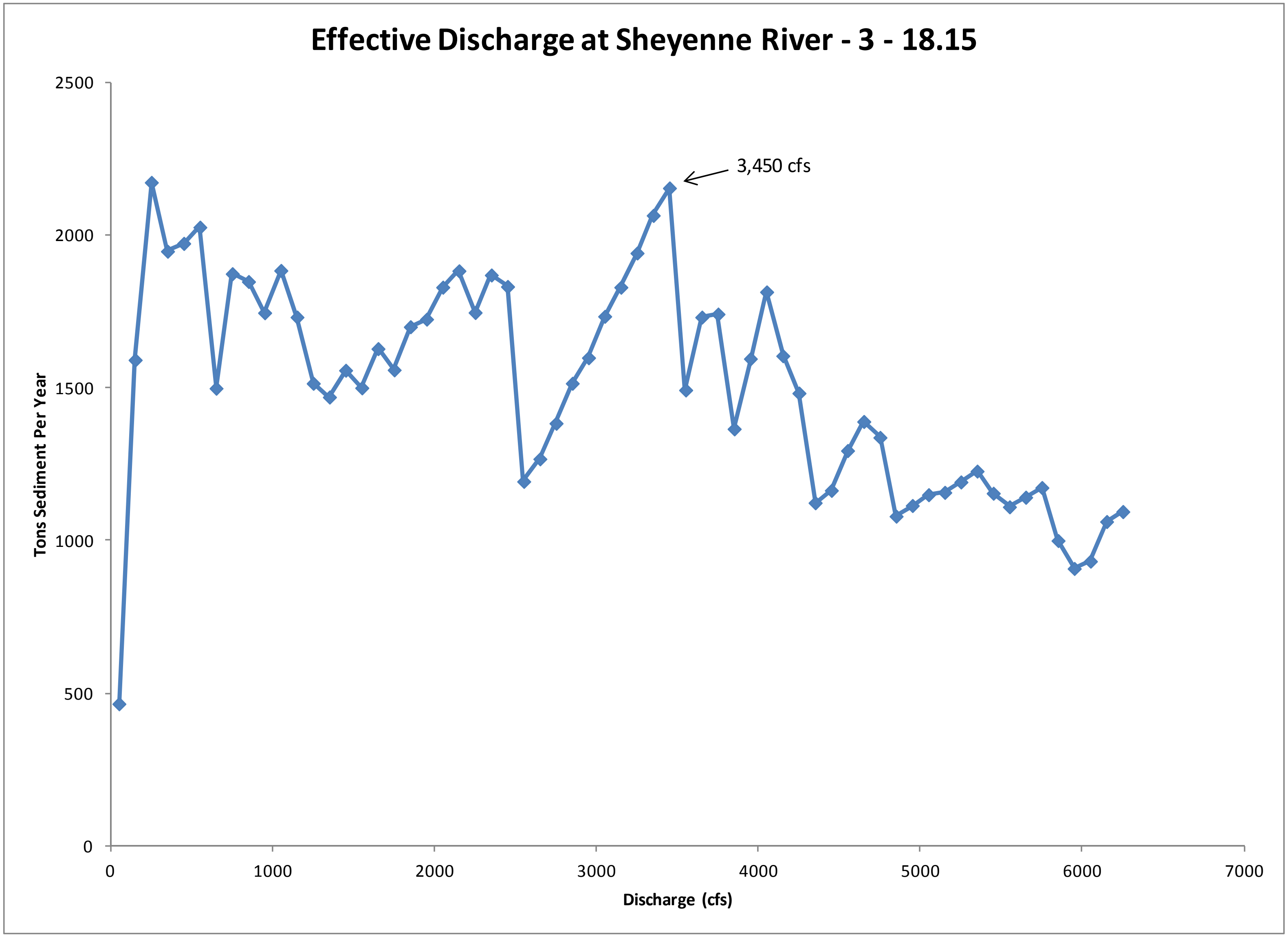


Figure 4-14. Sediment Transport Histogram for Sheyenne River – 3 – 18.15

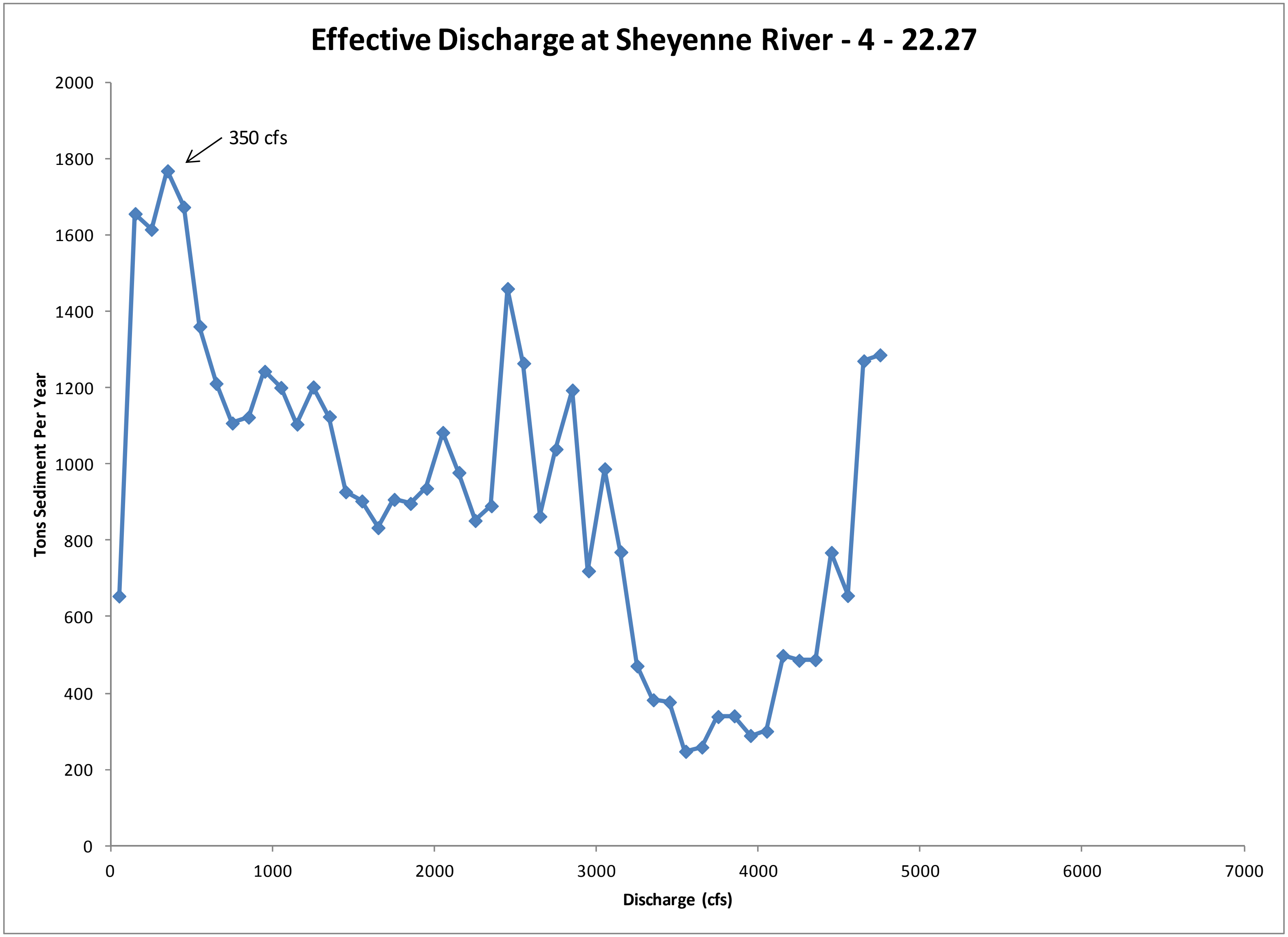


Figure 4-15. Sediment Transport Histogram for Sheyenne River – 4 – 22.27

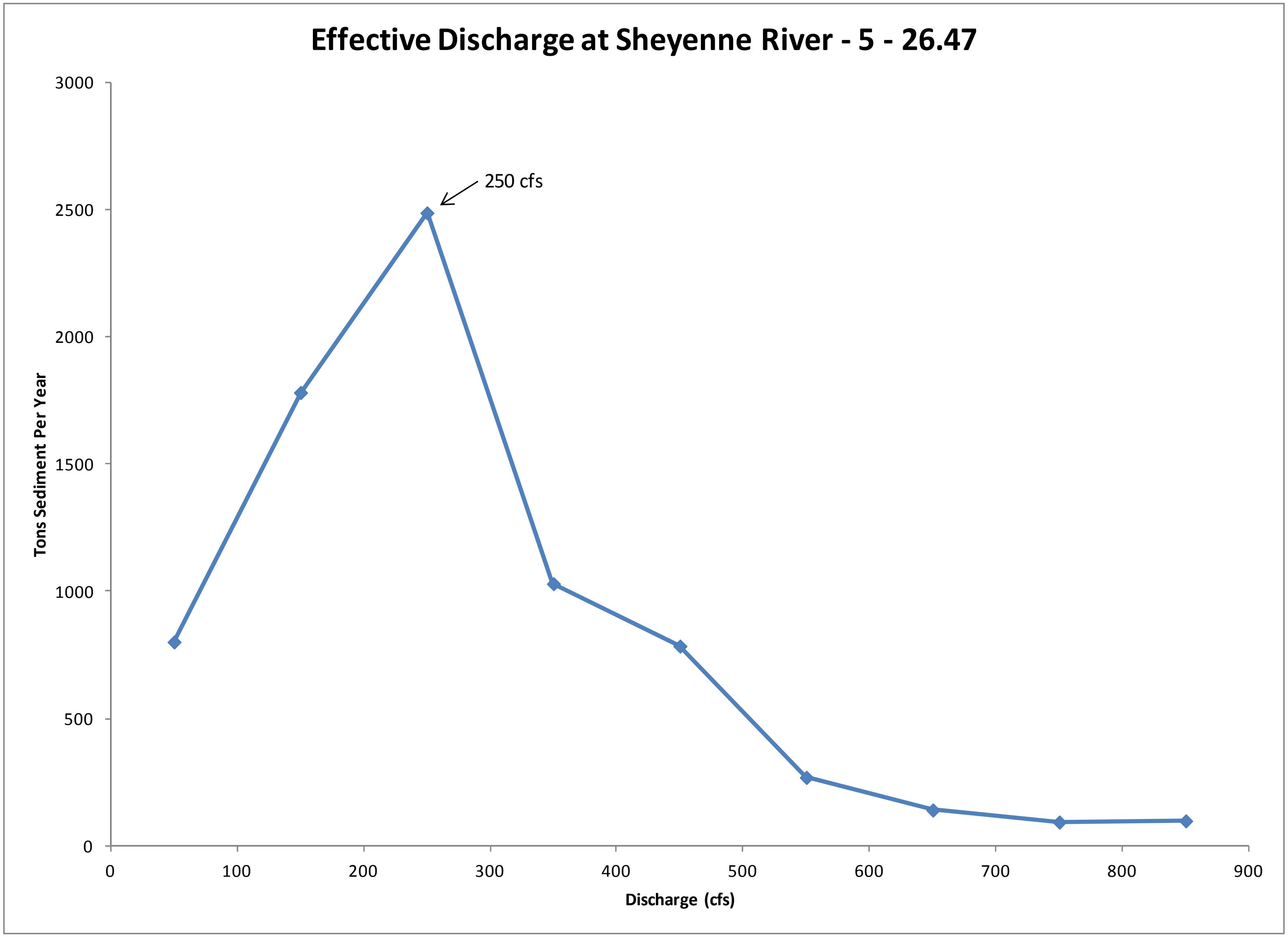


Figure 4-16. Sediment Transport Histogram for Sheyenne River – 5 – 26.47

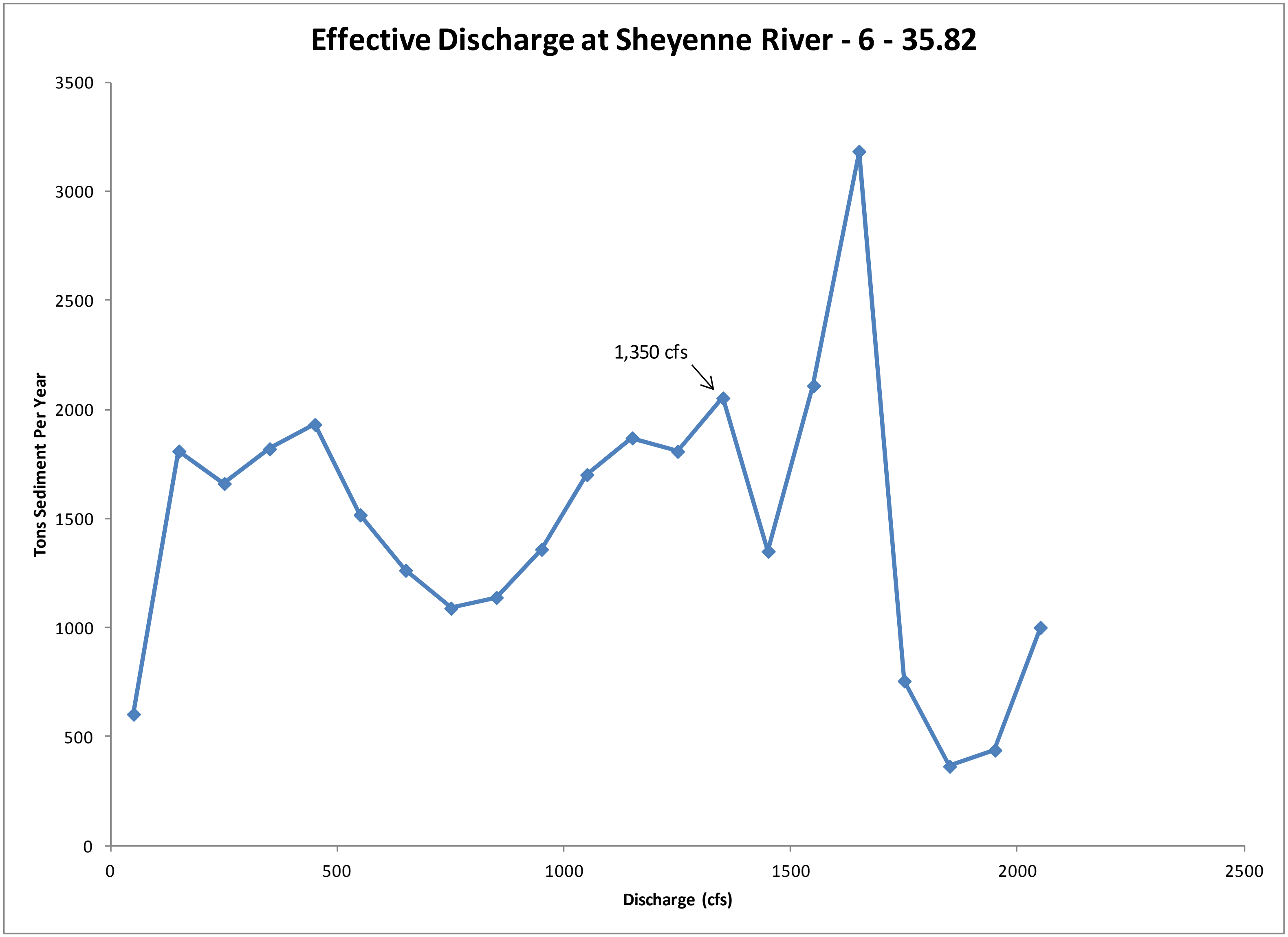


Figure 4-17. Sediment Transport Histogram for Sheyenne River – 6 – 35.82

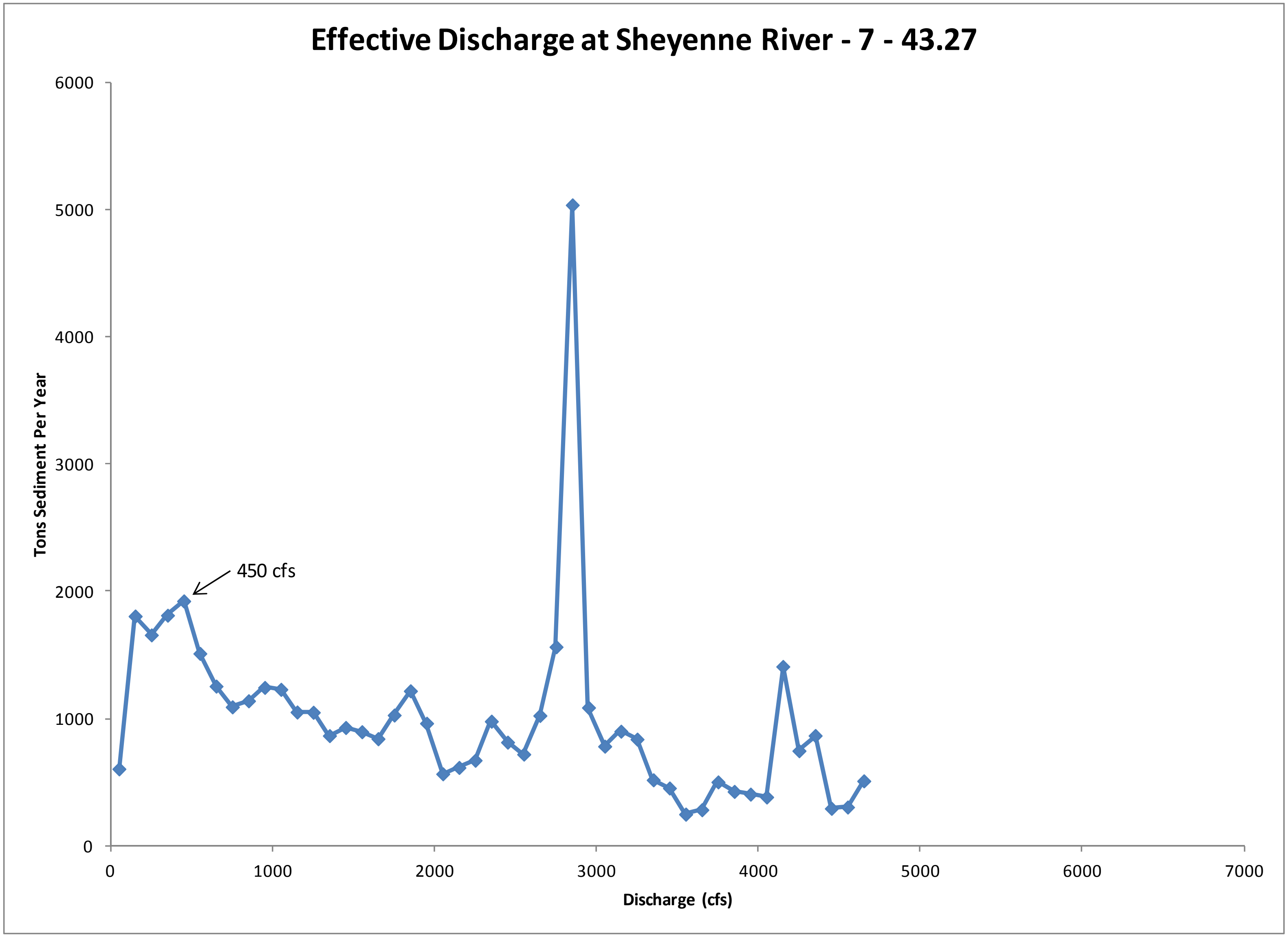


Figure 4-18. Sediment Transport Histogram for Sheyenne River – 7 – 43.27

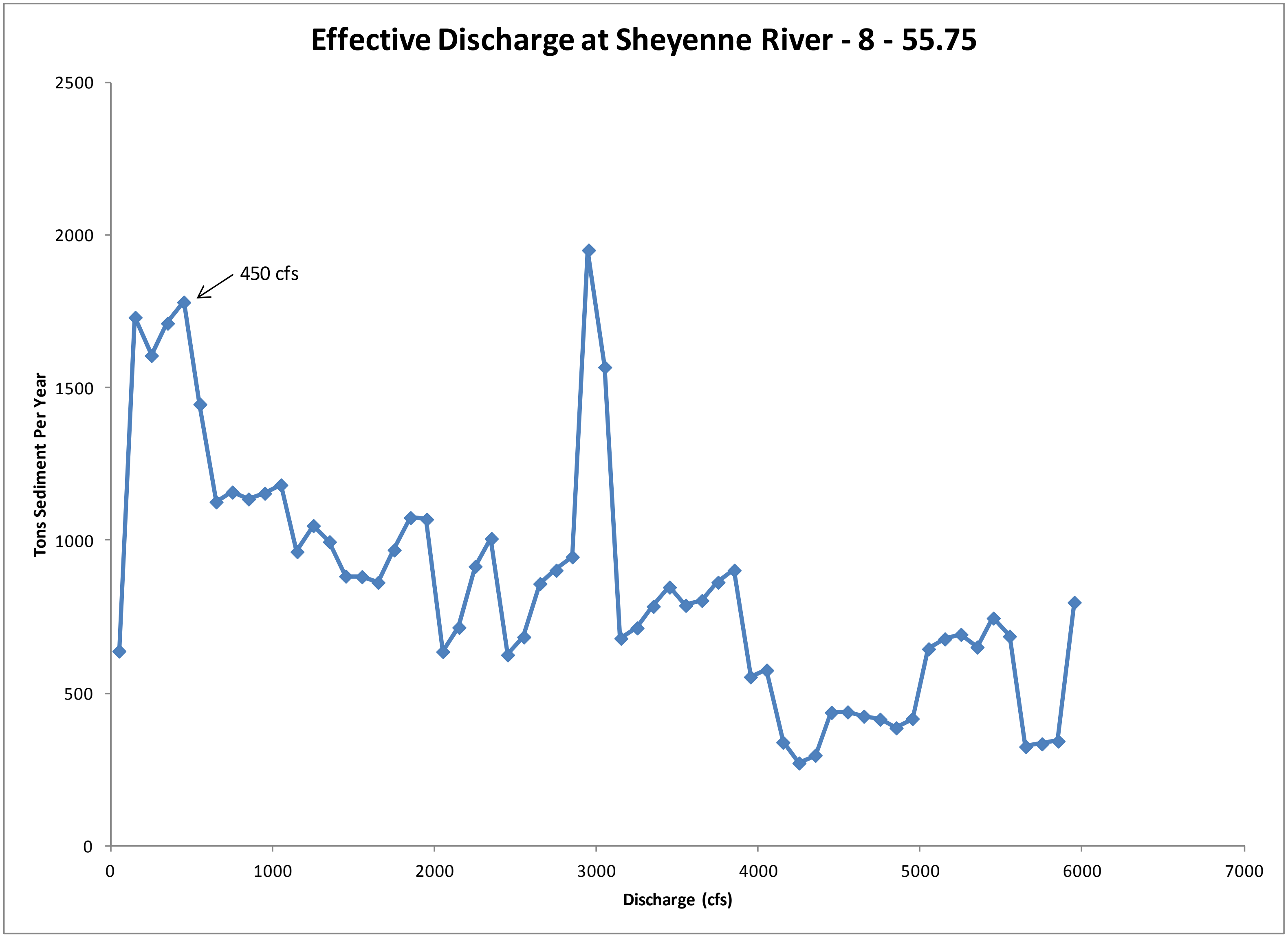


Figure 4-19. Sediment Transport Histogram for Sheyenne River – 8 – 55.75

4.2.2.3 Maple River Effective Discharge Calculations

Suspended sediment measurements were recorded at one site on the Maple River: 1) 05060100 – Maple River below Mapleton [site 5 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for the site were plotted against the average daily discharge as shown in Figure 4-20. As the suspended sediment transport plots for both the Red River and Sheyenne River indicate that the sediment transport functions developed for each of those streams is applicable throughout the entire stream, the same assumption is made for the Maple River because additional sites are not available. The equation for the suspended sediment transport rating curve developed for the Maple River is:

$$Q_{sediment} = 0.0405(Q\ )^{1.3018}\ (R^2 = 0.90)$$

The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Maple River detailed study reaches are shown in Figure 4-21 and Figure 4-22. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Maple River detailed study reaches.

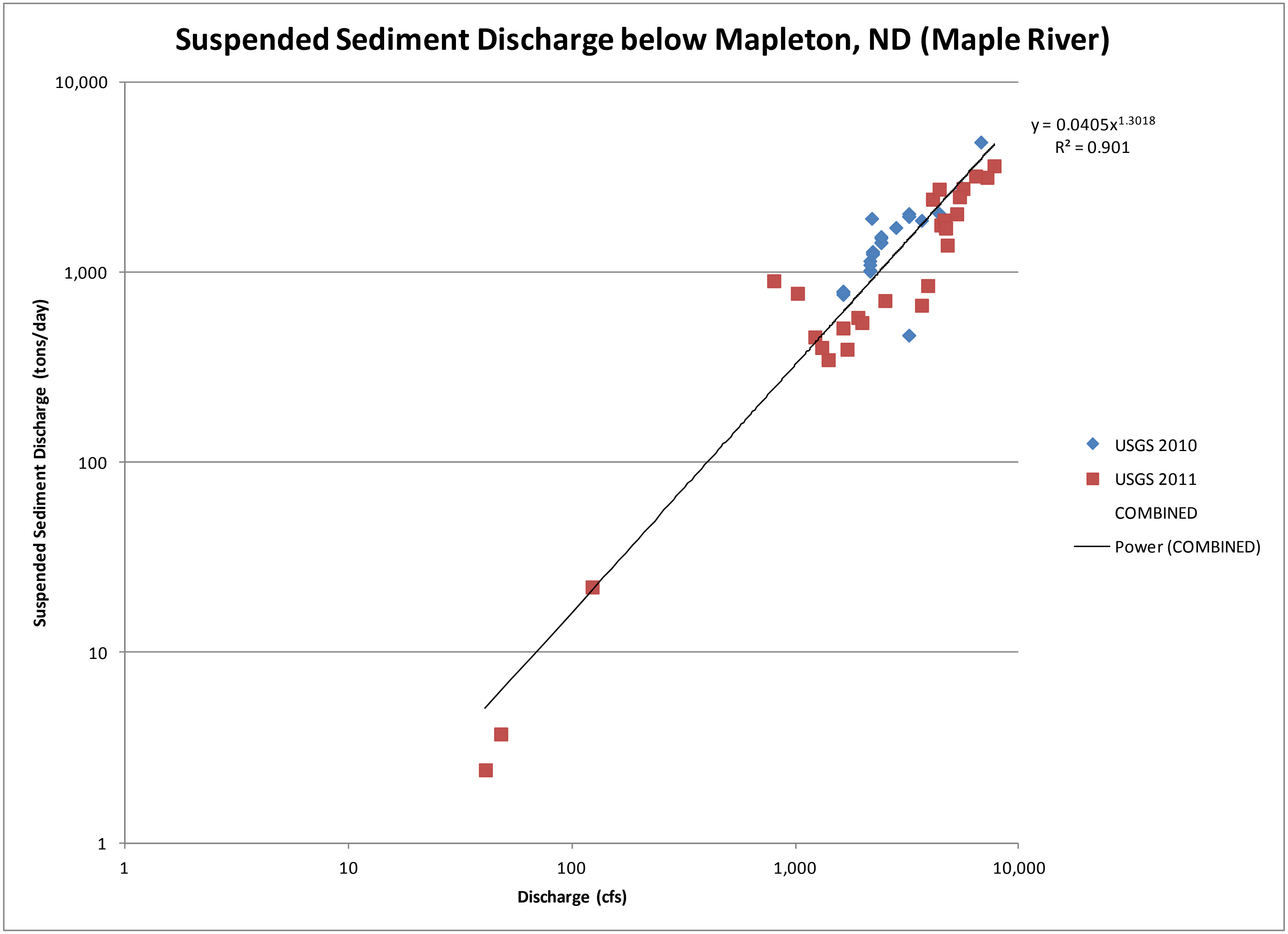


Figure 4-20. Suspended Sediment Discharge for Maple River

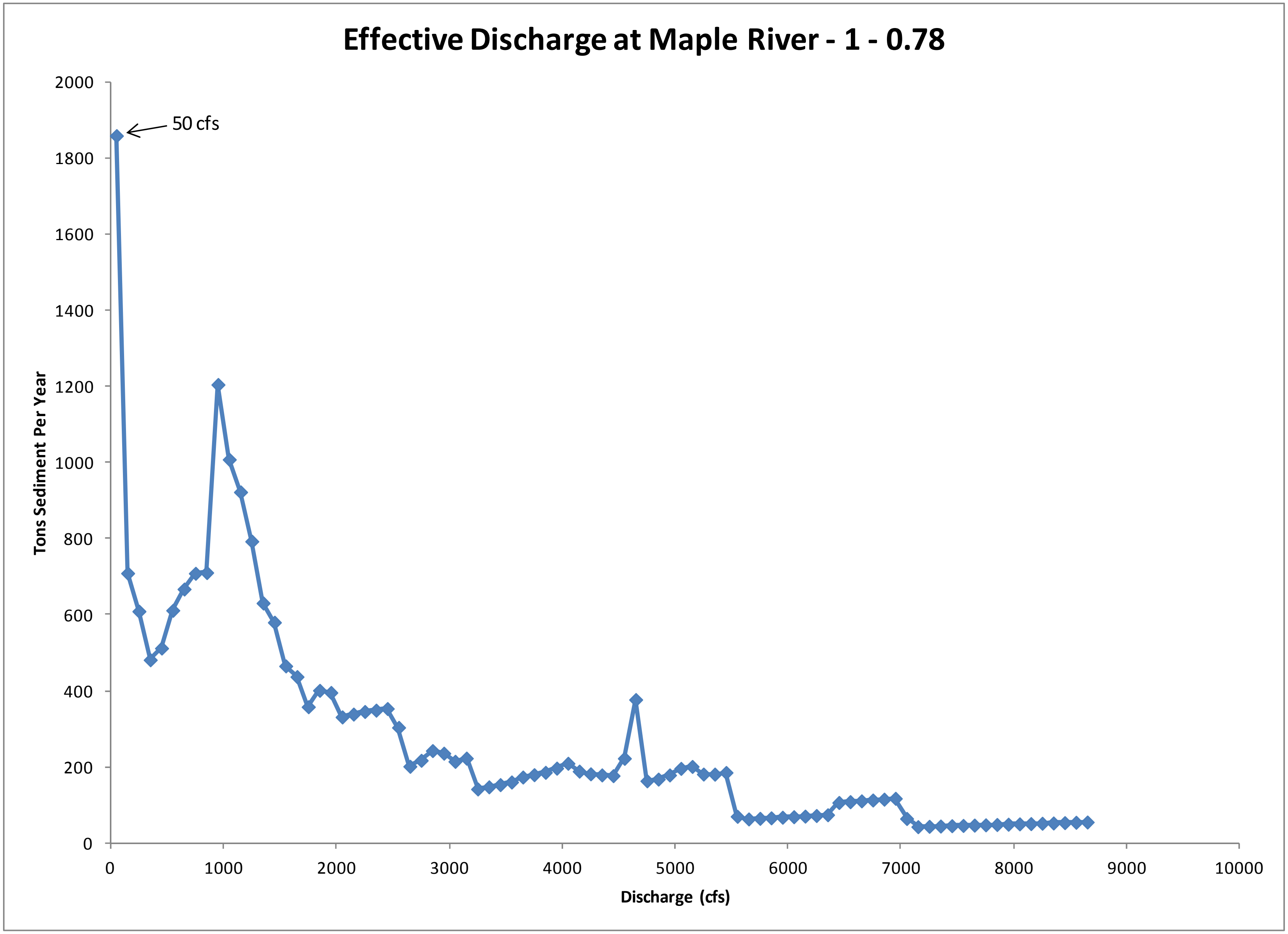


Figure 4-21. Sediment Transport Histogram for Maple River – 1 – 0.78

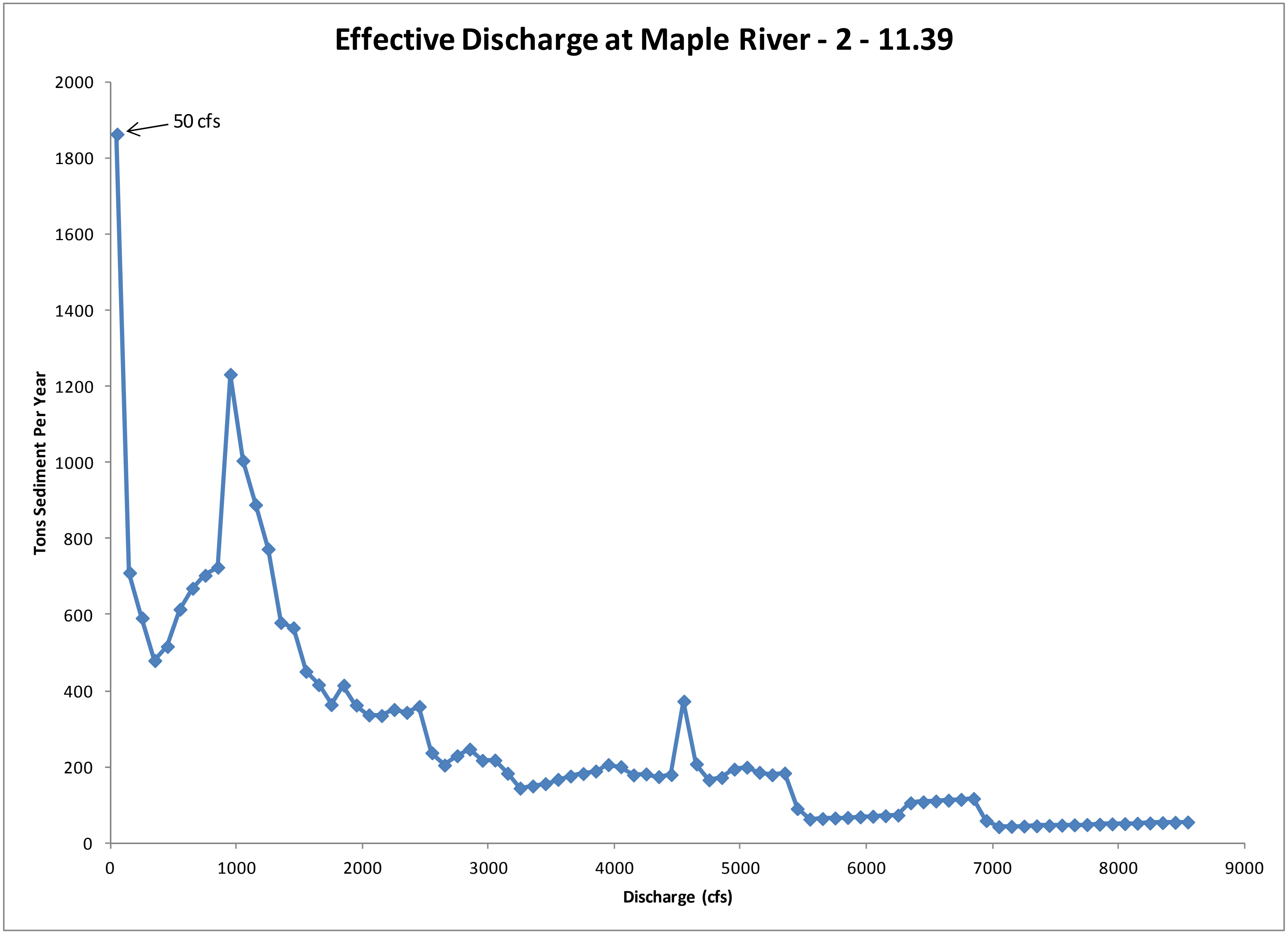


Figure 4-22. Sediment Transport Histogram for Maple River – 2 – 11.39

4.2.2.4 Wild Rice River Effective Discharge Calculations

Suspended sediment measurements were recorded at one site on the Wild Rice River: 1) 464243096495100 – Wild Rice River below near St. Benedict [site 6 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for the site were plotted against the average daily discharge as shown in Figure 4-23. As the suspended sediment transport plots for both the Red River and Sheyenne River indicate that the sediment transport functions developed for each of those streams is applicable throughout the entire stream, the same assumption is made for the Wild Rice River because additional sites are not available. The equation for the suspended sediment transport rating curve developed for the Wild Rice River is:

$$Q_{sediment} = 0.030788(Q)^{1.2531} \quad (R^2 = 0.85)$$

It is noted that suspended sediment concentration measurements were not collected below flows of 100 cfs. However, the curve is assumed applicable for all flows both within and outside of the range of measured values. As shown in Sections 4.2.2.1 and 4.2.2.2, the Red River and Sheyenne River datasets reasonably fit the derived relationship between stream and sediment discharge throughout a very wide range of flows. Therefore, it is assumed that the Wild Rice River does so as well and that the curve can be extrapolated outside of the range of measured values. The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Wild Rice River detailed study reaches are shown in Figure 4-24 through Figure 4-29. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Wild Rice River detailed study reaches.

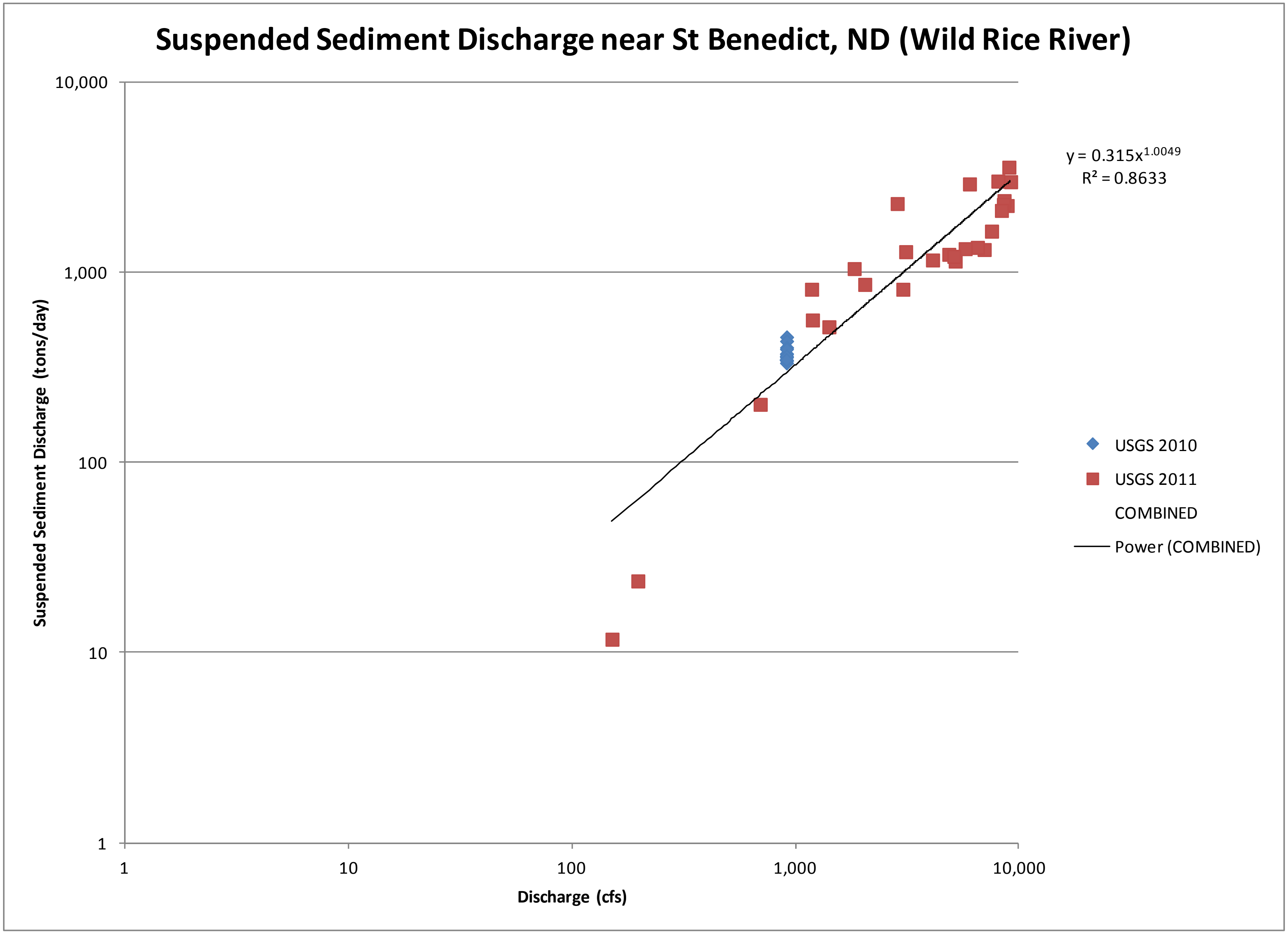


Figure 4-23. Suspended Sediment Discharge for Wild Rice River

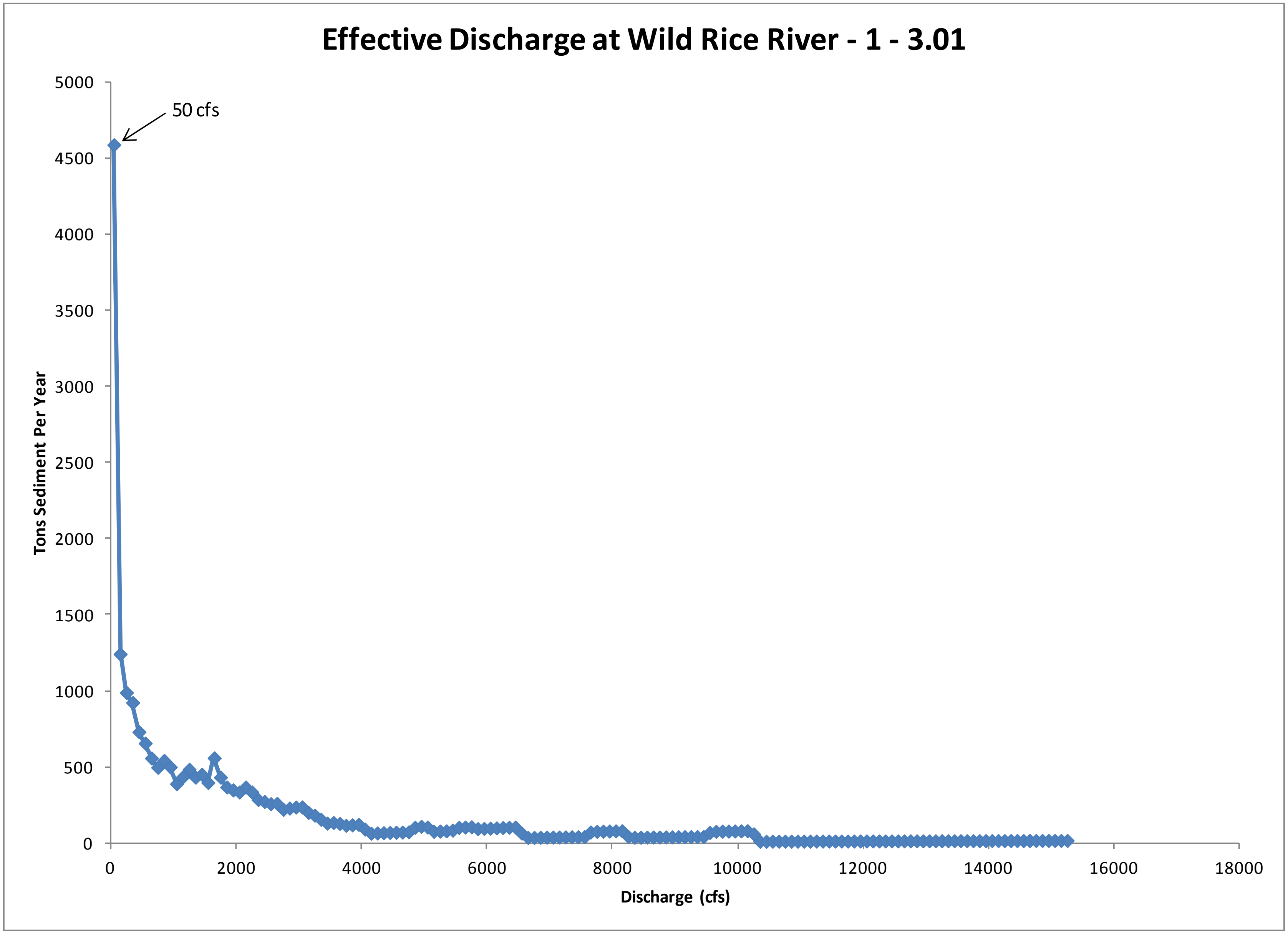


Figure 4-24. Sediment Transport Histogram for Wild Rice River – 1 – 3.01

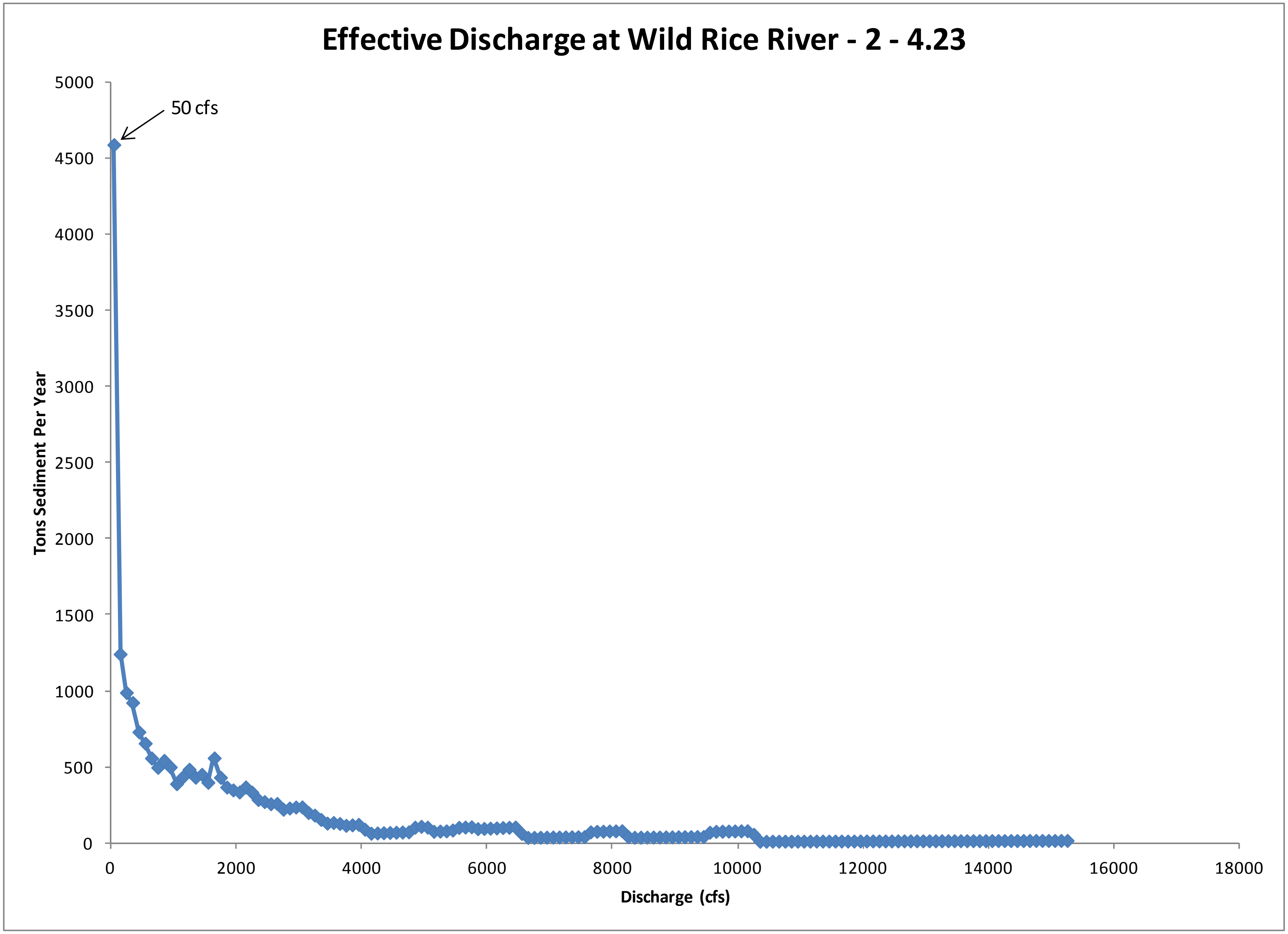


Figure 4-25. Sediment Transport Histogram for Wild Rice River – 2 – 4.23

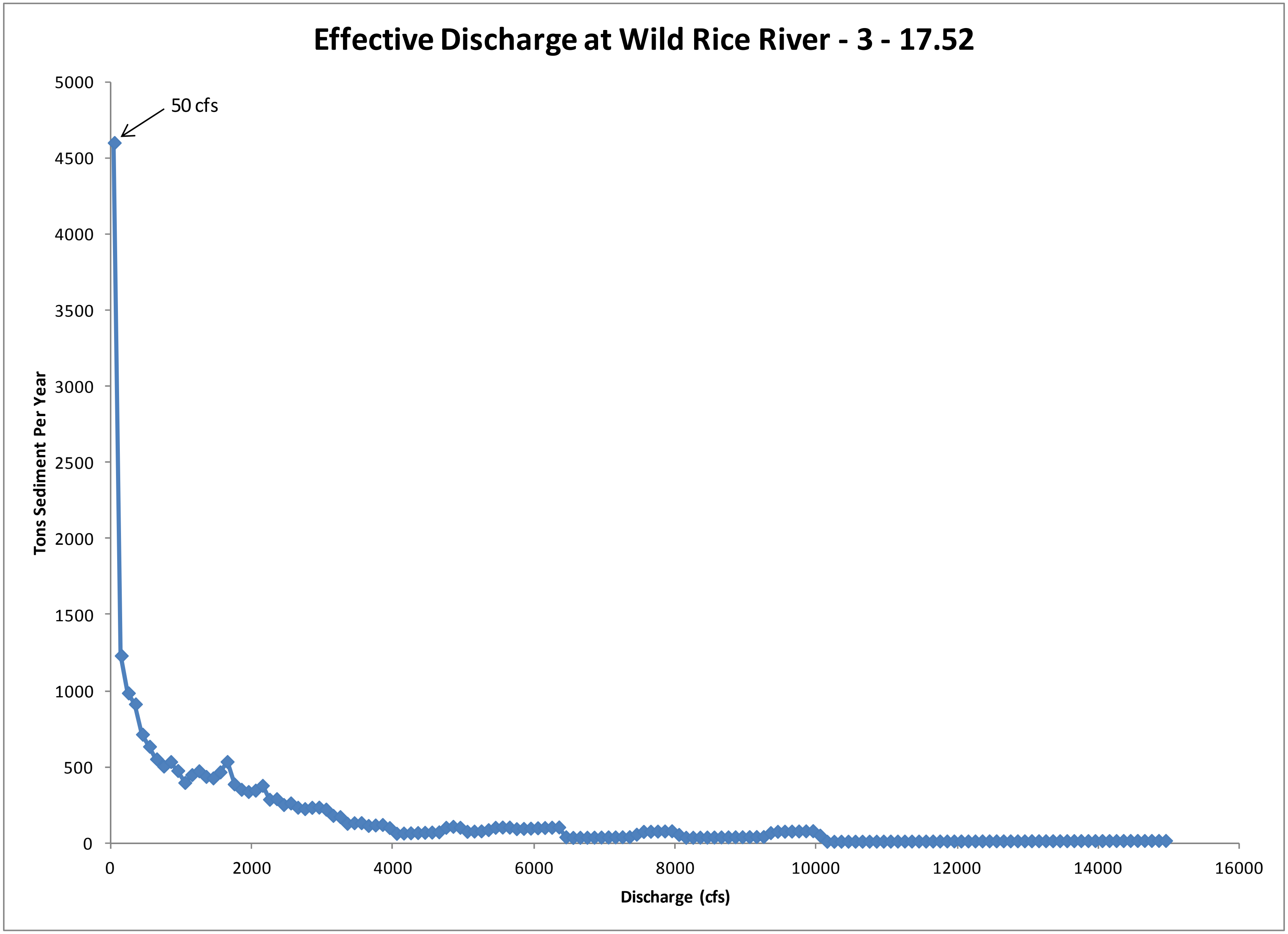


Figure 4-26. Sediment Transport Histogram for Wild Rice River – 3 – 17.52

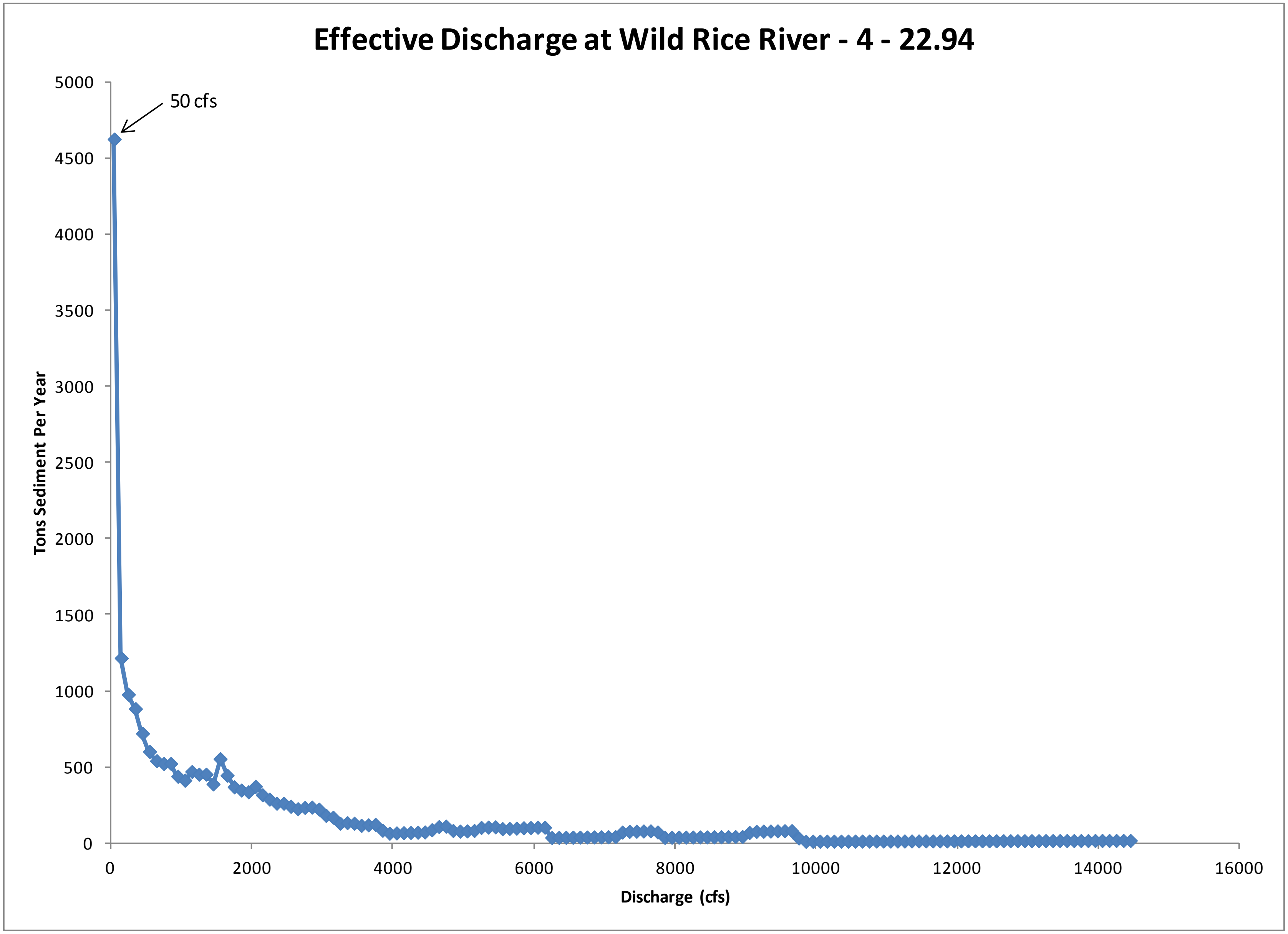


Figure 4-27. Sediment Transport Histogram for Wild Rice River – 4 – 22.94

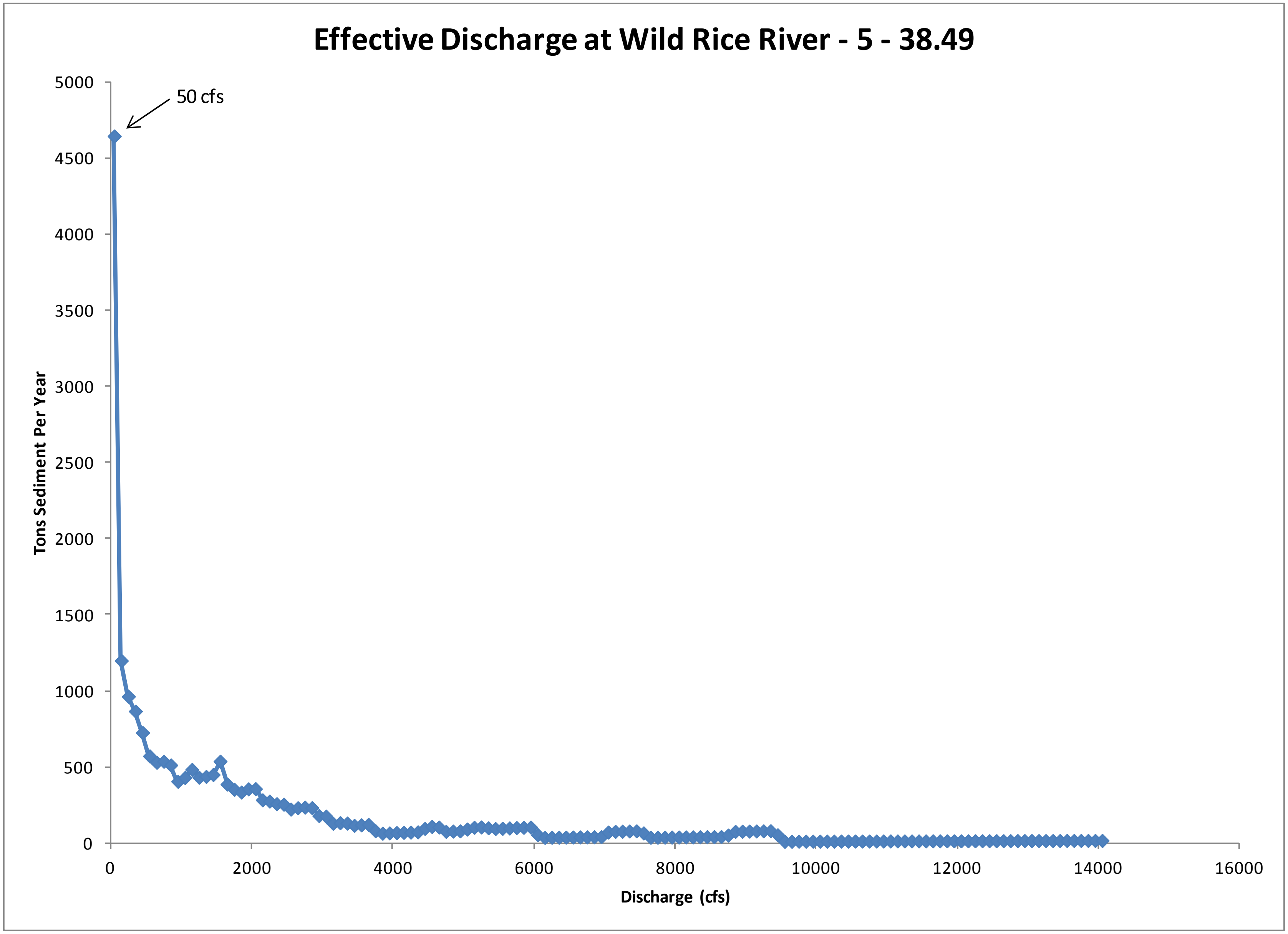


Figure 4-28. Sediment Transport Histogram for Wild Rice River – 5 – 38.49

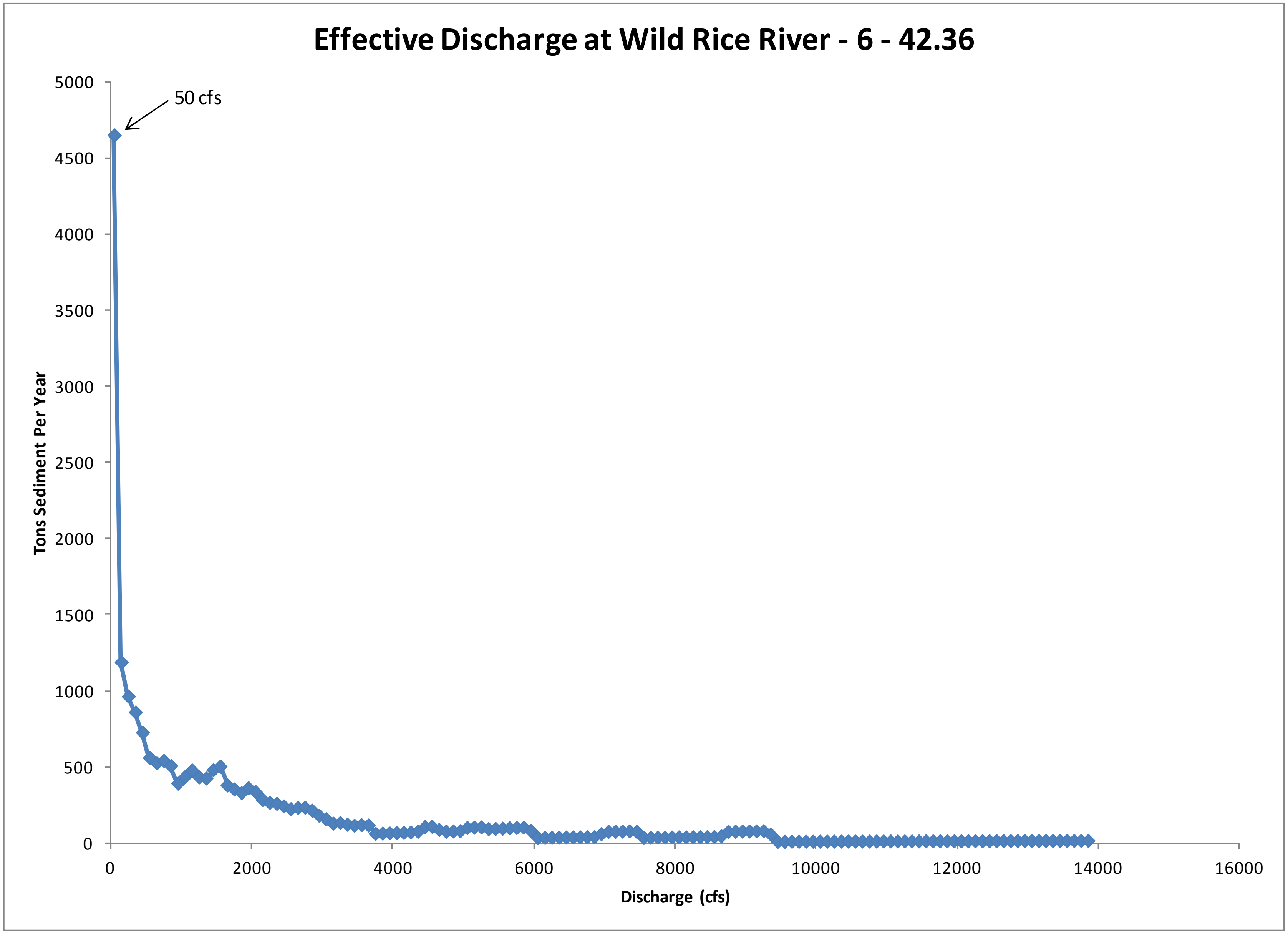


Figure 4-29. Sediment Transport Histogram for Wild Rice River – 6 – 42.36

4.2.2.5 Rush River Effective Discharge Calculations

Suspended sediment measurements were recorded at one site on the Rush River: 1) 05060550 – Rush River near Prosper [site 7 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for the site were plotted against the average daily discharge as shown in Figure 4-30. As the suspended sediment transport plots for both the Red River and Sheyenne River indicate that the sediment transport functions developed for each of those streams is applicable throughout the entire stream, the same assumption is made for the Rush River because additional sites are not available. The equation for the suspended sediment transport rating curve developed for the Rush River is:

$$Q_{sediment} = 0.030788(Q\ )^{1.2531}\ (R^2 = 0.85)$$

The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Rush River detailed study reaches are shown in Figure 4-31 and Figure 4-32. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Rush River detailed study reaches.

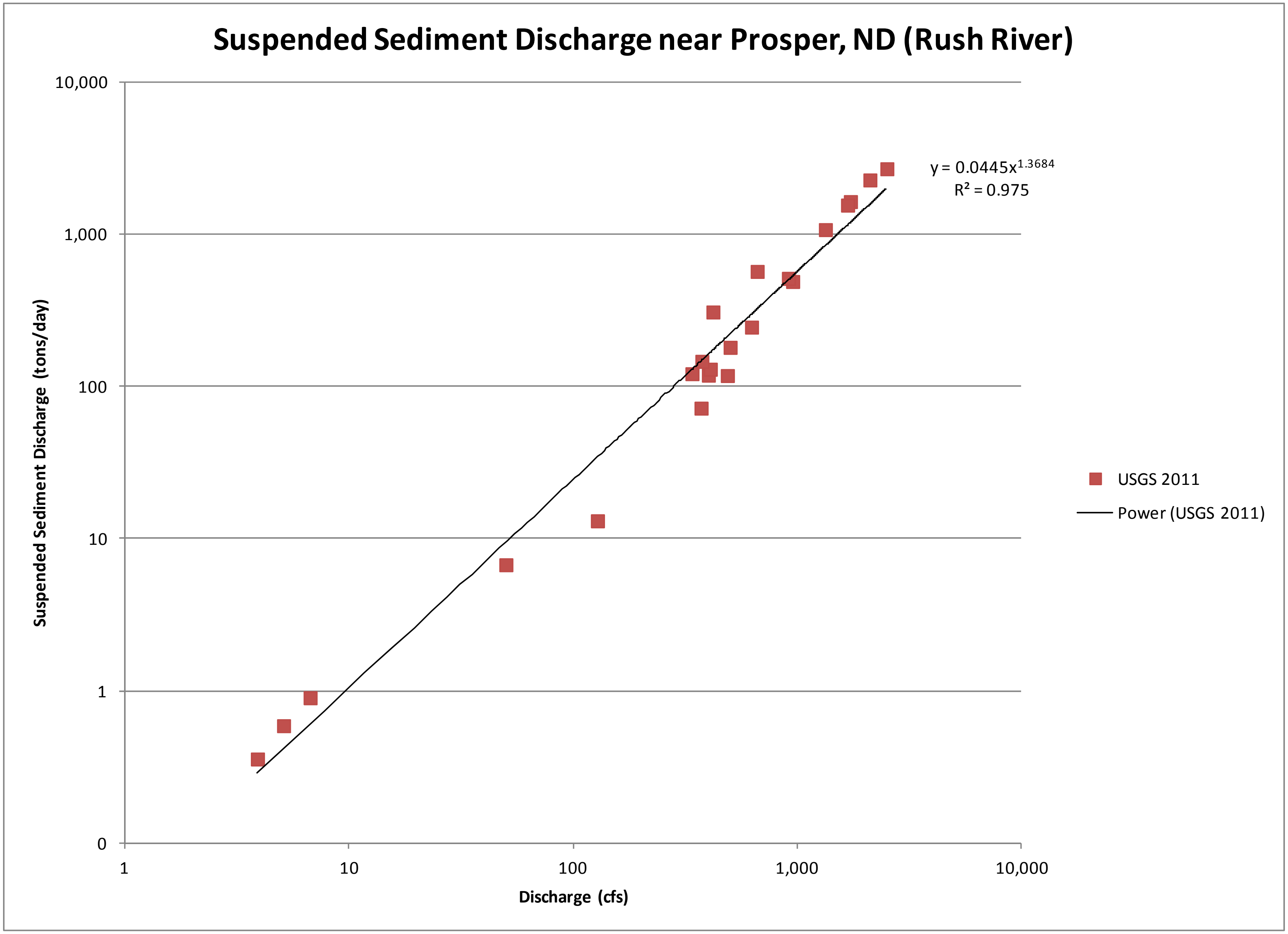


Figure 4-30. Suspended Sediment Discharge for Rush River

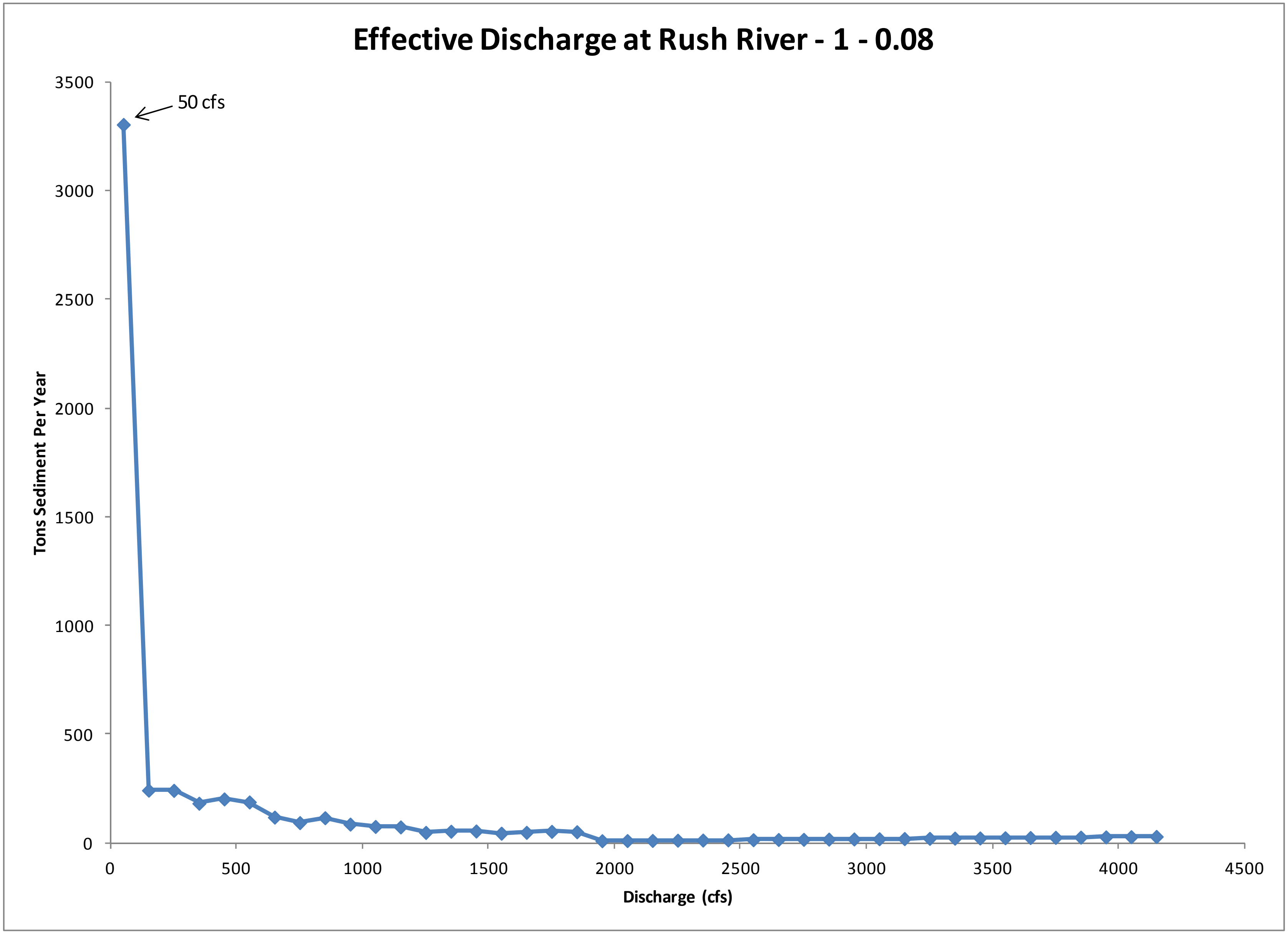


Figure 4-31. Sediment Transport Histogram for Rush River – 1 – 0.08

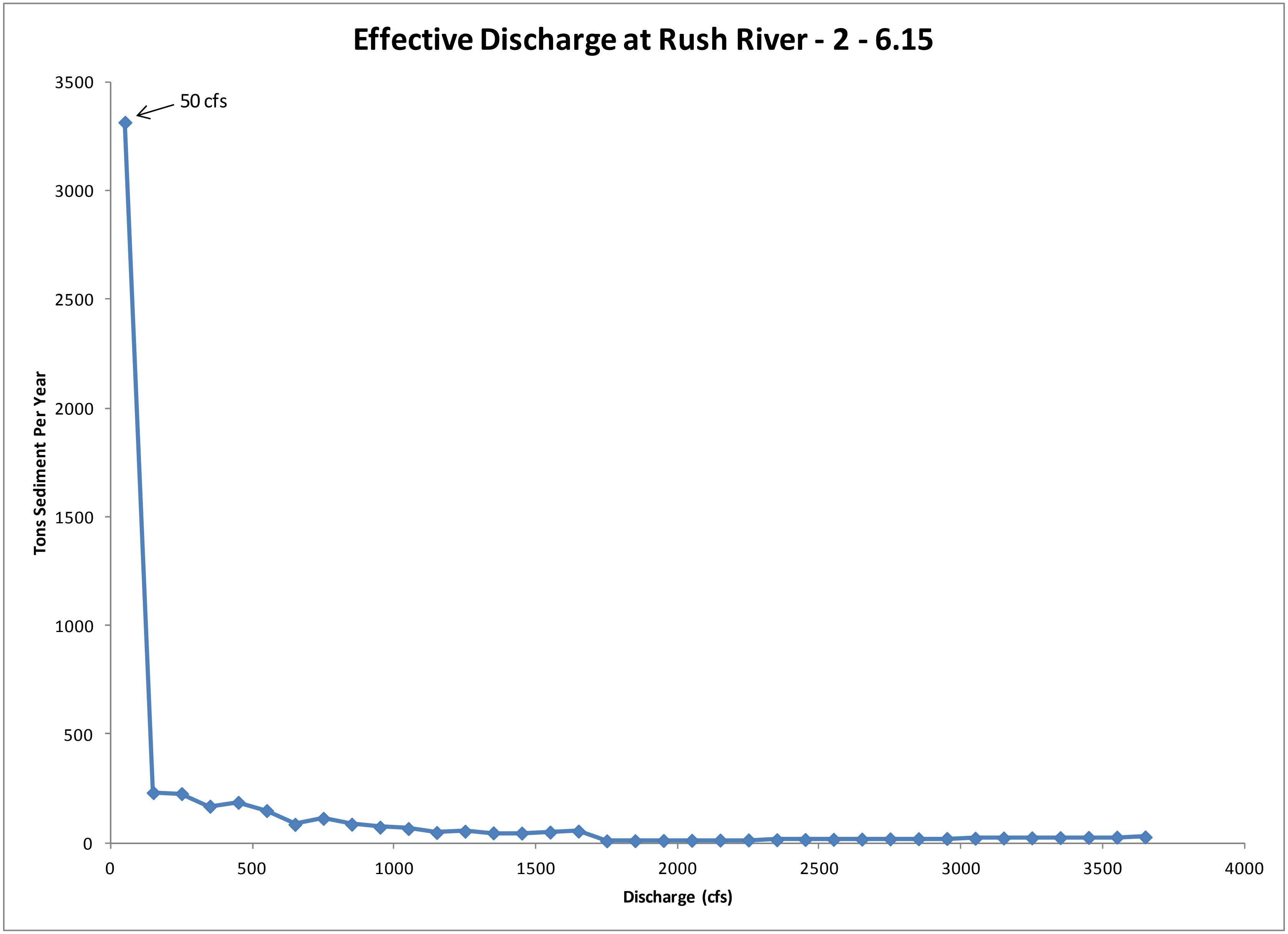


Figure 4-32. Sediment Transport Histogram for Rush River – 2 – 6.15

4.2.2.6 Lower Rush River Effective Discharge Calculations

Suspended sediment measurements were recorded at one site on the Lower Rush River: 1) 465752096573000 – Lower Rush River east of Prosper [site 8 in USGS (2011b) sediment sampling report]. The suspended sediment transport rates for the site were plotted against the average daily discharge as shown in Figure 4-33. As the suspended sediment transport plots for both the Red River and Sheyenne River indicate that the sediment transport functions developed for each of those streams is applicable throughout the entire stream, the same assumption is made for the Lower Rush River because additional sites are not available. The equation for the suspended sediment transport rating curve developed for the Lower Rush River is:

$$Q_{sediment} = 0.030788(Q\ )^{1.2531}\ (R^2 = 0.85)$$

The discharge-duration curves, calculated for each detailed study reach as outlined in Section 4.4.1.1, were used to determine the duration of each 100 cfs interval, which in turn was used to calculate the sediment transport histogram for each detailed study reach. The sediment transport histograms for the Lower Rush River detailed study reaches are shown in Figure 4-34 and Figure 4-35. The discharge at which the maximum amount of sediment transport occurred is considered the effective discharge. Table 4-3 on page 4-46 summarizes the results of the effective discharge method for the Lower Rush River detailed study reaches.

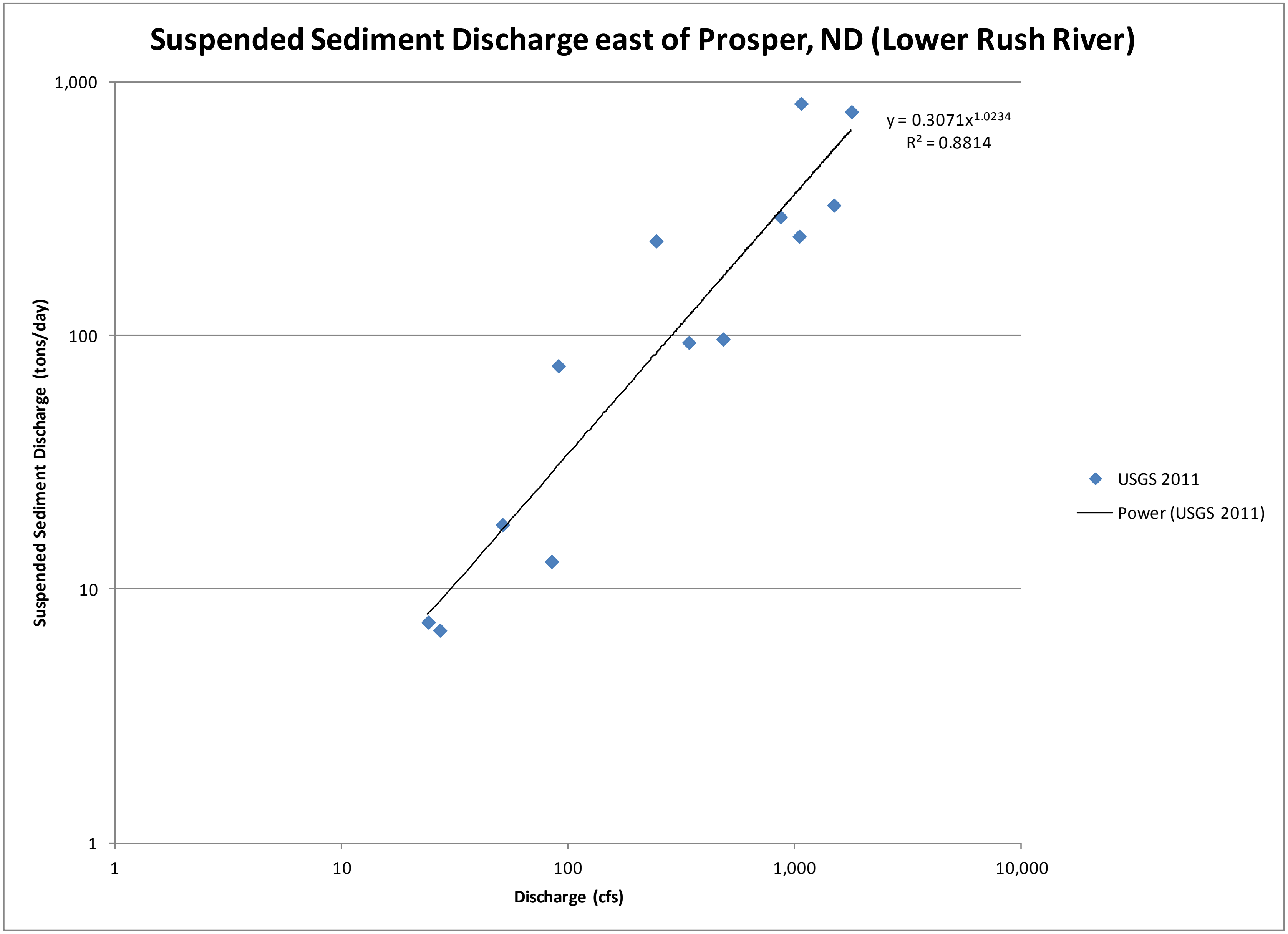


Figure 4-33. Suspended Sediment Discharge for Lower Rush River Site

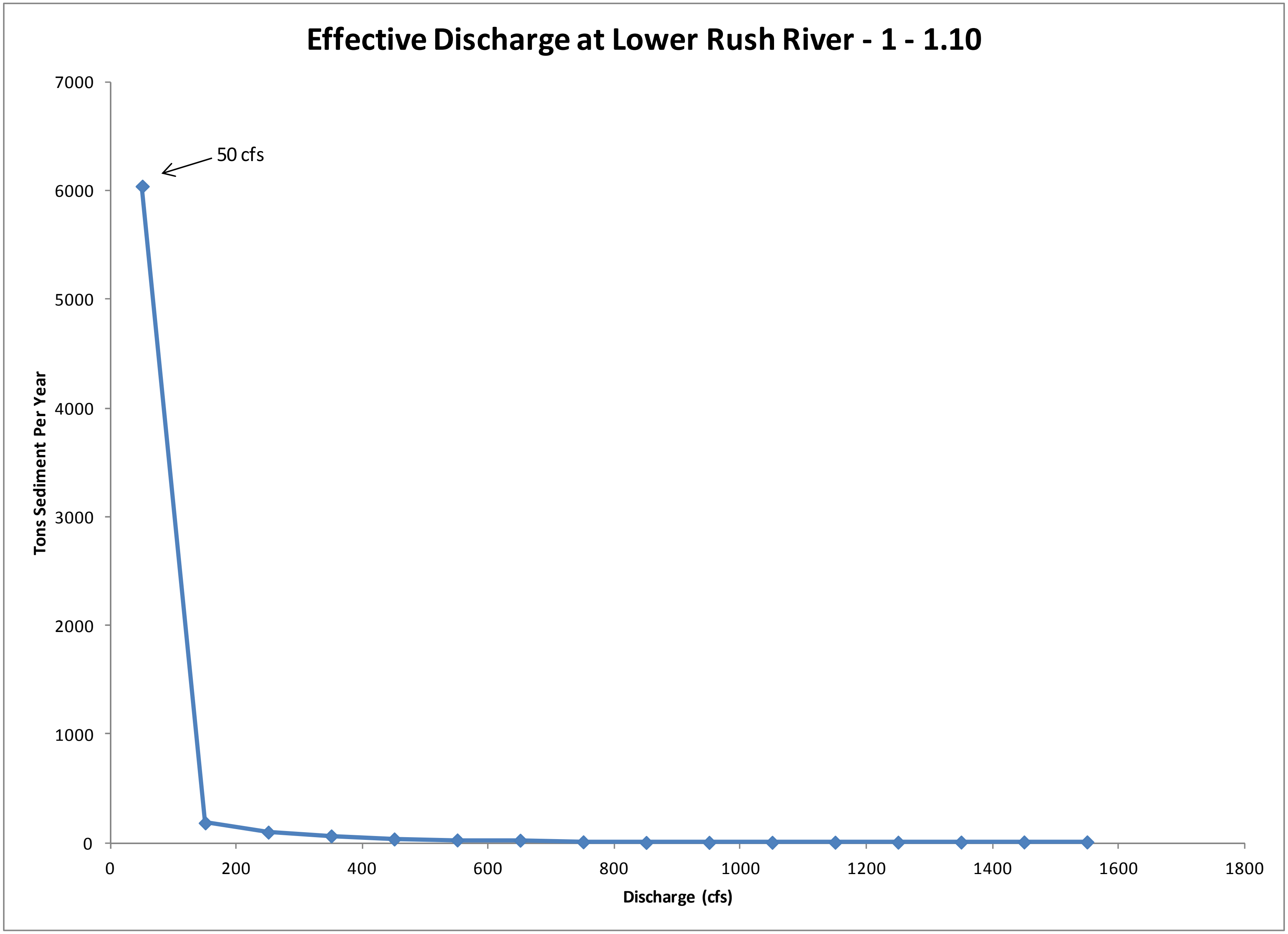


Figure 4-34. Sediment Transport Histogram for Lower Rush River – 1 – 1.10

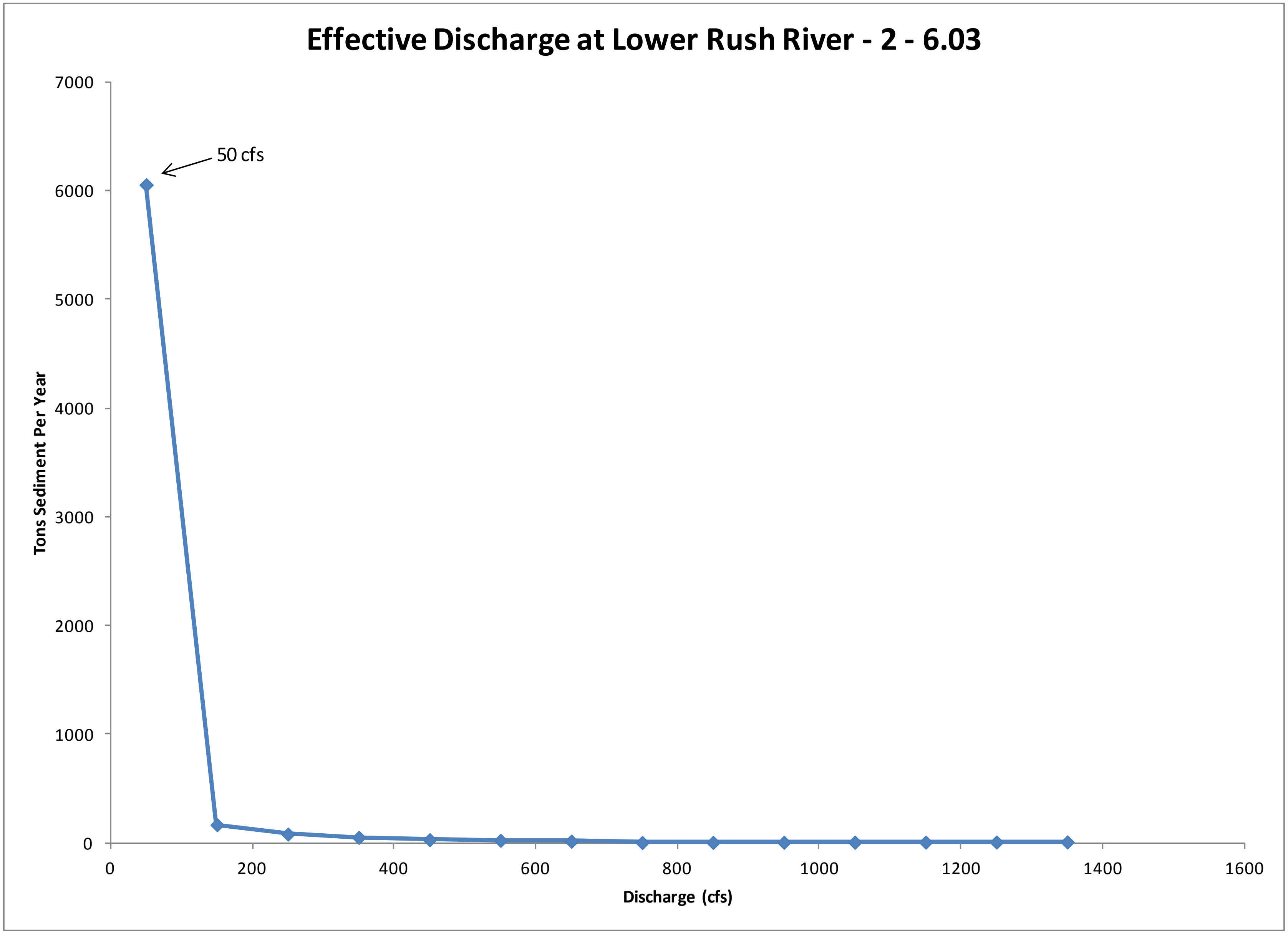


Figure 4-35. Sediment Transport Histogram for Lower Rush River – 2 – 6.03

4.2.2.7 Effective Discharge Calculations Summary

The results of the effective discharge method are shown in Table 4-3. In general, the ratios of the channel-forming discharge using the effective discharge method to the contributing drainage area are not consistent within the system. This is attributed to the fact that the streams within the study area are considered supply-limited streams. They are generally able to transport all of the fine sediment that is supplied to them. As a result, there is not a direct and consistent correlation between water discharge and sediment discharge. The amount of material being transported by the stream is directly related to the amount of sediment that is supplied to the stream and does not reflect the capacity of the stream to transport sediment. This produces inconsistencies in the results provided by the effective discharge method.

Table 4-3. Channel-Forming Discharges Using the Effective Discharge Method

Type	Location	Discharge (cfs)	Discharge Per Area (cfs/mi^2)
Detailed Reach	Lower Rush River-1-1.10	50	0.84
Detailed Reach	Lower Rush River-2-6.03	50	0.94
Detailed Reach	Maple River-1-0.78	50	0.03
Detailed Reach	Maple River-2-11.39	50	0.03
Detailed Reach	Red River-1-410.65	750	0.06
Detailed Reach	Red River-2-419.14	750	0.07
Detailed Reach	Red River-3-440.57	450	0.08
Detailed Reach	Red River-4-452.52	450	0.08
Detailed Reach	Red River-5-463.56	450	0.08
Detailed Reach	Red River-6-470.23	450	0.13
Detailed Reach	Red River-7-492.47	450	0.13
Detailed Reach	Red River-8-521.18	450	0.13
Detailed Reach	Rush River-1-0.08	50	0.32
Detailed Reach	Rush River-2-6.15	50	0.36
Detailed Reach	Sheyenne River-1-4.20	3,750	0.71
Detailed Reach	Sheyenne River-2-11.56	3,550	0.70
Detailed Reach	Sheyenne River-3-18.15	3,450	0.69
Detailed Reach	Sheyenne River-4-22.27	350	0.10
Detailed Reach	Sheyenne River-5-26.47	250	0.07
Detailed Reach	Sheyenne River-6-35.82	1,350	0.39
Detailed Reach	Sheyenne River-7-43.27	450	0.13
Detailed Reach	Sheyenne River-8-55.75	450	0.13
Detailed Reach	Wild Rice River-1-3.01	50	0.02
Detailed Reach	Wild Rice River-2-4.23	50	0.02
Detailed Reach	Wild Rice River-3-17.52	50	0.03
Detailed Reach	Wild Rice River-4-22.94	50	0.03
Detailed Reach	Wild Rice River-5-38.49	50	0.03
Detailed Reach	Wild Rice River-6-42.36	50	0.03

4.2.3 Recurrence Interval Method

Recurrence intervals were estimated for the bankfull and effective discharges to compare with published values for similar streams. The recurrence interval analysis uses the annual maximum flood series to predict discharges for various recurrence intervals. The recurrence intervals of the bankfull and effective discharges were estimated by log interpolation, as shown in the following equation:

$$RI_{CF} = RI_{MF} * 10\wedge\left[\frac{(Q_{CF} - Q_{MF})}{(Q_{LF} - Q_{MF})} * log\left(\frac{RI_{LF}}{RI_{MF}}\right)\right]$$

where RI_i is the recurrence interval (i.e., 1.13-year) for the specified event and Q_i is the discharge (cfs) for the specified event. The subscript CF denotes channel-forming, MF denotes the bounding more frequent event (i.e., 1.11-year), and LF denotes the bounding less frequent event (i.e., 1.25-year). The discharges for the bounding events used in the log interpolation were calculated using values provided by the St. Paul District.

Table 4-4 summarizes the recurrence intervals estimated for the bankfull and effective discharges for each detailed study reach. The average recurrence interval of the bankfull discharge in the study area is 1.28 years, ranging from 1.05 to 1.67 years, while the average recurrence interval of the effective discharge method is 1.19 years, ranging from <1.01 to 2.19 years.

Two recent studies completed in the Upper Midwest have identified channel-forming recurrence intervals ranging from 1.0 year to 1.7 years (Haucke and Clancy, 2011; Johnson and Padmanabhan, 2010). The study by Haucke and Clancy (2011) focused on relatively small streams (maximum bankfull flow rate of approximately 900 cfs) in southwestern Wisconsin. The average channel-forming discharge recurrence interval as determined in the study is 1.1 years, with recurrence intervals ranging from 1.0 to 1.4 years. The study by Johnson and Padmanabhan (2010) focused on relatively small streams (maximum bankfull flow of approximately 1,200 cfs) in the Red River basin. The average channel-forming discharge recurrence interval in this study is 1.46 years, with recurrence intervals ranging from 1.26 years to 1.70 years. While the Johnson and Padmanabhan (2010) study focused on streams within the Red River basin, the studied stream locations were not located within the current study area.

However, other investigations have found that less frequent events, such as the 1.5-year or 2-year recurrence interval floods are a good approximation of channel-forming discharge (e.g., Dunne and Leopold, 1978; Bray, 1982). In these studies, bed material is mobilized during larger, less frequent flood events, contributing significantly to changes in channel geometry. In these streams, the larger the flood event, the larger the amount of bedload transport. Therefore, large floods dominate the overall shape of the channel in bedload streams, as reflected in the larger channel-forming discharge recurrence intervals.

Table 4-4. Channel-Forming Discharge Method Comparison for Current Conditions

Identifier	Bankfull Discharge Method		Effective Discharge Method	
	Discharge (cfs)	Recurrence Interval (yrs)	Discharge (cfs)	Recurrence Interval (yrs)
Buffalo River-1-1.19	420	1.05	1/	1/
Lower Rush River-1-1.10	65	1.13	50	1.09
Lower Rush River-2-6.03	60	1.13	50	1.10
Maple River-1-0.78	650	1.16	50	<1.01
Maple River-2-11.39	650	1.16	50	<1.01
Red River-1-410.65	4,700	1.19	750	<1.01
Red River-2-419.14	4,280	1.21	750	<1.01
Red River-3-440.57	2,380	1.26	450	1.01
Red River-4-452.52	2,380	1.26	450	1.01
Red River-5-463.56	2,380	1.27	450	1.01
Red River-6-470.23	1,780	1.25	450	1.01
Red River-7-492.47	1,650	1.23	450	1.02
Red River-8-521.18	1,650	1.23	450	1.02
Rush River-1-0.08	150	1.21	50	1.05
Rush River-2-6.15	150	1.23	50	1.05
Sheyenne River-1-4.20	1,900	1.47	3,750	2.17
Sheyenne River-2-11.56	1,750	1.45	3,550	2.17
Sheyenne River-3-18.15	1,680	1.44	3,450	2.19
Sheyenne River-4-22.27	1,030	1.50	350	1.08
Sheyenne River-5-26.47	2/	2/	250	1.05
Sheyenne River-6-35.82	860	1.38	1,350	1.82
Sheyenne River-7-43.27	1,200	1.67	450	1.11
Sheyenne River-8-55.75	1,000	1.50	450	1.12
Wild Rice River-1-3.01	600	1.31	50	1.01
Wild Rice River-2-4.23	600	1.31	50	1.01
Wild Rice River-3-17.52	517	1.26	50	1.01
Wild Rice River-4-22.94	517	1.27	50	1.01
Wild Rice River-5-38.49	517	1.28	50	1.01
Wild Rice River-6-42.36	517	1.28	50	1.01
Wolverton Creek-1-0.64	130	1.14	1/	1/
Wolverton Creek-2-2.02	130	1.15	1/	1/

1/ Effective discharge method could not be used given the lack of available data.

2/ Bankfull discharge could not be calculated due to modeling uncertainties.

In contrast, the streams within the Red River Basin primarily transport material as suspended load, much of which originates from the adjacent floodplains. While large floods do occur in the Red River Basin streams, these floods do not have the same ability to shape the stream channels in the same manner as the bedload-dominated streams. As discussed in Section 4.2.2, the channel boundary materials are resistant to erosion. Additionally, large floods occurring in the Red River Basin typically occur because of snowmelt or rain on snow runoff. Because the northward-flowing streams encounter ice jams, the large floods in the Red River Basin cannot generate the same high velocities necessary to mobilize sediments and shape channels. Therefore, the limited impact of large floods on the shape of the channels in the Red River Basin is reflected in the relatively small channel-forming discharge recurrence intervals.

4.2.4 Channel-Forming Discharge for Current Conditions Summary

The bankfull discharge and effective discharge methods were used to estimate the channel-forming discharge for the detailed study reaches. Recurrence intervals were estimated for the results and compared to published values to evaluate the applicability of each method. Nearly all of the recurrence intervals for the bankfull and effective discharges are within the range of values (1.0 to 1.7 years) published in two recently completed studies for Upper Midwest streams. However, the effective discharge recurrence interval values are situated at the extremes of this range. In addition, there is a lack of a consistent increase in discharge from upstream to downstream, as would be expected with increasing contributing drainage area. Further, the supply limited nature of the study streams and lack of significant bedload transport limits the applicability of the effective discharge method. The recurrence intervals for the bankfull discharges are generally situated near the average of the published range of values. The bankfull discharge method is generally more consistent with other published studies and appears to have greater applicability for estimating channel-forming discharge. Table 4-5 summarizes the results of the channel-forming discharge for each study reach.

Table 4-5. Channel-Forming Discharges and Recurrence Intervals for Current Conditions

Identifier	Bankfull Discharge Method	
	Discharge (cfs)	Recurrence Interval (yrs)
Buffalo River-1	420	1.05
Lower Rush River-1	65	1.13
Lower Rush River-2	60	1.13
Maple River-1	650	1.16
Maple River-2	650	1.16
Red River-1	4,700	1.19
Red River-2	4,280	1.21
Red River-3	2,380	1.26
Red River-4	2,380	1.26
Red River-5	2,380	1.27
Red River-6	1,780	1.25
Red River-7	1,650	1.23
Red River-8	1,650	1.23
Rush River-1	150	1.21
Rush River-2	150	1.23
Sheyenne River-1	1,900	1.47
Sheyenne River-2	1,750	1.45
Sheyenne River-3	1,680	1.44
Sheyenne River-4	1,030	1.50
Sheyenne River-5	[1/]	[1/]
Sheyenne River-6	860	1.38
Sheyenne River-7	1,200	1.67
Sheyenne River-8	1,000	1.50
Wild Rice River-1	600	1.31
Wild Rice River-2	600	1.31
Wild Rice River-3	517	1.26
Wild Rice River-4	517	1.27
Wild Rice River-5	517	1.28
Wild Rice River-6	517	1.28
Wolverton Creek-1	130	1.14
Wolverton Creek-2	130	1.15

[1/] Bankfull discharge could not be determined.

4.3 Channel-Forming Discharge for Historic Conditions

Historical channel-forming discharge can potentially be determined using one of the three methods (bankfull, effective discharge, recurrence interval) discussed in the previous sections. However, the bankfull method requires the use of bankfull indicators to estimate the bankfull water surface elevation. Because historic data regarding bankfull indicators were not available, this method could not be used to determine the historic channel-forming discharge. The effective discharge method was shown in the previous sections not to be reliable for estimating the channel-forming discharge for current conditions. Therefore, the effective discharge method could not be reliably used for determining the historic channel-forming discharge. However, the recurrence interval method can be used to determine the historic channel-forming discharge if sufficient data exists for the historic period of interest. The historic period of interest was the 'dry' period in the record, defined by the St. Paul District as the years 1941 and earlier. The USGS gages within the study area having historic discharge records prior to 1941 are listed in Table 4-6.

Table 4-6. Historic Stream Gage Information

Gage Number	Gage Name	Begin of Record	Nearby Detailed Study Reach
05053000	Wild Rice River near Abercrombie	1932	Wild Rice River – 6 – 42.36
05054000	Red River at Fargo	1901	Red River – 4 – 452.52
05059500	Sheyenne River at West Fargo	1929	Sheyenne River – 5 – 26.47

As shown in Table 4-6, the historic period of record for USGS gages 0505300 – Wild Rice River near Abercrombie and 05059500 – Sheyenne River at West Fargo is 9 and 12 years, respectively. This relatively short record length is not sufficient to produce a reliable statistical analysis of peak flows. The remaining USGS gage with a sufficient period of historic record, 05054000 – Red River at Fargo, was assessed using HEC-SSP (USACE, 2010d) to determine the historic channel-forming discharge.

As established in Section 4.2.3, the recurrence interval of the current channel-forming discharge at detailed study reach Red River – 4 – 452.52 (which encompasses USGS gage 05054000 – Red River at Fargo) is 1.26 years. Therefore, to determine the historical channel-forming discharge, HEC-SSP was set up to compute the historic discharge for the 1.26-year event using annual peak discharge data from USGS gage 05054000 – Red River at Fargo that encompassed the years 1901-1941. Results of the flood frequency analysis indicate that the historic channel-forming discharge for the Red River of the North at Fargo is approximately 943 cfs compared to the current value of 2,380 cfs (a 152% increase). The recurrence interval of the 2,380 cfs discharge is 2.4 years in the historical period, compared to a 1.26-year recurrence interval in the current years. While one data point does not allow for reliable estimation of historic channel-forming discharges across the entire study area, qualitatively it can be assumed that the historic channel-forming discharges throughout the study area were likely less than the current channel-forming discharges.

4.4 Discharge-Duration and Elevation-Duration Curves

The discharge-duration curve shows what percent of time a given discharge is equaled or exceeded under a certain hydrologic regime. Discharge-duration curves have been used to check if channel-forming discharge estimates are reasonable (Biedenharn et al., 2000). Given an elevation versus discharge relationship for a cross section, an elevation-duration curve may be constructed from a discharge-duration curve. This curve shows the percent of time that the water level is at or above any given elevation in the cross section for a given discharge scenario. This type of curve is useful for estimating the effect of water levels on plant communities.

4.4.1 Discharge-Duration Curves

4.4.1.1 Current Conditions

Discharge-duration curves were provided by the St. Paul District at three general locations throughout the study area: 1) at the upstream end of each stream within the study area; 2) at the mouth of each stream within the study area; and 3) at USGS gages within the study area. These discharge-duration curves were created using all available gaged data after the year 1941, the year in which the hydrologic conditions for the study area were determined by the St. Paul District to have changed from relatively dry to relatively wet (USACE, 2011). However, because stream gages were not typically located at the detailed study reaches, an interpolation procedure was needed to estimate the discharge-duration curves at each detailed study reach. The "discharge-duration curve method" based on drainage area, as outlined by Biedenharn et al. (2000), was used. The drainage area of each of the detailed study reaches previously established and shown in Table 3-1 was used to construct the discharge-duration curves for the detailed study reaches.

The interpolation procedure used to develop the detailed study reach discharge-duration curves is graphically shown in Figure 4-36. The drainage area is plotted on the horizontal axis while the discharge is plotted on the vertical axis for each percentage equaled or exceeded level. The vertical line represents the location of detailed study reach Red River-5-463.56, located upstream of the Fargo gage. The discharge-duration curve for this detailed study reach was developed by determining the discharge at which the vertical line crosses each percent time equaled or exceeded line. Figure 4-36 is presented to illustrate the method used in the study, however, all interpolations were accomplished numerically rather than graphically.

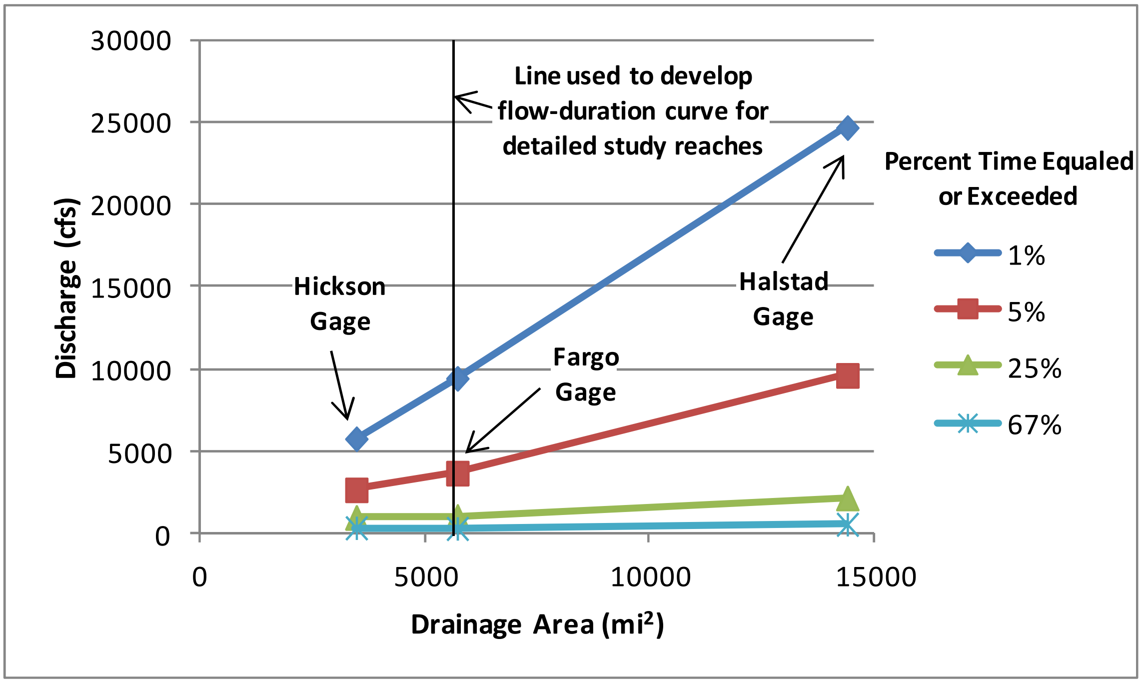


Figure 4-36. Graphical Representation of Discharge-Duration Curve Interpolation Procedure

The existing Horace and West Fargo Sheyenne River Diversions required specific assumptions to be made in the construction of the discharge-duration curves at the two detailed study reaches protected by these diversions. The curve for Sheyenne River – 5 – 26.47 was assumed to be equal to the curve provided by the St. Paul District for USGS gage 05059500 – Sheyenne River at West Fargo for flows within the protected channel only. This assumption is valid because the West Fargo Diversion conveys all flow from the Sheyenne River around that detailed study reach and gage site above a discharge of approximately 900 cfs. Therefore, only a negligible amount of localized flow was assumed to enter the protected portion of the Sheyenne River between Sheyenne River – 5 – 26.47 and USGS gage 05059500 – Sheyenne River at West Fargo.

The discharge values for general study reach Sheyenne River – 6 (downstream of the Horace Diversion) were assumed to be the difference between the discharge for USGS gage 05059300 – Sheyenne River above Diversion near Horace and the discharge passing over the Horace Diversion weir. The flow over the Horace Diversion weir was calculated based on the relationship between flow in the Horace Diversion measured at USGS gage 05059310 – Sheyenne River Diversion near Horace and the flow at USGS gage 05059300 – Sheyenne River above Diversion near Horace as shown in Figure 4-37.

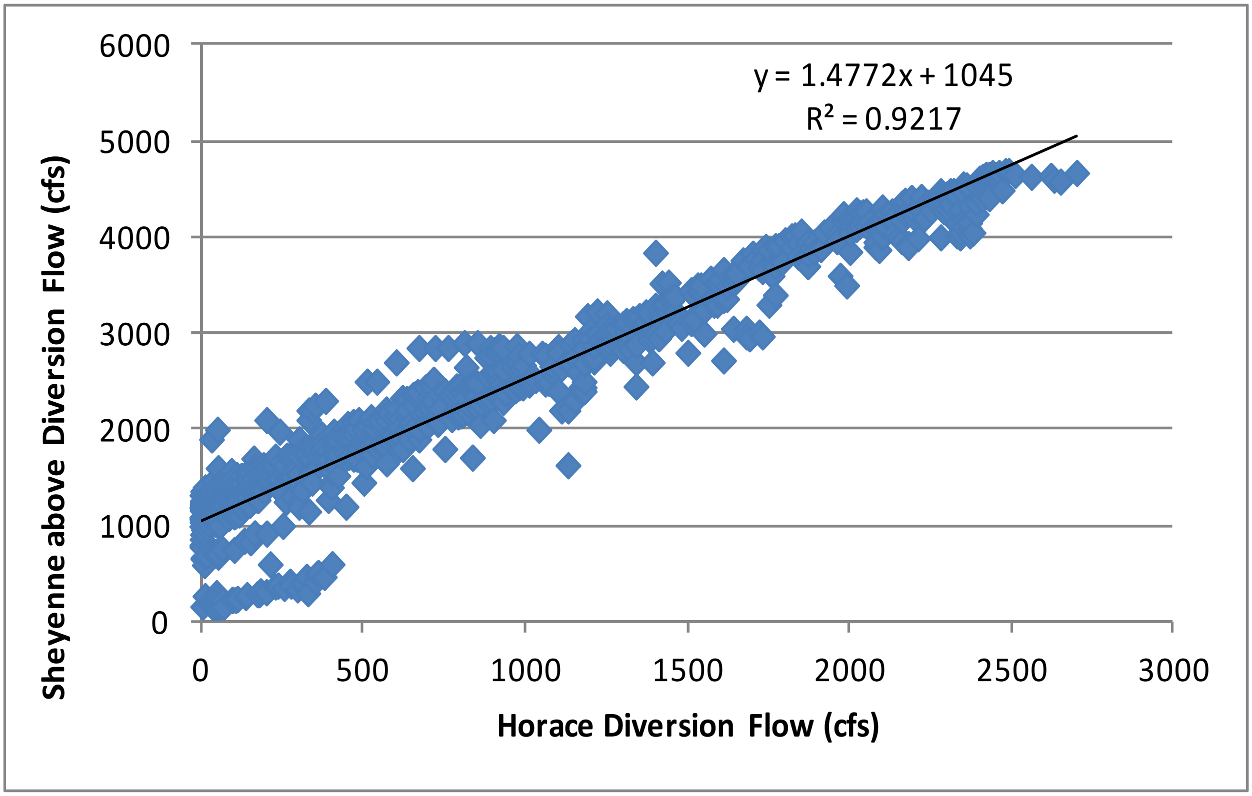


Figure 4-37. Relationship between Horace Diversion and Sheyenne River above Diversion Flows

The relationship between the flows for the two sites was determined using the following equation:

$$Q_{upstream} = 1.4772\ (Q_{diversion}) + 1045$$

where $Q_{upstream}$ is the flow at USGS gage 05059300 – Sheyenne River above Diversion near Horace and $Q_{diversion}$ is the flow entering into the diversion measured at USGS gage 05059310 – Sheyenne River Diversion near Horace. This relationship was used to calculate the amount of flow diverted from the Sheyenne River via the Horace Diversion based on a given flow at the gaged site located upstream of the Diversion. Because the discharge entering the junction is known and the discharge leaving the junction via the Diversion can be calculated using the relationship, the discharge leaving the junction via Sheyenne River – 6 can be calculated as the difference between the two. Because only a negligible amount of localized flow was assumed to enter the protected stretch of the Sheyenne River between the upstream extent of general study reach Sheyenne River – 6, located downstream of the Horace Diversion, and Sheyenne River – 6 – 35.82, the discharge-duration curves at these two locations were considered to be equivalent. The current conditions discharge-duration curves developed for each detailed study reach are shown in Appendix C.

Discharge-duration curves have been used to check if channel-forming discharge estimates are reasonable (Biedenharn et al., 2000). Biedenharn et al. compiled data from a number of studies to study the relationship between the percentage of days the channel-forming discharge was equaled or exceeded for sand bedded streams to the total drainage area of a study site. The comparison indicated that a positive correlation exists between drainage area and the percent time the channel-forming discharge was equaled or exceeded. The same relationship was analyzed in this study. Table 4-7 displays the percent of time the average channel-forming discharge was equaled or exceeded for each detailed study reach.

Figure 4-38 displays the relationship between percent of time the channel-forming discharge equaled and exceeded and the drainage area, as highlighted in Table 4-7. The data compiled by Biedenharn et al. are also displayed in Figure 4-38. A comparison of the two sets of values indicates that the channel-forming discharges determined for this study are generally in line with those determined in previous studies.

Table 4-7. Comparison of Drainage Area versus Exceedence Percentages for Average Channel-Forming Discharges

Detailed Reach	Drainage Area (mi^2)	Channel-Forming Discharge (cfs)	Percent of Time Discharge Equaled or Exceeded
Buffalo River-1-1.19	994.1	420	11
Lower Rush River-1-1.10	59.39	65	2.4
Lower Rush River-2-6.03	53.35	60	2.4
Maple River-1-0.78	1,482	650	8
Maple River-2-11.39	1,460	650	8
Red River-1-410.65	12,267	4,700	9.7
Red River-2-419.14	11,044	4,280	9.6
Red River-3-440.57	5,763	2,380	9.4
Red River-4-452.52	5,718	2,380	9.3
Red River-5-463.56	5,603	2,380	9.2
Red River-6-470.23	3,591	1,780	11.5
Red River-7-492.47	3,461	1,650	12.3
Red River-8-521.18	3,421	1,650	11.8
Rush River-1-0.08	154.6	150	2.6
Rush River-2-6.15	139.3	150	2.4
Sheyenne River-1-4.20	5,249	1,900	7.8
Sheyenne River-2-11.56	5,086	1,750	8
Sheyenne River-3-18.15	4,968	1,680	8
Sheyenne River-4-22.27	3,483	1,030	6.2
Sheyenne River-5-26.47	3,476	[1/]	[1/]
Sheyenne River-6-35.82	3,433	860	8[2/]
Sheyenne River-7-43.27	3,423	1,200	5.4
Sheyenne River-8-55.75	3,406	1,000	6.6
Wild Rice River-1-3.01	2,012	600	7.7
Wild Rice River-2-4.23	2,011	600	7.7
Wild Rice River-3-17.52	1,970	517	7.4
Wild Rice River-4-22.94	1,905	517	7.2
Wild Rice River-5-38.49	1,862	517	7
Wild Rice River-6-42.36	1,847	517	7
Wolverton Creek-1-0.64	103.0	130	3
Wolverton Creek-2-2.02	99.13	130	2.8

[1/] Bankfull discharge could not be determined.

[2/] Reach affected by existing diversion

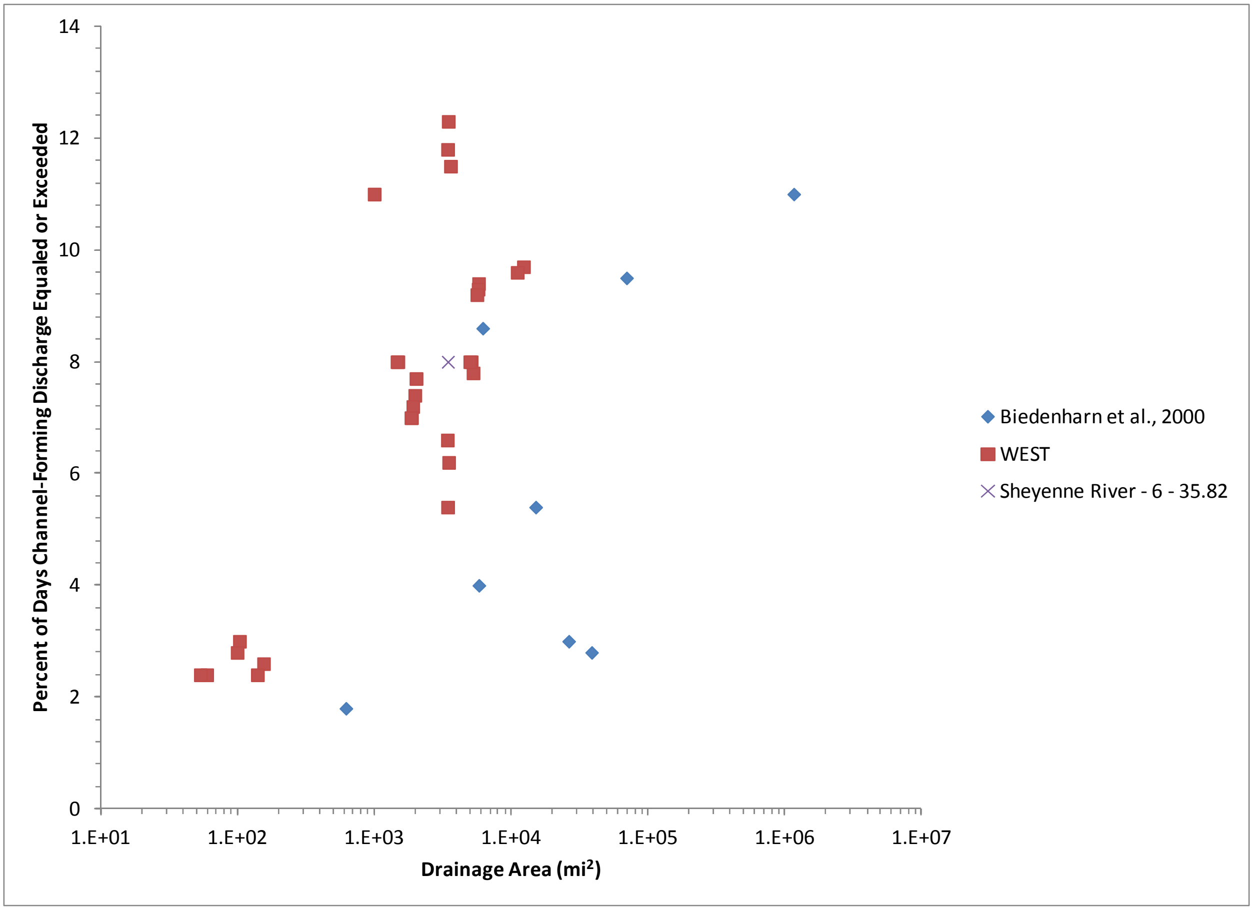


Figure 4-38. Channel-Forming Discharge Duration and Drainage Area Relationship

4.4.1.2 Historic Conditions

Historic discharge-duration curves were created for any gage in the study area with a record existing prior to the year 1941. The year 1941 was selected as the break between current and historic conditions because the current discharge-duration curves developed by the St. Paul District used records from 1941 to present. The USGS gages within the study area having historic discharge records prior to 1941 are listed in Table 4-6 above. The mean daily discharge records for the three gages listed in Table 4-6 were used to develop the historic discharge-duration curves at those sites. However, because only one gage site, for which the historic discharge-duration curves could be developed, existed on each stream, interpolations to detailed study reaches could not be completed. Rather, only the detailed study reaches located near the gage sites were assigned historic discharge-duration curves. The detailed study reaches for which historic discharge-duration curves were developed are listed in Table 4-6. The historic discharge-duration curves are shown in Appendix D.

4.4.1.3 Future Conditions

Future conditions discharge-duration curves were also developed by the St. Paul District for the Minnesota and North Dakota diversion alignments at the same three general locations as noted in Section 4.4.1.1. The same interpolation procedure used to develop the discharge-duration curves for all the detailed study reaches was used for the diversion alignment alternatives. The future conditions discharge-duration curves developed for each detailed study reach are shown in Appendix E.

4.4.1.4 Discharge-Duration Curve Comparison

A comparison of the historic, current and future (with project) discharge-duration values for the 50-, 5-, and 0.5-percent exceedence flows is shown in Table 4-8. A graphical comparison of the historic, current and future (with project) discharge-duration curves for Red River – 4 – 452.52, Wild Rice River – 6 – 42.36, and Sheyenne River – 5 – 26.47 is shown in Figure 4-39, Figure 4-40, and Figure 4-41, respectively. As shown in Figure 4-39 and Figure 4-40, the historic conditions discharge-duration curves have significantly lower discharges compared to the current and future (with project) curves. Climatic changes as well as changes in farming practices, including increased density and efficiency of field drains, are likely the primary causes for the larger discharges compared to historic conditions.

Figure 4-41 shows that historic discharges are lower than the current and future (with project) discharges from the 99.999 percent to the 5 percent equaled or exceeded point, but at less frequent discharges, the historic discharges are higher than the current and future (with project) discharges. This occurs because the historic conditions data was collected during the time period prior to the existence of the West Fargo Diversion and therefore measured all of the flow in the Sheyenne River at the West Fargo gage site. The current and future (with project) conditions do not reflect this same scenario, as high flows are diverted around the West Fargo gage site via the West Fargo Diversion. Therefore, a comparison of the historic, current, and future (with project) conditions cannot be made for Sheyenne River – 5 – 26.47.

Comparisons of the historic, current, and future (with project) conditions trends shown in Figure 4-39 and Figure 4-40 indicate that the current and future (with project) conditions discharge-duration curves have greater discharges than the historic conditions curves. It is therefore assumed that the other study streams, for which historic data does not exist, would show a similar comparison between historic and current conditions. The remaining 28 detailed study reaches that were not plotted only exhibit differences between the current and future (with project) conditions for the detailed study reaches that are located within the area protected by the proposed diversion alignments. In this case, the less-frequent durations (0.5% and sometimes 5%) exhibit a decrease in discharge for the same duration percentage. An example of the impact of the diversions to the future flows is shown in Figure 4-39. As seen in the figure, the discharges for the Red River are capped at 10,000 cfs for the future (with project) conditions.

Table 4-8. Comparison of Selected Points on Discharge-Duration Curves

Detailed Reach	Discharge (cfs) for Select Percent of Time											
	Historic Conditions			Current Conditions			LPP Alternative			FCP Alternative		
	50%	5%	0.5%	50%	5%	0.5%	50%	5%	0.5%	50%	5%	0.5%
Buffalo River-1-1.19	[1]	[1]	[1]	58	851	3,280	58	851	3,280	58	851	3,280
Lower Rush River-1-1.10	[1]	[1]	[1]	[3]	26	231	[2]	[2]	[2]	[3]	26	231
Lower Rush River-2-6.03	[1]	[1]	[1]	[3]	23	207	[3]	23	207	[3]	23	207
Maple River-1-0.78	[1]	[1]	[1]	19	1,001	3,956	19	1,002	2,300	19	1,001	3,956
Maple River-2-11.39	[1]	[1]	[1]	19	986	3,896	19	986	3,896	19	986	3,896
Red River-1-410.65	[1]	[1]	[1]	796	8,137	28,233	796	8,137	28,233	796	8,137	28,233
Red River-2-419.14	[1]	[1]	[1]	734	7,299	25,463	650	6,372	18,442	734	7,299	25,463
Red River-3-440.57	[1]	[1]	[1]	463	3,681	13,502	461	3,650	10,000	461	3,650	10,000
Red River-4-452.52	204	1,384	4,487	461	3,650	13,400	461	3,650	10,000	461	3,650	10,000
Red River-5-463.56	[1]	[1]	[1]	463	3,598	13,101	461	3,650	10,000	461	3,650	10,000
Red River-6-470.23	[1]	[1]	[1]	493	2,689	7,876	453	2,752	6,000	493	2,689	7,876
Red River-7-492.47	[1]	[1]	[1]	490	2,610	7,495	490	2,610	7,495	490	2,610	7,495
Red River-8-521.18	[1]	[1]	[1]	3,421	3,421	3,421	3,421	3,421	3,421	3,421	3,421	3,421
Rush River-1-0.08	[1]	[1]	[1]	[3]	67	600	[2]	[2]	[2]	[3]	67	600
Rush River-2-6.15	[1]	[1]	[1]	[3]	60	540	[3]	60	540	[3]	60	540
Sheyenne River-1-4.20	[1]	[1]	[1]	189	2,720	8,434	142	2,442	4,424	189	2,720	8,434
Sheyenne River-2-11.56	[1]	[1]	[1]	181	2,581	7,977	139	2,329	4,175	181	2,581	7,977
Sheyenne River-3-18.15	[1]	[1]	[1]	176	2,481	7,647	137	2,248	3,995	176	2,481	7,647
Sheyenne River-4-22.27	[1]	[1]	[1]	110	1,222	3,486	110	1,221	1,728	110	1,222	3,486
Sheyenne River-5-26.47	22	312	1,201	82	317	563	82	317	563	82	317	563
Sheyenne River-6-35.82	[1]	[1]	[1]	121	1,149	1,795	121	1,149	1,795	121	1,149	1,795
Sheyenne River-7-43.27	[1]	[1]	[1]	120	1,265	3,471	120	1,265	3,471	120	1,265	3,471
Sheyenne River-8-55.75	[1]	[1]	[1]	115	1,277	4,123	115	1,277	4,123	115	1,277	4,123
Wild Rice River-1-3.01	[1]	[1]	[1]	8	881	4,812	8	898	4,000	8	881	4,812
Wild Rice River-2-4.23	[1]	[1]	[1]	8	881	4,810	8	898	4,000	8	881	4,810
Wild Rice River-3-17.52	[1]	[1]	[1]	8	863	4,713	8	863	4,713	8	863	4,713
Wild Rice River-4-22.94	[1]	[1]	[1]	7	835	4,560	7	835	4,560	7	835	4,560
Wild Rice River-5-38.49	[1]	[1]	[1]	7	812	4,433	7	812	4,433	7	812	4,433
Wild Rice River-6-42.36	[3]	56	388	7	804	4,390	7	804	4,390	7	804	4,390
Wolverton Creek-1-0.64	[1]	[1]	[1]	3	80	410	3	80	[2]	3	80	410
Wolverton Creek-2-2.02	[1]	[1]	[1]	3	77	394	3	77	394	3	77	394

[1] could not be calculated due to lack of historic gage data

[2] all flow is routed into the ND Diversion upstream of this detailed study reach

[3] no value due to zero flow in discharge-duration curve

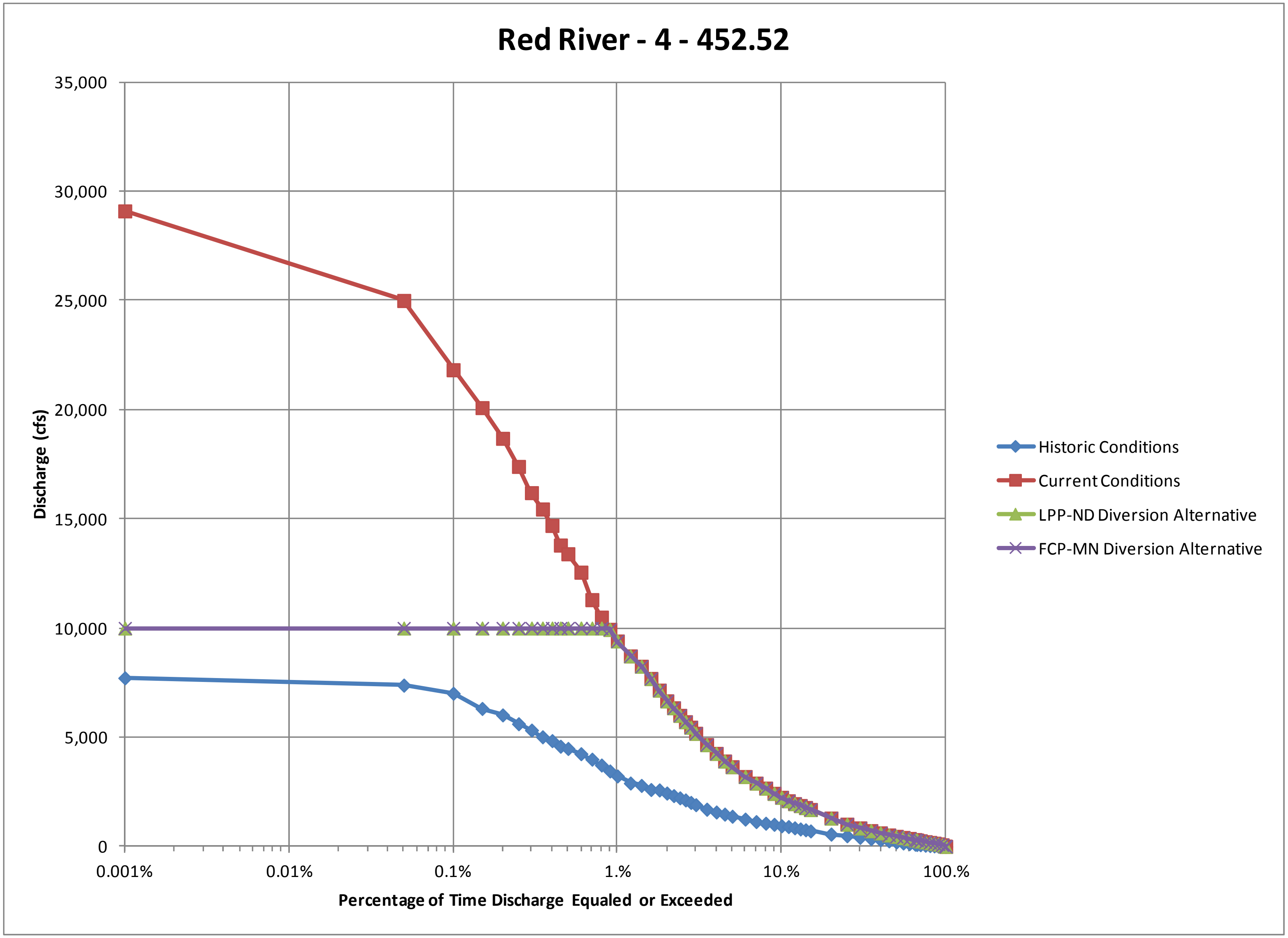


Figure 4-39. Comparison of Discharge-Duration Curves for Red River – 4 – 452.52

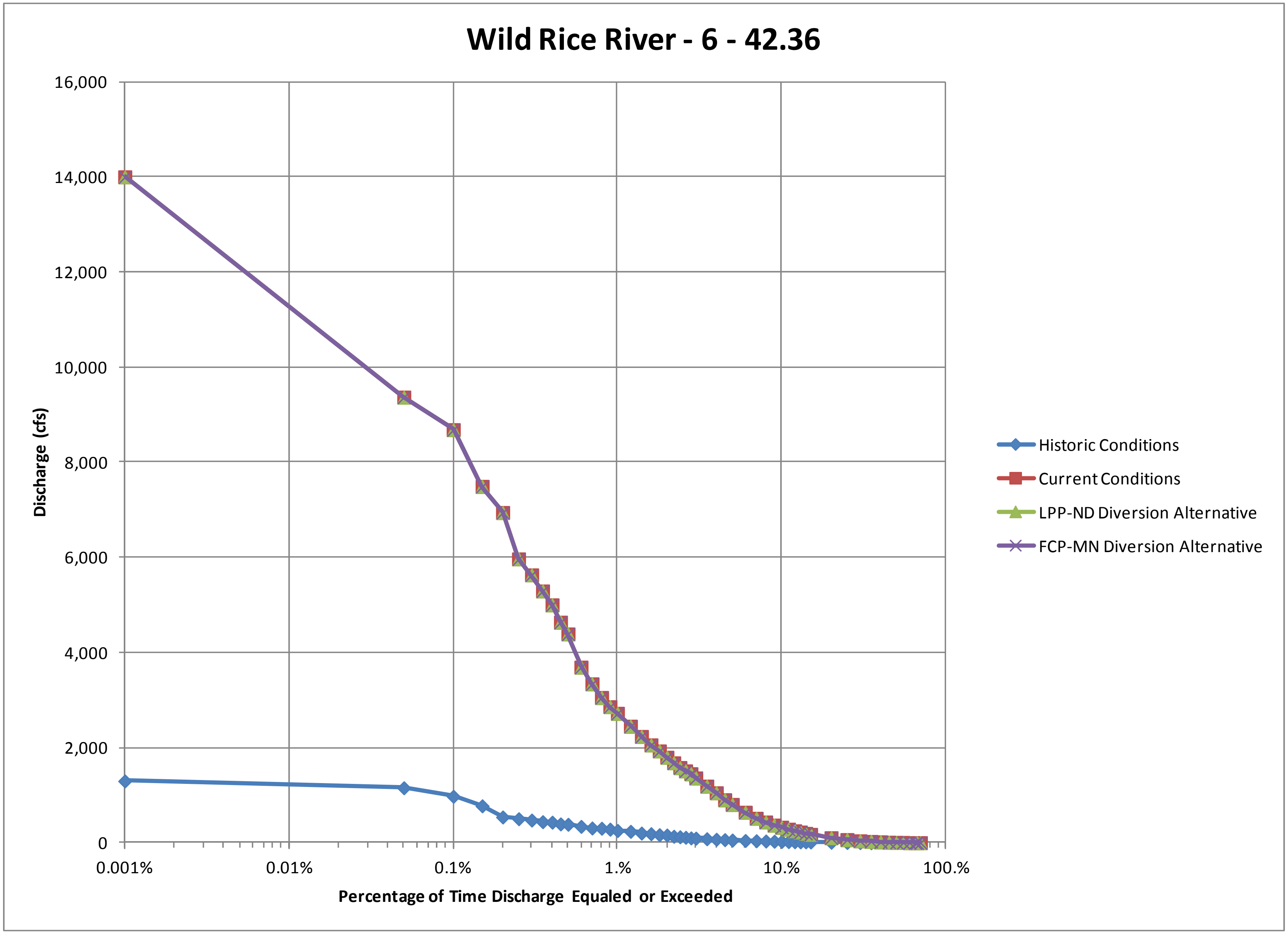


Figure 4-40. Comparison of Discharge-Duration Curves for Wild Rice River – 6 – 42.36

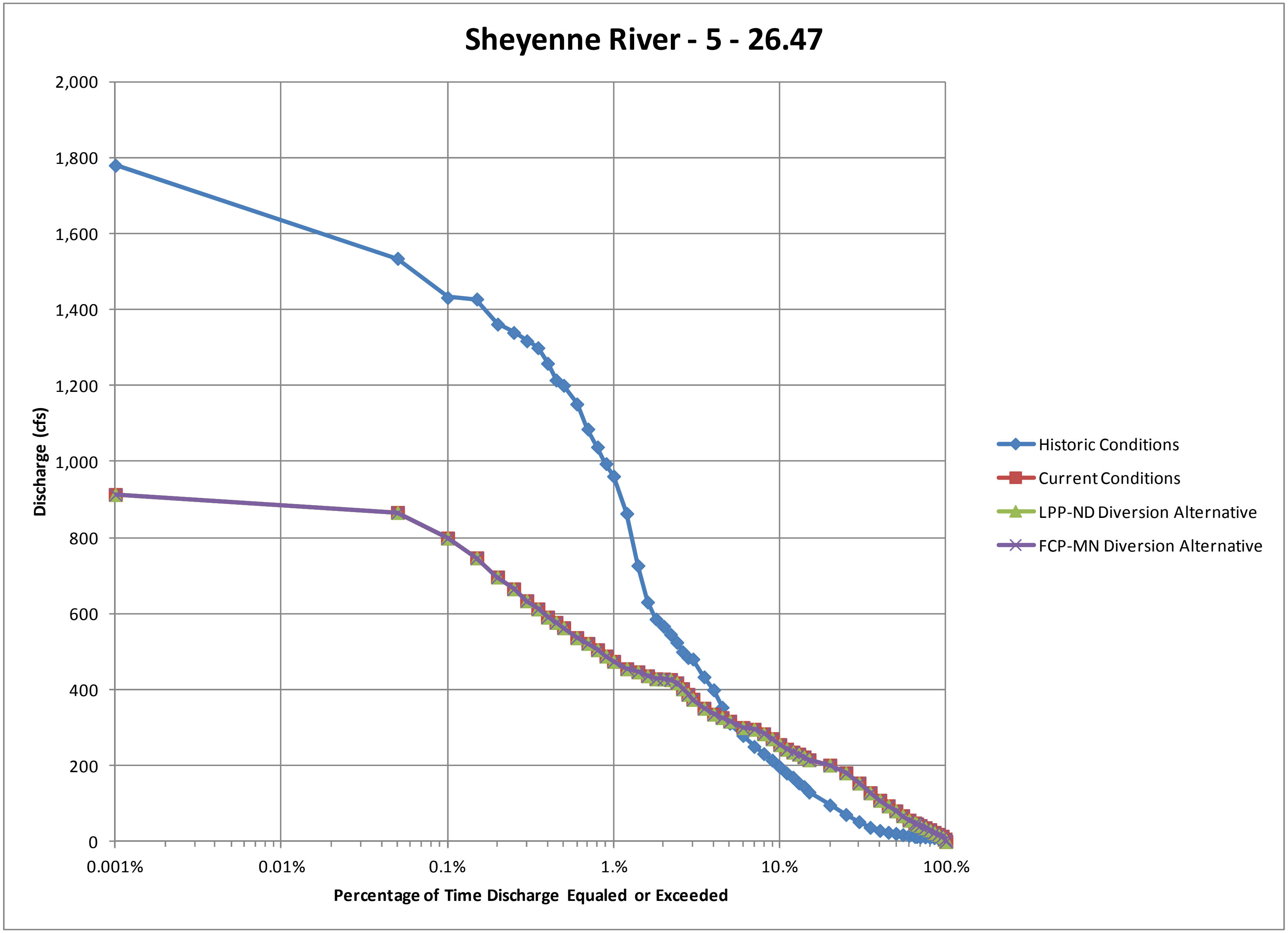


Figure 4-41. Comparison of Discharge-Duration Curves for Sheyenne River – 5 – 26.47

4.4.2 Elevation-Duration Curves

Elevation-duration curves reflect the percentage of time the water surface reaches or exceeds a given elevation based upon the flow record and local hydraulic conditions. Elevation-duration curves were produced for current, historic and future (with project) conditions using the methods described in the following sections.

4.4.2.1 Current Conditions

Elevation-duration curves were calculated using a modified version of the previously described HEC-RAS bankfull models. The hydraulic models were modified by extending the cross-section geometry to the floodplain elevation (at which the flow would transition from a one-dimensional downstream flow direction to a more lateral two-dimensional flow direction), whichever was less. The discharge-duration curves used in the modeling to develop the elevation-duration curves were limited to the duration value at which the bank overtopping occurs in either the downstream main stem stream or the downstream detailed study reach if this duration value occurred more frequently than did the bank overtopping duration value. Therefore, some of the developed elevation-duration curves do not extend to the higher water surface elevations associated with the less frequent discharges. Additionally, the elevation-duration curve for reach Sheyenne River – 5, located in West Fargo, was limited to those discharges for which the flood control gates at the upstream and downstream ends of the general study reach were open. When the flood control gates are closed, the water surface elevations in the channel are artificially controlled and can no longer be related to the discharge in the channel.

To create the elevation-duration curves, the current condition discharge-duration curves were specified as flow profiles in the HEC-RAS models. Downstream boundary conditions were based on water surface elevations corresponding to the discharge with the same duration in the main stem stream elevation-duration model. The resulting water surface elevations for each of the flow profiles were used to develop the elevation-duration curve. The current conditions elevation-duration curves are presented in Appendix F.

4.4.2.2 Historic Conditions

Hydraulic models with adequate historic cross section data covering the detailed study reaches do not exist. Therefore, historic elevation-duration curves were created for the three USGS gages in the study area that had a gage record existing prior to the year 1941. The historic elevation-duration curves were developed from the historic discharge-duration curves and historic USGS stage-discharge rating tables. For each gage location, the elevation-duration curve was developed from the historic discharge-duration curve provided by the St. Paul District and the USGS stage-discharge rating table having an effective date closest to the year 1941. The historic rating table used for gage 05053000 – Wild Rice River near Abercrombie was effective for the year 1941. The historic rating table used for the gage 05054000 – Red River at Fargo was effective for the year 1943. The historic rating table used for the gage 05059500 – Sheyenne River at West Fargo was effective for the year 1942.

An example calculation of one point on the elevation-duration curve for the Fargo gage is as follows: The 1-percent exceedence discharge of 3,227 cfs at the Fargo gage corresponds to a gage height of 11.90 ft. The gage height was converted from the gage datum to the NAVD88 vertical datum by adding 862.74 ft to the gage height. Therefore, a water surface elevation of 874.64 ft was found to correspond with a discharge of 3,227 cfs at the Fargo gage, indicating that an elevation of 874.64 ft is equaled or exceeded 1-percent of the time. This conversion was completed for all exceedence percentages at each of the three gage sites. Only the detailed study reaches nearest the three gages, which are listed in Table 4-6, could be assigned historical elevation-duration curves. The historic elevation-duration curves are presented in Appendix G.

4.4.2.3 Future Conditions

Elevation-duration curves were produced for future conditions using the extended cross section HEC-RAS models described in Section 4.4.2.1. Control structures and aqueducts to be constructed as a part of the two future alternative diversion alignments were incorporated into the extended cross section HEC-RAS models to assess backwater impacts. However, because the extended cross section HEC-RAS models are steady-state and therefore not able to model floodplain storage, the maximum modeled discharge for reaches upstream of the diversion structures and aqueducts was limited to the discharge at which flow began to enter the diversion channel. For example, all discharges up to the discharge corresponding with the 3.6-year event were allowed to pass through the control structure on the Red River. Therefore, the elevation-duration curves for detailed study reaches Red River-7-492.47 and Red River-8-521.18 were limited to discharges equal to or less than the 3.6-year discharge.

In order to include the higher discharges in the elevation-duration curves for the reaches located upstream of the control structures and aqueducts, the maximum water surface elevations as modeled in the USACE future conditions unsteady HEC-RAS models for the 10-year, 50-year, 100-year, and 500-year flow were added to the elevation-duration curves, as possible. The future conditions elevation-duration curves are presented in Appendix H.

4.4.2.4 Elevation-Duration Curve Comparison

Comparison of the current and historic conditions elevation-duration curves indicates that the water surface elevations have increased from the historic to current conditions. The increased water surface elevations are likely due to discharge increases, as the historic cross section comparisons (see Section 6.2) indicate that channel geometry has stayed relatively constant from historic to current conditions. However, comparison of the current and future (with project) conditions elevation-duration curves indicate that water surface elevations remain generally constant, except within the areas protected by the diversions. The water surface elevations within the protected areas are expected to decrease compared to the current conditions due to the reduction in flows that will be passing through the areas. To illustrate these trends, the elevations which are equaled or exceeded 50-, 5-, and 0.5-percent of time for the historic, current, and future (with project) flow conditions are shown in Table 4-9.

Table 4-9. Comparison of Selected Points on Elevation-Duration Curves

Detailed Reach	Elevation (ft, NAVD) for Select Percent of Time Equaled or Exceeded)											
	Historic Conditions			Current Conditions			LPP Alternative			FCP Alternative		
	50%	5%	0.5%	50%	5%	0.5%	50%	5%	0.5%	50%	5%	0.5%
Buffalo River-1-1.19	1/	1/	1/	849.84	862.32	4/	849.84	862.32	4/	849.84	862.32	4/
Lower Rush River-1-1.10	1/	1/	1/	3/	882.73	4/	2/	2/	2/	3/	882.73	4/
Lower Rush River-2-6.03	1/	1/	1/	3/	892.20	4/	3/	892.20	895.36	3/	892.20	4/
Maple River-1-0.78	1/	1/	1/	881.12	885.67	4/	881.12	885.26	889.99	881.12	885.67	4/
Maple River-2-11.39	1/	1/	1/	891.01	896.32	4/	891.01	896.32	4/	891.01	896.32	4/
Red River-1-410.65	1/	1/	1/	844.94	859.48	874.87	844.94	859.48	874.87	844.94	859.48	874.87
Red River-2-419.14	1/	1/	1/	850.67	863.42	4/	850.52	863.19	877.67	850.67	863.42	4/
Red River-3-440.57	1/	1/	1/	862.89	873.42	4/	862.87	873.24	883.90	862.87	873.37	4/
Red River-4-452.52	1/	872.74	878.14	876.65	880.57	4/	876.65	880.56	889.33	876.65	880.57	4/
Red River-5-463.56	1/	1/	1/	879.95	885.43	4/	879.94	885.50	894.17	879.94	885.50	4/
Red River-6-470.23	1/	1/	1/	880.33	888.44	4/	880.32	888.54	897.59	880.34	888.58	4/
Red River-7-492.47	1/	1/	1/	890.03	897.97	4/	890.03	898.02	4/	890.03	897.98	4/
Red River-8-521.18	1/	1/	1/	909.23	915.24	4/	909.23	915.24	4/	909.23	915.24	4/
Rush River-1-0.08	1/	1/	1/	3/	877.69	4/	2/	2/	2/	3/	877.69	4/
Rush River-2-6.15	1/	1/	1/	3/	888.16	4/	3/	888.16	892.54	3/	888.16	4/
Sheyenne River-1-4.20	1/	1/	1/	858.15	870.00	4/	857.53	869.22	880.33	858.15	870.00	4/
Sheyenne River-2-11.56	1/	1/	1/	867.06	878.04	4/	866.48	877.31	883.67	867.06	878.04	4/
Sheyenne River-3-18.15	1/	1/	1/	872.33	883.80	4/	871.93	883.08	888.24	872.33	883.80	4/
Sheyenne River-4-22.27	1/	1/	1/	879.04	887.73	4/	879.04	887.42	891.25	879.04	887.73	4/
Sheyenne River-5-26.47	880.53	884.13	889.93	5/	5/	5/	5/	5/	5/	5/	5/	5/
Sheyenne River-6-35.82	1/	1/	1/	897.65	905.20	4/	897.65	905.19	4/	897.65	905.20	4/
Sheyenne River-7-43.27	1/	1/	1/	903.21	912.39	4/	903.28	912.40	4/	903.21	912.39	4/
Sheyenne River-8-55.75	1/	1/	1/	915.59	924.91	4/	915.59	924.91	4/	915.59	924.91	4/
Wild Rice River-1-3.01	1/	1/	1/	880.31	889.20	4/	880.30	889.30	898.51	880.31	889.20	4/
Wild Rice River-2-4.23	1/	1/	1/	886.21	890.14	4/	886.21	890.22	899.16	886.21	890.14	4/
Wild Rice River-3-17.52	1/	1/	1/	891.62	900.29	4/	891.74	900.13	4/	891.62	900.29	4/
Wild Rice River-4-22.94	1/	1/	1/	894.98	903.19	4/	894.98	903.15	4/	894.98	903.19	4/
Wild Rice River-5-38.49	1/	1/	1/	904.26	913.66	4/	904.26	913.66	4/	904.26	913.66	4/
Wild Rice River-6-42.36	1/	911.06	912.01	909.58	915.46	4/	909.58	915.48	4/	909.58	915.46	4/
Wolverton Creek-1-0.64	1/	1/	1/	886.36	892.60	4/	886.36	892.60	2/	886.36	892.60	4/
Wolverton Creek-2-2.02	1/	1/	1/	895.54	897.98	4/	895.54	897.98	4/	895.54	897.98	4/

1/ could not be calculated due to lack of historic gage data

2/ all flow is routed into the ND Diversion upstream of this detailed study reach

3/ no value due to zero flow in discharge-duration curve

4/ elevation could not be calculated due to flows overtopping the banks

5/ elevation could not be determined

A graphical comparison of the historic, current, and future (with project) elevation-duration curves for Red River – 4 – 452.52 and Wild Rice River – 6 – 42.36, is shown in Figure 4-42 and Figure 4-43, respectively. As shown in these figures, the historic conditions elevation-duration curves are below the current and future (with project) curves at each of the locations. This is a direct result of the greater discharges for the current and future conditions compared to historic conditions as previously discussed in Section 4.4.1.4.

Figure 4-42 also shows the similarity of the elevation-duration curves for LPP and FCP diversion alignments compared with the current conditions discharge-duration curve below elevation 889.0 feet, which corresponds to a discharge of 10,000 cfs. Flows less than 10,000 cfs remain in the Red River channel. Flows in excess of 10,000 cfs are diverted into the diversion channel. Therefore, water surface elevations in the protected area of the Red River below the diversion point are expected to remain fairly stable during high flow events in excess of 10,000 cfs.

As seen in Figure 4-44, the elevation-duration curve for Wild Rice 3 – 17.52 shows that the curves for the LPP and FCP diversion alignments are similar to the current conditions curve for the lower water surface elevations that occur about 1-percent of the time or more. For the FCP diversion alignment, the elevation-duration curve continues to match the current conditions curve for higher elevations, which occur less frequently. However, for the LPP diversion alignment the elevations increase above the current conditions curve. This reflects the planned staging of floodwaters upstream of the diversion when the discharge in the Wild Rice River exceeds a 3.6-year annual recurrence interval peak event of approximately 2,900 cfs.

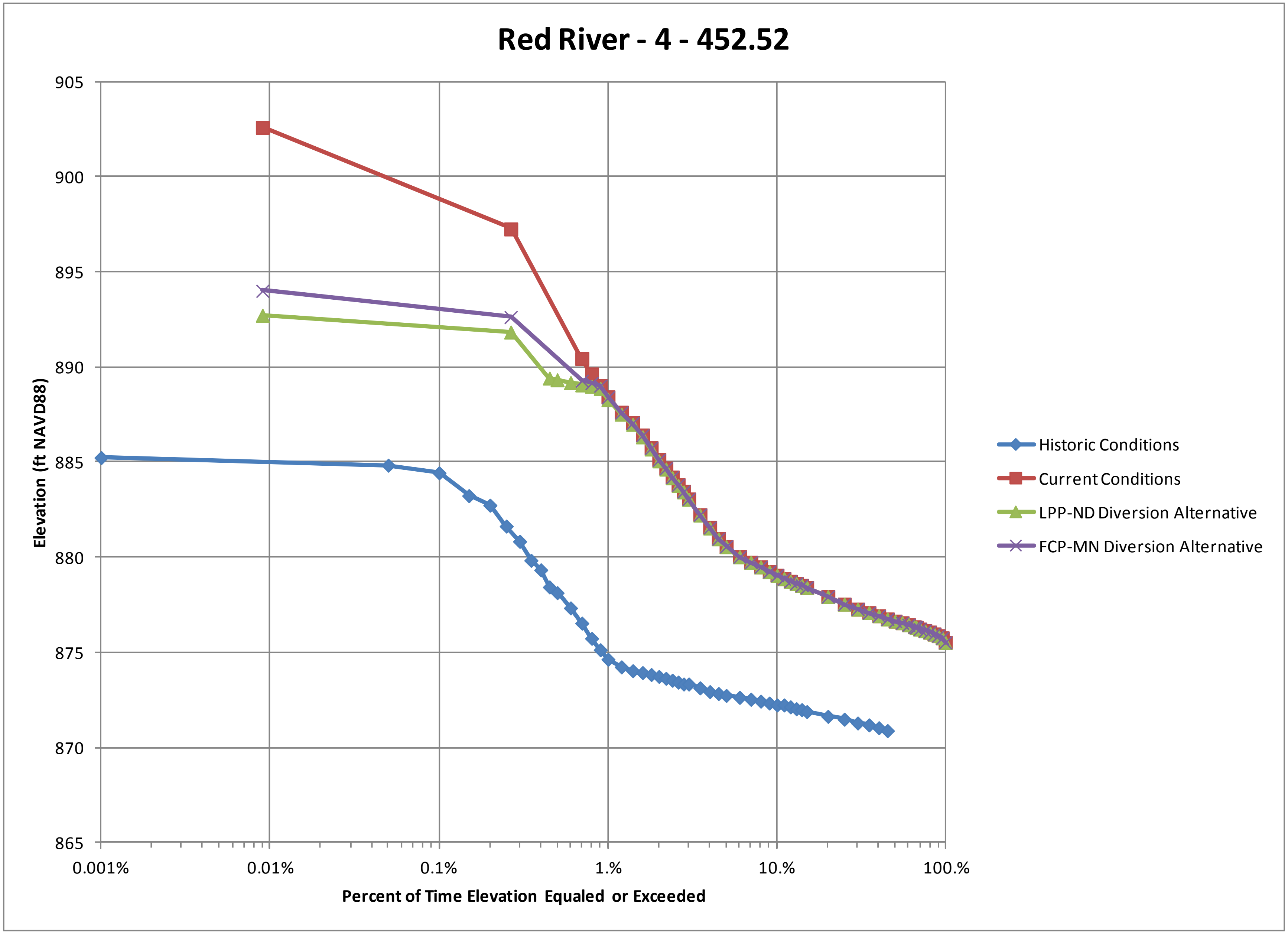


Figure 4-42. Comparison of Elevation-Duration Curves for Red River – 4 – 452.52

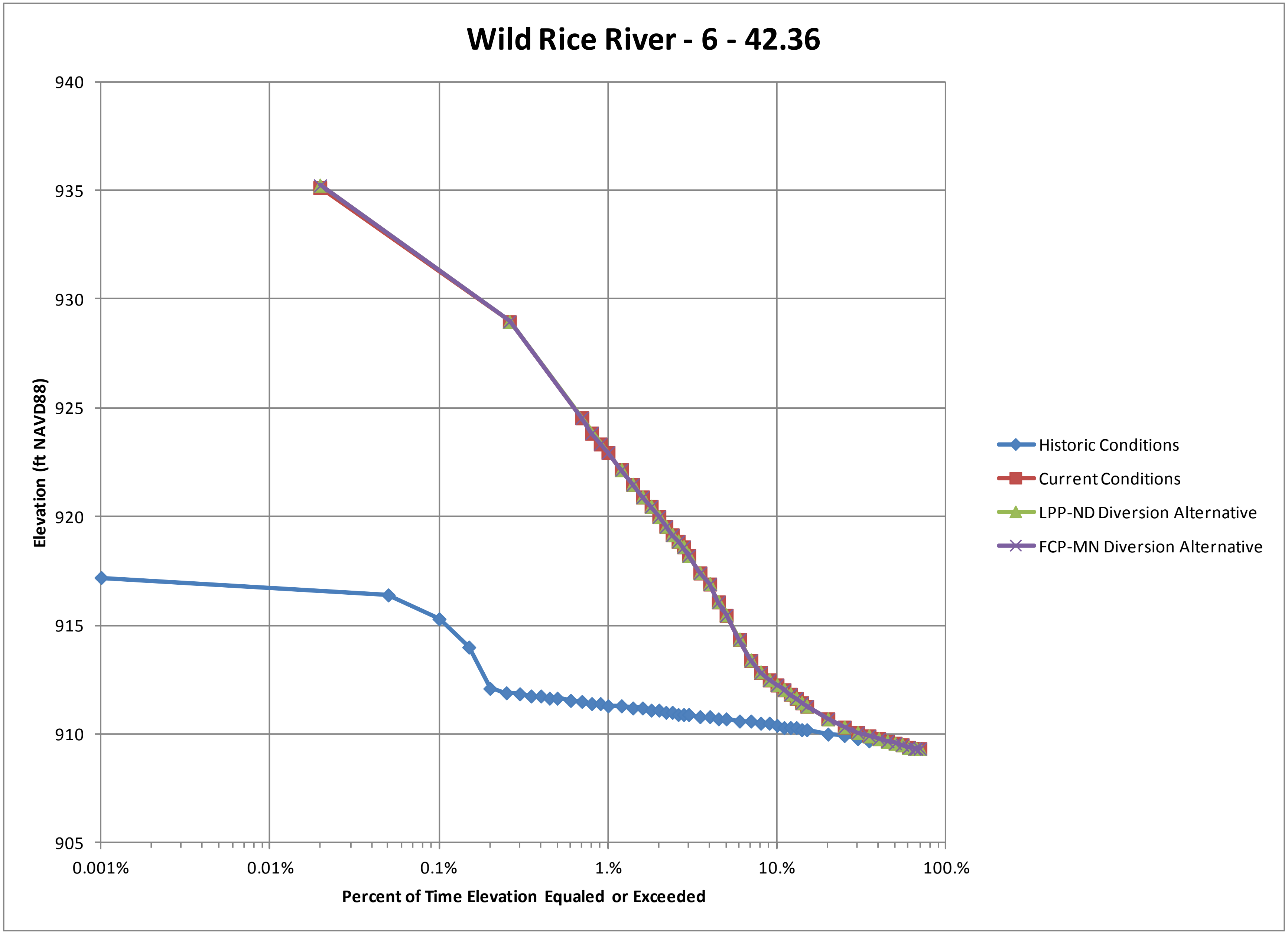


Figure 4-43. Comparison of Elevation-Duration Curves for Wild Rice River – 6 – 42.36

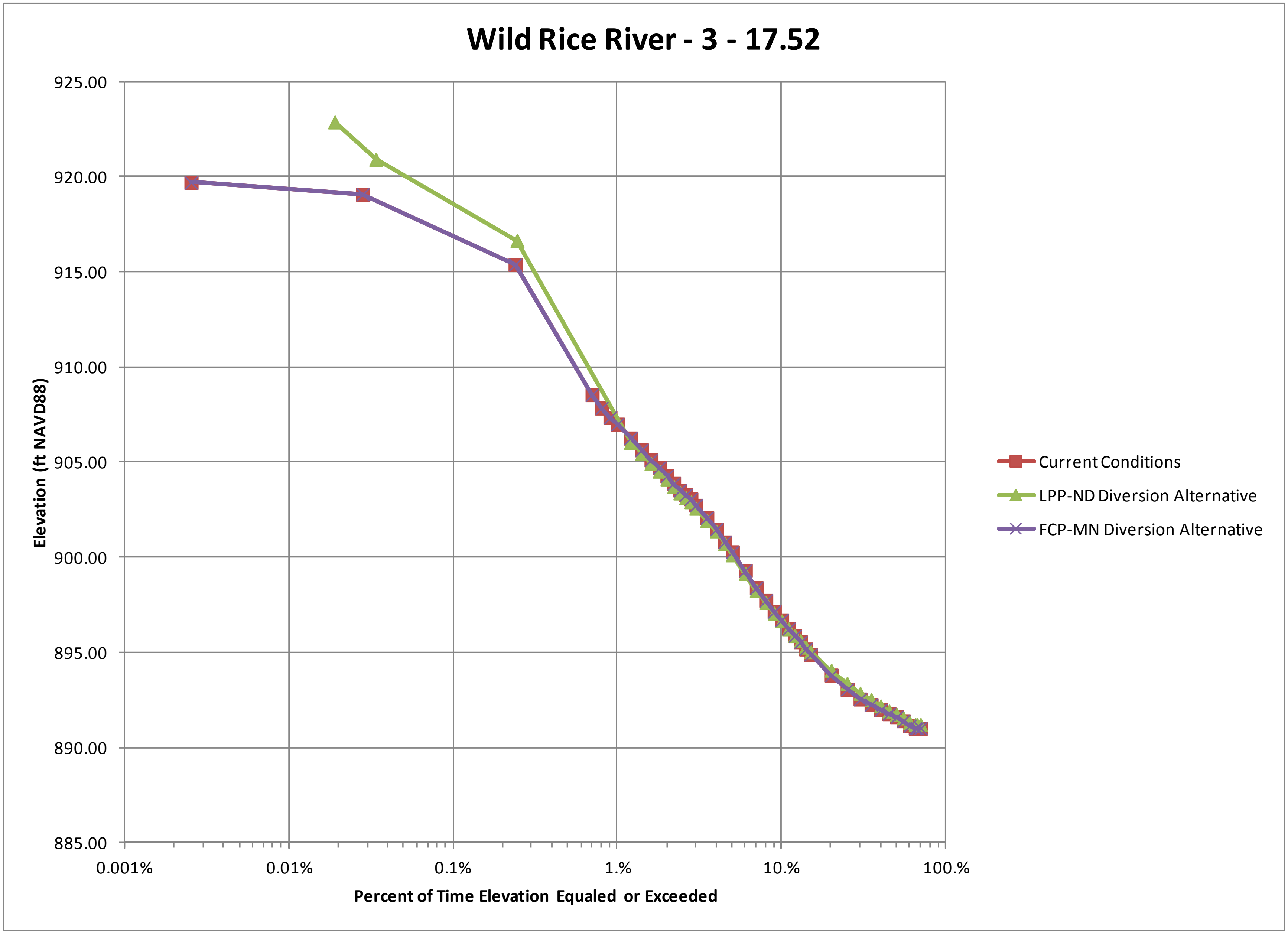


Figure 4-44. Comparison of Elevation-Duration Curves for Wild Rice River – 3 – 17.52

4.5 Specific Gage Analysis

4.5.1 Specific Gage Record Development

A specific gage record is a chart of river stage versus time for a specific discharge at a particular stream gage location. Each stage data point for the specific discharge was obtained from a rating table established by the USGS for the gaging location. The USGS establishes rating tables based on field measurements collected over a period of months or years. Once a rating table is established, additional field measurements are collected to assess the rating table accuracy over time. If the additional field measurements indicate that the current rating table is no longer accurate, the USGS creates a new rating table based on the most recent field measurements. Comparing stage values from consecutive rating tables for a specific discharge can indicate increasing (likely due to channel aggradation) or decreasing (likely due to channel degradation) stage trends over time. Consistent increasing or decreasing trends over a period of many years for a specific gage record indicate that the stream is not in equilibrium at that location. A specific gage analysis was completed for eleven USGS stream gages located within or near the project area to discern if consistent stage trends were evident.

Rating tables for each gage were provided by the USGS in either electronic or paper format. At each gage location, specific gage records were created for high, medium, and low flows. The creation of three records for each gage minimized the possibility of misinterpreting trends that appeared only at one discharge. The discharge for the high flow specific gage record was set equal to the 20-percent annual chance (5-year) event. The discharge for the low flow specific gage record was set equal to the 99-percent annual chance (1.01-year) event. The discharge for the medium flow record was calculated as the average of the high flow and low flow discharges. The discharges for the high, medium, and low flow records for each gaging location are shown in Table 4-10.

Table 4-10. Discharges Used to Create Specific Gage Records

Gage Number	Gage Name	Specific Gage Record Discharge (cfs)		
		Low	Medium	High
05051522	Red River at Hickson	292	3,096	5,900
05053000	Wild Rice River near Abercrombie	27	2,005	3,983
05054000	Red River at Fargo	306	4,953	9,600
05059000	Sheyenne River near Kindred	151	1,576	3,000
05059300	Sheyenne River above Diversion near Horace	415	2,320	4,224
05059310	Sheyenne River Diversion near Horace	222	1,154	2,085
05059480	Sheyenne River Diversion at West Fargo	822	2,343	3,864
05059500	Sheyenne River at West Fargo	146	1,548	2,950
05060100	Maple River below Mapleton	77	2,107	4,137
05062000	Buffalo River near Dilworth	152	1,916	3,679
05064500	Red River at Halstad	1,395	11,048	20,700

If the minimum and maximum discharge for a rating table did not encompass the high, medium, and/or low flow value(s), the stage(s) from that rating table were not included in the record(s). For example, the maximum discharge for the first rating table for gage 05051522 - Red River at Hickson was 3,280 cfs. Because the high discharge for this specific gage record (5,900 cfs) was greater than the maximum discharge for the rating table, the data point could not be included in the specific gage record. Therefore, the record began with the next rating table with a maximum discharge greater than 5,900 cfs.

Significant high flows and hydraulic control structure installations have the potential to impact specific gage records dramatically in a relatively short period of time. As a result, the timing of these events was identified as a vertical line on the specific gage records to help evaluate whether these particular events had any impact on the specific gage record. The timing of significant high flows was selected as the day the 10-percent annual chance discharge (14,500 cfs) at USGS Gage 05054000 – Red River at Fargo was exceeded. The dates for the significant high flow events are shown in Table 4-11. The year in which hydraulic control structures were constructed or modified is shown in Table 4-12.

Table 4-11. Dates of High Discharge Events at Gage 05054000 – Red River at Fargo

Date	Discharge (cfs)
4/07/1943	16,000
4/16/1952	16,200
4/14/1969	24,800
4/03/1978	17,000
4/19/1979	17,200
4/09/1989	18,600
4/17/1997	27,800
4/14/2001	20,200
4/05/2006	19,800
3/28/2009	29,100

Table 4-12. Control Structure Installations and Modifications

Year	Stream	Structure Name/Channel Modification
1929	Red River	Fargo Midtown Dam Installed
1933	Red River	Fargo North Dam Installed
1933	Red River	Fargo South Dam Installed
1937	Red River	Hickson Dam Installed
1937	Red River	Christine Dam Installed
1942	Red River	White Rock Dam Installed
1950	Sheyenne River	Baldhill Dam Installed
1953	Red River	Orwell Dam Installed
1961	Red River	Fargo Midtown Dam Rebuilt
1992	Sheyenne River	Sheyenne River Diversion Completed

The specific gage records developed for each gage are shown in Appendix I.

4.5.2 Specific Gage Record Analysis

An underlying assumption in a specific gage record analysis is that the rating tables were developed using reliable, accurate data. Inaccurate data resulting from incorrect discharge or stage measurements has the potential to artificially create or mask trends for periods in the record. Additionally, high discharges tend to exhibit a higher variability in stage because these discharges are experienced less often than the lower discharges. Therefore, when field measurements are made at these less frequent discharges, the rating table is more likely to be revised (possibly significantly) due to the relatively few measurements at these values. Another issue to consider is that the hydraulics are more variable at high flows than they are at low flows. For example, as flows overtop the channel banks, seasonal variations in roughness in combination with more complex two-dimensional flow patterns can lead to differing stage and discharge relationships. These issues were considered during the analysis of the specific gage records.

Analysis of the specific gage records reveals that 4 of the 11 gaging locations do not display any apparent trends or abnormalities. These included 05051522 – Red River at Hickson, 05059300 – Sheyenne River above Diversion near Horace, 05060100 – Maple River below Mapleton, and 05062000 – Buffalo River near Dilworth. Stream reaches near gaging locations with specific gage records that do not display any consistently increasing or decreasing trends or abnormalities were considered to be in equilibrium.

One gage, 05054000 – Red River at Fargo, exhibited significant abrupt increases in stage. Three of the gaging locations, 05053000 – Wild Rice River near Abercrombie, 05059000 – Sheyenne River near Kindred, and 05064500 – Red River at Halstad, exhibited consistent decreasing trends in stage; while one gage location, 05059500 – Sheyenne River at West Fargo, displayed an increasing trend in stage. Two gaging locations, 05059310 – Sheyenne River Diversion near Horace and 05059480 – Sheyenne River Diversion at West Fargo, showed short-term decreases in stage following implementation of the diversion project, followed by relatively stable conditions. Whereas changes in the specific gage records for certain gages could be linked to hydraulic control structure installations and revisions, the occurrence of large flood events exceeding the 10% annual chance discharge could not be conclusively linked to shifts in the specific gage record. A brief review of the field measurement records at the gaged sites indicates that measurements are taken on average once a month. Therefore, it is assumed that if large changes occurred because of large flood events, the USGS would have data available that could be used to update the curves. In most instances, the curves were not updated by the USGS following flood events, signifying that notable stage changes did not occur. In the instances that the curves were updated closely following a flood event, notable differences in the stage were not exhibited. Therefore, it was concluded that the occurrence of large flood events exceeding the 10% annual chance discharge does not appear to influence the specific gage stage trends.

Gage 05054000 – Red River at Fargo exhibited three significant changes in the specific gage record (see Figure 4-45). In 1914, a large decrease in the stages for the low and medium discharges occurred. Around 1930, a large increase in the stages for the low and medium discharges occurred. In 1961, a large increase in the stages for all three discharges occurred. The cause of the decrease in 1914 is unknown. The increase around 1930 is attributed to the construction of the Fargo Midtown Dam located downstream of the gaging location. The increase in 1961 is attributed to the reconstruction of the Fargo Midtown Dam in which the crest of the dam was raised. Outside of the periods in which these abrupt changes occurred, the gage record indicates that the Red River at Fargo has remained relatively stable.

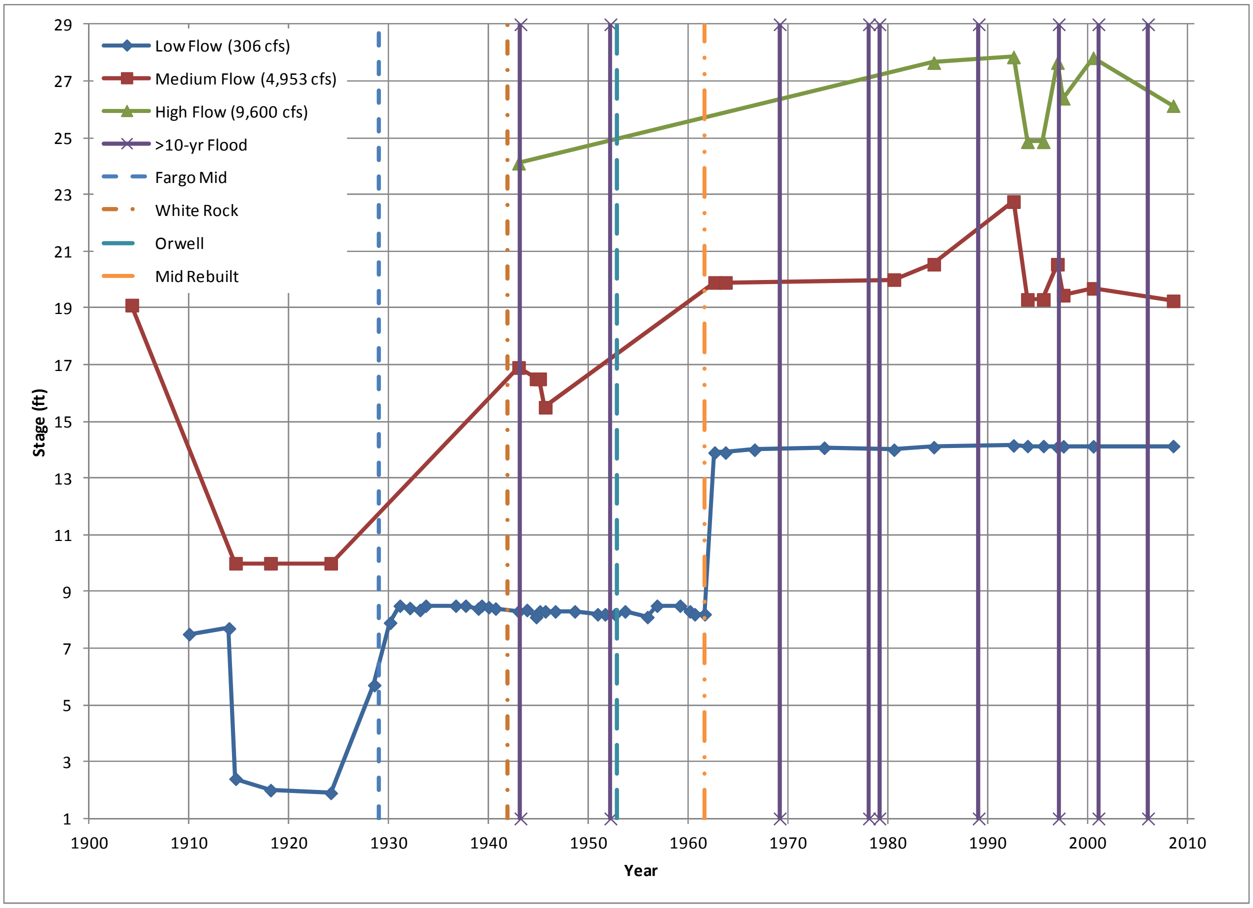


Figure 4-45. Specific Gage Record for Red River at Fargo - 05054000

Four of the gage locations exhibited consistent trends that were assumed to be linked to a change in the channel geometry. Three gages, 05053000 – Wild Rice River near Abercrombie, 05059000 – Sheyenne River near Kindred, and 05064500 – Red River at Halstad, exhibit consistent downward trends in stage, which could indicate that the channels in those areas have been degrading with time. For the Wild Rice River gage, the decrease occurs primarily in recent years, from 1989 to 2008. However, the Sheyenne River (Figure 4-46) and Red River (Figure 4-47) gages show decreasing trends in stage for the entirety of their records. It should be noted that although the Red River at Halstad gage shows a decreasing trend in stage, the other two Red River gages located further upstream have remained relatively stable. This is the likely a result of their location immediately upstream of the Hickson and Fargo Midtown dams. The dams are controlling the hydraulics and the channel gradient at the gage site, which has likely resulted in the stability of their stage-discharge relationships.

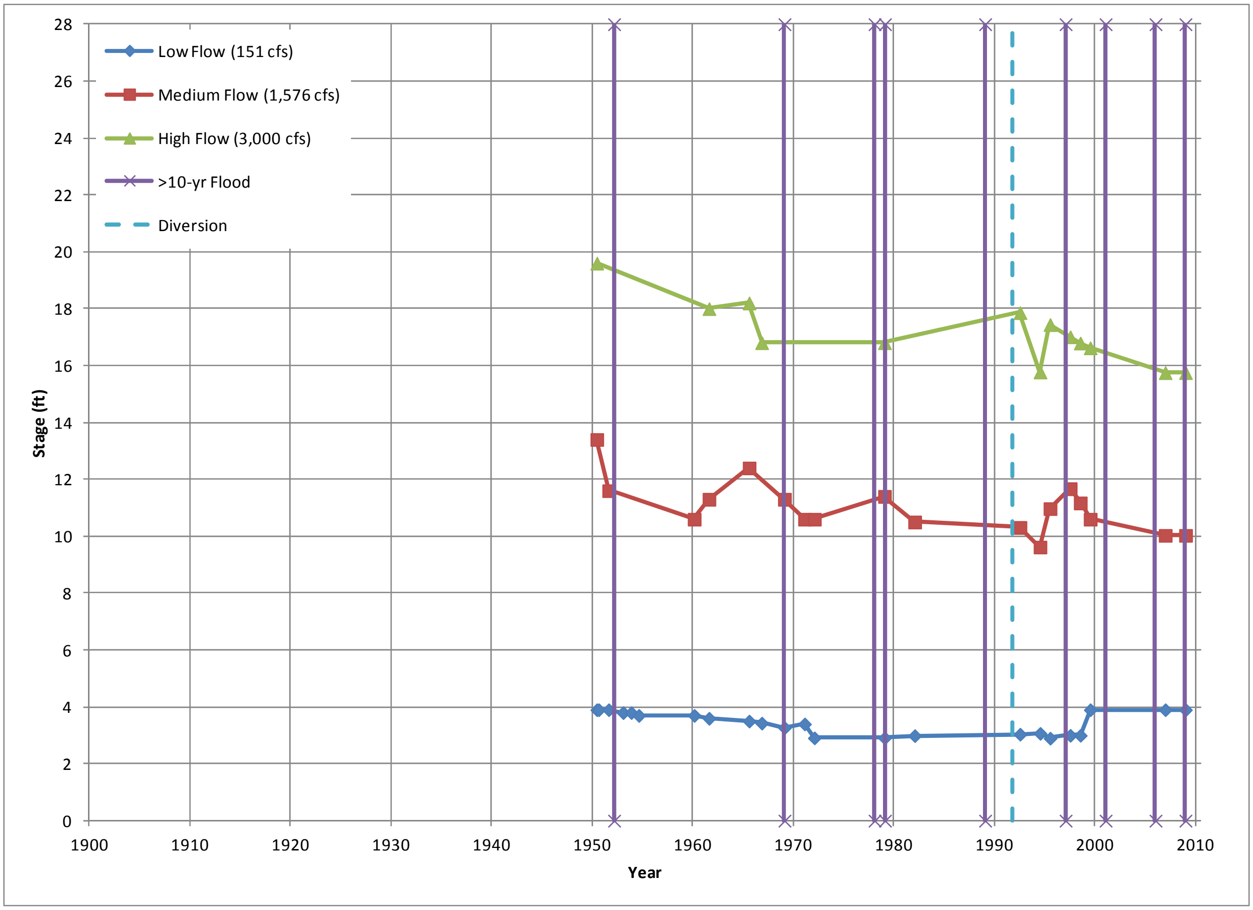


Figure 4-46. Specific Gage Record for Sheyenne River near Kindred - 05059000

Additionally, as seen in Figure 4-47 the stage at the Halstad gage dropped approximately 3 feet in a relatively short period of time between 1992 and 2000. A review of historic photography indicated that the bridge on which the Halstad gage is located was rebuilt along a different alignment sometime between 1997 and 2003. USGS personnel stated that the bridge was replaced in 1999 and that it is unknown if the gage datum shifted due to the bridge realignment. As a result, no conclusions can be made with regard to the observed reduction in stage.

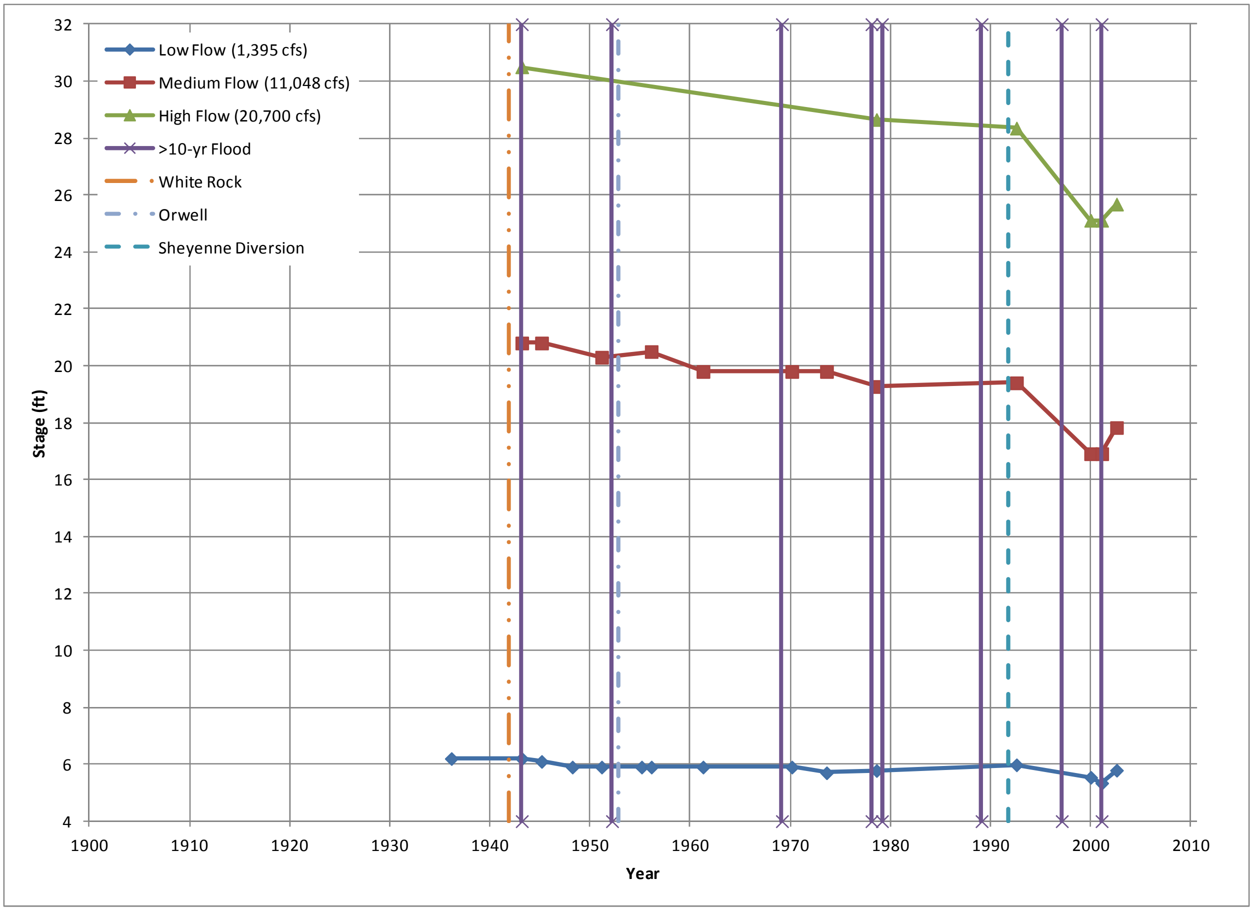


Figure 4-47. Specific Gage Record for Red River at Halstad - 05064500

As seen in Figure 4-48, Gage 05059500 – Sheyenne River at West Fargo had about a 1 foot increase in stage following the 1969 flood for the high flow yet no significant changes occurred for the medium and low flows. This suggests that the flood waters may have deposited enough sediment in the overbanks to have altered the stage-discharge relationship for the high flow events while the medium and low flow stages remained unchanged. There is also about a 2-foot increase in stage for the medium and high flows following the completion of the Sheyenne River Diversion project. The stage increase following the completion of the Sheyenne River Diversion project is likely due to the backwater effects of the control structure located at the downstream confluence of the Sheyenne River and Sheyenne River Diversion. As such, the stage-discharge relationship for the period following the implementation of the Sheyenne Diversion may not be reliable depending on how the gates at the control structure are operated.

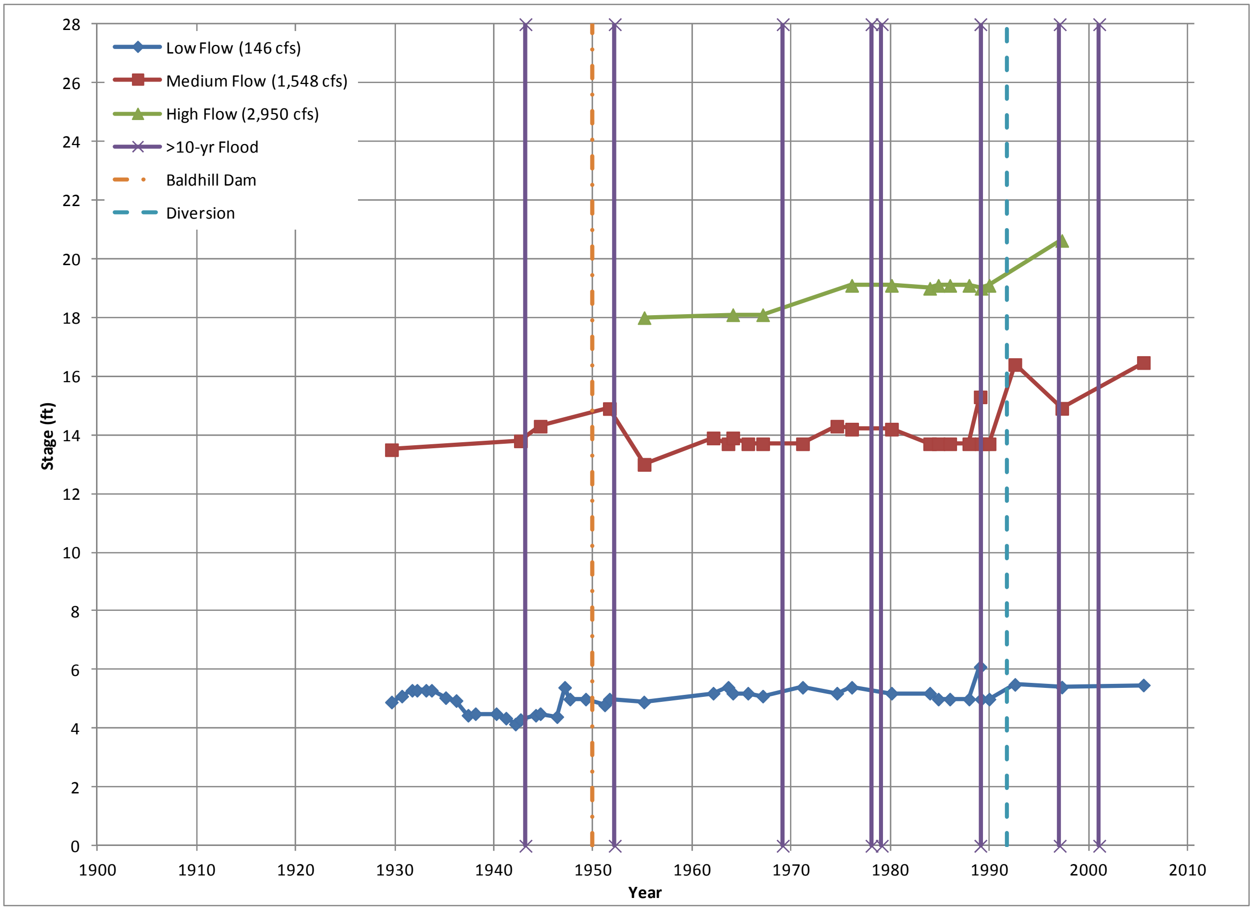


Figure 4-48. Specific Gage Record for Sheyenne River at West Fargo - 05059500

Gages 05059310 – Sheyenne River Diversion near Horace (Figure 4-49) and 05059480 – Sheyenne River Diversion at West Fargo both exhibited stage decreases of one to two feet in the first few years following the implementation of the Fargo Diversion project. Stages since then have remained fairly stable. It is understood that the diversion channel experienced some degradation in the vicinity of the gaging stations during the first few high flow and that riprap was later placed to stabilize the channel and prevent further degradation.

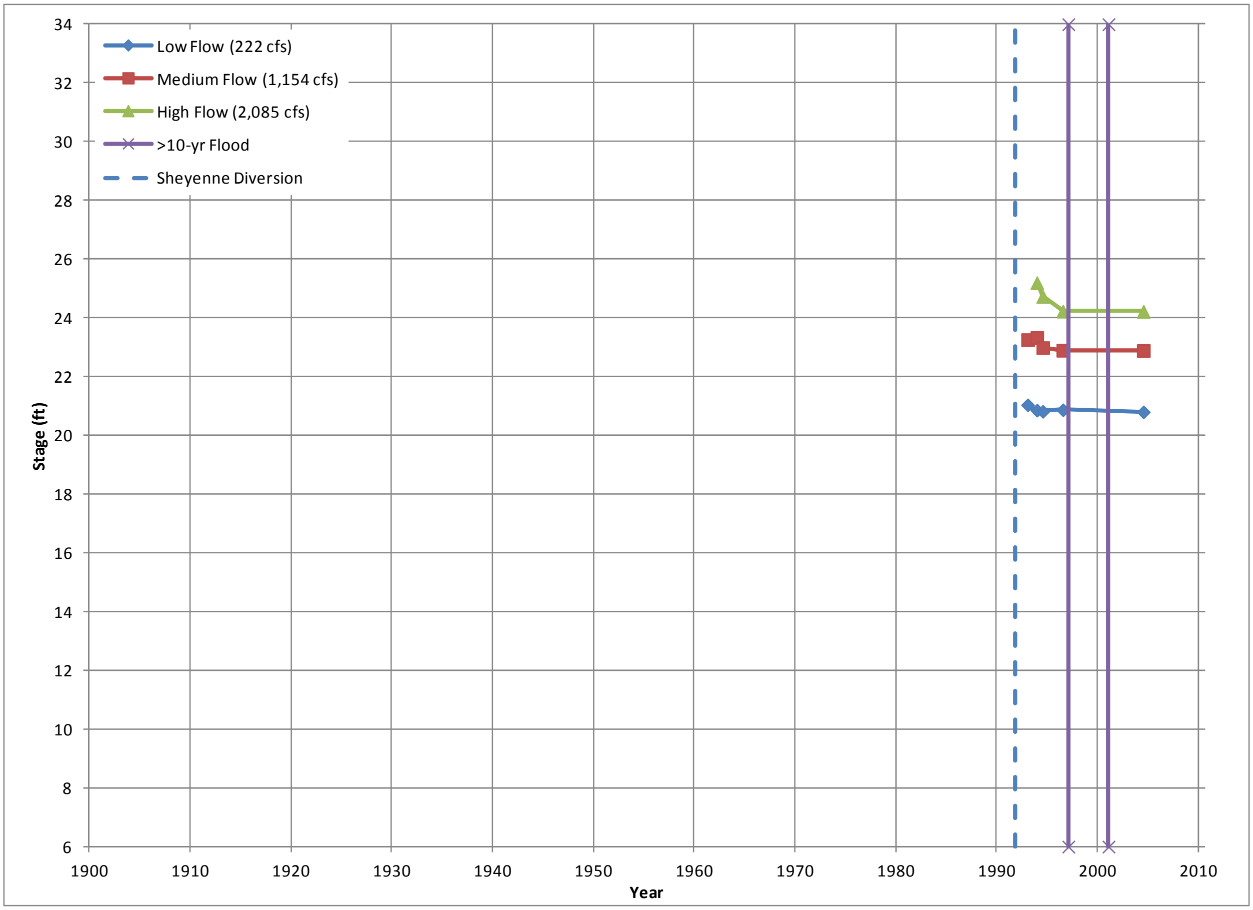


Figure 4-49. Specific Gage Record for Sheyenne River Diversion near Horace - 05059310

A summary of the trends observed in the specific gage record analysis is provided in Table 4-13.

Table 4-13. Specific Gage Record Analysis Summary

Gage Number	Gage Name	Stage Trend	Possible Cause
05064500	Red River at Halstad	Decreasing	Unknown
05054000	Red River at Fargo	Step Increases/Steady	Fargo Midtown Dam
05051522	Red River at Hickson	Steady	-
05059500	Sheyenne River at West Fargo	Increasing	Aggradation/Downstream Control Structure
05059480	Sheyenne River Diversion at West Fargo	Initial Decrease then Steady	Initial Degradation then Riprap Lining
05059310	Sheyenne River Diversion near Horace	Initial Decrease then Steady	Initial Degradation then Riprap Lining
05059300	Sheyenne River above Diversion near Horace	Steady	-
05059000	Sheyenne River near Kindred	Decreasing	Degradation
05053000	Wild Rice River near Abercrombie	Decreasing	Degradation
05060100	Maple River below Mapleton	Steady	-
05062000	Buffalo River near Dilworth	Steady	-

4.6 Hydrology Assessment Conclusions

Channel-forming discharges were assessed using the bankfull discharge, effective discharge, and recurrence interval methods for the current conditions. Channel-forming discharges determined using the effective discharge method were found to be widely variable and did not correlate well with the channel-forming discharges estimated using the bankfull discharge method. The average recurrence interval of the bankfull discharge method was 1.28 years, with a low recurrence interval of 1.05 years and a high recurrence interval of 1.67 years. The effective discharge method resulted in a much higher average and much wider range of recurrence interval, with an average value of 2.10 years, a low value of 1.02 years, and a high value of 4.83 years. The Red River and its tributaries are considered to be supply limited streams. They are generally able to transport all of the fine sediment that is supplied to them. As a result, there is not a direct and consistent correlation between water discharge and sediment discharge. The amount of material being transported by the stream is directly related to the amount of sediment that is supplied to the stream and not necessarily the capacity of the stream to transport sediment. This produces inconsistencies in the results provided by the effective discharge method. Because of the inconsistencies of the effective discharge results and the results of other studies completed in the Upper Midwest, the bankfull discharge method was selected for estimation of the channel-forming discharge for each study reach.

Historic channel-forming discharges were also estimated using the recurrence interval method and flood frequency data for historic flows at the USGS gage Red River of the North at Fargo, ND. The results indicate that the current channel-forming discharge has increased 152% compared to the historic channel-forming discharge. These results are considered to be applicable to detailed study reach Red River – 4 – 452.52. Sufficient historical flow data does not exist for the remaining study reaches. However, similar increases in channel-forming discharge are likely to have occurred.

Discharge-duration analyses for the historic, current, and future (with project) conditions were completed to assess whether notable changes in discharge have occurred and whether future notable changes are expected to occur. The current and future (with project) conditions discharge-duration curves have greater discharges than the historic conditions curves for the sites for which data was available. It is therefore assumed that the remaining detailed study reaches, for which historic data did not exist, also have greater discharges. Comparison of the current conditions to the future with project LPP and FCP scenarios discharge-duration analyses indicated that the discharges are expected to remain the same except in areas protected by the proposed diversion alignments. In the protected areas, the lower more frequent flows will be essentially identical whereas the higher less frequent flows would be reduced as a result of the diversion of flow into the diversion alignments. For the LPP alignment, the Red River and Wild Rice River flows are capped at the 27.8-percent annual chance (3.6-year) peak discharge. For the Sheyenne River and Maple River, flows larger than the 50-percent annual chance (2-year) peak discharge are diverted into the diversion alignment. For the Rush and Lower Rush Rivers, all flows are captured by the diversion channel. Only local inflows will drain to the channel downstream of the diversion. For the FCP alignment, the Red River flows are capped at the 27.8-percent annual chance peak (3.6-year) discharge.

Elevation-duration analyses were also completed for the historic, current, and future conditions. In general, the water surface elevations have increased from the historic to current conditions as a result of an increase in discharges. Water surface elevations are also expected to increase from current to future (with project) conditions for detailed study reaches located in areas that will be used to stage the flow upstream of the diversion inlet structures. However, water surface elevations are expected to decrease from current to future (with project) conditions in areas protected by the diversion alignments.

Specific gage analyses indicates that the water surface elevations at the USGS gages within the study area have remained relatively stable or have exhibited a slight decrease in water surface elevation throughout their period of record. Seven of the eleven gages have relatively stable stage-discharge relationships. Two gages, 05053000 – Wild Rice River near Abercrombie and 05059000 – Sheyenne River near Kindred show a decreasing trend in stage, which indicates potential long-term degradation of the channels. One gage, 05064500 – Red River at Halstad, shows a decreasing trend in stage; however, that trend cannot be attributed to any specific cause due to the change in gage location. One gage, 05059500 – Sheyenne River at West Fargo, shows an increasing trend in stage, which suggests potential long-term aggradation of the channel. This may be the result of backwater from the gated control structure located approximately 0.5 miles downstream of the gage site. Results of the specific gage analysis generally support the conclusions of the historic cross section comparisons discussed in Section 6.2.

5 Geomorphic Stream Classifications

5.1 General

Stream classification systems are intended to categorize streams based on their common morphologic attributes. A thorough stream classification can potentially allow predictions for future stream behavior to be made. A number of classification systems, with ranging levels of complexities, have been proposed over the years. Three classification systems were considered for this study. The three systems are the Rosgen System, the Schumm Method, and the Brice Method. The following sections discuss these classification systems and the results of their application to this study.

5.2 Rosgen Stream Classification System

5.2.1 General

The Rosgen stream classification system (Rosgen, 1996) is broken up into four levels of classification varying from broad geomorphic characterization down to very detail-specific description and assessment. The four levels, per Rosgen (1996), are described below.

Level I, the most basic level, describes the geomorphic characteristics that result from the integration of basin relief, landform, and valley morphology. The dimension, pattern, and profile of rivers are used to delineate geomorphic types at a coarse-scale. Many of the Level I criteria can be determined from topographic and landform maps, and from aerial photography. Even at this broad level, however, individual reaches are delineated and kept unique within the fluvial system.

Level II provides a more detailed morphological description of stream types extrapolated from field-determined reference reach information. The channel entrenchment, dimensions, patterns, profile, and boundary materials are quantified at this level and are described by discreet categories of stream types. This level provides a consistent quantitative morphological assessment and provides a higher-resolution of information with utility for management applications.

Level III describes the existing condition (or state) of the stream as it relates to its stability, response potential, and function. At this level, additional field parameters are evaluated that influence the stream state (e.g., riparian vegetation, sediment supply, flow regime, debris occurrence, depositional features, channel stability, bank erodibility, and direct channel disturbances). Level III analyses are both reach- and feature-specific and are especially useful as a basis for integrating companion studies.

Level IV, the most in-depth level, requires measurements to verify process relationships inferred from the Rosgen Levels I through III analyses. The objective is to establish empirical relationships for use in prediction (e.g., to develop Manning’s n values from measured velocity; correlating bedload versus discharge by stream type to determine sediment transport relationships; or calculating hydraulic geometry from gaging station data). The developed empirical relationships are specific to individual stream types for a given state and enable extrapolation to other similar reaches for which Level IV data is not available. Using relationships developed at Level IV, existing data from gage stations and research sites can be analyzed and extrapolated to similar stream types. Note, however, that without the geomorphic context provided by the preceding analyses, it is difficult to accurately extrapolate information obtained at Level IV. Thus, full use of the hierarchy from Level I to Level IV enables extrapolation and incorporation of existing data that could not otherwise be applied. The Level IV analysis was not completed as a part of this study.

Level II and III classifications were completed for each detailed study reach as a part of this study. Level II classifications focus on questions of sediment supply, stream sensitivity to disturbance, potential for natural recovery, channel response to changes in flow regime, and fish habitat potential (Rosgen, 1996). The end result of the Level II classification is to determine the Rosgen stream type for each detailed study reach. Level II classifications require the use of observations made during the field investigation efforts and channel geometry captured during the 2010 and 2011 cross-sectional surveys. Specifically, the Level II Rosgen classifications are based on five parameters (Rosgen, 1996):

1. Entrenchment Ratio: The top width when the stream is flowing at twice bankfull depth divided by the top width at bankfull. The top widths at twice bankfull depth (used to establish the Rosgen entrenchment ratio) often exceeded the boundaries of the cross sections. In these cases, 2008 LiDAR data was used to extend the cross sections to elevations equal to the elevation at twice the bankfull depth. The relatively large widths at twice the bankfull depths resulted in high entrenchment ratios for most of the Red River basin streams.
2. Width/Depth Ratio: The ratio of the top width divided by the mean or average depth at bankfull. The HEC-RAS models, described in Chapter 4, were used to develop the width/depth ratios.
3. Sinuosity: The ratio of stream length to valley length. The sinuosity was determined based on the total stream length to valley length within each general study reach.
4. Slope: The slope of the water surface. The slopes used for the Rosgen classifications were the energy slopes from the HEC-RAS model, and were less than 0.001 (the lowest threshold for slope used by the Rosgen system) for all detailed study reaches.
5. Dominant Channel Materials: The sediment gradation curves for the bed and bank material samples collected during the field investigation efforts are described in Section 3.4. The median grain size (D_{50}) from the samples was used to categorize the channel material.

The Level III classification describes the existing stream condition or “state” and any departure of the stream from its ideal conditions. Level III classifications do not necessarily provide a singular result; rather, they summarize the important conclusions regarding stream condition and stability. Level III classifications take into consideration a number of hydrologic, biologic, ecologic, and anthropogenic factors in addition to the parameters used in the Level II classification. Specifically, the Level III Rosgen classifications are based on nine parameters (Rosgen, 1996):

1. Riparian Vegetation: The vegetation types and percent site coverage were estimated in the field. Riparian vegetation can indicate stream reaches which are most vulnerable to disturbance.
2. Flow Regime: The streamflow regimes are determined based on the type of flow category (i.e., perennial, ephemeral) and the flow source (i.e., snowmelt, spring-fed).
3. Size and Stream Order: Bankfull width, the width of the stream during bankfull discharges, is used to describe stream size. Stream order is a numbering sequence based on the joining of two similarly ordered streams. For example, two first order streams (those without any definable tributaries) combine to form a second order stream; two second order streams combine to form a third order stream, and so forth.
4. Depositional Pattern: Depositional features within the streams are noted based on the type of features observed. Depositional features can include point bars, diagonal bars, mid-channel bars, islands, side bars, and delta bars.
5. Meander Pattern: Channel meander patterns were determined using aerial imagery. Meander geometry characteristics can be used to assess the effects of changes in width/depth ratios, bank erosion estimates, sediment supply; and changes in pattern, dimension, and slope on channel stability.
6. Debris and Channel Blockages: The extent and type of debris forming channel blockages was noted during the field observations. Debris can affect stream stability and sediment storage, among other factors.
7. Channel Stability Rating: Pfankuch (1975) developed a system to rate channel stability. Included in the rating are three primary factors: sediment supply, bed stability, and width/depth ratio state. The Pfankuch method observations were recorded during the field investigation.
8. Bank Erosion Potential: A number of different factors were assessed to determine the ability of stream banks to resist erosion: the ratio of stream bank height to bankfull stage; the ratio of riparian vegetation rooting depth to stream bank height; the degree of rooting density; the composition of stream bank materials; stream bank angle; bank material stratigraphy and presence of soil lenses; and bank surface protection afforded by debris and vegetation. The various stream bank conditions are assigned numerical indices to quantitatively assess the susceptibility of the stream bank to erosion.
9. Altered Channel State: The dimensions, patterns, slope, and materials of anthropogenically-altered stream channels were compared with historic stream channels to assess the impact of manmade changes.

The Rosgen System provides predictions of the sensitivity to a disturbance (such as a long-term change in flows and/or sediment supply), the lateral and vertical stability, and other characteristics such as the tendency to form point bars. The predictive ability of the classification in determining channel response is subject to debate (Juracek and Fitzpatrick, 2003; Roper et al., 2008; Simon et al., 2007). Assuming that the classification system provides valid predictions, it is still difficult to draw firm conclusions due to the qualitative nature of the predictions.

Each one of the detailed study reaches was classified using the Rosgen system for two purposes; firstly, to aid in communication when discussing the channel reaches and secondly, to predict approximate rates at which the morphology of the sections might change in response to the future flow scenarios. In spite of possible limitations in the predictive capability of the Rosgen system, it was believed that the results would still be beneficial when viewed in conjunction with the other analyses completed as a part of this study.

5.2.2 Rosgen System Classification

5.2.2.1 Level II

Table 5-1 provides a summary of the Level II Rosgen System classifications for the detailed study reaches. Figure 5-1 provides the relationship between stream characteristics shown in Table 5-1 and the Rosgen stream type classification. As seen in the Table, the study reaches were classified into B6, C6, E5, or E6 stream types. Additionally, the Level II Rosgen classification of each general study reach is shown in Figure 5-2. The completed Level II Rosgen forms are provided in Appendix J. Items that are grayed out on the Rosgen forms were considered not applicable to this study.

According to Rosgen (1996), the B6, E6, and E5 channel types are fairly stable while the C6 channel type is susceptible to changes in river conditions. A more detailed description of the channel types is provided below.

The B6 stream type is a moderately entrenched system, incised in cohesive materials, with channel slopes less than 4%. Gradients less than 0.02 are denoted as a B6c to indicate the very low gradients of many B6 stream types. The B6 stream types are found in narrow valleys containing cohesive residual soils; in depositional landscapes composed of fine, wind deposited (Loess) materials formed as gently sloping terrain; and on well vegetated alluvial fans. B6 stream types are generally stable due to the effects of moderate entrenchment and lower width/depth ratios. Additionally, riparian vegetation associated with the B6 type is generally very dense, except in arid environments and plays an important role in maintaining channel stability and lower width/depth ratios. These stream types are “washload” rather than “bedload” streams, and thus, have a characteristically low bed material sediment supply and an infrequent occurrence of sediment deposition. The B6 stream type has an entrenchment ratio between 1.4 and 2.2, a width/depth ratio greater than 12, moderate sinuosity between 1.2 and 1.5, and a bed composed of silt/clay sized material.

The C6 stream type is slightly entrenched, meandering, silt-clay dominated, riffle pool channel with a well-developed floodplain. Generally, C6 stream channels have gentle gradients of less than 2%. Gradients less than 0.001 are denoted as a C6c- to indicate the very low gradients of many C6 stream types. The C6 stream channel displays a lower width/depth ratio than all of the other C stream types due to the cohesive nature of stream bank materials. The riffle/pool sequence for the C6 stream type is, on average 5-7 bankfull channel widths in length. The stream banks are generally composed of silt, clay, and organic materials, with the stream beds exhibiting little difference in pavement and sub-pavement material composition. Rates of lateral adjustment are influenced by the presence and condition of riparian vegetation. Sediment supply is moderate to high, unless stream banks are in a highly eroded condition. Bedload sediment yields for the stream types are typically low, reflecting the presence of fine bed and bank materials and gentle channel slopes. The C6 stream type is very susceptible to shifts in both lateral and vertical stability caused by direct channel disturbance and changes in flow and sediment supply of the contributing watershed. The C6 stream type has an entrenchment ratio greater than 2.2, a width/depth ratio greater than 12, moderate to high sinuosity greater than 1.2, and a bed composed of silt/clay sized material.

The E5 stream type has high sinuosity, gentle to moderately steep channel gradients, and very low channel width/depth ratios. Due to the inherently stable nature of the bed and banks, this stream type can develop with a wide range of channel slopes. Sinuosities and meander width ratios decrease, however, with an increase in slope. Streambanks are composed of materials finer than that of the dominant channel bed materials, and are typically stabilized with extensive riparian or wetland vegetation that forms densely rooted sod mats from grasses and grass like plants, as well as woody species. The E5 stream types are hydraulically efficient channel forms and they maintain a high sediment transport capacity. The narrow and relatively deep channels maintain a high resistance to plan form adjustment, which results in channel stability without significant downcutting. The E5 stream channels are very stable unless the streambanks are disturbed, and significant changes in sediment supply and/or streamflow occur. The E5 stream type has an entrenchment ratio greater than 2.2, a width/depth ratio less than 12, high sinuosity greater than 1.5, and a bed composed of sand sized material.

The E6 stream type has low to moderate sinuosity, gentle to moderately steep channel gradients, and very low channel width/depth ratios. The E6 stream type is typically seen as a riffle/pool system with the dominant channel materials composed of silt and clay interspersed with organic materials. Channel slopes are less than 2% with a high number having slopes of less than 0.01%. Due to the inherently stable nature of the bed and banks, this stream type can exist on a wide range of slopes. The sinuosity decreases, however, with an increase in slope. The meander width ratio, which is the belt width divided by the bankfull width also decreases with an increase in slope. Stream banks are composed of materials similar to those of the dominant bed materials and are typically stabilized by riparian or wetland vegetation that forms densely rooted sod mats from grasses and grass like plants as well as woody species. Typically, the E6 stream channel has high meander width ratios. The E6 stream types are hydraulically efficient forms, as they require the least cross sectional area per unit of discharge. The narrow and relatively deep channels maintain a high resistance to plan form adjustment, which results in channel stability without significant downcutting. The E6 stream channels are very stable unless the stream banks are disturbed and significant changes in sediment supply and/or streamflow occur. The E6 stream type has an entrenchment ratio greater than 2.2, a width/depth ratio less than 12, high sinuosity greater than 1.5, and a bed composed of silt/clay sized material.

The majority of the detailed study reaches (classified as B6c, E5, or E6) are stable based upon the Rosgen stream type definitions. However, according to the Rosgen classification system, the detailed study reaches on the Red River, classified as C6c-, are potentially unstable both laterally and vertically due to changes in flow and sediment supply. All of the other analyses completed as part of this study indicate that the Red River is not shifting laterally or vertically over time. Therefore, it is concluded that the Rosgen system incorrectly classifies the Red River stream type. Because the bankfull discharge value for Sheyenne River – 5 – 26.47 could not be determined, the Rosgen Level II assessment could not be completed for this detailed study reach.

Table 5-1. Level II Rosgen Classification for Detailed Study Reaches

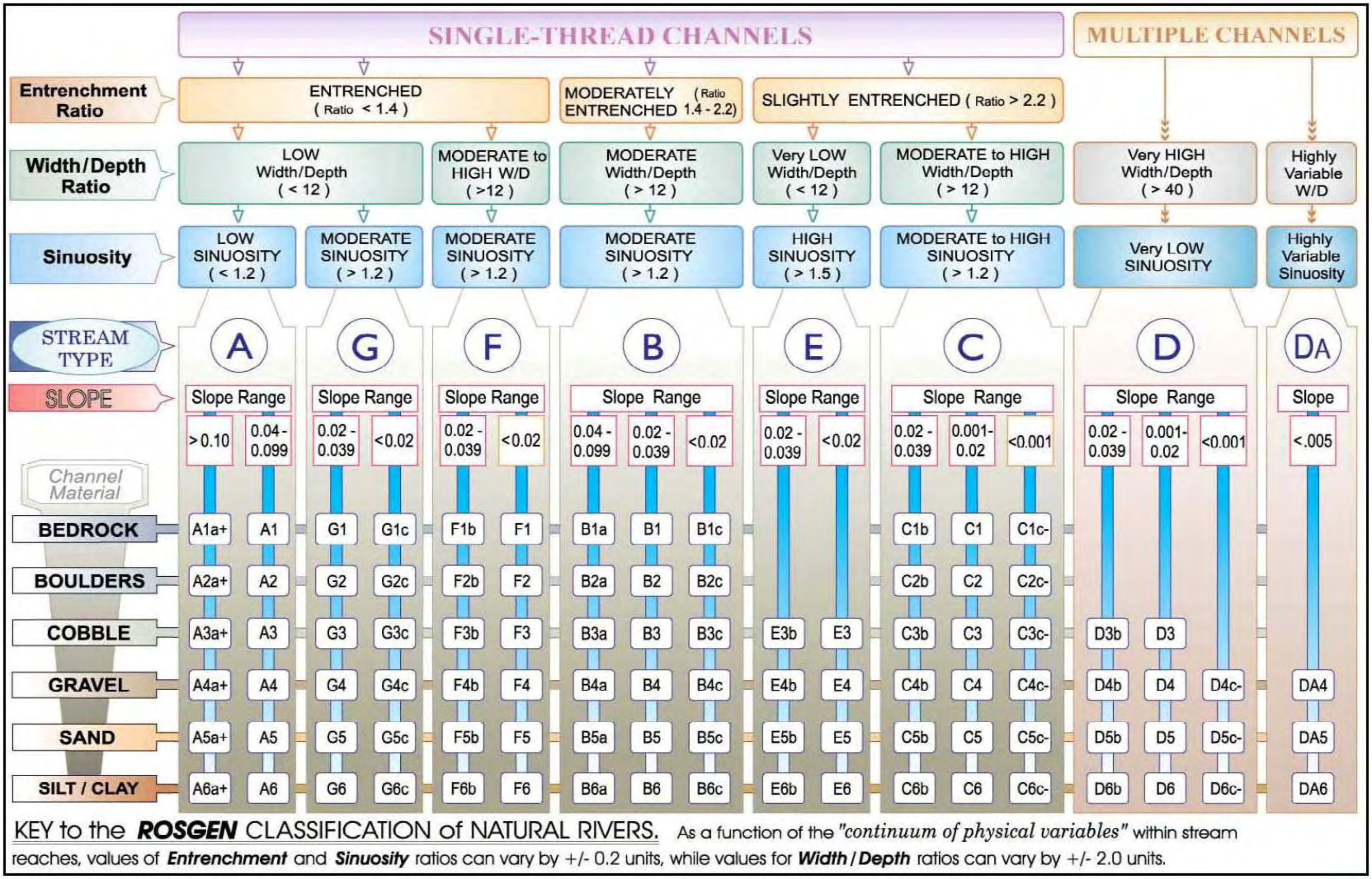
Detailed Study Reach	Entrenchment Ratio[1]	Width/Depth Ratio[2]	Sinuosity	Rosgen Classification
Buffalo River-1-1.19	2.7	11.5	2.2	E6
Lower Rush River-1-1.10	1.6	25.5	-	B6c[3]
Lower Rush River-2-6.03	1.4	38.7	1.3	B6c[3]
Maple River-1-0.78	5.5	11.7	2.2	E6
Maple River-2-11.39	9.3	11.1	1.7	E6
Red River-1-410.65	3.7	15.6	2.0	C6c-
Red River-2-419.14	5.2	13.1	2.2	C6c-
Red River-3-440.57	4.6	13.9	2.2	C6c-
Red River-4-452.52	4.4	15.5	2.2	C6c-
Red River-5-463.56	6.6	12.9	2.4	C6c-
Red River-6-470.23	3.4	12.7	2.3	C6c-
Red River-7-492.47	3.3	13.6	2.6	C6c-
Red River-8-521.18	5.7	20.8	2.6	C6c-
Rush River-1-0.08	2.5	11.5	-	E6[3]
Rush River-2-6.15	2.9	8.7	1.4	E6[3]
Sheyenne River-1-4.20	5.0	9.2	2.8	E6
Sheyenne River-2-11.56	7.1	12.6	1.5	E5
Sheyenne River-3-18.15	5.7	10.0	1.9	E6
Sheyenne River-4-22.27	7.5	8.4	1.8	E6
Sheyenne River-5-26.47	[4/]	[4/]	[4/]	[4/]
Sheyenne River-6-35.82	11.3	9.1	1.8	E6
Sheyenne River-7-43.27	11.2	8.0	1.8	E6
Sheyenne River-8-55.75	12.0	9.0	4.0	E5
Wild Rice River-1-3.01	4.2	11.3	3.9	E6
Wild Rice River-2-4.23	3.4	13.5	2.3	E6
Wild Rice River-3-17.52	2.0	12.1	1.5	E6
Wild Rice River-4-22.94	1.9	13.4	1.8	B6c
Wild Rice River-5-38.49	3.2	10.6	1.9	E6
Wild Rice River-6-42.36	2.1	12.6	2.7	E6
Wolverton Creek-1-0.64	1.9	12.2	1.7	B6c
Wolverton Creek-2-2.02	5.3	7.6	1.3	E6[3]

[1] Entrenchment ratios from 1 to 1.4 are "entrenched," those from 1.4 to 2.2 are "moderate," and those greater than 2.2 are "slight." The Rosgen system allows for entrenchments to vary +/- 0.2 from the classification boundaries of 1.4 and 2.2.

[2] The Rosgen system allows for width/depth ratios to vary +/- 2.0 from the boundary of 12.

[3] The channel dimensions of the Lower Rush River, Rush River, and upstream Wolverton Creek detailed study reaches are primarily the result of anthropogenic alterations. Therefore, the classification of these streams is greatly influenced by these alterations rather than natural channel-forming processes.

[4/] Bankfull discharge could not be determined, as discussed in Section 4.2.1.



KEY to the ***ROSGEN*** CLASSIFICATION of NATURAL RIVERS. As a function of the *"continuum of physical variables"* within stream reaches, values of ***Entrenchment*** and ***Sinuosity*** ratios can vary by +/- 0.2 units, while values for ***Width / Depth*** ratios can vary by +/- 2.0 units.

Figure 5-1. Rosgen Stream Classification Diagram (Rosgen, 2006)

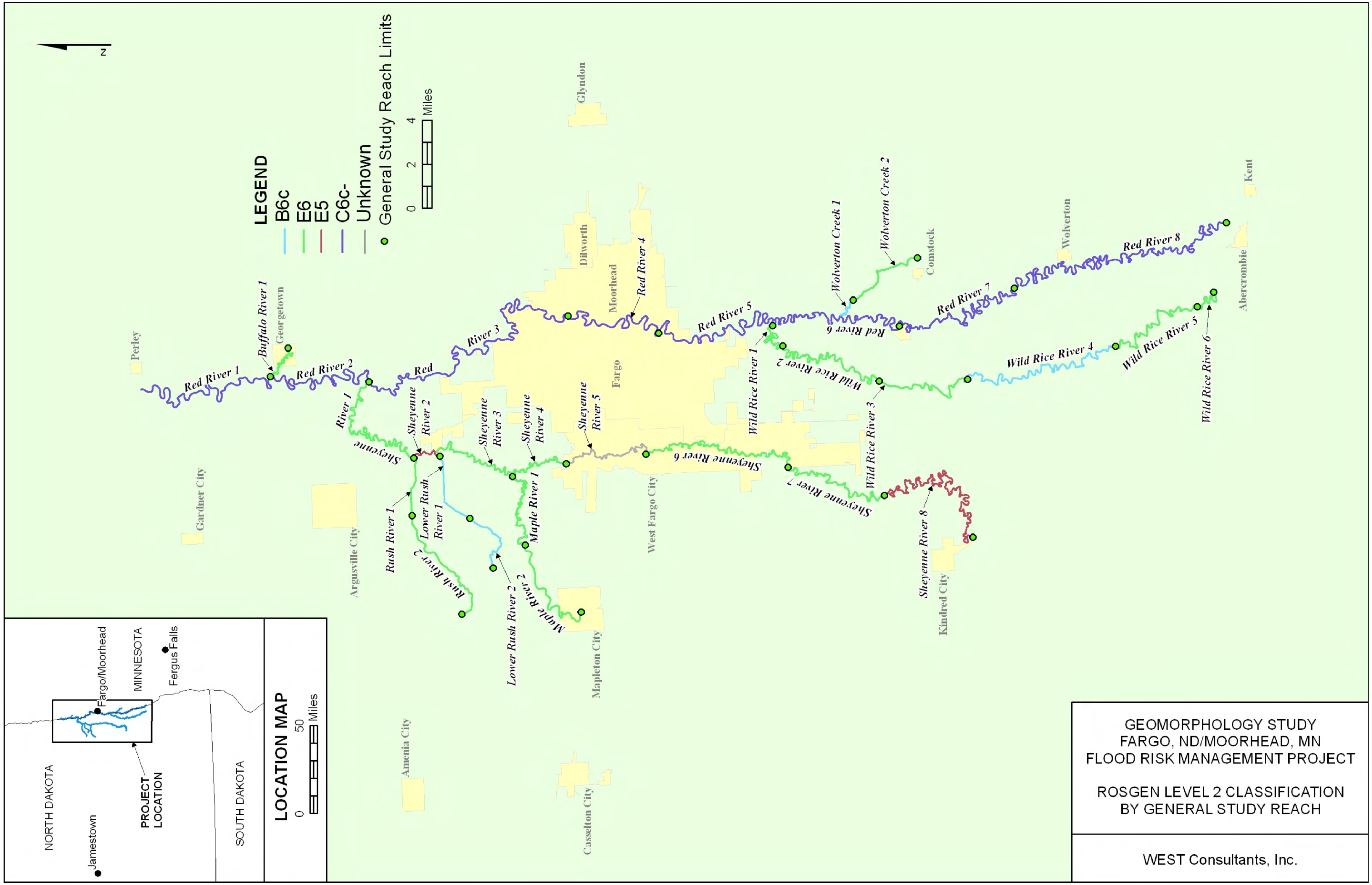


Figure 5-2. Rosgen Level II Classification

5.2.2.2 Level III

The Rosgen Level III assessment uses specific channel stability indices to assess stream condition and stability and is generally used to formulate site- and process-specific mitigation. The stream condition and stability is assessed using a series of worksheets, figures, and tables. While the results of the analyses do not provide a singular quantifiable conclusion as in the case of the Level II analyses, they do provide a qualitative rating with regard to vertical and lateral stability and assess the potential for the channel to succeed from one stream type to another. The following paragraphs summarize the results of each applicable worksheet. Descriptions and summaries of each worksheet utilized in the Rosgen Level III analyses are explained in the following paragraphs. Qualitative ratings for each detailed study reach are presented on a summary worksheet (Worksheet 3-22). The completed Level III Rosgen forms, including the summary worksheet, are provided in Appendix K. Items that are grayed out on the Rosgen forms were not considered applicable to this study.

WORKSHEET 3-1: RIPARIAN VEGETATION

Riparian vegetation site coverages were classified during the 2010/2011 field investigations. Specifically, the percent of site coverage covered by canopy, shrub, herbaceous, leaf or needle litter, and bare ground was estimated. Observations of the vegetative conditions for each detailed study reach are shown in Table 5-2. While Rosgen indicates that riparian vegetation has a marked influence on the stability of streams (Rosgen, 1996), observations and other analyses completed and discussed in this report indicates that vegetation coverage does not have a significant impact on stream stability. Typical benefits from vegetation including surface protection and increased strength from root penetration do not appear to affect the stability of the banks. Rather, the soil types and moisture conditions appear to have the greatest influence on bank stability.

Table 5-2. Rosgen Level III Riparian Vegetation Summary

Detailed Study Reach	Percent Canopy	Percent Shrub Layer	Percent Herbaceous	Percent Litter Layer	Percent Bare Earth
Buffalo River-1-1.19	10	2	3	0	85
Lower Rush River-1-1.10	0	20	48	2	30
Lower Rush River-2-6.03	0	15	85	0	0
Maple River-1-0.78	1	58	36	0	5
Maple River-2-11.39	1	48	49	0	2
Red River-1-410.65	5	20	10	0	65
Red River-2-419.14	10	15	10	0	65
Red River-3-440.57	1	2	2	0	95
Red River-4-452.52	1	2	5	1	91
Red River-5-463.56	1	3	5	0	91
Red River-6-470.23	2	1	1	0	96
Red River-7-492.47	15	40	20	5	20
Red River-8-521.18	10	35	15	5	35
Rush River-1-0.08	0	10	10	0	80
Rush River-2-6.15	0	0	94	1	5
Sheyenne River-1-4.20	2	10	22	6	60
Sheyenne River-2-11.56	2	3	10	10	75
Sheyenne River-3-18.15	1	0	5	0	94
Sheyenne River-4-22.27	3	10	7	20	60
Sheyenne River-5-26.47	3	40	27	10	20
Sheyenne River-6-35.82	2	40	43	10	5
Sheyenne River-7-43.27	1	5	2	1	91
Sheyenne River-8-55.75	3	38	7	2	50
Wild Rice River-1-3.01	3	3	5	10	79
Wild Rice River-2-4.23	5	10	10	5	70
Wild Rice River-3-17.52	10	25	5	5	55
Wild Rice River-4-22.94	15	5	15	5	60
Wild Rice River-5-38.49	15	10	5	10	60
Wild Rice River-6-42.36	20	20	5	5	50
Wolverton Creek-1-0.64	1	27	27	15	30
Wolverton Creek-2-2.02	0	13	15	2	70

WORKSHEET 3-2 THROUGH 3-6: STREAM STABILITY INDICIES

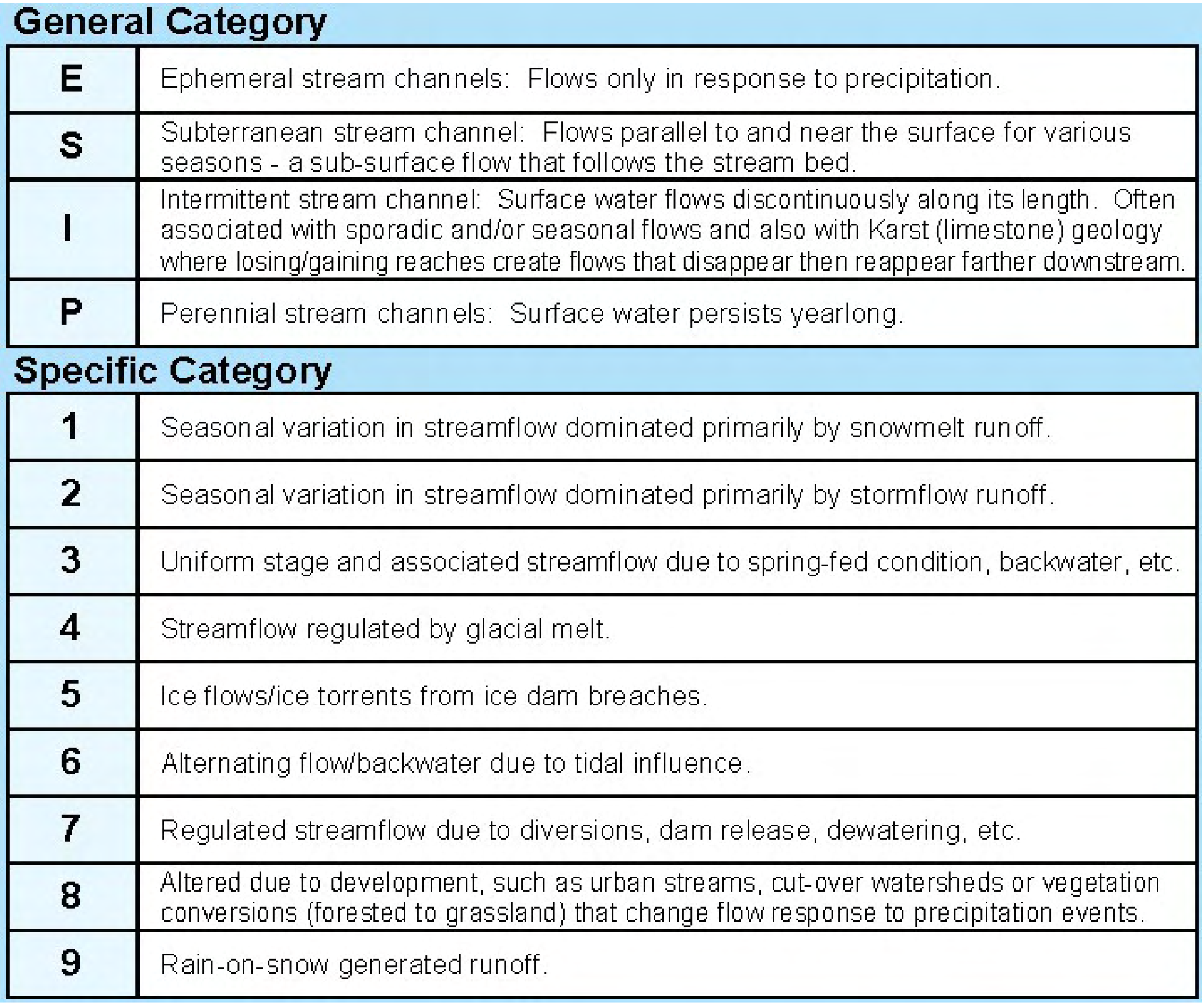
The flow regime, stream size, meander pattern, depositional pattern, and channel blockage characteristics of each of the detailed study reaches were classified during the 2010/2011 field investigations and through use of current aerial imagery. Flow regime classifications were completed in accordance with the Rosgen scheme shown in Figure 5-3. All of the streams besides the Lower Rush River were classified as perennial streams (general category P). The Lower Rush River was classified as an ephemeral stream (general category E). All of the streams were fit into specific categories 1, 2, and 9, indicating that at different times throughout the year, streamflow is generated by either snowmelt runoff, stormflow runoff, or rain-on-snow runoff, respectively. Additionally, the Maple River, Red River, and Sheyenne River detailed study reaches were classified in specific category 7, as they are all affected to a certain extent by dam operations upstream of the study reaches. Finally, detailed study reaches Red River – 3 – 440.57, Red River – 4 – 452.52, and Sheyenne River – 5 – 26.47 were classified in specific category 8 due to their location within developed areas of the watershed. The results of the flow regime investigation are shown in Table 5-3. It is noted that the flow regime classifications do not directly influence the stability classification of the streams.

Stream size classifications were completed in accordance with the Rosgen scheme shown Figure 5-4. The stream classification varied based on the bankfull top width of the stream. The smallest streams in the study area were the Wolverton Creek detailed study reaches, and the largest were the Red River detailed study reaches. The stream size investigation results are shown in Table 5-3. It is noted that the stream size classifications do not directly influence the stability classification of the streams.

Meander patterns were identified using current aerial imagery and were compared to the classification system shown in Figure 5-5. Meander pattern classification is used in the assessment of lateral stability. In general, the smaller streams were classified as “M1”, indicating stable channels. The larger streams were generally classified as having “M2” meander patterns, indicating a greater likelihood of lateral channel instability when solely considering meander pattern. The results of the meander pattern classifications are shown in Table 5-3.

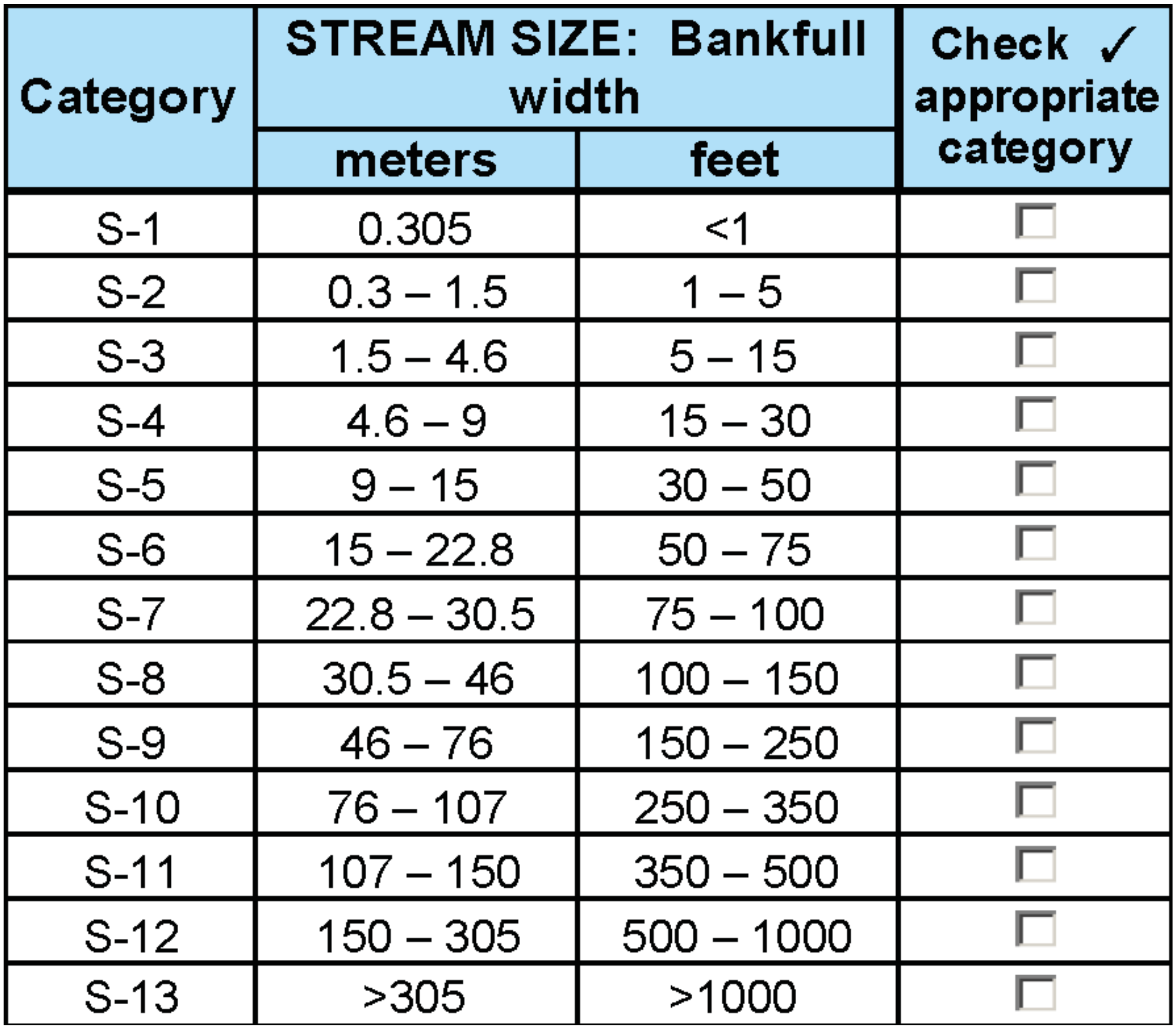
Depositional patterns were assessed using the classification scheme shown in Figure 5-6. None of the detailed study reaches contained depositional features, indicating that the channels are laterally and vertically stable. The results of the depositional pattern classifications are shown in Table 5-3.

The level of debris blockage varied considerably between detailed study reaches. As such, the impact of the debris blockages on sediment deposition in the channels, and hence, vertical stability varied considerably. The classification scheme for the debris blockages is shown in Figure 5-7 and the results of the classifications are shown in Table 5-3.



General Category	
E	Ephemeral stream channels: Flows only in response to precipitation.
S	Subterranean stream channel: Flows parallel to and near the surface for various seasons - a sub-surface flow that follows the stream bed.
I	Intermittent stream channel: Surface water flows discontinuously along its length. Often associated with sporadic and/or seasonal flows and also with Karst (limestone) geology where losing/gaining reaches create flows that disappear then reappear farther downstream.
P	Perennial stream channels: Surface water persists yearlong.
Specific Category	
1	Seasonal variation in streamflow dominated primarily by snowmelt runoff.
2	Seasonal variation in streamflow dominated primarily by stormflow runoff.
3	Uniform stage and associated streamflow due to spring-fed condition, backwater, etc.
4	Streamflow regulated by glacial melt.
5	Ice flows/ice torrents from ice dam breaches.
6	Alternating flow/backwater due to tidal influence.
7	Regulated streamflow due to diversions, dam release, dewatering, etc.
8	Altered due to development, such as urban streams, cut-over watersheds or vegetation conversions (forested to grassland) that change flow response to precipitation events.
9	Rain-on-snow generated runoff.

Figure 5-3. Flow Regime Classification (Rosgen, 2006)



Category	STREAM SIZE: Bankfull width		Check ✓ appropriate category
	meters	feet	
S-1	0.305	<1	☐
S-2	0.3 – 1.5	1 – 5	☐
S-3	1.5 – 4.6	5 – 15	☐
S-4	4.6 – 9	15 – 30	☐
S-5	9 – 15	30 – 50	☐
S-6	15 – 22.8	50 – 75	☐
S-7	22.8 – 30.5	75 – 100	☐
S-8	30.5 – 46	100 – 150	☐
S-9	46 – 76	150 – 250	☐
S-10	76 – 107	250 – 350	☐
S-11	107 – 150	350 – 500	☐
S-12	150 – 305	500 – 1000	☐
S-13	>305	>1000	☐

Figure 5-4. Stream Size Classification (Rosgen, 2006)

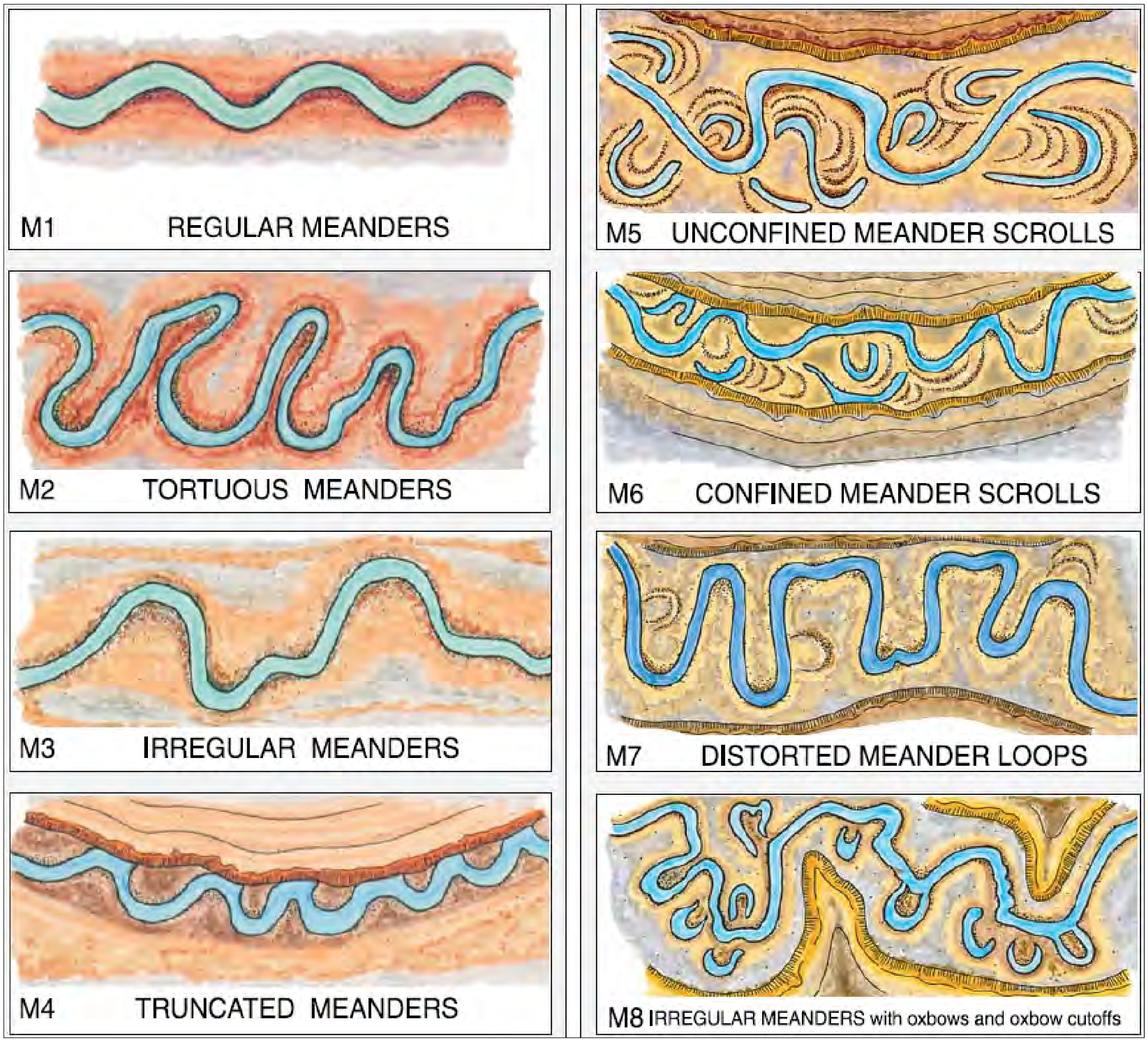


Figure 5-5. Meander Pattern Classification (Rosgen, 2006)

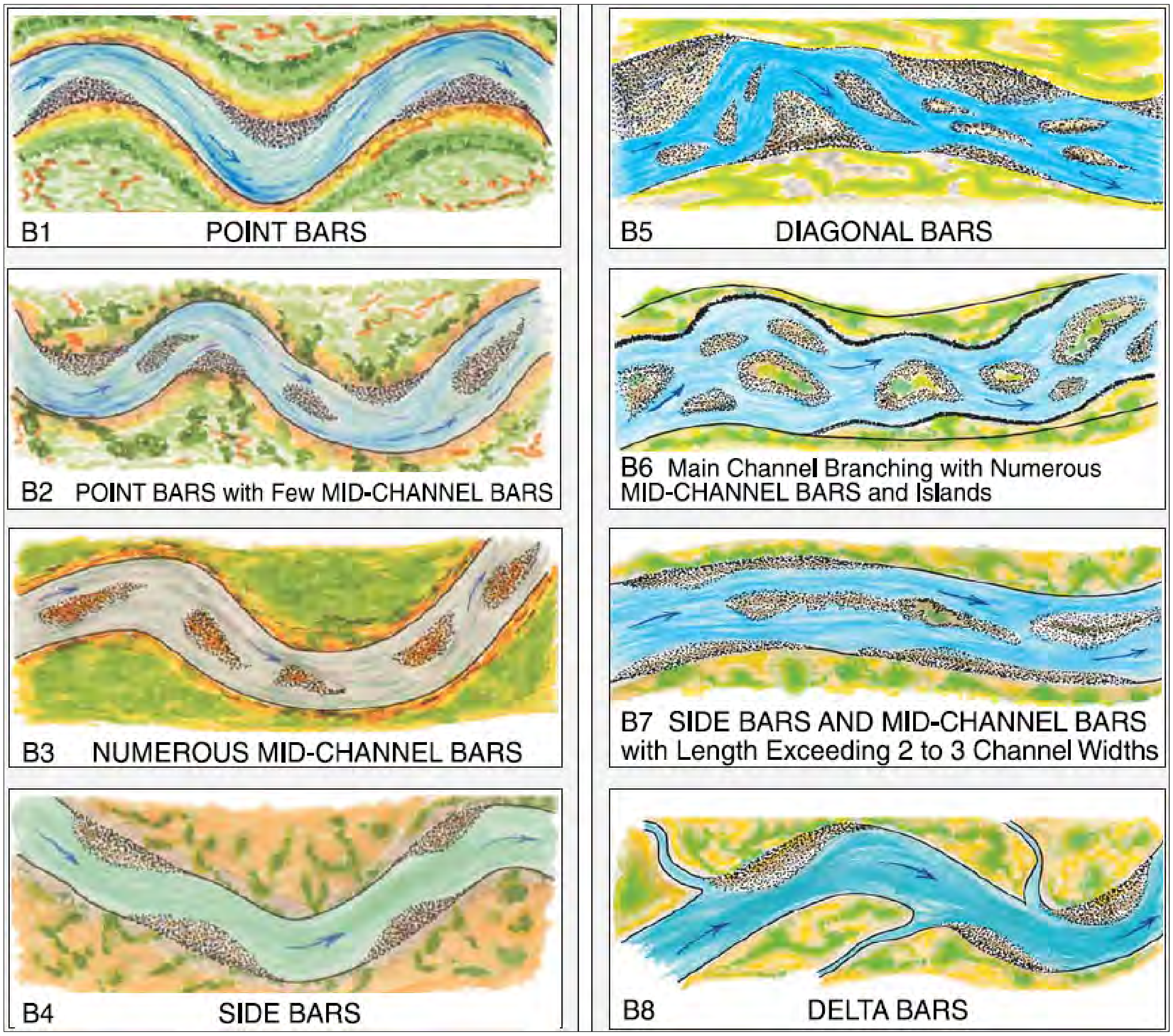
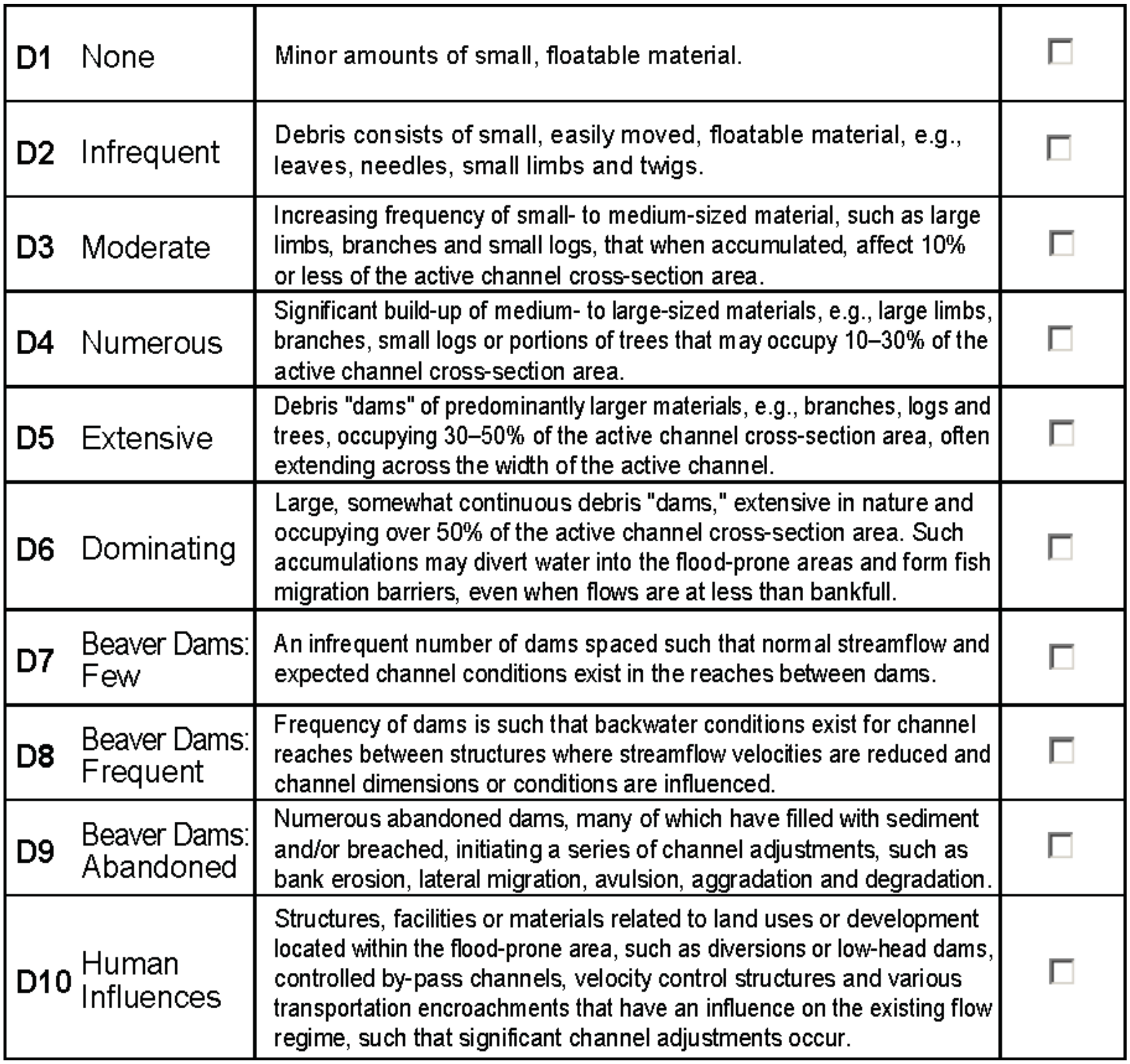


Figure 5-6. Depositional Pattern Classification (Rosgen, 2006)



D1	None	Minor amounts of small, floatable material.	☐
D2	Infrequent	Debris consists of small, easily moved, floatable material, e.g., leaves, needles, small limbs and twigs.	☐
D3	Moderate	Increasing frequency of small- to medium-sized material, such as large limbs, branches and small logs, that when accumulated, affect 10% or less of the active channel cross-section area.	☐
D4	Numerous	Significant build-up of medium- to large-sized materials, e.g., large limbs, branches, small logs or portions of trees that may occupy 10–30% of the active channel cross-section area.	☐
D5	Extensive	Debris "dams" of predominantly larger materials, e.g., branches, logs and trees, occupying 30–50% of the active channel cross-section area, often extending across the width of the active channel.	☐
D6	Dominating	Large, somewhat continuous debris "dams," extensive in nature and occupying over 50% of the active channel cross-section area. Such accumulations may divert water into the flood-prone areas and form fish migration barriers, even when flows are at less than bankfull.	☐
D7	Beaver Dams: Few	An infrequent number of dams spaced such that normal streamflow and expected channel conditions exist in the reaches between dams.	☐
D8	Beaver Dams: Frequent	Frequency of dams is such that backwater conditions exist for channel reaches between structures where streamflow velocities are reduced and channel dimensions or conditions are influenced.	☐
D9	Beaver Dams: Abandoned	Numerous abandoned dams, many of which have filled with sediment and/or breached, initiating a series of channel adjustments, such as bank erosion, lateral migration, avulsion, aggradation and degradation.	☐
D10	Human Influences	Structures, facilities or materials related to land uses or development located within the flood-prone area, such as diversions or low-head dams, controlled by-pass channels, velocity control structures and various transportation encroachments that have an influence on the existing flow regime, such that significant channel adjustments occur.	☐

Figure 5-7. Debris Blockage Classification (Rosgen, 2006)

Table 5-3. Rosgen Level III Stream Stability Indices Summaries

Detailed Study Reach	Flow Regime	Stream Size	Meander Patterns	Depositional Patterns	Channel Blockages
Buffalo River-1-1.19	P1, P2, P9	S-7	M1	None	D1, D2, D3, D4, D5
Lower Rush River-1-1.10	E1, E2, E9	S-5	M1	None	D1
Lower Rush River-2-6.03	E1, E2, E9	S-7	M1	None	D1
Maple River-1-0.78	P1, P2, P7, P9	S-6	M2	None	D1, D5
Maple River-2-11.39	P1, P2, P7, P9	S-6	M1	None	D2
Red River-1-410.65	P1, P2, P7, P9	S-9	M2	None	D2, D3
Red River-2-419.14	P1, P2, P7, P9	S-9	M2	None	D1, D2, D3
Red River-3-440.57	P1, P2, P7, P8, P9	S-8	M2	None	D2
Red River-4-452.52	P1, P2, P7, P8, P9	S-9	M2	None	D2
Red River-5-463.56	P1, P2, P7, P9	S-8	M2	None	D2
Red River-6-470.23	P1, P2, P7, P9	S-8	M2	None	D3
Red River-7-492.47	P1, P2, P7, P9	S-8	M2	None	D1, D2, D3, D4
Red River-8-521.18	P1, P2, P7, P9	S-8	M2	None	D1, D2, D3
Rush River-1-0.08	P1, P2, P9	S-5	M1	None	D1
Rush River-2-6.15	P1, P2, P9	S-4	M1	None	D2
Sheyenne River-1-4.20	P1, P2, P7, P9	S-7	M2	None	D3
Sheyenne River-2-11.56	P1, P2, P7, P9	S-8	M2	None	D3
Sheyenne River-3-18.15	P1, P2, P7, P9	S-7	M2	None	D3
Sheyenne River-4-22.27	P1, P2, P7, P9	S-4	M2	None	D2
Sheyenne River-5-26.47	P1, P2, P7, P8, P9	S-6	M2	None	D4
Sheyenne River-6-35.82	P1, P2, P7, P9	S-6	M2	None	D2
Sheyenne River-7-43.27	P1, P2, P7, P9	S-7	M2	None	D2
Sheyenne River-8-55.75	P1, P2, P7, P9	S-6	M2	None	D3
Wild Rice River-1-3.01	P1, P2, P9	S-7	M2	None	D3, D4
Wild Rice River-2-4.23	P1, P2, P9	S-7	M2	None	D3
Wild Rice River-3-17.52	P1, P2, P9	S-6	M2	None	D1, D2, D3, D4
Wild Rice River-4-22.94	P1, P2, P9	S-7	M2	None	D1, D2, D3
Wild Rice River-5-38.49	P1, P2, P9	S-6	M2	None	D1, D2, D4, D5
Wild Rice River-6-42.36	P1, P2, P9	S-7	M2	None	D1, D2, D3
Wolverton Creek-1-0.64	P1, P2, P9	S-4	M1	None	D4, D5
Wolverton Creek-2-2.02	P1, P2, P9	S-4	M1	None	D1

WORKSHEET 3-7: DEGREE OF CHANNEL INCISION

The degree of channel incision can be determined using the Bank-Height Ratio (BHR), as developed by Rosgen. BHR is calculated by dividing the height of the low bank above the channel thalweg elevation by the maximum bankfull depth. A BHR value of one (1) indicates that the low bank elevation is equal to the bankfull water surface elevation. As the BHR increases, the relative level of incision also increases (Figure 5-8) and bank stability decreases. The BHR calculations and the corresponding degree of channel incision stability rating are shown in Table 5-4. The channels stability rating ranges from "Stable" to "Deeply Incised".

The relative level of incision values are used to assess vertical stability for channel degradation, with the deeply incised ratings indicating a greater likelihood of channel degradation.

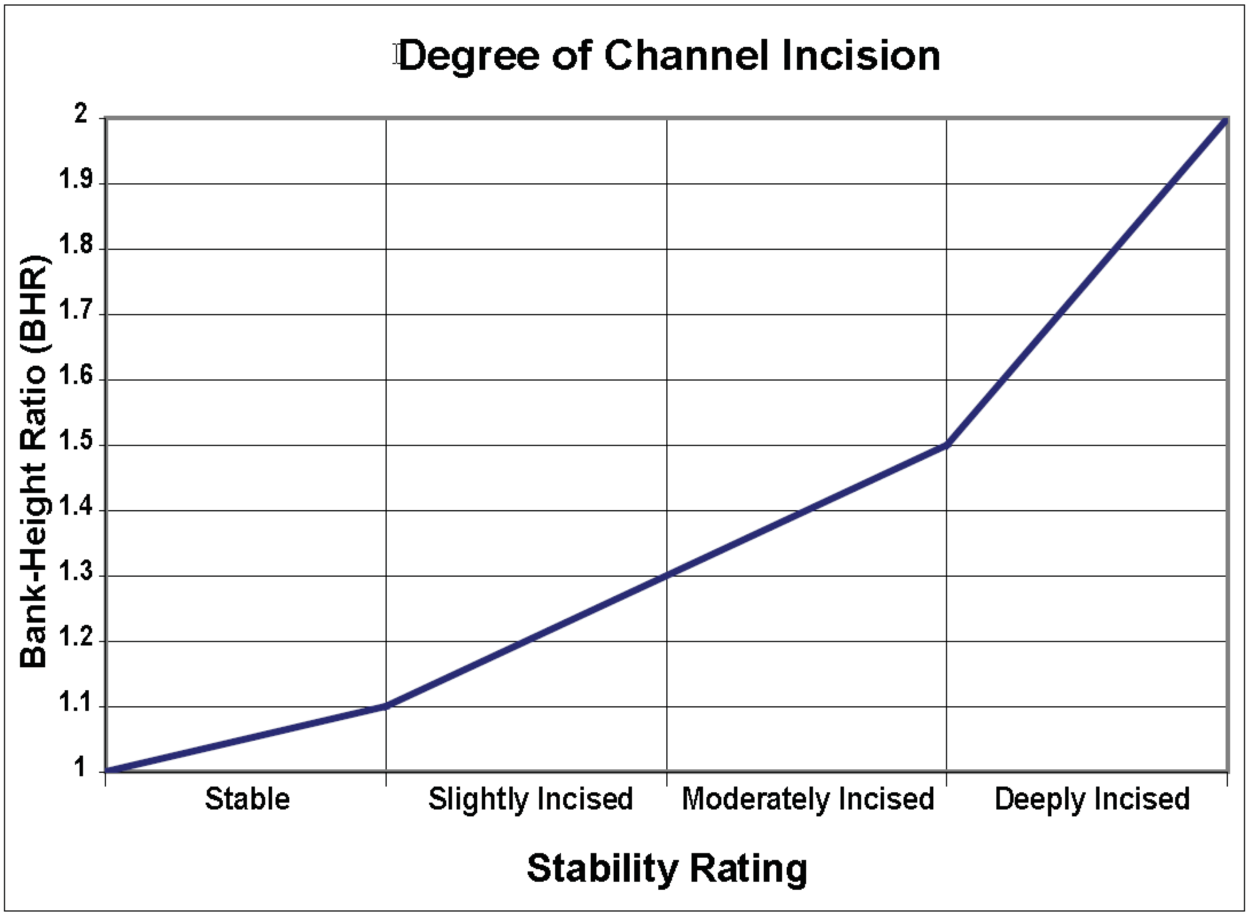


Figure 5-8. Degree of Channel Incision Classification (Rosgen, 2006)

Table 5-4. Rosgen Level III Degree of Channel Incision Summary

Detailed Study Reach	Low Bank Height (ft)	Max Bankfull Depth (ft)	Bank-Height Ratio	Degree of Incision Stability Rating
Buffalo River-1-1.19	17.4	9.0	1.9	Deeply Incised
Lower Rush River-1-1.10	4.8	2.9	1.7	Deeply Incised
Lower Rush River-2-6.03	6.2	2.9	2.1	Deeply Incised
Maple River-1-0.78	10.2	9.1	1.1	Stable
Maple River-2-11.39	9.3	9.0	1.0	Stable
Red River-1-410.65	23.9	17.9	1.3	Slightly Incised
Red River-2-419.14	31.0	16.6	1.9	Deeply Incised
Red River-3-440.57	18.0	13.5	1.3	Slightly Incised
Red River-4-452.52	16.0	15.0	1.1	Stable
Red River-5-463.56	21.7	17.6	1.2	Slightly Incised
Red River-6-470.23	27.3	16.2	1.7	Deeply Incised
Red River-7-492.47	24.0	13.3	1.8	Deeply Incised
Red River-8-521.18	20.1	6.6	3.0	Deeply Incised
Rush River-1-0.08	15.1	5.2	2.9	Deeply Incised
Rush River-2-6.15	5.1	5.0	1.0	Stable
Sheyenne River-1-4.20	19.0	14.7	1.3	Slightly Incised
Sheyenne River-2-11.56	20.1	13.0	1.5	Moderately Incised
Sheyenne River-3-18.15	16.9	12.9	1.3	Slightly Incised
Sheyenne River-4-22.27	17.7	12.8	1.4	Moderately Incised
Sheyenne River-5-26.47	[1/]	[1/]	[1/]	[1/]
Sheyenne River-6-35.82	15.9	11.6	1.4	Moderately Incised
Sheyenne River-7-43.27	23.0	14.8	1.6	Deeply Incised
Sheyenne River-8-55.75	21.2	13.1	1.6	Deeply Incised
Wild Rice River-1-3.01	8.8	10.2	0.9	Stable
Wild Rice River-2-4.23	9.8	8.5	1.2	Slightly Incised
Wild Rice River-3-17.52	19.8	8.7	2.3	Deeply Incised
Wild Rice River-4-22.94	17.1	8.2	2.1	Deeply Incised
Wild Rice River-5-38.49	24.6	9.6	2.6	Deeply Incised
Wild Rice River-6-42.36	19.6	8.4	2.3	Deeply Incised
Wolverton Creek-1-0.64	5.1	3.3	1.5	Moderately Incised
Wolverton Creek-2-2.02	5.1	4.8	1.1	Stable

[1/] Could not be determined.

WORKSHEET 3-8: WIDTH/DEPTH RATIO STATE

The width/depth ratio state is based on a comparison of the measured width/depth ratio to the width/depth ratio of a stable reference reach. Because the use of a reference reach does not apply for this study, the reference reach width/depth ratio was assumed equal to the existing width/depth ratio. As a result, the width/depth ratio state stability rating was rated as “Stable” for all of the detailed study reaches.

WORKSHEET 3-9: DEGREE OF CHANNEL CONFINEMENT

The degree of channel confinement is determined from the Meander Width Ratio (MWR), which equals the meander belt width divided by the bankfull width. The MWR for the project reach is divided by the MWR for a reference reach to determine the degree of channel confinement. A relatively small MWR indicates an unconfined channel, while large values indicate higher degrees of channel confinement. Because the use of a reference reach does not apply for this study, the reference MWR was assumed equal to the existing MWR. The degree of confinement stability rating was therefore rated as “Unconfined” for all of the detailed study reaches.

The existing MWR was compared to the range of values expected based upon the Rosgen Level II Classification for each detailed study reach, as outlined in Rosgen (2006). Table 5-5 shows the results of this comparison. Of the 28 detailed study reaches for which MWR could be determined, 11 of the detailed study reaches had MWRs within the expected range, 13 of the detailed study reaches had MWRs below the expected range, and 4 of the detailed study reaches had MWRs above the expected range. The 13 detailed study reaches having existing MWRs below the expected range of values are likely continuing to slowly, over geologic time, increase the meander belt width. Three of the four detailed study reaches exhibiting higher than expected MWRs (Lower Rush River – 2 – 6.03, Rush River – 2 – 6.15, and Wolverton Creek – 1 – 0.64) are likely the result of anthropogenic channel modifications and therefore were not used to predict future changes in channel morphology. While Wild Rice River – 4 – 22.94 also exhibits a higher than expected MWR, it would be expected to transition to an E6 stream type by becoming slightly more entrenched rather than changing its meander belt width and/or bankfull width. The detailed study reaches with MWRs within the expected range are likely in dynamic equilibrium and are not expected to change significantly. It should be noted that the potential morphologic changes discussed above are expected to occur over a geologic timescale and not within the life of the proposed diversion alignment alternatives.

Table 5-5. Rosgen Level III Meander Width Ratio

Detailed Study Reach	MWR	Rosgen Level II Classification	Expected MWR Range	Calculated MWR Compared to Expected MWR
Buffalo River-1-1.19	9.3	E6	20-40	Below Range
Lower Rush River-1-1.10	[1]	B6c	[1]	[1]
Lower Rush River-2-6.03	24.3	B6c	2-8	Above Range
Maple River-1-0.78	10.8	E6	20-40	Below Range
Maple River-2-11.39	25.4	E6	20-40	Within Range
Red River-1-410.65	15.6	C6c-	4-20	Within Range
Red River-2-419.14	14.9	C6c-	4-20	Within Range
Red River-3-440.57	14.0	C6c-	4-20	Within Range
Red River-4-452.52	17.2	C6c-	4-20	Within Range
Red River-5-463.56	17.1	C6c-	4-20	Within Range
Red River-6-470.23	11.1	C6c-	4-20	Within Range
Red River-7-492.47	16.6	C6c-	4-20	Within Range
Red River-8-521.18	9.4	C6c-	4-20	Within Range
Rush River-1-0.08	[1]	E6	[1]	[1]
Rush River-2-6.15	86.9	E6	20-40	Above Range
Sheyenne River-1-4.20	14.3	E6	20-40	Below Range
Sheyenne River-2-11.56	13.2	E5	20-40	Below Range
Sheyenne River-3-18.15	16.4	E6	20-40	Below Range
Sheyenne River-4-22.27	12.9	E6	20-40	Below Range
Sheyenne River-5-26.47	13.5	[2]	[2]	[2]
Sheyenne River-6-35.82	16.9	E6	20-40	Below Range
Sheyenne River-7-43.27	12.7	E6	20-40	Below Range
Sheyenne River-8-55.75	16.9	E5	20-40	Below Range
Wild Rice River-1-3.01	11.5	E6	20-40	Below Range
Wild Rice River-2-4.23	8.8	E6	20-40	Below Range
Wild Rice River-3-17.52	18.2	E6	20-40	Below Range
Wild Rice River-4-22.94	20.1	B6c	2-8	Above Range
Wild Rice River-5-38.49	23.1	E6	20-40	Within Range
Wild Rice River-6-42.36	17.8	E6	20-40	Below Range
Wolverton Creek-1-0.64	12.4	B6c	2-8	Above Range
Wolverton Creek-2-2.02	25.8	E6	20-40	Within Range

[1] Not calculated due to significant channelization

[2] Could not be determined

WORKSHEET 3-10: PFANKUCH CHANNEL STABILITY RATING

The Pfankuch channel stability rating evaluates the capacity of stream channels to resist erosion and to recover from and adjust to changes in flow and sediment production (Pfankuch, 1975). Figure 5-9 shows the Pfankuch channel stability rating method, as adopted by Rosgen. Adjustments were made by WEST field personnel when evaluating the channels based on the high clay content of the channel boundaries. The bank rock content, rock angularity, and brightness categories were all assumed equal to an excellent rating except for those detailed study reaches with channel boundary materials containing significant quantities of sand. High numerical scores indicate unstable channels. However, what is considered to be a high numerical score value varies based upon the potential Level II stream type. For this study, the potential stream type was assumed equal to the existing stream type as the streams are assumed to be in equilibrium. Table 5-4 shows the results of the Pfankuch method for each detailed study reach. All of the detailed study reaches are rated as either “Good” or “Fair”, indicating that the channels are either stable or moderately unstable, respectively.

Location	Key	Category	Excellent		Good		Fair		Poor	
			Description	Rating	Description	Rating	Description	Rating	Description	Rating
Upper Banks	1	Landform slope	Bank slope gradient <30%.	2	Bank slope gradient 30–40%.	4	Bank slope gradient 40–60%.	6	Bank slope gradient > 60%.	8
	2	Mass erosion	No evidence of past or future mass erosion.	3	Infrequent. Mostly healed over. Low future potential.	6	Frequent or large, causing sediment nearly yearlong.	9	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	12
	3	Debris jam potential	Essentially absent from immediate channel area.	2	Present, but mostly small twigs and limbs.	4	Moderate to heavy amounts, mostly larger sizes.	6	Moderate to heavy amounts, predominantly larger sizes.	8
	4	Vegetative bank protection	> 90% plant density. Vigor and variety suggest a deep, dense soil-binding root mass.	3	70–90% density. Fewer species or less vigor suggest less dense or deep root mass.	6	50–70% density. Lower vigor and fewer species from a shallow, discontinuous root mass.	9	<50% density plus fewer species and less vigor indicating poor, discontinuous and shallow root mass.	12
Lower Banks	5	Channel capacity	Bank heights sufficient to contain the bankfull stage. Width/depth ratio departure from reference width/depth ratio = 1.0. Bank-Height Ratio (BHR) = 1.0.	1	Bankfull stage is contained within banks. Width/depth ratio departure from reference width/depth ratio = 1.0–1.2. Bank Height Ratio (BHR) = 1.0–1.1.	2	Bankfull stage is not contained. Width/depth ratio departure from reference width/depth ratio = 1.2–1.4. Bank-Height Ratio (BHR) = 1.1–1.3.	3	Bankfull stage is not contained; overbank flows are common with flows less than bankfull. Width/depth ratio departure from reference width/depth ratio >1.4. Bank-Height Ratio (BHR) >1.3.	4
	6	Bank rock content	> 65% with large angular boulders. 12"+ common.	2	40–65%. Mostly boulders and small cobbles 6–12".	4	20–40%. Most in the 3–6" diameter class.	6	<20% rock fragments of gravel sizes, 1–3" or less.	8
	7	Obstructions to flow	Rocks and logs firmly imbedded. Flow pattern w/o cutting or deposition. Stable bed.	2	Some present causing erosive cross currents and minor pool filling. Obstructions fewer and less firm.	4	Moderately frequent, unstable obstructions move with high flows causing bank cutting and pool filling.	6	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	8
	8	Cutting	Little or none. Infrequent raw banks <6".	4	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	6	Significant. Cuts 12–24" high. Root mat overhangs and sloughing evident.	12	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	16
	9	Deposition	Little or no enlargement of channel or point bars.	4	Some new bar increase, mostly from coarse gravel.	8	Moderate depostion of new gravel and coarse sand on old and some new bars.	12	Extensive deposit of predominantly fine particles. Accelerated bar development.	16
Bottom	10	Rock angularity	Sharp edges and corners. Plane surfaces rough.	1	Rounded corners and edges. Surfaces smooth and flat.	2	Corners and edges well rounded in 2 dimensions.	3	Well rounded in all dimensions, surfaces smooth.	4
	11	Brightness	Surfaces dull, dark or stained. Generally not bright.	1	Mostly dull, but may have <35% bright surfaces.	2	Mixture dull and bright, i.e., 35–65% mixture range.	3	Predominantly bright, > 65%, exposed or scoured surfaces.	4
	12	Consolidation of particles	Assorted sizes tightly packed or overlapping.	2	Moderately packed with some overlapping.	4	Mostly loose assortment with no apparent overlap.	6	No packing evident. Loose assortment, easily moved.	8
	13	Bottom size distribution	No size change evident. Stable material 80–100%.	4	Distribution shift light. Stable material 50–80%.	8	Moderate change in sizes. Stable materials 20–50%.	12	Marked distribution change. Stable materials 0–20%.	16
	14	Scouring and deposition	<5% of bottom affected by scour or deposition.	6	5–30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	12	30–50% affected. Deposits and scour at obstructions, constrictions and bends. Some filling of pools.	18	More than 50% of the bottom in a state of flux or change nearly yearlong.	24
	15	Aquatic vegetation	Abundant growth moss-like, dark green perennial. In swift water too.	1	Common. Algae forms in low velocity and pool areas. Moss here too.	2	Present but spotty, mostly in backwater. Seasonal algae growth makes rocks slick.	3	Perennial types scarce or absent. Yellow-green, short-term bloom may be present.	4
			Excellent Total =		**Good Total =**		**Fair Total =**		**Poor Total =**	

Stream Type	A1	A2	A3	A4	A5	A6	B1	B2	B3	B4	B5	B6	C1	C2	C3	C4	C5	C6	D3	D4	D5	D6
Good (Stable)	38-43	38-43	54-90	60-95	60-95	50-80	38-45	38-45	40-60	40-64	48-68	40-60	38-50	38-50	60-85	70-90	70-90	60-85	85-107	85-107	85-107	67-98
Fair (Mod. Unstable)	44-47	44-47	91-129	96-132	96-142	81-110	46-58	46-58	61-78	65-84	69-88	61-78	51-61	51-61	86-105	91-110	91-110	86-105	108-132	108-132	108-132	99-125
Poor (Unstable)	48+	48+	130+	133+	143+	111+	59+	59+	79+	85+	89+	79+	62+	62+	106+	111+	111+	106+	133+	133+	133+	126+

Stream Type	DA3	DA4	DA5	DA6	E3	E4	E5	E6	F1	F2	F3	F4	F5	F6	G1	G2	G3	G4	G5	G6
Good (Stable)	40-63	40-63	40-63	40-63	40-63	50-75	50-75	40-63	60-85	60-85	85-110	85-110	90-115	80-95	40-60	40-60	85-107	85-107	90-112	85-107
Fair (Mod. Unstable)	64-86	64-86	64-86	64-86	64-86	76-96	76-96	64-86	86-105	86-105	111-125	111-125	116-130	96-110	61-78	61-78	108-120	108-120	113-125	108-120
Poor (Unstable)	87+	87+	87+	87+	87+	97+	97+	87+	106+	106+	126+	126+	131+	111+	79+	79+	121+	121+	126+	121+

Grand Total =

Existing Stream Type =

***Potential Stream Type =**

Modified Channel Stability Rating =

*Rating is adjusted to potential stream type, not existing.

Figure 5-9. Modified Pfankuch Classification (Rosgen, 2006)

Table 5-6. Rosgen Level III Pfankuch Channel Stability Rating Summary

Detailed Study Reach	Pfankuch Point Total	Pfankuch Stability Rating
Buffalo River-1-1.19	85	Fair
Lower Rush River-1-1.10	47	Good
Lower Rush River-2-6.03	41	Good
Maple River-1-0.78	66	Fair
Maple River-2-11.39	57	Good
Red River-1-410.65	77	Good
Red River-2-419.14	87	Fair
Red River-3-440.57	66	Good
Red River-4-452.52	71	Good
Red River-5-463.56	68	Good
Red River-6-470.23	72	Good
Red River-7-492.47	99	Fair
Red River-8-521.18	85	Good
Rush River-1-0.08	55	Good
Rush River-2-6.15	73	Fair
Sheyenne River-1-4.20	84	Fair
Sheyenne River-2-11.56	78	Fair
Sheyenne River-3-18.15	79	Fair
Sheyenne River-4-22.27	81	Fair
Sheyenne River-5-26.47	78	Fair
Sheyenne River-6-35.82	73	Fair
Sheyenne River-7-43.27	72	Fair
Sheyenne River-8-55.75	91	Fair
Wild Rice River-1-3.01	68	Fair
Wild Rice River-2-4.23	66	Fair
Wild Rice River-3-17.52	79	Fair
Wild Rice River-4-22.94	75	Fair
Wild Rice River-5-38.49	72	Fair
Wild Rice River-6-42.36	83	Fair
Wolverton Creek-1-0.64	78	Fair
Wolverton Creek-2-2.02	61	Good

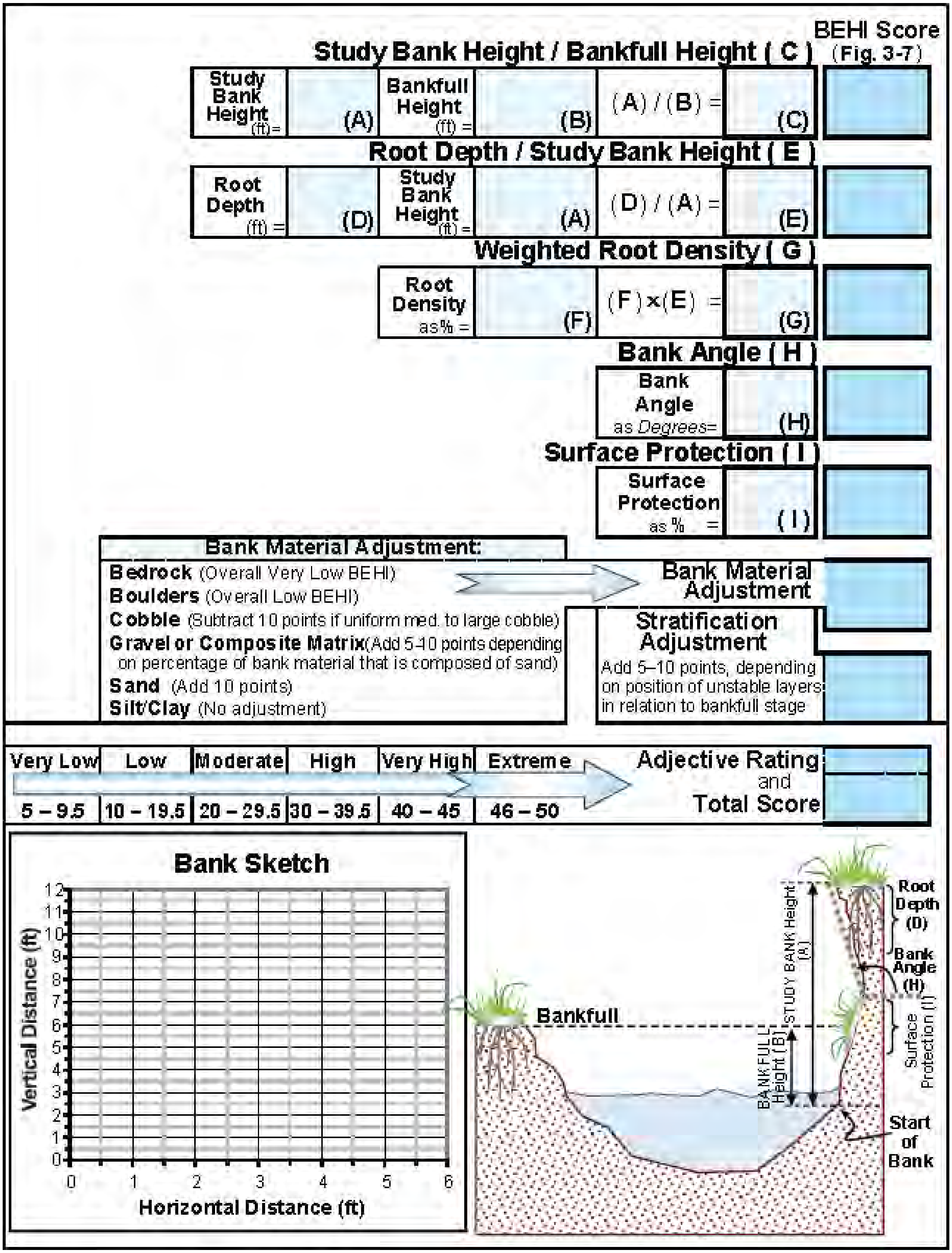
WORKSHEET 3-11 THROUGH 3-13: STREAMBANK EROSION PREDICTION

A number of variables were measured and assessed during the 2010/2011 field investigations to predict streambank erosion. These variables are used as inputs to two bank erosion estimation tools developed by Rosgen: the Bank Erosion Hazard Index (BEHI) and Near-Bank Stress (NBS). The two ratings are used in combination to estimate annual streambank erosion rates.

The BEHI evaluates the susceptibility to erosion for multiple erosional processes (Rosgen, 2006). Seven variables are assessed as part of the BEHI system: study bank height to bankfull height ratio, root depth to study bank height ratio, root density, bank angle, surface protection percentage, bank material type, and bank material stratification. Calculations for these seven variables are completed on Worksheet 3-11, shown in Figure 5-10. A BEHI rating between 1 and 10 is assigned to each of the variable values using the charts shown in Figure 5-11. Based on the total score for the BEHI variables, the BEHI is assigned a rating that indicates the erosion risk ranging from “Very Low” to “Extreme”.

The second bank erosion estimation tool is the NBS assessment. This assessment indicates potential disproportionate energy distributions in the near-bank region, defined by Rosgen as the nearest third of the channel cross-section associated with the bank being evaluated (Rosgen, 2006). Greatly disproportionate energy distributions will accelerate streambank erosion, while a more even distribution indicates that the channel is likely stable. Seven different methods can be used to determine the NBS value (Figure 5-12), ranging from simple channel planform evaluations to complex velocity profile measurements completed at the site of interest. Velocity profile distributions (Method 7) were measured during the 2010/2011 field investigations at a number of detailed study reaches. The velocity gradient for all measured detailed study reaches was less than 0.5 ft/sec/ft, indicating a “Very Low” NBS rating. Given the similarity in planform and channel slopes for the majority of the study reaches, the “Very Low” classification was also applied to the detailed study reaches for which velocity gradients were not measured.

The BEHI and NBS ratings for each of the detailed study reaches are shown in Table 5-7. All of the detailed study reaches were classified as having “High” or “Very High” BEHI ratings and a “Very Low” NBS rating, except for Wolverton Creek – 1 – 0.64, which had a “Moderate” BEHI rating and a “Very Low” NBS rating. According to Figure 5-13, the “High” / “Very High” and “Very Low” combination yields a bank erosion rate of 0.165 feet/year. The “Moderate” and “Very Low” combination exhibited for Wolverton Creek – 1 – 0.64 yields a bank erosion rate of 0.092 feet/year. Both of these annual erosion rate values are comparable to the lateral migration rates estimated by Brooks (2003) at meander bends on the Red River near St. Jean Baptiste, Manitoba. Brooks (2003) estimated the lateral erosion rates to vary between 0.13 and 0.26 feet/year. These small bank erosion rates are also consistent with results of the historic aerial photography evaluation discussed in Section 6.1.8.



BEHI Score (Fig. 3-7)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) = (A) Bankfull Height (ft) = (B) (A) / (B) = (C)

Root Depth / Study Bank Height (E)

Root Depth (ft) = (D) Study Bank Height (ft) = (A) (D) / (A) = (E)

Weighted Root Density (G)

Root Density as% = (F) (F) x (E) = (G)

Bank Angle (H)

Bank Angle as *Degrees* = (H)

Surface Protection (I)

Surface Protection as % = (I)

Bank Material Adjustment:

Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform med. to large cobble)
Gravel or Composite Matrix (Add 5-10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (No adjustment)

Bank Material Adjustment

Stratification Adjustment

Add 5–10 points, depending on position of unstable layers in relation to bankfull stage

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score

Figure 5-10. BEHI Calculation Worksheet (Rosgen, 2006)

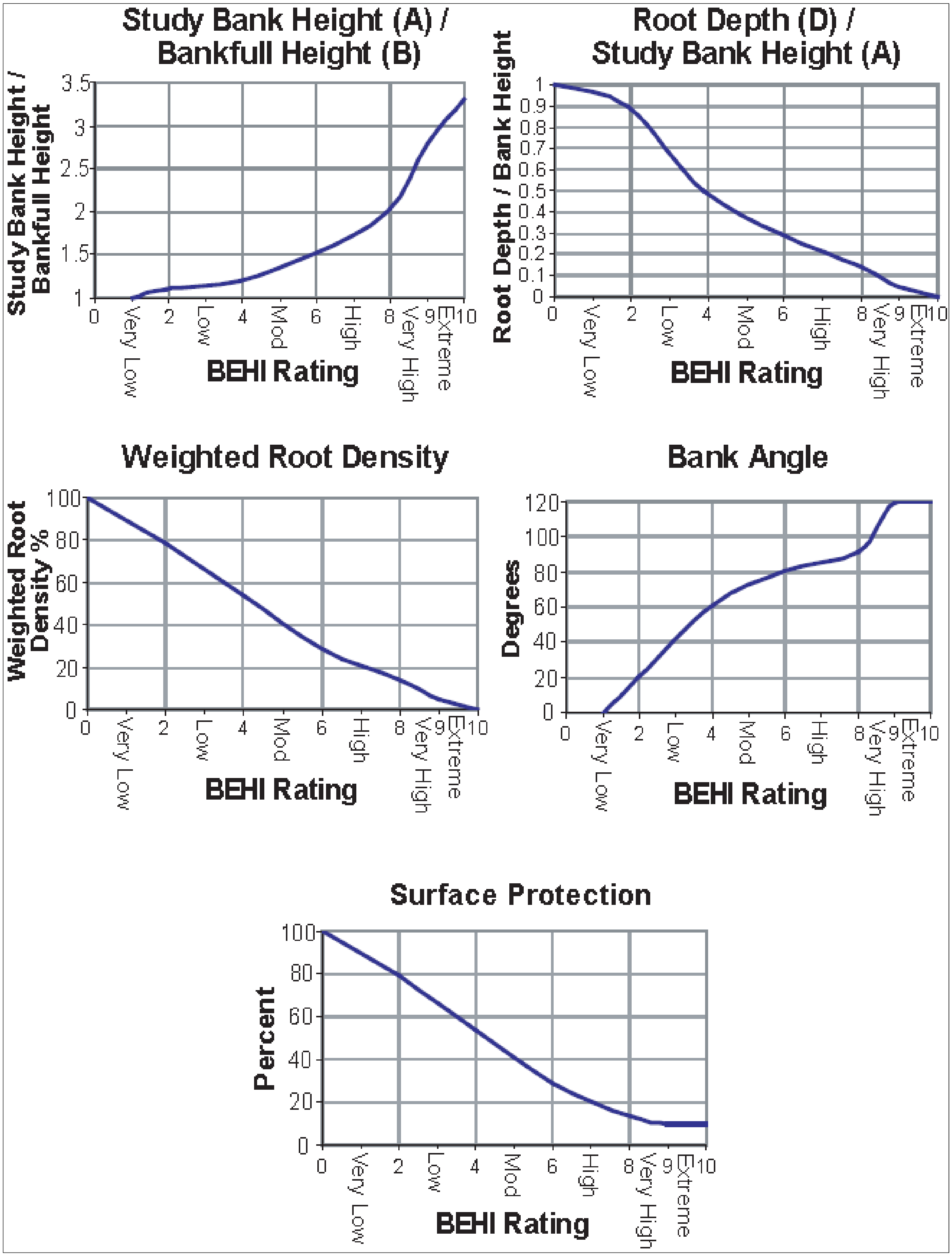
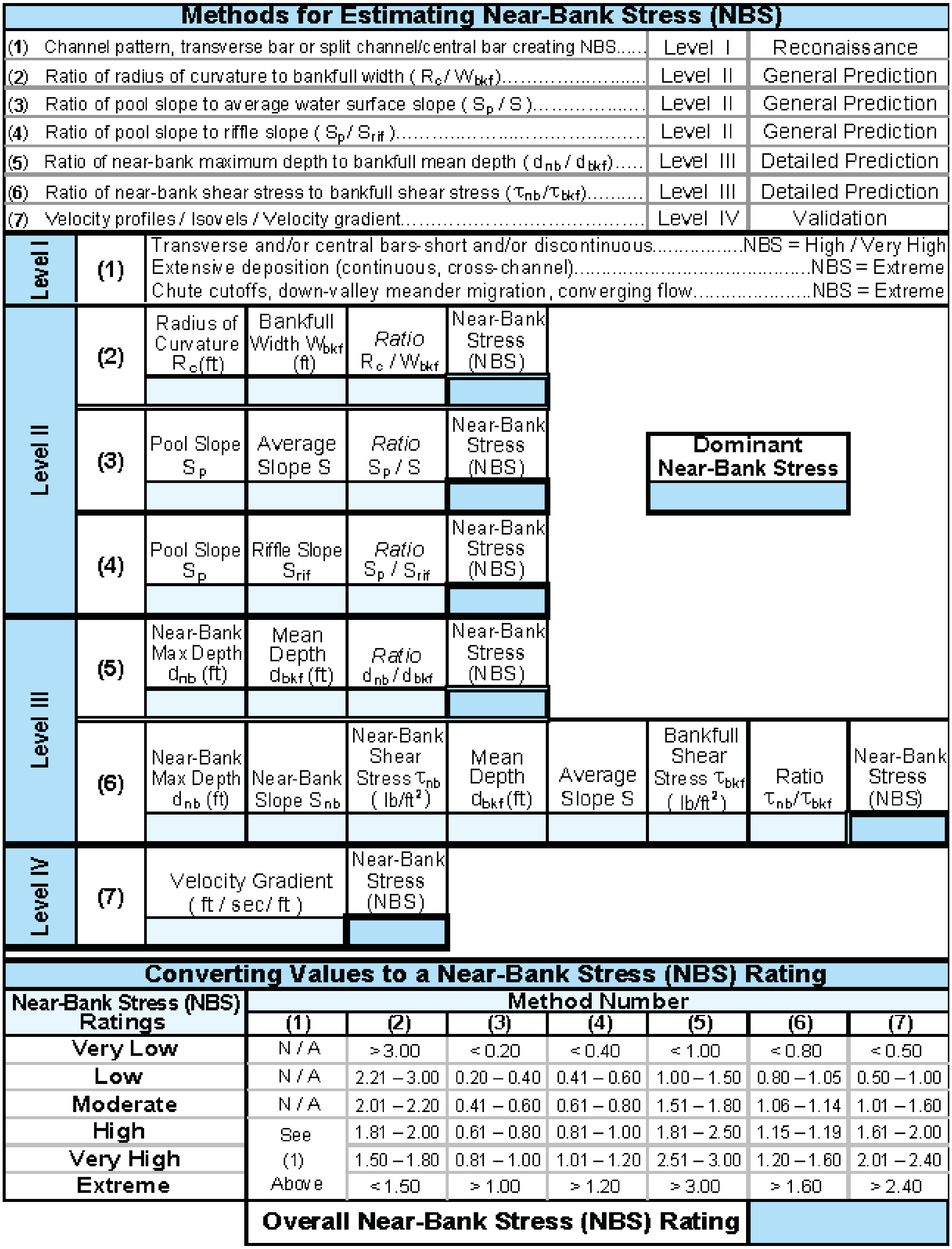


Figure 5-11. BEHI Calculation Figures (Rosgen, 2006)



Methods for Estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS……	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})………………	Level II	General Prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)………………	Level II	General Prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})………………………………	Level II	General Prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})…..	Level III	Detailed Prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb}/τ_{bkf})………	Level III	Detailed Prediction
(7) Velocity profiles / Isovels / Velocity gradient……………………………………	Level IV	Validation

Level I

(1)

Transverse and/or central bars-short and/or discontinuous……………NBS = High / Very High
Extensive deposition (continuous, cross-channel)…………………………………NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow…………………NBS = Extreme

Level II

(2)

Radius of Curvature R_c(ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft²)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft²)	Ratio τ_{nb}/τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

Velocity Gradient (ft / sec/ ft)	Near-Bank Stress (NBS)

Converting Values to a Near-Bank Stress (NBS) Rating

Near-Bank Stress (NBS) Ratings	Method Number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See (1) Above	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High		1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme		< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) Rating	

Figure 5-12. Near-Bank Stress Estimation Method (Rosgen, 2006)

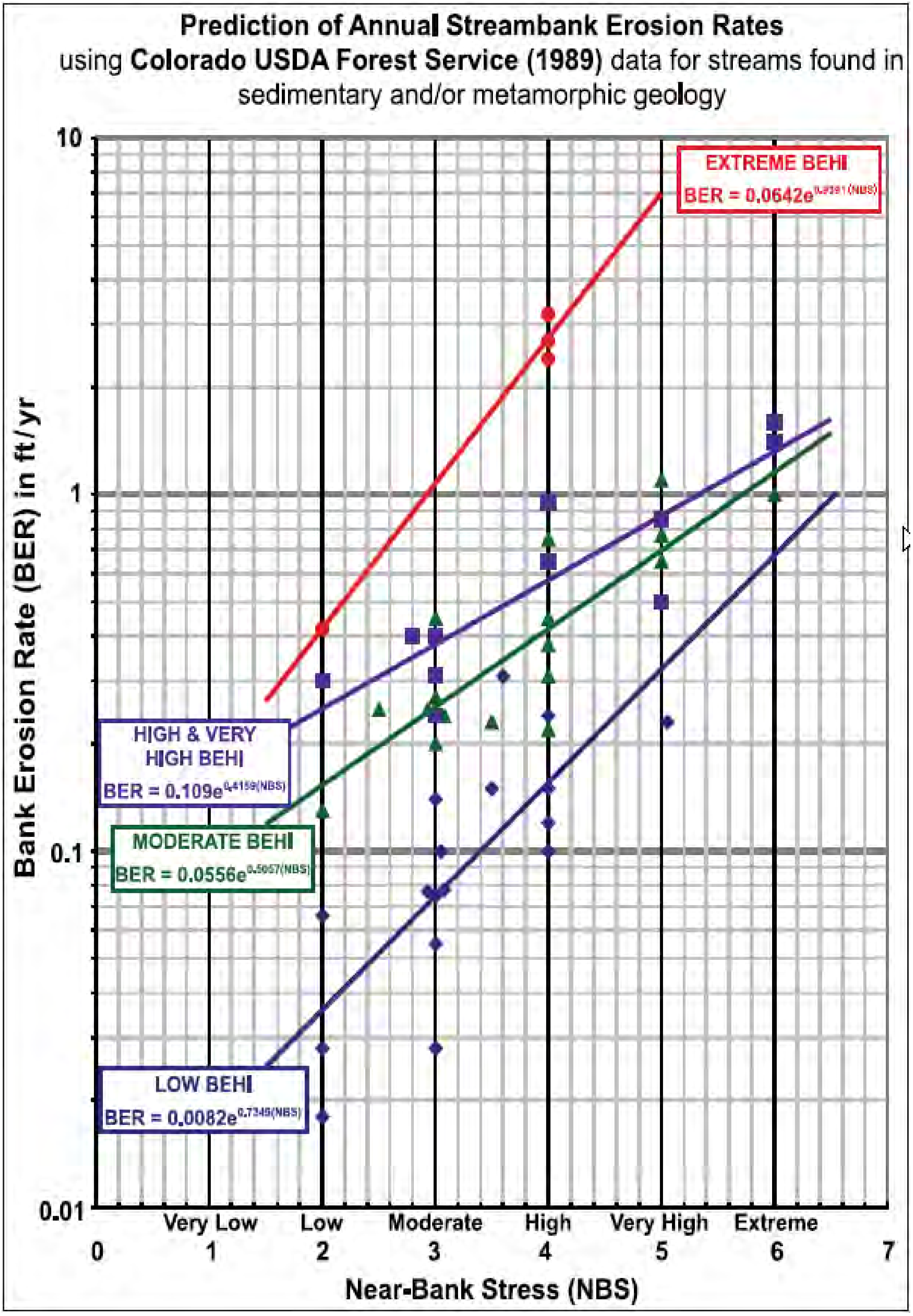


Figure 5-13. Bank Erosion Rate Estimation Method (Rosgen, 2006)

Table 5-7. Rosgen Level III Streambank Erosion Prediction Summaries

Detailed Study Reach	BEHI Score	BEHI Rating	Dominant Near-Bank Stress	Bank Erosion Rate (ft/yr)
Buffalo River-1-1.19	39	High	Very Low	0.165
Lower Rush River-1-1.10	37	High	Very Low	0.165
Lower Rush River-2-6.03	38	High	Very Low	0.165
Maple River-1-0.78	37	High	Very Low	0.165
Maple River-2-11.39	41	Very High	Very Low	0.165
Red River-1-410.65	38	High	Very Low	0.165
Red River-2-419.14	38	High	Very Low	0.165
Red River-3-440.57	36	High	Very Low	0.165
Red River-4-452.52	33	High	Very Low	0.165
Red River-5-463.56	38	High	Very Low	0.165
Red River-6-470.23	38	High	Very Low	0.165
Red River-7-492.47	39	High	Very Low	0.165
Red River-8-521.18	38	High	Very Low	0.165
Rush River-1-0.08	37	High	Very Low	0.165
Rush River-2-6.15	34	High	Very Low	0.165
Sheyenne River-1-4.20	36	High	Very Low	0.165
Sheyenne River-2-11.56	37	high	Very Low	0.165
Sheyenne River-3-18.15	37	High	Very Low	0.165
Sheyenne River-4-22.27	37	High	Very Low	0.165
Sheyenne River-5-26.47	[1/]	[1/]	Very Low	[1/]
Sheyenne River-6-35.82	32	High	Very Low	0.165
Sheyenne River-7-43.27	39	High	Very Low	0.165
Sheyenne River-8-55.75	37	High	Very Low	0.165
Wild Rice River-1-3.01	31	High	Very Low	0.165
Wild Rice River-2-4.23	33	High	Very Low	0.165
Wild Rice River-3-17.52	39	High	Very Low	0.165
Wild Rice River-4-22.94	39	High	Very Low	0.165
Wild Rice River-5-38.49	39	High	Very Low	0.165
Wild Rice River-6-42.36	39	High	Very Low	0.165
Wolverton Creek-1-0.64	27	Moderate	Very Low	0.092
Wolverton Creek-2-2.02	33	High	Very Low	0.165

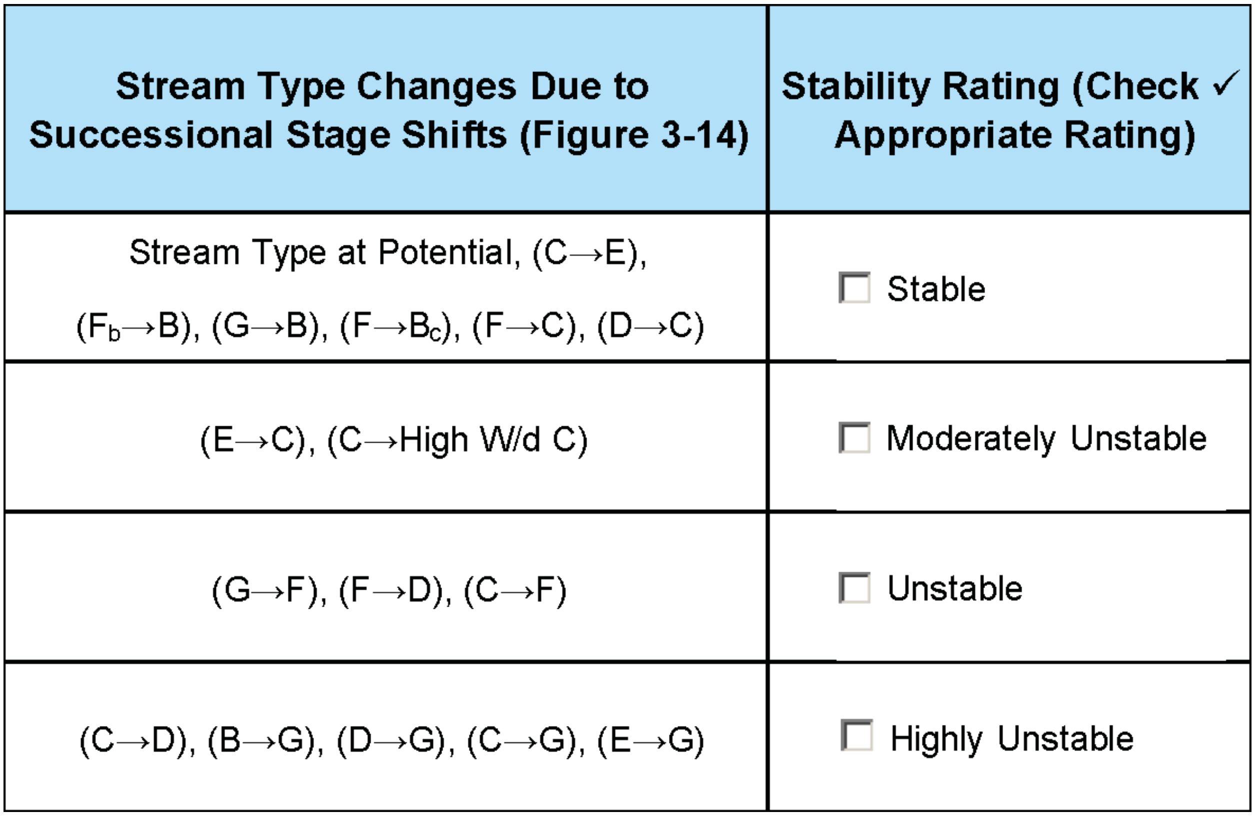
[1/] Could not be determined.

WORKSHEET 3-14 AND 3-15: SEDIMENT COMPETENCE/ENTRAINMENT AND TRANSPORT CAPACITY

Sediment competence is the ability of the river to move the largest particle made available to it from the immediate upstream supply (Rosgen, 2008). A bar sediment sample is collected to infer the largest particle size that is made available to the stream reach being assessed. To maintain stability, a stream needs to be able to transport the largest size of sediment and have the capacity to transport the total volume of sediment that is supplied to it from upstream. When a river does not have the competence to transport the upstream supply, it is considered transport limited, and aggradation would be expected. When a river has the ability to transport a greater amount of sediment than the upstream supply, it is considered supply limited, and, in the absence of erosion resistant bed material, degradation would be expected. Worksheet 3-14 could not be completed because depositional features such as sand or gravel bars were not observed during the field data collection efforts. Worksheet 3-15 did not need to be completed since the results of the size distribution analyses were reported by Midwest Testing (see Appendix B) on a similar form.

WORKSHEET 3-16: STREAM CHANNEL SUCCESSION STAGE SHIFT

For Worksheet 3-16, the stream types were considered to be at potential per the discussion for Worksheet 3-8. As a result, all of the detailed study reaches were classified as stable for this worksheet (Figure 5-14).



Stream Type Changes Due to Successional Stage Shifts (Figure 3-14)	Stability Rating (Check ✓ Appropriate Rating)
Stream Type at Potential, (C→E), (F_b→B), (G→B), (F→B_c), (F→C), (D→C)	☐ Stable
(E→C), (C→High W/d C)	☐ Moderately Unstable
(G→F), (F→D), (C→F)	☐ Unstable
(C→D), (B→G), (D→G), (C→G), (E→G)	☐ Highly Unstable

Figure 5-14. Stage Shift Stability Rating Method (Rosgen, 2006)

WORKSHEET 3-17 THROUGH 3-21: PROCESS-BASED CHANNEL STABILITY

The cumulative results of the Level III Rosgen assessment are presented in Worksheets 3-17 through 3-21. Worksheets 3-17 through 3-21 use the previous Level III worksheets results and results from a sediment transport model POWERSED, developed by Rosgen, to classify the lateral stability, vertical stability for aggradation, vertical stability for degradation, channel enlargement prediction, and sediment supply rating for each detailed study reach. POWERSED is dependent upon changes in either hydraulic geometry or flow conditions to predict changes in the sediment transport capacity of the channel. However, POWERSED does not take into account changes in sediment supply as a result of flow diversions, as will occur for the proposed project. Therefore, the POWERSED analysis is considered an inadequate tool to evaluate changes in sediment transport capacity for this project. The POWERSED worksheets were completed as if the diversions did not remove sediment, but the results of the POWERSED analysis were input into the Rosgen Level III Worksheet 3-18 and Worksheet 3-19 assuming the diversions do convey sediment at the same rate they convey flow. Therefore, the vertical stability criteria 2 on Worksheet 3-18 was assumed to not cause deposition (assigned a value of 2 points), while vertical stability criteria on Worksheet 3-19 was assumed to not induce incision of the channel (assigned a value of 2 points).

Worksheet 3-17 evaluates lateral stability using the width to depth ratio (from Worksheet 3-8), depositional pattern (from Worksheet 3-5), meander pattern (from Worksheet 3-4), BEHI/NBS combination (from Worksheet 3-13), and degree of confinement (from Worksheet 3-9) assessments and ratings. Worksheet 3-18 evaluates vertical stability for aggradation using the sediment competence (from Worksheet 3-14), sediment capacity (POWERSED), width to depth ratio (from Worksheet 3-8), stream succession state (from Worksheet 3-16), depositional patterns (from Worksheet 3-5), and debris blockages (from Worksheet 3-6) assessments and ratings. Worksheet 3-19 evaluates vertical stability for degradation using the sediment competence (from Worksheet 3-14), sediment capacity (POWERSED), BHR (from Worksheet 3-7), stream succession states (from Worksheet 3-16), and degree of confinement (from Worksheet 3-9) assessments and ratings. Worksheet 3-20 evaluates channel enlargement prediction using the stream succession states (from Worksheet 3-16), lateral stability (from Worksheet 3-17), vertical stability for aggradation (from Worksheet 3-18), and vertical stability for degradation (from Worksheet 3-19) results. Finally, Worksheet 3-21 evaluates sediment supply rating using the lateral stability (from Worksheet 3-17), vertical stability for aggradation (from Worksheet 3-18), vertical stability for degradation (from Worksheet 3-19), channel enlargement prediction (from Worksheet 3-20), and Pfankuch channel stability rating (from Worksheet 3-10) results. The stability ratings from Worksheets 3-17 through 3-21 are summarized in Table 5-8 and are shown in Figure 5-20 through Figure 5-24. It is noted that because a reliable bankfull discharge value for Sheyenne River – 5 – 26.47 could not be determined, the Rosgen Level III assessment was not conducted for this detailed study reach.

The lateral stability rating (Figure 5-15) ranges from “Stable” to “Moderately Unstable”. The smaller streams, including the Buffalo River, Lower Rush River, Rush River, and Wolverton Creek were rated as “Stable”, while the larger streams, including the Maple River, Red River, Sheyenne River, and Wild Rice River were rated as “Moderately Unstable”. The difference in the lateral stability rating between the large and small river systems is that the large river systems were considered to have more tortuous meander patterns while the small river systems had more regular meander patterns. Within the Rosgen classification system, the more tortuous meanders of the larger river systems equate to a higher possibility of lateral instability.

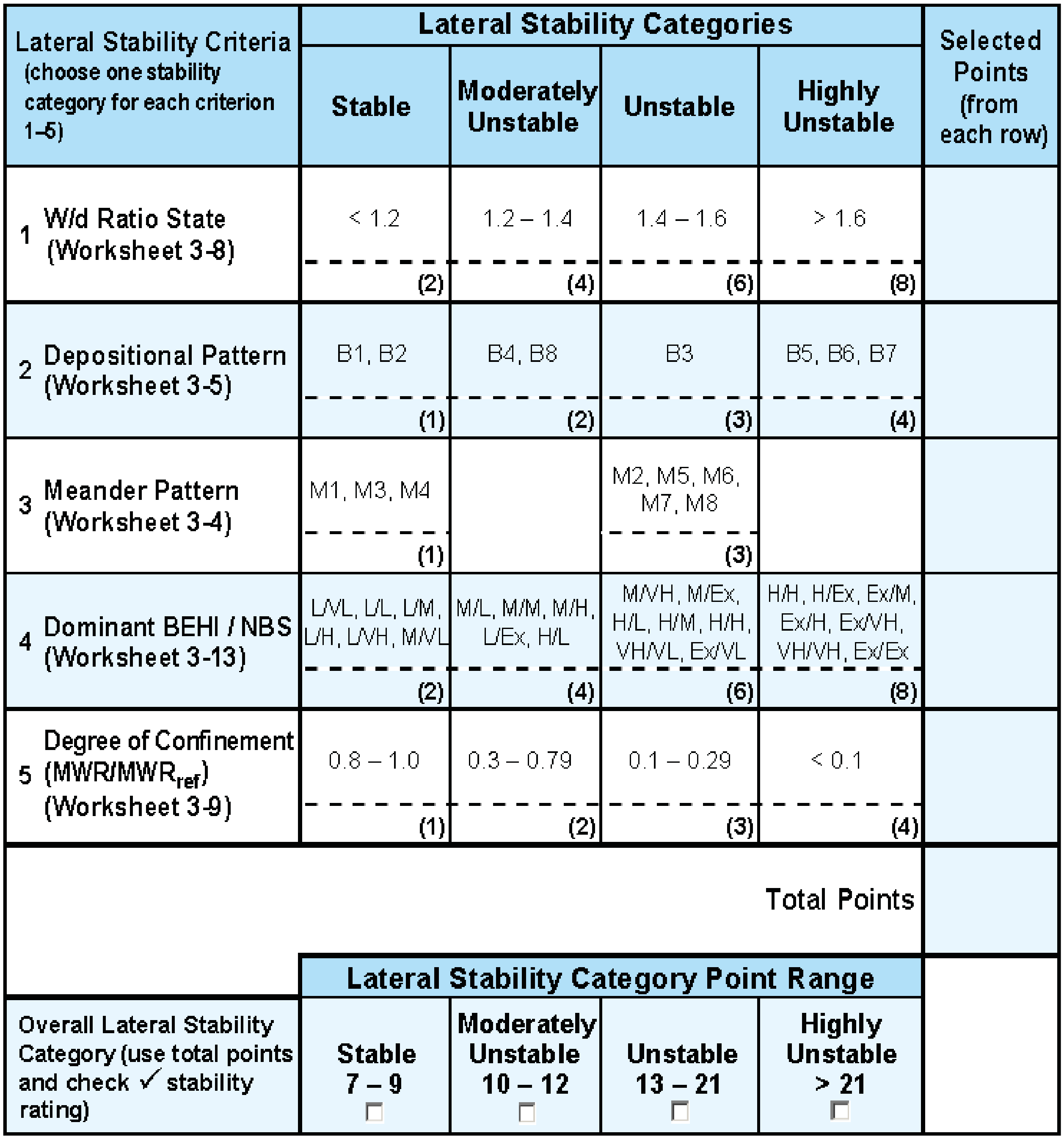
The vertical stability rating for aggradation (Figure 5-16) for all of the study streams was rated as “No Deposition”. All of the stream reaches appear to have sufficient capacity to transport all of the sediment that is supplied to them. Therefore, no significant aggradation is expected within the channels of the study streams.

The vertical stability rating (Figure 5-17) for incision ranged from "Slightly Incised" to "Not Incised". Those reaches that were rated as "Slightly Incised" had a larger Bank-Height Ratio (BHR), which is the ratio of the lowest bank height to the bankfull depth.

The channel enlargement prediction (Figure 5-18) ranged from "No Increase" to "Slight Increase". The smaller streams, including the Buffalo River, Lower Rush River, Maple River, Rush River, and Wolverton Creek are not expected to increase in size and are therefore considered to be in dynamically stable. According to the Rosgen analysis, some of the study reaches along the Red River, Sheyenne River and Wild Rice River would be expected to slightly increase in size. This expectation is based on the combination of the "Moderately Unstable" rating for lateral stability and the "Slightly Incised" rating for vertical stability for degradation.

Channel sediment supply ratings (Figure 5-19) were qualitatively established based on the channel stability assessment ratings and the Pfankuch channel stability rating conducted for each detailed study reach. The sediment supply rating is used to further classify the overall stability assessments and identify areas of potential impairment. All of the detailed study reaches besides Wolverton Creek – 1 – 0.64 had a "Moderate" sediment supply rating which indicates that all of the reaches will produce a moderate amount of sediment from their banks and beds. Wolverton Creek – 1 – 0.64 had a "Low" sediment supply rating due to the overall stability as noted on Worksheets 3-10, 3-17, 3-18, 3-19, and 3-20. According to Rosgen (2006), sediment supply ratings of "High" or "Very High" are typically targeted for potential mitigation efforts. Therefore, the study reaches are considered sufficiently stable such that mitigation efforts would not be necessary.

Worksheets 3-17 through 3-21 indicate that the majority of the detailed study reaches can be considered either highly or moderately stable, similar to the findings of the Level II analysis. Therefore, the channels are not expected to experience significant changes in lateral or vertical stability as a result of either the FCP or LPP diversion channel alignment alternatives.



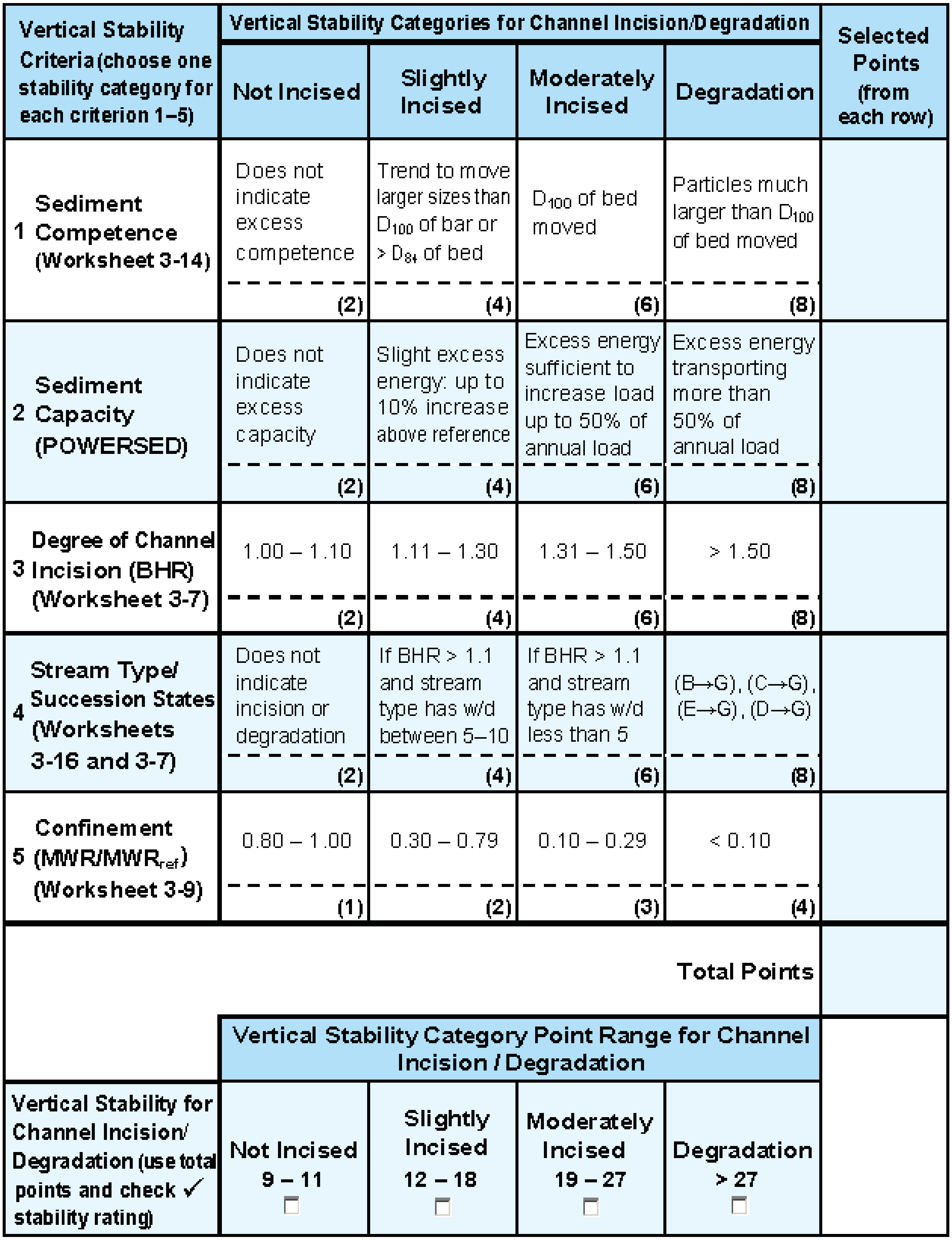
Lateral Stability Criteria (choose one stability category for each criterion 1–5)	Lateral Stability Categories				Selected Points (from each row)
	Stable	Moderately Unstable	Unstable	Highly Unstable	
1 W/d Ratio State (Worksheet 3-8)	< 1.2 (2)	1.2 – 1.4 (4)	1.4 – 1.6 (6)	> 1.6 (8)	
2 Depositional Pattern (Worksheet 3-5)	B1, B2 (1)	B4, B8 (2)	B3 (3)	B5, B6, B7 (4)	
3 Meander Pattern (Worksheet 3-4)	M1, M3, M4 (1)		M2, M5, M6, M7, M8 (3)		
4 Dominant BEHI / NBS (Worksheet 3-13)	L/VL, L/L, L/M, L/H, L/VH, M/VL (2)	M/L, M/M, M/H, L/Ex, H/L (4)	M/VH, M/Ex, H/L, H/M, H/H, VH/VL, Ex/VL (6)	H/H, H/Ex, Ex/M, Ex/H, Ex/VH, VH/VH, Ex/Ex (8)	
5 Degree of Confinement (MWR/MWR$_{ref}$) (Worksheet 3-9)	0.8 – 1.0 (1)	0.3 – 0.79 (2)	0.1 – 0.29 (3)	< 0.1 (4)	
				Total Points	
	Lateral Stability Category Point Range				
Overall Lateral Stability Category (use total points and check ✓ stability rating)	Stable 7 – 9 ☐	Moderately Unstable 10 – 12 ☐	Unstable 13 – 21 ☐	Highly Unstable > 21 ☐	

Figure 5-15. Lateral Stability Prediction Worksheet (Rosgen, 2006)

Vertical Stability Criteria (choose one stability category for each criterion 1–6)	**Vertical Stability Categories for Excess Deposition / Aggradation**				**Selected Points (from each row)**
	No Deposition	**Moderate Deposition**	**Excess Deposition**	**Aggradation**	
1 Sediment Competence (Worksheet 3-14)	Sufficient depth and/or slope to transport largest size available **(2)**	Trend toward insufficient depth and/or slope - slightly incompetent **(4)**	Cannot move D_{35} of bed material and/or D_{100} of bar material **(6)**	Cannot move D_{16} of bed material and/or D_{100} of bar or sub-pavement size **(8)**	
2 Sediment Capacity (POWERSED)	Sufficient capacity to transport annual load **(2)**	Trend toward insufficient sediment capacity **(4)**	Reduction up to 25% of annual sediment yield of bedload and/or suspended sand **(6)**	Reduction over 25% of annual sediment yield for bedload and/or suspended sand **(8)**	
3 W/d Ratio State (Worksheet 3-8)	1.0 – 1.2 **(2)**	1.2 – 1.4 **(4)**	1.4 – 1.6 **(6)**	>1.6 **(8)**	
4 Stream Succession States (Worksheet 3-16)	Current stream type at potential or does not indicate deposition/ aggradation **(2)**	(E→C) **(4)**	(C→High W/d C), (B→High W/d B), (C→F) **(6)**	(C→D), (F→D) **(8)**	
5 Depositional Patterns (Worksheet 3-5)	B1 **(1)**	B2, B4 **(2)**	B3, B5 **(3)**	B6, B7, B8 **(4)**	
6 Debris / Blockages (Worksheet 3-6)	D1, D2, D3 **(1)**	D4, D7 **(2)**	D5, D8 **(3)**	D6, D9, D10 **(4)**	
				Total Points	

	Vertical Stability Category Point Range for Excess Deposition / Aggradation			
Vertical Stability for Excess Deposition / Aggradation (use total points and check ✓ stability rating)	**No Deposition 10 – 14** ☐	**Moderate Deposition 15 – 20** ☐	**Excess Deposition 21 – 30** ☐	**Aggradation > 30** ☐

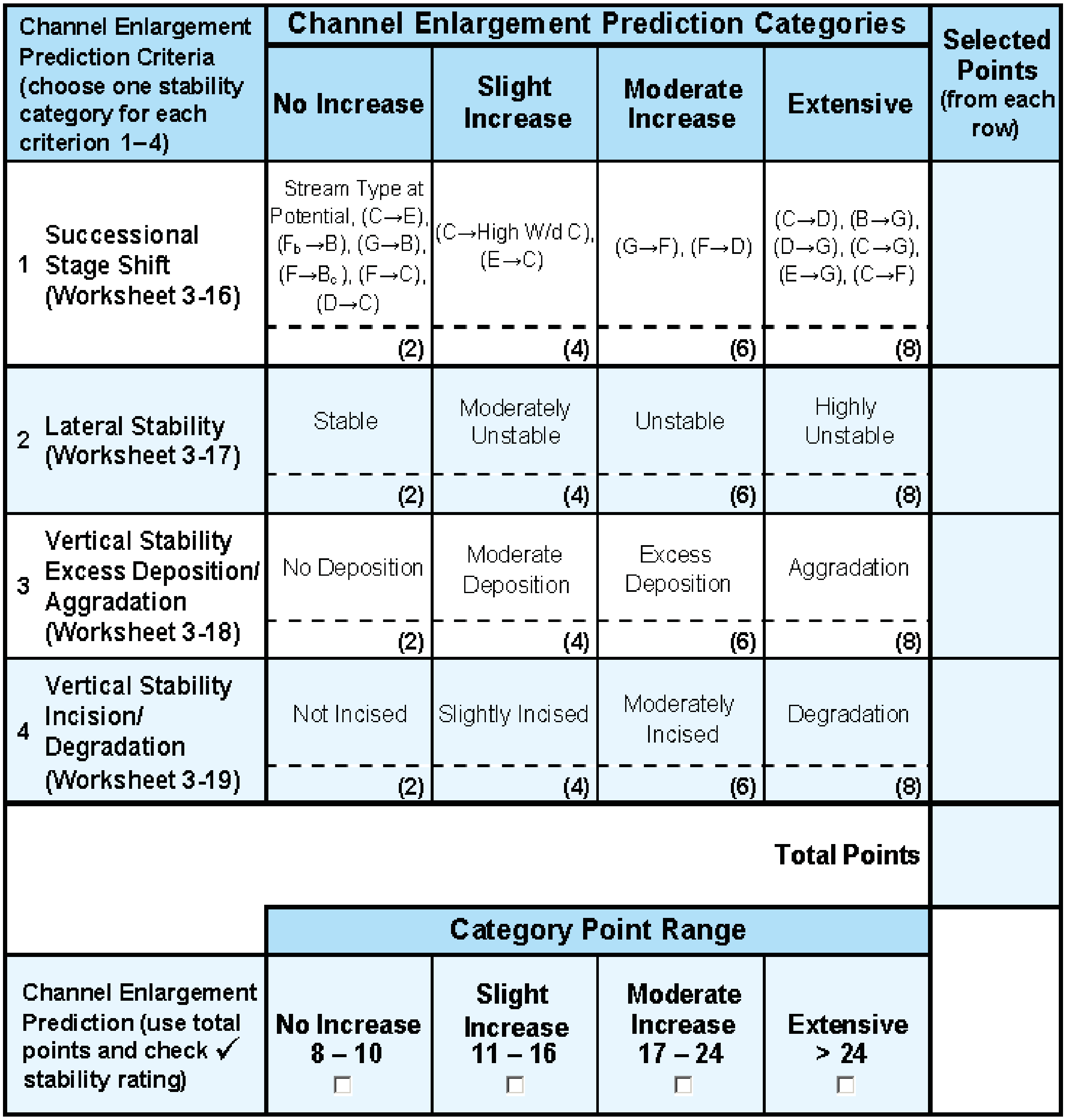
Figure 5-16. Vertical Stability Prediction for Deposition Worksheet (Rosgen, 2006)



Vertical Stability Criteria (choose one stability category for each criterion 1–5)	Vertical Stability Categories for Channel Incision/Degradation				Selected Points (from each row)
	Not Incised	Slightly Incised	Moderately Incised	Degradation	
1 Sediment Competence (Worksheet 3-14)	Does not indicate excess competence (2)	Trend to move larger sizes than D_{100} of bar or > D_{84} of bed (4)	D_{100} of bed moved (6)	Particles much larger than D_{100} of bed moved (8)	
2 Sediment Capacity (POWERSED)	Does not indicate excess capacity (2)	Slight excess energy: up to 10% increase above reference (4)	Excess energy sufficient to increase load up to 50% of annual load (6)	Excess energy transporting more than 50% of annual load (8)	
3 Degree of Channel Incision (BHR) (Worksheet 3-7)	1.00 – 1.10 (2)	1.11 – 1.30 (4)	1.31 – 1.50 (6)	> 1.50 (8)	
4 Stream Type/ Succession States (Worksheets 3-16 and 3-7)	Does not indicate incision or degradation (2)	If BHR > 1.1 and stream type has w/d between 5–10 (4)	If BHR > 1.1 and stream type has w/d less than 5 (6)	(B→G), (C→G), (E→G), (D→G) (8)	
5 Confinement (MWR/MWR_{ref}) (Worksheet 3-9)	0.80 – 1.00 (1)	0.30 – 0.79 (2)	0.10 – 0.29 (3)	< 0.10 (4)	
				Total Points	

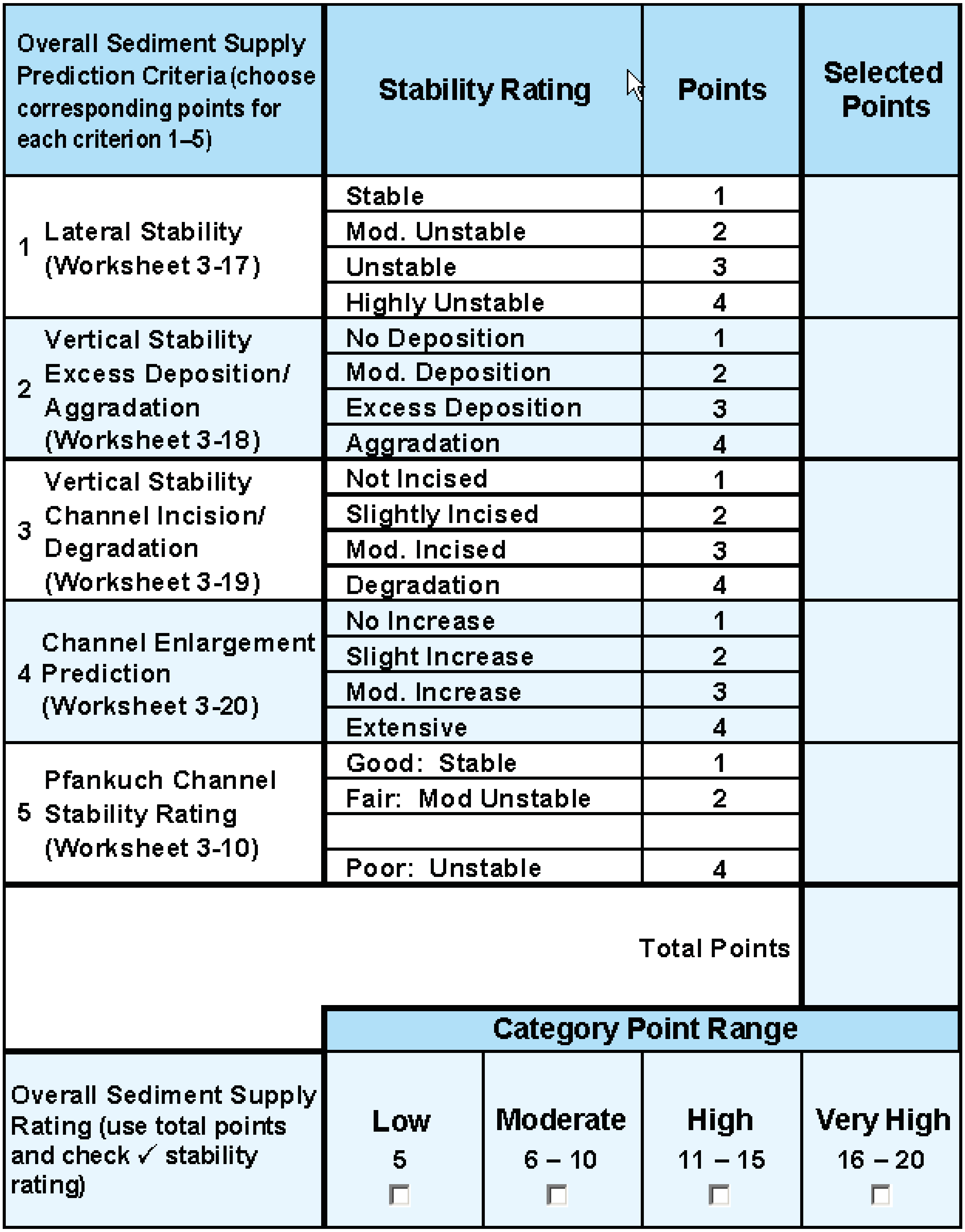
	Vertical Stability Category Point Range for Channel Incision / Degradation			
Vertical Stability for Channel Incision/ Degradation (use total points and check ✓ stability rating)	Not Incised 9 – 11 ☐	Slightly Incised 12 – 18 ☐	Moderately Incised 19 – 27 ☐	Degradation > 27 ☐

Figure 5-17. Vertical Stability Prediction for Incision Worksheet (Rosgen, 2006)



Channel Enlargement Prediction Criteria (choose one stability category for each criterion 1–4)	Channel Enlargement Prediction Categories				Selected Points (from each row)
	No Increase	Slight Increase	Moderate Increase	Extensive	
1 **Successional Stage Shift (Worksheet 3-16)**	Stream Type at Potential, (C→E), (F_b→B), (G→B), (F→B_c), (F→C), (D→C) (2)	(C→High W/d C), (E→C) (4)	(G→F), (F→D) (6)	(C→D), (B→G), (D→G), (C→G), (E→G), (C→F) (8)	
2 **Lateral Stability (Worksheet 3-17)**	Stable (2)	Moderately Unstable (4)	Unstable (6)	Highly Unstable (8)	
3 **Vertical Stability Excess Deposition/ Aggradation (Worksheet 3-18)**	No Deposition (2)	Moderate Deposition (4)	Excess Deposition (6)	Aggradation (8)	
4 **Vertical Stability Incision/ Degradation (Worksheet 3-19)**	Not Incised (2)	Slightly Incised (4)	Moderately Incised (6)	Degradation (8)	
				Total Points	
	Category Point Range				
Channel Enlargement Prediction (use total points and check ✓ stability rating)	**No Increase 8 – 10** ☐	**Slight Increase 11 – 16** ☐	**Moderate Increase 17 – 24** ☐	**Extensive > 24** ☐	

Figure 5-18. Channel Enlargement Prediction Worksheet (Rosgen, 2006)



Overall Sediment Supply Prediction Criteria (choose corresponding points for each criterion 1–5)	Stability Rating	Points	Selected Points
1 Lateral Stability (Worksheet 3-17)	Stable	1	
	Mod. Unstable	2	
	Unstable	3	
	Highly Unstable	4	
2 Vertical Stability Excess Deposition/ Aggradation (Worksheet 3-18)	No Deposition	1	
	Mod. Deposition	2	
	Excess Deposition	3	
	Aggradation	4	
3 Vertical Stability Channel Incision/ Degradation (Worksheet 3-19)	Not Incised	1	
	Slightly Incised	2	
	Mod. Incised	3	
	Degradation	4	
4 Channel Enlargement Prediction (Worksheet 3-20)	No Increase	1	
	Slight Increase	2	
	Mod. Increase	3	
	Extensive	4	
5 Pfankuch Channel Stability Rating (Worksheet 3-10)	Good: Stable	1	
	Fair: Mod Unstable	2	
	Poor: Unstable	4	
		Total Points	

	Category Point Range			
Overall Sediment Supply Rating (use total points and check ✓ stability rating)	Low 5 ☐	Moderate 6 – 10 ☐	High 11 – 15 ☐	Very High 16 – 20 ☐

Figure 5-19. Sediment Supply Rating Worksheet (Rosgen, 2006)

Table 5-8. Rosgen Level III Process-Based Channel Stability Summaries

Detailed Study Reach	Worksheet 3-17 Lateral Stability	Worksheet 3-18 Vertical Stability for Aggradation	Worksheet 3-19 Vertical Stability for Degradation	Worksheet 3-20 Channel Enlargement Prediction	Worksheet 3-21 Sediment Supply Prediction
Buffalo River-1-1.19	Stable	No Deposition	Slightly Incised	No Increase	Moderate
Lower Rush River-1-1.10	Stable	No Deposition	Slightly Incised	No Increase	Moderate
Lower Rush River-2-6.03	Stable	No Deposition	Slightly Incised	No Increase	Moderate
Maple River-1-0.78	Moderately Unstable	No Deposition	Not Incised	No Increase	Moderate
Maple River-2-11.39	Moderately Unstable	No Deposition	Not Incised	No Increase	Moderate
Red River-1-410.65	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-2-419.14	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-3-440.57	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-4-452.52	Moderately Unstable	No Deposition	Not Incised	No Increase	Moderate
Red River-5-463.56	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-6-470.23	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-7-492.47	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Red River-8-521.18	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Rush River-1-0.08	Stable	No Deposition	Slightly Incised	No Increase	Moderate
Rush River-2-6.15	Stable	No Deposition	Not Incised	No Increase	Moderate
Sheyenne River-1-4.20	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-2-11.56	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-3-18.15	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-4-22.27	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-5-26.47	[1/]	[1/]	[1/]	[1/]	[1/]
Sheyenne River-6-35.82	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-7-43.27	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Sheyenne River-8-55.75	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wild Rice River-1-3.01	Moderately Unstable	No Deposition	Not Incised	No Increase	Moderate
Wild Rice River-2-4.23	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wild Rice River-3-17.52	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wild Rice River-4-22.94	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wild Rice River-5-38.49	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wild Rice River-6-42.36	Moderately Unstable	No Deposition	Slightly Incised	Slight Increase	Moderate
Wolverton Creek-1-0.64	Stable	No Deposition	Slightly Incised	No Increase	Moderate
Wolverton Creek-2-2.02	Stable	No Deposition	Not Incised	No Increase	Low

[1/] Could not be determined.

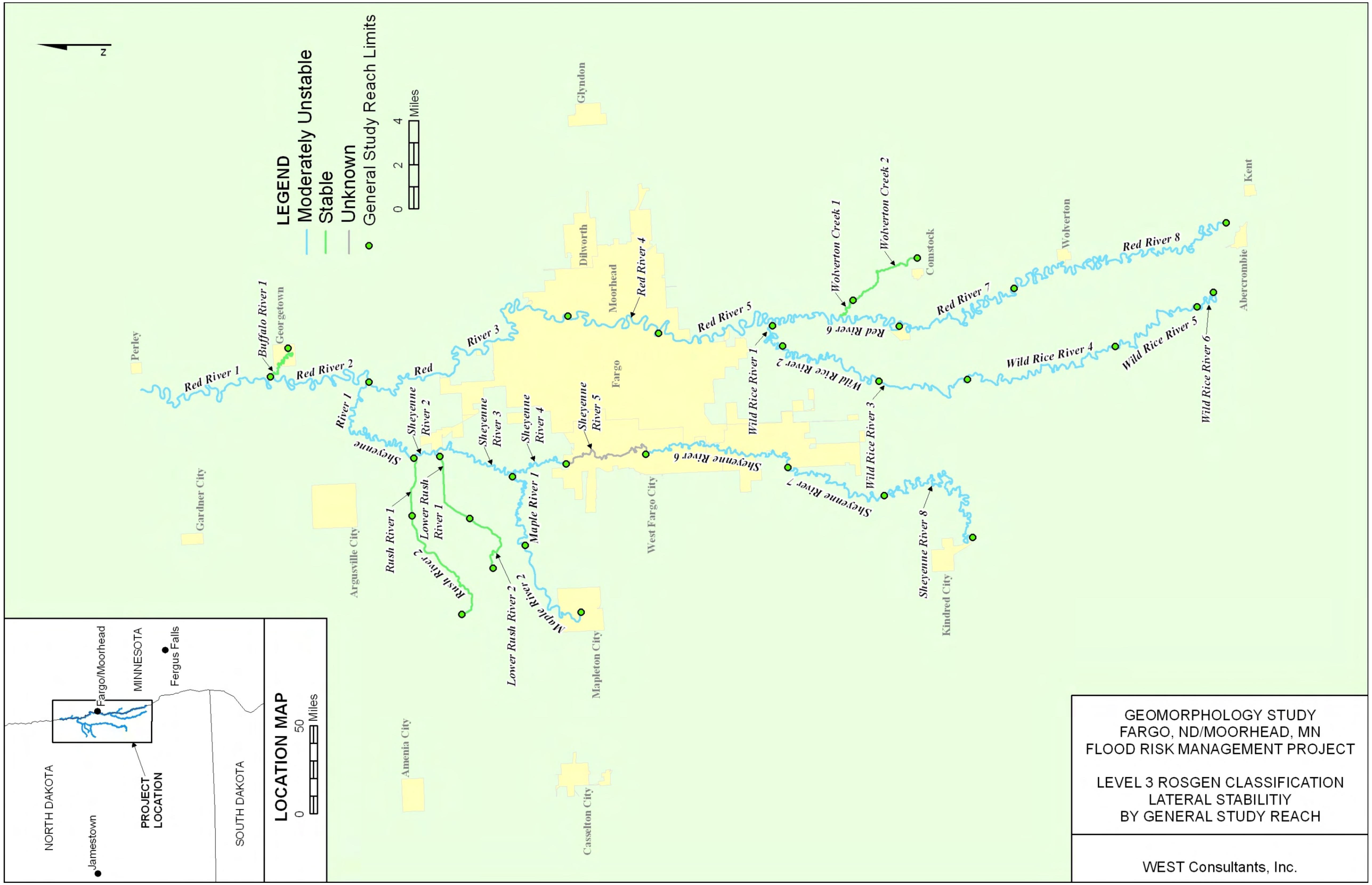


Figure 5-20. Rosgen Level III Classification – Lateral Stability

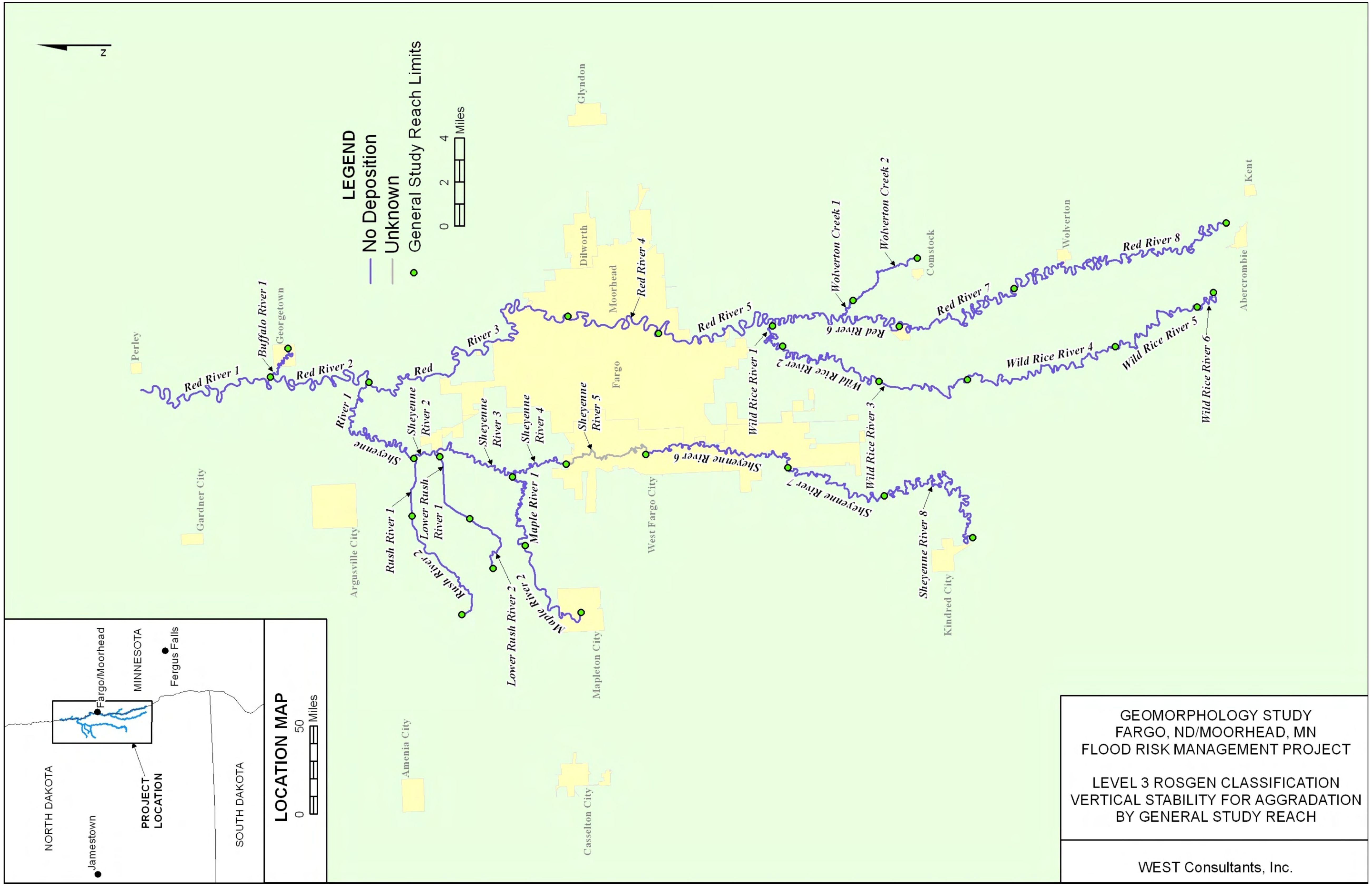


Figure 5-21. Rosgen Level III Classification – Vertical Stability for Aggradation

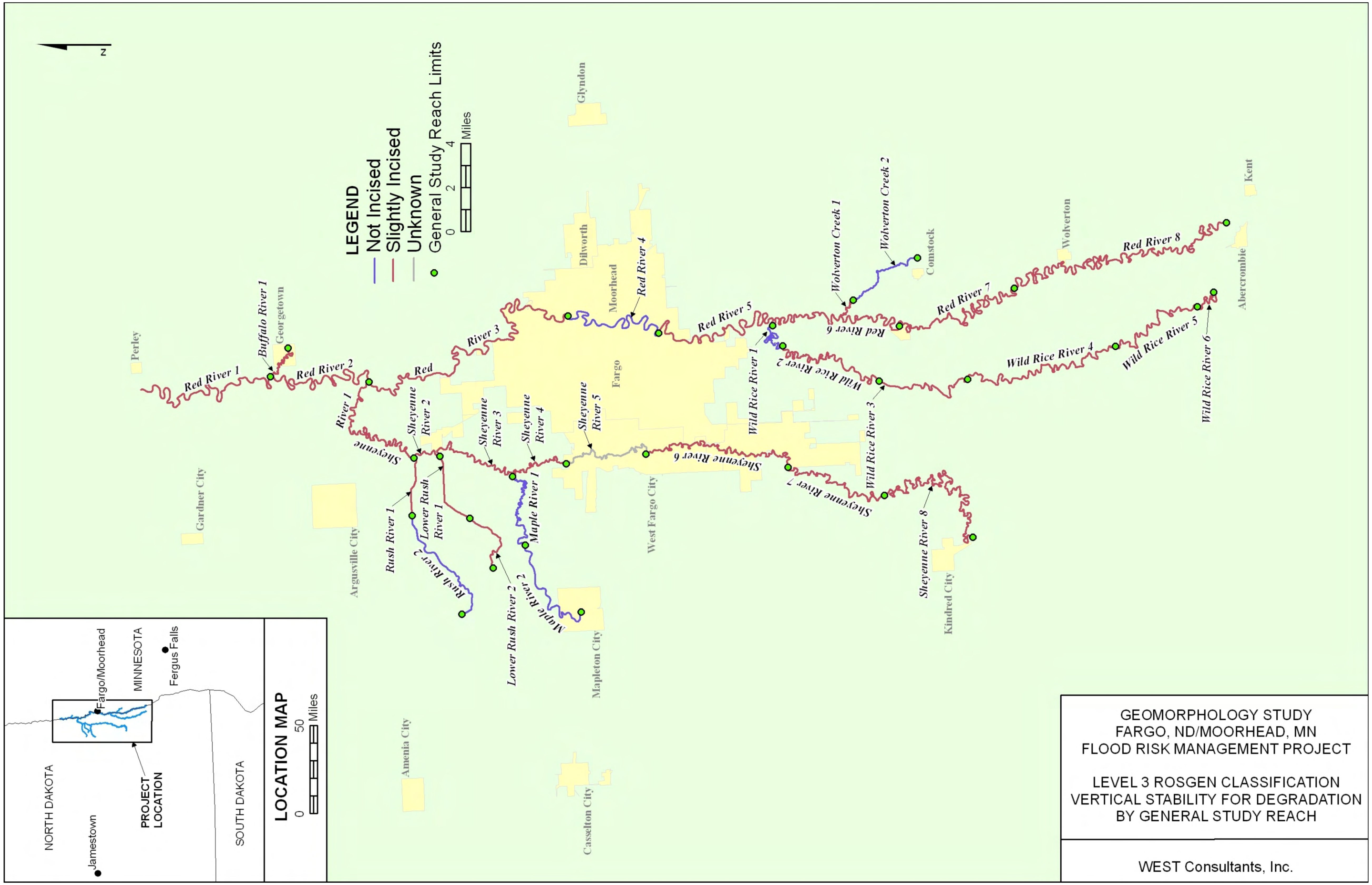


Figure 5-22. Rosgen Level III Classification – Vertical Stability for Degradation

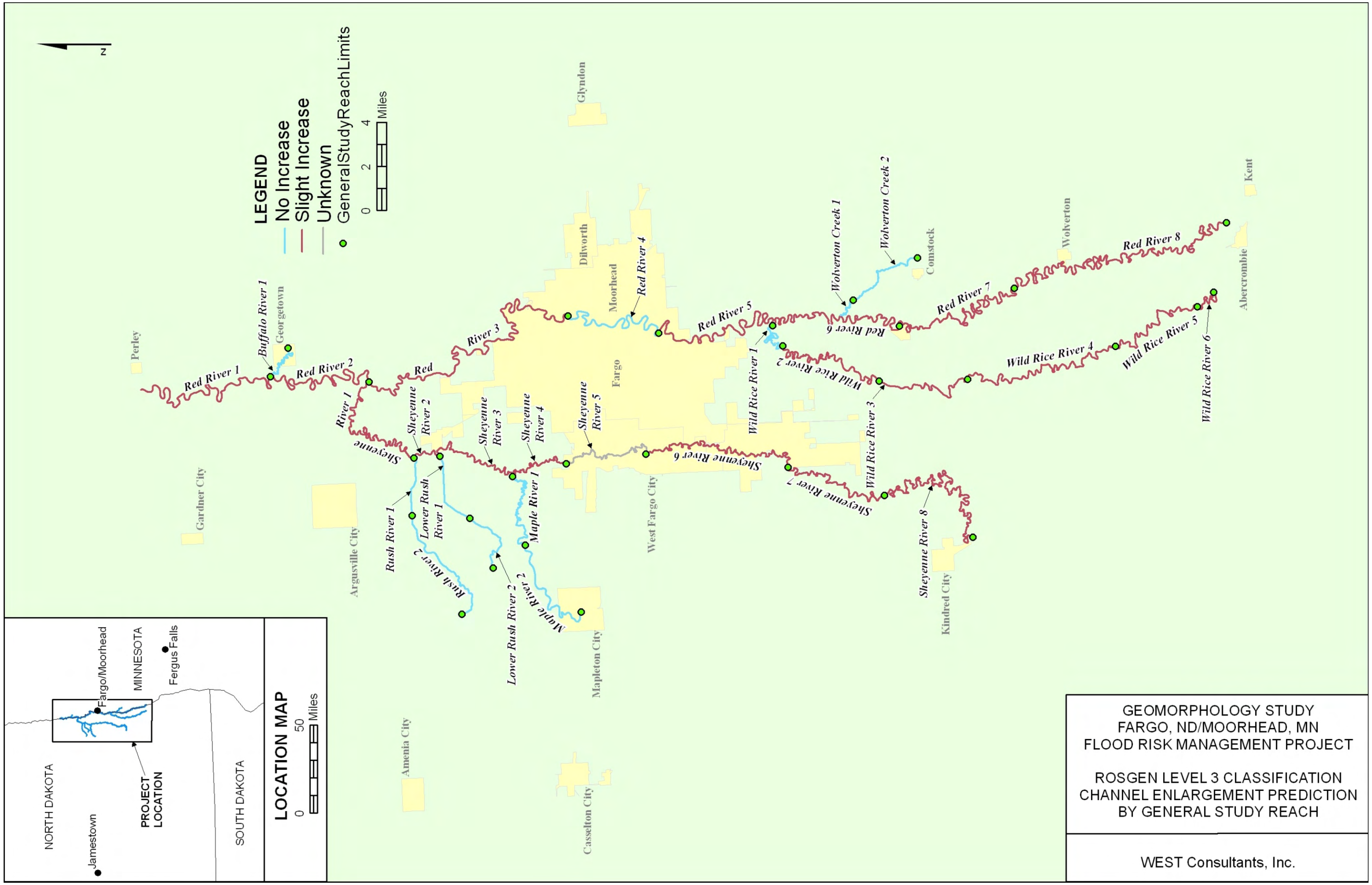


Figure 5-23. Rosgen Level III Classification – Channel Enlargement Prediction

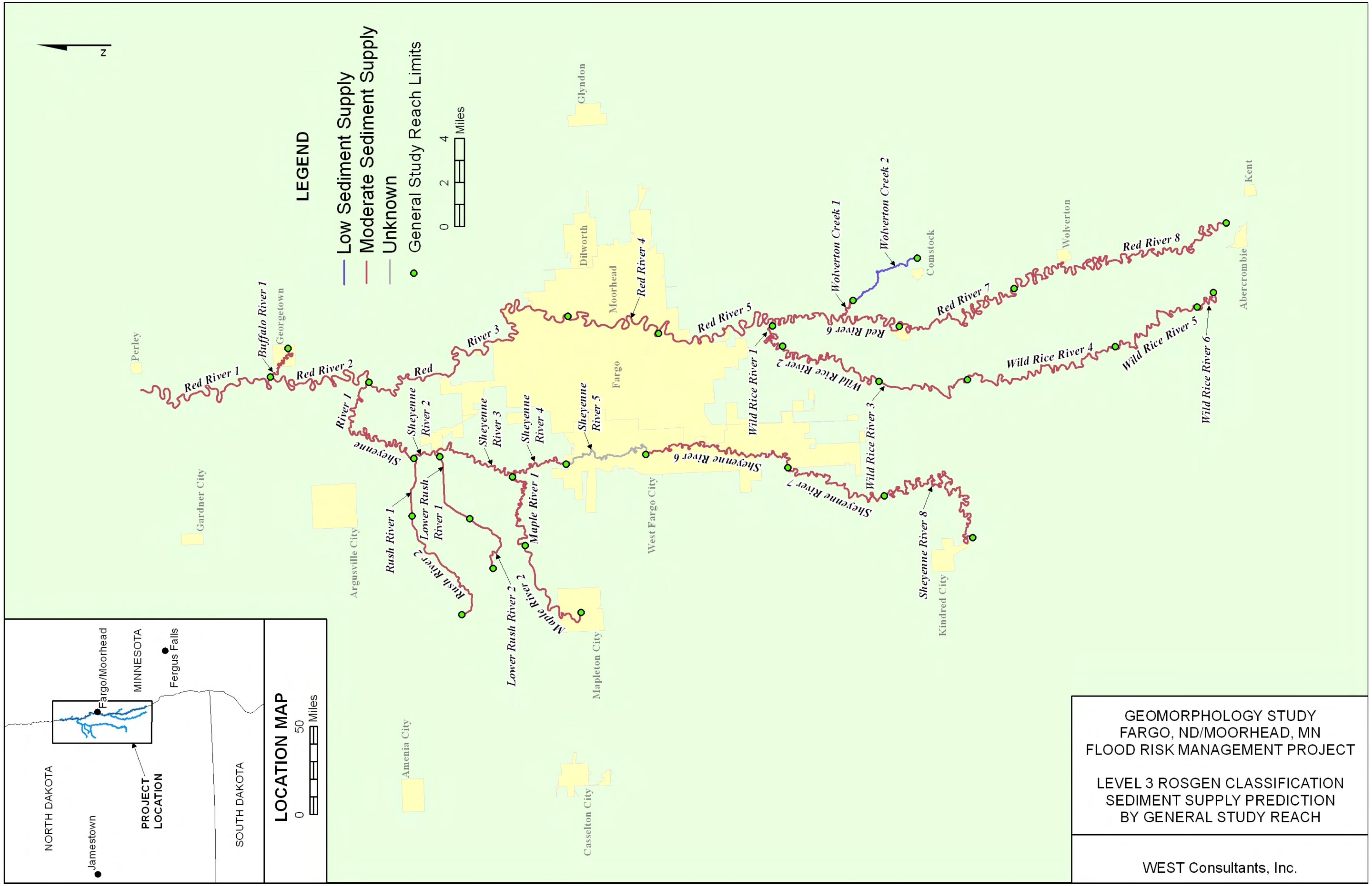


Figure 5-24. Rosgen Level III Classification – Sediment Supply Prediction

5.3 Schumm and Brice Methods

5.3.1 General

Two other classification methods, the Schumm Method (1977) and the Brice Method (1975), were also evaluated for this study. Following a thorough evaluation of each method, the method able to provide the most relevant information for this study was used to perform the morphological classifications for the study streams.

5.3.2 Schumm Method

The Schumm Method is a process-based stream classification system developed using data and observations from streams located in the Midwestern United States, predominantly within the Great Plains area. Rivers studied in the development of the method were alluvial, generally having a well-formed floodplain, and contained less than 20 percent coarse gravel (Schumm, 1963). The Schumm Method uses the type and amount of material transported (and the associated mode of its transport) as its defining criterion for classification. According to the Schumm Method, the three types of material transport methods are suspended load, mixed load, and bedload, and the three types of alluvial channels are stable, depositing, and eroding, allowing for nine distinct classifications. The Schumm Method classification scheme is shown in Table 5-9.

5.3.3 Brice Method

The Brice Method is a process-based stream classification system developed through the analysis of aerial photography dating from the mid 1930s to the late 1960s. The aerial photography covered alluvial rivers located throughout 38 states, including North Dakota and Minnesota. The Brice method uses the degree and character of sinuosity, braiding, and anabranching to classify streams. There are 15 degrees and characters of sinuosity, 13 of braiding, and 16 of anabranching. The Brice Method classification system is shown in Figure 5-25.

Table 5-9. Schumm Method of Stream Classification for Alluvial Channels (Schumm, 1963)

Mode of Sediment Transport	Percentage of Silts/Clays in Channel Bed and Bank	Suspended Load (Percentage of Total Load)	Channel Stability		
			Stable (graded stream)	Depositing (excess load)	Eroding (deficiency of load)
Suspended Load	20-100	97-100	Stable suspended load channel. Width/Depth ratio less than 10; sinuosity usually greater than 2.0; gradient relatively gentle.	Depositing suspended load channel. Major deposition on banks cause narrowing of channel; streambed deposition minor.	Eroding suspended load channel. Streambed erosion predominant; initial channel widening minor.
Mixed Load	5-20	65-97	Stable mixed load channel. Width/Depth ratio greater than 10, less than 40; sinuosity usually less than 2.0, greater than 1.3; gradient moderate.	Depositing mixed load channel. Initial major deposition on banks followed by streambed deposition.	Eroding mixed load channel. Initial streambed erosion followed by channel widening.
Bedload	0-5	30-65	Stable bedload channel. Width/Depth ratio greater than 40; sinuosity usually less than 1.3; gradient relatively steep.	Depositing bedload channel. Streambed deposition and island formation.	Eroding bedload channel. Little streambed erosion; channel widening predominant.

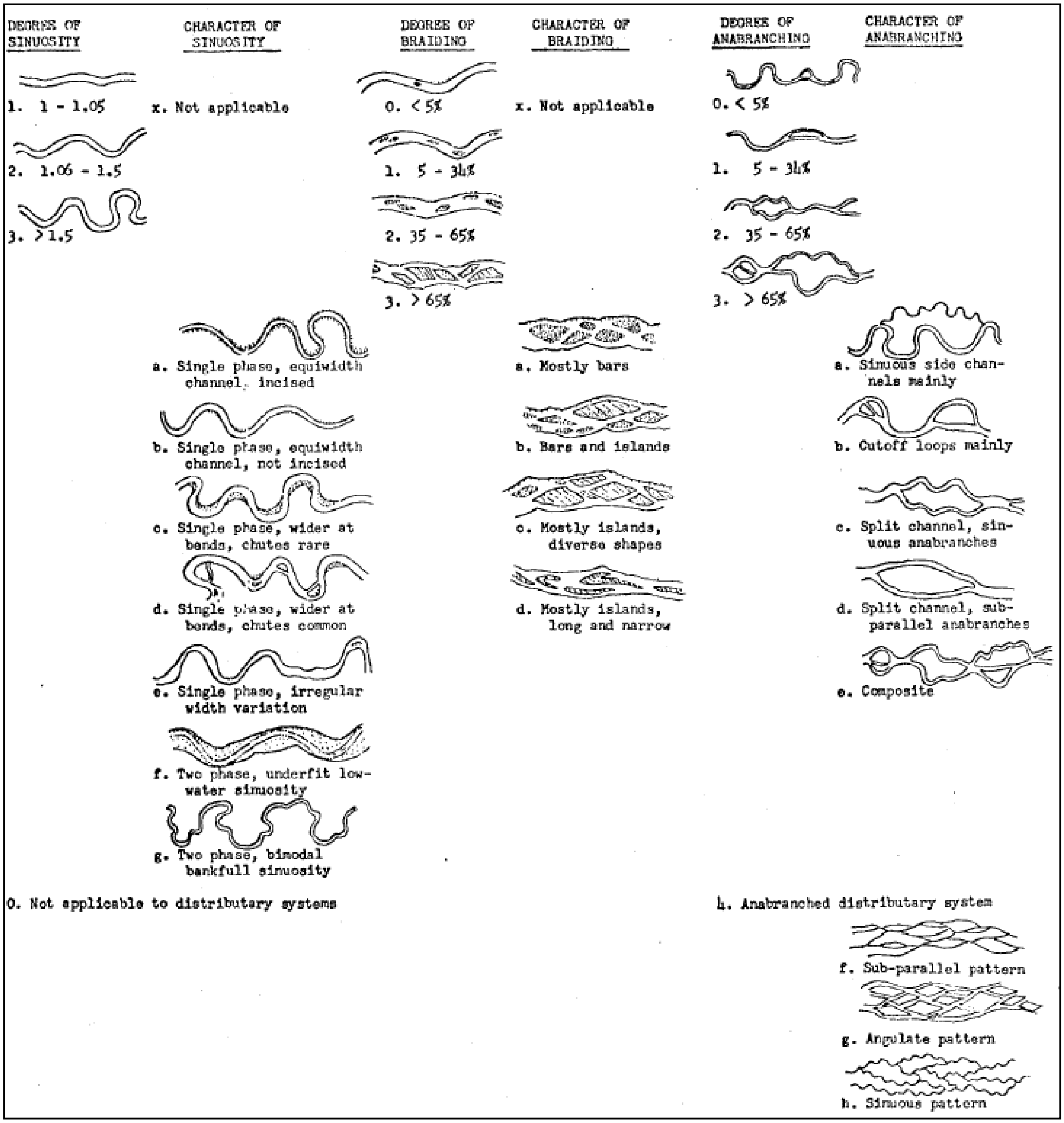


Figure 5-25. Brice Method of Stream Classification for Alluvial Channels (Brice, 1975)

5.3.4 Selected Classification System

The Schumm Method was selected as the method whose results were most relevant for this study. This conclusion was reached based on two items: i) the Schumm Method was developed in the Great Plains area of the US, which is where this project is located; and ii) the Schumm Method provides an indication of the stability of the channel. In contrast, the Brice Method used data from across the US for its development. While the Brice Method classifies streams, it does not provide an indication for the degree of channel stability.

In comparison to the Rosgen Method, the Schumm Method provides additional information for the geomorphic assessment of this study. The Schumm Method is a process-based classification system that identifies the processes causing the channel to be either stable or unstable. The Rosgen method, however, is a form-based classification system that identifies the spatial appearance of the channel. Once the spatial appearance of the channel has been identified, the channel can be classified and, based on the classification and associated data, labeled as stable or unstable. Therefore, the stability of the streams was able to be determined using two distinctly different approaches.

The detailed study reaches were classified according to the Schumm Method as follows. As shown in Table 3-2 and Table 3-3, the stream channels in the study are all comprised of at least twenty percent silts/clays. Additionally, the USGS determined that “contribution of total measured bedload during the event for each of the [sample] sites was less than 1 percent of the total sediment load” (Blanchard et al., 2011). Therefore, the streams within the study area can all be classified as suspended load streams. First, the sinuosity of the channels is greater 2.0 for a majority of the reaches. Second, the gradient of all streams is relatively gentle. Third, an analysis on the width of the streams over time, discussed in Section 6.1.6, indicates that the channels are neither narrowing nor widening at a discernible rate. While the width/depth ratios are not less than 10 for most of the detailed study reaches, this is not considered to indicate instability of the system. As the stream banks slump following large events that deposit material on the bank, such as those events that occurred prior to the 2010 and 2011 field surveys, the bankfull top width will increase and then decrease with time as future sedimentation occurs along the bank. Therefore, the width/depth ratios likely change over time because of geotechnical instabilities. The value of the width/depth ratio will depend on when during the slumping/sedimentation cycle the survey measurements are taken. A more detailed discussion of this process is located in Section 6.1.8. Therefore, the streams within the study area are considered to be stable suspended load channels according to the Schumm Method. Results of the stream classification per the Schumm Method are shown in Table 5-10.

Table 5-10. Schumm Classification for Detailed Study Reaches

Detailed Study Reach	Schumm Classification
Buffalo River-1-1.19	Stable Suspended Load Channel
Lower Rush River-1-1.10	Stable Suspended Load Channel
Lower Rush River-2-6.03	Stable Suspended Load Channel
Maple River-1-0.78	Stable Suspended Load Channel
Maple River-2-11.39	Stable Suspended Load Channel
Red River-1-410.65	Stable Suspended Load Channel
Red River-2-419.14	Stable Suspended Load Channel
Red River-3-440.57	Stable Suspended Load Channel
Red River-4-452.52	Stable Suspended Load Channel
Red River-5-463.56	Stable Suspended Load Channel
Red River-6-470.23	Stable Suspended Load Channel
Red River-7-492.47	Stable Suspended Load Channel
Red River-8-521.18	Stable Suspended Load Channel
Rush River-1-0.08	Stable Suspended Load Channel
Rush River-2-6.15	Stable Suspended Load Channel
Sheyenne River-1-4.20	Stable Suspended Load Channel
Sheyenne River-2-11.56	Stable Suspended Load Channel
Sheyenne River-3-18.15	Stable Suspended Load Channel
Sheyenne River-4-22.27	Stable Suspended Load Channel
Sheyenne River-5-26.47	Stable Suspended Load Channel
Sheyenne River-6-35.82	Stable Suspended Load Channel
Sheyenne River-7-43.27	Stable Suspended Load Channel
Sheyenne River-8-55.75	Stable Suspended Load Channel
Wild Rice River-1-3.01	Stable Suspended Load Channel
Wild Rice River-2-4.23	Stable Suspended Load Channel
Wild Rice River-3-17.52	Stable Suspended Load Channel
Wild Rice River-4-22.94	Stable Suspended Load Channel
Wild Rice River-5-38.49	Stable Suspended Load Channel
Wild Rice River-6-42.36	Stable Suspended Load Channel
Wolverton Creek-1-0.64	Stable Suspended Load Channel
Wolverton Creek-2-2.02	Stable Suspended Load Channel

5.4 Geomorphic Stream Classification Conclusions

Classification of the detailed study reaches using the Rosgen Level II classification system indicated that the streams within the study area are generally stable. The majority of the streams were classified as B6c, E5, or E6 stream types. The B6c stream type is generally stable, while the E5 and E6 stream types are inherently stable and maintain a high resistance to planform changes. The one exception is the classification of the Red River. All of the Red River detailed study reaches are classified at C6c-, which according to Rosgen are very susceptible to shifts in both lateral and vertical stability. While the Red River detailed study reaches were classified as unstable based on their stream classification, all of the other analyses completed as part of this study indicate that the Red River is not susceptible to shifts in both lateral and vertical stability. Therefore, the Rosgen stability rating for a C6c- stream type is not applicable to the Red River.

Analyses completed using the Rosgen Level III classification system indicate that all of the reaches are classified as being either stable or only moderately unstable laterally. All of the detailed study reaches are predicted by the Level III method to experience no or only slight degradation over time. The findings of the Level III classification method reinforce the findings of the Level II findings in that the channels are predicted to generally remain stable over time.

The Schumm Method indicates that all 31 detailed study reaches are classified as stable suspended load channels. Classification of the detailed study reaches as stable using the Schumm Method further reinforces the results of the Rosgen Method, especially when considering that the Schumm Method uses a process-based classification rather than a form-based classification like the Rosgen Method. Two completely different methodologies provide the same result, which allows for a confident prediction that the streams within the study area are generally stable and are not expected to change significantly.

6 Stability Analysis

6.1 Aerial Photography Analysis

An analysis of current and historical aerial imagery was conducted to provide information related to channel planform including sinuosity, channel migration rates, meander amplitudes and frequencies, and changes in riparian vegetation over time. Current and historical aerial imagery covering the study area was obtained from the St. Paul District. One current and two historical aerial imagery data sets were used to evaluate current and historic channel planform characteristics. However, the time period for each historic aerial imagery dataset was not consistent across the entire study area. Therefore, the year for each aerial image was selected based on both image quality and the period of time between each image. The years of aerial imagery used are detailed in Table 6-1.

Table 6-1. Aerial Imagery Source Dates

Stream	Year 1	Year 2	Year 3
Buffalo River	2010	1965	1939
Lower Rush River	2010	1997	1962
Maple River	2010	1997	1962
Red River	2010	1978	1939
Rush River	2010	1997	1962
Sheyenne River	2010	1997	1962
Wild Rice River	2010	1997	1941
Wolverton Creek	2010	1965	1939

As part of the analysis of the aerial imagery, the stream banklines were digitized as shapefiles in ArcEditor Version 9.3 at a consistent scale of 1:3,000. The banklines provided the foundation from which subsequent sets of line work were derived and calculations were made. Because image quality differed significantly between years, a consistent scale ensures that the photos were digitized at the same level of accuracy for each image. For each stream, the banklines were first delineated using the 2010 aerial imagery (Year 1). The 2010 bankline delineations were used as a starting point for creating the Year 2 and Year 3 delineations so that only discernible changes in bank location were captured for these datasets. This was done to preclude small changes in bank location that could not be definitively supported by the historic imagery. The digitized banklines are shown in Panel 1 through Panel 19 in Appendix Q. Once the streambanks were digitized, the stream centerline shapefiles were created using the "Collapse Dual Lines to Centerline" tool in ArcToolbox (ESRI, 2009). Centerlines obtained from the "Collapse Dual Lines to Centerline" tool are very similar and for the most part identical to what would be obtained if the stream centerline were digitized separately. Due to the significant total length of the study reaches, this tool was used for reasons of efficiency and to provide a reproducible result. The stream centerlines were used to determine channel sinuosity, meander amplitudes, and frequencies. After the stream centerlines were created, the banklines were broken into segments and categorized based on the dominant vegetation type (or lack thereof) existing along the stream bank.

A number of potential error sources exist that could affect the results of the analyses. These generally fall into two categories (FGDC, 1998):

- systematic, image registration component
- random feature identification and digitization component

The systematic error component primarily includes the rectification process for the aerial imagery. While modern image capture techniques and equipment allow for the automatic ortho-rectification of imagery during initial capture, this process must be completed manually for historic imagery. Several steps are involved with the conversion of historic aerial photographs to a final ortho-image product that is compatible with GIS and ready to be used as a source for the generation of derivative data sets. During the initial collection phase, photographs are taken from camera equipment mounted to an aircraft flying at a fixed elevation. The scale of the photographs is determined by the elevation of the airplane and resolution of the camera equipment. Next, the developed images are scanned at a chosen resolution (in dots per inch, DPI) that is reasonable for the source image (i.e., such that the quality/resolution of the original image is maintained). Finally, the image is ortho-rectified using GIS or other appropriate mapping software. This involves identification of matching points between the imagery being rectified and some previously rectified imagery or GIS data. The identification of match points allows the software to warp the image using a linear, quadratic or cubic transformation such that the match points chosen on the image being rectified match exactly or closely with the match points identified on the source image or data. During this process, match points cannot always be exactly matched through the warping process, thus resulting in error in the rectification process. This error is typically quantified by the rectification software and reported as root mean square error (RMSE).

The 2010 aerial imagery was automatically rectified during its capture using GPS systems aboard the plane that captured the images. As a result, the 2010 aerial imagery was used as the baseline imagery against which all other imagery was rectified. All other aerial images were rectified by the St. Paul District; however, the RMSE values for the rectified images are unknown as are the DPI settings at which the historic imagery was scanned (though it is assumed this was done at a setting appropriate for the source imagery). A study by Hughes, et al. (2006) indicated that aerial photos can be consistently rectified to an accuracy of approximately ±16 feet, with an approximately 10 percent chance of greater error; however, that value is based on parameters specific to their study (source photographs taken at 1:20,000 and scanned at 600 DPI for an effective resolution of 1m per pixel) and cannot be applied directly to this analysis.

Another source of error results from the differing quality of the aerial images. The 2010 aerial images appear to be of the highest quality and resolution while the historic images are generally of lower quality. In general, the oldest images have the lowest quality. Lower image resolution makes the placement of the lines less certain. Additionally, the 2010 data were the only color imagery available while the remaining images were only available in black and white. While this did not substantially impact the ability to define the banklines, it did affect the ability to correctly identify vegetation type along the banks.

The random error component includes operator error during the stream bank delineation process. At the map scale of 1:3,000 used for digitization, a distance of 0.1 inches is equivalent to 25 feet on the ground. At this scale, the width of the line within the GIS that is used to delineate the banklines is equivalent to approximately 8 feet on the ground. While digitizing at a larger scale may help reduce this type of error, it is ultimately impractical due to the varying level of quality of the multiple imagery datasets used in this process (i.e., while a larger scale renders objects larger on the operator's screen, they become more pixilated and therefore more difficult to interpret). While the higher quality datasets may support use of a slightly larger scale, this is not possible across all available imagery data and a consistent scale is necessary to avoid influencing measured changes between years of data with digitizing scale error. As a result, small changes in channel location cannot be evaluated using the available historic aerial photography.

The final source of random error and likely largest overall source of error arises from interpretation of the actual top of bank location. Often, channel banklines are simply digitized as the edge of water from aerial imagery. While this method is fairly common, variations in water level between subsequent years of imagery can have significant influence on the resulting calculations causing possibly erroneous results, and therefore must be used carefully. For example, it was noted that portions of the Red River were experiencing high water and some level of flooding during the capture of the Year 2 imagery. Because of these potential errors from digitizing the edge of water, bank lines for this analysis were based on the estimated top of bank location. While vegetation along the riparian corridors in some areas is absent or only consists of short grasses, the majority of the water courses are bordered by mature forest whose canopy often overhang the banks and obscures the banks making identification of the actual top of bank locations particularly difficult. Because of uncertainly in the identification of top of bank locations small changes in banklines between years were not considered. Year 1 (2010) lines were digitized first because the quality of the imagery provided the best estimate of true bank location. For subsequent years, the banklines were only modified where it was fairly clear that bank locations had indeed moved. The threshold used varied somewhat depending on the location and the year of imagery being used in the analysis. Typically, the minimum threshold was approximately 15-20 feet. It is important to note that while this threshold was used to help overcome some of the uncertainties with bank identification due to the random feature identification and digitization component of the error (such as vegetation hiding bank locations), the identified movement is still subject to the systematic, image registration component of the error. In some locations, the amount of error in image registration could easily exceed the 15-20 foot threshold used. Ultimately, since the total error could not be quantified, the threshold was based on judgment of limiting factors that contributed to uncertainty in bank identification, such as image quality and vegetation.

Due to the number and type of error sources and lack of data on the scanning and rectification process, the actual amount of error associated with the analysis of historic aerial imagery is unknown; therefore, the resulting calculations must be considered carefully and appropriately applied. Sinuosity, meander migration rates, meander amplitudes and frequencies, bank erosion, large woody debris, and bank vegetation are discussed in the following sections.

6.1.1 Sinuosity

Sinuosity is defined as the ratio of the channel length to the down valley distance (Leopold, et. al., 1992). Rivers with a sinuosity between 1 and1.5 are considered to range between straight and sinuous; those with a value of 1.5 or greater are defined as meandering (Leopold, et al., 1992). Sinuosity was calculated for each general study reach for three separate years based on the stream centerline developed from the aerial imagery. The centerline distance was divided by the straight line distance between the upstream and downstream endpoints of each general study reach. Calculations were not made for the Rush 1 and Lower Rush 1 sites as the lower reaches of these two watercourses have undergone significant historic channelization and straightening. The sinuosity values calculated for each general study reach are summarized in Table 6-2.

Table 6-2. Sinuosity Calculated from Orthophotos

General Study Reach	Sinuosity (ft/ft)			Year 3 to Year 2 Change	Year 2 to Year 1 Change	Year 3 to Year 1 Change
	Year 3 (oldest)	Year 2	Year 1 (youngest)			
Buffalo River 1	2.2	2.2	2.2	0.5%	-0.5%	0.0%
Lower Rush River 1	[1]	[1]	[1]	[1]	[1]	[1]
Lower Rush River 2	1.3	1.3	1.3	-0.8%	0.0%	-0.8%
Maple River 1	2.2	2.1	2.2	-0.5%	0.5%	0.0%
Maple River 2	1.7	1.7	1.7	0.6%	0.0%	0.6%
Red River 1	[2]	2.0	2.0	[2]	0.5%	[2]
Red River 2	2.2	2.2	2.2	0.9%	0.0%	0.9%
Red River 3	2.3	2.2	2.2	-4.9%	0.0%	-5.1%
Red River 4	2.2	2.2	2.2	-2.7%	0.0%	-2.8%
Red River 5	2.4	2.4	2.4	0.0%	0.4%	0.4%
Red River 6	2.2	2.3	2.3	0.4%	0.0%	0.4%
Red River 7	2.6	[2]	2.6	[2]	[2]	0.4%
Red River 8	2.6	[2]	2.6	[2]	[2]	-1.2%
Rush River 1	[1]	[1]	[1]	[1]	[1]	--[1]
Rush River 2	1.4	1.4	1.4	0.0%	0.7%	0.7%
Sheyenne River 1	2.9	2.8	2.8	-2.1%	-0.4%	-2.5%
Sheyenne River 2	1.5	1.5	1.5	0.0%	0.0%	0.0%
Sheyenne River 3	1.9	1.9	1.9	-1.6%	0.0%	-1.6%
Sheyenne River 4	1.8	1.8	1.8	0.0%	0.0%	0.0%
Sheyenne River 5	1.8	1.7	1.7	-6.1%	0.0%	-6.5%
Sheyenne River 6	1.8	1.8	1.8	-2.7%	0.0%	-2.8%
Sheyenne River 7	1.8	1.8	1.8	0.0%	0.0%	0.0%
Sheyenne River 8	4.0	4.0	4.0	-2.0%	0.3%	-1.8%
Wild Rice River 1	4.0	3.9	3.9	-2.3%	-0.3%	-2.6%
Wild Rice River 2	2.3	2.3	2.3	0.4%	0.0%	0.4%
Wild Rice River 3	1.5	1.5	1.5	0.0%	0.0%	0.0%
Wild Rice River 4	1.8	1.8	1.8	-1.1%	0.0%	-1.1%
Wild Rice River 5	1.9	1.9	1.9	0.0%	0.0%	0.0%
Wild Rice River 6	2.7	2.7	2.7	0.0%	0.0%	0.0%
Wolverton Creek 1	1.8	1.7	1.7	-2.8%	0.0%	-2.9%
Wolverton Creek 2	1.3	1.3	1.3	0.0%	-0.8%	-0.8%

[1] sinuosity not calculated due to significant channelization

[2] sinuosity not calculated due to limited/partial aerial imagery coverage

As seen in Table 6-2, Sheyenne River 8 and Wild Rice River 1 each have sinuosity values of around four, which means that these reaches have a much greater channel length per down valley distance than the other study stream reaches. Wild Rice River 1 is a relatively short reach compared to the other reaches and has very large meander bend that, although prominent in that reach, appears similar in planform to upstream reaches but is likely skewing the sinuosity value to the high side.

Sheyenne River 8 is a sufficiently long reach to prevent a single meander bend from skewing the sinuosity value. Further, it exhibits a two-phase, bi-modal meander pattern (see Figure 5-25) that is absent for the other stream reaches. Because of the proximity of this reach to the sandy beach deposits of glacial Lake Agassiz, there is likely to be a greater supply of sand to this reach compared with downstream reaches. The sediment transport capacity in Sheyenne River 8 appears to be insufficient to transport all of the sand that is supplied to it from upstream. As a result, the channel has responded by shifting laterally at a slightly greater rate and increasing its overall channel length, which is approximately 2 times longer than downstream reaches, to accommodate storage of the additional sand.

6.1.2 Meander Migration Rates

Quantification of historic meander migration rates can be useful for predicting future behavior of rivers under certain conditions. Additionally, historic rates can serve as a base line for observation of future channel migration rates. Migration rates were calculated for each of the detailed study reaches, except Rush 1 and Lower Rush 1, which have experienced significant historic channelization and straightening. Wolverton 1 and 2 were excluded due to the poor quality of the historic aerial imagery and the associated uncertainty in determination of bank lines for those relatively narrow reaches.

Meander migration can take numerous forms aside from down valley migration (translation); these include expansion, extension, rotation, or combinations of these types (Figure 6-1). Meander migration rates were calculated using a methodology similar to the guidance found in National Cooperative Highway Reach Program Report 533 (NCHRP, 2004). Circles were inscribed along the channel centerlines at each meander bend for each of the 3 years of data. Typically, these circles would be drawn such that they define the outer banklines; however, due to the relatively dense vegetation along many of the banks and the associated difficulty in accurately defining the bank lines, centerlines were used as a proxy. In ArcGIS, centroids were calculated for each of the circles and XY coordinates assigned to these centroids. The linear distance between the centroids for each meander, for each of the 3 years was then calculated using the differences between the coordinates. The distances between meander centroids of differing years represent the channel migration (Figure 6-2). The calculated distances were averaged for each detailed study reach and are shown in Table 6-3. As seen in Table 6-3, very little channel migration was observed.

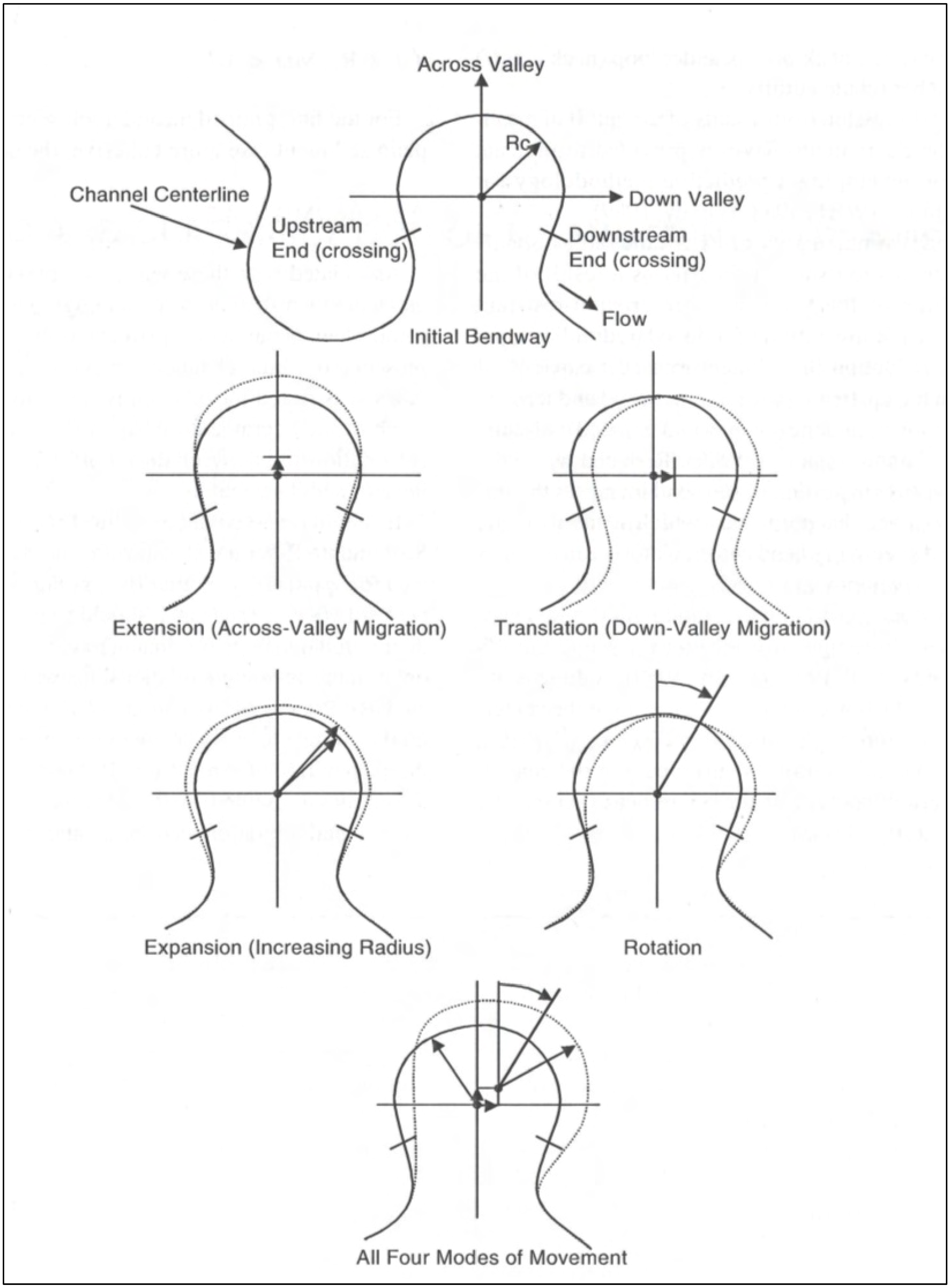


Figure 6-1. Types of Meander Migration (NCHRP, 2004)

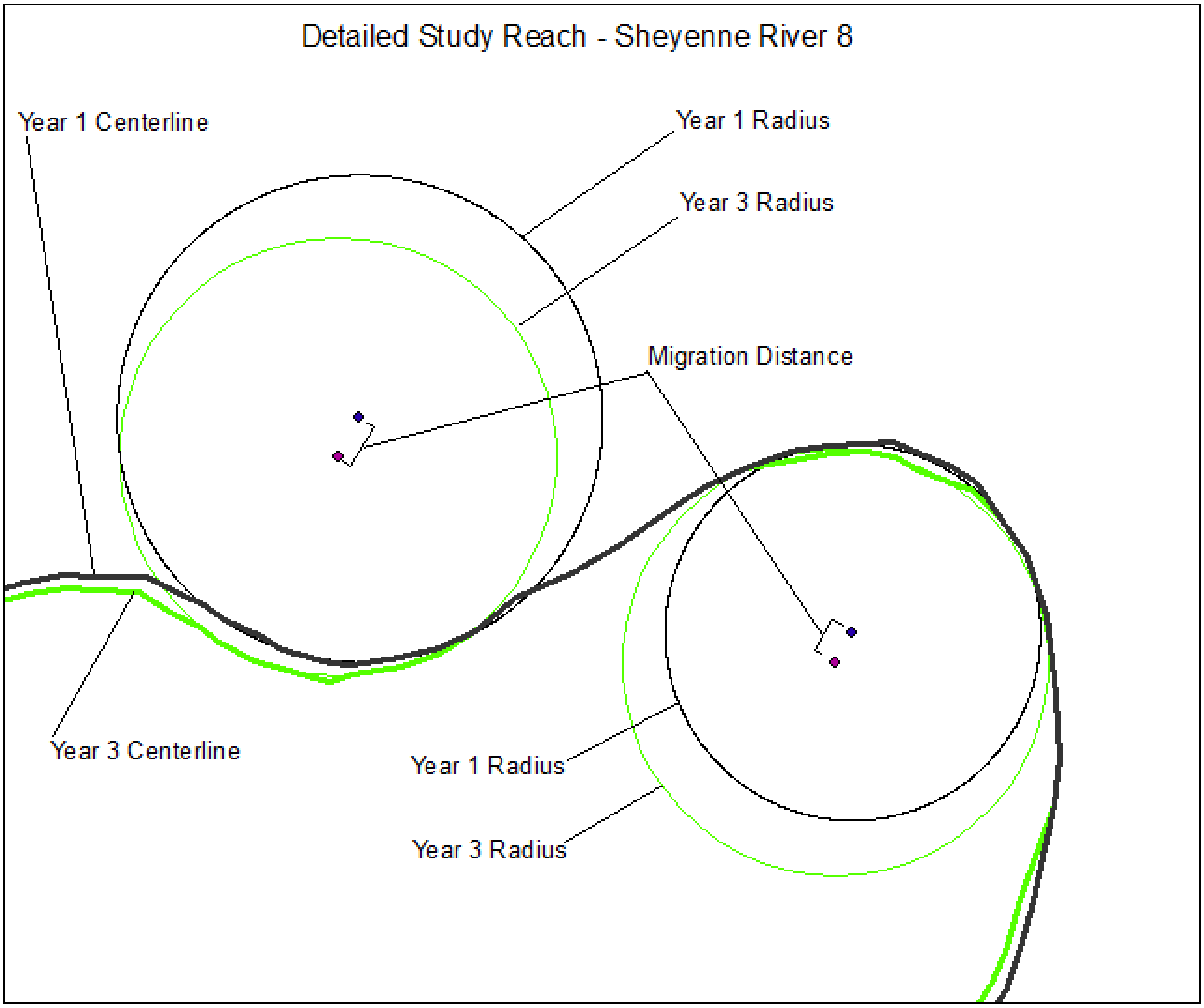


Figure 6-2. Sample of Meander Migration Calculation Methodology

Table 6-3. Meander Migration Rates for the Detailed Study Reaches

Detailed Study Reach	Migration Rate Year 3 to Year 2 (ft)	Migration Rate Year 2 to Year 1 (ft)	Migration Rate Year 3 to Year 1 (ft)	# Meanders Used in Calculation
Buffalo River-1-1.19	0	0	0	3
Lower Rush River-1-1.10	[1]	[1]	[1]	[1]
Lower Rush River-2-6.03	0	0	0	3
Maple River-1-0.78	0	0	0	5
Maple River-2-11.39	0	0	0	4
Red River-1-410.65	0	0	0	2
Red River-2-419.14	0	0	0	4
Red River-3-440.57	0	0	0	3
Red River-4-452.52	0	0	0	2
Red River-5-463.56	0	0	0	2
Red River-6-470.23	0	0	0	2
Red River-7-492.47	0	0	0	2
Red River-8-521.18	0	0	0	7
Rush River-1-0.08	[1]	[1]	[1]	[1]
Rush River-2-6.15	0	0	0	2
Sheyenne River-1-4.20	0	0	0	3
Sheyenne River-2-11.56	0	0	0	3
Sheyenne River-3-18.15	0	0	0	3
Sheyenne River-4-22.27	0	0	0	2
Sheyenne River-5-26.47	0	0	0	2
Sheyenne River-6-35.82	0	0	0	2
Sheyenne River-7-43.27	3	0	2	4
Sheyenne River-8-55.75	1	1	1	7
Wild Rice River-1-3.01	0	0	0	4
Wild Rice River-2-4.23	0	0	0	4
Wild Rice River-3-17.52	0	0	0	2
Wild Rice River-4-22.94	0	0	0	4
Wild Rice River-5-38.49	0	0	0	3
Wild Rice River-6-42.36	0	0	0	5
Wolverton Creek-1-0.64	[2]	[2]	[2]	[2]
Wolverton Creek-2-2.02	[2]	[2]	[2]	[2]

[1] not calculated due to significant channelization

[2] not calculated due to poor image quality

6.1.3 Meander Amplitude and Frequency

A meander is a bend in a sinuous watercourse. Two common measures of meander geometry are amplitude and frequency (wavelength). As defined by Leopold et al. (1964), meander amplitude is the lateral distance between tangential lines drawn at the centerline of adjacent meander apexes (cross valley distance between meander apexes) while meander frequency is distance between tangential lines drawn at the inflection points bounding two successive meanders.(down valley distance between inflection/crossover points) (Figure 6-3).

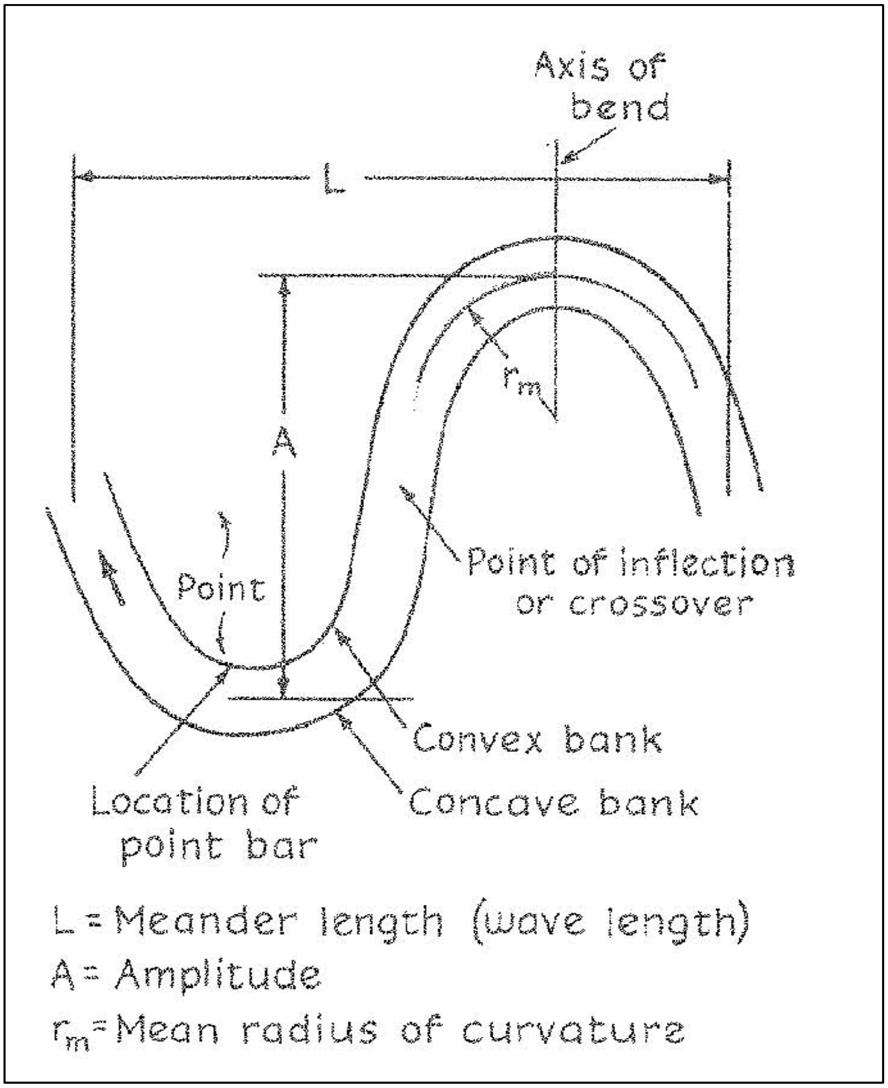


Figure 6-3. Definitions of Amplitude and Frequency (Leopold et al., 1964)

Amplitude and frequency for each detailed study reach were calculated for three different years based on the centerlines digitized from aerial imagery. Inflection points between meanders were identified and a smooth line was drawn connecting the inflection points; with each line being assumed equal to one half of the frequency (Figure 6-4). The largest distance between the smoothed line connecting two inflection points and the channel centerline was measured for each meander and was assumed to equal one half of the amplitude. The half amplitude and half frequency measurements were multiplied by two and then averaged for each detailed study reach. Calculations were not made for the Rush 1 and Lower Rush 1 sites as the lower reaches of these two rivers have undergone significant historic channelization and straightening. Summaries of the calculated values for each detailed study reach along with a comparison of changes between measured years are provided in Table 6-4 and Table 6-5. It should be noted that the meander amplitude was calculated for the entire length of each general study reach while the meander migration was calculated only along the length of the detailed study reaches. Accordingly, while for most study reaches there is no change in meander amplitude or meander migration, a reach may show a very small change in one measurement but not the other.

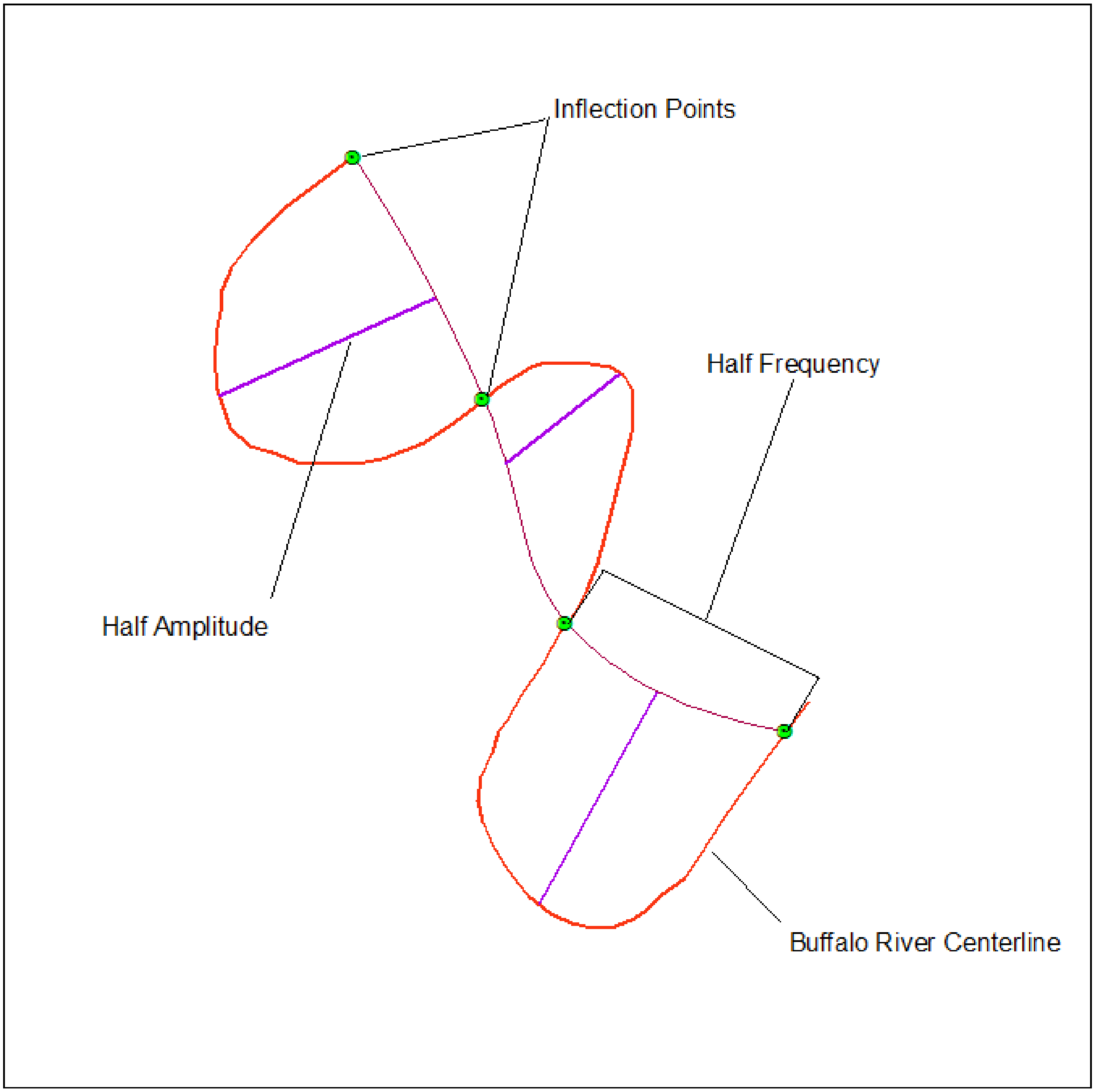


Figure 6-4. Meander Amplitude and Wavelength Calculation Method

Table 6-4. Average Meander Amplitude for Detailed Study Reaches

Detailed Study Reach	Amplitude (ft) Year 3 (oldest)	Year 2	Year 1 (youngest)	Year 3 to Year 2 Change	Year 2 to Year 1 Change	Year 3 to Year 1 Change
Buffalo River-1-1.19	557	557	557	0%	0%	0%
Lower Rush River-1-1.10	[1]	[1]	[1]	[1]	[1]	[1]
Lower Rush River-2-6.03	524	524	524	0%	0%	0%
Maple River-1-0.78	260	260	260	0%	0%	0%
Maple River-2-11.39	898	898	898	0%	0%	0%
Red River-1-410.65	[2]	2,034	2,052	[2]	1%	[2]
Red River-2-419.14	916	924	924	1%	0%	1%
Red River-3-440.57	1,406	1,406	1,406	0%	0%	0%
Red River-4-452.52	2,446	2,446	2,446	0%	0%	0%
Red River-5-463.56	680	655	655	-4%	0%	-4%
Red River-6-470.23	1,715	1,701	1,701	-1%	0%	-1%
Red River-7-492.47	1,941	1,941	1,941	0%	0%	0%
Red River-8-521.18	548	548	548	0%	0%	0%
Rush River-1-0.08	[1]	[1]	[1]	[1]	[1]	[1]
Rush River-2-6.15	322	322	322	0%	0%	0%
Sheyenne River-1-4.20	869	869	869	0%	0%	0%
Sheyenne River-2-11.56	376	376	376	0%	0%	0%
Sheyenne River-3-18.15	1,224	1,228	1,236	0%	1%	1%
Sheyenne River-4-22.27	487	487	487	0%	0%	0%
Sheyenne River-5-26.47	769	769	769	0%	0%	0%
Sheyenne River-6-35.82	631	631	631	0%	0%	0%
Sheyenne River-7-43.27	456	456	456	0%	0%	0%
Sheyenne River-8-55.75	498	498	498	0%	0%	0%
Wild Rice River-1-3.01	338	338	333	0%	-2%	-2%
Wild Rice River-2-4.23	382	390	390	2%	0%	2%
Wild Rice River-3-17.52	1,102	1,102	1,102	0%	0%	0%
Wild Rice River-4-22.94	694	694	694	0%	0%	0%
Wild Rice River-5-38.49	1,144	1,144	1,144	0%	0%	0%
Wild Rice River-6-42.36	468	468	468	0%	0%	0%
Wolverton Creek-1-0.64	93	104	104	11%	0%	10%
Wolverton Creek-2-2.02	86	97	97	14%	0%	12%

[1] not calculated due to significant channelization

[2] not calculated due to limited aerial imagery coverage

Table 6-5. Average Meander Frequency for Detailed Study Reaches

Detailed Study Reach	Frequency (ft)			Year 3 to Year 2 Change	Year 2 to Year 1 Change	Year 3 to Year 1 Change
	Year 3 (oldest)	Year 2	Year 1 (youngest)			
Buffalo River-1-1.19	681	681	681	0%	0%	0%
Lower Rush River-1-1.10	[1/]	[1/]	[1/]	[1/]	[1/]	[1/]
Lower Rush River-2-6.03	1,532	1,532	1,532	0%	0%	0%
Maple River-1-0.78	739	739	739	0%	0%	0%
Maple River-2-11.39	1,831	1,831	1,831	0%	0%	0%
Red River-1-410.65	[2/]	2,066	2,066	[2/]	0%	[2/]
Red River-2-419.14	2,242	2,248	2,248	0%	0%	0%
Red River-3-440.57	1,901	1,901	1,901	0%	0%	0%
Red River-4-452.52	2,750	2,750	2,750	0%	0%	0%
Red River-5-463.56	2,449	2,449	2,449	0%	0%	0%
Red River-6-470.23	1,310	1,310	1,310	0%	0%	0%
Red River-7-492.47	2,002	2,002	2,002	0%	0%	0%
Red River-8-521.18	1,298	1,298	1,298	0%	0%	0%
Rush River-1-0.08	[1/]	[1/]	[1/]	[1/]	[1/]	[1/]
Rush River-2-6.15	2,344	2,344	2,344	0%	0%	0%
Sheyenne River-1-4.20	1,238	1,238	1,238	0%	0%	0%
Sheyenne River-2-11.56	1,474	1,474	1,474	0%	0%	0%
Sheyenne River-3-18.15	1,533	1,551	1,538	1%	-1%	0%
Sheyenne River-4-22.27	923	923	923	0%	0%	0%
Sheyenne River-5-26.47	850	850	850	0%	0%	0%
Sheyenne River-6-35.82	936	936	936	0%	0%	0%
Sheyenne River-7-43.27	1,028	1,028	1,028	0%	0%	0%
Sheyenne River-8-55.75	1,265	1,265	1,265	0%	0%	0%
Wild Rice River-1-3.01	910	910	910	0%	0%	0%
Wild Rice River-2-4.23	738	745	745	1%	0%	1%
Wild Rice River-3-17.52	1,346	1,346	1,346	0%	0%	0%
Wild Rice River-4-22.94	1,514	1,514	1,514	0%	0%	0%
Wild Rice River-5-38.49	1,709	1,709	1,709	0%	0%	0%
Wild Rice River-6-42.36	1,353	1,353	1,353	0%	0%	0%
Wolverton Creek-1-0.64	285	314	314	10%	0%	9%
Wolverton Creek-2-2.02	615	625	625	2%	0%	2%

[1/] not calculated due to significant channelization
[2/] not calculated due to limited aerial imagery coverage

6.1.4 Meander Belt

Meander belt is defined by the United States Geological Survey as the area between lines drawn tangentially to the extreme limits of fully developed meanders (USGS, 1995). This is the total area over which a meandering river might be expected to occupy some portion of, at some point in time. Meander belt width is always larger than meander amplitude as belt width is measured from the outside bends of the river rather than from the channel centerline as is the procedure for determining meander amplitude. Furthermore, depending on the regularity of the meanders, the belt width may be considerably larger than the average amplitude (Figure 6-5).

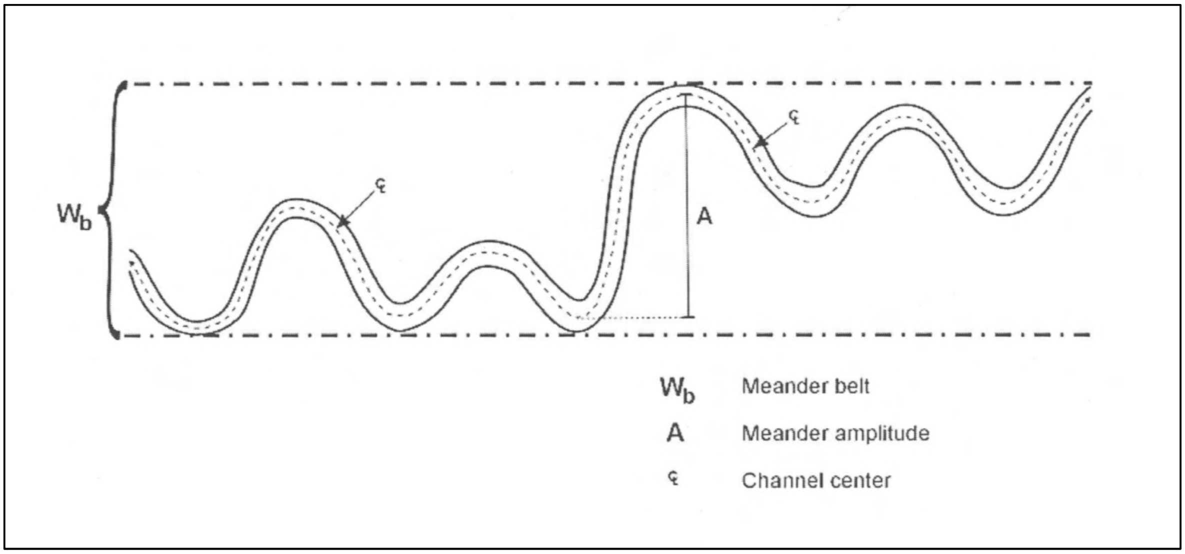


Figure 6-5. Example of a Specific Meander Defining the Meander Belt Width for a Reach (Parish Geomorphic, 2004)

Meander belt width was determined for Year 1, Year 2, and Year 3 for each detailed study reach except for Rush 1 and Lower Rush 1, which have experienced considerable historic channelization. Year 2 and Year 3 for Wolverton 1 and Wolverton 2 were excluded from this analysis due to the poor quality of the historic aerial imagery and associated uncertainty in determination of bank lines for those reaches. Meander belt width was determined in the following manner. Lines were digitized in GIS along the outside bank of the extreme meanders of each detailed study reach. In many cases the extreme meanders were located outside of (upstream or downstream) the detailed study reach; therefore the belt width lines were extended beyond the limits of the detailed study reaches in order to avoid incorrectly biasing the calculation towards a narrower width by not incorporating the extreme meanders (Figure 6-6). The meander belt width lines were converted to polygons and then clipped to the extents of the detailed study reaches. Centerlines for the belt width polygons were automatically generated using ArcGIS. The calculated areas for the belt width polygons were divided by the centerline length to provide an average belt width for each detailed study reach (Table 6-6). The average belt widths for most study streams showed no measureable change over the time scale of the available data. The maximum calculated % change value for all study reaches is 2%, and occurs for reach Red River 2. At this location, this value might be due to error associated with identification of the bank lines due to flooding and high water levels at the time the Year 2 imagery was collected. Although, it was ultimately impossible to quantify the error associated with the various parts of the stability analysis, the range of error is likely at least +/- 5%, and the 2% value falls within this range. It should be noted that historic meander belt widths for the period preceding the Year 3 photography were not defined. It is therefore possible that historic meander belt widths are different from those reported herein. Although not part of the scope of work for this project, additional analysis of available LiDAR data could be conducted to further investigate the historic lateral extents of the study streams. However, the data used in the evaluation is considered sufficient for the purpose of defining the recent historic and future stability of the study streams.

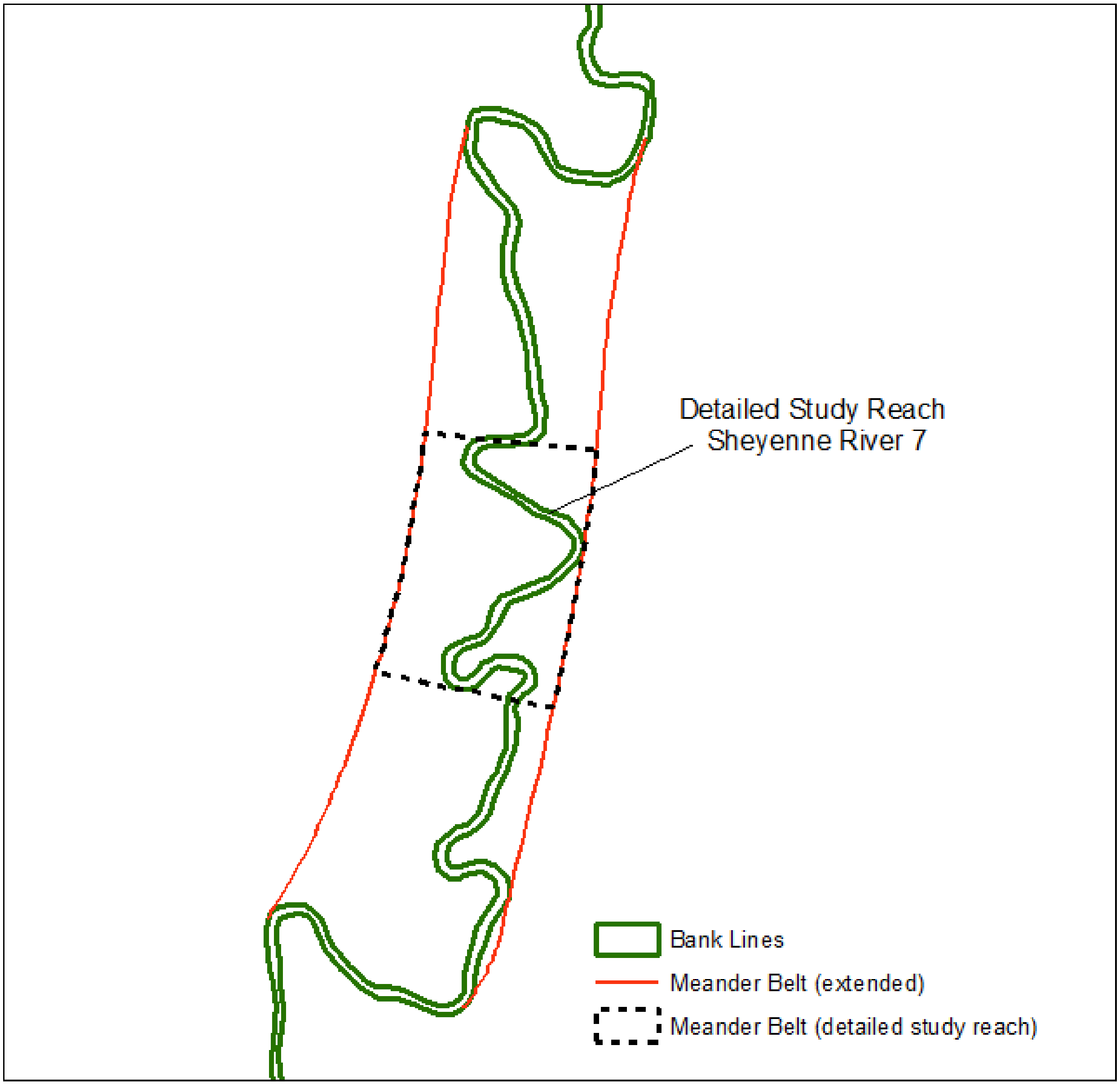


Figure 6-6. Example of Meander Bend Digitizing Procedure

Table 6-6. Average Meander Belt Widths

Detailed Study Reach	Year 3 (oldest) (ft)	Year 2 (ft)	Year 1 (youngest) (ft)	Year 3 to Year 2 Change (%)	Year 2 to Year 1 Change (%)	Year 3 to Year 1 Change (%)
Buffalo River-1-1.19	953	953	953	0%	0%	0%
Lower Rush River-1-1.10	--[1]	--[1]	--[1]	--[1]	--[1]	--[1]
Lower Rush River-2-6.03	663	663	663	0%	0%	0%
Maple River-1-0.78	1284	1284	1284	0%	0%	0%
Maple River-2-11.39	2333	2333	2333	0%	0%	0%
Red River-1-410.65	--[2]	2320	2330	--[2]	0%	--[2]
Red River-2-419.14	3575	3639	3639	2%	0%	2%
Red River-3-440.57	2945	2945	2945	0%	0%	0%
Red River-4-452.52	1890	1890	1890	0%	0%	0%
Red River-5-463.56	1646	1646	1646	0%	0%	0%
Red River-6-470.23	1895	1880	1880	-1%	0%	-1%
Red River-7-492.47	3096	3121	3121	1%	0%	1%
Red River-8-521.18	2568	2568	2568	0%	0%	0%
Rush River-1-0.08	--[1]	--[1]	--[1]	--[1]	--[1]	--[1]
Rush River-2-6.15	1408	1408	1408	0%	0%	0%
Sheyenne River-1-4.20	2100	2100	2100	0%	0%	0%
Sheyenne River-2-11.56	1861	1861	1861	0%	0%	0%
Sheyenne River-3-18.15	1736	1736	1749	0%	1%	1%
Sheyenne River-4-22.27	1243	1243	1243	0%	0%	0%
Sheyenne River-5-26.47	2230	2230	2230	0%	0%	0%
Sheyenne River-6-35.82	1744	1744	1744	0%	0%	0%
Sheyenne River-7-43.27	1646	1646	1646	0%	0%	0%
Sheyenne River-8-55.75	2807	2807	2807	0%	0%	0%
Wild Rice River-1-3.01	1940	1940	1940	0%	0%	0%
Wild Rice River-2-4.23	1608	1608	1608	0%	0%	0%
Wild Rice River-3-17.52	1344	1344	1344	0%	0%	0%
Wild Rice River-4-22.94	2633	2633	2633	0%	0%	0%
Wild Rice River-5-38.49	2019	2019	2019	0%	0%	0%
Wild Rice River-6-42.36	2214	2214	2214	0%	0%	0%
Wolverton Creek-1-0.64	679	--[3]	--[3]	--[3]	--[3]	--[3]
Wolverton Creek-2-2.02	221	--[3]	--[3]	--[3]	--[3]	--[3]

[1/] not calculated due to significant channelization
[2/] not calculated due to limited aerial imagery coverage
[3/] not calculated due to poor image quality

6.1.5 Trends in Sedimentation Features

The aerial imagery for Years 1, 2 and 3 were reviewed for identifiable depositional features such as mid-channel bars, point bars, delta bars, and side bars in order to identify temporal trends in sedimentary features. In addition to this GIS based exercise, a Deposition Patterns worksheet was completed for each detailed study reach as part of the Level II Rosgen analysis. Detailed information for that analysis is provided in Appendix J.

No depositional features were identified on the aerial imagery for any year within the general study reaches. This is in agreement with observations made during the field visits in which no depositional features were noted with the exception of one small side bar noted on detailed reach Wolverton 1. Water levels were generally high (close to bankfull) for most reaches during both field visits and it is possible that some depositional features could exist that were not exposed during the field visits and that are not visible on the aerial imagery due to water levels or image resolution. However, based on the relative stability of the system, lack of channel migration, and makeup of the primary bank and bed materials, it is believed that the likelihood of significant depositional features being present along the study streams is minimal.

6.1.6 Changes in Channel Width

Channel top width is an important parameter for geomorphic characterization. Over time, repeated measurements can provide insight into channel dimension trends and provides one measure of channel stability. Average channel top widths for each detailed study reach were calculated for three different years based on bank lines digitized from aerial imagery. Year 2 and Year 3 for Wolverton 1 and 2 were excluded from this analysis due to the poor quality of the historic aerial imagery and associated uncertainty in determination of bank lines for those reaches. Summaries of the calculated values for each detailed study reach along with a comparison of changes between measured years are provided in Table 6-7. Calculated top width changes for most detailed study reaches are small and fall within the error associated with the digitization process. Larger values found on Lower Rush 2 and Rush 2 are due narrowing as a resulting of channelization, while the narrowing shown on Maple River 1 is due to Year 3 including the area of two abandoned (but still connected) meanders.

Table 6-7. Average Channel Top Widths

Detailed Study Reach	Top Width (ft)			Year 3 to Year 2 Change	Year 2 to Year 1 Change	Year 3 to Year 1 Change
	Year 3 (oldest)	Year 2	Year 1 (youngest)			
Buffalo River-1-1.19	70	70	70	0.0%	0.0%	0.0%
Lower Rush River-1-1.10	35	34	34	-2.9%	0.0%	-2.9%
Lower Rush River-2-6.03	38	35	35	-7.9%	0.0%	-8.6%
Maple River-1-0.78	61	59	55	-3.3%	-6.8%	-10.9%
Maple River-2-11.39	75	70	72	-6.7%	2.9%	-4.2%
Red River-1-410.65	164	167	168	1.8%	0.6%	2.4%
Red River-2-419.14	143	155	157	8.4%	1.3%	8.9%
Red River-3-440.57	132	139	139	5.3%	0.0%	5.0%
Red River-4-452.52	152	151	152	-0.7%	0.7%	0.0%
Red River-5-463.56	155	151	151	-2.6%	0.0%	-2.6%
Red River-6-470.23	121	122	122	0.8%	0.0%	0.8%
Red River-7-492.47	120	120	121	0.0%	0.8%	0.8%
Red River-8-521.18	127	[1]	130	[1]	[1]	2.3%
Rush River-1-0.08	26	26	26	0.0%	0.0%	0.0%
Rush River-2-6.15	28	26	24	-7.1%	-7.7%	-16.7%
Sheyenne River-1-4.20	99	97	97	-2.0%	0.0%	-2.1%
Sheyenne River-2-11.56	98	98	98	0.0%	0.0%	0.0%
Sheyenne River-3-18.15	97	95	97	-2.1%	2.1%	0.0%
Sheyenne River-4-22.27	87	84	86	-3.4%	2.4%	-1.2%
Sheyenne River-5-26.47	73	71	71	-2.7%	0.0%	-2.8%
Sheyenne River-6-35.82	80	79	80	-1.3%	1.3%	0.0%
Sheyenne River-7-43.27	90	90	92	0.0%	2.2%	2.2%
Sheyenne River-8-55.75	98	94	100	-4.1%	6.4%	2.0%
Wild Rice River-1-3.01	75	76	77	1.3%	1.3%	2.6%
Wild Rice River-2-4.23	70	72	72	2.9%	0.0%	2.8%
Wild Rice River-3-17.52	84	81	84	-3.6%	3.7%	0.0%
Wild Rice River-4-22.94	77	76	77	-1.3%	1.3%	0.0%
Wild Rice River-5-38.49	76	76	76	0.0%	0.0%	0.0%
Wild Rice River-6-42.36	80	80	80	0.0%	0.0%	0.0%
Wolverton Creek-1-0.64	[2]	[2]	26	[2]	[2]	[2]
Wolverton Creek-2-2.02	[2]	[2]	25	[2]	[2]/	[2]/

[1] not calculated due to limited/partial aerial imagery coverage

[2] not calculated due to poor image quality

6.1.7 Large Woody Debris

Bank erosion, bank failures, floods, animal activity, and other processes often cause trees within the riparian corridor to fall into watercourses. This material, which protrudes into or lies within the watercourse, is generally referred to as Large Woody Debris (LWD). LWD, as defined by biologists, consists of logs (partial or complete trees with root wads attached) with a diameter of 4 inches or greater and minimum lengths of 6 feet (CDEP, date unknown). The presence (or lack) of LWD can be an indicator of bank stability, as systems that contain significant LWD may be experiencing bank instabilities due to erosion. Furthermore, the presence of LWD can also be an indicator of future channel stability, as LWD can have a discernible impact on river hydraulics and flow patterns. For example, blockages from LWD can direct flow towards the banks, causing further erosion and possibly undermining additional bank vegetation that may become LWD, in a self-perpetuating cycle. While LWD can be identified from quality aerial imagery, as was done in this analysis, it is useful to verify through field visits the processes that contribute to the presence of LWD. For example, while beaver activity could be the cause for the presence of LWD in a system, it is important to note that the debris is not the result of erosion and geotechnical instabilities. While this LWD might be expected to modify flow dynamics, it may not necessarily be indicative of significant, immediate bank instability.

For this analysis, LWD was identified using the 2010 aerial imagery within ArcGIS. Identification of relative abundance of woody material within the detailed study reaches was conducted as part of the field investigation and is included as part of the Rosgen analysis; however, that data was not included in this GIS based analysis. While the definition of LWD debris is clear, identification of LWD using aerial imagery is challenging. LWD at the smaller end of the size spectrum may not be clearly identifiable within the imagery. The GIS operator also needs to distinguish LWD (which is already difficult to discern given imagery quality limitations) from shadows, overhanging snags, and natural hydraulic features that are discernible in imagery, such as riffles or waves. Lastly, LWD that has accumulated within or on the upstream faces of structures may not be identifiable unless they are of significant size. For this analysis, only LWD that could be reasonably identified by the operator has been included. Furthermore, no attempt was made to identify or count individual pieces of LWD that might be present in larger blockages or clusters and each ‘point’ of LWD discernible in the imagery is counted as a single piece for calculation purposes. Therefore, while this exercise presents an estimate of LWD density within each of the reaches and despite that in a limited number of cases misidentification might occur, the calculations likely underestimates the actual LWD counts present at the time the imagery was captured. LWD counts and unit densities were calculated for 2010 for each general study reach and are presented in Table 6-8. While the 2010 LWD count data provides a good base line for future surveys, the quality of all other historic imagery was deemed too poor to accurately identify LWD; therefore, no rates of change between years were calculated. The observed range of density values shown in Table 6-8 is considered to be low. In general, very little LWD was observed within the study area and that which was observed tended to be single pieces/trees, or small clusters. Where found, the LWD were rarely in quantities large enough to block significant portions of the channel.

Table 6-8. 2010 Large Woody Debris Counts

General Study Reach	2010 (Year 1)	
	Count	Density (#/mile)
Buffalo River-1	3	0.9
Lower Rush River - 1	0	0.0
Lower Rush River - 2	0	0.0
Maple River - 1	2	0.3
Maple River - 2	1	0.2
Red River - 1	11	0.9
Red River - 2	22	2.1
Red River - 3	32	1.6
Red River - 4	14	1.5
Red River - 5	27	2.2
Red River - 6	37	2.9
Red River - 7	39	2.8
Red River - 8	61	2.3
Rush River - 1	0	0.0
Rush River - 2	0	0.0
Sheyenne River - 1	7	0.6
Sheyenne River - 2	1	0.6
Sheyenne River - 3	4	0.6
Sheyenne River - 4	5	1.1
Sheyenne River - 5	4	0.6
Sheyenne River - 6	13	1.1
Sheyenne River - 7	2	0.2
Sheyenne River - 8	10	0.6
Wild Rice River - 1	0	0.0
Wild Rice River - 2	5	0.5
Wild Rice River - 3	0	0.0
Wild Rice River - 4	8	0.7
Wild Rice River - 5	14	1.8
Wild Rice River - 6	3	1.1
Wolverton Creek - 1	0	0.0
Wolverton Creek - 2	1	0.2

6.1.8 Bank Erosion Rates

Bank erosion is part of the natural process of channel migration within a meandering river system. While a river system may be considered dynamically stable in terms of its type of planform (i.e. it may be moving/migrating but is not actively shifting between major planform types; meandering, braided, etc.), meandering systems such as the Red River and its tributaries still migrate over time.

The processes by which banks erode generally fall into two categories; fluvial entrainment, and subaqueous weakening and weathering (Thorne, 1982). With fluvial entrainment, material is transported downstream after being entrained directly from the bank or after bank failure due to erosion of the bank toe. Weakening and weathering of the bank can cause bank material entrainment, instability, and failure through the processes of frost heaving, rainfall, and positive pore water pressure as water levels decrease.

Bank erosion rates were calculated for each detailed study reach for the time periods spanning Year 3 to Year 2, Year 2 to Year 1, and Year 3 to Year 1. Rush 1 and Lower Rush 1 were excluded due to considerable historic channelization. Wolverton 1 and 2 were excluded due to the poor quality of the historic aerial imagery and the associated uncertainty in determination of bank lines for those relatively narrow reaches. The rates were calculated using the digitized bank lines in the following way. The general study reach bank lines for each of the 3 years were converted into polygons and clipped down to the detailed study reach extents. For each set of bank line polygons being compared (e.g. Year 1 and Year 2) a derivative set of polygons were created using the Intersect function in ArcGIS. The newly created polygons include the ‘slivers’ that represent area assumed to be lost due to channel migration (Figure 6-7). The areas of the slivers were summed to compute the total area lost in each reach. The area lost was then divided by the length of the detailed study reach to calculate an erosion area per unit stream length. To estimate an erosion rate, the erosion area was divided by the number of years between the aerial images from which the two sets of banks lines were derived. The calculated erosion rates for the general study reaches are summarized in Table 6-9, Table 6-10, and Table 6-11.

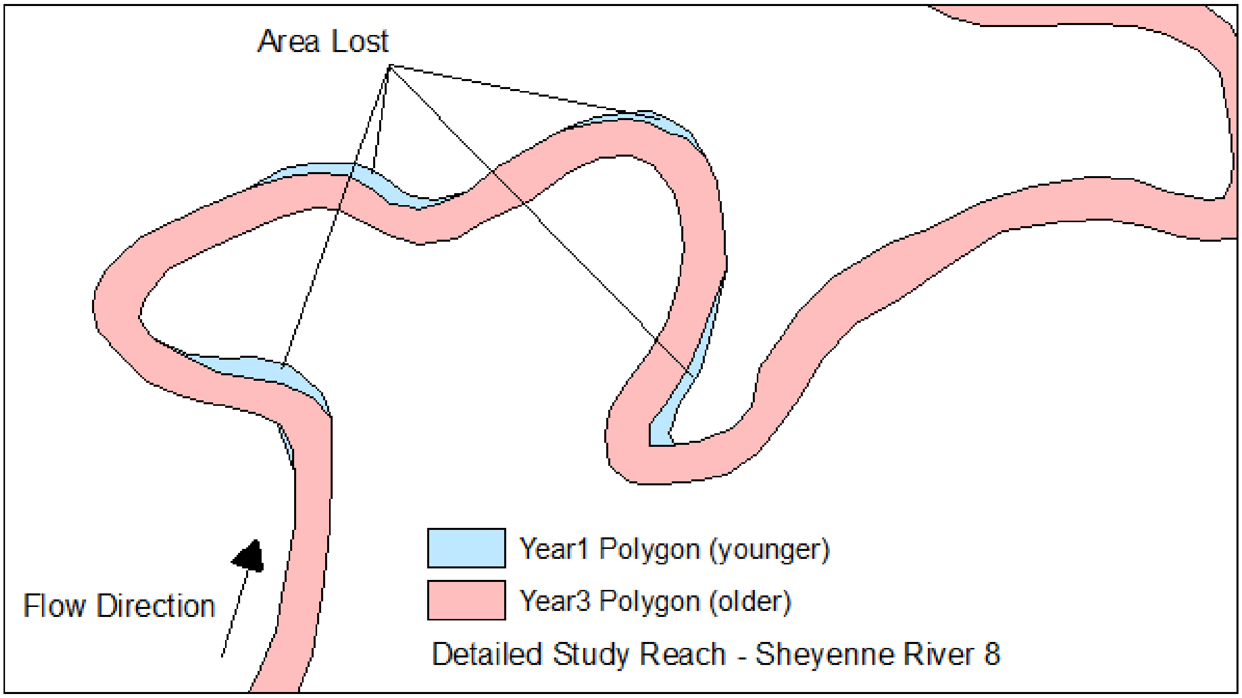


Figure 6-7. Sample Reach Showing ‘Slivers’ of Area Lost Due to Bank Erosion

Table 6-9. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 3 to Year 2

Detailed Study Reach	Area Lost in Reach (ft^2)	Time Period (yrs)	Area Lost in Reach per Year (ft^2)	Acres Lost per Year	Acres Lost per Year per Mile of River
Buffalo River-1-1.19	0	26	0	0.00	0.00
Lower Rush River-1-1.10	[1/]	35	[1/]	[1/]	[1/]
Lower Rush River-2-6.03	0	35	0	0.00	0.00
Maple River-1-0.78	0	35	0	0.00	0.00
Maple River-2-11.39	0	35	0	0.00	0.00
Red River-1-410.65	[2/]	39	[2/]	[2/]	[2/]
Red River-2-419.14	8,538	39	219	0.01	0.00
Red River-3-440.57	0	39	0	0.00	0.00
Red River-4-452.52	0	39	0	0.00	0.00
Red River-5-463.56	0	39	0	0.00	0.00
Red River-6-470.23	0	39	0	0.00	0.00
Red River-7-492.47	8,985	39	230	0.01	0.00
Red River-8-521.18	[2/]	39	[2/]	[2/]	[2/]
Rush River-1-0.08	[1/]	35	[1/]	[1/]	[1/]
Rush River-2-6.15	0	35	0.0	0.00	0.00
Sheyenne River-1-4.20	0	35	0.0	0.00	0.00
Sheyenne River-2-11.56	0	35	0.0	0.00	0.00
Sheyenne River-3-18.15	0	35	0.0	0.00	0.00
Sheyenne River-4-22.27	0	35	0.0	0.00	0.00
Sheyenne River-5-26.47	0	35	0.0	0.00	0.00
Sheyenne River-6-35.82	0	35	0.0	0.00	0.00
Sheyenne River-7-43.27	17,288	35	494.0	0.01	0.02
Sheyenne River-8-55.75	32,200	35	920.0	0.02	0.02
Wild Rice River-1-3.01	0	56	0.0	0.00	0.00
Wild Rice River-2-4.23	42,929	56	766.6	0.02	0.05
Wild Rice River-3-17.52	0	56	0.0	0.00	0.00
Wild Rice River-4-22.94	0	56	0.0	0.00	0.00
Wild Rice River-5-38.49	0	56	0.0	0.00	0.00
Wild Rice River-6-42.36	0	56	0.0	0.00	0.00
Wolverton Creek-1-0.64	[3/]	26	[3/]	[3/]	[3/]
Wolverton Creek-2-2.02	[3/]	26	[3/]	[3/]	[3/]

[1/] not calculated due to significant channelization

[2/] not calculated due to limited/partial aerial imagery coverage

[3/] not calculated due to poor image quality

Table 6-10. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 2 to Year 1

Detailed Study Reach	Area Lost in Reach (ft^2)	Time Period (yrs)	Area Lost in Reach per Year (ft^2)	Acres Lost per Year	Acres Lost per Year per Mile of River
Buffalo River-1-1.19	0	45	0.0	0.00	0.00
Lower Rush River-1-1.10	1/	13	1/	1/	1/
Lower Rush River-2-6.03	0	13	0	0.00	0.00
Maple River-1-0.78	0	13	0	0.00	0.00
Maple River-2-11.39	0	13	0	0.00	0.00
Red River-1-410.65	14,999	32	469	0.01	0.01
Red River-2-419.14	42,188	32	1,318	0.03	0.02
Red River-3-440.57	0	32	0	0.00	0.00
Red River-4-452.52	0	32	0	0.00	0.00
Red River-5-463.56	0	32	0	0.00	0.00
Red River-6-470.23	0	32	0	0.00	0.00
Red River-7-492.47	0	32	0	0.00	0.00
Red River-8-521.18	2/	32	2/	2/	2/
Rush River-1-0.08	1/	13	1/	1/	1/
Rush River-2-6.15	0	13	0	0.00	0.00
Sheyenne River-1-4.20	0	13	0	0.00	0.00
Sheyenne River-2-11.56	0	13	0	0.00	0.00
Sheyenne River-3-18.15	0	13	0	0.00	0.00
Sheyenne River-4-22.27	0	13	0	0.00	0.00
Sheyenne River-5-26.47	0	13	0	0.00	0.00
Sheyenne River-6-35.82	0	13	0	0.00	0.00
Sheyenne River-7-43.27	11,273	13	867	0.02	0.03
Sheyenne River-8-55.75	10,420	13	802	0.02	0.02
Wild Rice River-1-3.01	0	13	0	0.00	0.00
Wild Rice River-2-4.23	0	13	0	0.00	0.00
Wild Rice River-3-17.52	0	13	0	0.00	0.00
Wild Rice River-4-22.94	4,107	13	316	0.01	0.01
Wild Rice River-5-38.49	0	13	0	0.00	0.00
Wild Rice River-6-42.36	0	13	0	0.00	0.00
Wolverton Creek-1-0.64	3/	45	3/	3/	3/
Wolverton Creek-2-2.02	3/	45	3/	3/	3/

1/not calculated due to significant channelization
2/not calculated due to limited/partial aerial imagery coverage
3/not calculated due to poor image quality

Table 6-11. Calculated Bank Erosion Rates for Detailed Study Reaches, Year 3 to Year 1

Detailed Study Reach	Area Lost in Reach (ft^2)	Time Period (yrs)	Area Lost in Reach per Year (ft^2)	Acres Lost per Year	Acres Lost per Year per Mile of River
Buffalo River-1-1.19	0	71	0.0	0.00	0.00
Lower Rush River-1-1.10	[1]	48	[1]	[1]	[1]
Lower Rush River-2-6.03	0	48	0	0.00	0.00
Maple River-1-0.78	0	48	0	0.00	0.00
Maple River-2-11.39	0	48	0	0.00	0.00
Red River-1-410.65	[2]	71	[2]	[2]	[2]
Red River-2-419.14	49,790	71	701	0.02	0.01
Red River-3-440.57	0	71	0	0.00	0.00
Red River-4-452.52	0	71	0	0.00	0.00
Red River-5-463.56	0	71	0	0.00	0.00
Red River-6-470.23	0	71	0	0.00	0.00
Red River-7-492.47	8,985	71	127	0.00	0.00
Red River-8-521.18	31,225	71	440	0.01	0.01
Rush River-1-0.08	[1]	48	[1]	[1]	[1]
Rush River-2-6.15	0	48	0	0.00	0.00
Sheyenne River-1-4.20	0	48	0	0.00	0.00
Sheyenne River-2-11.56	0	48	0	0.00	0.00
Sheyenne River-3-18.15	0	48	0	0.00	0.00
Sheyenne River-4-22.27	0	48	0	0.00	0.00
Sheyenne River-5-26.47	0	48	0	0.00	0.00
Sheyenne River-6-35.82	0	48	0	0.00	0.00
Sheyenne River-7-43.27	27,976	48	583	0.01	0.02
Sheyenne River-8-55.75	39,941	48	832	0.02	0.02
Wild Rice River-1-3.01	0	69	0	0.00	0.00
Wild Rice River-2-4.23	42,929	69	622	0.01	0.04
Wild Rice River-3-17.52	0	69	0	0.00	0.00
Wild Rice River-4-22.94	3,763	69	55	0.00	0.00
Wild Rice River-5-38.49	0	69	0	0.00	0.00
Wild Rice River-6-42.36	0	69	0	0.00	0.00
Wolverton Creek-1-0.64	[3]	71	[3]	[3]	[3]
Wolverton Creek-2-2.02	[3]	71	[3]	[3]	[3]

[1] not calculated due to significant channelization
[2] not calculated due to limited/partial aerial imagery coverage
[3] not calculated due to poor image quality

The estimated bank erosion rates for the majority of the detailed study reaches are zero. The remaining non-zero rates are very small, and most likely fall within the error associated with aerial imagery analysis of this type. Overall, very little meander migration and bank erosion is discernible within the total study area over the time scale being analyzed. While there is certainly some bank erosion occurring within the study area, it is generally minor enough that it is difficult to distinguish from error associated with the process of rectification and identification of the banklines in the aerial imagery. It is also important to note that while some detailed study reaches show zero values, some erosion may be happening within the general study reach but outside the detailed study reach, though the erosion in these areas is still considered minimal and in most cases is difficult to distinguish from error.

While bank erosion calculations were only made for the detailed study reaches, the entire study area was reviewed in order to identify discernible bank erosion that might have occurred outside the detailed study reaches. No areas with discernible erosion were noted and with few exceptions all areas in which channel locations had moved discernibly over time were associated with human activity, most notably realignments due to bridge reconstruction and various straightening and channelization projects. However, a few areas were noted where meanders have likely been naturally abandoned and converted to oxbow lakes. While in some cases the meander was abandoned within the time frame of the imagery used for this analysis, the cutoff process likely began long before the date of the oldest imagery, given that the bank erosion and migration process appears to only be discernible over times periods that are much longer than those associated with this analysis (Figure 6-8, Figure 6-9, and Figure 6-10).

During the field investigation efforts, large numbers of bank failures were observed throughout the project area within many of the study reaches (Figure 6-11 and Figure 6-12). Rotational slip failures often result from erosion of the bank toe and are a common failure mechanism in cohesive banks (Thorne, 1982). It should be noted that the observed bank failures are not necessarily indicators of instability associated with lateral channel migration. As discussed previously, the calculated lateral channel migration rate is essentially zero for a majority of the detailed study reaches assessed, even in those reaches where significant bank failures were observed. Additionally, the analysis of available historic channel geometry found the calculated lateral channel migration rates to also be essentially zero. The majority of the cross sections analyzed did not show measurable channel migration. A plausible explanation for why bank failures that are not necessarily associated with lateral channel migration are occurring along the study streams is provided in the following paragraphs.

The Red River and its tributaries undergo overbank flooding on a regular basis. As floodwaters begin to overtop the channel banks, much of the suspended sediment load (in this case clay, silt, and some locations, sand) is deposited along the top of the bank due to the reduction in velocities and ponding that occurs. During the field investigation following the 2011 spring flooding, it was noted that these deposits were several inches to over a foot deep in places, thereby adding additional weight (loading) on the banks.

It appears that the characteristics of the clay soils, saturation of the bank material during long periods of flooding, and the added weight of the overbank sediment deposits, results in bank slumping and subsequent long-term erosion of the failed bank material within the channel. An illustration of this repeating cycle of overbank sediment deposition, bank slumping, and toe erosion is shown in Figure 6-13. Although the repeated cycle of overbank deposition, bank slumping and toe erosion results in temporary changes to the channel width, it does not result in significant migration of the channel. However, as previously discussed, channel migration is likely occurring, albeit at a relatively low rate of a few inches per year. The cohesive nature of the clay soils (which provides resistance to erosion) combined with the low energy gradient of the stream channels (which results in low erosion potential), prevents significant erosion from occurring. The erosion that is occurring, is taking place at the toe of the bank failure along the outside of the meander bend. The long-term erosion rate for the toe of the bank failure is slightly greater than the long-term deposition rate for the top of the bank. Along the inside of the meander bend, deposition along the top of bank is slightly greater than erosion along the toe. This results in the relatively low rates of channel migration for the study streams. Based on the available data, the evolution of the cut-offs shown in Figure 6-8, Figure 6-9, and Figure 6-10 appears to progress very slowly; however as the neck between the upstream and downstream side of the bends narrow, it is possible that the bank failures and the significant flooding that occurs on a regular basis provide the mechanism or catalyst for the final cut-off to occur. It would be expected that in unprotected areas this natural evolution would continue as before; however, in the protected areas, the possible mechanisms that cause the final cutoff to occur (bank failure and flooding) would be reduced and/or eliminated, thereby slowing the final cut-off of the bend(s).

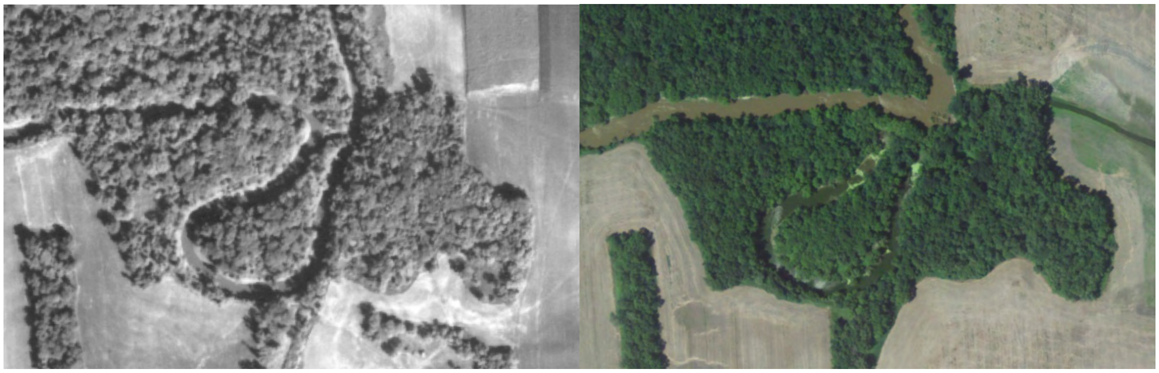


Figure 6-8. Abandoned Meander, Sheyenne River - 8 (left – 1962, right – 2010)

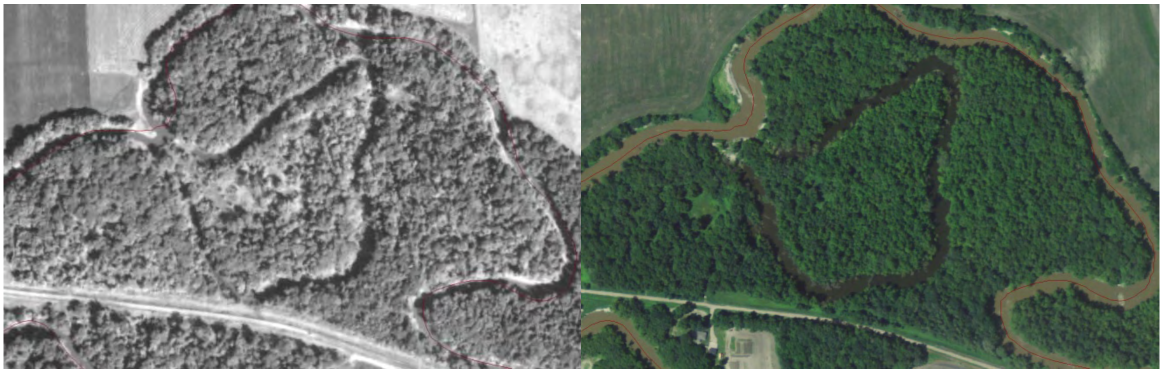


Figure 6-9. Abandoned Meander, Sheyenne River - 8 (left – 1962, right – 2010)

Figure 6-10. Meander Cutoff, Red River - 8 (left – 1939, right – 2010)

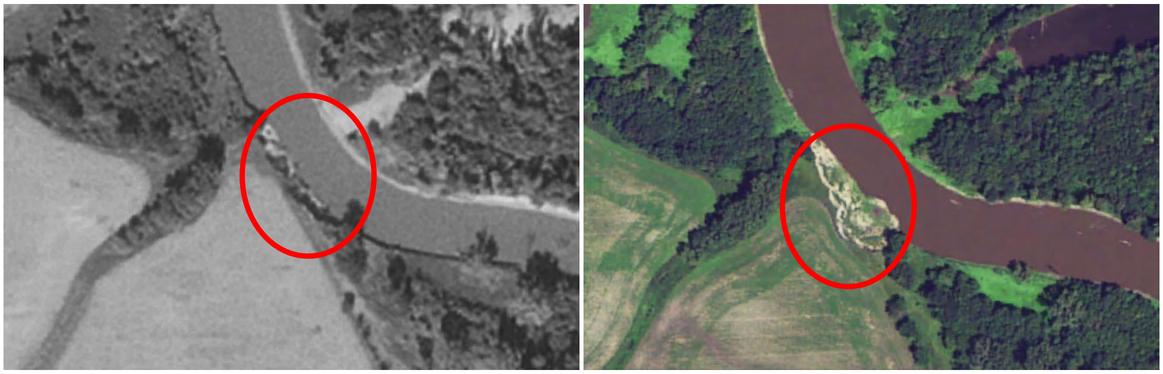


Figure 6-11. Example of Bank Failure, Red River – 8 (left – 1997, right – 2010)

Figure 6-12. Bank Slumping along Sheyenne River - 1

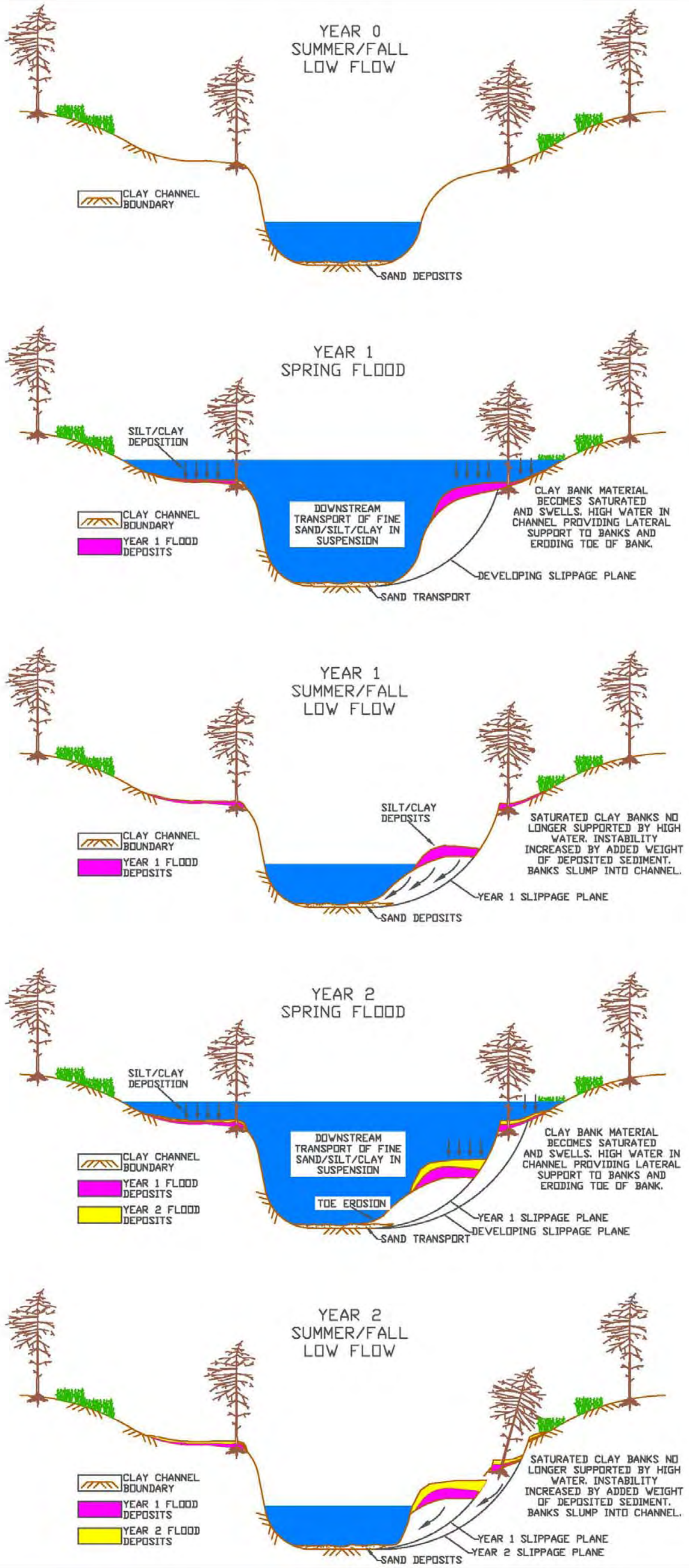


Figure 6-13. Cycle of Overbank Depositions, Bank Slumping, and Toe Erosion

6.1.9 Riparian Vegetation

Along with hydraulic forces and bank material, riparian vegetation is one of the primary influences on bank stabilization (Thorne, 1982). The root structure of bank vegetation can increase the shear strength of soil, while above ground; vegetation can reduce stream velocities and act as a protective layer, decreasing the influence of surface erosion processes. Bank vegetation was classified in order to identify historic trends in bank vegetation types and to determine if a relationship exists between vegetation type and the rate of channel migration.

For this GIS based exercise, estimates of the dominant category of bank vegetation along each general study reach were based on the available aerial imagery for Years 1, 2, and 3. The calculations, which determine what percentage of the total length of each reach is dominated by what category of vegetation, were calculated in the following manner. Within the GIS, the previously digitized bank lines were split into smaller increments and attributed according to the underlying vegetation observed in the aerial imagery. Bank vegetation was classified into one of four categories: canopy (trees), mixed vegetation (consisting of a combination of trees, grass, and shrubs), non-canopy (grass and shrubs), and bare earth (no vegetation). However, no attempt was made to distinguish individual species from the aerial imagery. While canopy was relatively easy to identify, correctly identifying the three remaining categories was difficult due to image resolution, and in particular the lack of color in the pre-2010 imagery; therefore, care should be taken when interpreting the results. A summary of the aerial vegetation survey is presented in Table 6-12.

During the field investigation, information on riparian vegetation at the detailed study reach level was recorded on Riparian Vegetation data sheets as part of the Level II Rosgen analysis (Appendix J). In contrast to the aerial image analysis, the field based calculations measure the percent area of the banks covered by each category based on vegetation basal area; consequently, canopy values are much smaller and bare ground values are much higher than those calculated by the GIS based analysis.

Field visits in 2010 and 2011 both followed significant flooding events in the range of 5% to 2% annual chance exceedence (20- to 50-year floods). Floods in this system are typically the result of spring rain and snow melt events and are characterized by floodwaters that remain high for a month or more at a time. While the exact impact on bank vegetation due to extended submergence is unknown, it was observed during the 2011 field visit that considerable amounts of bank vegetation appeared to have been eroded, buried by sedimentation, or drowned during the spring and summer flooding.

Due to the small or zero values for channel migration rates, no quantifiable conclusions can be drawn regarding effect of bank vegetation on channel migration. While it is known that vegetation can markedly increase bank stability and reduce erosion rates, thereby slowing channel migration, it is likely that vegetation may have less influence on erosion and migration within this system. Within the project area, bank stability and resistance to significant migration are largely due to the relatively low velocities experienced during major flooding and the highly cohesive nature of the clay soils, which are the predominant bed and bank material.

Table 6-12. Summary of Aerial Vegetation Survey

General Study Reach	Year 3 (oldest)				Year 2				Year 1 (youngest)			
	Percent Canopy	Percent Non-Canopy	Percent Mixed	Percent Bare Earth	Percent Canopy	Percent Non-Canopy	Percent Mixed	Percent Bare Earth	Percent Canopy	Percent Non-Canopy	Percent Mixed	Percent Bare Earth
Buffalo River-1	87	0	13	0	94	1	4	1	31	4	60	5
Lower Rush River-1	1	99	0	0	1	99	0	0	1	99	0	0
Lower Rush River-2	13	77	10	0	0	100	0	0	0	100	0	0
Maple River-2	1	74	25	0	2	82	15	1	1	87	11	1
Maple River-1	20	53	20	6	27	38	17	18	0	51	36	13
Red River-1	[1/]	[1/]	[1/]	[1/]	61	5	32	2	45	29	14	12
Red River-2	69	0	27	4	69	5	23	3	61	11	26	2
Red River-3	68	3	28	1	82	5	13	1	60	10	25	5
Red River-4	80	7	13	1	74	6	20	0	56	7	31	5
Red River-5	53	5	36	5	76	6	18	0	78	6	16	0
Red River-6	80	1	14	5	76	7	17	0	81	3	11	5
Red River-7	62	1	33	4	90	9	1	0	87	1	5	7
Red River-8	78	1	14	7	[1/]	[1/]	[1/]	[1/]	64	3	22	11
Rush River-1	0	100	0	0	1	98	1	0	1	98	1	0
Rush River-2	0	100	0	0	0	95	1	5	0	99	1	0
Sheyenne River-1	88	2	10	0	62	9	24	5	58	22	16	4
Sheyenne River-2	97	0	3	0	93	3	0	3	87	4	9	0
Sheyenne River-3	80	5	14	1	78	1	12	10	76	8	13	3
Sheyenne River-4	81	2	17	0	85	1	9	5	71	2	26	1
Sheyenne River-5	87	5	8	1	90	3	2	5	79	7	13	1
Sheyenne River-6	82	2	14	1	82	3	9	7	78	9	13	0
Sheyenne River-7	90	0	9	1	82	5	10	4	69	8	21	2
Sheyenne River-8	90	1	8	0	89	2	6	3	87	4	6	3
Wild Rice River-1	28	7	61	5	80	7	13	0	54	8	19	19
Wild Rice River-2	29	15	52	3	58	16	22	4	43	25	20	12
Wild Rice River-3	19	24	55	2	89	3	3	4	83	7	3	6
Wild Rice River-4	53	4	40	3	87	5	7	0	83	7	9	2
Wild Rice River-5	57	4	39	1	87	7	6	0	80	12	8	1
Wild Rice River-6	69	6	21	4	88	6	6	0	82	11	4	3
Wolverton Creek-1	22	47	30	0	6	67	24	3	41	25	34	0
Wolverton Creek-2	1	97	2	0	0	100	0	0	1	90	10	0

[1/] not calculated due to limited/partial aerial imagery coverage

6.2 Cross Section Geometry

An analysis of current and historical cross sectional geometry was conducted to provide information related to changes in top width, average depth, and channel area over time and to assess if these changes indicated whether the channels are adjusting towards or away from regime channel geometry. The assessment methodology and results are provided in the following sections.

6.2.1 Current Geometric Comparison Baseline Data

The survey data obtained in 2010 and 2011 as part of this study, as discussed in Section 3.3, is considered to represent the current cross sectional geometry. To assess whether notable changes in stream cross-sectional geometry occurred between the 2010 and 2011 cross-sectional data collection efforts, any location in which the 2010 and 2011 survey data overlapped was evaluated. A total of one Sheyenne River, three Rush River, and five Lower Rush River locations were surveyed in both 2010 and 2011. The Sheyenne River and Rush River comparisons did not show any notable changes between the 2010 and 2011 survey data (Figure 6-14). All five locations on the Lower Rush River, however, did show aggradation from 2010 to 2011 (Figure 6-15). It is noted that the Lower Rush River is channelized and has a densely vegetated channel bottom. The dense vegetation is efficient at trapping suspended sediment that would otherwise flow through the stream as wash load. In contrast, the channels of the Sheyenne River and Rush River do not contain vegetation and therefore allow the majority of the suspended sediment load to be transported downstream. Because the vegetation characteristics of the Sheyenne River and Rush River channels are much more representative of the streams for which overlapping 2010 and 2011 survey data does not exist (Buffalo River, Maple River, Red River, Wild Rice River, and Wolverton Creek), it is assumed that these streams likely did not experience notable changes in channel geometry due to the spring 2011 flooding. Therefore, with the exception of the Lower Rush River, it is concluded that single, large flood events are unlikely to cause notable changes to the shape and size of the channels within the study area.

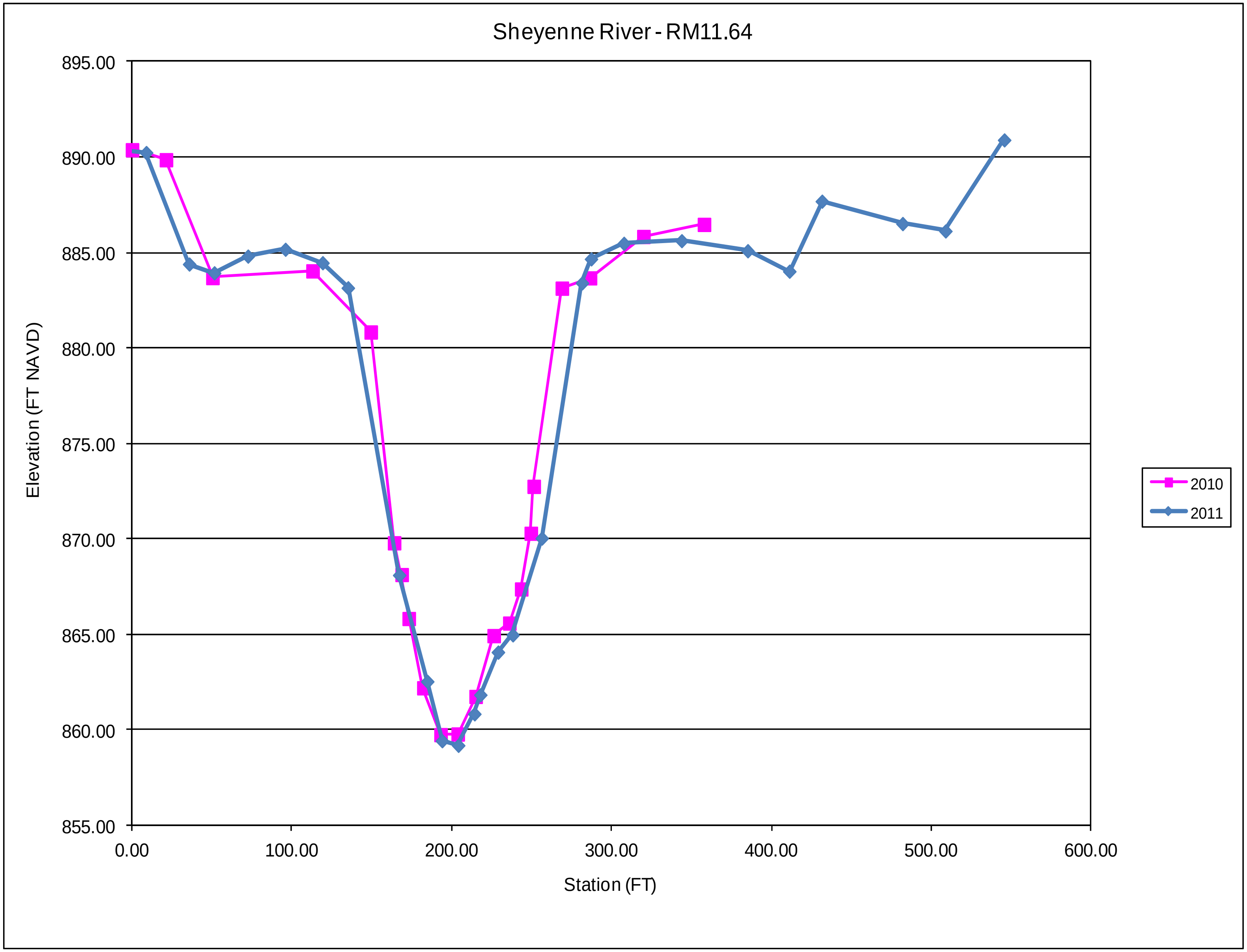


Figure 6-14. Example of No Notable Cross-Sectional Changes Occurring Between 2010 and 2011 on the Sheyenne River

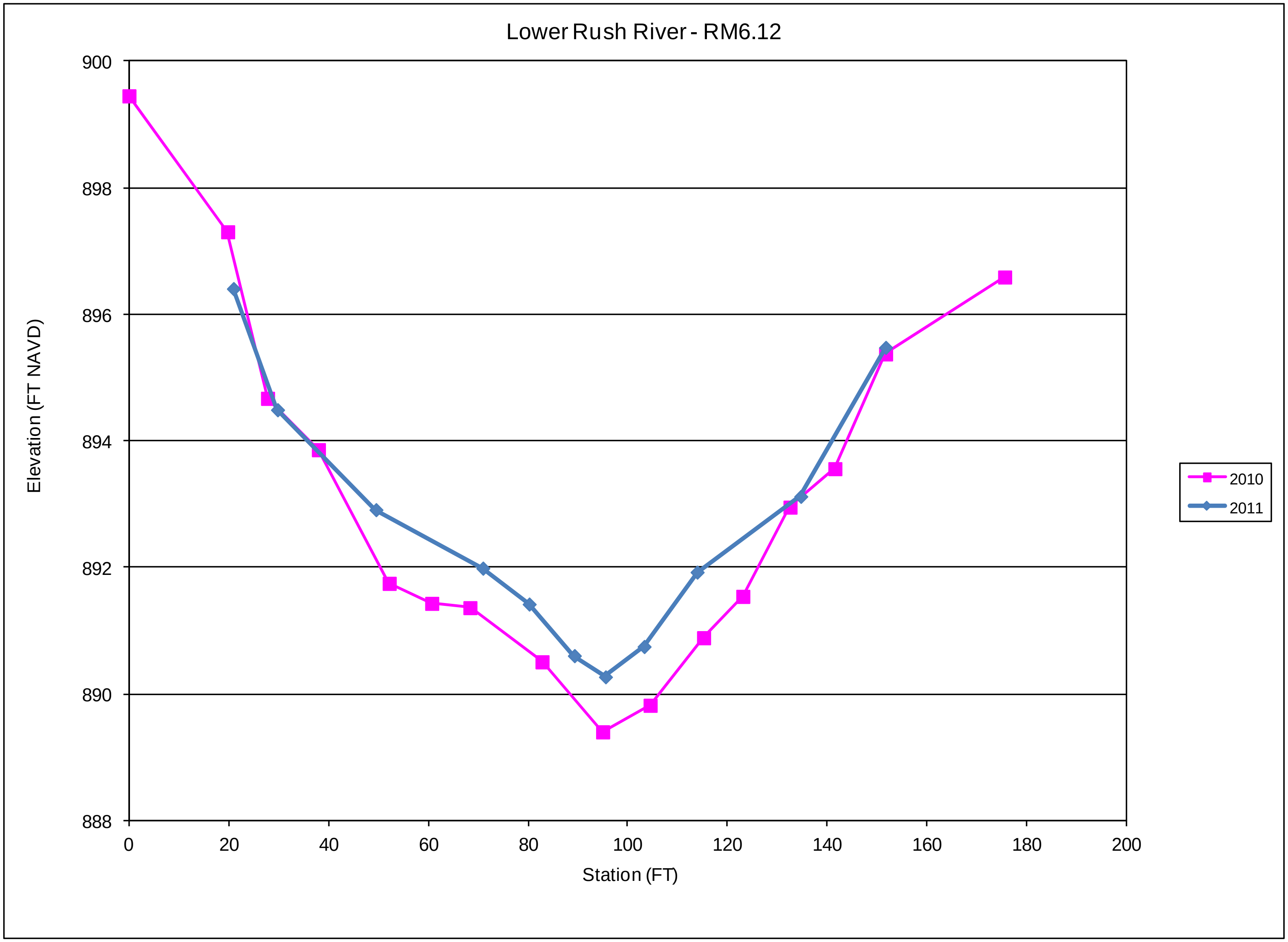


Figure 6-15. Example of Notable Cross-Sectional Changes Occurring Between 2010 and 2011 on the Lower Rush River

6.2.2 Historic Geometric Comparison Plots

Historical cross sectional geometry was obtained from the St. Paul District. One current (noted as 2010) and up to five historical geometric data sets were used to evaluate current and historic channel cross section characteristics. The years of historic geometric data used are shown in Table 6-13. As seen in the table, many of the study streams have only two datasets available for comparison. This reduces the certainty of any conclusions regarding trends in channel geometry changes for these streams.

Table 6-13. Cross Sectional Geometry Source Dates

Stream	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Buffalo River	2010	2004	1967			
Lower Rush River	2010	1964				
Maple River	2010	2003	1947			
Red River	2010	1999	1983	1978	1960	1943
Rush River	2010	1966				
Sheyenne River	2010	1940				
Wild Rice River	2010	1988				
Wolverton Creek	2010	2000				

A total of 42 locations were selected to compare current and historical sections (Appendix L). Current and historic cross sections were considered valid for comparison if their georeferenced location was within approximately 100 feet of each other on a relatively straight stretch of river, or within approximately 50 feet of each other on a river bend. Of these, 2 were on the Buffalo River, 3 on the Lower Rush River, 3 on the Maple River, 13 on the Red River, 1 on the Rush River, 9 on the Sheyenne River, 9 on the Wild Rice River, and 2 on Wolverton Creek. The stream, river station, cross section identifier, and years of available data for each cross section are shown in Table 6-14.

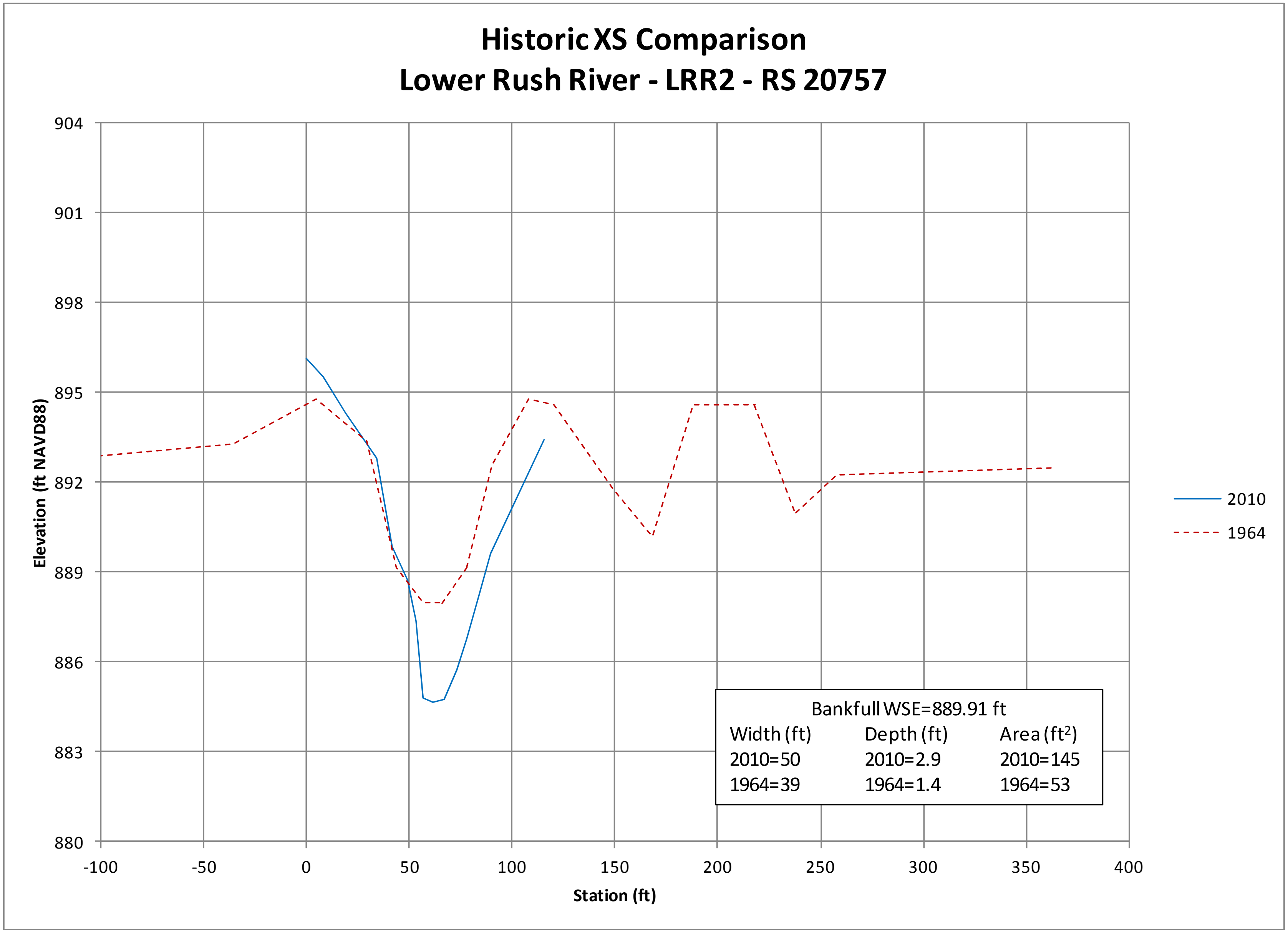
Table 6-14. Cross Sections Used to Compare Historic and Current Geometry

Stream	Station	XS ID	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Buffalo River	1305	B1	2010	2004	1967			
Buffalo River	7224	B2	2010	2004				
Lower Rush River	451	LR1	2010	1964				
Lower Rush River	20757	LR2	2010	1964				
Lower Rush River	33017	LR3	2010	1964				
Maple River	2437	M1	2010	2003				
Maple River	6343	M2	2010		1947			
Maple River	36198	M3	2010	2003	1947			
Red River	2219762	R1	2010			1978		
Red River	2254328	R2	2010			1978		1943
Red River	2288183	R3	2010			1978		
Red River	2359548	R4	2010		1983			1943
Red River	2380772	R5	2010		1983		1960	1943
Red River	2400488	R6	2010		1983	1978		
Red River	2437441	R7	2010		1983	1978		
Red River	2448951	R8	2010			1978		
Red River	2515596	R9	2010			1978		
Red River	2537700	R10	2010	1999		1978		
Red River	2562789	R11	2010	1999		1978		
Red River	2672724	R12	2010			1978		
Red River	2762274	R13	2010			1978		
Rush River	394	Ru1	2010	1966				
Sheyenne River	63841	S1	2010	1940				
Sheyenne River	115599	S2	2010	1940				
Sheyenne River	117965	S3	2010	1940				
Sheyenne River	158429	S4	2010	1940				
Sheyenne River	189121	S5	2010	1940				
Sheyenne River	230797	S6	2010	1940				
Sheyenne River	255972	S7	2010	1940				
Sheyenne River	316964	S8	2010	1940				
Sheyenne River	337323	S9	2010	1940				
Wild Rice River	3145	WR1	2010	1988				
Wild Rice River	18332	WR2	2010	1988				
Wild Rice River	24208	WR3	2010	1988				
Wild Rice River	61751	WR4	2010	1988				
Wild Rice River	82497	WR5	2010	1988				
Wild Rice River	85196	WR6	2010	1988				
Wild Rice River	125885	WR7	2010	1988				
Wild Rice River	162498	WR8	2010	1988				
Wild Rice River	227263	WR9	2010	1988				
Wolverton Creek	3106	W1	2010	2000				
Wolverton Creek	11329	W2	2010	2000				

The cross sections were selected based primarily on the following criteria. First, it was desired to include at least two cross section locations from each general study reach. Second, it was desired that at least one of these two cross section locations be located within the detailed study reach. Finally, the proximity of successive cross sections and the number of historic data sets available for each cross section location was assessed to finalize the selections. The current and historic data for each cross section were then plotted to compare the changes in the channel geometry. It should be noted that the horizontal accuracy of the historic cross section locations is unknown. Therefore, the horizontal locations for the starting and ending points for each historic cross section are also unknown. As a result, the stationing of the historic cross sections was manually adjusted as appropriate to visually align the historic channel with the current channel.

Geometric characteristics of each cross section were developed to quantify any cross-sectional changes over time. Three parameters were calculated using the bankfull WSE elevation determined in the HEC-RAS bankfull models (see Section 4.2.1). Based on this bankfull WSE, the top width, hydraulic depth, and cross-sectional area for each cross section for each comparison year was calculated and is listed in a box on the lower right portion of each comparative plot.

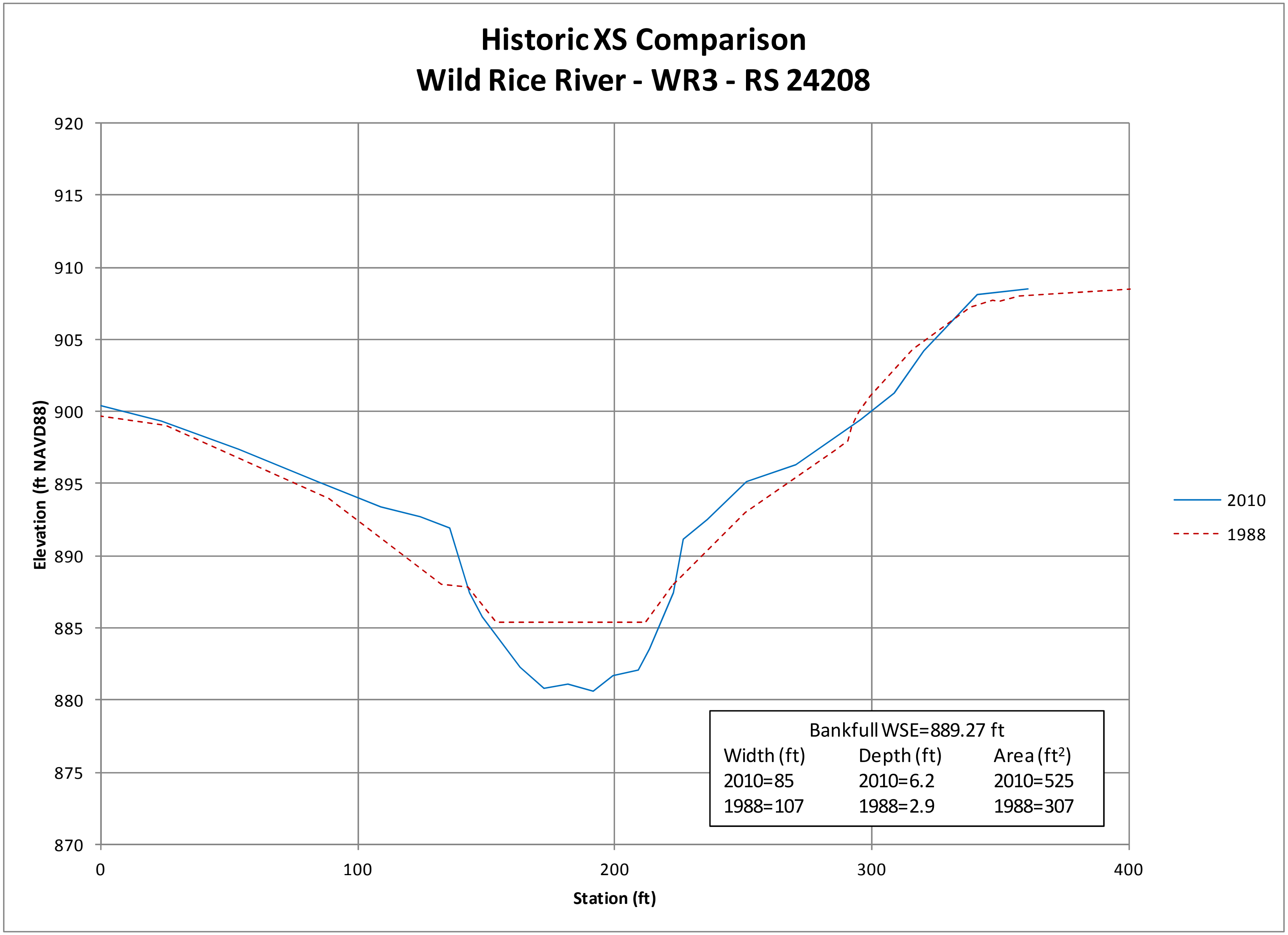
A review of the comparative cross section plots revealed potential issues with historic cross sections for two of the study streams. As seen in Figure 6-16, the Lower Rush River appeared to change rather discernibly in comparison to the rest of the streams. However, this is likely the result of channelization that occurred in 1971 to provide flood protection along the Lower Rush River. The Lower Rush River channel was straightened and enlarged and a number of different structures were added, replaced, and removed (USACE, 1971). Therefore, large changes in the channel geometry resulting from the flood control project are expected. As seen in Figure 6-17, the Wild Rice River cross section geometry from 1988 appears to be missing the in-channel portion of the survey. All of the cross sections from the 1988 survey are seen to have a flat channel bottom, which is considered unlikely and probably represents the water surface elevation at the time of the survey. Therefore, the changes in the cross section geometry for Wild Rice River between 1988 and 2010 are unknown.



Bankfull WSE=889.91 ft

Width (ft)	Depth (ft)	Area (ft^2)
2010=50	2010=2.9	2010=145
1964=39	1964=1.4	1964=53

Figure 6-16. Example Lower Rush River Cross-Section Comparison



Bankfull WSE=889.27 ft

Width (ft)	Depth (ft)	Area (ft^2)
2010=85	2010=6.2	2010=525
1988=107	1988=2.9	1988=307

Figure 6-17. Example Wild Rice River Cross-Section Comparison

Cross sections for the remaining six streams were reviewed to assess changes in channel geometry with time. The top width for the most historic cross section geometry was compared to the top width for the current cross section geometry and the rate of change between the two years was calculated. Similarly, the rate of change in hydraulic depth was evaluated. The calculation results for the two geometry parameters are shown in Table 6-15. Changes in top width of at least 0.5 feet per year and hydraulic depth of at least 0.1 feet per year were deemed large enough to warrant individual evaluation of the cross sections to determine the potential cause of the change. The 12 cross sections warranting further evaluation are identified in bold text in Table 6-15 and are discussed below. The remaining cross sections did not have sufficient changes in geometry to warrant further evaluation. All of the comparative cross section plots are provided in Appendix L.

Table 6-15. Cross Section Geometric Change Rates

Stream	Station	XS ID	Top Width Rate of Change (ft/yr)	Hydraulic Depth Rate of Change (ft/yr)
Buffalo River	1305	B1	-0.1	0.0
Buffalo River	7224	B2	0.2	**0.2**
Maple River	2437	M1	-0.4	**0.2**
Maple River	6343	M2	0.2	0.0
Maple River	36198	M3	**-0.6**	0.0
Red River	2219762	R1	**1.6**	**0.1**
Red River	2254328	R2	0.1	0.0
Red River	2288183	R3	**1.3**	**0.1**
Red River	2359548	R4	-0.3	0.0
Red River	2380772	R5	-0.2	0.0
Red River	2400488	R6	**-3.2**	**0.2**
Red River	2437441	R7	**1.5**	**0.1**
Red River	2448951	R8	0.3	**0.1**
Red River	2515596	R9	0.4	**0.1**
Red River	2537700	R10	**-0.6**	**0.1**
Red River	2562789	R11	-0.3	0.0
Red River	2672724	R12	-0.4	0.0
Red River	2762274	R13	0.2	0.0
Rush River	394	Ru1	-0.1	0.0
Sheyenne River	63841	S1	-0.1	0.0
Sheyenne River	115599	S2	0.1	0.0
Sheyenne River	117965	S3	-0.1	0.0
Sheyenne River	158429	S4	-0.2	0.0
Sheyenne River	189121	S5	-0.2	0.0
Sheyenne River	230797	S6	0.1	0.0
Sheyenne River	255972	S7	-0.3	0.0
Sheyenne River	316964	S8	0.2	0.0
Sheyenne River	337323	S9	0.0	0.0
Wolverton Creek	3106	W1	0.2	**0.3**
Wolverton Creek	11329	W2	**0.9**	0.0

Figure 6-18 shows that while the hydraulic depth of the Buffalo River has changed, the thalweg elevation has not. One possible explanation is that a geotechnical bank failure may have previously occurred along the left bank (as reflected in the 2004 survey), but was eroded away by the time the 2010 survey was completed.

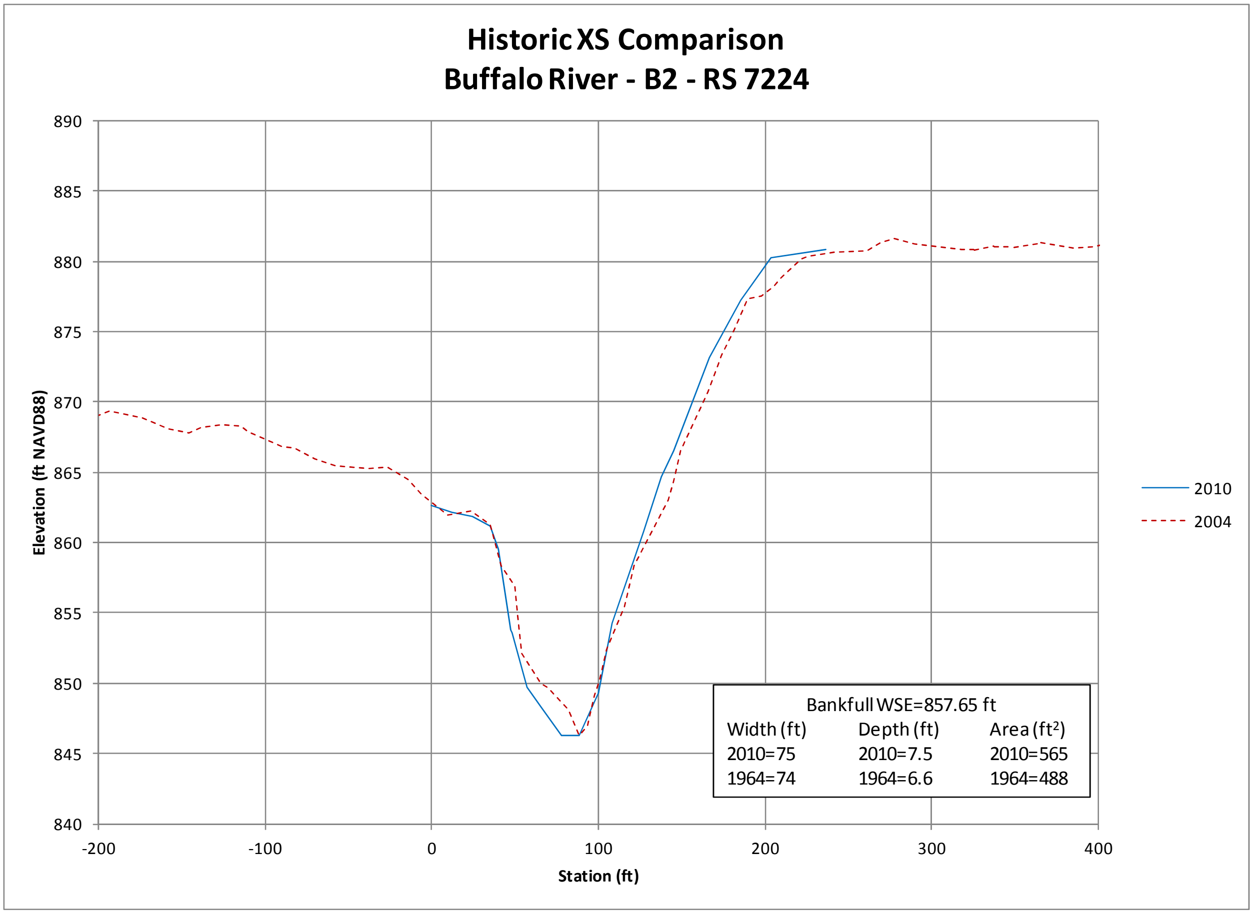


Figure 6-18. Historic Cross Section Comparison for Location B2

Figure 6-19 shows that the channel bottom of the Maple River has degraded between the 2003 and 2010 surveys. Changes to the Maple River weir structure located approximately 1,600 feet downstream of this cross section may have occurred and would explain the degradation shown in Figure 6-19. However, it is unknown whether changes to the weir structure have occurred. Maple River Dam 2 is located approximately 33,600 feet upstream of this cross section. Given the significant distance and relatively small size of the structure, it is considered unlikely that Maple River Dam 2 has affected the degradation that has occurred at this cross section.

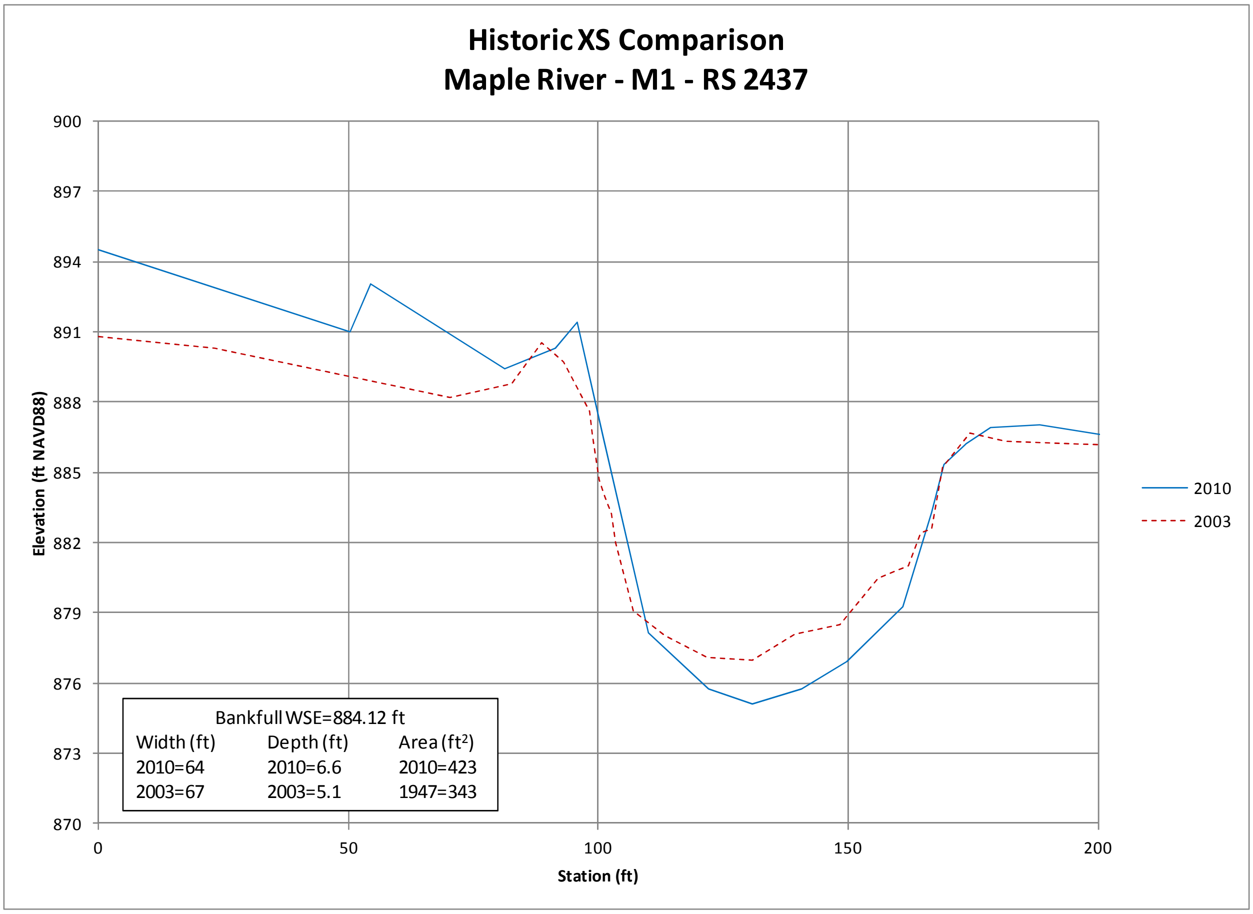


Figure 6-19. Historic Cross Section Comparison for Location M1

Figure 6-20 shows a consistent channel aggradation trend in the Maple River at Cross Section M3 between 1947 and 2010. There also appears to be discernible narrowing of the channel between 2003 and 2010. This cross section is located immediately upstream of Maple River Dam 2, which forms the downstream end of what appears to be a channelized reach. Therefore, the resulting channel geometry changes are significantly influenced by anthropogenic changes to the channel.

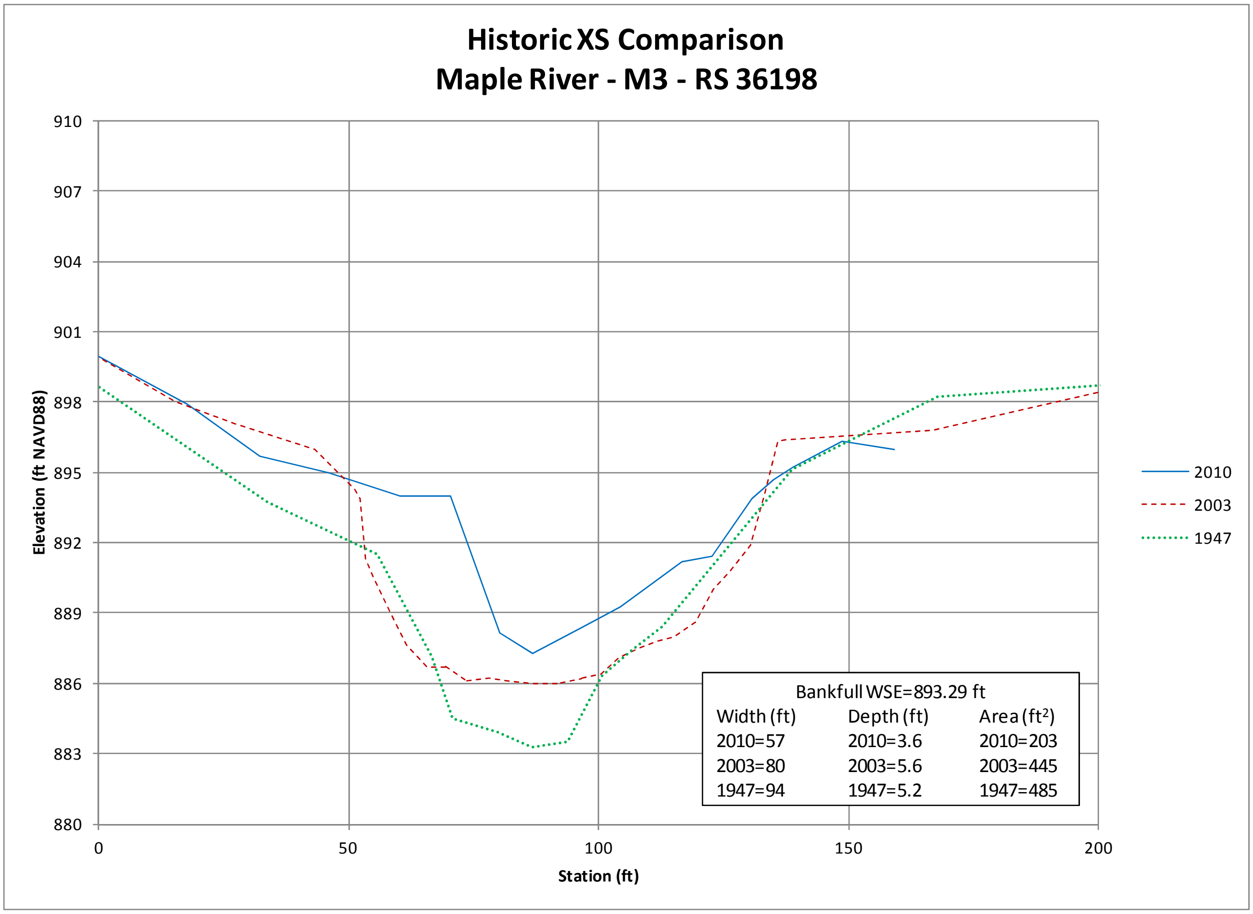


Figure 6-20. Historic Cross Section Comparison for Location M3

Figure 6-21 shows channel widening and degradation at Red River cross section R1 between the years 1978 and 2010. However, cross section comparisons at other locations along the Red River indicate that either the 1978 data are not an accurate representation of the historic channel geometry or that the cross section locations are not comparable. For example, Figure 6-22 shows that the 1943 and 2010 surveys are similar while the 1978 survey is discernibly different. It is unlikely that the channel and overbank geometry changed significantly between 1943 and 1978 and then changed back to something very similar to 1943 as is reflected in the 2010 survey. Therefore, changes in geometry associated with the 1978 survey data are considered erroneous.

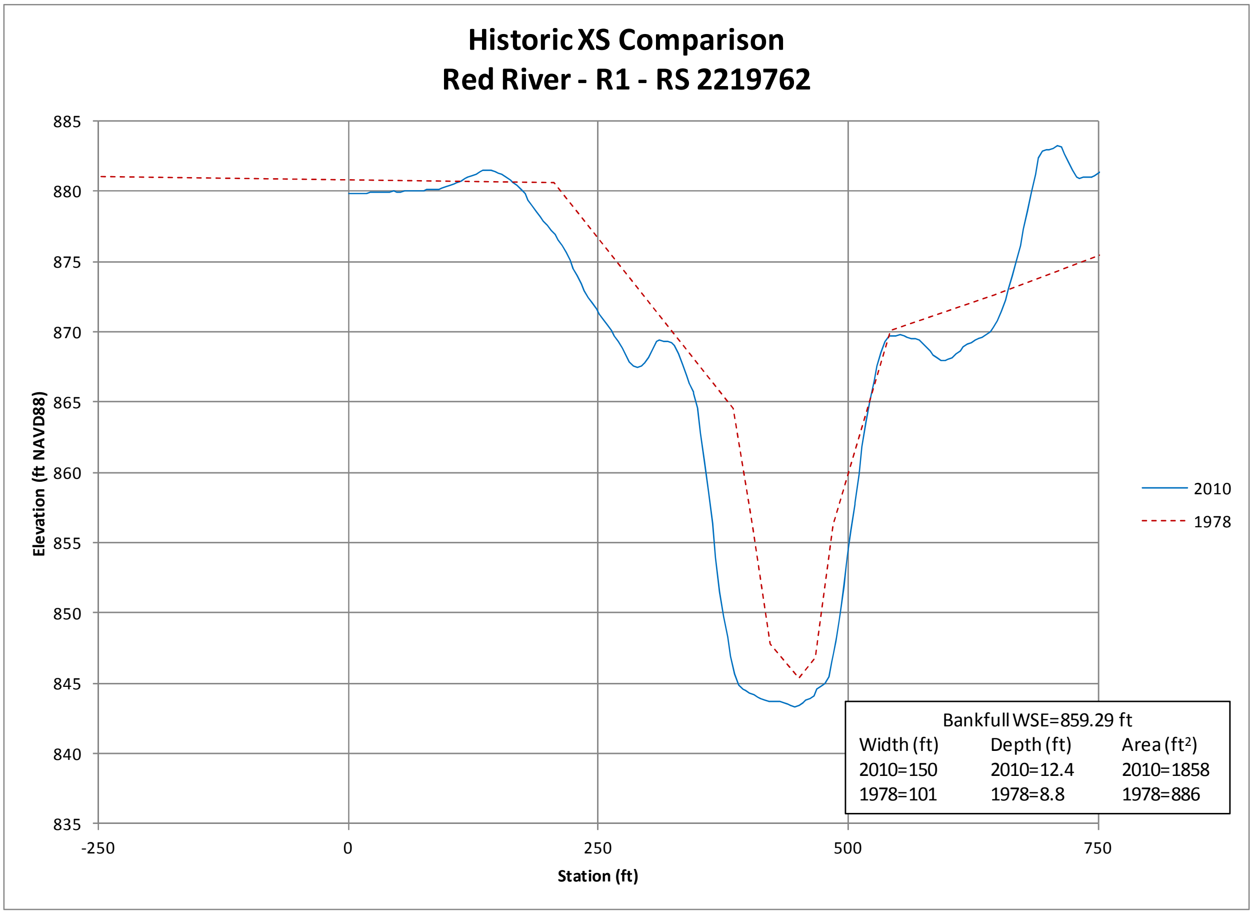


Figure 6-21. Historic Cross Section Comparison for Location R1

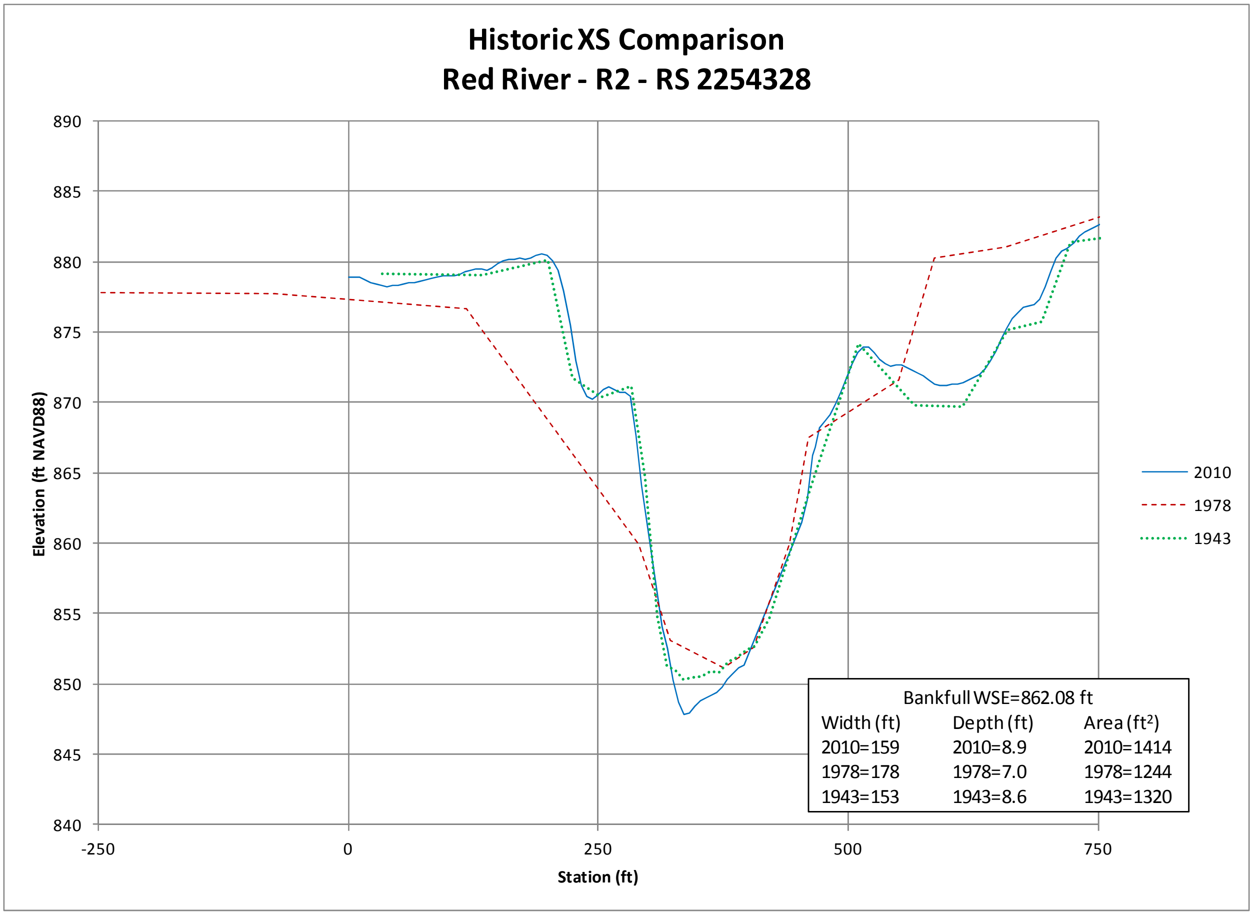


Figure 6-22. Historic Cross Section Comparison for Location R2

Figure 6-23 shows channel widening and degradation between 1978 and 2010. However, as previously discussed, any changes resulting from a comparison of the 1978 and 2010 survey data are considered inaccurate.

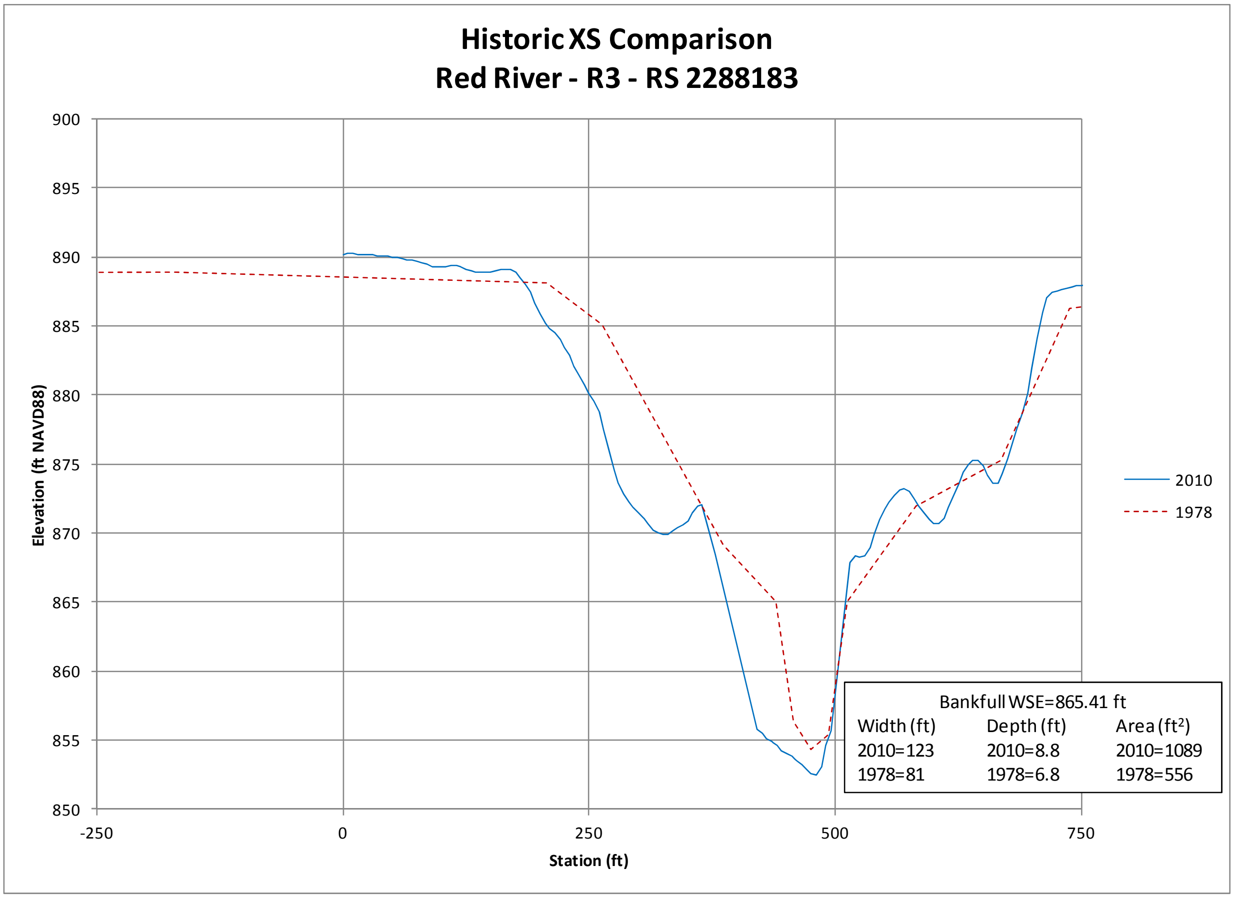


Figure 6-23. Historic Cross Section Comparison for Location R3

Figure 6-24 shows differences in elevations for Red River cross section R6, especially in the overbank region, when comparing the 1983 and 2010 data to the 1978 data. Again, the 1978 data is considered erroneous. However, a comparison of the 1983 and 2010 data indicates that the channel has degraded slightly over time. The Fargo Midtown Dam is downstream of the location of Cross Section R6. The Midtown Dam was replaced with a rock ramp in 1999. This is a possible cause of the degradation that has occurred at this location.

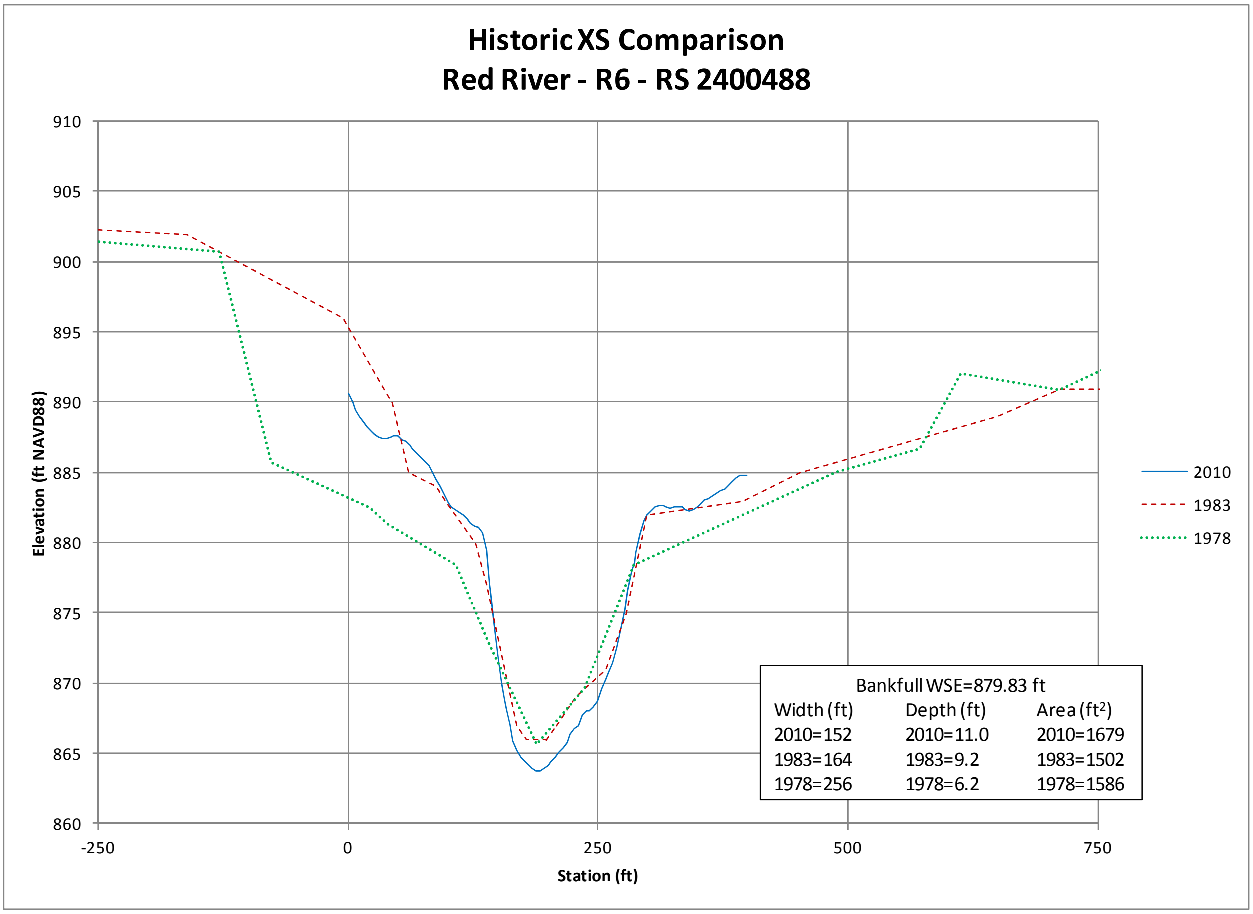


Figure 6-24. Historic Cross Section Comparison for Location R6

Figure 6-25 shows that Red River cross section R7 appears to be degrading between 1983 and 2010. Both the bankfull top width and hydraulic depth appear to be increasing with time. This cross section is located immediately upstream of the 52nd Avenue South bridge. As a result, the bridge may be influencing the channel geometry at this location.

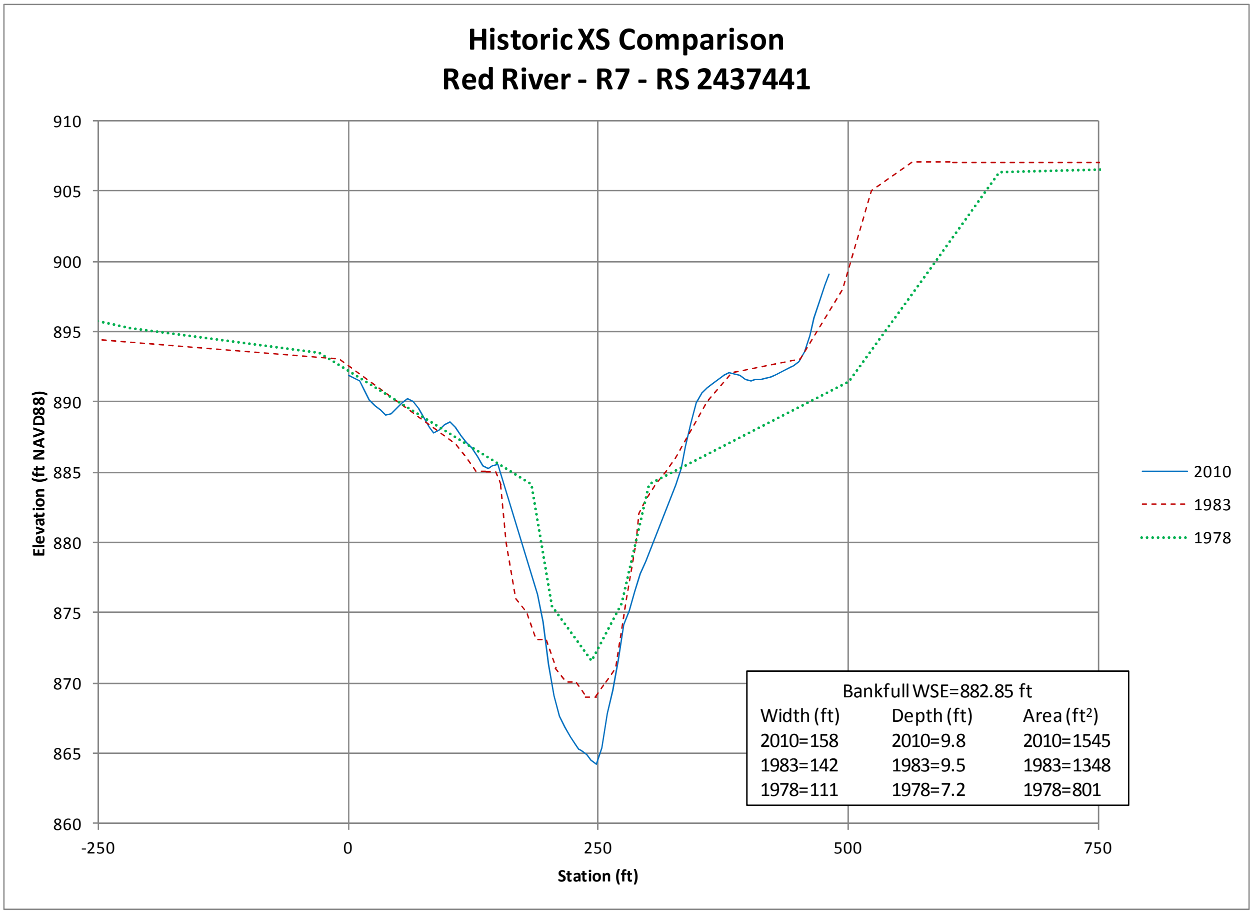


Figure 6-25. Historic Cross Section Comparison for Location R7

Figure 6-26 shows that Red River cross section R8 has experienced channel degradation between 1978 and 2010. However, as previously discussed, the 1978 cross section data are considered to be erroneous. Therefore, changes in geometry for this location are unknown.

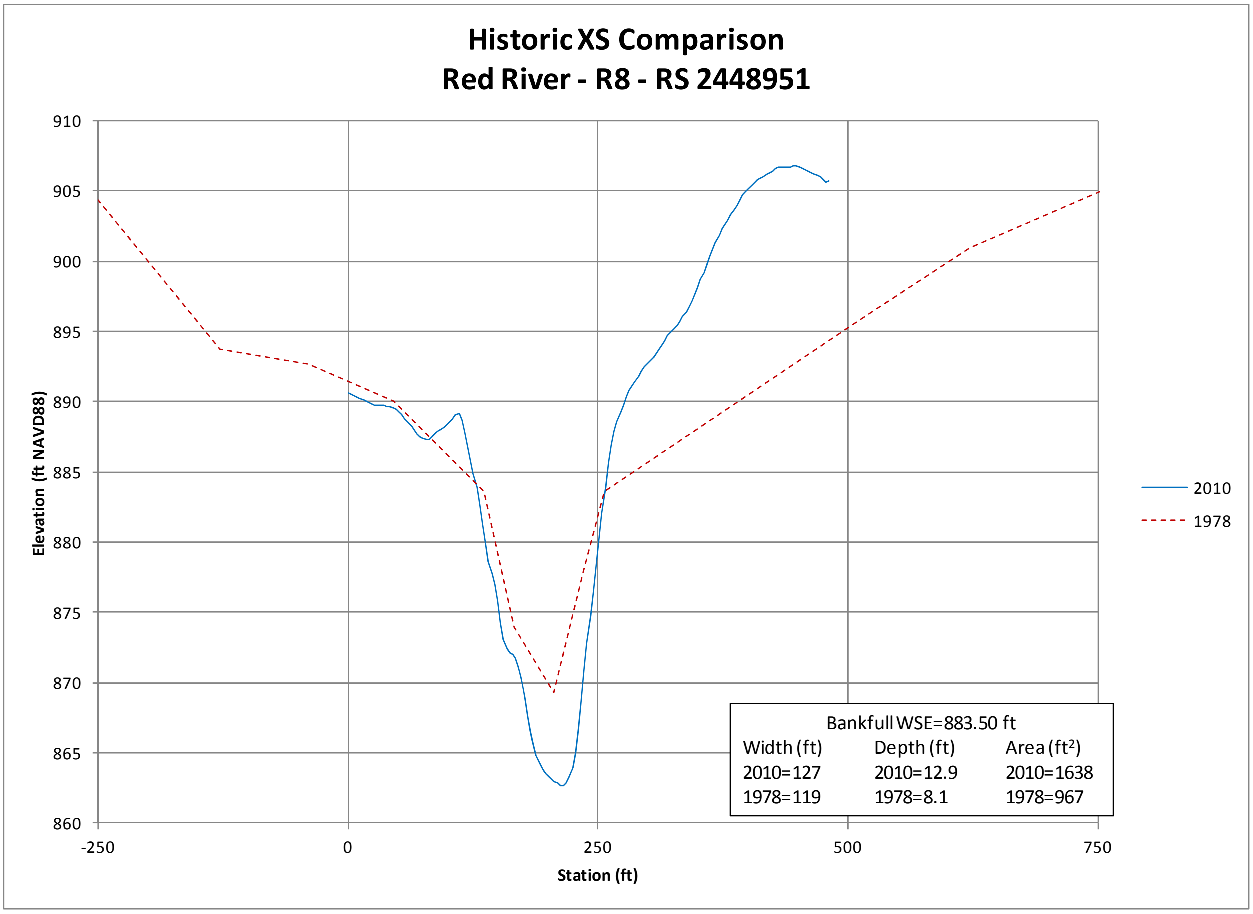


Figure 6-26. Historic Cross Section Comparison for Location R8

Figure 6-27 shows that Red River cross section R9 has experienced channel degradation between 1978 and 2010. However, as previously discussed, the 1978 cross section data are considered to be erroneous. Therefore, changes in geometry for this location are unknown.

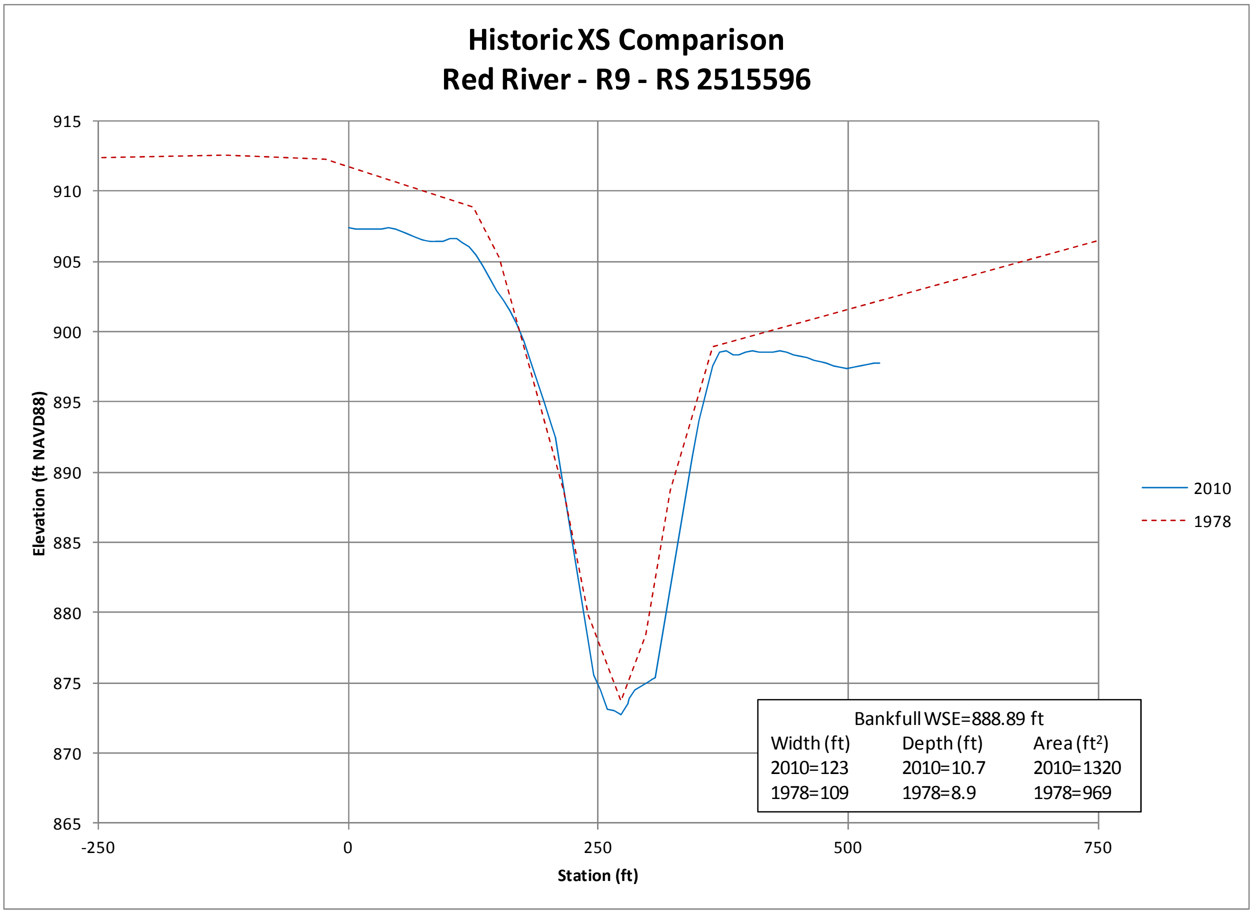


Figure 6-27. Historic Cross Section Comparison for Location R9

Figure 6-28 shows that Red River cross section R10 has degraded and narrowed slightly over time between 1999 and 2010. The cause of these changes is unknown as no structures are located nearby that would influence this location.

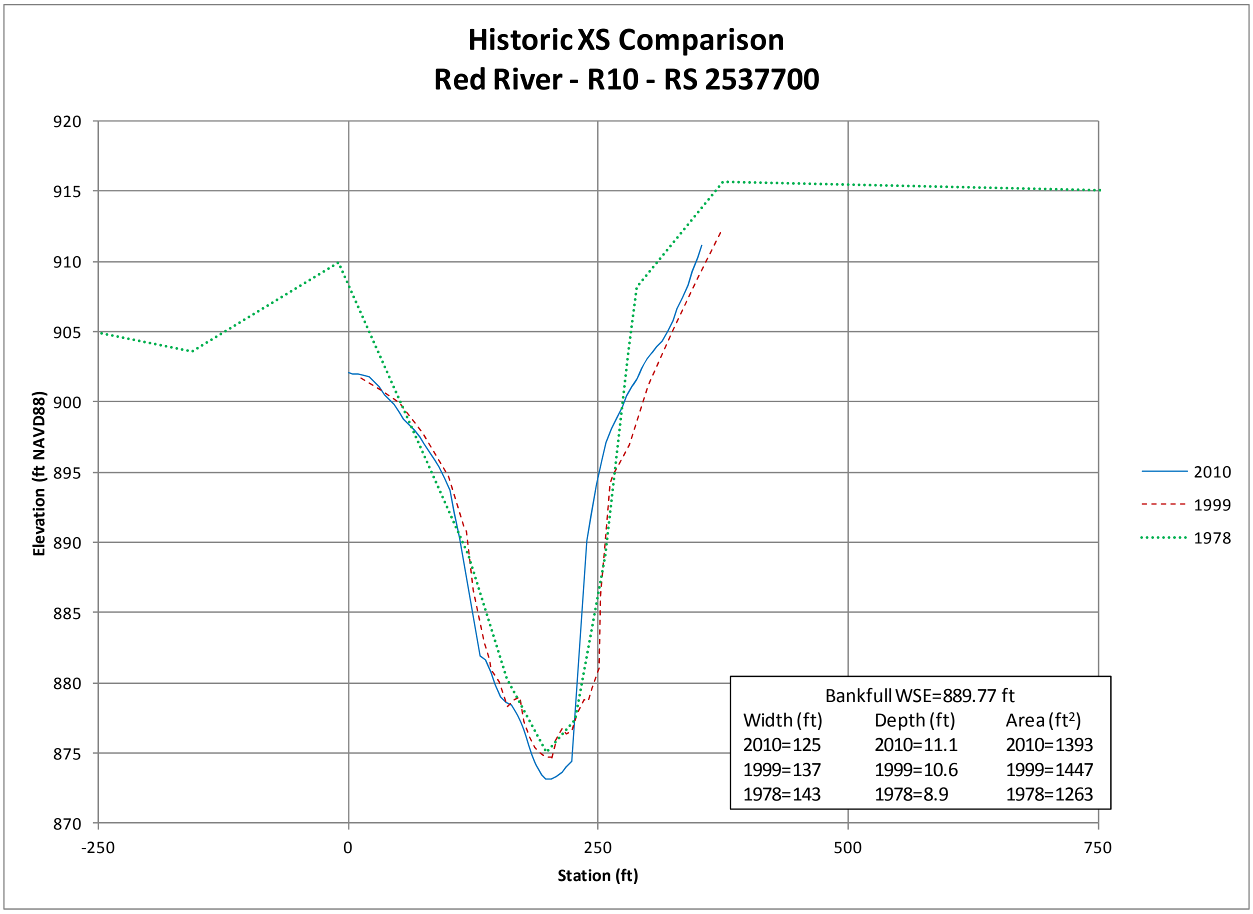


Figure 6-28. Historic Cross Section Comparison for Location R10

Figure 6-29 shows that Wolverton Creek cross section W1 has degraded between 2000 and 2010. This is likely the result of a new box culvert that was installed on County Road 59 where it crosses Wolverton Creek. Therefore, the resulting channel geometry changes are significantly influenced by anthropogenic changes to the channel.

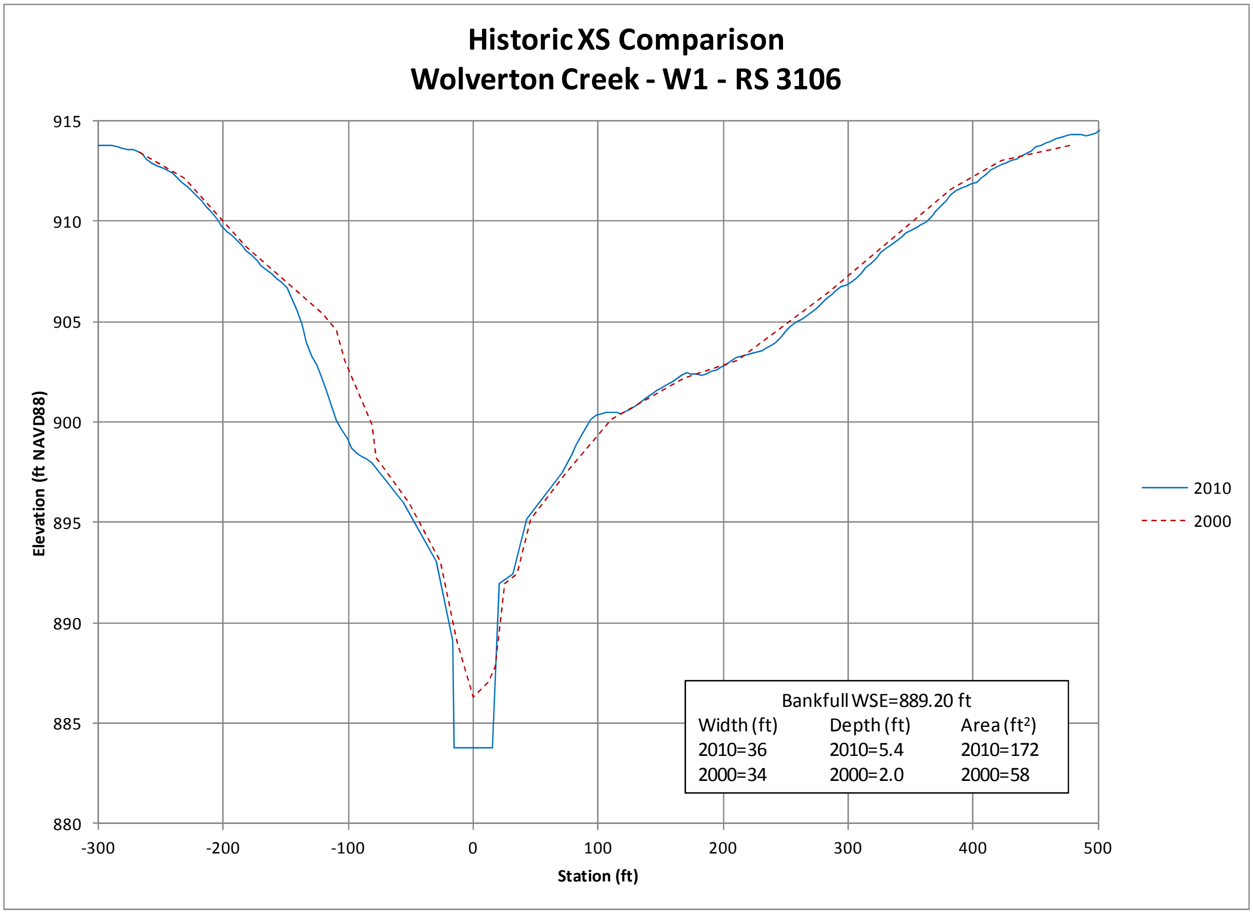


Figure 6-29. Historic Cross Section Comparison for Location W1

Figure 6-30 shows that Wolverton Creek cross section W2 has experienced channel widening at the bankfull elevation between 2000 and 2010. It appears that a geotechnical bank failure occurred along the left bank and is reflected in the 2010 survey, resulting in an increase in bankfull top width. It is also noted that the thalweg elevation decreased approximately 2.3 feet between 2000 and 2010. One possible explanation is that this decrease is the result of anthropogenic changes to the watercourse intended to increase the flow capacity of the channel.

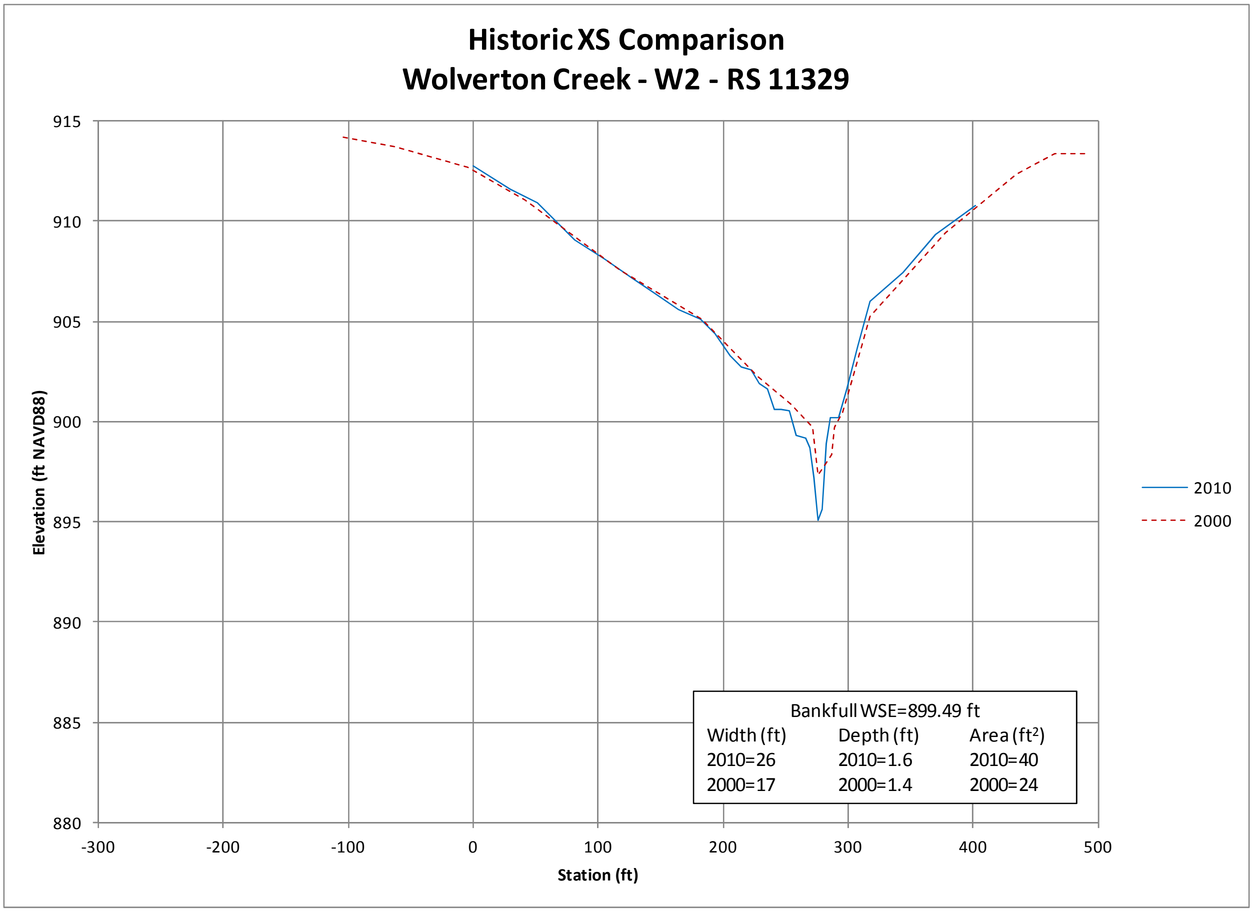


Figure 6-30. Historic Cross Section Comparison for Location W2

The historic cross section comparisons indicate that, with the exception of localized impacts from human caused modifications, there have been no significant changes to the channel geometry over time. While certain individual cross sections were consistently widening or narrowing over time, reach wide or river wide trends in bankfull top width changes are not occurring. Of the 42 historic cross sections examined for changes in bankfull top width, 3 were narrowing, 2 were widening, and 37 either did not have a trend, could be discounted based on human alterations near the cross section, or could not be assessed due to poor quality survey data. In the same respect, while certain individual cross sections were consistently degrading, reach wide or river wide trends in hydraulic depth changes are not occurring. Of the 42 cross sections evaluated, only 5 appear to be degrading. The remaining 37 cross sections either did not have a top width trend, could be discounted based on human alterations near the cross section, or could not be assessed due to poor quality survey data. The historic cross section comparison results suggest that the channels within the project area are stable and that flow changes resulting from the proposed diversion alignment alternatives are not expected to significantly affect the geomorphology of the streams within the study area. However, localized impacts may occur near the proposed diversion structures.

6.2.3 Regime Channel Geometry Methods

Regime theory was developed over a century ago by British engineers working on irrigation canals in what is now India and Pakistan. Canals that required little maintenance were said to be “in regime”, meaning that they conveyed the imposed water and sediment loads in a state of dynamic equilibrium, with width, depth, and slope varying about some long-term average. These engineers developed empirical formulas linking low-maintenance canal geometry and design discharge by fitting data from relatively straight canals carrying near-constant discharge.

Fifty years later, hydraulic geometry formulas similar to regime relationships were developed by geomorphologists studying stable, natural rivers. In this way, the concept of regime theory or a regime channel has been extended to natural alluvial channels. An alluvial channel is considered to be “in regime” when there is no net change in its discharge capacity or morphology over a period of years. A regime channel essentially represents a stable channel in equilibrium conditions under which the channel has adjusted its slope, width, depth, and velocity to achieve stable conditions given a consistent supply of water and sediment over a period of time.

Regime theory continues to be the subject of considerable research and is of great practical interest. It has been used extensively in river engineering to design stable channels and to assess channel stability for existing channels. The theory has been applied to river systems subject to hydrologic and hydraulic condition changes in order to predict channel response (e.g., USACE, 1994).

The regime method is an empirical method that relies on available data and attempts to determine appropriate relationships from the data. The usefulness of this method depends on the quality of the data and the validity of the assumed form of the relationships. It has always been acknowledged that the various coefficients derived may not be truly constant but may vary slightly. Furthermore, the equations should only be applied in situations similar to those for which the data were collected.

The use of channel regime relations requires the watershed and stream channel characteristics of the reach in question to be similar to the data set or consistent with the implied assumptions used to develop the channel regime relations. An implied assumption in regime theory is that channels have the ability to change geometric shape over the engineering timescale due to natural processes. It was shown in the historic cross section comparisons that the streams do not have the ability to do so. Rather, the channels are shaped over a geologic timescale, due to the cohesive nature of the channel boundaries as well as the sediment supply-limited state of the channel. Because of the inherent lack of certainty in the predictive capabilities of regime channel methods, predictions of future channel geometric changes for the study streams were not developed.

6.3 Stability Analysis Conclusions

All but three of the study reaches have sinuosity values that exceed 1.5 and are considered meandering as defined by Leopold, et al. (1992). Rush River – 2, Lower Rush River – 2, and Wolverton Creek – 2 have values of less than 1.5 and are defined as sinuous; however, based on the observed planform each of these reaches have likely experienced some historic straightening (though not as extensively as Rush River – 1 and Lower Rush River – 1 which were excluded from the analysis for that reason) and are therefore poor indicators of the system's behavior.

Typically, meandering watercourses migrate over time as their outer banks are eroded by fluvial processes. The results of the sinuosity, meander migration, amplitude and frequency, belt width, channel width, and bank erosion calculations, demonstrate that the study reaches appear to be in a state of relative stability, showing little change between subsequent years. The calculated rates of change between years are either zero or small non-zero values that are likely within the range of error expected for the various processes used for their determination.

Due to the small or zero values for channel migration rates, no quantifiable conclusions can be drawn regarding effect of bank vegetation on channel migration. While it is known that vegetation can markedly increase bank stability and reduce erosion rates, thereby slowing channel migration, it is likely that vegetation may have less influence on erosion and migration within this system. Within the project area, bank stability and resistance to significant migration are largely due to the relatively low velocities experienced during major flooding and the highly cohesive nature of the clay soils, which are the predominant bed and bank material.

Trends in migration, bank erosion, planform, and other indicators of geomorphic stability are predominantly controlled by flow rates and sediment loads. Though the hydrologic record for this system is considered to be non-stationary (with discharges on the increase) and sediment-limiting structures (gates, diversions, and weirs/dams) have been constructed during the historic imagery analysis period, little geomorphic change was observed. That some limited amounts of migration are observable in the historic record, along with the presence of abandoned meanders, demonstrates that the river channels are indeed migrating, but at a very slow rate, with significant changes occurring over time scales that exceed the range used for this analysis. Furthermore, the system appears to be relatively insensitive to long-term changes in discharge and sediment availability.

Analysis of historic and current cross sections also provided useful insight into the stability of the system. While certain cross sections were consistently widening or narrowing, a consistent trend in width changes was not observed throughout the entire system. Of the 42 historic cross sections examined for changes in bankfull top width, 3 were narrowing, 2 were widening, and 37 either did not have a trend, could be discounted based on human alterations near the cross section, or could not be assessed due to poor survey data. Again, while certain cross sections were consistently degrading, a consistent trend in hydraulic depth changes was not observed throughout the entire system. Of the 42 cross sections evaluated, 5 appear to be degrading and 37 either did not have a trend, could be discounted based on human alterations near the cross section, or could not be assessed due to poor survey data.

Overall, the stability assessment indicates that the stream systems are in dynamic equilibrium. Laterally, these streams are not migrating or changing width with any discernible pattern over the time scales of the available data. Any significant migration of the channels appears to occur over timescales of hundreds if not thousands of years. In fact, a channel migration study by Brooks (2003) for a portion of the Red River of the North located further north in Manitoba, Canada found that lateral migration rates average about 1.6 inches per year. Available historic cross section data and the results of the specific gage analysis suggest that some of the stream channels may be degrading over the long-term, but the available data is not sufficient to be conclusive or determine any long-term rate. Brooks (2003) found that the vertical incision rate to be very small, averaging .02 inches per year.

The stability assessment analyses indicate that the streams are not significantly impacted by changes in discharge or sediment availability, likely due to the highly cohesive banks and beds that exist throughout a majority of the system, the low energy gradient of the streams, and the lack of a significant supply of coarse sediment. Therefore, future changes in discharge and/or sediment supply are not expected to result in major channel planform or cross-section geometry changes.

7 Sediment Impact Analysis

7.1 Future Flow Conditions

Discharge-frequency, discharge-duration, and elevation-duration curves were developed for select locations within the FCP and LPP alignments. The methods used to develop of these hydrology curves are outlined in the following sections.

7.1.1 FCP Alignment

A single set of hydrology curves (discharge-frequency, discharge-duration, and elevation-duration) was developed for the FCP alignment. Only one set of curves was needed since significant additional inflows do not occur along the length of the FCP alignment. The discharge-frequency and discharge-duration curves were developed for the upstream inflow point of the FCP alignment alternative by subtracting the future conditions (FCP alignment) curves from the current conditions curves provided by the St. Paul District for the USGS gage 05054000 – Red River at Fargo. The elevation-duration curve was developed using HEC-RAS following the same procedures outlined in Section 4.4.2. The future conditions hydrology curves developed for the FCP alignment alternative are provided in Appendix M.

7.1.2 LPP Alignment

Hydrology curves (discharge-frequency, discharge-duration, and elevation-duration) were developed for the LPP diversion alignment at the upstream end of the diversion channel, at major inflow locations, and at selected local drains. The major inflow locations include the Red River, Wild Rice River, Sheyenne River, Maple River, Lower Rush River, and Rush River. Future conditions curves and current conditions curves were provided by the St. Paul District. The discharge-frequency and discharge-duration curves for inflows to the diversion channel from the Red River and Sheyenne River were calculated by subtracting the future conditions curves from the current conditions curves for USGS gage 05054000 – Red River at Fargo and 05059500 – Sheyenne River at West Fargo, respectively. The difference between the curves yielded the amount of flow entering the diversion at those points. The discharge-frequency and discharge-duration curves for inflows to the diversion channel from the Wild Rice River and Maple River were calculated by subtracting the future conditions curves from the current conditions curves for the Wild Rice River at mouth and Maple River at mouth locations, respectively. The discharge-frequency and discharge-duration curves for inflows to the diversion channel from the Lower Rush River and Rush River were future conditions curves for the Lower Rush River at Diversion and Rush River at Diversion locations, respectively.

Discharge-frequency and discharge-duration curves for local drains were calculated using representative curves for USGS gage 05060500 – Rush River at Amenia, provided by the St. Paul District, and scaling the values on the curve by the ratio of the drainage area for the gage site and the drainage area for the minor inflow locations. This gage was considered to be a representative gage as it measures flow from a relatively small drainage area, similar to the smaller drainage areas of the local drains, and is located in a similar hydrologic setting.

The curves developed for the Red River inflow point to the diversion channel were used for the reach of the diversion between the Red River and the Wild Rice River. For the reach of the diversion channel downstream of the Wild Rice River inflow point, the Wild Rice River inflow curves were added to the Red River inflow curves, and so on downstream at each of the major inflow points and local drain inputs. The elevation-duration curves for the diversion channel were developed for the first cross section located downstream of each of the major inflow points and local drainage locations. The curves were developed using HEC-RAS following the same procedures outlined in Section 4.4.2. The future conditions hydrology curves developed for the LPP alignment alternative are provided in Appendix N.

7.2 Future Channel-Forming Discharge

A number of methods were considered for estimating future channel-forming discharges. These methods included the bankfull discharge, effective discharge, and recurrence interval procedures used for estimating the current conditions channel-forming discharges. An evaluation of channel shear stress was also conducted in an attempt to estimate the future channel-forming discharge. The conclusions regarding the various methods are summarized in the following paragraphs.

The bankfull discharge method is dependent upon the identification of bankfull indicators that are collected via field observations. Because this method requires field investigations to be completed, it cannot be conducted for future conditions. Therefore, the bankfull method is not applicable for predicting future channel-forming discharges.

The effective discharge method is typically considered the most appropriate means of estimating future channel-forming discharges. However, as discussed in Section 4.2.2, the results of the effective discharge method were not sufficiently consistent to estimate the current conditions channel-forming discharge for the study streams. This is likely due to the lack of a reliable relationship between flow rate and sediment discharge. Therefore, the effective discharge method could not be used with confidence to predict the future conditions channel-forming discharge.

The recurrence interval at which the proposed diversion alignments begin to divert flow from stream channels was calculated to be 3.6-years for the Red River and Wild Rice River and 2-years for the Sheyenne River. These recurrence intervals are greater than the range of recurrence intervals calculated for the current conditions bankfull method discharges. Therefore, using the same recurrence interval to predict future channel-forming discharges would yield the same result as the current channel-forming discharges.

As discussed above, the future conditions channel-forming discharge could not be quantitatively determined for areas protected by the proposed diversion alignments using the available methods. However, qualitative conclusions regarding the effect of the proposed alternatives on the channel forming discharge can be deduced. The size of a stream channel is related to the shear stresses created by flowing water along its contact with the bed and banks and the ability of the bed and bank material to resist those shear stresses. Over time, with all other factors staying consistent, the channel geometry will approach equilibrium and remain relatively constant. However, when the hydrology is reduced, such as in areas protected by the proposed diversion alternatives, the maximum shear stresses acting on the channel will also be reduced. The lower shear stresses would be expected to result in a reduction in the channel size over a geologic timescale as it adjusts itself toward a new equilibrium condition. However, the geometry of the channels is not expected to change significantly during the life of the proposed diversion project.

All of the study streams, except the Sheyenne River, are primarily composed of clay- and silt-sized sediment, which is transported as wash load. By definition, wash load is not deposited in appreciable quantities within the channel and therefore is not a primary factor that controls the channel morphology. The Sheyenne River has a much greater supply of sand compared to the other streams. However, the majority of its sediment load is transported in suspension. With the exception of Reach 8, the amount of sand that is supplied to the Sheyenne River does not appear to be a primary factor that influences the morphology of channel. The erosion of the cohesive bed and bank materials found within the study streams is the primary process that is continuing to form the channels. The width, depth, and slope of the channel are based on the balance between the erosive shear forces of the flowing water and the erosion resistance (shear strength) of the bed and bank materials. As demonstrated by the analysis if historic cross section data presented in Section 6.2, the historic changes in the overall geometry of the study streams has been extremely minor. In other words, the cohesive bed and banks are highly resistant to erosion.

The elimination of the high flow events associated with the diversion alternatives is expected to reduce the erosive shear forces and therefore reduce the annual sediment transport capacity within the protected channels. However, the percentage of time that the high flow events occur is small; and therefore, the overall reduction in the duration of erosive shear forces is expected to be minor. A comparison of the average annual shear stress values indicates that the LPP and FCP alignment alternatives reduce the average annual shear stress in the protected reaches by less than 5-percent compared with the Existing Conditions. As a result, the reduction in the channel-forming discharge is also expected to of a similar small percentage. Over the long-term, it is expected that the channels within the protected reaches will become smaller because of the altered hydrology. However, the reduction in size is likely to be minor.

For the reaches located upstream and downstream of the area protected by the proposed diversion alignments, the future channel-forming discharge is expected to be the same as the current channel-forming discharge.

7.3 Sediment Delivery Analysis

In order to evaluate potential changes in sedimentation patterns that could occur due to impacts from the FCP and LPP alignments, sediment assessment models were constructed using the SIAM (Sediment Impact Assessment Model) feature in HEC-RAS. SIAM compares the annual sediment transport capacity of a reach to the annual sediment supply and provides an indication of whether aggradation, degradation, or equilibrium may occur. The input required to the SIAM module includes cross section data for the study reach, annualized flow-duration data, bed material gradations, an appropriate sediment transport function, wash load criteria, and annualized sediment input volumes (broken down by grain size fractions).

Historically, dozens of transport functions have been developed and it is well known that sediment transport is very sensitive to many variables (USACE, 2010c). Accordingly, it is important that the transport function chosen for the analysis should have been developed using similar sediment gradation and hydraulic conditions to what is found in the project area. SIAM includes six different functions to compute sediment transport capacity over a range of bed material sizes, including Ackers-White, Engelund-Hansen, Laursen-Copeland, Meyer-Peter Müller, Toffaleti, and Yang. The dominant bed and bank material for the Red River and its tributaries is cohesive clay. None of the transport functions available in SIAM were developed based on clay size materials. Of the six available transport functions, all but Laursen-Copeland were developed from data based on sand or larger sized particles, making them poor choices for this analysis. While Laursen-Copeland was developed for material sizes that extend to the range of coarse silt, finer silts and clay size particles are outside the range of applicability. The Laursen-Copeland function was selected for all sediment reaches; however, it should be noted that applying this function to predominantly clay-sized material gives results that are extrapolated well beyond the range of the data used to derive the functions. This could result in the compounding of extrapolation errors in addition to the already large uncertainty that is associated with sediment transport calculations.

Further complicating the available transport functions, SIAM does not have the ability to address cohesive sediment, which is a distinguishing characteristic of the majority of the sediment in the study reaches. While the standard sediment transport module (HEC-6) in HEC-RAS does provide the option to enter erosion parameters manually for cohesive sediments (should that data be known), this feature is not available in SIAM and it would be expected that SIAM would over predict the erosion and transportation of cohesive sediments.

Finally, SIAM assumes there is no limitation on bed material supply and that erosion will continue indefinitely from the bed until the sediment transport capacity is satisfied. While this assumption may work well with systems in which the dominant bed materials are non-cohesive, it does not translate well to the Red River system and can result in over predictions of degradation that are far in excess of what would likely occur.

Though the SIAM analysis was completed, the results were ultimately considered unreliable due a variety of reasons, including (among other items) limitations of the available transport formula and the unlimited bed assumption. Due to the uncertainty in the results, the SIAM analysis and results have been not been included in the main body of this report. The complete SIAM analysis along with more detailed information on the various limitations and difficulties encountered can be found in Appendix P.

In light of the lack of reliability of the SIAM analysis, and in order to give some quantitative indication as to ability of the study reaches to transport the sediments found in the system, two brief exercises were conducted. A comparison of reach average velocities and shear stresses to published threshold values for soils was made and bankfull reach averaged channel velocity and shear stress are provided in Table 7-1. A selection of soil threshold values for shear and velocity are provided in Table 7-2 (Chang, 1988). As shown in Table 7-1, all study reaches have shear stresses or average velocities that are below the threshold for sticky clay. All study reaches, with the exception of Lower Rush 2, have average channel velocities and/or average channel shear stresses that are equal to or in excess of the maximum permissible threshold values for fine colloidal sand. As neither of the future conditions scenarios are expected to significantly alter or reduce bankfull flows for any study reach (except for Rush 1 and Lower Rush 1), it is expected that all study reaches could mobilize and transport fines sands, when considered on a reach averaged basis. Furthermore, bankfull flows for current and future conditions will remain inadequate to mobilize significant amounts of cohesive clay from the channel beds.

Table 7-1. Reach Averaged Channel Velocity and Shear Stress for Bankfull Conditions

General Study Reach	Q (cfs)	Avg Channel Velocity (ft/sec)	Avg Shear Stress (lb/ft^2)
Buffalo 1	420	1.14	0.03
Lower Rush 1	65	1.01	0.07
Lower Rush 2	60	0.53	0.02
Maple 1	650	1.64	0.04
Maple 2	650	1.44	0.04
Red River 1	4700	2.30	0.04
Red River 2	4280	2.68	0.06
Red River 3	2380	1.98	0.06
Red River 4	2380	1.82	0.07
Red River 5	2380	1.42	0.03
Red River 6	1780	1.39	0.05
Red River 7	1650	1.53	0.04
Red River 8	1650	1.74	0.06
Rush 1	150	1.35*	0.08*
Rush 2	150	1.48	0.08
Sheyenne 1	1900	2.49	0.17
Sheyenne 2	1750	1.84	0.11
Sheyenne 3	1680	1.78	0.11
Sheyenne 4	1030	1.80	0.14
Sheyenne 5	580	1.59	0.09
Sheyenne 6	860	1.65	0.09
Sheyenne 7	1200	1.72	0.11
Sheyenne 8	1000	1.48	0.10
Wild Rice 1	6000	1.06	0.04
Wild Rice 2	6000	1.29	0.06
Wild Rice 3	517	1.08	0.02
Wild Rice 4	517	1.28	0.05
Wild Rice 5	517	0.98	0.03
Wild Rice 6	517	1.21	0.05
Wolverton 1	130	1.72	0.14
Wolverton 2	130	1.79	0.10

* Does not include velocity and shear stress from XS 11119 (weir) due to significant skewing of reach average results

Table 7-2. Threshold Values for Shear and Velocity

Boundary Type	Permissible Shear Stress (lb/ft^2)	Permissible Velocity (ft/sec)
Fine colloidal sand	0.02-0.03	1.5
Stiff clay	0.26	3-4.5

For the second exercise, a comparison of sediment transport potentials for the Sheyenne River, calculated by SIAM was made and is provided in Table 7-3. The table is limited to results for the Sheyenne River as it is the only study reach with appreciable quantities of material above the washload threshold set in SIAM. The transport potential is computed for each grain size as though it comprised 100% of the bed material. While this is a hypothetical condition, it provides a measure of comparison between scenarios other than the aggradation/degradation results, which were determined to be unreasonable due to the unlimited bed assumption. The calculated transport potentials are similar for all scenarios in SR4 through SR8. While it might be expected that there would be a reduction in transport potential for larger grain sizes in the protected areas this is not seen in the results and is likely due to the clipping of high flows from the model discharges as discussed in previous sections. A notable reduction in transport potential for all grain sizes is seen in SR1, SR2, and SR3 for the LPP scenario. This is likely a result of LPP diversion reducing flows in the upper reaches of the Sheyenne as well as intercepting all or most of the flows from the Maple River, Lower Rush River, and Rush River, which flow into SR3, SR2, and SR1, respectively.

Table 7-3. Comparison of SIAM Sediment Transport Potentials for the Sheyenne River

Reach	Scenario	Sediment Transport Potential per Grain Class (tons/year)						
		6, VFS	7, FS	8, MS	9, CS	10, VCS	11, VFG	12, FG
Sheyenne River-1	Current	349,996	36,234	9,179	3,664	887	11	0
	FCP	350,326	36,266	9,185	3,666	889	11	0
	LPP	231,742	23,552	6,111	2,227	536	0	0
Sheyenne River-2	Current	640,755	69,154	15,567	7,448	3,109	826	6
	FCP	641,069	69,199	15,576	7,452	3,111	827	6
	LPP	399,854	42,518	10,096	4,592	1,511	237	6
Sheyenne River-3	Current	141,206	14,226	3,556	1,201	285	4	0
	FCP	141,229	14,229	3,556	1,201	285	4	0
	LPP	91,653	8,940	2,245	609	59	0	0
Sheyenne River-4	Current	62,786	5,973	1,502	473	14	0	0
	FCP	62,789	5,973	1,502	473	14	0	0
	LPP	66,686	6,386	1,612	478	2	0	0
Sheyenne River-5*	Current	17,316	1,537	289	58	0	0	0
	FCP	17,316	1,537	289	58	0	0	0
	LPP	17,473	1,553	289	62	0	0	0
Sheyenne River-6	Current	55,833	5,309	1,348	306	6	0	0
	FCP	55,833	5,309	1,348	306	6	0	0
	LPP	58,594	5,606	1,427	323	16	0	0
Sheyenne River-7	Current	50,101	4,762	1,241	303	0	0	0
	FCP	50,101	4,762	1,241	303	0	0	0
	LPP	51,780	4,873	1,274	308	0	0	0
Sheyenne River-8	Current	45,254	4,225	1,035	257	0	0	0
	FCP	45,254	4,225	1,035	257	0	0	0
	LPP	45,254	4,225	1,035	257	0	0	0

* Reach SR5 in model has estimated gate operation and is missing two known structures

7.4 Low Flow Channel Design – LPP Diversion Alignment Alternative

Channel geometry parameters were provided to the USACE for a low flow channel within the LPP diversion alignment alternative. The channel design was submitted by email to Mr. Aaron Buesing with the St. Paul District on November 4, 2011.

7.5 Staging Area Deposition – LPP Diversion Alignment Alternative

An estimate of deposition in the staging area was detailed in Attachment 5, Appendix F, Exhibit I of the Flood Risk Management Report (USACE, 2011). The estimate of deposition was not included in the referenced report; however, an email that included the deposition evaluation was provided and reviewed. The conclusions of the review were submitted by email to Ms. Michelle Schneider with the St. Paul District on February 17, 2012.

7.6 Sediment Impact Analysis Conclusions

Discharge-frequency, discharge-duration, and elevation-duration curves were developed for select locations within the FCP and LPP alignments. These future flow characteristics were used to compute sediment transport within the diversion alternatives. Additional detailed sediment transport evaluations for existing and alternative conditions were conducted for all other involved watercourses using the SIAM module within HEC-RAS. The results of the SIAM analysis were determined to be problematic due the lack of a suitable sediment transport function within the software applicable to cohesive sediments and the general characteristics of the involved watercourses. Alternatively, an evaluation of the general sediment transport ability of each reach of the involved watercourses was conducted. The evaluation results indicate that all study reaches could mobilize and transport fines sands, when considered on a reach-averaged basis.

Future channel-forming discharge was assessed through an evaluation the average annual shear stress expected to occur within each stream. When hydrologic inputs to a stream are reduced, such as in areas protected by the proposed diversion alignment alternatives, the maximum shear stresses acting on the channel will also be reduced. Therefore, the reductions in average annual shear stress are expected to be linked to the reduction in channel-forming discharge. Comparison of future conditions shear stresses to current conditions shear stresses indicated that the LPP and FCP alignment alternatives reduced the average annual shear stress in protected reaches by less than 5-percent compared to the existing conditions. For the reaches located upstream and downstream of the area protected by the proposed diversion alignments, the future channel-forming discharge is expected to be the same as the current channel-forming discharge.

8 Monitoring Plan

Given the inherent stability of the stream channels within the study area, the monitoring needs for the project are expected to be minimal. The following four tasks are recommended for monitoring the geomorphic response of the stream channels and diversion channel to the proposed project:

8.1 Aerial Photography Evaluation

Future aerial photography should be compared with previous aerial photography and bank line delineation shapefiles (included in Appendix Q). The United States Department of Agriculture (USDA) National Agricultural Imagery Program (NAIP) obtains new photography about every 1 to 2 years that covers the project area. The data can be obtained from http://datagateway.nrcs.usda.gov/. The imagery is already rectified and georeferenced so it can be easily overlain in GIS for comparison purposes. The effort should focus on locating areas where obvious lateral shifts in the bank location have occurred compared to previous data sets. Significant shifts in channel locations with a rate of change greater than previously estimated should be flagged for further investigation and the bank lines should be delineated for comparison with future imagery data. Changes in vegetation type and density should also be evaluated. Although, there does not appear to be a direct link between vegetation and lateral channel stability, this evaluation could help identify areas where the geotechnical stability of the banks may have changed. Again, areas with significant changes in vegetation should be flagged for further investigation. Following completion of the diversion project, the aerial photography evaluation should occur at the same frequency as the availability of new aerial photography (every 1 to 2 years). If no significant changes have occurred after 5 years, the frequency can be reduced to every 4 to 5 years. If no significant changes have occurred after 15 years, the frequency can be reduced to every 10 years. This evaluation should be repeated at a minimum of every 10 years. It should also be conducted following significant flood events.

8.2 Field Reconnaissance

A reconnaissance of the detailed study reaches should be conducted immediately prior to the completion of the diversion project and of the diversion channel immediately following its completion (to establish baseline conditions) and every 5 years thereafter for the first 10 years. If no significant changes in the channel morphology are noted, the frequency can be reduced to every 10 years. If after 20 years, no significant changes in channel morphology are noted, the field reconnaissance efforts can cease. At a minimum, a color photographic log with GPS locations should be created to document the reconnaissance observations for comparison with previous documentation. Further, if significant changes are found to be occurring along certain streams or stream reaches, future reconnaissance efforts could be focused on only these locations.

For each of the areas flagged for further investigation by the aerial photography evaluation, a site specific field reconnaissance should be conducted to understand the local conditions of the site and to help understand the causation for the noted changes. At a minimum, color photographs should be taken to document the conditions of the site. Subsequent visits to the site can be made at a frequency consistent with the magnitude and rate of the noted changes and the significance of the potential consequences resulting for those changes.

8.3 Cross Section Surveys

A total of 206 cross sections have been established to allow for monitoring of changes in channel geometry following the completion of the project. The cross sections were selected based on one of the following criteria:

- The cross section is located within a detailed study reach
- One or more historic cross section surveys were conducted in the same location
- The cross section is located immediately upstream or downstream of the proposed diversion alignments.

The georeferenced polyline cross section and endpoint shapefiles are located in the geodatabase located in Appendix Q. Additionally, Appendix O displays the X and Y coordinates (in the NAD 1983 North Dakota State Plane South FIPS 3302 feet coordinate system) for the polyline endpoints in a tabular format. The number of cross sections established for each stream is summarized in Table 8-1.

Table 8-1. Summary of Cross Sections for Monitoring

Stream	Number of Cross Sections
Buffalo River	6
Lower Rush River	13
Maple River	15
Red River of the North	54
Rush River	15
Sheyenne River	51
Wild Rice River	41
Wolverton Creek	11

Cross section surveys should be conducted immediately prior to the completion of the diversion project (to establish baseline conditions and for comparison with previous surveys) and every 5 years following its completion for the first 10 years. If no significant changes in the channel morphology are noted, the frequency can be reduced to every 10 years. If after 20 years, no significant changes in channel morphology are noted, the cross section survey efforts can cease. Further, if significant changes are found to be occurring only along certain streams or stream reaches, future cross section survey efforts could be focused on only those locations.

Cross section surveys should be conducted along the diversion channel immediately following its completion and every 5 years for the first 10 years. If no significant changes in the channel geometry are noted, the frequency can be reduced to every 10 years. If after 20 years, no significant changes in channel geometry are noted, the cross section survey efforts can cease. Further, if significant changes are found to be occurring only along certain reaches, future cross section survey efforts could be focused on only those locations. Cross section surveys should also be conducted immediately following the first significant flood event to evaluate the ability of the diversion channel to convey sediment.

8.4 Communication with Local Agencies

Annual or more frequent communication should be established with representatives from local agencies with regard to channel morphology. Interested stakeholders in channel morphology would include the involved counties and cities, farming co-ops, USDA-NRCS, North Dakota and Minnesota Fish and Game agencies, USGS, US Fish and Wildlife, college extension services and involved irrigation and drainage districts. Such communication efforts would allow for the real or perceived changes in channel morphology identified by these agencies and/or their constituents to be documented and flagged for further evaluation. Regular communications would help focus the previously mentioned monitoring efforts and allow for concerns to be documented and appropriately addressed.

9 Future Conditions Effects

9.1 Sedimentation/Erosion Potential

Results of the geomorphic assessment indicate that the involved study reaches are not prone to significant change in morphology over short or even moderate periods of time. Channel migration rates are on the order of a few inches per year. The erosion resistant nature of the cohesive glacial lake bed soils and the very flat gradient of the channels prevent significant changes in channel cross section geometry and results in very low rates of lateral migration. Further, the sediment supply from upstream and the surrounding landscape is generally composed of silt- and clay-sized material with only minor amounts of sand-sized material. The study streams appear to have sufficient capacity to transport nearly all of the sediment that is supplied to them in suspension as wash load. This is reflected in the poor relationship between sediment discharge and river discharge seen in Section 4.2.2. The sediment discharge rates vary significantly based upon the sediment supply. The relatively small portion of sand-sized material that is transported both in suspension and along the bed does not appear to significantly influence the channel morphology. Rather, the sand-sized material appears to be transient and where found tends to form a relatively thin layer that overlies the cohesive clay and silt bed of the channel. As evidence of the lack of significant bedload, no depositional features such as point bars or mid-channel bars were observed within the study reaches.

Although the Sheyenne River has a relatively greater proportion of sand-sized material compared to the other study streams, the underlying cohesive clay and silt bed still appears to control the overall channel geometry and rate of lateral migration within the study area. As previously mentioned, the greater abundance of sand within the Sheyenne River is the result of the river traversing the ancient beach deposits of glacial Lake Agassiz in the portion of the basin located upstream from the study area. As a result, a relatively larger amount of sand-sized material is supplied to the study reaches of the Sheyenne River. This material is transported as both suspended load and bed load. Again, alluvial channel features that are typically associated with sand bed rivers are not present along the project's study reaches. This suggests that the Sheyenne River (with the exception of Reach 8) has the capacity to transport the majority of the sand-sized material that is supplied to it from upstream as suspended load. It also suggests that the sand deposits that are occurring within the channel are not altering the hydraulic conditions sufficiently to increase the erosion potential. As previously mentioned, Sheyenne River Reach 8 appears have insufficient transport capacity to convey all of the sand that is supplied to it from upstream. As a result, the channel has responded by shifting laterally at a slightly greater rate and increasing its overall channel length, which is approximately 2 times longer than downstream reaches, to accommodate the storage of additional sand.

Although significant sedimentation does not appear to be occurring within the channels, sediment deposits were observed in the overbank areas adjacent to the channels. For the Sheyenne River, the overbank deposits included a high proportion of sand-sized material interbedded with silt- and clay-sized material as seen in Figure 9-1. The majority of the sand deposits were located at or near the top of the bank and often form a natural levee features as seen in Figure 9-2. Further away from the channel, the overbank deposits consisted of mainly silts and clays as seen in Figure 9-3. For the remainder of the study streams, the overbank deposits consisted of mainly silts and clays.


10.03.2011

Figure 9-1. Sheyenne River Overbank Sand Deposits Interbedded with Clays and Silts


10.03.2011

Figure 9-2. Natural Levee Formed by Sand Deposition along the Sheyenne River

Figure 9-3. Silt and Clay Deposits in the Overbank Area of the Sheyenne River

The potential for increased sedimentation or erosion within the stream channels as a result of the proposed project (FCP and LPP alignments) is considered to be low. Although the maximum discharge along the protected channels will be reduced by the project, the channels will continue to have sufficient capacity to transport nearly all the sediment that is supplied to them. It is noted that the extremely fine-grained silts and clays in the system are highly transportable and will continue to be transported as wash load through the channels. As previously discussed, effects on sand-sized sediment supplies from the Sheyenne River may be more discernible. However, the cohesive bed and banks will continue to provide resistance to significant morphologic change in the channels.

The potential for sedimentation in overbank areas will be altered by the LPP diversion alignment. For areas upstream of the diversion, along the Red River, Wild Rice River, and Wolverton Creek, where water will be intentionally staged in overbank areas during flood events, the floodplains will be inundated by sediment-laden waters for a longer period of time compared to the current conditions (see Figure 4-44). This will result in overbank sedimentation rates that will exceed the current conditions. It is expected that the sediment deposits will vary relative to the channel location. The greatest thickness of deposits will be located immediately adjacent to the channel banks and will decrease in thickness with distance from the channel. An example of overbank sedimentation observed along Maple River Reach 1 following the spring and summer 2011 flooding is shown in Figure 9-4.

Figure 9-4. Clay and Silt Overbank Sediment Deposits along Maple River - 2

For the reaches that are protected by the FCP and LPP diversion alignments, overbank sedimentation rates will be reduced or eliminated compared to the existing conditions. For the FCP alignment, this includes Red River Reaches 3, 4, 5, and a portion of 6. For the LPP alignment, this includes Red River Reaches 3-6, Wild Rice River Reaches 1-2, Wolverton Creek Reach 1, Sheyenne River Reaches 1-5, Maple River Reach 1, Lower Rush River Reach 1, and Rush River Reach 1.

9.2 Changes in Sediment Transport Rates

Because the study streams are considered to be supply limited, the sediment transport capacity nearly always exceeds the sediment supply. Therefore, the sediment transport rates are equivalent to the rate at which sediment is supplied to the stream channels. The supply of sediment to the reaches that are protected by FCP or LPP diversion alternatives is expected to be reduced. The reduction in sediment supply results from the diversion of flow and sediment as well as a reduction in contributing drainage area that supplies sediment to the protected channels. Therefore, the sediment transport rate is also expected to decrease within these reaches.

Changes in sediment transport are related to changes in hydrology are described by Lanes Relationship (1955) and is graphically displayed in Figure 9-5:

$$Q_s D_{50} \alpha QS$$

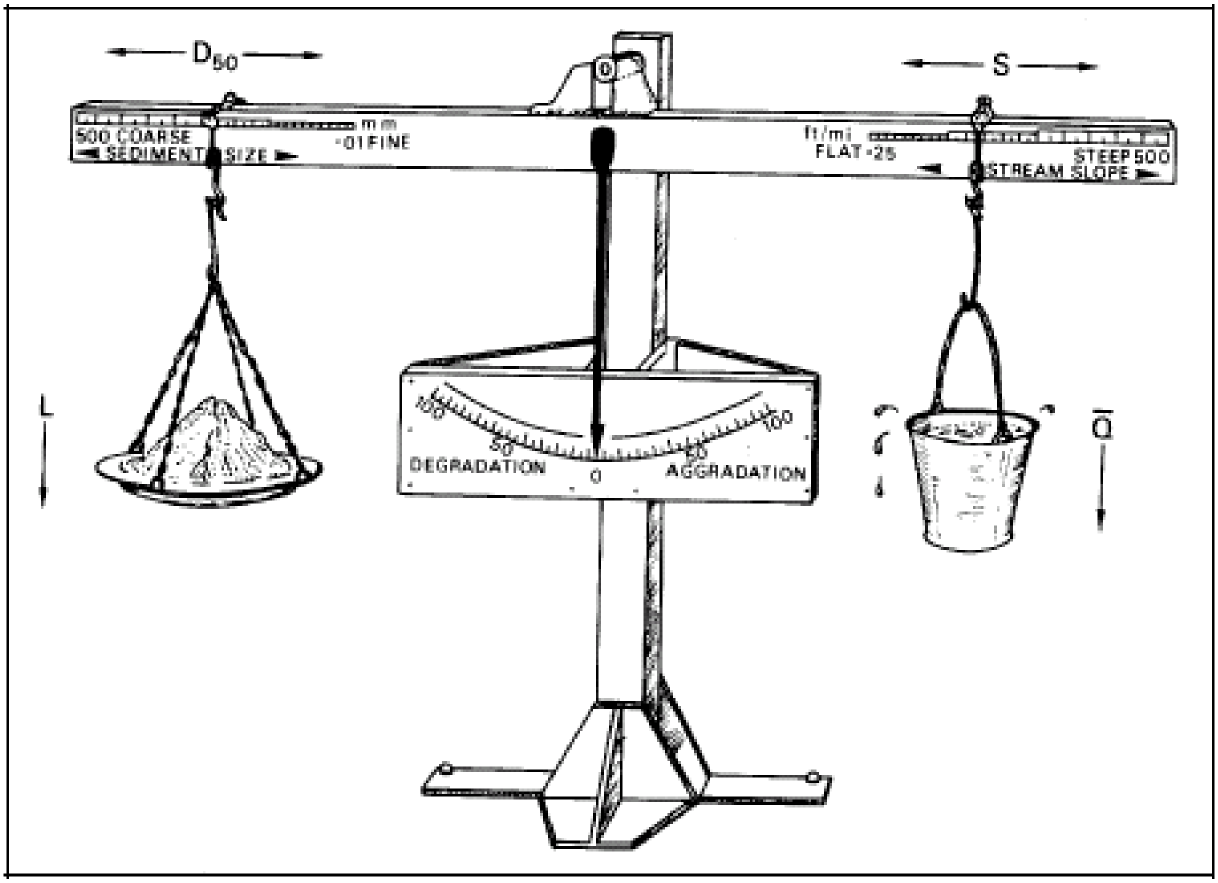


Figure 9-5. Lanes Relationship (1955)

where Q_s is the bed sediment discharge, D_{50} in the median diameter of bed material, Q is the discharge, and S is the bed slope. For the protected reaches, Q will be reduced slightly. In order to maintain equilibrium, the bed slope (S) would have to increase slightly by decreasing channel sinuosity and/or the bed sediment discharge (Q_s) and/or bed material size (D_{50}) would have to decrease slightly. If the supply of bed sediment from upstream is not altered, aggradation of the bed would be expected. However, the bed material for most of the study reaches is generally composed of cohesive clay and silt that once entrained in the flow is transported as wash load and is therefore not expected to deposit within the channel.

The sand supplies from the Sheyenne River are currently transported as a combination of suspended load and bed load. The lack of major sand bars observed within the channels indicates that the majority of the sand is transported as suspended load. Major sand deposits were observed in overbank areas both upstream of the existing Horace to West Fargo diversion (Reaches 7-8) and downstream of the diversion confluence (Reaches 1-4). The proposed LPP diversion will affect sand transport in several ways. Where flow is diverted, it can be assumed that a generally proportionate volume of the total suspended sand load will be diverted. Where hydraulic control such as weirs or gates obstruct or block flow, corresponding accumulations of sand should be expected. If the diversion of flow results in an uneven diversion of the total sand load, a potential exists for a greater portion of the sand load to be transported as bedload.

9.3 Potential Morphologic Changes

As previously discussed, since the majority of the sediment is transported as wash load, the morphology of the channels does not appear to be sensitive to the existing sediment transport rates. The minor amount of sand transported by the stream channels is not sufficient to form depositional features that would alter the channel morphology. The cohesive clays and silts that form the channel bed and bank provide sufficient erosion resistance to prevent significant changes in channel shape and location. As previously mentioned, only Sheyenne River Reach 8 was found to have sufficient sand to be influencing the morphology of the stream. Reach 8 is the only reach to exhibit a two phase bi-modal sinuous planform (see Figure 5-25). It also has a much greater sinuosity value of 4 compared with downstream reaches that have values averaging 1.8. Because of the proximity of this reach to the sandy beach deposits of glacial Lake Agassiz, there is likely to be a greater supply of sand to this reach compared with downstream reaches. The sediment transport capacity in Reach 8 appears to be insufficient to transport all of the sand that is supplied to it from upstream. As a result, the channel has responded by shifting laterally at a slightly greater rate and increasing its overall channel length, which is approximately 2 times longer than downstream reaches, to accommodate the storage of additional sand. The proposed LPP diversion alignment is located sufficiently downstream from Sheyenne River Reach 8, that there is not expected to be any impact on the existing channel morphology from the project.

Changes in the sediment supply and therefore the rate of transport are not expected to significantly impact the channel morphology. However, as previously discussed, the reaches of the Red River, Wild Rice River and Wolverton Creek located upstream of the LPP diversion that will be affected by backwater from the staging of floodwaters upstream of the diversion are likely to experience an increased rate of overbank sedimentation. The more frequent inundation of the floodplain and saturation of the channel banks as well as the weight of the additional sediment are likely to exacerbate bank slumping that is already naturally occurring in these reaches. However, it is unknown whether this will result in discernible changes in the channel geometry over the long-term. Given that the current rate of channel migration is relatively low at only a few inches per year, it follows that the base of the bank slumps, located along the outside of a meander bend, is generally eroding at a slightly higher rate than the rate of deposition at the top of the slumps. Along the inside of the meander bend, the opposite is occurring. With more frequent inundation from the staging of floodwaters and therefore a greater rate of overbank deposition, the rate of deposition may outpace the rate of erosion. Over the long-term, this could result in a decrease in channel width. However, the decrease is likely to be small and will be highly dependent of the future hydrologic conditions in the basin.

For the reaches that will be protected by the diversion alignment alternatives, the overbank flooding is expected to be minimal to nonexistent. As a result, deposition of sediment in the overbank areas is expected to decrease compared to current conditions. This would be expected to reduce the rate of bank slumping. The reduction in flow is also expected to reduce the rate of erosion along the outside of the meander bends. As a result, the currently small rate of channel migration is expected to be reduced.

9.4 Potential Effects on Riparian Vegetation

Moderate changes to riparian vegetation conditions are expected as a result of the FCP and LPP alignment alternatives. For areas protected by the diversion, riparian vegetation will not be subject to extended periods of inundation by floodwaters nor significant burial by overbank sediment deposits. Additionally, damage from ice flows is expected to be reduced. The trees and shrubs would be expected to encroach on the channel compared with current conditions and be less impacted by bank slumping. An example of the riparian conditions that might be expected to occur along those reaches protected by the diversion alignment is shown in Figure 9-6, which is a photo that was taken along Sheyenne River Reach 5. Reach 5 is currently protected from flooding by the West Fargo Diversion.

Figure 9-6. Riparian Vegetation Conditions along Sheyenne River - 5

For the reaches upstream of the LPP diversion channel within the floodwater staging area, the riparian vegetation will be subject to greater periods of inundation and greater burial by overbank sediment deposits. However, according to the St. Paul District (USACE, 2012) the majority of the floodplain species are adapted to inundation by floodwaters and partial burial by sediment during the dormant season. However, if the inundation by floodwaters extends into the growing season, they are likely to be stressed, which would make them more susceptible to disease and insects. Additionally, there could be greater damage from ice flows. As a result, the trees and shrubs may tend to retreat away from the channel. If this occurs, seasonal grasses or other vegetation types better suited to such conditions will be more prominent in these areas. The increased rate of bank slumping would also be expected to result in fewer trees in close proximity to the channel. An example of the riparian vegetation conditions that might be expected within the staging areas upstream of the diversion is shown in Figure 9-7, which is a photo that was taken along Sheyenne River Reach 1 following the spring and summer flood of 2011.

Figure 9-7. Riparian Vegetation Conditions along Sheyenne River - 1

The impacts on the channel morphology as a result of changes in the riparian vegetation conditions are expected to be minimal. There does not appear to be any significant increase in erosion resistance for banks that have greater root density or vegetative cover. The slippage surface of the rotational bank slumps is typically below the depth of root penetration. Therefore, the riparian vegetation generally does not add sufficient resistance to prevent or reduce movement along the slippage surface. In fact, the added weight of the trees located on the slumping portion of the bank may tend to accelerate movement of the slumping material.

9.5 Conclusions for Future Conditions

In the following sections, the expected impacts on the geomorphology of each of the study streams are discussed. Additionally, the expected impacts of sedimentation within the FCP and LPP diversion channels are presented.

9.5.1 Buffalo River

The Buffalo River is a tributary to the Red River and is located downstream of where both the LPP and FCP diversion would flow into the Red River. The bed and banks are formed from cohesive clay and silt that is resistant to significant erosion. The specific gage analysis, bank erosion analysis, channel migration analysis, Rosgen analyses, and historic cross section analysis indicate that Buffalo River Reach 1 is very stable and is unlikely to be impacted by changes in hydrology or sediment supply. Further, the only hydraulic impact on the Buffalo River will be a slight increase in backwater from increased flows in the Red River created by the FCP diversion. This would not be expected to have a significant impact on the morphology of the Buffalo River.

9.5.2 Lower Rush River

The Lower Rush River is a tributary to the Sheyenne River and will be entirely intercepted by the LPP diversion. No impacts to the morphology are expected as a result of the FCP diversion. The Lower Rush River has been significantly altered by channelization to increase flood capacity. Its bed and banks are composed of cohesive clay and silt. The bank erosion analysis, channel migration analysis and Rosgen analyses indicate that Reaches 1 and 2 are both very stable. Reach 2 is located upstream of the LPP diversion channel and is not expected to be impacted. Reach 1 is located downstream of the LPP diversion and will no longer receive flow and sediment from Reach 2. Reach 1 will receive only local runoff and sediment inputs. It will also be partially inundated by backwater from high flows in the Sheyenne River. This will result in sediment deposition within the backwatered portion of Reach 1. However, the backwater is not expected to be significant given that this portion of the Sheyenne River is protected from high flows by the LPP diversion. Inflowing sediment from local drains would be expected to deposit within the channel of Lower Rush River Reach 1. A localized buildup of sediment at the drain outlets should be expected since there is likely to be insufficient flow in the channel to transport the inflowing sediment. Reach 1 is expected to decrease in width and depth in the future as a result of the LPP diversion.

9.5.3 Maple River

The Maple River is a tributary to the Sheyenne River and will be partially intercepted by the LPP diversion. No impacts to the morphology are expected as a result of the FCP diversion. Reach 1 has a bed composed of cohesive clay and silt, which is overlain by a layer of sand. Reach 2 has a bed composed of cohesive clay and silt. The banks of Reach 1 and 2 are composed mostly of cohesive clay and silt with a minor amount of sand. The bank erosion analysis, channel migration analysis, specific gage analysis, and Rosgen analyses indicate that Reaches 1 and 2 are both very stable. The historic cross section comparison suggests that Reach 1 has degraded by several feet. The historic cross section comparison for Reach 2 suggests that the channel has aggraded significantly. However, the available historic cross section in this reach is located immediately upstream of a grade control structure. It is unknown when the structure was built, but the channel appears to be responding to its presence as expected.

The LPP alignment will cross the Maple River within the upper portion of Reach 1. Therefore, Reach 2 and the upper portion of Reach 1 are not expected to be impacted by the diversion. The hydrology for the lower portion of Reach 1, located downstream of the diversion, will be reduced. Discharge less than or equal to the 2-year annual recurrence interval flow will pass downstream into the lower portion of Reach 1. The continuation of frequently occurring flows in Reach 1 is expected to maintain the existing channel morphology.

9.5.4 Red River

The Red River has a bed and banks that are generally composed of cohesive clays and silts. Reaches 3, 4, 7, and 8 were seen to have a moderate portion of sand in the bed. However, the sand was generally observed to form a relatively thin layer over the consolidated clay and silt bed. The banks along Reaches 2, 7, and 8 also contained a moderate portion of sand. Reaches 7 and 8 are located near the sandy beach deposits of glacial Lake Agassiz. Reach 2 is located just downstream from the confluence with the Sheyenne River. The Rosgen analysis indicated that the Red River is moderately unstable. However, the meander migration analysis indicated that all of the reaches are stable. The bank erosion analysis indicated that Reaches 2, 7, and 8 had small but measurable bank erosion. The remaining reaches had no measureable bank erosion. The historic cross section analysis indicated that Reaches 2, 3, 7, and 8 are degrading slightly and that Reach 4 is decreasing in width and Reach 5 is increasing in width. The specific gage analysis indicated that the Red River at Halstad, MN, located a significant distance downstream of Reach 1, is degrading slightly and that the Red River at Hickson, ND, located in Reach 7, is stable.

The FCP diversion alignment will divert water in excess of the 3.6-year flood from the Red River near the upstream end of Reach 5 and will convey the water downstream to its confluence with the Red River located near the upstream end of Reach 2. Reaches 3, 4 and most of 5 will be protected from flooding by the FCP diversion. As a result, overbank sediment deposition will be discernibly reduced and should help reduce bank slumping. The riparian trees and shrubs would be expected to encroach on the channel compared with current conditions and be less impacted by bank slumping.

Because sand-sized bed material currently forms a relatively thin discontinuous layer over the cohesive bed of the Red River, no significant aggradation or degradation is expected along the reaches that would be protected by the FCP diversion alignment. The very upstream end of Reach 2, located between the Sheyenne River confluence and the FCP diversion confluence, may experience minor aggradation if the sand load that is supplied by the Sheyenne River exceeds the transport capacity of the protected portion of the Red River. As a result, Reach 1 and the portion of Reach 2 located downstream of the FCP diversion may experience a slight reduction in sand load. The bed material in these reaches is composed of cohesive clays and silts that are erosion resistant and would not be expected to experience significant degradation resulting from a reduced supply of sand. However, there is a high percentage of sand in the banks along Reach 2. A reduction in the supply of sand may help reduce slumping of the sandy overbank deposits along this reach. The morphology of Reaches 6-8, located upstream of the FCP diversion, are not expected to be impacted.

The LPP diversion will divert water in excess of the 3.6-year flood from the Red River at a location that is approximately at the midpoint of Reach 6 and will convey water to the west and north where it will pick up water from the Wild Rice, Sheyenne, Maple, Lower Rush, and Rush Rivers. The diversion will reenter the Red River near the downstream end of Reach 2, at a point just upstream of the confluence with the Buffalo River. Most of Reach 2, all of Reaches 3-5, and the lower half of Reach 6 will be protected by the LPP diversion. As a result, overbank sediment deposition will be discernibly reduced and should help reduce bank slumping. The riparian trees and shrubs may tend to encroach on the channel compared with current conditions and be less impacted by bank slumping.

Reaches 1 and 2 may experience a slight decrease in the supply of sand-sized material as a result of the LPP diversion. The transport capacity of the Sheyenne River will be reduced slightly and there is likely to be deposition and storage of sand within the diversion channel. The bed material in Reaches 1 and 2 is generally composed of cohesive clays and silts that are erosion resistant and would not be expected to experience significant degradation as a result of a reduced supply of sand. However, there is a high percentage of sand in the banks along Reach 2. A reduction in the supply of sand may help reduce slumping of the sandy overbank deposits along this reach.

The portion of Reach 6 located upstream of the diversion and most of Reach 7 will be inundated by staging of floodwater for the LPP diversion alternative. This will result in increased overbank sedimentation and could exacerbate existing bank slumping. The expected depth of additional overbank deposition resulting from the project is unknown. In order for this to be determined, additional analysis beyond the scope of this study would be required. Increased frequency of inundation may cause the trees and shrubs to be more susceptible to disease, insects and damage from ice flows and therefore may tend to retreat away from the channel. If this were to occur, they are likely be replaced by seasonal grasses or other vegetation types suited to such conditions. The increased rate of bank slumping would also be expected to result in fewer trees in close proximity to the channel.

9.5.5 Rush River

The Rush River is a tributary to the Sheyenne River and will be entirely intercepted by the LPP diversion. No impacts to the morphology are expected as a result of the FCP diversion. The Rush River has been significantly altered by channelization to increase flood capacity. Its bed and banks are composed of cohesive clay and silt. The bank erosion analysis, channel migration analysis and Rosgen analyses indicate that Reaches 1 and 2 are both very stable. Reach 2 is located upstream of the LPP diversion channel and is not expected to be impacted. Reach 1 is located downstream of the LPP diversion and will no longer receive flow and sediment from Reach 2. Reach 1 will receive only local runoff and sediment inputs. It will also be partially inundated by backwater from high flows in the Sheyenne River. This will result in sediment deposition within the backwatered portion of Reach 1. However, the backwater is not expected to be significant given that this portion of the Sheyenne River will be protected from high flows by the LPP diversion. Inflowing sediment from local drains would be expected to deposit with the channel of Rush River Reach 1. A localized buildup of sediment at the drain outlets should be expected since there is likely to be insufficient flow in the channel to transport the inflowing sediment. Reach 1 is expected to decrease in width and depth in the future as a result of the LPP diversion.

9.5.6 Sheyenne River

The Sheyenne River is a tributary to the Red River with its confluence located at the upstream end of Red River Reach 2. The bed and banks are generally composed of sand, silt, and clay with the percentage of sand generally increasing in the upstream direction. Available boring logs indicate that the sandy sediments are underlain by cohesive clays and silts. The Rosgen analysis indicated that the Sheyenne River is stable. The meander migration analysis indicated that all of the reaches are stable. The bank erosion analysis indicated that Reaches 7 and 8 had small but measurable bank erosion. The remaining reaches had no measureable bank erosion. The historic cross section analysis indicated that Reaches 4 and 8 are degrading slightly and that Reach 2 aggrading slightly. Reach 6 is decreasing in width and Reach 8 is increasing in width. The specific gage analysis indicated that the Sheyenne River near Kindred, ND, located in Reach 8, is degrading slightly and that the Sheyenne River at West Fargo, located in Reach 5, is aggrading slightly.

There is a potential for minor changes to the morphology of the lower portion of Sheyenne River Reach 1 as a result of the FCP diversion. Since the Red River will be protected from high flows at its confluence with the Sheyenne River, backwater conditions in the lower portion of Reach 1 will be reduced. This may reduce overbank inundation and sedimentation and therefore increase bank stability and possibly vegetation density.

The LPP diversion will divert flow above the 2-year recurrence interval flood into the diversion channel. Most of Reach 7 and all of 8 are located upstream of the diversion and are not expected to be impacted by the diversion. Reaches 1-6 will be protected by the diversion. Reach 5 will also continue to be protected by the West Fargo Diversion and therefore will not be impacted by the LPP diversion. Reach 6 is located downstream of the existing Horace to West Fargo diversion. The LPP diversion is expected to provide a similar level of flood protection to Reach 6; therefore, no significant morphologic changes are expected. Reaches 1-4 are not currently protected by a diversion. Therefore, the LPP diversion is expected to discernibly reduce overbank sediment deposition which should help reduce bank slumping. The riparian trees and shrubs may tend to encroach on the channel compared with current conditions and be less impacted by bank slumping.

9.5.7 Wild Rice River

The Wild Rice River is a tributary to the Red River with its confluence located upstream of the FCP diversion and downstream of the LPP diversion. No impacts to the morphology are expected as a result of the FCP diversion. The bed and banks are generally composed of cohesive clay and silt that is resistant to significant erosion. A small portion of sand was found in the bed and banks along Reaches 5 and 6. Minor bank erosion was measured in Reaches 2 and 4. The remaining reaches had no measurable bank erosion. No historic cross sections data were available for this river. The specific gage analysis indicated that Reach 6 has been slowly degrading. The Rosgen analyses and channel migration analysis indicate that all reaches are very stable.

Reach 1 and most of Reach 2 will be protected by the LPP diversion. As a result, overbank sediment deposition will be discernibly reduced and should help reduce bank slumping. The riparian trees and shrubs may tend to encroach on the channel compared with current conditions and be less impacted by bank slumping.

Reach 4 and the lower portion of Reach 5 will be inundated by staging of floodwater for the LPP diversion alternative. This will result in increased overbank sedimentation and could exacerbate existing bank slumping. The expected depth of additional overbank deposition resulting from the project is unknown. In order for this to be determined, additional analysis beyond the scope of this study would be required. Increased frequency of inundation may cause the trees and shrubs to be more susceptible to disease, insects and damage from ice flows and therefore may tend to retreat away from the channel. If this were to occur, they are likely be replaced by seasonal grasses or other vegetation types suited to such conditions. The increased rate of bank slumping would also be expected to result in fewer trees in close proximity to the channel.

9.5.8 Wolverton Creek

Wolverton Creek is a tributary to the Red River with its confluence located upstream of the FCP diversion and downstream of the LPP diversion. No impacts to the morphology are expected as a result of the FCP diversion. The bed and banks are formed from cohesive clay and silt that is resistant to significant erosion. The Rosgen analyses indicate that Wolverton Creek is very stable and is unlikely to be impacted by changes in hydrology or sediment supply. The historic cross section analysis indicated that the top width has increased slightly and the channel has degraded somewhat. Reach 2 will be inundated by staging of floodwater for the LPP diversion alternative. This will result in increased overbank sedimentation and could exacerbate existing bank slumping. Increased frequency of inundation may cause the trees and shrubs to be more susceptible to disease, insects and damage from ice flows and therefore may tend to retreat away from the channel. If this were to occur, they are likely be replaced by seasonal grasses or other vegetation types suited to such conditions. The increased rate of bank slumping would also be expected to result in fewer trees in close proximity to the channel. Reach 1 is located downstream of the LPP diversion. Therefore, overbank areas are expected to be inundated less frequently which should reduce bank slumping. The riparian trees and shrubs may tend to encroach on the channel compared with current conditions and be less impacted by bank slumping.

9.5.9 FCP Channel

The FCP diversion channel will divert a portion of the flow from the Red River to prevent discharges in the Red River at Fargo, ND from exceeding the 3.6-year recurrence interval flood. The Red River does not have a significant supply of sand. Therefore, the diverted flow will be transporting clay- and silt-sized particles. These fine-grained sediments are expected to stay in suspension within the diversion channel. No significant sediment deposition would be expected. The lower end of the FCP channel is generally steeper than the upstream reaches. Erosion of the channel bed would be expected at this location unless protected by armoring.

9.5.10 LPP Channel

The LPP diversion channel will divert a portion of flow from the Red River and Wild Rice River to prevent discharges in the Red River at Fargo, ND from exceeding the 3.6-year recurrence interval flow. It will also divert a portion of the flow from the Sheyenne River and Maple River to prevent the discharge in the portion of the channel downstream immediately downstream of the diversion from exceeding the 2-year recurrence interval flow. All flows from the Lower Rush River and Rush River will be diverted into the LPP diversion channel.

The Red River and Wild Rice River do not have a significant supply of sand. Therefore, the diverted flow will be transporting clay- and silt-sized particles. These fine-grained sediments are expected to stay in suspension within the diversion channel. No significant sediment deposition would be expected for the portion of the LPP diversion located upstream of the Sheyenne River. The Sheyenne River transports a significant supply of sand-sized sediment in suspension. The Maple River also transports sand-sized sediment in suspension. However, it is a much less significant source compared to the Sheyenne River.

The finer grained portion of the suspended sand load is expected to be supplied to the LPP diversion channel. This material would be expected to form localized deposits around hydraulic structures and along the inside of bends in the diversion channel alignment. A preliminary low flow channel design was developed and provided to the St. Paul District for the portion of the LPP channel located below the confluence with the Lower Rush River. The low flow channel would be expected to efficiently transport the inflowing sand load. However, during high flow events in the LPP channel, sand deposits would be expected to form along the margins of the low flow channel. Some future maintenance should be expected in order to maintain the desired hydraulic capacity with the diversion channel. Additional sediment transport analysis is recommended to further understand the potential amounts and extents of sedimentation as well as probable maintenance requirements along the LPP Diversion channel.

10 Summary and Conclusions

In the preceding chapters, a detailed study of the potential geomorphic impacts associated with the proposed Fargo/Moorhead Flood Risk Reduction Project was conducted. The study included detailed assessments of hydrology, geomorphic stream classification, historic channel plan form and cross section geometry data, and sediment transport. A synthesis of the geomorphic analysis results were then used to predict potential impacts for alternative future conditions. The overall conclusions of the study include the following:

10.1 Hydrology Assessment

Channel-forming discharges for current conditions were estimated for the various involved water courses were assessed using multiple methods. The average recurrence interval for channel forming discharges was estimated to be 1.28 years, with a low recurrence interval of 1.05 years and a high recurrence interval of 1.67 years. The defined values are consistent with the results of other studies completed in the Upper Midwest.

Historic channel-forming discharges were also estimated using flood frequency data for historic flows at the USGS gage Red River of the North at Fargo, ND. The results indicate that the current channel-forming discharge has increased 152% compared to the historic channel-forming discharge. Sufficient historical flow data does not exist for the study reaches. However, similar increases in channel-forming discharge are likely to have occurred.

Discharge-duration analyses for the historic, current, and future (with project) conditions were completed to assess whether notable changes in discharge have occurred and whether future notable changes are expected to occur. The current and future (with project) conditions discharge-duration curves have greater discharges than the historic conditions curves for the sites for which data was available. Comparison of the current conditions to the future with project LPP and FCP scenarios discharge-duration analyses indicated that the discharges are expected to remain the same except in areas protected by the proposed diversion alignments. In the protected areas, the lower more frequent flows will be essentially identical whereas the higher less frequent flows would be reduced as a result of the diversion of flow into the diversion alignments. For the LPP alignment, the Red River and Wild Rice River flows are capped at the 27.8-percent annual chance (3.6-year) peak discharge. For the Sheyenne River and Maple River, flows larger than the 50-percent annual chance (2-year) peak discharge are diverted into the diversion alignment. For the Rush and Lower Rush Rivers, all flows are captured by the diversion channel and only local inflows will drain to the channel downstream of the diversion. For the FCP alignment, the Red River flows are capped at the 27.8-percent annual chance peak (3.6-year) discharge.

Elevation-duration analyses were also completed for the historic, current, and future conditions. In general, the water surface elevations have increased from the historic to current conditions as a result of an increase in discharges. Water surface elevations are also expected to increase from current to future (with project) conditions for detailed study reaches located in areas that will be used to stage the flow upstream of the diversion inlet structures. However, water surface elevations are expected to decrease from current to future (with project) conditions in areas protected by the diversion alignments.

Specific gage analyses indicate that the water surface elevations at the USGS gages within the study area have remained relatively stable or have exhibited a slight decrease in water surface elevation throughout their period of record. Seven of the eleven gages have relatively stable stage-discharge relationships. Three gages, 05053000 – Wild Rice River near Abercrombie, 05059000 – Sheyenne River near Kindred, and 05064500 – Red River at Halstad show a decreasing trend in stage, which indicates potential long-term degradation of the channels. One gage, 05059500 – Sheyenne River at West Fargo, shows an increasing trend in stage, which suggests potential long-term aggradation of the channel.

10.2 Geomorphic Stream Classification

Classifications of the detailed study reaches were made using several methods The Rosgen Level II classification system were conducted and indicate that the streams within the study area are generally stable with the exception of the Red River. All of the Red River detailed study reaches are classified as very susceptible to shifts in both lateral and vertical stability. While the Red River detailed study reaches were classified by as unstable, examination of historic data indicate that the Red River is not shifting noticeably over time and therefore is not unstable.

Analyses completed using the Rosgen Level III classification system indicate that the majority of the reaches are classified as being either stable or only moderately unstable laterally, with only 3 of the 31 detailed study reaches classified as unstable. All of the detailed study reaches are predicted by the Level III method to experience no or slight degradation over time. The findings of the Level III classification method reinforce the findings of the Level II findings in that the channels are predicted to remain generally stable over time.

The Schumm Stream Classification Method indicates that all 31 detailed study reaches are classified as stable suspended load channels. Classification of the detailed study reaches as stable using the Schumm Method further reinforce the results of the Rosgen Method, considering that the Schumm Method uses a process-based classification rather than a form-based classification like the Rosgen Method. Two completely different methodologies provided the same result, which allows for a confident prediction that the streams within the study area are generally stable and are not expected to change significantly in the future.

10.3 Stability Analysis

Available historic aerial photography and cross section data were evaluated to assess the stability of the involved watercourses. All but three of the study reaches have sinuosity values that exceed 1.5 and are considered meandering as defined by Leopold, et al. (1992). The other two are defined as sinuous, but were likely affected by historic straightening. Typically, meandering watercourses migrate over time as their outer banks are eroded by fluvial processes.

The results of assessments of historic sinuosity, meander migration, amplitude and frequency, belt width, channel width, and bank erosion conditions, demonstrate that the study reaches appear to be in a state of relative stability, showing little change between subsequent years. The calculated rates of change between years are either zero or small non-zero values that are likely within the range of error inherency to the methods used for their determination. Within the project area, bank stability and resistance to significant migration are largely due to the relatively low velocities experienced during major flooding and the generally erosion resistant nature of the highly cohesive clay soils, which are the predominant bed and bank material. The involved watercourses appear to be relatively insensitive to long-term changes in discharge and sediment availability.

Analysis of historic and current cross sections provided useful insight into the stability of the system. While certain cross sections were found to be consistently widening or narrowing, a consistent trend in width changes was not observed throughout the entire system. Of the 30 historic cross sections examined, 13 were narrowing, 10 were widening, and 7 had no discernible trend. In an effort to understand the relative stability of channel cross sections, the width and depth data for the cross sections were compared to estimates derived from regime equations for channel width and depth. A wide range of results from the regime assessment did not allow definitive conclusions to be drawn regarding both the ability of the employed methodology to predict the regime width or depth accurately for the project area or the relative stability of the channels.

Although there is not sufficient data to suggest that there is a general system-wide widening or narrowing of the channels with time, the data does indicate that there may be general degradation occurring within the system. Of the 30 cross sections evaluated, 18 appear to be degrading, 2 appear to be aggrading, and 10 had no discernible trend.

Overall, the stability assessment indicates that the streams in the study area are in dynamic equilibrium. Laterally, these streams are not migrating or changing width with any discernible pattern over the time scales of the available data. Any significant migration of the channels appears to occur over timescales of hundreds if not thousands of years.

Generally, the stability assessment analyses conducted indicate that the involved watercourses are not significantly impacted by changes in discharge or sediment availability, likely due to the highly cohesive banks and beds that exist throughout a majority of the system, the low energy gradient of the streams, and the lack of a significant supply of coarse sediment. Therefore, future changes in discharge and/or sediment supply are not expected to result in major channel planform or cross-section geometry changes.

10.4 Sediment Impact Analysis

Discharge-frequency, discharge-duration, and elevation-duration curves were developed for select locations within the FCP and LPP alignments. These future flow characteristics were used to compute sediment transport within the diversion alternatives. Additional detailed sediment transport evaluations for existing and alternative conditions were conducted for all other involved watercourses using the SIAM module within HEC-RAS. The results of the SIAM analysis were determined to be problematic due the lack of a suitable sediment transport function within the software applicable to cohesive sediments and the general characteristics of the involved watercourses. Alternatively, an evaluation of the general sediment transport ability of each reach of the involved watercourses was conducted. The evaluation results indicate that all study reaches could mobilize and transport fines sands, when considered on a reach-averaged basis.

Future channel-forming discharge was assessed through an evaluation the average annual shear stress expected to occur within each stream. When hydrologic inputs to a stream are reduced, such as in areas protected by the proposed diversion alignment alternatives, the maximum shear stresses acting on the channel will also be reduced. Therefore, the reductions in average annual shear stress are expected to be linked to the reduction in channel-forming discharge. Comparison of future conditions shear stresses to current conditions shear stresses indicated that the LPP and FCP alignment alternatives reduced the average annual shear stress in protected reaches by less than 5-percent compared to the existing conditions. For the reaches located upstream and downstream of the area protected by the proposed diversion alignments, the future channel-forming discharge is expected to be the same as the current channel-forming discharge.

10.5 Monitoring Plan

Given the inherent stability of the stream channels within the study area, the need for monitoring potential geomorphic impacts of the proposed project are limited. A plan for monitoring the geomorphic response of the stream channels to the proposed project was developed that involves aerial photography evaluations, field reconnaissance, channel cross section surveys and regular communication with project stakeholders. The frequency of monitoring will decrease over time after project completion, assuming that significant adverse impacts from the project do not occur.

10.6 Future Conditions

Results of the geomorphic assessment indicate that the involved study reaches are not prone to significant change in morphology over short or even moderate periods of time. Channel migration rates are on the order of a few inches per year. The erosion resistant nature of the cohesive glacial lake bed soils and the very flat gradient of the channels prevent significant changes in channel cross section geometry and results in very low rates of lateral migration. Further, the sediment supply from upstream and the surrounding landscape is generally composed of silt- and clay-sized material with only minor amounts of sand-sized material. The study streams appear to have sufficient capacity to transport nearly all of the sediment supplied to them in suspension as wash load.

Although the Sheyenne River has a relatively greater proportion of sand-sized material compared to the other study streams, the underlying cohesive clay and silt bed still appears to control the overall channel geometry and rate of lateral migration within the study area. As previously mentioned, the greater abundance of sand within the Sheyenne River is the result of the river traversing the ancient beach deposits of glacial Lake Agassiz in the portion of the basin located upstream from the study area. As a result, a relatively larger amount of sand-sized material is supplied to the study reaches of the Sheyenne River. This material is transported as both suspended load and bed load. Again, alluvial channel features that are typically associated with sand bed rivers are not present along the project’s study reaches. This suggests that the Sheyenne River generally has the capacity to transport the majority of the sand-sized material that is supplied to it from upstream sources.

Significant sediment deposition would not be expected within the FCP Diversion channel because the Red River does not have a significant supply of sand. The fine-grained sediments entering the FCP channel from the Red River are expected to stay in suspension within the diversion channel. The lower end of the FCP channel is generally steeper than the upstream reaches. Erosion of the channel bed would be expected at this location unless protected by armoring.

Localized deposits around hydraulic structures and along the inside of bends in the LPP Diversion channel alignment downstream of the Sheyenne River would be expected due to the significant supply of sand-sized sediment transported in suspension by the Sheyenne River. Some future maintenance should be expected in order to maintain the desired hydraulic capacity with the diversion channel. Additional sediment transport analysis is recommended to further understand the potential amounts and extents of sedimentation as well as probable maintenance requirements along the LPP Diversion channel.

The expected changes to the geomorphology of each of the study streams for the LPP and FCP diversion alternative were presented in Section 9.5 and are summarized in Table 10-1 and Table 10-2, respectively. As seen in the tables, bank stability and riparian vegetation density are expected to slightly increase in the reaches that are protected from high flows by the proposed LPP and FCP diversion alignments. Conversely, bank stability and riparian vegetation density are expected to slightly decrease in the staging areas upstream of the LPP diversion alignment as a result of more frequent overbank inundation and sedimentation. The only expected significant changes in channel geometry are for Reach 1 of the Rush River and Reach 1 of the Lower Rush River. Since all flow in the Rush and Lower Rush will be diverted by the LPP diversion alignment, local runoff and backwater from the Sheyenne River is expected to cause sedimentation in the portion of these streams located downstream from the diversion. Therefore, the channel size for these reaches would be expected to decrease over time.

Table 10-1. Predicted Geomorphology Impacts Resulting from LPP Diversion Alternative

General Study Reach	Bank Stability	Channel Migration Rate	Bankfull Depth	Bankfull Width	Riparian Vegetation Density	Predicted Discernible Changes to Geomorphology
Buffalo River 1	0	0	0	0	0	No
Lower Rush River 1	0	0	-	-	+	Yes
Lower Rush River 2	0	0	0	0	0	No
Maple River 1	+	0	0	0	+	Minor
Maple River 2	0	0	0	0	0	No
Red River 1	0	0	0	0	0	No
Red River 2	+	0	0	0	+	Minor
Red River 3	+	0	0	0	+	Minor
Red River 4	+	0	0	0	+	Minor
Red River 5	+	0	0	0	+	Minor
Red River 6 d/s of diversion	+	0	0	0	+	Minor
Red River 6 u/s of diversion	-	0	0	0	-	Minor
Red River 7	-	0	0	0	-	Minor
Red River 8	0	0	0	0	0	No
Rush River 1	0	0	-	-	+	Yes
Rush River 2	0	0	0	0	0	No
Sheyenne River 1	+	0	0	0	+	Minor
Sheyenne River 2	+	0	0	0	+	Minor
Sheyenne River 3	+	0	0	0	+	Minor
Sheyenne River 4	+	0	0	0	+	Minor
Sheyenne River 5	0	0	0	0	0	No
Sheyenne River 6	0	0	0	0	0	No
Sheyenne River 7	0	0	0	0	0	No
Sheyenne River 8	0	0	0	0	0	No
Wild Rice River 1	+	0	0	0	+	Minor
Wild Rice River 2	+	0	0	0	+	Minor e
Wild Rice River 3	-	0	0	0	-	Minor
Wild Rice River 4	-	0	0	0	-	Minor
Wild Rice River 5	0	0	0	0	0	No
Wild Rice River 6	0	0	0	0	0	No
Wolverton Creek 1	+	0	0	0	+	Minor
Wolverton Creek 2	-	0	0	0	-	Minor

(0) No Change, (+) increasing, (-) decreasing

Table 10-2. Predicted Geomorphology Impacts Resulting from FCP Diversion Alternative

General Study Reach	Bank Stability	Channel Migration Rate	Bankfull Depth	Bankfull Width	Riparian Vegetation Density	Predicted Discernible Changes to Geomorphology
Buffalo River 1	0	0	0	0	0	No
Lower Rush River 1	0	0	0	0	0	No
Lower Rush River 2	0	0	0	0	0	No
Maple River 1	0	0	0	0	0	No
Maple River 2	0	0	0	0	0	No
Red River 1	0	0	0	0	0	No
Red River 2 d/s of diversion	+	0	0	0	0	Minor
Red River 2 u/s of diversion	0	0	-	0	0	Minor
Red River 3	+	0	0	0	+	Yes
Red River 4	+	0	0	0	+	Yes
Red River 5	+	0	0	0	+	Yes
Red River 6	+	0	0	0	+	Yes
Red River 7	0	0	0	0	0	No
Red River 8	0	0	0	0	0	No
Rush River 1	0	0	0	0	0	No
Rush River 2	0	0	0	0	0	No
Sheyenne River 1	+	0	0	0	+	Minor
Sheyenne River 2	0	0	0	0	0	No
Sheyenne River 3	0	0	0	0	0	No
Sheyenne River 4	0	0	0	0	0	No
Sheyenne River 5	0	0	0	0	0	No
Sheyenne River 6	0	0	0	0	0	No
Sheyenne River 7	0	0	0	0	0	No
Sheyenne River 8	0	0	0	0	0	No
Wild Rice River 1	0	0	0	0	0	No
Wild Rice River 2	0	0	0	0	0	No
Wild Rice River 3	0	0	0	0	0	No
Wild Rice River 4	0	0	0	0	0	No
Wild Rice River 5	0	0	0	0	0	No
Wild Rice River 6	0	0	0	0	0	No
Wolverton Creek 1	0	0	0	0	0	No

(0) No Change, (+) increasing, (-) decreasing

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12 Quality Control

All analyses conducted for the development of this report were reviewed for their quality and completeness on an ongoing basis by all members of the study team. Team members involved in the development of this report are listed below along with their qualifications.

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An independent detailed review was also conducted by the technical review team members listed below along with their qualifications.

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Reviews were also completed by the St. Paul and Omaha Districts of the USACE and an independent reviewer. Technical reviewers from the St. Paul District were Michelle Larson, P.E., and Aaron Buesing, P.E. Technical reviewers from the Omaha District were Mark Nelson, P.E., Richard Donovan, P.E., Roger Kay, P.E., and Dan Pridal, P.E. The independent reviewer was Miguel Wong, Ph.D., P.E., of Barr Engineering, Inc. Comments made by the reviewers and the responses to those comments are provided in Appendix R.

Quality Control Certification

This is to certify that the analysis and documentation developed for the Geomorphology Study of the Fargo, ND / Moorhead, MN Flood Risk Management Project has been prepared and reviewed in accordance with the Quality Control Plan dated December 2010.

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