TransCanada Keystone Pipeline, L.P.
Keystone XL Pipeline

Missouri River Scour Analysis

Project Number:

TAL-00053888-60

Submitted By:
exp Energy Services Inc.
1300 Metropolitan Blvd.
Tallahassee, FL 32308
T: 850.385.5441
F: 850.385.5523
www.exp•com

Document Control Number:

KXL1399-EXP-A-PLN-0002

Rev	Date (yyyy-mm-dd)	Issue	Prepared by	Checked by	Approved by	Project Manager	Client
A	2017-08-02	IFR	EXP	Stephen Skoropat	Richard Gale	Richard Gale	TCPL
B	2017-08-09	IFR	EXP	Mike Aubele	Richard Gale	Richard Gale	TCPL
0	2017-08-10	IFU	EXP	Mike Aubele	Richard Gale	Richard Gale	TCPL
1	2017-09-27	IFU	EXP	Mike Aubele	Richard Gale	Richard Gale	TCPL

Legal Notification

This report was prepared by EXP Energy Services Inc. for the Keystone XL Pipeline Project.

Any use which a third party makes of this report, or any reliance on or decisions to be made based on it, are the responsibility of such third parties. EXP Energy Services Inc. accepts no responsibility for damages, if any, suffered by any third party as a result of decisions made or actions based on this project.

Acronyms and Abbreviations

cfs	cubic feet per second
FEMA	Federal Emergency Management Agency
HDD	Horizontal Directional Drilling
HEC-RAS	U.S. Army Corps of Engineers, Institute for Water Resources, Hydrologic Engineering Center's River Analysis System
MMI	Morrison-Maierle
TS	Technical Supplement
BOR	U.S. Bureau of Reclamations
USACE	U.S. Army Corps of Engineers

Table of Contents

List of Appendices

List of Figures

List of Tables

1.0 Introduction

The proposed Keystone XL Pipeline crosses the Missouri River downstream of the Fort Peck Spillway. The planned crossing method for this crossing is horizontal directional drilling (HDD) for 2,592 feet at a depth of approximately 53 feet below the lowest surveyed river elevation. An evaluation of the potential for vertical scour is necessary at stream crossings to ensure that the pipeline is buried deep enough to prevent contact between the pipeline and flowing surface water throughout the 50-year to 100-year design life of the pipeline. As a part of the engineering design effort, this report details the scour analysis performed in support of the HDD design for the Missouri River Water Crossing.

2.0 Hydraulic Analysis

The original hydraulic model of the Missouri River was generated in the U.S. Army Corps of Engineers (USACE) Institute for Water Resources, Hydrologic Engineering Center's River Analysis System (HEC-RAS) v4.1 and was compiled in November 2011 by Morrison-Maierle (MMI), an **exp** subcontractor responsible for conducting a scour analysis in support of the design of the HDD crossing at the Missouri River. In performing that analysis, MMI collected information necessary to generate a hydraulic model. The data used in the model included survey sonar readings of the Missouri River 0.5 mile upstream and downstream of the crossing location, six survey cross-sections at 1,000-foot intervals, and crossing-specific sediment samples. In researching the input parameters and collecting the available data, MMI acquired and applied the same Manning roughness coefficient (n) at the crossing location that was used by the Federal Emergency Management Agency (FEMA) for modeling the section of the Missouri River for flood insurance purposes. The HEC-RAS model input parameters for Manning's roughness coefficient is 0.024 for the main channel and 0.06 for the floodplain.

2.1 Hydraulic Model Updates

In discussions with USACE, a number of input parameters were agreed upon to assist in the scour prediction and provide the information requested in the Section 408 permit application process. A number of sensitivity analyses that were of interest to USACE are evaluated for scour potential, but not as consideration for the crossing design.

2.2 Design Model Input Parameter Selection

This section describes the input parameters that were selected for the model. Several model updates and refinements were made to provide a more accurate scour prediction based on the latest available information.

2.2.1 Design Event

The following design events were selected for the scour analysis: The 2-Year, 5-Year, 10-Year, 50-Year, 100-Year and 500-Year. The flowrate at each return frequency is defined in the Fort Peck Spillway release probability relationships and is provided in Appendix A. The release curve adopted in 2013 incorporates the data collected for a 2011 extreme event that took place in the river. These flowrates were used as the upstream inflow portion in the model. The flowrate associated with each design return frequency is provided in Table 1 below. The hydraulic outputs from each of the design events were evaluated using the analysis tool provided in the HEC-RAS water surface profiles computer program.

The design life of the project is 50 to 100 years. The 100-year frequency flood is stipulated by the Pipeline and Hazardous Materials Safety Administration (PHMSA) for the analysis of bed scour for buried utility transmission lines carrying toxic or flammable materials crossing designated floodplains. In addition, under Section 10 of Rivers and Harbors Act (33 United States Code 401 et seq.) and in consultation with the Montana Department of Environmental Quality (MDEQ) and USACE, navigable water crossings are to be evaluated using the 100 and 500-Year flood frequency event for scour. The 500-year spillway release flow was used for estimating bed scour at the crossing location. Selecting a 500-year return frequency approximates the likelihood at 9.5 to 18 percent of occurring within the lifespan of the project.

A risk analysis is required to determine the appropriate level of design. Return frequencies that are not tied to quantifiable extreme event frequencies and those that go beyond a 500- or 40,000-year event are more prone to inaccuracy and determination of the level of risk becomes difficult when considering the validity of the assumptions used in the analysis. While there is always the possibility of operational issues outside of direct relation to inclement weather, a release of this magnitude would most certainly have to align and be compounded by a full reservoir and an infrequently large inflow condition to have the worst-case scenario from the spillway.

2.2.2 Milk River Inflow

The Milk River confluence is located approximately 1,500 feet downstream of the proposed pipeline crossing location. The average seasonal flow for the period of May until July from United States Geological Survey (USGS) gage 06174500 Milk River near Nashua was used as a conservatively low estimate for the inflow contribution for this scour analysis to determine the highest potential of scour. These flows are presented in Appendix A. A summary of the inflow used in the model for the selected return frequencies is provided in Table 1.

TABLE 1

Design Inflow for the Missouri River HDD Crossing Hydraulic Model

Inflow\Return Frequency	**2-Year**	**5-Year**	**10-Year**	**50-Year**	**100-Year**	**500-Year**	**Worst-Case***
Modeled Fort Peck Dam Spillway Flow (cfs) (Hydrologic Statistics USACE)	15,000	17,000	25,000	48,000	60,000	95,000	350,000
Milk River seasonal flow (cfs)	1,000	1,000	1,000	1,000	1,000	1,000	1,000
Total modeled flow (cfs)	16,000	18,000	26,000	49,000	61,000	96,000	351,000
Milk River at Nashua peak design flow (cfs)	5,750	12,200	17,200	28,600	33,400	44,100	71,000

---

* used extrapolated value for 40,000-year return frequency

The assumption on Milk River inflow significantly lowers the 500-year design flow predicted at the Milk River gage from 44,100 cubic feet per second (cfs) to 1,000 cfs. For the worst-case sensitivity analysis that is described below, the 350,000 cfs flow condition has a 40,000-year return frequency when extrapolating from the Fort Peck release-probability curve. This would result in a decrease from 71,000 cfs, down to the 1,000 cfs wet weather seasonal average that has been conservatively assumed for the hydraulic model.

2.2.3 Bed Sediment

Two bed samples were collected by MMI at the crossing location to use in the scour analysis. They represent the best local data possible for determining the bed material composition. For design purposes, the best available information was used for this scour analysis. It is more likely that the sample is representative of the exposed bed material as it was taken several months after the large release event of June 2011. The two site samples were analyzed and were found to have similar characteristics. The two independent samples resulted in grain size distribution profiles with a mean grain size diameter by weight (D_{50}) of 3.5 mm and 3.8 mm.

The more conservative D_{50} of 3.5 mm was used for the design scour analysis to provide the higher scour potential. It is more likely to be representative of the sand and gravel layers that are the result of scour and refill cycle of the river, which has been occurring at the site on a geologic time scale prior to the construction of the dam.

2.3 Model Refinements

Additional model refinements were made to reflect information collected for improved representation of bank stationing and the blocking off the Milk River to prevent allowing it to be used as extra conveyance capacity downstream. In addition, to predict the maximum potential scour depth under all scenarios, a critical flow condition was assumed at the downstream boundary condition for the design model.

Consideration was taken for the probability that these more conservative assumptions may occur simultaneously in a compounded event that would allow for the full depth of predicted scour. While this is unlikely to be the case, the results would represent a conservative estimate of scour depth.

2.4 Sensitivity Analysis

As described above, several sensitivity runs were conducted to assist in the review of the Section 408 permit application for informational purposes. These include:

- A worst-case scenario modelled where the spillway release reaches the maximum capacity of 350,000 cfs, the maximum flow that can be released at high pools from the gates;
- A D50 of 1.737 mm to determine the impact sediment bed size has to the predicted scour value; and

- Downstream boundary condition to allow for discharge at normal flow to determine the impact on scour values.

Additional details on the sensitivity analysis are discussed in the results section.

The HEC-RAS hydraulic analysis and model output is provided in Appendix E.

As described previously, the hydraulic model output was used in the scour calculations using the methodology recommended by the U. S. Bureau of Reclamation (BOR). This methodology provides tested and effective scour predictions with the appropriate level of safety needed for the design of pipelines under natural streams.

3.0 Scour Analysis

The objective of the scour analysis is to assist in determining the proper design elevation for the HDD under the Missouri River. As previously discussed, the input parameters were selected to provide conservative scour depth predictions for the 500-year event. These include the use of projected peak spillway release flows with downstream average seasonal Milk River inflows, selection of the smaller size of sampled bed material, defined stream channel width, thalweg slope, and base flood elevations. Therefore, the predicted scour depths are expected to be conservative in nature.

3.1 Scour Method Selection

The objective of all methods utilized for the evaluation of vertical-scour potential is an estimate of the vertical-scour depth expected in response to a specified flood discharge. The flood discharge that was specified is an estimate of one that is exceeded in magnitude only once every 500 years on average or the 500-year spillway release (Linsley et al. 1992). Since more than one method was used in the evaluation of the stream crossing, a range of scour-depth estimates was generated.

3.2 Total Scour

In accordance with National Engineering Handbook Technical Supplement 14B (TS14B, 2007), the total scour calculated within the river is the sum of long-term degradation and general scour. The methods available for predicting depths of total scour are derived empirically from labs and normally extrapolated from observed field data. Yet, the science of predicting scour is inexact and constantly under development for a variety of conditions. Therefore, models apply a conservative approach toward the selection of input parameters and in the estimation of potential depths of scour that may occur using the most applicable datasets.

3.3 General River Bed Scour

General scour on a natural channel is due to variable velocities at constrictions and meanders along a given stream. This uneven flow results in vortices that are created in the water column. As the science of scour analysis is not well defined, multiple methods are needed to predict scour based on equations that have been developed for specific locations or conditions. Therefore, several methods are presented to confirm and check the results against each other.

As described previously, the BOR Regime Equation Method was selected for the prediction of scour depth. This method includes calculating general scour by the application of the Neill, Lacey, and Blench Regime Equations. The BOR Regime Equation method is well established and has been used extensively. It is based on empirical data with documented and specific usage for the safe construction of pipelines under natural channels. It properly addresses the concerns of constructing a pipeline under a waterway and provides a straightforward calculation methodology that can be checked against other methods. The BOR Regime Method considers scour from bend scour, scour caused by debris, and bedform scour. All three equations were used, and the results were compared against each other to check for agreement. The average of the BOR Regime equations was used to predict the scour depth for the design. In addition, the calculations were checked against additional scour prediction methods described in TS14B and BOR and those calculations are provided in Appendix A.

3.4 HEC-RAS Contraction Scour Method

The HEC-RAS design function provides hydraulic design functions to determine scour caused as water is constricted through a bridge section. As a check of the scour analysis, a quick reference and check of the BOR method was made against the result from this method. In this analysis, clear-water conditions were used in the function to provide a more conservative estimate for scour. The HEC-RAS contraction scour method is not a good predictor of scour for a natural stream. The contraction scour calculations the model performs assumes the upstream flow is required to flow through a constricted space, as would normally occur under a bridge structure. This affects the flow calculation by increasing velocities through the constricted section. This effect is most prevalent for very large flowrates that also extend onto the floodplain. This increased flowrate provides for a more conservative estimate of the predicted scour and is provided as a check of the BOR method.

3.5 Potential Channel Degradation

Analysis of bed-level trends in the Fort Peck Reach of the Missouri River has shown that bed degradation as a direct result of the 1937 closure of Fort Peck Dam has reduced thalweg elevations. Evidence of this is found in the bank heights that have increased by an average of six feet. Future degradation from dam closure is projected to be minimal (Simon, Thomas, Curini, and Shields 2002).

In the review of the Fort Peck Downstream Sediment Trends Study, a drop-in bed elevation is also confirmed. Figures 6-10 and 6-12 in Appendix C depict the Active Bed and Thalweg Elevation Profile from the stud. They indicate that a large amount of degradation occurred following the construction of the Fort Peck Dam, and has largely stabilized since about 1956. These figures appear to indicate that a drop of four to six feet occurred between 1936 and 1956. The 2012 values seem to indicate some further degradation, however the trend for ultimate slope does not support this conclusion. It seems to indicate a slight potential for aggradation as the channel finds an equilibrium balance. In discussion with USACE, an allowance for degradation of two feet has been agreed upon as an estimate for future degradation. As the degradation component of total scour is long-term, the additional two feet are added to the BOR method scour depth as an estimate for the formation of an armor layer at the crossing location.

4.0 Sensitivity Analysis

4.1 Bed Sediment Size Sensitivity

USACE suggested the use of the D_{50} from the collected bed samples from the Fort Peck Downstream Sediment Trends Study (Missouri River Fort Peck Downstream Sediment Trends Study, 2013). There was a wide variation in the "median bed material size ranging from 0.2 mm up to 13 mm" in the collected dataset near the Dam (Missouri River Fort Peck Downstream Sediment Trends Study, 2013).

For informational purposes the USACE requested a sensitivity analysis using the average of the D_{50} from the collected 2014 bed samples taken at the two nearest sediment collection points RM 1764 and 1761. The D_{50} of 1.737 mm was an average of the 1.080 mm and 2.395 mm collected at those sites. This represents decreasing the collected sample at the site by 50% from what was observed in Keystone's samples.

4.2 Boundary Flow Condition

A sensitivity analysis for the downstream boundary control of normal flow condition was tested to determine the impact on the predicted scour depths.

4.3 Worst-Case Scenario

The worst-case scenario with the spillway release at the maximum capacity of 350,000 cfs was used at the request of USACE. The results from this run do not represent the design criteria.

5.0 Lateral Migration Analysis

Stream lateral migration is a concern if it threatens to impact the operations of the project. To address this concern, a lateral migration analysis was conducted to determine the long-term potential for bank movement and erosion near the crossing location. The figures from the analysis are provided in Appendix D. Fixed survey points from a survey completed in May of 2008 are overlaid on the variously dated aerials. The 2008 surveyed top of bank break lines are provided for visual reference. For this analysis, single frame, National Aerial Photography Program (NAPP) and National High Altitude Program (NHAP) aerial images from the historical photograph archives made available in high resolution by the United States Department of Agriculture (USDA) and USGS were obtained. These images were georeferenced and overlaid with the reference layers described above. The streambanks from the 1971 single frame aerial photographs were digitized and compared against the 2015 aerial imagery. The stream centerlines were then processed and the extent of lateral migration was projected. For the 50 and 100-year service life of the pipeline, the potential lateral migration was estimated to be 50 feet and 100 feet, respectively. The conservative estimate of 100 feet for the potential lateral migration has been incorporated into the scour analysis results.

In addition, a bank erosion analysis for the record flow and extended spillway release event in 2011 was performed. The May 2008 top of bank appears to be unchanged compared to the 2015 aerial photograph. The extent of the flooding can be observed in the 2011 aerial photograph.

These figures show relatively little bank movement caused by the June 2011 record flow release. Despite a continuous release beyond the 10-Year Design flow for nearly 3 months from the spillway, bank erosion is nearly imperceptible in the aerial imagery.

Due to inherent shortcomings in using just aerial imagery to determine stream bank migration, a cross sectional view based on historical data available at the crossing location was compiled. Appendix D provides survey data from 2008, November 2011, and 1978 FEMA cross section data collected in support of the hydraulic model for designating flood zones. These 3 cross sections were overlaid on the cross sections made available in the Sediment Trend Study.

A comparison of data obtained from the original FEMA model, Keystone’s survey data collected at the pipeline crossing location in 2008, and the November 2011 survey data does not indicate any evidence of bank erosion from the release in 2011. A slight narrowing and deepening of the channel is noticeable, likely the result of scour during the 2011 event.

Based on the analysis of a single event, it would take a much larger and more prolonged release event than the 2011 flood before it could potentially cause significant bank erosion.

6.0 Model Results

The results from the scour analysis are provided in Table 2 and are shown in Figure 1. Table 3 provides the summary of the Blodgett Mean and Max, Degradation, BOR Regime Equations Method, and additional checks provided by HEC-RAS Contraction, BOR Envelope, BOR Competent Velocity and BOR Mean Velocity methods. The supporting individual scour analysis calculation sheets are provided in Appendix A. Under both the 500-Year design and worst-case scenario sensitivity analysis, the pipeline remains intact and unexposed.

The HDD profile shows that the pipeline is at an elevation of 1,957 feet, this is 53 feet below the lowest river elevation of 2,010 feet. The HDD is proposed to be constructed with a 3,600-foot radius of curvature. At the closest distance of the pipe to the low point in the stream, a cover of 43 feet is expected. By assuming the scour erodes into the bank to allow for a 100-foot migration of the low point in the channel reduces the cover over the pipe by an additional 9 feet. This scenario would leave 34 feet of cover over the pipeline.

Scour depths were compared and averaged for each crossing in accordance with the recommendations in the BOR methodology. This methodology was used in part as bend scour is included in the selection of the adjustment factor and is recognized as an effective and safe method for the prediction of scour. Typically, the BOR equations for scour were based on a reference plane of the surface water elevation, but the method recommends adding the depth to the bottom of the channel as an adequate factor of safety. In accordance with the BOR methodology, the average scour depths were applied to the thalweg elevations to achieve the appropriate factor of safety.

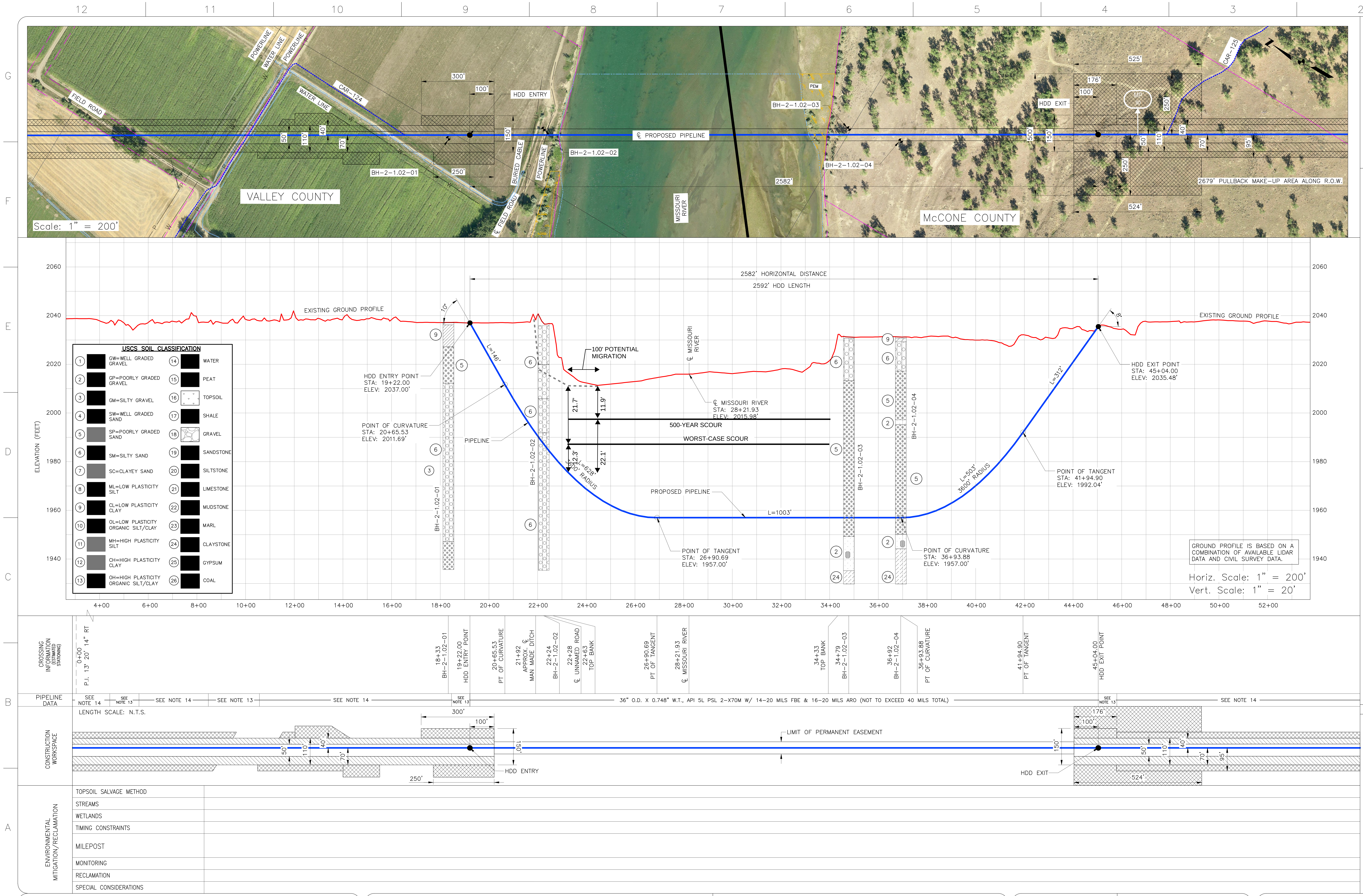
Results were checked against TS14B on the regime calculation sheet, TS14B Blodgett max equation, BOR Envelope, BOR Competent Velocity, and BOR Mean Velocity Methods. All methods described rely heavily on real empirical data and represent scour from many types of streams. The Blodgett and BOR methodologies include the effects of bend and bedform scour.

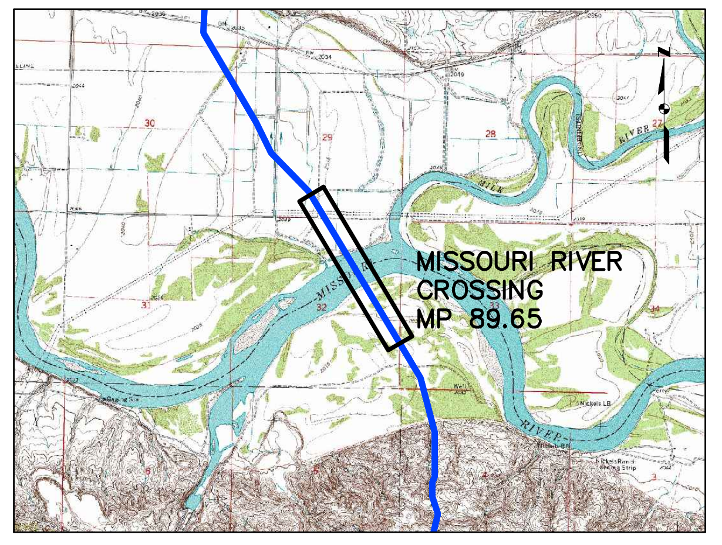
A review of the comparison checks indicates the values from the BOR methodology are appropriate for all design events run. The calculations are consistent and the BOR results are greater than the rest of the checks. The predicted scour for the 500-year design event is 11.9 feet. This leaves 22.1 feet of cover remaining. In addition, none of the maximum scour calculations presented in the table as checks would predict pipe exposure. The additional checks were provided to give confidence in the results of the scour predictions.

The Sensitivity Analysis for the 350,000 cfs worst-case scenario has a predicted scour of 21.7 feet. This leaves 12.3 feet of cover over the pipeline. The high value predicted by Neill Regime scour are exceptionally high relative to the subsequent checks made across the different methods. This is also significantly greater than the Blodgett Max and BOR Envelope method, both of which generally indicate the maximum amount of scour observed in the empirical dataset. This scour analysis indicates the pipe remains covered during the worst-case scenario.

While the results predict the pipe would remain covered during the worst-case scenario, a wide path of flow will occur to allow flood flows to travel downstream, thereby reducing the overall average flow observed in the main channel. Under the worst-case scenario, there is extensive flooding downstream of the spillway. At the crossing location, the width of inundation is predicted to be 11,000 feet wide. The devastation will be immense on or near the floodplain for the entire length of the river. However, design of pipeline valves would withstand the potential inundation and flows of such a massive flood event.

These extreme flows would have significant impact downstream with many other stakeholders. While those decisions are being made, pipeline operators would have adequate time to respond and shut in operations.





INSTALLATION NOTES

1) ACCESS: ALL EQUIPMENT MUST ACCESS THE SITE ALONG THE CONSTRUCTION RIGHT-OF-WAY FROM PUBLIC OR APPROVED PRIVATE ROADS.

2) WORK SPACE: WORK SPACE LIMITS ARE DEPICTED. CLEARING WILL BE RESTRICTED TO THE WORK SPACES INDICATED AT THE ENTRY AND EXIT POINTS AND PULLBACK MAKE-UP AREA ALONG THE RIGHT-OF-WAY. NO CLEARING BETWEEN THE ENTRY AND EXIT POINTS OF THE HDD EXCEPT WHERE APPROVED BY THE ENVIRONMENTAL INSPECTOR.

3) WATER SOURCE: DRILL WATER AND PRE-INSTALLATION HYDROSTATIC TEST WATER SHALL BE OBTAINED FROM AN APPROVED SOURCE. THE CONTRACTOR SHALL SCREEN THE INTAKE HOSE TO PREVENT THE ENTRAINMENT OF FISH OR DEBRIS AND IN ACCORDANCE WITH THE CONSTRUCTION MITIGATION AND RECLAMATION PLAN (CMRP) AND PROJECT REQUIREMENTS. THE HOSE SHALL BE KEPT OFF THE BOTTOM OF THE WATER BODY.

4) HYDROSTATIC TEST: PRE-INSTALLATION HYDROSTATIC TEST SHALL BE CONDUCTED IN ACCORDANCE WITH PERMIT REQUIREMENTS. THE CONTRACTOR SHALL DISCHARGE HYDROSTATIC TEST WATER IN ACCORDANCE WITH PROJECT PERMITS. DISCHARGES WILL BE SENT TO AN UPLAND LOCATION NEAR THE WITHDRAWAL POINT AS DIRECTED BY THE ENVIRONMENTAL INSPECTOR. DISCHARGES SHALL NOT CAUSE EROSION OR SEDIMENTATION. TO REDUCE THE VELOCITY OF THE DISCHARGE, THE CONTRACTOR SHALL UTILIZE AN ENERGY-DISSIPATING DEVICE AS DESCRIBED IN THE CMRP.

5) SPILL-PREVENTION: ALL PUMPS SHALL BE SET IN SECONDARY CONTAINMENT AND IN ACCORDANCE WITH THE SPILL PREVENTION CONTROL AND COUNTERMEASURE PLAN (SPCC). EQUIPMENT AND PUMPS OPERATING WITHIN 100 FEET OF ANY WATER BODY OR WETLAND SHALL BE OPERATED AND REFUELED IN ACCORDANCE WITH THE SPCC PLAN. EQUIPMENT REFUELING AND STORAGE OF HAZARDOUS MATERIALS, FUELS, ETC. SHALL BE CONDUCTED AT LEAST 100 FEET FROM WATER BODIES AND WETLANDS. EACH CONSTRUCTION CREW SHALL HAVE ON HAND SUFFICIENT TOOLS AND MATERIALS TO STOP LEAKS AND SUPPLIES OF ABSORBENT AND BARRIER MATERIALS TO ALLOW RAPID CONTAINMENT AND RECOVERY OF SPILLED MATERIALS.

6) EROSION AND SEDIMENT CONTROL: CONTRACTOR SHALL SUPPLY, INSTALL AND MAINTAIN SEDIMENT CONTROL STRUCTURES IN ACCORDANCE WITH CONTRACT DOCUMENTS. CONTRACTOR SHALL INSTALL ADDITIONAL EROSION CONTROL STRUCTURES AS DIRECTED BY THE ENVIRONMENTAL INSPECTOR.

7) PRIOR TO PIPE PULLBACK, CONTRACTOR'S ACTUAL DRILL PROFILE SHALL BE SUBMITTED TO KEYSTONE FOR APPROVAL.

8) INSTALLATION: THE PIPE SECTION FOR THE DRILLED CROSSING SHALL BE MADE UP WITHIN THE RIGHT-OF-WAY AT THE DRILL EXIT POINT AS SHOWN. CONTRACTOR SHALL ASSESS THE NEED FOR AND SUPPLY APPROPRIATE BALLAST DURING PULLBACK.

9) MUD DISPOSAL: CONTRACTOR SHALL DISPOSE OF EXCESS DRILLING MUD AS DIRECTED BY THE COMPANY REPRESENTATIVE IN ACCORDANCE WITH PERMIT CONDITIONS. UNDER NO CIRCUMSTANCES SHALL DRILLING FLUID BE DISPOSED OF IN WATER BODIES OR WETLANDS. ANY DRILLING MUD WHICH INADVERTENTLY EXITS AT POINTS OTHER THAN THE ENTRY AND EXIT POINTS SHALL BE CONTAINED AND COLLECTED TO THE EXTENT PRACTICAL AND DISPOSED OF AS DIRECTED BY THE COMPANY REPRESENTATIVE IN ACCORDANCE WITH PERMIT CONDITIONS.

10) CLEANUP/STABILIZATION/RESTORATION: ALL DISTURBED AREAS SHALL BE RETURNED TO THE ORIGINAL CONTOURS. DISTURBED AREAS SHALL BE SEEDED AS SPECIFIED IN PROJECT DOCUMENTS.

11) NOMINAL WORKING SPACE DIMENSIONS ARE SHOWN. LARGER AREAS MAY BE REQUIRED IN IRREGULAR TERRAIN. UPDATED DIMENSIONS MAY BE PROVIDED AFTER LOCAL TOPOGRAPHICAL SURVEYS ARE PERFORMED.

12) CONTRACTOR SHALL FOLLOW REFERENCE SPECIFICATIONS. REFER TO KEYSTONE CMRP, KEYSTONE CONSTRUCTION SPECIFICATIONS, PROJECT ENVIRONMENTAL REQUIREMENTS FOR THIS SITE SPECIFIC DETAIL, PART 195 OF THE CODE OF FEDERAL REGULATIONS (LATEST EDITION), ASME B31.4, AND API 1102.

13) 36" O.D. X 0.618" W.T., API 5L PSL 2-X70M W/14-20 MILS & 16-20 MILS ARO (NOT TO EXCEED 40 MILS TOTAL)

14) 36" O.D. X 0.465" W.T., API 5L PSL 2-X70M W/14-20 MILS FBE

15) MAINLINE EQUIPMENT MUST DRIVE AROUND THIS CROSSING ON EXISTING ROADS.

16) EQUIPMENT IS TO BE CLEANED AND DRIED PRIOR TO MOVING TO THE R.O.W. AND BEFORE LEAVING THE DRILL SIDE ON THE SOUTH SIDE OF THE RIVER.

17) MATURE COTTONWOOD TREES SHOULD BE PRESERVED WHERE PRACTICAL ON THE CONSTRUCTION R.O.W. SOUTH OF THE RIVER.

LEGEND

◎	CL P.I.	—U—	UNDERGROUND UTILITY	— · — · —	HEADCUT AREA
●	ENTRY OR EXIT POINT	—T—	TELEPHONE LINE	—✳—	EXCLUSION FENCE
⊗	GEOTECHNICAL BOREHOLE	— — —	PROPERTY PARCEL		
⚐	WARNING SIGN	— - - —	SECTION LINE		
━	PIPELINE ROUTE	■	COUNTY LINE		
●	CATHODIC PROTECTION TEST STATION	☐	PERMANENT EASEMENT BOUNDARY		
— - —	ROAD CL	▨	TEMPORARY WORKSPACE BOUNDARY		
——	ROAD EDGE	▩	ADDITIONAL TEMPORARY WORKSPACE		
— - —	FIELD PATH	┄	PERMANENT ACCESS ROAD		
┼─┼	RAILWAY	┄	TEMPORARY ACCESS ROAD		
—X—	FENCE	━	EXISTING GROUND		
—//—	FOREIGN PIPELINE	☐	WATER BODY		
—W—	WATER LINE	☐	WETLAND BOUNDARY		
—P—	OVERHEAD POWERLINE				

REFERENCE DRAWINGS

DRAWING No	TITLE
4360-03-ML-02-027	ALIGNMENT SHEET

REVISION			APPROVAL						
REV No	DATE	DESCRIPTION	PROJECT CODE	DRAFTER	DRAFTING CHECKER	DESIGNER	DESIGN CHECKER	PROJECT MANAGER	COMPANY
00	2013-05-31	ISSUED FOR CONSTRUCTION	2095406	EXP	TLB	BLS	KJM	KJM	EXP
0A	2016-12-12	ISSUED FOR REVIEW	2095406	EXP	ALS	DS	KJM	BW	EXP

PROFESSIONAL ENGINEER/RPT
FIRM: EXP ENERGY SERVICES, INC.
FIRM LICENSE: F057873

PERMIT/ ENG. APPROVAL
DATE

REV. NO. DATE PERMIT NUMBER:

TransCanada
In business to deliver

exp Energy Services Inc.
t: +1.850.385.5441 | f: +1.850.385.5523
1300 Metropolitan Blvd
Tallahassee, FL 32308
USA
www.exp.com

KEYSTONE XL (NPS 36 2014) VALLEY SECTION

FIA # 4360
CHAINAGE: MP 89.65
DISCIPLINE # 03

FIGURE 1.
MISSOURI RIVER HDD INSTALLATION
KEYSTONE XL PROJECT
VALLEY & McCONE COUNTY, MONTANA

SCALE AS SHOWN
DRAWING No 4360-03-ML-03-002
REV 0A

TC_UD_BR.DWG 22X34

CADD DRAWING: DO NOT MAKE MANUAL REVISIONS

PLOTTED SIZE: ANSI D (22x34)

ID
TIME
DESIGNFILE

TABLE 2

Total Potential Scour Depths for the Missouri River HDD Crossing Design

Recurrence Interval (year)	Design Flow (cfs)	Total Potential Scour Depth (ft)	Estimated Remaining Cover (ft)
2	15,000	5.9	28.1
5	17,000	6.1	27.9
10	25,000	6.8	27.2
50	48,000	8.8	25.2
100	60,000	9.7	24.3
500	95,000	11.9	22.1

Bed Sample Grain Size Distribution

D_{50} = 3.5 mm (0.14 inch)
D_{90} = 22 mm (0.87 inch)
D_{95} = 26 mm (1 inch)
Lowest elevation of crossing - 2,010 feet
Top of pipe at river low point (station 24+50) - 1,967 feet
Top of pipe at nearest bank station 23+50 - 1,976 feet

TABLE 3

Scour Analysis Summary Results

						USBOR Regime Scour Method*				General Scour			
Recurrence Interval (year)	Flow (cfs)	Total Potential Scour Depth (ft)	Blodgett Mean	Blodgett Max	Degradation	Average USBOR Regime	Neill	Lacey	Blench	HEC-RAS Contraction[†]	Envelope	Competent Velocity	Mean Velocity
2	15,000	5.9	2.4	10.9	2	**3.9**	2.9	5.8	2.9	0.0	4.8	0.8	3.1
5	17,000	6.1				**4.1**	3.1	6.1	3.1	1.0	4.9	1.1	3.3
10	25,000	6.8				**4.8**	3.9	6.9	3.7	1.4	5.3	2.0	3.8
50	48,000	8.8				**6.8**	6.1	8.6	5.6	2.9	6.1	3.9	5.5
100	60,000	9.7				**7.7**	7.3	9.3	6.4	3.6	6.4	4.9	6.3
500	95,000	11.9				**9.9**	10.2	10.8	8.7	6.1	7.2	7.9	8.2
Worst-case[†]	350,000	21.7				**19.7**	24.5	16.0	18.7	21.0	9.5	25.7	15.7

---

* based on empirical data, includes bend, local and bedform scour

† for informational purposes only

TABLE 4

500-Year Design, Sensitivity Analysis

							USBOR Regime Scour Method*				General Scour			
Input Parameter	D_{50} (mm)	Downstream Boundary Condition	Total Potential Scour Depth (ft)	Blodgett Mean	Blodgett Max	Degradation	Average BOR Regime	Neill	Lacey	Blench	HEC-RAS Contraction[†]	Envelope	Competent Velocity	Mean Velocity
Baseline Design	3.5	Critical Flow	11.9	2.4	10.9	2	**9.9**	10.2	10.8	8.7	6.1	7.2	7.9	8.2
D_{50}[†]	1.737	Critical Flow	12.1	2.6	11.8		**10.1**	8.8	12.2	9.3	9.7	7.2	9.9	8.2
Boundary Control	3.5	Normal Flow	11.9	2.4	10.9		**9.9**	10.2	10.8	8.7	4.5	7.2	5.3	9.4

---

* based on empirical data, includes bend, local and bedform scour

† for informational purposes only

6.1 Sensitivity Analysis

The results of the sensitivity analysis are presented in Table 3 and Table 4. Table 3 presents the worst-case scenario and is in the previous section. Table 4 presents sensitivity analysis results of the scour analysis under the 500-year design event.

6.2 Bed Sediment Size

The reduction of D_{50} by 50 percent increases the predicted scour from BOR equations Lacey and Blench, but the difference is nearly offset by an equivalent decrease in the Neill Regime scour prediction. One of the input parameters required in the Neill Regime Equation is an exponent (m) which varies from 0.67 to 0.85 depending on sediment size. For the sensitivity analysis, the D_{50} value decreased in size from medium gravel to very coarse sand. Therefore, the associated value for (m) decreased from 0.76 to 0.67. The reduction in the Neill equation calculation is due to the reclassification of the sediment as the D_{50} decreased in size.

Several of the checks of the scour analysis presented in the table predict an increase in scour. They are presented for comparison purposes only and are not relied on for the final scour depth prediction. The HEC-RAS Contraction scour and Competent Velocity Methods indicate that scour would increase up to 59 percent and 25 percent respectively for the 500-year design event. As discussed previously, the HEC-RAS contraction scour is not likely an appropriate measure for the scour prediction on an open natural stream. As the Missouri River is an open natural stream at the crossing location without any bridge structure, this method results in overpredicting the scour. In contrast, the Blodgett maximum scour prediction which is entirely dependent on the D_{50} predicts a minor increase in scour of 8 percent from the 500-year design event. The results from the envelope and mean velocity methods are unaffected by a change in D_{50}.

The Fort Peck Sediment Trends Study indicated high variability in the sediment samples collected near the crossing location. However, the bed samples collected are not representative of the substrate bed material. On page 7-1 of that study, the authors note that the samples obtained “are more likely indicative of the most recently deposited or exposed sediments at the sampling location at the time of the sample.”

Regardless, it would be unlikely that an extended layer of smaller sized material would be encountered with the variability shown in the samples to significantly impact the results. The history of the effort in collecting and analyzing the trend in sediment particle size seems to indicate there is significant variability in collected bed material. This suggests that even if a pocket of fine sediment were encountered, it would not extend for a significant depth given the variability in the bed samples. Appendix B compiles the bed sample data collected from the Fort Peck Downstream Sediment Trends Study. The information presented does not indicate a significant change in the D_{50} for any extended depth within the channel bed. However, reviewing the historical bed sample collection efforts in the Ft. Peck Study, it appears that if any variation were to occur, it would more likely increase rather than decrease the representative D_{50}.

The samples that were collected for the scour analysis were for the specific purpose of performing a scour analysis at the crossing location. While supplemental data was provided for review and analyzed, much of the data was determined unlikely to be representative of the material that would be encountered during scouring of the bed. In contrast, the samples collected at the site are consistent with the geotechnical data collected for the HDD crossing at Borehole #2, which indicates a 15-foot layer which contains gravel material. The presence of this layer indicates there likely is a sufficient local source to form an armor layer in the active bed. The borelogs from the Geotech Report are provided in Appendix F. This borehole is the one nearest to the lowest point in the stream.

Based on the information provided above, the collected sample D_{50} appears to be the most appropriate to use for the scour analysis without additional information. Further discussion on the appropriateness of use of sediment samples collected for the Fort Peck Downstream Sediment Trends Study is provided in Appendix B.

6.3 Boundary Control

The sensitivity analysis with a downstream boundary control of normal flow condition had little impact on predicted scour for the 500-year event. It has a more significant impact on the worst-case scenario as the conveyance issues would decrease velocities at the crossing location. The design model assumes a free discharge boundary condition. An assumption of normal boundary control is the more likely scenario. However, for the purposes of the scour analysis the assumption to determine the greater scour prediction was used. By assuming free discharge at the boundary condition and allowing critical flow to occur, the increases in velocities impact the HEC-RAS Contraction and Competent Velocity scour calculations by increasing the predicted scour by 74 percent and 49 percent respectively. While these additional scour methods predict an increase in scour, they are not being relied on in the scour depth prediction and are being presented for information purposes only. Although an assumption of normal boundary control is the more likely scenario, for the purposes of the scour analysis the assumption to determine the greater scour prediction was used.

6.4 Limitations on Applicability

The sensitivity analysis was performed running the 500-year design model under the worst-case scenario. However, attempting to apply the results of the sensitivity analysis directly for the worst-case scenario may not be realistic since there are many unknown factors that have a great influence on the predicted scour, including but not limited to:

- The selection of conservative values used in the Design model may not be applicable for the worst-case scenario as they are primarily based on empirical data;
- Reduced conveyance downstream due to unsurveyed obstructions in the 2-mile-wide flow path on the floodplain that decrease velocities experienced at the crossing location;
- Downstream inflows that add to the backwater condition and decrease velocities at the crossing location.

As such, it would be impractical to extend the assumptions used in the scour analysis as they were developed from empirical data which most likely don’t encompass the conditions for the worst-case scenario. The main channel can contain the 500-year design flow at the crossing location. However, for the worst-case scenario, flooding extends widely in the floodplain. Additional data acquisition is needed to precisely determine the likely scour at the crossing location for such a scenario, including fully projecting the flow contribution from the Milk River downstream of the crossing location, establishing a probable downstream boundary control, surveying for obstructions and ineffective areas to the flow along the floodplain, collecting additional sediment samples and more detailed model refinements to more accurately predict the likely scour potential. While the selected model input parameters represent an evaluation based on the best available information at the time, any other application of the model results beyond its intended use should review the model carefully as to suitability of the assumptions used.

6.5 Conservative Nature of the Scour Analysis

The scour predictions presented in the scour analysis are at the high end of the maximum predicted scour based on Blodgett maximum envelope calculations. In the collection of data at 21 sites over a long period of time, which included effects of degradation and many forms of scour, the amount of scour as predicted in the 500-year design and worst-case scenario is far beyond any that are predicted through this dataset, and is likely unrealistic for a number of reasons.

The conservative assumptions as discussed previously that are built into the hydraulic model include:

- Assuming bank erosion and scour occurs at the nearest point to the pipeline crown which would assume a migration of the channel by 100. This assumes a project life of 100 years and bank erosion continues through the existing high bank. In addition, the historical channel corridor is the existing floodplain to the south. Absent this migration, an additional 9 feet of cover would be gained;

- Using the smaller of two grain size distributions rather than the average of two site-specific sediment samples that were collected;
- Results for the 500-year and worst-case scenario are more conservative than any of the empirical data has shown. Selecting a 500-year Design event is more conservative than the typically used 100-year design;
- Assuming the pipeline is operational despite a service life of anywhere between 50-100 years or 0.1-0.25 percent of the worst-case scenario event frequency;
- Assuming critical flow as the downstream control, thereby allowing higher velocities and a higher scour prediction. During such an extreme event, significant backwater effects are expected due to limited conveyance capacity as well as additional flow contributions downstream; and
- Assuming downstream inflow for the Milk River is not experiencing the same event phenomenon. The flow contribution at the Milk River confluence is average seasonal flow rather than concurrent flood flow. This assumption allows more flow out of the system and these higher velocities allow for higher scour predictions. More than likely, during such an extreme event there will be comparative increases in flow contributions throughout the system and there will be significant backwater effects due to a limitation in conveyance capacity. The modeled Milk River inflow is less than 3% of the projected peak flows from the 100-, 500- or 40,000-year return event.

In addition, there are many layers of mitigative actions that would remove most of the hazard the pipeline installation may cause. These include the installation of a Supervisory Control and Data Acquisition (SCADA) system, leak detection system, and remotely operated valves near the crossing location, where the shut-in of the pipe can be completed in minutes. There will also be pipeline monitoring by in-line inspection, yearly surveys, regular communication with landowners, routine maintenance to ensure depth of cover is maintained over the pipeline, damage prevention plan, spill prevention and contingency plans to ensure emergency crews are nearby and ready to respond, and awareness of USACE Missouri River Mainstem Reservoir Bulletins posted during extreme weather events. These layers significantly reduce the risk of a breach or significant release as a result of the installation of the pipeline.

7.0 Summary

The results of this scour analysis indicate that the scour for the 500-year design event is 11.9 feet. This leaves 22.1 feet of cover remaining over the pipeline. Upon completion of construction, a cross-sectional survey to establish baseline conditions should be conducted. Thereafter, monitoring and verification of the scour model should be made when advanced notice can be given for the use of spillway and the flowrate is expected to exceed 20,000 cfs. This includes taking cross sectional surveys 500 feet upstream and downstream at 100 foot. A potential of lateral migration of up 100 feet encroachment for a 100-year project life to the northern bank is estimated. The HDD entry is 380 feet from the bank and will not be impacted. However, it is recommended that should any observation indicate lateral migration beyond 50 feet from the existing bank, mitigation measures should then be considered.

In addition, a sensitivity analysis for the worst-case flow scenario of 350,000 cfs was analyzed. The results indicate that it will generate an additional scour of 9.8 feet. This would leave 12.3 feet of cover when the scour is applied to the lowest elevation of the Missouri River and allowed to migrate to the nearest point of the pipeline in the HDD curvature under the river. Neither the projected 500-year design event nor the worst-case event present a significant risk to expose the pipe as proposed. However, model results indicate that an extreme event of this magnitude would have floodwaters significantly overtopping the banks and would extend for two miles wide at the crossing location, and impact many who are downstream of the spillway along the Missouri River floodplain. This flowrate has never been observed at this location, the results indicate that many along the floodplain would be severely impacted and the devastation would be widespread under these very unlikely circumstances.

The worst-case scenario model run was performed as a sensitivity analysis with the intent to estimate the upper limit of potential scour along the main channel of the Missouri River and compare it to the HDD crossing design. Based on the results of the analysis, it does not appear that a modification to the design of the HDD is warranted.

In regards to the safety and integrity of the pipeline at this crossing location, based on the model result and scour analysis performed, the current design depth is adequate to protect against potential scour resulting from the 500-year design and the worst-case scenario.

8.0 References

Blench, T., 1969, “Mobile-Bed Fluviology: A Regime Theory Treatment of Rivers for Engineers and Hydrologists,” Second Edition, University of Alberta Press, Edmonton, Alberta.

Chang, Howard H. 2002. “Fluvial Processes in River Engineering,” Krieger Publishing, Malabar, FL, 432 p.

Chow, V.T. 1959. “Open-Channel Hydraulics,” McGraw-Hill, New York, NY, 680 p.

Emmett, William. 1972. “Hydraulic Geometry of Some Alaskan Streams South of Yukon River,” USGS Open File Report OFR 72-018.

Expe Wilcock, P.R., Kenworthy, S.T. and Crowe, J.C. 2001. Experimental study of the transport of mixed sand and gravel, Water Resources Research, 37(12), 3349-.3358.

Lagasse, P.F., W.J. Spitz, L.W. Zevenbergen, and D.W. Zachman (Owen Ayres & Associates, Inc., Fort Collins, CO). 2004. “Handbook for Predicting Stream Meander Migration,” National Cooperative Highway Research Program Report 533, Transportation Research Board of the National Academies, 66 p. and Appendices.

Linsley, Ray K., Joseph B. Franzini, David L. Freyberg, and George Tchobanoglous. 1992. “Water-Resources Engineering,” Fourth Edition., Irwin McGraw-Hill, Boston, 841 p.

Hydrologic Statistics Technical Report Missouri River Basin Water Management Division Omaha, Nebraska. September 2013.

Missouri River Fort Peck Downstream Sediment Trends Study, Updated April 2013. U.S. Army Corps of Engineers Missouri River Basin. M.R.B. Sediment Memorandum 28.

Missouri River Mainstem Reservoir System, Master Water Control Manual, Missouri River Basin. 2006.

Neill, C.R., 1973. "Guide to Bridge Hydraulics," published for Road and Transportation Association of Canada.

Part 654 National Engineering Handbook Technical Supplement 14B, 2007. Scour Calculations, Publication 210–VI–NEH.

Pemberton E.L & Lara, J.M. (1984). "Computing Degradation and Local Scour." Technical Guideline for Bureau of Reclamation, U.S. Department of Interior, Bureau of Reclamation, Denver, CO.

Simon, A., Thomas, R.E., Curini, A. and Shields, F.D., Jr. 2002. Case Study: Channel Stability of the Missouri River, Eastern Montana, Journal of Hydraulic Engineering, ASCE, 128(10): 880-890.

Transport of Gravel and Sediment Mixtures of Parker’s Chapter 3 for ASCE Manual 54.

Trow Engineering Consultants, Inc., 1996, “Water-Crossing Design and Installation Manual,” prepared for the Offshore and Onshore Design Application Supervisory Committee of PRC International (copyright to American Gas Association).

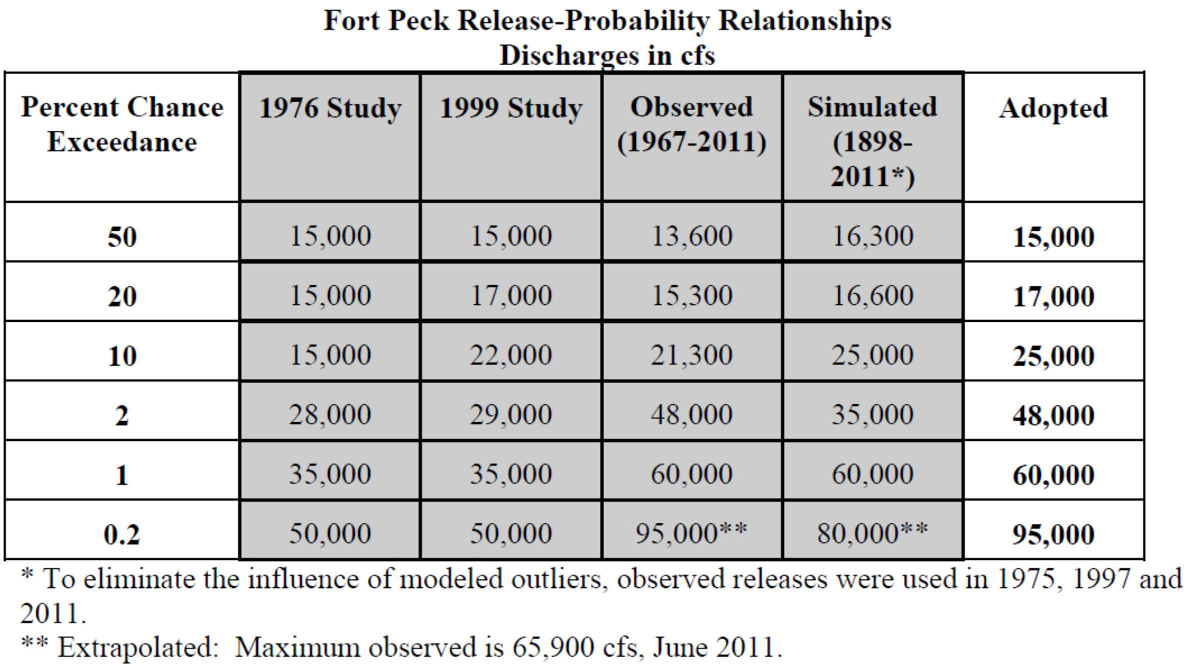
U.S. Army Corps of Engineers, Channel Stability Assessment for Flood Control Projects (1994a). Publication 1110-2-1418.

U.S. Army Corps of Engineers (1994b). Hydraulic Design of Flood Control Channel. Publication 1110-2-1601.

Appendix A –
Detailed Scour Calculation for Scour Analysis

Design Flow Input Parameters

The newly adopted release curves incorporate the data collected for the 2011 extreme event. A copy of Table 5 on page 15 2013 release probability relationships for the Fort Peck Dam from the “Hydrologic Statistics Technical Report: Missouri River Basin Water Management Division Omaha, Nebraska,” dated September 2013 is provided for convenience below:



Fort Peck Release-Probability Relationships
Discharges in cfs

Percent Chance Exceedance	1976 Study	1999 Study	Observed (1967-2011)	Simulated (1898-2011*)	Adopted
50	15,000	15,000	13,600	16,300	**15,000**
20	15,000	17,000	15,300	16,600	**17,000**
10	15,000	22,000	21,300	25,000	**25,000**
2	28,000	29,000	48,000	35,000	**48,000**
1	35,000	35,000	60,000	60,000	**60,000**
0.2	50,000	50,000	95,000**	80,000**	**95,000**

* To eliminate the influence of modeled outliers, observed releases were used in 1975, 1997 and 2011.

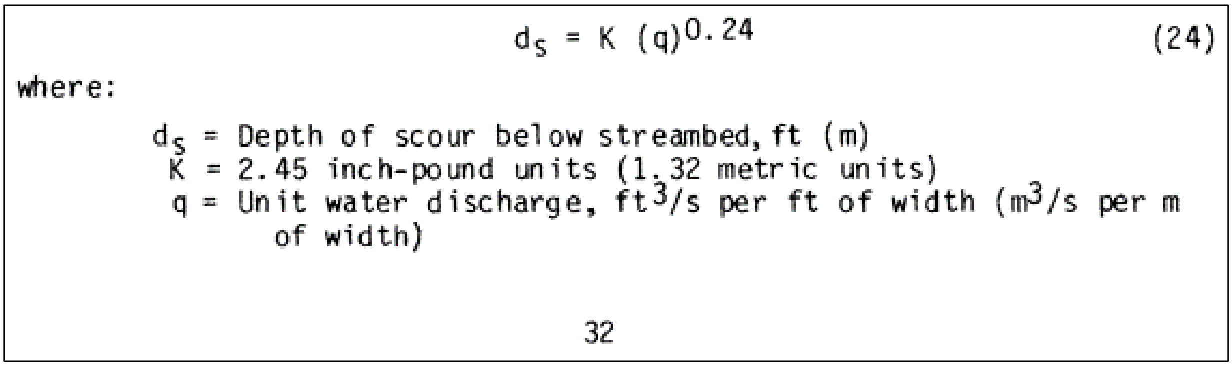
** Extrapolated: Maximum observed is 65,900 cfs, June 2011.

USBOR Envelope Curve Method Scour Calculations				
Recurrence Interval (year)	**Main Channel Flow (cfs)**	**Main Channel Top Width (ft)**	**Unit Discharge (cfs/ft)**	***Scour (ft)****
2	15,000	891	17	4.8
5	17,000	920	18	4.9
10	25,000	1023	24	5.3
50	48,000	1070	45	6.1
100	60,000	1074	56	6.4
500	95,000	1082	88	7.2
Sensitivity Analysis				
d_{50}=1.737mm	95,000	1082	88	7.2
DS BC=normal	94,988	1087	87	7.2
Worst-case†	306,099	1104	277	9.5

---

* provided as a check, empirical data based on slope of 0.004-0.008 ft/ft and d_{50} of 0.5-0.7mm

† for informational purposes, only



$$d_s = K\ (q)^{0.24} \qquad (24)$$

where:

d_s = Depth of scour below streambed, ft (m)
K = 2.45 inch-pound units (1.32 metric units)
q = Unit water discharge, ft^3/s per ft of width (m^3/s per m of width)

32

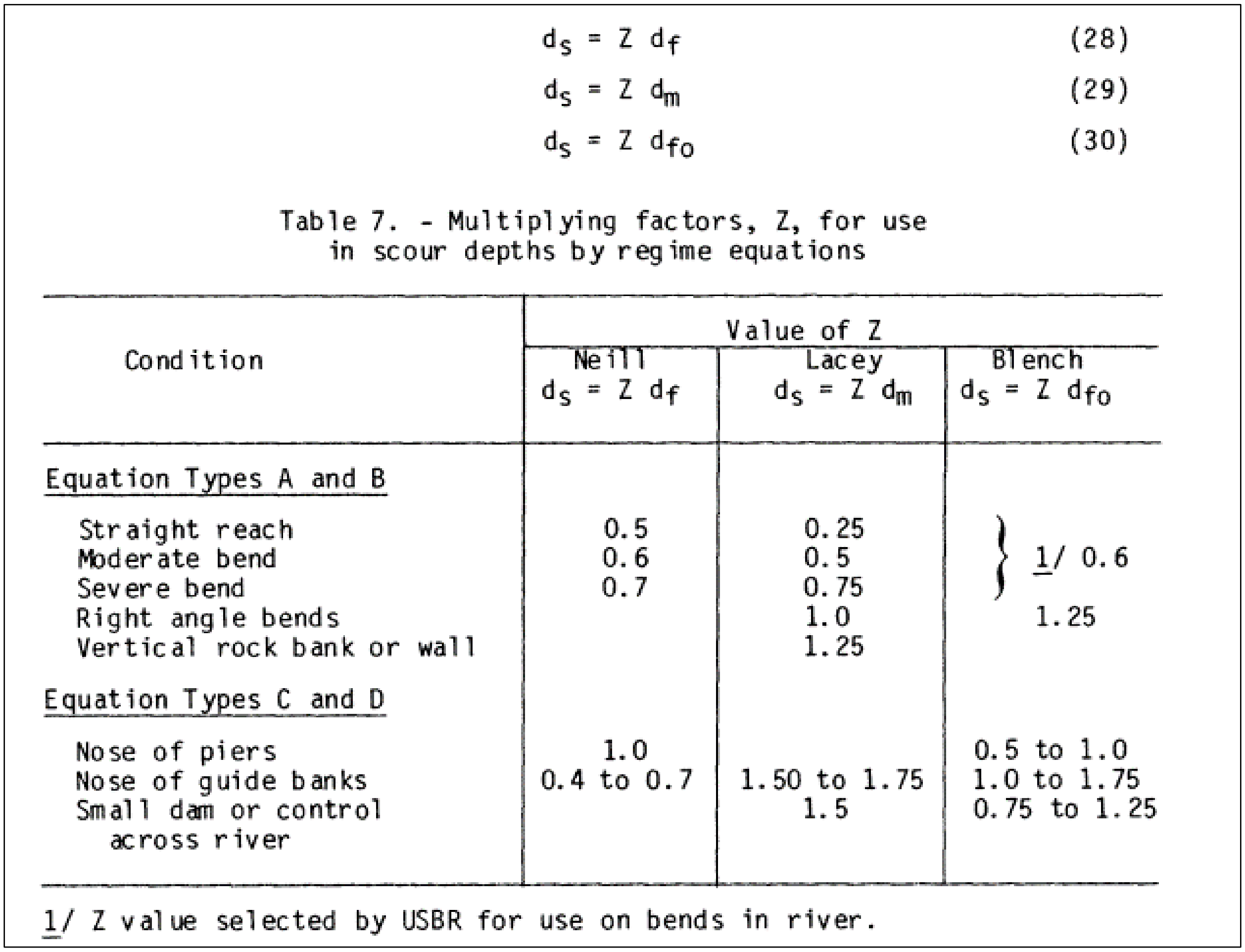
Source: Pemberton & Lara, 1984: Equation 24, page 32

Detailed Scour Calculation for Scour Analysis

USBOR Mean Velocity Method Scour Calculations

Recurrence Interval (year)	BOR Lacey Z Factor (severe bend)	Main Channel Mean Depth (ft)	Scour (ft)
2	0.75	4.17	3.1
5	0.75	4.36	3.3
10	0.75	5.03	3.8
50	0.75	7.31	5.5
100	0.75	8.40	6.3
500	0.75	10.98	8.2
Sensitivity Analysis			
d_{50}=1.737mm[†]	0.75	10.98	8.2
DS BC=normal	0.75	12.56	9.4
Worst-case[†]	0.75	20.99	15.7

[†] for informational purposes, only



$$d_s = Z\, d_f \qquad (28)$$

$$d_s = Z\, d_m \qquad (29)$$

$$d_s = Z\, d_{fo} \qquad (30)$$

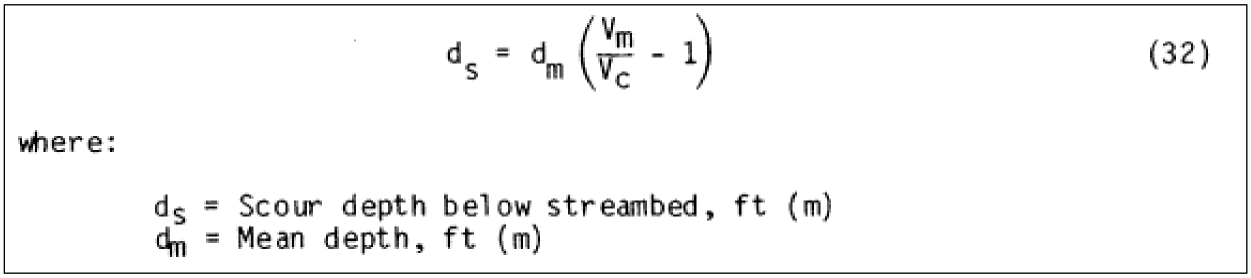
Table 7. - Multiplying factors, Z, for use in scour depths by regime equations

Condition	Value of Z Neill $d_s = Z\, d_f$	 Lacey $d_s = Z\, d_m$	 Blench $d_s = Z\, d_{fo}$
Equation Types A and B			
Straight reach	0.5	0.25	1/ 0.6
Moderate bend	0.6	0.5	
Severe bend	0.7	0.75	
Right angle bends		1.0	1.25
Vertical rock bank or wall		1.25	
Equation Types C and D			
Nose of piers	1.0		0.5 to 1.0
Nose of guide banks	0.4 to 0.7	1.50 to 1.75	1.0 to 1.75
Small dam or control across river		1.5	0.75 to 1.25

1/ Z value selected by USBR for use on bends in river.

Source: Pemberton & Lara, 1984: Equation 29, pages 36-37

Neill Competent Velocity Method Scour Calculations					
Recurrence Interval (year)	**D_{50} (mm)**	**Main Channel Mean Depth (ft)**	**Main Channel Mean Velocity (ft/s)**	**Competent Mean Velocity (ft/s) ***	**Scour (ft)**
2	3.5	4.17	4.04	3.4	0.8
5	3.5	4.36	4.24	3.4	1.1
10	3.5	5.03	4.86	3.5	2.0
50	3.5	7.31	6.13	4.0	3.9
100	3.5	8.40	6.65	4.2	4.9
500	3.5	10.98	8.00	4.7	7.9
Sensitivity Analysis					
d_{50}=1.737mm	1.74	10.98	8.00	4.2	9.9
DS BC=normal	3.5	12.56	6.96	4.9	5.3
Worst-case†	3.5	20.99	13.21	5.9	25.7
* from USBOR Figure 12, page 41 † for informational purposes, only					



$$d_s = d_m \left(\frac{V_m}{V_c} - 1 \right) \qquad (32)$$

where:

d_s = Scour depth below streambed, ft (m)
d_m = Mean depth, ft (m)

Source: Pemberton & Lara, 1984: Equation 32, page 38

Neill Scour Calculations

Recurrence Interval (year)	Main Channel Flow (cfs)	Bankfull Average Depth (ft)	Bankfull Flow (cfs)	Bankfull Top Width (ft)	Main Channel Top Width (ft)	Neill exponent m (0.67-0.85)	Neill Method (ft)	USBOR Neill Z Factor (severe bend)	Scour (ft)
2	15,000	4.2	15,000	891	891	0.76	4.2	0.70	2.9
5	17,000	4.2	15,000	891	920	0.76	4.5	0.70	3.1
10	25,000	4.2	15,000	891	1023	0.76	5.5	0.70	3.9
50	48,000	4.2	15,000	891	1070	0.76	8.8	0.70	6.1
100	60,000	4.2	15,000	891	1074	0.76	10.4	0.70	7.3
500	95,000	4.2	15,000	891	1082	0.76	14.6	0.70	10.2
Sensitivity Analysis									
d_{50}=1.737mm	95,000	4.2	15,000	891	1082	0.67	12.6	0.70	8.8
DS BC=normal	94,988	4.2	15,000	891	1087	0.76	14.6	0.70	10.2
Worst-case[†]	306,099	4.2	15,000	891	1104	0.76	35.1	0.70	24.5

Source: Pemberton & Lara, 1984: Equation 25, pages 34-37

Lacey Scour Calculations

Recurrence Interval (year)	Main Channel Flow (cfs)	Main Channel Top Width (ft)	D_{50} (mm)	Lacey Silt Factor	Lacey Method (ft)	USBOR Lacey Z Factor (severe bend)	Scour (ft)	***TS14B-23 check (ft)***[‡]
2	15,000	891	3.50	3.29	7.8	0.75	5.8	5.8
5	17,000	920	3.50	3.29	8.1	0.75	6.1	6.1
10	25,000	1023	3.50	3.29	9.2	0.75	6.9	6.9
50	48,000	1070	3.50	3.29	11.5	0.75	8.6	8.6
100	60,000	1074	3.50	3.29	12.4	0.75	9.3	9.3
500	95,000	1082	3.50	3.29	14.4	0.75	10.8	10.8
Sensitivity Analysis								
d_{50}=1.737mm	95,000	1082	1.74	2.32	16.2	0.75	12.2	12.2
DS BC=normal	94,988	1087	3.50	3.29	14.4	0.75	10.8	10.8
Worst-case[†]	306,099	1104	3.50	3.29	21.3	0.75	16.0	16.0

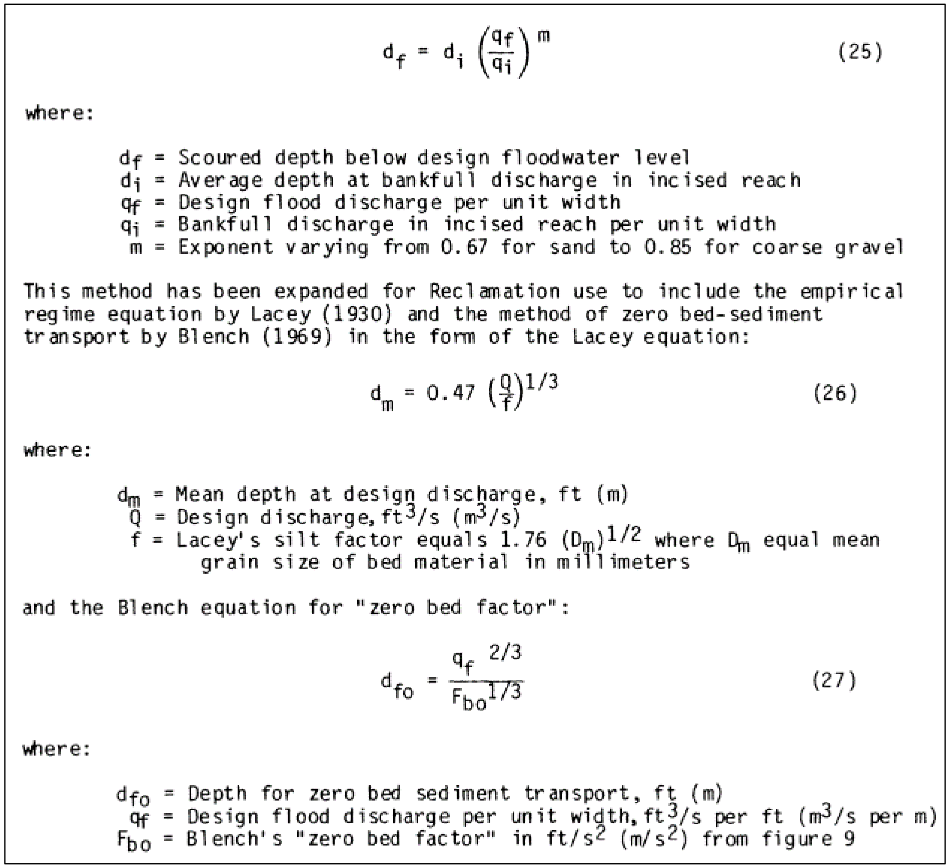
Source: Pemberton & Lara, 1984: Equation 26, pages 34-37

Blench Scour Calculations

Recurrence Interval (year)	Main Channel Flow (cfs)	Main Channel Top Width (ft)	Blench Zero Bed Factor (ft^2/s) *	Blench Method (ft)	USBOR Blench Z Factor	Scour (ft)	*TS14B-23 check (ft)*[‡]
2	15,000	891	2.52	4.8	0.60	2.9	3.0
5	17,000	920	2.52	5.1	0.60	3.1	3.2
10	25,000	1023	2.52	6.2	0.60	3.7	3.9
50	48,000	1070	2.52	9.3	0.60	5.6	5.8
100	60,000	1074	2.52	10.7	0.60	6.4	6.8
500	95,000	1082	2.52	14.5	0.60	8.7	9.1
Sensitivity Analysis							
d_{50}=1.737mm	95,000	1082	2.08	15.5	0.60	9.3	9.9
DS BC=normal	94,988	1087	2.52	14.5	0.60	8.7	9.1
Worst-case[†]	306,099	1104	2.52	31.2	0.60	18.7	19.7

---

* from BOR Figure 9, page 35
[†] for informational purposes, only
[‡] *Source: National Engineering Handbook TS14B, 2007: Equation TS14B-23, page 14*



$$d_f = d_i \left(\frac{q_f}{q_i}\right)^m \tag{25}$$

where:

d_f = Scoured depth below design floodwater level
d_i = Average depth at bankfull discharge in incised reach
q_f = Design flood discharge per unit width
q_i = Bankfull discharge in incised reach per unit width
m = Exponent varying from 0.67 for sand to 0.85 for coarse gravel

This method has been expanded for Reclamation use to include the empirical regime equation by Lacey (1930) and the method of zero bed-sediment transport by Blench (1969) in the form of the Lacey equation:

$$d_m = 0.47 \left(\frac{Q}{f}\right)^{1/3} \tag{26}$$

where:

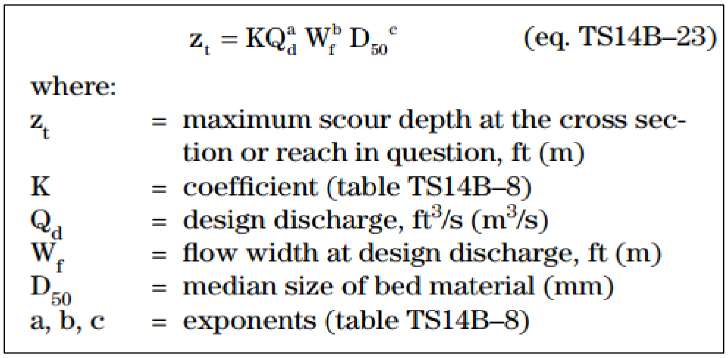
d_m = Mean depth at design discharge, ft (m)
Q = Design discharge, ft^3/s (m^3/s)
f = Lacey's silt factor equals $1.76\,(D_m)^{1/2}$ where D_m equal mean grain size of bed material in millimeters

and the Blench equation for "zero bed factor":

$$d_{fo} = \frac{q_f^{\,2/3}}{F_{bo}^{\,1/3}} \tag{27}$$

where:

d_{fo} = Depth for zero bed sediment transport, ft (m)
q_f = Design flood discharge per unit width, ft^3/s per ft (m^3/s per m)
F_{bo} = Blench's "zero bed factor" in ft/s^2 (m/s^2) from figure 9



$$z_t = KQ_d^a W_f^b D_{50}^c \qquad \text{(eq. TS14B–23)}$$

where:

z_t = maximum scour depth at the cross section or reach in question, ft (m)
K = coefficient (table TS14B–8)
Q_d = design discharge, ft^3/s (m^3/s)
W_f = flow width at design discharge, ft (m)
D_{50} = median size of bed material (mm)
a, b, c = exponents (table TS14B–8)

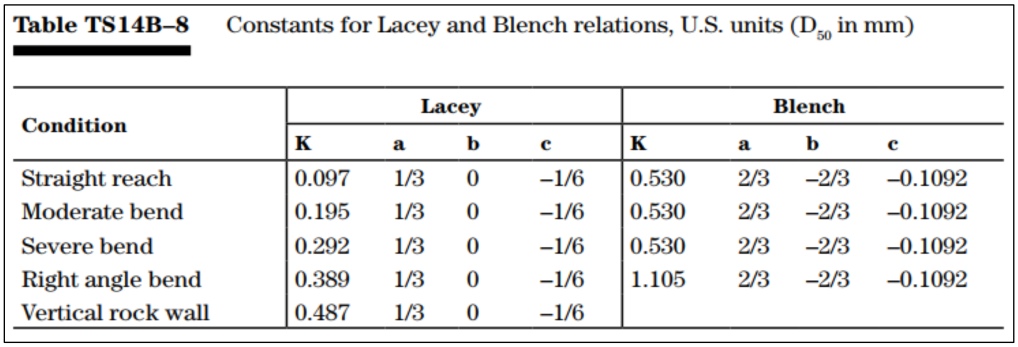


Table TS14B–8 Constants for Lacey and Blench relations, U.S. units (D_{50} in mm)

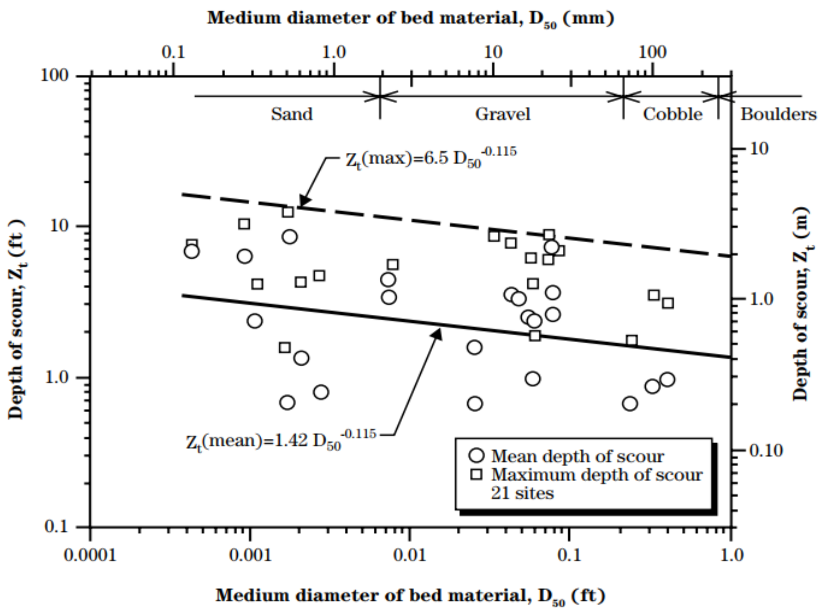
Condition	Lacey				Blench			
	K	**a**	**b**	**c**	**K**	**a**	**b**	**c**
Straight reach	0.097	1/3	0	–1/6	0.530	2/3	–2/3	–0.1092
Moderate bend	0.195	1/3	0	–1/6	0.530	2/3	–2/3	–0.1092
Severe bend	0.292	1/3	0	–1/6	0.530	2/3	–2/3	–0.1092
Right angle bend	0.389	1/3	0	–1/6	1.105	2/3	–2/3	–0.1092
Vertical rock wall	0.487	1/3	0	–1/6				

Source: Pemberton & Lara, 1984: Equation 27, pages 34-37

Blodgett Scour Calculation			
D_{50}	3.5	mm	Equation
Blodgett Z_t (mean)	2.4	ft	TS14B–21
Blodgett Z_t (max)	10.9	ft	TS14B–22
Sensitivity Analysis **Bed Size:**[†]			
D_{50}	1.737	mm	Equation
Blodgett Z_t (mean)	2.6	ft	TS14B–21
Blodgett Z_t (max)	11.8	ft	TS14B–22

[†] for informational purposes only

Figure TS14B–1 Scour observations from typical reaches of alluvial rivers



(210–VI–NEH, August 2007) TS14B–1

Source: National Engineering Handbook TS14B, 2007: pages 13-14

USGS gage 06174500 Milk River at Nashua MT

Seasonal Average:

Month	Flow (cfs)
May	1240
June	1070
July	664
Average	991

Model applies Milk River seasonal average flow of 1,000 cfs for scour analysis.

These monthly flows are obtained from the website on the following page.

USGS science for a changing world

USGS Home
Contact USGS
Search USGS

National Water Information System: Web Interface

USGS Water Resources

Data Category: Surface Water ▾ **Geographic Area:** United States ▾ GO

Click to hideNews Bulletins

- Please see news on new formats
- Full News

USGS Surface-Water Monthly Statistics for the Nation

The statistics generated from this site are based on approved daily-mean data and may not match those published by the USGS in official publications. The user is responsible for assessment and use of statistics from this site. For more details on why the statistics may not match, click here.

USGS 06174500 Milk River at Nashua MT

Time-series: Monthly statistics ▾ GO

Valley County, Montana
Hydrologic Unit Code 10050012
Latitude 48°07'48.19", Longitude 106°21'51.53" NAD83
Drainage area 22,452 square miles
Contributing drainage area 20,254 square miles
Gage datum 2,027.75 feet above NGVD29

Output formats
HTML table of all data
Tab-separated data
Reselect output format

00060, Discharge, cubic feet per second,

YEAR	Monthly mean in ft3/s (Calculation Period: 1939-10-01 -> 2017-05-31)											
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1939										122.1	113.5	150.5
1940	38.2	88.5	644.1	5,025	1,656	1,072	220.9	181.3	108.9	101.6	158.9	108.2
1941	80.7	78.7	977.3	843.6	70.9	364.1	91.5	77.3	105.5	66.5	120.5	175.1
1942	53.0	72.4	1,565	489.8	139.1	2,254	1,118	247.0	246.3	191.8	300.1	160.3
1943	140.2	137.9	2,868	5,974	547.9	3,577	970.3	270.3	226.3	241.5	340.4	184.7
1944	131.6	128.3	1,743	1,288	205.6	1,328	566.3	176.4	64.9	101.7	158.8	95.9
1945	80.8	185.2	1,057	379.4	72.0	129.1	60.5	72.9	68.8	64.3	92.1	88.9
1946	91.0	231.4	1,606	179.2	60.6	267.8	542.5	68.8	175.7	86.6	84.5	98.1
1947	129.0	117.9	1,754	4,127	381.9	663.2	180.2	629.7	187.7	175.1	176.0	145.5
1948	118.4	74.7	233.1	780.9	469.0	1,568	1,141	410.4	224.1	307.5	290.1	77.5
1949	38.5	38.9	619.5	468.7	211.5	96.3	49.0	123.9	138.0	93.1	98.1	46.1
1950	36.0	50.9	88.5	6,312	480.5	1,964	365.3	256.8	466.6	175.6	124.0	92.7

1951	82.9	92.5	539.2	5,847	2,210	537.6	305.5	435.4	661.1	470.5	382.2	220.9
1952	138.5	297.4	359.9	20,930	3,690	591.3	890.2	370.5	252.4	266.6	246.8	141.5
1953	117.3	138.4	394.6	302.1	2,093	6,611	1,031	524.9	281.4	196.4	280.8	199.9
1954	164.1	656.1	428.1	4,463	498.0	1,368	376.2	997.5	390.1	512.1	372.0	303.4
1955	187.1	175.0	466.1	7,341	5,008	1,771	1,969	616.3	374.0	353.0	275.8	221.0
1956	193.2	175.4	734.4	748.7	396.6	310.5	294.2	435.6	284.6	160.3	188.1	158.1
1957	130.3	149.6	574.2	592.1	628.3	438.4	149.5	284.5	314.9	163.5	218.5	161.3
1958	137.1	117.5	181.1	2,028	227.3	231.1	143.0	130.1	168.8	111.4	117.5	140.0
1959	93.7	113.8	3,478	1,075	335.9	329.9	580.9	278.5	263.0	190.6	167.3	217.1
1960	114.5	315.9	3,661	2,486	1,136	405.9	223.6	245.5	203.3	112.1	152.7	107.7
1961	107.6	111.4	202.2	60.6	38.8	107.6	14.6	45.1	59.9	56.8	106.9	59.7
1962	64.8	96.3	632.6	801.7	546.8	980.2	3,578	301.3	140.3	174.4	136.0	142.0
1963	98.6	796.0	1,084	308.0	231.4	1,448	1,136	316.5	198.0	82.6	151.9	118.6
1964	118.7	122.8	121.7	93.0	702.2	934.1	273.0	147.8	110.5	63.8	124.3	152.3
1965	134.2	155.7	243.2	5,059	4,342	1,410	3,084	892.3	666.7	541.7	547.2	314.5
1966	196.6	191.8	2,135	1,159	496.9	267.2	456.9	308.5	155.4	130.8	215.3	166.5
1967	152.3	160.4	1,878	5,844	4,716	1,388	240.6	135.6	286.1	139.5	144.6	199.2
1968	144.7	190.0	1,004	195.4	240.8	297.3	122.9	227.4	149.8	361.7	360.8	182.9
1969	129.8	173.9	915.8	6,071	1,655	274.0	1,929	251.1	178.7	188.5	171.0	198.8
1970	133.9	138.5	539.9	1,667	3,506	2,192	639.7	379.3	225.6	160.1	211.9	162.6
1971	156.0	710.4	1,273	2,279	510.7	355.1	123.7	98.3	197.2	114.6	184.9	116.9
1972	112.9	103.6	1,803	361.0	519.3	2,263	387.3	615.5	300.6	252.3	185.0	98.1
1973	102.7	161.3	258.1	260.2	175.5	191.3	196.0	51.6	110.9	90.7	137.3	100.4
1974	842.7	509.5	789.0	2,224	2,553	2,984	690.1	890.1	387.3	297.7	342.4	255.8
1975	195.0	109.3	193.1	2,453	5,207	1,634	1,533	783.0	512.6	423.3	690.7	362.9
1976	307.4	469.7	2,769	1,577	186.5	795.6	1,546	507.6	275.0	200.4	238.9	151.8
1977	112.6	310.1	297.9	26.6	146.9	133.4	25.9	23.1	75.2	98.8	81.3	75.1
1978	123.0	102.4	1,270	10,140	2,381	948.4	999.2	440.4	2,138	541.4	369.6	250.6
1979	179.5	182.1	4,396	7,766	3,800	662.5	818.3	370.6	246.9	172.5	184.9	178.9
1980	147.7	125.3	139.4	362.5	43.9	52.5	128.9	182.8	151.0	130.6	157.1	121.5
1981	156.6	215.0	142.1	15.1	112.0	246.7	131.2	142.6	97.1	167.0	144.3	128.5
1982	79.0	128.6	2,752	3,866	662.0	3,731	605.2	275.5	233.8	211.5	207.6	144.3
1983	160.3	683.2	397.6	191.2	512.9	110.2	939.2	88.1	179.4	96.3	118.5	39.7
1984	94.7	103.6	112.4	55.4	20.2	28.0	3.54	3.43	19.8	45.9	68.5	62.3
1985	60.0	72.5	102.3	41.3	17.9	139.1	11.0	175.7	61.1	149.6	117.6	123.2
1986	161.9	208.6	6,678	264.0	3,783	1,188	374.7	175.6	1,354	6,837	767.6	487.1
1987	373.9	518.2	1,580	1,711	263.9	259.4	263.0	439.0	164.7	177.1	114.9	197.9
1988	115.5	113.3	142.2	38.1	199.9	103.0	205.1	57.8	12.6	77.2	95.0	86.3
1989	65.8	59.8	577.4	889.5	225.4	251.8	133.7	236.9	180.7	149.5	184.3	136.8
1990	338.4	176.8	721.0	169.5	287.2	442.8	144.1	270.7	169.9	115.5	177.6	117.4
1991	109.5	138.2	245.9	110.1	374.4	711.0	2,664	193.0	175.5	131.6	187.7	177.7

1992	159.7	171.0	171.6	29.1	10.5	121.6	168.6	66.1	94.0	142.2	117.1	80.9
1993	69.4	84.3	1,832	425.8	127.7	232.5	2,561	1,754	848.7	920.0	362.2	296.0
1994	257.3	258.9	4,417	1,049	761.2	1,270	162.5	151.8	189.0	177.0	186.7	142.4
1995	104.2	94.6	86.7	80.7	85.8	1,118	632.4	149.5	160.3	292.4	241.7	224.5
1996	263.9	2,337	6,097	4,565	660.9	516.4	270.6	141.2	527.3	263.8	214.9	161.0
1997	255.2	784.6	3,488	4,762	397.1	1,137	576.1	244.5	285.1	296.8	204.8	165.8
1998	126.5	159.3	165.5	88.7	71.3	203.1	1,454	165.0	224.9	280.8	353.4	183.5
1999	141.6	241.1	4,012	635.3	1,438	1,123	342.0	206.9	305.2	247.2	217.9	156.4
2000	129.7	138.6	168.8	38.4	66.8	440.2	678.5	65.6	95.4	58.6	95.4	96.3
2001	99.2	88.4	452.6	61.7	12.4	700.5	301.4	86.6	43.1	34.4	61.1	53.8
2002	53.3	57.5	56.5	72.9	69.0	1,044	468.4	635.1	170.3	161.6	101.2	102.9
2003	96.8	94.6	1,321	516.1	733.7	182.9	98.8	99.4	103.1	143.6	150.3	83.2
2004	72.3	95.2	2,676	832.0	1,237	1,094	190.9	170.4	119.2	159.5	125.5	151.1
2005	127.7	200.4	192.3	163.9	90.1	1,310	203.2	90.8	140.6	94.4	134.8	131.9
2006	150.6	143.7	284.8	745.1	119.4	122.7	55.8	95.6	111.8	106.5	122.3	68.4
2007	67.1	71.8	572.0	236.8	1,069	2,623	180.7	69.1	107.6	82.2	114.2	90.3
2008	95.6	93.6	118.0	42.9	107.2	1,141	91.3	77.8	130.6	118.1	151.0	121.0
2009	106.6	119.1	816.5	749.6	977.6	156.8	161.0	170.2	125.2	131.6	166.9	108.8
2010	110.2	117.6	232.9	222.5	2,145	3,753	1,806	256.0	891.7	427.1	282.0	249.1
2011	266.6	633.8	1,900	12,030	8,361	14,200	1,910	553.8	472.1	417.6	380.9	354.7
2012	333.1	316.3	641.7	264.7	660.6	1,916	501.9	262.8	170.8	151.1	197.5	171.0
2013	198.0	262.0	488.8	1,419	712.9	5,908	1,296	589.3	598.5	388.3	363.3	344.2
2014	341.1	328.6	1,981	1,023	521.6	1,013	722.9	2,691	2,852	811.8	566.4	474.5
2015	297.1	465.0	1,821	390.8	397.2	349.3	272.9	316.7	127.0	230.1	253.3	175.2
2016	160.6	316.1	309.9	407.2	3,314	1,163	1,349	859.7	505.3	4,292	1,469	524.2
2017	358.5	1,834	3,379	1,035	291.3							
Mean of monthly Discharge	154	260	1,240	2,050	1,070	1,240	664	335	309	347	231	168

** No Incomplete data have been used for statistical calculation

---

Questions about sites/data?
Feedback on this web site
Automated retrievals
Help
Data Tips
Explanation of terms
Subscribe for system changes
News

Accessibility Plug-Ins FOIA Privacy Policies and Notices

U.S. Department of the Interior | U.S. Geological Survey

Title: Surface Water data for USA: USGS Surface-Water Monthly Statistics

URL: https://waterdata.usgs.gov/nwis/monthly?

Page Contact Information: Montana Water Data Support Team
Page Last Modified: 2017-09-23 00:30:44 EDT
1.15 0.99 vaww02

Montana Flood-Frequency and Basin-Characteristic Data

Flood-frequency data are based on recorded annual peak discharges through 1998. Peak discharges for specified frequencies (exceedance probabilities) were determined by fitting a log-Pearson Type 3 probability distribution to base 10 logarithms of recorded annual peak discharges as described by the Interagency Advisory Committee on Water Data (1982, Guidelines for Determining Flood Flow Frequency--Bulletin 17-B of the Hydrology Subcommittee: U.S. Geological Survey, Office of Water Data Coordination). **Note: Data are provisional and user is responsible for assessment and interpretation of flood-frequency data.**

Most of the basin characteristic data were measured in the 1970s from the best-scale topographic maps available at the time. Some data, such as mean annual precipitation, soil index data, and mean January minimum temperatures, were compiled from maps prepared by other agencies. Channel widths were measured in the field by USGS personnel.

The flood-frequency and basin characteristics data were used in a new flood-frequency report just published by the USGS, entitled "Methods for estimating Flood Frequency in Montana Based on Data through Water Year 1998" (Water-Resources Investigations Report 03-4308). Information about the equations described in that report can be found at the following link.

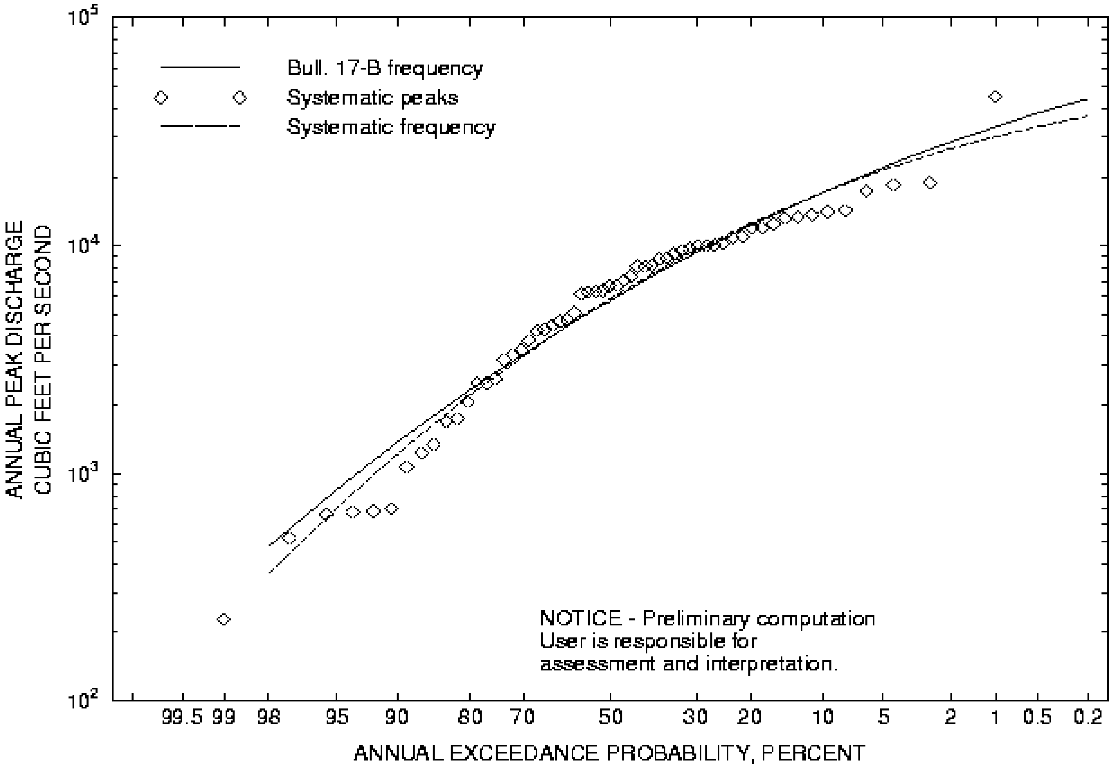
For more detailed information contact Wayne Berkas:
Phone: 406-457-5903 or by e-mail.

06174500 Milk River at Nashua, MT

Flood-frequency analysis based on period of record since beginning of flow regulation.

Annual peak discharge, in cubic feet per second (top line), for indicated exceedance probability, in percent (bottom line):

--	--	848	1360	2330	5750	12200	17200	23700	28600	33400	38100	44100
99.5	99	95	90	80	50	20	10	4	2	1	0.5	0.2



NOTE: Systematic peaks are those that are recorded within the period of gaged record. The computed systematic flood-frequency curve is based only on the systematic peaks. The computed Bulletin 17-B flood-frequency curve often is different from the systematic flood-frequency curve because of differences between station skew and regional skew, low- or high-outlier adjustments, or the presence of one or more historical peaks outside the systematic record. Historical peaks also result in historical adjusted plotting positions (exceedance probabilities) for all peaks.

Recorded Annual Peak Discharge:

06174500 Milk River at Nashua, MT

```
Location.-- Lat 48 07'47", Long 106 21'50", Hydrologic Unit 10050012.
Drainage area.-- 22332.0 square miles.
Datum of gage.--    2027.75 ft above sea level.
```

Table of annual peak discharge data [--, no data]

Water year	Date	Gage height (ft)		Discharge ft3/s		Date of Max. gage height	Maximum gage height (ft)
1940	Apr. 23, 1940	21.80		12000	_/5	--	--
1941	Mar. 31, 1941	17.67	_/1	6660	_/5	--	--
1942	June 6, 1942	--	_/2	6270	_/5	Mar. 20, 1942	14.98
1943	Apr. 2, 1943	26.97		17400	_/5	--	--
1944	Mar. 27, 1944	18.59	_/1	6700	_/25	--	--
1945	Mar. 28, 1945	12.08	_/1	2500	_/15	--	--
1946	July 11, 1946	12.74		5080	_/5	--	--
1947	Mar. 30, 1947	23.56	_/1	11000	_/15	--	--
1948	June 6, 1948	12.11		4760	_/5	--	--
1949	Apr. 1, 1949	--	_/2	2070	_/5	Mar. 23, 1949	7.62

```
 1950    Apr. 22, 1950    22.62        12500    _/5         --          --
 1951    Apr.  9, 1951      --  _/2    10100    _/5    Apr.  3, 1951  21.87
 1952    Apr. 18, 1952    31.38        45300    _/5         --          --
 1953    May  31, 1953    25.50        13400    _/5         --          --
 1954    Apr. 13, 1954    22.35        10900    _/5         --          --
 1955    Apr.  6, 1955    20.98        10200    _/5         --          --
 1956    Mar. 28, 1956      --  _/2     3170    _/5    Mar. 29, 1956  13.34
 1957    Mar. 30, 1957      --  _/2     1750    _/5    Mar. 29, 1957   8.74
 1958    Apr.  8, 1958    11.31         3840    _/5         --          --
 1959    Mar. 24, 1959    24.43 _/1    10000    _/15        --          --
 1960    Mar. 27, 1960    26.17        14200    _/5         --          --
 1961    Mar. 22, 1961      --  _/2      702    _/5    Feb.  6, 1961   4.05
 1962    July 17, 1962    20.30         9670    _/5         --          --
 1963    June 10, 1963    11.70         4250    _/5         --          --
 1964    June 20, 1964     9.40         3330    _/5         --          --
 1965    May   9, 1965    20.23 _/2     9610    _/5    Apr. 13, 1965  22.93 _/1
 1966    Mar. 25, 1966    21.35 _/1     7060    _/15        --          --
 1967    Mar. 30, 1967    25.39 _/1    12000    _/25        --          --
 1968    Mar.  9, 1968    10.43 _/1     2500    _/25        --          --
 1969    Apr.  8, 1969    19.34         8880    _/5         --          --
 1970    May   6, 1970    15.05         6320    _/5         --          --
 1971    Apr.  9, 1971    12.41 _/2     4670    _/25   Apr.  4, 1971  14.57 _/1
 1972    June 13, 1972    18.57         7360    _/5         --          --
 1973    July  3, 1973     4.21         1070    _/5         --          --
 1974    May  29, 1974    17.85         8140    _/5         --          --
 1975    May  12, 1975    18.13         8220    _/5         --          --
 1976    Mar. 23, 1976    20.20         9240    _/5         --          --
 1977    Feb. 26, 1977      --           690    _/15   Feb. 21, 1977   4.47 _/1
 1978    Apr.  5, 1978    28.93        18900    _/5         --          --
 1979    Mar. 27, 1979      --         14300    _/15   Mar. 28, 1979  29.58 _/1
 1980    Apr.  5, 1980     5.58         1350    _/5         --          --
 1981    June  5, 1981     3.63 _/2      666    _/5    Feb. 26, 1981   4.20 _/1
 1982    Mar. 31, 1982    19.27 _/2     8160    _/5    Mar. 30, 1982  20.54 _/1
 1983    July 17, 1983     8.42         2620    _/5         --          --
 1984                 1984      --           229    _/5    Dec. 18, 1983   3.73 _/1
 1985    Aug.  4, 1985     4.50 _/2     1230    _/5    Dec. 18, 1984   3.73 _/1
 1986    Mar.  8, 1986    30.09        18500    _/5         --          --
 1987    Oct.  8, 1986    26.11        13700    _/5         --          --
 1988    May  11, 1988     3.60          679    _/5         --          --
 1989    Mar. 30, 1989    15.11 _/1     4500    _/5         --          --
 1990    Mar. 17, 1990     9.27 _/1     1700    _/15        --          --
 1991    July  8, 1991    15.99         6170    _/5         --          --
 1992    June 18, 1992     3.30 _/2      523    _/5    Feb. 11, 1992   4.40 _/1
 1993    July 30, 1993    16.37         6380    _/5         --          --
 1994    Mar. 16, 1994    23.02 _/1     8800    _/5         --          --
 1995    June 26, 1995    10.40         3500    _/5         --          --
 1996    Mar. 20, 1996      --         10000    _/125  Mar. 20, 1996  23.71 _/1
 1997    Mar. 31, 1997    25.75        13300    _/5         --          --
 1998    July  8, 1998    11.68         4270    _/5         --          --

_/ Explanation of the footnotes used for Gage height data:
      1  Gage height affected by backwater.
      2  Gage height not the maximum for the year.

_/ Explanation of the footnotes used for Discharge data:
      1  Discharge is maximum daily average.
      2  Discharge is an estimate.
      5  Discharge affected to unknown degree by regulation or diversion.

_/ Explanation of the footnotes used for Maximum gage height data:
      1  Gage height due to backwater.
```

Basin Characteristics:

Value	Abbrev	Explanation
--	SLOPE	Main channel slope, in ft per mile

--	LENGTH	Total stream length, miles
--	ELEV	Mean basin elevation, ft above msl
--	EL6000	Percent of basin above 6,000 ft, msl
--	STORAGE	Percent of basin in lakes, ponds, and swamps
--	FOREST	Percent of basin in forest
--	SOIL_INF	Soil index, in inches
48.12972222	LAT_GAGE	Latitude of gage, in decimal degrees
106.36388889	LNG_GAGE	Longitude of gage, in decimal degrees
--	PRECIP	Mean annual precipitation, in inches
--	I24_2	Precipitation intensity for a 24-hour storm having a 2-year recurrence interval, in inches per hour
--	JANMIN	Mean minimum January temperature, in degrees F
--	WAC	Width of active channel, in feet
--	W2	Mean depth for active channel, in feet
--	WBF	Width of bankfull channel, in feet
--	W4	Mean depth of bankfull channel, in feet

Montana Flood-Frequency and Basin-Characteristic Data

Retrieved on: 2017.09.16 20:26:37

Appendix B – Review of Collection Sediment Bed Samples for Sensitivity Analysis

Review of Collected Sediment Bed Samples for Sensitivity Analysis

An attempt was made to use the geotechnical analysis logs and recorded survey notes for the samples collected near the crossing location to determine the D_{50} and D_{90} size. However, wide variation in characteristic and D_{50} were observed in the collected sample dataset, suggesting that the previous bed sampling effort did not provide a consistent substrate representation, but more likely represented the top of the local active layer at various levels in the channel.

Representative D_{50} for use in the Scour Analysis

The bed sample data near the crossing location was compiled and is presented in Appendix B. The original survey notes and complete dataset were reviewed based on the datasheets provided by USACE. For determining the elevation at which the sample was collected, the recorded gage depth and the surface water elevation were determined at the date of collection. The data from the recorded depth of the bed samples were compared with streamgage data to determine flow conditions and elevation at which the bed sample was acquired. A summary table is provided in the appendix showing very little correlation to depth and flow and a wide range of bed sample sizes.

For the 2014 bed samples, no water surface elevation data was recorded at the time the samples were taken to establish the elevation where the bed material was collected. Using available historical daily flow data from the stream gage located near Fort Peck Dam on the Missouri River, the water surface elevations could be estimated. The gage height records at the streamgage located nearest to the sampling location was limited. However, water quality records provided additional data and the approximate water surface elevation could be estimated at around 2,021 feet at the time of collection. Using that information while subtracting out the depth, gave an estimated depth of 2,013 feet for the northern sample, ,2016 feet for the middle sample, and 2,017 feet for the southern sample. The bed elevation at the crossing location is near 2,010 -2,014 feet, indicating that the samples taken were not of the substrate bed material. More than likely they are of transient dunes, and the south sample likely a finer representation due to vertical selective sorting. The laboratory experiments conducted in “Transport of Gravel and Sediment Mixtures” of “Parker’s Chapter 3 for ASCE Manual,” under the section “3.15.2 Extension of the Active Layer Model to Describe Vertical Sorting,” illustrate the process by which the active layer is transported downstream above the substrate layer. The sample from the inside bend likely took a smaller diameter bed representation at a higher level of the active layer. This is indicated by the finer representation than what is present in the rest of the active layer. It is not likely to be representative of the layer to be encountered during a scour event and should not be used to determine the depth of scour for the design event. This active layer and moving sand dune is comprised of downstream fining, abrasion of upstream gravel material, entrainment of the active bed layer, and settlement during baseflow and recession limb of inflow events. This layer forms due to the transport of bed material downstream and can selectively sort. It will typically have layers of finer material overlaid on a coarser layer.

The exact source of the material collected in the 2014 sampling is unknown. Defining the likely source allows for the categorization for appropriateness for use in the analysis. The samples could be from the upstream active layer, mixing and sorting of the local active layer during base flow or the substrate material. Most likely it is a mixture of all three.

In the Sediment Trends Study, it appears the 1978 sampling is an outlier and no detail is provided on the methodology used to combine four samples into a single datapoint. This also is the case for the 1973A sampling. The characteristics for these samples don't conform to any of the other samples collected at the crossing location. It is likely that these are not representative of the substrate material, but are likely from a moving active layer that is subjected to selective sorting. With the exceptions of the 1973A and 1978 samples as noted above, most samples had similar characteristics to the samples taken for the scour analysis. 2014A and 201C were much finer, and 1973B was much coarser. The D_{50} for the filtered dataset, five were smaller, and nine were larger than the sediment sample used for the design.

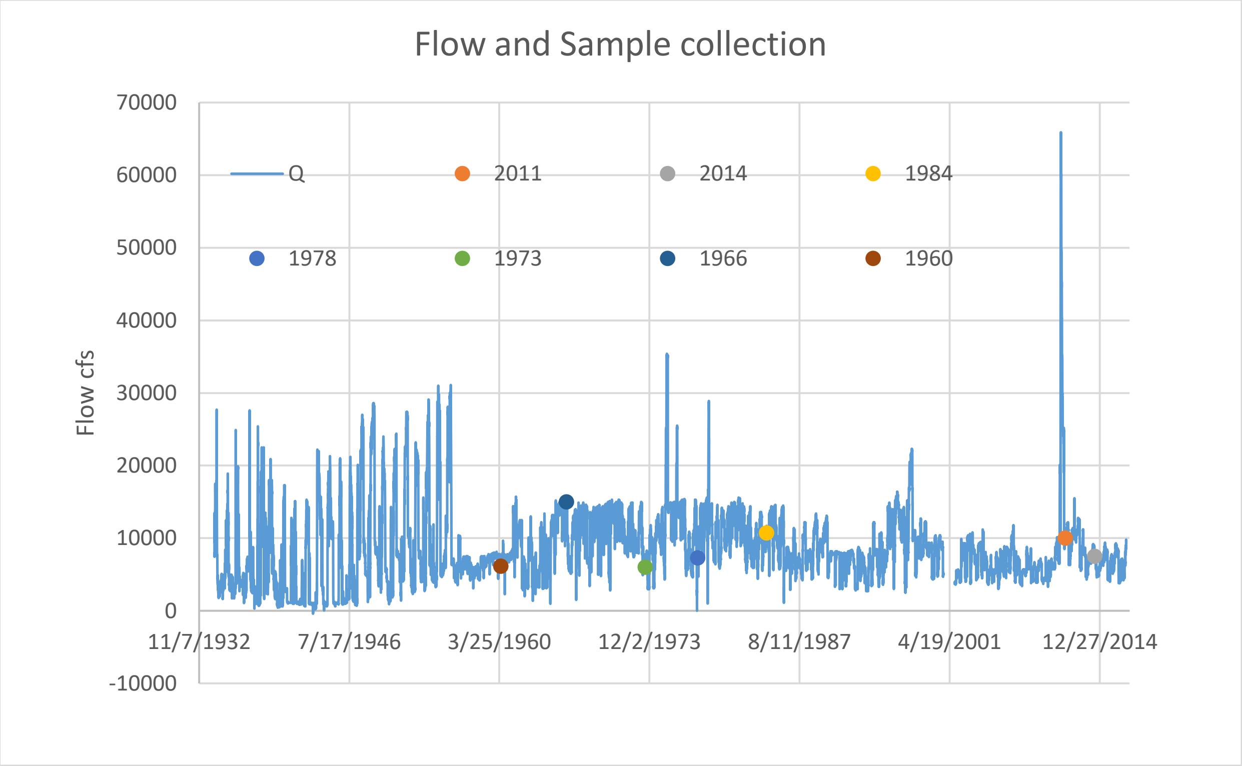
There is significant variation in the sample data collected, as noted above. This indicates significant variation from sample to sample. The wide variation of the collected bed layer data suggests the active bed could be both smaller and larger than the samples collected at the crossing location, with more datapoints indicating a larger mean diameter. A deeper sample of the substrate material would likely yield more consistent results than the samples collected of the active layer. Based on the data presented, it would unlikely for an extended layer to consist of only smaller diameter bed material for a significant depth given the variation in the sampling dataset.

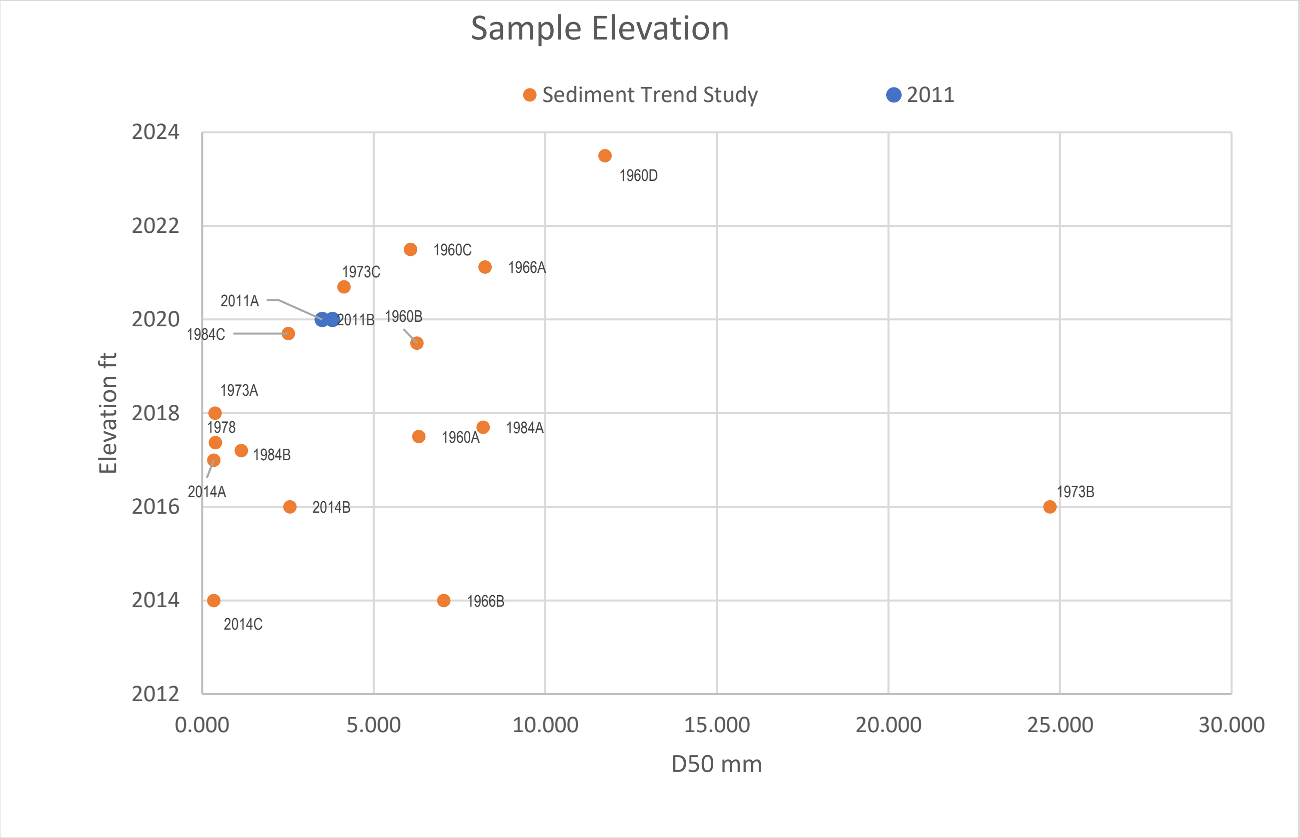
This suggests that the material collected by the sampler is highly dependent on location. There are numerous dynamics that occur depending on the location of the sampling. It is important to note that the samples were collected to support a Sediment Trends Study and were not taken precisely at the crossing location. The variation in the values in the Sediment Trends Study is most likely too great to have any confidence in using a singly value from them in a scour model and with the fact that sediment samples have been collected at the specific crossing location for the sole purpose of performing a scour analysis, and the samples align with the borehole data taken at the crossing location. In addition, the sample collection occurred 5 months after the 2011 event. The bed sample obtained directly following a scour event is more likely to represent the material that would be encountered and represent the layer to perform a scour analysis on and predict the depth of scour. The 2014 sample occurred 37 months after the 2011 event with no significant scouring event preceding it. It would have had adequate time to refill from the scour event and the channel to reconfigure the active layer following several minor events. The active layer and subsequent dune formations would then be the likely source of the collected samples in 2014.

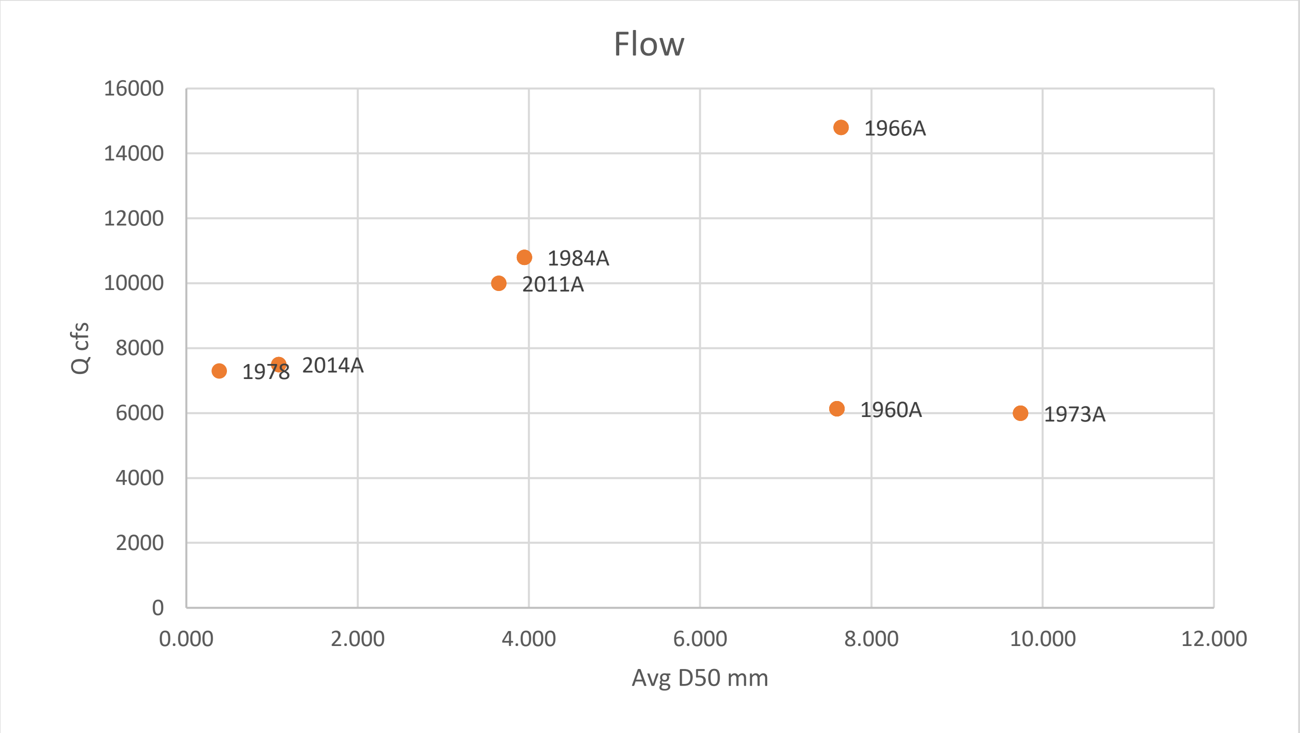
Armor Layer

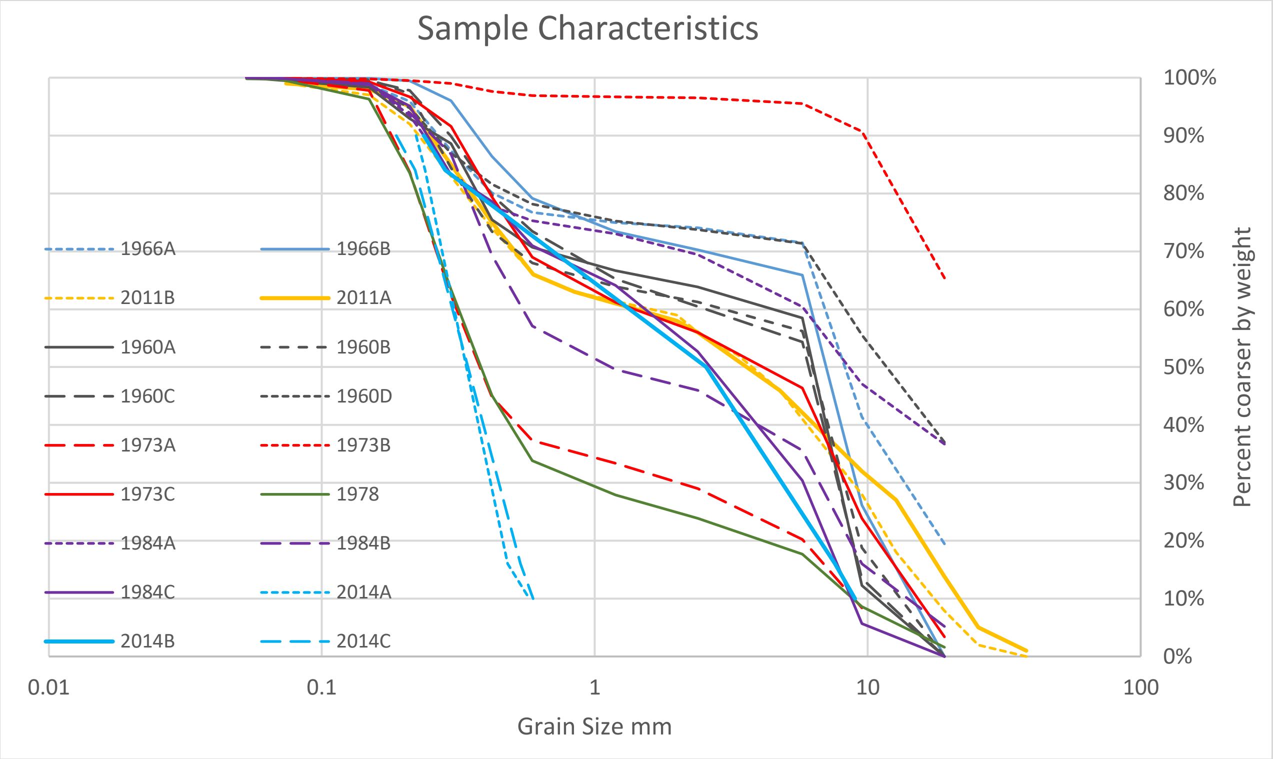
The armoring that occurs on the riverbed has developed due to river geomorphology that both deepen and broaden the valley of the floodplain over geologic timescales. The riverbed produces a self-armoring layer as events pass through over a very long period, leaving larger diameter bed material behind that is less likely to move to act as an armor layer in the channel. This can be significant as recent research indicates that this armor layer is not removed or eliminated with a significant event (Experimental Study of the Transport of Mixed Sand and Gravel), but goes deeper as fill is added back on the recession limb. This has occurred for many millennia, prior to the construction of the dam. The degradation phase has nearly completed and the substrate will likely remain consistent based on the bore logs at the crossing location. There is little evidence to suggest that the armor layer does not exist or that it will be transported away.

Missouri River Collected Bed Samples								
Crossing	**Year**	**D50 (mm)**	**Depth (ft)**	**Flow (cfs)**	**Surface water elevation (ft)**	**Sample elev (ft)**	**Avg d50 (mm)**	**Consolidated sample depths(ft) (avg used)**
	2011A	3.5	1	10000	2021	2020	3.650	
	2011B	3.8	1	10000	2021	2020	3.650	
RM1861.1	2014A	0.339	4	7500	2021	2017	1.080	
RM1861.1	2014B	2.557	5	7500	2021	2016	1.080	
RM1861.1	2014C	0.343	7	7500	2021	2014	1.080	
RM1861.1	1984A	8.185	6.5	10800	2024.2	2017.7	3.946	
RM1861.1	1984B	1.146	7	10800	2024.2	2017.2	3.946	
RM1861.1	1984C	2.508	4.5	10800	2024.2	2019.7	3.946	
RM1861.1	1978	0.383	*6.125*	7300	2023.5	2017.4	0.383	4.5,9,7,4
RM1861.1	1973A	0.379	*5.5*	6000	2023.5	2018	9.741	6,6.5,4
RM1861.1	1973B	24.709	7.5	6000	2023.5	2016	9.741	
RM1861.1	1973C	4.135	2.8	6000	2023.5	2020.7	9.741	
RM1861.1	1966A	8.246	*3.875*	14800	2025	2021.1	7.645	2.5,4.5,7.5,1
RM1861.1	1966B	7.043	11	14800	2025	2014	7.645	
RM1861.1	1960A	6.315	7.5	6140	2025	2017.5	7.597	
RM1861.1	1960B	6.261	5.5	6140	2025	2019.5	7.597	
RM1861.1	1960C	6.077	3.5	6140	2025	2021.5	7.597	
RM1861.1	1960D	11.737	1.5	6140	2025	2023.5	7.597	




Sample Elevation
● Sediment Trend Study
● 2011
Elevation ft
D50 mm
2024
2022
2020
2018
2016
2014
2012
0.000
5.000
10.000
15.000
20.000
25.000
30.000
1960D
1960C
1966A
1973C
2011A
2011B
1960B
1984C
1973A
1978
1984B
1960A
1984A
2014A
2014B
1973B
2014C
1966B


Flow
Q cfs
Avg D50 mm
16000
14000
12000
10000
8000
6000
4000
2000
0
0.000
2.000
4.000
6.000
8.000
10.000
12.000
1966A
1984A
2011A
1978
2014A
1960A
1973A


Sample Characteristics
1966A
1966B
2011B
2011A
1960A
1960B
1960C
1960D
1973A
1973B
1973C
1978
1984A
1984B
1984C
2014A
2014B
2014C
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
Percent coarser by weight
0.01
0.1
1
10
100
Grain Size mm

Appendix C –
Long Term Bed Elevation Change

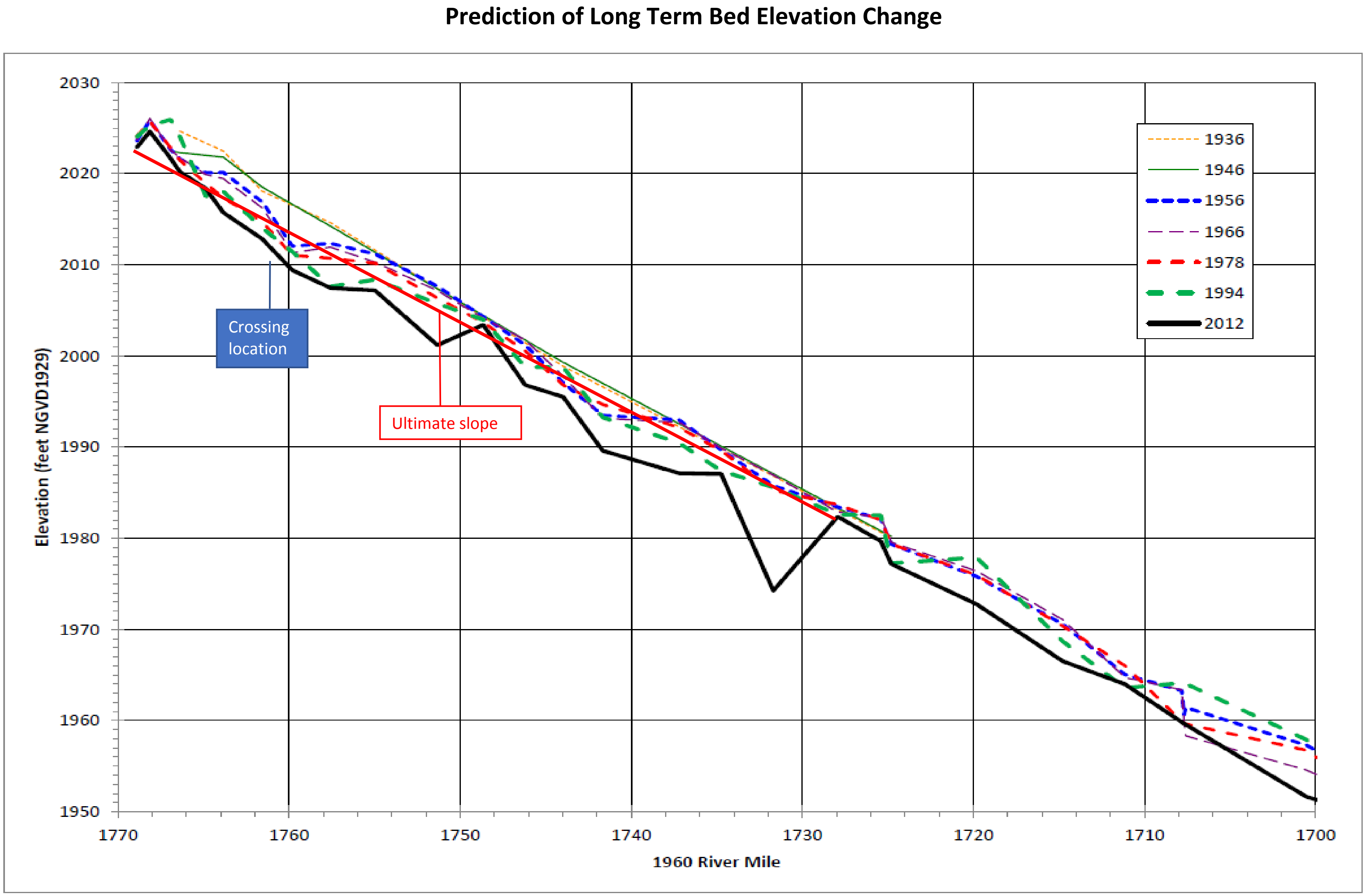


Figure 6-10. Active Channel Average Bed Elevation Profile (Beginning of Reach to RM 1700)

Supplemented with data from M.R.B Sediment Memorandum 28

Prediction of Long Term Bed Elevation Change

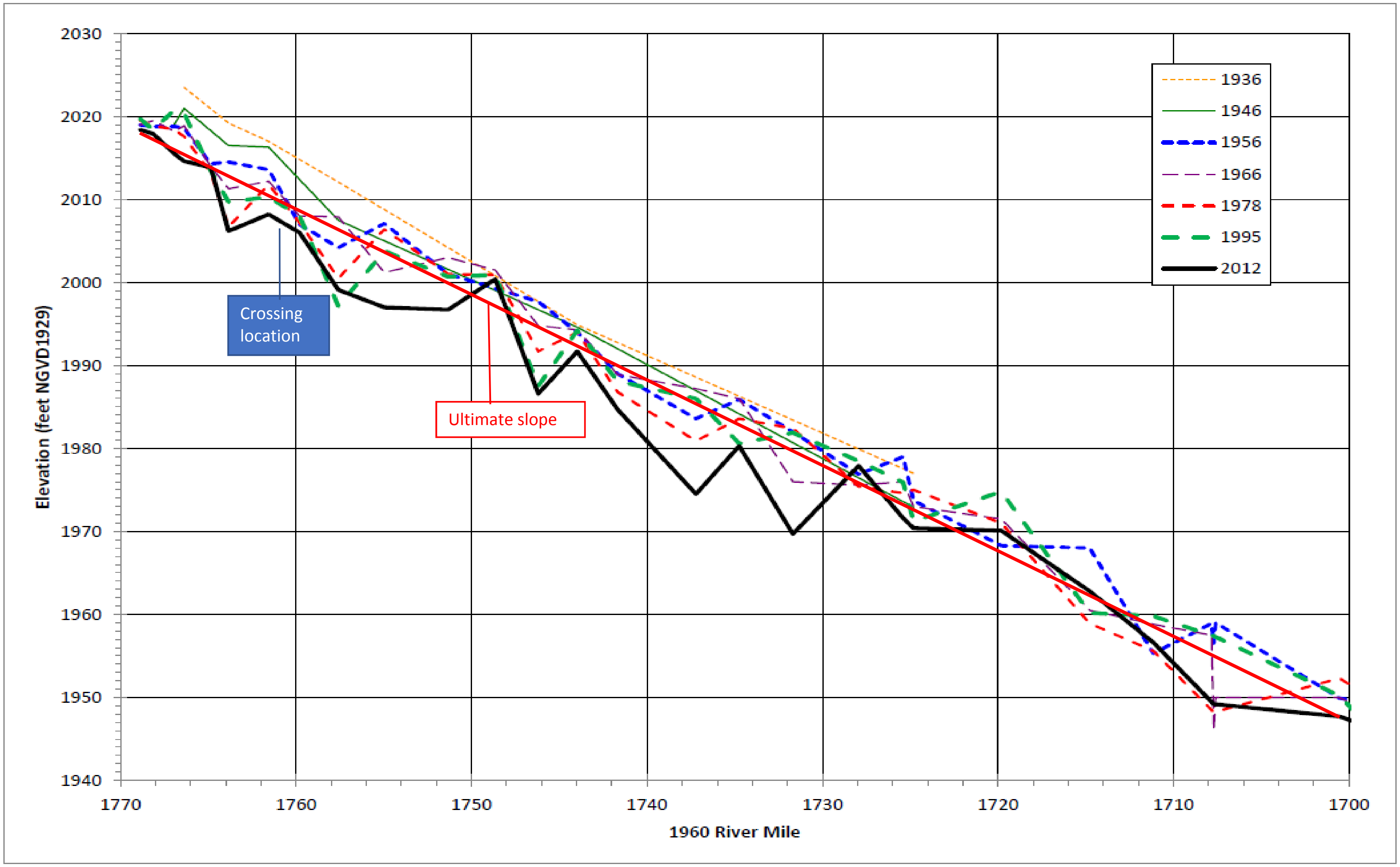
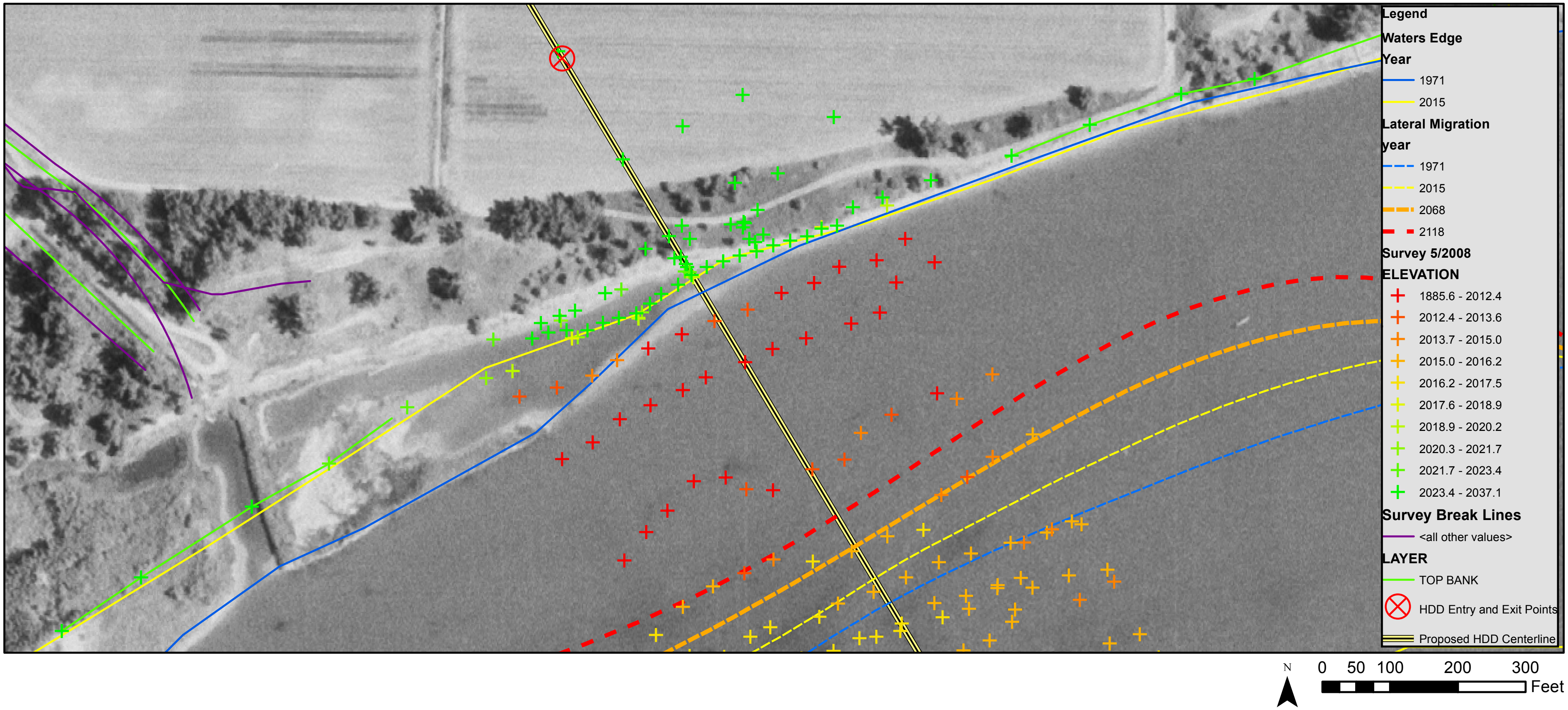


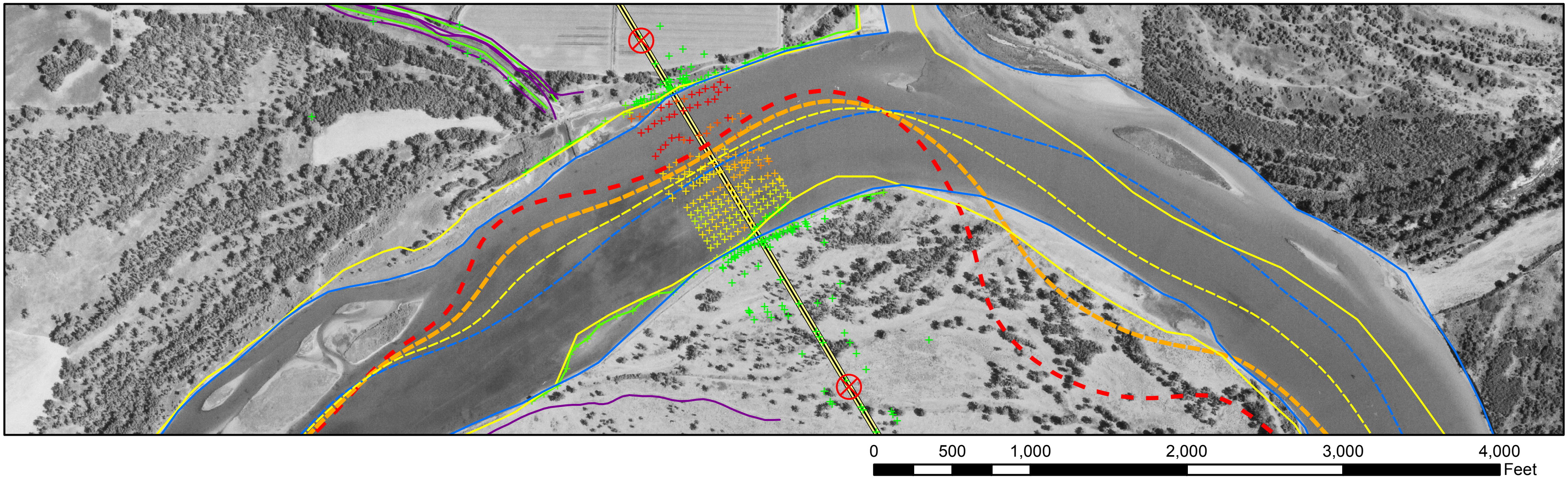
Figure 6-12. Thalweg Elevation Profile (Beginning of Reach to RM 1700)

Supplemented with data from M.R.B Sediment Memorandum 28

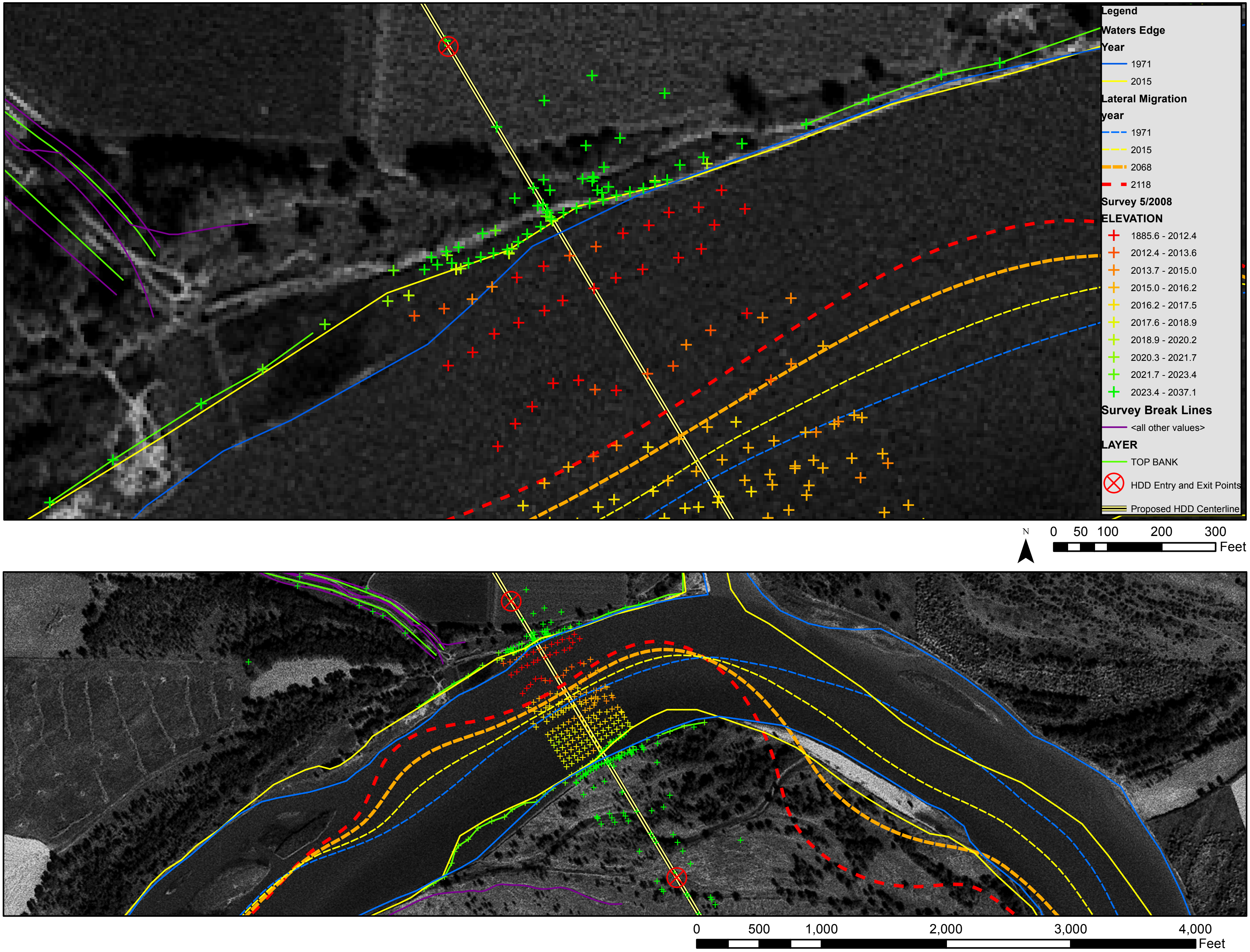
Appendix D –
Lateral Migration Analysis

Missouri River HDD Crossing Lateral Migration Analysis: 1971 Aerial

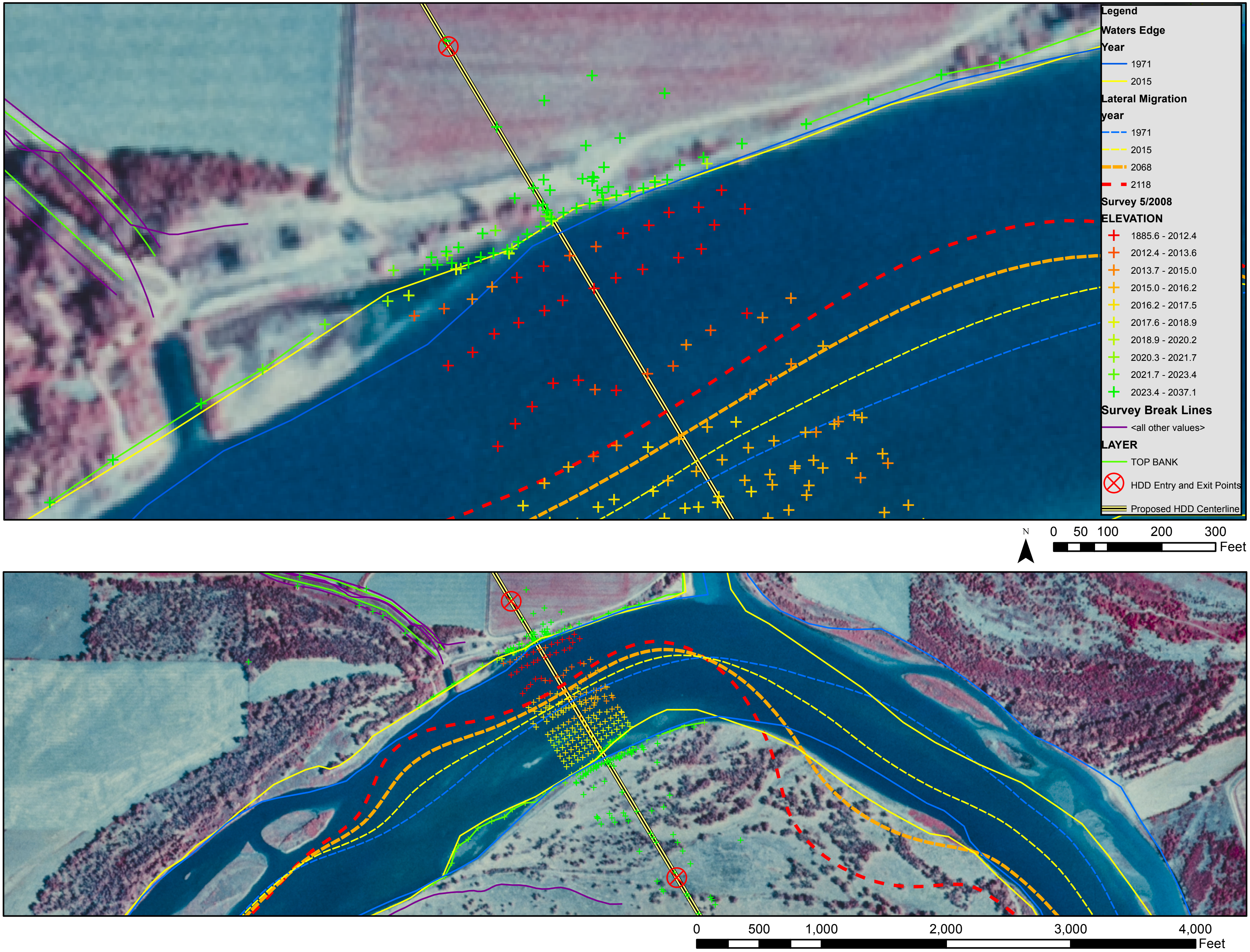




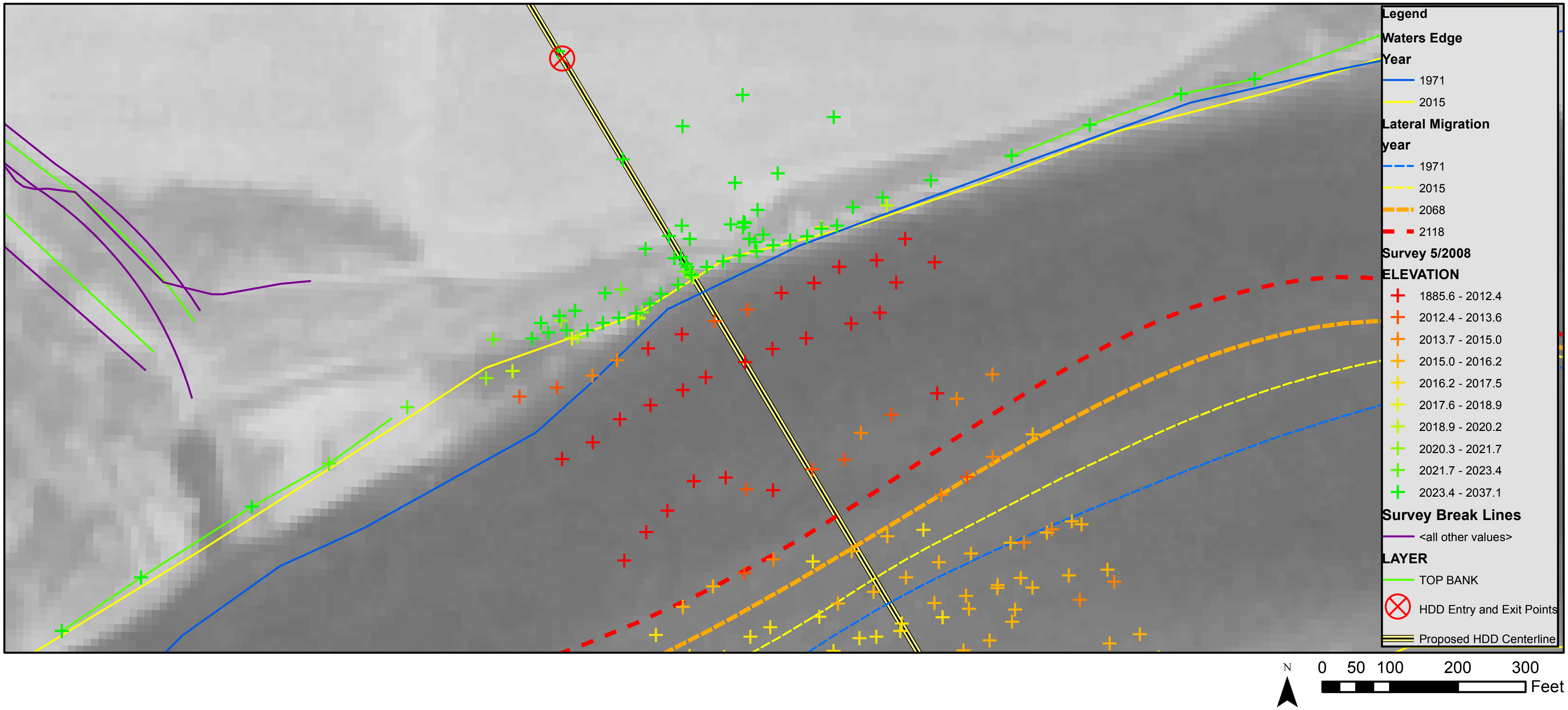
Missouri River HDD Crossing Lateral Migration Analysis: 1975 Aerial

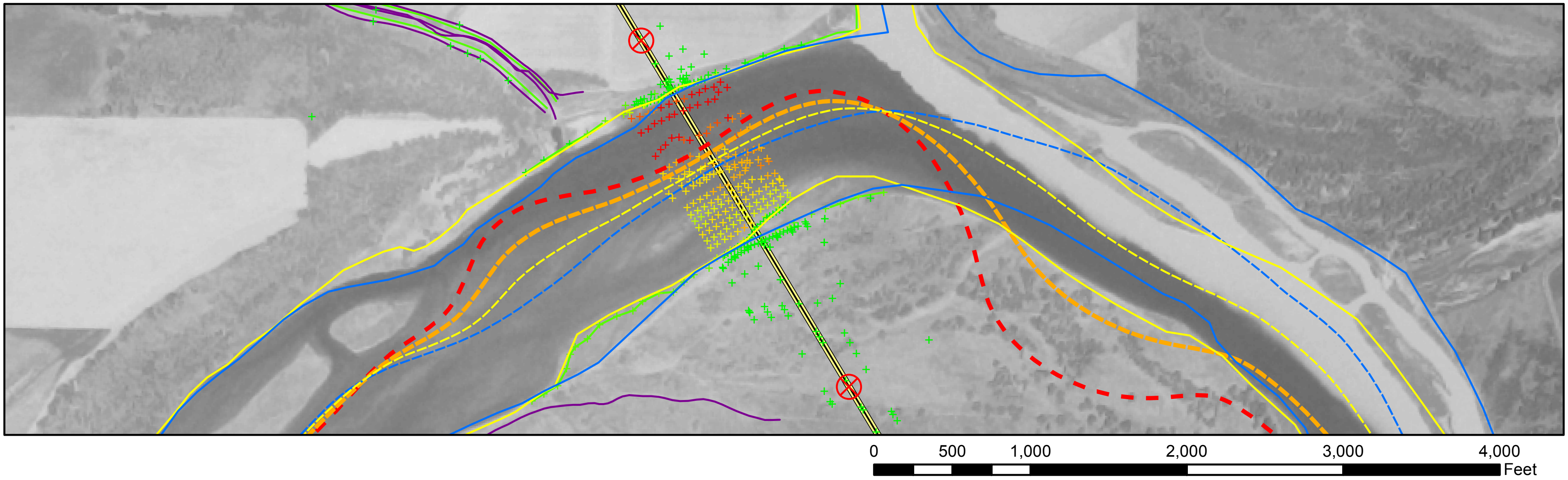


Missouri River HDD Crossing Lateral Migration Analysis: 1985 Aerial

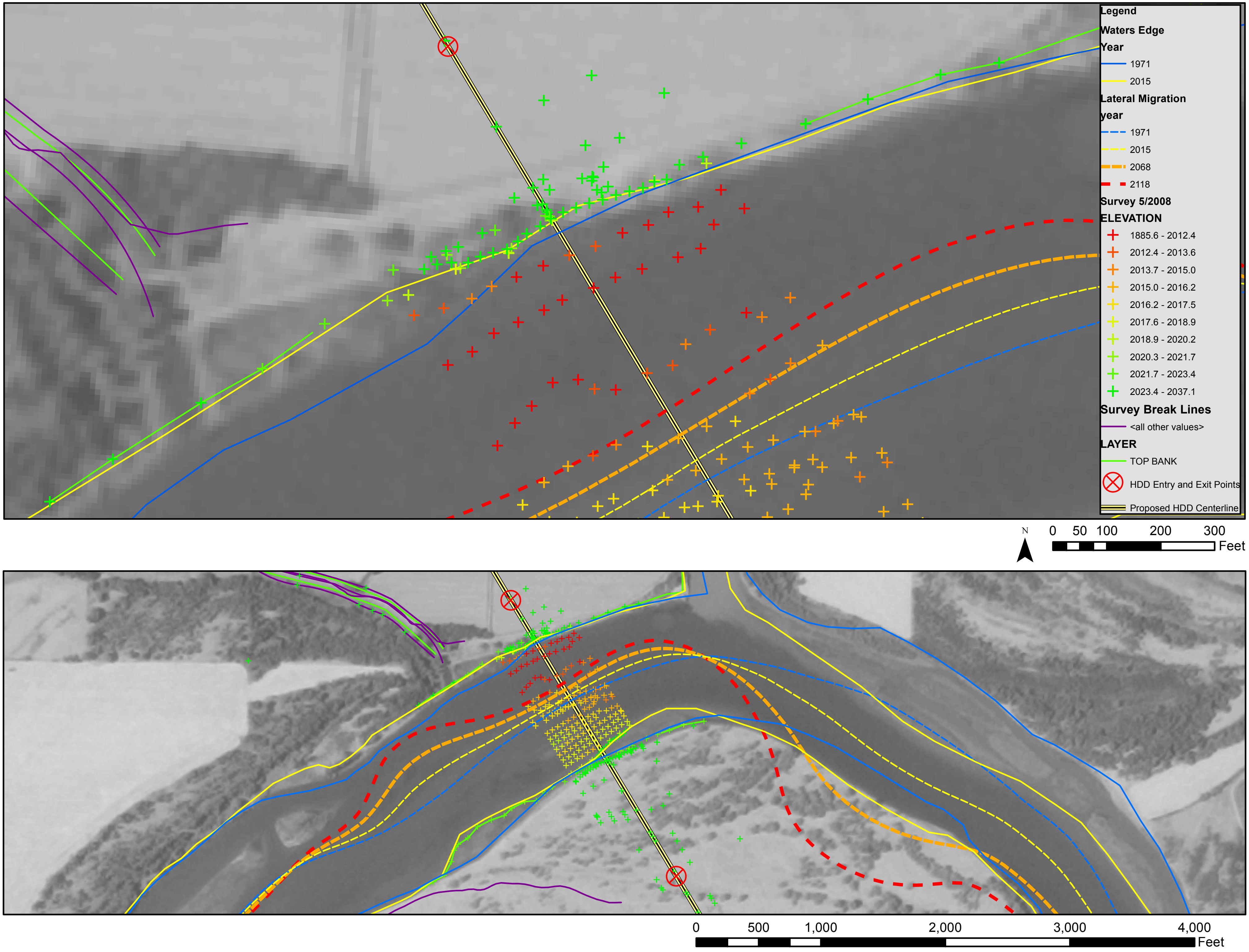


Missouri River HDD Crossing Lateral Migration Analysis: 1991 Aerial

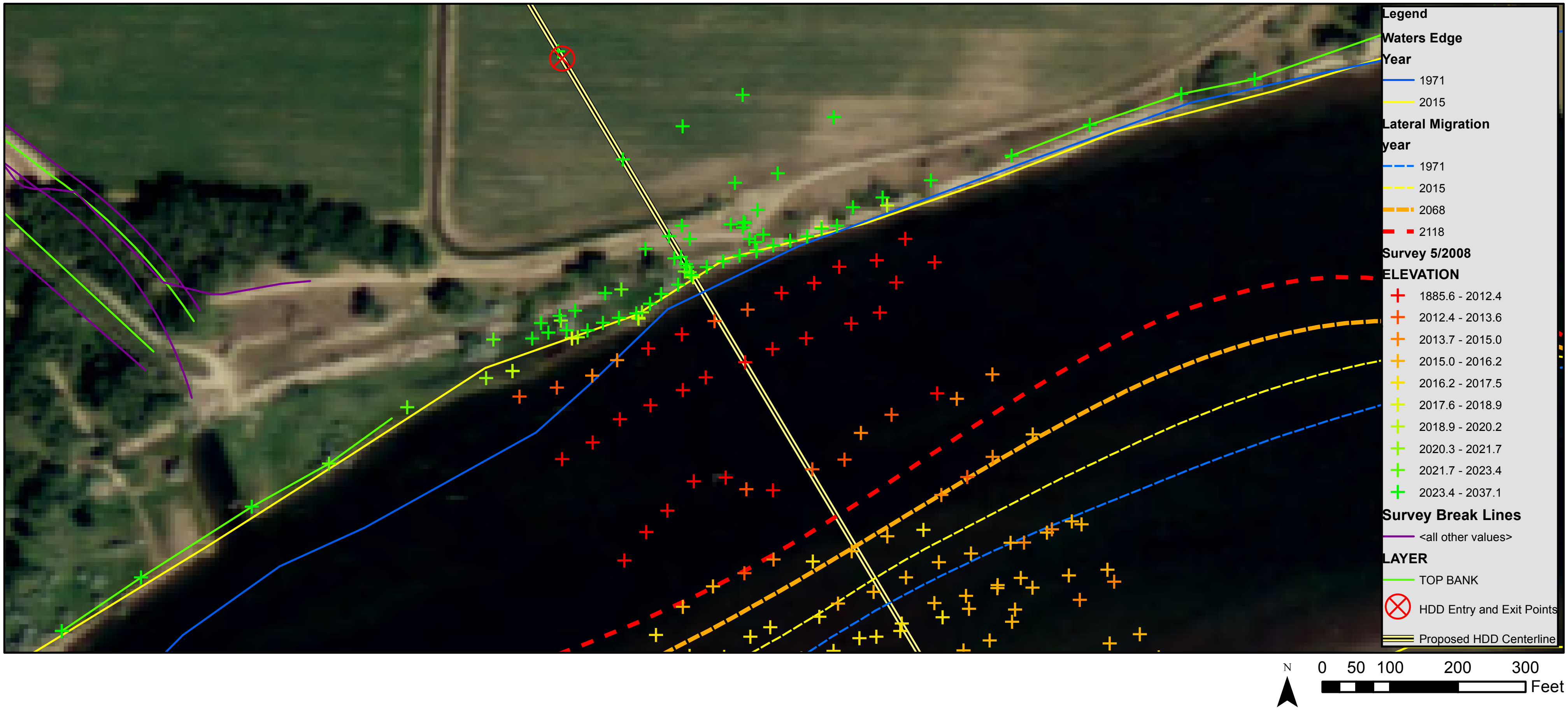


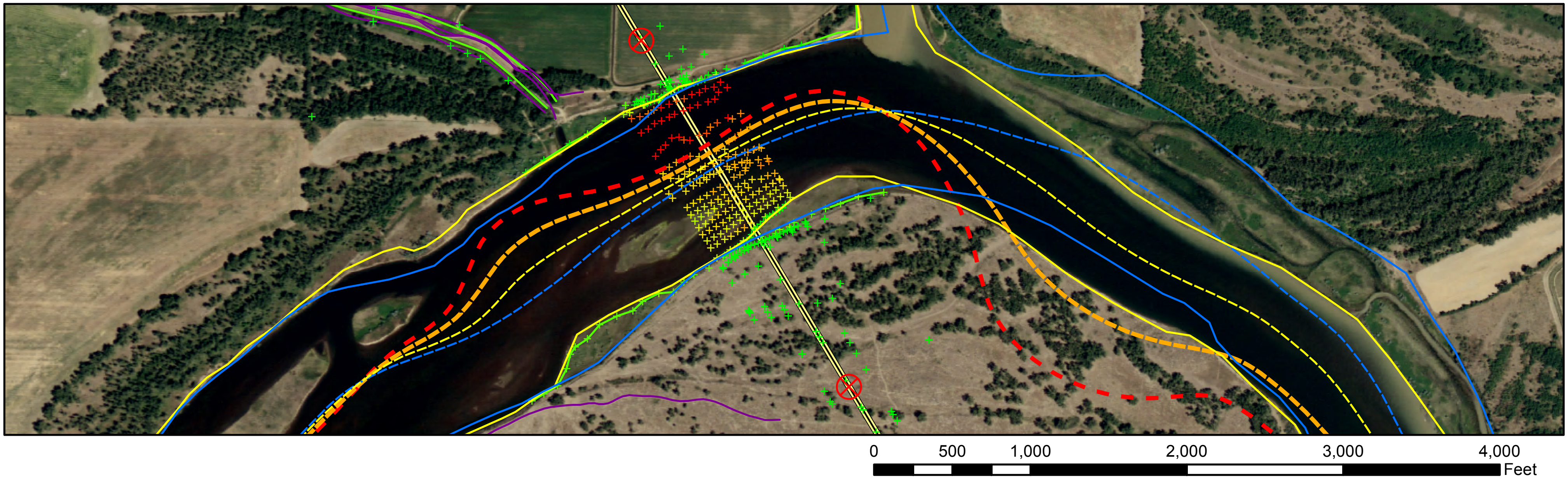


Missouri River HDD Crossing Lateral Migration Analysis: 1996 Aerial

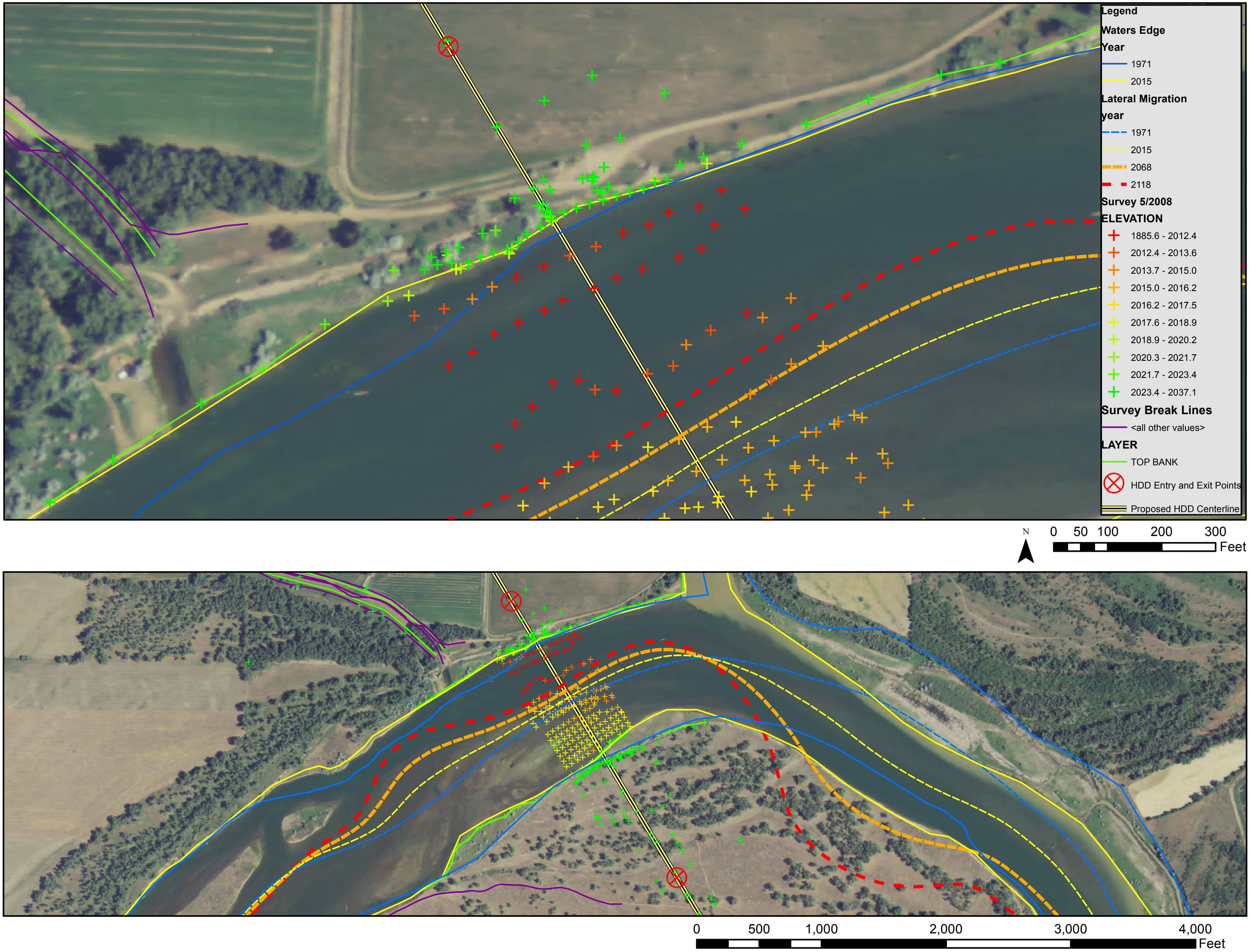


Missouri River HDD Crossing Lateral Migration Analysis: 2006 Aerial

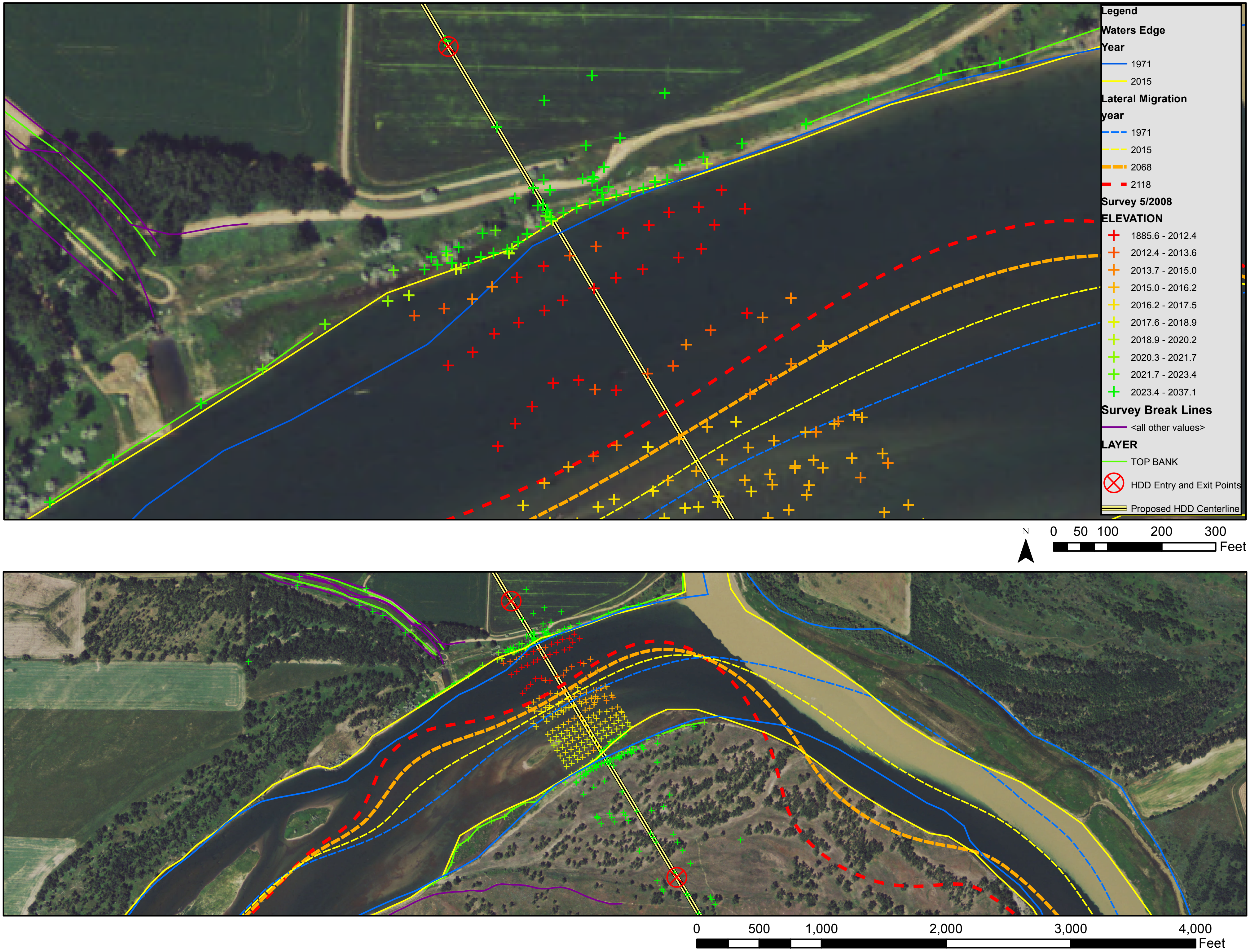




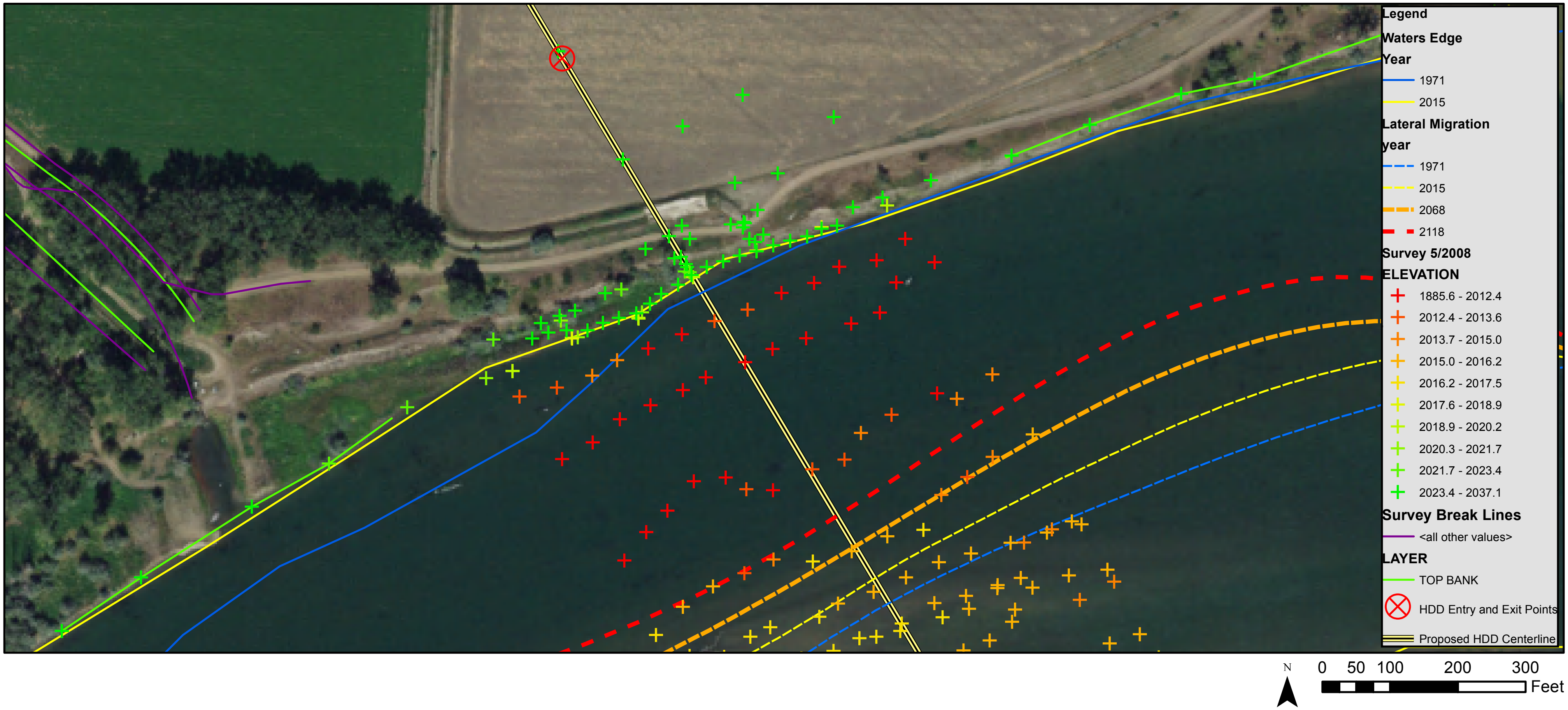
Missouri River HDD Crossing Lateral Migration Analysis: 2009 Aerial

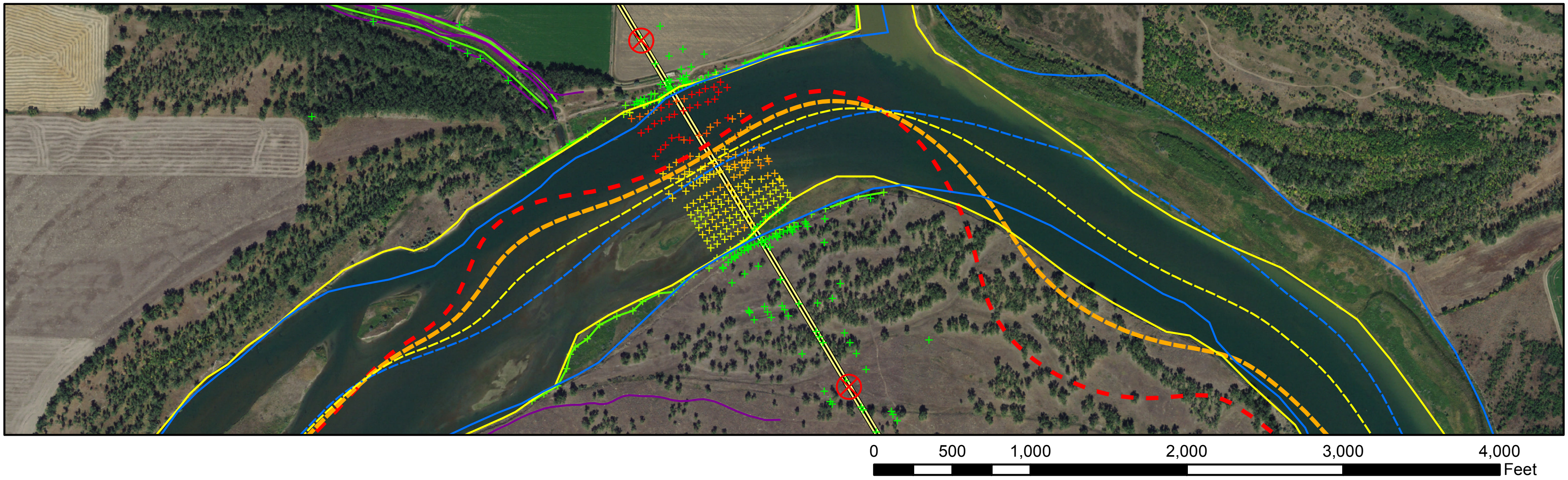


Missouri River HDD Crossing Lateral Migration Analysis: 2013 Aerial

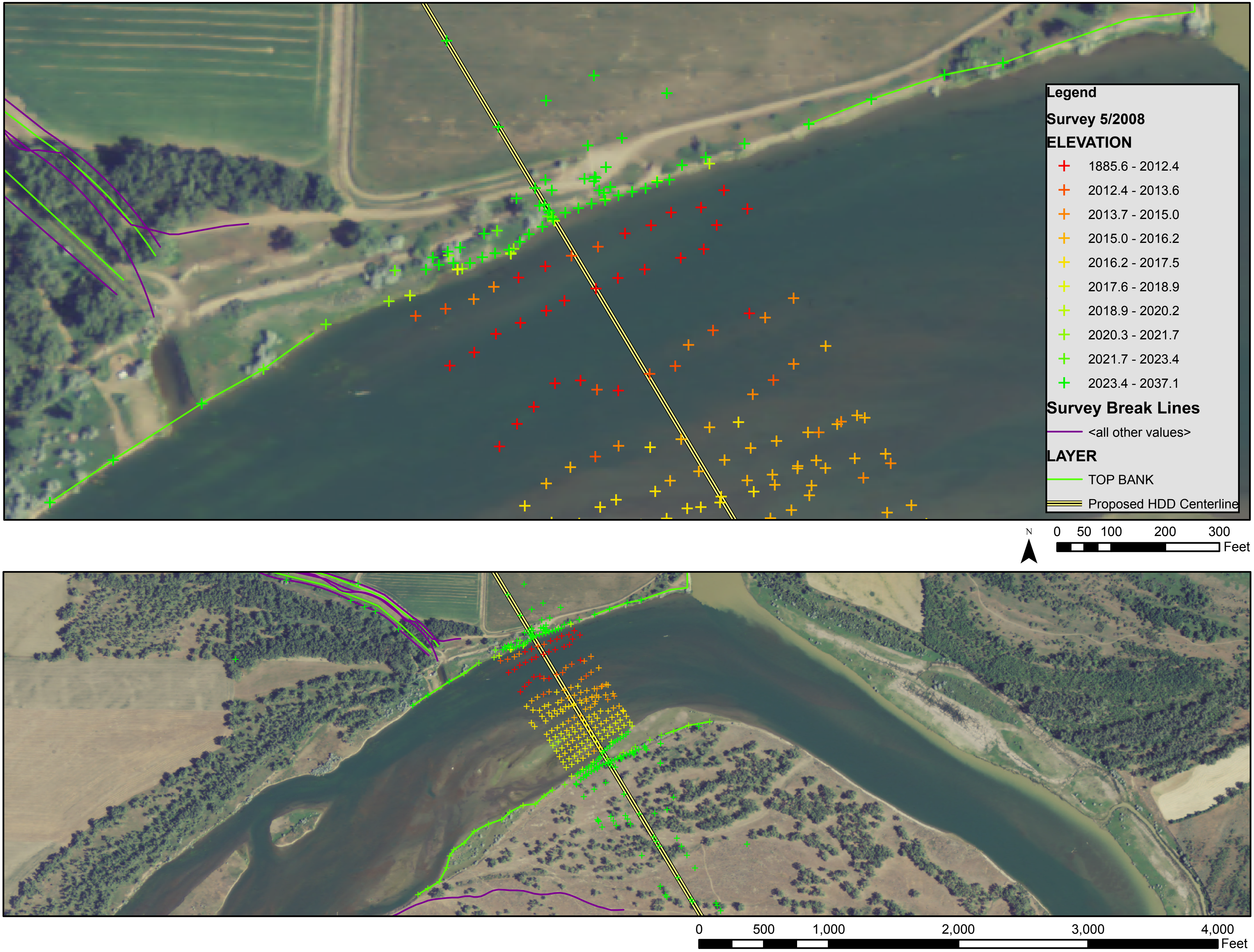


Missouri River HDD Crossing Lateral Migration Analysis: 2015 Aerial

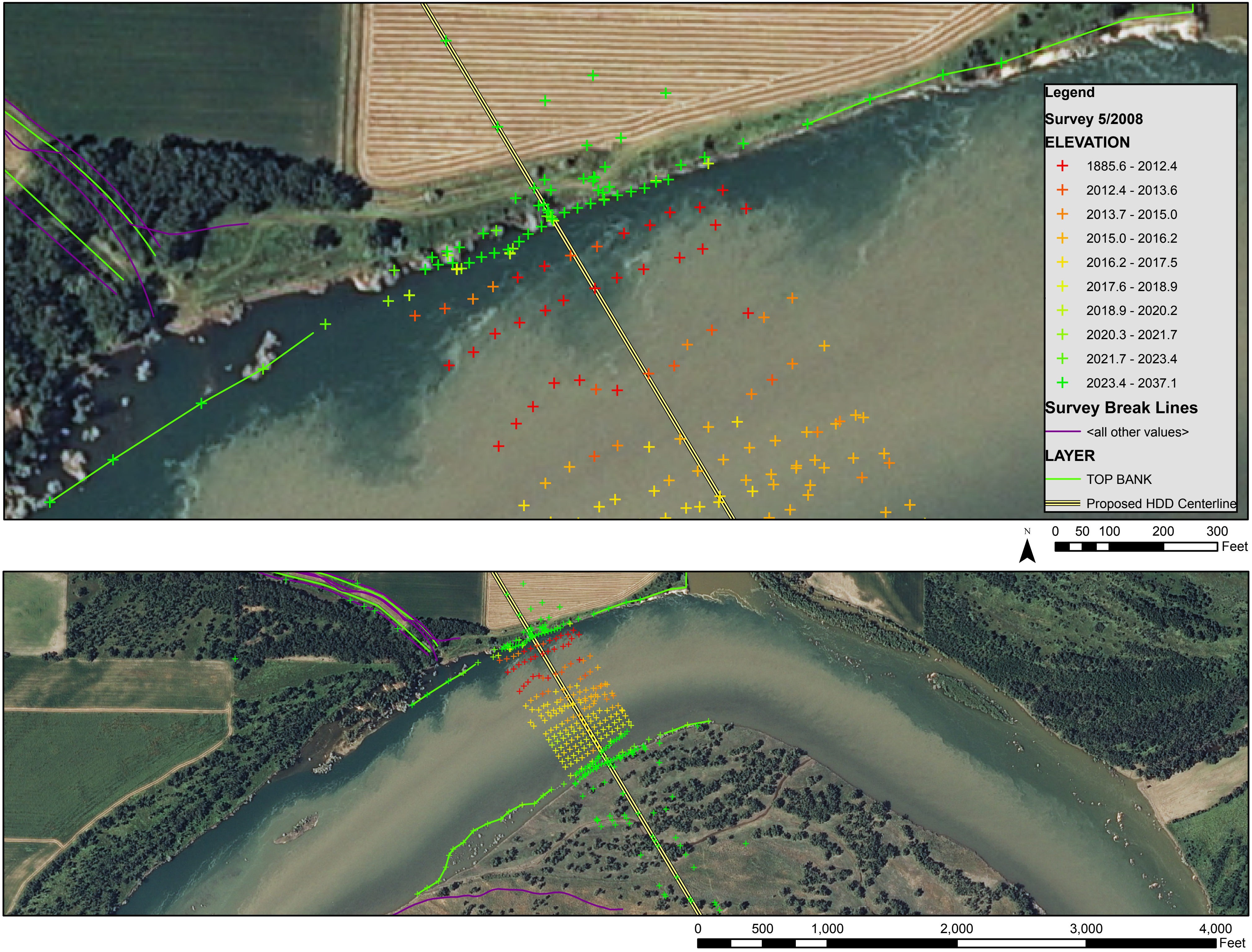




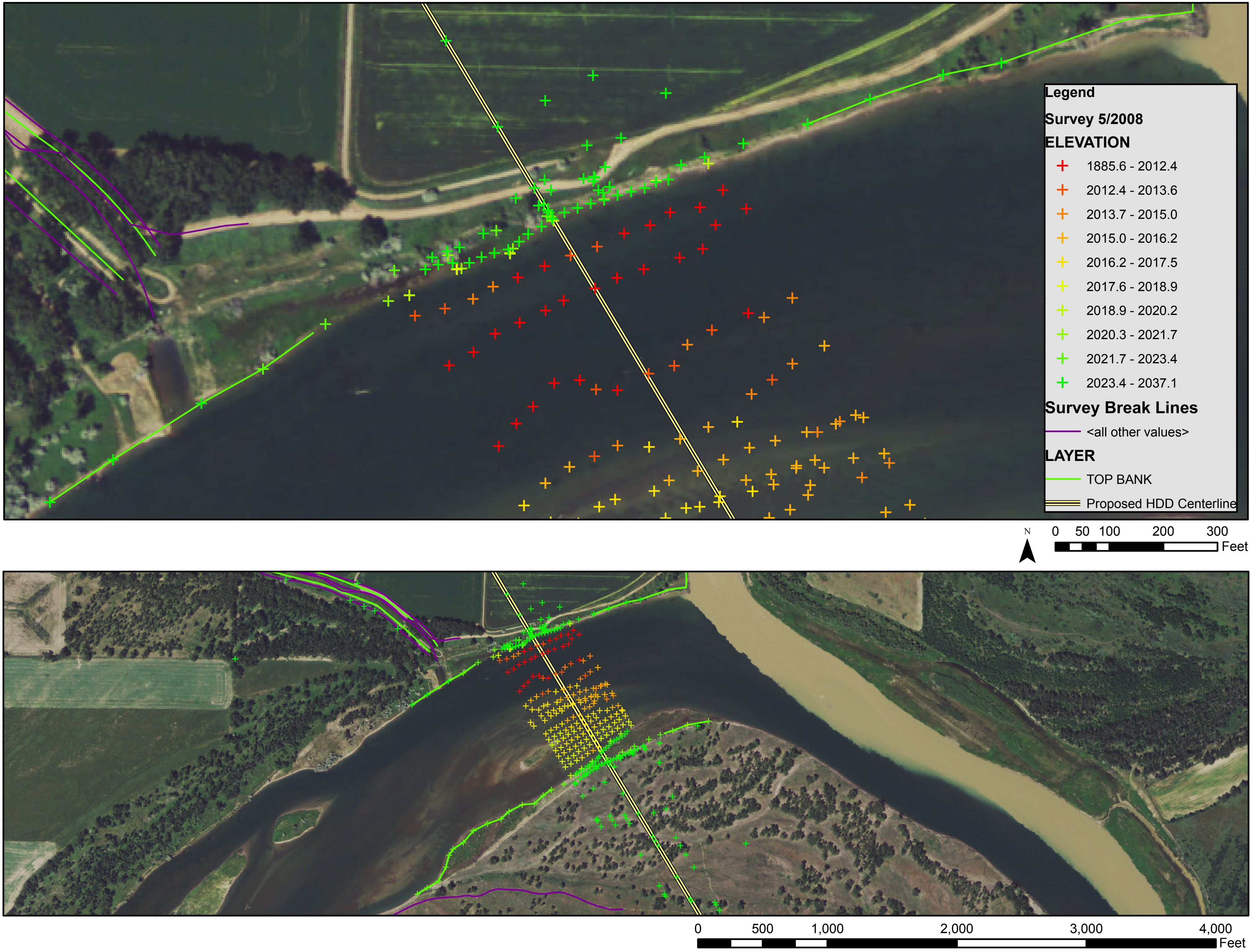
Missouri River HDD Crossing Bank Erosion Analysis: 2009 Aerial

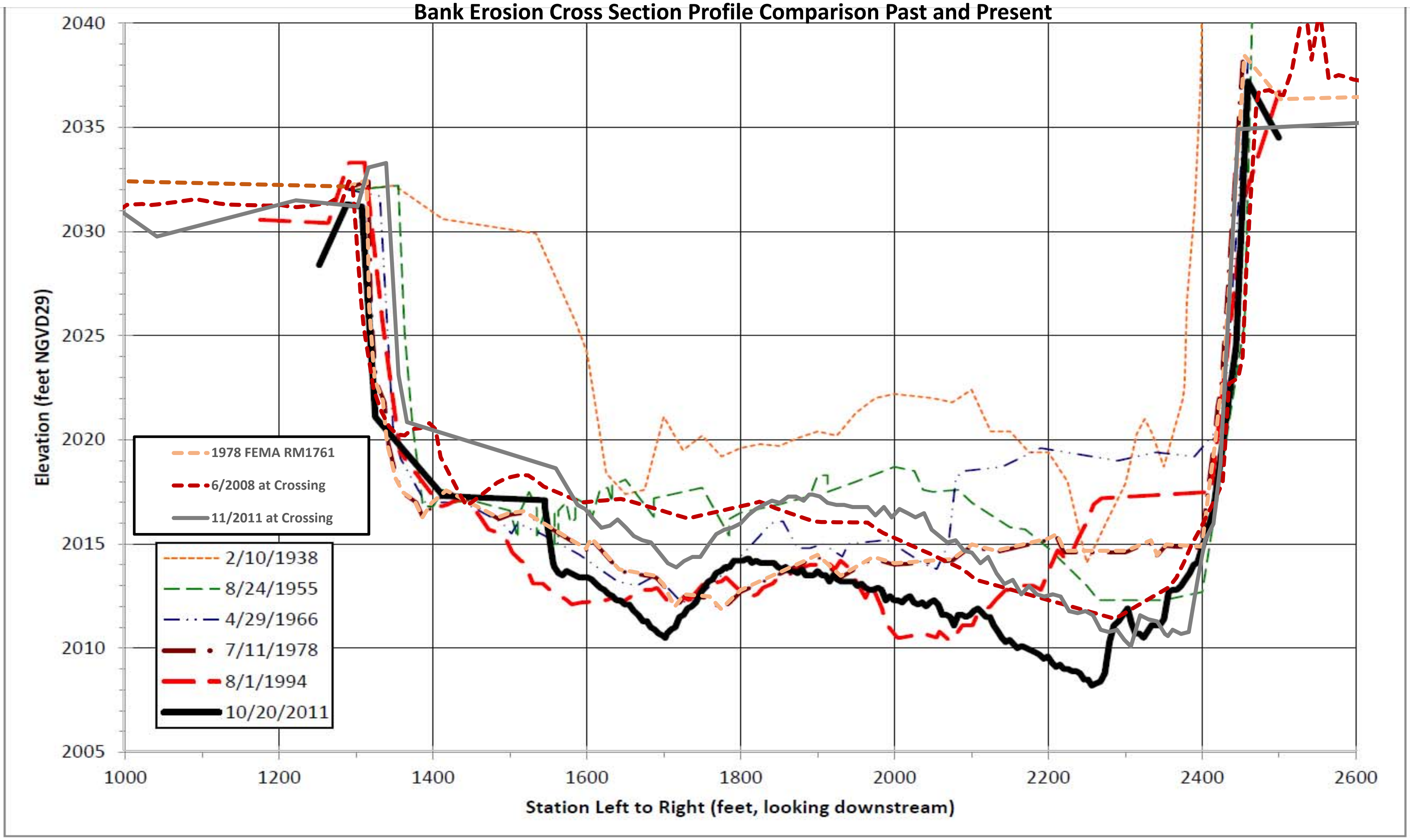


Missouri River HDD Crossing Bank Erosion Analysis: 2011 Aerial



Missouri River HDD Crossing Bank Erosion Analysis: 2013 Aerial

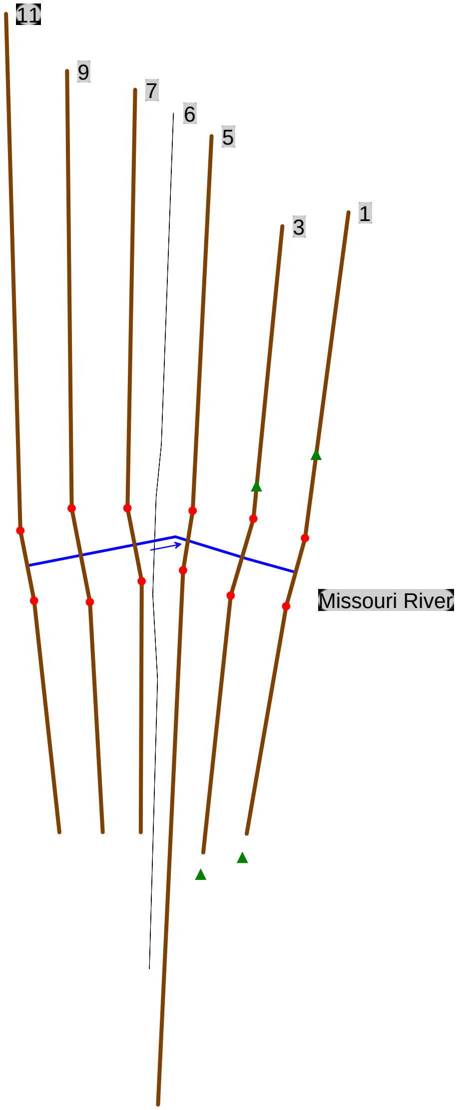




Supplemented with data from Fort Peck Downstream Sediment Trends Study 4/2013: Figure A-7. Cross-Section at 1761.56 (Range 1857.5) on Page A-7 of the M.R.B Sediment Memorandum 2

Appendix E –
HEC-RAS Model Output

HEC-RAS Plan View


11
9
7
6
5
3
1
Missouri River

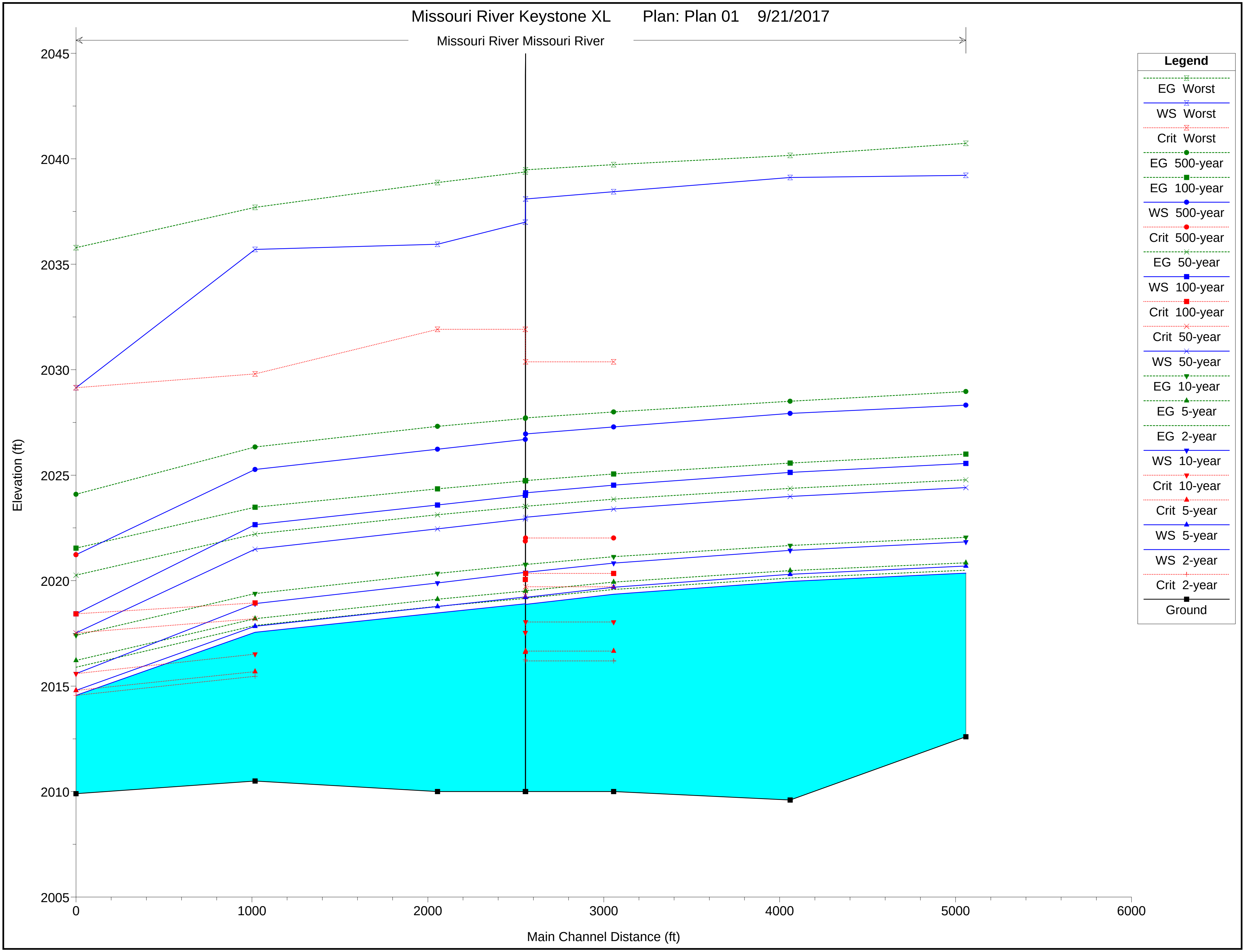
Hydraulic Summary Tables

HEC-RAS River: Missouri River Reach: Missouri River

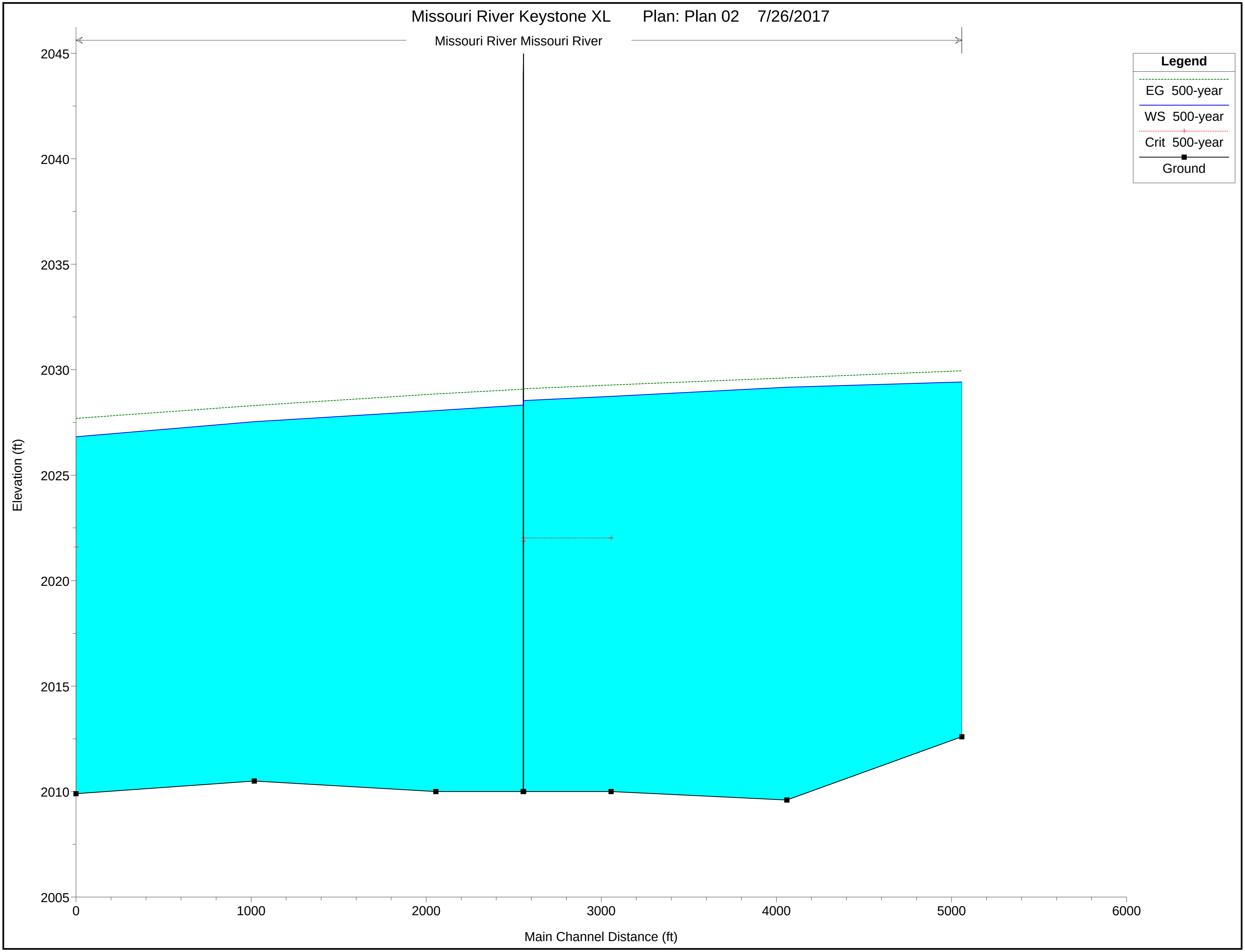
Reach	River Sta	Profile	Plan	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
				(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)	(sq ft)	(ft)	
Missouri River	11	2-year	Critical	15000.00	2012.60	2020.36		2020.49	0.000315	2.97	5043.06	1128.51	0.25
Missouri River	11	2-year	Normal	15000.00	2012.60	2021.34		2021.44	0.000164	2.43	6162.53	1139.49	0.18
Missouri River	11	5-year	Critical	17000.00	2012.60	2020.69		2020.84	0.000319	3.13	5422.80	1132.25	0.25
Missouri River	11	5-year	Normal	17000.00	2012.60	2021.79		2021.90	0.000162	2.55	6678.18	1144.51	0.19
Missouri River	11	10-year	Critical	25000.00	2012.60	2021.84		2022.05	0.000341	3.72	6729.05	1145.01	0.27
Missouri River	11	10-year	Normal	25000.00	2012.60	2023.04		2023.19	0.000194	3.06	8170.46	1218.49	0.21
Missouri River	11	50-year	Critical	48000.00	2012.60	2024.41		2024.78	0.000390	4.87	9846.45	1229.85	0.30
Missouri River	11	50-year	Normal	48000.00	2012.60	2025.62		2025.90	0.000246	4.23	11335.88	1238.07	0.25
Missouri River	11	100-year	Critical	60000.00	2012.60	2025.56		2026.00	0.000394	5.33	11260.03	1237.66	0.31
Missouri River	11	100-year	Normal	60000.00	2012.60	2026.77		2027.11	0.000262	4.70	12769.99	1284.36	0.26
Missouri River	11	500-year	Critical	95000.00	2012.60	2028.32		2028.97	0.000416	6.45	15010.64	1640.75	0.33
Missouri River	11	500-year	Normal	95000.00	2012.60	2029.42		2029.95	0.000309	5.87	16867.43	1776.24	0.29
Missouri River	11	Worst	Critical	350000.00	2012.60	2039.21		2040.73	0.000482	10.58	60392.72	8724.63	0.40
Missouri River	11	Worst	Normal	350000.00	2012.60	2040.61		2041.79	0.000360	9.54	75210.56	12419.93	0.35
Missouri River	9	2-year	Critical	15000.00	2009.60	2019.96		2020.12	0.000434	3.21	4680.11	1192.29	0.29
Missouri River	9	2-year	Normal	15000.00	2009.60	2021.17		2021.26	0.000186	2.44	6149.49	1248.34	0.19
Missouri River	9	5-year	Critical	17000.00	2009.60	2020.30		2020.47	0.000430	3.34	5083.12	1207.92	0.29
Missouri River	9	5-year	Normal	17000.00	2009.60	2021.63		2021.73	0.000179	2.53	6723.20	1258.79	0.19
Missouri River	9	10-year	Critical	25000.00	2009.60	2021.44		2021.67	0.000436	3.85	6486.17	1258.00	0.30
Missouri River	9	10-year	Normal	25000.00	2009.60	2022.85		2022.99	0.000195	3.02	8268.93	1263.90	0.21
Missouri River	9	50-year	Critical	48000.00	2009.60	2023.99		2024.37	0.000425	4.94	9716.61	1272.63	0.32
Missouri River	9	50-year	Normal	48000.00	2009.60	2025.37		2025.64	0.000271	4.15	11645.36	1535.16	0.25
Missouri River	9	100-year	Critical	60000.00	2009.60	2025.13		2025.58	0.000457	5.34	11287.54	1489.86	0.33
Missouri River	9	100-year	Normal	60000.00	2009.60	2026.51		2026.83	0.000298	4.53	13522.25	1753.70	0.27
Missouri River	9	500-year	Critical	95000.00	2009.60	2027.93		2028.51	0.000469	6.11	16130.42	1887.83	0.34
Missouri River	9	500-year	Normal	95000.00	2009.60	2029.17		2029.61	0.000315	5.39	19040.76	2605.14	0.29
Missouri River	9	Worst	Critical	350000.00	2009.60	2039.12		2040.16	0.000388	8.82	67332.53	10525.47	0.35
Missouri River	9	Worst	Normal	350000.00	2009.60	2040.57		2041.35	0.000276	7.81	84743.97	12592.92	0.30
Missouri River	7	2-year	Critical	15000.00	2010.00	2019.36	2016.20	2019.58	0.000673	3.81	3936.25	1074.68	0.35
Missouri River	7	2-year	Normal	15000.00	2010.00	2020.96	2016.20	2021.06	0.000209	2.61	5755.70	1154.82	0.21
Missouri River	7	5-year	Critical	17000.00	2010.00	2019.69	2016.66	2019.93	0.000680	3.95	4300.96	1119.94	0.36
Missouri River	7	5-year	Normal	17000.00	2010.00	2021.41	2016.66	2021.53	0.000216	2.70	6299.09	1227.61	0.21
Missouri River	7	10-year	Critical	25000.00	2010.00	2020.83	2018.04	2021.14	0.000632	4.46	5608.05	1153.52	0.36
Missouri River	7	10-year	Normal	25000.00	2010.00	2022.62	2018.04	2022.78	0.000239	3.20	7802.67	1268.22	0.23
Missouri River	7	50-year	Critical	48000.00	2010.00	2023.40	2019.71	2023.86	0.000604	5.45	8807.60	1295.67	0.37
Missouri River	7	50-year	Normal	48000.00	2010.00	2025.05	2019.71	2025.35	0.000294	4.38	11101.87	1486.14	0.27
Missouri River	7	100-year	Critical	60000.00	2010.00	2024.53	2020.34	2025.06	0.000569	5.84	10336.85	1423.36	0.37
Missouri River	7	100-year	Normal	60000.00	2010.00	2026.16	2020.34	2026.52	0.000304	4.82	12824.22	1618.60	0.28
Missouri River	7	500-year	Critical	95000.00	2010.00	2027.29	2022.02	2028.00	0.000524	6.79	14718.35	1758.78	0.37
Missouri River	7	500-year	Normal	95000.00	2010.00	2028.73	2022.02	2029.28	0.000341	5.94	17590.34	2410.04	0.30
Missouri River	7	Worst	Critical	350000.00	2010.00	2038.44	2030.37	2039.72	0.000444	9.97	71680.99	12922.83	0.38
Missouri River	7	Worst	Normal	350000.00	2010.00	2040.25	2030.37	2041.07	0.000280	8.36	95141.91	13003.26	0.31
Missouri River	6			Bridge									
Missouri River	5	2-year	Critical	15000.00	2010.00	2018.47		2018.78	0.000868	4.50	3332.90	858.50	0.40
Missouri River	5	2-year	Normal	15000.00	2010.00	2020.73		2020.85	0.000216	2.73	5490.18	1052.61	0.21
Missouri River	5	5-year	Critical	17000.00	2010.00	2018.77		2019.12	0.000894	4.73	3595.77	879.25	0.41
Missouri River	5	5-year	Normal	17000.00	2010.00	2021.19		2021.31	0.000212	2.85	5970.12	1059.38	0.21
Missouri River	5	10-year	Critical	25000.00	2010.00	2019.89		2020.34	0.000956	5.39	4634.81	978.16	0.44
Missouri River	5	10-year	Normal	25000.00	2010.00	2022.34		2022.53	0.000248	3.47	7198.06	1066.64	0.24
Missouri River	5	50-year	Critical	48000.00	2010.00	2022.45		2023.12	0.000865	6.56	7318.41	1067.34	0.44
Missouri River	5	50-year	Normal	48000.00	2010.00	2024.64		2025.02	0.000347	4.97	9659.50	1075.85	0.29
Missouri River	5	100-year	Critical	60000.00	2010.00	2023.58		2024.35	0.000817	7.04	8528.18	1072.69	0.44
Missouri River	5	100-year	Normal	60000.00	2010.00	2025.69		2026.17	0.000376	5.56	10793.62	1079.02	0.31
Missouri River	5	500-year	Critical	95000.00	2010.00	2026.23		2027.31	0.000793	8.35	11376.24	1080.64	0.45
Missouri River	5	500-year	Normal	95000.00	2010.00	2028.06		2028.85	0.000468	7.11	13382.25	1114.39	0.36
Missouri River	5	Worst	Critical	350000.00	2010.00	2035.95	2031.91	2038.87	0.001012	14.40	39482.09	8647.49	0.57
Missouri River	5	Worst	Normal	350000.00	2010.00	2039.34		2040.67	0.000435	10.48	77472.24	11634.82	0.38
Missouri River	3	2-year	Critical	16000.00	2010.50	2017.55	2015.47	2017.88	0.000879	4.58	3493.06	885.15	0.41
Missouri River	3	2-year	Normal	25050.00	2010.50	2020.23		2020.51	0.000406	4.21	5956.80	1066.09	0.30
Missouri River	3	5-year	Critical	18000.00	2010.50	2017.84	2015.69	2018.19	0.000886	4.80	3748.40	890.51	0.41
Missouri River	3	5-year	Normal	27050.00	2010.50	2020.72		2020.99	0.000377	4.21	6423.94	1118.62	0.29
Missouri River	3	10-year	Critical	26000.00	2010.50	2018.91	2016.52	2019.39	0.000890	5.51	4718.50	922.13	0.43
Missouri River	3	10-year	Normal	35050.00	2010.50	2021.85		2022.18	0.000389	4.64	7556.20	1242.32	0.30
Missouri River	3	50-year	Critical	49000.00	2010.50	2021.49	2018.20	2022.21	0.000879	6.81	7194.23	1203.31	0.45
Missouri River	3	50-year	Normal	58050.00	2010.50	2024.01		2024.55	0.000555	5.88	9868.66	1599.52	0.36
Missouri River	3	100-year	Critical	61000.00	2010.50	2022.66	2018.94	2023.48	0.000862	7.27	8388.30	1330.21	0.45
Missouri River	3	100-year	Normal	70050.00	2010.50	2025.04		2025.64	0.000660	6.22	11260.02	1958.67	0.39
Missouri River	3	500-year	Critical	96000.00	2010.50	2025.27		2026.33	0.001124	8.28	11602.58	2013.88	0.52
Missouri River	3	500-year	Normal	105050.00	2010.50	2027.53		2028.30	0.000584	7.03	15348.23	2569.35	0.39
Missouri River	3	Worst	Critical	351000.00	2010.50	2035.70	2029.80	2037.70	0.000763	11.87	43277.66	6467.74	0.49
Missouri River	3	Worst	Normal	360050.00	2010.50	2039.02		2040.21	0.000392	9.51	65060.22	7968.23	0.36
Missouri River	1	2-year	Critical	16000.00	2009.90	2014.56	2014.56	2015.89	0.006116	9.25	1729.31	653.85	1.00
Missouri River	1	2-year	Normal	25050.00	2009.90	2019.66	2015.50	2020.01	0.000591	4.72	5306.27	1294.22	0.35
Missouri River	1	5-year	Critical	18000.00	2009.90	2014.79	2014.79	2016.22	0.005863	9.57	1881.29	655.28	1.00

Reach	River Sta	Profile	Plan	Q Total	Min Ch El	W.S. Elev	Crit W.S.	E.G. Elev	E.G. Slope	Vel Chnl	Flow Area	Top Width	Froude # Chl
				(cfs)	(ft)	(ft)	(ft)	(ft)	(ft/ft)	(ft/s)	(sq ft)	(ft)	
Missouri River	1	5-year	Normal	27050.00	2009.90	2020.18	2015.68	2020.51	0.000591	4.64	5828.30	1416.56	0.35
Missouri River	1	10-year	Critical	26000.00	2009.90	2015.59	2015.59	2017.41	0.005468	10.82	2402.84	660.17	1.00
Missouri River	1	10-year	Normal	35050.00	2009.90	2021.33	2016.42	2021.70	0.000590	4.87	7195.53	1578.45	0.36
Missouri River	1	50-year	Critical	49000.00	2009.90	2017.52	2017.52	2020.26	0.004757	13.27	3692.75	672.37	1.00
Missouri River	1	50-year	Normal	58050.00	2009.90	2023.42	2018.21	2023.96	0.000590	5.94	9774.86	1596.16	0.37
Missouri River	1	100-year	Critical	61000.00	2009.90	2018.43	2018.43	2021.54	0.004544	14.16	4308.83	687.82	1.00
Missouri River	1	100-year	Normal	70050.00	2009.90	2024.37	2019.57	2025.00	0.000590	6.39	10961.15	1604.25	0.38
Missouri River	1	500-year	Critical	96000.00	2009.90	2021.23	2021.23	2024.09	0.004684	13.57	7073.17	1577.60	1.00
Missouri River	1	500-year	Normal	105050.00	2009.90	2026.82	2021.60	2027.69	0.000590	7.48	14037.80	1625.10	0.40
Missouri River	1	Worst	Critical	351000.00	2009.90	2029.14	2029.14	2035.78	0.003542	20.67	17003.96	1687.19	1.00
Missouri River	1	Worst	Normal	360050.00	2009.90	2037.73	2029.39	2039.65	0.000590	11.66	49104.57	7641.07	0.44

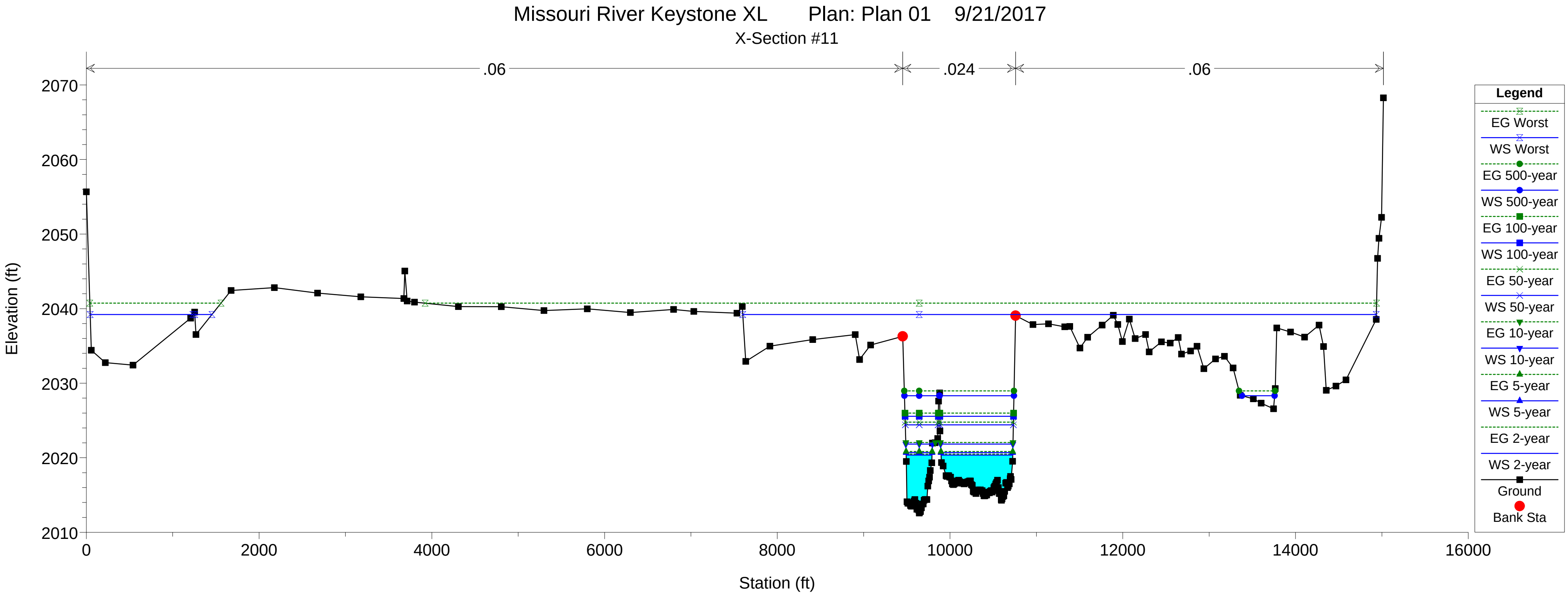
Profiles

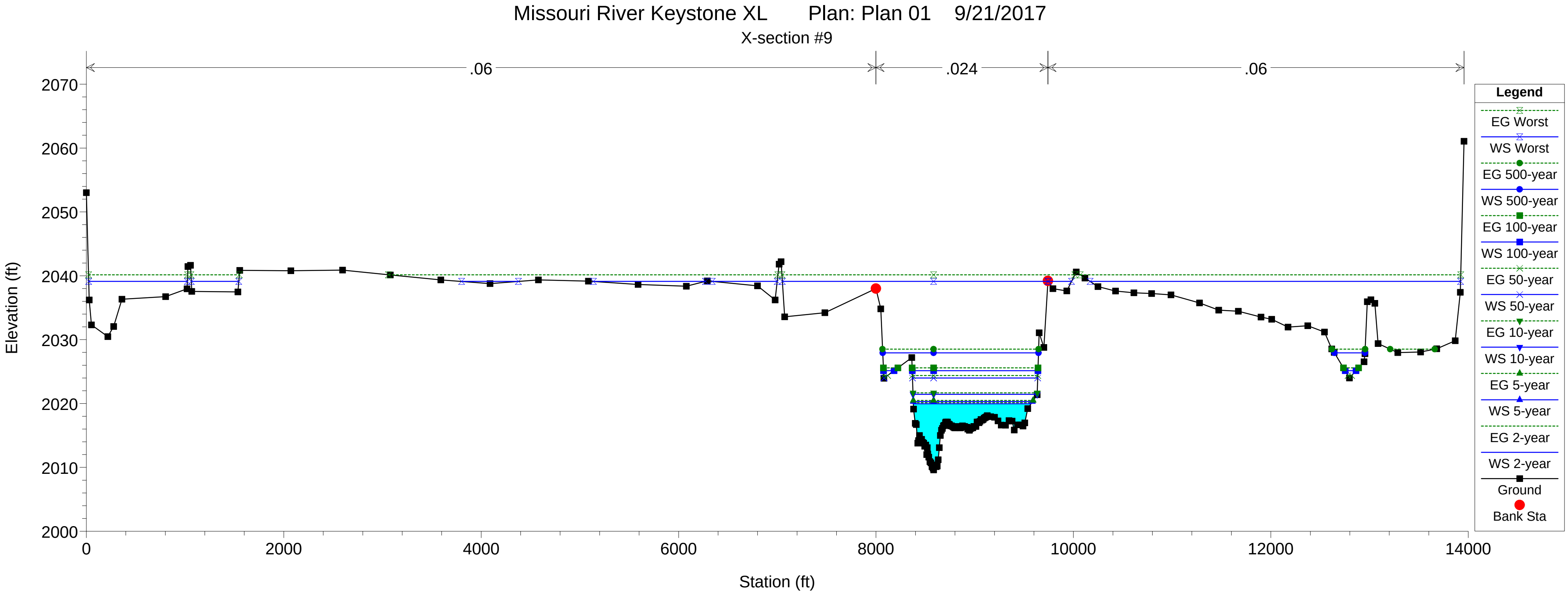

Missouri River Keystone XL Plan: Plan 01 9/21/2017
Missouri River Missouri River
Elevation (ft)
2045
2040
2035
2030
2025
2020
2015
2010
2005
0
1000
2000
3000
4000
5000
6000
Main Channel Distance (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
EG 100-year
WS 500-year
Crit 500-year
EG 50-year
WS 100-year
Crit 100-year
Crit 50-year
WS 50-year
EG 10-year
EG 5-year
EG 2-year
WS 10-year
Crit 10-year
Crit 5-year
WS 5-year
WS 2-year
Crit 2-year
Ground

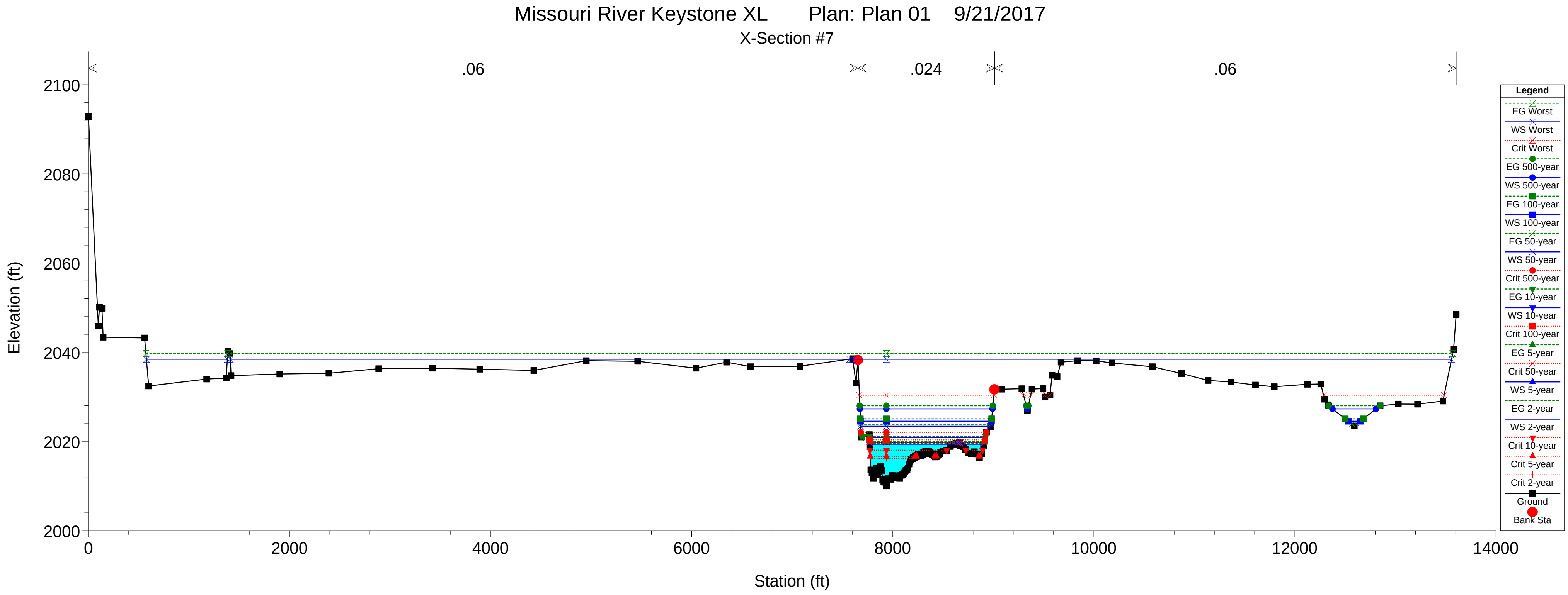
Profile: Normal Flow Sensitivity Analysis

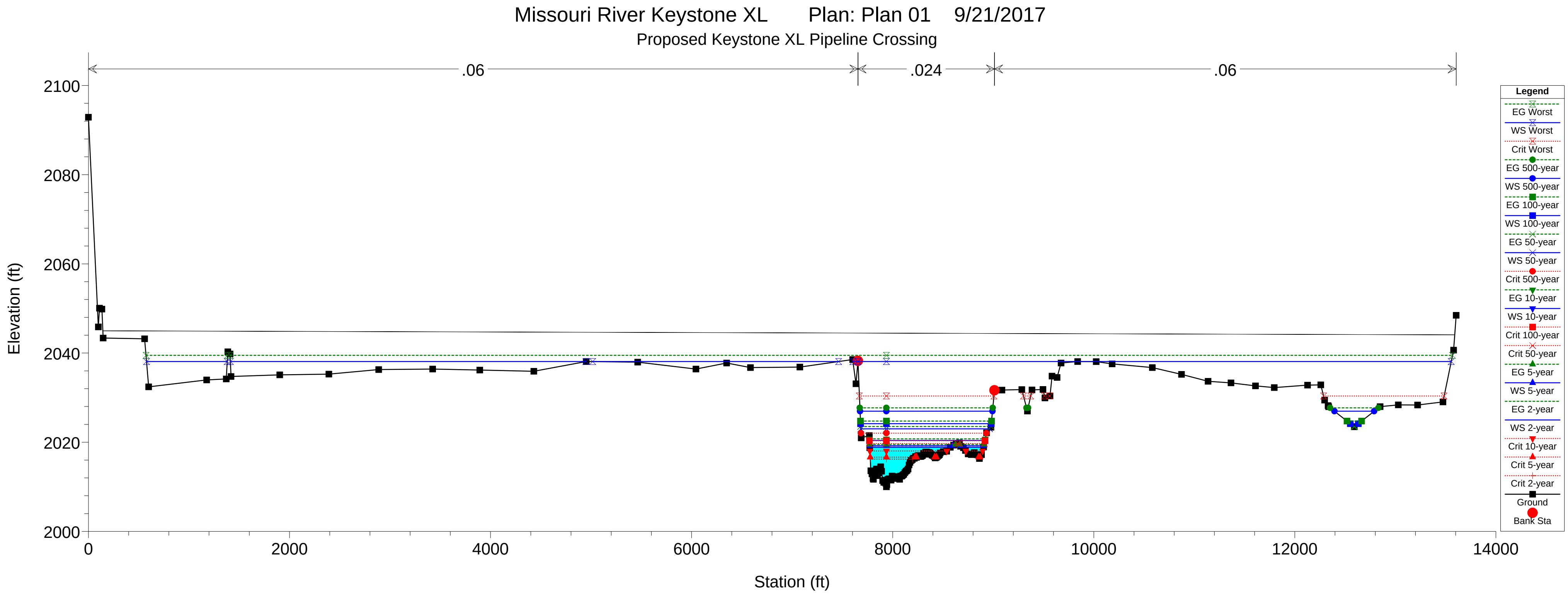

Missouri River Keystone XL Plan: Plan 02 7/26/2017
Missouri River Missouri River
Legend
EG 500-year
WS 500-year
Crit 500-year
Ground
Elevation (ft)
2045
2040
2035
2030
2025
2020
2015
2010
2005
0
1000
2000
3000
4000
5000
6000
Main Channel Distance (ft)

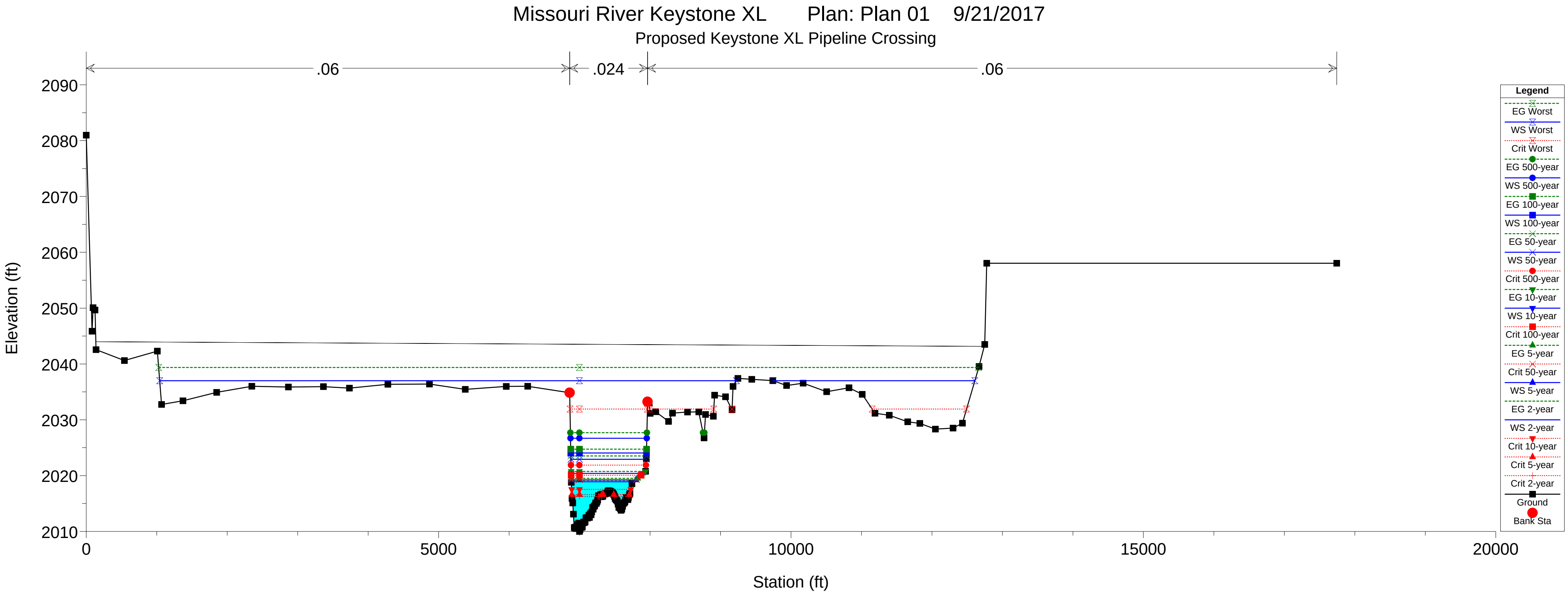
Cross Sections

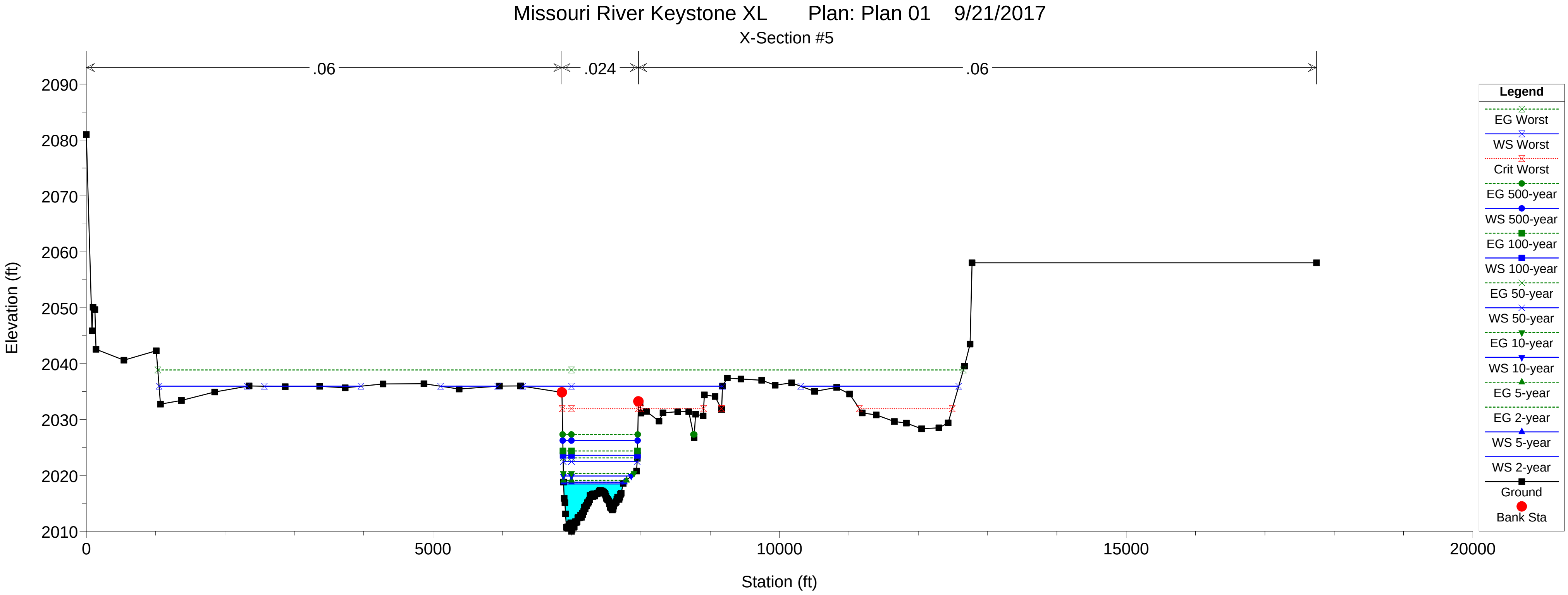

Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-Section #11
.06
.024
.06
Elevation (ft)
2070
2060
2050
2040
2030
2020
2010
0
2000
4000
6000
8000
10000
12000
14000
16000
Station (ft)
Legend
EG Worst
WS Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
EG 10-year
WS 10-year
EG 5-year
WS 5-year
EG 2-year
WS 2-year
Ground
Bank Sta

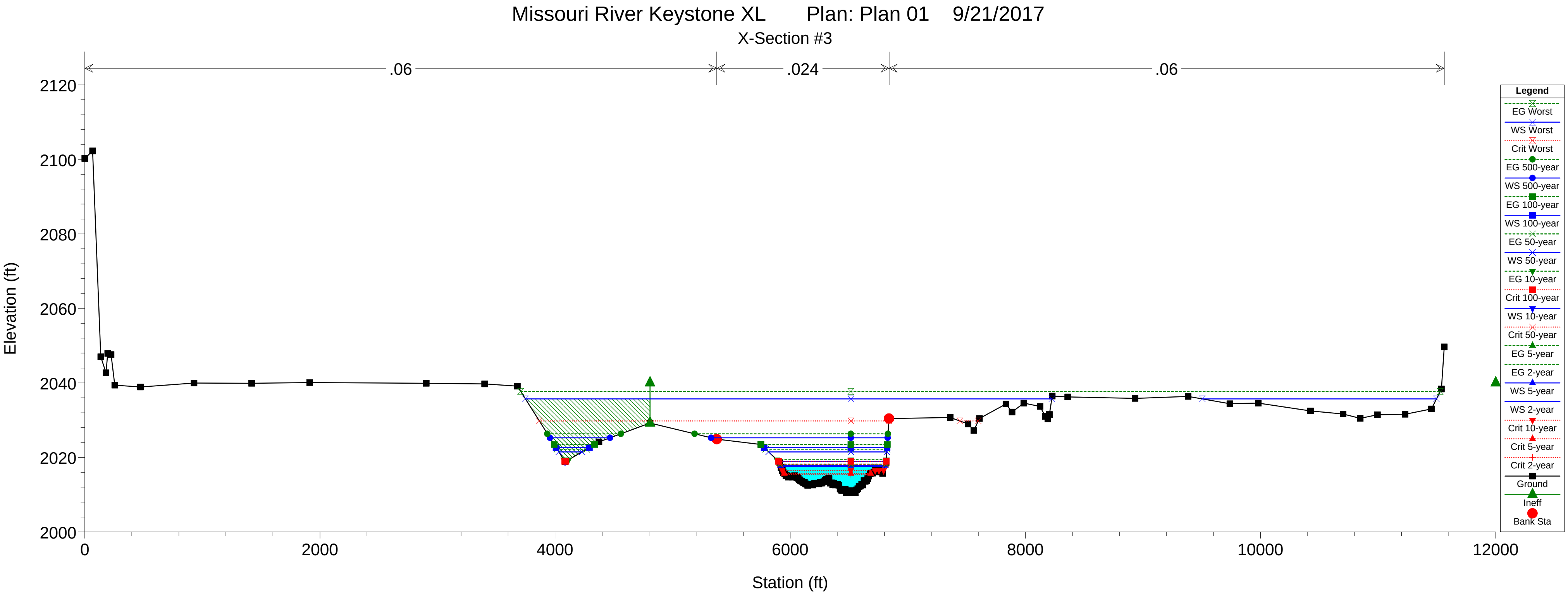

Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-section #9
.06
.024
.06
Elevation (ft)
2070
2060
2050
2040
2030
2020
2010
2000
0
2000
4000
6000
8000
10000
12000
14000
Station (ft)
Legend
EG Worst
WS Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
EG 10-year
WS 10-year
EG 5-year
WS 5-year
EG 2-year
WS 2-year
Ground
Bank Sta

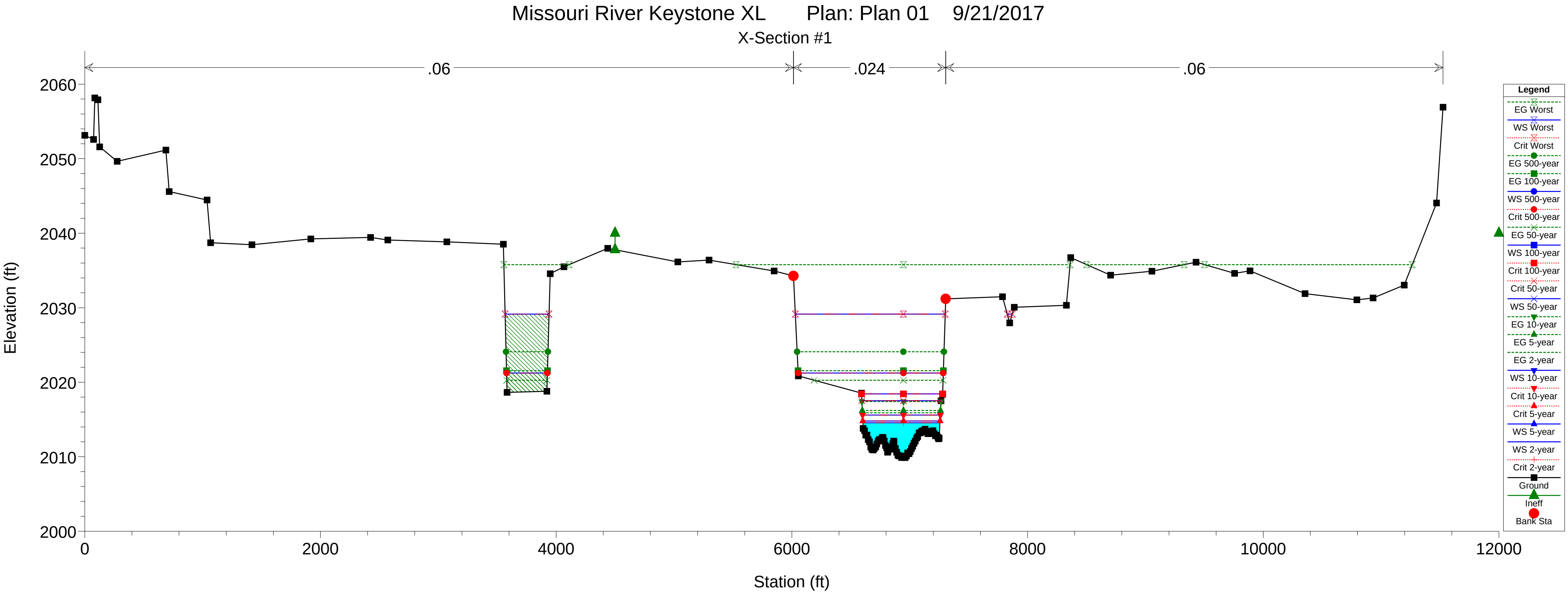

Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-Section #7
.06
.024
.06
Elevation (ft)
2100
2080
2060
2040
2020
2000
0
2000
4000
6000
8000
10000
12000
14000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
Crit 500-year
EG 10-year
WS 10-year
Crit 100-year
EG 5-year
Crit 50-year
WS 5-year
EG 2-year
WS 2-year
Crit 10-year
Crit 5-year
Crit 2-year
Ground
Bank Sta


Missouri River Keystone XL Plan: Plan 01 9/21/2017
Proposed Keystone XL Pipeline Crossing
.06
.024
.06
Elevation (ft)
2100
2080
2060
2040
2020
2000
0
2000
4000
6000
8000
10000
12000
14000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
Crit 500-year
EG 10-year
WS 10-year
Crit 100-year
Crit 50-year
EG 5-year
WS 5-year
EG 2-year
WS 2-year
Crit 10-year
Crit 5-year
Crit 2-year
Ground
Bank Sta

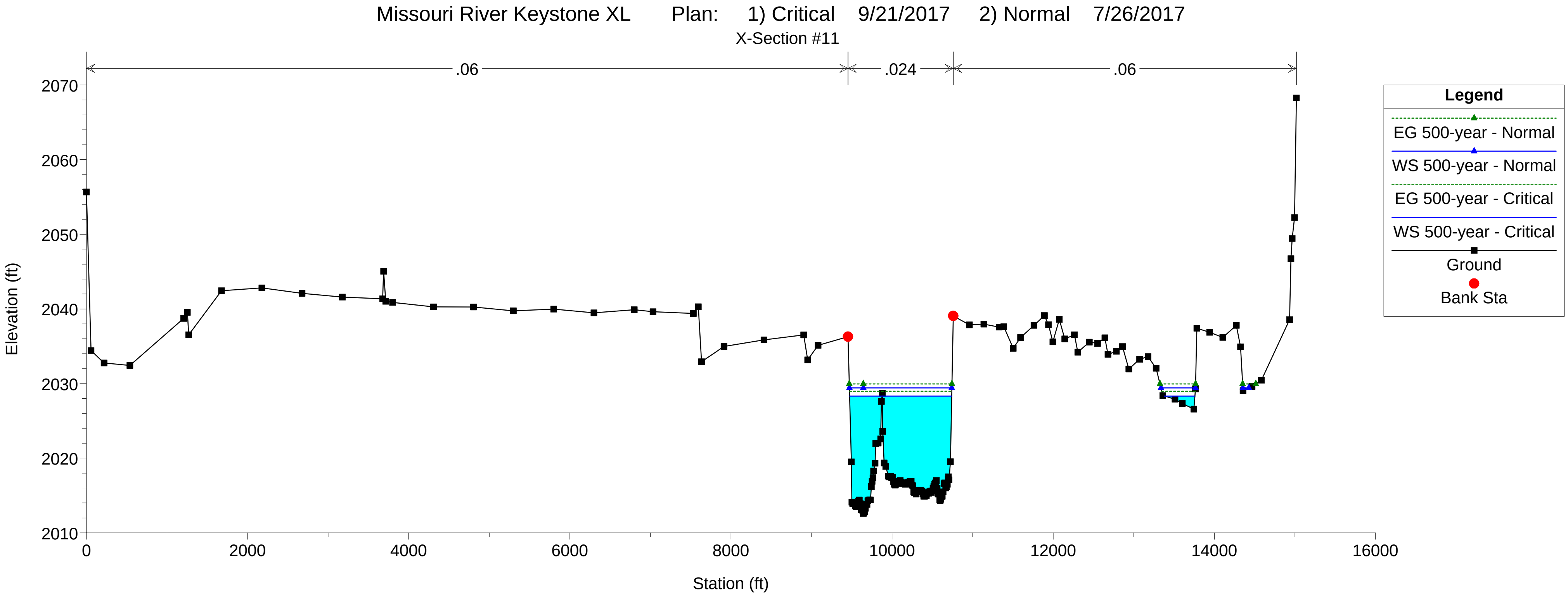

Missouri River Keystone XL Plan: Plan 01 9/21/2017
Proposed Keystone XL Pipeline Crossing
.06
.024
.06
Elevation (ft)
2090
2080
2070
2060
2050
2040
2030
2020
2010
0
5000
10000
15000
20000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
Crit 500-year
EG 10-year
WS 10-year
Crit 100-year
EG 5-year
Crit 50-year
WS 5-year
EG 2-year
WS 2-year
Crit 10-year
Crit 5-year
Crit 2-year
Ground
Bank Sta

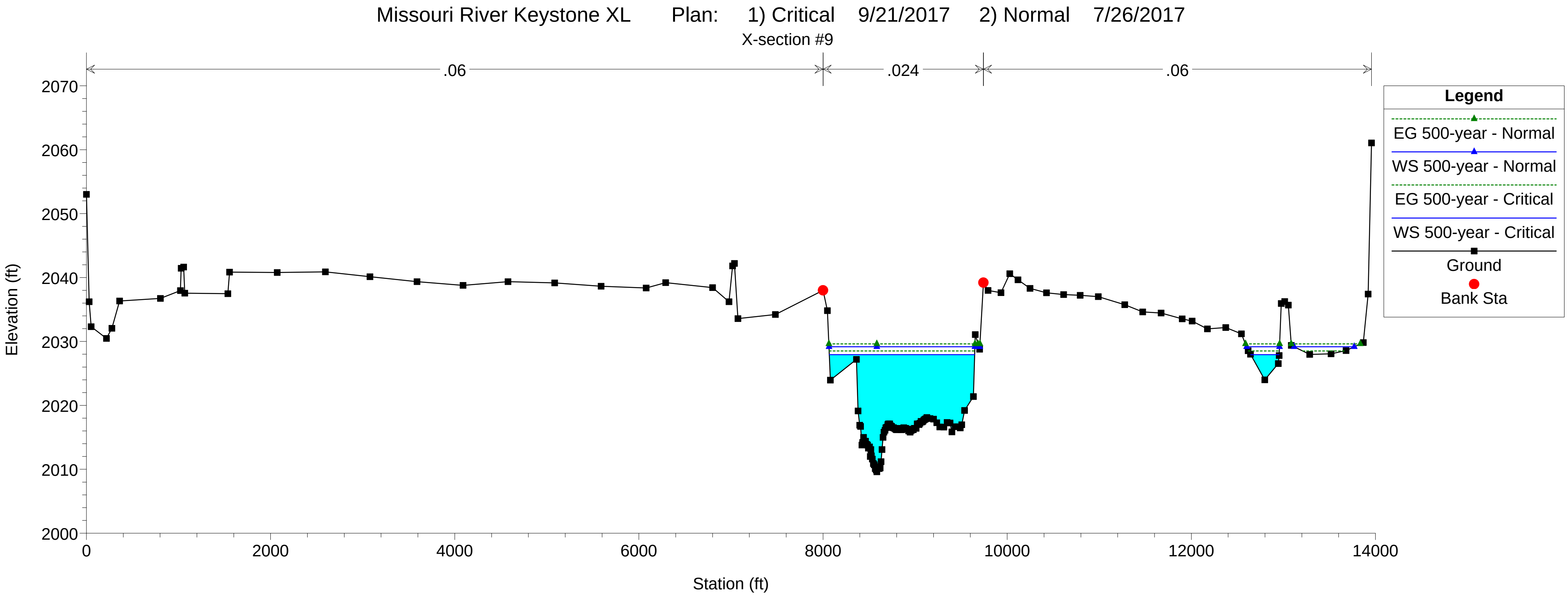

Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-Section #5
.06
.024
.06
Elevation (ft)
2090
2080
2070
2060
2050
2040
2030
2020
2010
0
5000
10000
15000
20000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
EG 10-year
WS 10-year
EG 5-year
EG 2-year
WS 5-year
WS 2-year
Ground
Bank Sta

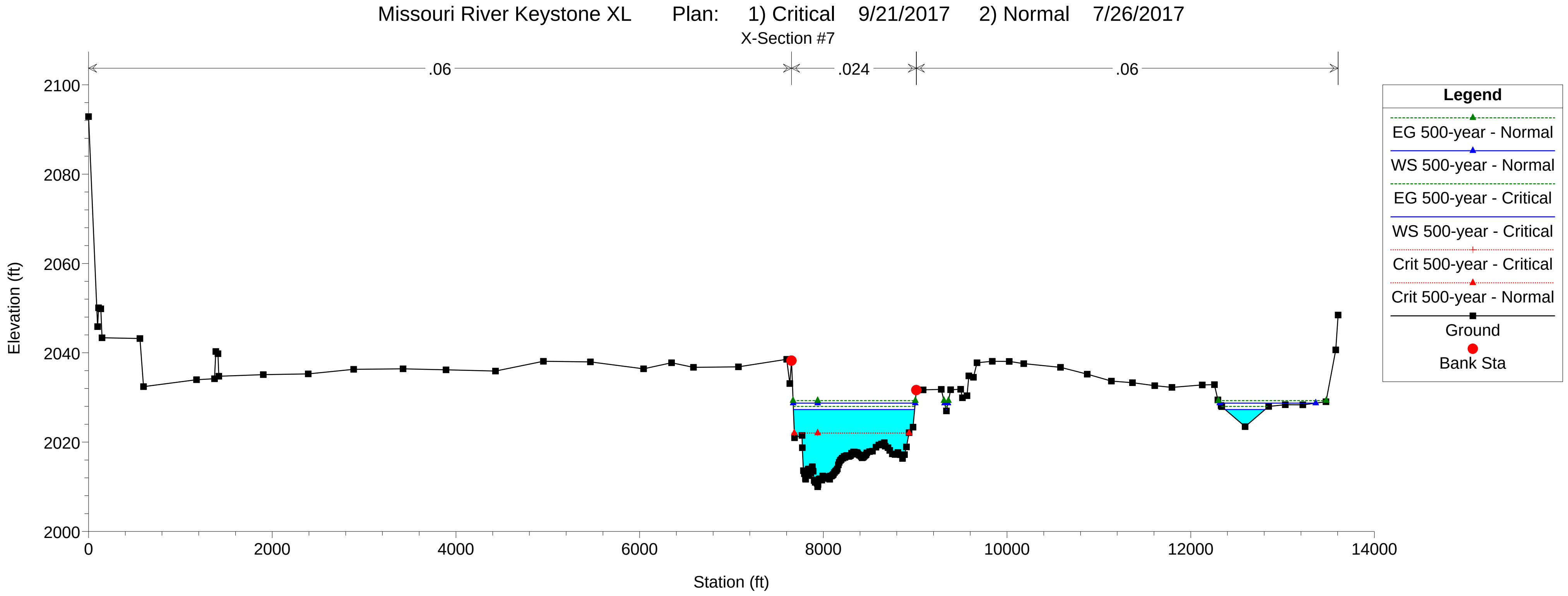

Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-Section #3
.06
.024
.06
Elevation (ft)
2120
2100
2080
2060
2040
2020
2000
0
2000
4000
6000
8000
10000
12000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
WS 500-year
EG 100-year
WS 100-year
EG 50-year
WS 50-year
EG 10-year
Crit 100-year
WS 10-year
Crit 50-year
EG 5-year
EG 2-year
WS 5-year
WS 2-year
Crit 10-year
Crit 5-year
Crit 2-year
Ground
Ineff
Bank Sta


Missouri River Keystone XL Plan: Plan 01 9/21/2017
X-Section #1
.06
.024
.06
Elevation (ft)
2060
2050
2040
2030
2020
2010
2000
0
2000
4000
6000
8000
10000
12000
Station (ft)
Legend
EG Worst
WS Worst
Crit Worst
EG 500-year
EG 100-year
WS 500-year
Crit 500-year
EG 50-year
WS 100-year
Crit 100-year
Crit 50-year
WS 50-year
EG 10-year
EG 5-year
EG 2-year
WS 10-year
Crit 10-year
Crit 5-year
WS 5-year
WS 2-year
Crit 2-year
Ground
Ineff
Bank Sta

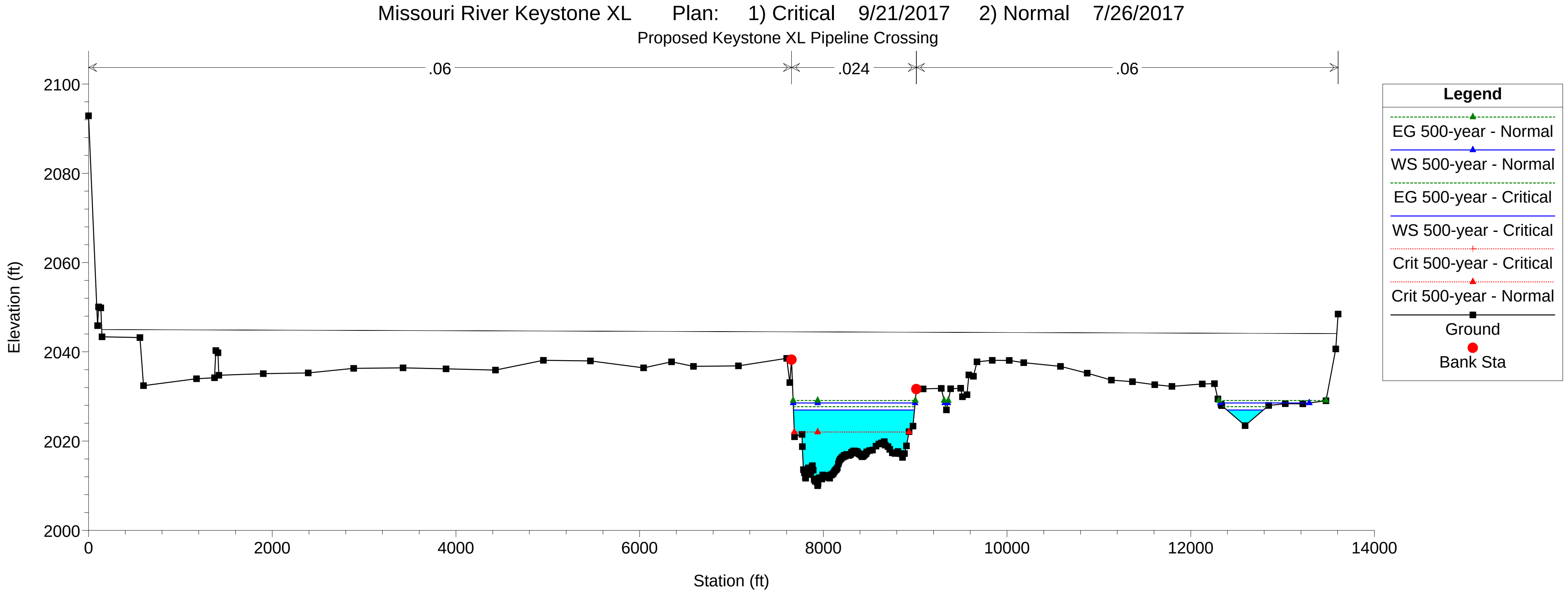
Cross Sections: Normal Flow Sensitivity Analysis


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017
X-Section #11
.06
.024
.06
Elevation (ft)
2010
2020
2030
2040
2050
2060
2070
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000
16000
Legend
EG 500-year - Normal
WS 500-year - Normal
EG 500-year - Critical
WS 500-year - Critical
Ground
Bank Sta

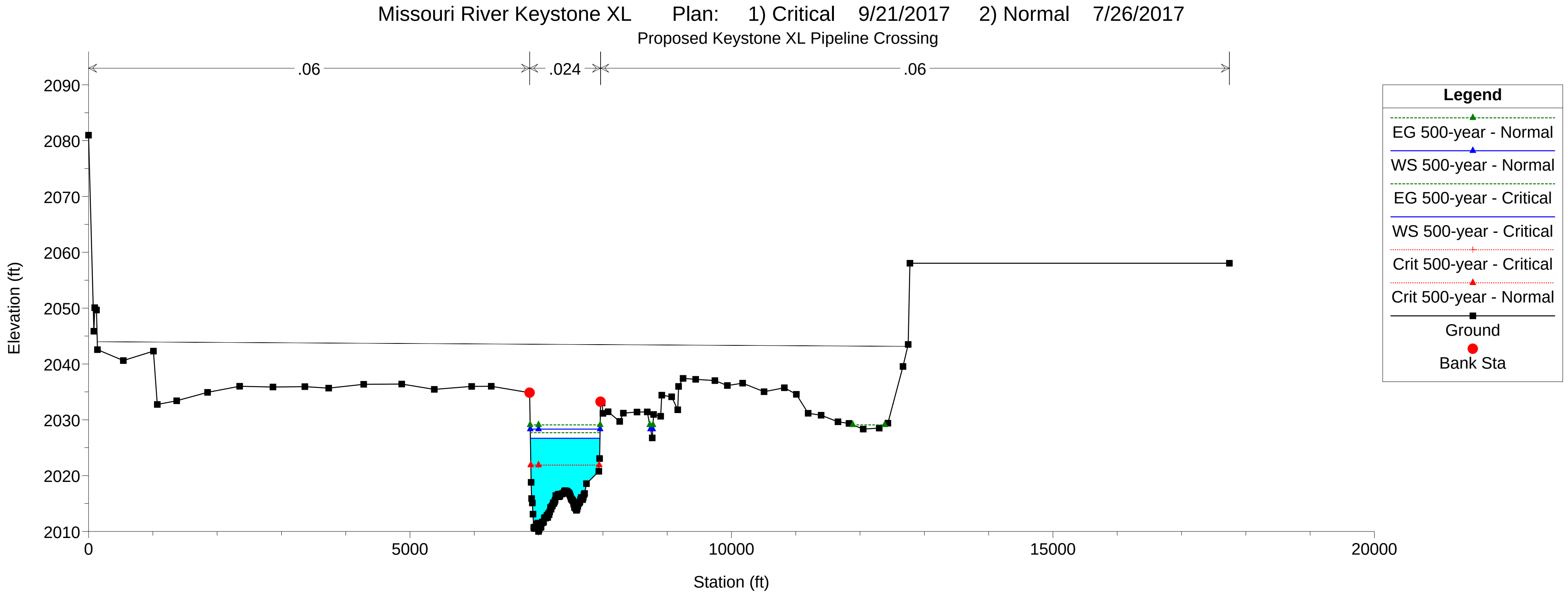

Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017
X-section #9
.06
.024
.06
Elevation (ft)
2000
2010
2020
2030
2040
2050
2060
2070
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000
Legend
EG 500-year - Normal
WS 500-year - Normal
EG 500-year - Critical
WS 500-year - Critical
Ground
Bank Sta


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017

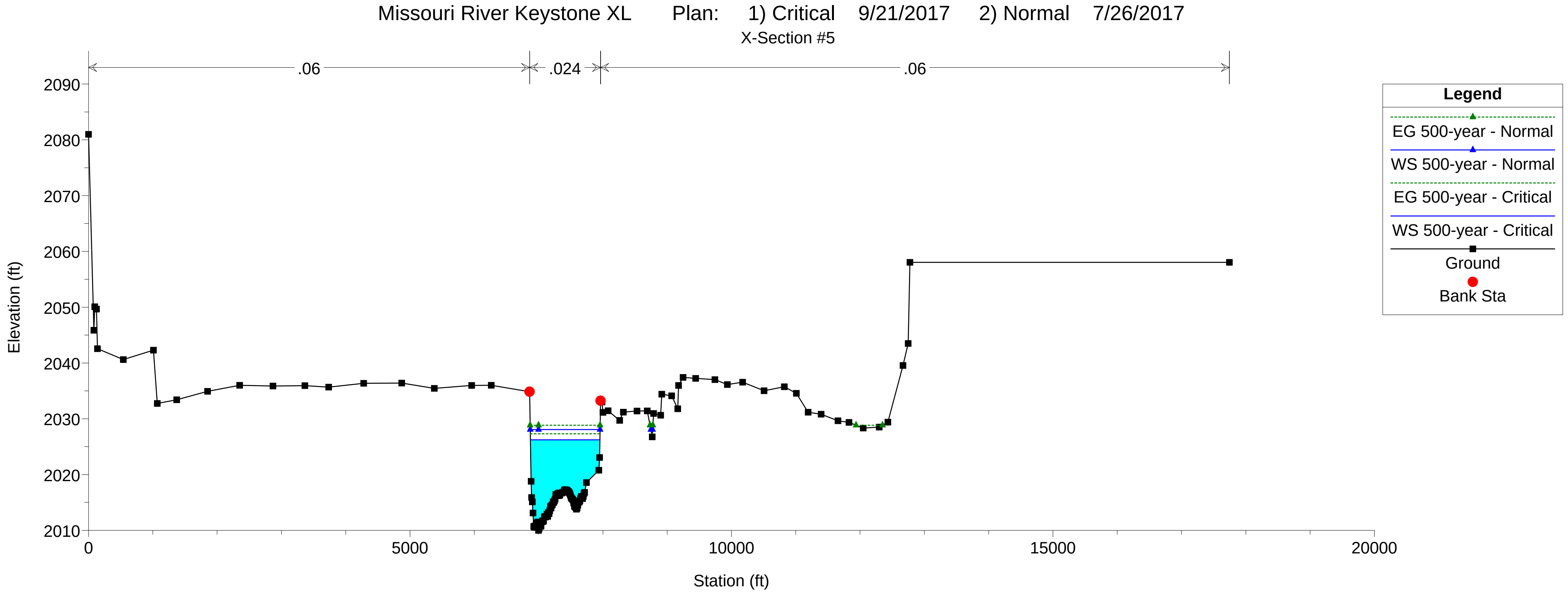
X-Section #7


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017

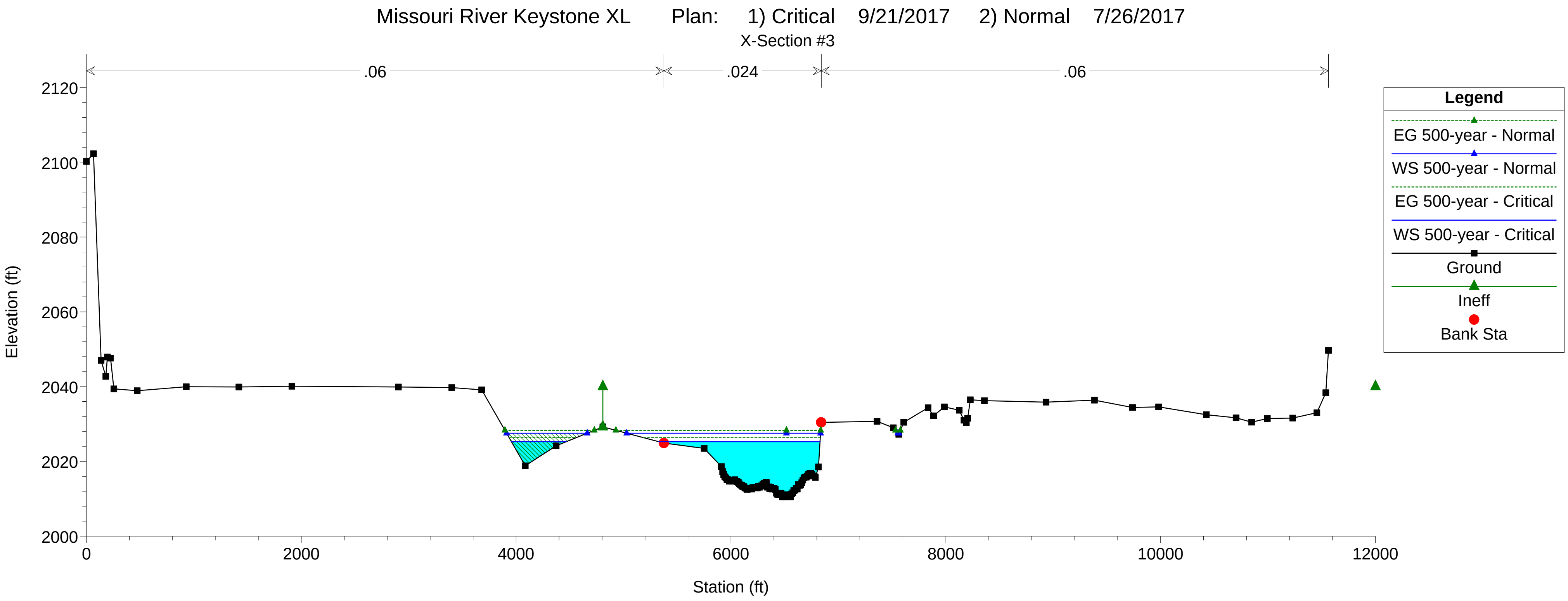
Proposed Keystone XL Pipeline Crossing

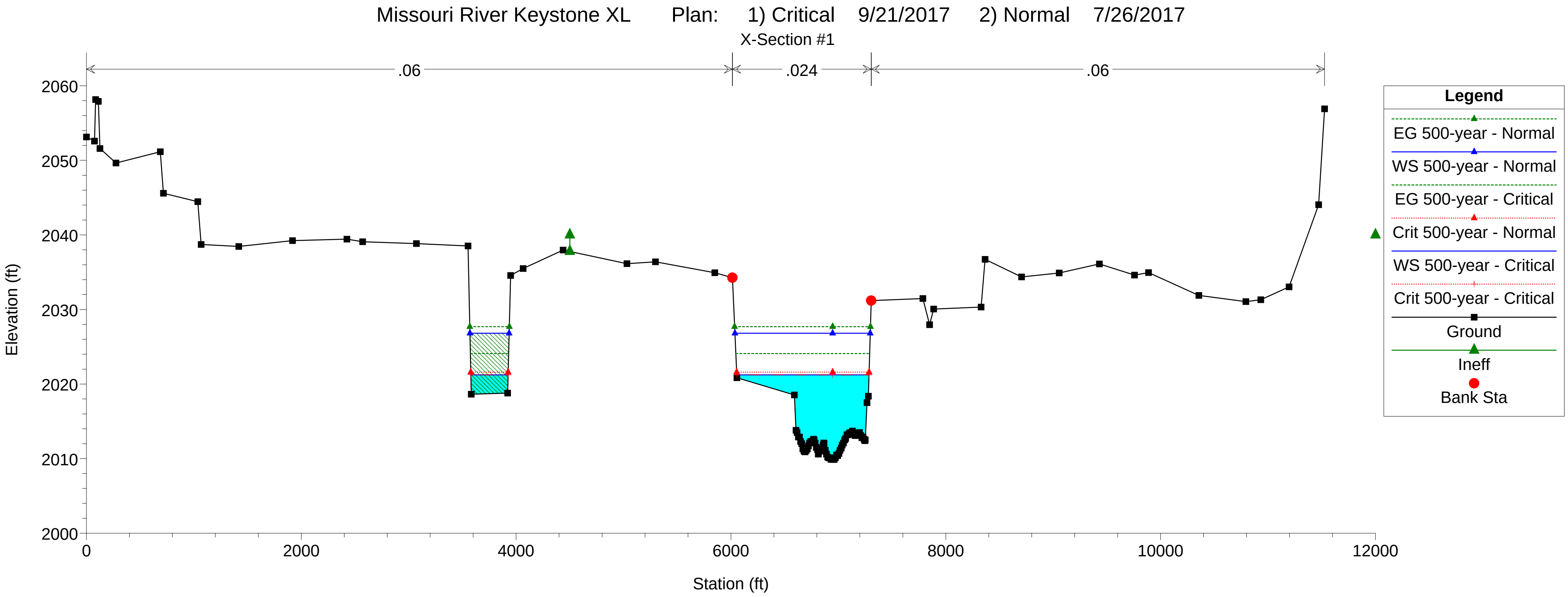

Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017

Proposed Keystone XL Pipeline Crossing


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017

X-Section #5


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017
X-Section #3
.06
.024
.06
Elevation (ft)
2120
2100
2080
2060
2040
2020
2000
0
2000
4000
6000
8000
10000
12000
Station (ft)
Legend
EG 500-year - Normal
WS 500-year - Normal
EG 500-year - Critical
WS 500-year - Critical
Ground
Ineff
Bank Sta


Missouri River Keystone XL Plan: 1) Critical 9/21/2017 2) Normal 7/26/2017
X-Section #1
.06
.024
.06
Elevation (ft)
2060
2050
2040
2030
2020
2010
2000
0
2000
4000
6000
8000
10000
12000
Station (ft)
Legend
EG 500-year - Normal
WS 500-year - Normal
EG 500-year - Critical
Crit 500-year - Normal
WS 500-year - Critical
Crit 500-year - Critical
Ground
Ineff
Bank Sta

Summary Hydraulic Tables at Crossing Location

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 2-year

E.G. Elev (ft)	2019.16	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.25	Wt. n-Val.		0.024	
W.S. Elev (ft)	2018.90	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2016.26	Flow Area (sq ft)		3713.12	
E.G. Slope (ft/ft)	0.000636	Area (sq ft)		3713.12	
Q Total (cfs)	15000.00	Flow (cfs)		15000.00	
Top Width (ft)	891.01	Top Width (ft)		891.01	
Vel Total (ft/s)	4.04	Avg. Vel. (ft/s)		4.04	
Max Chl Dpth (ft)	8.90	Hydr. Depth (ft)		4.17	
Conv. Total (cfs)	594637.6	Conv. (cfs)		594637.6	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		892.57	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.17	
Alpha	1.00	Stream Power (lb/ft s)		0.67	
Frctn Loss (ft)	0.37	Cum Volume (acre-ft)		182.63	
C & E Loss (ft)	0.01	Cum SA (acres)		48.76	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 5-year

E.G. Elev (ft)	2019.51	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.28	Wt. n-Val.		0.024	
W.S. Elev (ft)	2019.23	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2016.61	Flow Area (sq ft)		4005.75	
E.G. Slope (ft/ft)	0.000662	Area (sq ft)		4005.75	
Q Total (cfs)	17000.00	Flow (cfs)		17000.00	
Top Width (ft)	919.58	Top Width (ft)		919.58	
Vel Total (ft/s)	4.24	Avg. Vel. (ft/s)		4.24	
Max Chl Dpth (ft)	9.23	Hydr. Depth (ft)		4.36	
Conv. Total (cfs)	660704.3	Conv. (cfs)		660704.3	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		921.24	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.18	
Alpha	1.00	Stream Power (lb/ft s)		0.76	
Frctn Loss (ft)	0.38	Cum Volume (acre-ft)		196.74	
C & E Loss (ft)	0.01	Cum SA (acres)		49.43	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 10-year

E.G. Elev (ft)	2020.76	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.37	Wt. n-Val.		0.024	
W.S. Elev (ft)	2020.39	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2017.54	Flow Area (sq ft)		5139.56	
E.G. Slope (ft/ft)	0.000719	Area (sq ft)		5139.56	
Q Total (cfs)	25000.00	Flow (cfs)		25000.00	
Top Width (ft)	1022.75	Top Width (ft)		1022.75	
Vel Total (ft/s)	4.86	Avg. Vel. (ft/s)		4.86	
Max Chl Dpth (ft)	10.39	Hydr. Depth (ft)		5.03	
Conv. Total (cfs)	932334.1	Conv. (cfs)		932334.1	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		1024.79	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.23	
Alpha	1.00	Stream Power (lb/ft s)		1.10	
Frctn Loss (ft)	0.41	Cum Volume (acre-ft)	0.01	250.53	
C & E Loss (ft)	0.01	Cum SA (acres)	0.22	52.39	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 50-year

E.G. Elev (ft)	2023.52	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.58	Wt. n-Val.		0.024	
W.S. Elev (ft)	2022.93	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2019.28	Flow Area (sq ft)		7829.34	
E.G. Slope (ft/ft)	0.000693	Area (sq ft)		7829.34	
Q Total (cfs)	48000.00	Flow (cfs)		48000.00	
Top Width (ft)	1070.35	Top Width (ft)		1070.35	
Vel Total (ft/s)	6.13	Avg. Vel. (ft/s)		6.13	
Max Chl Dpth (ft)	12.93	Hydr. Depth (ft)		7.31	
Conv. Total (cfs)	1823129.0	Conv. (cfs)		1823129.0	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		1073.40	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.32	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 50-year (Continued)

Alpha	1.00	Stream Power (lb/ft s)		1.94	
Frctn Loss (ft)	0.39	Cum Volume (acre-ft)	7.54	386.72	
C & E Loss (ft)	0.01	Cum SA (acres)	5.62	56.52	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 100-year

E.G. Elev (ft)	2024.73	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.69	Wt. n-Val.		0.024	
W.S. Elev (ft)	2024.05	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2020.06	Flow Area (sq ft)		9023.21	
E.G. Slope (ft/ft)	0.000679	Area (sq ft)		9023.21	
Q Total (cfs)	60000.00	Flow (cfs)		60000.00	
Top Width (ft)	1074.08	Top Width (ft)		1074.08	
Vel Total (ft/s)	6.65	Avg. Vel. (ft/s)		6.65	
Max Chl Dpth (ft)	14.05	Hydr. Depth (ft)		8.40	
Conv. Total (cfs)	2303370.0	Conv. (cfs)		2303370.0	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		1077.79	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.35	
Alpha	1.00	Stream Power (lb/ft s)		2.36	
Frctn Loss (ft)	0.37	Cum Volume (acre-ft)	15.50	450.25	
C & E Loss (ft)	0.01	Cum SA (acres)	8.06	57.78	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: 500-year

E.G. Elev (ft)	2027.69	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.99	Wt. n-Val.		0.024	
W.S. Elev (ft)	2026.70	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2021.88	Flow Area (sq ft)		11881.80	
E.G. Slope (ft/ft)	0.000688	Area (sq ft)		11881.80	
Q Total (cfs)	95000.00	Flow (cfs)		95000.00	
Top Width (ft)	1082.04	Top Width (ft)		1082.04	
Vel Total (ft/s)	8.00	Avg. Vel. (ft/s)		8.00	
Max Chl Dpth (ft)	16.70	Hydr. Depth (ft)		10.98	
Conv. Total (cfs)	3622480.0	Conv. (cfs)		3622480.0	
Length Wtd. (ft)	499.00	Wetted Per. (ft)		1087.36	
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.47	
Alpha	1.00	Stream Power (lb/ft s)		3.75	
Frctn Loss (ft)	0.37	Cum Volume (acre-ft)	56.08	624.75	
C & E Loss (ft)	0.01	Cum SA (acres)	20.56	73.91	

Plan: Critical   Missouri River   Missouri River RS: 6   BR D   Profile: Worst

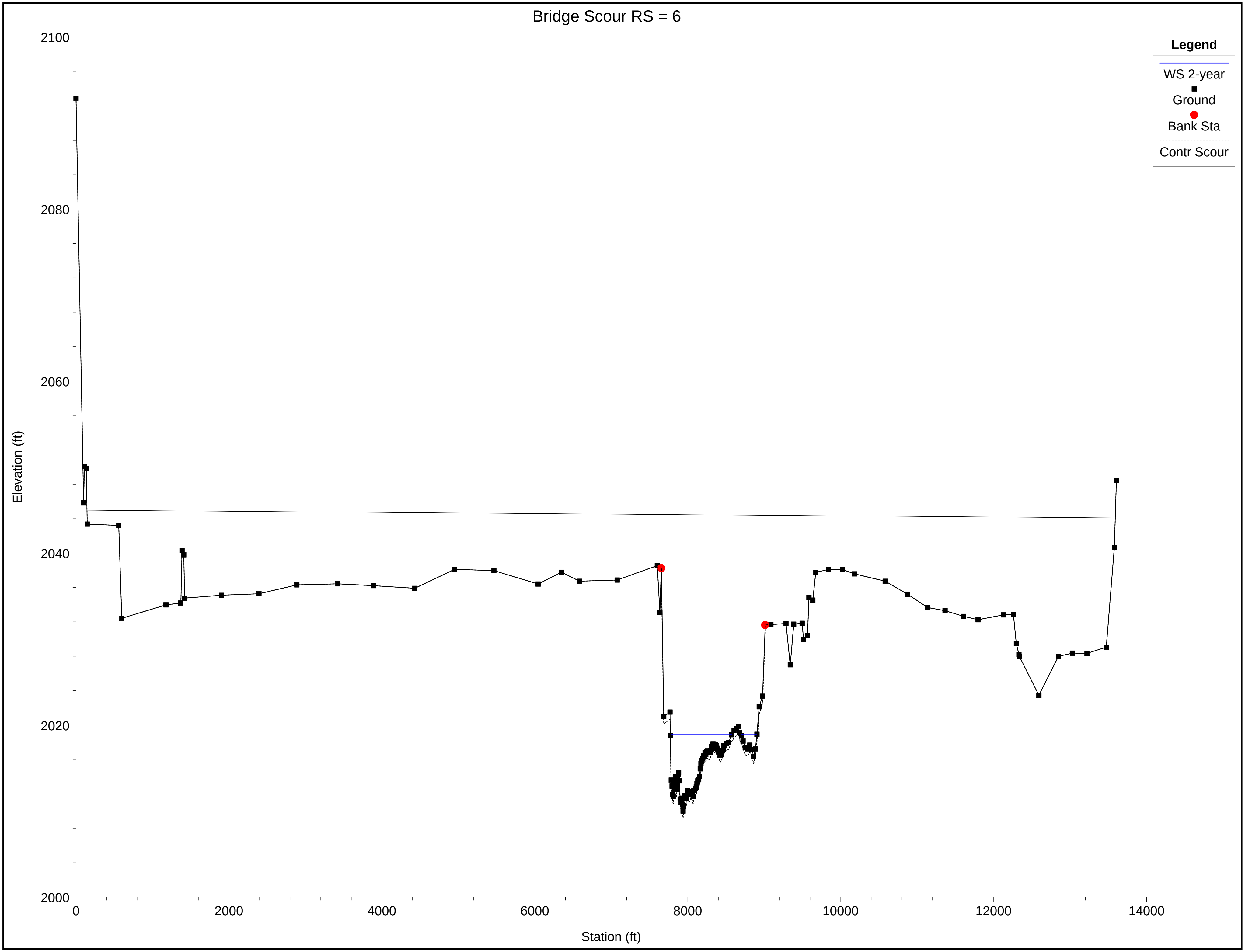
E.G. Elev (ft)	2039.37	Element	Left OB	Channel	Right OB
Vel Head (ft)	2.38	Wt. n-Val.	0.060	0.024	0.060
W.S. Elev (ft)	2037.00	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2031.91	Flow Area (sq ft)	8338.86	23169.50	18858.13
E.G. Slope (ft/ft)	0.000796	Area (sq ft)	8338.86	23169.50	18858.13
Q Total (cfs)	350000.00	Flow (cfs)	7406.08	306098.80	36495.18
Top Width (ft)	11044.94	Top Width (ft)	5817.70	1104.00	4123.23
Vel Total (ft/s)	6.95	Avg. Vel. (ft/s)	0.89	13.21	1.94
Max Chl Dpth (ft)	26.99	Hydr. Depth (ft)	1.43	20.99	4.57
Conv. Total (cfs)	12406520.0	Conv. (cfs)	262525.0	10850350.0	1293653.0
Length Wtd. (ft)	499.00	Wetted Per. (ft)	5818.05	1113.79	4125.25
Min Ch El (ft)	2010.00	Shear (lb/sq ft)	0.07	1.03	0.23
Alpha	3.17	Stream Power (lb/ft s)	0.06	13.65	0.44
Frctn Loss (ft)	0.45	Cum Volume (acre-ft)	599.97	1352.31	542.01
C & E Loss (ft)	0.05	Cum SA (acres)	168.54	75.19	138.69

Summary Hydraulic Tables at Crossing Location: Normal Flow Sensitivity Analysis

Plan: Normal Missouri River Missouri River RS: 6 BR D Profile: 500-year

E.G. Elev (ft)	2029.08	Element	Left OB	Channel	Right OB
Vel Head (ft)	0.75	Wt. n-Val.		0.024	0.060
W.S. Elev (ft)	2028.33	Reach Len. (ft)	499.00	499.00	499.00
Crit W.S. (ft)	2021.88	Flow Area (sq ft)		13647.26	26.66
E.G. Slope (ft/ft)	0.000436	Area (sq ft)		13647.26	26.66
Q Total (cfs)	95000.00	Flow (cfs)		94988.30	11.71
Top Width (ft)	1120.79	Top Width (ft)		1086.93	33.86
Vel Total (ft/s)	6.95	Avg. Vel. (ft/s)		6.96	0.44
Max Chl Dpth (ft)	18.32	Hydr. Depth (ft)		12.56	0.79
Conv. Total (cfs)	4547486.0	Conv. (cfs)		4546926.0	560.7
Length Wtd. (ft)	499.00	Wetted Per. (ft)		1093.24	34.06
Min Ch El (ft)	2010.00	Shear (lb/sq ft)		0.34	0.02
Alpha	1.00	Stream Power (lb/ft s)		2.37	0.01
Frctn Loss (ft)	0.23	Cum Volume (acre-ft)	136.05	829.03	0.46
C & E Loss (ft)	0.00	Cum SA (acres)	36.08	74.49	0.85

2-Year Contraction Scour Hydraulic Tables

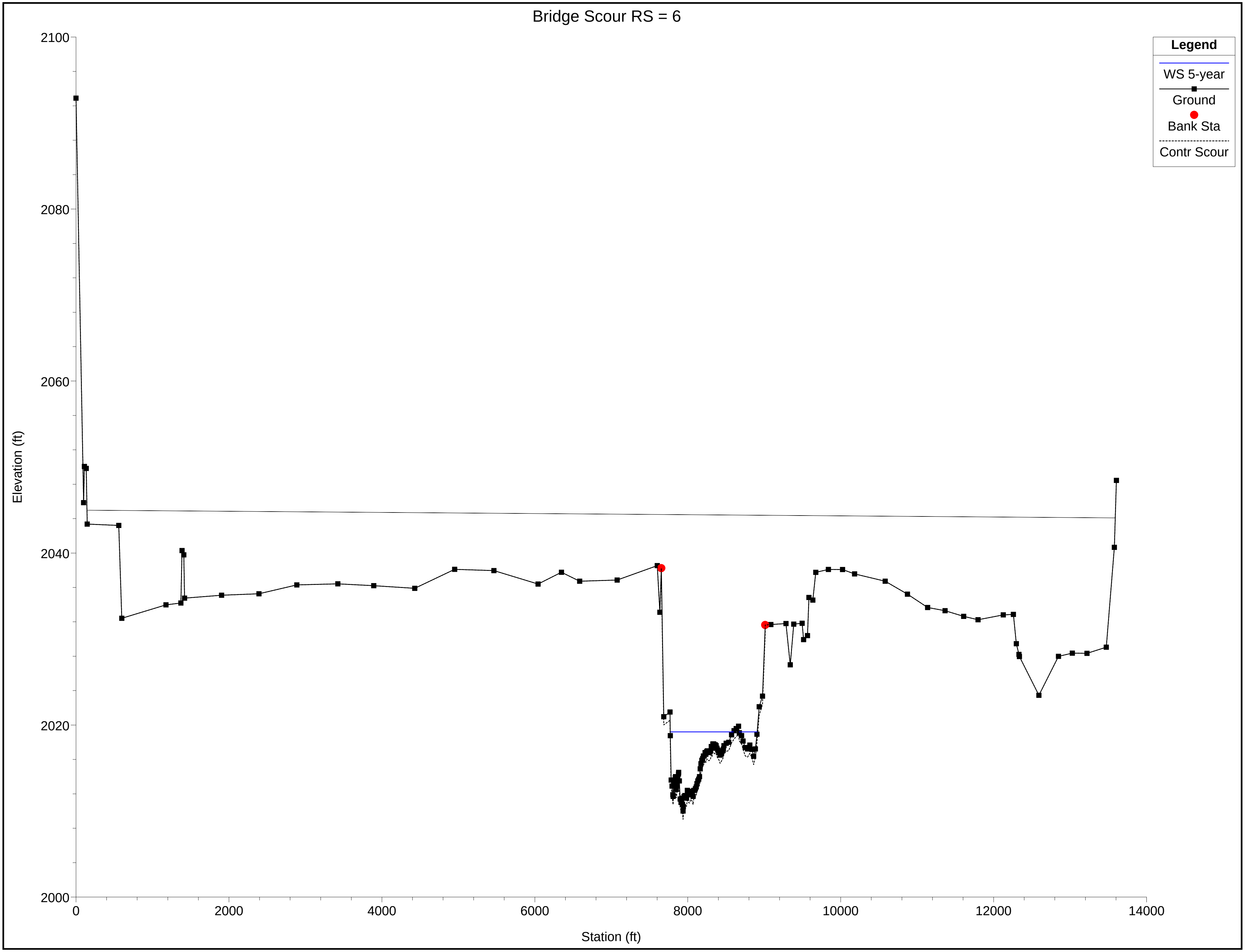

Bridge Scour RS = 6
Legend
WS 2-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		3.93	
	Approach Velocity (ft/s):		3.21	
	Br Average Depth (ft):		3.39	
	BR Opening Flow (cfs):		15000.00	
	BR Top WD (ft):		1012.31	
	Grain Size D50 (mm):		3.50	
	Approach Flow (cfs):		15000.00	
	Approach Top WD (ft):		1192.29	
	K1 Coefficient:		0.590	
Results				
	Scour Depth Ys (ft):		0.83	
	Critical Velocity (ft/s):			
	Equation:		Clear	

Combined Scour Depths

5-Year Contraction Scour Hydraulic Tables

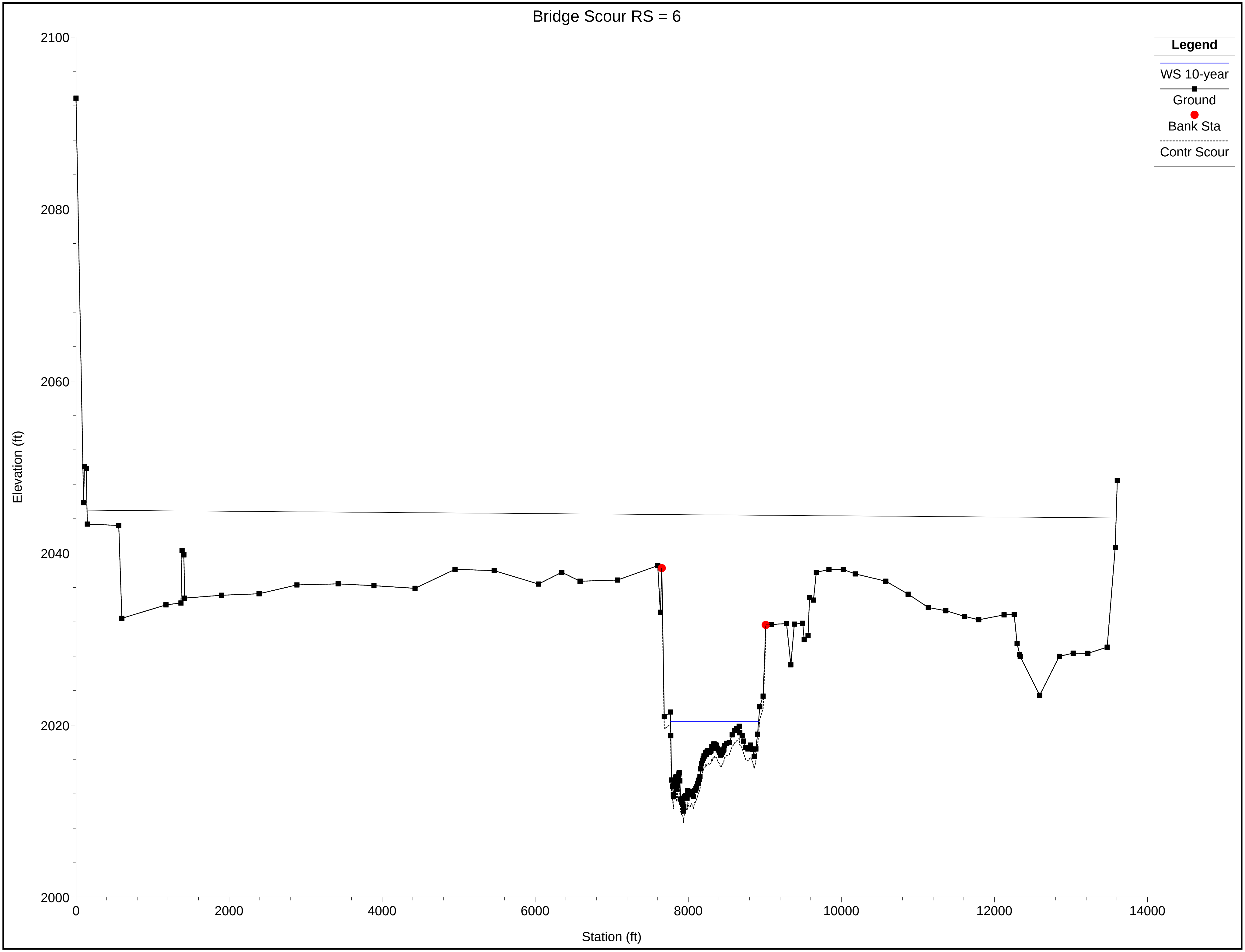

Bridge Scour RS = 6
Legend
WS 5-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		4.21	
	Approach Velocity (ft/s):		3.34	
	Br Average Depth (ft):		3.56	
	BR Opening Flow (cfs):		17000.00	
	BR Top WD (ft):		1060.15	
	Grain Size D50 (mm):		3.5	
	Approach Flow (cfs):		17000.00	
	Approach Top WD (ft):		1207.92	
	K1 Coefficient:		0.590	
Results				
	Scour Depth Ys (ft):		0.95	
	Critical Velocity (ft/s):			
	Equation:		Clear	

Combined Scour Depths

10-Year Contraction Scour Hydraulic Tables

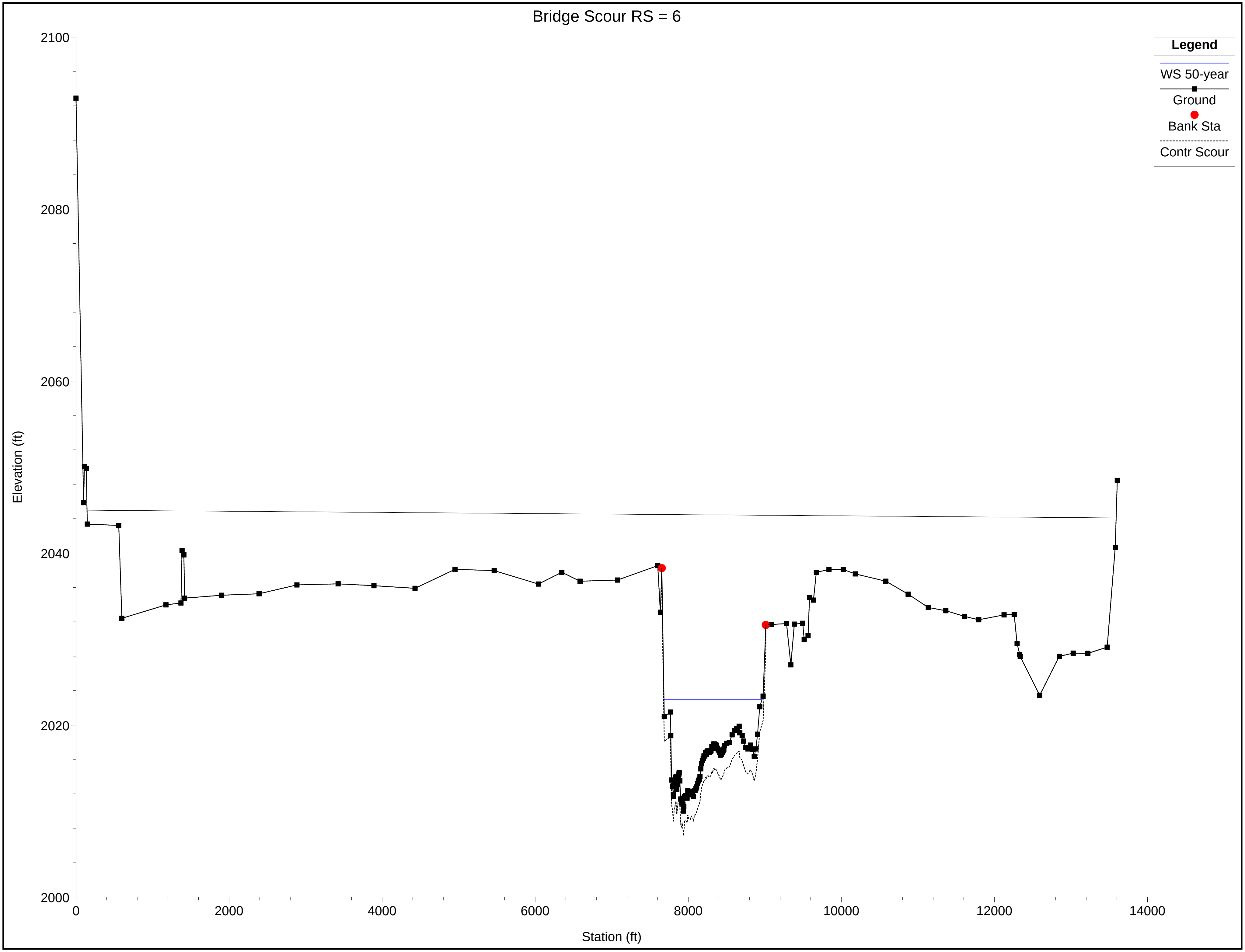

Bridge Scour RS = 6
Legend
WS 10-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		5.16	
	Approach Velocity (ft/s):		3.85	
	Br Average Depth (ft):		4.44	
	BR Opening Flow (cfs):		25000.00	
	BR Top WD (ft):		1149.08	
	Grain Size D50 (mm):		3.5	
	Approach Flow (cfs):		25000.00	
	Approach Top WD (ft):		1258.00	
	K1 Coefficient:		0.590	
Results				
	Scour Depth Ys (ft):		1.42	
	Critical Velocity (ft/s):			
	Equation:		Clear	

Combined Scour Depths

50-Year Contraction Scour Hydraulic Tables

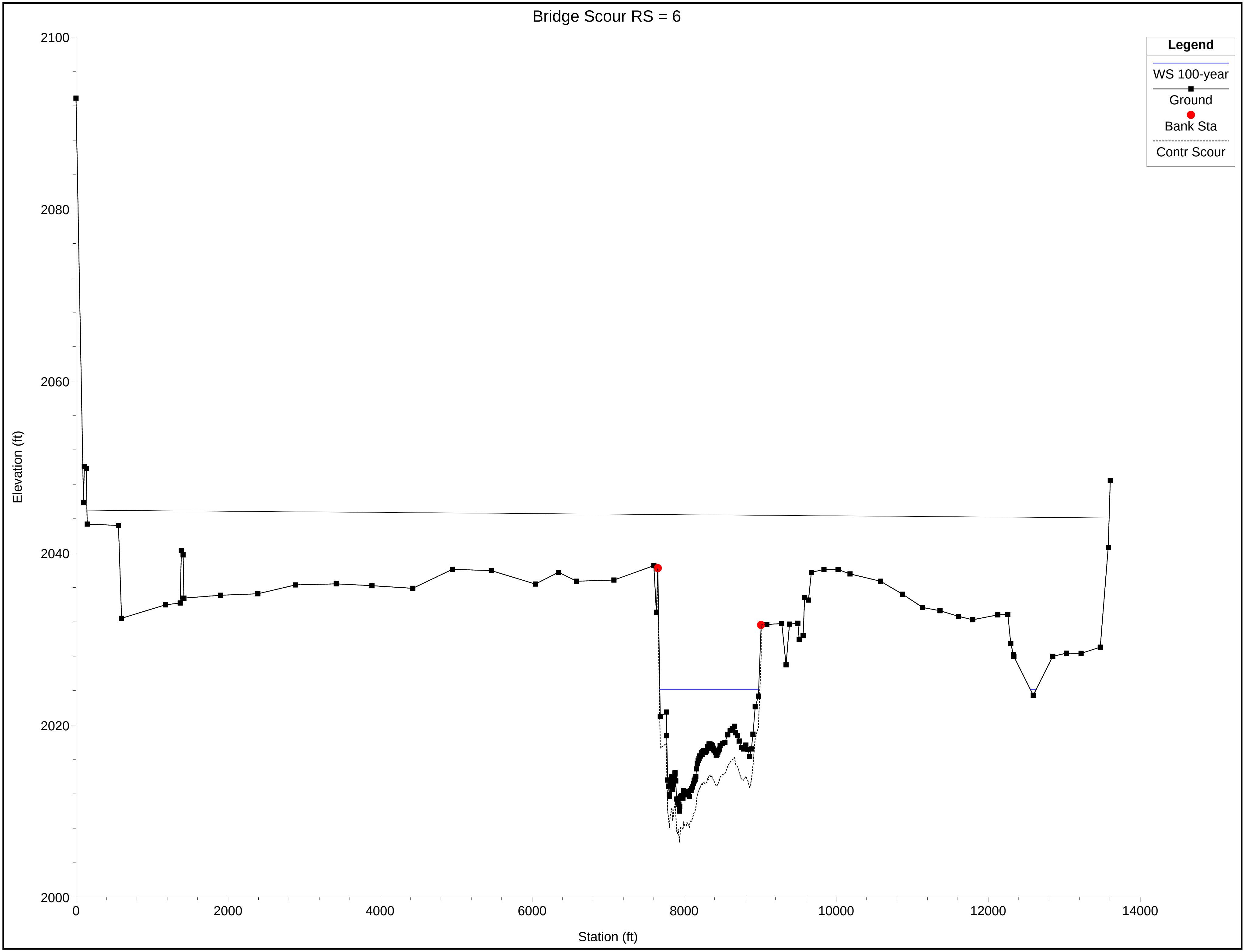

Bridge Scour RS = 6
Legend
WS 50-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

	Left	Channel	Right
Input Data			
Average Depth (ft):		7.64	
Approach Velocity (ft/s):		4.94	
Br Average Depth (ft):		6.47	
BR Opening Flow (cfs):		48000.00	
BR Top WD (ft):		1282.42	
Grain Size D50 (mm):		3.5	
Approach Flow (cfs):		48000.00	
Approach Top WD (ft):		1272.63	
K1 Coefficient:		0.590	
Results			
Scour Depth Ys (ft):		2.87	
Critical Velocity (ft/s):			
Equation:		Clear	

Combined Scour Depths

100-Year Contraction Scour
Hydraulic Tables



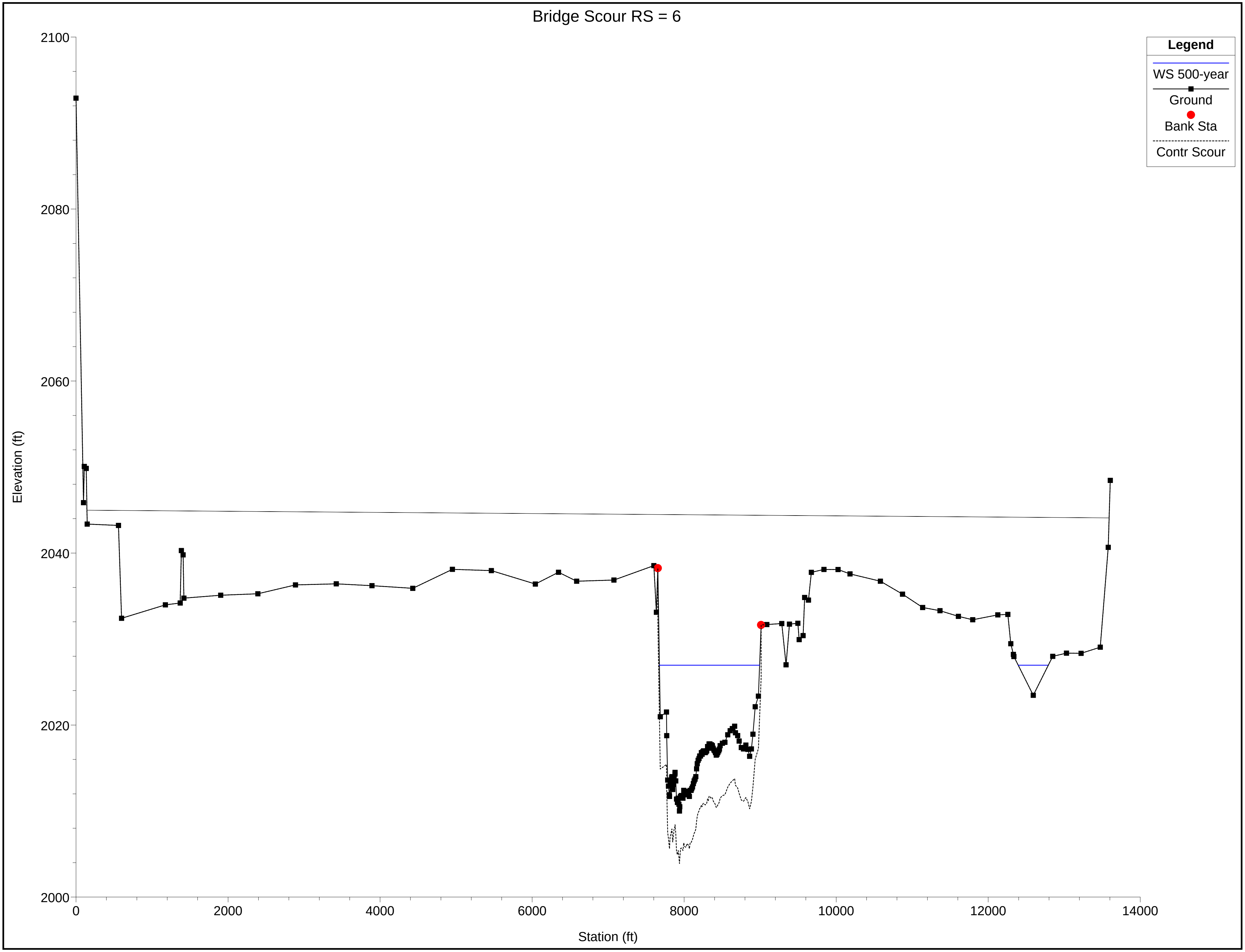
Bridge Scour RS = 6
Legend
WS 100-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		8.13	0.57
	Approach Velocity (ft/s):		5.34	0.36
	Br Average Depth (ft):		7.53	0.35
	BR Opening Flow (cfs):		59991.15	8.85
	BR Top WD (ft):		1300.40	79.41
	Grain Size D50 (mm):		3.5	3.5
	Approach Flow (cfs):		59977.52	22.49
	Approach Top WD (ft):		1380.09	109.77
	K1 Coefficient:		0.590	0.590
Results				
	Scour Depth Ys (ft):		3.64	0.00
	Critical Velocity (ft/s):			
	Equation:		Clear	Clear

Combined Scour Depths

500-Year Contraction Scour
Hydraulic Tables

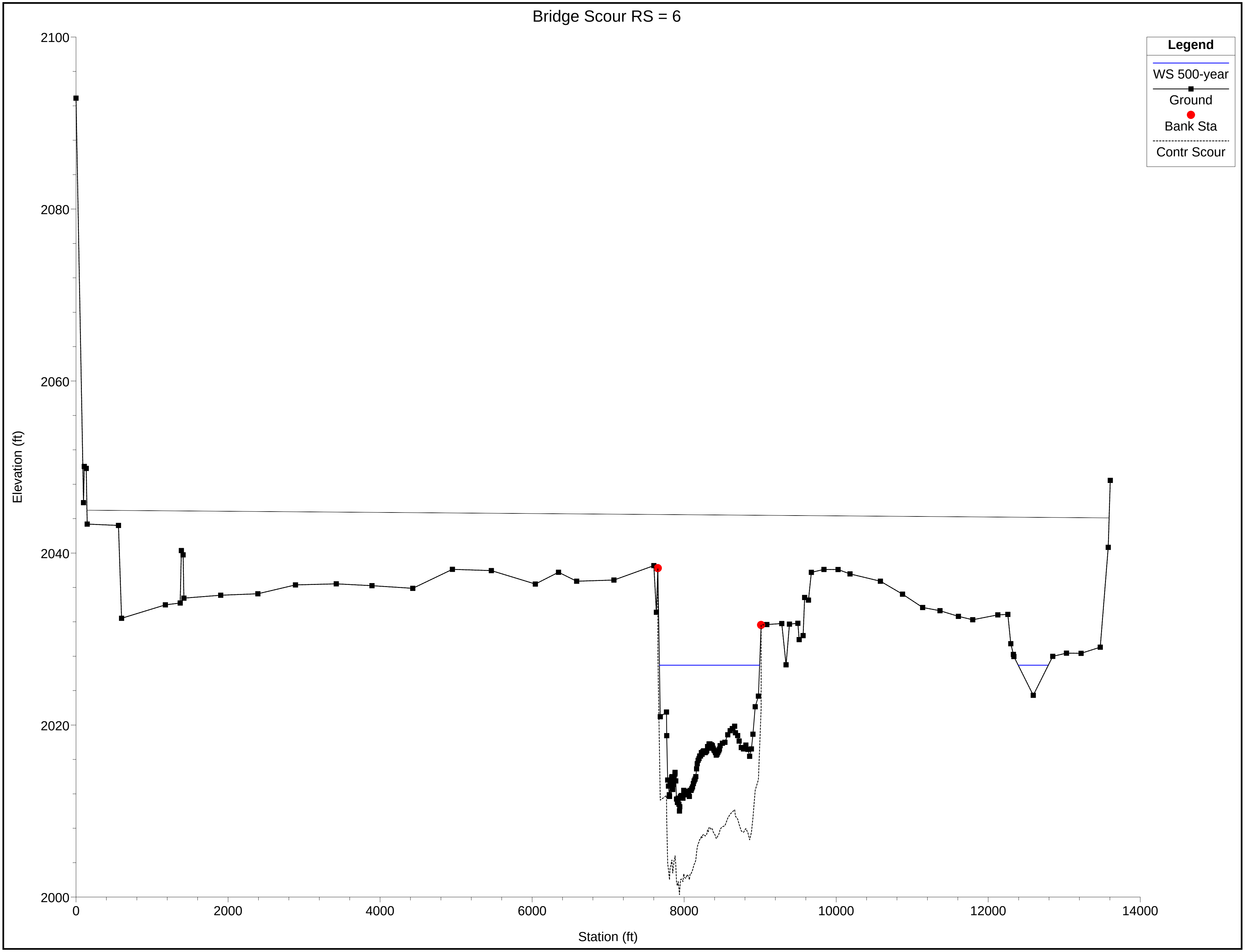

Bridge Scour RS = 6
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000
Legend
WS 500-year
Ground
Bank Sta
Contr Scour

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		9.78	2.26
	Approach Velocity (ft/s):		6.11	0.92
	Br Average Depth (ft):		10.21	1.75
	BR Opening Flow (cfs):		94400.52	599.47
	BR Top WD (ft):		1317.74	395.50
	Grain Size D50 (mm):		3.5	3.5
	Approach Flow (cfs):		94354.65	645.36
	Approach Top WD (ft):		1578.23	309.60
	K1 Coefficient:		0.590	0.590
Results				
	Scour Depth Ys (ft):		6.09	0.00
	Critical Velocity (ft/s):			
	Equation:		Clear	Clear

Combined Scour Depths

D_{50}=1.737 mm Sensitivity Analysis Contraction Scour Hydraulic Tables

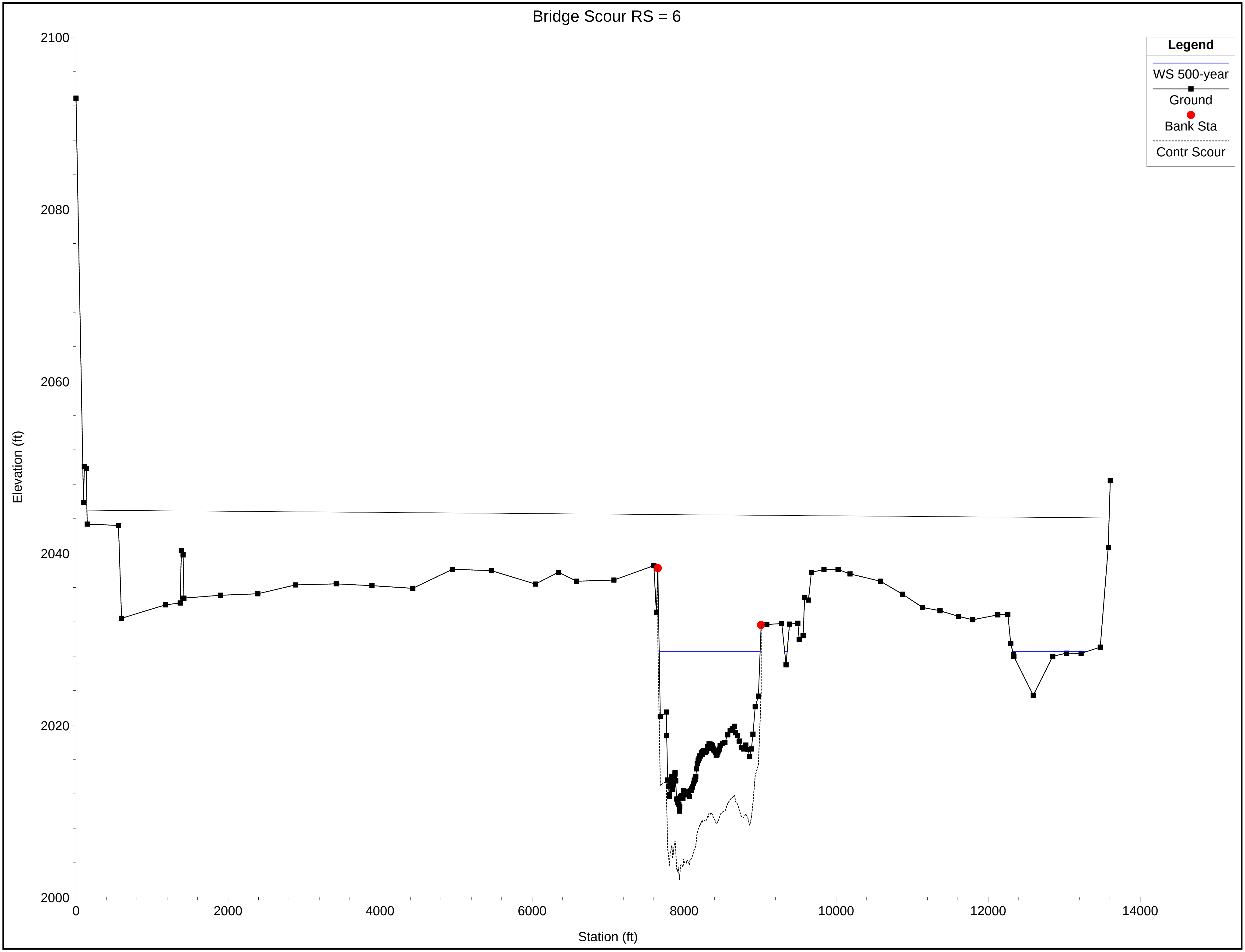

Bridge Scour RS = 6
Legend
WS 500-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
0
2000
4000
6000
8000
10000
12000
14000
Station (ft)

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):		9.78	2.26
	Approach Velocity (ft/s):		6.11	0.92
	Br Average Depth (ft):		10.21	1.75
	BR Opening Flow (cfs):		94400.52	599.47
	BR Top WD (ft):		1317.74	395.50
	Grain Size D50 (mm):		1.74	1.74
	Approach Flow (cfs):		94354.65	645.36
	Approach Top WD (ft):		1578.23	309.60
	K1 Coefficient:		0.640	0.590
Results				
	Scour Depth Ys (ft):		9.70	0.00
	Critical Velocity (ft/s):			
	Equation:		Clear	Clear

Combined Scour Depths

Normal Flow Sensitivity Analysis Contraction Scour Hydraulic Tables

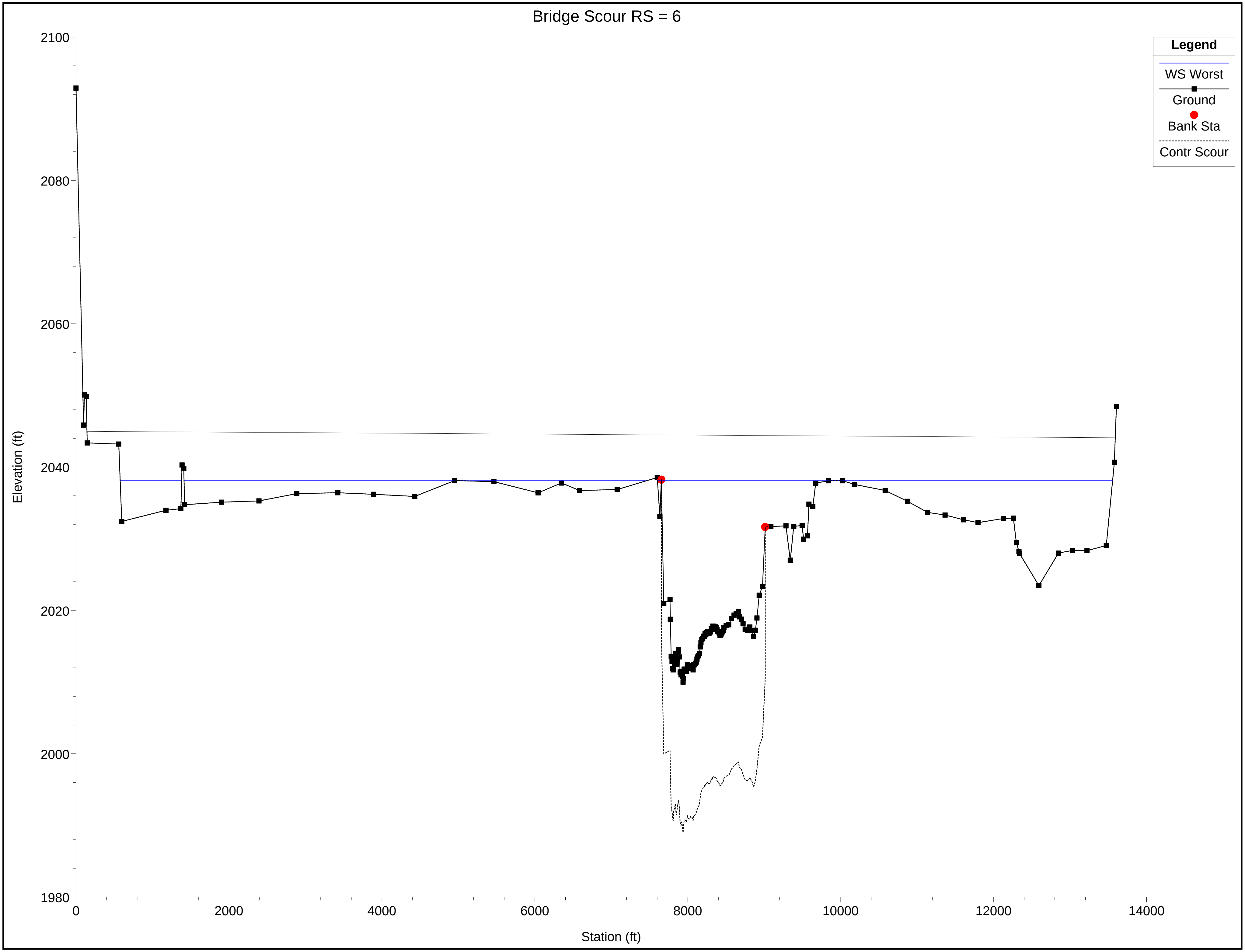

Bridge Scour RS = 6
Legend
WS 500-year
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
Station (ft)
0
2000
4000
6000
8000
10000
12000
14000

Contraction Scour

	Left	Channel	Right
Input Data			
Average Depth (ft):		10.91	1.63
Approach Velocity (ft/s):		5.39	0.76
Br Average Depth (ft):		11.71	1.57
BR Opening Flow (cfs):		93990.78	1009.22
BR Top WD (ft):		1327.54	1001.12
Grain Size D50 (mm):		1.74	1.74
Approach Flow (cfs):		93749.09	1250.92
Approach Top WD (ft):		1594.03	1011.10
K1 Coefficient:		0.640	0.590
Results			
Scour Depth Ys (ft):		8.00	0.00
Critical Velocity (ft/s):			
Equation:		Clear	Clear

Combined Scour Depths

Worst-case Sensitivity Analysis Contraction Scour Hydraulic Tables


Bridge Scour RS = 6
Legend
WS Worst
Ground
Bank Sta
Contr Scour
Elevation (ft)
2100
2080
2060
2040
2020
2000
1980
0
2000
4000
6000
8000
10000
12000
14000
Station (ft)

Contraction Scour

		Left	Channel	Right
Input Data				
	Average Depth (ft):	1.96	19.57	5.98
	Approach Velocity (ft/s):	1.06	8.82	1.65
	Br Average Depth (ft):	1.94	20.92	5.61
	BR Opening Flow (cfs):	13385.15	292760.50	43854.31
	BR Top WD (ft):	6834.89	1358.73	4542.55
	Grain Size D50 (mm):	3.50	3.50	3.50
	Approach Flow (cfs):	9950.51	300749.00	39300.48
	Approach Top WD (ft):	4794.77	1741.70	3989.00
	K1 Coefficient:	0.590	0.590	0.590
Results				
	Scour Depth Ys (ft):	0.00	21.01	0.00
	Critical Velocity (ft/s):			
	Equation:	Clear	Clear	Clear

Combined Scour Depths

Appendix F –
Geotech Report: Borehole 2

Tetra Tech
2535 Palmer Street
Missoula, MT 59806
Phone: 406-543-3045
Fax: 406-543-3088

Figure No. 2
LOG OF BORING

TETRA TECH

Project Name: Keystone XL Pipeline Project - Priority 2008 Sites - Montana Facilities			Project Number: 9570103
Borehole Location: Refer to Site Map (Missouri River)		Borehole Number: BH-2.1.02-02	Sheet 1 of 3
Stationing:	Hammer Type: Automatic	Driller: Mark Medley	Logger: Jeremy Dierking
Drilling Equipment: CME-55 ATV	Borehole Diameter (in): 6.00	Date Started: 10-29-08	Date Finished: 10-29-08
Elevation and Datum: Ground: 2037.06		Notes: N17465199.3 E1316514.2 qu = Pocket Penetrometer Reading c = Torvane Reading	

DEPTH (ft)	DRILL OPERATION	DRILL PRESSURE (psi)	DRILL RATE (mph)	CORE PERCENT RECOVERY	ROCK QUALITY DESIGNATION (RQD)	SAMPLE	RECOVERY (%)	STANDARD PENETRATION TEST SPT	MOISTURE CONTENT (%)	DRY DENSITY (pcf)	LIQUID LIMIT LL	PLASTICITY INDEX PI	MINUS NO. 200 (%)	GRAPHIC LOG	MATERIAL DESCRIPTION	DEPTH (ft)	REMARKS
															TOPSOIL, organic material, dark brown, moist (12 in. thick).	1.00	
															Silty SAND and Sandy lean CLAY, alternating seams 3 to 6 in. thick, medium stiff to stiff, loose, brown, moist, fine grained, non-plastic to low plasticity.		
5																	
						☒	100	3-3-3	27								qu = 2.25 tsf c = 0.6 tsf
10																	
						⧓	40	8	27		46	28	52				qu = 2.5 tsf c = 0.6 tsf
15																	
						☒	65	2-3-4	22								
															Silty SAND, very loose to loose, brown, wet, fine grained, non-plastic.	▽17.00	
																▼	
20																	
						■			28				20				qu = 0.5 tsf c = 0.15 tsf
						☒	100	3-4-2							Flowing sands below water table.		
25																	
						☒	100	3-2-3									
30																	
						☒	100	3-3-4							Poorly graded SAND with silt and gravel, medium dense, brown to gray, wet, fine grained sand and gravel, subangular to subrounded gravel, non-plastic.	31.00	
35																	
						☒	100	5-6-5									

Operation Types:
- Mud Rotary
- Continuous Flight Auger
- Wash Rotary
- Auger
- Air Rotary
- Diamond Core
- Drive Casing

Sampler Types:
- ☒ Split Spoon
- ■ Shelby
- Bulk Sample
- Grab Sample
- Penetrometer
- Vane Shear
- ⧓ California Ring
- Testpit

WATER LEVEL OBSERVATIONS

While Drilling ▽ 17.00 ft Upon Completion of Drilling ▼ 19.00 ft
Time After Drilling
Depth To Water (ft) ▼
Remarks: Flowing sand below groundwater table.

Tetra Tech
2535 Palmer Street
Missoula, MT 59806
Phone: 406-543-3045
Fax: 406-543-3088

Figure No. 2
LOG OF BORING

TETRA TECH

Project Name: Keystone XL Pipeline Project - Priority 2008 Sites - Montana Facilities			Project Number: 9570103
Borehole Location: Refer to Site Map (Missouri River)		Borehole Number: BH-2.1.02-02	Sheet 2 of 3
Stationing:	Hammer Type: Automatic	Driller: Mark Medley	Logger: Jeremy Dierking
Drilling Equipment: CME-55 ATV	Borehole Diameter (in): 6.00	Date Started: 10-29-08	Date Finished: 10-29-08
Elevation and Datum: Ground: 2037.06		Notes: N17465199.3 E1316514.2 qu = Pocket Penetrometer Reading c = Torvane Reading	

DEPTH (ft)	DRILL OPERATION	DRILL PRESSURE (psi)	DRILL RATE (mph)	CORE PERCENT RECOVERY	ROCK QUALITY DESIGNATION (RQD)	SAMPLE	RECOVERY (%)	STANDARD PENETRATION TEST SPT	MOISTURE CONTENT (%)	DRY DENSITY (pcf)	LIQUID LIMIT LL	PLASTICITY INDEX PI	MINUS NO. 200 (%)	GRAPHIC LOG	MATERIAL DESCRIPTION	DEPTH (ft)	REMARKS
40						☒	80	7-7-8	14				12		Poorly graded SAND with silt and gravel (continued).		
45						☒	100	7-7-8							Approximately 3 in. coarse grained sand at 45 ft. Poorly graded SAND with silt, medium dense to dense, brown to gray, wet, fine grained, non-plastic.	45.00	qu = 0.75 tsf
50						☒	100	11-14-17									qu = 1.5 tsf
55						☒	100	6-7-6									
60						☒	100	9-21-25									qu = 2.0 tsf
65						☒	100	6-8-9							Lean clay seam from 65.5 to 66 ft.		
70						☒	100	4-5-5									
75						☒	100	4-5-10									

Operation Types:
- Mud Rotary
- Continuous Flight Auger
- Wash Rotary
- Auger
- Air Rotary
- Diamond Core
- Drive Casing

Sampler Types:
- ☒ Split Spoon
- Shelby
- Bulk Sample
- Grab Sample
- Penetrometer
- Vane Shear
- California Ring
- Testpit

WATER LEVEL OBSERVATIONS

While Drilling ▽ 17.00 ft Upon Completion of Drilling ▼ 19.00 ft
Time After Drilling
Depth To Water (ft)
Remarks: Flowing sand below groundwater table.

Tetra Tech
2535 Palmer Street
Missoula, MT 59806
Phone: 406-543-3045
Fax: 406-543-3088

Figure No. 2

LOG OF BORING

TETRA TECH

Project Name: Keystone XL Pipeline Project - Priority 2008 Sites - Montana Facilities		Project Number: 9570103	
Borehole Location: Refer to Site Map (Missouri River)		Borehole Number: BH-2.1.02-02	Sheet 3 of 3
Stationing:	Hammer: Type: Automatic	Driller: Mark Medley	Logger: Jeremy Dierking
Drilling Equipment: CME-55 ATV	Borehole Diameter (in): 6.00	Date Started: 10-29-08	Date Finished: 10-29-08
Elevation and Datum: Ground: 2037.06		Notes: N17465199.3 E1316514.2 qu = Pocket Penetrometer Reading c = Torvane Reading	

DEPTH (ft)	DRILL OPERATION	DRILL PRESSURE (psi)	DRILL RATE (mph)	CORE PERCENT RECOVERY	ROCK QUALITY DESIGNATION (RQD)	SAMPLE	RECOVERY (%)	STANDARD PENETRATION TEST SPT	MOISTURE CONTENT (%)	DRY DENSITY (pcf)	LIQUID LIMIT LL	PLASTICITY INDEX PI	MINUS NO. 200 (%)	GRAPHIC LOG	MATERIAL DESCRIPTION	DEPTH (ft)	REMARKS
						☒									Poorly graded SAND with silt (continued).		
80						☒	100	3-3-3									
85						☒	100	8-14-21									
90						☒	100	12-14-14									qu = 3.0 tsf
95						☒	100	8-10-21	21				8				qu = 4.0 tsf c = 0.4 tsf
100						☒	100	11-33-13								101.50	

Bottom of Boring at 101.5 ft

Operation Types:		Sampler Types:	
Mud Rotary	Auger	Split Spoon	Penetrometer
Continuous Flight Auger	Air Rotary	Shelby	Vane Shear
Wash Rotary	Diamond Core	Bulk Sample	California Ring
	Drive Casing	Grab Sample	Testpit

WATER LEVEL OBSERVATIONS

While Drilling ▽ 17.00 ft Upon Completion of Drilling ▼ 19.00 ft
Time After Drilling
Depth To Water (ft)
Remarks: Flowing sand below groundwater table.