Houston-Moore Group, LLC

In conjunction with

BARR

HDR

Kadrmas Lee & Jackson

SRF Consulting Group, Inc.

Diversion works in a washload dominated-sediment transport river with limited channel migration, yet very meandering

February 25th, 2013

Upper Midwest
Stream Restoration Symposium

Acknowledgments

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USDA ARS United States Department Of Agriculture Agricultural Research Service

US Army Corps of Engineers

University of Pittsburgh — Veritas 1787 Virtus

HMG Houston-Moore Group

Moorhead Minnesota

City of Fargo

Flood Diversion Authority

What about the river?

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- The Mouse River, like any other river or stream, will have areas of observable erosion and sedimentation under natural conditions. Furthermore, changes over time in a river's course (called channel migration) are common, with erosion occurring on the outer banks of river bends and sedimentation on the inner banks as the river channel continuously reworks itself across its valley. Rivers move sediment in addition to water; this is their natural behavior. A river in a state of equilibrium does not translate into a channel of fixed dimensions or a completely static alignment. On the contrary, a river in equilibrium moves a bit in one place while not moving much in another place. Maintaining such equilibrium is the challenge for any project.

from "Mouse River Enhanced Flood Protection Plan, Erosion and Sedimentation Study" (January 2013)

The Fargo-Moorhead (FM) Area Diversion Project

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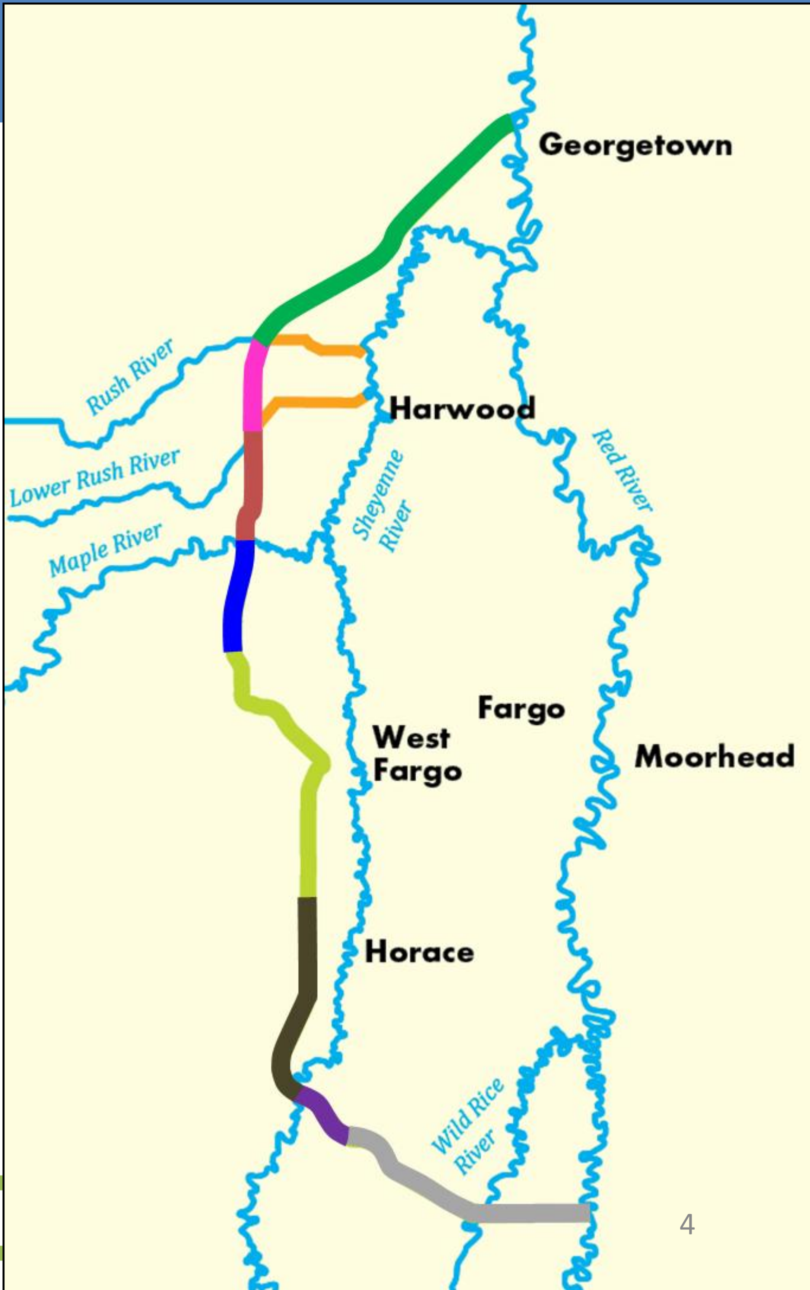
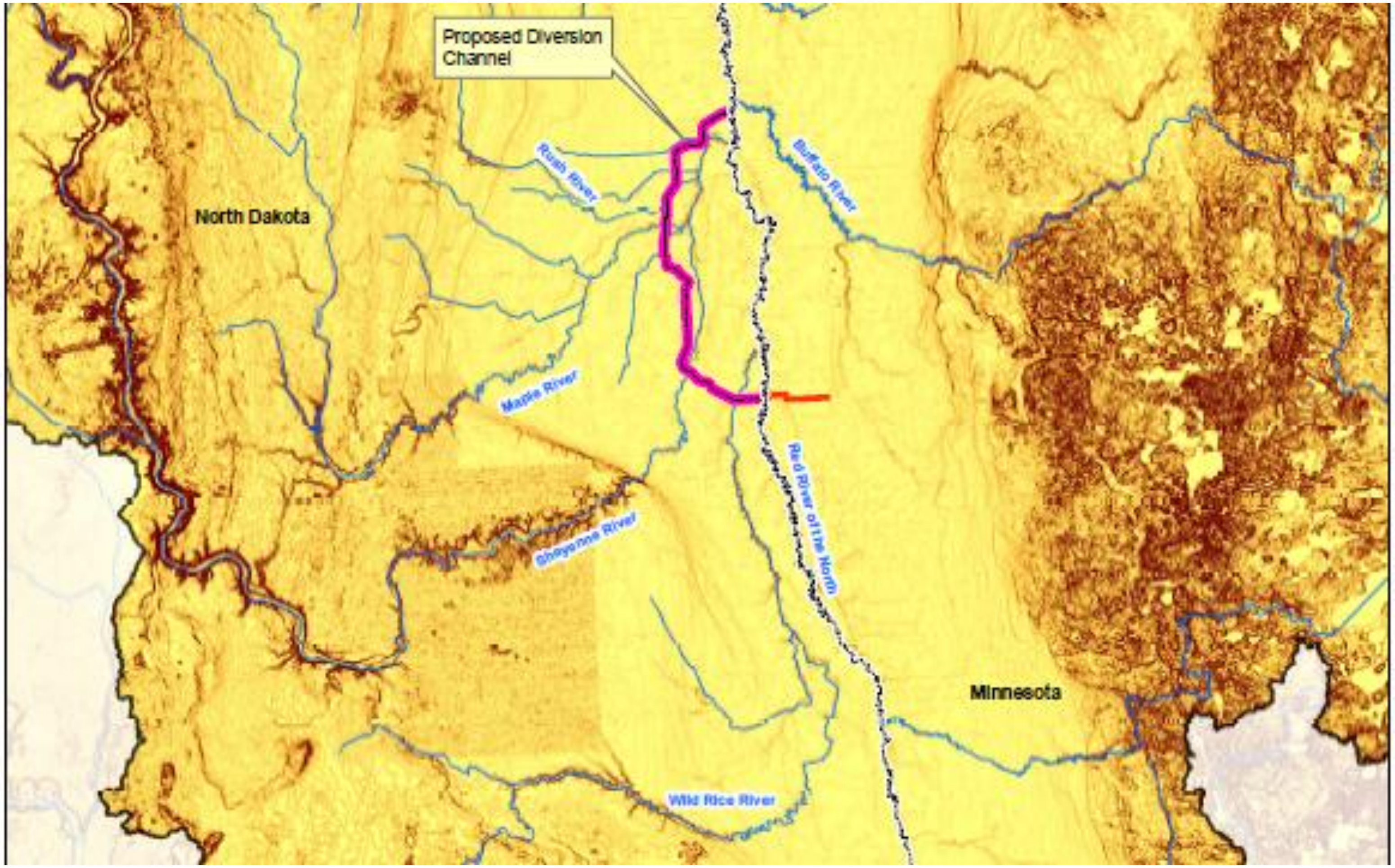
- **Primary Design Considerations**
  - To provide flood risk reduction for events as large as the 100-yr event in the Red River of the North (RRN)
  - To allow for flood fighting efforts up to the 500-yr event in the RRN
  - To avoid catastrophic failure of the diversion works during most extreme events (SPF, or possibly PMF)
- **Major Project Features**
  - 35 miles of diversion channel
  - Low flow channel
  - Staging area
  - Control structures (gated) on the RRN and WRR
  - Main diversion inlet (gated)
  - Aqueducts and spillways on the Sheyenne River (ShR) and Maple River (MR)
  - Rock ramps on the LRR and RR
  - Diversion outlet



The big picture

- **Geology**
  - Red River Valley occupies the **flat** plain that once was the bed of glacial Lake Agassiz, which remained in existence from approximately 11,500 to 7,500 years BP
  - 150 to 300 foot layer of primarily **silts and clays** over a 50-60 mile wide area stretching from south of Breckenridge, Minnesota to Winnipeg, Manitoba
  - Glacial rivers flowing into the glacial lake shorelines created deltas of coarser sediment (sands and gravels) that are mostly buried beneath later lake-deposited fine sediment
- **Flooding**
  - The RRN has exceeded flood stage in 48 of the past 109 years, including every year from 1993 through 2011
  - Flood of record in 2009 corresponded to approximately a 50-year event in the RRN
  - When it floods, the **floodplain is several miles wide** but the **flow velocities** (even in the main stem) are **relatively low**
- **Unique diversion in the Red River Valley?**
  - Two existing diversions in ShR in operation since 1992
  - Manitoba Floodway built in 1968, and expansion completed in 2011

Very flat



Proposed Diversion Channel
North Dakota
Rush River
Buffalo River
Maple River
Sheyenne River
Red River of the North
Minnesota
Wild Rice River

Mostly cohesive sediment

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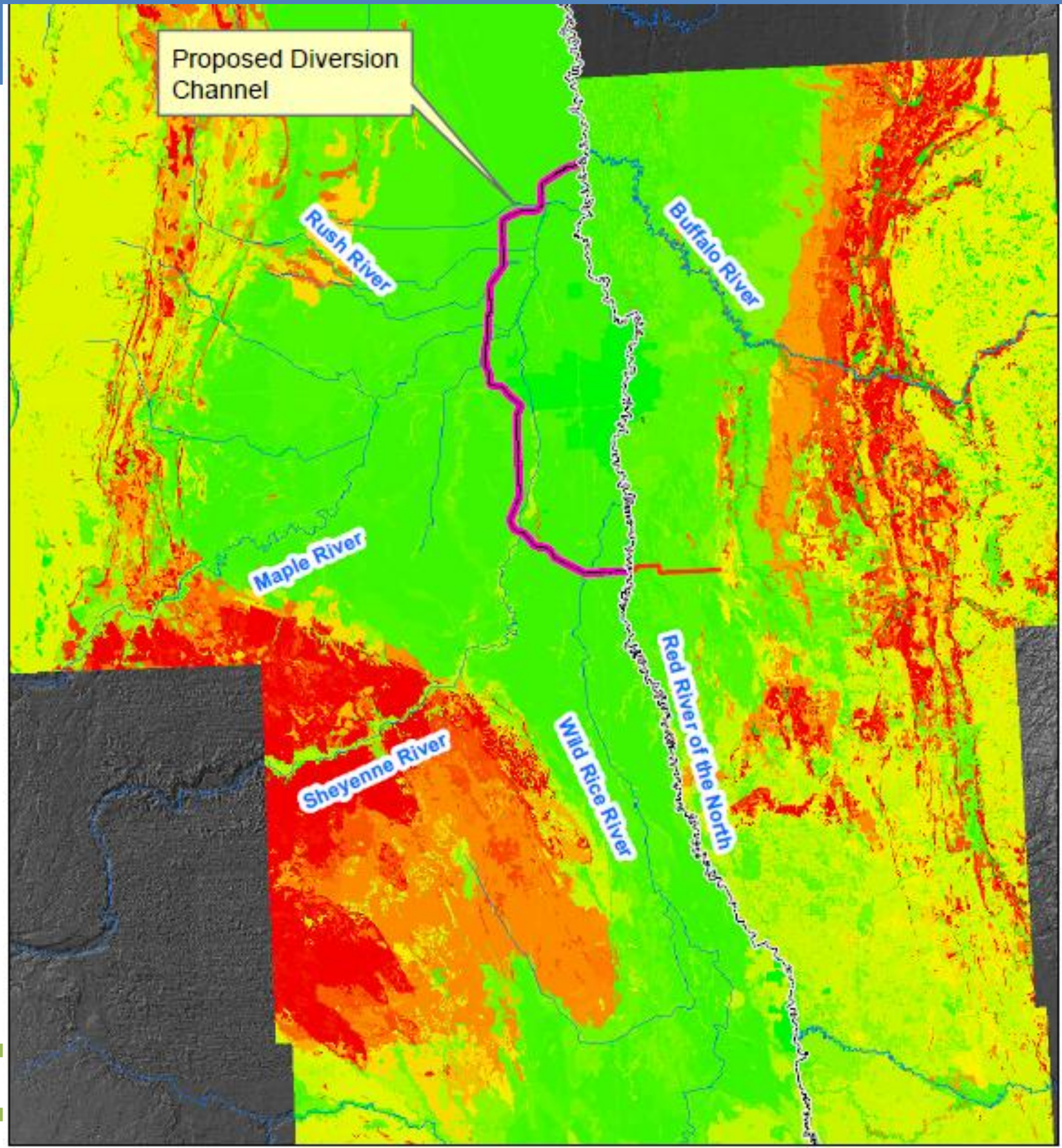
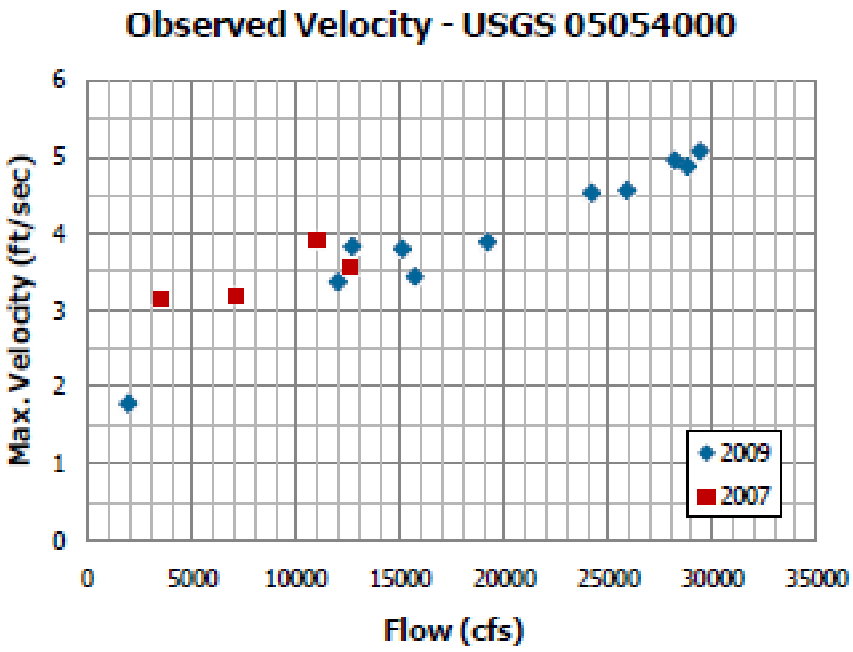
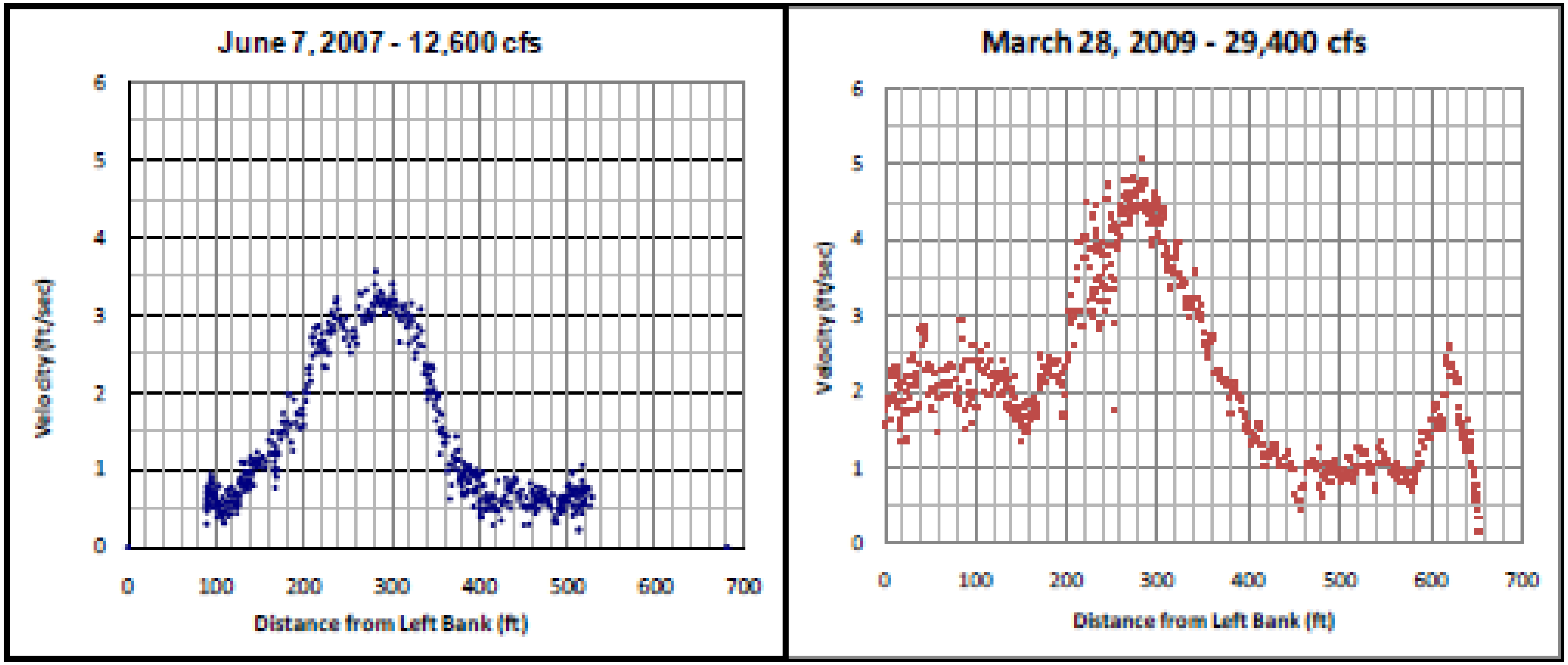


Not that high maximum flow velocities



Approaching <1 fps near channel banks



Sediment transport measurements

- **Measurements**
  - Suspended sediment transport rate and grain size distribution (both depth-integrated and point samples)
  - Bedload transport rate and grain size distribution
  - Bed sediment grain size distribution
- **Sources**
  - USGS historic
  - Buffalo River in 2006
  - South Fargo Flood Control Project in 2008
  - USGS for FM Area Diversion Project, including
    - high flow 2010,
    - high flow 2011,
    - low flow 2011, and
    - 2012 (unpublished)
  - WEST Consultants for FM Area Diversion Project, including
    - 2010, and
    - 2011

Sediment loading – USGS high flow 2010

Site Name	Time Period[1]	Total Flow (million ft^3)	Total Suspended Sediment Load (tons)	Total Bedload (tons)[2]	Total Sediment Load (tons)
Wild Rice River near St. Benedict	March 18, 2010 - March 31, 2010	8,780	43,260	31.8 (0.07%)	43,300
Sheyenne River above Sheyenne River Diversion near Horace	March 24, 2010 - April 7, 2010	5,340	119,590	40.7 (0.03%)	119,630
Sheyenne River at Horace	March 24, 2010 - April 7, 2010	2,580	56,370	9.3 (0.01%)	56,380
Maple River below Mapleton	March 19, 2010 - April 6, 2010	4,660	31,520	70.9 (0.2%)	31,600
Red River of the North near Christine	March 18, 2010 - March 31, 2010	10,030	30,780	171 (0.6%)	30,950
Red River of the North near Fargo	March 18, 2010 - March 31, 2010	19,810	72,080	27.6 (0.04%)	72,110

Sediment loading – USGS high flow 2011

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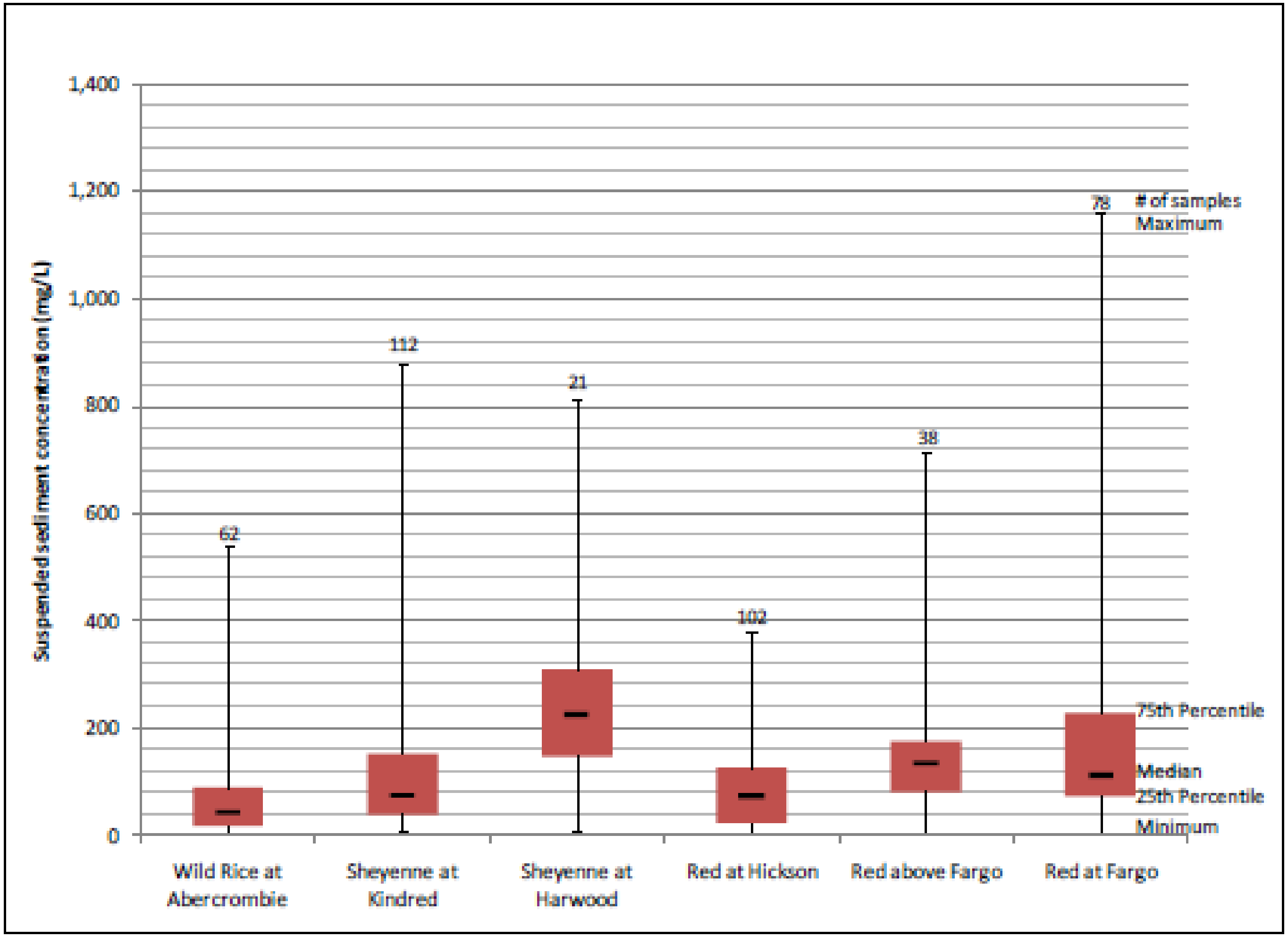
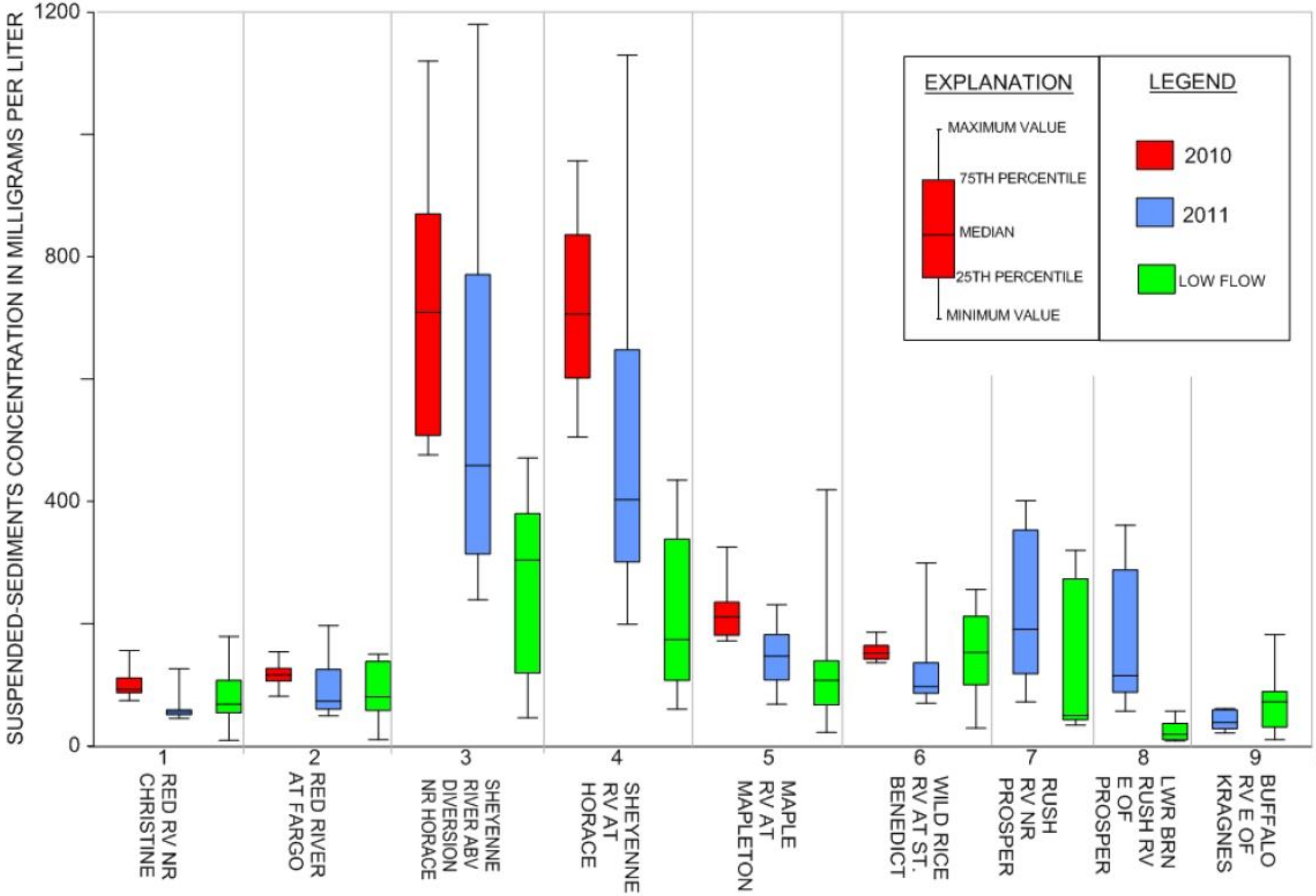
Site Name	Time Period[1]	Total Flow (million ft^3)	Total Sus. Sed. Load (tons)	Total Bedload (tons)[2]	Total Sed. Load (tons)
Wild Rice River near St. Benedict	April 6, 2011 - May 16, 2011	17,960	67,610	195 (0.3%)	67,800
Sheyenne River above Sheyenne River Diversion near Horace	April 9, 2011 - May 16, 2011	14,730	175,130	84.0 (0.05%)	175,220
Sheyenne River at Horace	April 9, 2011 - May 16, 2011	7,060	72,450	220 (0.3%)	72,670
Maple River below Mapleton	April 7, 2011 - May 16, 2011	11,900	47,220	104 (0.2%)	47,320
Red River of the North near Christine	April 6, 2011 - May 16, 2011	26,710	49,700	756 (1.5%)	50,450
Red River of the North near Fargo	April 6, 2011 - May 16, 2011	48,650	117,460	91.7 (0.08%)	117,550

- Transport in **suspension** is significantly greater than as bedload
- The mass balance for the RRN closes, i.e., **no net erosion or deposition!**
- **Similar** flow and sediment **partitioning** at **ShR diversions**

SSC – USGS historic



SSC – USGS 2010 and 2011

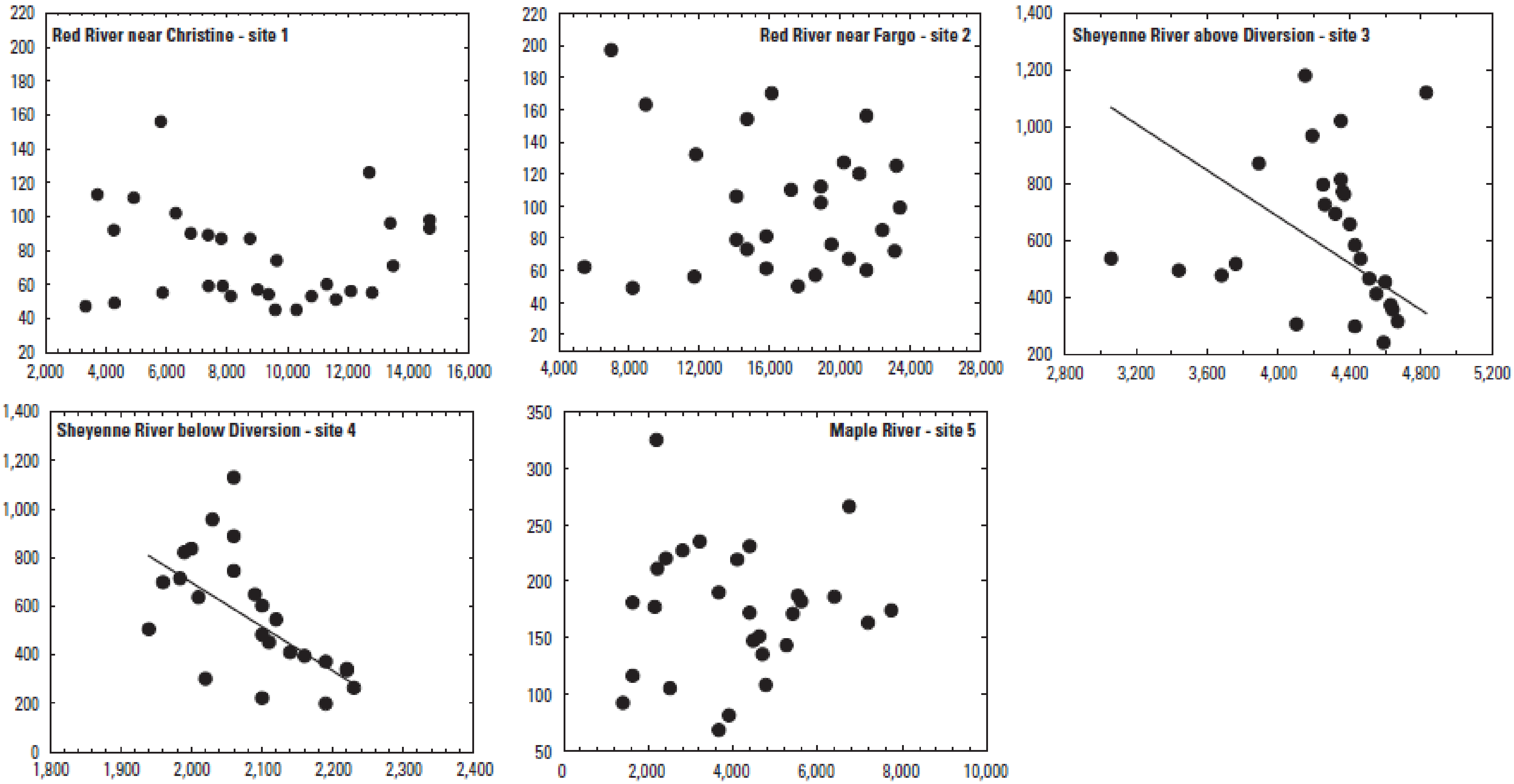


SSC – USGS 2012 (unpublished)

- **RRN**
  - values mostly ranging between 50 and 250 mg/L
  - a couple of measurements 800-900 mg/L
- **ShR**
  - values mostly ranging between 100 and 450 mg/L
- **MR**
  - values mostly below 150 mg/L
  - a couple of measurements 700-800 mg/L

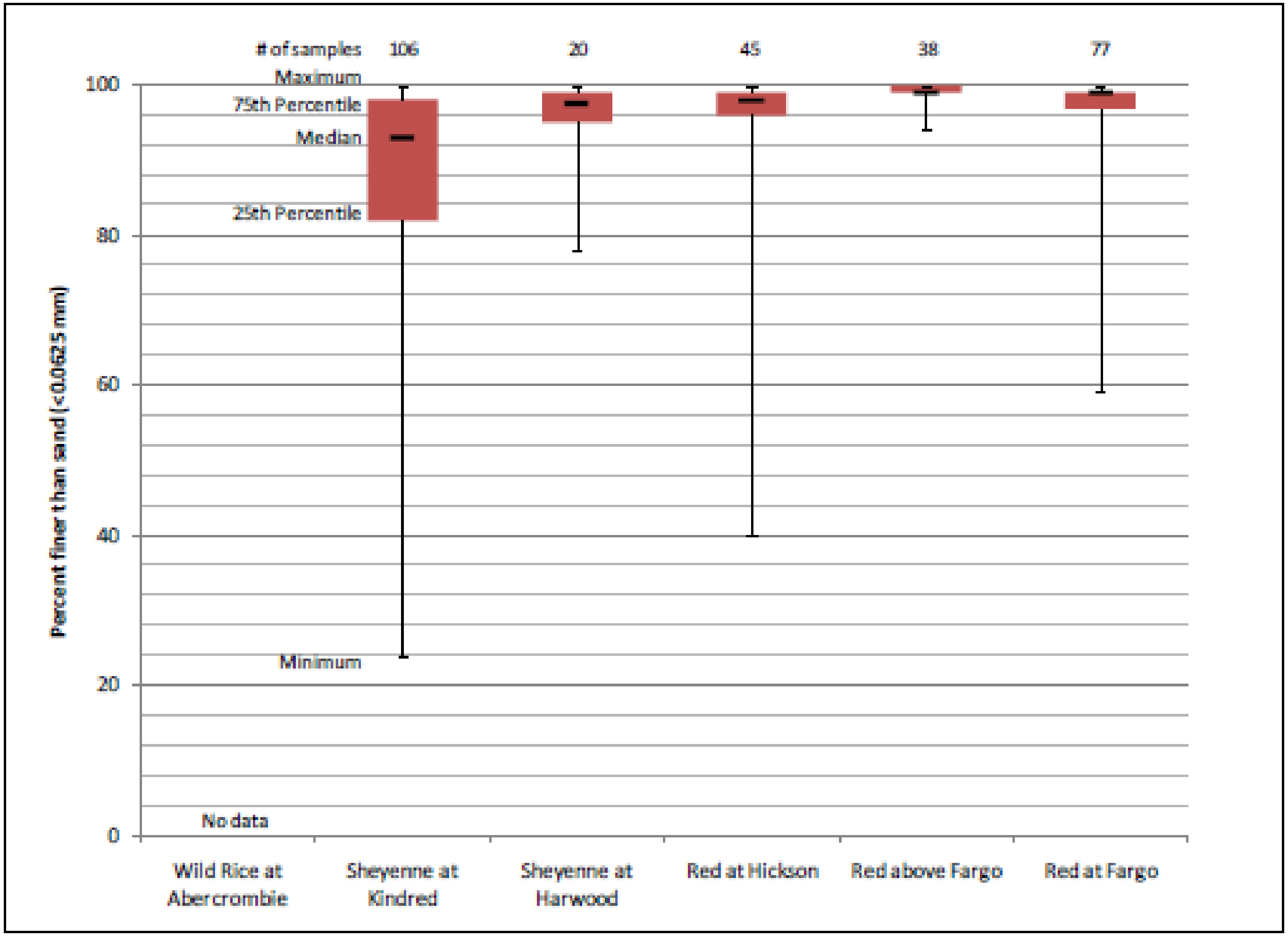
Any relationship between SSC and flow? (figures "borrowed" from USGS)

BARR



- A **consistent relationship** between sediment transport rates and flows is **not evident**

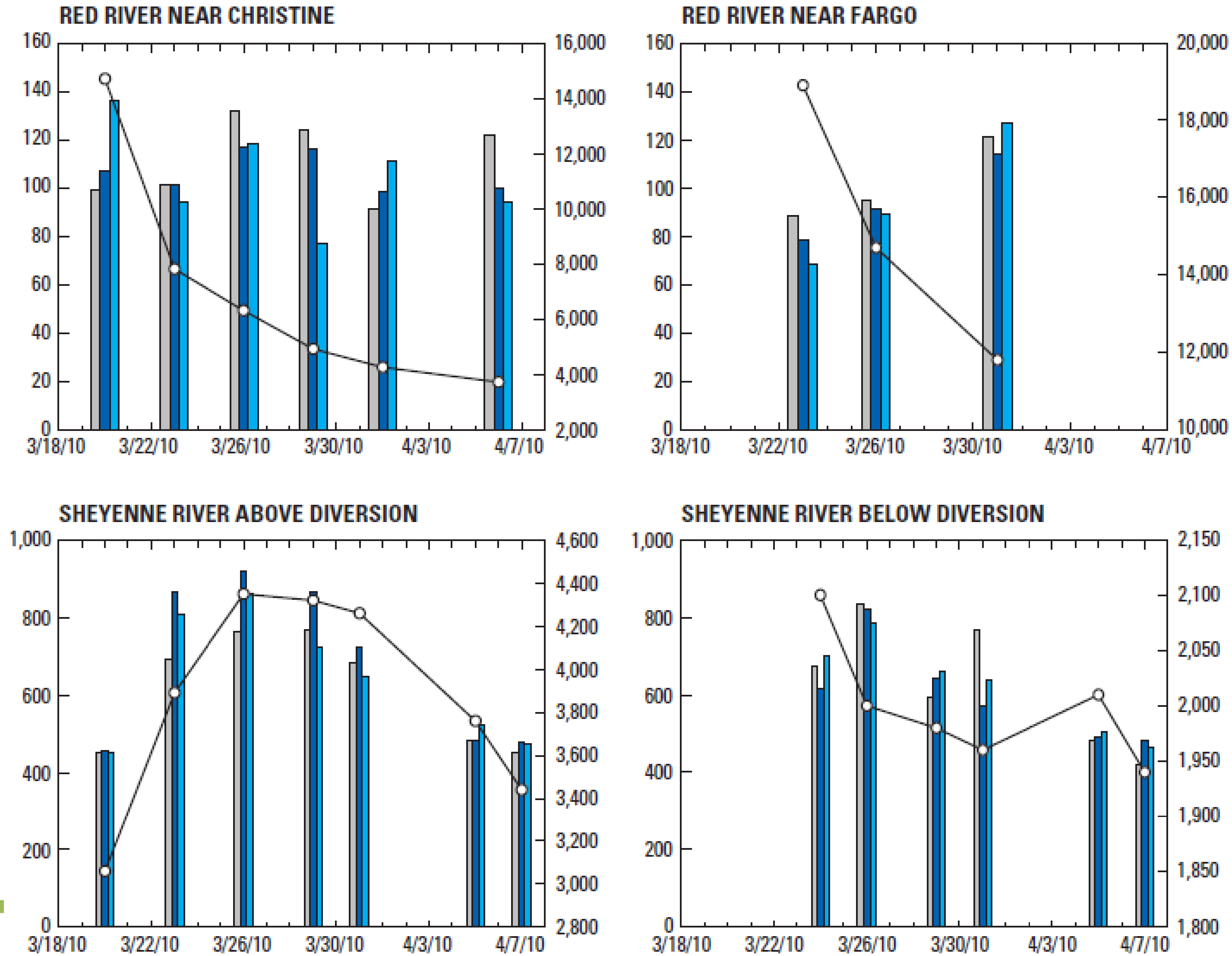
GSD suspended sediment – USGS historic



GSD suspended sediment – USGS high flow 2010 and 2011

- **RRN**
  - In **2010**, 11 out of 12 measurements in RRN **near Christine** have depth-integrated suspended sediment gradations with more than **89%** finer than sand. In **2011**, 17 out of 18 measurements have more than **87%** finer than sand
  - In **2010**, 10 measurements in RRN **near Fargo** have depth-integrated suspended sediment gradations with more than **96%** finer than sand. In **2011**, 18 out of 19 measurements have more than **92%** finer than sand
- **ShR**
  - In **2010**, 7 measurements in ShR **u/s diversion** have depth-integrated suspended sediment gradations with **70%-84%** finer than sand. In **2011**, 16 measurements have **57%-81%** finer than sand
  - In **2010**, 6 out of 7 measurements in ShR **d/s diversion** have depth-integrated suspended sediment gradations with **78%-83%** finer than sand (other has 95%). In **2011**, 16 measurements have **70%-90%** finer than sand
- **MR**
  - In **2010**, 10 out of 11 measurements in MR **below Mapleton** have depth-integrated suspended sediment gradations with more than **93%** finer than sand. In **2011**, 15 out of 17 measurements have more than **93%** finer than sand

Vertical profile of SSC – USGS 2010 high flow (figures "borrowed" from USGS)



Vertical profile of SSC – USGS low flow 2012 (unpublished)

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Sheyenne River u/s diversion

Date	Location	SSC (mg/L) per vertical point				Q approx
		top	middle	middle-2	bottom	(cfs)
03/20/2012		356	358		375	842
04/04/2012		172	147		185	688
04/19/2012		125	175		221	808
04/30/2012		391	214		319	866
06/29/2012		245	245		258	474
10/03/2012	left	133	136		166	510
10/03/2012	middle	156	123		173	510
10/03/2012	right	120	122	168	124	510

Sheyenne River d/s diversion

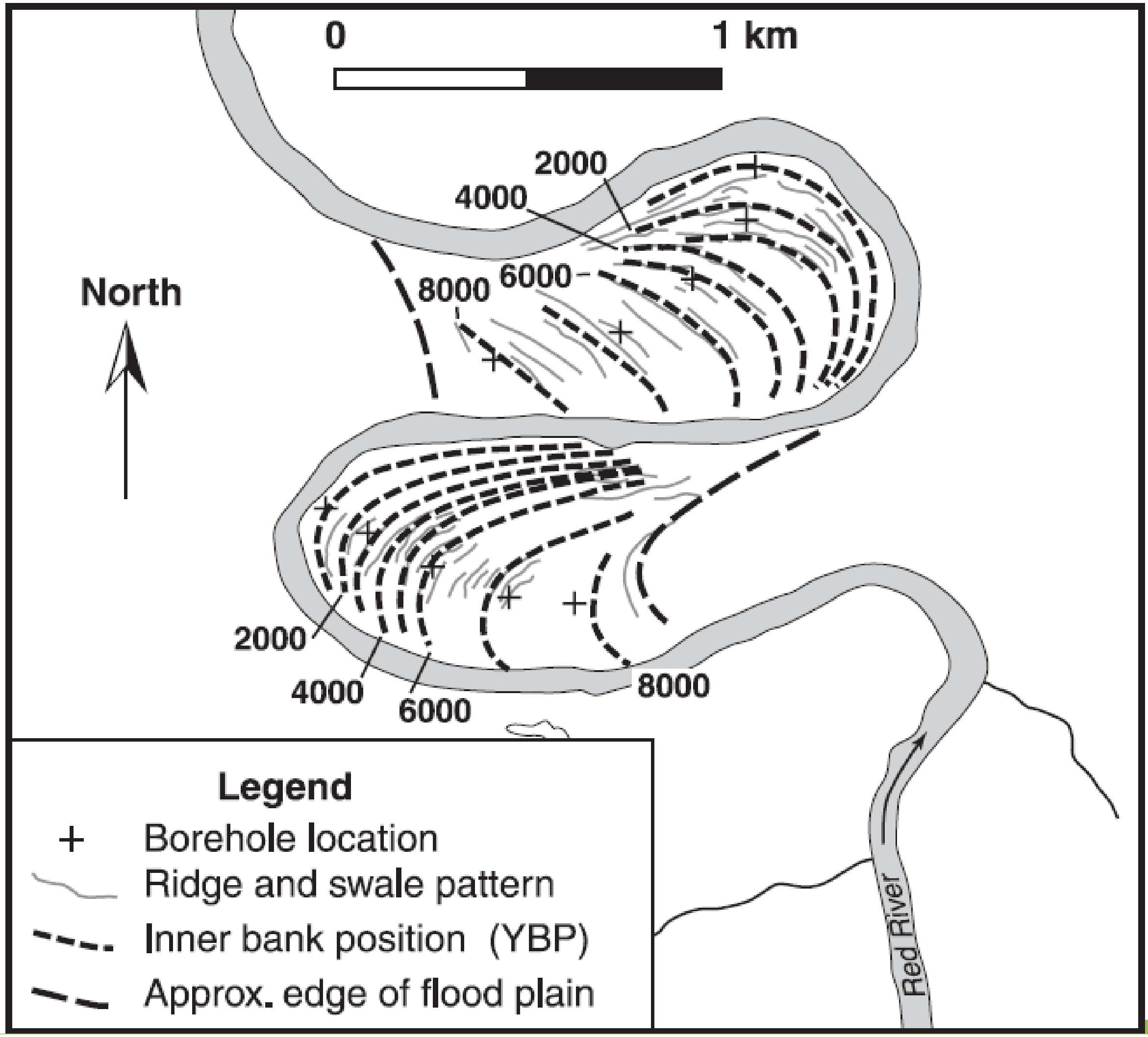
Date	Location	SSC (mg/L) per vertical point					Q approx
		top	middle	middle-2	middle-3	bottom	(cfs)
03/20/2012		410	431			443	842
04/04/2012		179	194			248	688
04/19/2012		266	239			220	808
04/30/2012		348	232			359	866
06/29/2012		251	239			254	474
10/03/2012	left	142	146			154	510
10/03/2012	middle	149	137	158		132	510
10/03/2012	right	131	183	193	159	181	510

Sheyenne River near Kindred

Date	Location	SSC (mg/L) per vertical point				Q approx
		top	middle	middle-2	bottom	(cfs)
03/21/2012		241	248		253	584
04/04/2012		148	186		217	676
04/20/2012		120	136		165	754
04/30/2012		209	176		184	861
06/29/2012		258	286		266	487
10/03/2012	left	124	139	162	137	508
10/03/2012	middle	182	123	148	192	508
10/03/2012	right	126	147		235	508

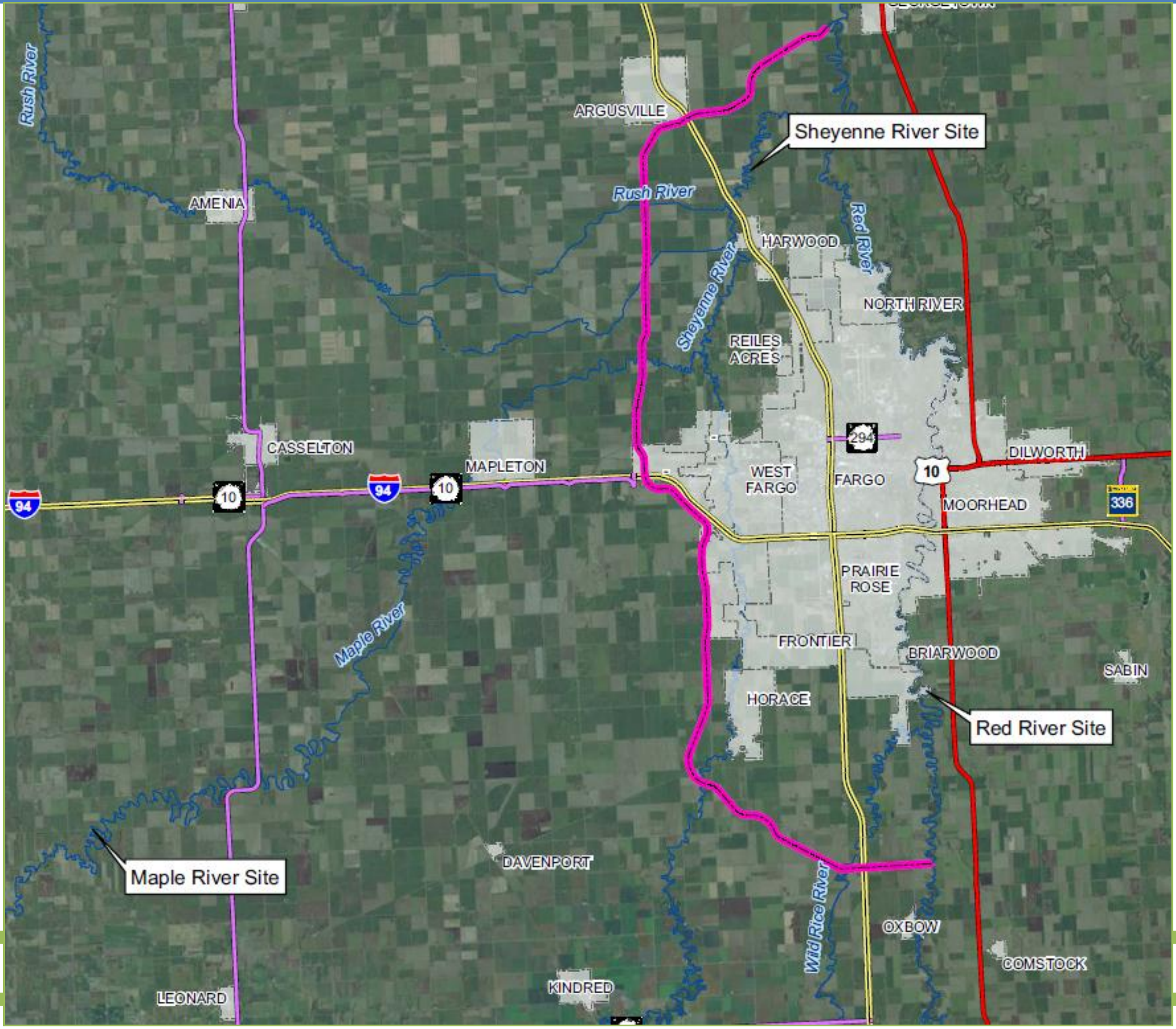
- No Rouse profile for high or low flows (or, **uniform vertical profile of SSC**)

Channel migration rates during Holocene

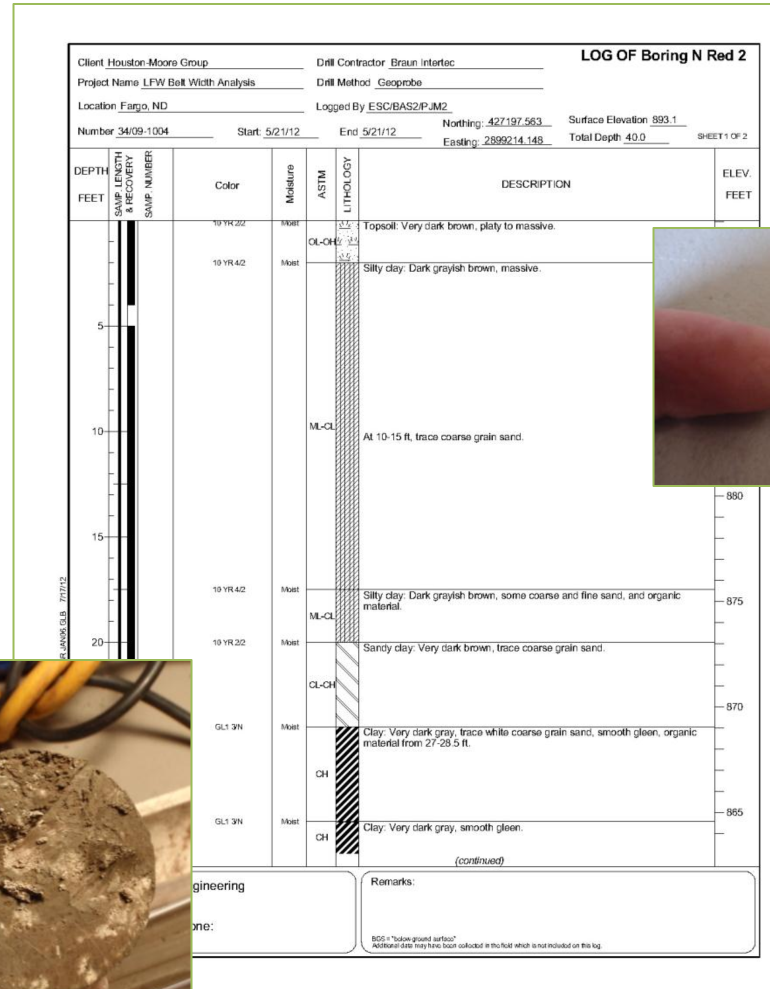


From Brooks, 2003

Field investigation sites



Components of field investigation



LOG OF Boring N Red 2

Client Houston-Moore Group
Drill Contractor Braun Intertec
Project Name LFW Belt Width Analysis
Drill Method Geoprobe
Location Fargo, ND
Logged By ESC/BAS2/PJM2
Number 34/09-1004
Start 5/21/12
End 5/21/12
Northing: 427197.563
Easting: 2899214.148
Surface Elevation 893.1
Total Depth 40.0
SHEET 1 OF 2

Color	Moisture	ASTM	DESCRIPTION
10 YR 2/2	Moist	OL-OH	Topsoil: Very dark brown, platy to massive.
10 YR 4/2	Moist	ML-CL	Silty clay: Dark grayish brown, massive. At 10-15 ft, trace coarse grain sand.
10 YR 4/2	Moist	ML-CL	Silty clay: Dark grayish brown, some coarse and fine sand, and organic material.
10 YR 2/2	Moist	CL-CH	Sandy clay: Very dark brown, trace coarse grain sand.
GL1 3/N	Moist	CH	Clay: Very dark gray, trace white coarse grain sand, smooth gleen, organic material from 27-28.5 ft.
GL1 3/N	Moist	CH	Clay: Very dark gray, smooth gleen.

DEPTH FEET: 5, 10, 15, 20

ELEV. FEET: 880, 875, 870, 865

(continued)

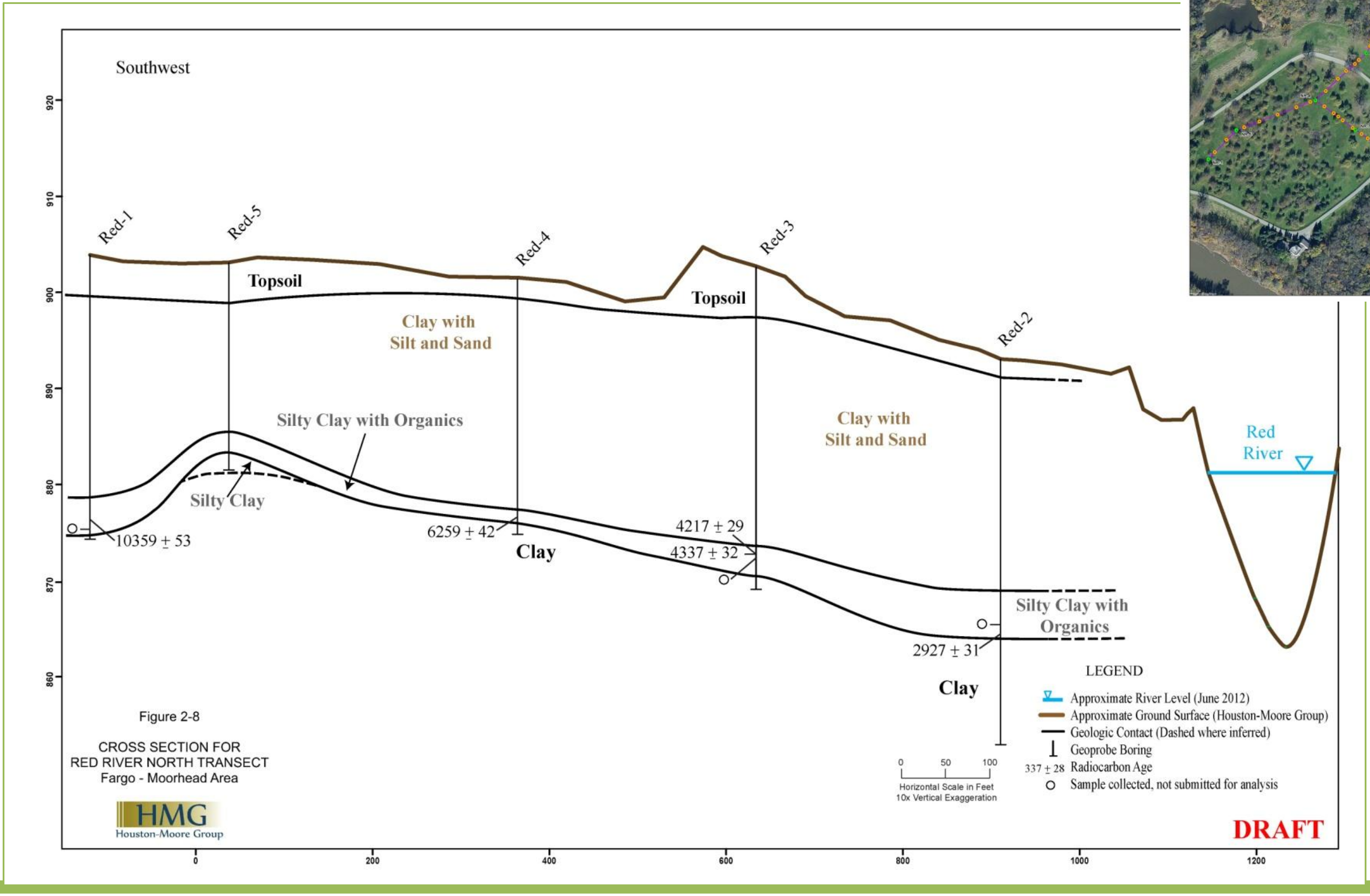
gineering

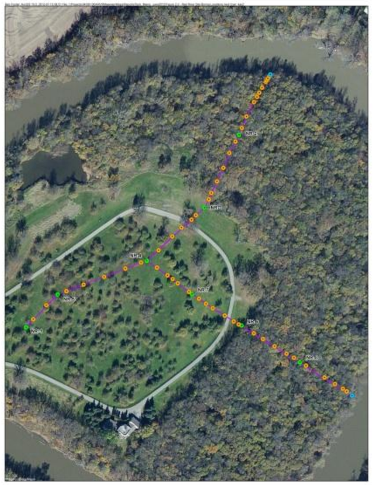
one:

Remarks:

BGS = "below ground surface"
Additional data may have been collected in the field which is not included on this log.

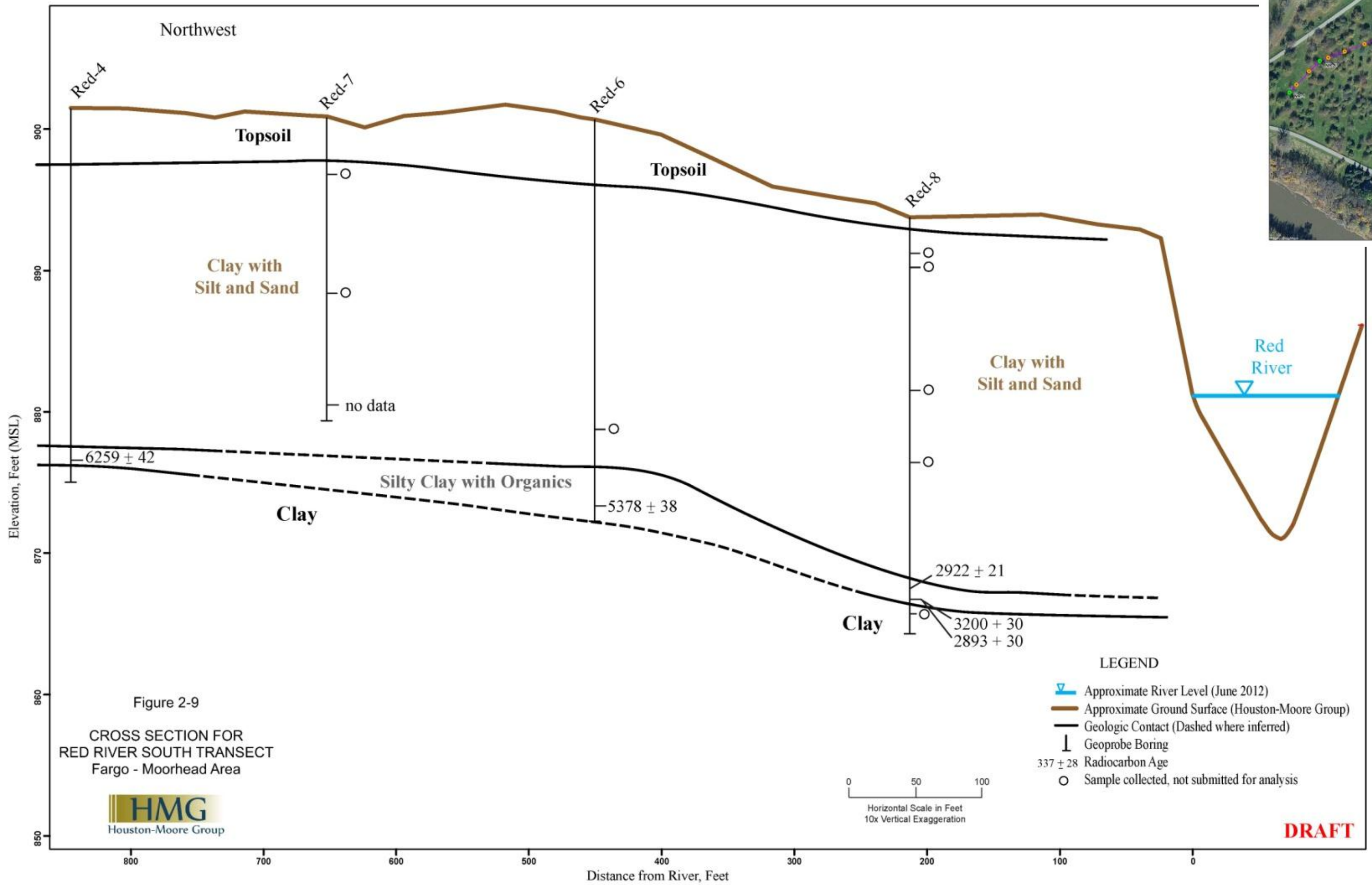
RRN: SW-NE Transect

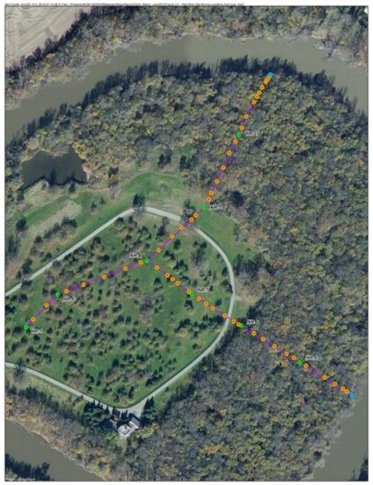




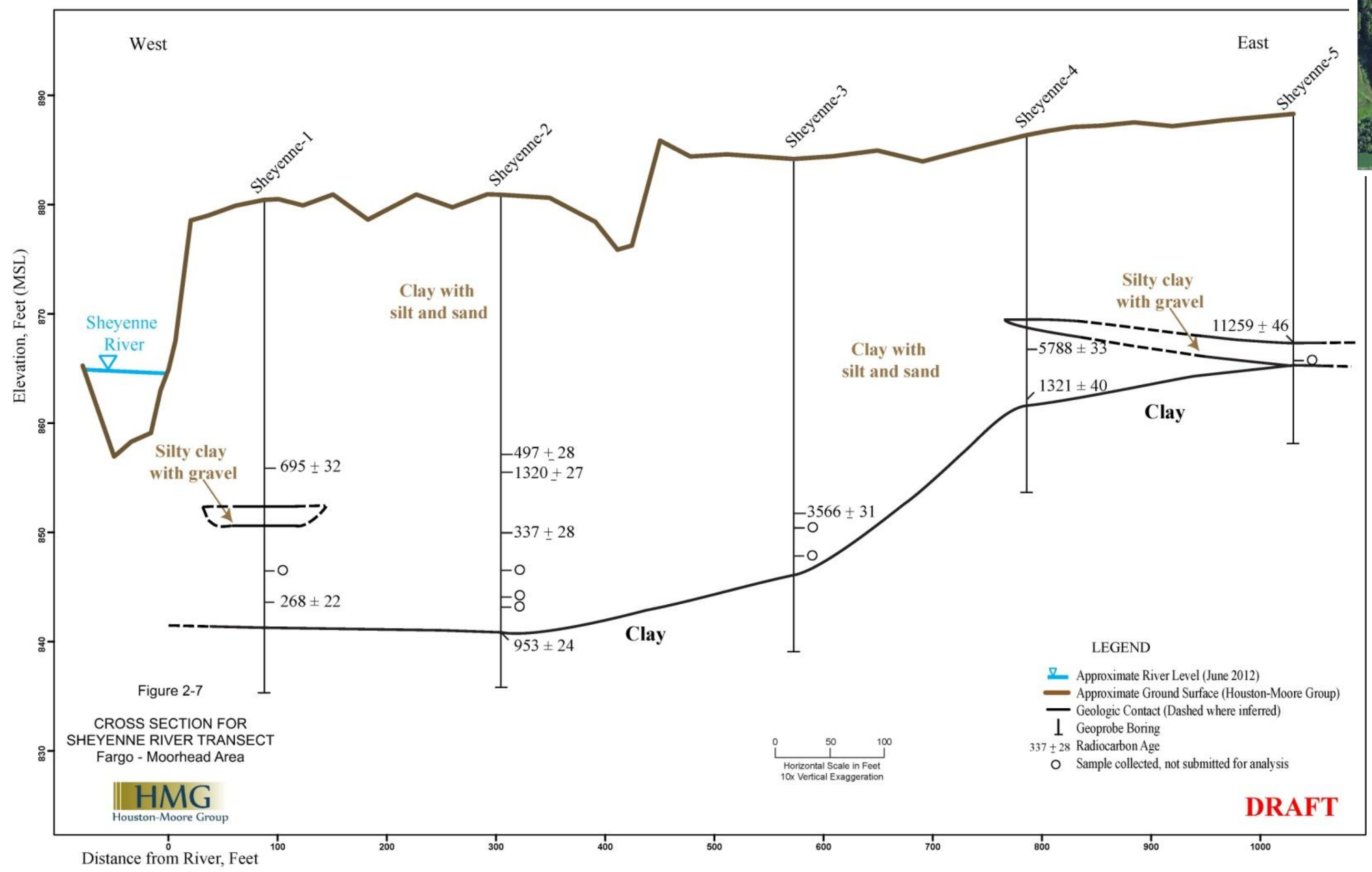
RRN: SE-NW Transect

BARR



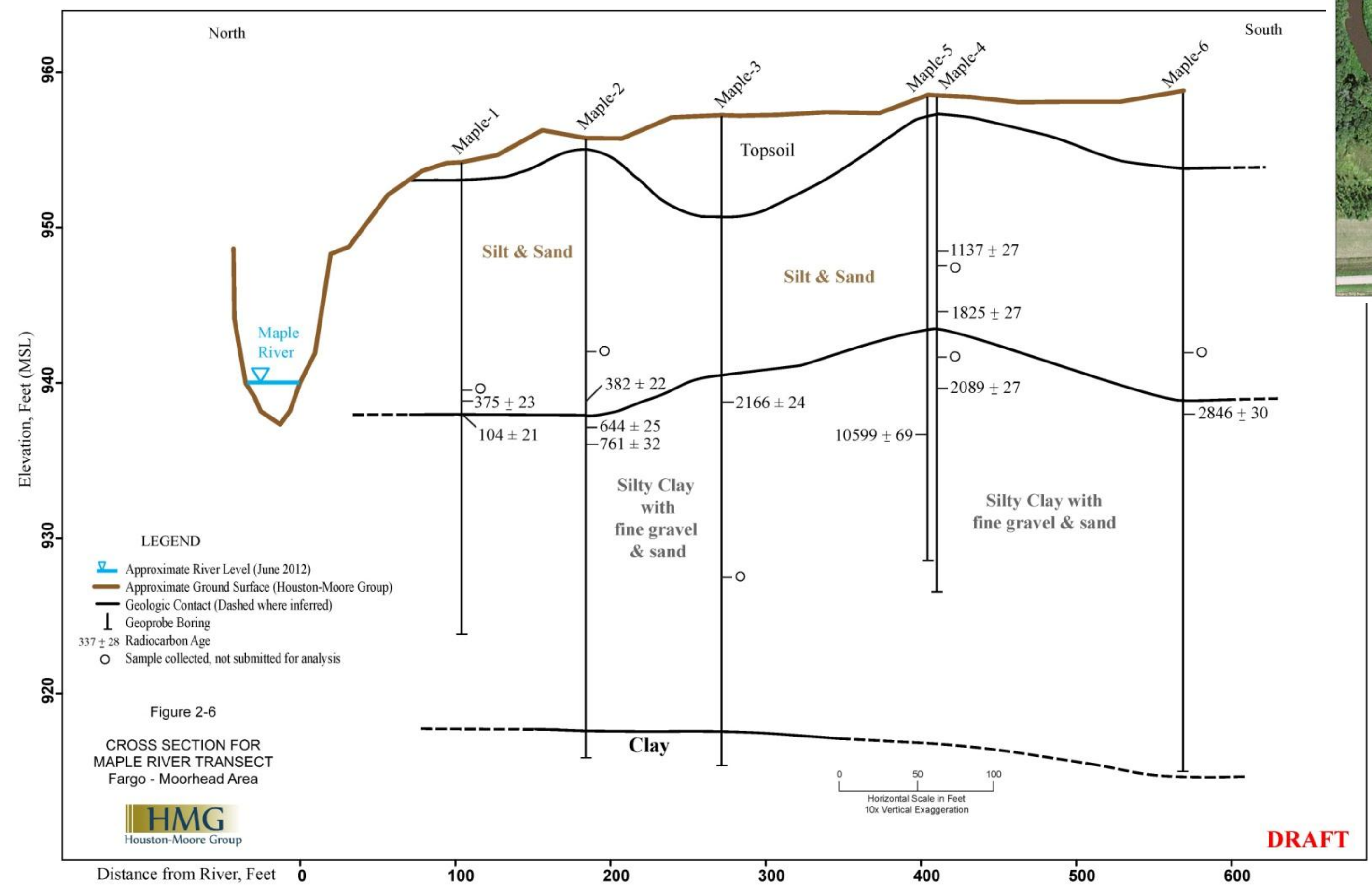


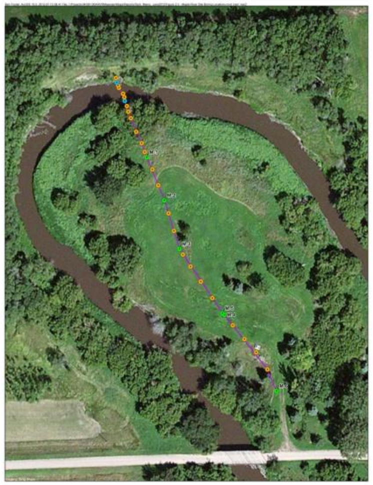
Sheyenne River



Maple River

BARR





Lateral channel migration

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Locations	Distance between Locations (ft)	Ages of Bank - Borehole or Borehole - Borehole (^{14}C yrs BP)	Difference in Averaged Age (^{14}C yr BP)	Upper and Lower Difference in Age Range at 1σ (^{14}C yr BP)	Average Rate of Channel Migration (ft/^{14}C yr)	Range of Average Rate of Channel Migration at 1σ (ft/^{14}C yr)
Red River of the North Transect #1 (NE-SW)						
Bank to Red-2	235	0-2,927	2,927	2,896-2,959	0.08	0.079-0.081
Red-2 to Red-3	277	2,927-4,277	1,350	1,230-1,473	0.21	0.188-0.225
Red-3 to Red-4	268	4,277-6,259	1,982	1,848-2,113	0.14	0.127-0.145
Red-4 to Red-1	473	6,259-10,359	4,100	4,005-4,194	0.12	0.113-0.118
Red River of the North Transect #2 (SE-NW)						
Bank to Red-8	214	0-3,005	3,005	2,863-3230	0.07	0.066-0.075
Red-8 to Red-6	237	3,005-4,133	1,128	0-2547	0.21	0.093->237.2
Red-6 to Red-4	394	4,133-6,259	2,126	806-3438	0.19	0.115-0.489
Sheyenne River Transect (E-W)						
Bank to Sheyenne-1	130	0-777	777	750-803	0.17	0.162-0.173
Sheyenne-2 to Sheyenne-4	**478**	**777-3,566**	**2,789**	**0-3,288**	**0.17**	**0.145->478**
Sheyenne-2 to Sheyenne-5	**723**	**111-11,259**	**11,148**	**10,236-10,996**	**0.06**	**0.066-0.071**
Maple River Transect (N-S)						
Bank to Maple-1	104	0-239	239	83-398	0.44	0.262-1.253
Maple-1 to Maple-2	80	239-595	356	0-710	0.22	0.113->80
Maple-2 to Maple-4	222	595-1,684	1,089	317-1,756	0.20	0.126-0.701
Maple-4 to Maple-6	159	1,684-2,846	1,162	700-1,765	0.14	0.090-0.227
Maple-1 to Maple -6	**460**	**239-2,846**	**2,607**	**2,418-2,792**	**0.18**	**0.165-0.190**

Notes:

Bold – Averaged between non-adjacent boreholes

Main findings

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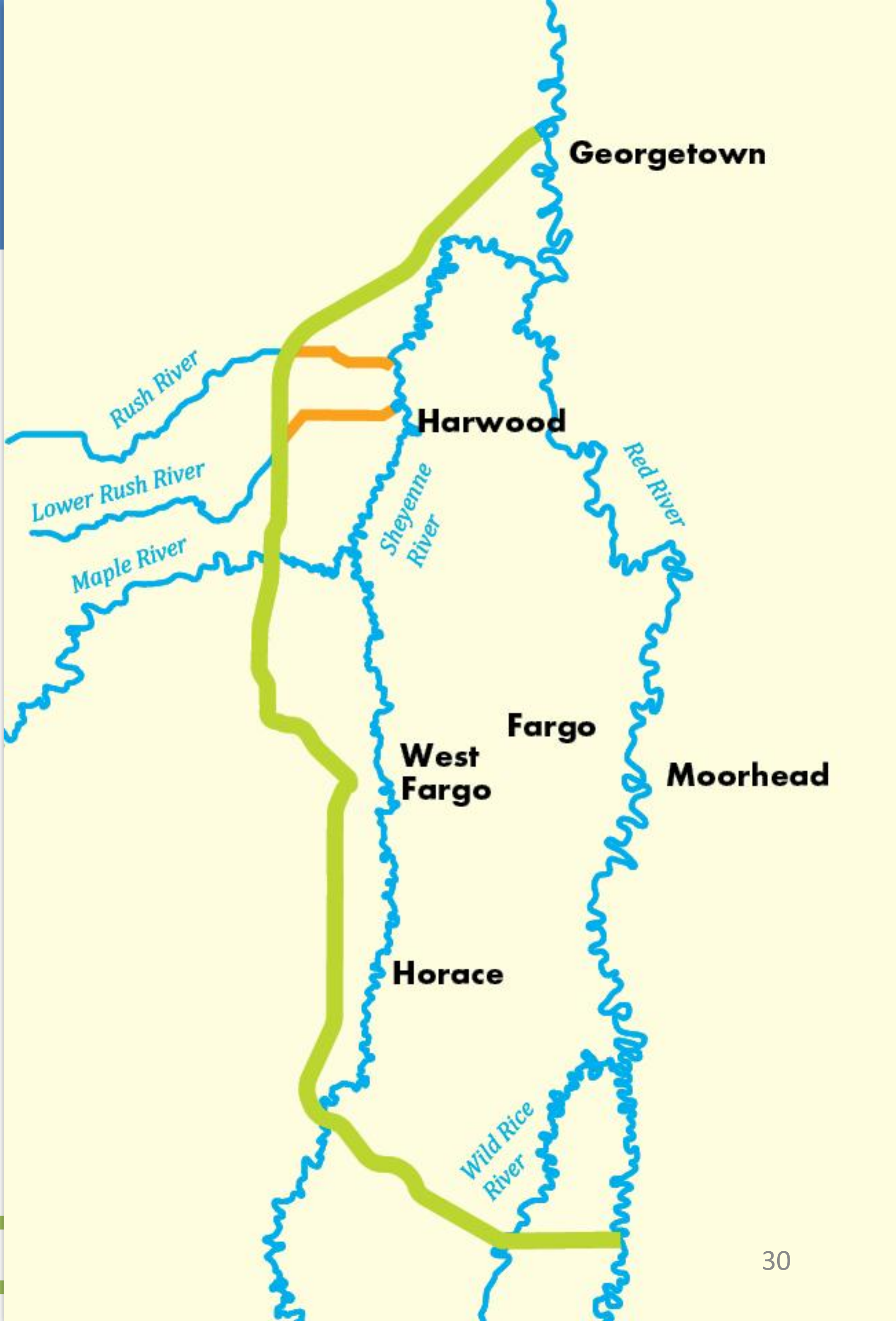
- Typical migration rate of **0.1 to 0.2 feet/carbon year**. Channel migration rates are extremely low, if not negligible, consistent with Brooks investigations in Manitoba and also with analysis of historical aerial photography by WEST Consultants

- Different from Brooks investigations in Manitoba, **migration rates have not changed systematically over the last 10,000 years**

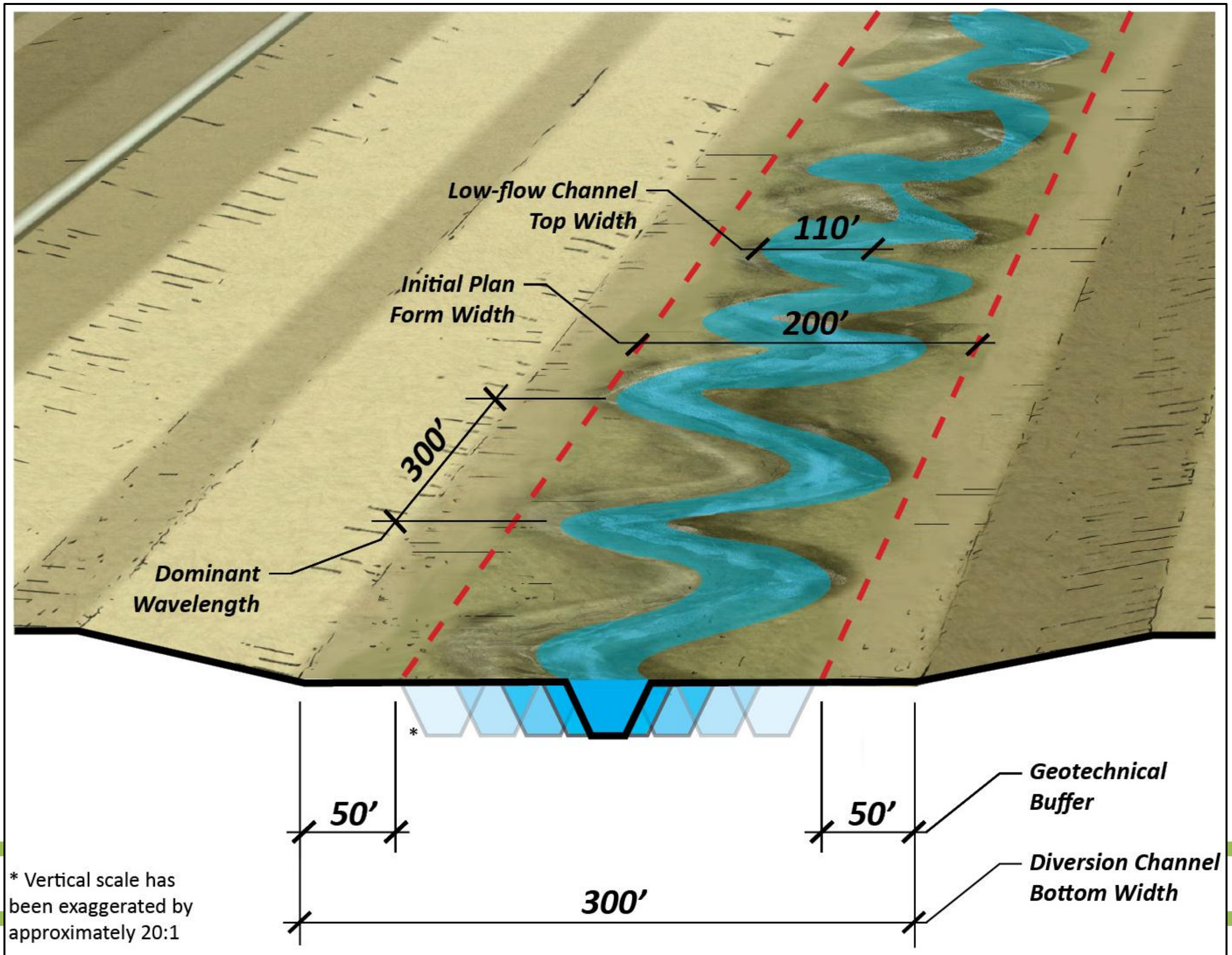
Low-Flow Channel (LFC) overview

- **Proposed Diversion Channel collects runoff from:**
  - The Rush and Lower Rush Rivers
  - Eleven county and local drainage ditches
  - High flows from the Maple, Sheyenne, Wild Rice, and Red Rivers
- **A meandering Low-Flow Channel is planned for the bottom of the Diversion Channel**
  - The Low-Flow Channel will be sized to convey water and sediment downstream to the Red river



LFC overview

"What is the probability that the LFC will remain within a prescribed meander belt width?"



Meandering statistics of rivers near the study area

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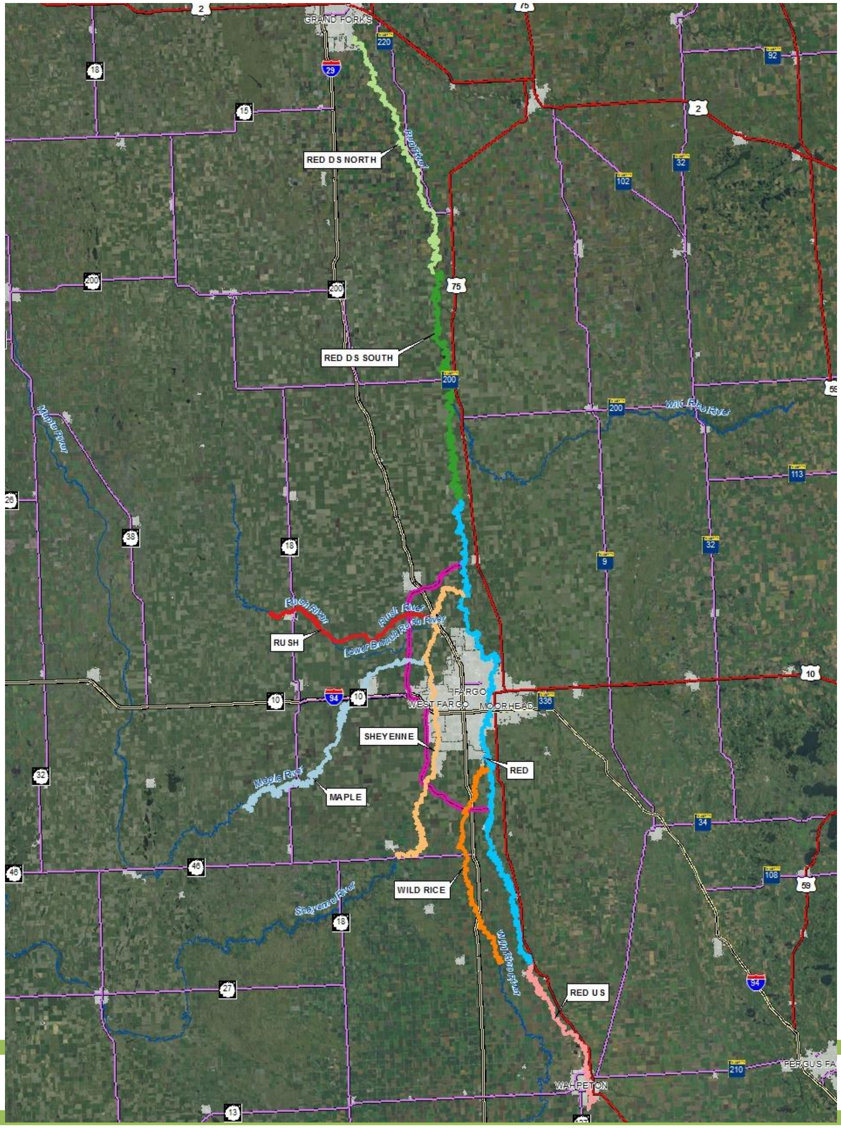
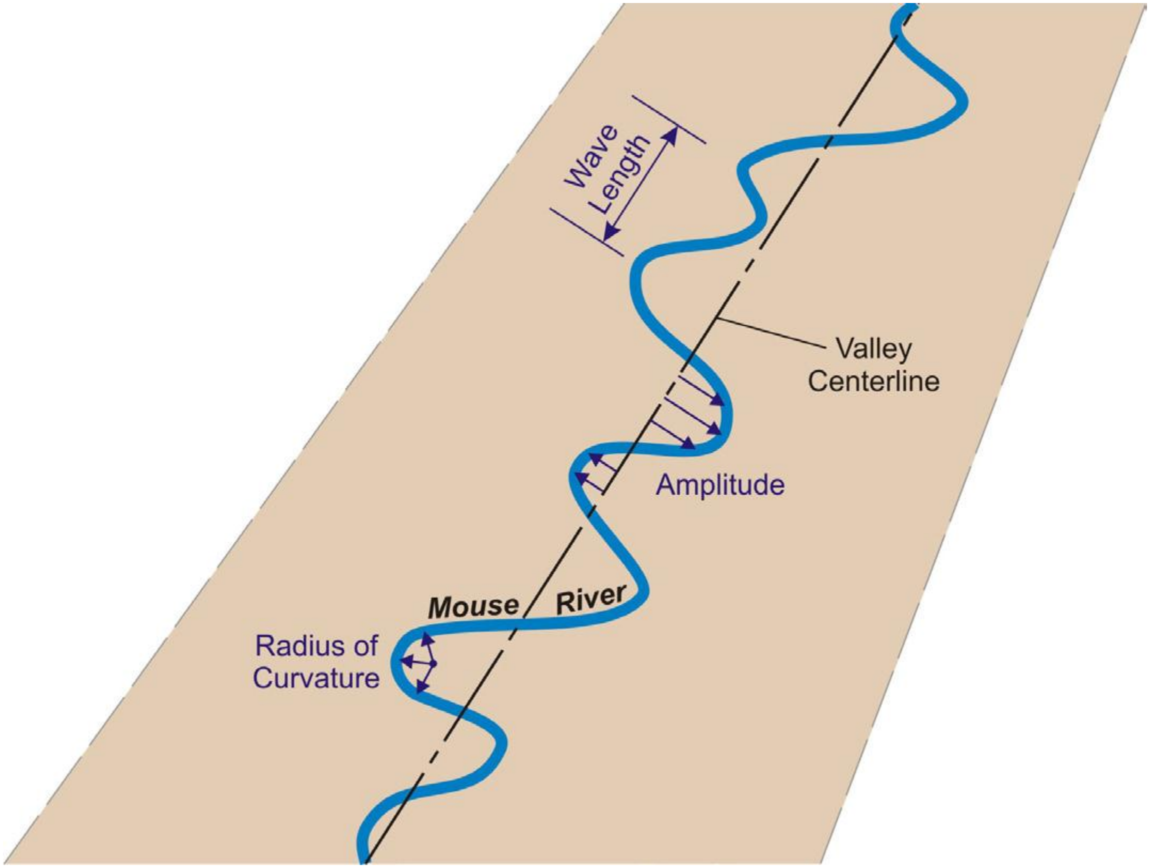
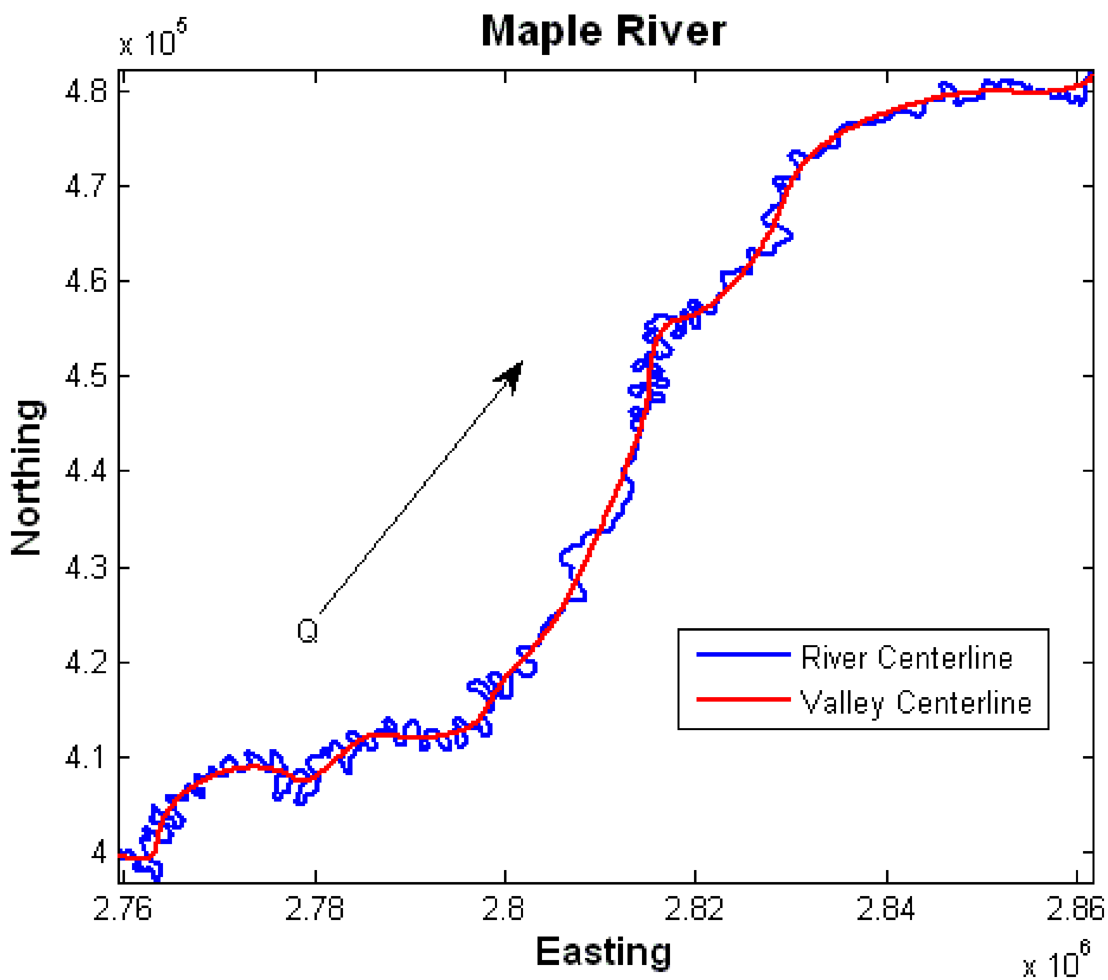
- **Five rivers near the study area were analyzed**
  - The Red River of the North, Rush River, Maple River, Sheyenne River, and the Wild Rice River
  - The Red River of the North was broken up into four reaches, making a total of eight reaches analyzed
  - Lower Rush River was not analyzed because the extent of available data was limited to channelized reach



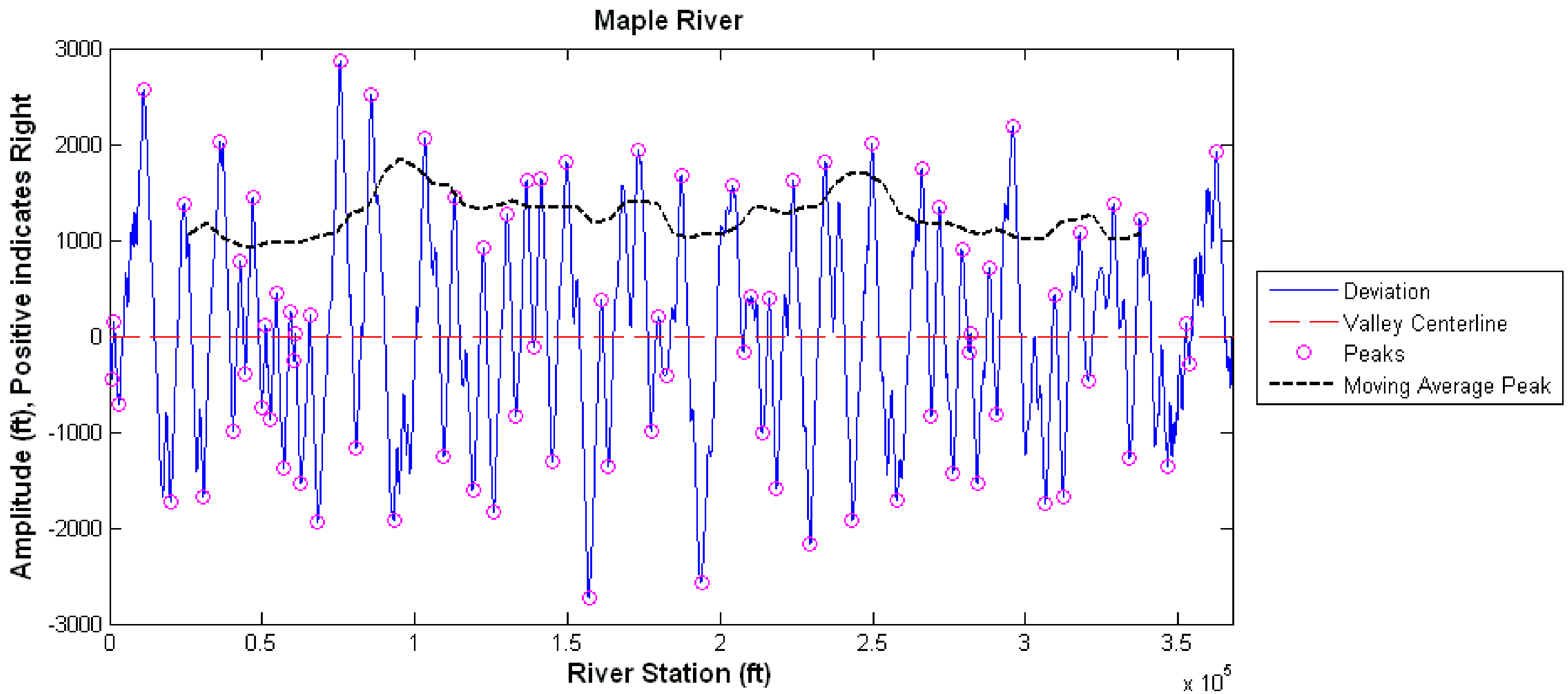
River planform characteristics



Valley and river centerlines

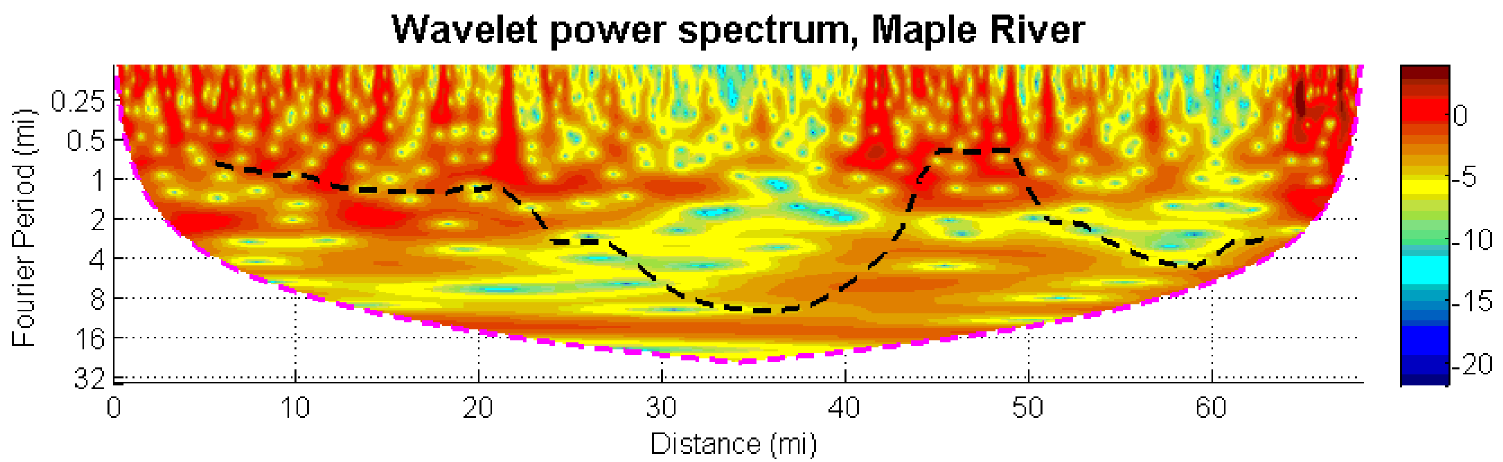


Amplitude

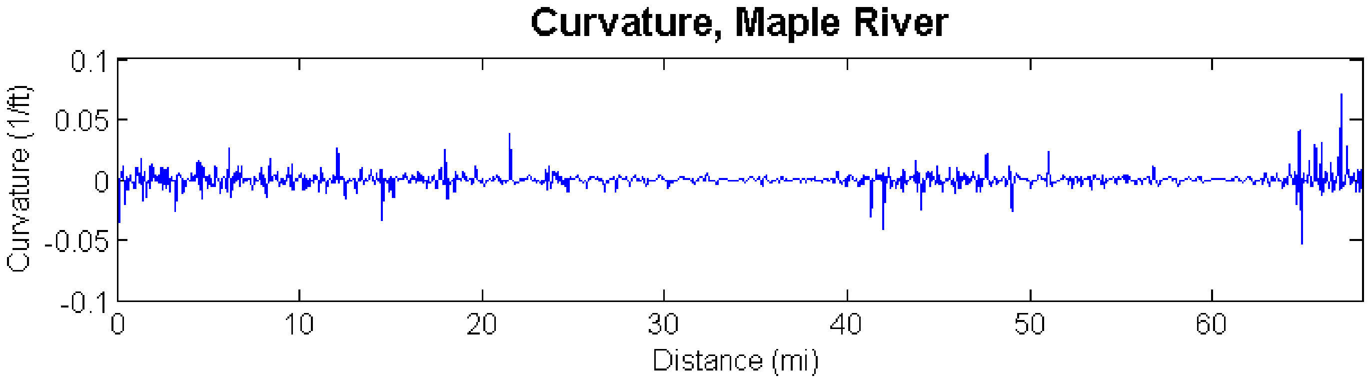


Maple River
Amplitude (ft), Positive indicates Right
3000
2000
1000
0
-1000
-2000
-3000
0
0.5
1
1.5
2
2.5
3
3.5
River Station (ft)
x 10^5
Deviation
Valley Centerline
Peaks
Moving Average Peak

Wavelength

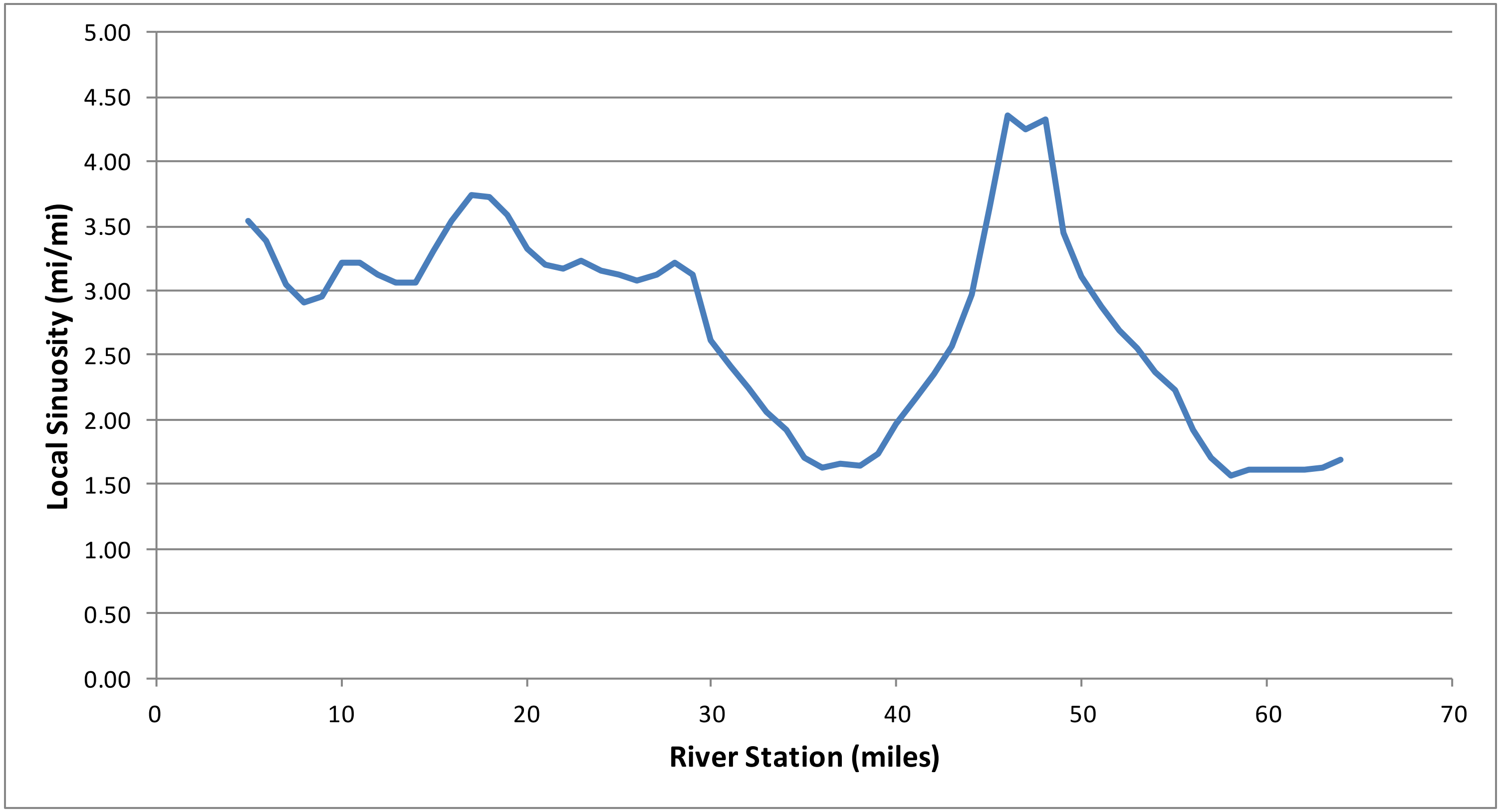


Wavelet power spectrum, Maple River
Fourier Period (mi)
0.25
0.5
1
2
4
8
16
32
0
10
20
30
40
50
60
Distance (mi)
0
-5
-10
-15
-20



Curvature, Maple River
Curvature (1/ft)
0.1
0.05
0
-0.05
-0.1
0
10
20
30
40
50
60
Distance (mi)

Sinuosity



5.00
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Local Sinuosity (mi/mi)
0
10
20
30
40
50
60
70
River Station (miles)

Design constraints for LFC

- **Channel Width**
  - Efficient hydraulic conveyance and sediment transport
- **Amplitude**
  - Bottom width of the main diversion channel
  - Buffer for geotechnical purposes
- **Wavelength**
  - Top width of low-flow channel
- **Sinuosity**

Analysis results

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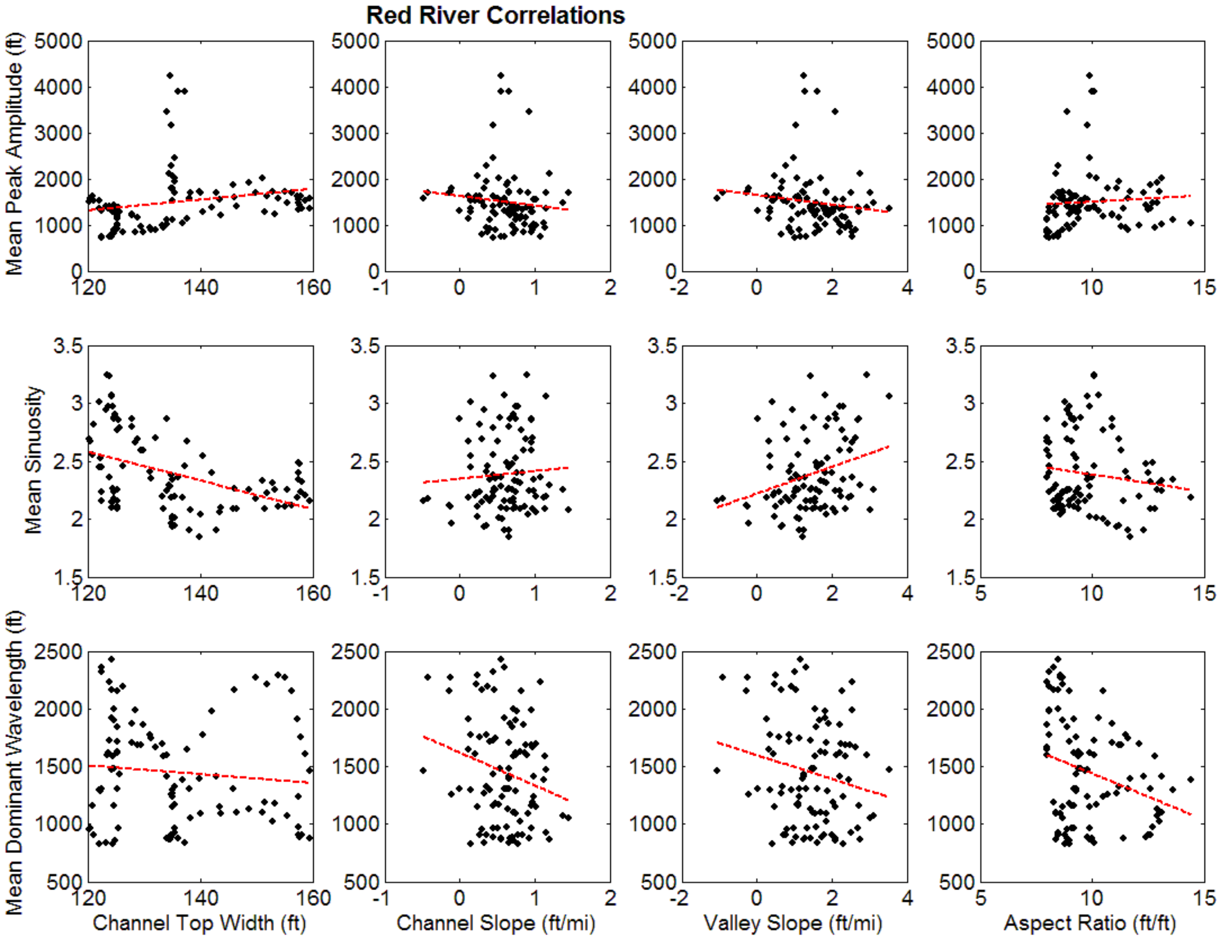
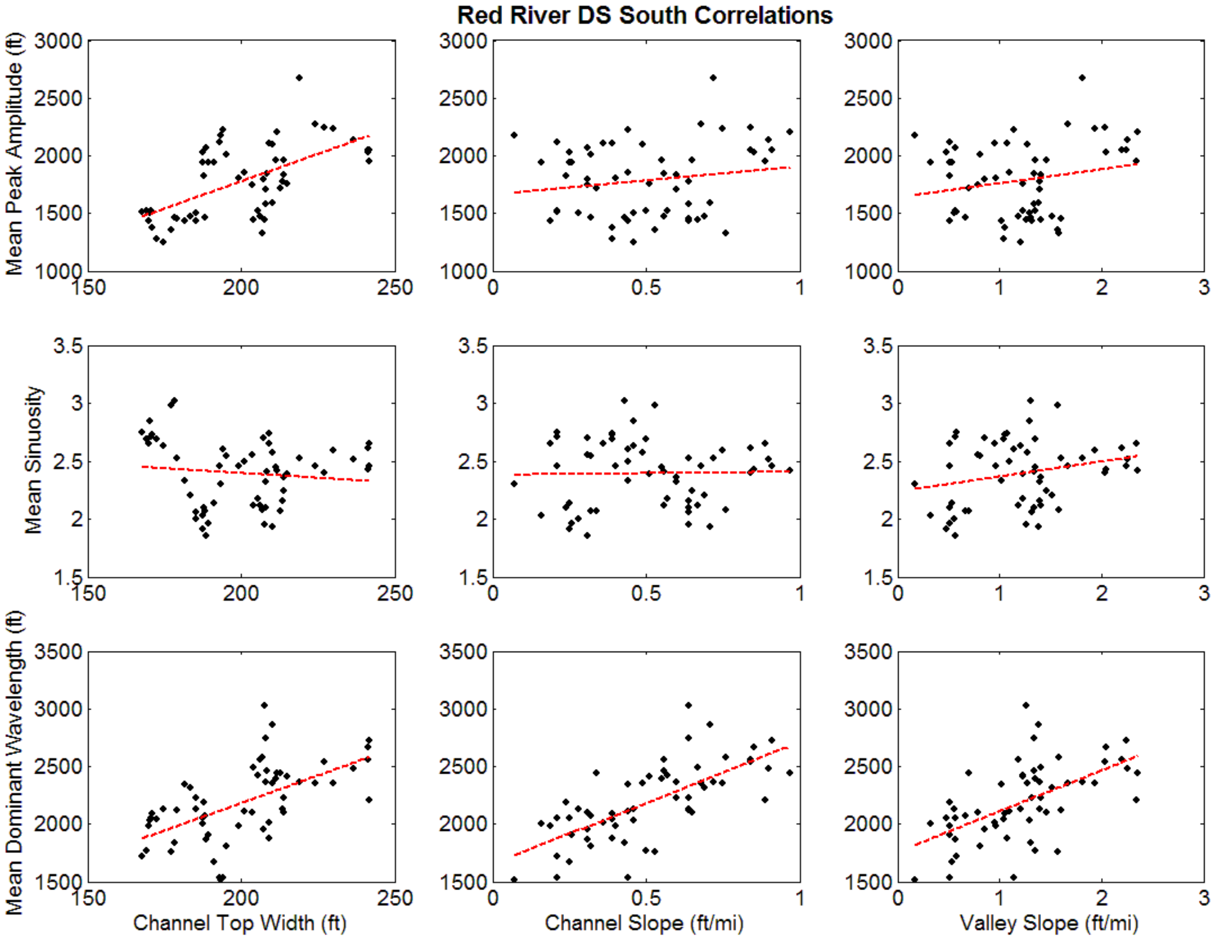
Reach Name	Amplitude (ft)	Wavelength (ft)	Sinuosity
Maple River	1,210	400	2.49
Red River of the North US	946	2,480	1.78
Red River of the North	1,290	1,820	2.30
Red River of the North DS South	1,700	1,760	2.38
Red River of the North DS North	1,440	2,300	1.78
Rush River	442	810	1.44
Sheyenne River	905	1,120	2.03
Wild Rice River	866	1,210	1.95

- **"Magnitudes" of the local rivers cannot be matched**
- Look for relationships or trends to inform the design of the LFC

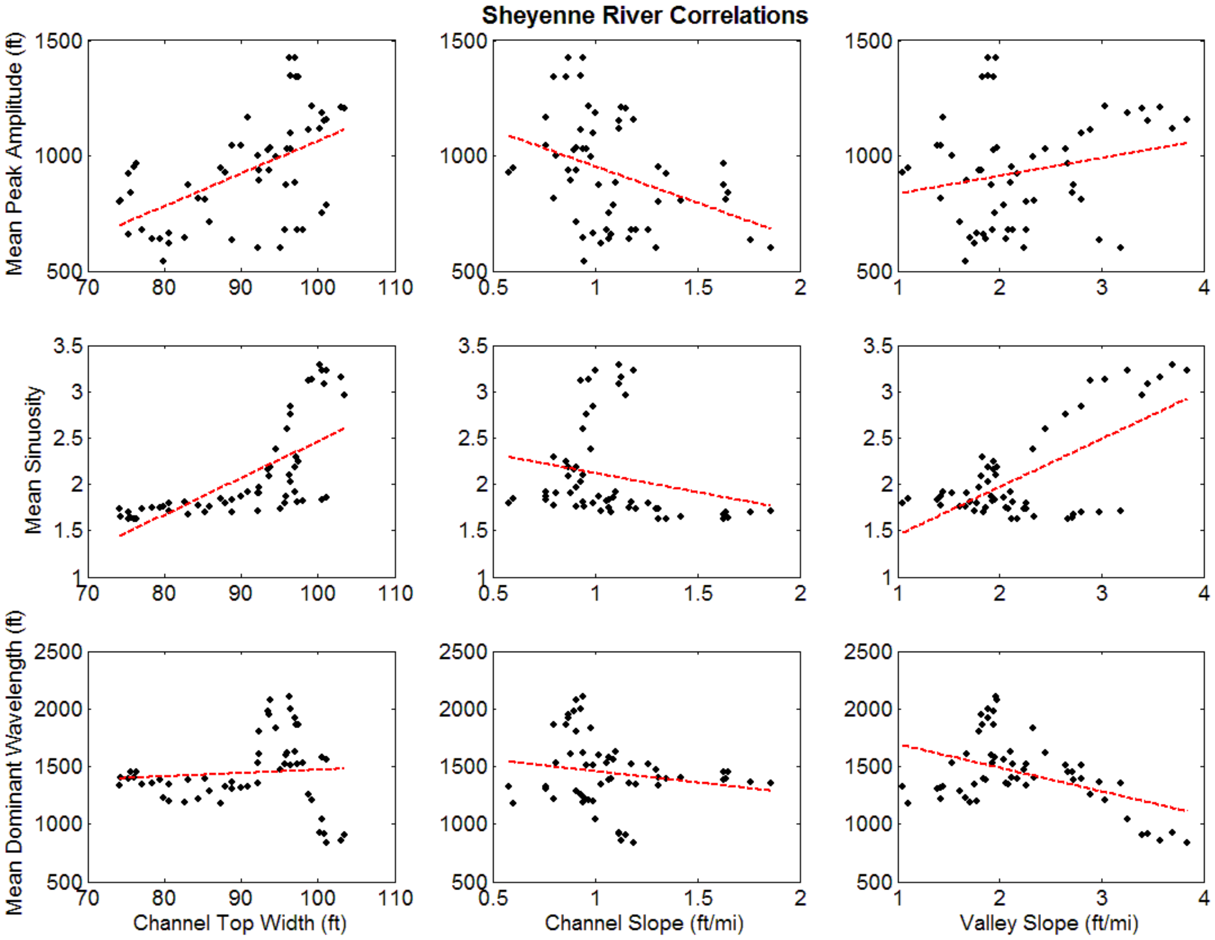
Red River of the North (through Fargo)



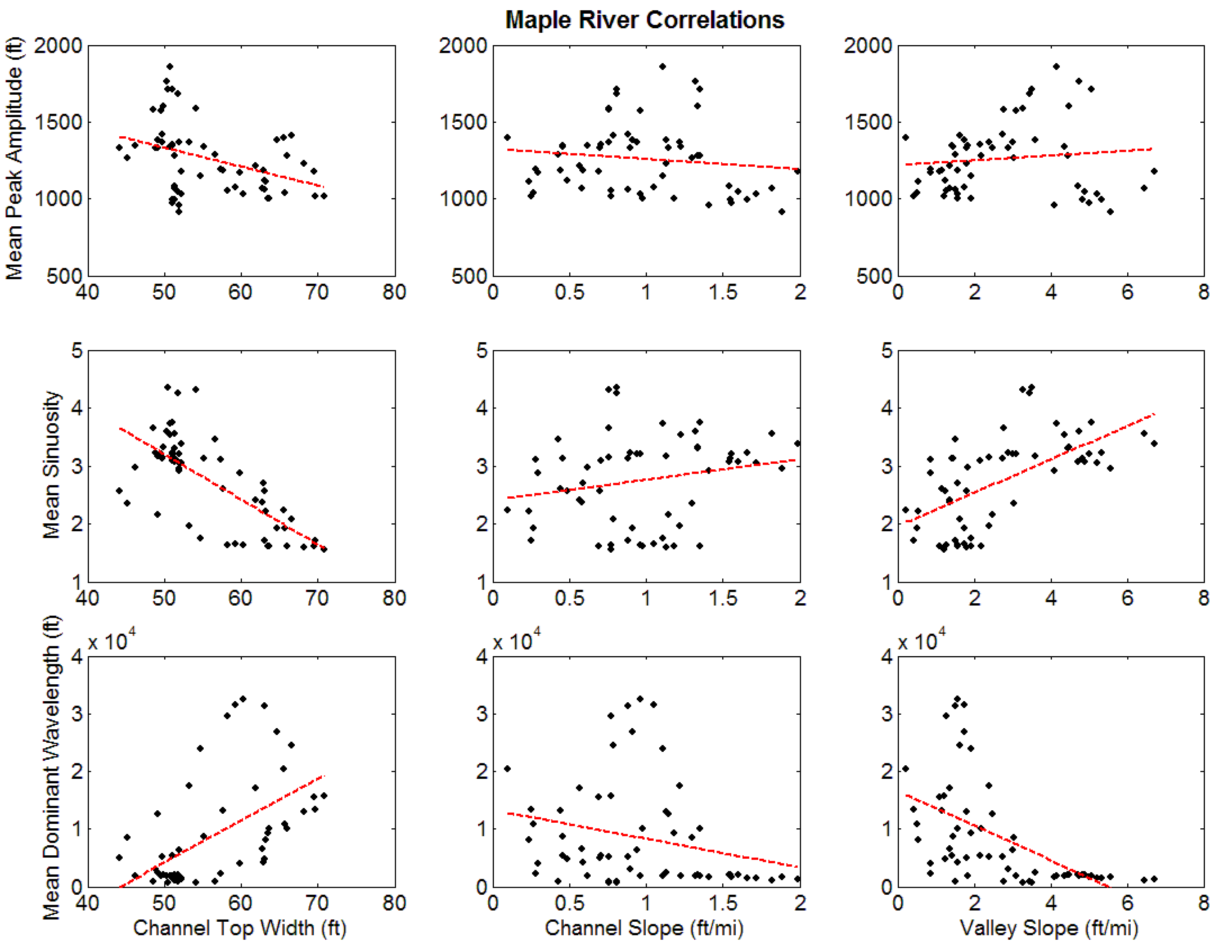
Red River of the North (DS South)



Sheyenne River



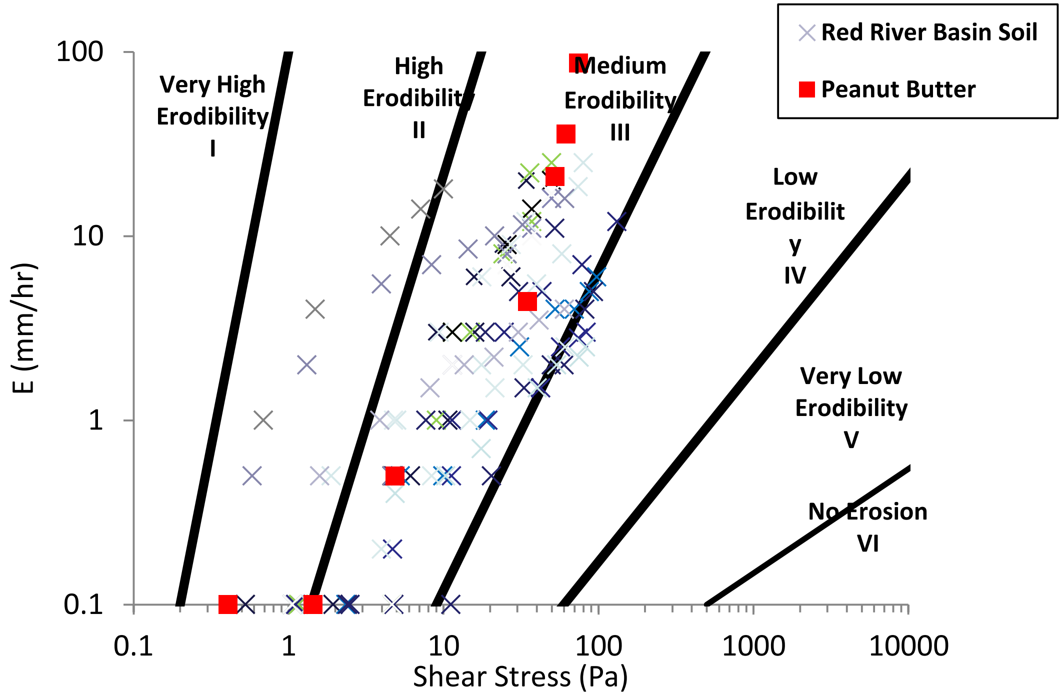
Maple River



Maple River Correlations
Mean Peak Amplitude (ft)
Mean Sinuosity
Mean Dominant Wavelength (ft)
x 10^4
Channel Top Width (ft)
Channel Slope (ft/mi)
Valley Slope (ft/mi)

Main findings
(figure "borrowed" from USACE)

- **It appears that most relationships are weak and/or inconsistent**
- **Possible explanation is that the local systems are not hydraulically driven**
  - Unique soil conditions are more controlling than the hydraulics in this region
  - Possibly the rivers were formed following the last glaciation and have not moved significantly since
  - Potentially, there is no ideal planform to target; instead the design can be driven by engineering constraints



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RVR Meander modeling

RVR Meander Overview

1. **Hydrodynamics** – water surface elevations & velocities
2. **Bed morphodynamics** – transverse bed slope
3. **Bank erosion** – hydraulic erosion as well as mass failure (e.g. cantilever or planar bank failure)

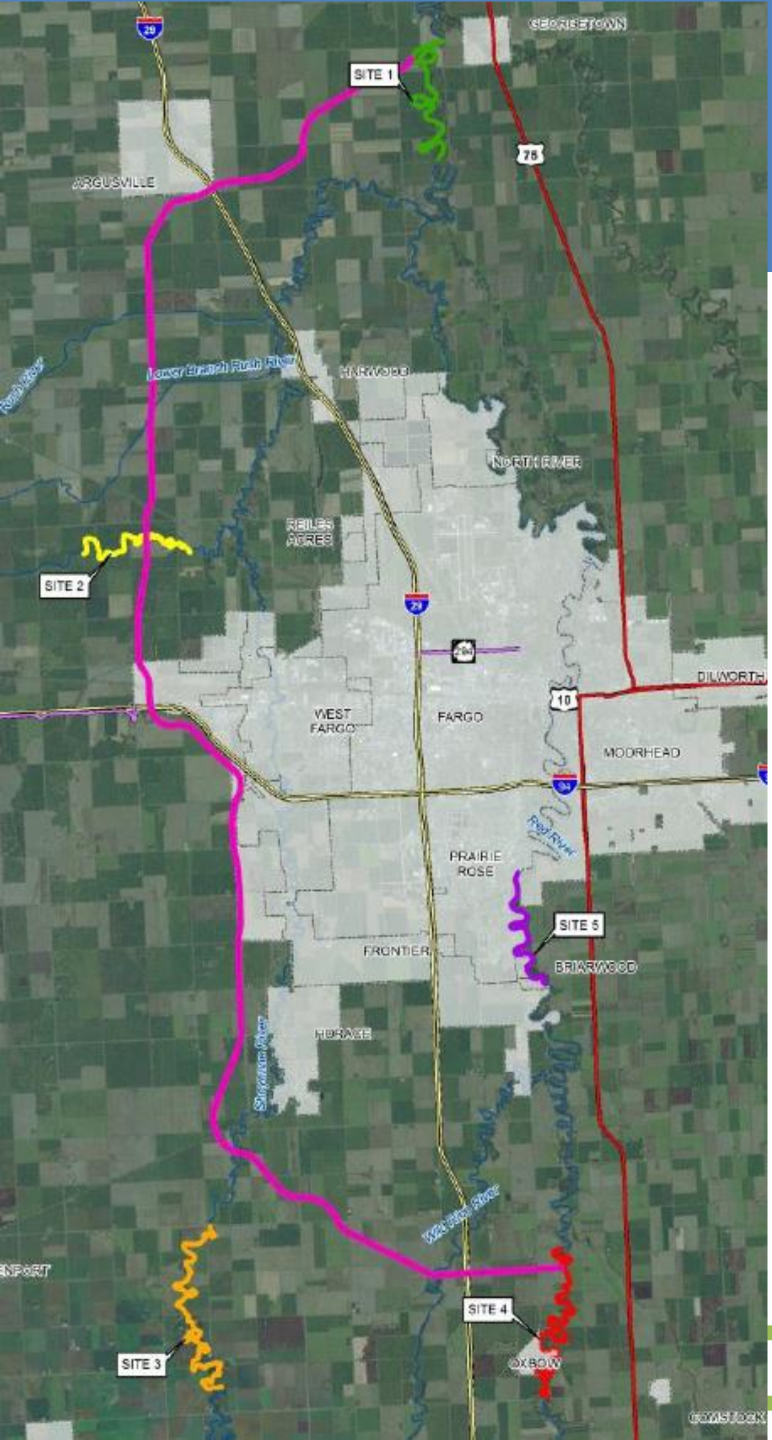
Analysis Methodology

1. **Model Calibration** – Deterministic simulations of rivers near the proposed Diversion Channel
2. **Monte Carlo Analysis** – Probabilistic evaluation of Low-Flow Channel reaches
3. **Summary of Results**

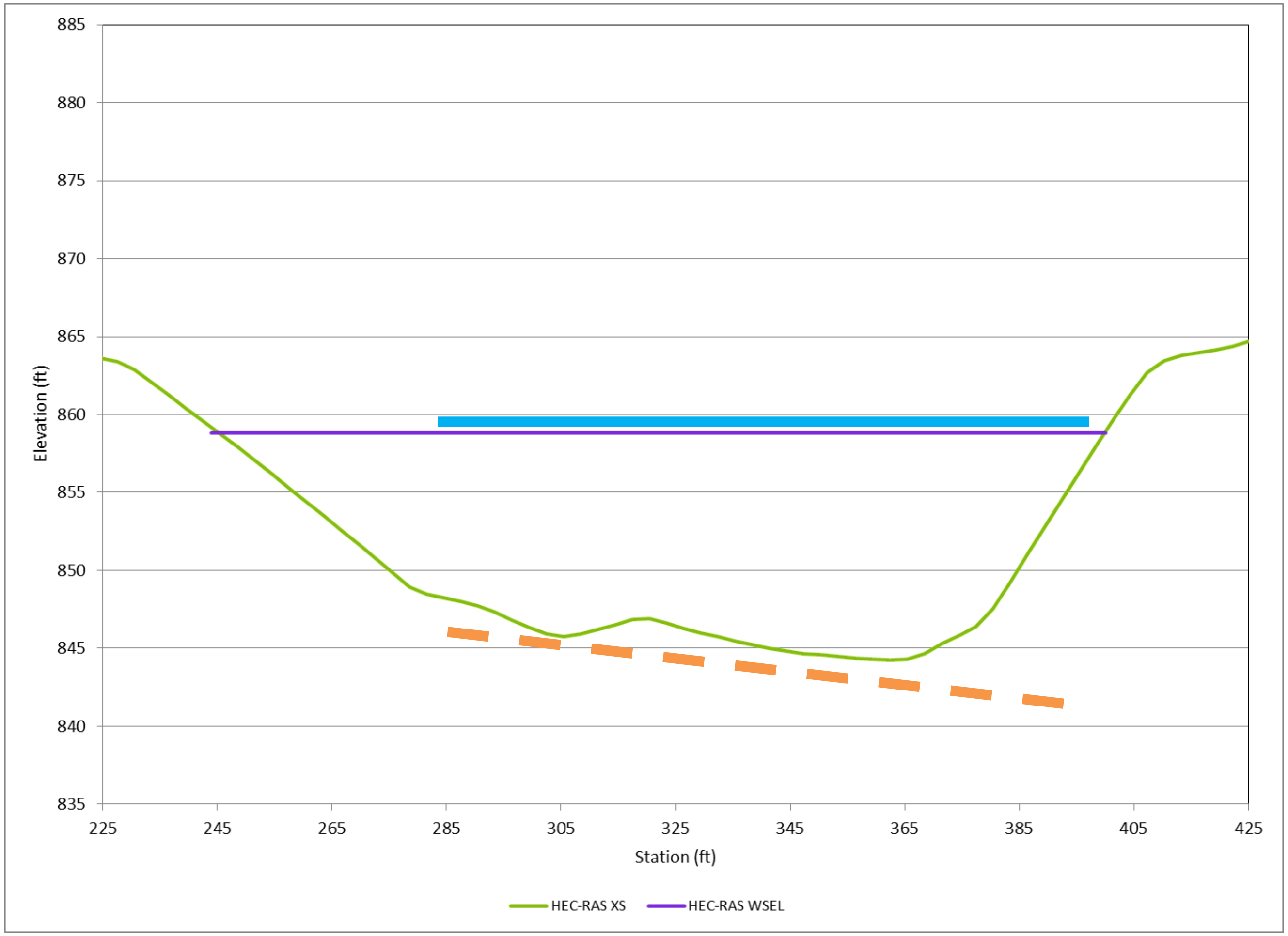
RVR Meander model calibration

- **Step 1: Site Selection**
  - Channel movement?
  - Human impacts?
  - Available survey data?
- **Step 2: Calibrate Hydrodynamics**
  - Match transverse bed slope
  - Match HEC-RAS water surface elevations
  - Validate velocity distribution using ADH
- **Step 3: Calibrate Migration Rate**
  - Match historical aerial photographs

Step 1: Site selection



Step 2: Calibrate hydrodynamics

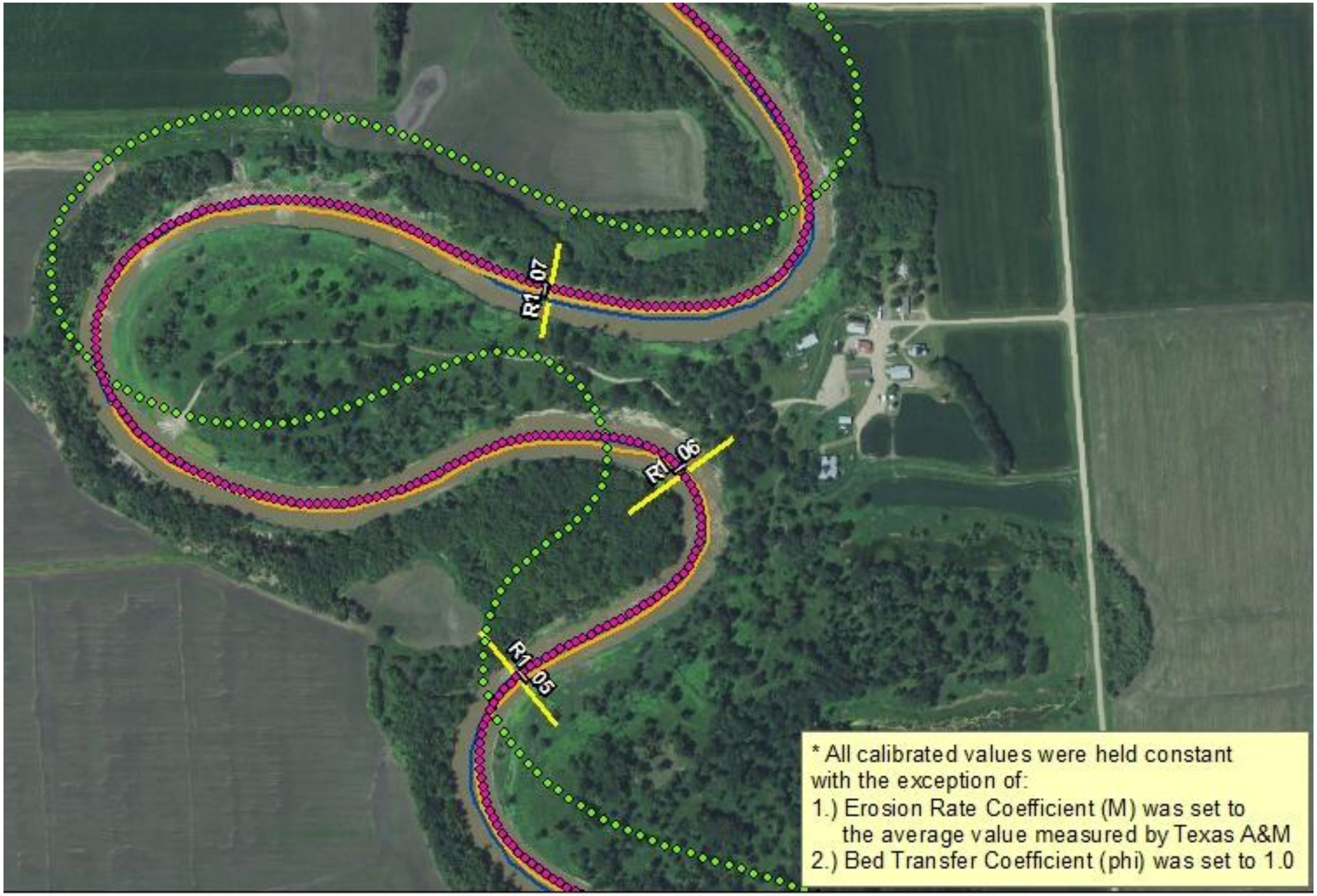


Step 3: Calibrate channel migration

- Determine simulation length from flow-duration curves
- Adjust critical shear stress (τ) and erosion rate coefficient (M)
- Compare migration distance of river centerlines from model and historical aerial photography

Example results of a meander on Calibration Site 1

How sensitive is the calibration?



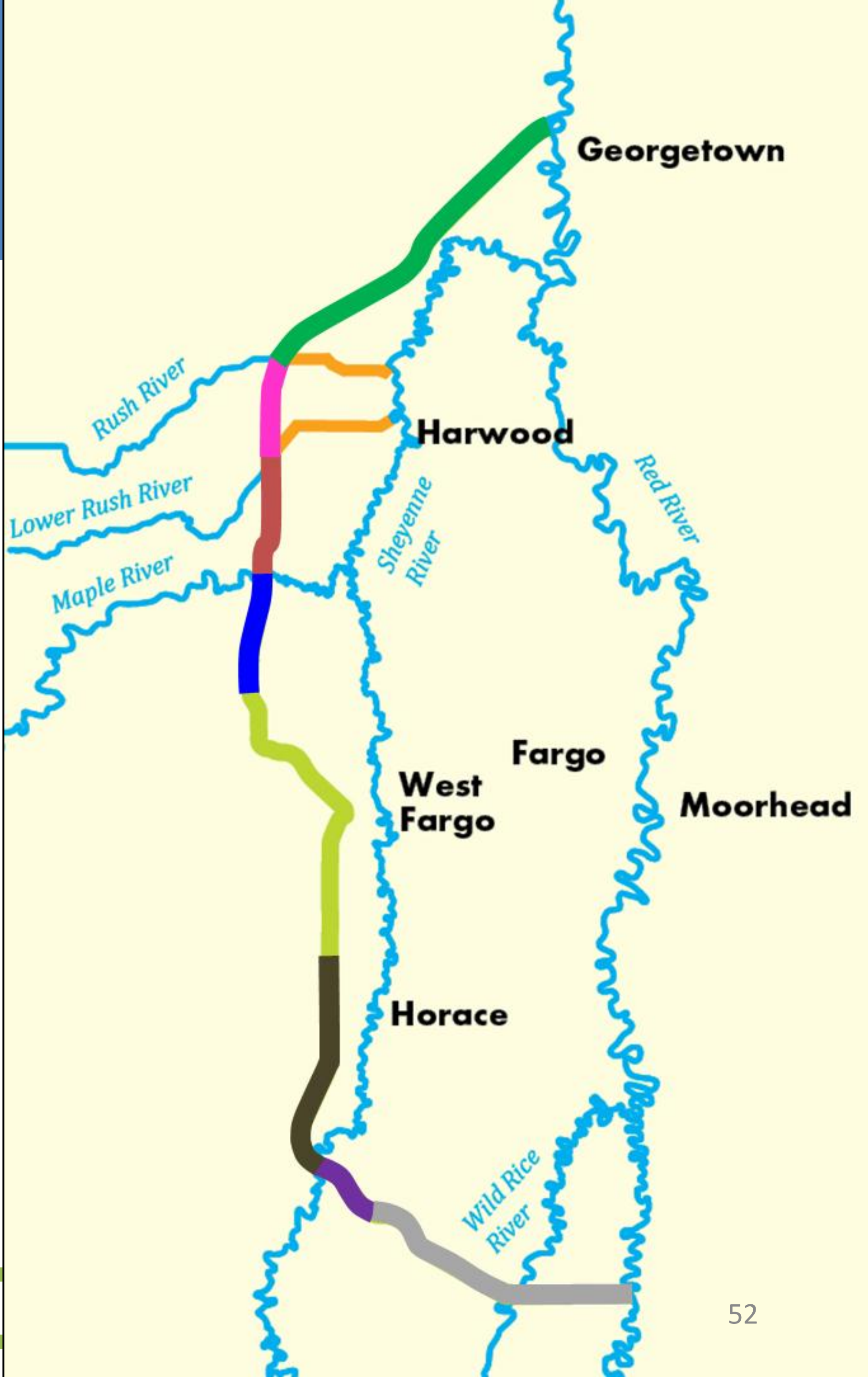
Example simulation results of a meander on Calibration Site 1 using uncalibrated parameters

Main findings

- The RVR Meander models could be calibrated using **reasonable model inputs**
- Calibrated parameters:
  - scour factor
  - Critical shear stress
  - Erosion rate coefficient
- RVR Meander was able to match the observed migration, even where the **channel has moved very little**, as seen in historical aerial photography

Probabilistic Evaluation of the LFC

- **Reach Definition Considerations**
  - Divided based on proposed inlets to Diversion Channel – constant flow and LFC geometry
  - Try to begin and end at locations where the LFC is assumed to be fixed – bridges or hydraulic structures

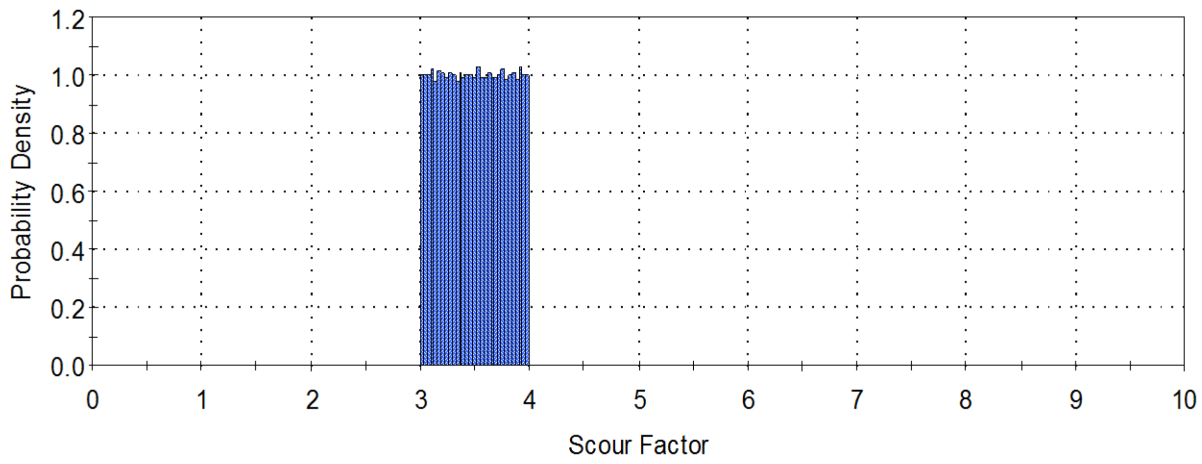


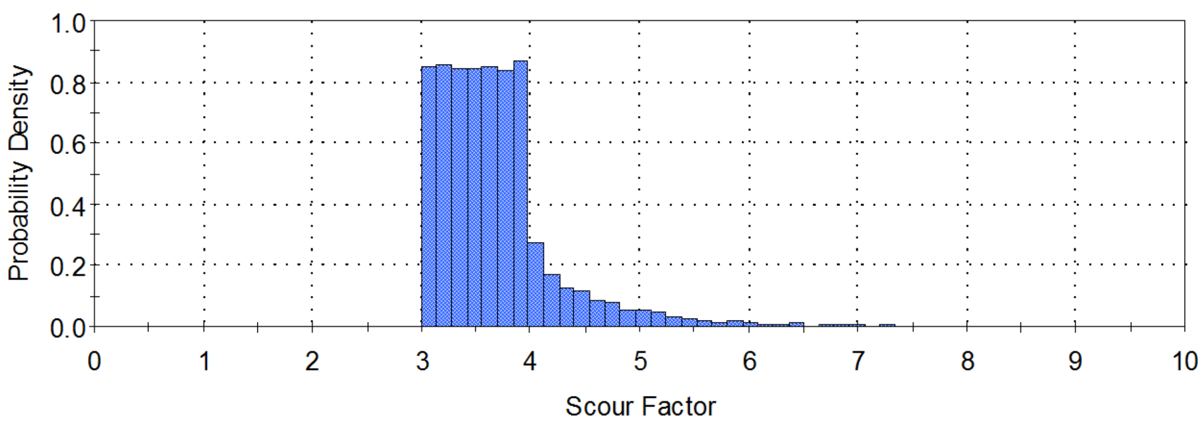
Input parameters

Variable Input Parameters

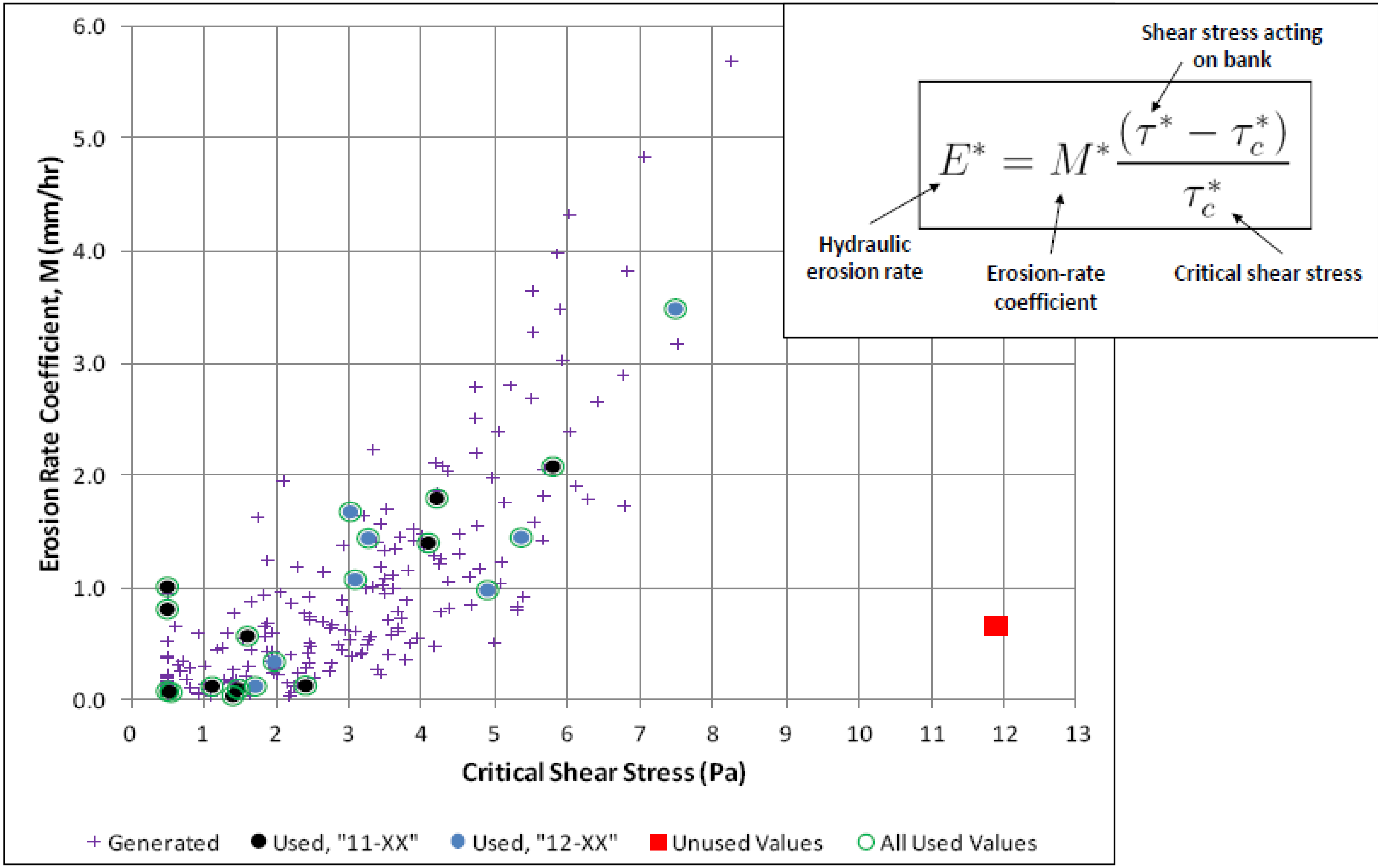
- **Calibrated Parameters**
  - Scour Factor *(Uniform Distribution)*
  - Bed Shear Stress Transfer Coefficient *(Discrete)*
- **Erodibility Parameters (from USACE/Texas A&M test work)**
  - Critical Shear Stress *(Normal Distribution)*
  - Erosion Rate Coefficient *(Exponential Distribution)*
- **Hydrodynamic Parameters**
  - Manning’s Coefficient *(Triangular Distribution)*
  - Flows *(Log-Normal Distribution)*

Scour factor



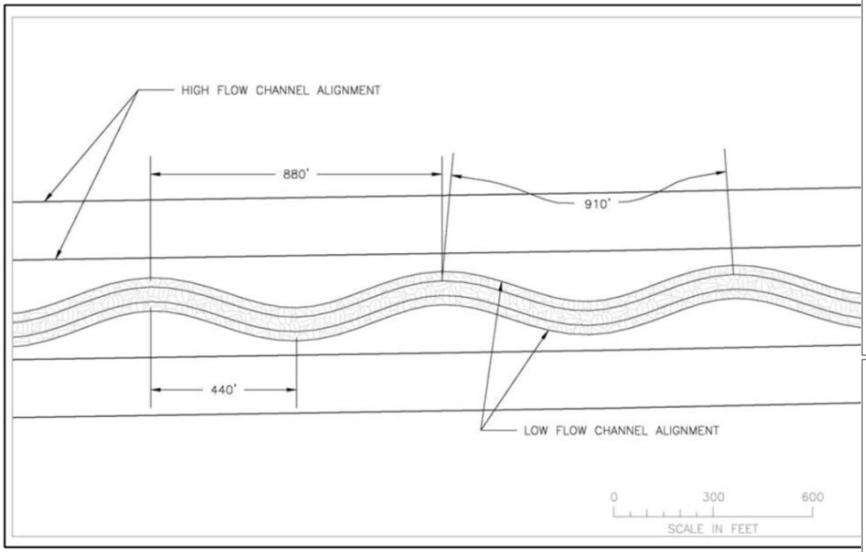


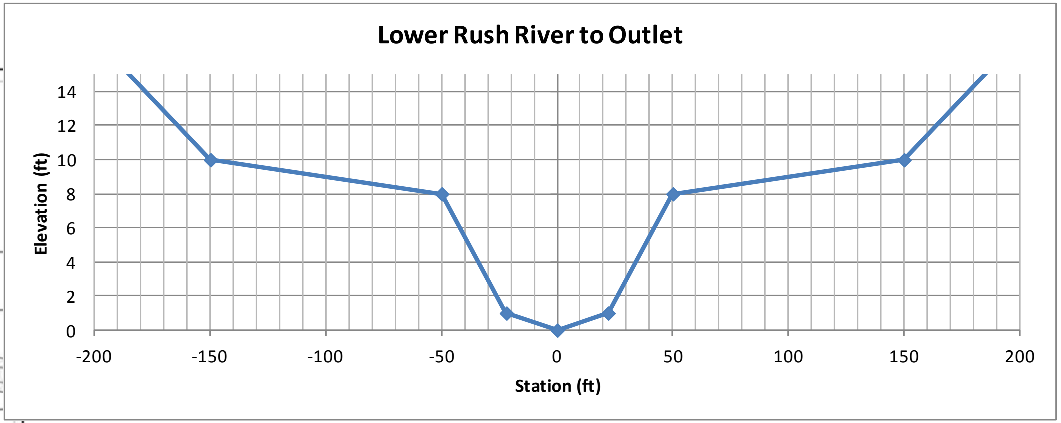
Soil erodibility

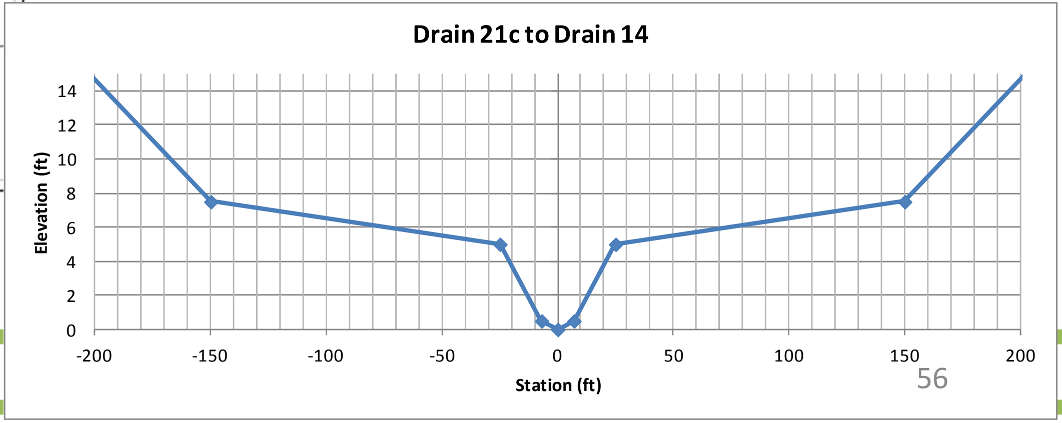


Other model considerations

- Initial Planform *(Sine Curve Pattern)*
- Cross Section Geometry *(Trapezoidal Shape)*
- Simulation Duration *(50-Years & 100-Years)*







Monte Carlo simulations

- **Reach 1 Simulations**
  - Discharge (i.e. hydrograph timing)
  - Side Slopes
  - Bottom Width
  - **Wavelength**
  - **Amplitude**
  - Scour Factor
  - Intermediate Fixed Points
  - Construction Phasing
- **Reach 5 Simulations**
  - **Wavelength**
  - Amplitude
  - Scour Factor
  - Intermediate Fixed Points

Base Simulation Parameters

	Reach 1	**Reach 5**
Bottom Width	48-ft	24-ft
Side Slopes	4H :1V	4H :1V
Wavelength	880-ft	880-ft
Amplitude	50-ft	70-ft
Flows	No Reduction	No Reduction

Key questions that RVR Meander model attempts to answer

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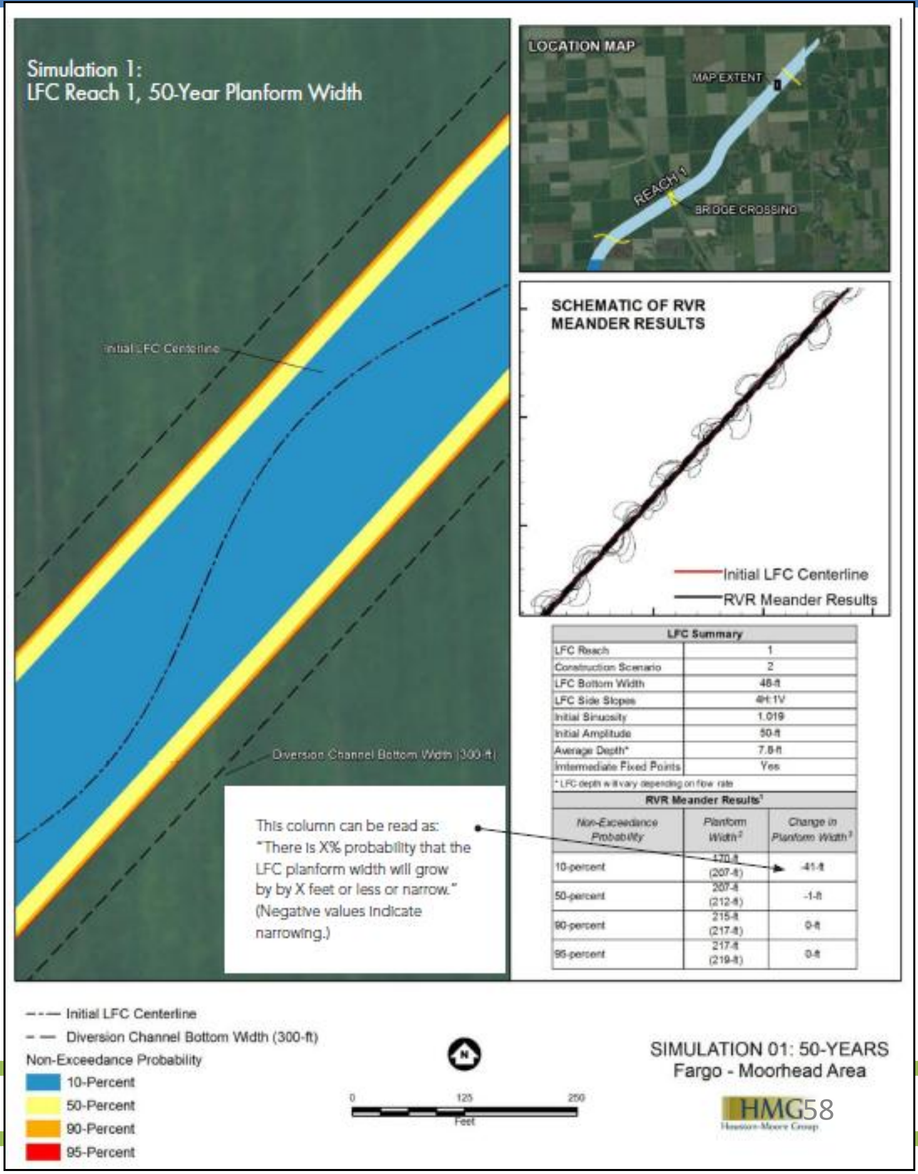
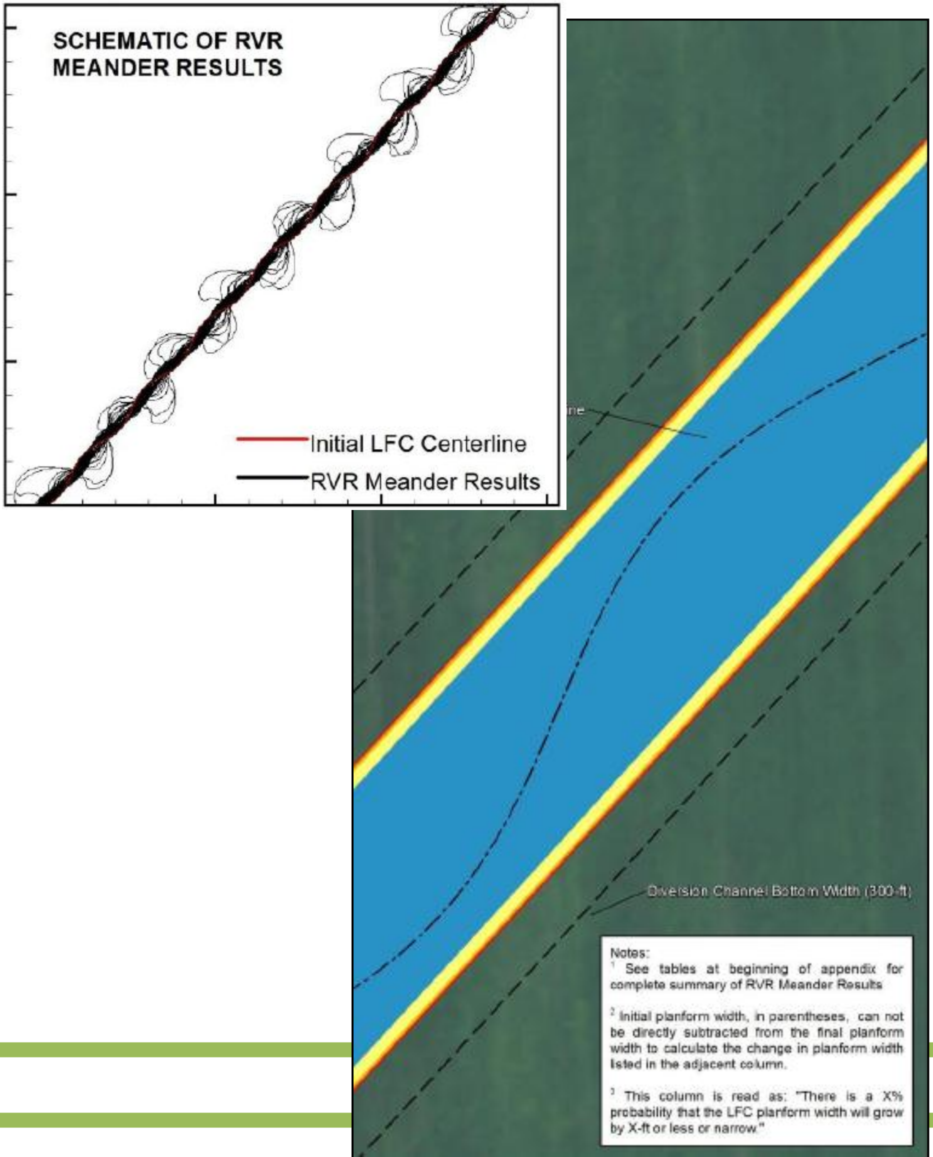
- Address the question:

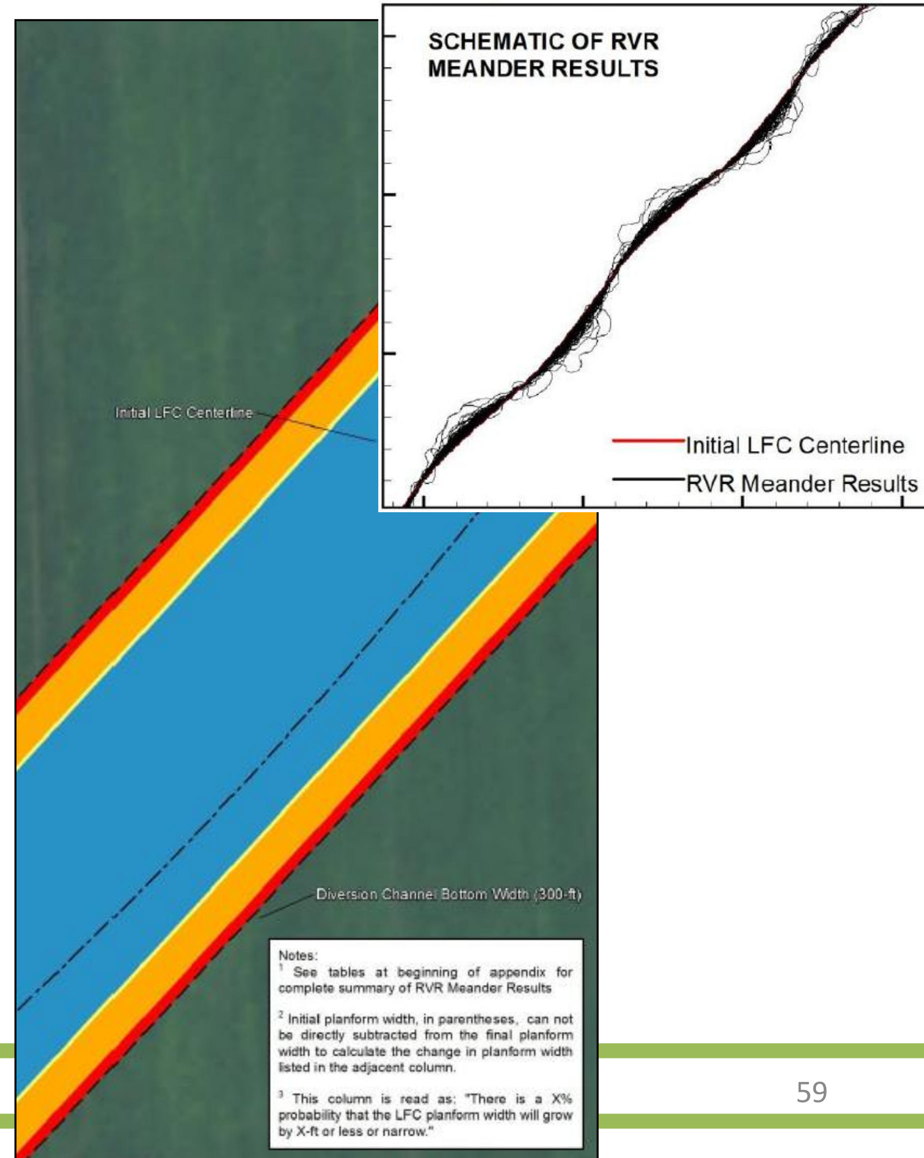
  "What is the probability that the LFC will remain within a prescribed belt width?"

- Model results can be used to begin to address inherent uncertainty in the magnitude of lateral migration
- Stakeholders can use model results to determine the amount of risk they are willing to accept and plan for future operation and maintenance costs



Probabilistic evaluation results





How to use the results?

- RVR Meander model can be applied to non-uniform initial planforms
- The model can be used as a tool by the design team to check the proposed planform for the Low-Flow Channel

Proposed methodology

1. Determine the required LFC cross section geometry

- The probabilistic evaluation indicated that the cross section geometry may not be a sensitive parameter in determining lateral migration
- Therefore, the design of the cross section should be based on other design considerations – hydraulic conveyance, sediment transport capacity, geotechnical requirements, etc…

Proposed methodology

2. Select a wavelength

- Select a wavelength that does not promote widening of the planform width

$$\lambda_{min} = \frac{2\pi B}{(\sqrt{2}C_f\beta(A - 1 + F_{ch})^{.5}}$$

- Where:
  - λ_{min} is the arc wavelength required for the planform width to widen
  - B is the LFC half-width
  - Cf is the friction coefficient
  - β is the ration of the LFC half width (B) and depth
  - A is the scour factor
  - F_{ch} is the Froude number

(Equation from work done by Johannesson and Parker, 1985)

Proposed methodology

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3. Select initial amplitude

- Select initial amplitude based on the desired “buffer” determined by the Local Sponsors and the USACE

Proposed methodology

BARR

4. Verify the selected LFC planform

- Check the selected initial planform using RVR Meander