# Sunrise River

# Geomorphic Study

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## General Scope of the Study

A geomorphic study for the Sunrise River Watershed was performed in an effort to better understand the existing conditions in the watershed from a steam morphology perspective. The study was done as part of an US Army Corps of Engineers Feasibility Study and intended to provide a general analysis and inform parallel efforts including a watershed-wide TMDL being performed by Minnesota Pollution Control Agency.

The scope on the geomorphic study summarized in this report included:

- Identification & collection of available data
    - Historic aerial photos
    - GIS data (watershed delineations, stream centerline, etc.)
    - Best available digital elevation data
- Field data collection at stream sites throughout basin
    - Identification and measurement of bankfull width and depth
    - Description of bed material
    - Assessment of channel stability using Pfankuch method
    - Collection of bed material and eroding bank material at several sites, and analysis of the those samples for grain size distribution and phosphorus concentration
    - General observations
- Other data collection
    - Fall 2009 leaf-off high resolution aerial photos of streams of interest
    - Full cross section xyz surveys of several reaches throughout the basin
- Analysis of data
    - Identification of historic stream plan-form changes from aerial photos
    - Calculation of morphological parameters at each field site and creation of spatial database

Detailed descriptions of the methods used in the study is outlined below, followed an analysis of the overall trends and conclusions. A database of geomorphic parameters, a series of maps, and supporting data are included as appendices.

## Description of GIS methods

### Stream Slope Estimate

Profiles of the stream slope throughout the study area were extracted along the digitized stream centerline from the digital elevation model (DEM) created for this study (which combined Chisago County LiDAR data with less detailed USGS NED data). Although the DEM near the water surface does not have a high level of accuracy, this method provides a good generalized elevation profile of the streams in the watershed. These approximate slopes were utilized in the calculation of several geomorphic parameters at each field site using a normal flow assumption.

### Sinuosity

Stream sinuosity was calculated for each 0.3-mile stream segment using an automated GIS process where the stream line length was divided by the straight line distance between the starting and ending point of each line. The result, shown on Plate 3, provides a good indication of the variation of stream sinuosity throughout the watershed.

### Drainage Area

The drainage area for each Sunrise River field site was calculated using the GIS sub-watershed and minor stream centerline layers.

## Description of Field Methods

### Field Site Selection

The field sites were selected such that the spatial extent of the streams of interest was well represented. Ability to access the sites also played a role in determination of actual locations. Care was taken to avoid much of the direct influence of bridges, as sites were commonly located within 5-10 stream meander lengths of bridges.

### General Approach to the Calculation of Field Site Parameters

Geomorphic parameters were determined for each field site based on inputs such as bed material sediment size, slope, sinuosity, and flood-prone width. The intent was not to produce highly accurate information at each site, rather to identify trends and water-shed wide characteristics. Factors such as backwater from impoundments, flow resistance formulation used, or errors in the bankfull width/depth determination could influence the results at individual sites; but the overall trend will be apparent.

### Bankfull Dimensions

At each field site, the bankfull dimensions of the channel were estimated. The bankfull water surface elevation was typically identified as the lowest depositional flat area at the inside of river bends or the elevation where the stream clearly was connected to its larger floodplain. Each site was walked for several river bends upstream and downstream to look closely for trends in erosion or depositions patterns as well as vegetation pattern. Field visits included 2 engineers with training in stream geomorphology and observations were discussed before making a final determination of the bankfull dimensions. Bankfull dimensions were measured using a survey level and 100-ft tape.

### Bed Material

A description of the bed material was made based on field observations at each site, and a $50^{th}$ percentile (D50) grain size was typically estimated based on the field description of the material. Bed material samples were taken and analyzed for grain size distribution at several sites to verify descriptions. Actual bed material grain sizes were fairly complex in terms of sediment layering and variability of materials within individual reaches. In the field descriptions and samples were typically made at stream “crossings” (i.e. straight reaches between bends with relatively uniform flow across the section).

### Flood Prone Width

Flood prone width for each field site was determined using a combination of field observations, detailed LiDAR data, and FEMA floodplain maps.

### Stream Stability Scoring

A Pfankuch channel stability rating was performed for the majority of field sites, which consisted of a rating of the reach for 15 individual parameters which resulted in a reach score and a channel stability rating adjusted for the Rosgen stream type. Results of the Pfankuch ratings are shown on Plate 8.

### Stream Classification (Rosgen)

A stream class according to Rosgen was applied to each field site. The classification uses Bankfull Width, Bankfull Depth, Flood-prone Depth, Bed Material and slope as inputs. Stream classification results are shown on Plate 11.

## Hydraulic Resistance at Field Sites

The flow condition during a bankfull event at each of the field sites was determined using a Manning-Stickler hydraulic resistance formulation, which is described by the following equations.

$$V = C_Z u_*$$

where,

$$C_Z = \alpha_r \left(\frac{H}{k_s}\right)^{1/6} \qquad \text{(Chezy coefficient)}$$

$$u_* = \sqrt{gHS} \qquad \text{(Shear velocity)}$$

In order to apply the formulation to the field sites using the available measured data (Bankfull Depth, Slope, and Bed Material Grain Size), the following empirical relations and constants were applied:

$$k_s = 3D_{90} \qquad \text{(Roughness Height)}^{1}$$

$$D_{90} = D_{50}\sigma_g^{1.28} \qquad \text{(Estimate for log-normal Grain Size Distribution)}^{2}$$

$$\sigma_g = 1.5 \qquad \text{(Geometric Standard Deviation of Grain Size Distribution)}^{3}$$

[1] Typical value, from Chapter 5 of (Parker 2004)
[2] Suggestion relation for a log-normal grain size distribution of bed material, from Chapter 5 of (Parker 2004)
[3] Typical value, from Chapter 5 of (Parker 2004)

$$\alpha_r = 8.32$$ (dimensionless constant in Manning-Strickler formulation of Hydraulic Resistance)[4]

The formulation is appropriate under plane bed conditions (i.e. no bed forms such as dunes), but when dunes are present the formulation must be adjusted to account for the additional resistance that is created from their presence. It is assumed that the velocity of flow is not affected by the presence of bed-forms, but that the bed-forms cause an increase in flow depth[5] (Parker 2004). In the case of dune presence, empirical relationships can be used to define their effect on flow depth. The following relationship was used at each Sunrise River field site:

1) $$V = \alpha_r \left(\frac{H_s}{k_s}\right)^{1/6} \sqrt{gH_sS}$$ (Velocity, dependant on the depth without bed-forms, $H_s$)

2) $$\frac{H_sS}{RD} = 0.5 + 0.7\left[\left(\frac{HS}{RD}\right)\left(\frac{V}{\sqrt{gH}}\right)^{0.7}\right]^{0.8}$$ (Effect of dunes)[6]

Definitions:

| | |
|---|---|
| $V$ | Velocity |
| $H_s$ | Flow depth without presence of bed-forms |
| $H$ | Flow depth with presence of bed-forms (field measured bankfull flow depth) |
| $k_s$ | Roughness height |
| $S$ | Bankfull Slope |
| $g$ | Acceleration due to gravity |
| $R$ | Submerges specific weight of sediment, used 1.65 |
| $D$ | Diameter of bed material, used 50th percentile |

The set of two equations with two unknowns ($H_s$ and $V$) allow for computation of the flow conditions at bankfull when dunes are present.

### Determination of dune presence at bankfull flow

The resulting dimensionless parameters of Shields Stress and Reynolds Particle number (defined below) were computed and plotted against the plane bed/dune/ripple criteria defined by the empirical data[7] and used as a guide in determining the existence/non-existence of dunes during bankfull flow at each of the field sites.

[4] Value taken from Chapter 9 of (Parker 2004)
[5] Einstein decomposition described in Chapter 9 (Parker 2004)
[6] From Chapter 9 of (Parker 2004)
[7] Relationship of Chabert and Chauvin was used, from Chapter 8 of (Parker 2004)

$$\tau_* = \frac{HS}{RD}$$ Definition of Dimensionless Shields Stress

$$Re_p = \frac{\sqrt{RgD}D}{\upsilon}$$ Definition of Dimensionless Reynolds Particle number

Where "$\nu$" is the kinematic viscosity of water.

For each of the Sunrise River field sites, the selection of dune regime at bankfull flow ("no dunes" or "dunes") was made based on the results shown on Plate 12, and the appropriate hydraulic resistance formulation was applied.

### Equivalent "Manning's N" Value

Hydraulic resistance is commonly estimated with a "manning's n" value which is usually based on empirical data in a fashion that doesn't directly use bed material grain size as predictor as was done for this study. For each of the Sunrise River field sites, the equivalent "manning's n" value was back-calculated with the following equation.

$$n = \frac{1.49H^{2/3}S^{1/2}}{V}$$ (Velocity in ft/s, and H in feet)

## Other Geomorphic Parameters at Field Sites

### Shear Stress

The shear stress was computed at each field site assuming normal flow with the following equation.

$$\tau_b = \rho g H S$$

where,

| | |
|---|---|
| $\tau_b$ | Shear Stress |
| $\rho$ | Density of water |
| H | Bankfull Depth |
| S | Bankfull Slope |

### Stream Power

Stream power (per unit of stream width) is equal to the product of the velocity and shear stress, and can be correlated to sediment transport capacity of the stream. The results of the stream power calculation are shown on Plate 7.

### Bankfull Flow Rate

The bankfull flow rate was estimated based on the field data at each site as the product of velocity, width and depth. The results are shown spatially on Plate 6.

### Critical Diameter

The critical diameter for transport was calculated at each site using the Shields Criteria for the threshold of motion, which is defined by the following relationship.

$$\tau_s^* = 0.5\left[0.22Re_p^{-0.6} + 0.06(10)^{\left(-7.7Re_p^{-0.6}\right)}\right]$$

$\tau_s^*$ Shields stress associated with the flow depth without dunes (Parker 2004)

The data from the field sites are on a threshold of motion plot in Plate 12, and shown spatially on Plate 9. This critical diameter can be thought of as the largest size particle that will be transported by the stream during a bank-full flow event.

## Trends, Conclusions, and general observations:

The streams of the Sunrise River watershed have a general trend of increasing slopes and stream power from upstream to downstream. The Main Stem of the Sunrise downstream of Kost Dam and the North Branch of the Sunrise downstream of Highway 95 (first crossing upstream of City of North Branch) in particular are reaches with markedly increased slopes (on the order of 0.001 ft/ft) compared to the rest of the watershed. These reaches generally correspond with the presence of visible, tall cut banks where active erosion is taking place. The calculated geomorphic parameters verify this overall trend, and it is clear that the great majority sediment supply due to in-in stream erosion is from these reaches.

Although several eroding banks along the streams are present in the lower portion of the watershed, and several sets of historical aerial photos are available back to 1938; it proved difficult to quantify the stream bank erosion or rate of erosion at specific banks due to the relatively small migration of the channel, quality of the historic photos, and error associated with the geo-rectification of the historic photos. Therefore volumetric estimates of annual stream-bank erosion were not made.

The upper reaches of the watershed are typically characterized by wide flood plains and flatter slopes (typically less than 0.0004 ft/ft). Analysis of historical photos indicates that the streams in the upper watershed commonly erode new channels and leave oxbows within the floodplain as they typically have very little constraint in terms of high banks. The historic channel shifts tend to leave the streams with a similar overall sinuosity, indicating similar sediment transport capacity. Several impoundments exist in the upper basin, all of which trap nearly all of the sand size sediments and a large percentage of the finer sediments that enter from upstream. As evidenced by the low slopes, lack of high banks, and historically stable sinuosity, and the presence of impoundments; the upper reaches do not contribute a large amount of sediment to the Sunrise River system.

The presence of reddish heavy clay was noted along the North Branch and Sunrise Main Stem downstream of Kost Dam. Clay clasts of various sizes were noted as part of the bed material at several locations; and field site MS9 has a bed that consists of a solid, thick layer of the clay. This material is of significance to the geomorphology of the system as the clay particles being transported have properties than effect their transport that are different that those of quartz sand which is typically assumed in sediment transport calculations such as specific gravity, ability to break into smaller pieces with minimal energy, and ability to change shape under load. The layer of clay at site MS9 is significant as the material requires high shear stress to erode due to the cohesive properties of the clay, and is likely preventing downward erosion of the stream bed in the area.

## Bibliography

Parker, Gary. *1D Sediment Trasport Morphodynamics E-Book.* 2004.

Rosgen, Dave. *Watershed Assessment of River Stability and Sediment Supply (WARSSS).* Wildland Hydrology, 2006.

Strum, Terry W. *Open Channel Hydraulics.* McGraw-Hill, 2001.

# **Appendix 1:**

Field Site Data

Measured and Calculated Parameters

| River Reach<br>Site | | North Branch<br>Site 1 | North Branch<br>Site 2 | North Branch<br>Site 3 | North Branch<br>Site 4 | North Branch<br>Site 5 | North Branch<br>Site 6 | North Branch<br>Site 7 | North Branch<br>Site 8 |
|---|---|---|---|---|---|---|---|---|---|
| Site ID | | NB1 | NB2 | NB3 | NB4 | NB5 | NB6 | NB7 | NB8 |
| Bottom Material Description | | very fine sand | fine sand | fine gravel | medium to fine sand | medium sand | fine sand | fine gravel | fine sand |
| D50 | mm | 0.1 | 0.2 | 2 | 0.35 | 0.4 | 0.2 | 3 | 0.2 |
| Bankfull Width | ft | 10 | 12.5 | 20 | 22 | 50 | 25 | 43 | 40 |
| Bankfull Depth | ft | 2.28 | 2.3 | 2.22 | 2.75 | 1.83 | 3.1 | 4 | 4 |
| Flood prone width | ft | 460 | 225 | 200 | 350 | 700 | 450 | 450 | 450 |
| River Slope | | 0.001 | 0.001 | 0.0005 | 0.0005 | 0.000375 | 0.000375 | 0.0008 | 0.0008 |
| Valley Slope | | 0.0015 | 0.0018 | 0.00085 | 0.0008 | 0.0009375 | 0.0006375 | 0.0012 | 0.0012 |
| Sinuosity | | 1.5 | 1.8 | 1.7 | 1.6 | 2.5 | 1.7 | 1.5 | 1.5 |
| Estimated Drainage Area | $mi^2$ | 8.90 | 13.80 | 28.30 | 38.20 | 52.80 | 54.00 | 56.20 | 63.40 |
| Width to Depth Ratio | | 4.39 | 5.43 | 9.01 | 8.00 | 27.32 | 8.06 | 10.75 | 10.00 |
| Bankfull Hydraulic Radius | ft | 1.6 | 1.7 | 1.8 | 2.2 | 1.7 | 2.5 | 3.4 | 3.3 |
| Bankfull Cross Sectional Area | $ft^2$ | 23 | 29 | 44 | 61 | 92 | 78 | 172 | 160 |
| Entrenchment Ratio | | 46.0 | 18.0 | 10.0 | 15.9 | 14.0 | 18.0 | 10.5 | 11.3 |
| Stream Class (Rosgen) | | E5 | E5 | E4 | E5 | C5c- | E5 | E4 | E5 |
| Estimated Bankfull Veloctiy | ft/s | 4 | 4 | 3 | 3 | 2 | 3 | 6 | 4 |
| Estimated Bankfull Flow | cfs | 83 | 104 | 141 | 175 | 206 | 202 | 954 | 683 |
| Total Bankfull Shear Stress | $lb/ft^2$ | 0.142 | 0.144 | 0.069 | 0.086 | 0.043 | 0.073 | 0.200 | 0.200 |
| Equivalent Mannings "n" | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Critical Grain Size at Bankfull | mm | 5.5 | 6.2 | 7.7 | 4.6 | 3.3 | 3.4 | 20.2 | 7.5 |
| Pfankuch Stability Score | | | | | | Fair | Fair | Fair | |
| Bankfull Stream Power | lb/ft-s | 0.52 | 0.52 | 0.22 | 0.25 | 0.10 | 0.19 | 1.11 | 0.85 |
| Sheilds Stress (skin, D50) | | 1.42 | 0.84 | 0.10 | 0.33 | 0.19 | 0.40 | 0.20 | 1.01 |
| Reynolds Particle Number (Bankfull D50) | | 4 | 11 | 360 | 26 | 32 | 11 | 661 | 11 |

| River Reach<br>Site | | North Branch<br>Site 9 | North Branch<br>Site 10 | North Branch<br>Site 11 | Hay Creek<br>Site 2 | West Branch<br>Site 1 | West Branch<br>Site 2 | South Branch<br>Site 1 | South Branch<br>Site 2 |
|---|---|---|---|---|---|---|---|---|---|
| Site ID | | NB9 | NB10 | NB11 | Hay2 | WB1 | WB2 | SB1 | SB2 |
| Bottom Material Description | | gravel | gravel | medium sand | 85% sand / 15% gravel | fine sand | medium gravel | fine sand | fine sand |
| D50 | mm | 10 | 9 | 0.25 | 0.8 | 0.25 | 7 | 0.12 | 0.12 |
| Bankfull Width | ft | 38 | 44 | 42 | 30 | 25 | 25 | 26 | 20 |
| Bankfull Depth | ft | 3.9 | 5.3 | 4.9 | 3.5 | 2.8 | 2 | 2.75 | 2.3 |
| Flood prone width | ft | 390 | 390 | 380 | 275 | 330 | 440 | 200 | 160 |
| River Slope | | 0.0008 | 0.0011 | 0.0012 | 0.0018 | 0.00027 | 0.0007 | 0.0004 | 0.00034 |
| Valley Slope | | 0.001408 | 0.002035 | 0.002088 | 0.0027 | 0.0004104 | 0.001015 | 0.00044 | 0.000544 |
| Sinuosity | | 1.76 | 1.85 | 1.74 | 1.5 | 1.52 | 1.45 | 1.1 | 1.6 |
| Estimated Drainage Area | $mi^2$ | 66.80 | 75.10 | 77.80 | 14.20 | 44.20 | 52.30 | 40.70 | 47.00 |
| Width to Depth Ratio | | 9.74 | 8.30 | 8.57 | 8.57 | 8.93 | 12.50 | 9.45 | 8.70 |
| Bankfull Hydraulic Radius | ft | 3.2 | 4.3 | 4.0 | 2.8 | 2.3 | 1.7 | 2.3 | 1.9 |
| Bankfull Cross Sectional Area | $ft^2$ | 148 | 233 | 206 | 105 | 70 | 50 | 72 | 46 |
| Entrenchment Ratio | | 10.3 | 8.9 | 9.0 | 9.2 | 13.2 | 17.6 | 7.7 | 8.0 |
| Stream Class (Rosgen) | | E4 | E4 | E5 | E5 | C5c- | C4c- | n/a | E5 |
| Estimated Bankfull Veloctiy | ft/s | 4 | 7 | 6 | 6 | 2 | 3 | 2 | 2 |
| Estimated Bankfull Flow | cfs | 662 | 1524 | 1209 | 635 | 155 | 142 | 178 | 98 |
| Total Bankfull Shear Stress | $lb/ft^2$ | 0.195 | 0.364 | 0.367 | 0.394 | 0.047 | 0.087 | 0.069 | 0.049 |
| Equivalent Mannings "n" | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Critical Grain Size at Bankfull | mm | 20.0 | 36.5 | 13.6 | 20.5 | 2.7 | 9.5 | 2.9 | 2.3 |
| Pfankuch Stability Score | | Fair | | | Fair | Good | | Good | Fair |
| Bankfull Stream Power | lb/ft-s | 0.87 | 2.38 | 2.16 | 2.38 | 0.10 | 0.25 | 0.17 | 0.10 |
| Sheilds Stress (skin, D50) | | 0.06 | 0.12 | 1.53 | 0.74 | 0.24 | 0.04 | 0.56 | 0.42 |
| Reynolds Particle Number (Bankfull D50) | | 4023 | 3435 | 16 | 91 | 16 | 2356 | 5 | 5 |

| River Reach<br>Site | | Sunrise Main Stem<br>Site 1 | Sunrise Main Stem<br>Site 2 | Sunrise Main Stem<br>Site 4 | Sunrise Main Stem<br>Site 3 | Sunrise Main Stem<br>Site 5 | Sunrise Main Stem<br>Site 6 |
|---|---|---|---|---|---|---|---|
| Site ID | | MS1 | MS2 | MS4 | MS3 | MS5 | MS6 |
| Bottom Material Description | | gravel | very fine sand | very fine sand | 25% gravel 75% coarse sand | medium sand | very fine sand |
| D50 | mm | 5 | 0.07 | 0.07 | 0.5 | 0.4 | 0.05 |
| Bankfull Width | ft | 26 | 24 | 47 | 58 | 54 | 55 |
| Bankfull Depth | ft | 1.1 | 1.6 | 2.9 | 2.3 | 2.5 | 3.4 |
| Flood prone width | ft | 175 | 750 | 775 | 525 | 620 | 825 |
| River Slope | | 0.00045 | 0.00045 | 0.00016 | 0.00025 | 0.00025 | 0.0002 |
| Valley Slope | | 0.00062 | 0.00086 | 0.00022 | 0.00040 | 0.00048 | 0.00038 |
| Sinuosity | | 1.37 | 1.9 | 1.4 | 1.6 | 1.9 | 1.9 |
| Estimated Drainage Area | $mi^2$ | 49.60 | 54.10 | 164.30 | 232.70 | 248.90 | 251.00 |
| Width to Depth Ratio | | 23.64 | 15.00 | 16.21 | 25.22 | 21.60 | 16.18 |
| Bankfull Hydraulic Radius | ft | 1.0 | 1.4 | 2.6 | 2.1 | 2.3 | 3.0 |
| Bankfull Cross Sectional Area | $ft^2$ | 29 | 38 | 136 | 133 | 135 | 187 |
| Entrenchment Ratio | | 6.7 | 31.3 | 16.5 | 9.1 | 11.5 | 15.0 |
| Stream Class (Rosgen) | | C4c- | C5c- | C5c- | C4c- | C5c- | C5c- |
| Estimated Bankfull Veloctiy | ft/s | 2 | 2 | 2 | 2 | 2 | 2 |
| Estimated Bankfull Flow | cfs | 46 | 77 | 224 | 300 | 299 | 362 |
| Total Bankfull Shear Stress | $lb/ft^2$ | 0.031 | 0.045 | 0.029 | 0.036 | 0.039 | 0.042 |
| Equivalent Mannings "n" | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Critical Grain Size at Bankfull | mm | 3.8 | 2.1 | 1.3 | 3.1 | 2.9 | 1.6 |
| Pfankuch Stability Score | | Good | Good | | Good | Good | Good |
| Bankfull Stream Power | lb/ft-s | 0.05 | 0.09 | 0.05 | 0.08 | 0.09 | 0.08 |
| Sheilds Stress (skin, D50) | | 0.02 | 0.62 | 0.36 | 0.15 | 0.17 | 0.62 |
| Reynolds Particle Number (Bankfull D50) | | 1422 | 2 | 2 | 45 | 32 | 1 |

| River Reach<br>Site | | Sunrise Main Stem<br>Site 7 | Sunrise Main Stem<br>Site 8 | Sunrise Main Stem<br>Site 9 | Sunrise Main Stem<br>Site 14 | Sunrise Main Stem<br>Site 13 | Sunrise Main Stem<br>Site 10 |
|---|---|---|---|---|---|---|---|
| Site ID | | MS7 | MS8 | MS9 | MS14 | MS13 | MS10 |
| Bottom Material Description | | medium sand | medium sand | gravel over heavy clay | 50% gravel 50% sand | gravel / cobbles | cobbles |
| D50 | mm | 0.4 | 0.5 | 5 | 5 | 8 | 8 |
| Bankfull Width | ft | 63 | 50 | 65 | 78 | 53 | 58 |
| Bankfull Depth | ft | 3.2 | 3.4 | 1.6 | 3.81 | 4.52 | 3.7 |
| Flood prone width | ft | 600 | 450 | 650 | 300 | 350 | 300 |
| River Slope | | 0.0009 | 0.0009 | 0.0006 | 0.0003 | 0.0003 | 0.0019 |
| Valley Slope | | 0.00131 | 0.00149 | 0.00168 | 0.00036 | 0.00039 | 0.00266 |
| Sinuosity | | 1.45 | 1.65 | 2.8 | 1.2 | 1.3 | 1.4 |
| Estimated Drainage Area | $mi^2$ | 269.00 | 272.00 | 276.00 | 380.00 | 380.50 | 380.70 |
| Width to Depth Ratio | | 19.69 | 14.71 | 40.63 | 20.47 | 11.73 | 15.68 |
| Bankfull Hydraulic Radius | ft | 2.9 | 3.0 | 1.5 | 3.5 | 3.9 | 3.3 |
| Bankfull Cross Sectional Area | $ft^2$ | 202 | 170 | 104 | 297 | 240 | 215 |
| Entrenchment Ratio | | 9.5 | 9.0 | 10.0 | 3.8 | 6.6 | 5.2 |
| Stream Class (Rosgen) | | C5c- | C5 | C5c- | C4c- | C4c- | C3c- |
| Estimated Bankfull Veloctiy | ft/s | 4 | 4 | 2 | 3 | 3 | 7 |
| Estimated Bankfull Flow | cfs | 820 | 715 | 249 | 898 | 750 | 1480 |
| Total Bankfull Shear Stress | $lb/ft^2$ | 0.180 | 0.191 | 0.060 | 0.071 | 0.085 | 0.439 |
| Equivalent Mannings "n" | | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| Critical Grain Size at Bankfull | mm | 8.5 | 9.4 | 6.9 | 7.6 | 9.2 | 43.0 |
| Pfankuch Stability Score | | Fair | Fair | Good | Good | Fair | Good |
| Bankfull Stream Power | lb/ft-s | 0.73 | 0.80 | 0.14 | 0.22 | 0.27 | 3.03 |
| Sheilds Stress (skin, D50) | | 0.58 | 0.51 | 0.04 | 0.04 | 0.03 | 0.16 |
| Reynolds Particle Number (Bankfull D50) | | 32 | 45 | 1422 | 1422 | 2879 | 2879 |

| River Reach<br>Site | | Sunrise Main Stem<br>Site 11 | Sunrise Main Stem<br>Site 12 |
|---|---|---|---|
| Site ID | | MS11 | MS12 |
| Bottom Material Description | | cobbles | cobbles |
| D50 | mm | 8 | 8 |
| Bankfull Width | ft | 72 | 57 |
| Bankfull Depth | ft | 3.8 | 5.2 |
| Flood prone width | ft | 325 | 650 |
| River Slope | | 0.0019 | 0.0019 |
| Valley Slope | | 0.00304 | 0.00266 |
| Sinuosity | | 1.6 | 1.4 |
| Estimated Drainage Area | $mi^2$ | 381.00 | 383.00 |
| Width to Depth Ratio | | 18.95 | 10.96 |
| Bankfull Hydraulic Radius | ft | 3.4 | 4.4 |
| Bankfull Cross Sectional Area | $ft^2$ | 274 | 296 |
| Entrenchment Ratio | | 4.5 | 11.4 |
| Stream Class (Rosgen) | | C3c- | C3c- |
| Estimated Bankfull Veloctiy | ft/s | 7 | 9 |
| Estimated Bankfull Flow | cfs | 1920 | 2564 |
| Total Bankfull Shear Stress | $lb/ft^2$ | 0.451 | 0.617 |
| Equivalent Mannings "n" | | 0.0 | 0.0 |
| Critical Grain Size at Bankfull | mm | 45.5 | 60.2 |
| Pfankuch Stability Score | | Good | Good |
| Bankfull Stream Power | lb/ft-s | 3.17 | 5.34 |
| Sheilds Stress (skin, D50) | | 0.17 | 0.23 |
| Reynolds Particle Number (Bankfull D50) | | 2879 | 2879 |

# Appendix 2: Plates

**Plate1. Elevation Map of Basin**

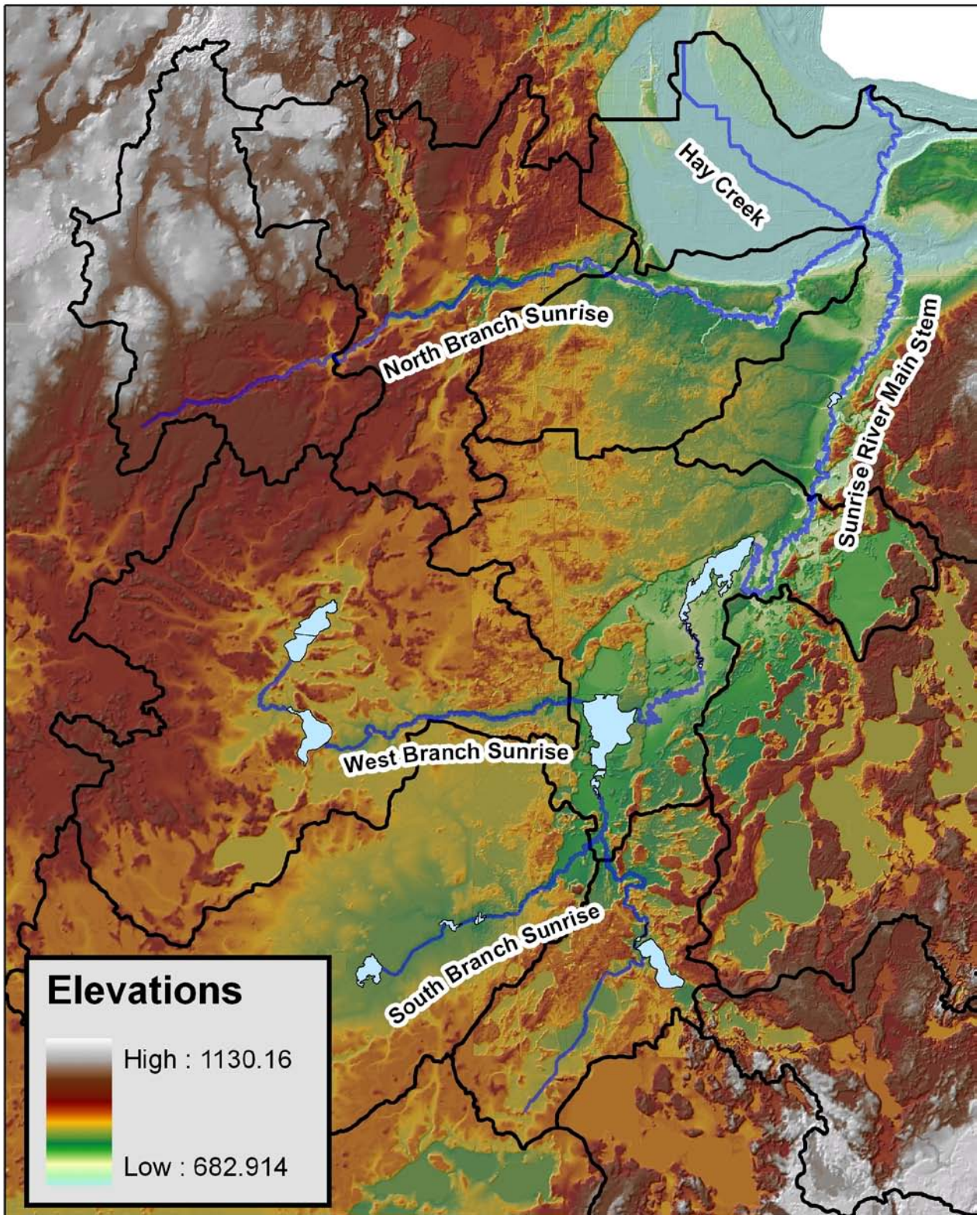

**Plate 2. Map of Stream-wise River Slopes**

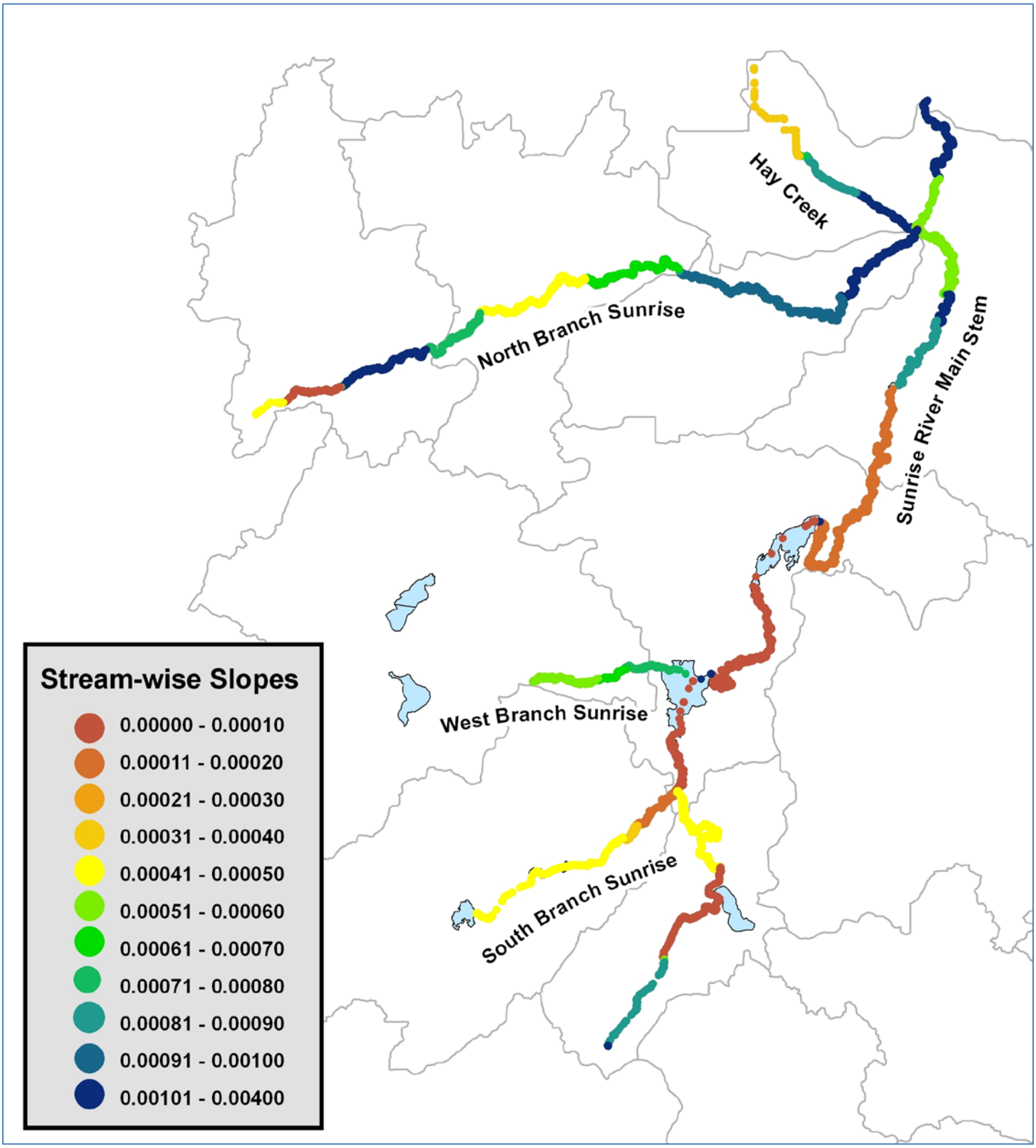

**Plate 3. Map of Reach Sinuosity**

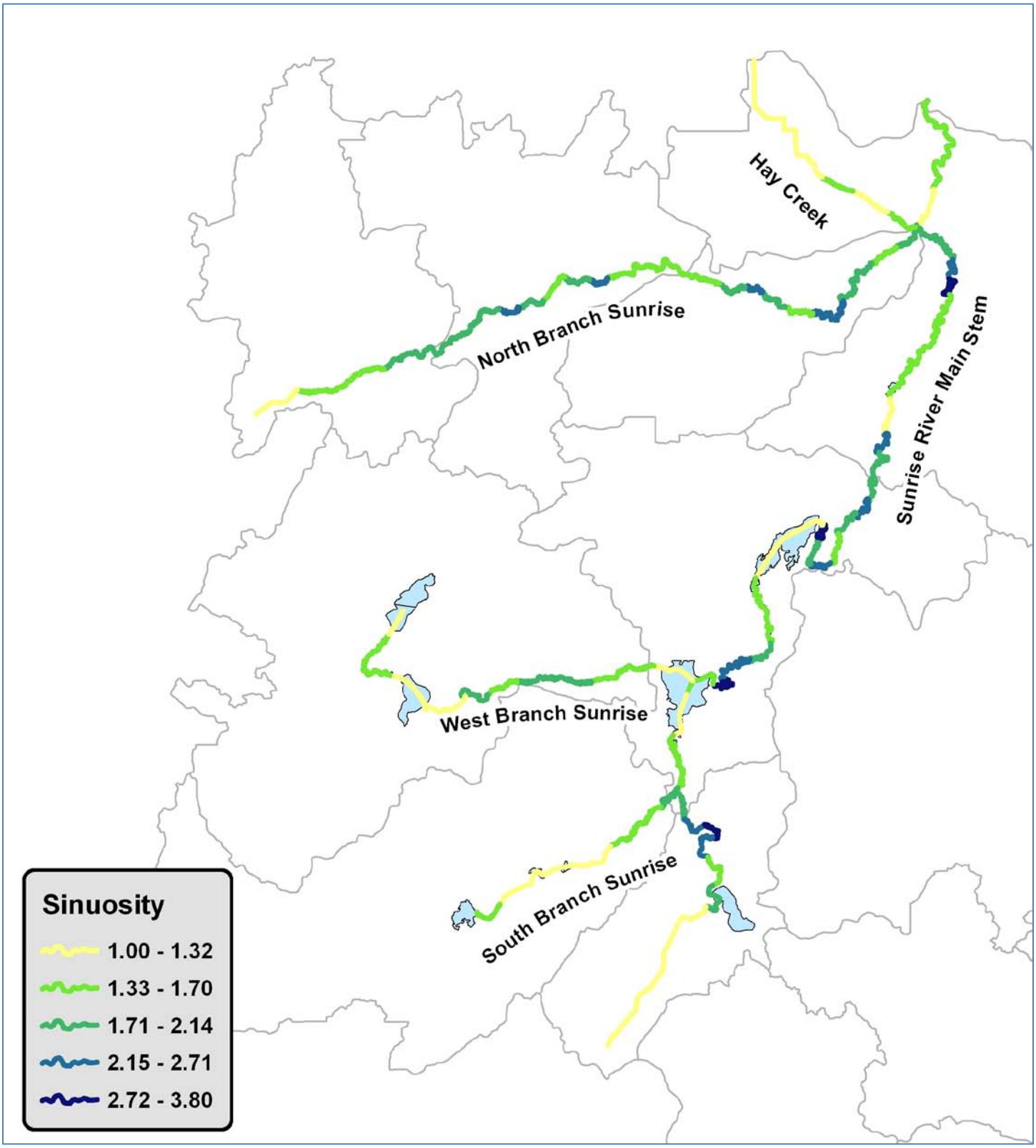

**Plate 4. Map of Field Site Locations & Names**

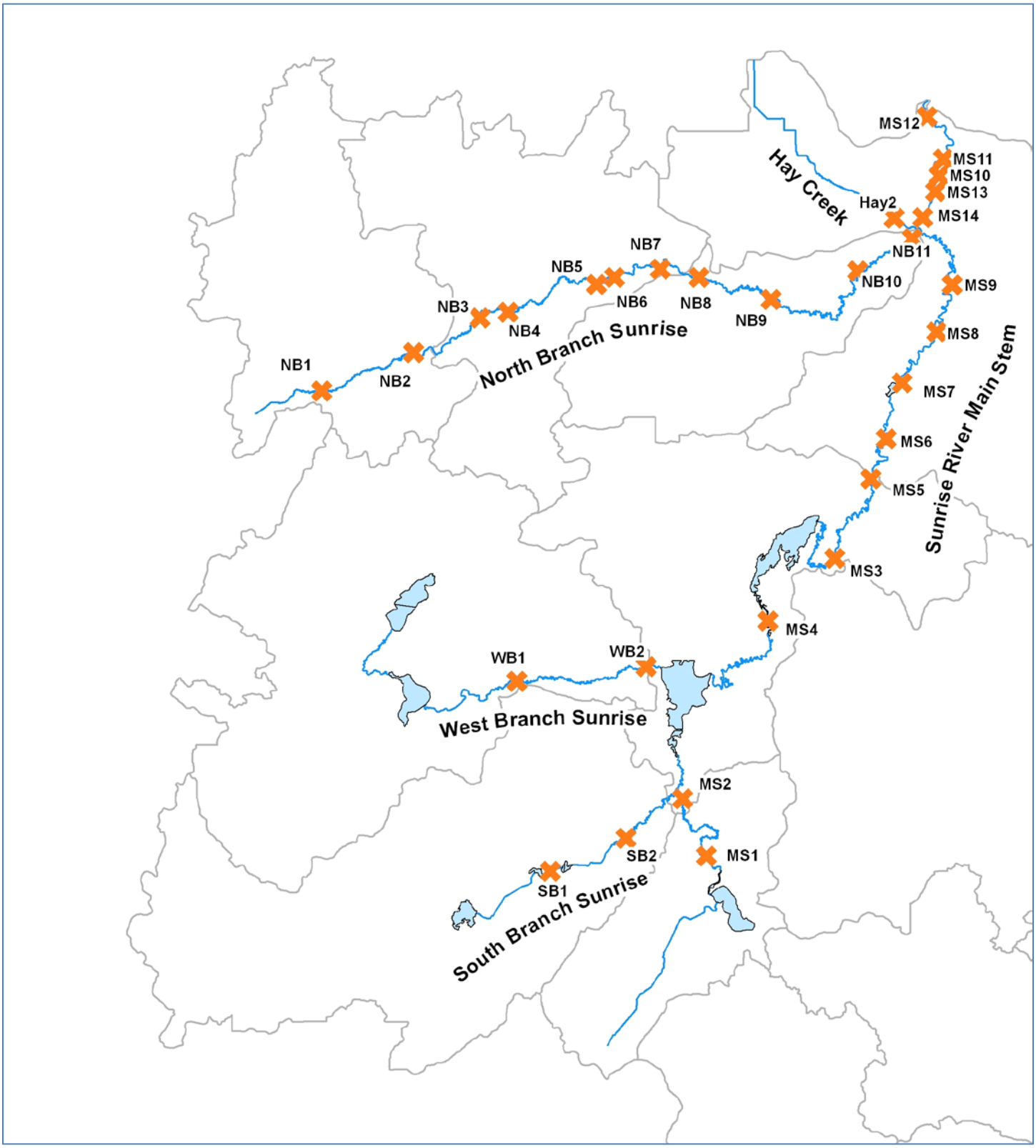

**Plate 5. Historic Stability of Stream Centerlines**

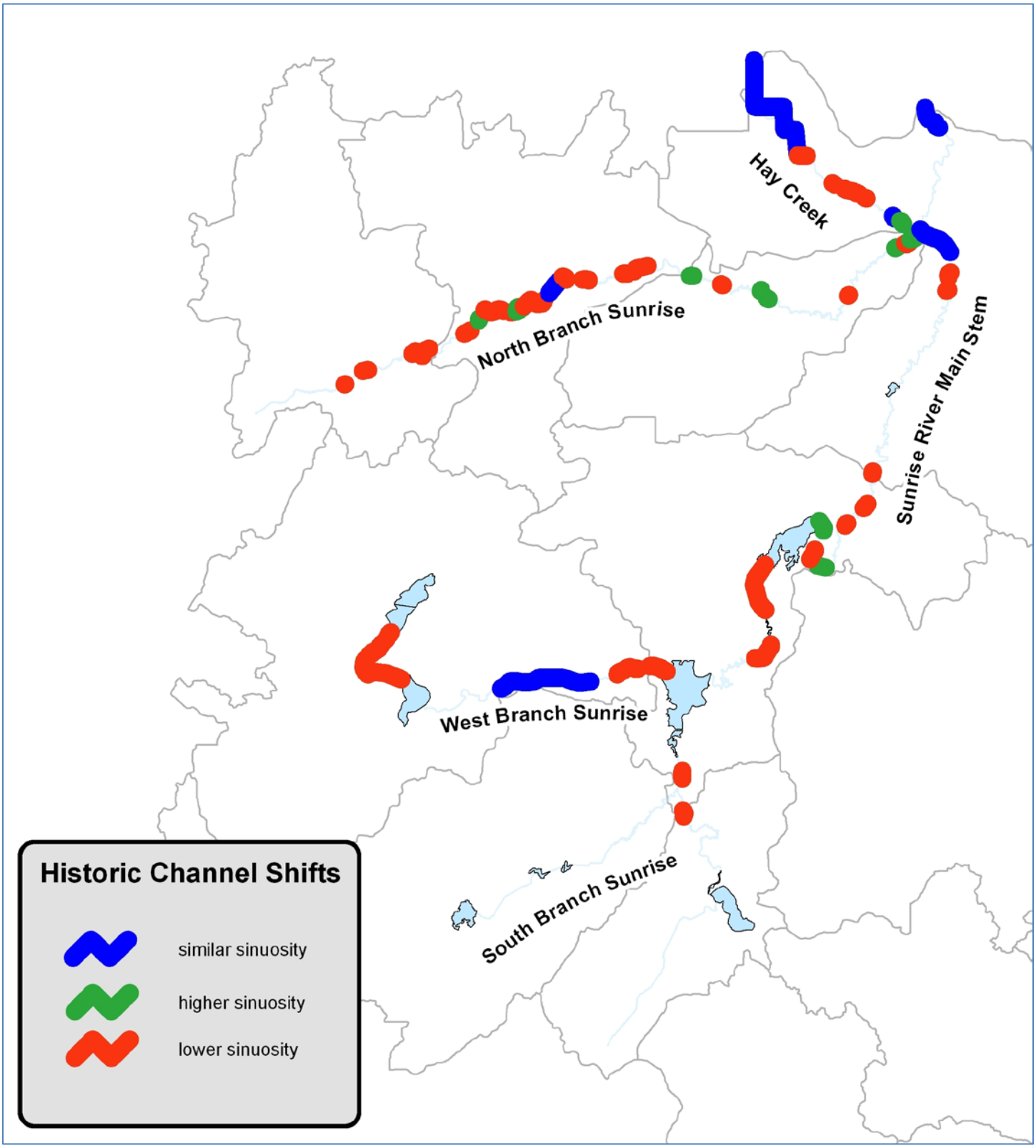

**Plate 6. Map of Estimated Bankfull Flow**

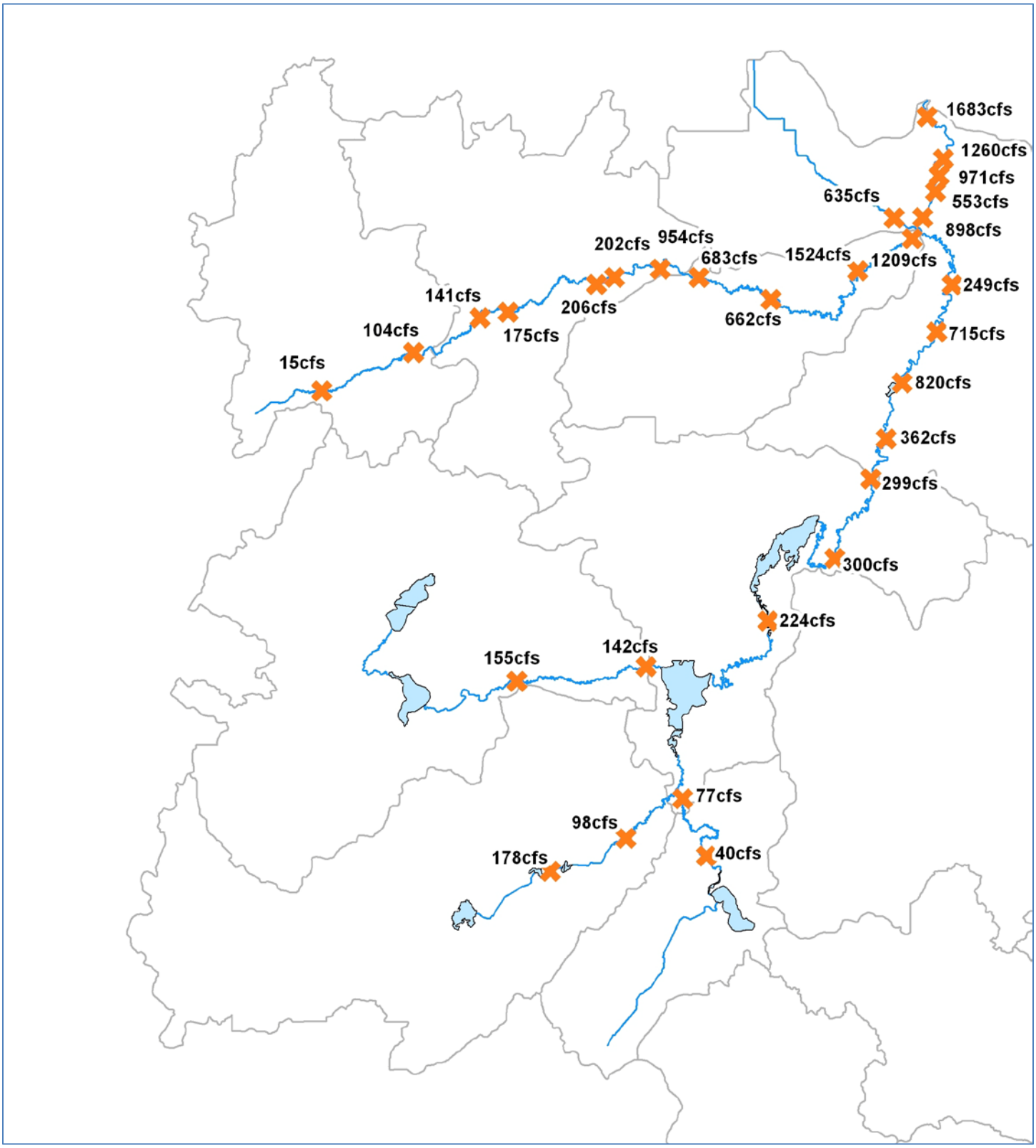

**Plate 7. Map of Calculated Bankfull Stream Power**

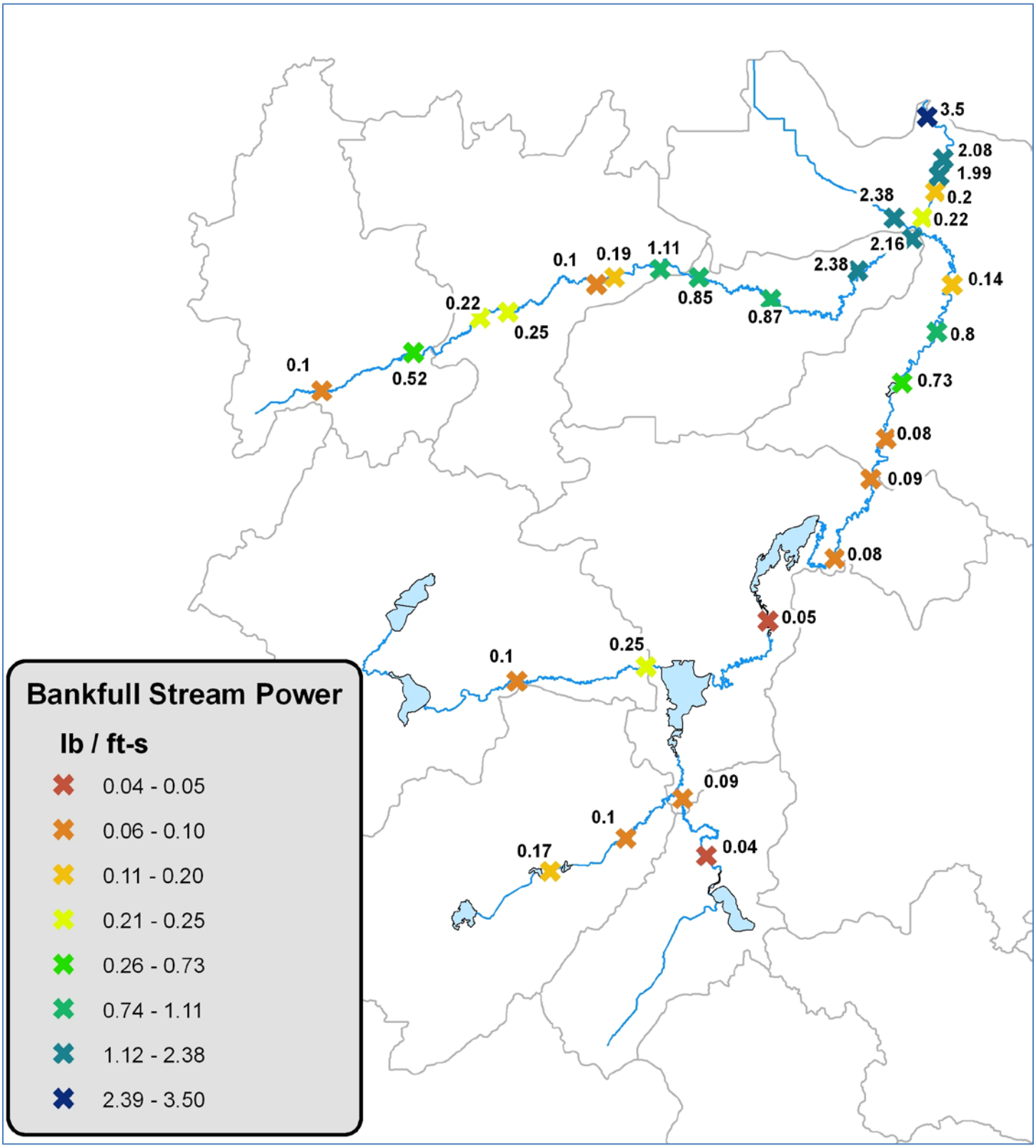

**Plate 8. Map of Pfankuch Channel Stability Rating**

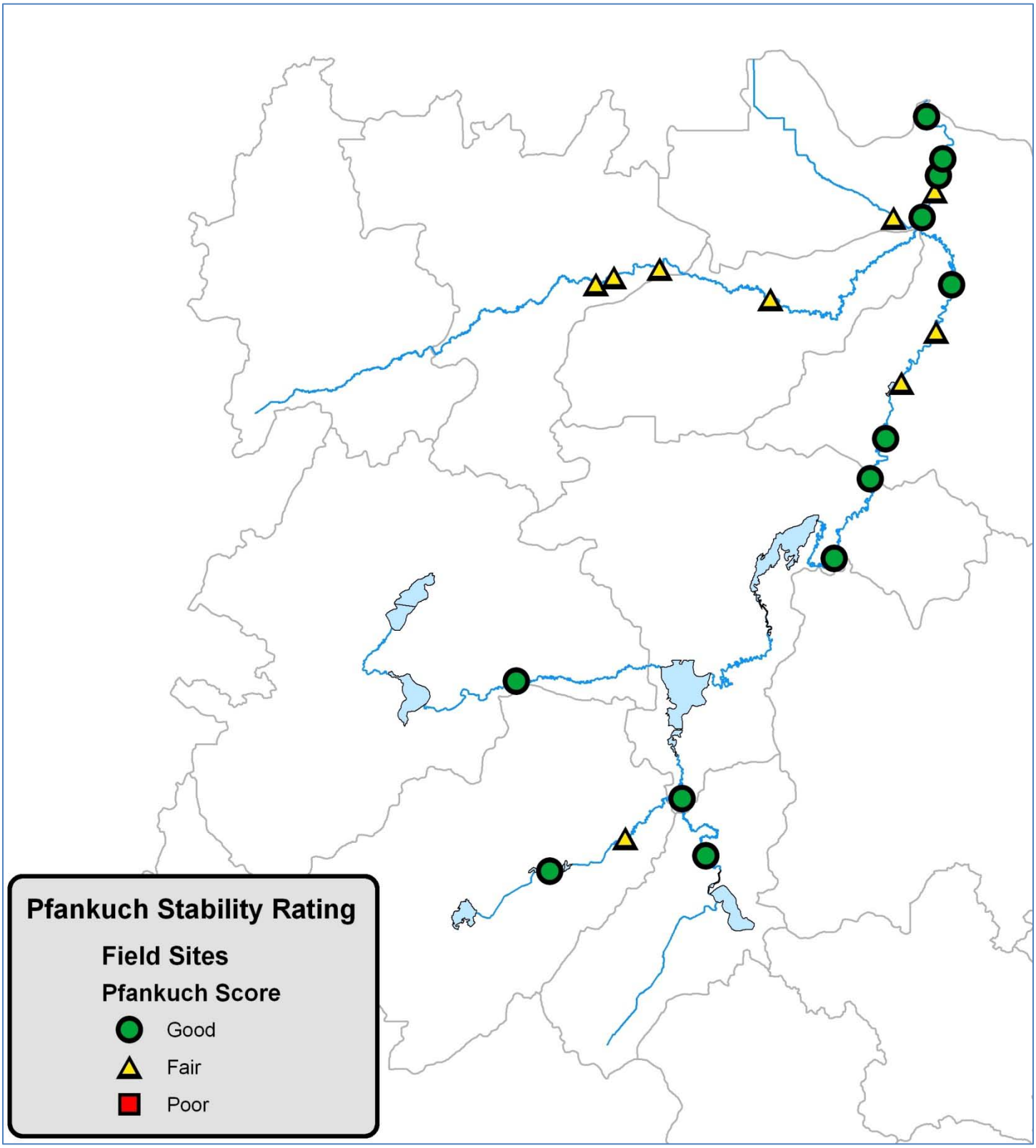

**Plate 9. Map of Critical Grain Size for Transport at Bankfull**

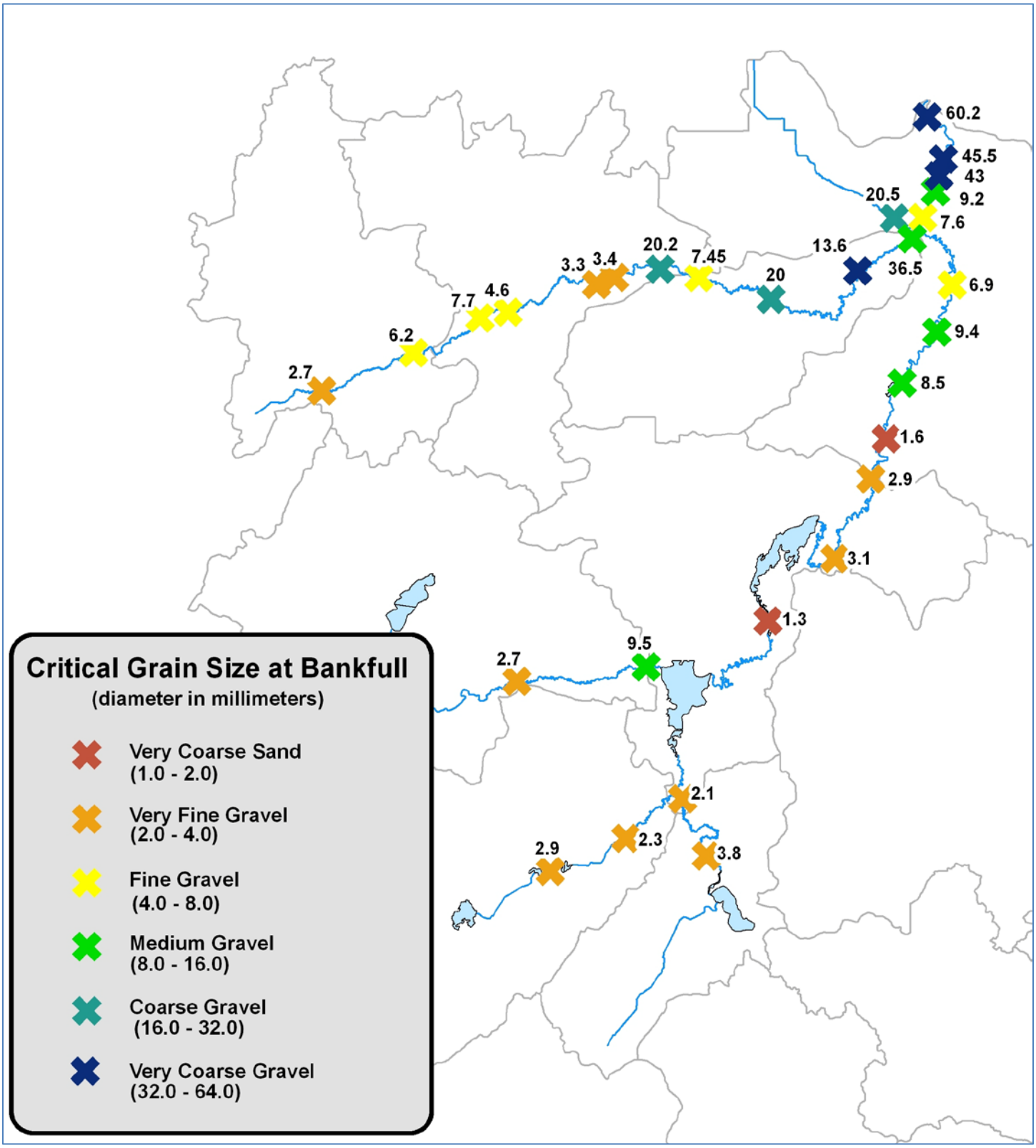

**Plate 10. Map of Equivalent Manning's N values**

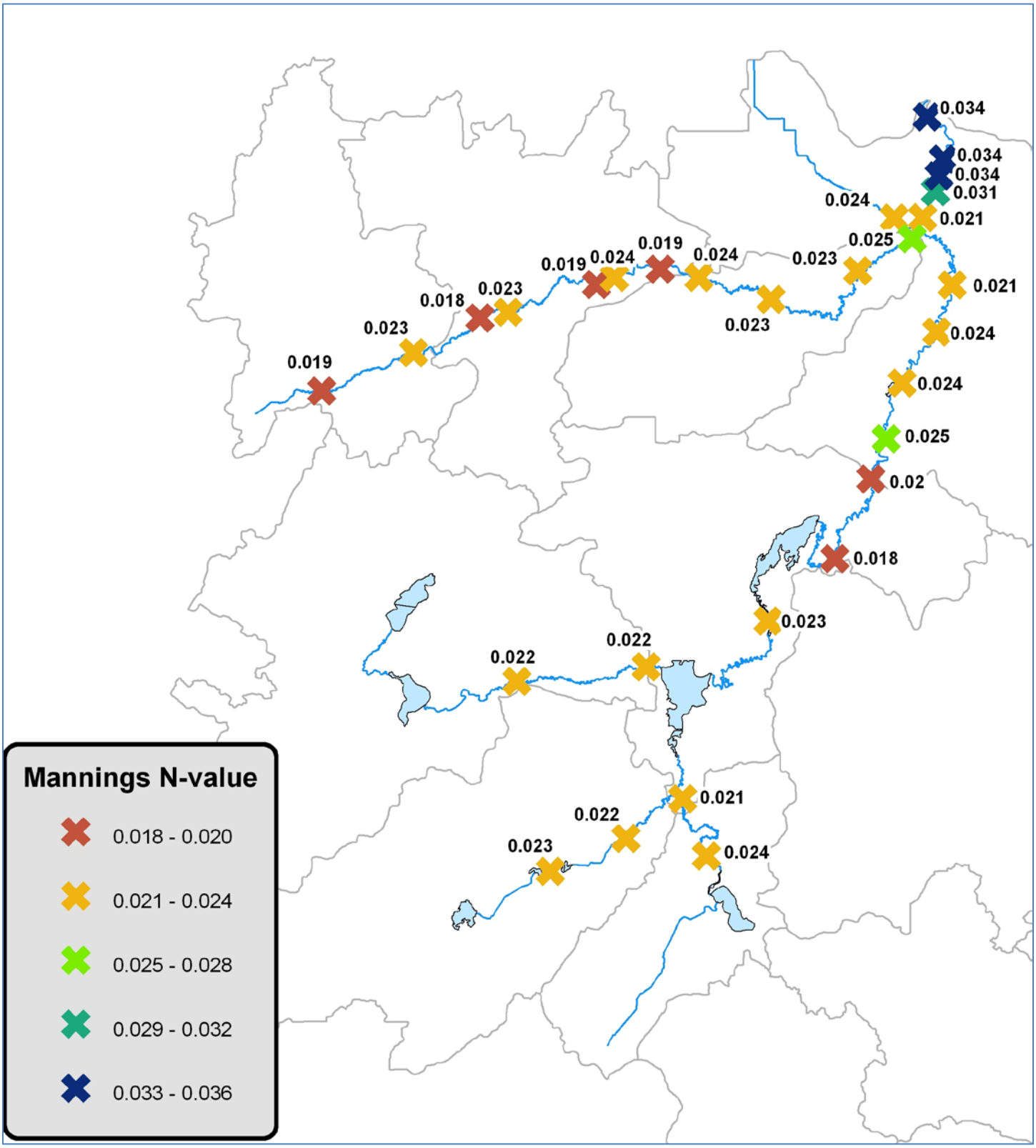

**Plate 11. Map of Rosgen Classifications**

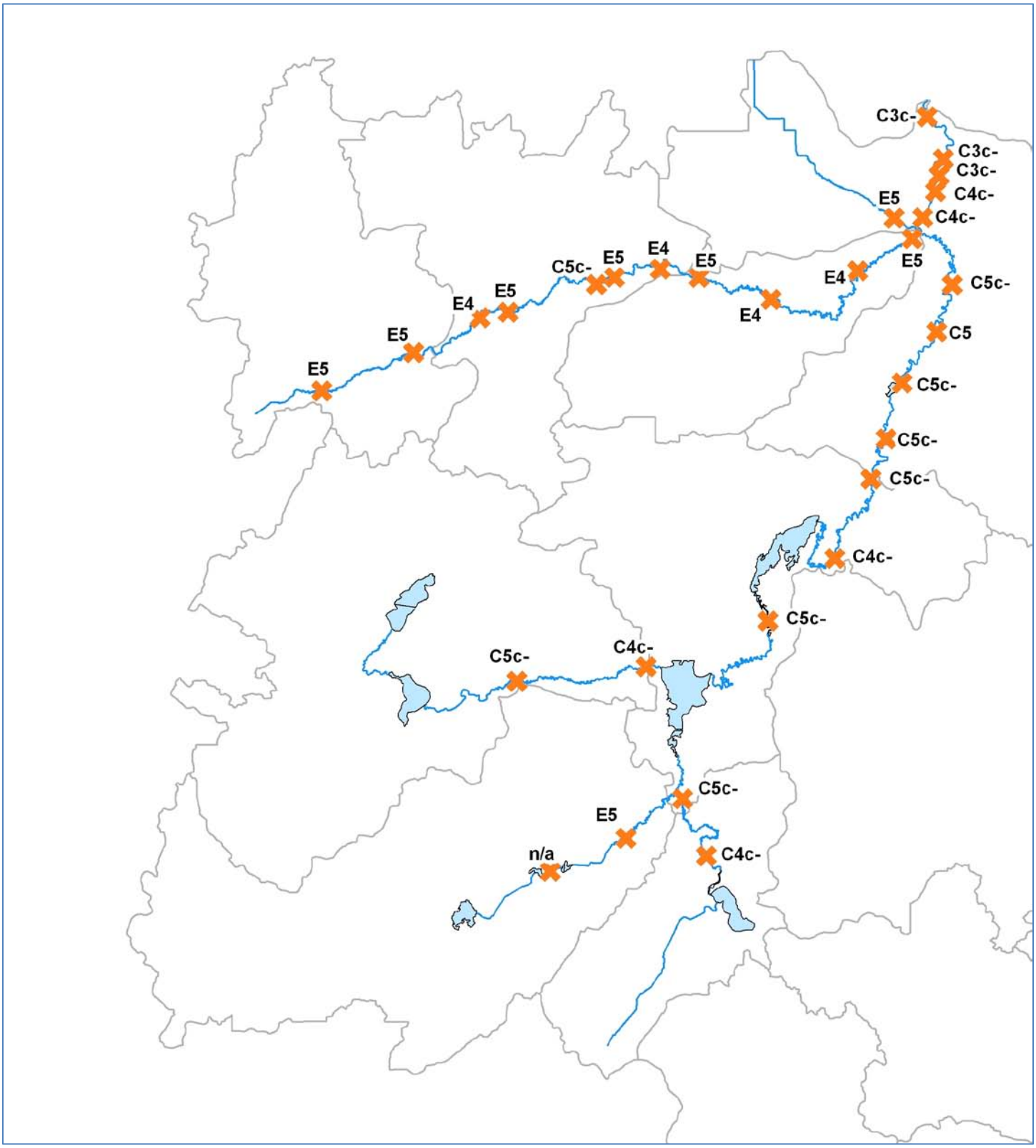

**Plate 12. Shields Diagram Identification of Dune Regime & Threshold of Motion**

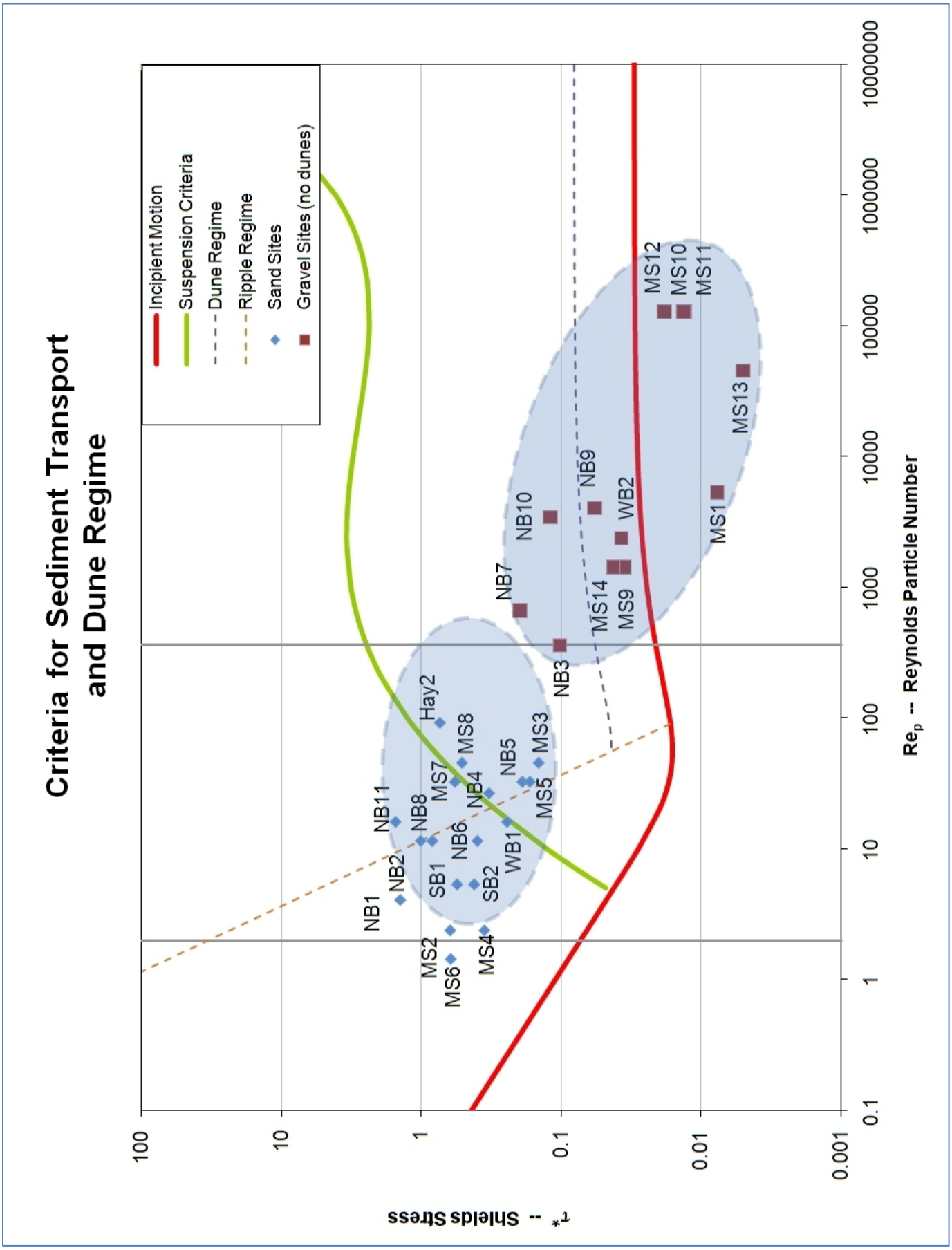
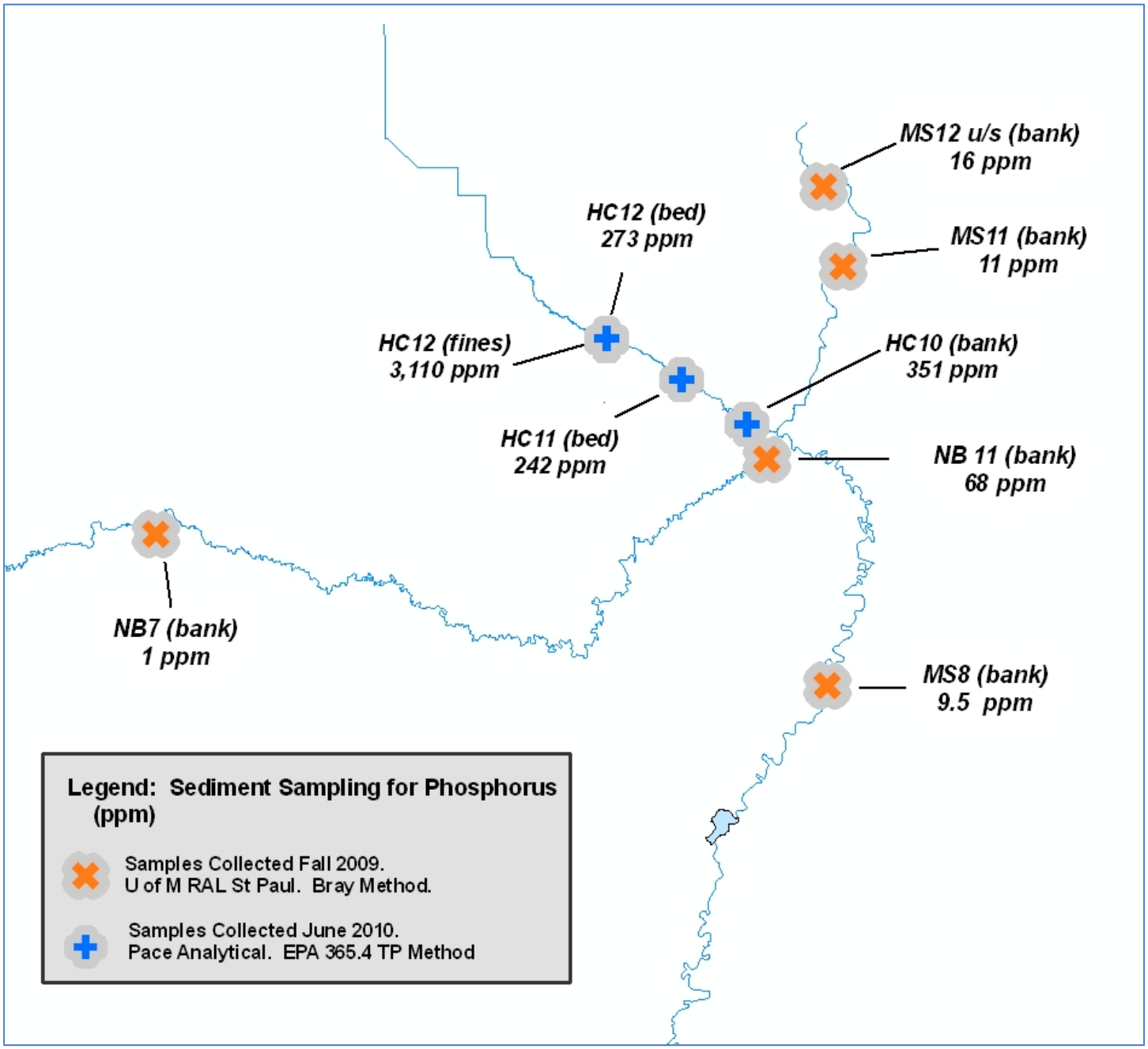
**Plate 13. Phosphorus Concentrations of Sediment Samples**