Lake Superior Streams Sediment Stressor Investigation

Brad Hansen
Leah Hall
Chris Lenhart
John Nieber
University of Minnesota-Twin Cities
and Karen Gran
University of Minnesota-Duluth
July 2016

Final Report to Minnesota Pollution Control Agency

Grant project summary

Project title: Lake Superior Streams Sediment Stressor Investigation

Organization (Grantee): MPCA

Project start date: 8/01/14 Project end date: 6/30/2016 Report submittal date: 7/31/2016

Grantee contact name: John Nieber Title: Professor

Address: 1390 Eckles Ave.

City: St. Paul State: MN Zip: 55108

Phone number: 612-625-6724 Fax: 612-624-3005 Email: Nieber@umn.edu

Basin (Red, Minnesota, St. Croix, etc.) /Watershed & 8 digit HUC:: Lake Superior South County: St. Louis and Lake

Project type (check one):

☒ Clean Water Partnership
☐ Total Maximum Daily Load (TMDL)/Watershed Restoration or Protection Strategy (WRAPS) Development
☐ 319 Implementation
☐ 319 Demonstration, Education, Research
☐ TMDL/WRAPS Implementation

Grant funding

Final grant amount: $199,981.67 Final total project costs: $182,047.24.

Matching funds: Final cash: $0 Final in-kind: $2,672.96 Final Loan: $0

MPCA project manager: Karen Evans

For TMDL/WRAPS development or TMDL/WRAPS implementation projects only

Impaired reach name(s):

AUID or DNR Lake ID(s):

Listed pollutant(s):

303(d) List scheduled start date: Scheduled completion date:

AUID = Assessment Unit ID
DNR = Minnesota Department of Natural Resources

Table of Contents

Executive summary

Problem Statement

A number of North Shore streams and tributaries are listed as impaired for turbidity due to excess sediment. More recently, biological life impairments have also been documented in several North Shore streams with links to erosion and sediment issues. Associated with these sediment issues are potential increases in sediment and pollutant loadings to surface waters. The relative contribution of sediment from different sources in North Shore streams is not well known. Potential sources of erosion include bluffs, stream banks, openlands, ravines and roads. The percentage of potential erosion from each source will vary with the changes in landuse, geology and geomorphic setting between watersheds. Defining and quantifying the critical sources of sediment for each stream, a required step in the Watershed Restoration and Protection Strategy (WRAPS) watershed work, is challenging because of the dense forest vegetation, steep terrain and often limited access to parts of the watershed.

Project Goals

Goal 1: Identify critical pathways and areas on the landscape that contribute a disproportionate amount of sediment stressors to selected streams located in LS South watersheds. The selected study streams and their associated watersheds will be evaluated as representative of the larger pool of stream types and conditions of LS South and North streams.This work in turn will help inform management of all streams and associated watersheds in Lake Superior South and North HUC 8 watersheds.

Goal 2: Identify, develop, and test a management prioritization framework. Prioritize areas of high erosion potential and sediment production for selected watersheds.

Project Highlights and Results

Two important findings from the project include the high percentage of the total suspended load that was attributed to bluff erosion and the increased runoff potential in areas of the watersheds associated with clay till soils which tend to promote gully and ravine formation.

Actual bluff erosion rates were calculated from bluffs scanned using terrestrial laser scanning (TLS) from eight bluffs on Amity Creek and the Lester River over a three-year period. Adjusting for differences in bluff size, the area-weighted average retreat rate was found to be -0.08 meters per year. The average retreat rate, bulk density of 1.43 g/cm^3, 98 percent fines, 10 percent large material and 68 percent vegetated surface area were used to calculate an estimated load from bluffs to Amity Creek of 620 tons/year. These same bluff parameters measured on Amity Creek bluffs combined with bluff surveys to obtain exposed surface area were extrapolated to the Sucker and Knife Rivers to get an estimate of fine sediment mass erosion. The estimated bluff erosion for the Sucker River was 211 tons/year and the Knife River 1818 tons/year. An indirect comparison of the estimated bluff loads to the best available annual load data for years with data was conducted. The calculated load from bluffs compared to total load ranged from 40-335% with an average of 81% for Amity Creek, 13-68% with an average of 39% for the Sucker River and 40-144% with an average of 73% for the Knife River

The second area of increased erosion potential focused on the presence of clay tills in the watersheds. In Lake Superior South the clay till forms a band that runs parallel to Lake Superior approximately 4 miles wide up to an elevation of 1200 feet. The clay till can be easily identified on LiDAR images and is classified as the Cuttre soil series by the NRCS.

A number of factors came together to demonstrate the importance of clay till regions of the watersheds as potential erosion and sediment producing hotspots.

1. Developed lands in the three watersheds are comprised mainly of hay fields or pasture. The percentage of developed land is small as a percent of the total drainage area of the three watersheds at about 2 to 5 percent. However, developed lands are concentrated in a band along the shore similar in location as the band of clay till. The percentage of developed lands on the clay till soils for the Sucker, Knife and Beaver Rivers was 24%, 13% and 25% respectively.

2. The highest erosion potential mapped by the erosion hotspot model and the majority of the eroding bluffs are located in the clay region.

3. The main branches of the three study watersheds have cut down to the Cromwell Formation leaving the easily transported finer textured clay till of the Barnum Formation exposed on the bluffs. Many of the smaller tributaries and ravines are currently down-cutting through the finer clay tills of the Barnum Formation. Thus, the supply of fine textured sediment is high. easily transported sediment to the streams is high.

4. Runoff potential is high because of the low permeability of the clay tills at the surface. Peak flows and suspended sediment contributions to streams will be greatest from watershed areas dominated by clay tills. Ravine erosion contributions were estimated at for the Knife River using the WEPP model (Appendix E)

In summary, erosion hotspots on the three study watersheds are definedas high stream power stream channels cutting through areas of low permeability easily transported clay, on the steepest part of the watershed where most of the developed land use in the watershed exists.

Prioritization Methodology

GIS based prioritization methods that are used successfully in agricultural and urban based landscapes are not as effective on North Shore landscapes. The easily identified land use variations that may drive erosion on agricultural and urban landscapes are not present on North Shore watersheds where 85 percent of the watershed is in forest or wetlands.The outcome of this methodology is tailored to the North Shore streams. The first step is the use of GIS analysis tools to zoom in on regions of the watershed with high erosion potential. The second step is field verification to collect data and locate specific sites within a vulnerable area. The main components of the methodology are listed below.

- LiDAR-derived (Light Detection and Ranging) digital elevation models
- Erosion Hotspot Model (EHM)
- NRCS Web Soil Survey (WSS)
- Openlands Model (MNDNR)
- Field surveys of river channels
- Road surveys
- BMP prioritization scoring matrix

The specific application of these tools to North Shore watersheds started with LiDAR mapping which was used to calculate the parameters for the Erosion Hotspot Model and as the initial screening tool to focusing in on areas of the watersheds that have high erosion potential.On North Shore landscapes the vulnerable clay tills areas are easily identified on LiDAR images. Field work identified these clay till regions as areas of very low infiltration which explained the high number of ravines depicted on the LiDAR images, NRCS Web Soil Survey (WSS) can be used to better define the extent of the clay tills and provide data about the soil physical properties such as hydraulic conductivity, particle size and bulk density that can be useful in designing and selecting best management practices.The Erosion Hotspot Model was successful in identifying potential bluff locations and helped reduce the time required to conduct field surveys by focusing in on stream reaches with the highest erosion potential.

The Openlands Model is specific to Minnesota’s North Shore. It helps zoom into locations on a smaller scale then the GIS based tools by locating small watersheds with a high percent of developed land. The model is useful in identifying and prioritizing which areas of a watershed openland management would be the most effective.

Once high priority areas are identified the best way to focus on specific bluffs or developed lands is a field survey. The field survey will locate specific sites with an area of high erosion potential that will have the greatest potential to reduce sediment loading with the least amount of expenditure. On North Shore streams the field survey would assess bluff size, location and soil properties, streambank stability, culvert function, and connectivity issues related to developed lands and roads.

Road surveys will identify issues related to culverts and the critical erosion areas related to steep road ditches running downslope directly to a main branch or tributary of a stream. Once an erosion hotspot has been identified and a decision made to address the erosion the prioritization matrix can be used by stakeholders to help focus in on the appropriate BMP.

Body of main report

Work Plan Objectives, Tasks and Activities Completed

Objective 1:Identify and select the streams/ watersheds for analysis. Start the calculation and mapping of sediment stressor "hotspots" for the selected streams. Verify bedrock locations using Minnesota Geological Survey maps.

> **Task A**:In consultation with MPCA staff, identify a list of streams/ watersheds to be analyzed using an "erosional hot spot model" developed via UMN led efforts.

The criteria used to select the study watersheds focused on data rich impaired streams that had already been hydrologically conditioned in Lake Superior South. A number of phone conversations and one meeting with MPCA staff resulted in the selection the Big Sucker, Knife/and tributaries and Beaver Rivers. No Lake Superior North streams were selected to reduce the travel time and costs due to road construction on highway 61.

> **Task B:**Calculate the erosional hotspot threshold-based model for selected watersheds including the generation of flow accumulation, flow direction, channel network, basin outline, and bluff delineation files.

The Erosion Hotspot Model was developed by Wick and Gran (2013) to predict erosion hotspots on the Amity, Tallmadge and French Rivers. It is a GIS-based model that uses LiDAR imaging to predict erosion hotspots on stream channels.Manopkawee and Gran (2015) further developed the model to assess the impact the 2012 storm had on stream channels in the Duluth area.
The Erosion Hotspot Model uses a combination of SPI (stream power index), radius of curvature, bankfull width, bend curvature and bedrock locations to create an erosion index that is calculated every 25 meters along stream channel. Using the Natural Break (Jenks) classification, stream power (SP) and bend curvature (BC) were divided into five categories for each stream. Each of the categories was given a score (1-5) for the SP and BC values. The scores were then summed and the total was assigned to each stream point. Each stream point was assigned a value between 2 and 10 and the erosion potential scored based on the four categories listed below.

- 2-4 = very low erosion potential
- 5-6 = low erosion potential
- 7-8 = moderate erosion potential
- 9-10 = high erosion potential

Bedrock location was then noted and any point that touched bedrock was set to have a very low erosion potential. A description of the process used to predict the erosion hotspots is in Appendix A.

Erosion hotspot maps were created for all the study watersheds including the Sucker River, East Beaver River, West Beaver River, Knife River, Captain Jacobson Creek, Stanley Creek, Little Knife River, and Tributary 1-4). The erosion hotspot maps were plotted on LiDAR images of the watersheds. An example of an erosion hotspot map created is shown in Figure 1 and the summary statistics are given in Table 1 and 2 below. All of the maps created for the study watersheds are located in Appendix D. Higher stream power and small bend curvature translates to more potential erosion. The Little Knife River had a higher average stream power than any of the main branches of the rivers even though it had a much smaller drainage area.

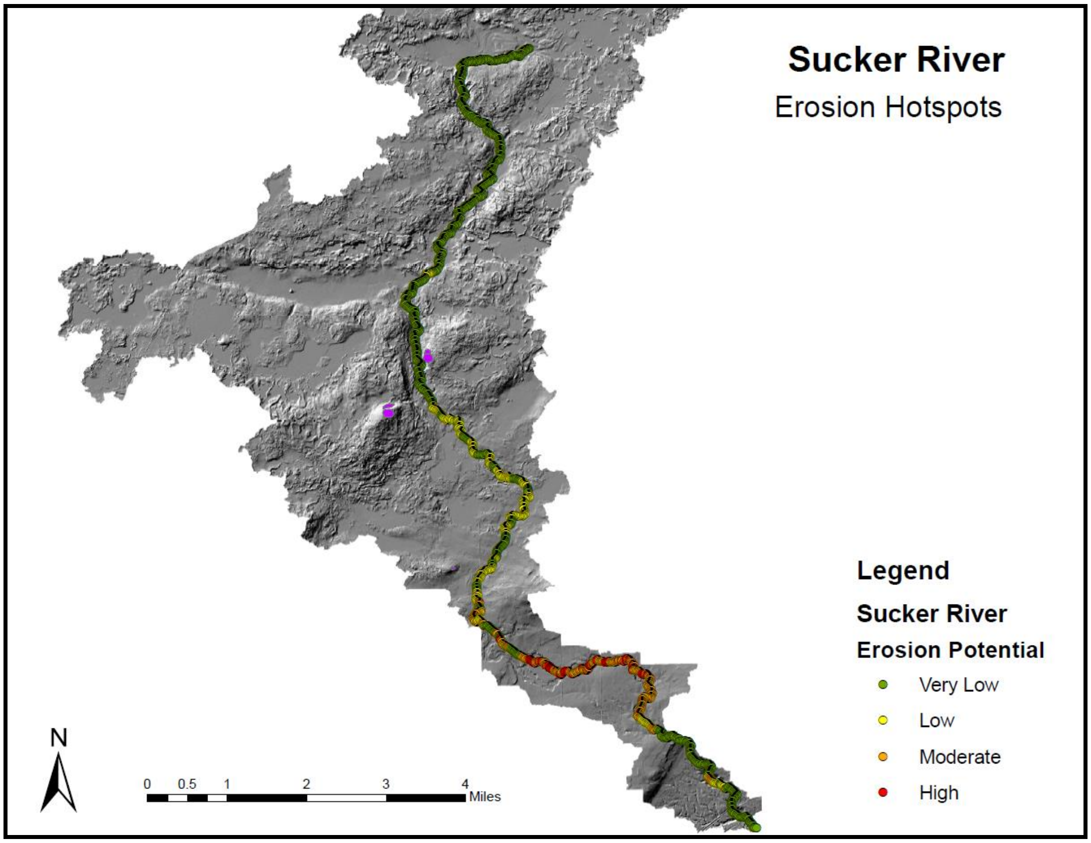


Figure 1. Erosion Hotspot map of Sucker River watershed.

Reach	Average Stream Power (watts/m^2)	Average Bend Curvature
Sucker	**48.72**	**3.59**
West Beaver	**38.34**	**6.98**
East Beaver	**43.90**	**4.32**
Knife: main branch	**34.37**	**8.98**

Table 1.Average stream power and bend curvature for the main branches of the study watersheds.

Reach	Average Stream Power (watts/m^2)	Average Bend Curvature
Captain Jacobson	**11.84**	**18.80**
Stanley	**11.07**	**15.36**
Tributary 1	**7.72**	**14.84**
Tributary 2	**7.20**	**31.3**
Tributary 3	**10.48**	**7.07**
Tributary 4	**8.50**	**12.14**
Little Knife	**57.78**	**11.65**

Table 2. Average stream power and bend curvature for the tributaries of the Knife River.

On the Sucker, West Beaver, East Beaver and Knife Rivers, the 10 locations with the highest erosion potential were identified and maps were created showing these points. These 10 locations were then compared with field identified bluff locations and maps were generated to show the results. An example of the maps is shown of the Sucker River in Figure 2. The 10 highest erosion potential locations were then evaluated for accessibility; including distance to the nearest road. An example of these maps is shown in Figure 3. The rest of these maps are located in Appendix D.

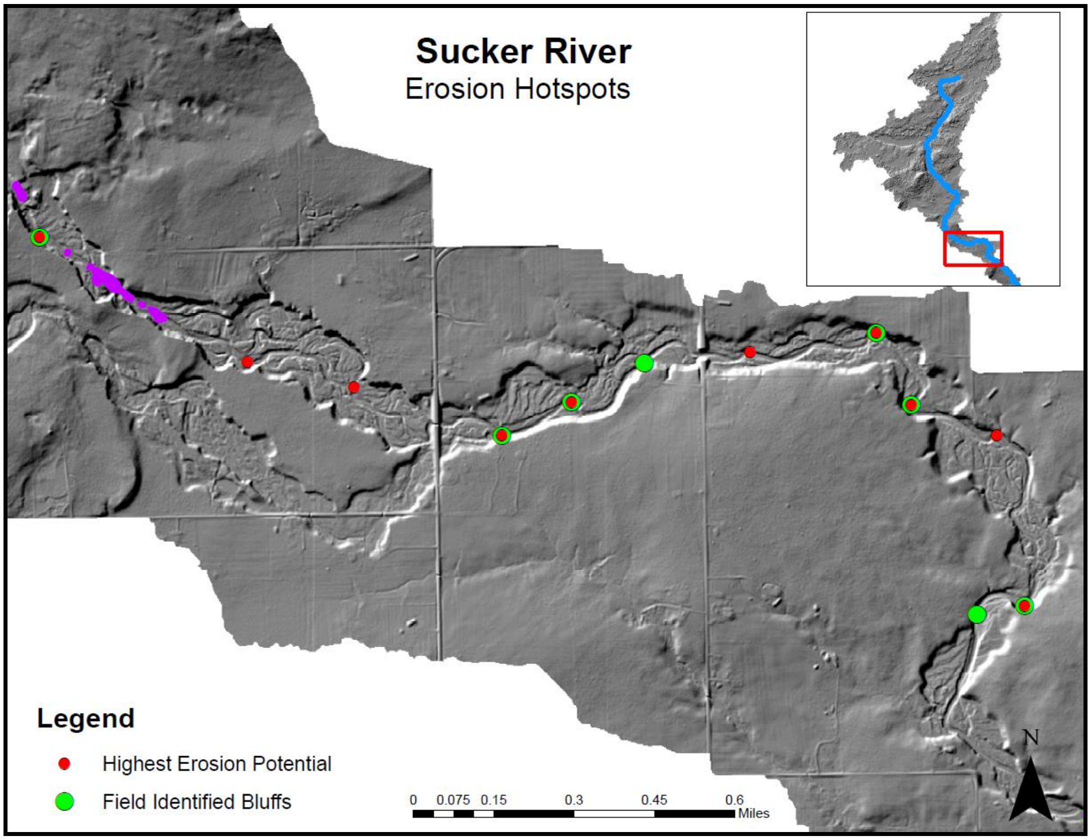


Figure 2. Top ten calculated erosion hotspots compared to known eroding bluff locations in the Sucker River.

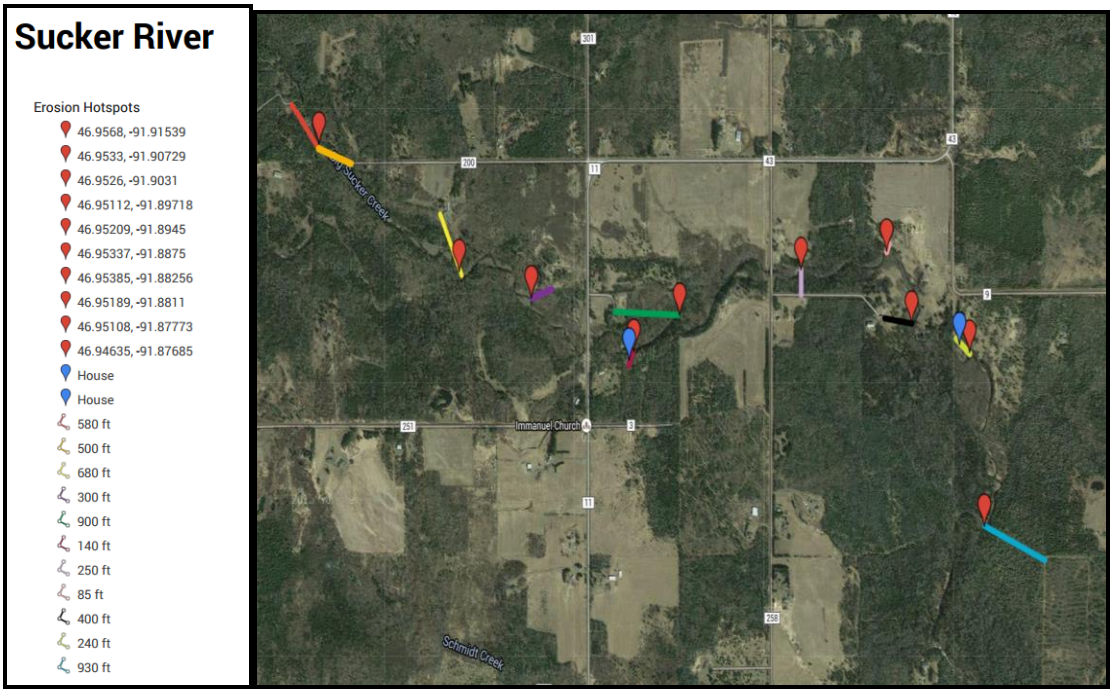


Figure 3. Access map to calculated erosion hotspots in the Sucker River.

Task C: Verify the location of bedrock in selected watersheds using Minnesota Geological Survey maps.

A number of the steeper slopes in Lake Superior stream channels are bedrock. LIDAR cannot differentiate between bedrock and glacial till. To improve the utility of the Erosional Hot Spot Model, bedrock data is incorporated into model inputs. A GIS layer of bedrock outcrops from the Minnesota Geological Survey (MGS) was used as a baseline for bedrock locations. We talked with the individual who had collected the field data for the bedrock maps. The process used to identify bedrock locations was to walk the stream corridors. Our field survey of the Sucker River verified none of the top ten calculated erosion hotspots correspond to bedrock locations. On the Knife River, field surveys completed by Lake County SWCD personnel and our own field surveys concluded none of the top ten highest ranking erosion hotspots correlated with bedrock. Only the MGS bedrock maps were used for the calculated erosion potential on the Beaver River. Because of the milder slopes, greater percentage of wetlands, smaller drainage areas, lack of bedrock and low erosion potential scores, bedrock locations in the upper reaches of the watersheds were not verified. An example of an erosion hotspot map of the East Branch Beaver River showing locations of bedrock is shown in Figure 4.

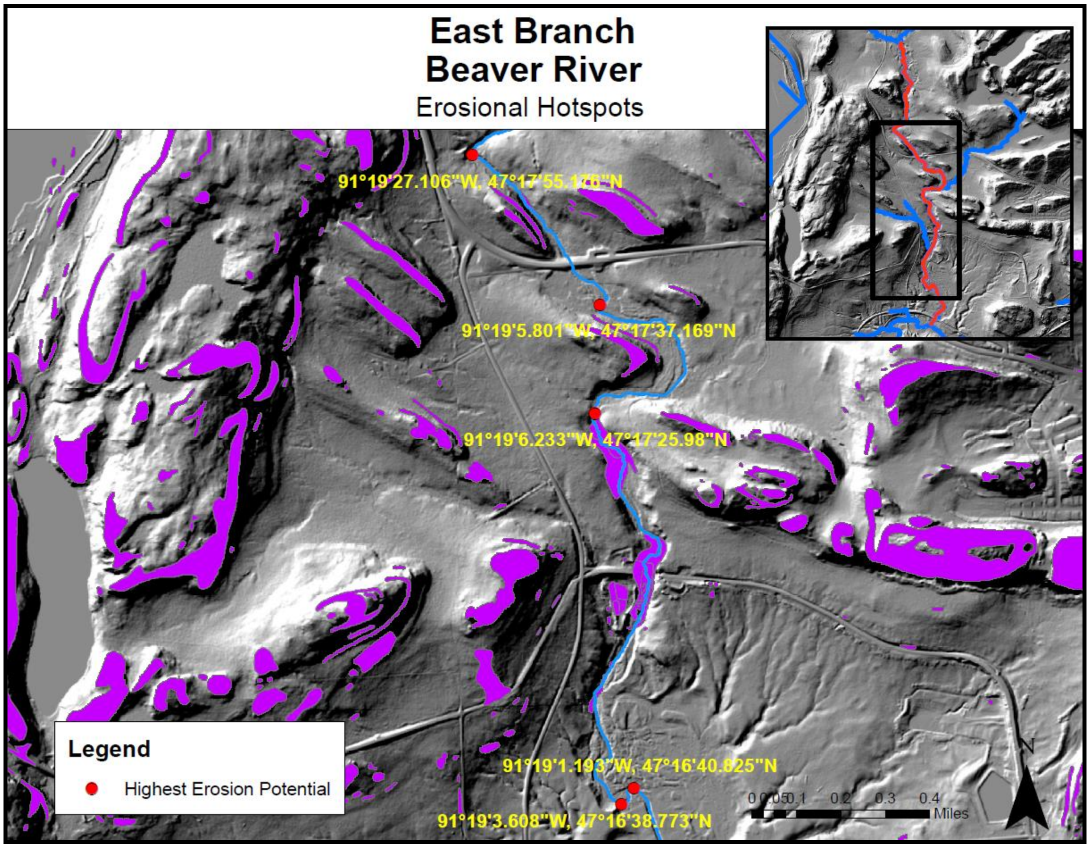


Figure 4. East Branch Beaver River erosion hotspot locations and MGS bedrock layer locations highlighted in purple.

Objective 2: Increase the accuracy of the model by improving the use and application of the angle of impingement calculation.

Task A: Manual delineations of stream meanders calculated using LiDAR and aerial photos.

Task B: Compare manual delineations to automated calculations of impingement.

Angle of impingement is defined as the angle at which the moving water intersects the bluff toe or streambank. Previous attempts to automate this component were limited by the resolution of a ruler and the small tight meanders found on many streams. The initial objective was to improve the measurement and application of the angle of impingement into the model by comparing automated calculations of the angle of impingement with manual delineations of the angle. The work done for Objective 2 Tasks A and B was modified to allow the use of a new technique developed by Manopkawee (2015), a UMD graduate student working with Karen Gran on Duluth streams. This method used a manual method of determining the radius of curvature which proved to work better than the angle of impingement method originally outlined in Task B. Manopkawee's work was conducted on Duluth streams. LiDAR was used to determine meander locations that incurred significant erosion from the 2012 storm. The manual method was field checked at a number of locations. This method replaced the originally proposed automated calculations of impingement angle and was used to delineate meanders and measure the radius of curvature for the erosion hotspot model outlined in Objective 1. An example of the manual delineation of radius of curvature is shown in Figure 5.

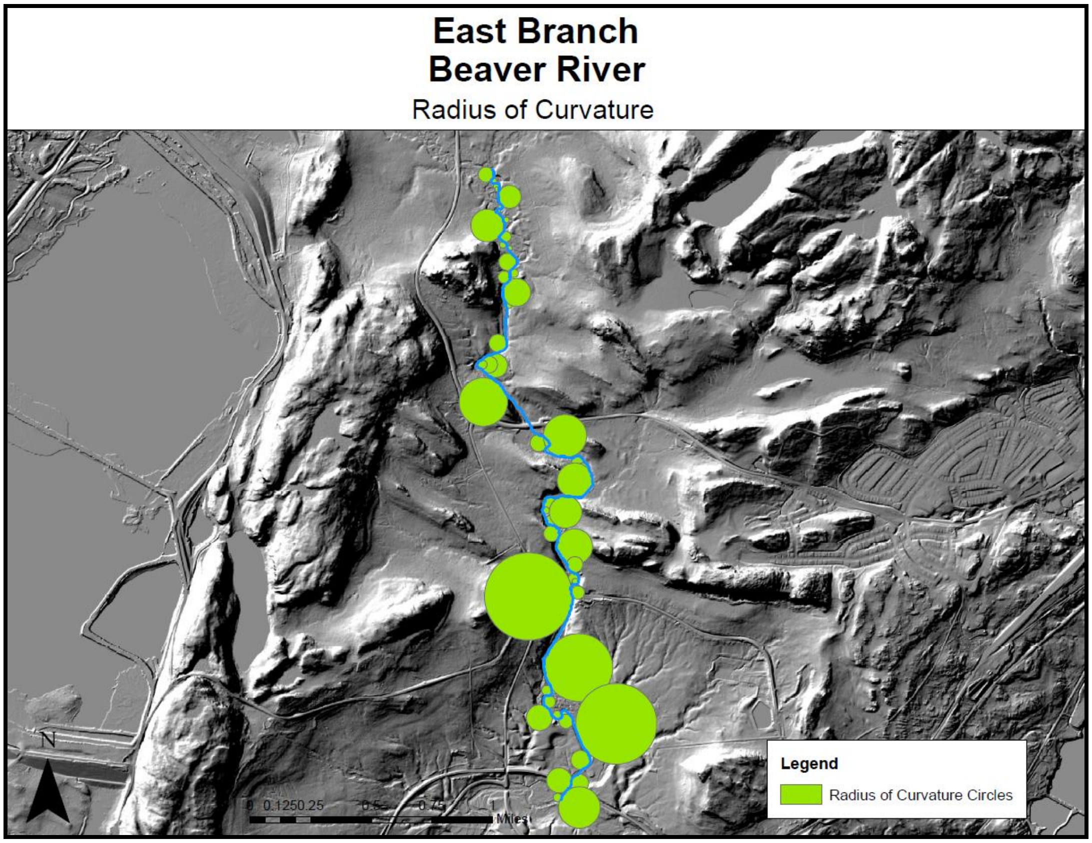


Figure 5. Manual delineation of the radius of curvature plotted every 25 meters along the stream channel on East Branch Beaver River.

Objective 3: Define the location and extent of ravines and bluffs in selected study watersheds

Task A: Delineate ravines and bluffs using methods developed at the University of Minnesota

Ravines and bluffs are landscape features that have the potential to produce significant amounts of sediment to the stream channel. To help predict a sediment load allocation these features were delineated in the three watersheds.

Ravines

Ravines were defined as gorges adjacent to the study streams that were visible in LiDAR 1200 feet or less in length. Maps were made showing the drainage area, surface area, and slope of each ravine in the Sucker River, Knife River, and Beaver River watersheds. The drainage area, surface area, and slope of the ravines were determined using LiDAR data and ArcGIS tools including spatial analyst and a hill-shade DEM.The surface area was defined as the steeper potentially more exposed area of the ravine readily apparent in the LiDAR image as opposed to the drainage area which included the contributing area above. On the Sucker River and Beaver River, all the ravines were marked and these measurements were made on each ravine. Because there were so many ravines on the Knife River they separated into three groups based on length. Each ravine in the three groups was assigned a number. Using a random number generator, ten ravines were selected from each category. The drainage area, surface area, and slope for the selected ravines were calculated using the same procedures listed above for the Sucker and Beaver River ravines. The values in each category were averaged. The average values were multiplied by the total number of ravines in each category to estimate the total surface and drainage area of ravines in each category. The totals for each category were then summed to get a total for each watershed. An example of one of the ravine maps is shown in Figure 6 and the number of ravines and total drainage area of all the ravines in each watershed is shown in Table 3. The rest of the ravine maps are located in Appendix D.

Ravine erosion rates were modeled for the Knife River watershed because it had by far the largest area of ravines in the study area.The WEPP model was used to predict ravine erosion rates given different land cover and slope characteristics (see Appendix E).

Bluffs

The original intent of this task was to delineate the bluffs on the three watersheds. Fortunate timing allowed us to redirect some of our resources and time to continue work Karen Gran had started in 2011, quantifying actual bluff erosion rates using Terrestrial Laser Scanning (TLS). The TLS was used to produce high resolution digital elevation maps (DEMs) of bluff surfaces. These DEMs were used to quantify geomorphic change and erosion rates over time. Karen Gran's work had focused on measuring multi-year bluff erosion rates on a series of bluffs on Amity Creek and Lester River. Previous bluff scan data from 2011 through 2013 on eight bluffs along Amity Creek and Lester River were combined with data scans collected from this project in fall 2014, and spring and fall 2015. An example of a bluff scan is shown in Figure 7.

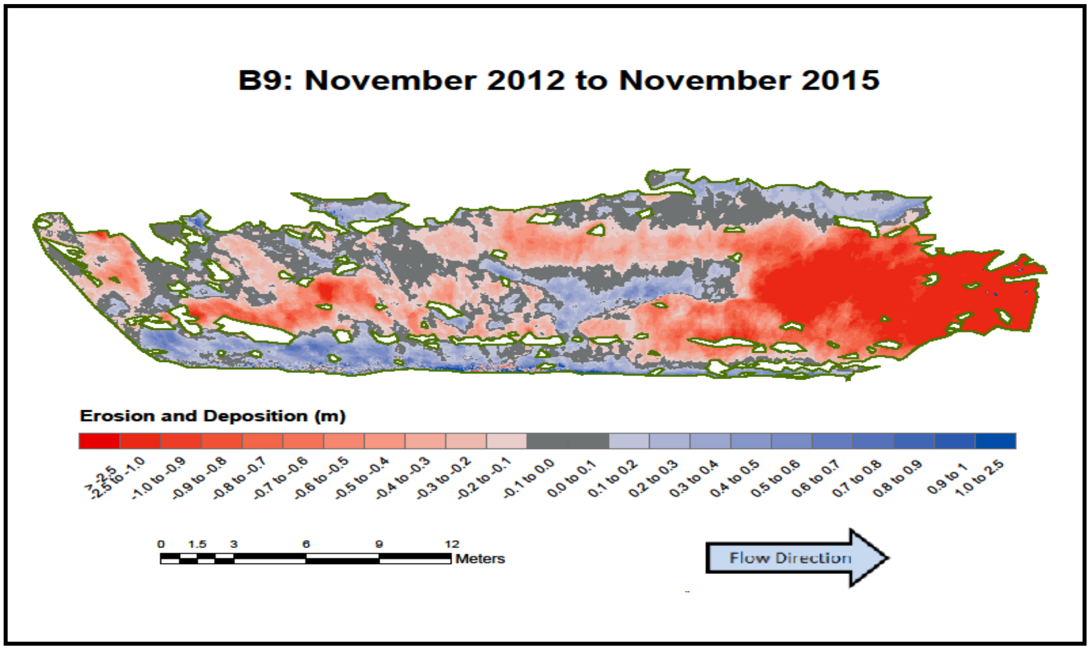
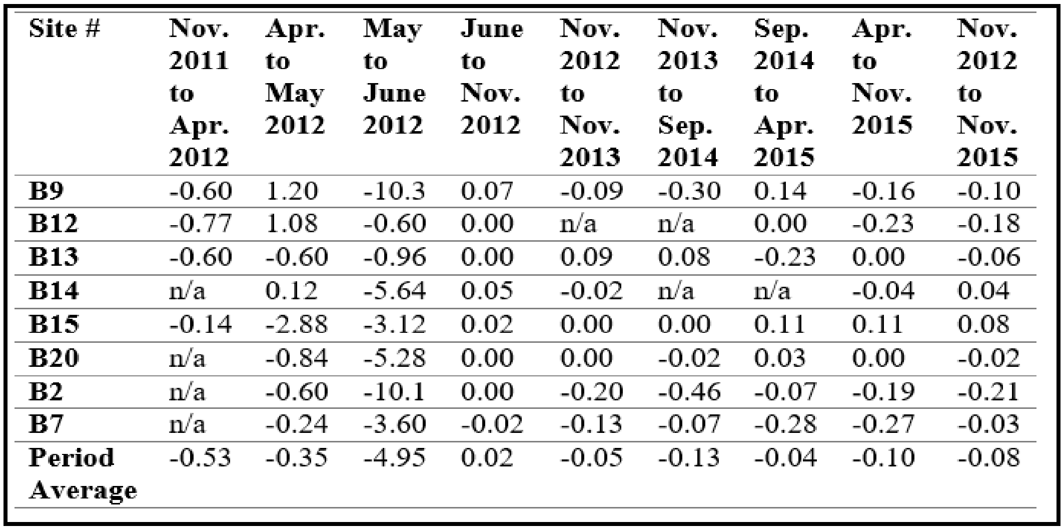


Figure 7. Bluff scan of an Amity Creek bluff. Red depicts areas of retreat and blue shows areas of deposition

The study watersheds are composed of four different till formations described by (Hobbs 2004). The tills are stratified in layers, dependent on their location in the watersheds. In general, the Knife River member of the Barnum formation is on top with the Moose Lake and Lakewood members below all on top of the Cromwell formation. Some combination of these tills was found in all the bluff locations scanned in Amity Creek and the Lester River (Neitzel 2014).

Geomorphic change was measured on eight of the study sites over a four-year period and change was detected in seven to nine periods for these bluffs. The time periods between scans ranged from one month to one year. The study as planned would have had four years of data. However, the 500- year flood event in June 2012 would have thrown off the average. Additionally, damage caused by the flood on the bluffs resulted in the loss of a number or control points (i.e. large rocks) needed to align the scans for use in detecting geomorphic change. Therefore, geomorphic change was differentiated on eight bluffs with consistent scan data over a three-year period, November 2012 to November 2015. The period average retreat rate over three years was 0.18 meters.Dividing the period average by the 3-year time period resulted in an average retreat rate of -0.06 meters per year. Adjusting for differences in bluff size, the area-weighted average retreat rate was calculated to be -0.08 meters per year. The bluff retreat rates for the 8 bluffs over the nine different time periods are shown in Table 4. Note that just the data from November 12th to November 15th was used to calculate the average retreat rate for each bluff located in the column labeled November 2012th to November 2015th. The -0.08 meters per year retreat rate is an average of the eight bluffs.



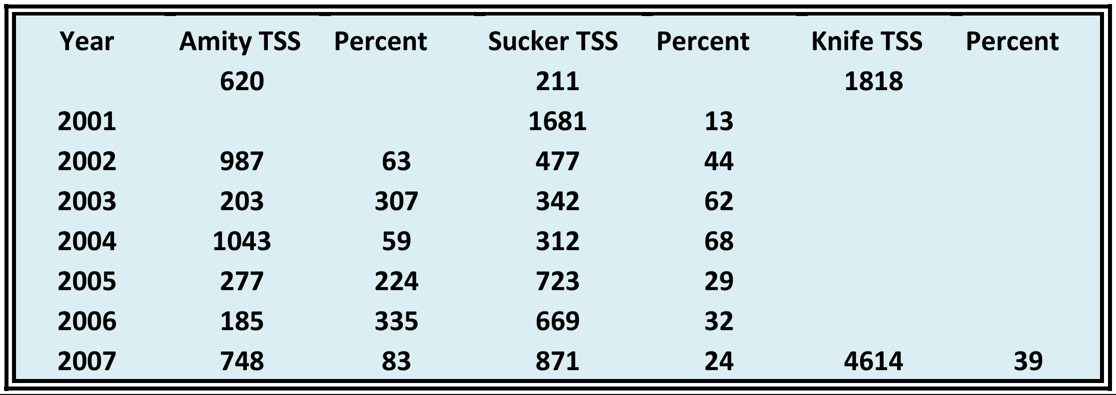
Site #	Nov. 2011 to Apr. 2012	Apr. to May 2012	May to June 2012	June to Nov. 2012	Nov. 2012 to Nov. 2013	Nov. 2013 to Sep. 2014	Sep. 2014 to Apr. 2015	Apr. to Nov. 2015	Nov. 2012 to Nov. 2015
B9	-0.60	1.20	-10.3	0.07	-0.09	-0.30	0.14	-0.16	-0.10
B12	-0.77	1.08	-0.60	0.00	n/a	n/a	0.00	-0.23	-0.18
B13	-0.60	-0.60	-0.96	0.00	0.09	0.08	-0.23	0.00	-0.06
B14	n/a	0.12	-5.64	0.05	-0.02	n/a	n/a	-0.04	0.04
B15	-0.14	-2.88	-3.12	0.02	0.00	0.00	0.11	0.11	0.08
B20	n/a	-0.84	-5.28	0.00	0.00	-0.02	0.03	0.00	-0.02
B2	n/a	-0.60	-10.1	0.00	-0.20	-0.46	-0.07	-0.19	-0.21
B7	n/a	-0.24	-3.60	-0.02	-0.13	-0.07	-0.28	-0.27	-0.03
Period Average	-0.53	-0.35	-4.95	0.02	-0.05	-0.13	-0.04	-0.10	-0.08

Table 4. Area weighted average retreat rate in meters per year shown for 9 time periods from 8 bluffs (see Appendix D for scanned bluff images)

The average erosion rate determined from the TLS scans were derived only from unvegetated bluffs. If this rate was applied to vegetated bluffs, it would overestimate bluff contribution due to sediment loading. To compensate for vegetation on the bluffs a field survey found 68 percent of the bluff surfaces were unvegetated. The total area of exposed un-vegetated bluff surface was measured to be 5,596 m^2 in Amity Creek. The average volume of sediment was calculated from the exposed surface area times the retreat rate and was found to be447.7 meter^3/year Multiplying the sediment volume by the average measured bulk density of 1.43 grams/cm^3 provided a total mass of sediment. The average percent fines of the bluff material were measured to be 98 percent. The amount of large gravel and rock eroding from bluffs that is considered too large to be easily transport by normal flows was estimated to be 10 percent.Multiplying the total mass of sediment by the percent fines and subtracting off the 10 percent for large material equaled a total easily transported load to Amity Creek of 620 tons/year.

The same complex of tills found in in the bluffs on Amity Creek and the Lester River are also found in the Knife and Sucker River bluffs (Hobbs 2002,2003, 2004). The Amity Creek values (average retreat rate of 0.08 meters/year, bulk density of 1.43 grams/cm^3, 98 percent fines, 10 percent large material and 68 percent vegetated surface area) were extrapolated to the Sucker and Knife Rivers to get an estimate of fine sediment mass erosion. The exposed bluff surface areas were calculated from a bluff survey of the Sucker River completed in 2015 for this project and previous bluff and streambank surveys of the Knife and Little Knife Rivers completed by Lake County SWCD. The average mass of fine sediment lost from the bluffs of the Sucker and Knife Rivers was 211 and 1818 tons/year, respectively.

These values were compared to measured loads for each river to see what percent of the total load was originating from bluffs. A direct comparison of the estimated bluff erosion contribution to TSS loads in the streams was not possible due to the load monitoring results for 2012 – 2015 are not yet available from the MPCA. An indirect comparison of the estimated bluff loads to the best available monitored loads for years with data is shown in Table 5. Load estimates for Amity Creek and the Sucker River from 2001 to 2010 were obtained from the MPCA North Shore Monitoring and the University of Minnesota Duluth Natural Resources Institute (NRRI) program for the open water season. Estimated annual sediment loads for the Knife Rivers were obtained from the USGS Scientific Investigation Report 2013. Because of the differences in precipitation and flow between the years the bluff scan data was measured and the years of available load estimates a range of values are expected. No attempt was made to compare precipitation and runoff conditions between years and loads measured for Amity Creek and Sucker River are likely underestimated due to seasonal versus monitoring at the sites. The calculated average load from bluffs in each watershed ranged from 40 to 335% with an average of 81% for Amity Creek, 13 to 68% with an average of 39% for Sucker River, and 40 to 144 with an average of 73% for Knife River.



Year	Amity TSS	Percent	Sucker TSS	Percent	Knife TSS	Percent
	620		211		1818	
2001			1681	13		
2002	987	63	477	44		
2003	203	307	342	62		
2004	1043	59	312	68		
2005	277	224	723	29		
2006	185	335	669	32		
2007	748	83	871	24	4614	39

2008					2256	81
2009	1151	54			1259	1.44
2010	1550	40			2302	79
2011					2013	90
2012						
2013						
Maximum	1550		1681		4614	
Minimum	185		312		1259	
Average	768	81	725	39	2489	73

Table 5. Estimated bluff erosion rate and yearly TSS loads (tons/year) and bluff load as a percent of the monitored load for the three study watersheds.

Additional data collected from the bluff scans looked at the retreat rate from two bluffs stabilization projects (2014 BHHR on Knife River and 2009 BSWCD on Amity Creek). The stabilization process on BHHR and BSWCD involved installing a stabilized bankfull bench that moves the river away from the bluff eliminating scour at the base of the bluff. The bluff face was not stabilized and can still erode. However, without fluvial scour, it is expected to erode less and the sediment that does erode will be captured on the bankfull bench. Table 6 shows the average retreat rate measured over three time periods was positive 5 out of 6 times. Positive retreat rate values mean that deposition is occurring. From September 2014 to November 2015, roughly 60 tons at the Knife River bluff (BHHR) and roughly 37 tons at the Amity Creek bluff (BSWCD) of silt and clay comprised sediment has been deposited on the bench currently inaccessible to river scour. The bluff scan work and analysis resulted in a Master thesis for Leah Hall the graduate student working on this project. The work is summarized in her thesis (Hall 2016).

Site #	Sep. 2014 to Apr. 2015	Apr. to Nov. 2015	Sep. 14 to Nov. 15
BHHR	0.25	0.06	0.12
BSWCD	-0.07	0.07	0.02

Table 6. Retreat rates (meters per time period) from two bluff stabilization projects.

Objective 4: Collection of field data to support, improve and provide input to model.

Task A: Ground verify bedrock locations not identified on MGS maps from Objective 1 Task 3.

Calculated erosion hotspots were compared to known eroding bluff locations on the Sucker and Knife Rivers. Very few bluffs exist on the Beaver River. On the Sucker River, six of the eight known bluff locations corresponded to calculated erosion hotspots. A field survey of the Sucker River verified the calculated erosion hotspots that did not correspond to bluff locations were not at bedrock locations. On the Knife River, none of the top ten highest-ranking erosion hotspots correlated with bedrock. Six of top ten hotspots corresponded to known bluff locations. The other four were eroding streambanks.

Task B: Measure bankfull width for angle of impingement calculation and at other locations deemed important for the project.

As explained in Objective 2 Task B the angle of impingement was not used for this analysis.

Task C: Field verify any questions about delineation of bluffs and ravines from Objective 3.

All bluff locations mapped on the erosion hotspot map of the Sucker River were field verified. A survey of the Knife River bluffs and eroding streambanks by Lake County SWCD and aerial photos taken in 2010 provided field verification of bluff locations. A number of ravines on the Beaver and Knife Rivers were field verified to determine the extent of exposed banks and vegetative cover.

Task D: Install passive siphon samplers to collect suspended sediment samples in the stream channel above and below selected high priority hotspots, bluffs, or ravines.

Seven passive siphon samplers were installed in the Knife and Sucker River watersheds. The samplers consist of a one-meter-long section of 0.25-meter diameter PVC pipe with a small six millimeter opening facing upstream and a second opening of the same size at the downstream end. Suspended sediment is collected through the small opening and retained in the sampler's large mid-section were the velocity decreases enough to allow sediment to settle out. A description of the samplers can be reviewed at http://pubs.usgs.gov/sir/2007/5282/pdf/sir20075282.pdf .

For the bluff erosion study, samplers were placed above and below a coarse eroding bluff on the Sucker River. Two samplers were also set up above and below a series of three closely spaced eroding clay bluffs on the Knife River. A second use of the samplers, not part of the original work plan, was a design of a paired watershed study. The objective was to determine if an increase in sediment loading could be attributed to developed lands as compared to a forested watershed. The paired watershed study controls were two forested watersheds paired with one watershed with thirty percent developed land. One sampler was installed in each of these watersheds. All seven samplers were installed in mid-April and removed August 4th.
The amount of sediment captured in each sampler is shown in Table 7. Stage was recorded multiple times a day using either a pressure transducer or a picture of a staff gauge taken by a trail cam. Flow was to be calculated from measured cross-sections and velocities to convert the weight of soil into a total load passing the sampler. Challenges in changing cross-sections, beaver interference, small differences in sediment captured and the loss of one sampler prevented any accurate total loads to be calculated.

To determine if there were differences in flow rates between the paired watersheds a comparison of flow rates was conducted. Flow rates were measured at low, medium and high flows at the developed watershed and one of the forested watersheds within an hour of each other. The results are shown in (Table 8). The developed land flows were higher at each flow range and averaged 18% higher than the forested watershed. The developed land watershed was 11% larger than the forested watershed. The watershed-adjusted weight of soil captured from the forested watershed was 7.96 grams compared to the 10.21 grams in the sampler installed in the watershed with 30% developed land. It was difficult to draw any conclusions from this one replication.

Location	**Sediment (grams)**
Sucker bluff US	**24.73**
Sucker bluff DS	**25.04**
Little Knife30 % developed	**10.21**
Little Knife forested	**7.17**
Knife Trib. forested	**NA**
Knife River bluff US	**164.73**
Knife River bluff DS	

Table 7. Weight of sediment captured in passive siphon samplers for all experiments.

	MeasuredFlow Rates CFS		
	30% Developed	**Forested**	**Forested/ 30% Developed land**
Low	**0.33**	**0.25**	**0.75**
Medium	**1.63**	**1.31**	**0.81**
High	**4.23**	**3.75**	**0.88**
		Ave	**0.82**

Table 8. Comparison of low, medium and high flows between forested watershed and 30% developed watershed

Task E: Measure critical shear stress on the toe slopes of bluffs or streambanks using the Cohesive Strength Meter. Measure the shear strength of dominant tills at bluff locations using a Borehole Shear Tester.

The Cohesive Strength Meter provides a measure of how easily a soil erodes due to the force applied by flowing water. The Borehole Shear Tester measures the shear strength of a soil, which provides some insight into how susceptible soils are to slumping or mass wasting. The study watersheds are composed of four different till formations. The tills are stratified in layers, dependent on their location in the watersheds. In general, the Knife River member of the Barnum formation is on top with the Moose Lake and Lakewood members below and the Cromwell formation on the bottom. These four tills were identified and classified by (Hobbs 2004). The clay bluffs found on North Shore streams are made up of some combination of these four tills. Critical shear and soil strength measurements were taken on all four of the different tills. The data from the critical shear and soil strength tests is shown in Table 9. When the particle size distribution of the tills exceeded 50 percent clay there was noticeable drop in soil strength. Critical shear values tended to be higher with the increase in clay content. This suggests that higher clay content tills will have lower soil strength but will be more resistant to erosion from fluvial scour.Some field evidence was observed where high clay content bluffs had a greater percent of the surface slumping as compared to lower clay content bluffs. Bluffs with lower clay count appeared to have more rill formation and less slumping.

Glacial Formation	Depth (meters)	Critical Shear N/M^2	Soil Strength kPa	Particle Size Percent
Barnum (Knife)	3 to 4	3.46	27	Sand 10 Silt20 Clay70
Barnum (Moose)	3	3.7	37	Sand 30 Silt20 Clay50
Barnum (Lakewood)	2	2.45	37	Sand 60 Silt20 Clay20
Cromwell	3	3	34	Sand 40 Silt50 Clay 10

Table 9. Critical shear and soil strength measurements for the common till layers in the study watersheds.

Developed lands in the three watersheds are comprised mainly of hay fields or pasture. Increases in peak flows due to excess runoff from developed lands can also contribute to excess sediment reaching the river. To help determine if developed lands are contributing to peak flows, additional field work not originally part of the work planned involved running infiltration tests on both open fields and forested areas. The hypothesis was that hayfields or pasture due to compaction from land use or removal of the organic layer would have a slower infiltration rate, potentially leading to increased runoff as compared to forested areas. Three sites all on the Cuttre clay till soil complex were chosen where open hayfields were immediately adjacent to wooded areas. At each site, ten replications were done in the field and ten in the forest. Ten replications were also done in the forest right on the clay till after the upper soil horizon was removed. The Phillip – Dunn infiltrometer was used to measure infiltration rates. The results of the tests are shown in Table 10. The infiltration rate in the field was approximately 10 times slower than the measured rate in the forest. However, the limiting factor that affects the infiltration rates on both landuses was the very low rates measured on the clay till horizon twenty to thirty centimeters below the surface

Infiltration Sites	Forested	Field	Clay till
1	57.7	5.78	0.02
2	48.7	6.7	0.009
3	31	2.65	0.04

Table 10. Forest, field and clay till infiltration rates in cm/minute from Phillip-Dunn infiltrometer test.

Objective 5:Develop and test a methodology to select and prioritize locations for restoration of high erosion/sediment production areas.

The key tasks of this objective were a literature review of other prioritization methods to assess how transferable other frameworks and decision scoring systems would be to North Shore landscapes and development of a prioritization scheme unique to North Shore streams. The literature review is located in Appendix C. The activities of Objectives 1-4: calculating erosion hotspots, delineating ravines, bluffs scans, interpreting LiDAR images, field work and watershed observations were used to identify high erosion sediment producing areas in the three study watersheds. The outcome of these objectives formed the basis for a methodology that is tailored to the North Shore streams. The first step is the use of GIS analysis tools to zoom in on regions of the watershed with high erosion potential. The second step is field verification to collect data and locate specific sites within a vulnerable area. The main components of the methodology are listed below. A discussion of how each of these tools was used specific to North Shore watersheds is in the results section.

- Erosion Hotspot Model (EHM)
- LiDAR-derived (Light Detection and Ranging) digital elevation models
- NRCS Web Soil Survey (WSS)
- Ground based Terrestrial Laser Scanning (TLS) producing high resolution DEM’s for streambanks and bluffs
- Openlands Model

- Field surveys of river channels
- Road surveys

A prioritization scoring matrix was also developed that is designed to prioritize the selection of available BMP's intended to reduce sediment or peak flows to the streams. The basic spreadsheet design was developed by (Product Arts 2010) with permission granted to use, modify and distribute the spreadsheet. It was based on a business model used to determine the value of a product versus the complexity to implement the product to market. The spreadsheet was modified to prioritize the selection of BMP's based on their environmental value versus the implementation complexity. The matrix consists of four spreadsheets including the Instructions, Scoring Matrix, Summary Scoring sheet and Priority Matrix chart. The instructions help guide users through the process. The Scoring Matrix shown in Figure 8 defines the BMP categories and criteria for scoring each candidate feature under consideration. It is divided into two major categories of Environmental Value and Implementation Complexity. Environmental Value includes the immediate reduction of sediment or peak flows to the system and the possible positive effects on the stream habitat and water quality improvement. Implementation Complexity includes the difficulties in developing the BMP, the challenges in funding, deploying, and maintaining the BMP, and building support of the watershed stakeholders. The columns indicate the primary criteria for scoring each BMP from weak to strong on a 1 to 10 scale. For example, a score of 1 for a BMP under the environmental categories would indicate little to no value while a score of 10 would be significant value. It is the opposite for implementation complexity with a score of 1 meaning low complexity and a score of 10 meaning significant complexity. Any score between 1 and 10 can be given. The Weighting column allows any specific criteria to be weighted higher or lower relative to the others. The weighting is only used in a final calculation.

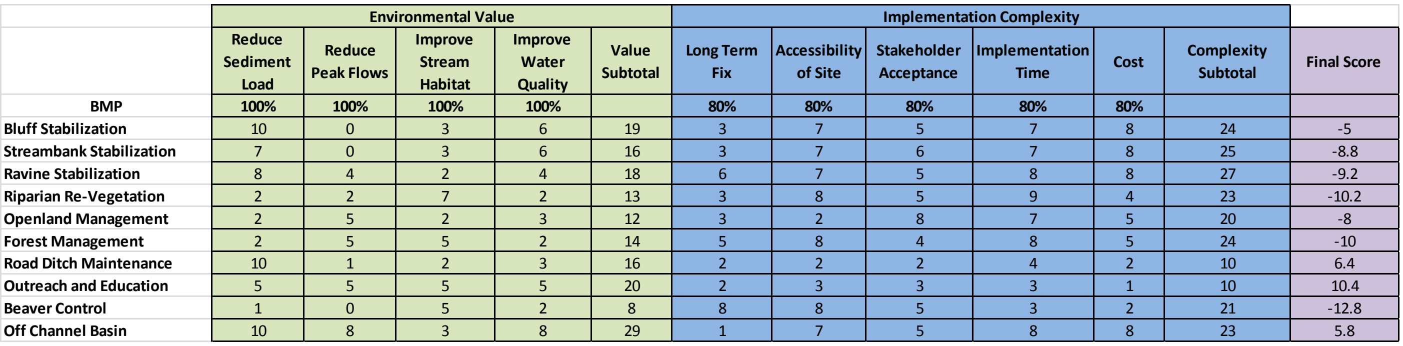
	BMP Prioritization	Weak (1)	Moderate (5)	Strong (10)	Weighting (%)	Score (0 – 10)
Environmental Value	**Reduce Sediment** Direct reduction of sediment to the stearm. For example a bluff stabilization or indirect through reduction of peak flows	Little or no reduction of sediment to stream channel	Does reduce sediment to the stream but on a limited scale: for example road ditch stabilization reduces sediment but on a limited scale because it is such a small % of the watershed	Direct reduction of a significant amount of sediment to the channel for example bluff and streambank stabilization	100%	10
	Improve habitat Habitat improved through the reduction of fines resulting in less embeddeness. Turbidity reduction allow fish to feed more efficiently	Little or no improvement in habitat	Habitat improved but on a limited scale or length of stream reach impacted	Habitat improvement significant enough to show up in improved habitat scores	100%	10
	Improve Water Quality Water quality improved through reduction of turbidity and lower phosphorous levels	Little or no improvement in water quality	Water quality improved but on a limited scale or length of stream reach impacted	Water quality improved enough to potentially remove stream from impaired waters list	100%	10
	Reduce Peak Flows Reduced peak flows would reduce the potential for soil erosion from channel related features, bluffs, streambank, ravines	Little or no reduction in peak flows	Peak flows reduced but on a limited scale or length of stream reach impacted	Peak flows reduced enough to lower erosion potential and improve turbidity and sediment loading values at monitoring stations	100%	10
Implementation Complexity	**Long term Fix** Longevity of the BMP. How long will it continue to be effective?	Will reduce sediment to the stream for 25 to 50 years without maintenance or repairs	Will reduce sediment to the stream for 10 to 25 years with some maintenance to remain effective	Reduces sediment to the stream for 1 to 10 years and needs to be maintained or redone to remain effective	100%	10
	Accessibility of site How accessible is the site or region	Site is easily accessible with no need to build access roads or acquire landowner permission	Landowner permission needed and or access road construction needed	Limited access with large up front cost to acquire or build access roads resulting in environmental damage	100%	10
	Implementation Time How long will it take to implement the BMP?	Time from start of BMP project planning to completion of the project 1-2 years	Time from start of BMP project planning to completion of the project 2-5 years	Time from start of BMP project planning to completion grater than 5 years	100%	10
	Stakeholder Satisfaction How acceptable will the BMP be to local stakeholders?	Agreement between private landowners, agencies and land managers that the environmental value is significantly greater than the implementation complexity	Agreement between private landowners, agencies and land managers there will be a enough positive environ. value to offset the implementation complexity	Environmental value not great enough to offset significant implementation complexity	100%	10
	Cost Up front construction costs and future maintenance costs	Low cost to benefit ratio no long term maintenance costs	Moderate resources needed to complete the project and some maintenance costs	High capital cost to deploy BMP and long term maintenance costs relative to other BMP's	100%	10

Figure 8. The Scoring Matrix defines the variables and outlines the scoring criteria

The Summary Scoring sheet shown in Figure 9 is used for the actual scoring of the BMP's using the Scoring Matrix as a guide. This is where you enter a score of 1 to 10 for each category based on your best judgment. The subtotals for Environmental Value, Implementation Complexity and Final Score will auto populate. A single final score is generated from the sum of the products of each of the weighting times the score. The scores of the Implementation Complexity are subtracted from the Environmental Value, as there is an inverse relationship between them. A high score on Environmental Value and low score on Implementation Complexity yields the highest total score. Conversely, a low score on Environmental Value with high score on Implementation Complexity will yield the lowest total score. An example of the summary scoring sheet is shown in Figure 9.

An example of the Priority Matrix sheet shown in Figure 10 is a four quad chart of the BMP's showing were an individual BMP ranks relative to the others. The BMP's are plotted on the chart based on the relationship between the Value and Complexity subtotals. It is divided up in four quads to help visually prioritize each BMP. Quads are labeled Priority 1, 2, 3 and 4. The scores populated in the Summary Scoring sheet and plotted on the chart are for example only and not intended to be recommendations by this report. The spreadsheet can be easily modified to add or subtract different categories for environmental value or complexity as well as the ability to change the BMP list to fit a specific erosion hotspot issue. The complete spreadsheet can be opened at the link below.

Feature Prioritization
Worksheet Final 6-09



	Environmental Value					Implementation Complexity						
	Reduce Sediment Load	Reduce Peak Flows	Improve Stream Habitat	Improve Water Quality	Value Subtotal	Long Term Fix	Accessibility of Site	Stakeholder Acceptance	Implementation Time	Cost	Complexity Subtotal	Final Score
BMP	**100%**	**100%**	**100%**	**100%**		**80%**	**80%**	**80%**	**80%**	**80%**		
Bluff Stabilization	10	0	3	6	19	3	7	5	7	8	24	-5
Streambank Stabilization	7	0	3	6	16	3	7	6	7	8	25	-8.8
Ravine Stabilization	8	4	2	4	18	6	7	5	8	8	27	-9.2
Riparian Re-Vegetation	2	2	7	2	13	3	8	5	9	4	23	-10.2
Openland Management	2	5	2	3	12	3	2	8	7	5	20	-8
Forest Management	2	5	5	2	14	5	8	4	8	5	24	-10
Road Ditch Maintenance	10	1	2	3	16	2	2	2	4	2	10	6.4
Outreach and Education	5	5	5	5	20	2	3	3	3	1	10	10.4
Beaver Control	1	0	5	2	8	8	8	5	3	2	21	-12.8
Off Channel Basin	10	8	3	8	29	1	7	5	8	8	23	5.8

Figure 9. Summary Scoring sheet used to rank the different BMP's.

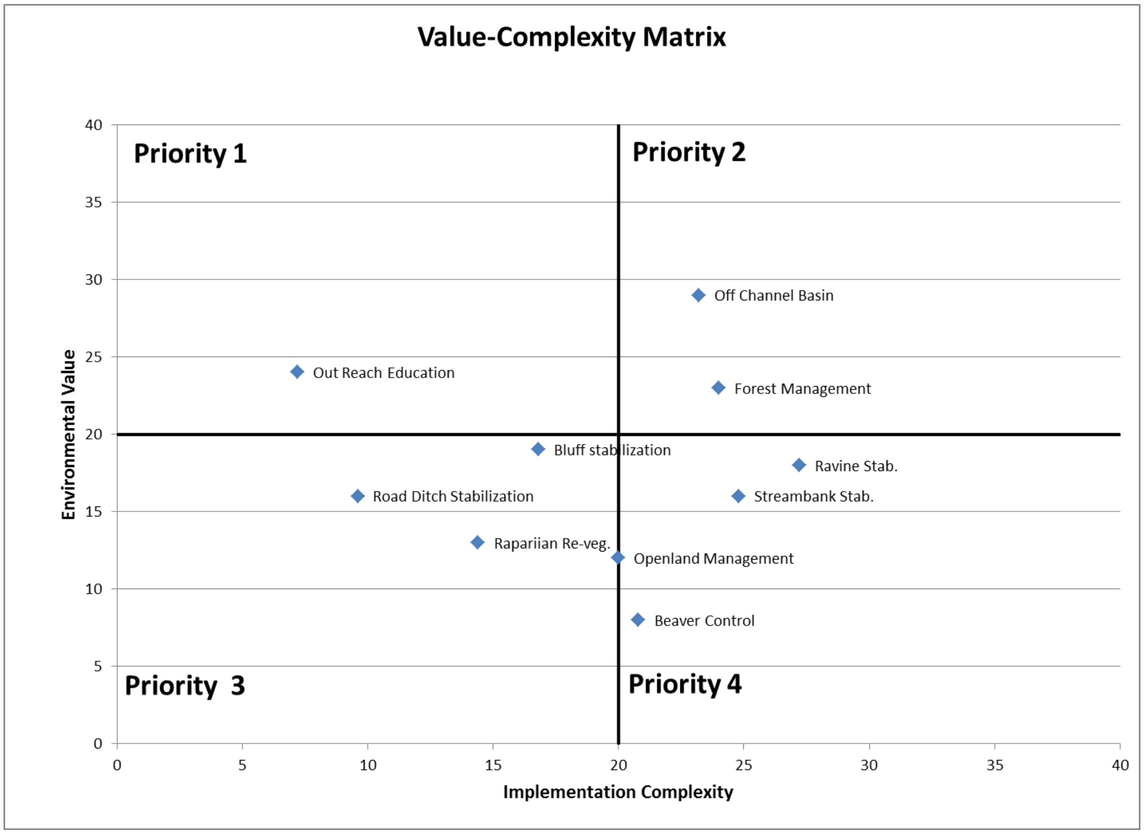


Figure 10. The Priority Matrix plot of the scores from the scoring summary.

Section II – Grant results

Two important results of the project were the high percentage of the total suspended load that was attributed to bluff erosion and increased runoff potential in areas of the watersheds associated with clay till soils.

Bluffs

As presented in Table 4 the calculated average load from bluffs in each watershed ranged from 40 to 335% with an average of 81% for Amity Creek, 13 to 68% with an average of 39% for Sucker River, and 40 to 144 with an average of 73% for Knife River. Even with some of the errors involved in comparing loads from different years to the years bluffs were scanned and different time periods for calculating total sediment loads it is apparent that bluffs are a major contributor to sediment loads in North Shore streams. The blufferosion process and properties of the clay tills can explain the reason for a large sediment contribution from bluffs. Bluffs are steep exposed soil surfaces with very little stable vegetation in place to slow erosion or slumping processes immediately adjacent to the river. As the river meanders up against a valley wall fluvial scour will cause the bluff to steepen. The shear strength of the soil is exceeded by gravitational forces causing large sections of the bluff to break free and slump down slope. The possibility of slumping is increased by pore water pressure. Pore water pressure on clay till can increase due to water infiltration into weathered clay cracks or large cracks opened up where the slumps have lost contact with the parent material. Pore water pressure acts as a lubricant and decreases the soil strength. As the soil strength decreases the material can more easily be overcome by gravitational forces. Clay bluffs are more susceptible to increased pore water pressure as the water infiltrating the cracks tends to build up in the soil profile instead of draining because of the very low infiltration rate of clay tills.

Undisturbed clay till actually has a high critical shear stress and is difficult to erode. However, the greatest percentage of the exposed bluff surface is exposed to the weathering processes of shrinking, swelling and the freeze-thaw cycle. These weathering processes break up the parent clay till making it much easier to be transport by rill erosion or sloughing of the surface layer due to saturation during spring thaw. Most bluffs have a mantle of loose clay till 6 to 60 centimeters thick that covers the undisturbed parent material. Because finer silt and clay make up the majority of the particle size distribution of the bluff clays, once the material reaches the stream it stays in suspension, is easily transported, and causes high turbidity readings.

As more data is collected on bluffs it may be possible to estimate what percent of the total load in a system can be attributed to bluffs. A survey to determine the area of exposed bluff surface could give an estimate of the tons per year expect from bluffs. The data from this project provides a start of this relationship and is presented in Figure 11.

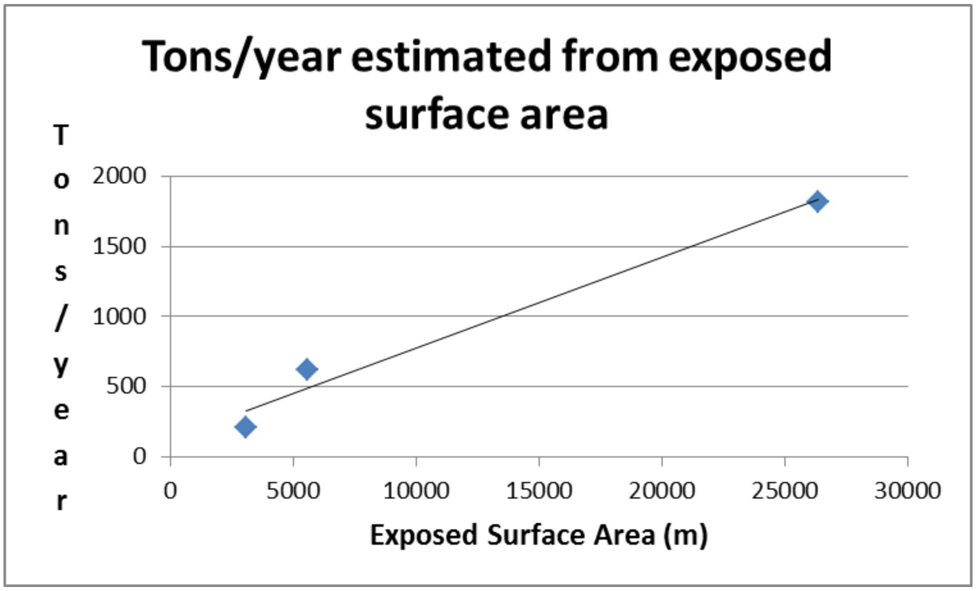


Figure 11 shows the relationship between exposed surface area and tons/year of sediment load.

Increased runoff potential of clay till

The second area of increased erosion potential focused on the presence of clay tills in the watersheds. The clay till is the result of a series of glacial advances of the Lake Superior lobe. Each retreat of the ice formed ice marginal lakes. The next ice advance would scour the lake sediments and deposit them on the current Lake Superior shoreline. Each successive advance reached a lower elevation and deposited finer grain tills than the previous advance. The deposited tills are currently identified as the Cromwell Formation at the bottom and the Barnum Formation with three members (Lakewood, Moose, and Knife) on top (Hobbs 2004). In the Lake Superior South watershed, clay till forms a band that runs parallel to Lake Superior up to 4 miles wide to an elevation of about 1200 feet. The till varies in depth from a few feet to 30 feet. The clay till is classified as the Cuttre soil series by the NRCS. A description of the Cuttre series can be found in Appendix B.

The till exposed at the surface over the greatest percentage of the watershed, is the Knife member of the Barnum formation. The percentage of fines in the Knife member averages about 95%, which is the highest percent fines of all the clay tills present on the

North Shore. The Moose and Lakewood members of the Barnum formation are exposed at the surface only in small bands between 1000 and 1200 feet of elevation. They both have about the same percentage of fines averaging 85% with the Moose member having a higher percentage of clay at 45% compared to the Lakewood at 20%. All three tills below the Knife are also present at the surface in stream channels that have eroded down through the Knife member. Figure 11 is a MGS map showing the location of the various tills (Hobbs 2003). The yellow shading is the finer Knife and Moose Lake members of the Barnum formation. The light blue shading shows areas the stream channel has cut down through the Knife member into a slightly coarser till below. The Cromwell shows at the surface only as a strip of dark blue higher in the watershed.

The increase in runoff potential from heavy clay soils is related to very low infiltration rates. The very low infiltration rates are due to low porosity and limited soil structure. The soil structure in clay soils can be further damaged due to compaction. Compaction and damage of the soil structure occurs more easily when the soil profile is wet. By nature, clay soils have limited drainage, stay wet longer, and generally have a very high water table. This means clay soils will be susceptible to compaction and structural soil damage for greater periods of time than coarser grained soils.

Any sort of development on clay soils will most likely increase the already high runoff potential by removing or compacting the upper organic layer, damaging soil structure due to compaction and exposing the soil surface to increased raindrop impact. Developed lands in the three watersheds are comprised mainly of hay fields or pasture. The percentage of developed land is small as a percent of the total drainage area of the three watersheds at about 2 to 5 percent. However, the developed lands are not distributed evenly over the entire watershed. They actually tend to be concentrated on the clay soils found in the watershed. Figure 12 shows the developed lands mostly as open hay fields or pasture concentrated in a band along the shore similar in location as the band of the heaviest clay till shown in Figure 11. Table 11 shows the percentage of each watershed that is comprised of clay till, the percent that developed lands makeup of the entire watershed and the percent of the clay acres in the watershed that have been developed.

Table 10 in the review of tasks section shows the comparison of measured infiltration rates between forested and developed lands and the clay layer twenty to thirty centimeters below the soil surface. The infiltration rate in the forest was about ten times greater than the field with the clay layer as expected with a very low rate. Even though the field infiltration rate is much less than the forest rate, initially under un-saturated conditions even a moderate to high rainfall intensity would not cause ponding in the field as 2.65 to 6.7 cm/min is still a high infiltration rate. However, if the rainfall event has a long enough duration, ponding leading to surface runoff will occur more quickly in the field because the upper 30 centimeters above the clay layer has a lower porosity and less water holding capacity. If the rainfall event continues long enough to fill the upper 12 inches of the forest profile, then the clay layer becomes the limiting factor to infiltration in both the field and the forest. Because of the confining clay layer under saturated conditions, theoretically runoff generated from both landuses would be the same. In practice, the surface runoff will be influenced by drainage pathways developed in the field versus the forest. The runoff in the forest has a more complex path to follow due to vegetation, roots, leaf litter, branches, and logs before it reaches an area of concentrated flow such as a ravine. Field runoff would tend to sheet and with fewer obstacles in place runoff more quickly thus increasing peak flows and erosion potential. Field roads, trails and livestock pathways also can increase the runoff potential related to develop lands.

The LiDAR images provide further evidence the clay till soils have greater runoff potential based on the number of ravines that are concentrated in areas of the watershed comprised of clay till versus coarser tills at higher elevations in the watershed. Figure 13 is a LiDAR image of the Knife River. The erosional signature of the clay till landscape shows up as having a much higher number of ravines compared to coarser tills in the watershed. This is probably due to the much lower infiltration rate leading to higher runoff potential. The topography of the clay tills is also smoother with more gradual slopes than other areas of the watershed. This flatter more even topography was probably the reason the limited agriculture in the watersheds concentrated on the clay soils. It was the only landscape in the watersheds with viable farmland.

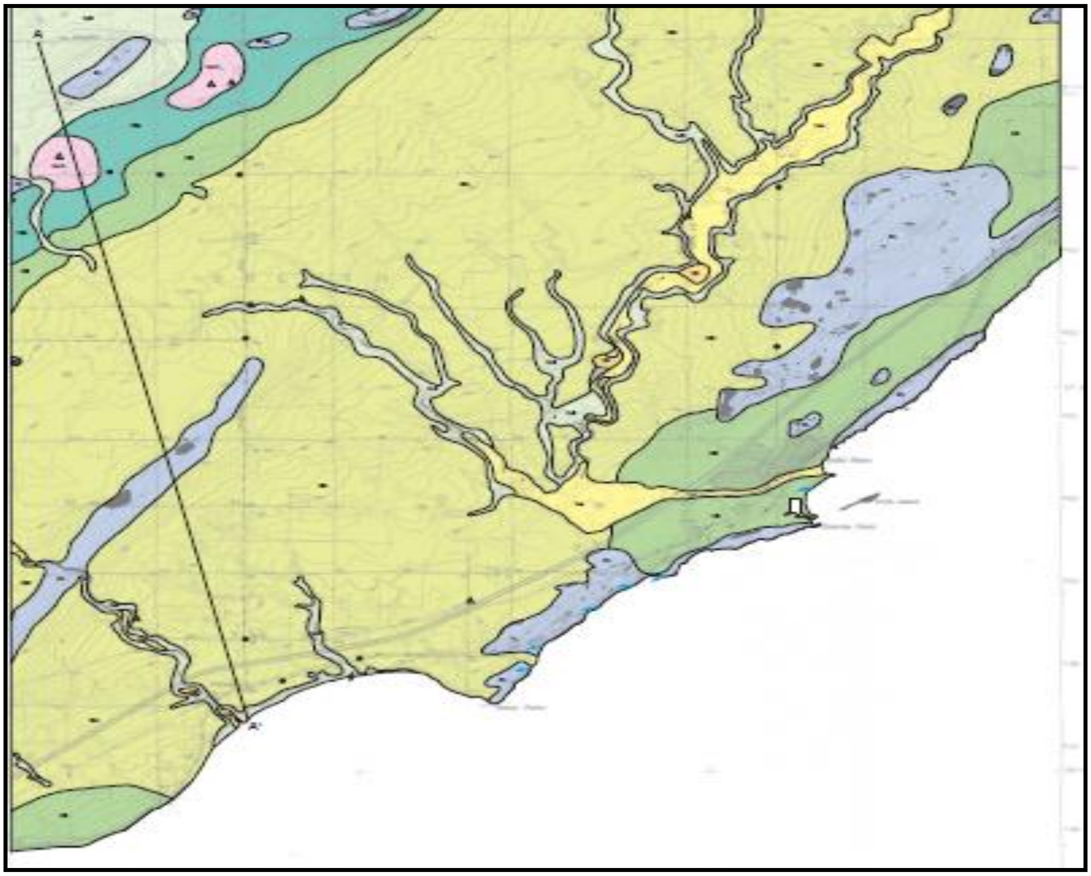


Figure 11. Surficial geology of the Knife River quadrangle

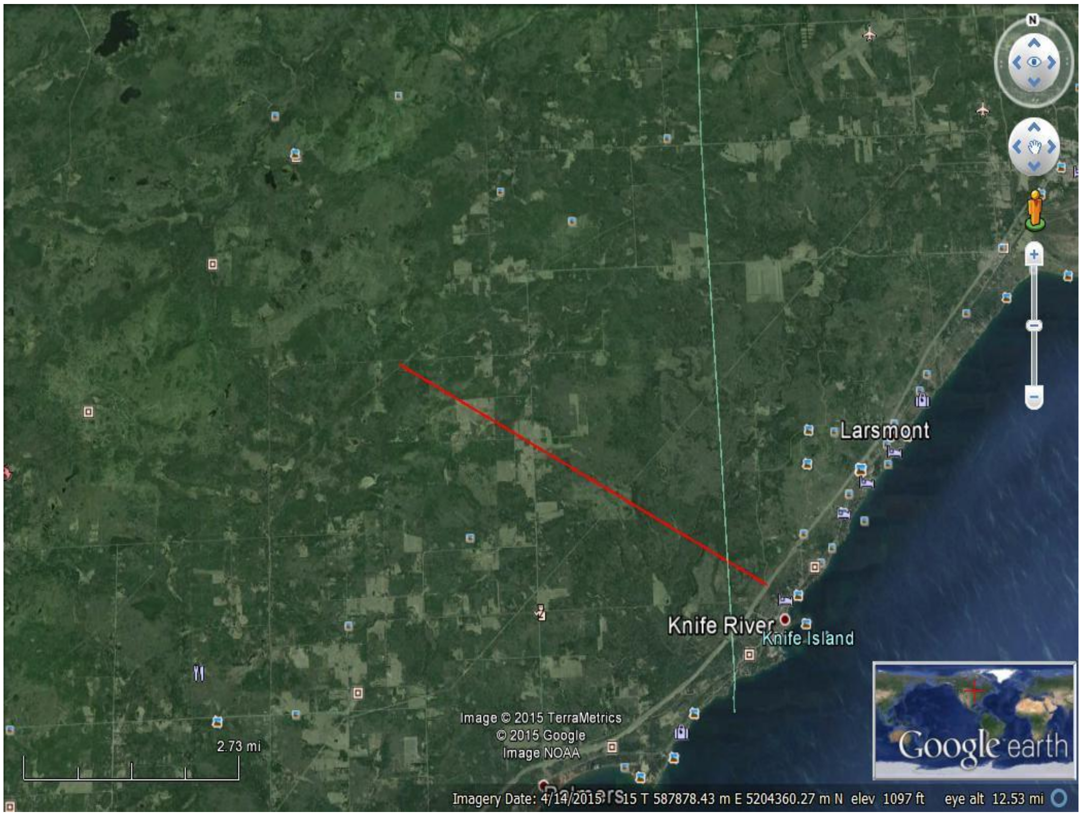


Figure 12. Developed lands coinciding with the location of the clay till The red line represents the extent of the clay till.

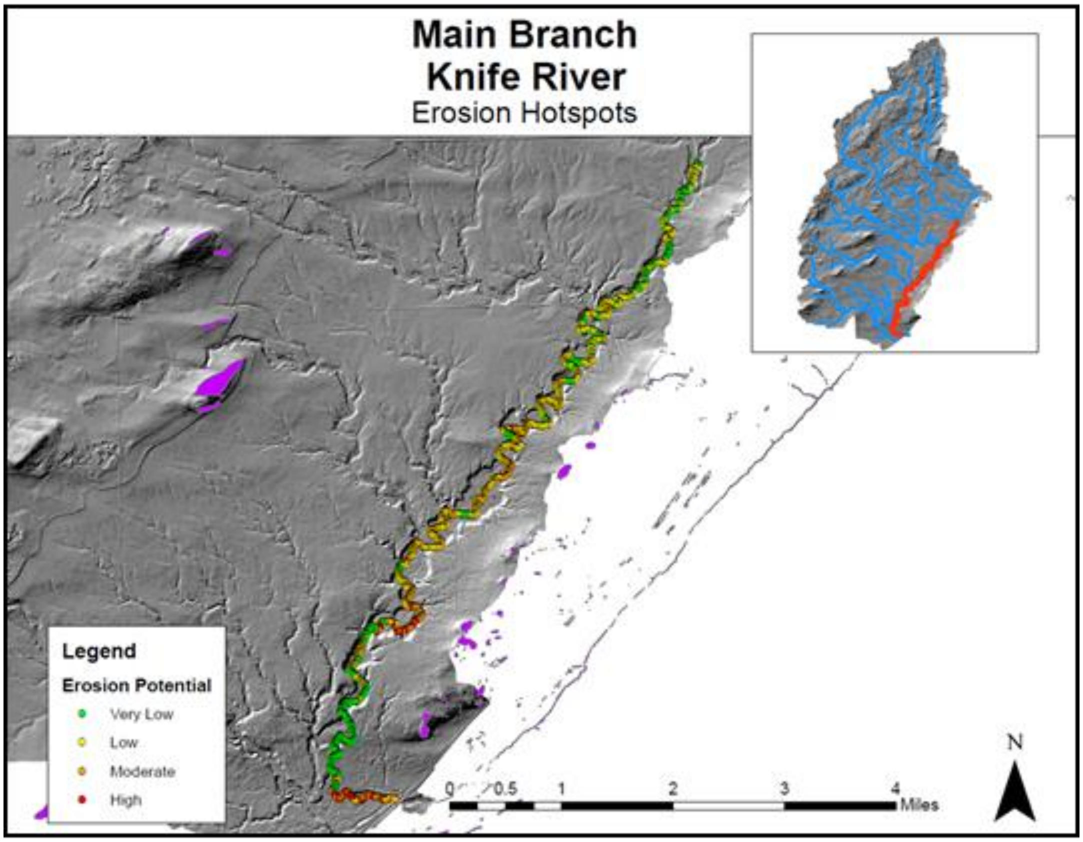


Figure 13. LiDAR image of the Knife River watershed showing the ravine formation on the clay till.

Watershed	Total acres	Acres of clay	% clay in watershed	% developed land	% of clay acres in developed land
Knife	53590	12725	36	6	13
Beaver	79329	3149	4	3	25
Sucker	25526	2086	8	3	24

Table 11. Percentage of each watershed that is comprised of clay till, the percent that developed lands makeup of the entire watershed and the percent of the clay acres in the watershed that have been developed.

Prioritization Methodology

The main components of the methodology are listed below. A description of how each of these tools was used specific to North Shore watersheds is given below.

- Erosion Hotspot Model (EHM)
- LiDAR-derived (Light Detection and Ranging) digital elevation models
- NRCS Web Soil Survey (WSS)
- Ground based Terrestrial Laser Scanning (TLS) producing high resolution DEM's for streambanks and bluffs
- Openlands Model
- Field surveys of river channels
- Road surveys

LiDAR imaging should be one of the first tools to use to provide a quick overview of a watershed in question. The surficial geology, specific landforms, stream channels and natural erosion patterns can all be determined from the images. They can provide a quick visual inspection to determine if there are obvious changes in the land forming process that may be driven by present day land use.

They also support the computer based tools such as the Erosion Hotspot model used in this project. Most of the parameters used in the EHM were derived from LiDAR images.

In this project it was discovered that the clay tills provided a signature easily observed on LiDAR images. The low infiltration rate of the heavy clay tills resulted in the formation of a number of ravines that are not present in sections of the watershed where the clay tills don't exist. If evidence of these clay tills exists on a LiDAR image the NRCS Web Soil Survey (WSS) can be used to better define the extent of the clay tills. The different soil classifications based on slope can help locate within a specific watershed where management activities would be best utilized. The soil survey lists all the soil physical properties such as hydraulic conductivity, particle size and bulk density that can be useful in determining best management practices.

If the watershed is fairly remote, doesn't have much available data or is relatively unfamiliar to land managers it would be a good candidate for the EHM. The model will identify high erosion potential areas and possible bluff locations. The EHM model successfully identified six of the eight bluff locations on the Sucker River and six of the top ten erosion hotspots identified on the Knife River corresponded to actual bluff locations. This information would save time and resources by focusing in on areas to conduct a field survey of the channel.

If the EHM predicts an area of high erosion potential that coincidences with the clay till landscapes it would be a worthwhile endeavor to conduct a channel survey. The channel survey can provide useful information such as; surface area of exposed bluffs, condition of stream banks, landuses immediately adjacent to the river channels not easily seen on images, changes in channel substrate, vegetation patterns, presence of woody debris and habitat. These surveys are critical in identifying specific erosional features to focus management of BMP placement.

The Openlands model was developed by the MNDNR. The basis of the model is the increase in peak flows from small watersheds that have been converted from forest to farmland. It uses an accumulation of slope, drainage area and percent openlands to focus in on the small watersheds that have the greatest potential to increase peak flows. The end product is a map of a large percent of the Minnesota North Shore where poly-lines of different colors indicate the presence of the most impacted small watersheds. This tool was used to identify the location of the forested versus thirty percent openlands paired watershed study this project monitored with passive sediment samplers. The model would also be useful in identifying and prioritizing which areas of a watershed openland management would be the most effective in decreasing peak flows.

There are a number of issues associated with roads. Numerous road crossings and the associated culverts can cause scour or provide concentrated flow pathways which can lead to increases in peak flows. The critical erosion hotspots identified were sections of steep road ditches running downslope directly to a main branch or tributary of a stream. These sections were usually located where a road ran down the valley wall to a stream crossing. While many miles of ditches remain well vegetated, these sections of ditch have enough stream power as the result of a large enough drainage area enhanced by the concentrated flow paths to down-cut through the vegetation into the exposed till.

Prioritization Matrix

Once an erosion hotspot has been identified and a decision made to address the erosion the prioritization matrix can be used by stakeholders to help focus in on the appropriate BMP.

Sucker River Watershed

The Sucker River watershed drainage area is 39.9 miles^2 with a stream length of 49.5 miles. Ninety-five percent of the watershed is either forest or wetland. Developed lands are about three percent, the majority of which are hay fields and pasture. The extent of clay tills in the watershed is small at 8% of the total watershed area because the drainage area where the Sucker River passes through the clay tills is narrow compared to the width of the upper watershed. This comparison can be seen in Figure 1 in the review tasks section. The highest erosion potential predicted by the erosion hotspot model is located in the lower quarter of the watershed, shown as red and yellow in Figure 1. This high erosion potential area is located in the same area as the clay till soils. It is also a section of the stream channel were most of the clay bluffs are located (Figure 2). Steam surveys also identified the stream channel through this reach as heavily impacted by the 2012 storm event. Large debris jams, scoured streambanks and bluffs, and large deposits of gravel on top of the previously existing streambed were all evidence of a very unstable reach. Figure 14 is a zoomed in section of the lower quarter of the watershed showing the area of the channel with the highest erosion potential and presence of a number of bluffs running through the clay till plain.

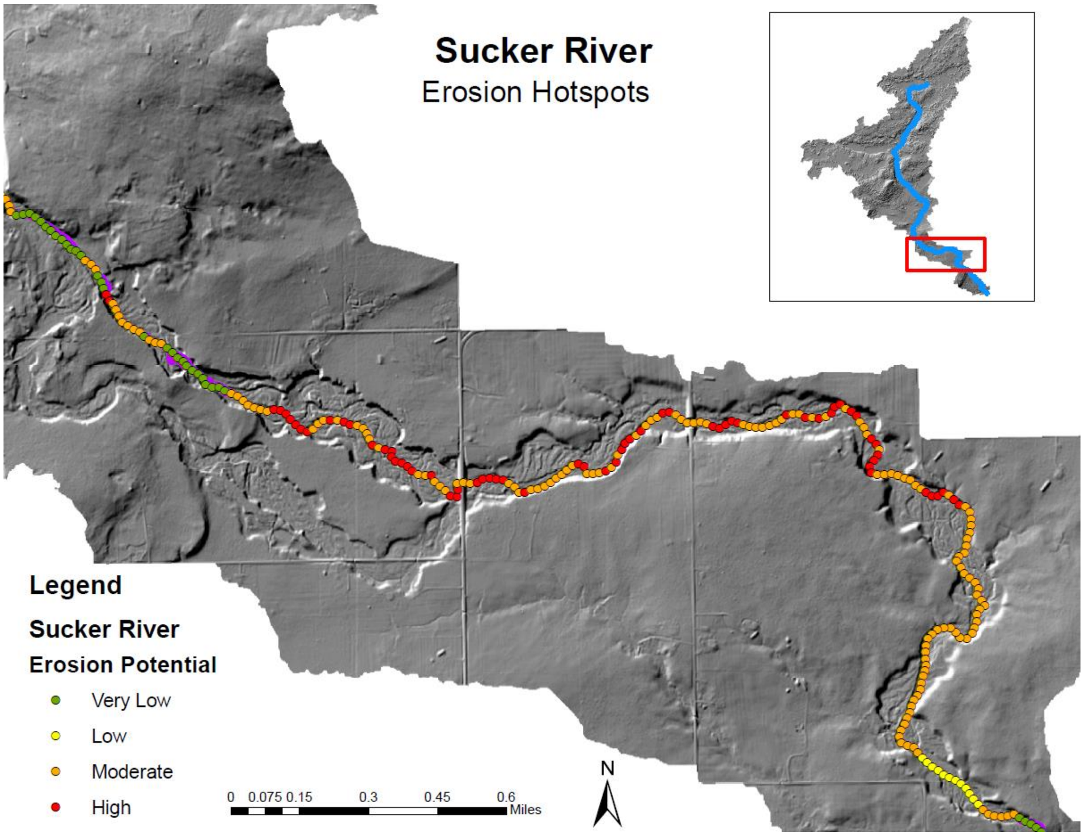


Figure 14. Zoomed in section of the Sucker River showing the location of the channel with the highest erosion potential running through the clay till

Knife River Watershed

The Knife River watershed has a drainage area of 84.3 miles^2 and a stream length of 181 miles. Ninety-four percent of the watershed is either forest or wetland. Developed lands are about 6 percent the majority of which are hay fields and pasture. The extent of clay tills in the watershed is the greatest of the three watersheds at 36% of the total watershed area with 13% of landuse on the clay till being developed. The erosional signature of the clay till landscape shows up well on the LiDAR map shown in Figure 15. Because of the correlation between clay till and ravine formation it also has the greatest number of ravines at 233 covering a total of 8.3 miles^2. The Knife River is one of the most turbid streams on the North Shore. It is easy to see why with 36 percent of the watershed comprised of clay till and the many miles of river channel that cuts through the clay till. Unlike most of the North Shore streams which run parallel to the slope leading down to Lake Superior and thus limiting the number of river miles cutting through the clay till, the Knife River runs perpendicular to the slope and parallel to the lake clay plain increasing the number of river miles cutting through the clay till as compared to other North Shore streams. Because so much of the main branch of the Knife River runs parallel to the slope it has the lowest average stream power at 34.37 and the most gradual bend curvature at 8.98 of the three study watersheds. This lower average erosion potential is offset by the fact so much of the channel runs through the clay tills which leads to the Knife River having the greatest total number of eroding bluff at 23. The large numbers of bluffs on the Knife River, as evidenced by the bluff scan data presented in the reviews task section, are the major source of sediment to the river, followed by the large total number of river miles cutting through the clay till and the large number of ravines.

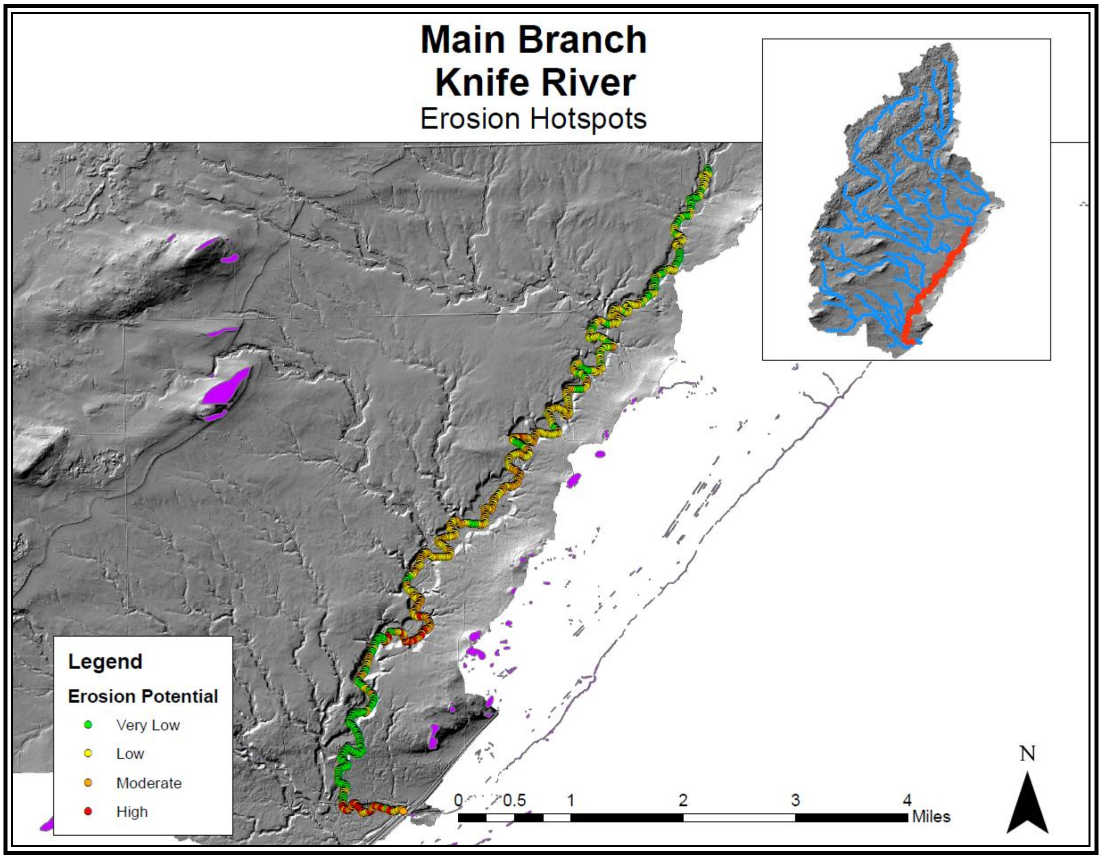


Figure 15. The erosional signature of the clay till shown on the erosional hotspot map of the Knife River.

Beaver River Watershed

The Beaver River watershed has a drainage area of 123 miles^2 and a stream length of 161 miles. 96% of the watershed is either forest or wetland. Developed lands are about 4% the majority of which are hay fields, pasture and some mining activity. The extent of clay tills in the watershed is 4% of the total watershed area with 25 percent of landuse on the clay till being developed. The erosional signature of the clay till landscape shows up well on the LiDAR map of the West Branch of the Beaver River shown in Figure 16.A limited amount of clay till is present in the East Branch of the Beaver River shown in Figure 17. The number of ravines including both river branches is 33 covering a total of 1.26 miles^2, all of which are located on the clay till. Figure 18 shows the confluence of the west and east branches of the Beaver River. The higher turbidity in the west branch is evidence of the greater amount of clay tills in the west branch compared to the east branch and the effect the clay has on river turbidity. The total number of bluffs in the watershed is unknown. Our limited river surveys did not find any. In consultation with land managers that are familiar with the watershed, the number is small somewhere between 3 and 6 mostly present in the west branch. While present and still a sediment source because of the small number compared to the large watershed area they are not contributing a large percent of the total sediment load to the Beaver River. The largest area of clay till is found in the upper reach of the west branch. Because of a milder slope and a very wide river valley, the potential for bluff formation and high erosion potential is lower through this section of clay till compared to the other study watersheds. Figure 19 is a picture of the West Branch flowing through the clay till. Bluff stabilization in the Beaver River to reduce sediment loads would be challenging as the bluffs are located in a fairly remote section of the watershed. Sediment load reduction should focus on land management of the clay till area on the West Branch.

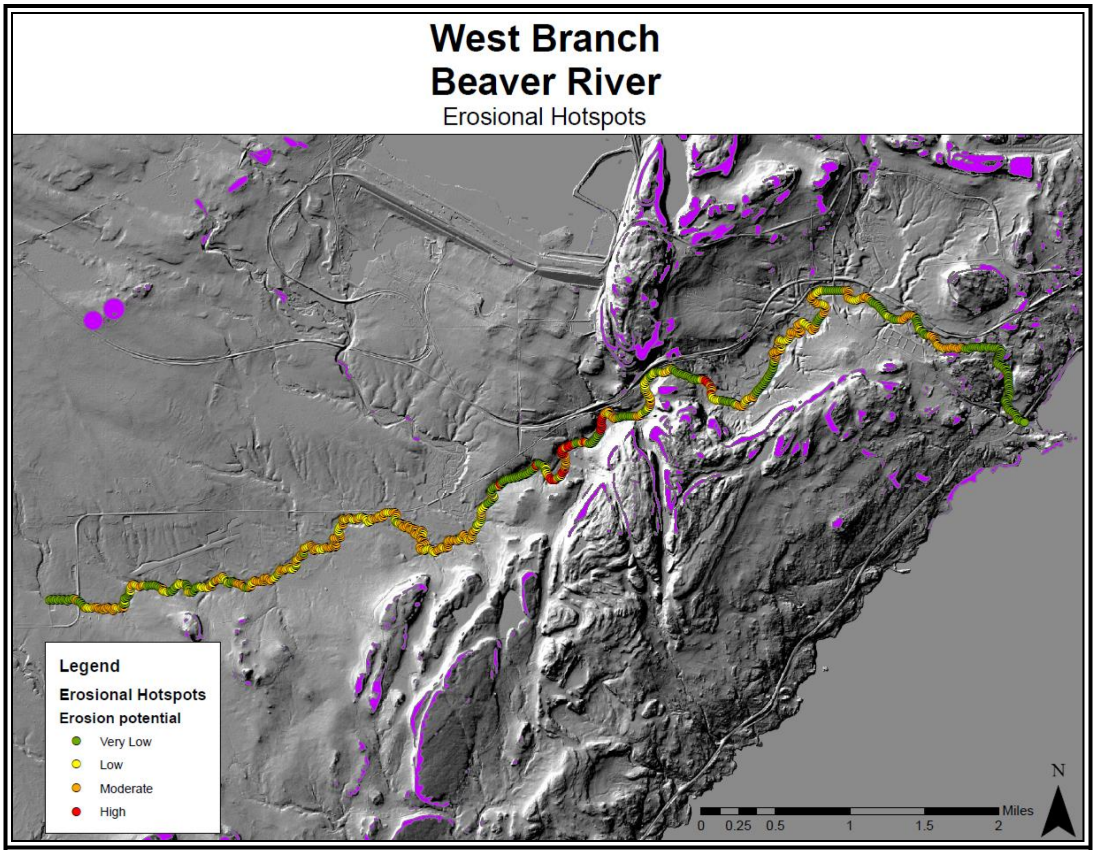


Figure 16. Erosion hotspot map of the West Branch Beaver River showing the location of the clay tills

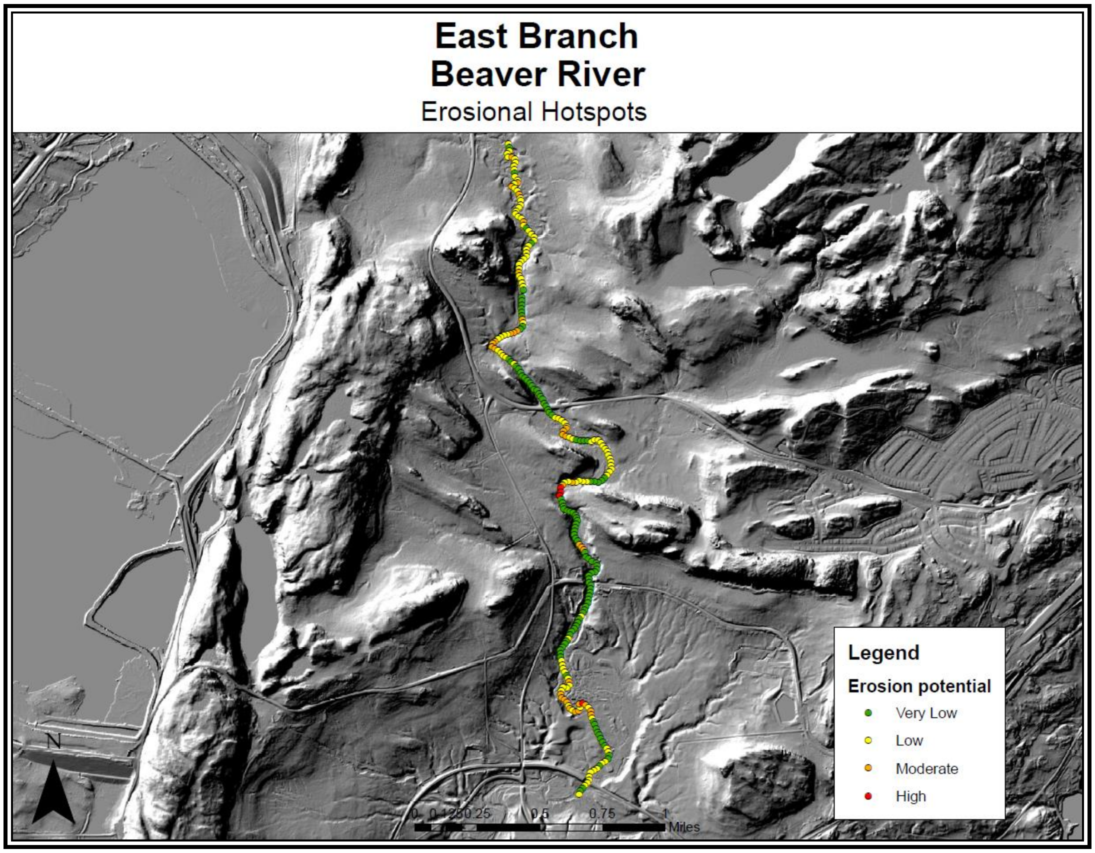


Figure 17. Erosion hotspot map of the East Branch Beaver River showing the location of the clay tills

Figure 18. Confluence of the West and East branches of the Beaver River showing the higher turbidity coming from the West branch due to the high amount of clay till.

Figure 19. Lower gradientsection of the west branch of the Beaver River flowing through the clay till

Conclusions

If the management goal of a North Shore stream is to reduce turbidity, the management activities should focus on the area of the watershed were the clay tills and eroding bluffs are located. A number of factors point to the region of clay tills as having a high potential for erosion and sediment production.

The elevation profile of most North Shore streams shows a gradually increasing slope from the upper reaches of the watershed that breaks sharply as it nears the lake resulting in a much steeper slope from about 1400 feet to Lake Superior. The location of the clay tills coincides with this steeper slope running from the Lake Superior shore up to an elevation of 1200 feet. The majority of bluffs are also found in this clay till region of high erosion potential. The main branches of the three study watersheds have cut down to the Cromwell Formation leaving the easily transported finer textured clay till of the Barnum Formation exposed on the bluffs. Many of the smaller tributaries and ravines are currently down-cutting through the finer clay tills of the Barnum Formation. Thus, sediment supply to the streams of easily transported, fine textured sediment is high. These river corridors, including the valley walls, bluffs, ravines and adjacent tributaries currently down-cutting through clay tills appear to be the major source of sediment to the three study watersheds. Bluffs alone can contribute 13 to 80% of the total load.

Developed landuse as a percent of the total watershed areas was 3 to 6%. Most of the developed landuse is located on the clay tills. Developed landuse on clay till soils in the watersheds ranged from13 to 25%. The clay till has a very low permeability and a seasonally high watertable both of which increase the runoff potential. Peak flows and suspended sediment contributions to streams would likely be greater from watershed areas dominated by clay tills (Cuttre complex). Fine clay and silt particles make up 70-98 percent of the particle size of the clay tills found in the study watersheds. Once these fine particles get into suspension they will not settle out and are easily transported by moving water which contributes to high turbidity.

Ravine and stream bank erosion were not assessed through direct measurements in this study because they were considered smaller sediment sources than bluffs. However WEPP modeling of ravines and Bank Erosion Hazard Index worksheet calculations suggest that ravines and stream banks are contributing some sediment to North Shore streams but together may contribute less than 25% of the fine sediment load in the Knife River for example (See Appendices E and F). Stream banks were estimated to contribute an estimated 700 tons/year from the main channel of the Knife River using the BANCS worksheet approach.

In summary, erosion hotspots witin the three study watersheds are defined as high stream power stream channels cutting through areas of low permeability easily transported clay, on the steepest part of the watershed where most of the developed land use exists. It would seem logical to focus management activities in both the channel and upland areas of the watersheds where clay tills are present. Schultz-Naas (2007) describes management solutions on clay soils of the Lake Superior basin.

Future Work

Bluffs in these watersheds have the potential to produce a large percentage of the total sediment load. Initial results of bluff scans done on two bluff restoration projects showed, roughly 60 tons at the Knife River bluff (BHHR) and 37 tons at the Amity Creek bluff (BSWCD) of sediment have been captured on the bank full bench. Without restoration, a significant amount of this sediment would have been scoured by the river contributing to the total load.

Bluff stabilization appears to be a good tool in terms of reducing the sediment load to the rivers. Because bluff stabilization is a relatively new tool, there remain some questions of its overall effectiveness as a long-term solution. It would be useful to have a better understanding of the evolution process bluffs undergo prior to stabilization and after stabilization. Pre-stabilization questions about soil properties and the susceptibility to pore water pressure or erosive forces unique to individual bluffs would be good information to have to help improve the design or predict the effectiveness of stabilization projects. Post stabilization questions include: Will the anticipated reduction in slope occur and how long will it take? At what slope will the bluff be stable enough for re-vegetation efforts to be successful? When is the best time to start re-vegetation efforts? What is the anticipated life span and sediment load reduction of the stabilization projects? What is the threshold limit of bluff exposed surface area in a watershed above which bluffs contribute a significant amount of sediment to the river compared to other sources?

Stream bank sources of sediment be assessed in as much detail including historical aerial photo analysis to see if channel width is changing in the Knife River and other north shore streams indicating a net increase in sediment loading. It seems likely that the large 2012 storm on the North Shore enlarged some of the north shore channels, producing disproportionately more sediment that year.

The total number of road miles in the Sucker River is 25; the Knife River has the most at 80 followed by the Beaver River at 45 miles. This means there are also the same numbers of ditch miles in the watershed that can act as concentrated flow pathways. Although the road density is small in these watersheds in woud be of interest to do a culvert survey and a modeling effort to determine the affect the flow pathways have on the peak flows.During small events these ditch pathways are probably not contributing much because they tend to pond water allowing for evaporation and infiltration. However, during large events when ponding turns into flowing water, the pathways basically add many miles of potential drainage area to the streams that would not have been natural connected without the road network.

Not considered in the road density are the many miles of logging trail, private field roads, walking trails, and driveways. Again though they are not a large percent of landuse in the watersheds if they are hydrologically connected to the streams in any way they can concentrate flow and increase erosion.

Products

86 - Erosion Hotspot Maps

52 - Bluff Scan Maps
12 - Ravine Maps

Section III – Final Expenditures

Final expenditures totaled $182,047.24.for the project

References

Hall L. R. (2016).Monitoring Bluff Erosion Rates Using Terrestrial Laser Scanning on Minnesota's North Shore Streams (Master's Thesis). University of Minnesota, St. Paul.

Hansen, B. Dutton, Nieber, Gorham. 2010. Poplar River Sediment Source Assessment. Unpublished report for the Minnesota Pollution Control Agency.

Hobbs H. C. (2002). Surficial Geology of the French River and Lakewood Quadrangles, St. Louis County, Minnesota. University of Minnesota and Minnesota Geological Survey Miscellaneous Map Series MAP M-127.

Hobbs, H.C. 2004. Late Wisconsinan Superior-Lobe deposits in the Superior Basin northeast of Duluth. Institute on Lake Superior Geology, 4-9 May, 2004. Field Trip 3: 86-98.

Manopkawee.P. Identifying Erosional Hotspots in Duluth-Area Streams after the 2012 Flood Using High-Resolution Aerial Lidar Data (Master's Thesis). University of Minnesota, Duluth.

Neitzel, G. (2013). Monitoring event-scale stream bluff erosion with repeat terrestrial laser scanning; Amity Creek, Duluth, MN (Master's Thesis). University of Minnesota, Duluth.

Nieber, J. L., Wilson, B. N., Ulrich, J. S., Hansen, B. J., and Canelon, D. J. (2008). Assessment of streambank and bluff erosion in the Knife River watershed. St. Paul, MN: University of Minnesota

Product Arts. (2010) Model of prioritization spreadsheet

Schultz-Naas, S. 2007. A Guide to Understanding the Hydrologic Condition of Wisconsin's Lake Superior Watersheds. Report Wisconsin Lake Superior Basin Partner Team. Ashland, Wisconsin: University of Wisconsin-Extension

Wick, M. J. (2013). Identifying erosional hotspots in streams along the North Shore of Lake Superior, Minnesota using high-resolution elevation and soils data (Master's Thesis). University of Minnesota, Duluth.

Appendix A

Erosion Hotspot Modeling Procedure:

- Stream Power Erosion Index:
  1. In ArcGIS, import a 3-meter DEM of the watershed of interest and delineate the basin using Spatial Analyst Hydrology toolbox. Hydrologically condition the stream network if necessary, based on the presence of any digital dams.
  2. Import the stream network to a new file and merge the stream segment of interest into one. Following, by using the “Split” tool, split the segment “Into Equal Parts”. Split it into segments that are 25 m long and then convert the polyline file to a point file using the “Feature to Point” tool (check the “Inside” option to ensure that all the points fall within the stream network).
  3. Next, clip the Accumulation Raster (created when delineating the watershed) to the watershed boundary and enlarge the river using the “Focal Statistics” tool (use the “Maximum statistic and a 10 cell x 10 cell rectangle). The output from this is an Accumulation Raster with the stream enlarged to be 10 cells wide, which is done to ensure that the data extracted is the accumulation of the stream itself.
  4. After, extract the data using the “Sample Tool” in Spatial Analyst. As inputs to this tool use the DEM, the accumulation raster with the enlarged river and the stream point file. Export the data as a .csv file and open the date in Excel.
  5. In Excel, add a “Distance” column and input values starting at 0 and spaced by 25 m, adding values for every point. Calculate slope for every point, using the elevation data exported from ArcMap and the distance over 100 m (i.e. “=ABS(SLOPE(D2:D6,E2:E6))”). Next, calculate stream power for all the points using the accumulation data imported from ArcMap raised to 0.5 and multiplied by slope (i.e. “=(A2^0.5)*S2”).
  6. Export the data back to ArcMap using the “Add XY Data” tool.

- Bend Curvature:
  1. In ArcMap, create a new polygon shapefile and starting “Editing” the new shapefile. Display your original DEM and the stream point file (the one that includes the stream power calculations) and working at a 1:4000 zoom, draw circles that best fit along the line of the river. Following, measure the radius of curvature of each circle, then selected all the stream points that are touching a circle and in the attribute table assign the radius of curvature value to each point.
  2. Next, measure the bankfull width using Google Earth for help and LiDAR at each point location and assign this value in the stream point file attribute table.
  3. With each point having a radius of curvature and a bankfull width and a new column for bend curvature. Calculate bend curvature by dividing the radius of curvature by the bankfull width.

- Erosion Hotspot Identification:
  1. Using the Natural Break (Jenks) classification, divide stream power and bend curvature into 5 categories. Assign each category a score from 1-5 for the stream power values and the bend curvature values. For example, the points that have stream power values that are in the highest category (largest stream power values) are assigned a 5 and the points that have stream power values that are in the lowest category (smallest stream power values) are assigned a 1. Additionally, the points that have bend curvatures values that are in the highest category (smallest bend curvature, since bend curvature decreases as river bends get tighter) are assigned a 5 and the points that have bend curvatures values that are in the lowest category (largest bend curvature, since bend curvature increases as the river straightens) are assigned a 1. Following this step, create a new column in the attribute table and sum the scores.
  2. Each point on the stream should now have a score from 2 to 10. The values can now be ranked by their erosion potential: 2-4 = very low erosion potential, 5-6 = low erosion potential, 7-8 = moderate erosion potential, and 9-10 = high erosion potential.

Lastly, turn on a bedrock shapefile over your watershed and display the point file ranked by erosion potential. Note any points that touch bedrock and set the value to a very low erosion potential (2).

Appendix B

CUTTRE Soil SERIES

The Cuttre series consists of very deep, somewhat poorly drained soils formed in clayey till on till plains. Permeability is extremely slow or very slow. Slopes typically are 0 to 3 percent but range to 8 percent. Mean annual precipitation is about 31 inches. Mean annual air temperature is about 40 degrees F.

TAXONOMIC CLASS: Very-fine, mixed, active, frigid Aeric Glossaqualfs

TYPICAL PEDON: Cuttre clay, on a concave, southeast facing, 1 percent slope in an area of mixed conifer and northern hardwoods at an elevation of about 860 feet. (Colors are for moist soil unless otherwise noted.)

A--0 to 3 inches; dark reddish brown (5YR 2.5/2) clay, dark reddish gray (5YR 4/2) dry; weak medium granular structure; friable; many fine and medium and few coarse roots; about 1 percent gravel; strongly acid; abrupt smooth boundary. (2 to 4 inches thick)

E/B--3 to 6 inches; 70 percent brown (7.5YR 5/2) clay loam (E), pinkish gray (7.5YR 7/2) dry; weak medium subangular blocky structure; friable; few faint reddish brown (5YR 4/3) clay films on faces of peds; many medium distinct brown (7.5YR 5/4) and few medium distinct strong brown (7.5YR 4/6) masses of iron accumulation; extends as tongue into and surrounds remnants of reddish brown (5YR 5/3) clay (Bt); weak medium subangular blocky structure; firm; many fine and medium and few coarse roots; about 1 percent gravel; strongly acid; clear wavy boundary.

B/E--6 to 12 inches; 70 percent reddish brown (2.5YR 4/4) clay (Bt); moderate medium angular blocky structure; firm; common distinct reddish brown (5YR 5/3) clay films on faces of peds; common brown (7.5YR 5/2) coatings of E material on faces of some Bt peds; penetrated by tongues of brown (7.5YR 5/2) clay loam (E), pinkish gray (7.5YR 7/2) dry; moderate medium subangular blocky structure; firm; common fine and medium roots; common medium prominent yellowish red (5YR 5/6) masses of iron accumulation; about 1 percent gravel; moderately acid; clear wavy boundary. (Glossic horizon - 2 to 15 inches thick)

Bt--12 to 25 inches; dark reddish brown (2.5YR 3/4) clay; moderate fine angular blocky structure; firm; common fine and few medium roots; common faint reddish brown (2.5YR 4/4) clay films on faces of peds; few brown (7.5YR 5/2) coatings of E material on faces of peds; few fine faint reddish brown (2.5YR 5/4) masses of iron accumulation; about 1 percent gravel; slightly alkaline; clear wavy boundary (5 to 19 inches thick)

Btk1--25 to 31 inches; dark reddish brown (2.5YR 3/4) clay; moderate fine angular blocky structure; firm; few fine and medium roots between peds; common faint reddish brown (2.5YR 4/4) clay films on faces of peds; common fine and medium irregular distinct light reddish brown (2.5YR 6/4) soft masses of calcium carbonate; strongly effervescent (11 percent calcium carbonate); about 1 percent gravel; moderately alkaline; clear wavy boundary.

Btk2--31 to 41 inches; reddish brown (2.5YR 4/4) clay; weak coarse angular blocky structure; firm; few fine roots between peds; few faint dark reddish brown (2.5YR 3/4) clay films on faces of peds; common medium and coarse irregular faint light reddish brown (2.5YR 6/4) soft masses of calcium carbonate; many very fine and fine irregular prominent black (N 2.5/0) soft masses of iron-manganese oxides; violently effervescent (14 percent calcium carbonate); about 2 percent gravel; moderately alkaline; gradual wavy boundary. (Combined thickness of the Btk horizon ranges from 15 to 45 inches)

BC--41 to 80 inches; reddish brown (2.5YR 4/4) clay; weak coarse prismatic structure; firm; few fine roots between peds; common medium irregular faint light reddish brown (2.5YR 6/4) soft masses of calcium carbonate and few medium irregular prominent greenish gray (5GY 6/1) carbonate coats on vertical faces of peds; many very fine and fine irregular prominent black (N 2.5/0) soft masses of iron-manganese oxides; violently effervescent (13 percent calcium carbonate); about 2 percent gravel; moderately alkaline. (0 to 50 inches thick)

TYPE LOCATION: Douglas County, Wisconsin; about 1/2 mile east and 2 1/2 miles north of Poplar; 50 feet south and 920 feet west of the northeast corner of section 30, T. 48 N., R. 11 W.; USGS Poplar, WI quad.; lat. 46 degrees, 37', 08" N. and long. 91 degrees, 47', 14" W.

RANGE IN CHARACTERISTICS: Depth to the base of the argillic horizon ranges from 40 to 60 inches. Depth to free carbonates ranges from 20 to 40 inches. The weighted average clay content of the particle-size control section ranges from 60 to 85 percent. These soils have linear extensibility of 6 cm or more in the upper 40 inches. Volume of gravel ranges from 0 to 6 percent throughout. Volume of cobbles ranges from 0 to 2 percent throughout. Mudflow lenses or remnant discontinuous disoriented varves occur in individual horizons in some pedons. Redox features occur in all layers between either the lower boundary of an Ap horizon or a depth of 10 inches below the mineral soil surface (whichever is deeper) and a depth of 16 inches. Aquic conditions occur within 20 inches for some time in most years. Cuttre soils react positively to alpha, alpha-dipyridyl at some time when the soil is saturated.

The A horizon has hue of 5YR, or 7.5YR, value of 2 or 3, and chroma of 1 to 3. Cultivated pedons have an Ap horizon with hue of 5YR or 7.5YR, value of 3 or 4, and chroma of 2 or 3. Reaction naturally ranges from very strongly acid to moderately acid but ranges to neutral, where the soil is limed.

Some pedons have an E horizon with hue of 2.5YR, 5YR or 7.5YR; value of 4 or 5, and chroma of 2 or 3. Colors of 4/3 or 5/3 have value dry of 7 or more. The E horizon is loam, silt loam, silty clay loam, clay loam, silty clay or clay.

Cuttre soils have a glossic horizon (E/B or B/E horizon or both). The E part has color like the E horizon described above. Typically, it is clay loam, silty clay loam, silty clay or clay but in some pedons, it is silt loam or loam in the upper part. The Bt part has hue of 2.5YR or 5YR, value of 3 to 5, and chroma of 3 to 6. It is silty clay loam, silty clay, or clay. Reaction is strongly acid or moderately acid.

The Bt horizon has hue of 2.5YR or 5YR, value of 3 or 4, and chroma of 4 to 6. Reaction is neutral or slightly alkaline. Typically, it is clay but sub-horizons of silty clay are in some pedons.

The Btk horizon has hue of 2.5YR or 5YR; value of 3 to 5; and chroma of 4 to 6. Reaction is slightly alkaline or moderately alkaline.

The BC horizon has hue of 2.5YR or 5YR and value of 3 to 5. It is moderately alkaline or strongly alkaline.

Some pedons have a C horizon with color, texture, and reaction like the BC horizon described above.

COMPETING SERIES: This is the Borea series. Borea soils have stratified loamy and sandy lacustrine deposits in the lower part of the series control section at a depth of 40 to 60 inches.

GEOGRAPHIC SETTING: Cuttre soils are on flats, drainageways, depressions and long backslopes on till plains. Slopes typically are 0 to 3 percent but range to 8 percent on backslopes and footslopes. They formed in clayey till derived from clayey lacustrine deposits. Mean annual precipitation ranges from 28 to 33 inches. Mean annual air temperature ranges from 36 to 43 degrees F. The frost free period ranges from about 90 to 120 days. Elevation ranges from 600 to 1000 feet.

GEOGRAPHICALLY ASSOCIATED SOILS: These are the Amnicon(T), Anton(T), Bergland, Borea(T), Miskoaki(T), and Sedgwick soils. The moderately well drained Amnicon soils, the well drained Miskoaki soils, and the poorly drained Bergland soils form a drainage sequence with Cuttre soils. The moderately well drained Anton soils and the somewhat poorly drained Borea soils form a drainage sequence in areas adjacent to some Cuttre soils where there is stratified loamy and sandy lacustrine deposits at 40 to 60 inches. The somewhat poorly drained Sedgwick soils are nearby where there is a loamy outwash mantle 10 to 24 inches thick over the clayey till.

DRAINAGE AND PERMEABILITY: Somewhat poorly drained. Runoff is low to high. Permeability is extremely slow or very slow. Cuttre soils have a perched seasonal high water table at a depth of 0.5 to 2.0 feet for much of the time from September to June in most years. On the steeper slopes the duration is about a month following snowmelt and/or periods of heavy rainfall.

USE AND VEGETATION: Most area are used for woodland. Some areas are used for cropland or pastureland. Oats, timothy, brome grass, bluegrass, alfalfa, and trefoil are the principal crops. Many areas which were formally cropland are now idle and are reverting to natural vegetation. Native vegetation is mixed deciduous and coniferous forest. Common trees are red maple, balsam fir, balsam poplar, quaking aspen, paper birch, bur oak, and willow. Common understory plants are speckled alder, redosier dogwood, black snakeroot, wild sarsaparilla, and bracken fern.

DISTRIBUTION AND EXTENT: Northern Wisconsin along Lake Superior (MLRA K92). This series is extensive.

MLRA SOIL SURVEY REGIONAL OFFICE (MO) RESPONSIBLE: St. Paul, Minnesota

SERIES ESTABLISHED: Douglas County, Wisconsin, 1994. The name is coined.

REMARKS: An Aeric Vertic subgroup should be proposed to recognize the vertic feature. Diagnostic horizons and features recognized in this pedon: ochric epipedon - 0 to 3 inches (A); glossic horizon - 3 to 12 inches (E/B, B/E); argillic horizon - 6 to 41 inches (B/E, Bt, Btk1, Btk2); vertic feature - linear extensibility is 6 cm or more in the upper 40 inches; aquic feature - redox features in all layers between a depth of 10 inches below the mineral soil surface and a depth of 16 inches and aquic conditions within 20 inches for some time in most years.

Appendix C. Restoration and Prioritization Literature Review

Agricultural Conservation Planning Framework (ACPF) (Mark Tomer, USDA-ARS)

Researchers at the National Laboratory of Agriculture and the Environment in Ames Iowa recognized that a comprehensive approach is necessary to reduce nutrient loads from agricultural watersheds. The Tomer Tool was developed to meet this need, based on the concept that water quality must be improved, while also taking into consideration the requirements of agricultural practices. The developers focused on creating a technology that works to improve and maintain agricultural soil health in addition to water quality. The framework of the tool looks to create watershed specific strategies to implement water quality BMPs and soil conservation practices (CPs) in a way that is flexible, efficient and effective. The outputs produced by the tool are not prescriptive and provide various conservation options that can be implemented on any scale, from a single farm to an entire watershed.

The framework used to make the Tomer Tool first looks at improving soil health, then controlling water within fields, then controlling water below fields, and lastly riparian health. The first step in the framework is to provide recommendations to improve soil heath by reducing tillage, effectively using nutrients, and using crop rotation to enhance organic matter in the soil. The rest of the steps in the framework are designed to be run on ArcGIS software using mapping algorithms created by the developers. These steps produce a series of maps that denote areas where specific BMPs would be beneficial for improving water quality. The Tomer Tool is comprised of five separate GIS toolboxes: stream network development, field characterization, precision conservation practice siting, impoundment siting, and riparian characterization.
The inputs needed for the tool are a hydroconditioned DEM and an input dataset from the Agricultural Conservation Planning Database, located in Ames, Iowa. The dataset consists of watershed boundaries, agriculture field boundaries, gridded soil survey geographic (GSSURGO) soils data, a six year land use history table, and a six year crop history table.

Tomer, M. et al. 2013. “Combining precision conservation technologies into a flexible framework to facilitate agricultural watershed planning. *Journal of Soil and Water Conservation* 68(5): 113A-120A.

Prioritization, Targeting and Measuring Water Quality Improvement Application (PTMApp)

PTMApp is a tool created by Houston Engineering Inc., which looks at using geospatial data to prioritize locations for conservation practices with the objective of improving water quality. The PTMApp focuses on identifying subwatersheds and fields that would have the most benefit from the implementation of BMPs and CPs. In addition, the tool looks to quantify the effectiveness of BMPs and CPs in the reduction of sediment and nutrient loads. The tool works by finding areas which are contributing high levels of sediment, nitrogen, and phosphorus to a downstream water body. This is accomplished by having GIS layers for sediment yield, total phosphorus (TP) and total nitrogen (TN), which are then ranked using a percentile ranking with a log-normal distribution. From these values, a Water Quality Index (WQI) is calculated using the ranked values. From this assessment, specific sites within these critical areas are identified for BMP placement. BMP placement within these critical watersheds is carried out based upon topographic characteristics, soil type and land use.
The PTMApp requires hydroconditioned DEM watershed boundaries, catchments, single year land use data, and soils data. The input data required by the PTMApp also includes estimations of sediment, phosphorus and nitrogen yields. The sediment yield data is estimated using the Revised Universal Soil Loss Equation (RUSLE). This equation shows that soil loss is equal to: rainfall and runoff factor (R) * soil erodibility factor (K) * length-slope factor (LS) *cover and management factor (C) * support practice factor (P). The values for these factors were derived from a 3 meter DEM or with literature values. Once the sediment yield is calculated, the sediment delivery ratio can be calculated. The TP and TN values are calculated with an empirical method using literature values based on land use. Once the total amount leaving the landscape is determined, a nutrient loss equation is incorporated to get the TP and TN contribution to the catchment outlet, sub watershed outlet and the large scale watershed outlet.

Houston Engineering, Inc. (HEI). 2013. PTMA BMPs and Measurement Methods. Technical Memorandum to the MPCA.

Erosion Vulnerability Analysis for Agricultural Lands (EVAAL)

EVAAL is a GIS-based analysis tool, created by the Wisconsin Department of Natural Resources (WDNR) Bureau of Water Quality that was developed to support the prioritization and implementation of agricultural best management practices for improving surface water quality. It evaluates locations of relative vulnerability to sheet, rill, and gully erosion using readily available information about topography, soils, rainfall, and land cover. It is intended to locate where Best Management Practices (BMPs) assessment should be prioritized.

EVAAL exists as a GIS toolbox. It produces an erosion vulnerability index, areas vulnerable to sheet and rill erosion, areas of potential gully erosion and areas hydrologically disconnected from surface water. It then prioritizes areas based on erosion risk and deprioritizes areas that are not often hydrologically connected to surface water. The BMP target locations can be interpreted at their base resolution or aggregated to the level of an agricultural field or other boundary. EVAAL was designed for use on smaller watersheds (~75km^2). The inputs required for the tool are a hydrologic conditioned DEM, watershed boundary, gSSURGO soil data, culvert polygons, precipitation frequency and duration data, national cropland data layer.

Wisconsin Department of Natural Resources. 2014. “Erosion Vulnerability Assessment for Agricultural Lands (EVAAL)”. http://dnr.wi.gov/topic/nonpoint/evaal.html.

Zonation Model

Zonation is a conservation planning framework and software. It is a decision support tool for conservation resource allocation. This tool identifies areas that are important for retaining habitat quality and connectivity for multiple species, habitats, ecosystems and ecosystem services, etc., while aiming for long-term persistence of biodiversity.
It produces a complementarity-based and balanced ranking of conservation priority over the entire landscape. Zonation gives a priority ranking by iteratively removing the grid cell or planning unit that leads to the smallest aggregate loss of conservation value, while accounting for total and remaining distributions of features, weights given to features and feature specific connectivity. The priority ranking starts with a full landscape and removes cells stepwise, minimizing loss, until there are none remaining. The least valuable cells are removed first, while the most important cells for maintaining biodiversity are kept until the end. Zonation provides for an analysis of data about the distribution of biodiversity features, such as species, ecosystems, environmental types or habitats, accounting for current occurrences and possibly for their future expected state, which is dependent on conservation intervention. It can also account for data about the spatial distribution of socio-economic factors relevant for finding conservation opportunities.

Zonation requires a raster layer for each biodiversity feature (species, ecosystems, ecosystem services, etc.) is included in the analysis. The output from zonation can be imported into GIS software to create maps and for further analysis.

This software is publically available. It can be used for reserve selection, reserve network expansion, evaluation of conservation area network, impact avoidance, balancing of alternative land uses, target-based planning and biodiversity offsetting. When including cost, it can also produce the most cost-efficient solutions.

University of Helsinki, Department of Biosciences. *CBIG Conservation Biology Informatics Group*. "Zonation Spatial Priority Ranking for Conservation and Land-Use Planning." <http://cbig.it.helsinki.fi/software/zonation/>.

Priority Management Zones (PMZs)

The primary objectives of this project is to create a process that provides a scalable, streamlined approach that combines GIS terrain and spatial analysis techniques with targeted site visits for pinpointing vulnerable lands where conservation implementation and funding will provide the most beneficial water quality improvements. It looks to provide repeatable and measurable methods for ranking vulnerable sites and is flexible. It allows for increasing complexity from the integration of other sources of data (modeling, soils, land cover, pourpoint stability, phosphorus indices, etc.) with terrain attributes to enhance decision-making. The process is meant to quickly and efficiently analyzes large watershed areas and quantify manageable number of high potential sites in a target area. It facilitates the development of watershed restoration and protection strategies and supports funding requirements that implementation projects be prioritized, targeted and measurable. Lastly, it assists with initiating conversations with agricultural producers, providing visual communication regarding potential conservation activities.

There are two components to the project. The first component is a GIS terrain analysis protocol. This was developed by Dr. Mulla and his staff at the University of Minnesota (Department of Soil, Water and Climate). It uses the state's LiDAR data sets to predict areas of the fields that have the greatest potential to concentrate flow/carry sediment & nutrients. A step-by-step document allows for the creation of maps that show target areas of Critical Source Areas (CSAs).

The second component is a suite of field evaluation tools to guide the assessment of the croplands and streams/ditches/conveyances in the project area to evaluate the importance of the site's potential for source reductions, interception treatment practices and improving channel stability or erosion control.

Wilson, Greg (Barr Engineering), David Mulla (University of Minnesota), Dylan Timm (University of Minnesota), and Jim Klang (Kieser & Associates). 2014. "Final Project Report for Identifying Priority Management Zones for Best Management Practice Implementation in Impaired Wetlands."

Stream Restoration Prioritization (SRP) Decision Support Tool for the Blue Earth River Basin

SRP is a tool that researchers can use to prioritize stream restoration in a relatively quick, productive and cost-effective way. The tool was created specifically to reduce stream bank and bluff erosion by prioritizing sites for restoration. The study to develop the tool was done in the Blue Earth River Basin, which is an area with a dramatically altered landscape and where agriculture is the dominant land use. The topography of the landscape ranges from hilly to flat and the soils are mostly poorly drained clay and silt/clay. Many of the streams in the area are entrenched and disconnected from their floodplains.

The SRP decision support tool calls to first do a preliminary screening. In this screening, one must find sites that are contributing large amounts of sediment due to bank or bluff erosion and are threatening damage to infrastructure or loss of land. This can be done by using aerial imagery to find stream locations of large bluffs, non-vegetated banks and where there is a high radii of curvature. The next step is to determine if restoration in even possible, which is done by communicating with landowners. Once a list of possible sites is set, then an estimation is made on the amount of erosion occurring at each site using LiDAR and GIS. The bank height, length of eroding bank and distance of the bank retreat need to also be determined as well as a priority set based on threats to infrastructure.

Following this preliminary screening and prioritization, field work is needed to confirm metrics previously found. The SRP tool calls for a use of the BANCS erosion estimation method. Lastly, there is a stream restoration prioritization score sheet, which is based on 13 metrics.

This sheet gives each site a score, which can then be used to rank and prioritize which sites for erosion control restoration projects.

Presnail, Mary Louise. "Prioritizing Stream Restoration: A decision support tool for use in restoring waters impaired by excess sediment in the Blue Earth River Basin in Minnesota." Thesis. University Of Minnesota, 2013. Print.

Minnesota Department of Agriculture Priority Setting in Watershed Restoration

Abstract
In support of TMDL work and related Clean Water Act planning in Minnesota, a decision tool was developed to identify stream reaches with high rates of sediment loading from erosion and to identify potential locations for implementing BMPs to reduce that erosion either through water storage or stream restoration/stabilization or vegetation management. A three-tiered approach was used to develop a system to prioritize river reaches for restoration or management to reduce sediment loading, given as:

1. Tier 1: GIS and aerial photo analysis to determine long-term stream bank erosion rates using a lateral migration tool
2. Tier 2: Field data collection and verification using BEHI/BANCs to document processes, bank heights and materials: further focus on specific sites
3. Tier 3: Selection of specifics sites for restoration: site specific tool including cost / benefit, logistics, ecology and water storage benefits (The Stream Restoration Prioritization (SRP) tool by Presnail 2013). The methods used to provide scientific backing for the above approach are described in the report.

Several different GIS tools were used to assess stream bank migration rates including one new tool developed for this project.After identifying reach of the stream for more detailed investigation, sites are assessed in the field using the BANCS method which utilizes predictions of bank erosion risk (BEHI) and erosive force or near bank stress (NBS) to verify locations of high bank erosion and to identify the processes of bank collapse occurring in the field. Several region-specific BANCS models were developed for Minnesota to increase the accuracy of the tool. The site specific stream restoration selection tool developed by Presnail (2013) can then be used to prioritize locations for stream restoration or related sediment-reduction practices based on sediment loading rate, secondary benefits, logistical, and economic issues related to project selection.

Lenhart, C. and Nieber, J. 2015.*MDA priority setting in watershed restoration*, Final report to Minnesota Department of Agriculture. St. Paul, Minnesota.

Lower Columbia River and Estuary Habitat Restoration Prioritization Framework

The Restoration Prioritization Framework was designed as a decision-making tool for the Lower Columbia River Estuary Partnership, to help identify the highest-priority sites for restoration. The underlying concepts are derived from regional applications of aquatic restoration theory. The framework uses the conceptual model that physical controlling factors (e.g., light, temperature, hydrology) drive the formation and maintenance of habitats and their ecological functions, and that stressors act on the controlling factors. The framework is two tiered and comprises. In Tier I, the framework uses a GIS-based approach to evaluate impacts from a variety of human "stressors" such as diking, agriculture, overwater structures, and flow restrictions. Data processing derives priority scores, which are then relinked to the geographic sites in the GIS. In this manner, all of the data and tools employed can be analyzed and queried in a geospatial context. In addition to the core impact assessment, the framework includes tools to incorporate information on hydrologic connectivity and existing function into the priority screening. Specific restoration project proposals are evaluated in Tier II, using information on cost, expected functional change, site size, and predicted probability of success. Each site is scored using the equation: Site Score=predicted change in site ecological functions * relevant measure of the area encompassed by the project * an estimate of the probability for the site to meet the goal (success) / cost of project. Using this framework, one can screen for impacted areas, prioritize areas based on desired ecological criteria, and evaluate selected projects.

Thom, Ronald M., Evan Haas, Nathan R. Evans, and Gregory D. Williams. "Lower Columbia River and Estuary Habitat Restoration Prioritization Framework." *Ecological Restoration* 29 1-2 (2011): 94-110.

Multicriteria Decision Analysis (MCDA) Methods

Multicriteria decision analysis (MCDA) methods have the potential to improve restoration decision making because they provide a systemic way to compare alternatives and quantify achievement of objectives, even when economic information is unavailable. The methods work to ensure that the decision process is balanced and systemic so that restoration decisions are more likely to reflect the stakeholder's values. MCDA methods have been applied to valuations of water quality, water supply and river management. It can help people to articulate and communicate value and focuses on ultimate objectives and can improve negotiation efficiency by helping parties to focus on the most important issues and provides means for documenting reasons for agreements.

MCDA uses five criteria based upon a subjective scoring system are used to prioritize the reaches. In our scoring system, a simplification of that from the actual study, '1' indicates highest desirability for restoration, and '0' indicates lowest. Values between 0 and 1 represent intermediate levels of desirability. The criteria are:
$x1$ = channel condition scores (i.e., incision, presence of riffles, bank stability, and embeddedness); 0 = excellent condition; 1 = poorest
$x2$ = drainage area and impact on other reaches; 0 = highly influenced by upstream reaches with little impact downstream; 1 = highly influences downstream reaches
$x3$ = feasibility; 0 = all privately owned or construction access problems; 1 = all County owned, no access problems
$x4$ = riparian enhancement potential; 0 = no riparian area available for enhancing stormwater retention; 1 = large area available

*x*5 = full restoration potential; 0 = existing infrastructure limits restoration to small impacted areas; 1=no restrictions preventing full restoration

Corsair, H.J., Jennifer Bassman Ruch, Pearl Q. Zheng, Benjamin F. Hobbs, and Joseph F. Koonce. "Multicriteria Decision Analysis of Stream Restoration: Potential and Examples." *Springer Science+Business Media B.V.* 18 (2009): 387-417.

Appendix D: Bluff scan images, Erosion Hotspot maps, and ravine delineation maps

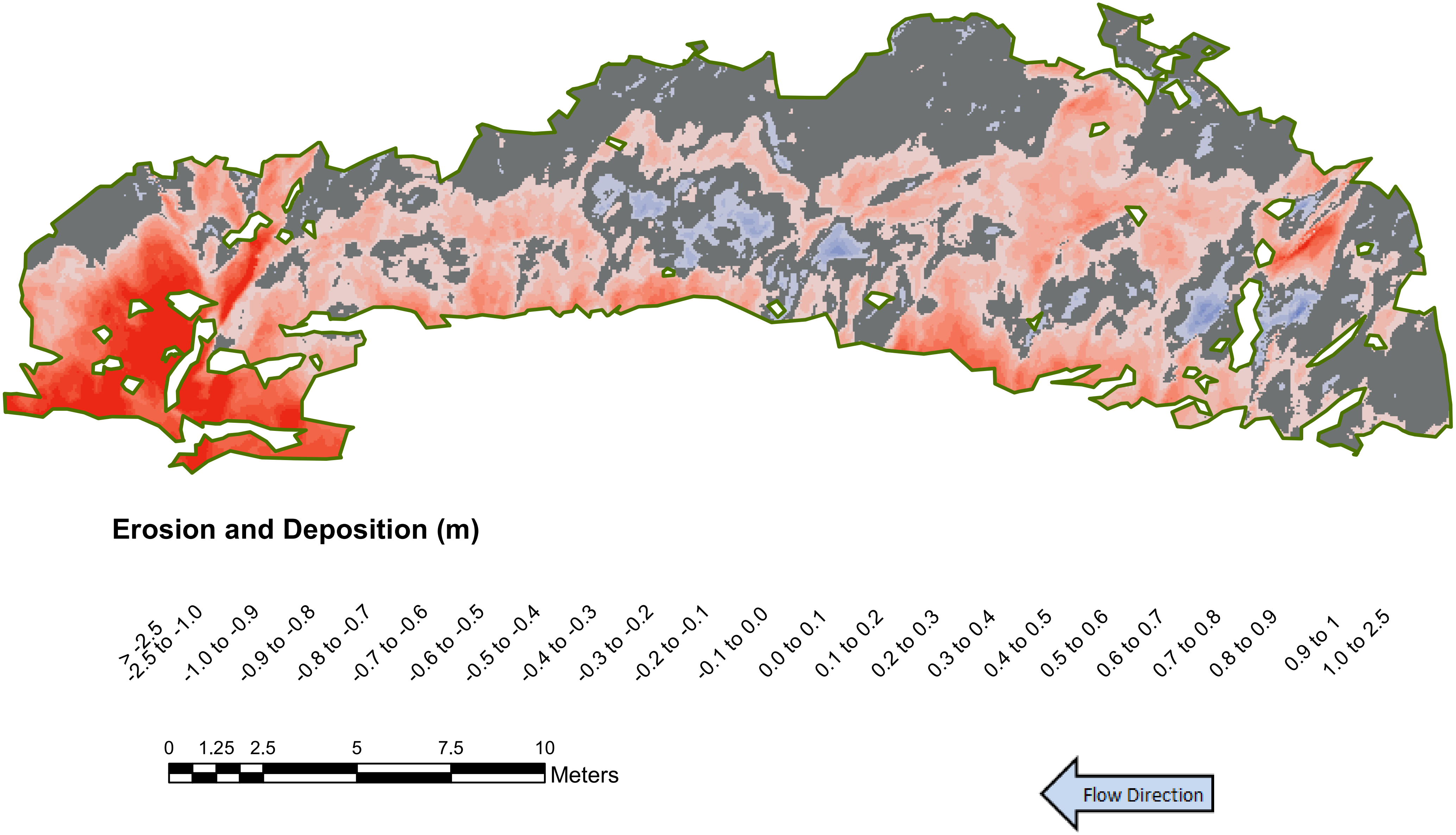
Bluff Scans: labeled “B” except for Hawk Hill Road: pages 39-90; see table of bluff names and sample dates below.

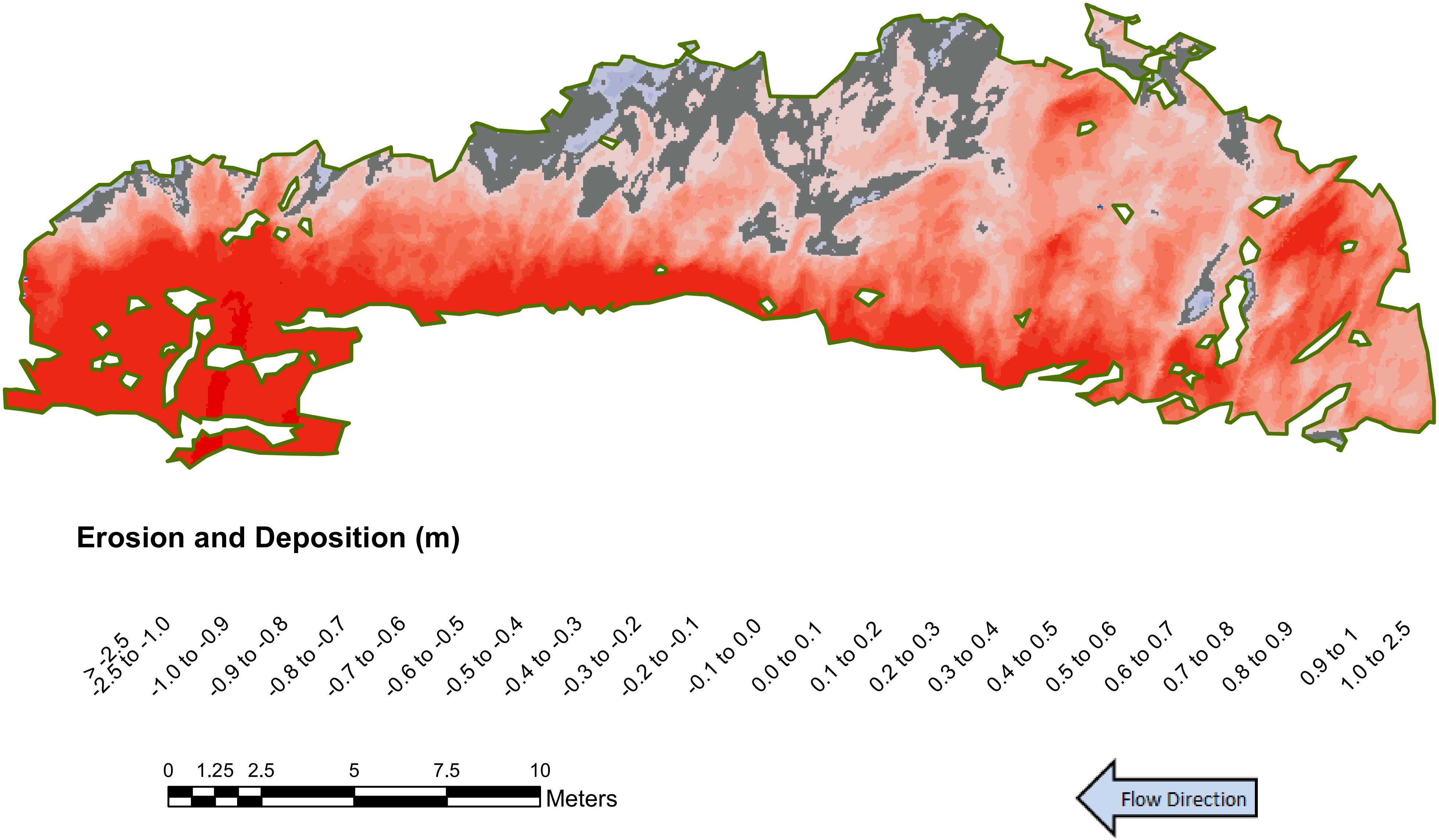
Erosion Hotspot Maps: radius of curvature, stream power index and erosion hotspots for study watersheds, pages 91-205

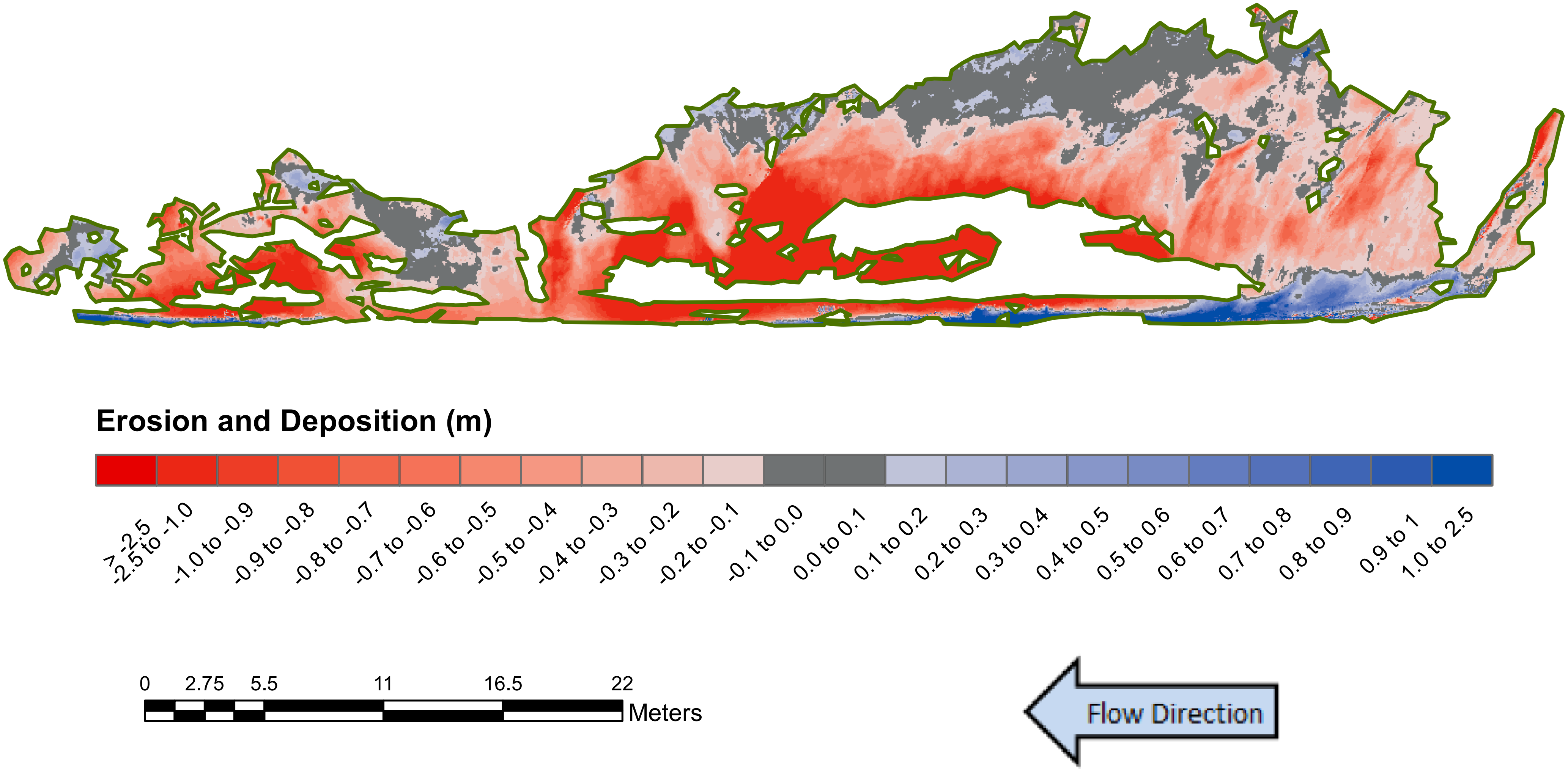
Ravine surface area, slope and drainage maps for the Beaver, Sucker and Knife River watersheds: pages 205-222

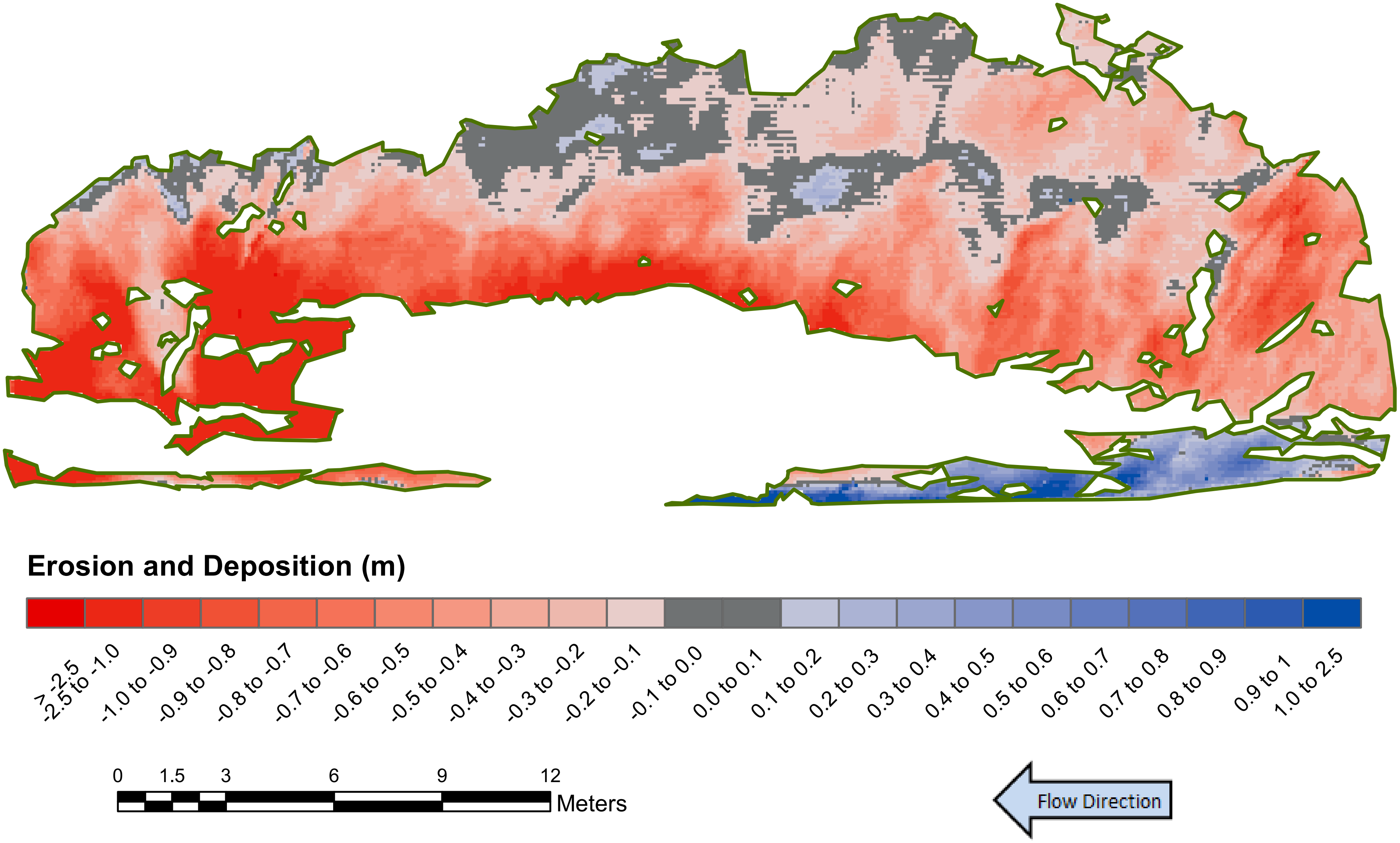
Table 4.1: Study Bluff Scan Dates

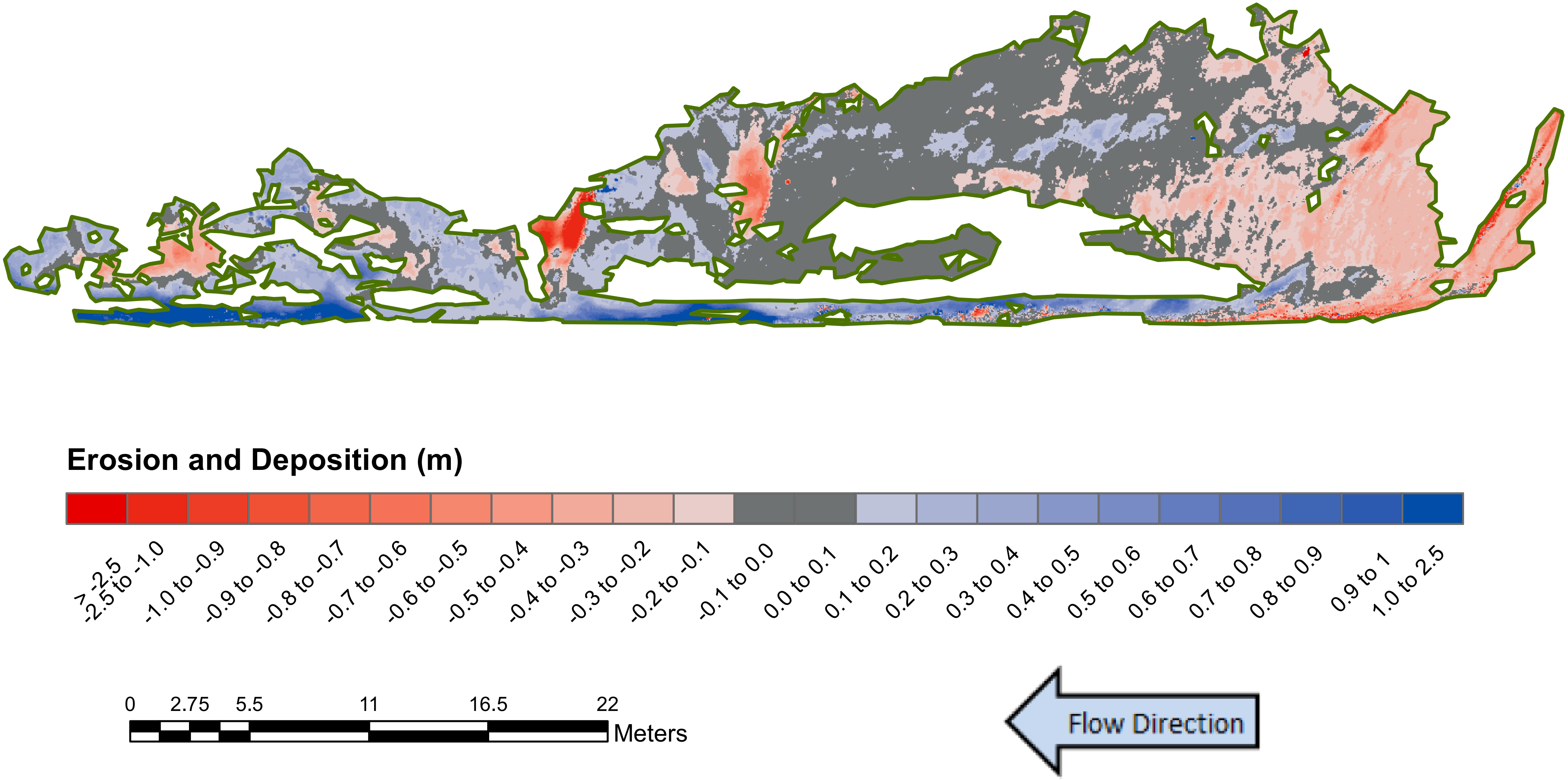
Stream	Bluff Name	2011	2012	2013	2014	2015
Amity	B9	November	April, May, June, November	November	September	April, November
Amity	B12	November	April, May, June, November		September	April, November
Amity	B13	November	April, May, June, November	November	September	April, November
Amity	B14		April, May, June, November	November	September	April, November
Amity	B15	November	April, May, June, November	November	September	April, November
Amity	B20		April, May, June, November	November	September	April, November
Lester	B2		April, May, June, November	November	September	April, November
Lester	B7		April, May, June, November	November	September	April, November
Knife	BHHR				September	April, November
Amity	BSWCD				September	April, November

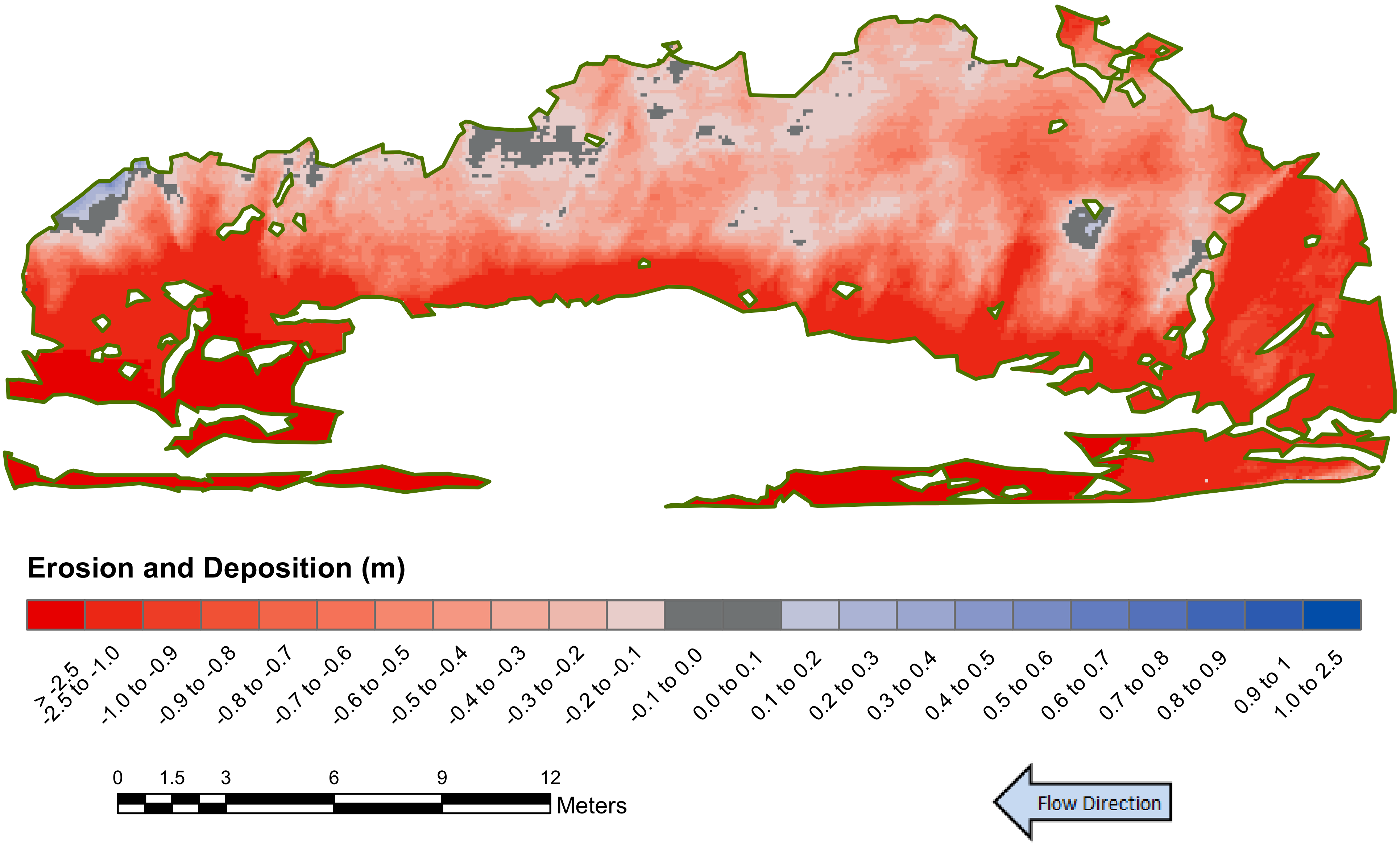

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.25
2.5
5
7.5
10
Meters
Flow Direction

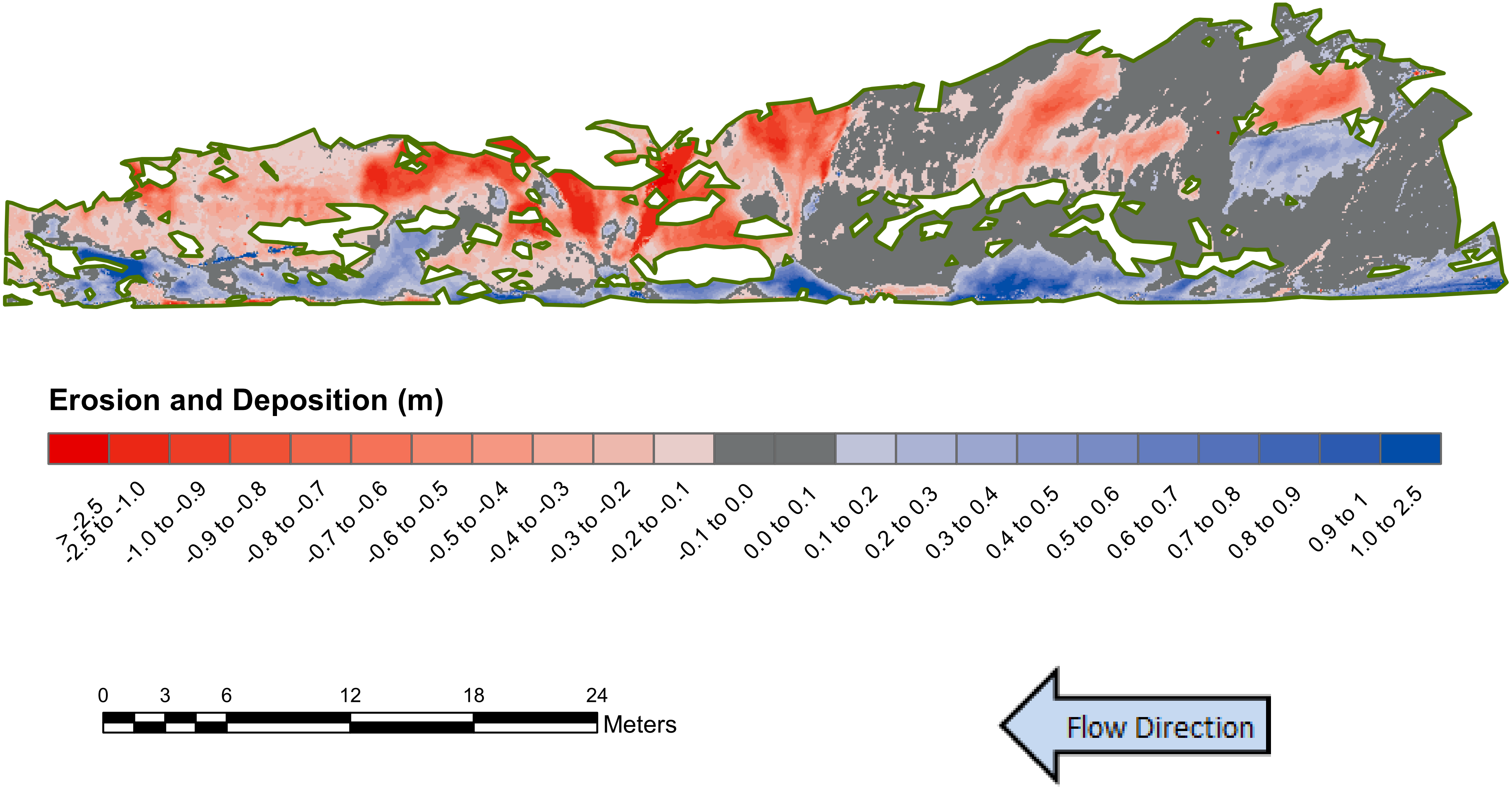

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.25
2.5
5
7.5
10
Meters
Flow Direction

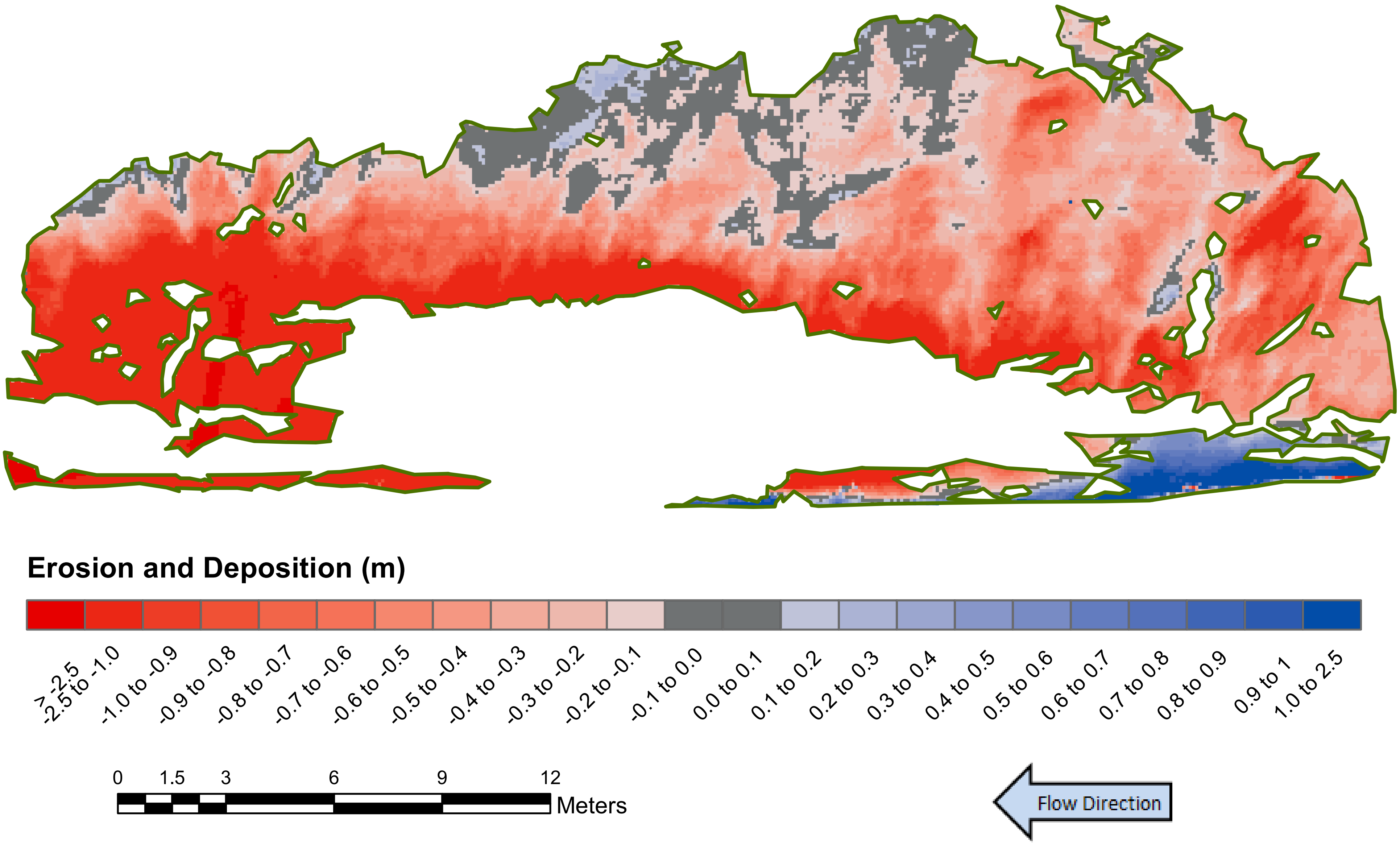

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2.75
5.5
11
16.5
22
Meters
Flow Direction

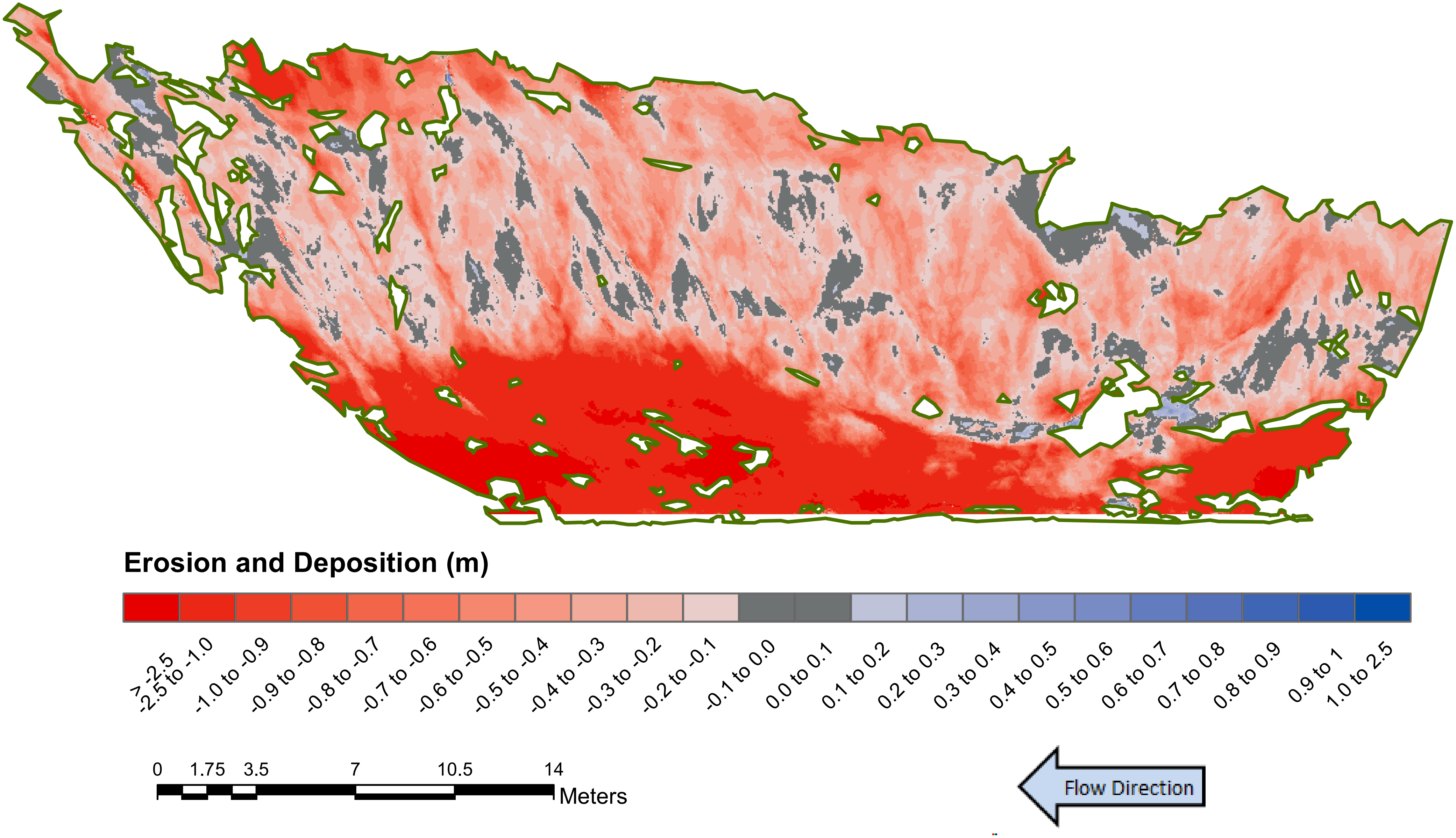

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.5
3
6
9
12
Meters
Flow Direction

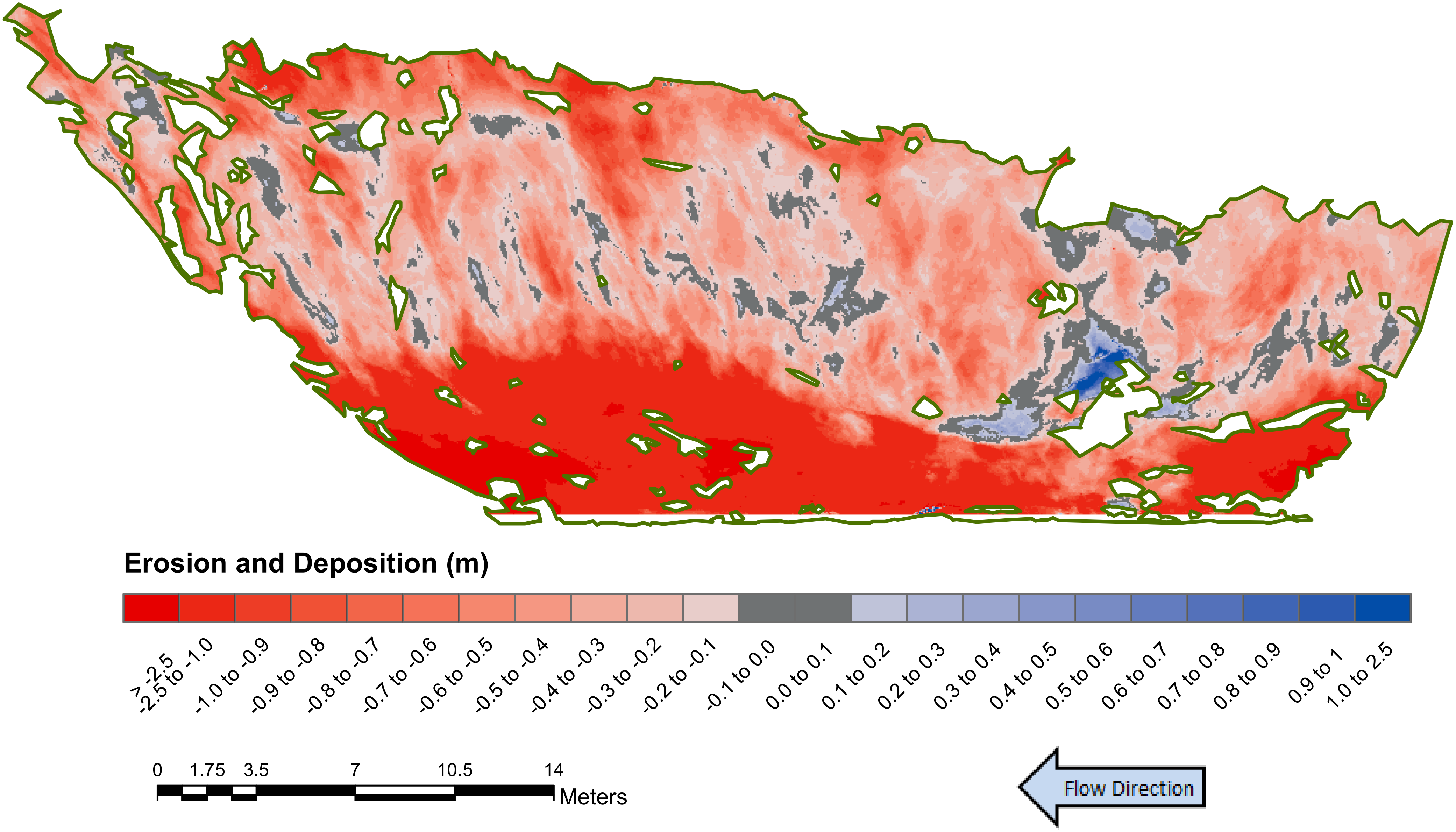

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2.75
5.5
11
16.5
22
Meters
Flow Direction

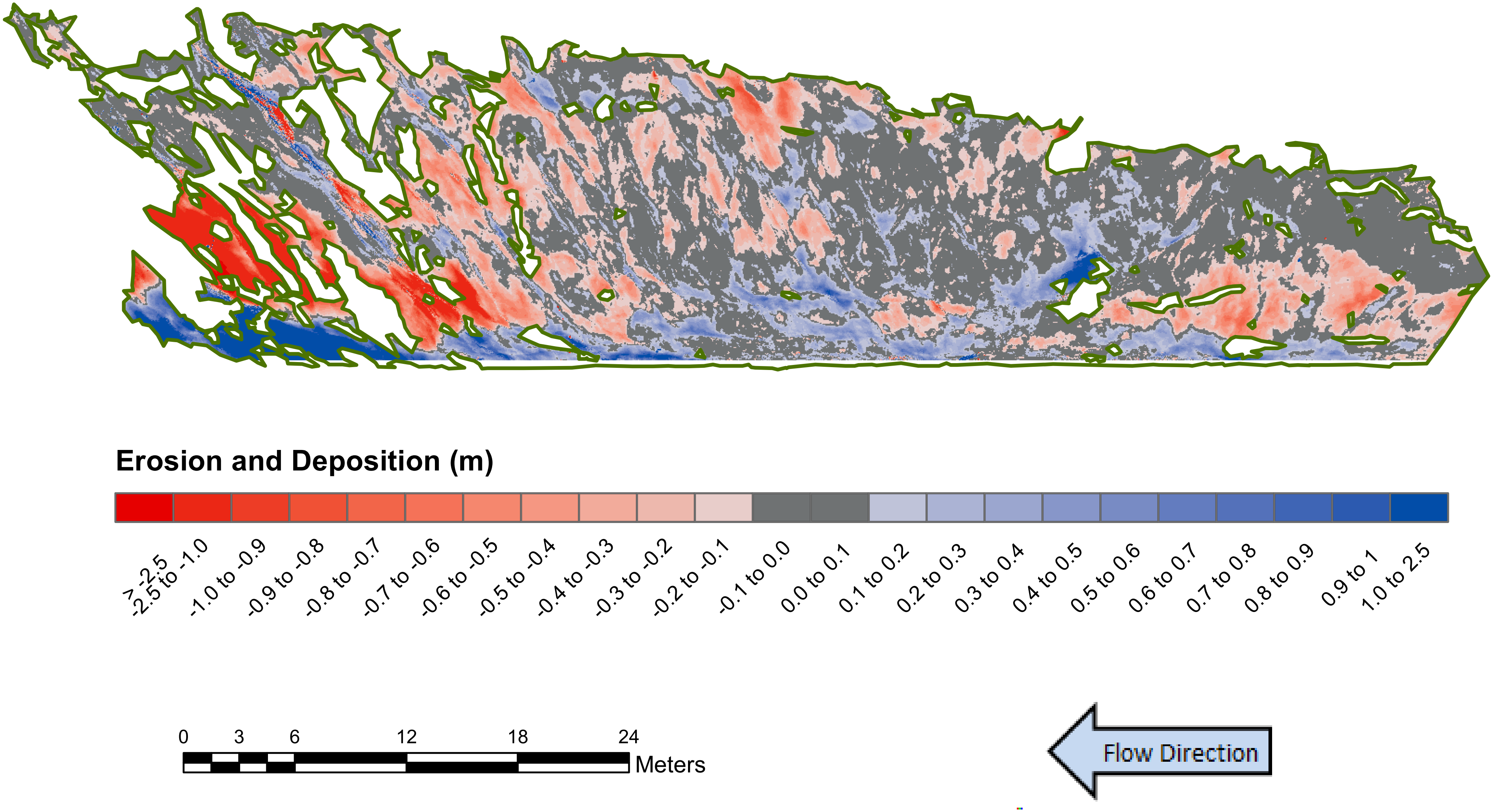

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.5
3
6
9
12
Meters
Flow Direction

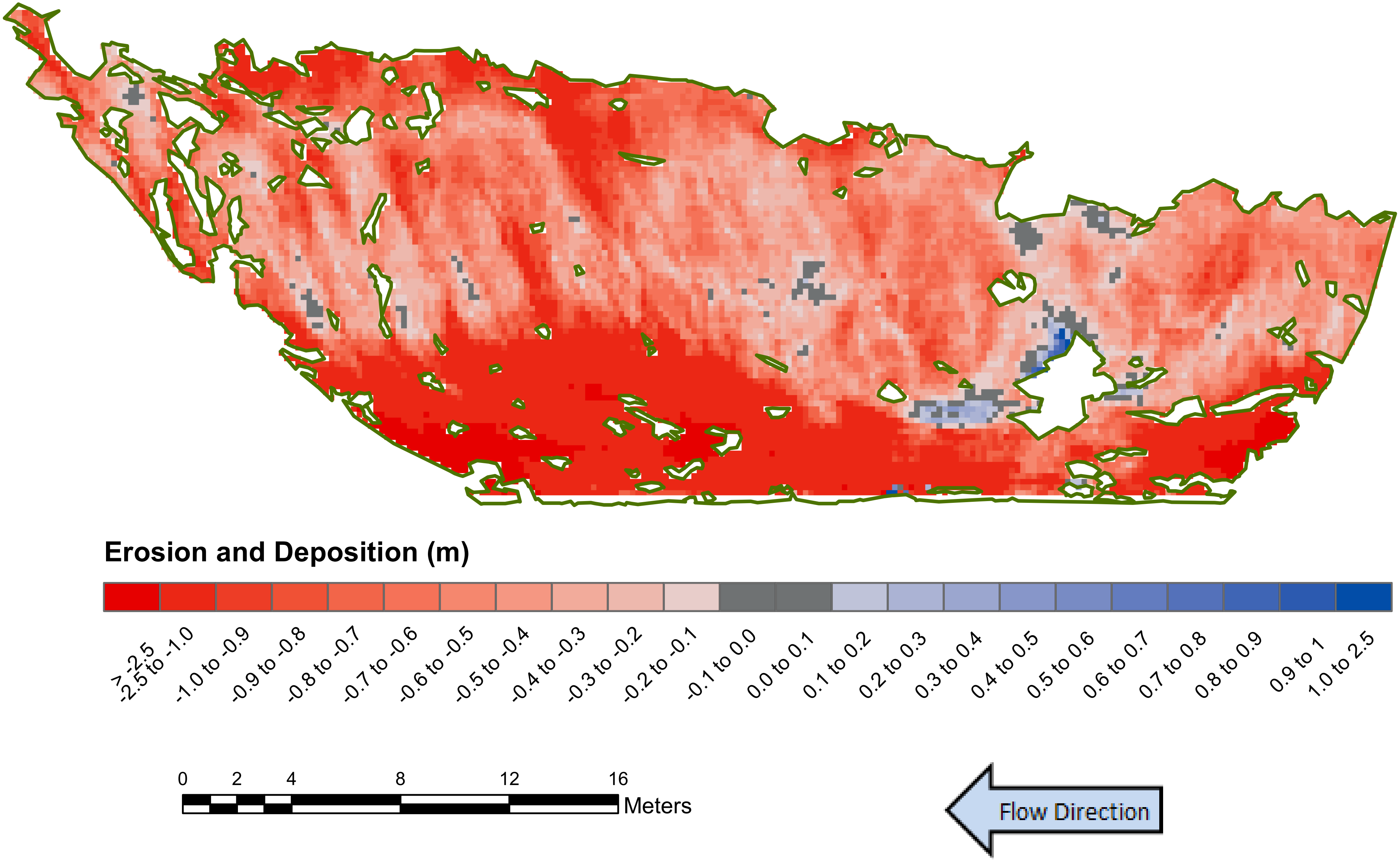

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
3
6
12
18
24
Meters
Flow Direction

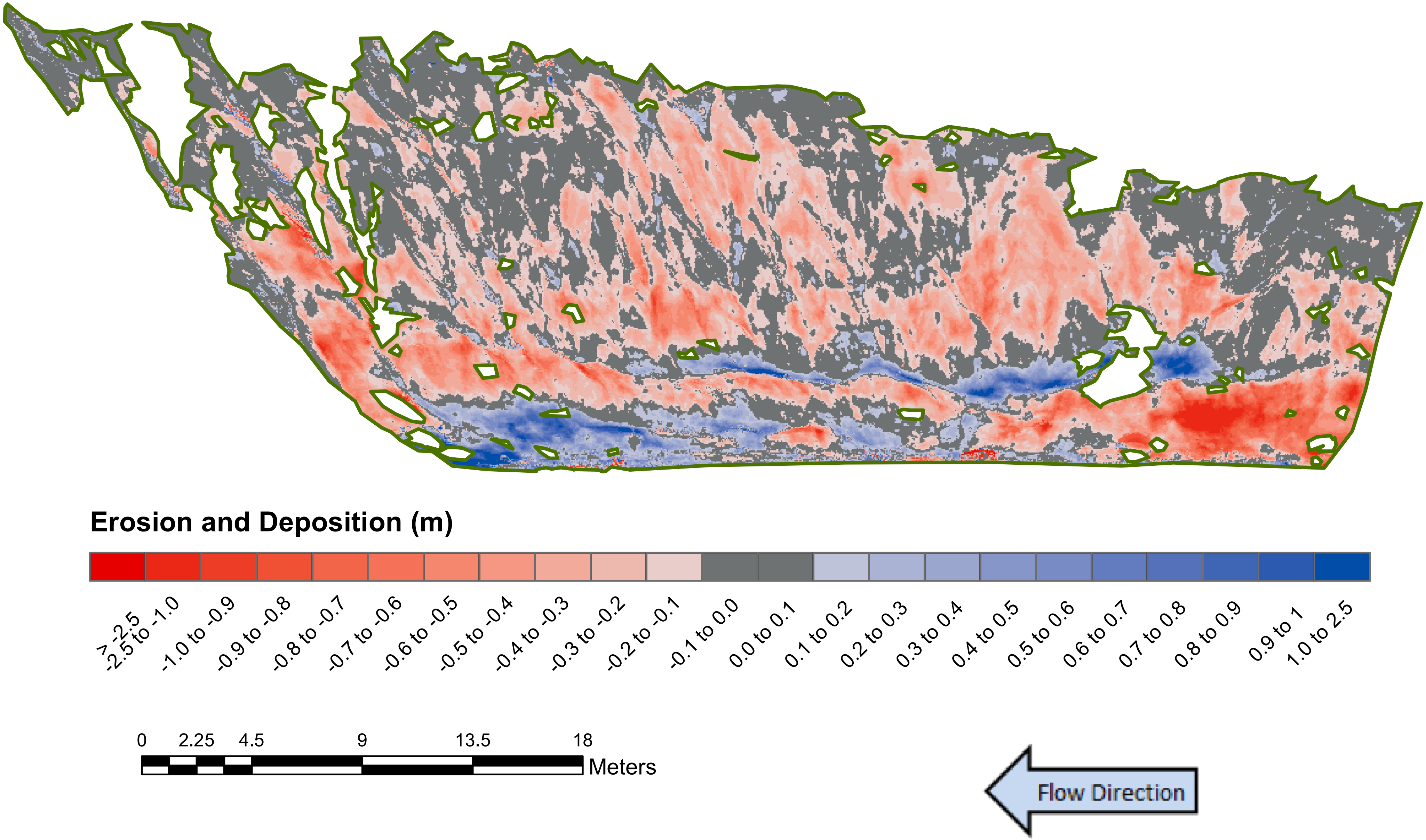

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.5
3
6
9
12
Meters
Flow Direction

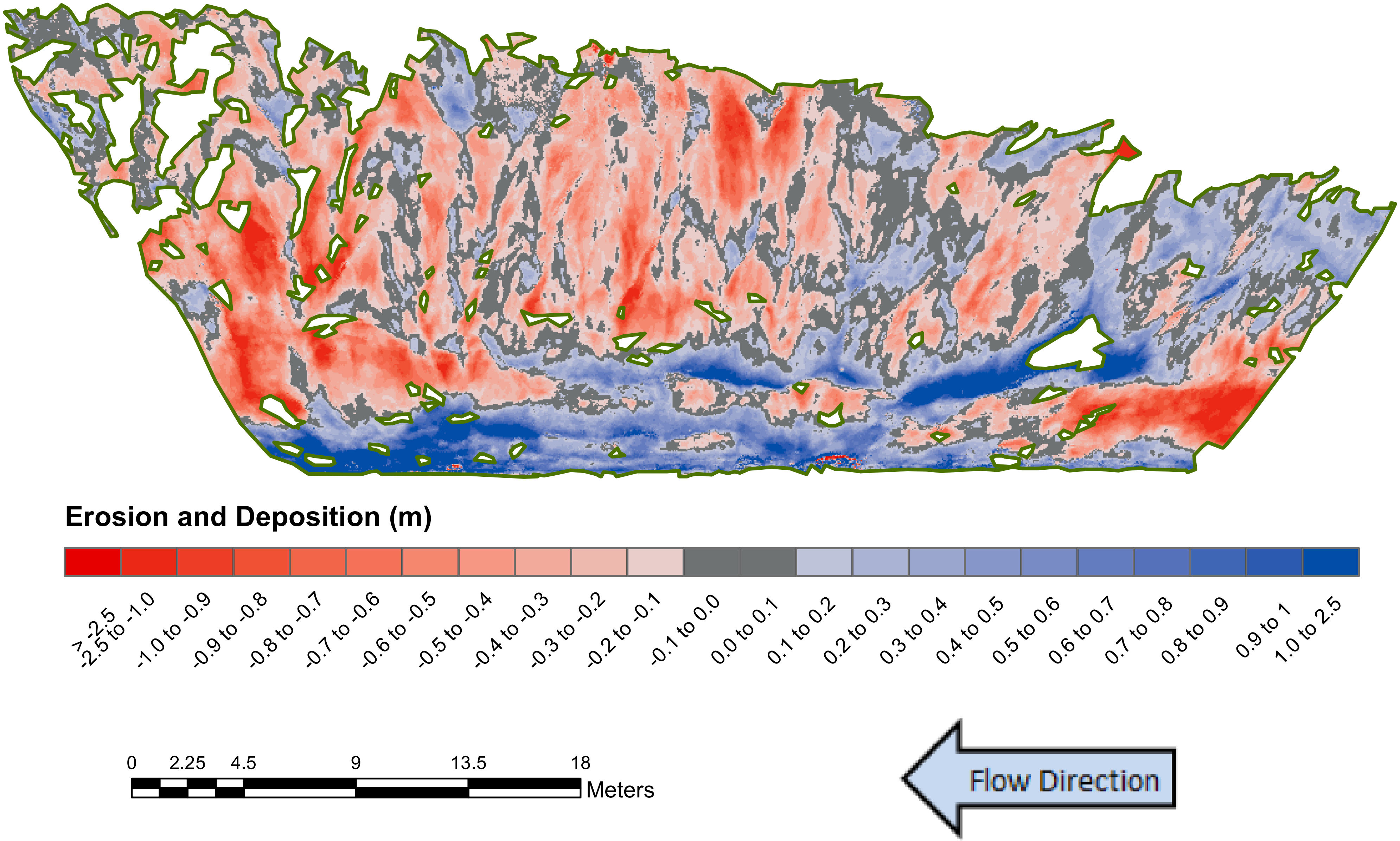

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.75
3.5
7
10.5
14
Meters
Flow Direction

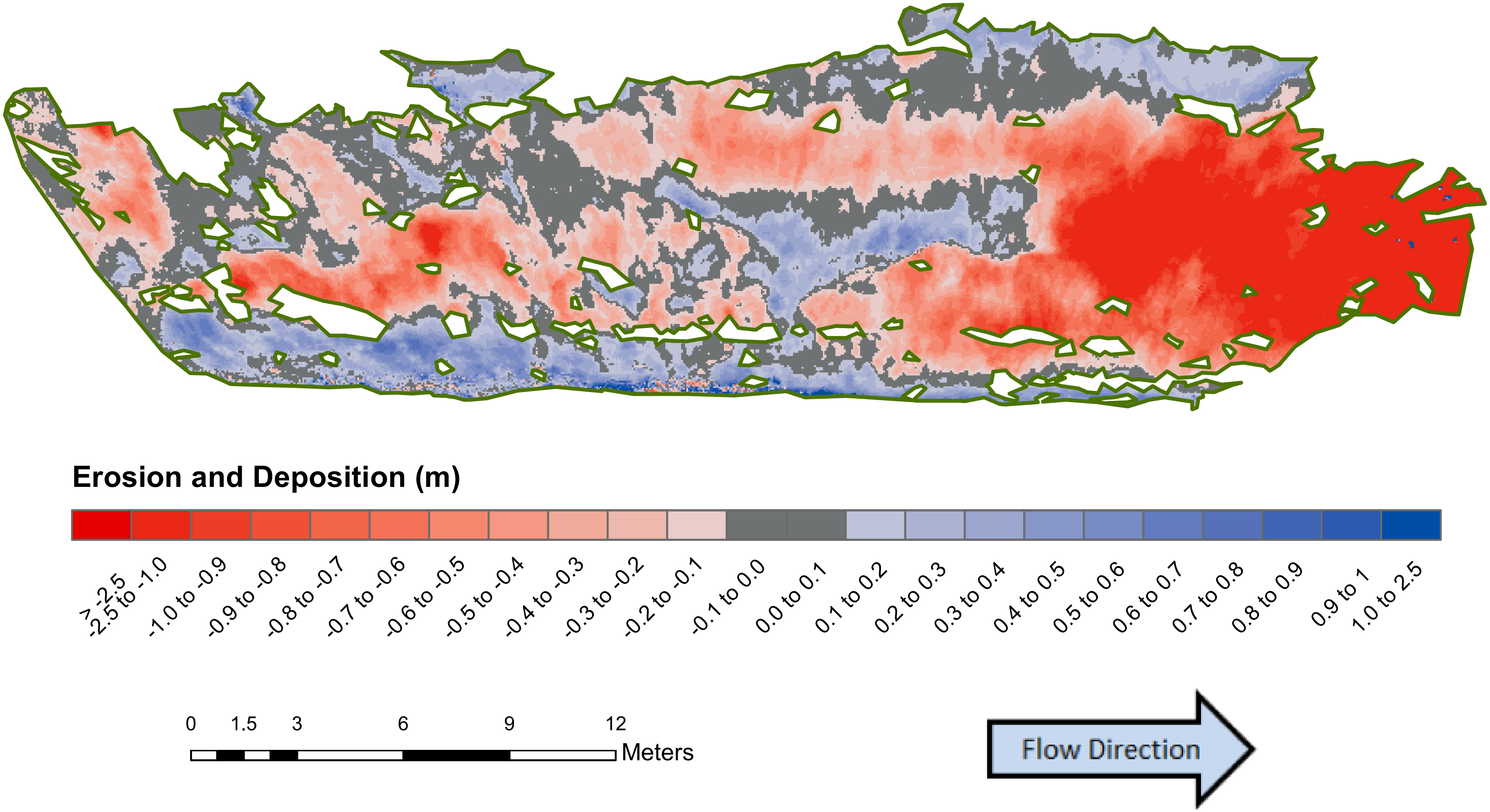

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.75
3.5
7
10.5
14
Meters
Flow Direction

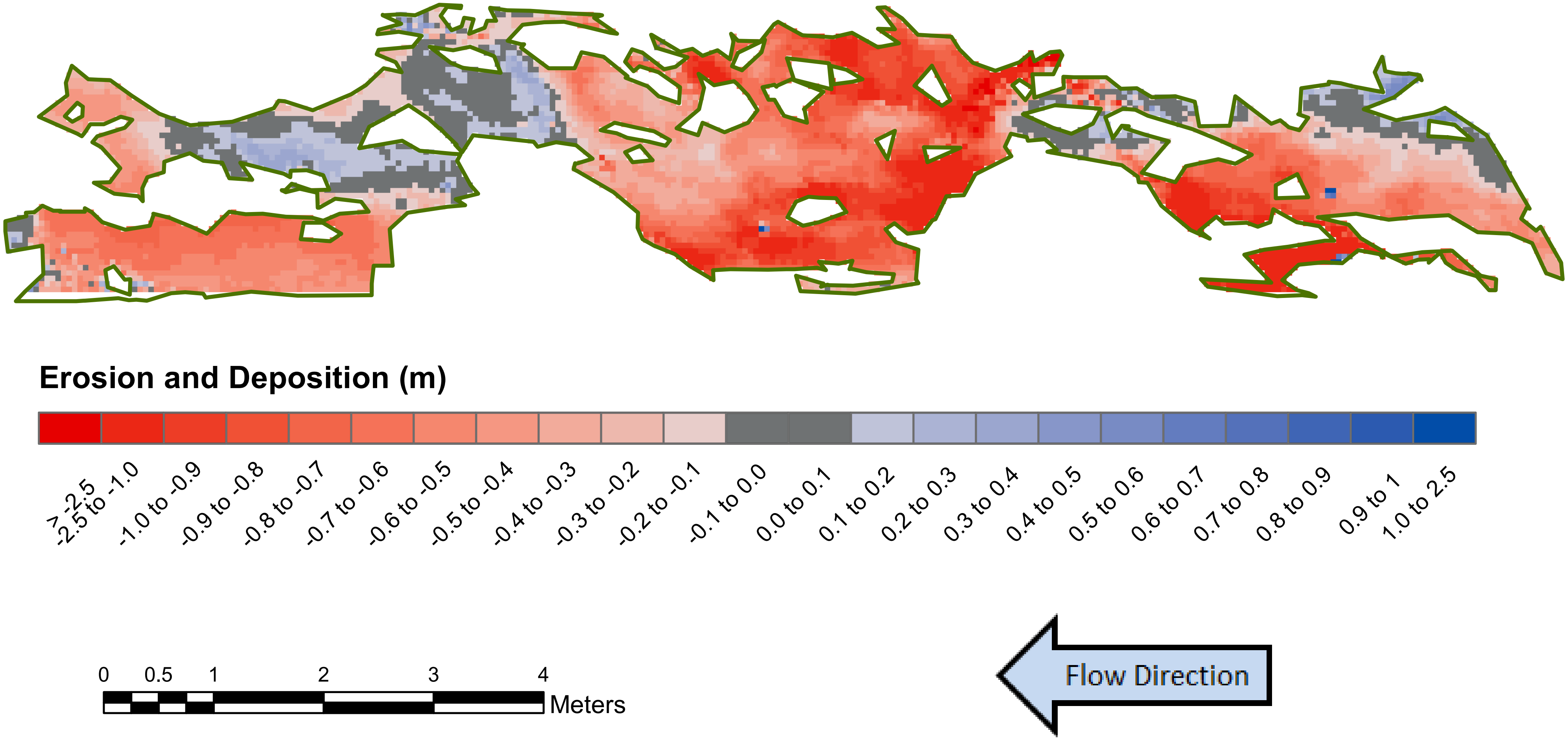

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
3
6
12
18
24
Meters
Flow Direction

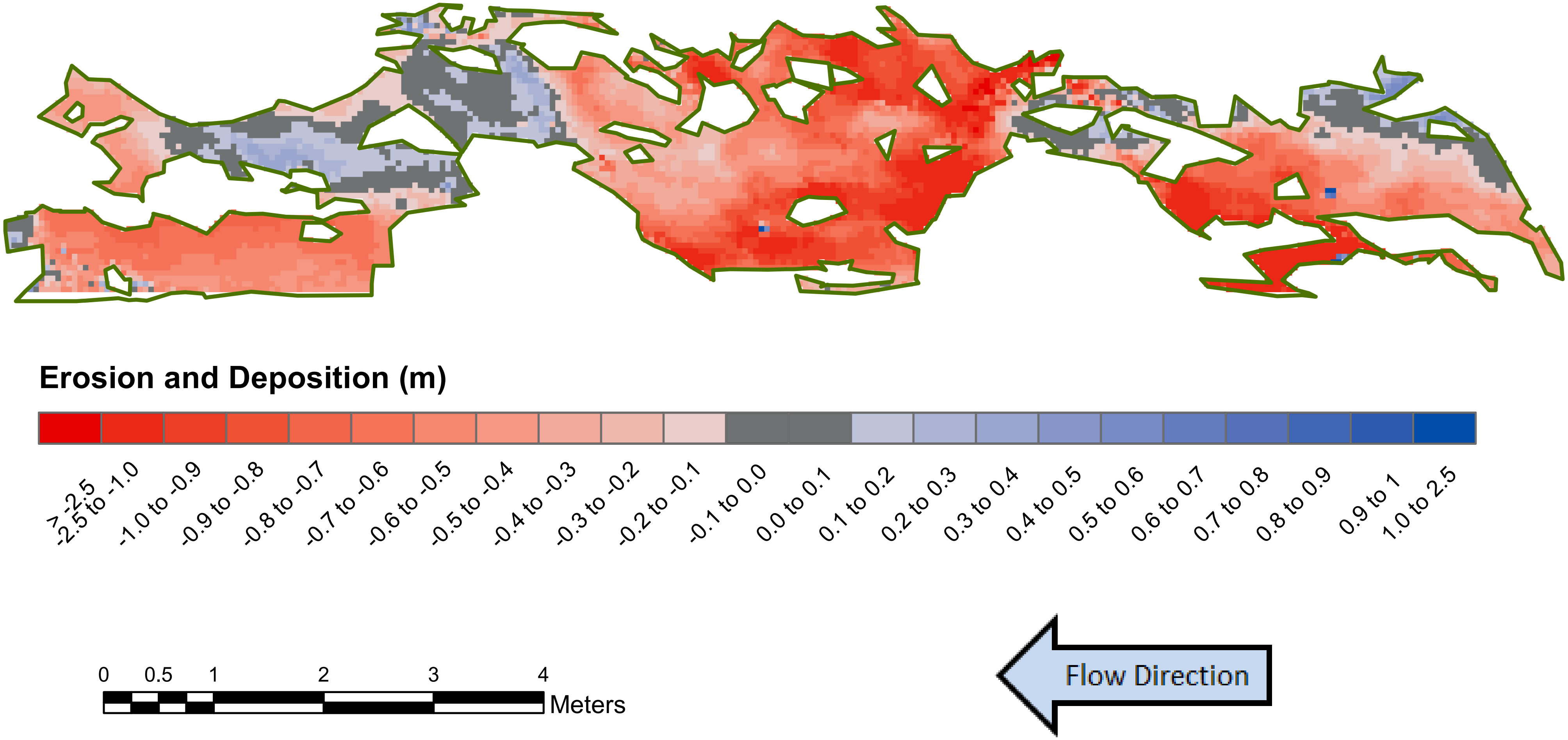

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction

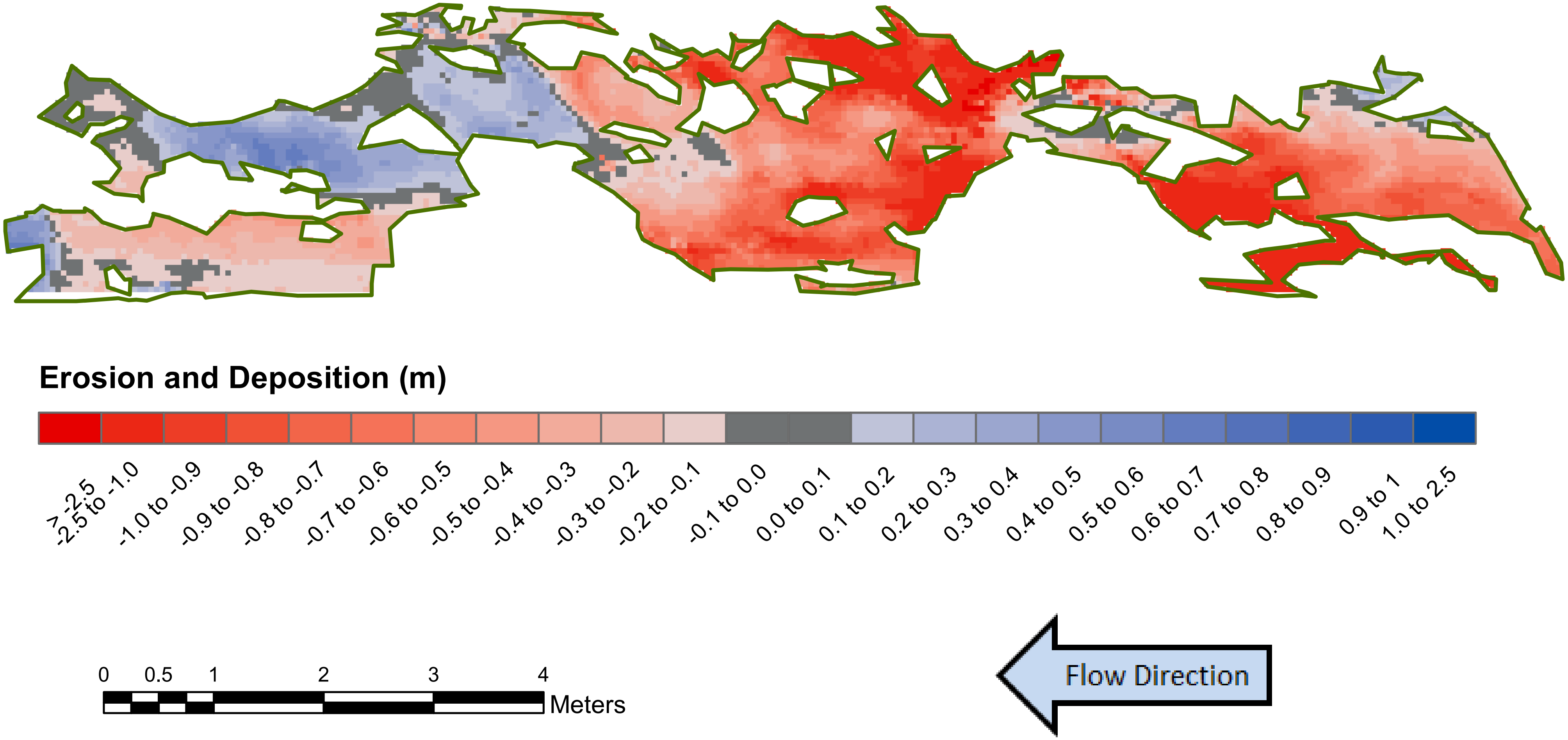

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2.25
4.5
9
13.5
18
Meters
Flow Direction

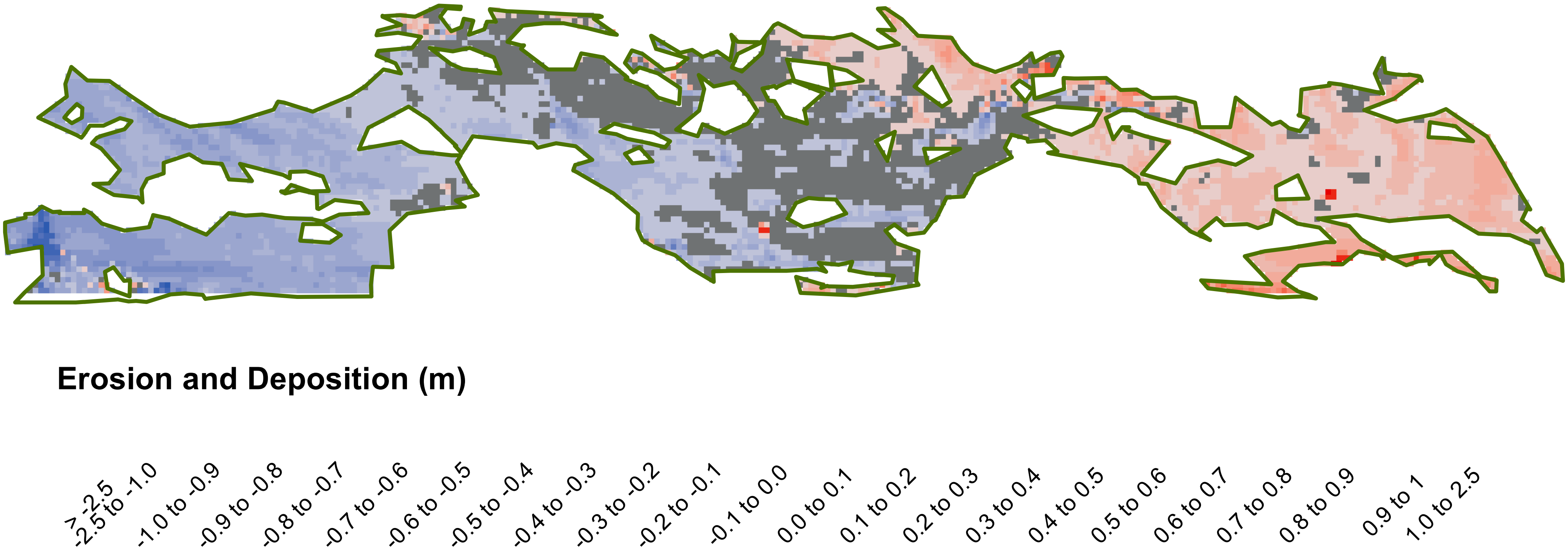

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2.25
4.5
9
13.5
18
Meters
Flow Direction

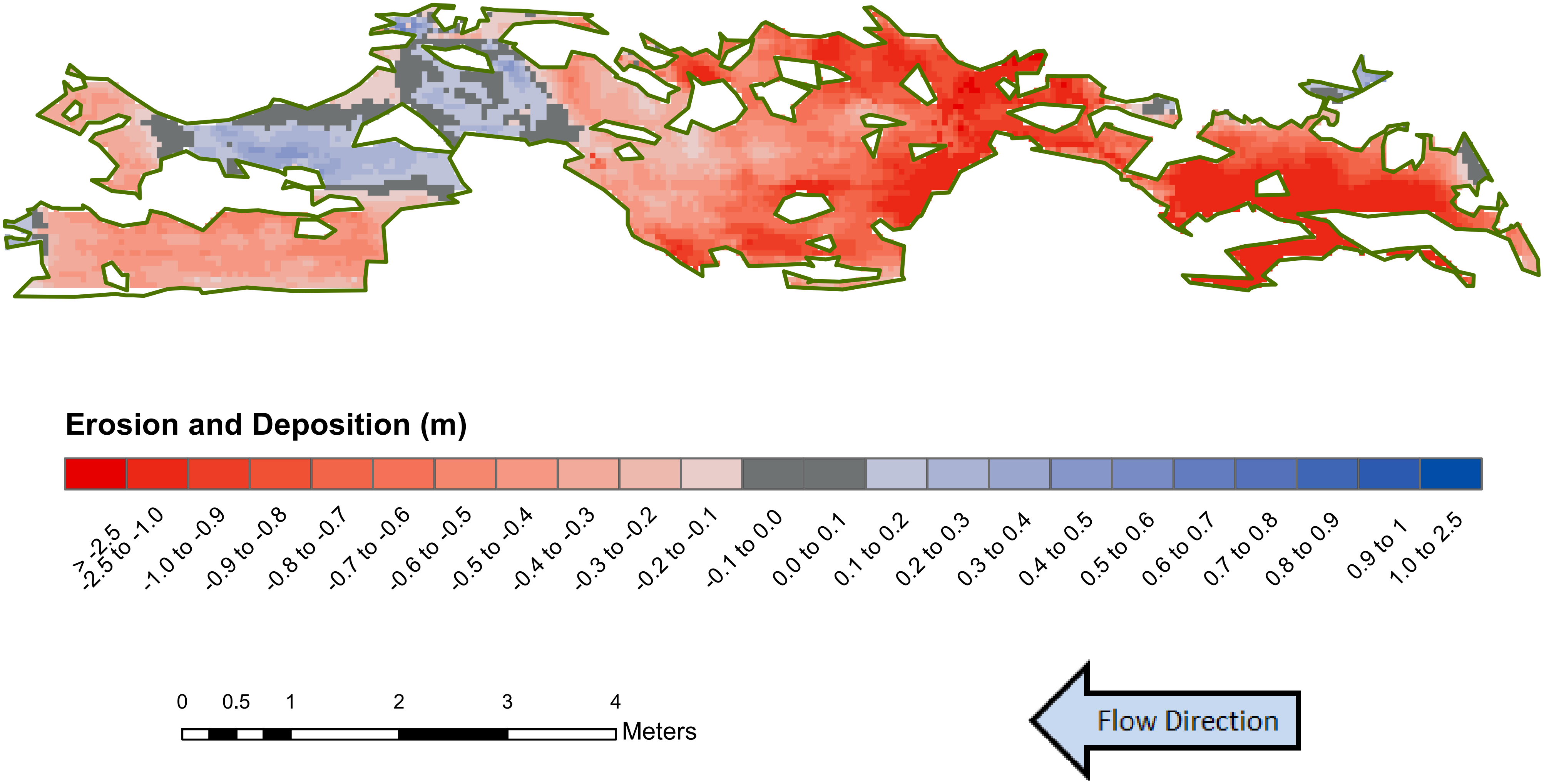

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.5
3
6
9
12
Meters
Flow Direction

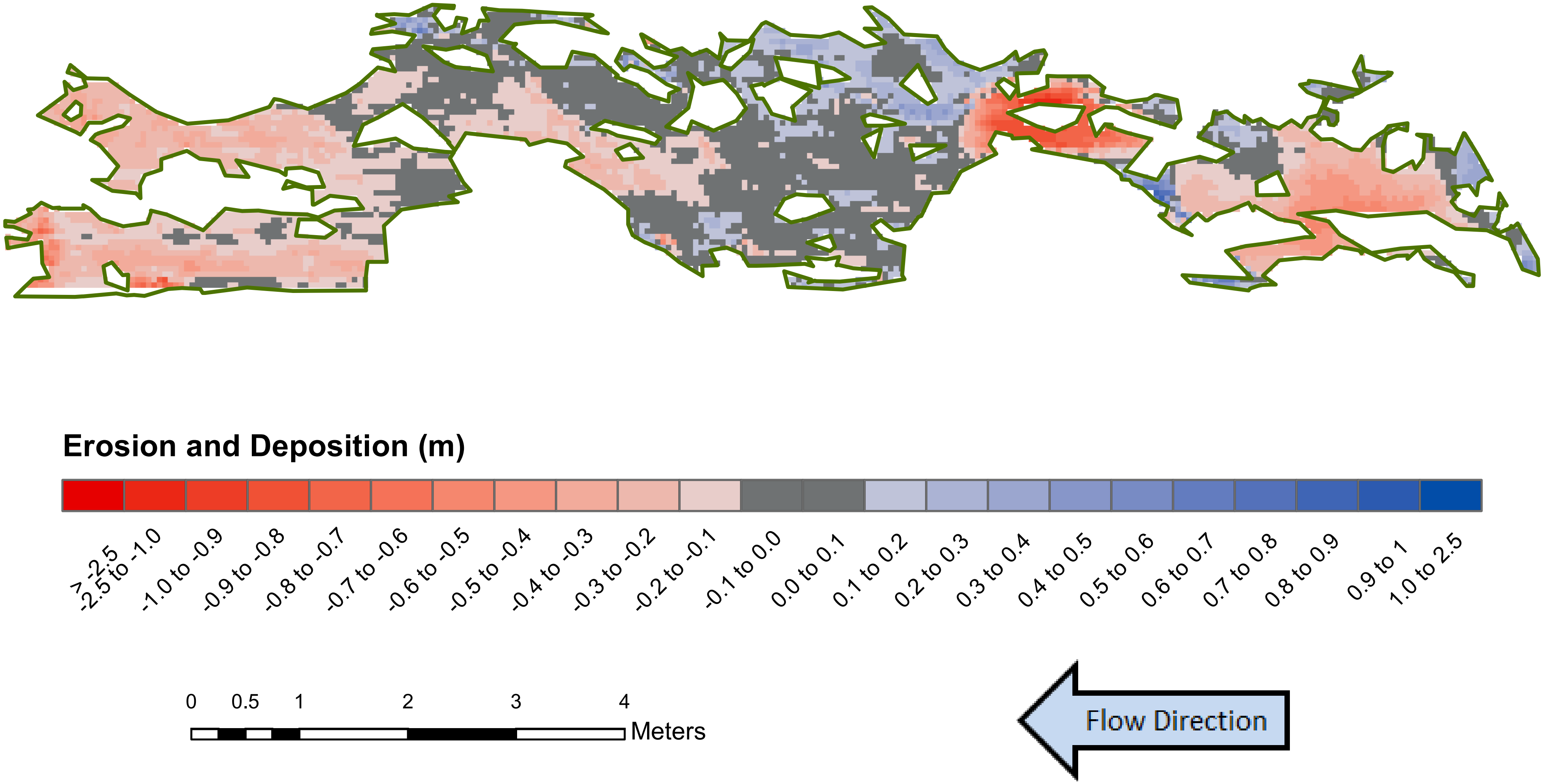

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

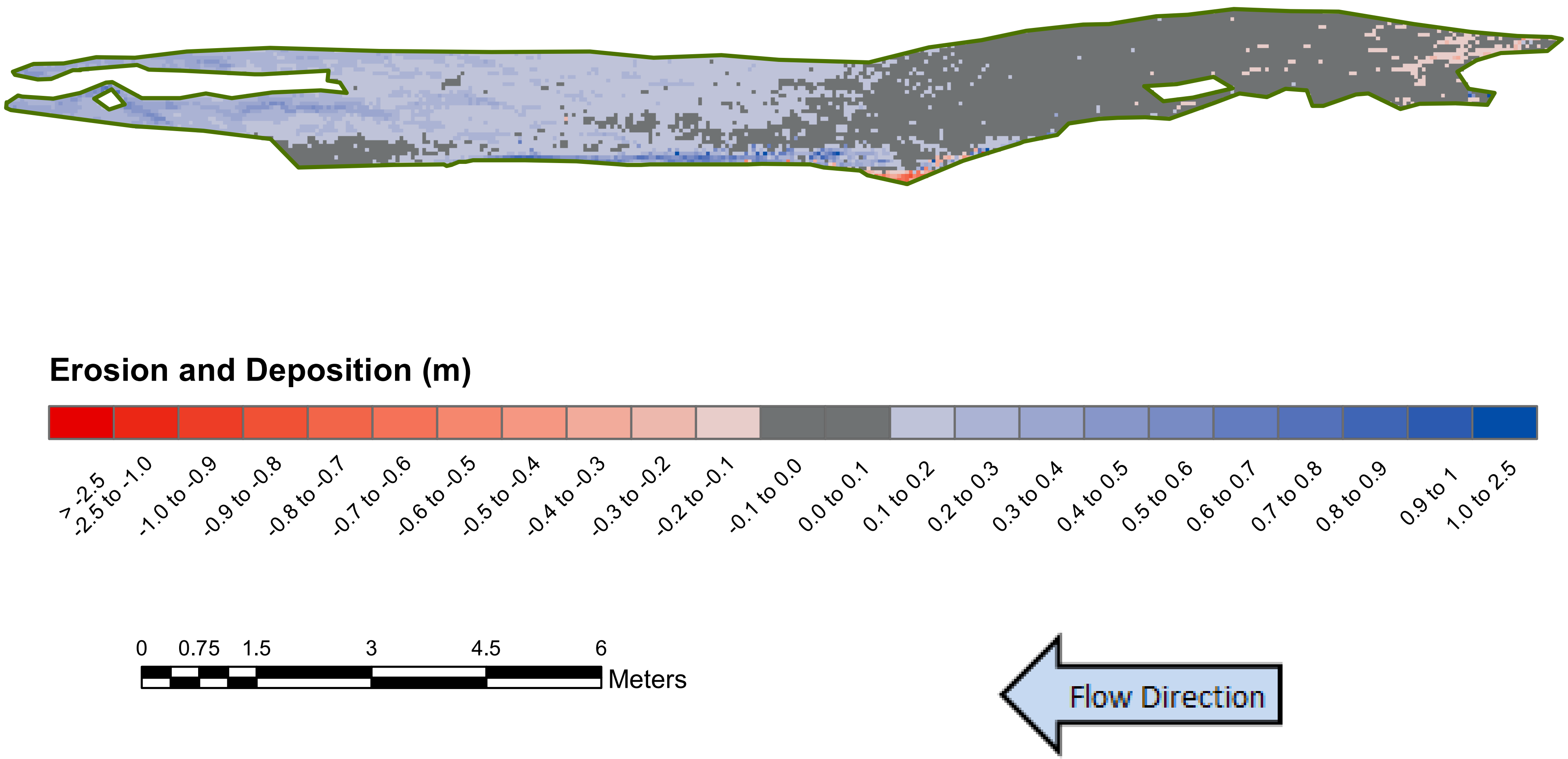

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

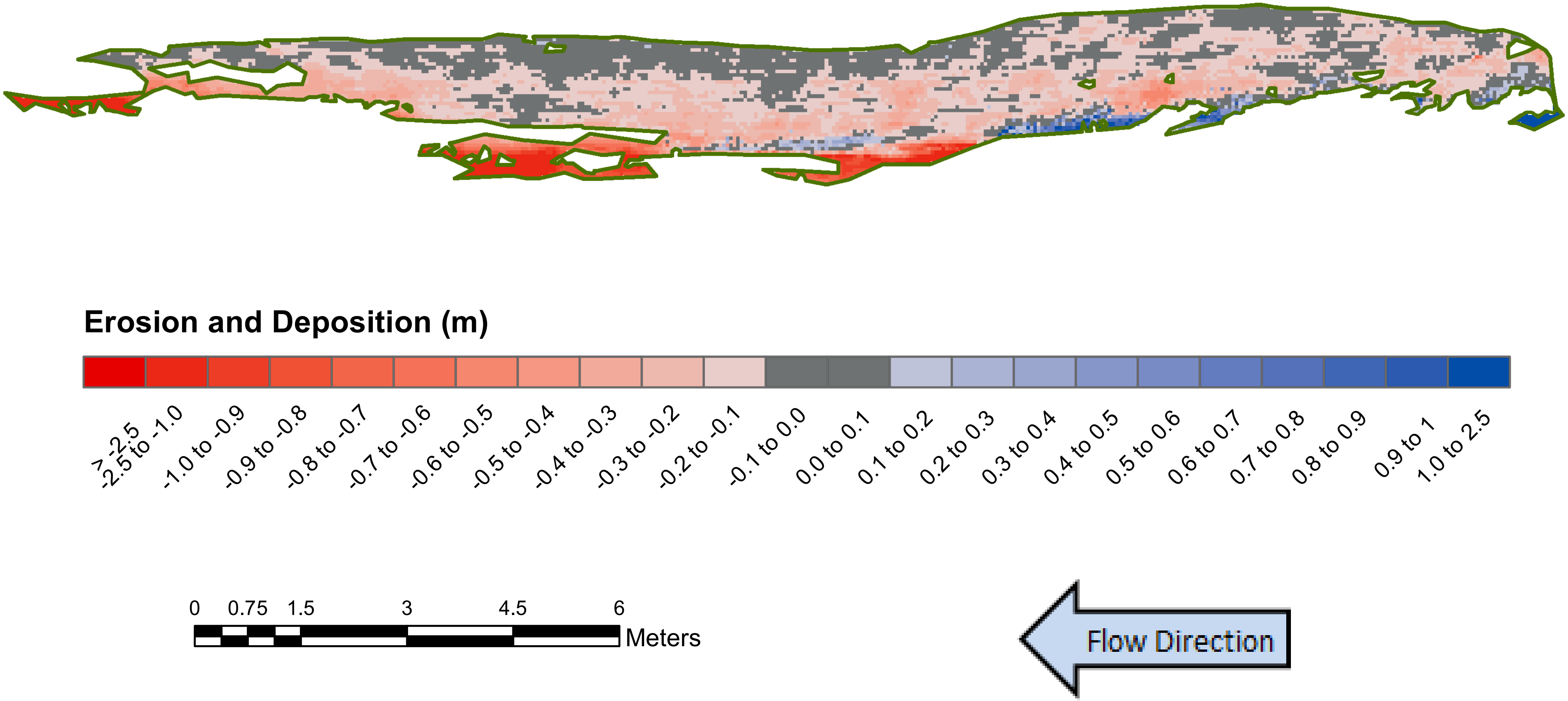

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

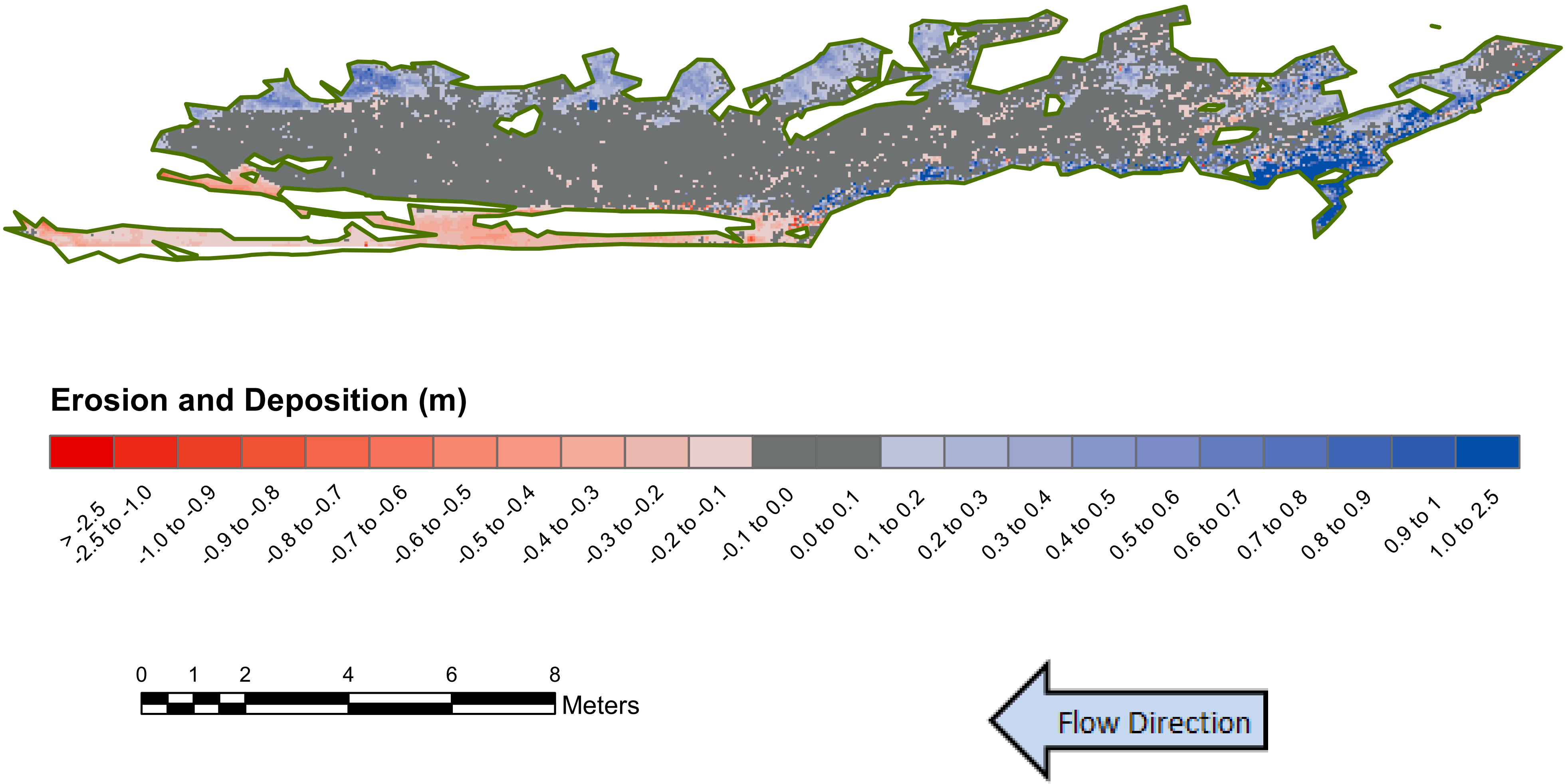

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5

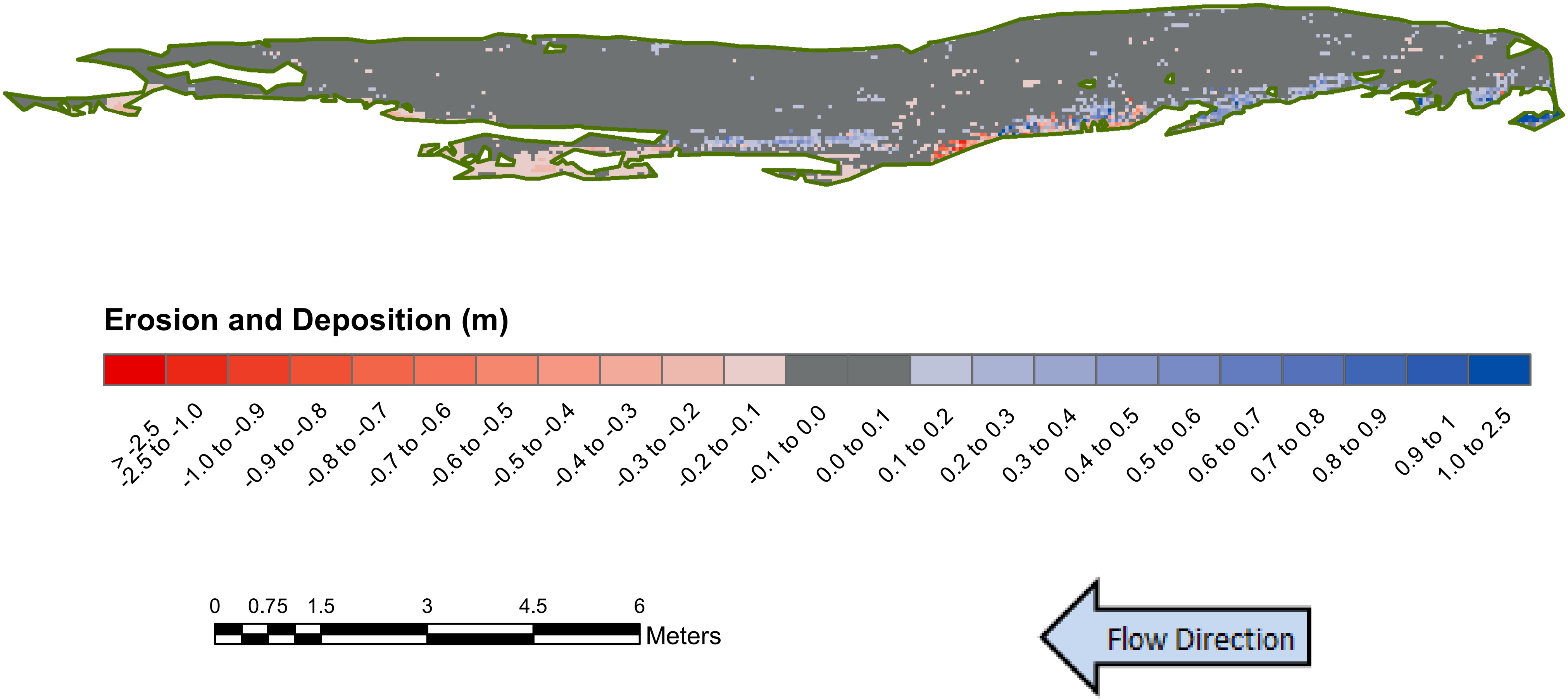

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

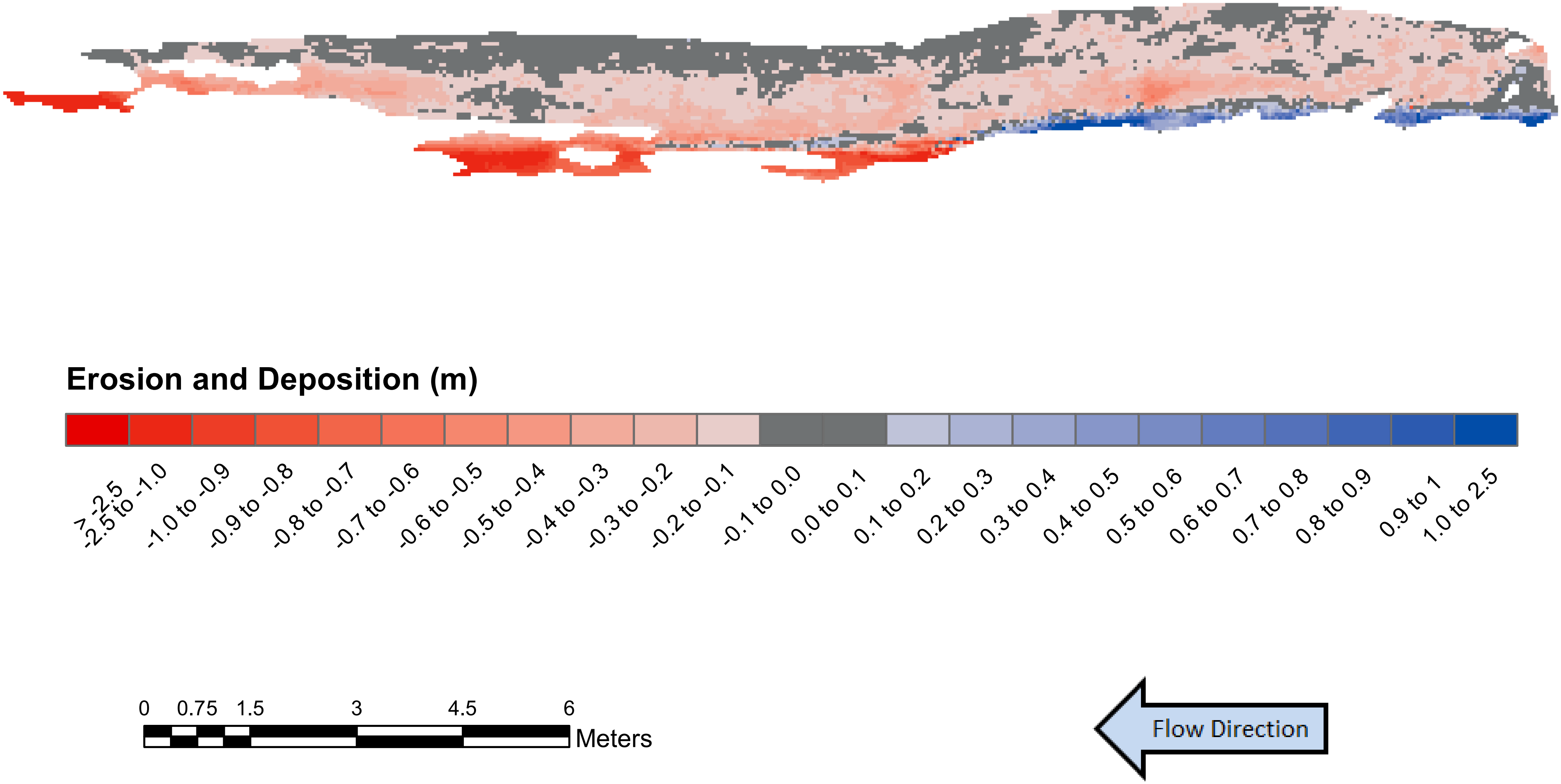

Erosion and Deposition (m)
>-2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

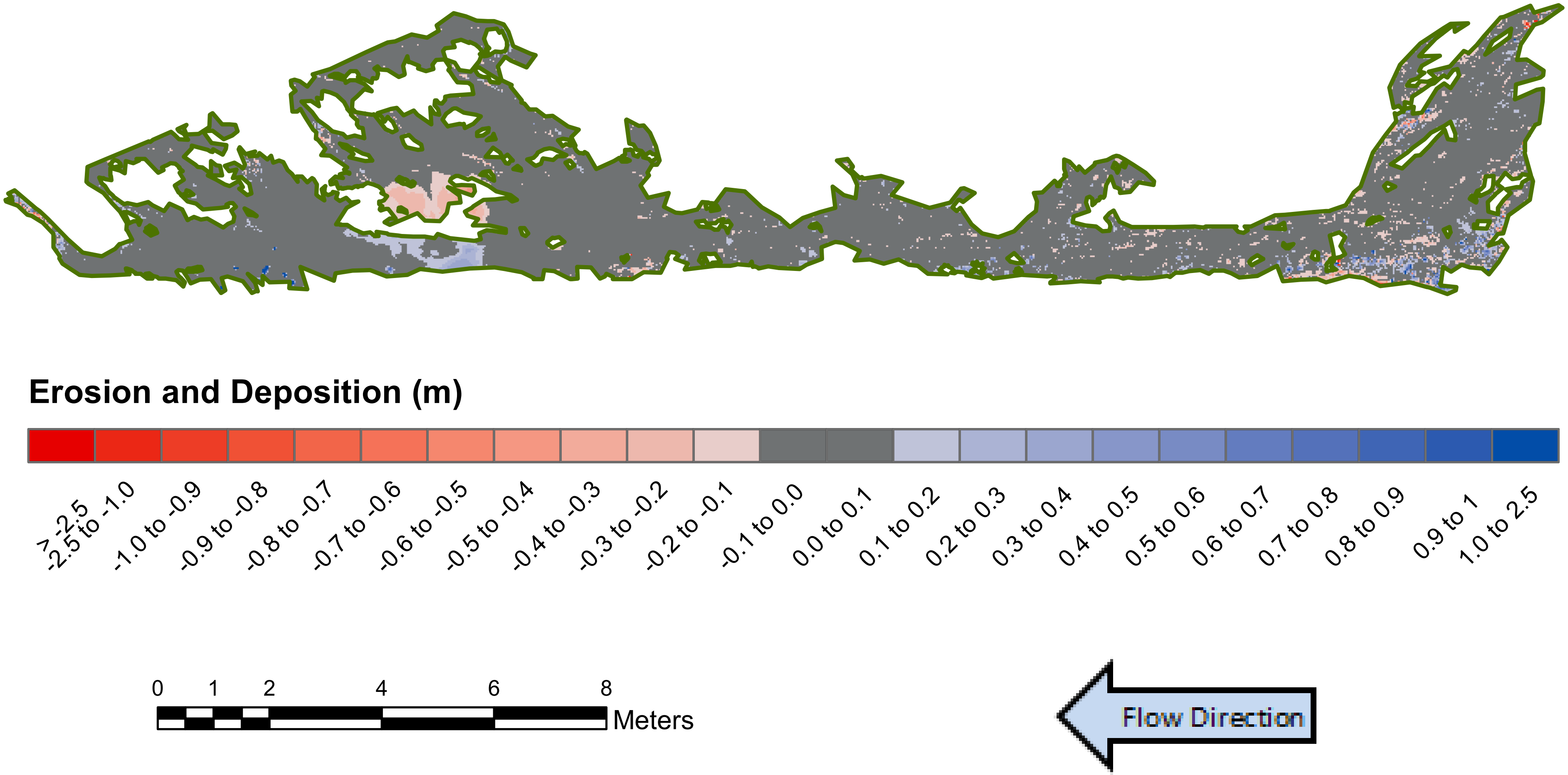

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

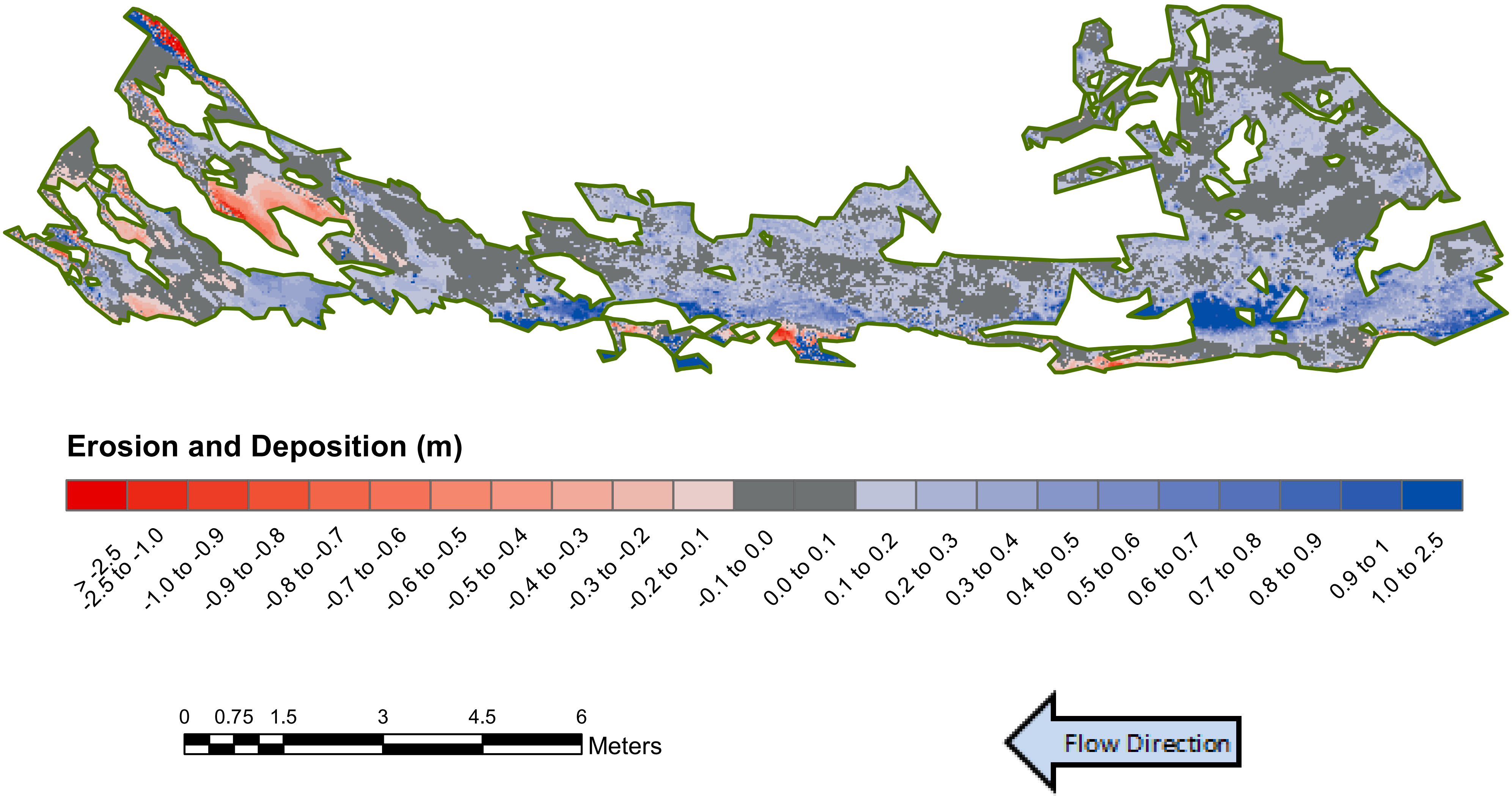

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

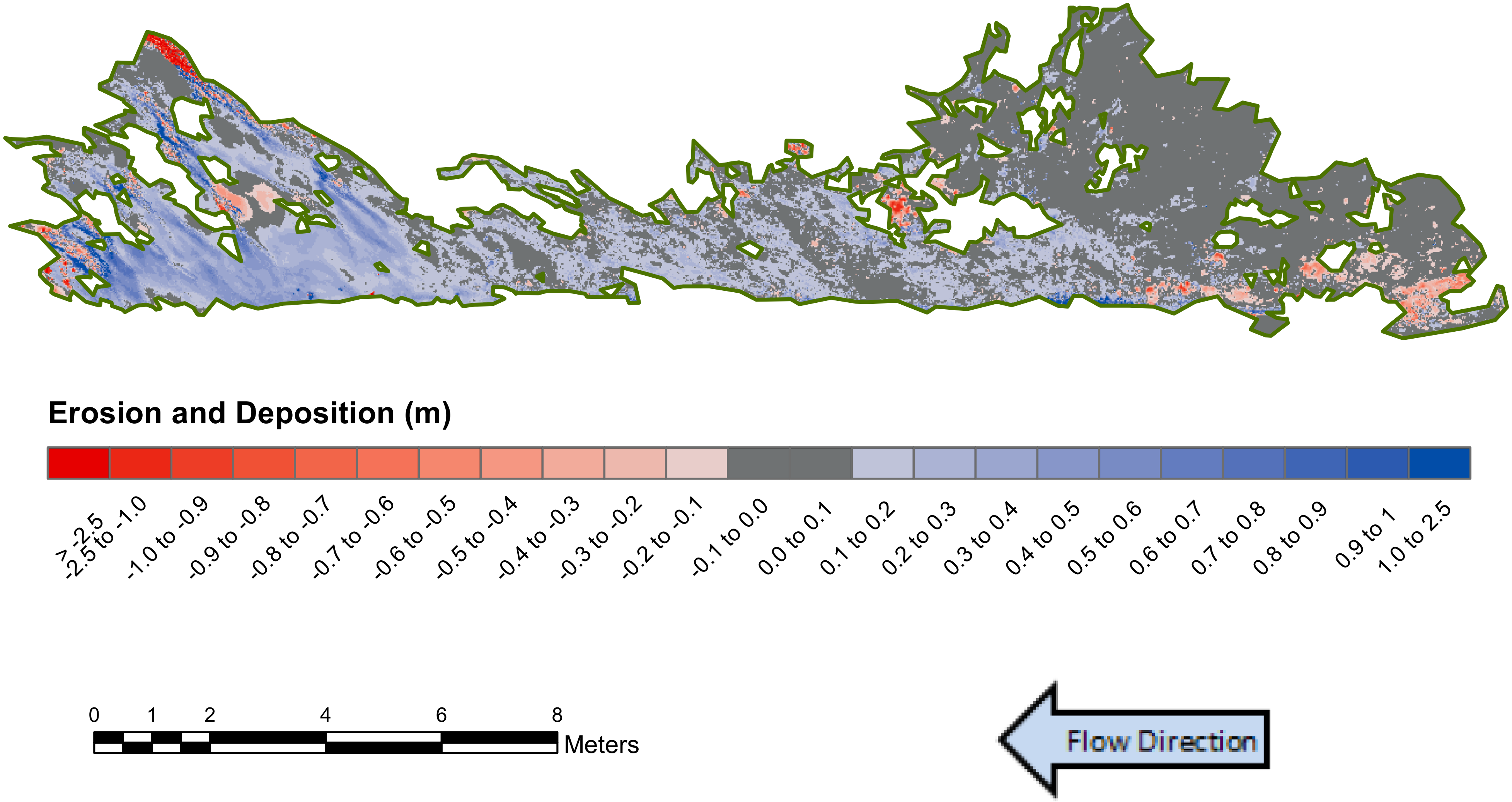

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0 1 2 4 6 8
Meters
Flow Direction

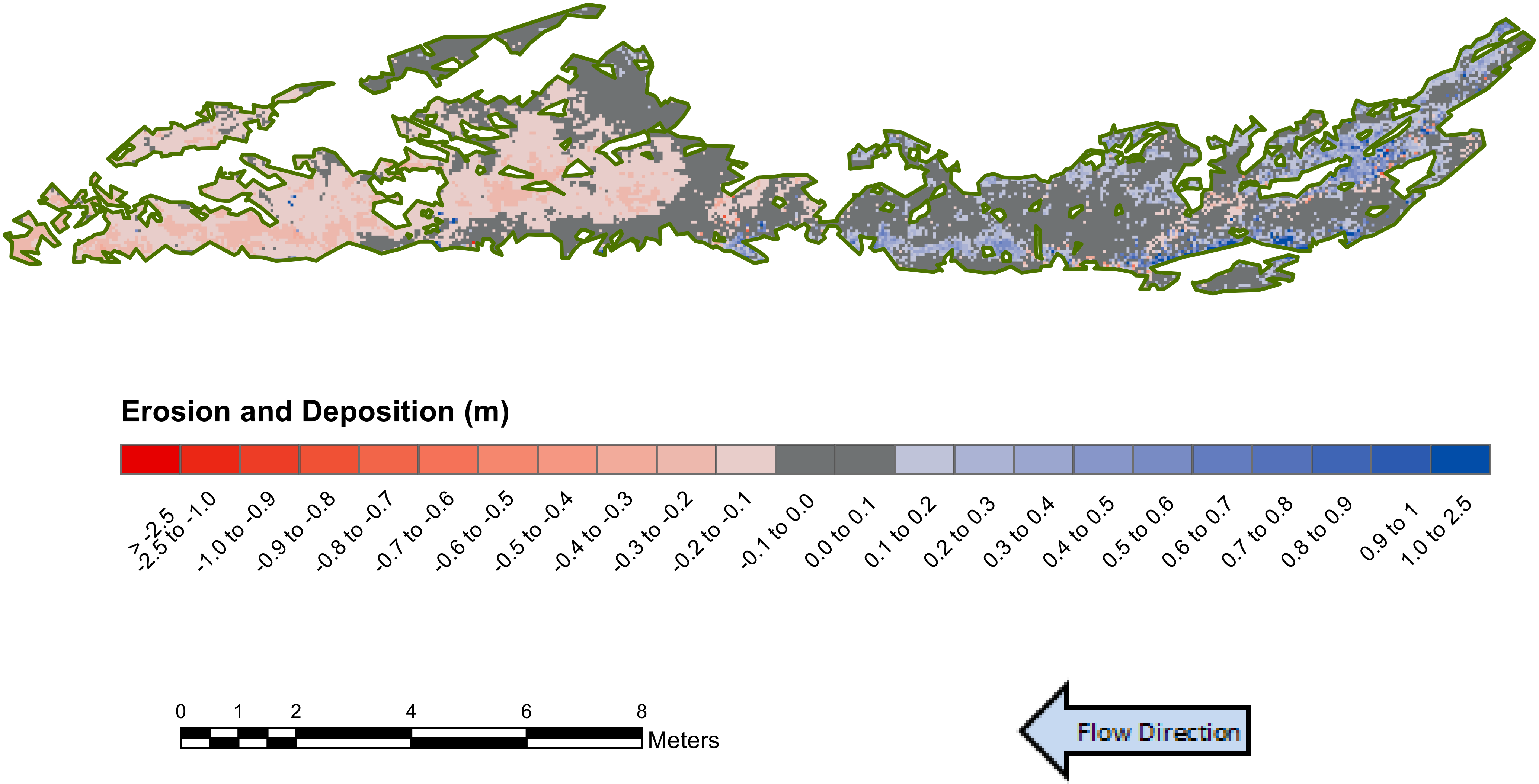

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

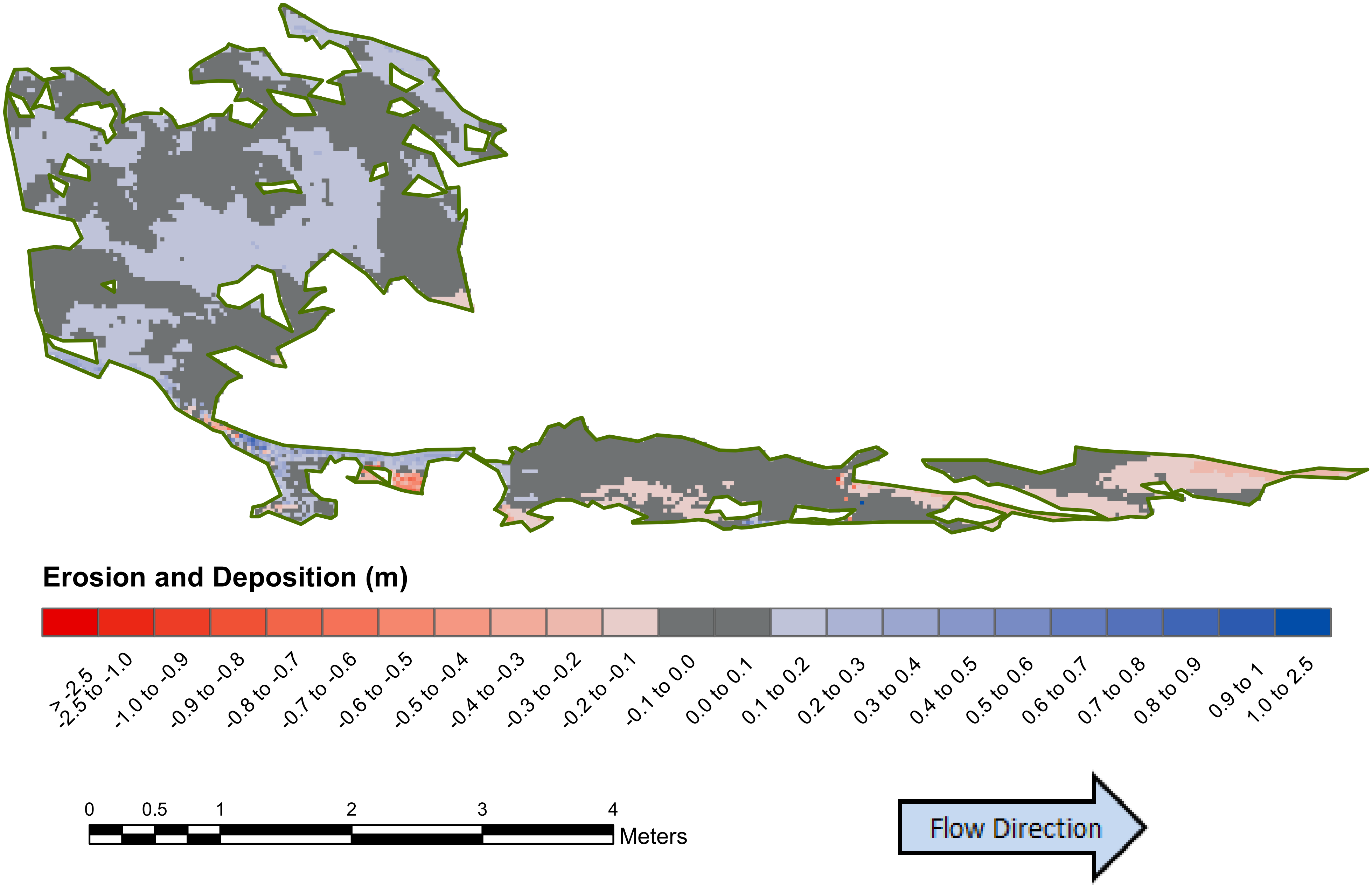

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

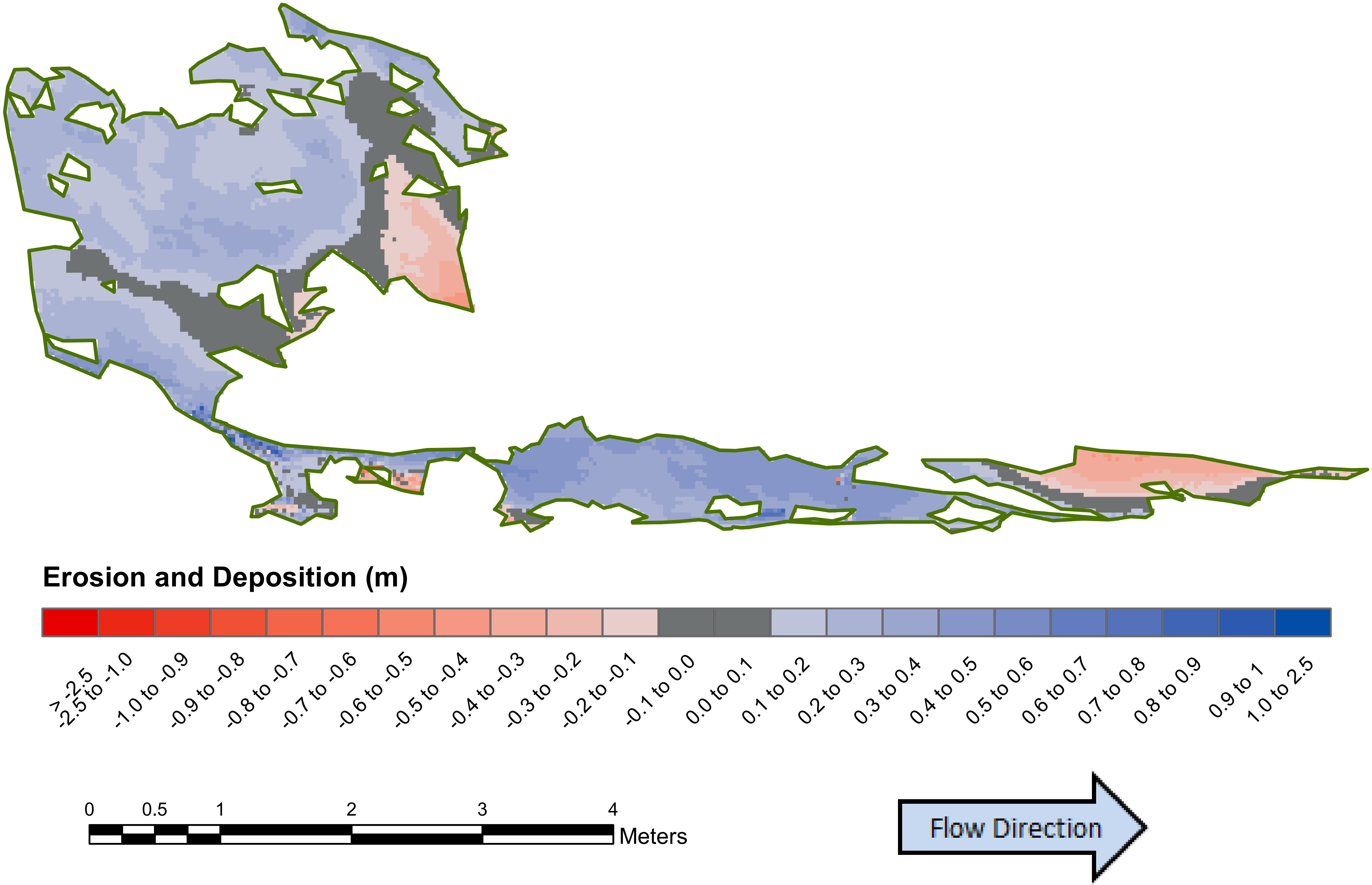

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1
2
4
6
8
Meters
Flow Direction

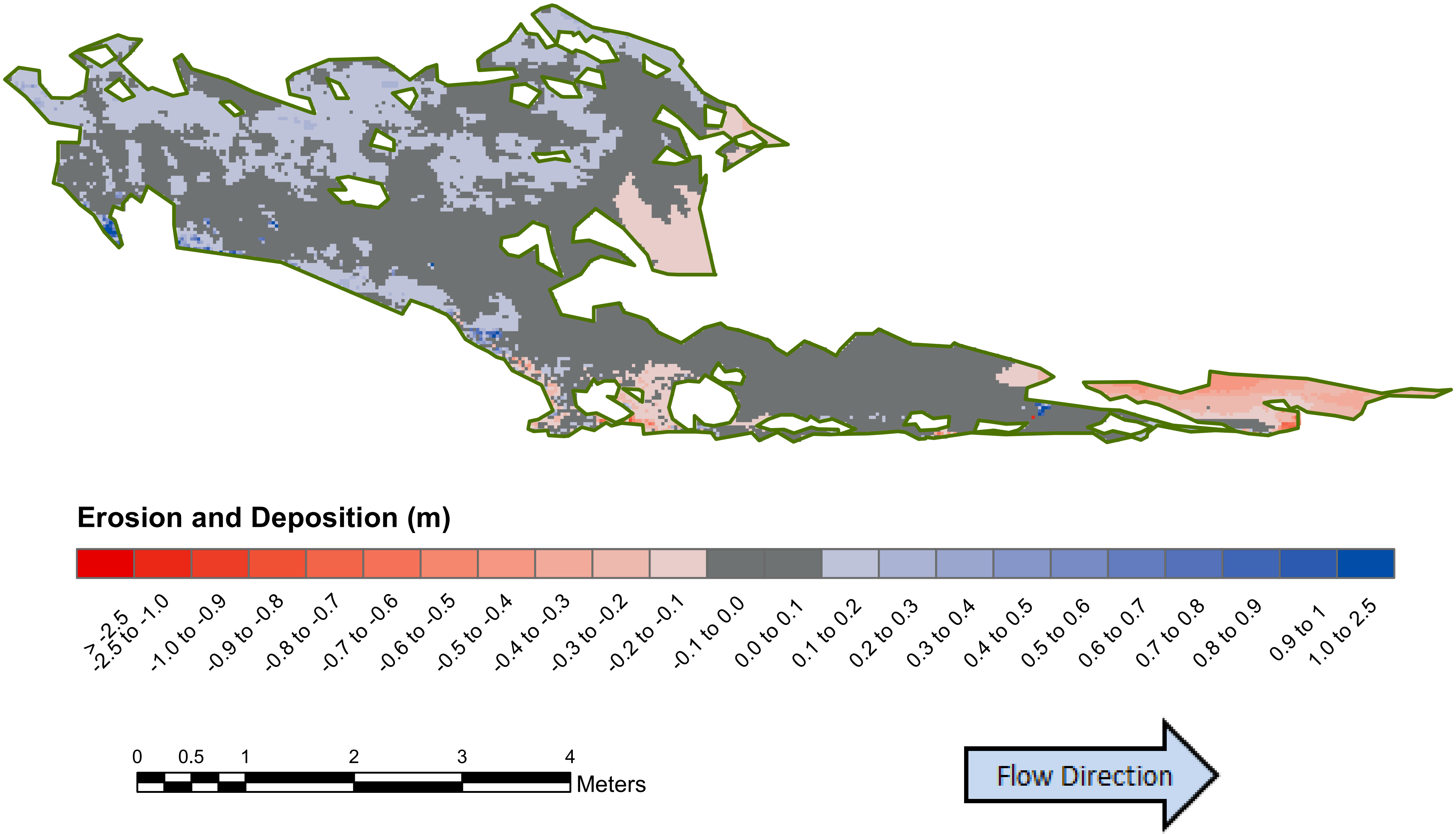

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

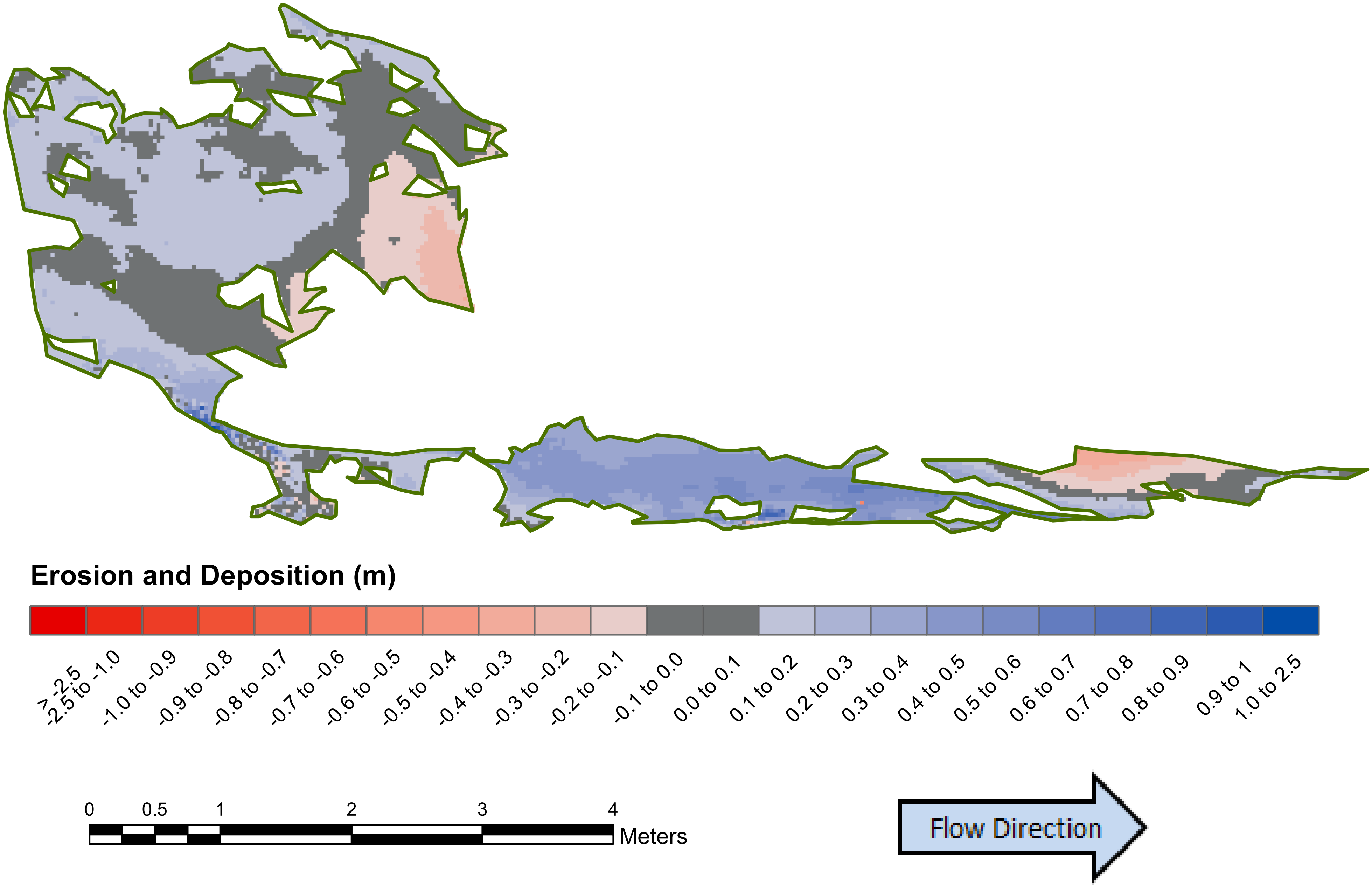

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1
2
4
6
8
Meters
Flow Direction

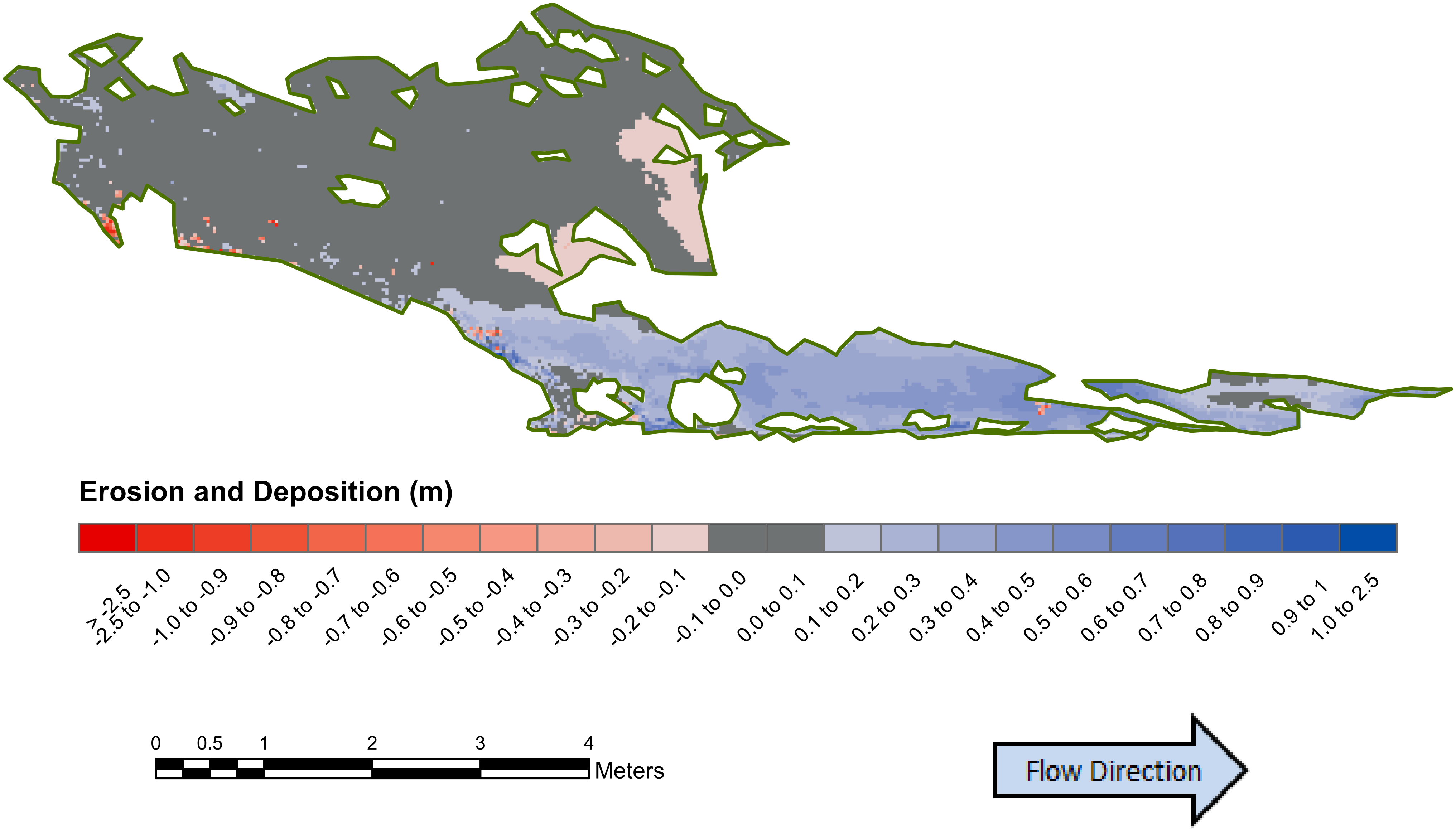

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1
2
4
6
8
Meters
Flow Direction

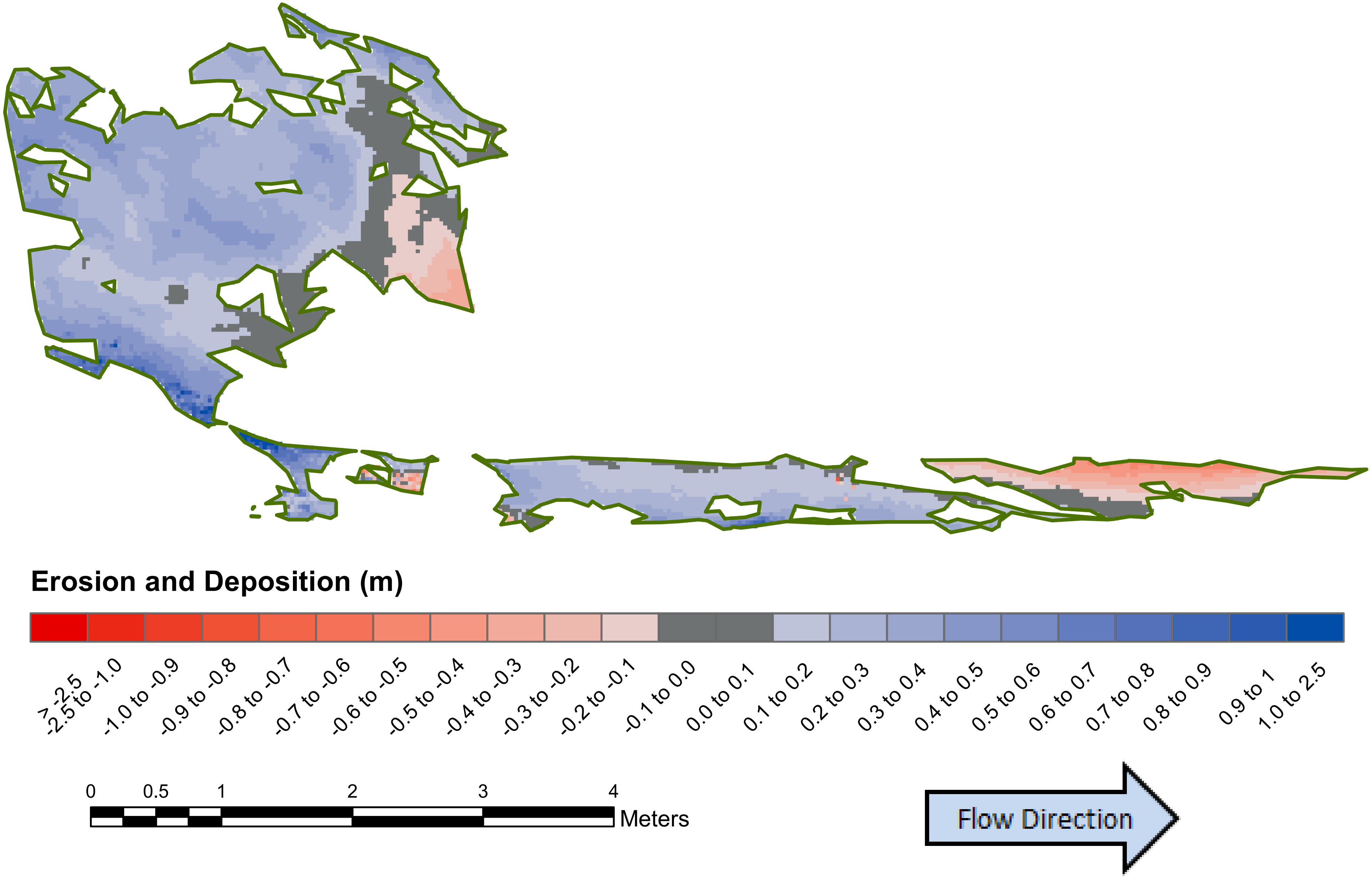

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

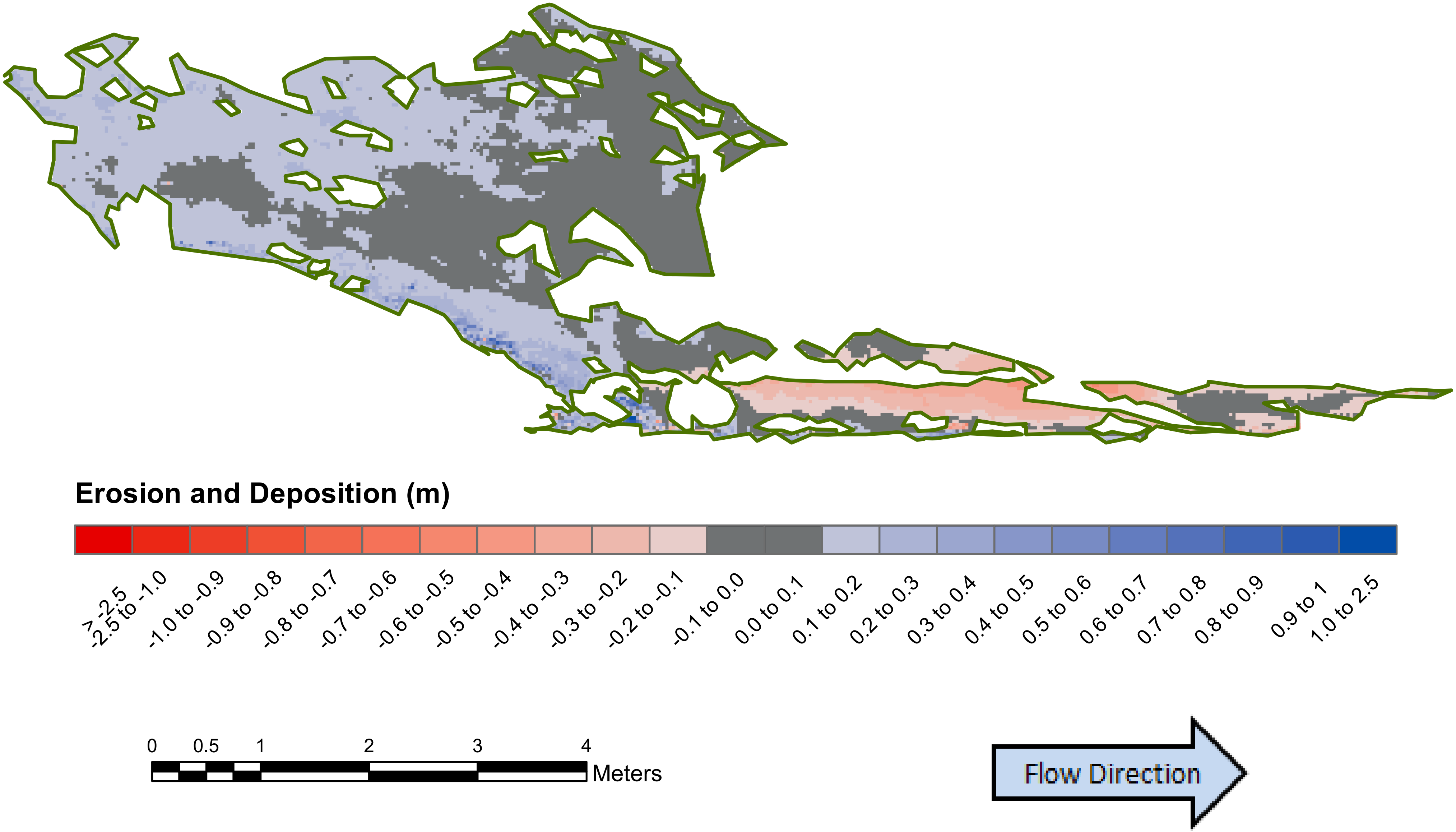

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

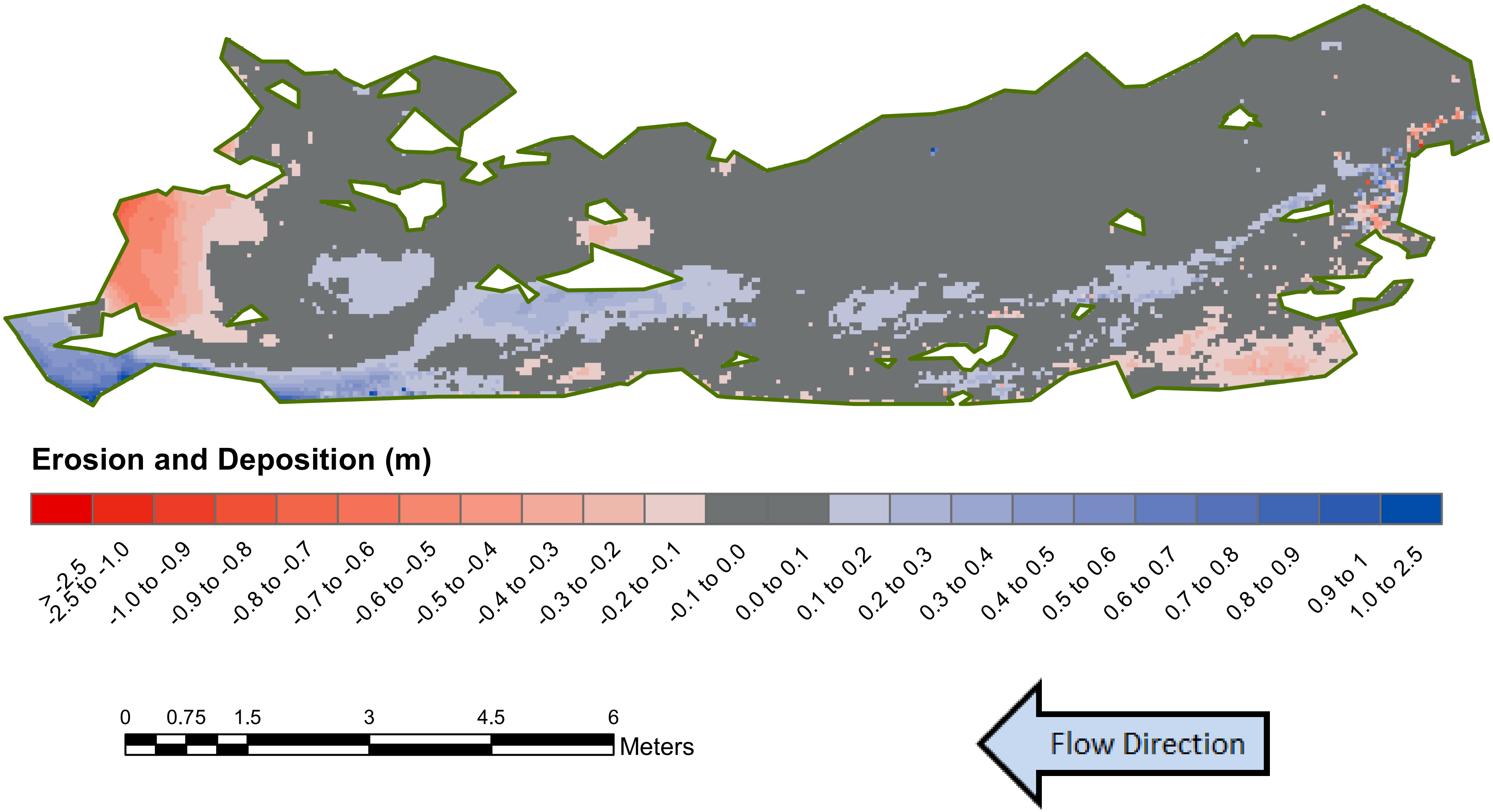

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

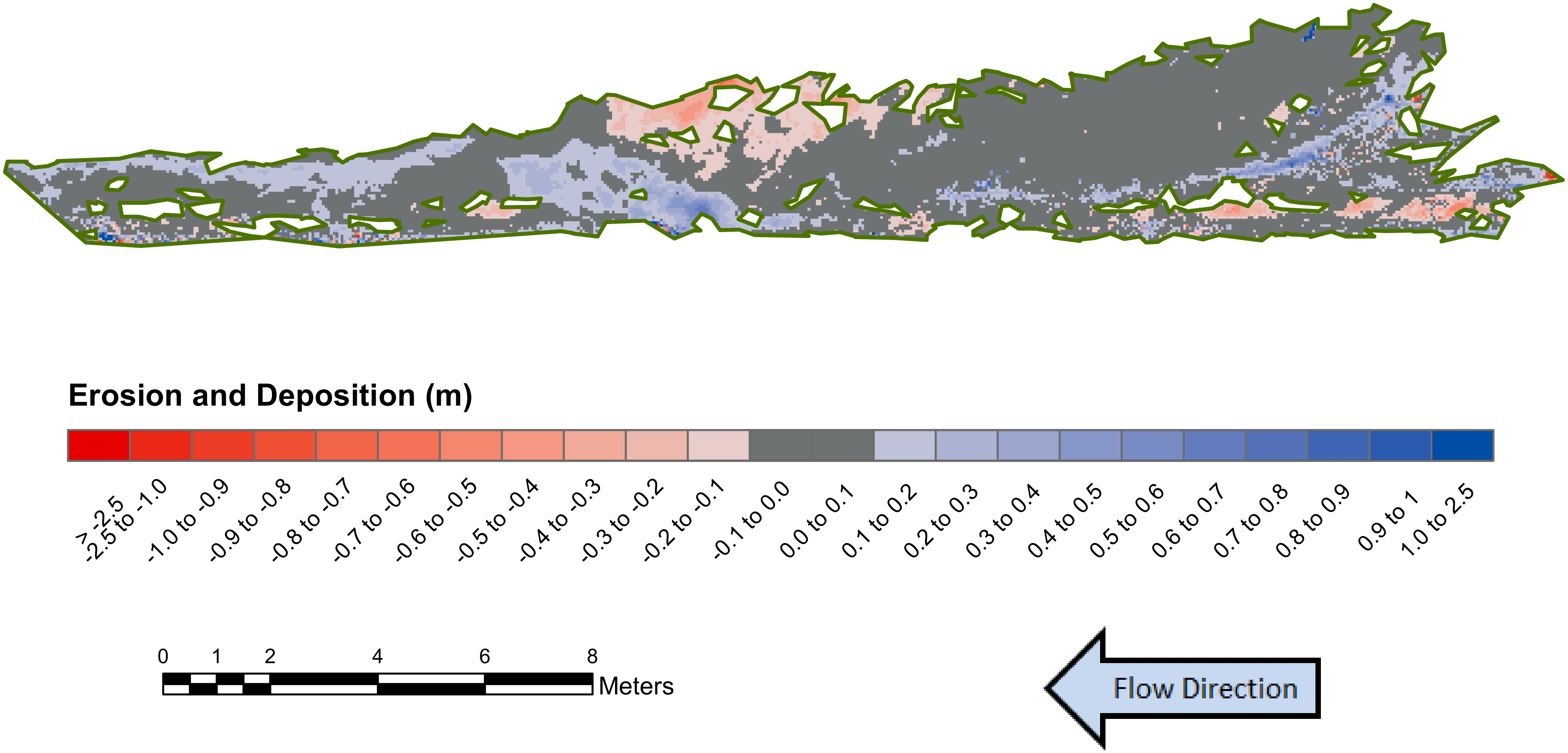

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

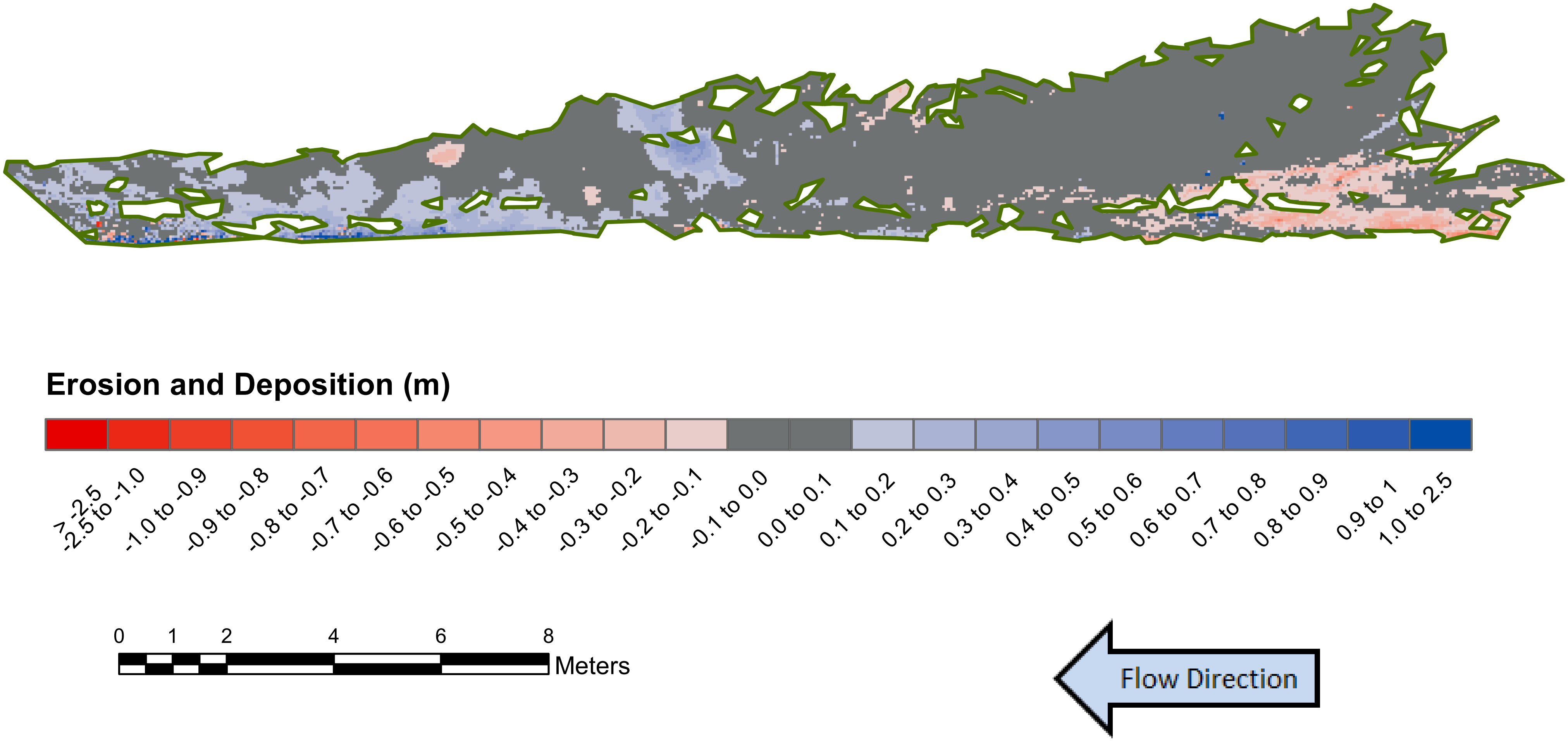

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

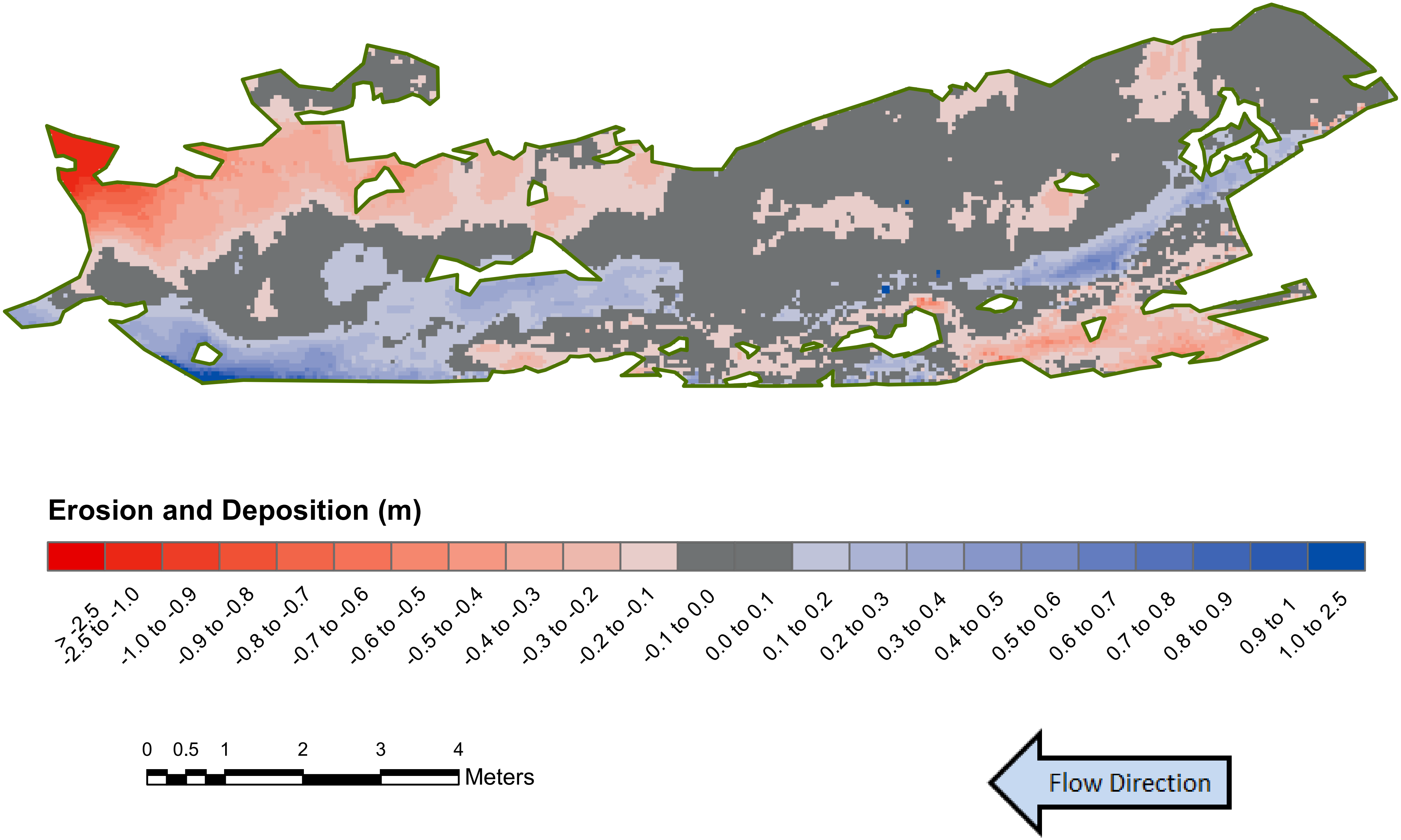

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

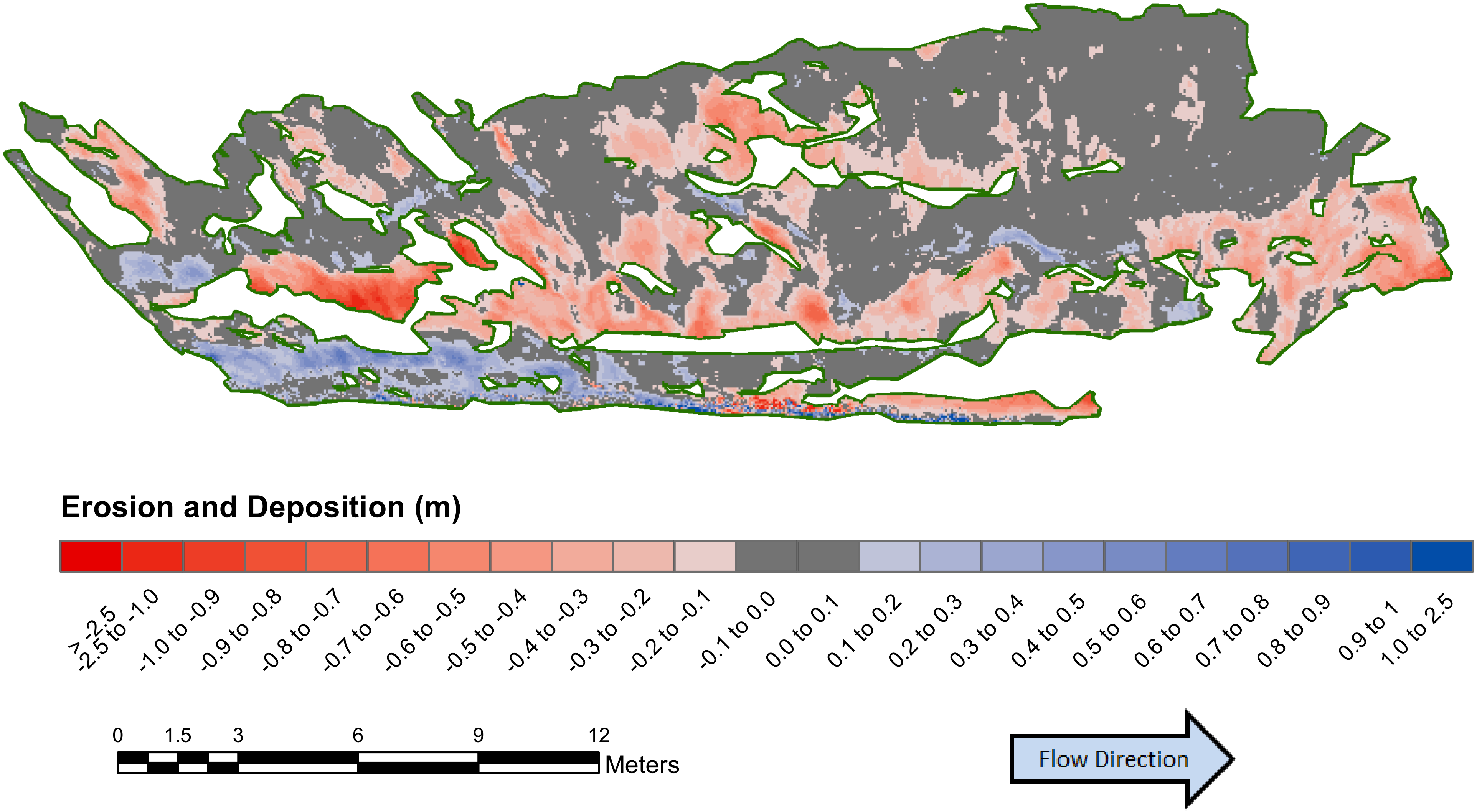

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.5
1
2
3
4
Meters
Flow Direction

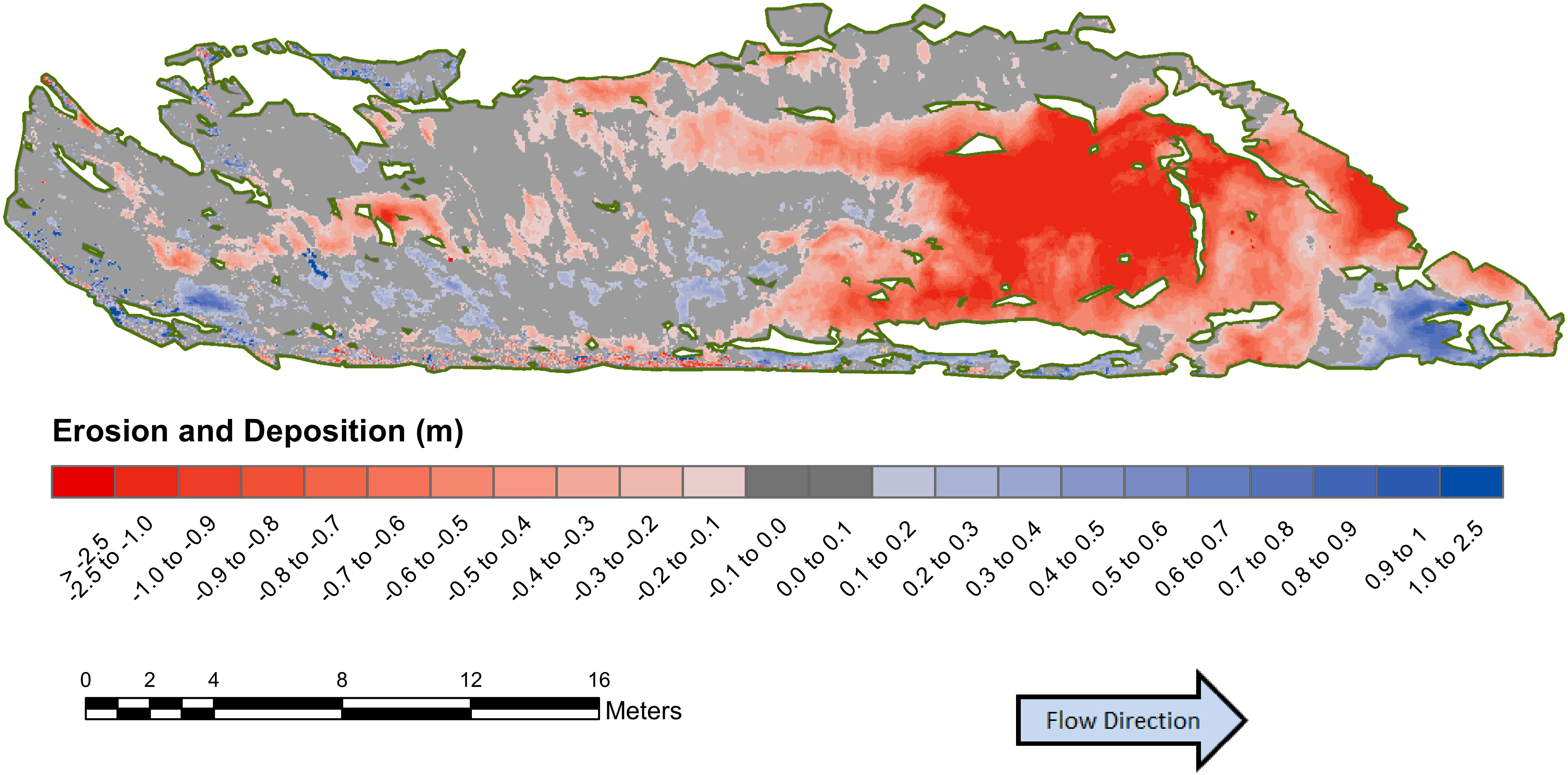

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
0.75
1.5
3
4.5
6
Meters
Flow Direction

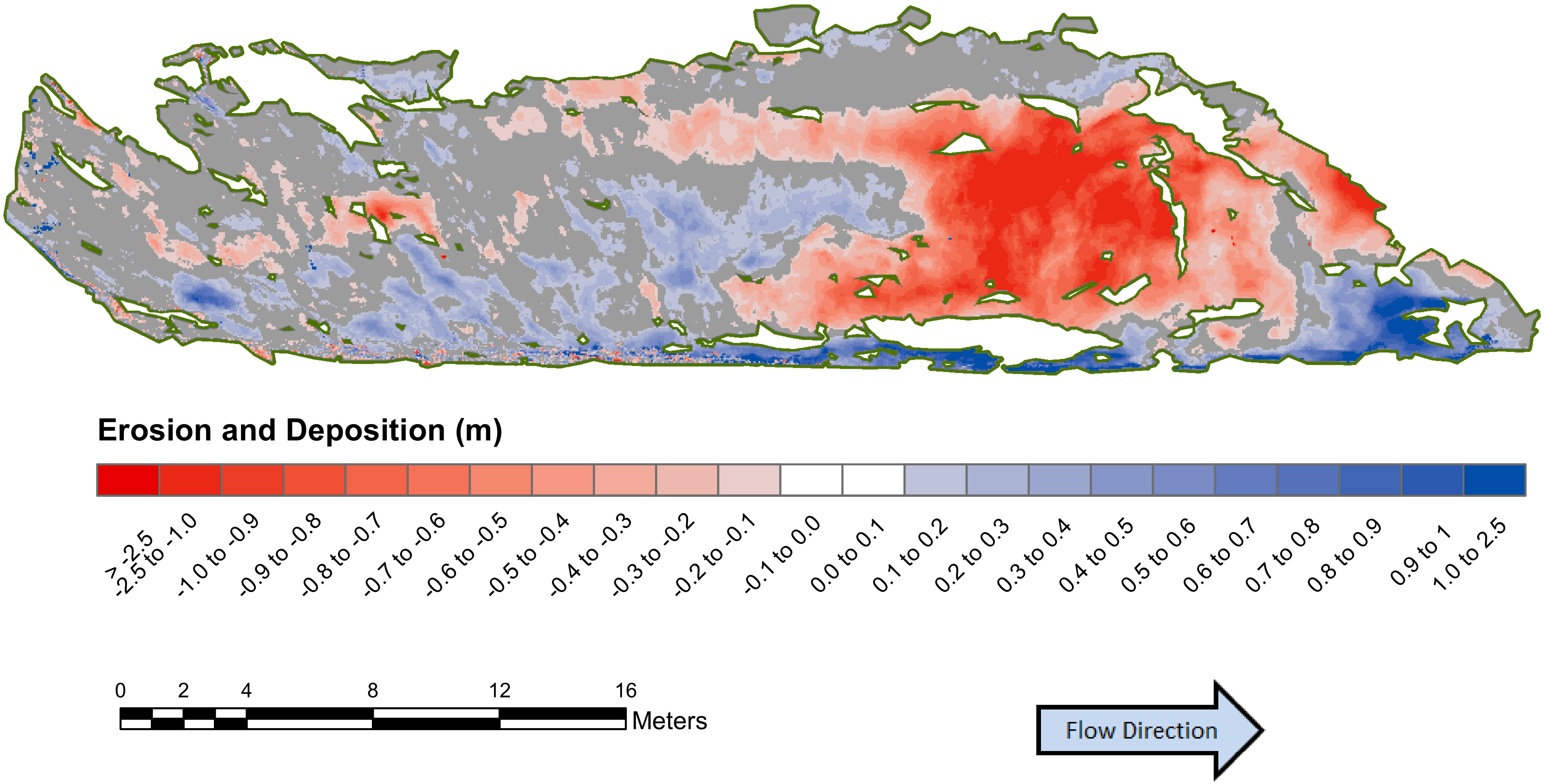

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1
2
4
6
8
Meters
Flow Direction

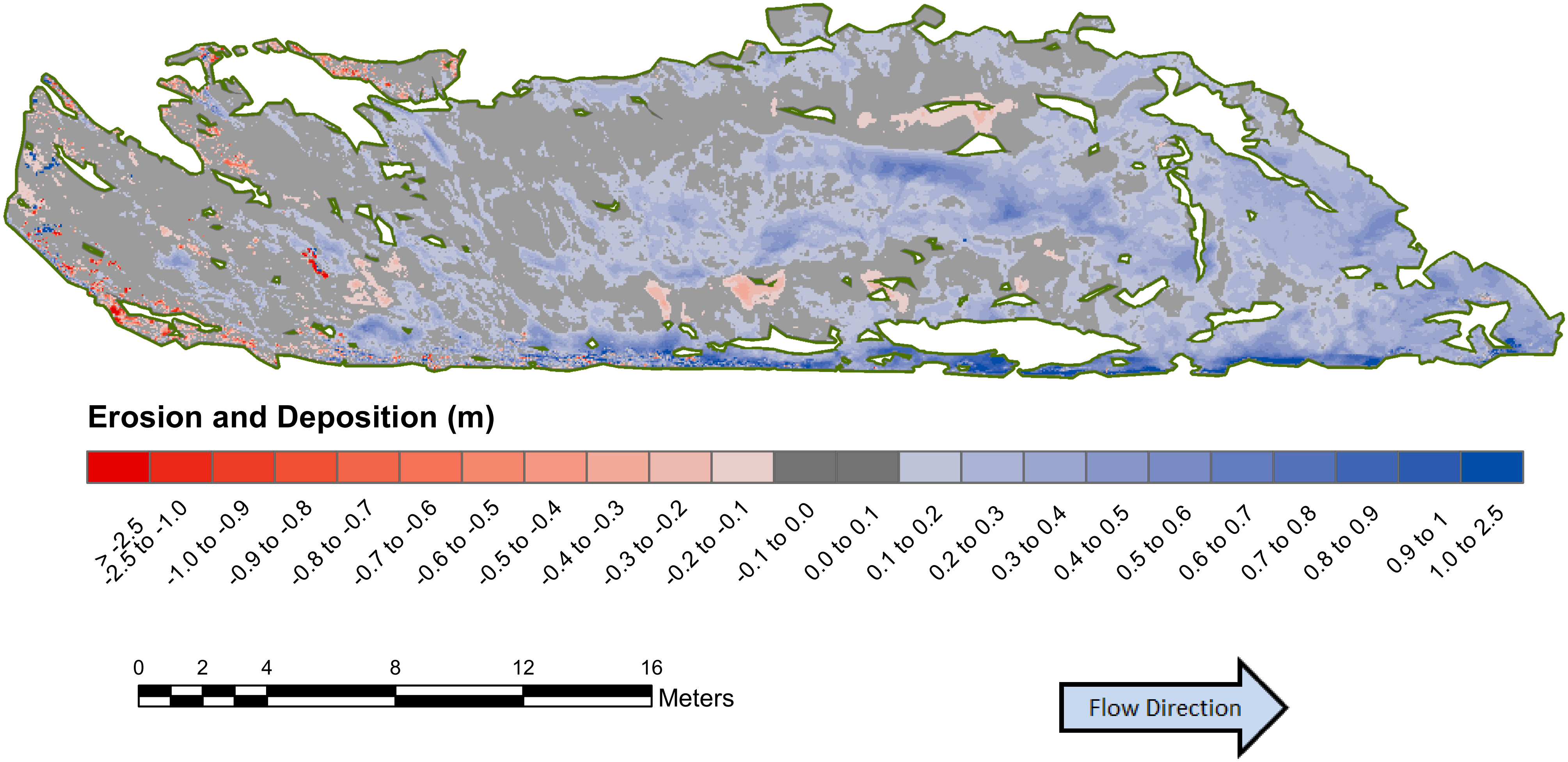

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1
2
4
6
8
Meters
Flow Direction

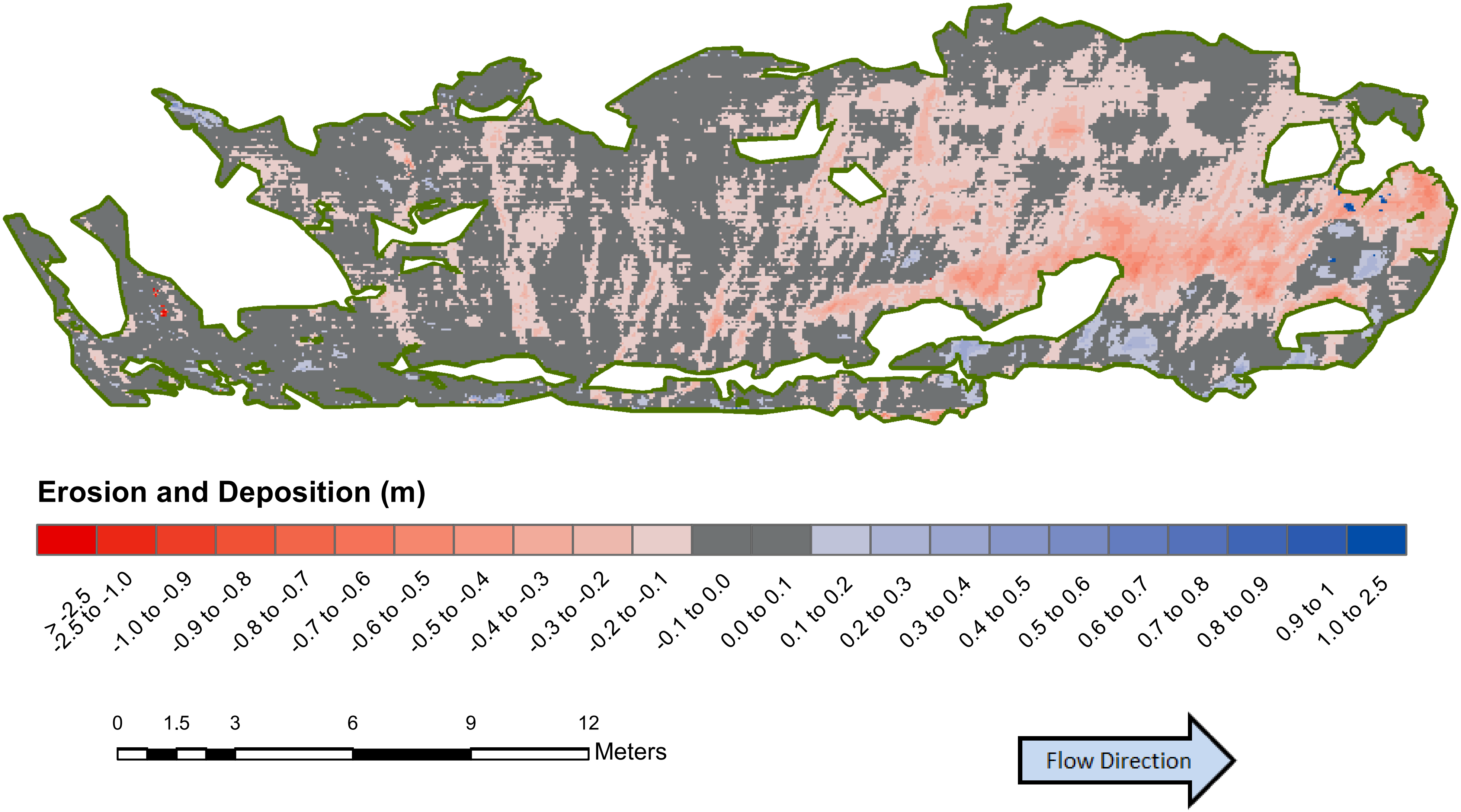

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0 0.5 1 2 3 4
Meters
Flow Direction

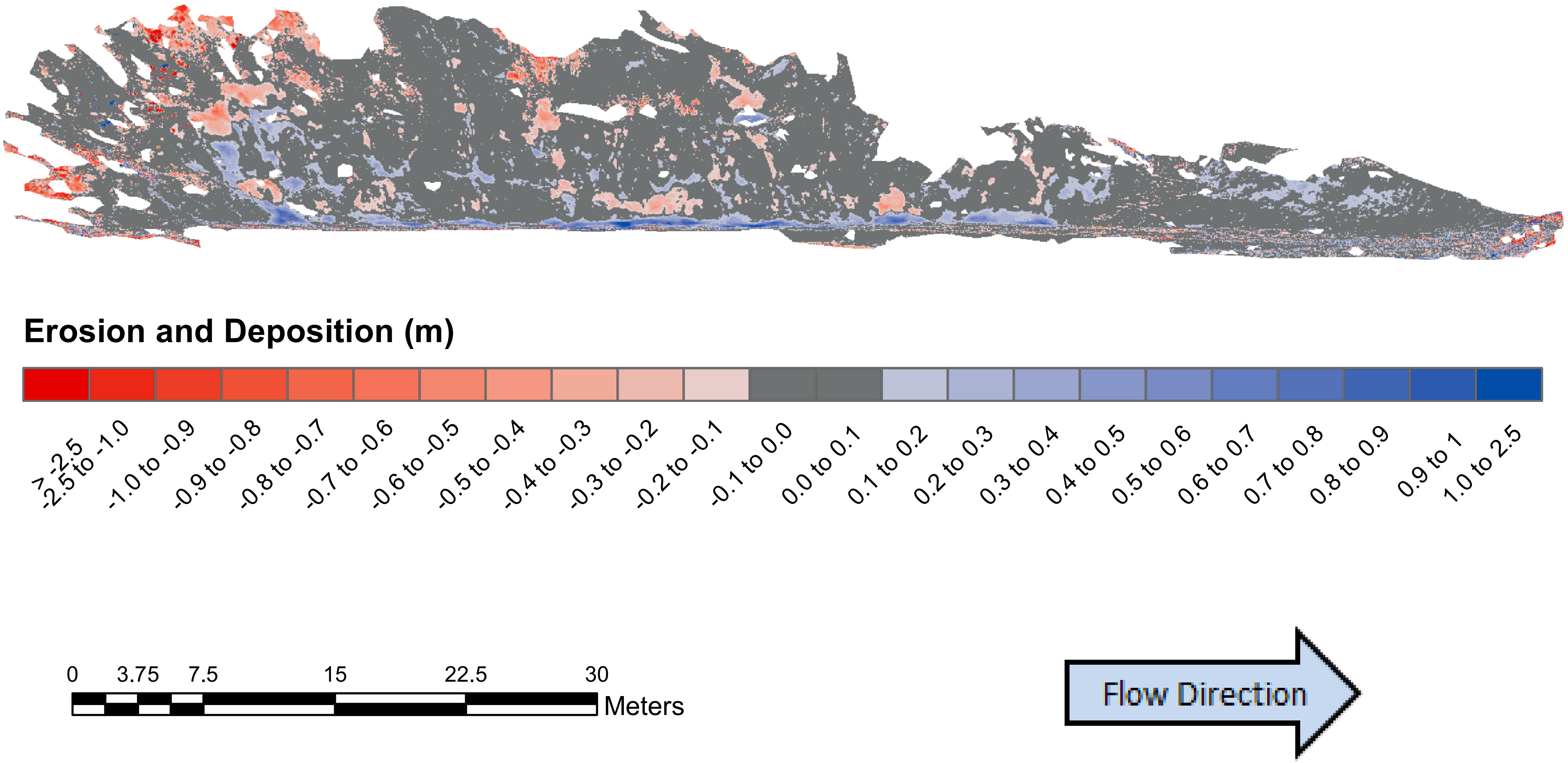

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0 1.5 3 6 9 12
Meters
Flow Direction

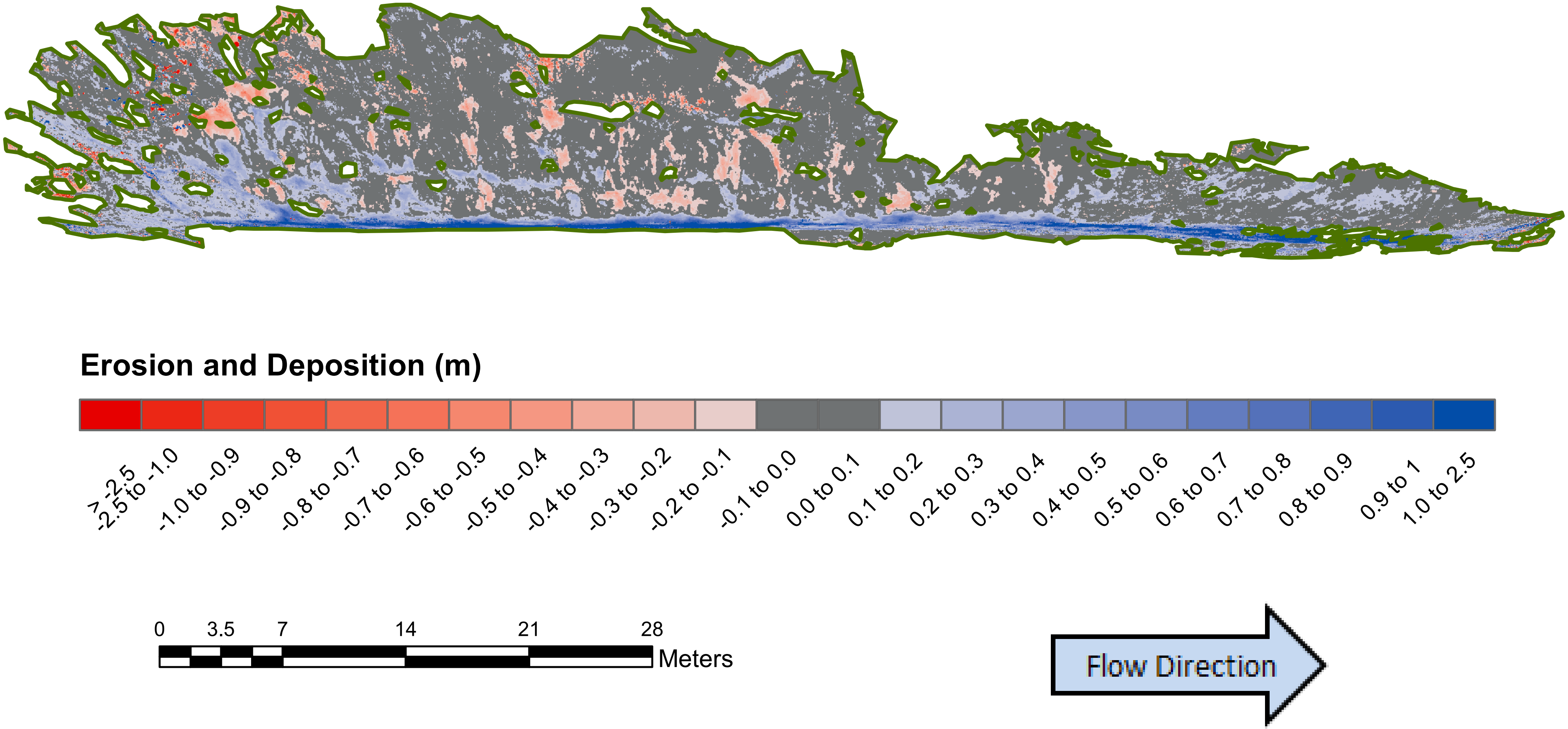

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction

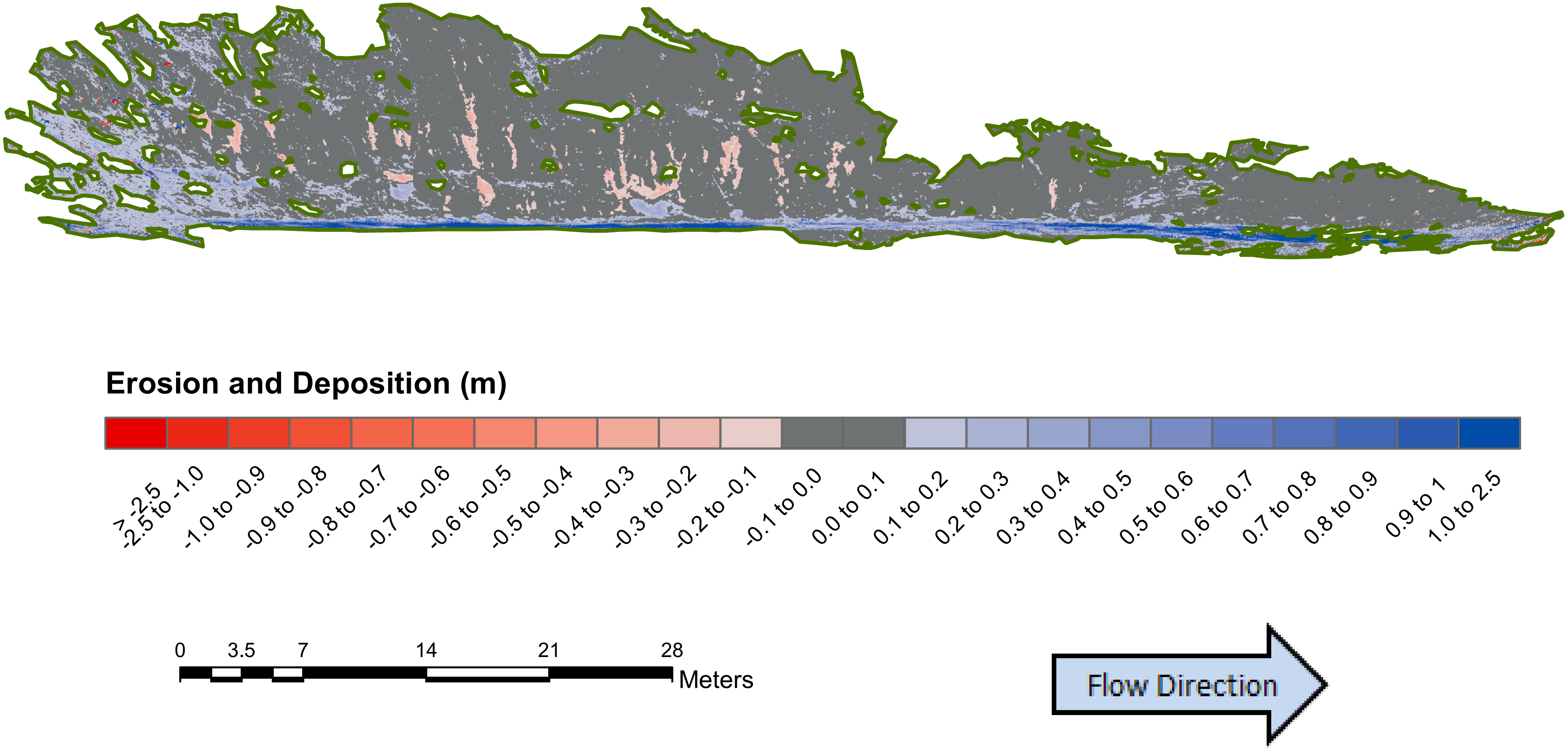

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction

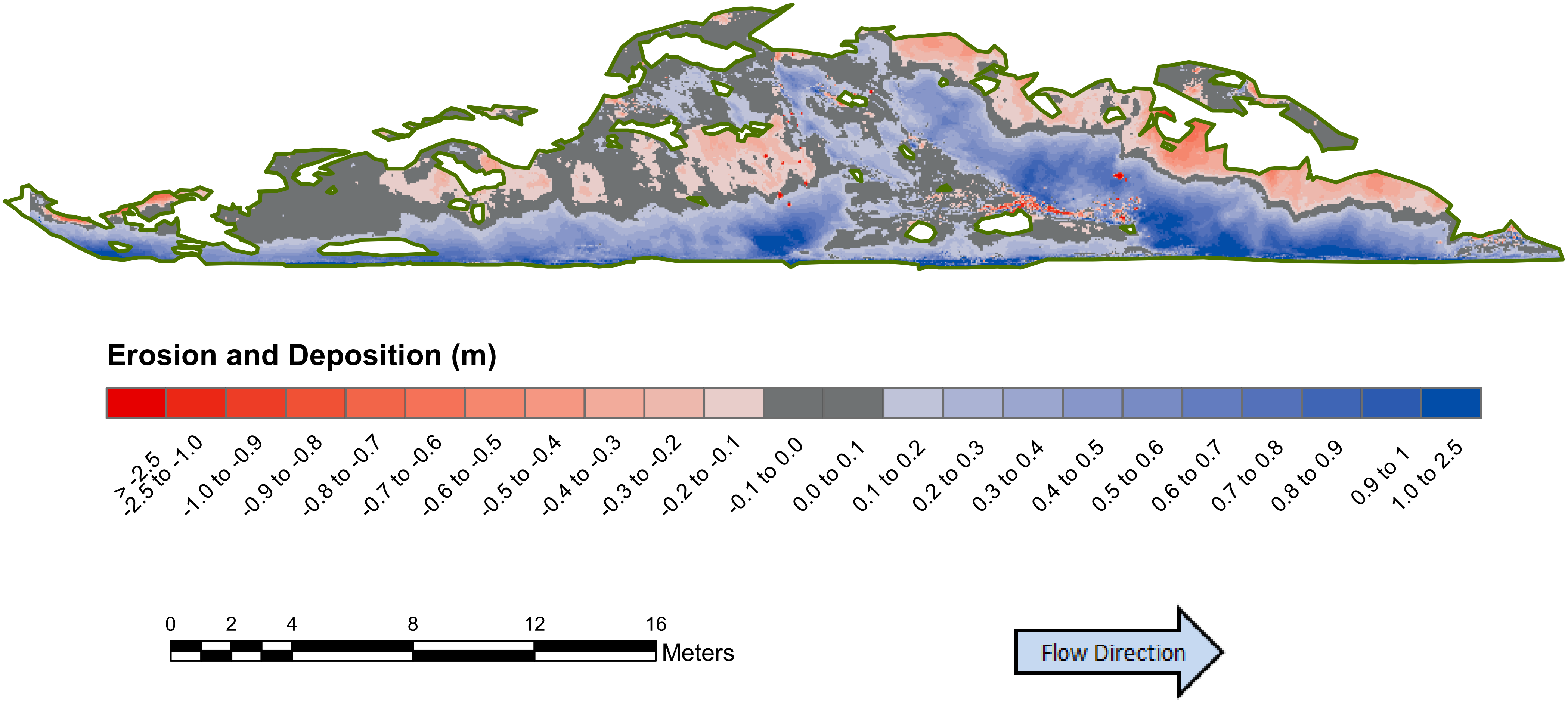

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction

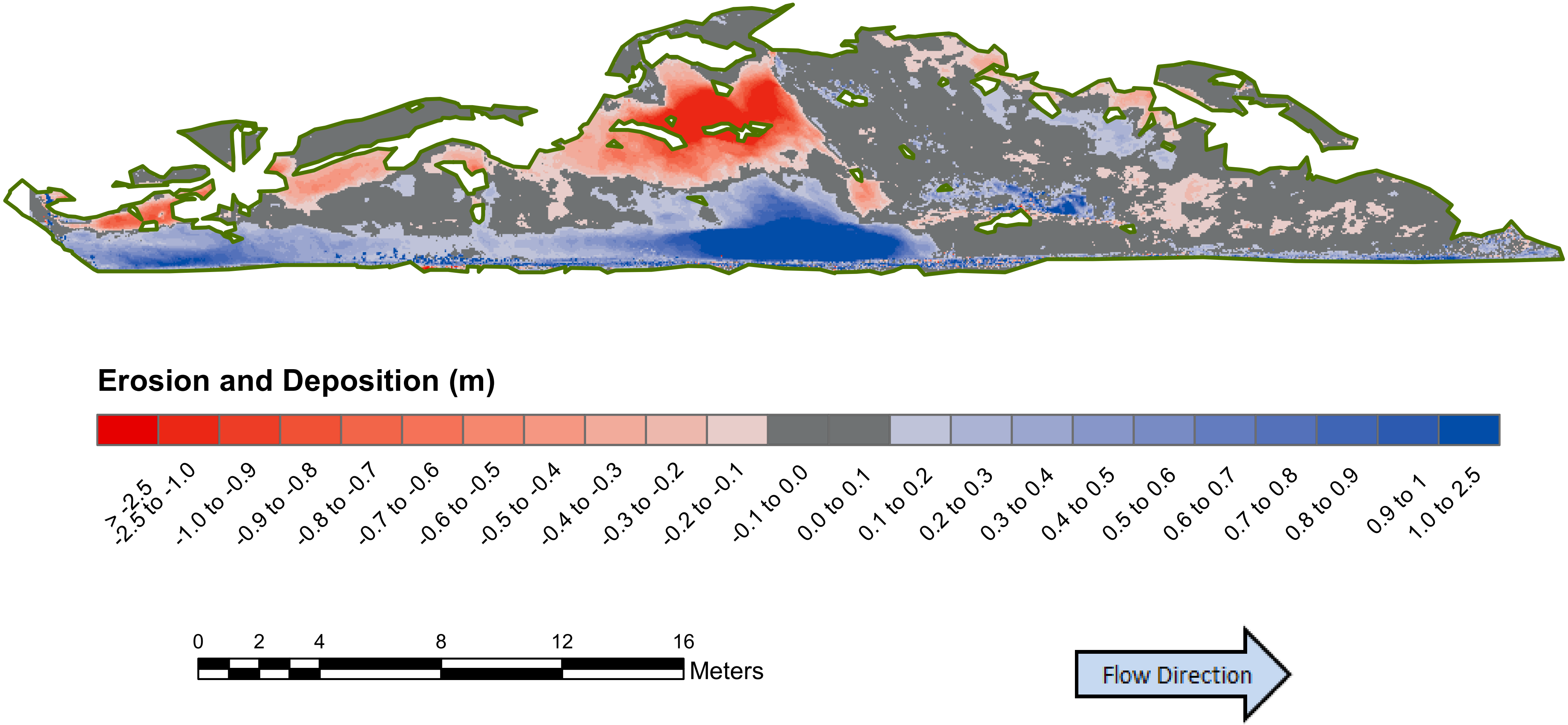

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
1.5
3
6
9
12
Meters
Flow Direction

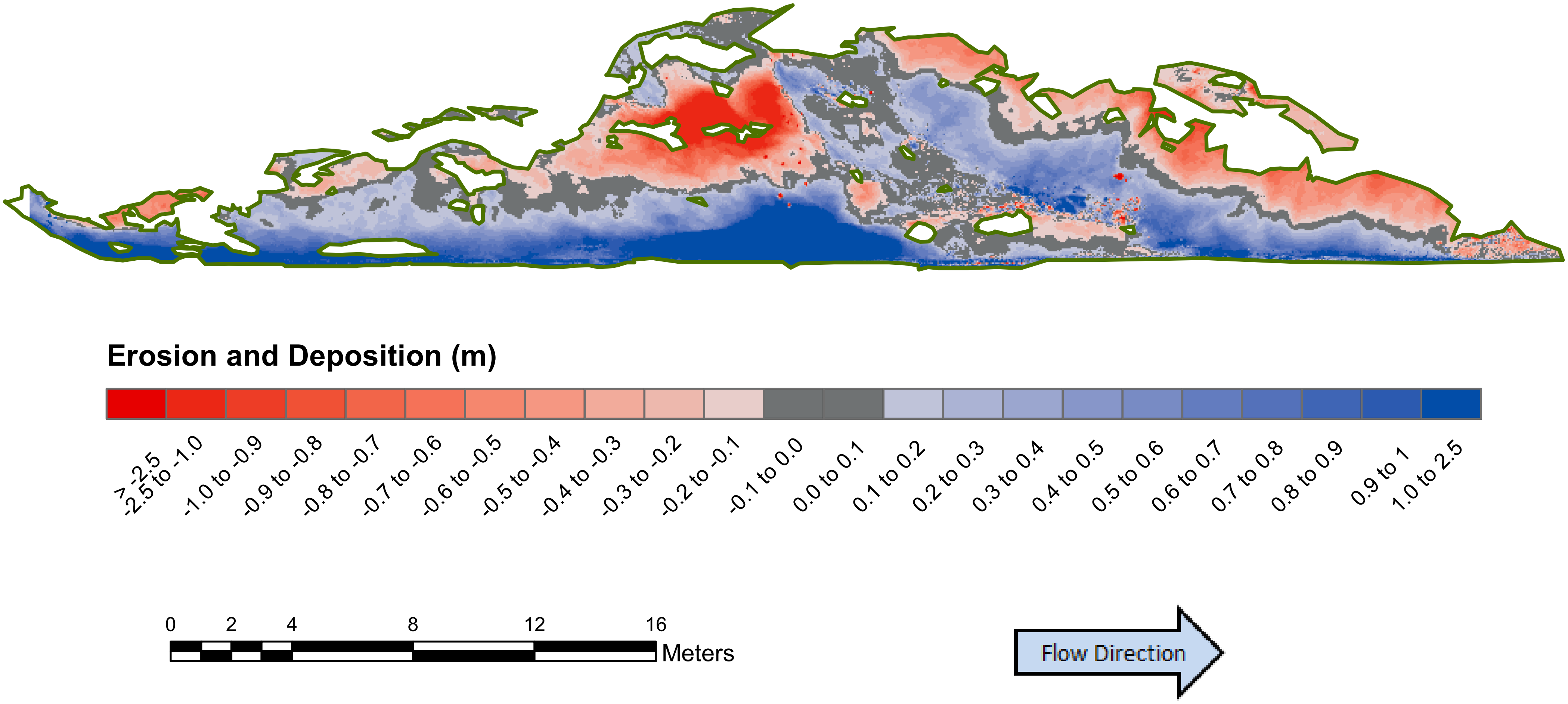

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
3.75
7.5
15
22.5
30
Meters
Flow Direction


Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
3.5
7
14
21
28
Meters
Flow Direction


Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
3.5
7
14
21
28
Meters
Flow Direction

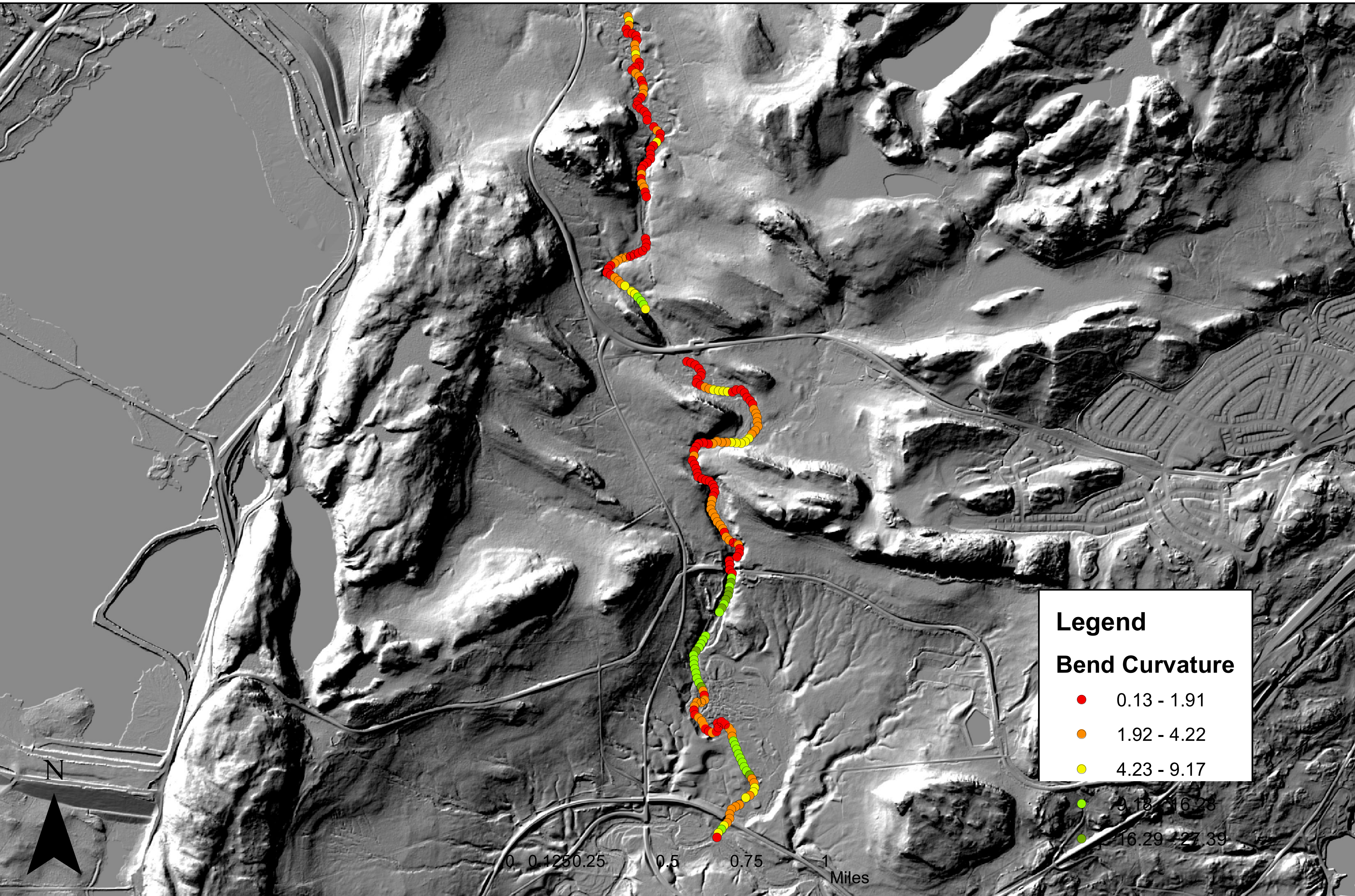

Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction


Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction


Erosion and Deposition (m)
> -2.5
-2.5 to -1.0
-1.0 to -0.9
-0.9 to -0.8
-0.8 to -0.7
-0.7 to -0.6
-0.6 to -0.5
-0.5 to -0.4
-0.4 to -0.3
-0.3 to -0.2
-0.2 to -0.1
-0.1 to 0.0
0.0 to 0.1
0.1 to 0.2
0.2 to 0.3
0.3 to 0.4
0.4 to 0.5
0.5 to 0.6
0.6 to 0.7
0.7 to 0.8
0.8 to 0.9
0.9 to 1
1.0 to 2.5
0
2
4
8
12
16
Meters
Flow Direction

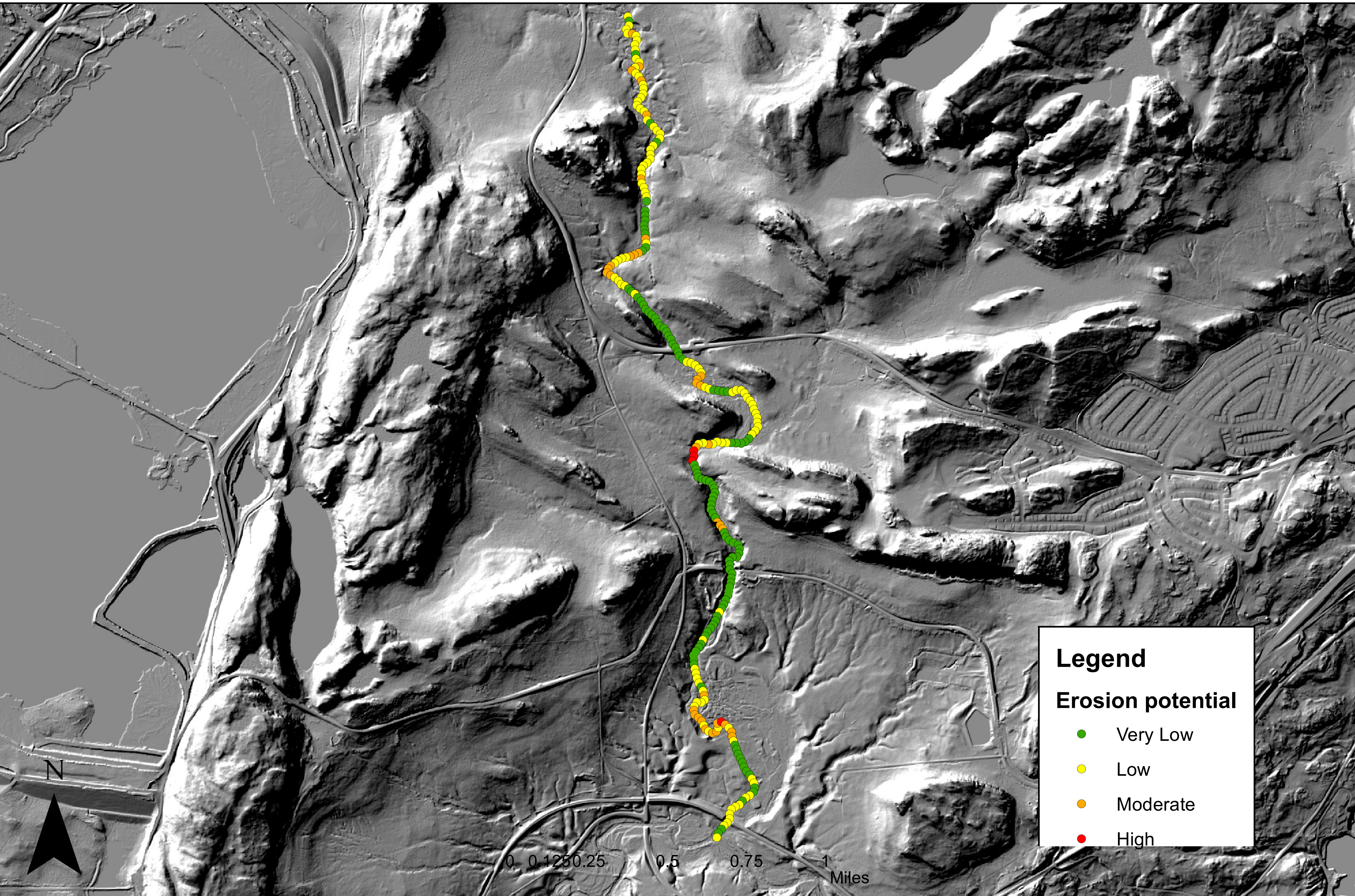
East Branch Beaver River

Bend Curvature



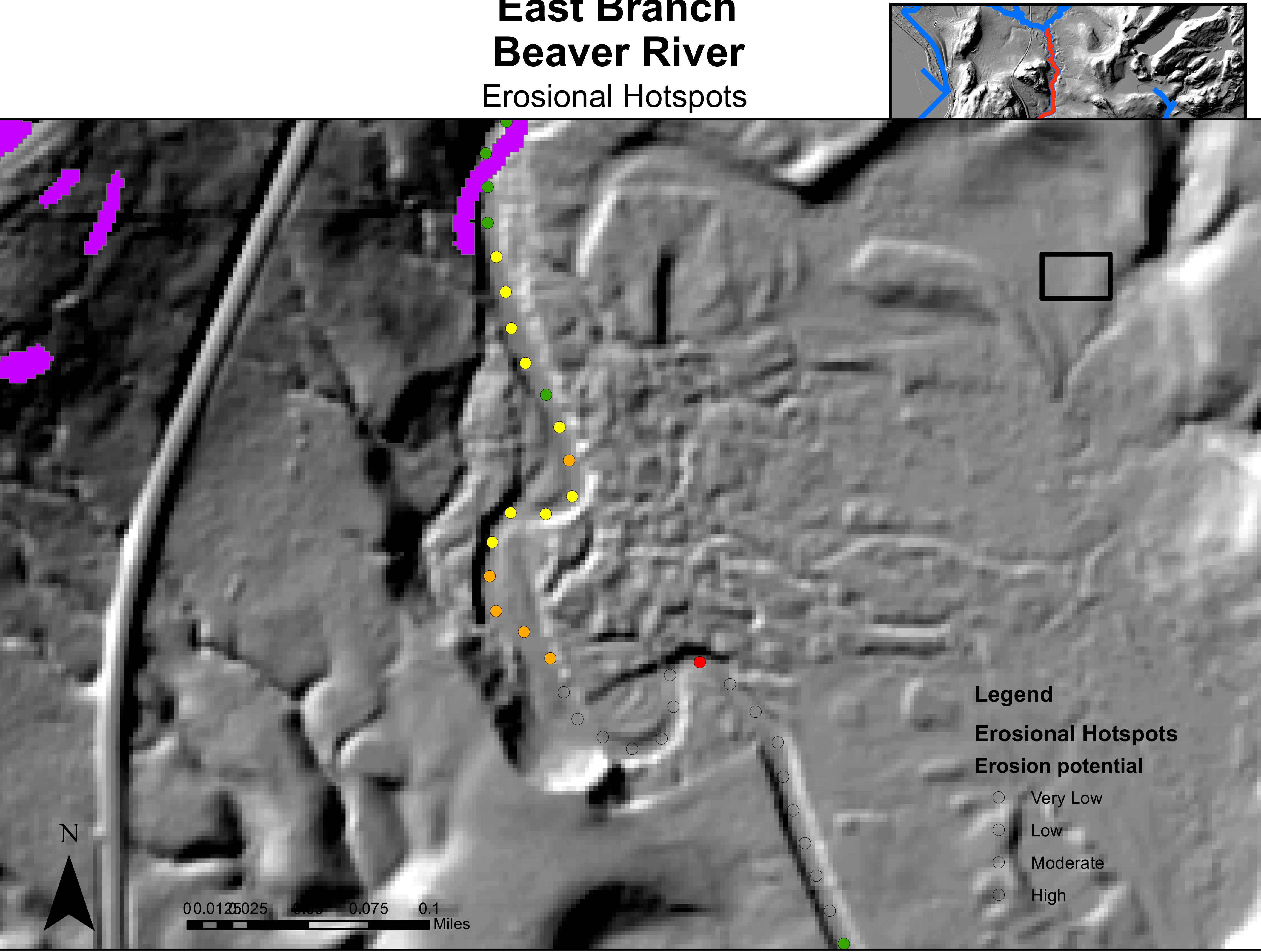
East Branch Beaver River

Erosional Hotspots



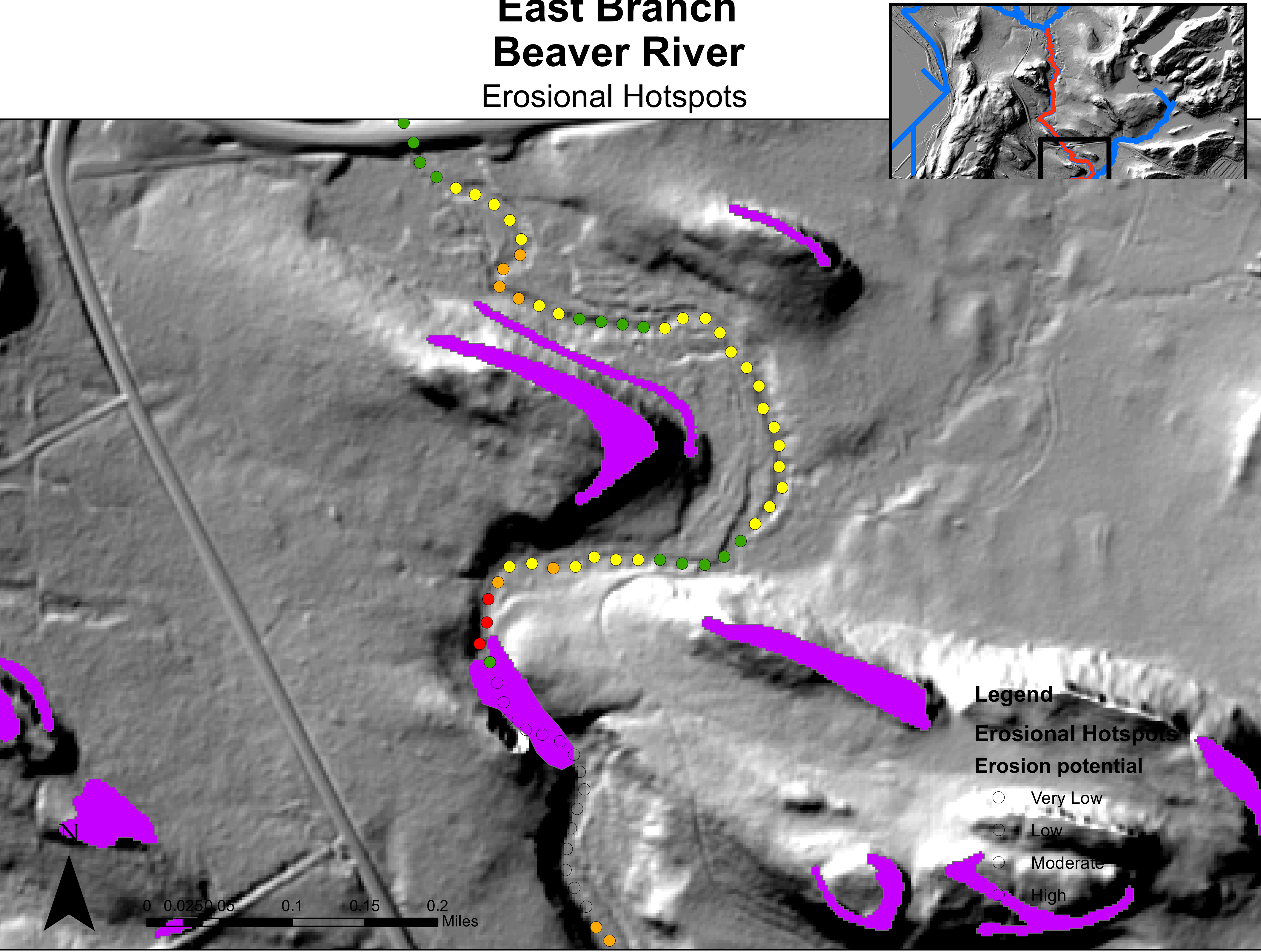
East Branch Beaver River

Erosional Hotspots



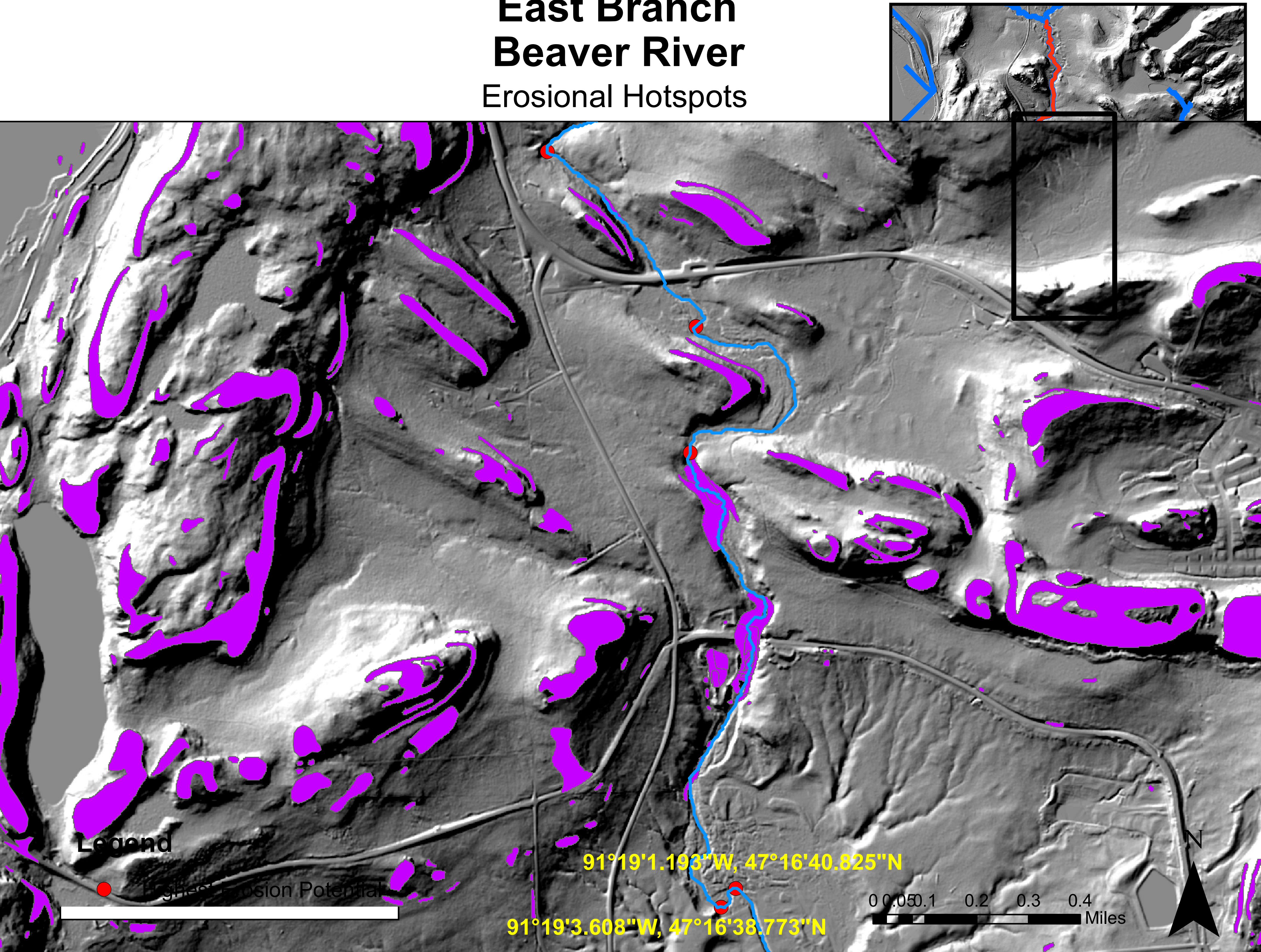
East Branch Beaver River

Erosional Hotspots



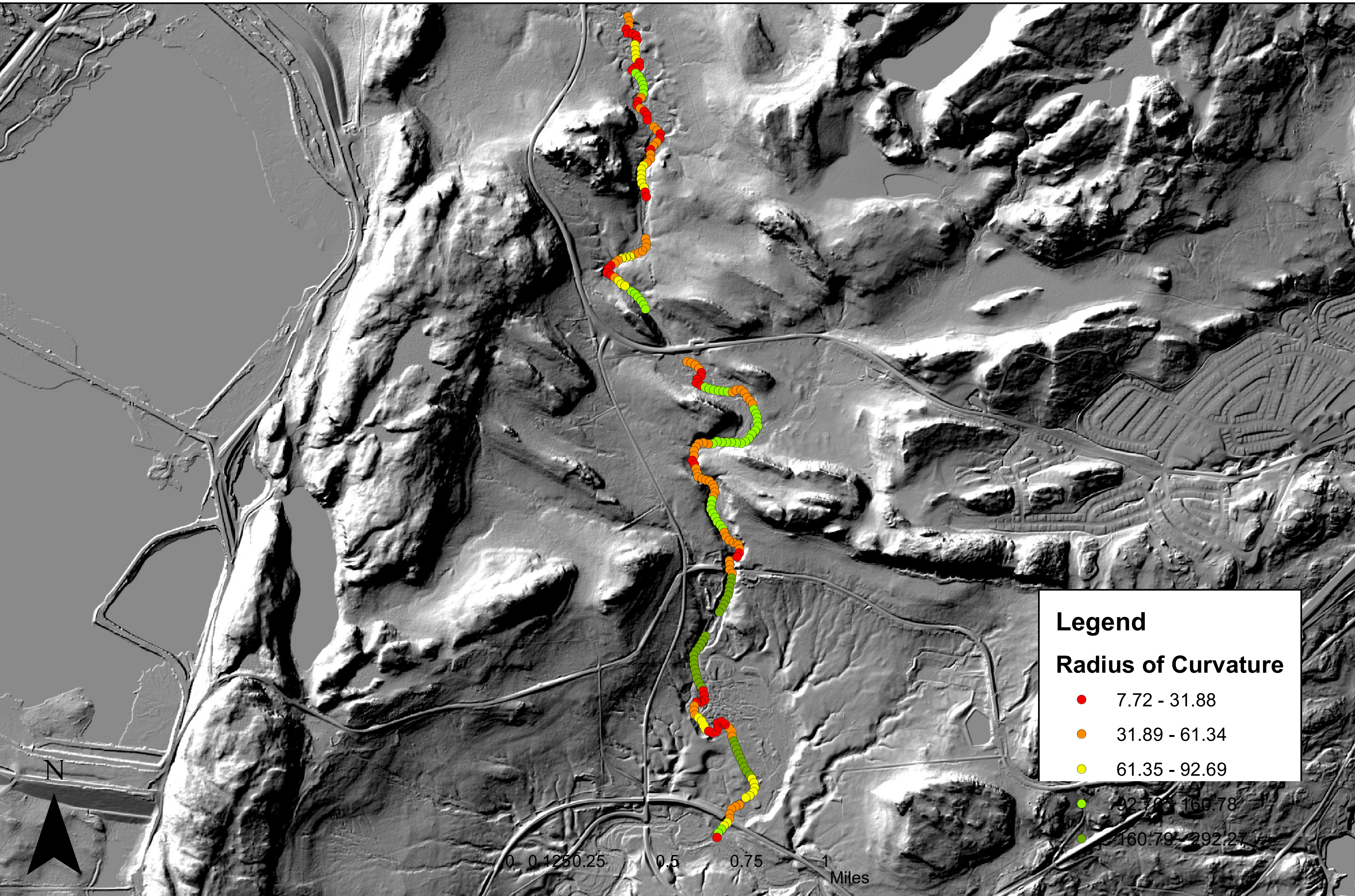
East Branch Beaver River

Erosional Hotspots



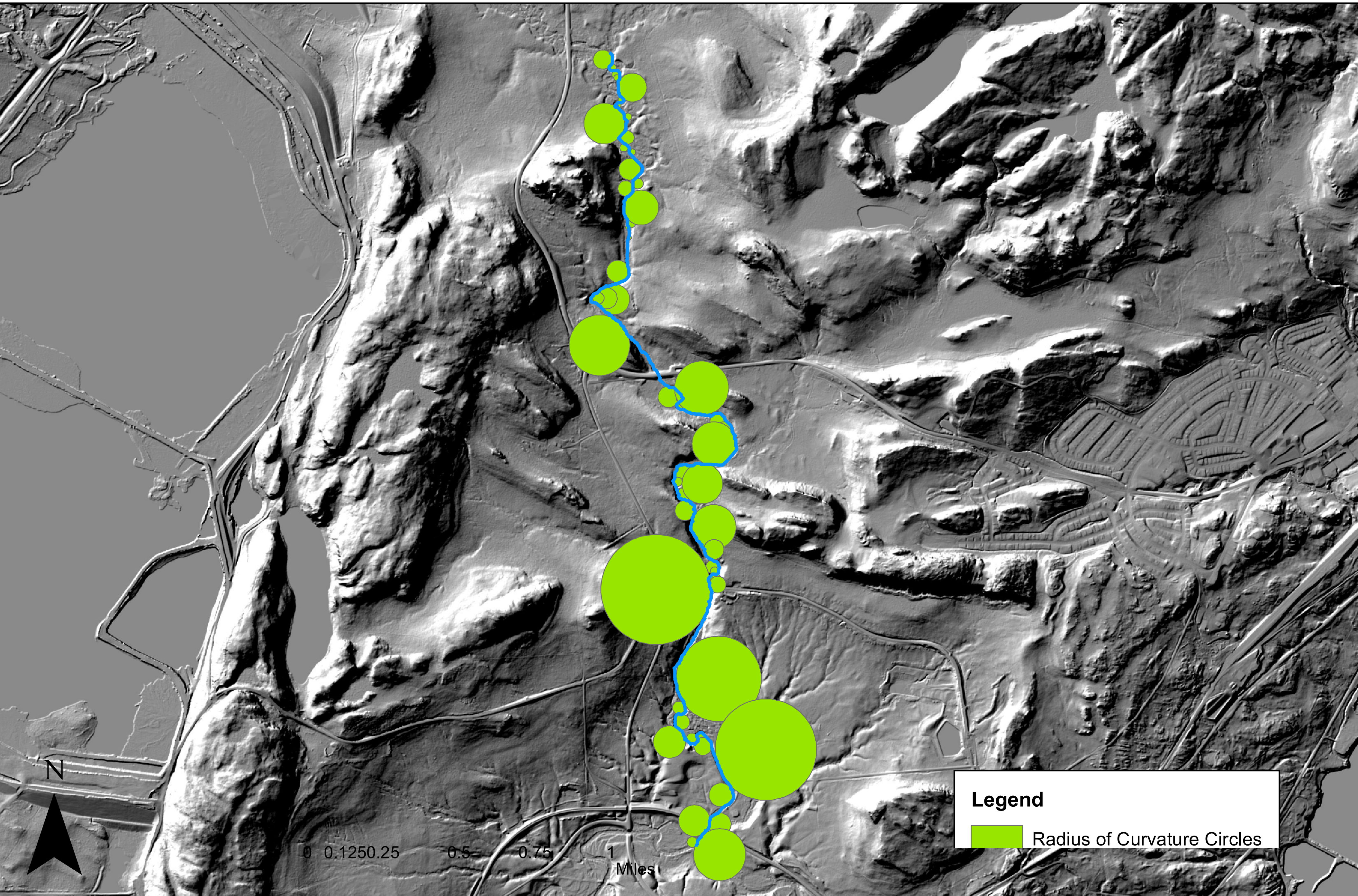
East Branch Beaver River

Radius of Curvature



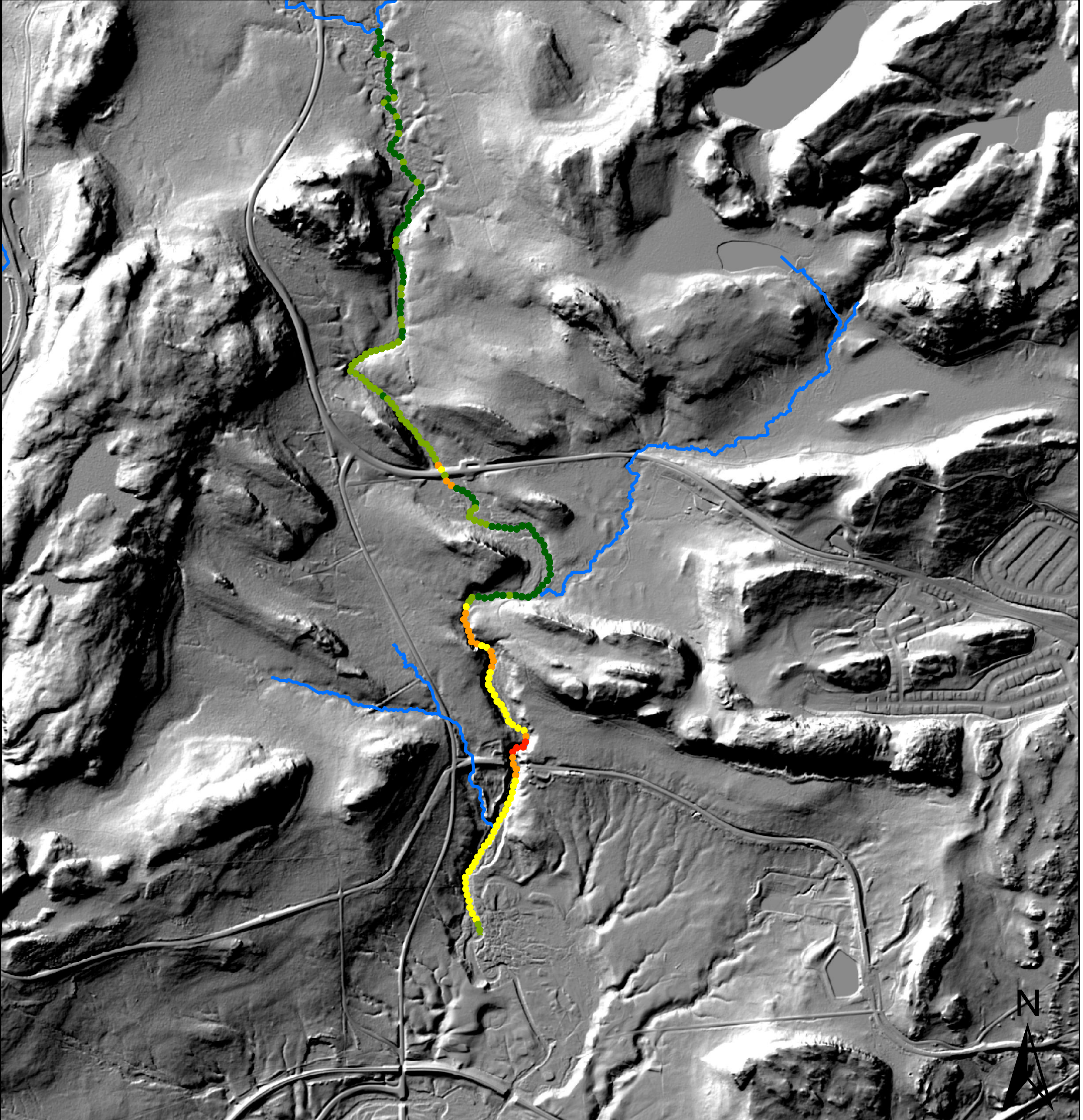
East Branch Beaver River

Radius of Curvature



East Branch Beaver River

Stream Power Index



This map shows points spaced every 25 m along the East Branch of the Beaver River and their associated stream power. The points with the highest associated stream power are colored in orange and red.

Legend

East Branch of Beaver River

Stream Power

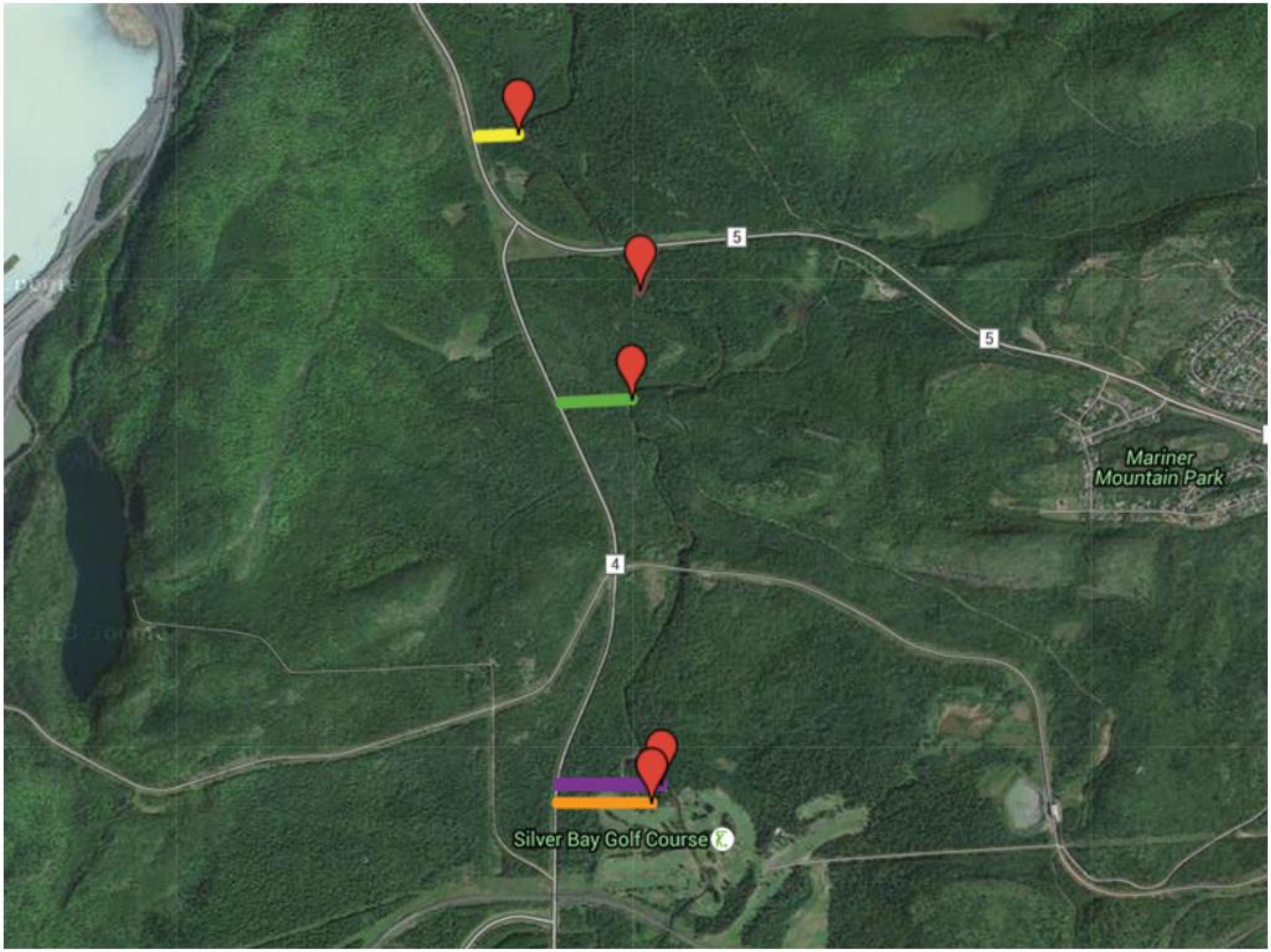
- ● 0.049265 - 15.984676
- ● 15.984677 - 45.421137
- ● 45.421138 - 104.400443
- ● 104.400444 - 249.053848
- ● 249.053849 - 484.110050

0 0.075 0.15 0.3 0.45 0.6 Miles

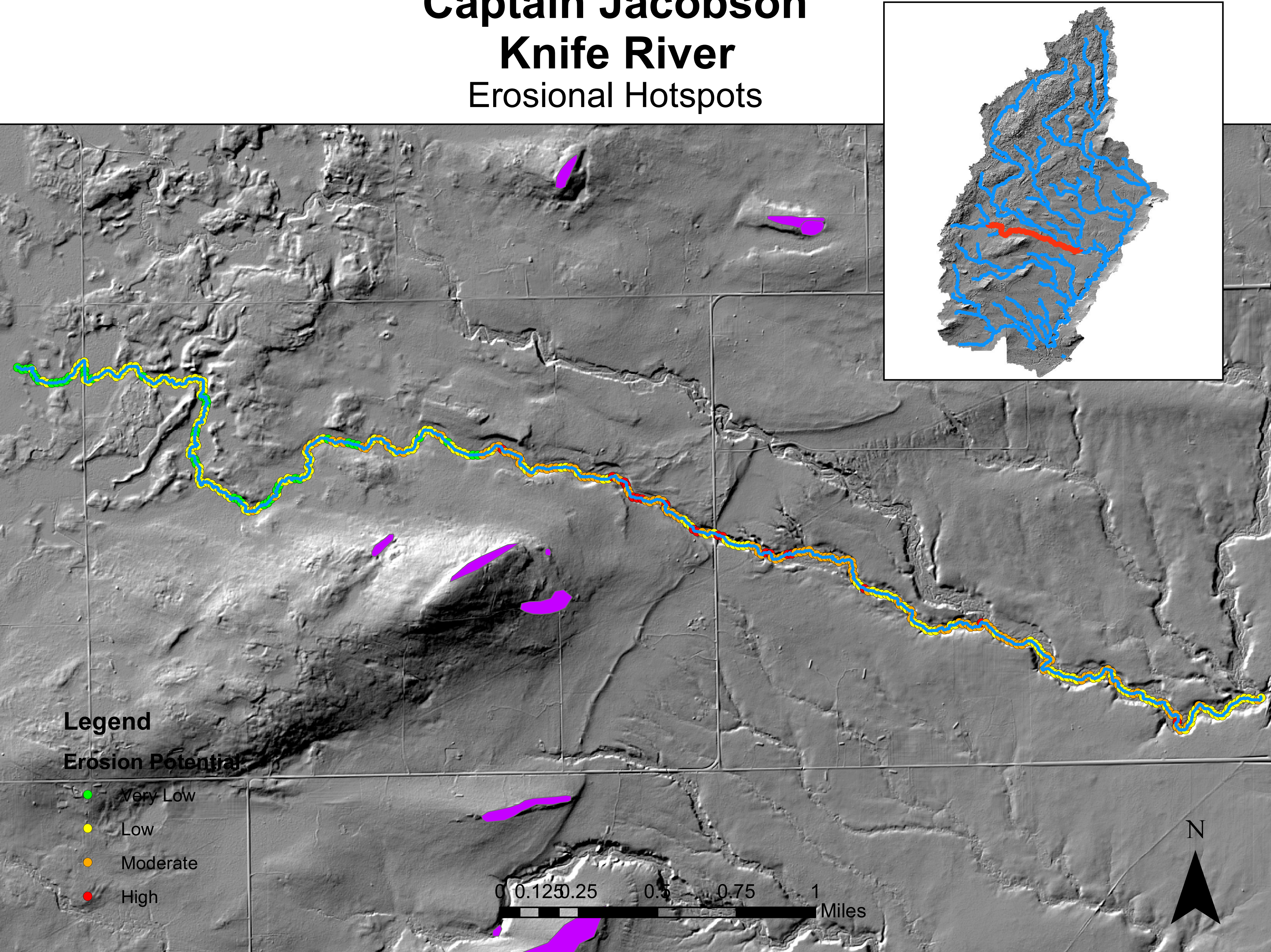
East Beaver

Erosion Hotspots

- 📍 47.27803, -91.31702
- 📍 47.27745, -91.31752
- 📍 47.29033, -91.31848
- 📍 47.29381, -91.31808
- 📍 47.29876, -91.32398
- 1,100 ft
- 1,200 ft
- 860 ft
- 480 ft
- 500 ft

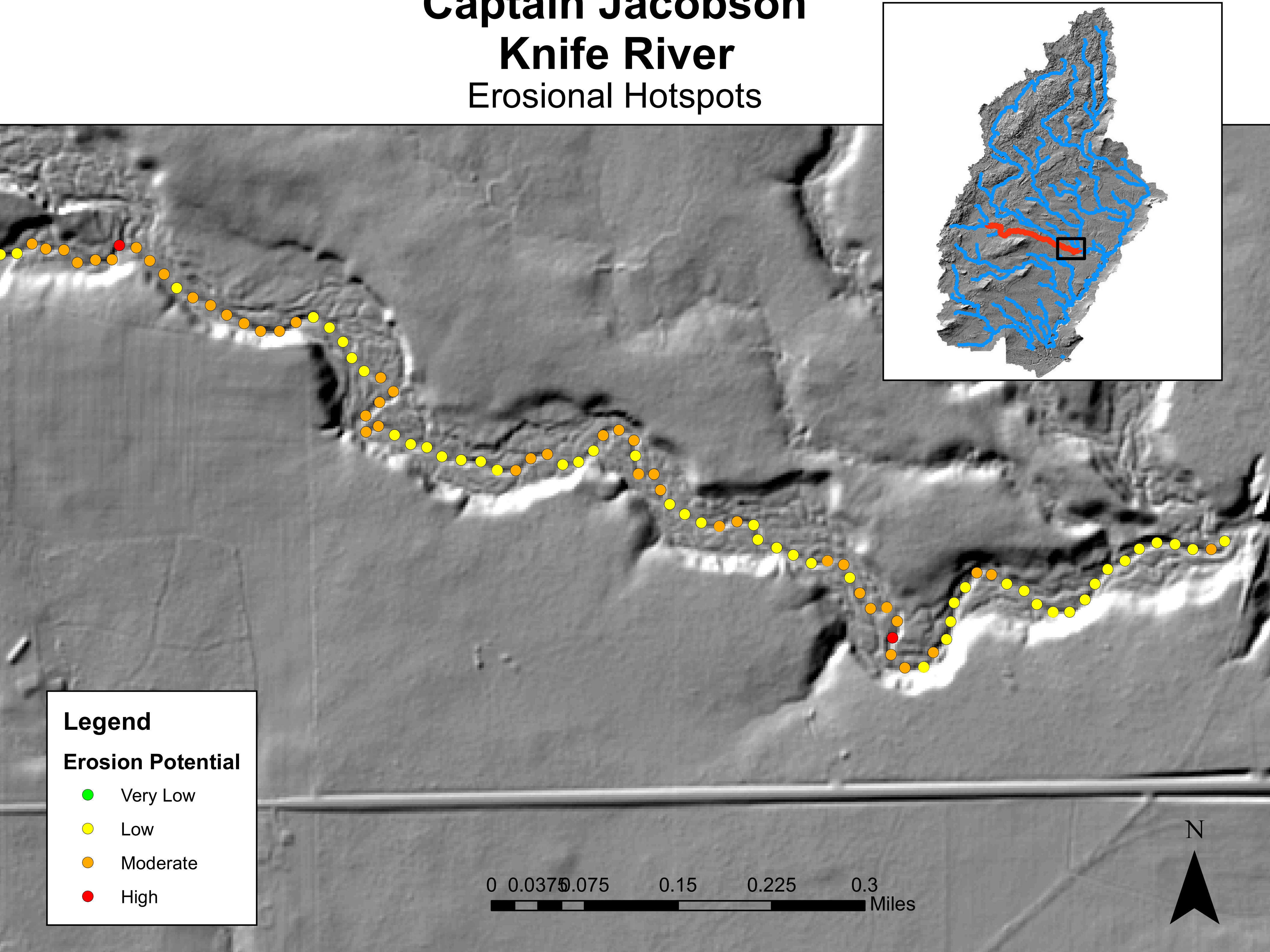


Captain Jacobson
Knife River
Erosional Hotspots

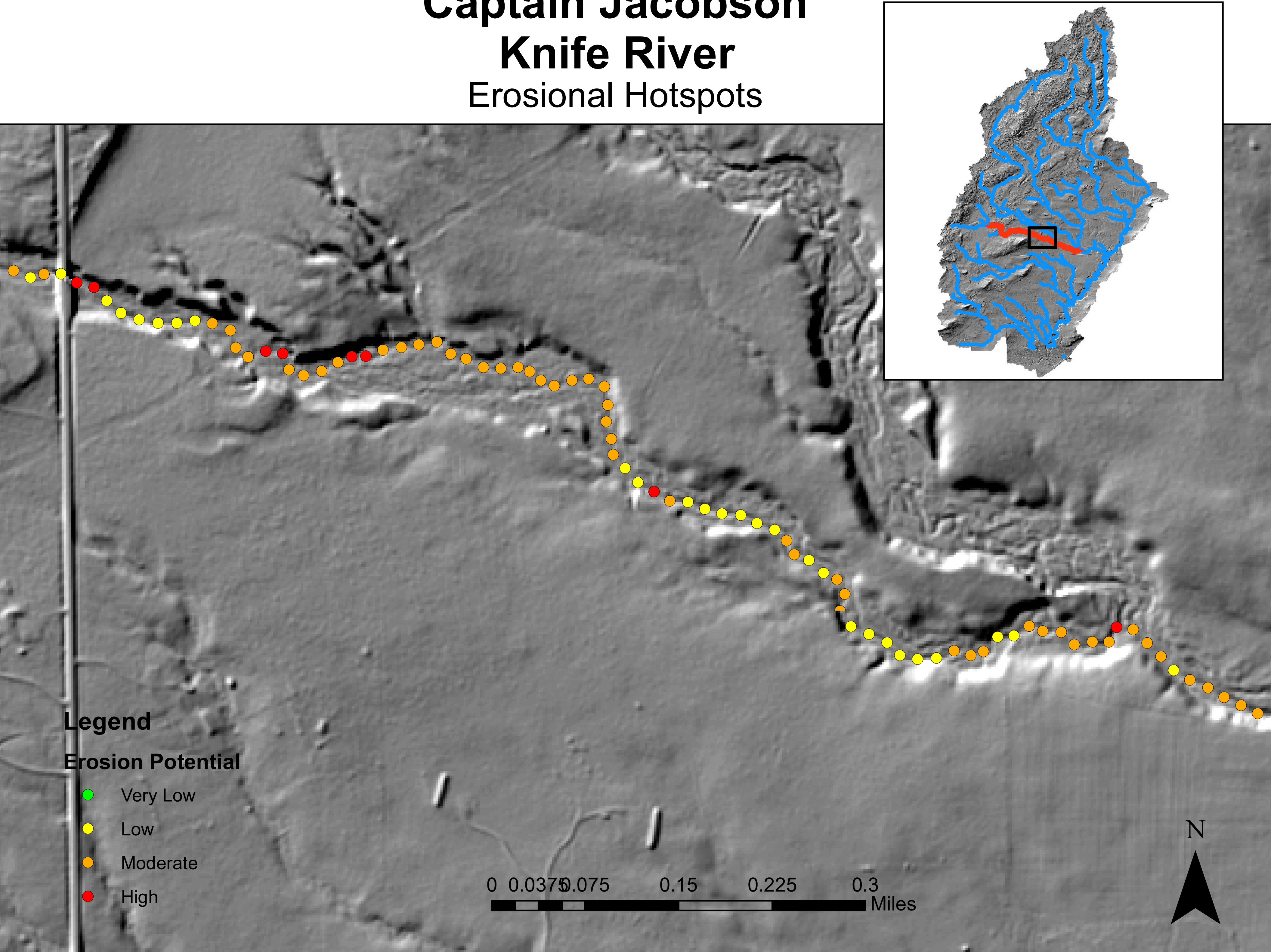


Captain Jacobson Knife River

Erosional Hotspots

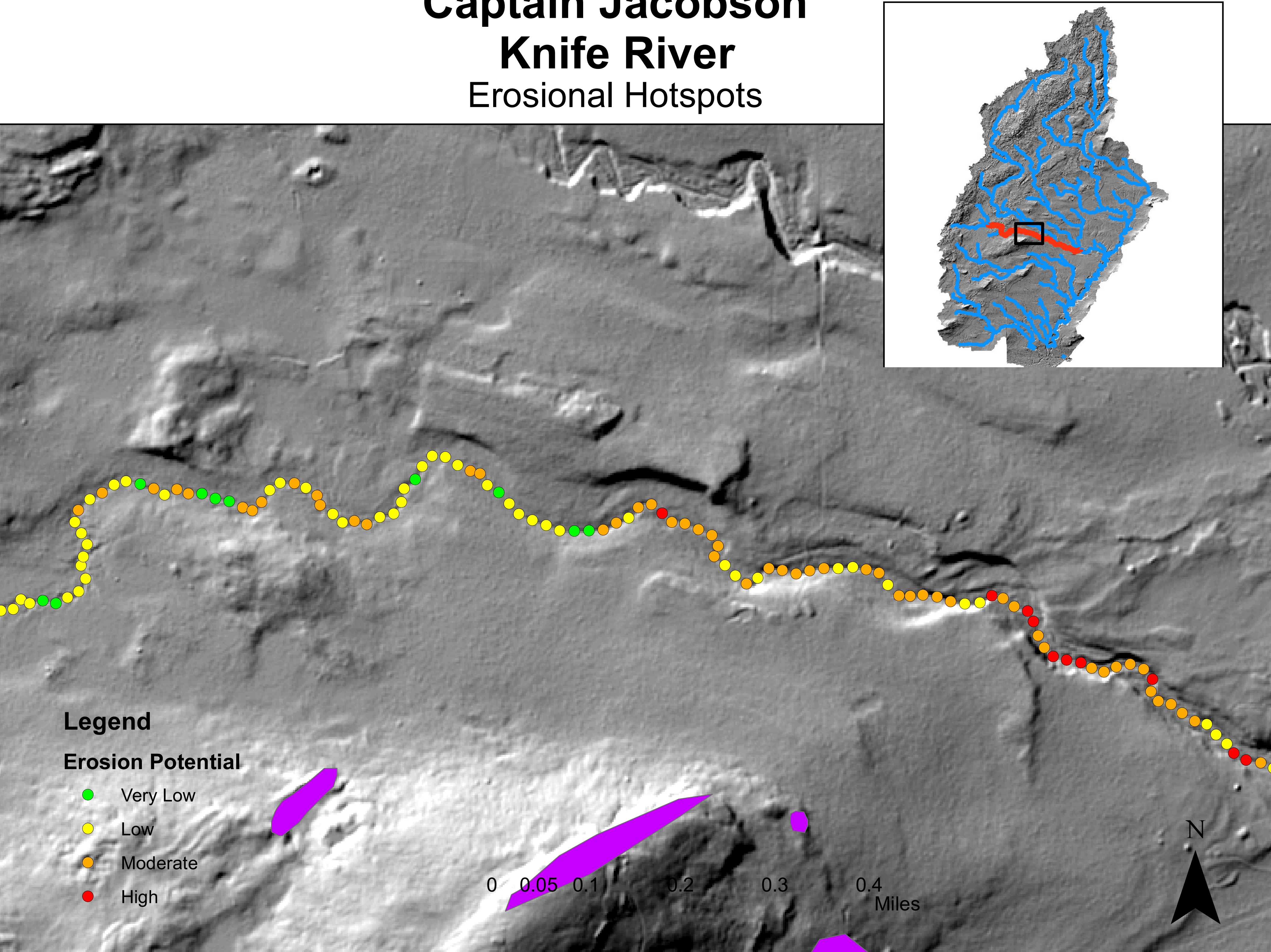


Captain Jacobson
Knife River
Erosional Hotspots



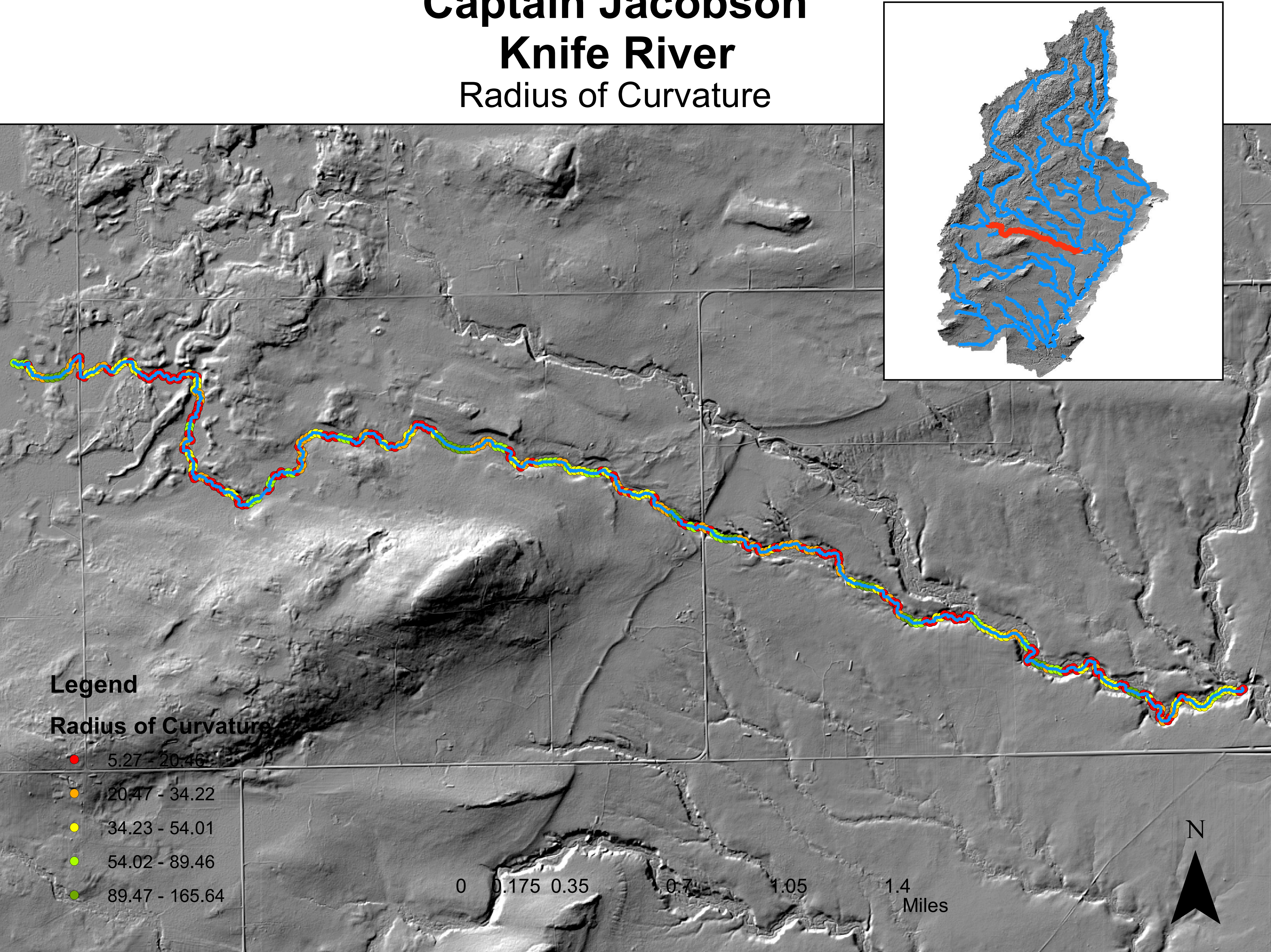
Captain Jacobson Knife River

Erosional Hotspots



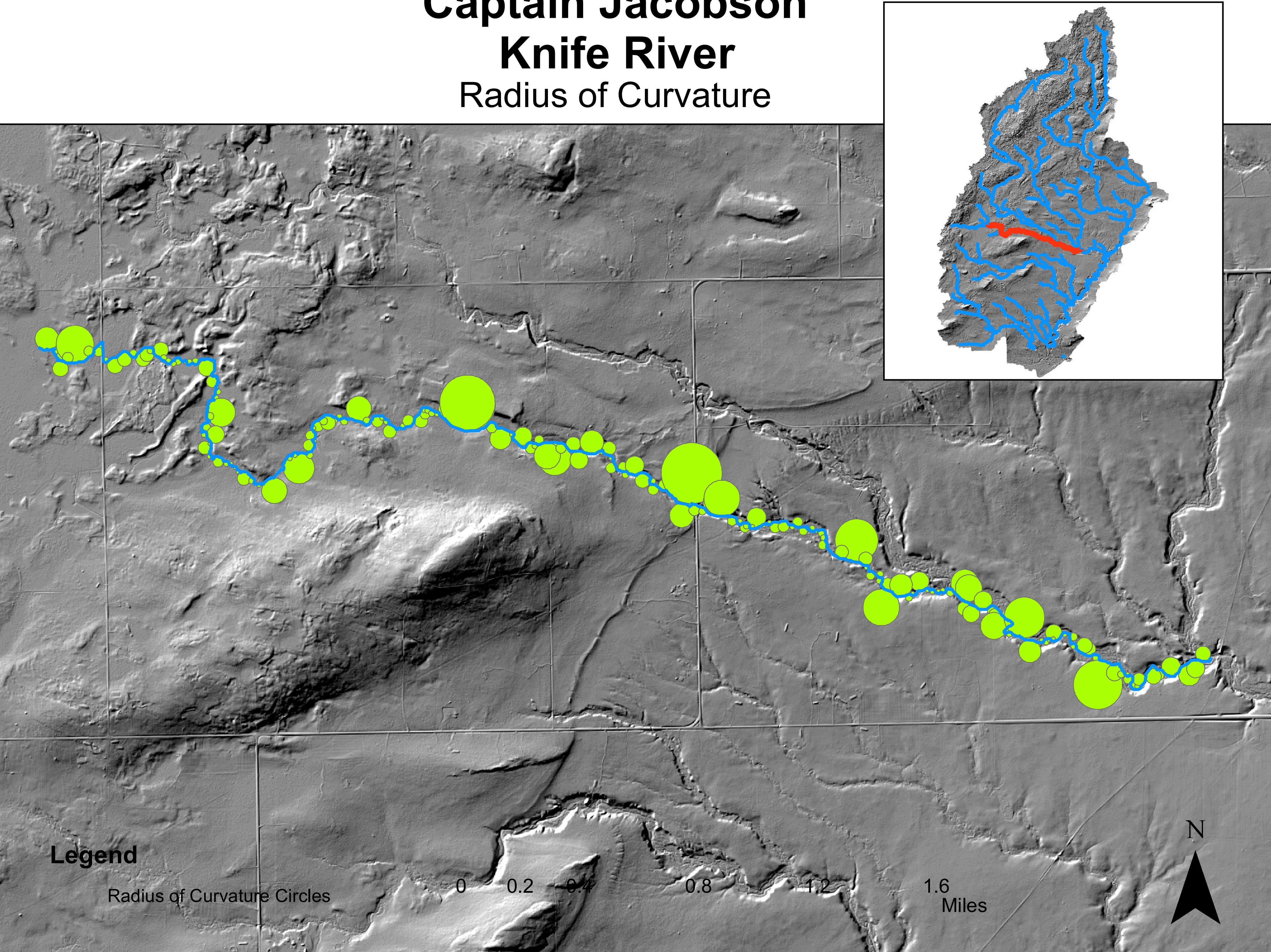
Captain Jacobson Knife River

Radius of Curvature



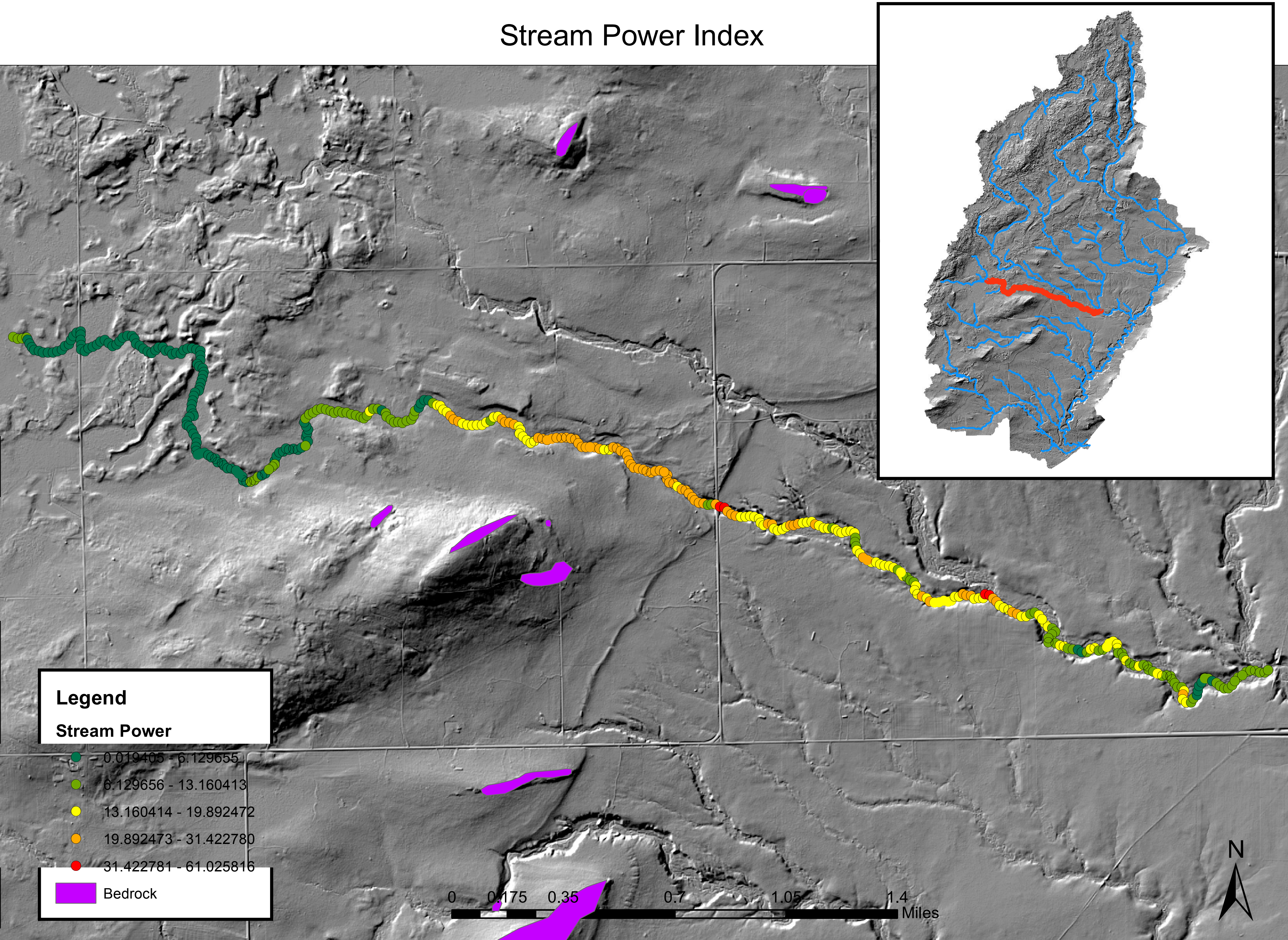
Captain Jacobson Knife River

Radius of Curvature



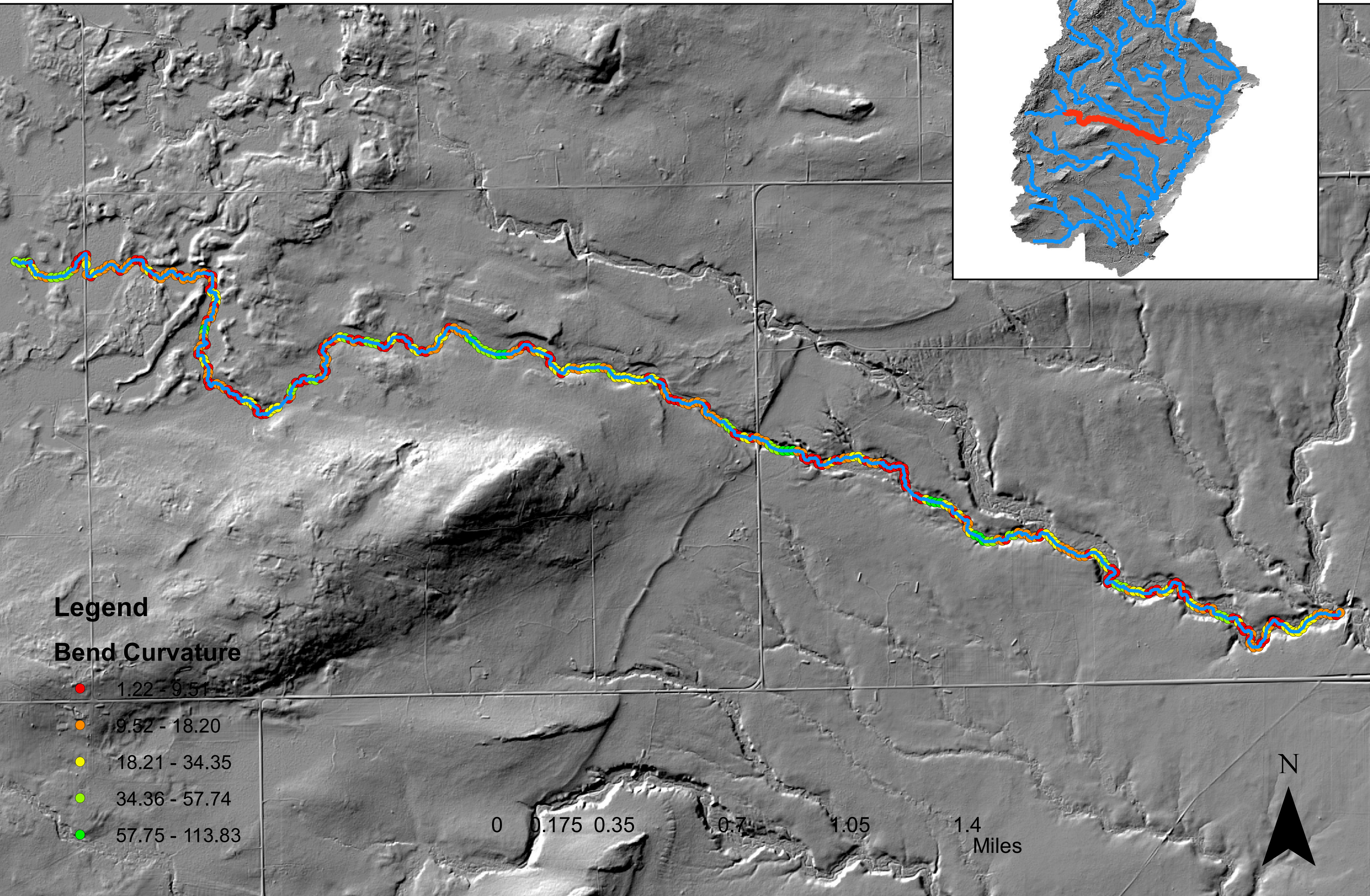
Knife River: Captain Jacobson Creek

Stream Power Index

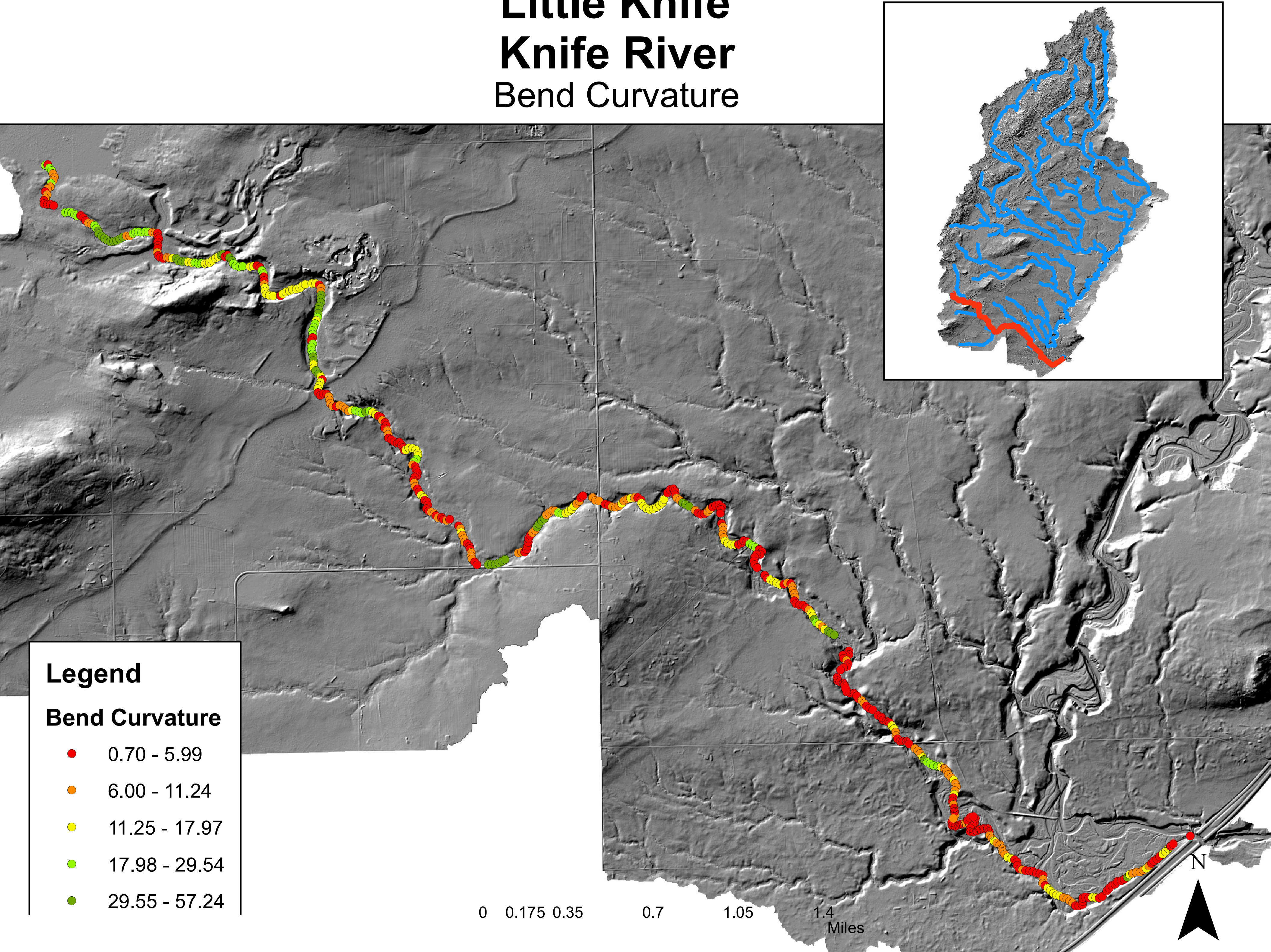


Captain Jacobson Knife River

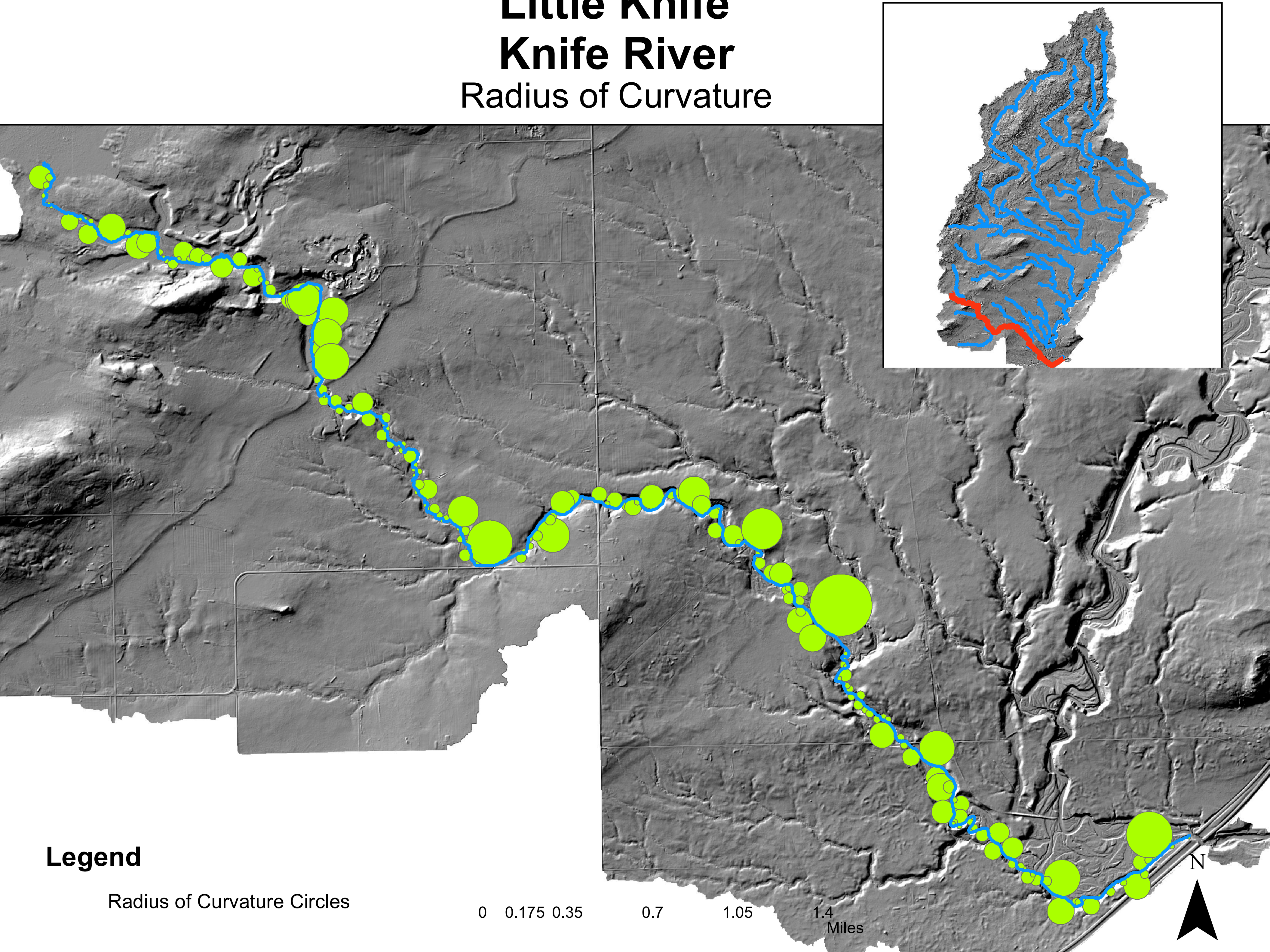
Bend Curvature



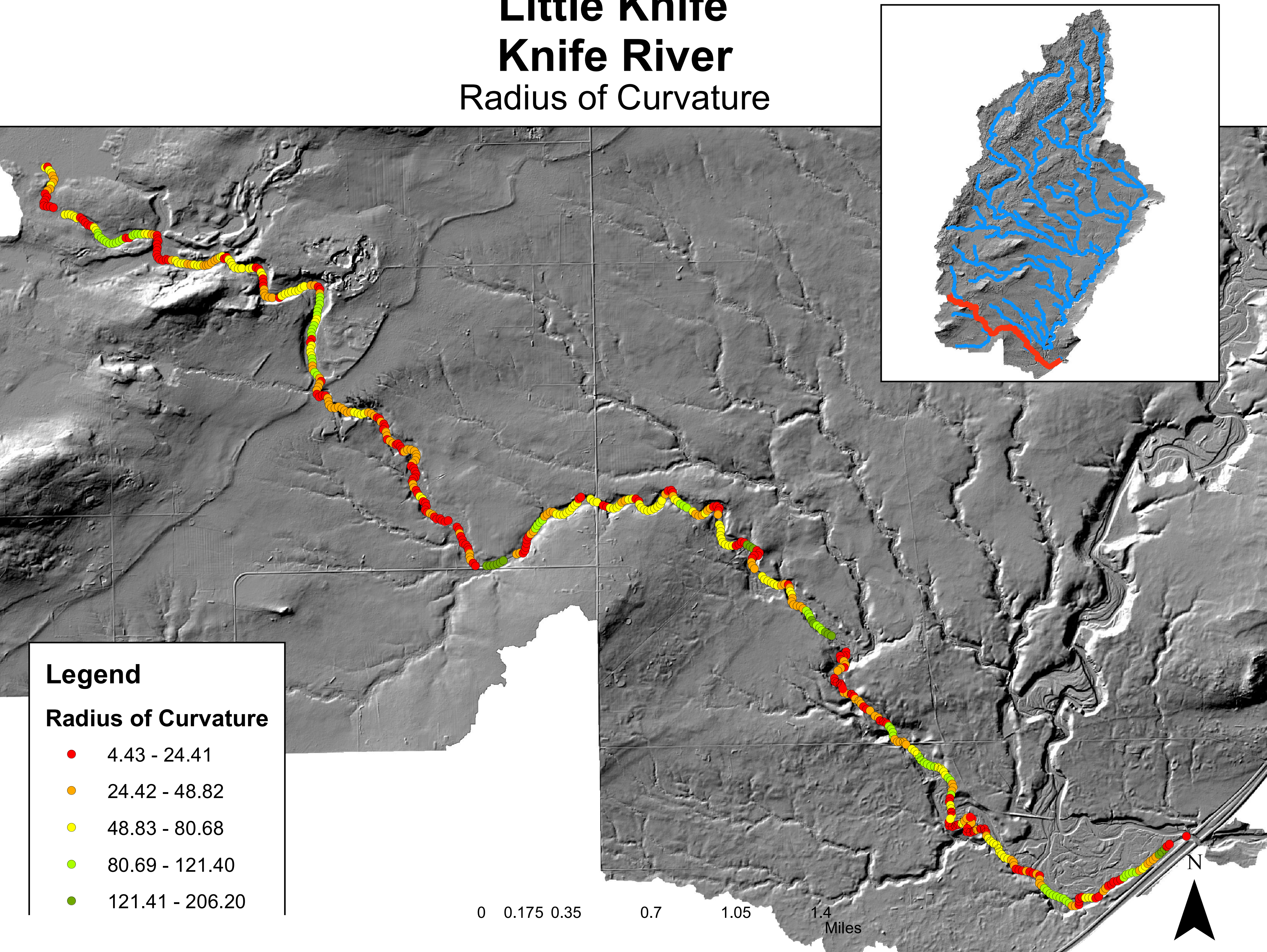
Little Knife
Knife River
Bend Curvature



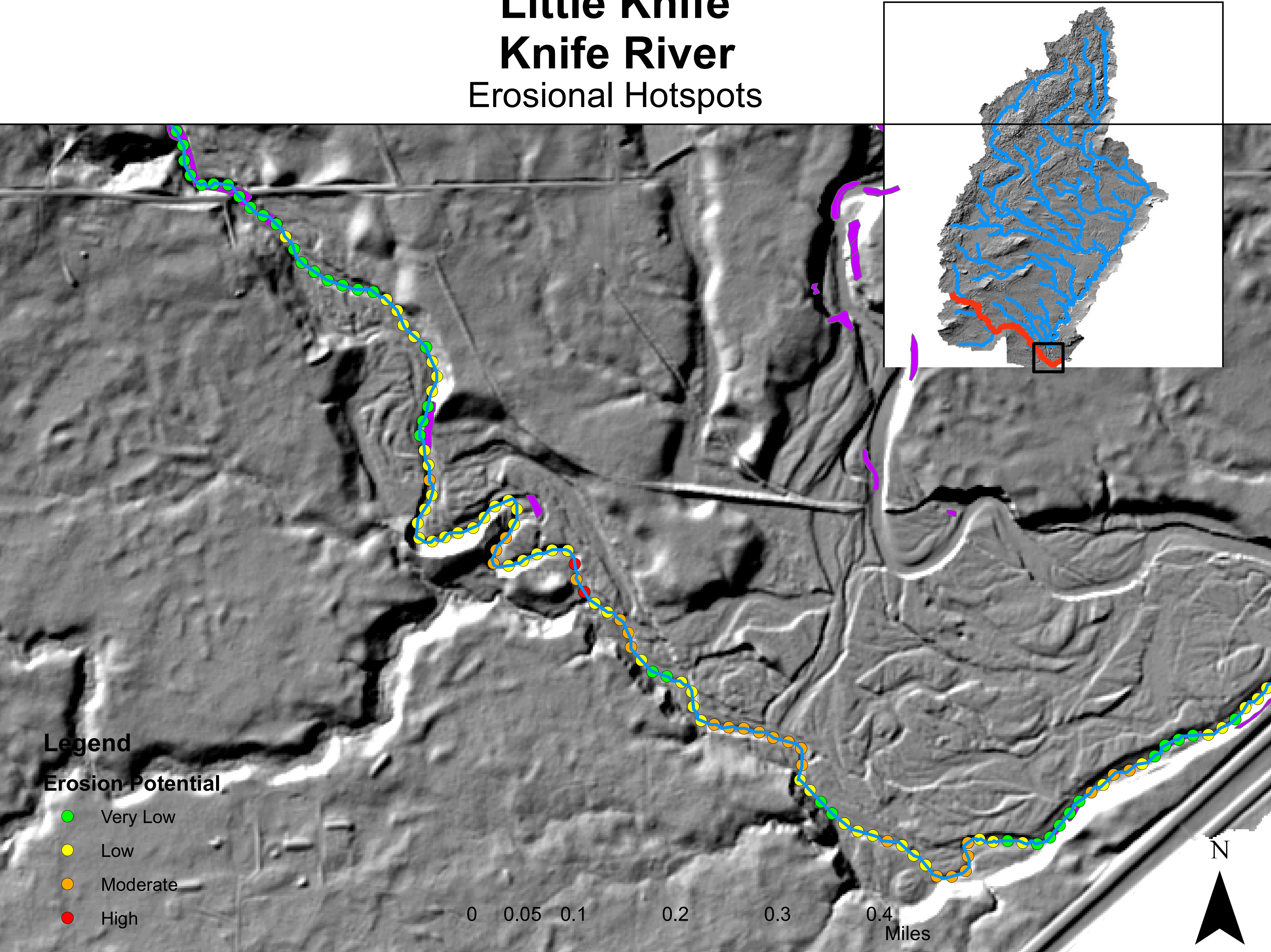
Little Knife
Knife River
Radius of Curvature



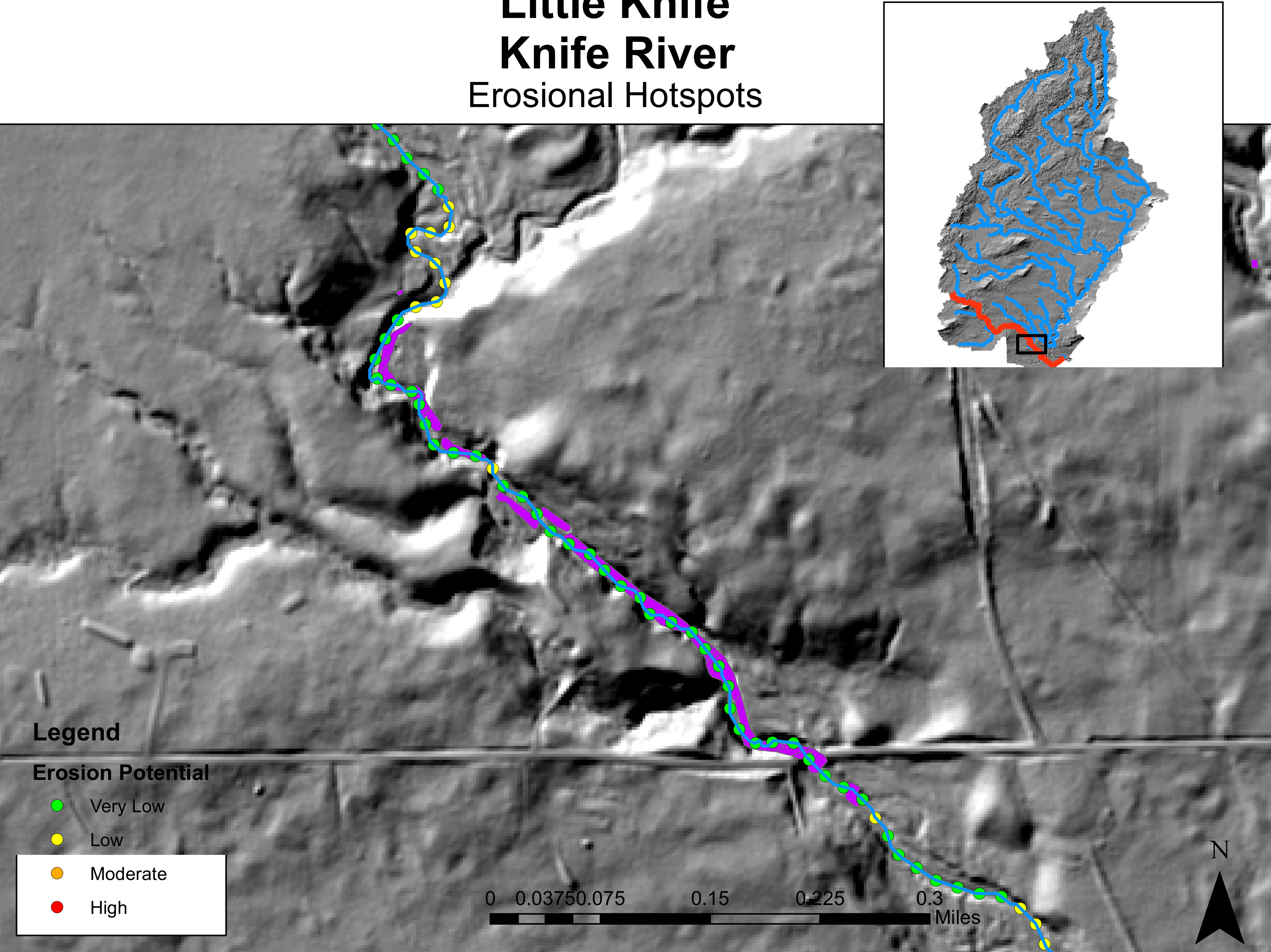
Little Knife
Knife River
Radius of Curvature



Little Knife
Knife River
Erosional Hotspots

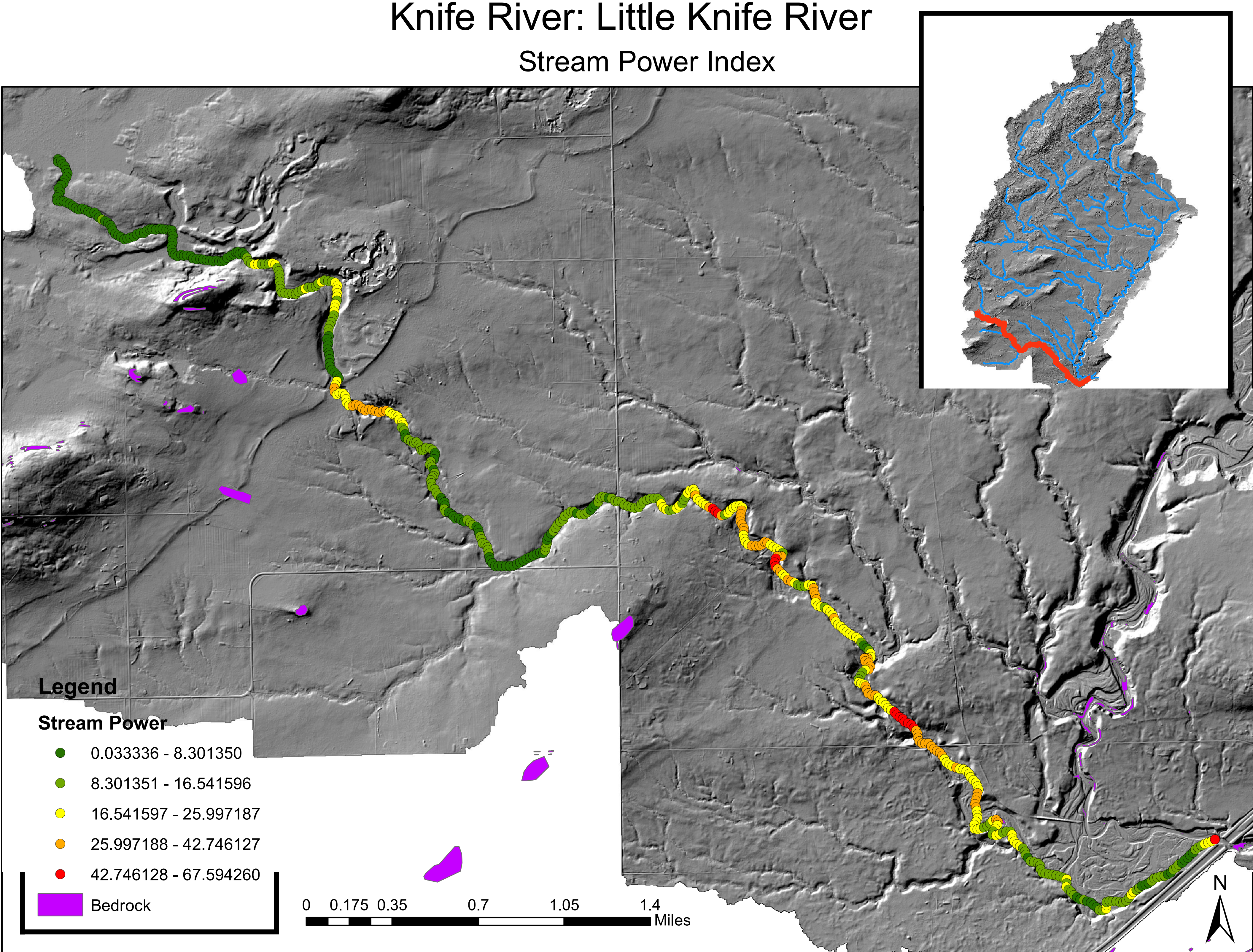


Little Knife
Knife River
Erosional Hotspots

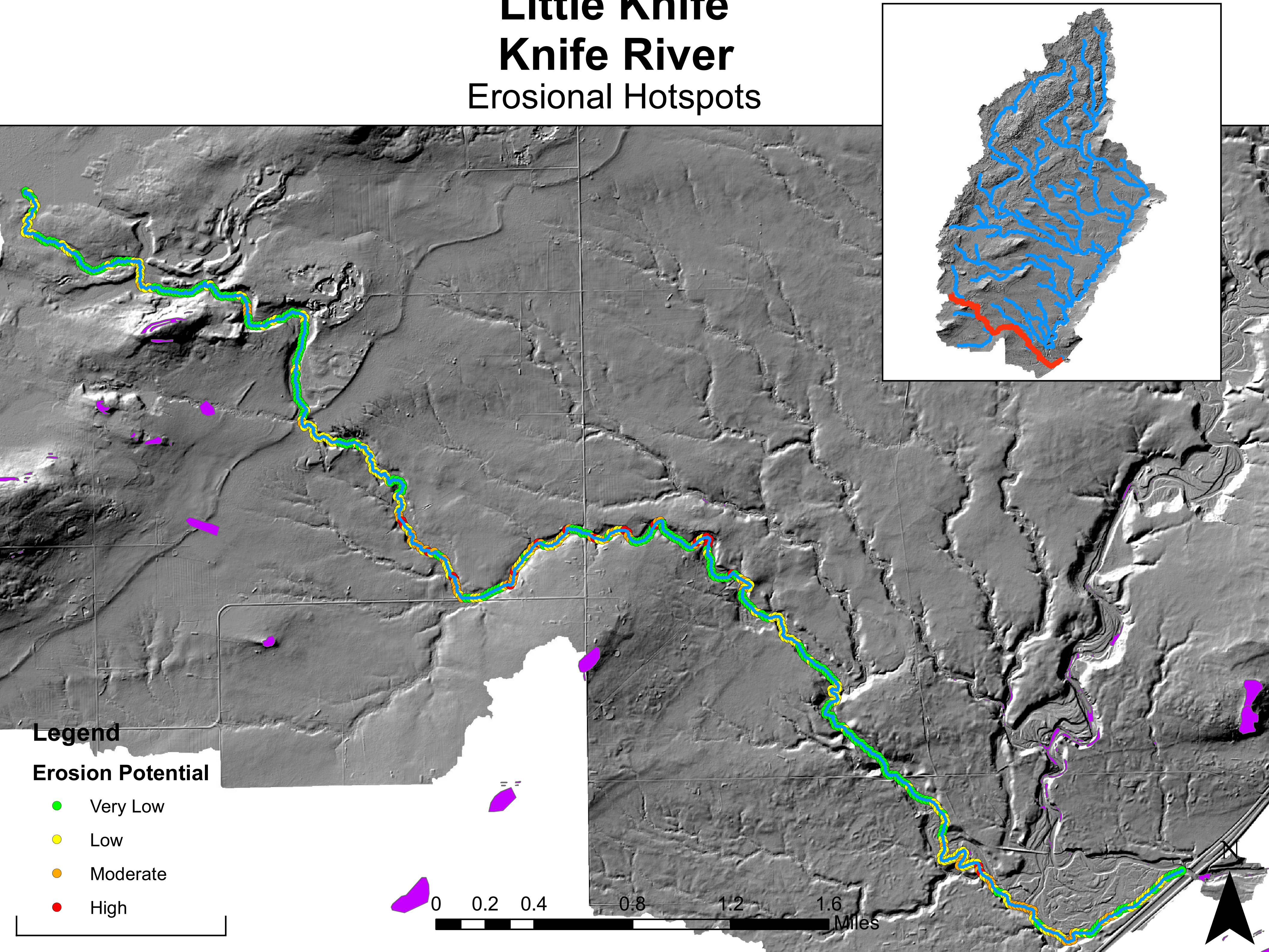


Knife River: Little Knife River

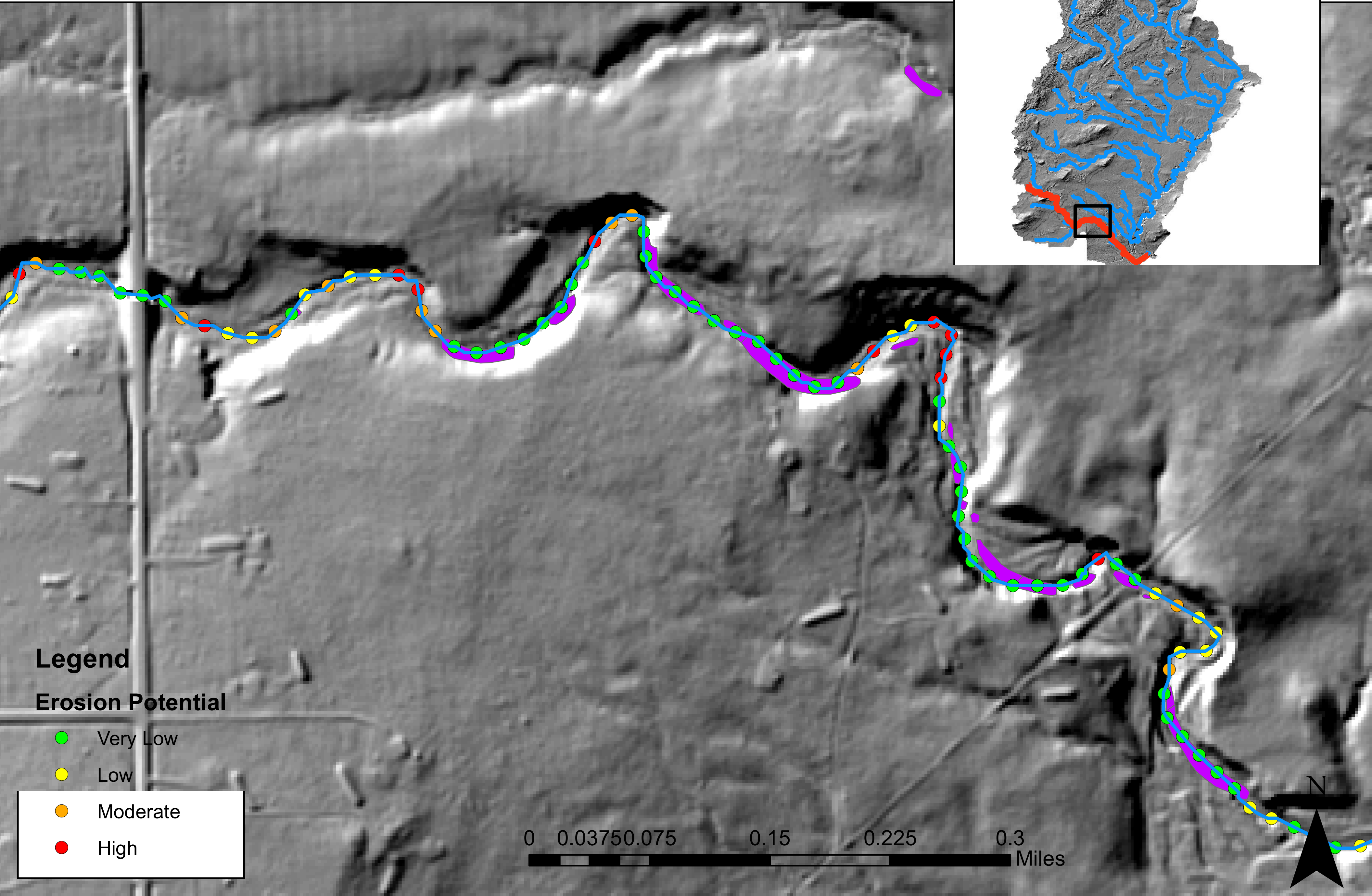
Stream Power Index



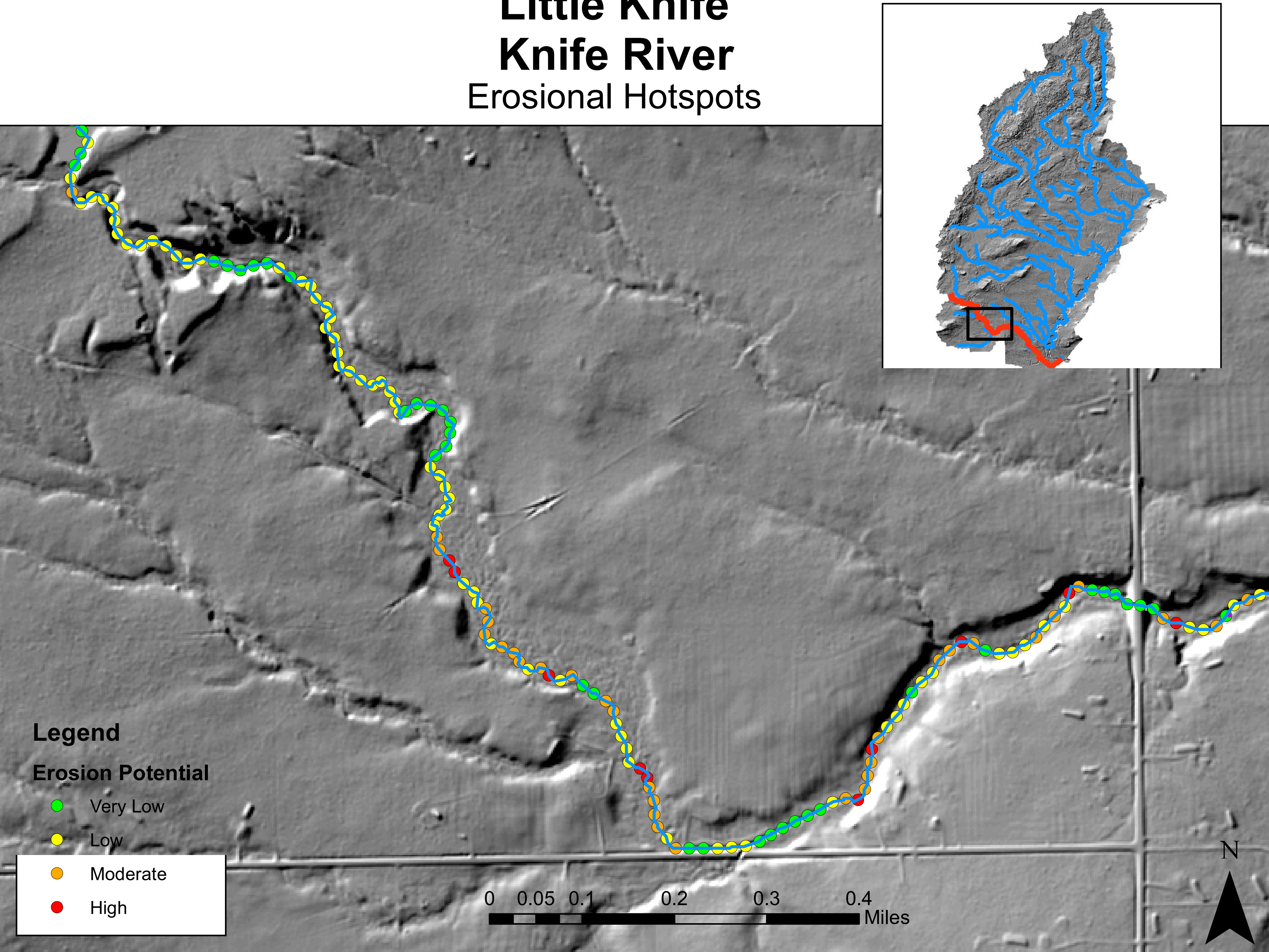
Little Knife
Knife River
Erosional Hotspots



Little Knife
Knife River
Erosional Hotspots



Little Knife
Knife River
Erosional Hotspots

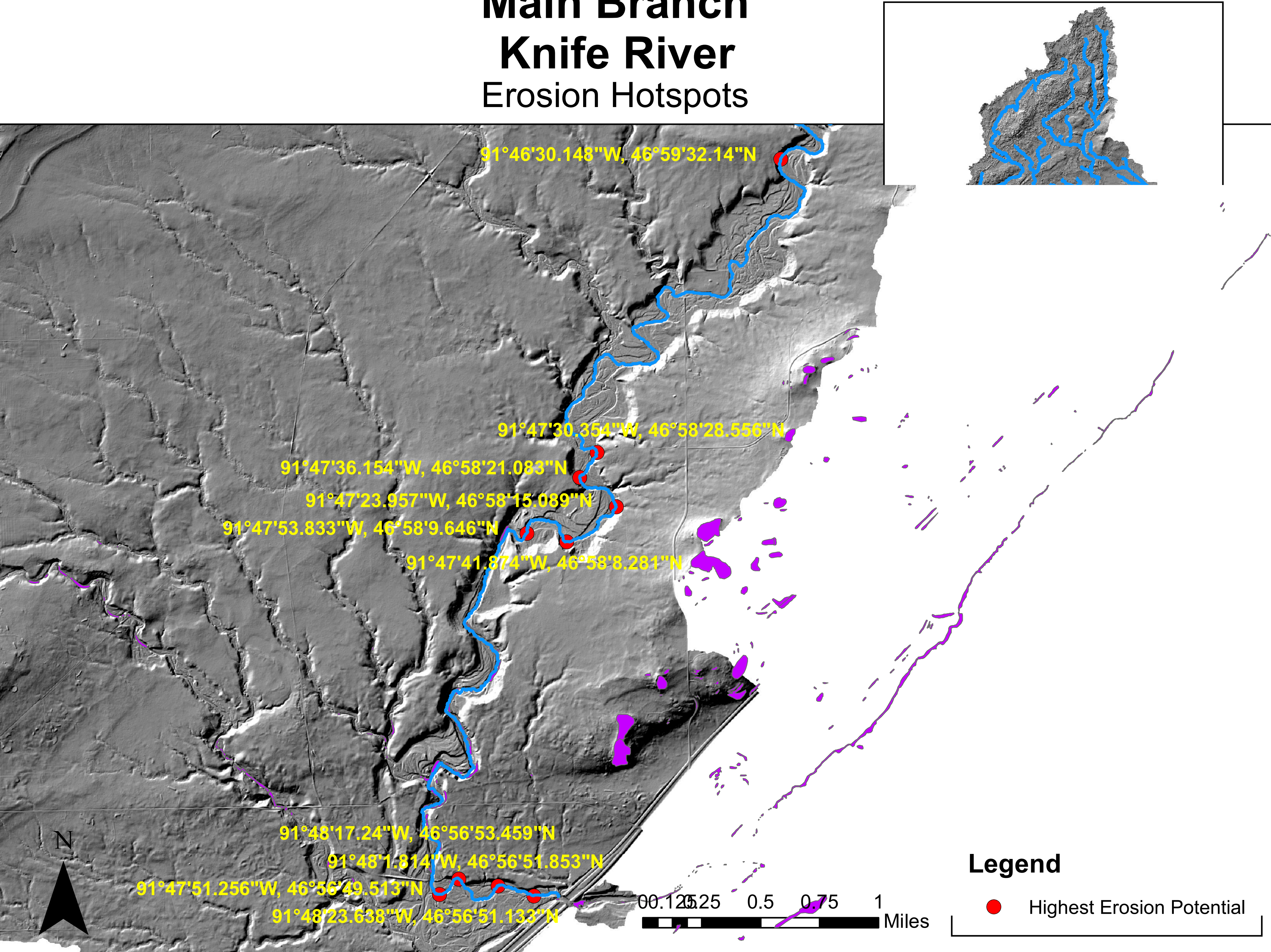


Knife River

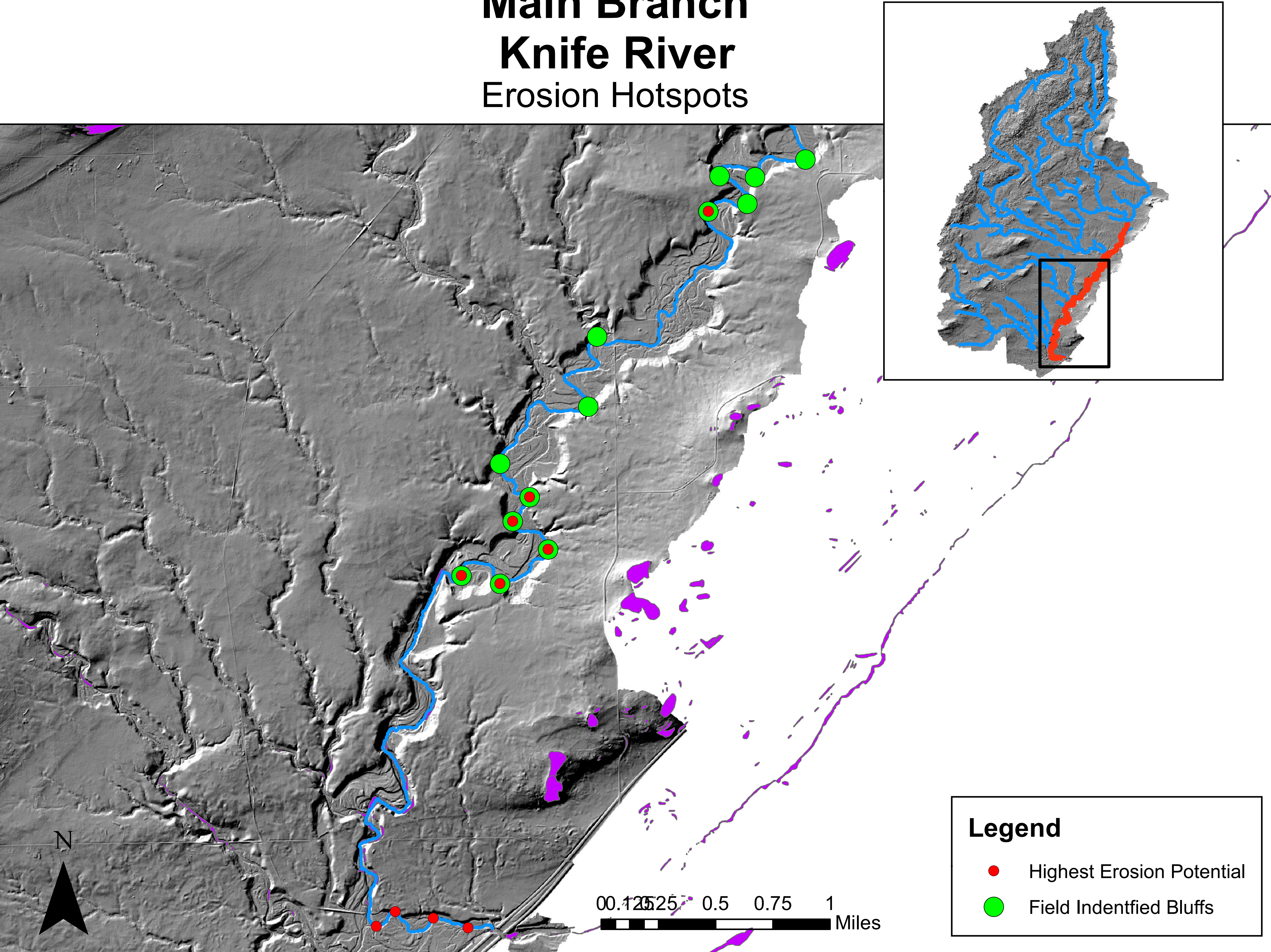
Erosion Hotspots

- 📍 46.96884, -91.79486
- 📍 46.96912, -91.79871
- 📍 46.94702, -91.80658
- 📍 46.94816, -91.80467
- 📍 46.94715, -91.79757
- 〰 360 ft
- 〰 1600 ft
- 〰 1800 ft
- 〰 1600 ft
- 〰 600 ft

Main Branch
Knife River
Erosion Hotspots

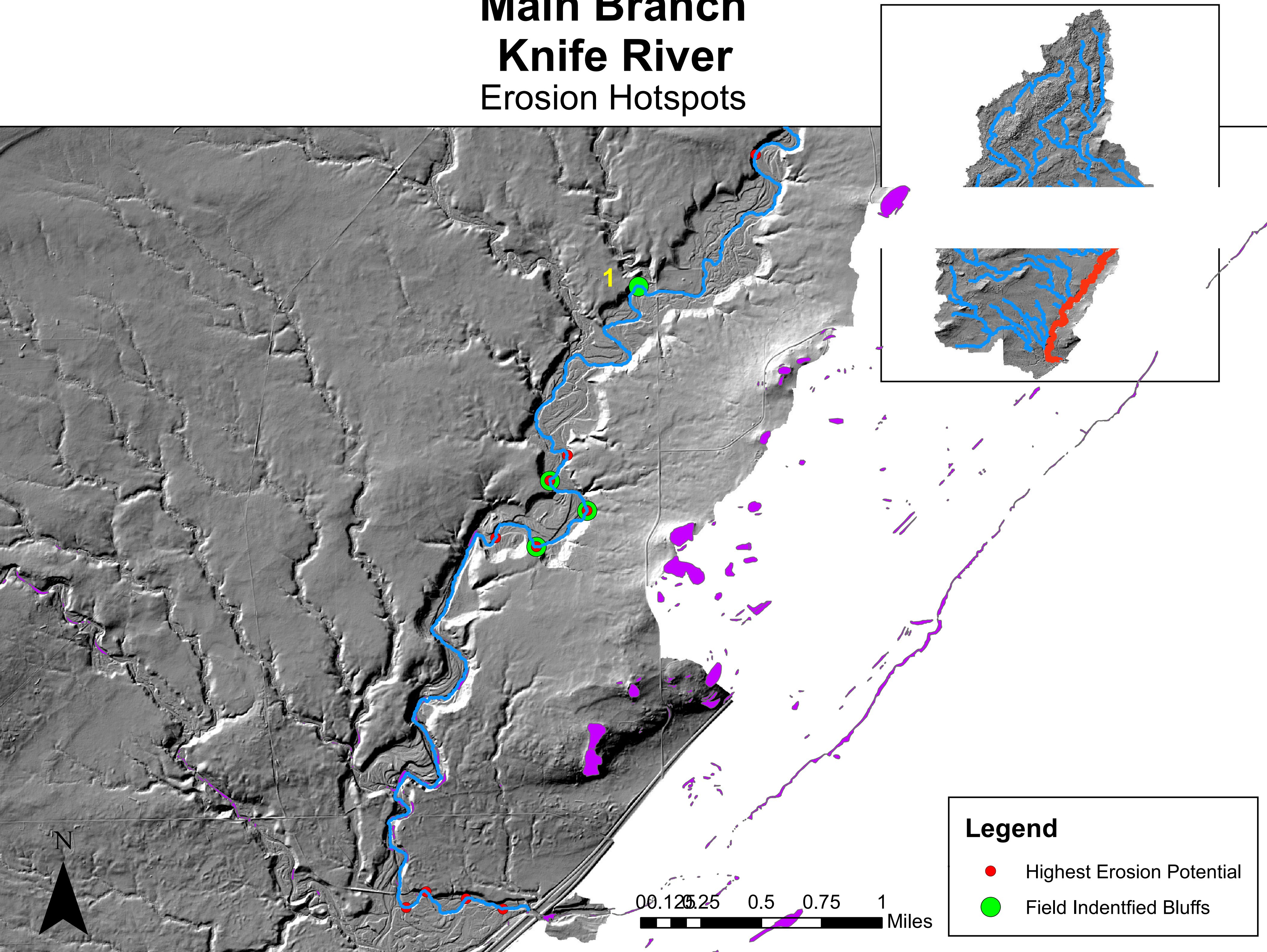


Main Branch
Knife River
Erosion Hotspots



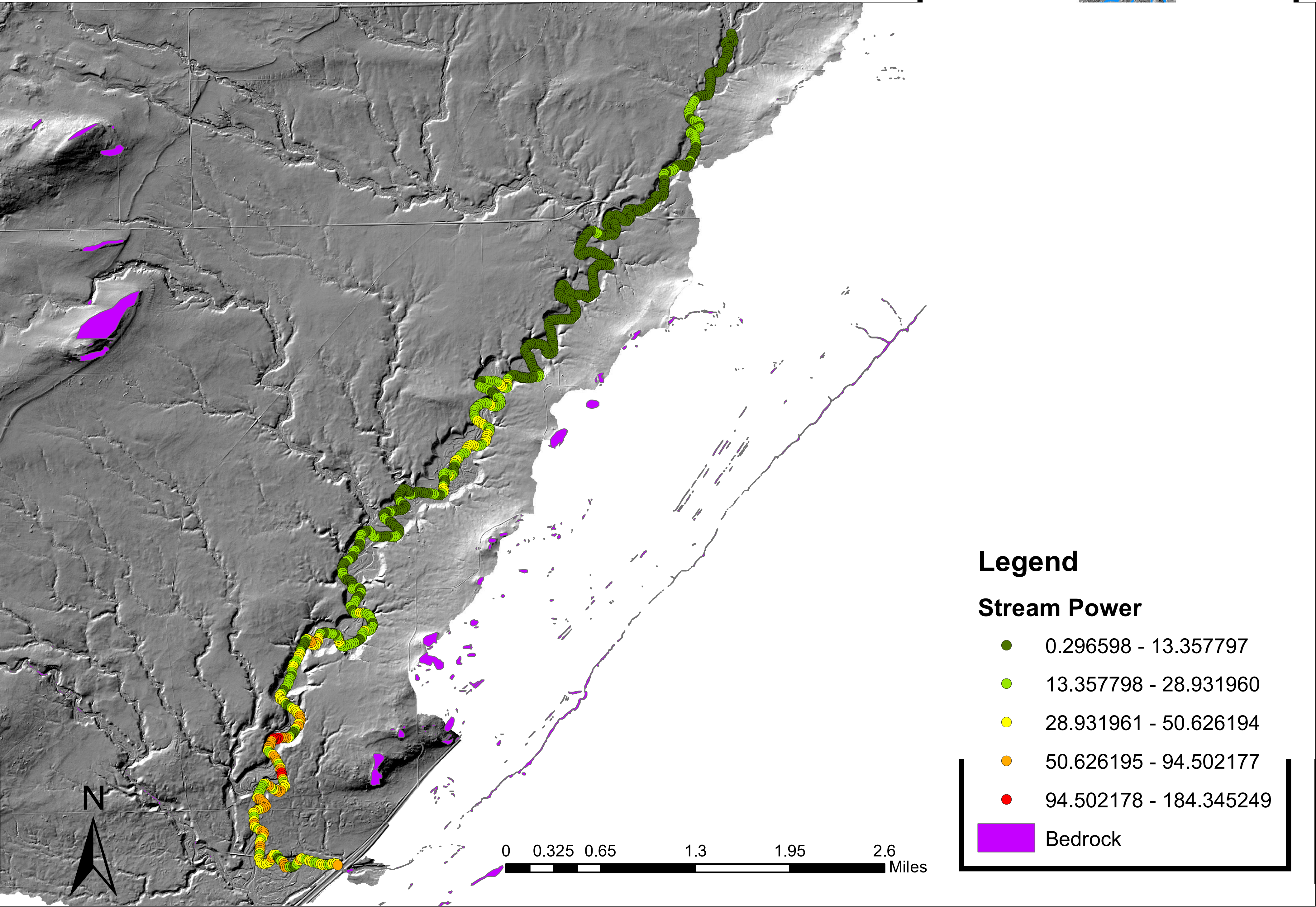
Main Branch Knife River

Erosion Hotspots

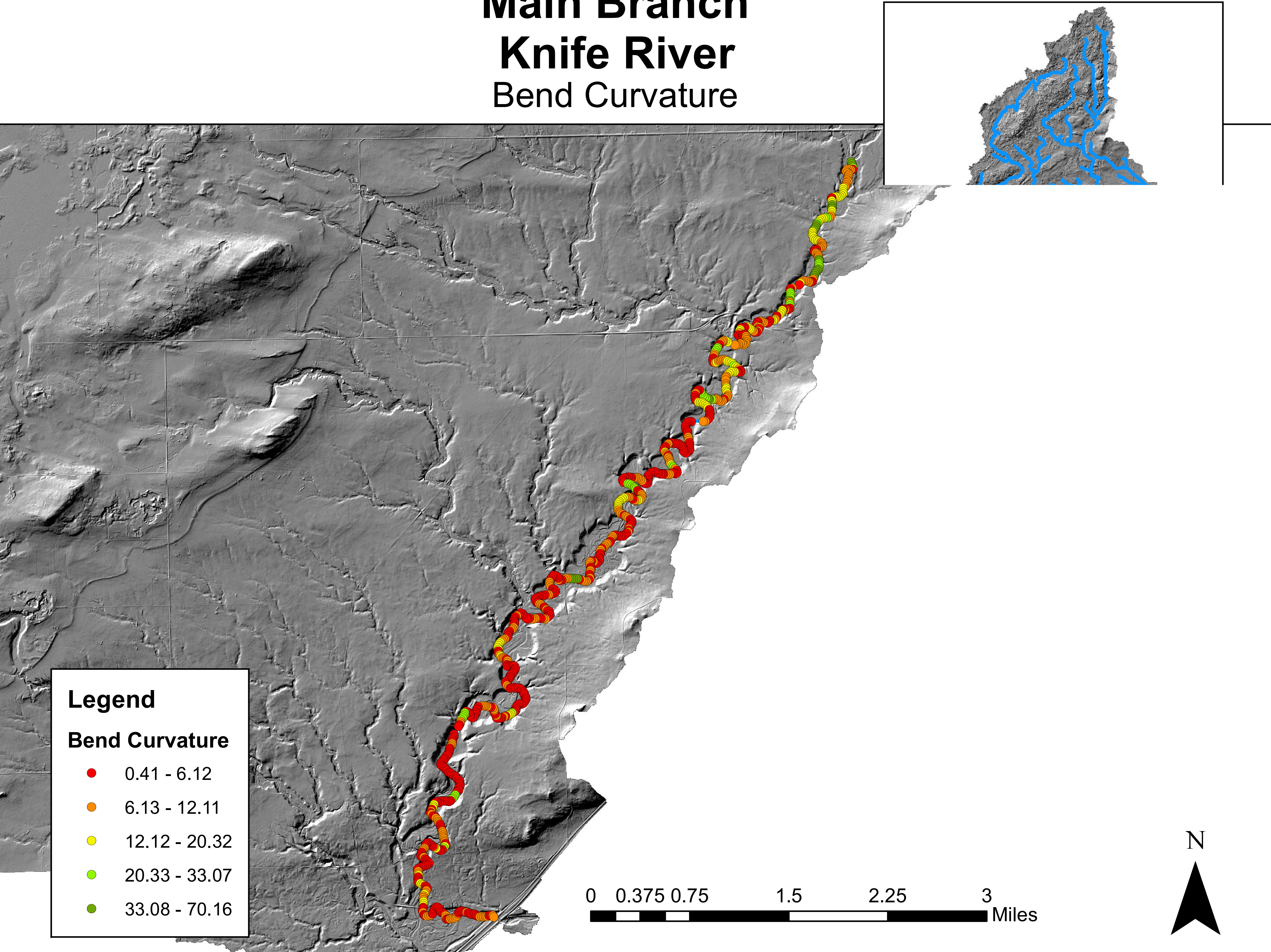


Knife River: Main Branch

Stream Power Index

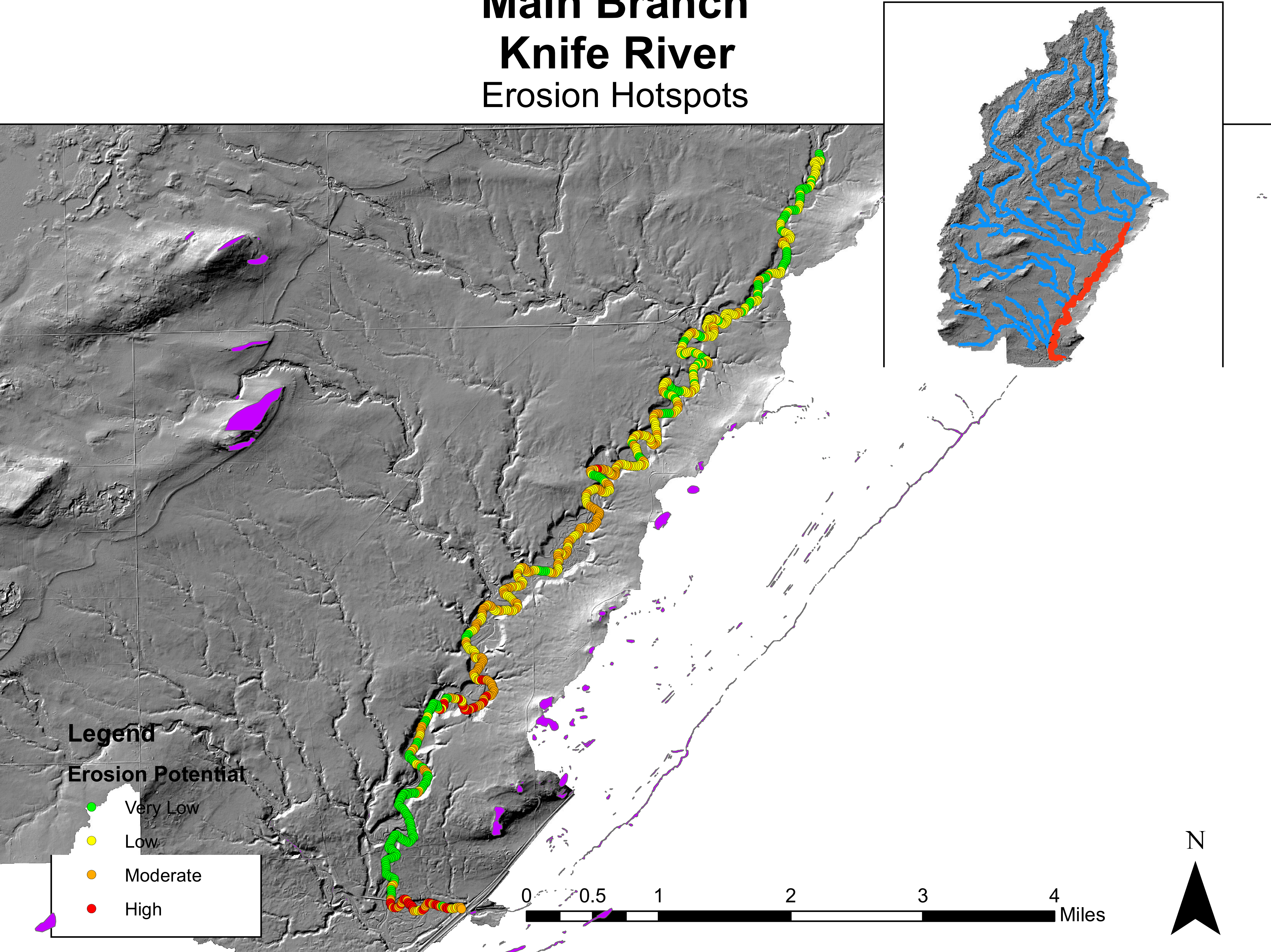


Main Branch
Knife River
Bend Curvature



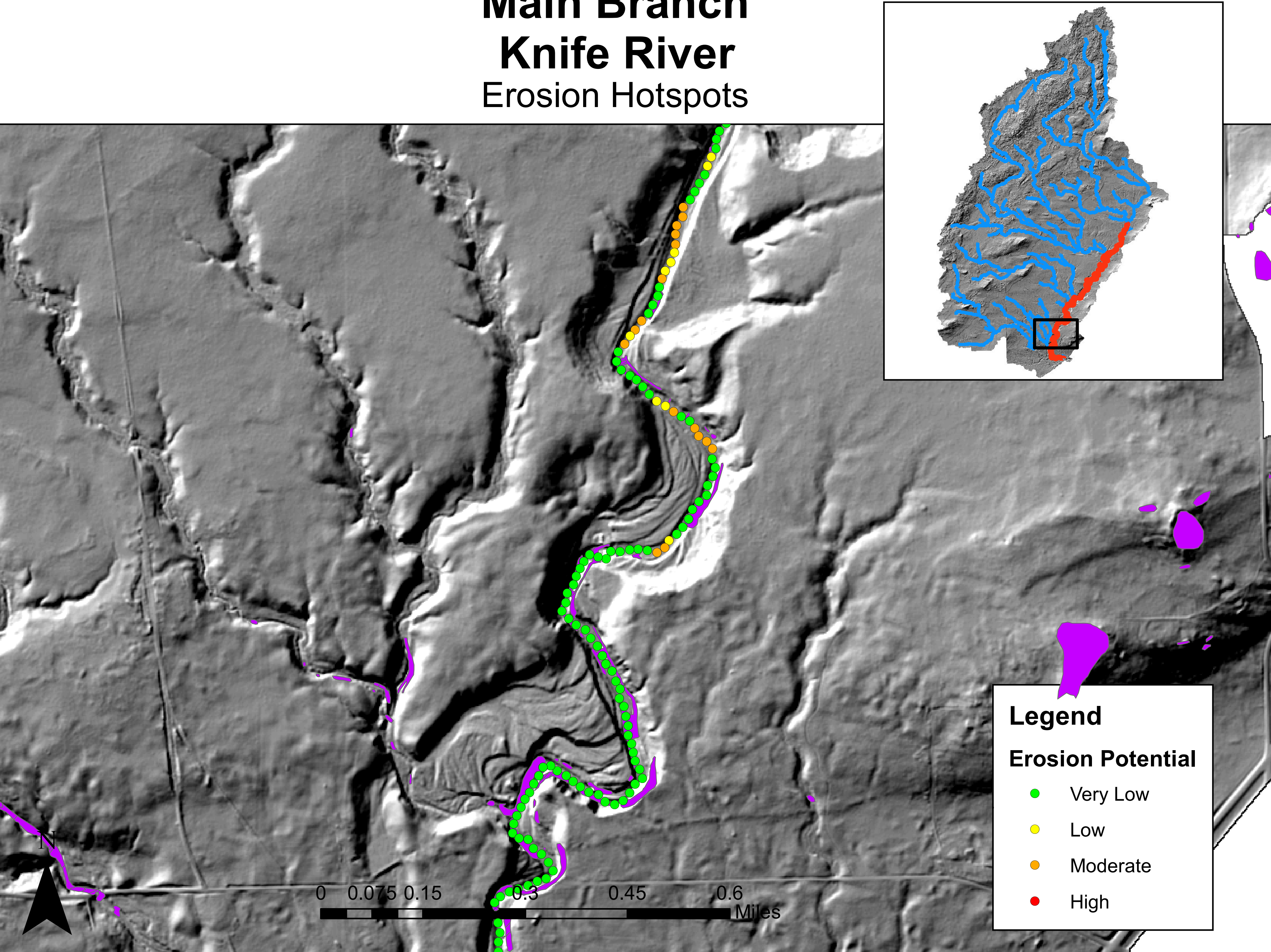
Main Branch Knife River

Erosion Hotspots



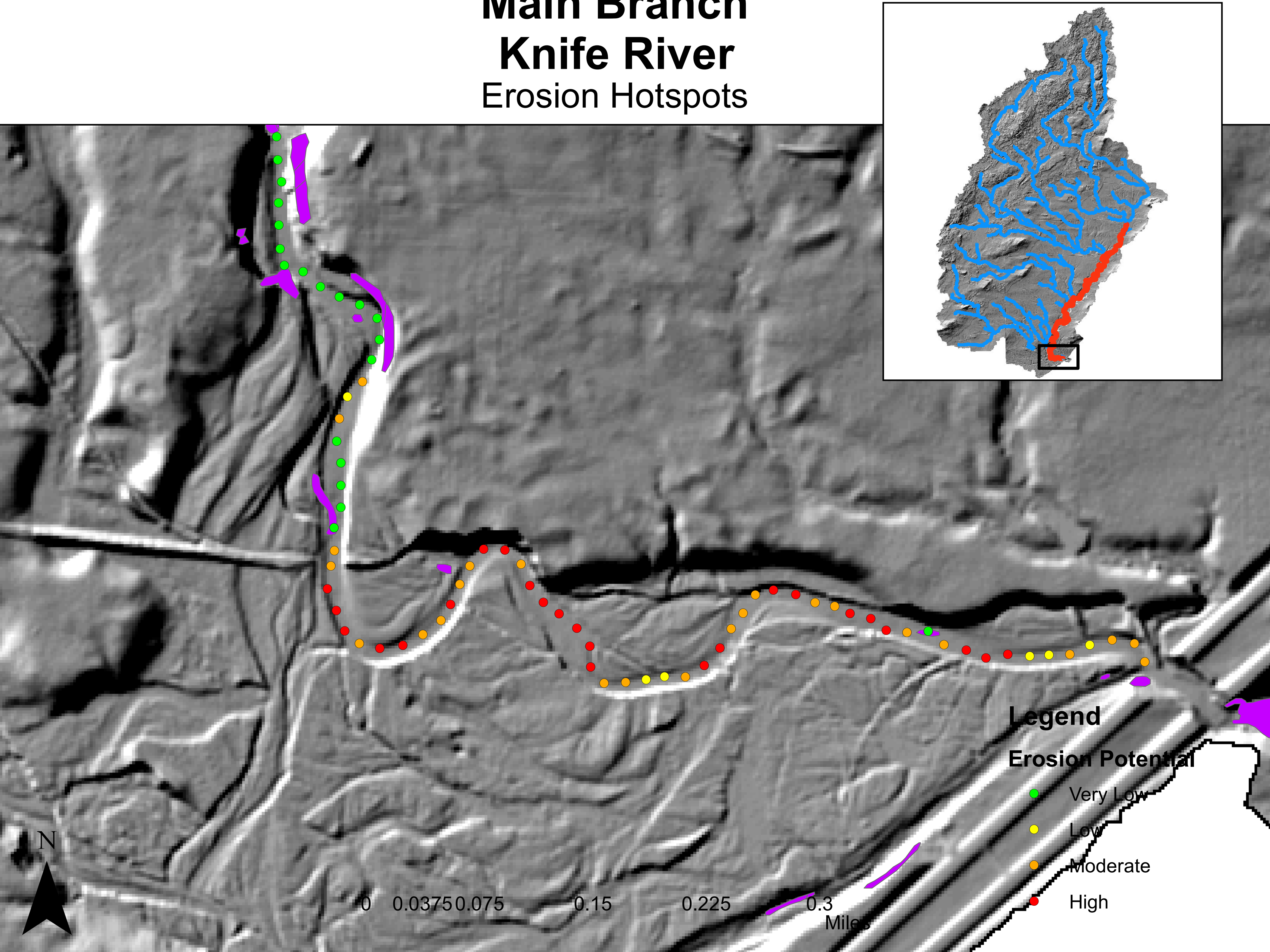
Main Branch Knife River

Erosion Hotspots



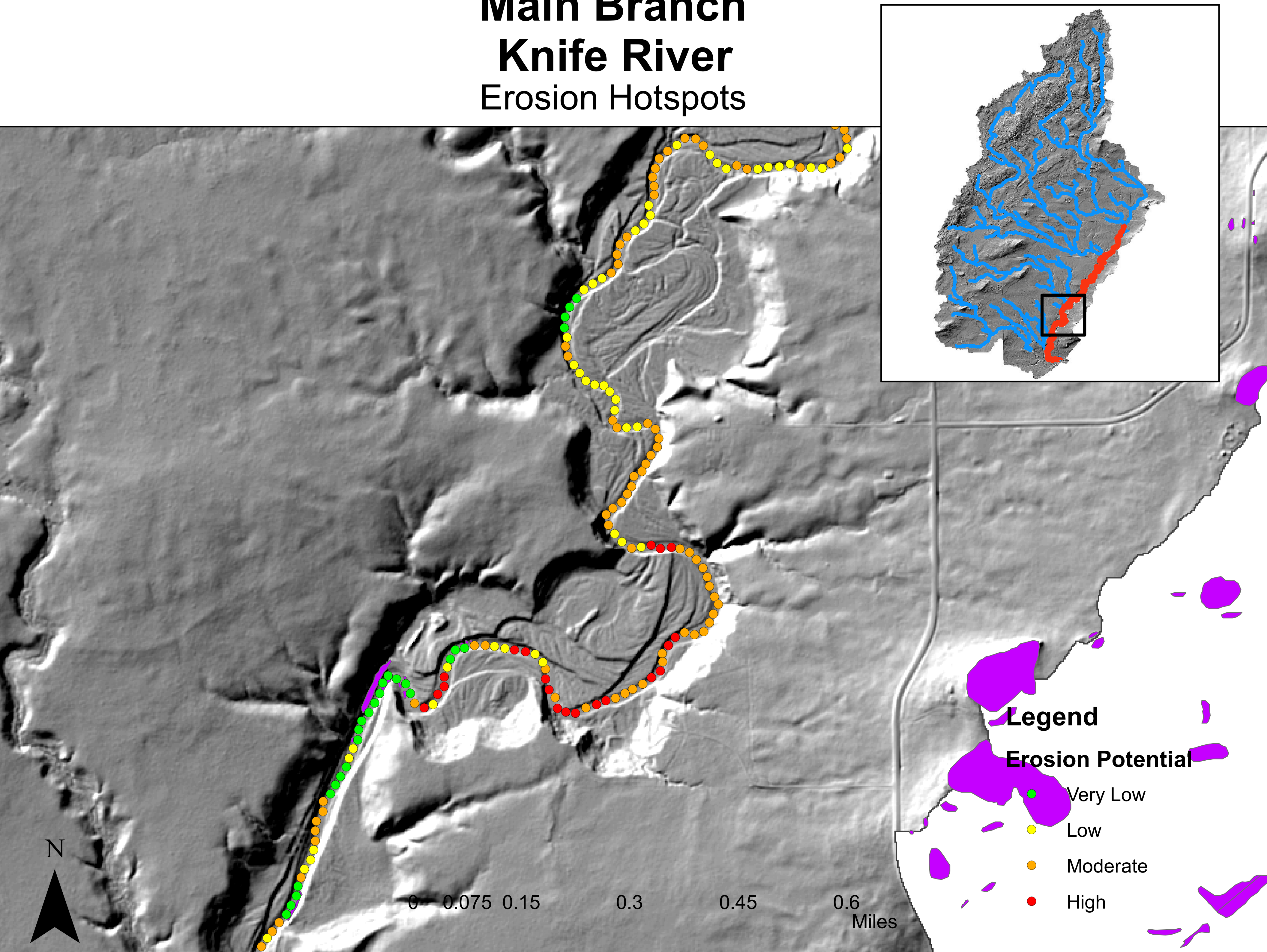
Main Branch Knife River

Erosion Hotspots



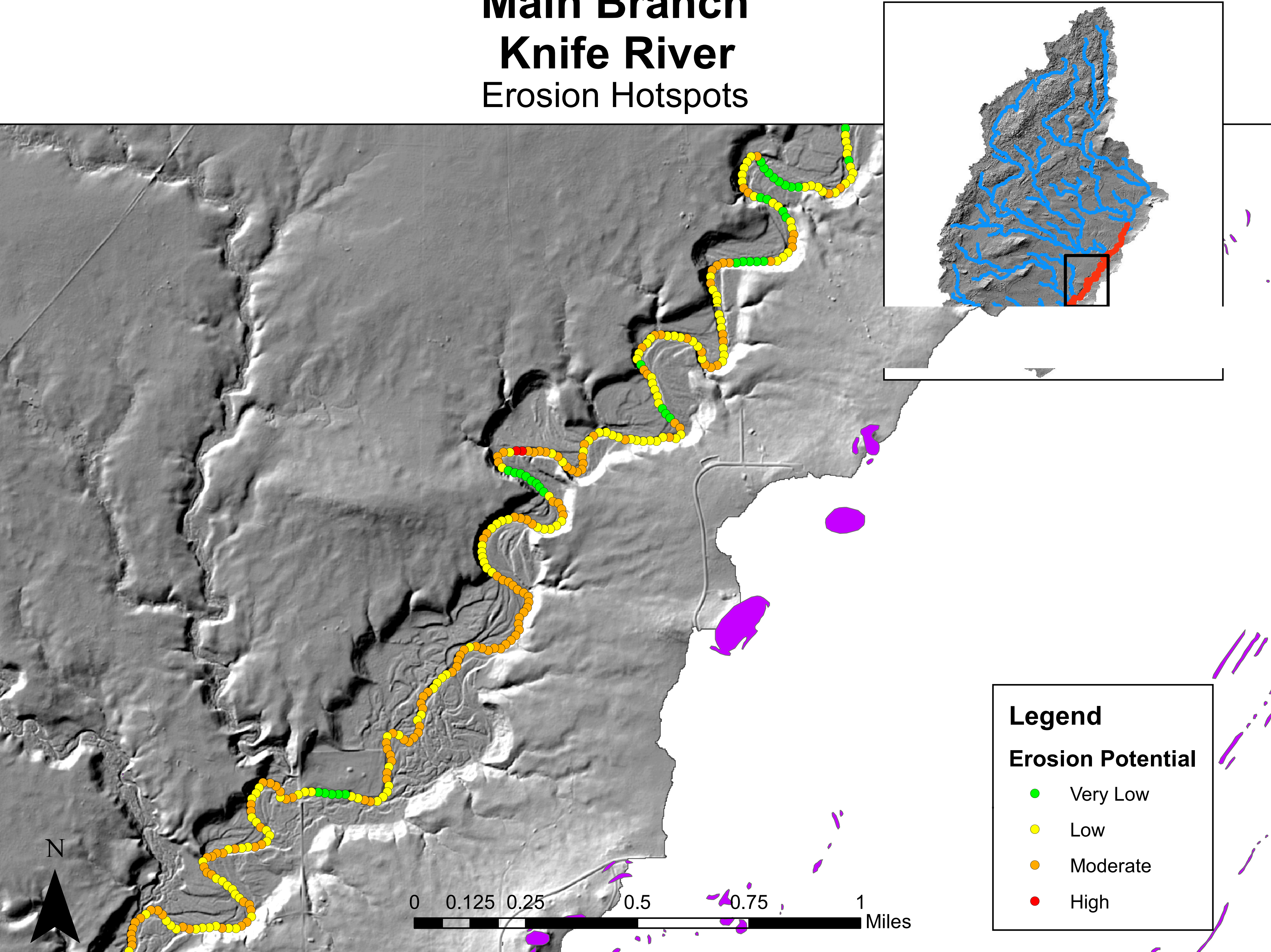
Main Branch Knife River

Erosion Hotspots



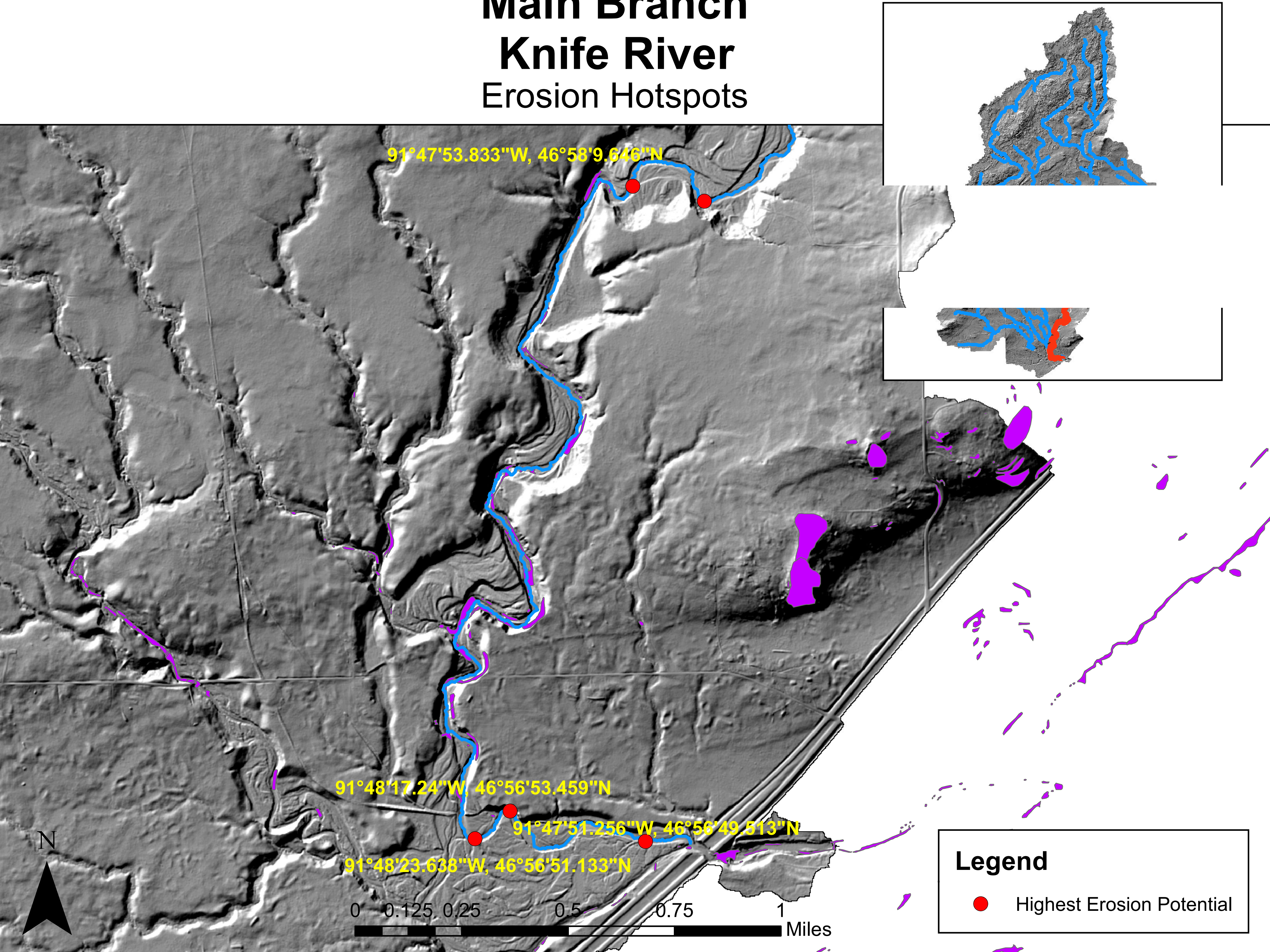
Main Branch Knife River

Erosion Hotspots



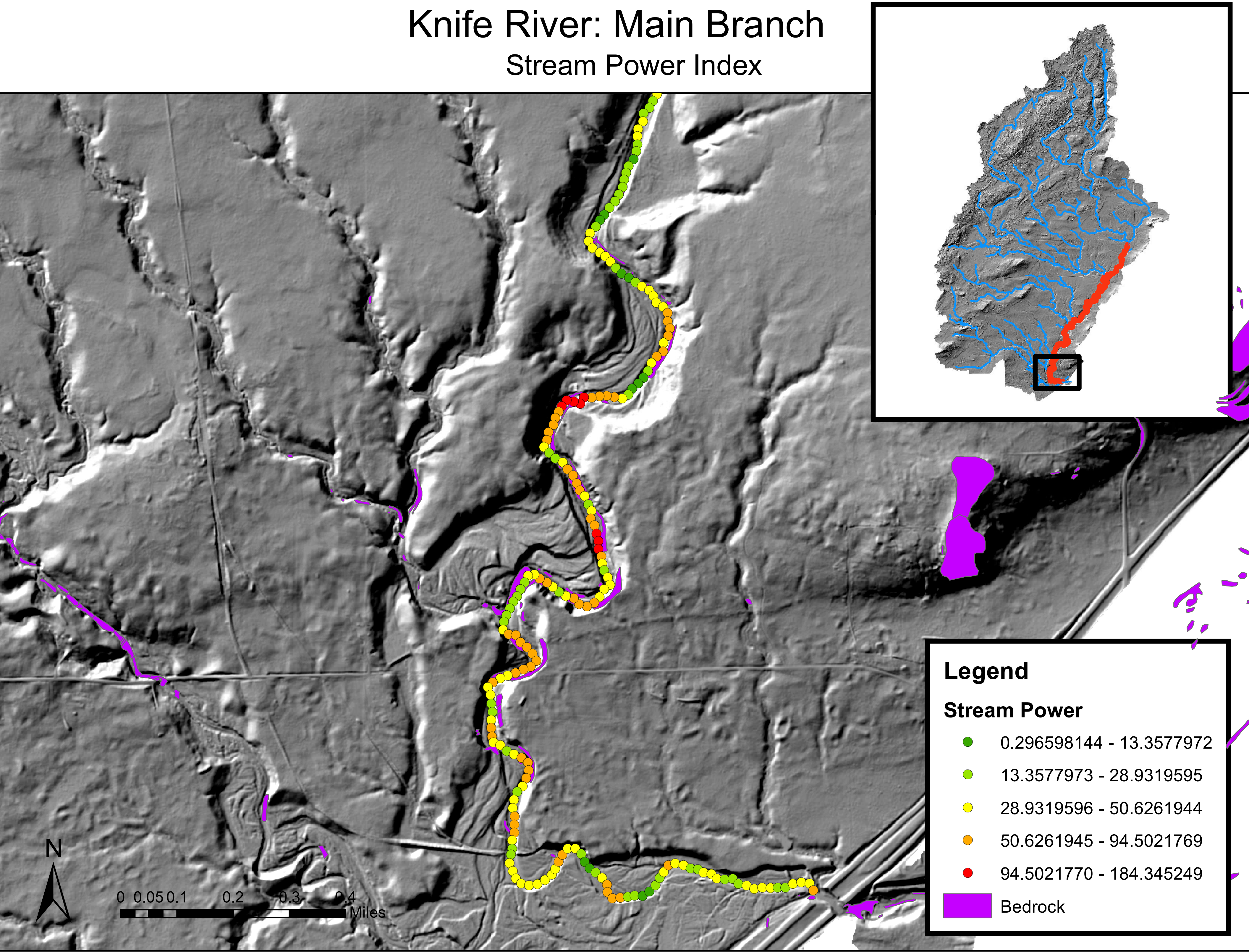
Main Branch Knife River

Erosion Hotspots



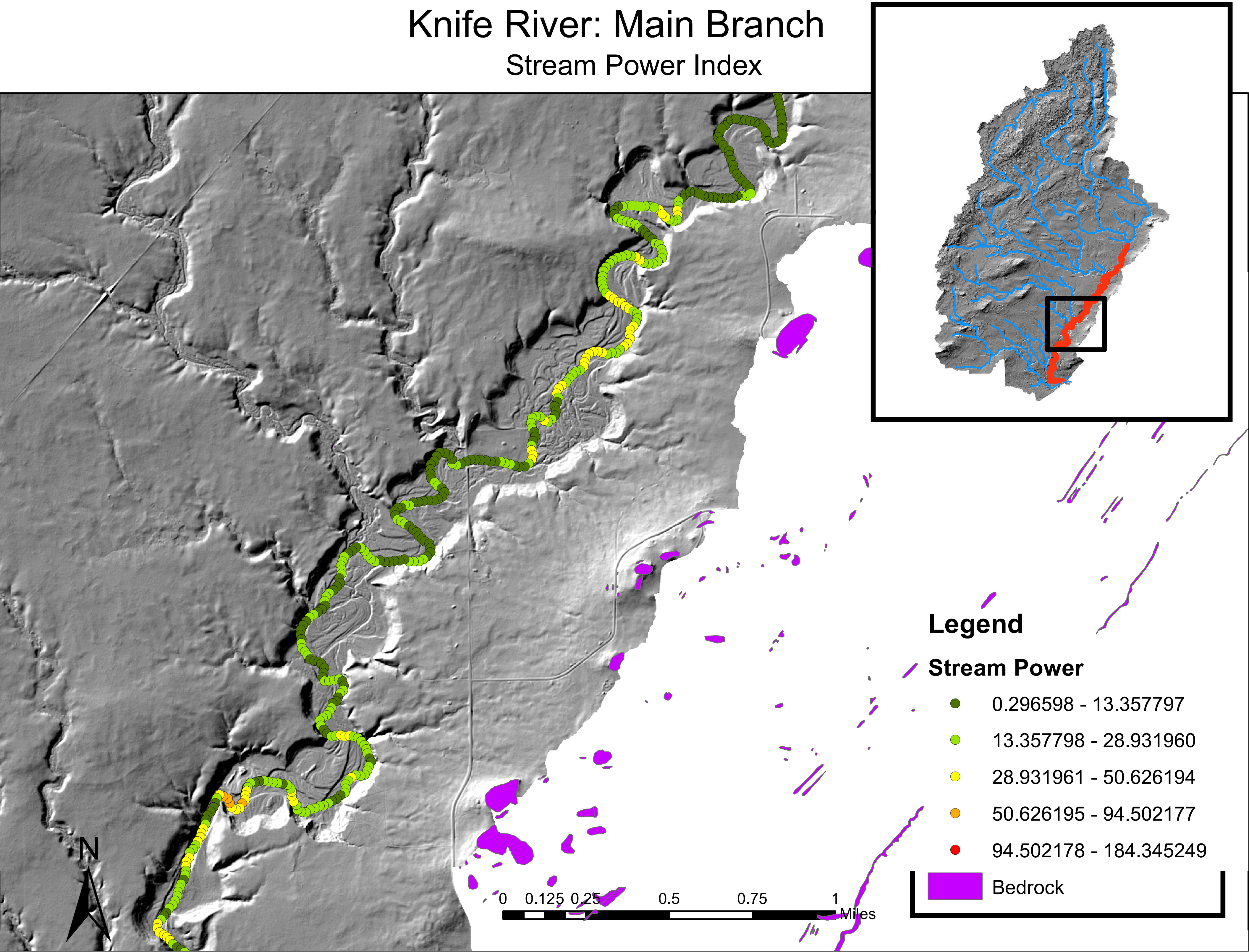
Knife River: Main Branch

Stream Power Index



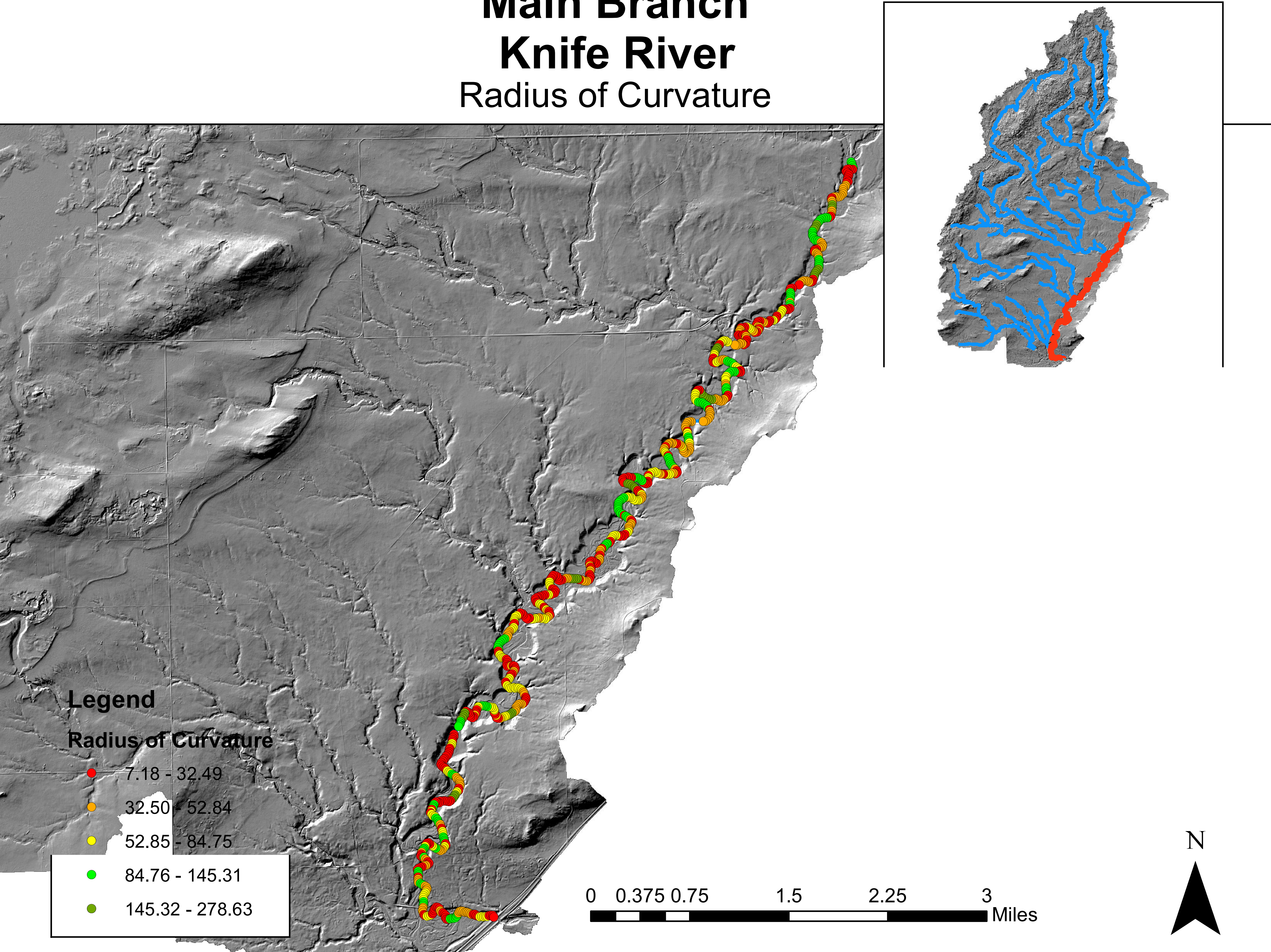
Knife River: Main Branch

Stream Power Index



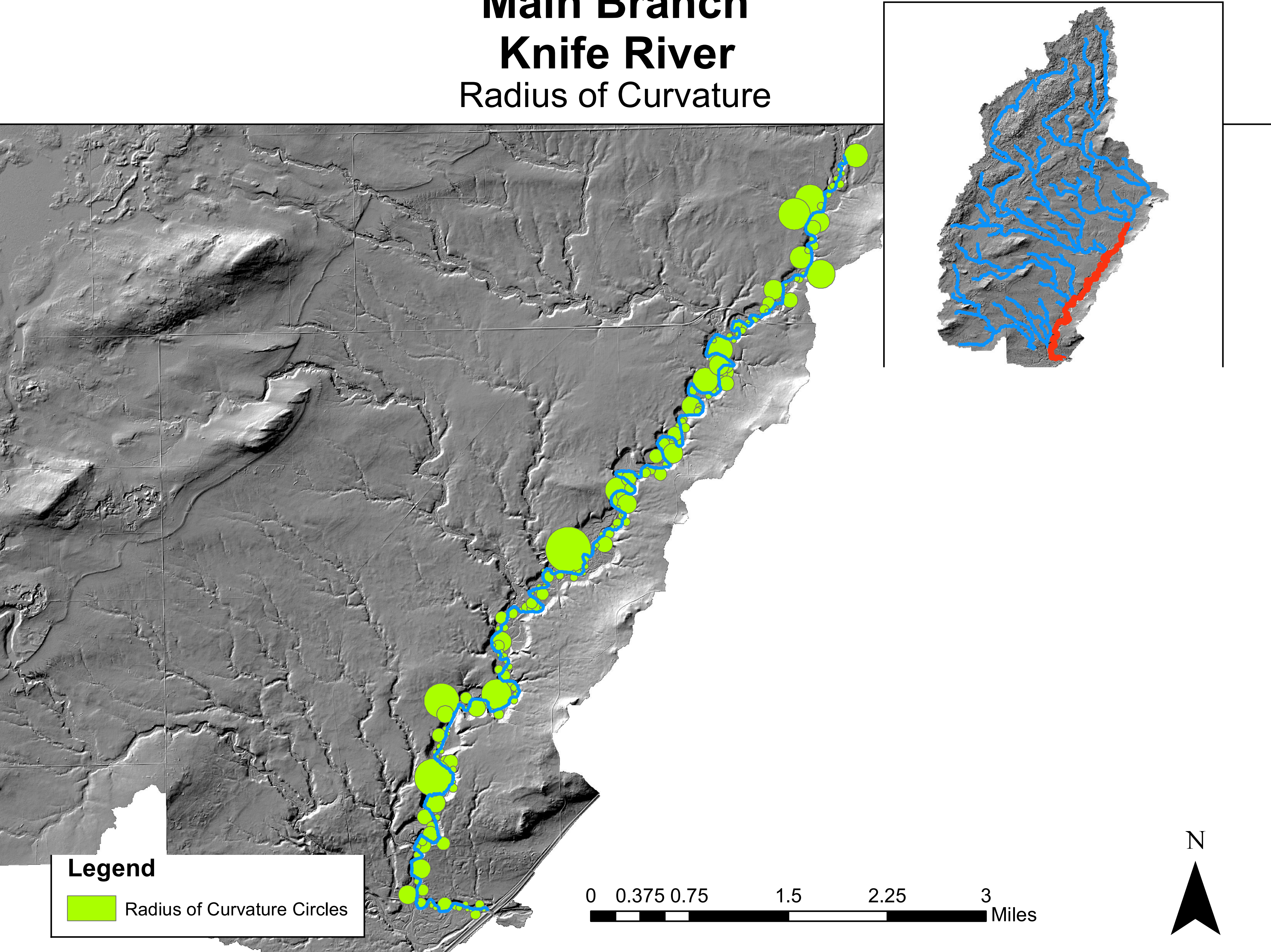
Main Branch Knife River

Radius of Curvature



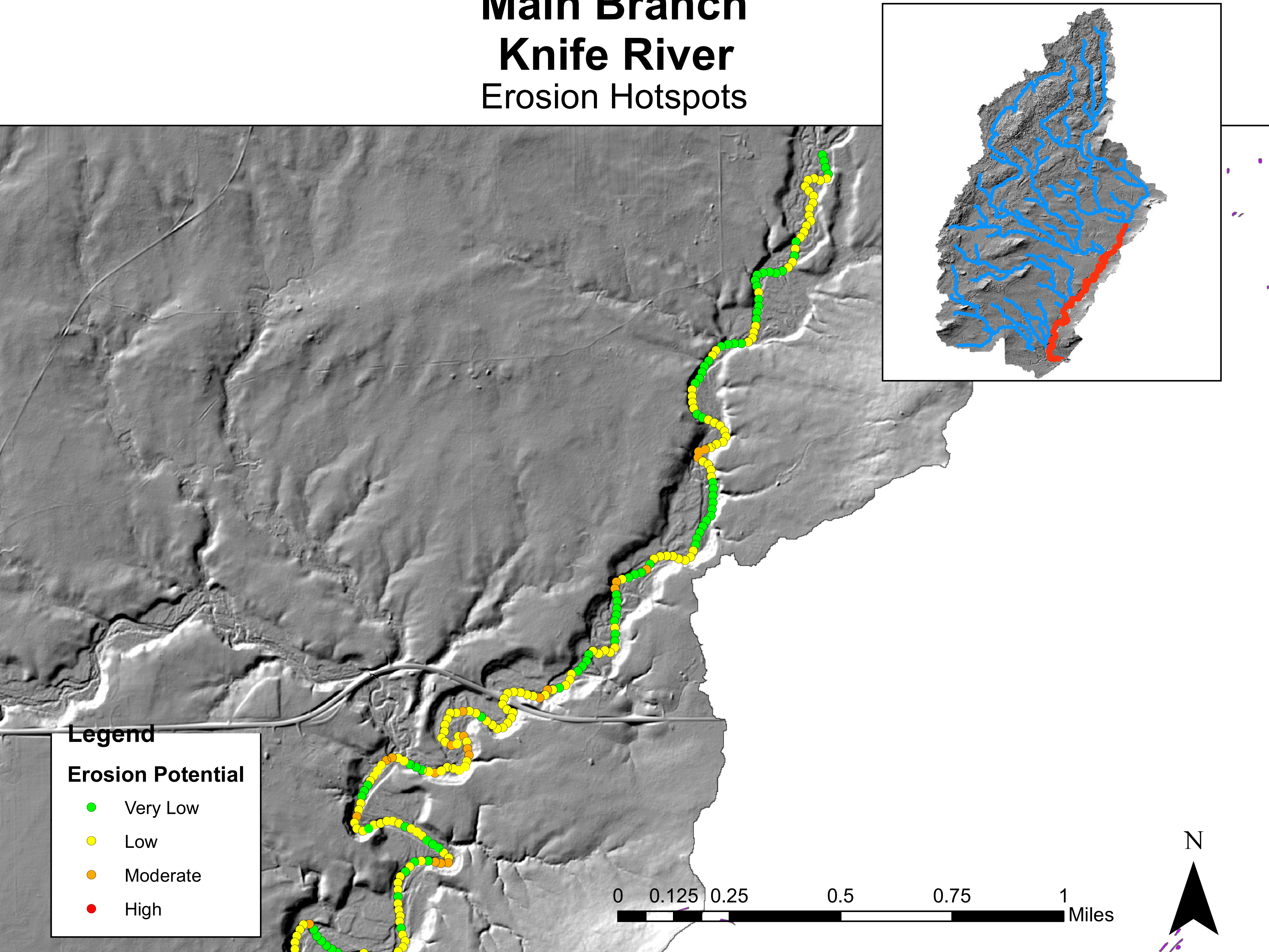
Main Branch Knife River

Radius of Curvature

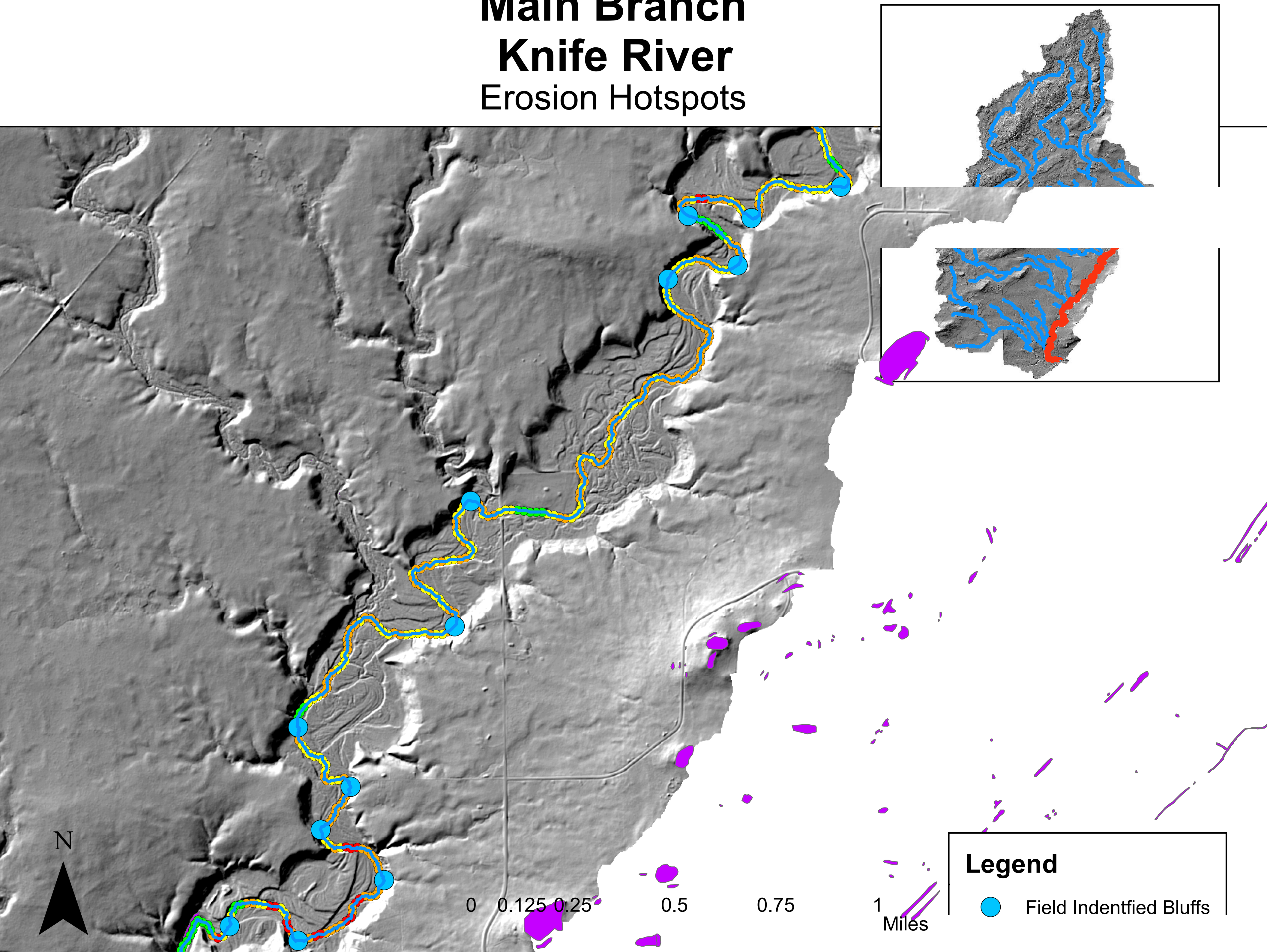


Main Branch Knife River

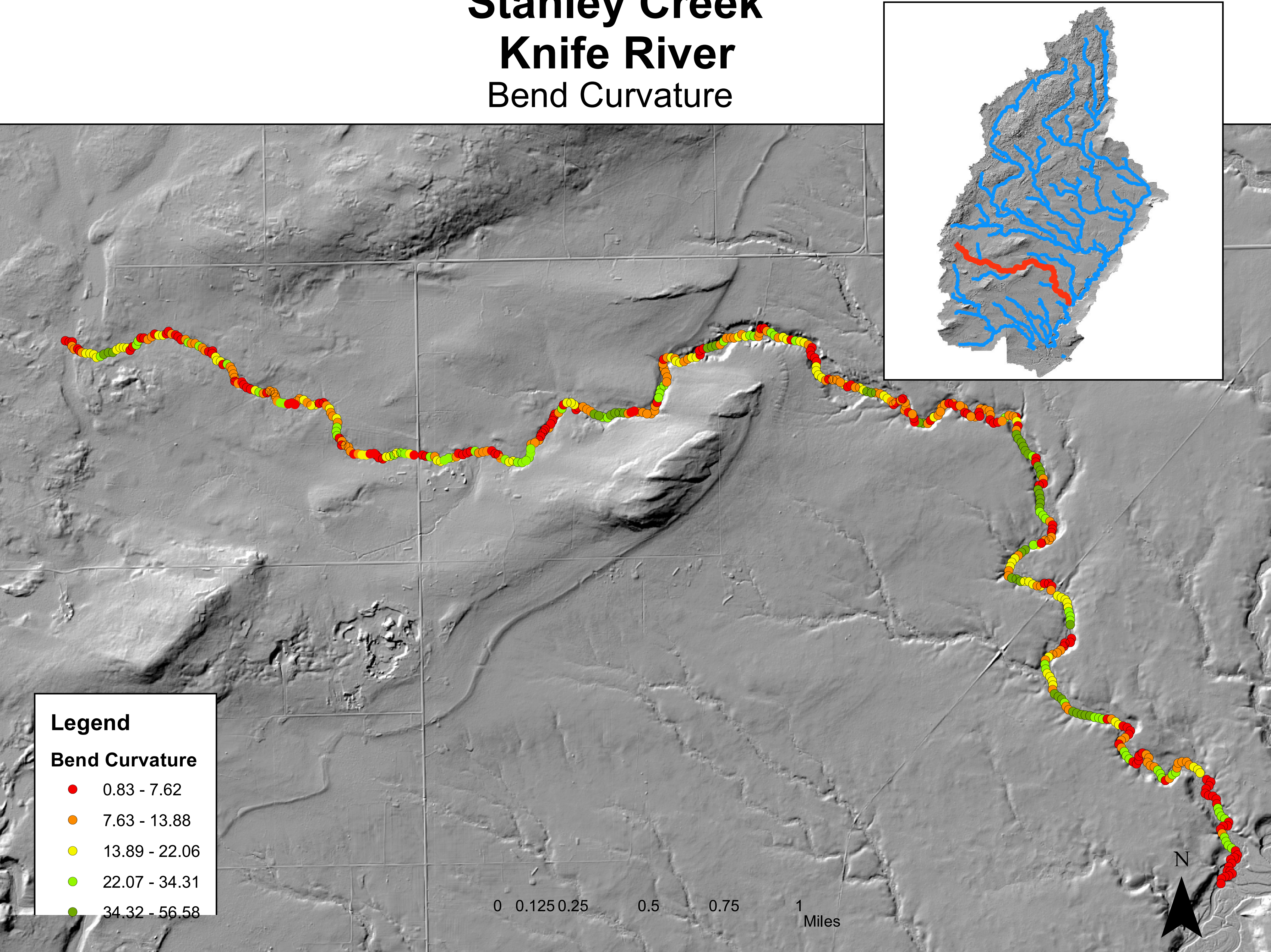
Erosion Hotspots



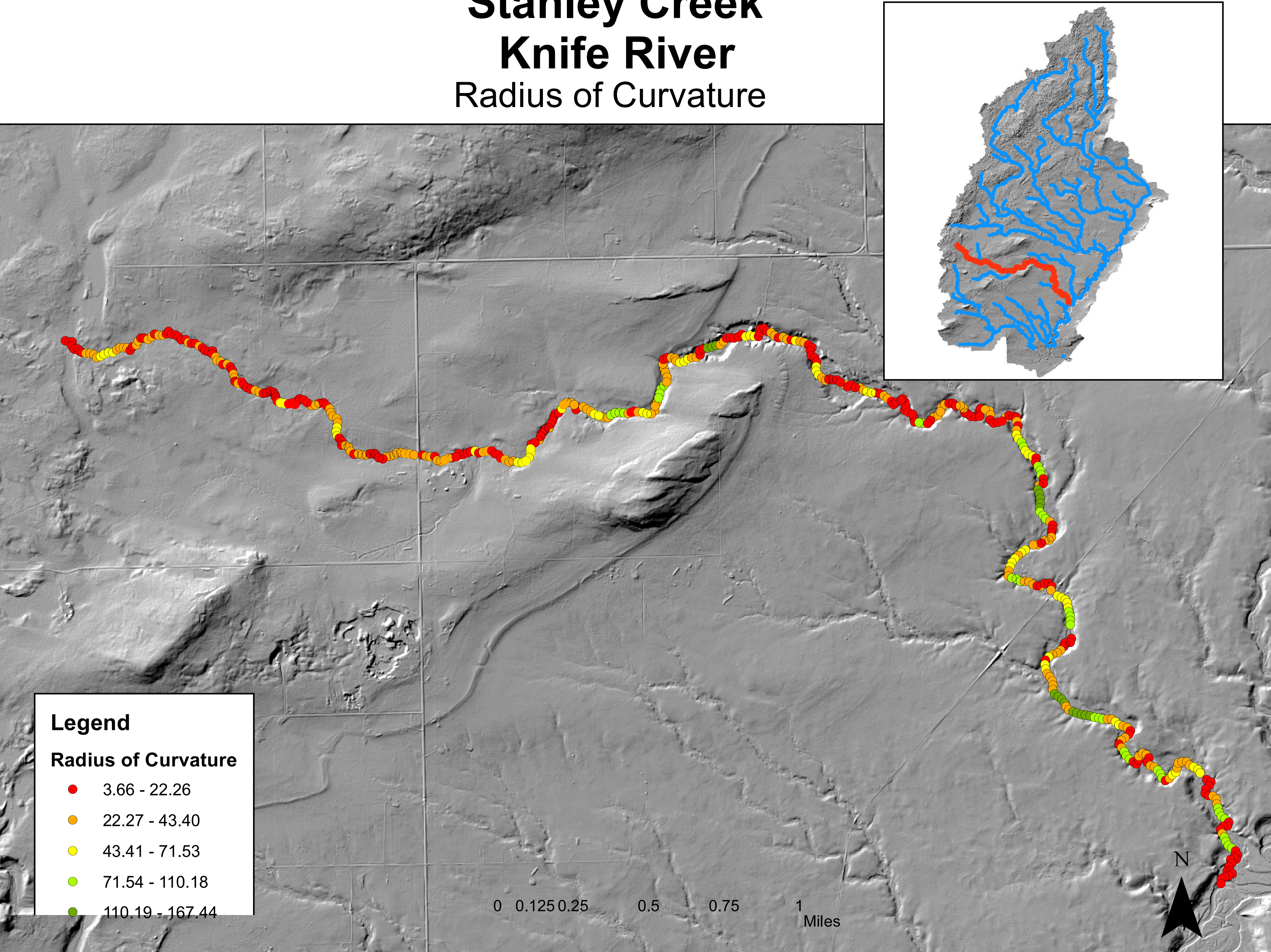
Main Branch
Knife River
Erosion Hotspots



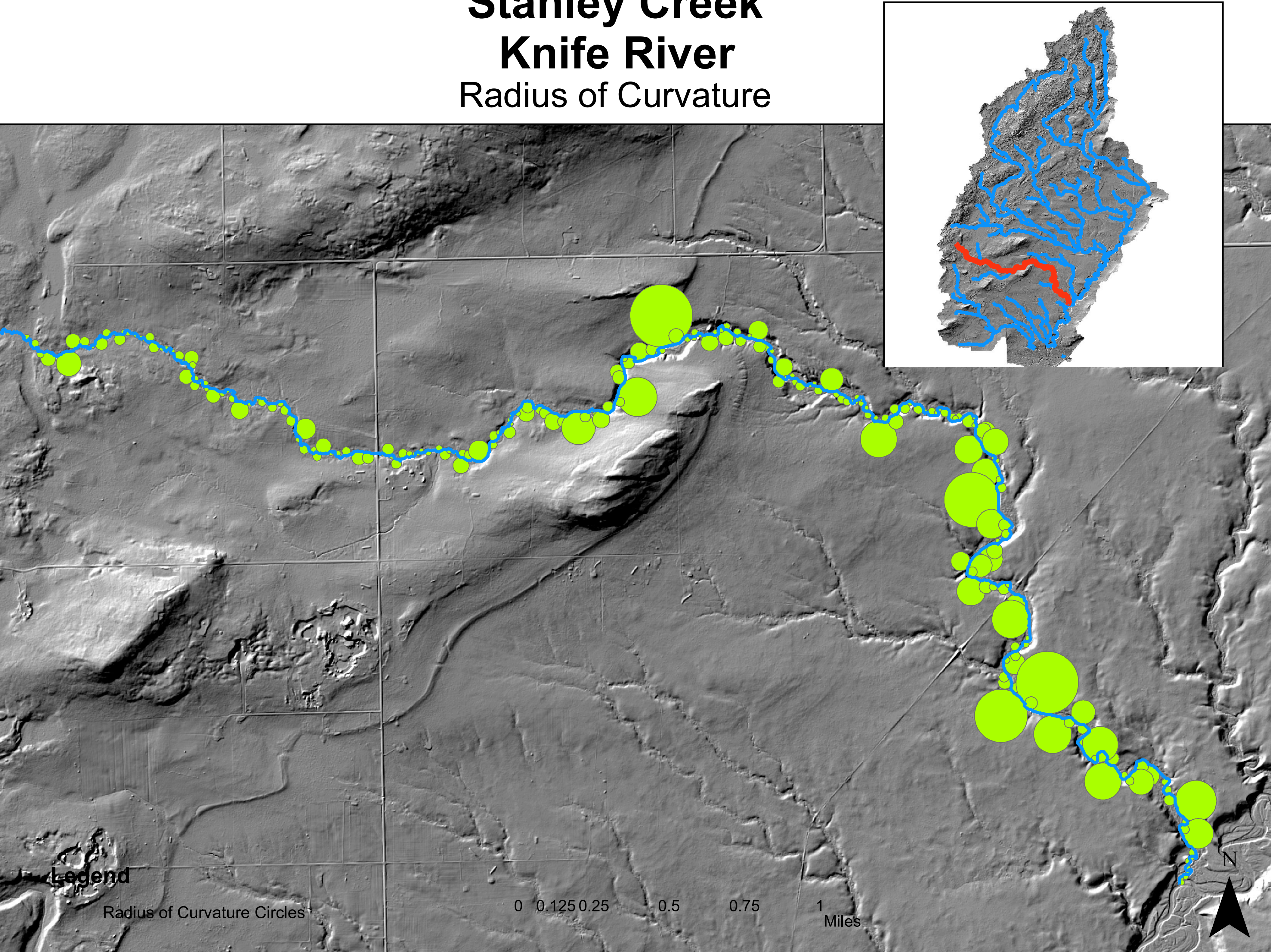
Stanley Creek
Knife River
Bend Curvature



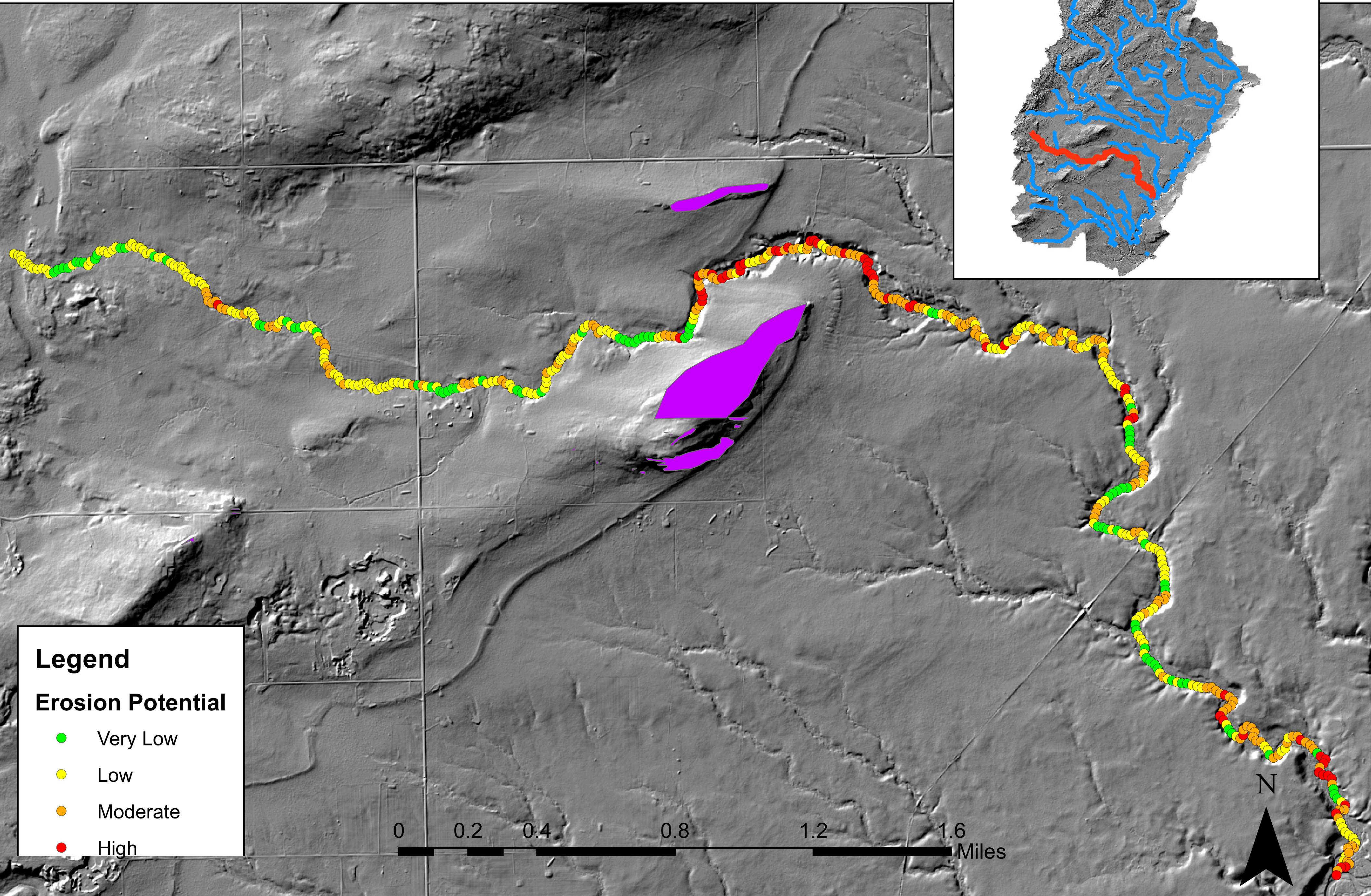
Stanley Creek
Knife River
Radius of Curvature



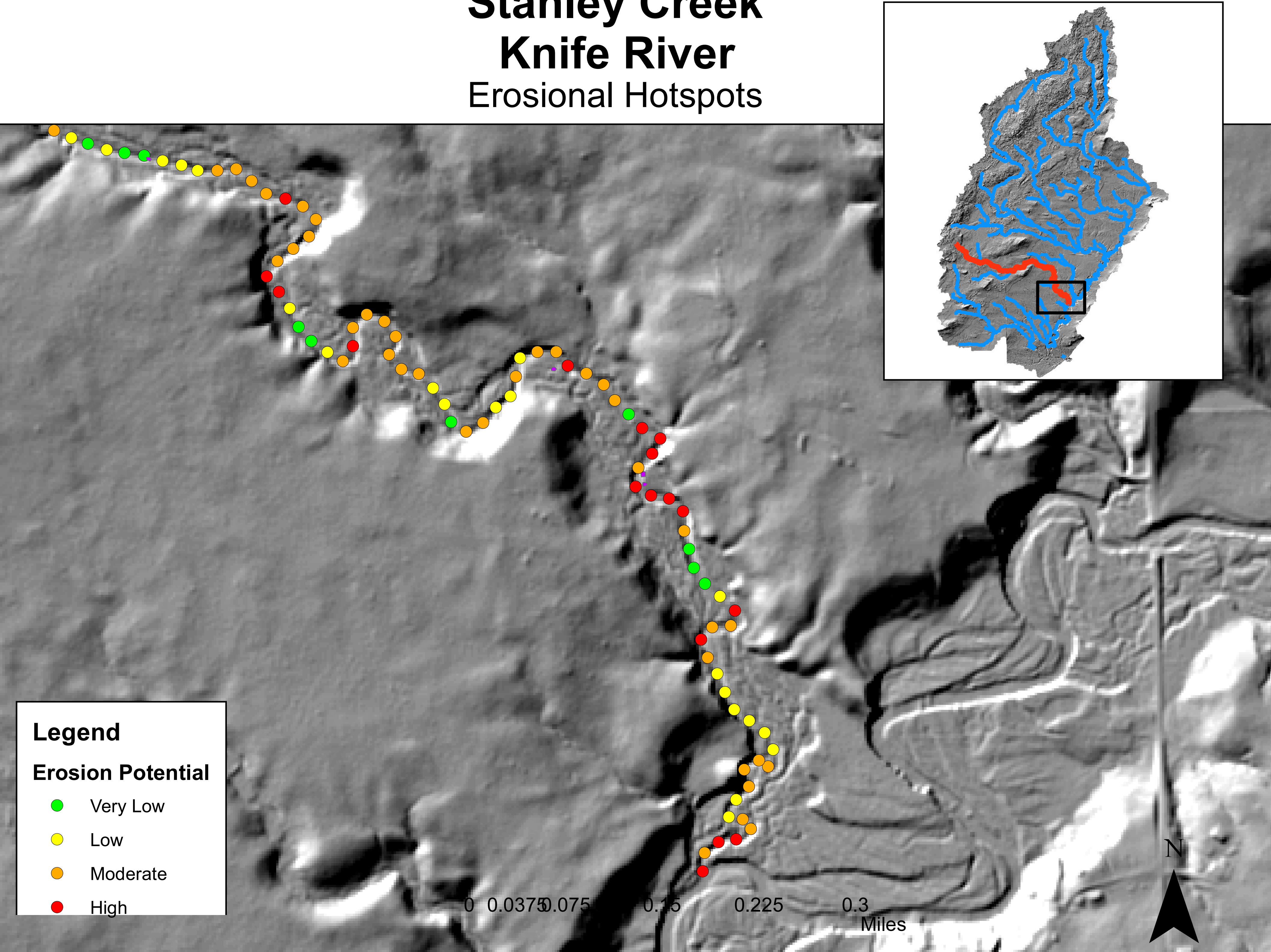
Stanley Creek
Knife River
Radius of Curvature



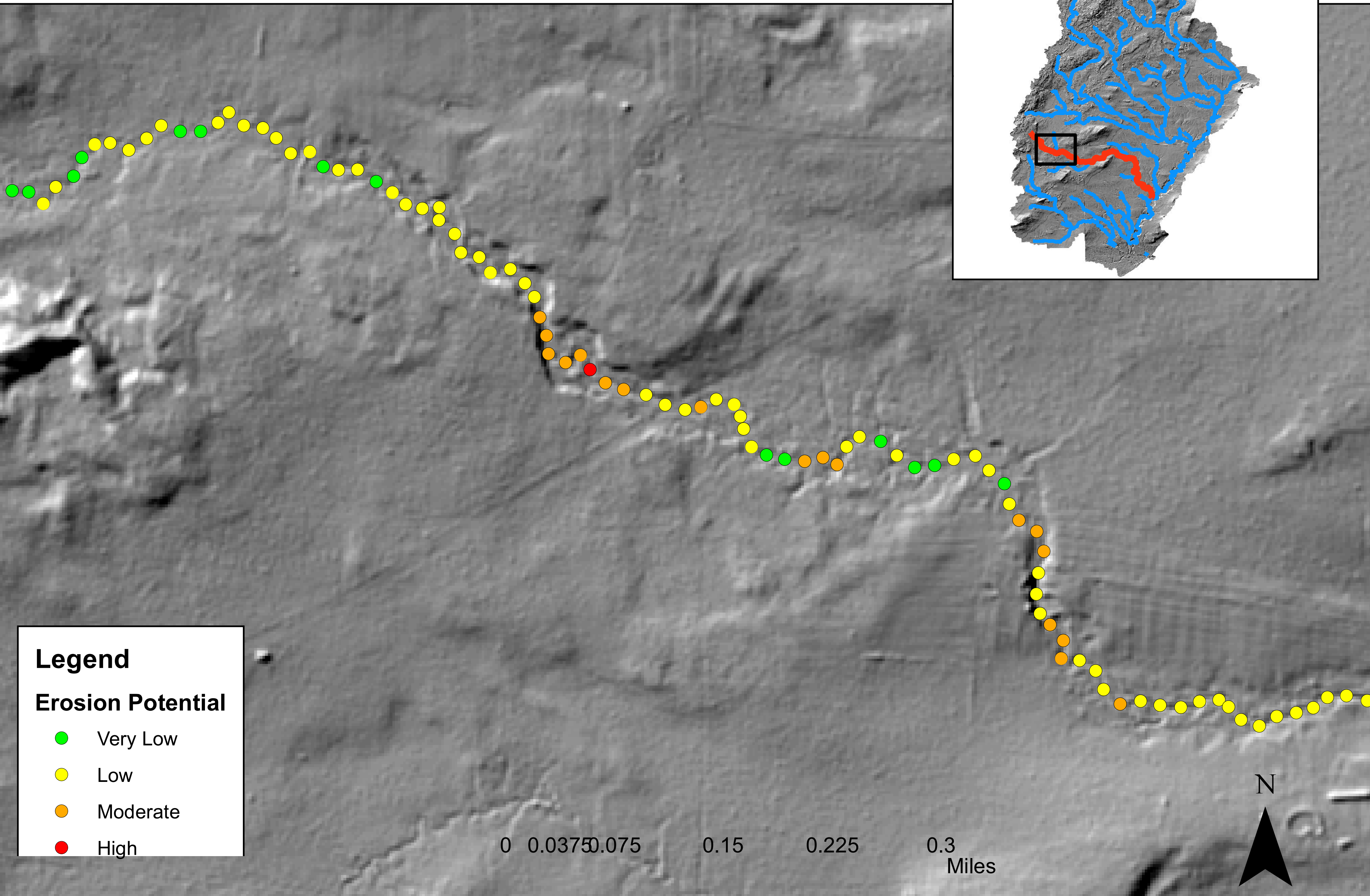
Stanley Creek
Knife River
Erosional Hotspots



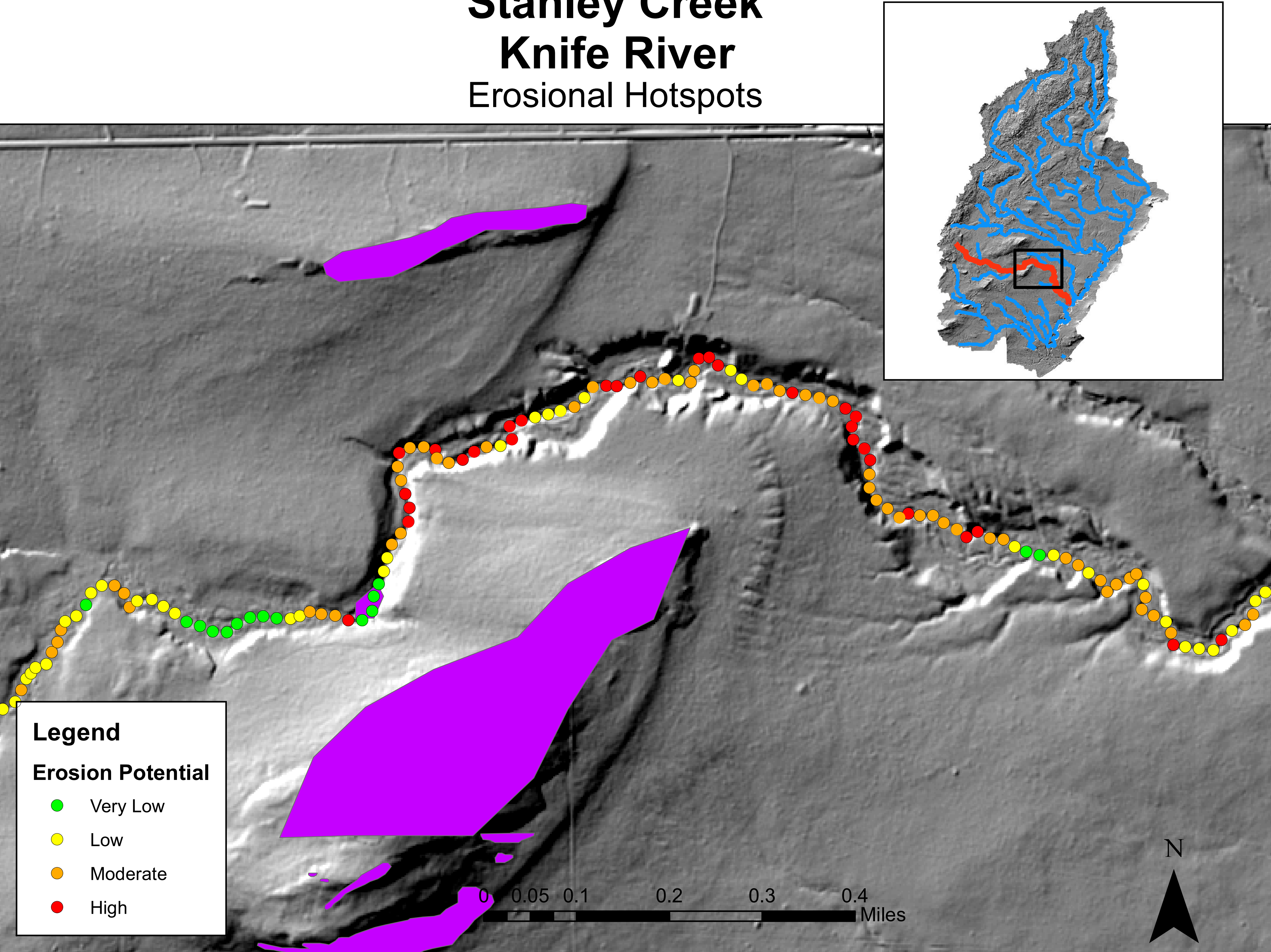
Stanley Creek
Knife River
Erosional Hotspots



Stanley Creek
Knife River
Erosional Hotspots

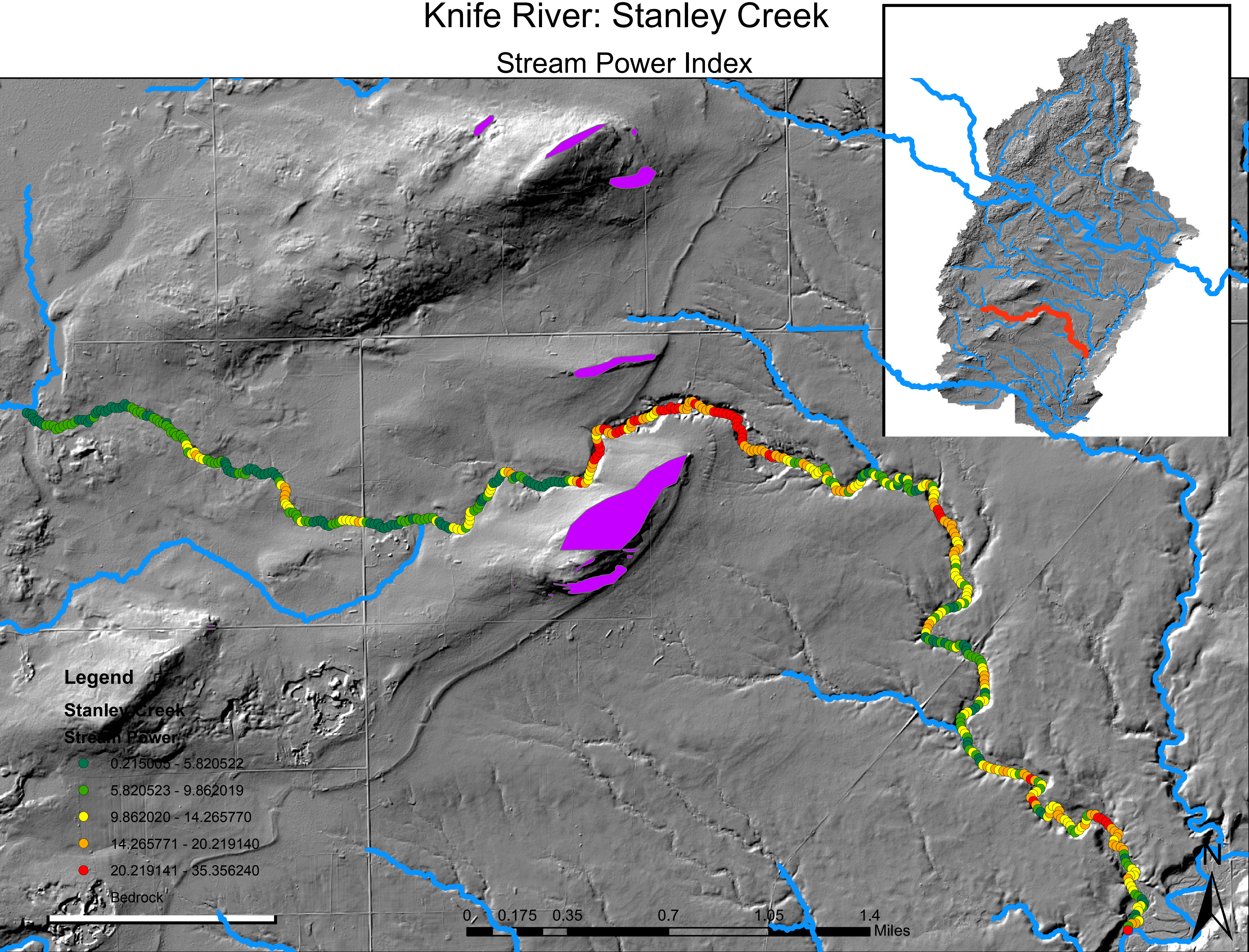


Stanley Creek
Knife River
Erosional Hotspots



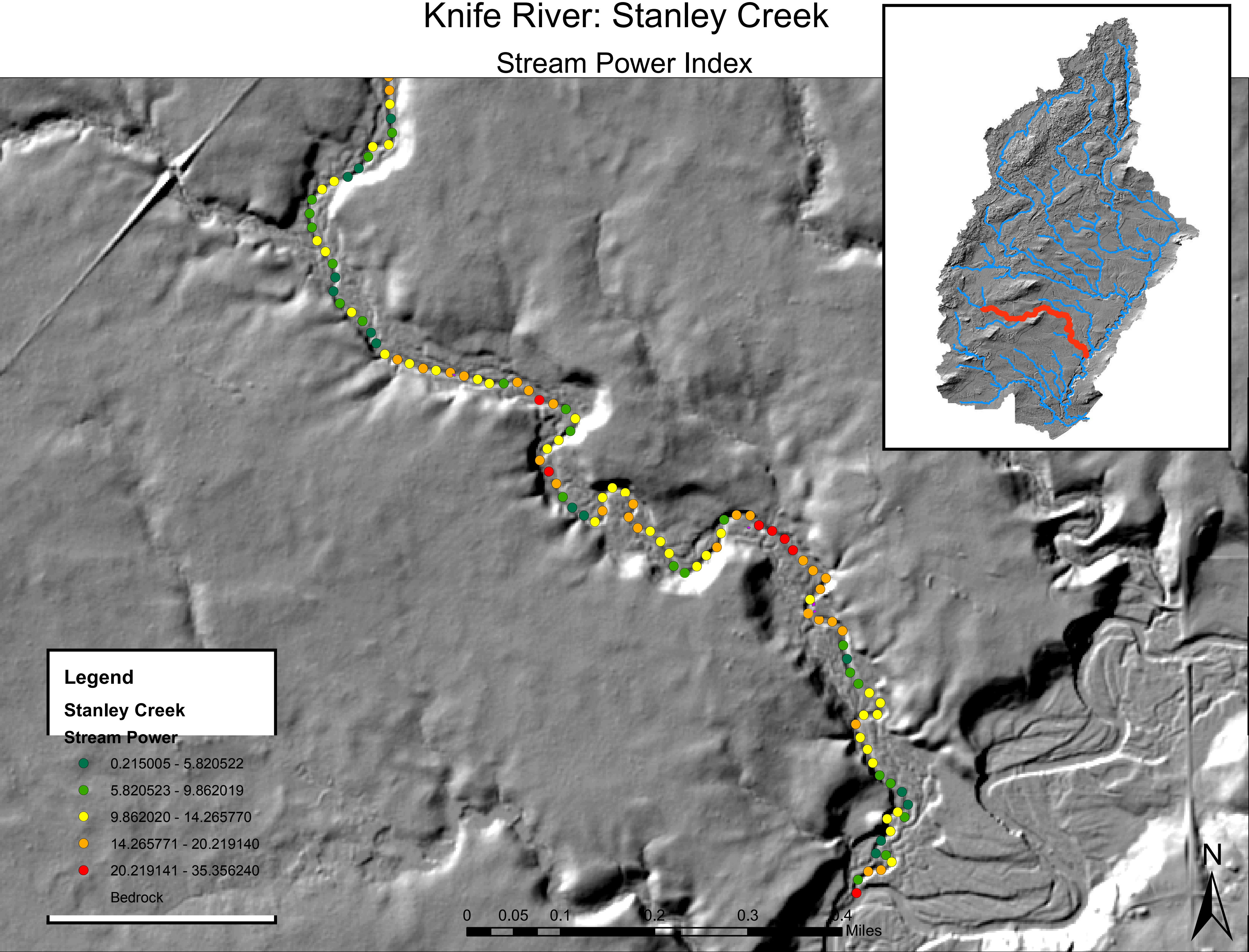
Knife River: Stanley Creek

Stream Power Index



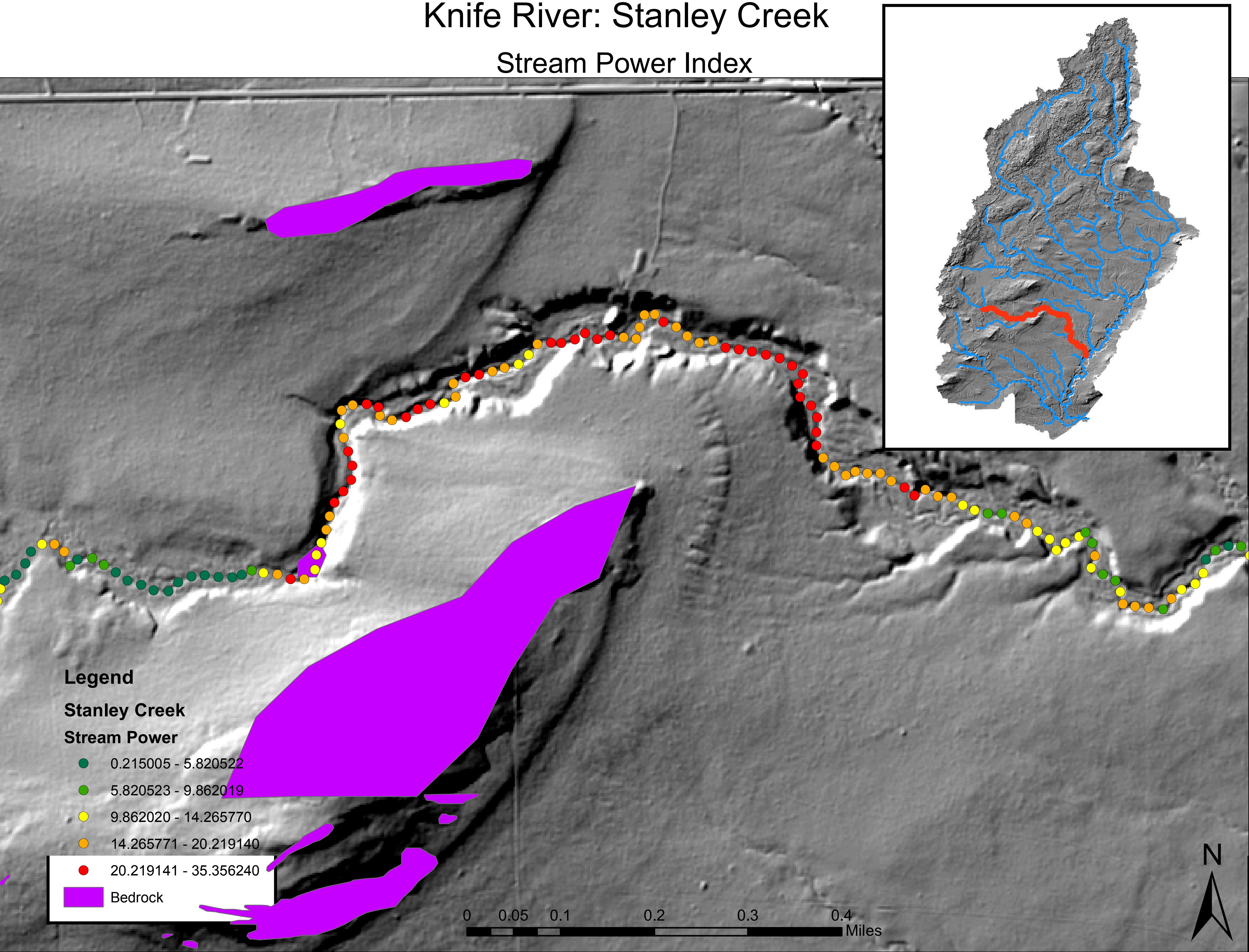
Knife River: Stanley Creek

Stream Power Index



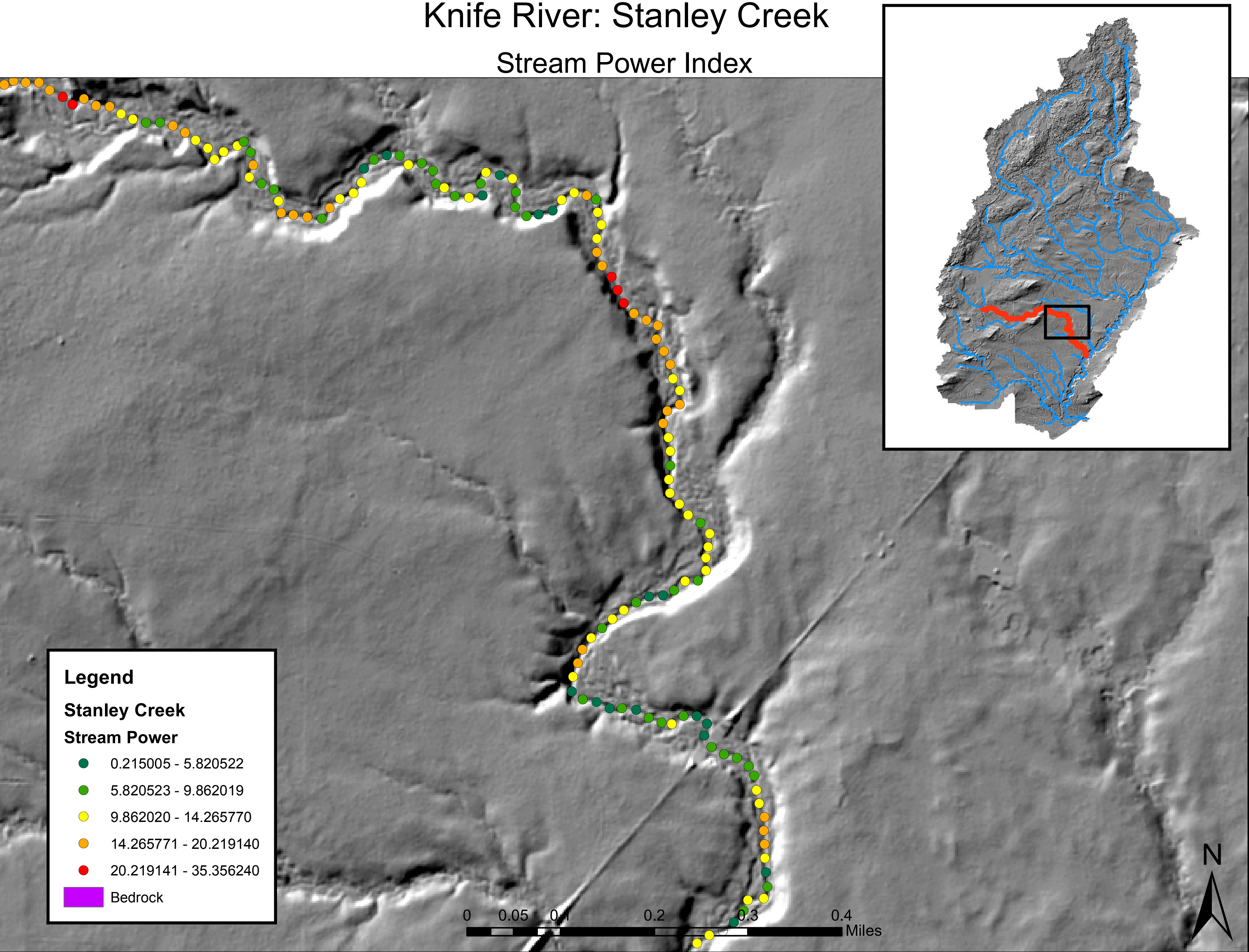
Knife River: Stanley Creek

Stream Power Index



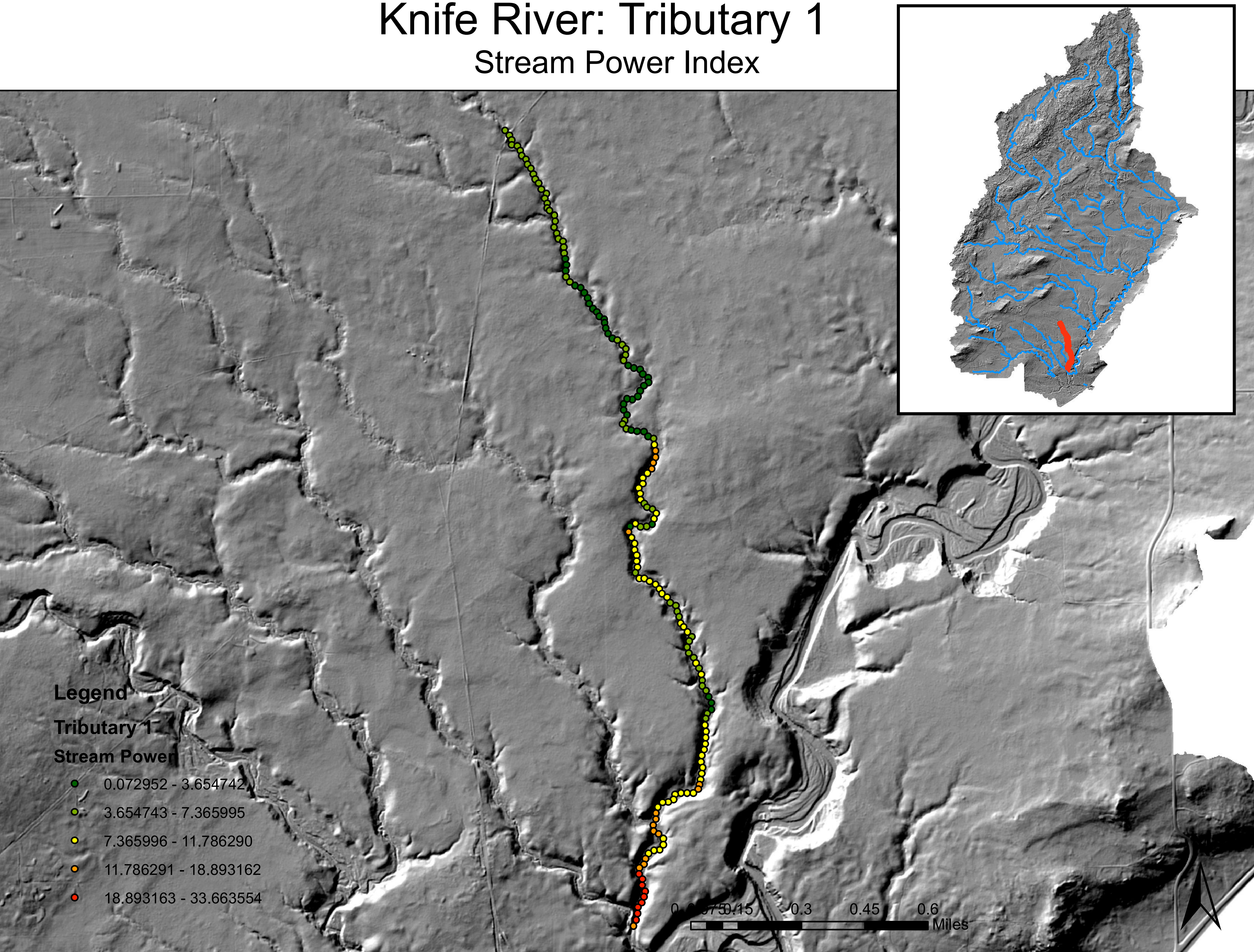
Knife River: Stanley Creek

Stream Power Index



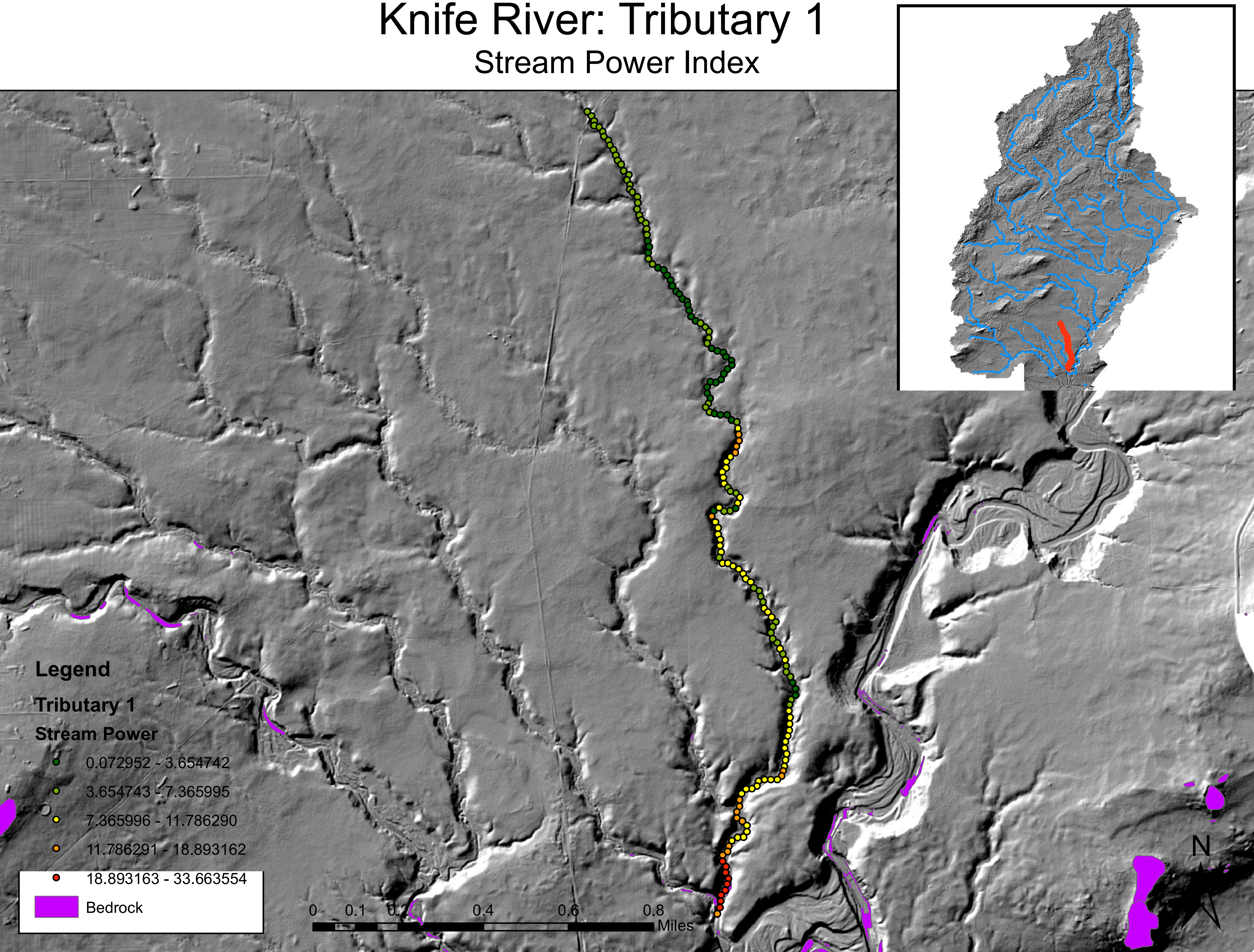
Knife River: Tributary 1

Stream Power Index

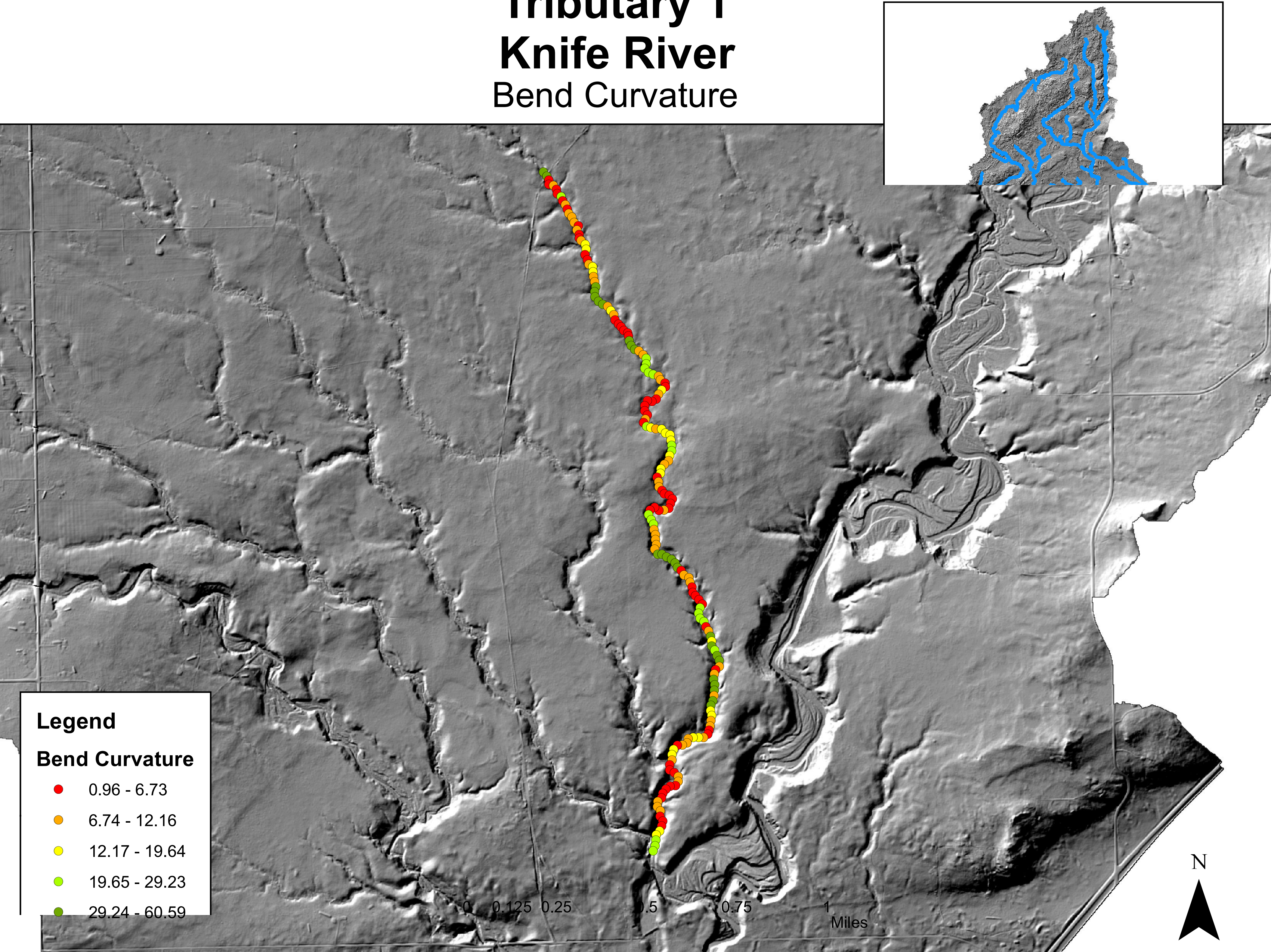


Knife River: Tributary 1

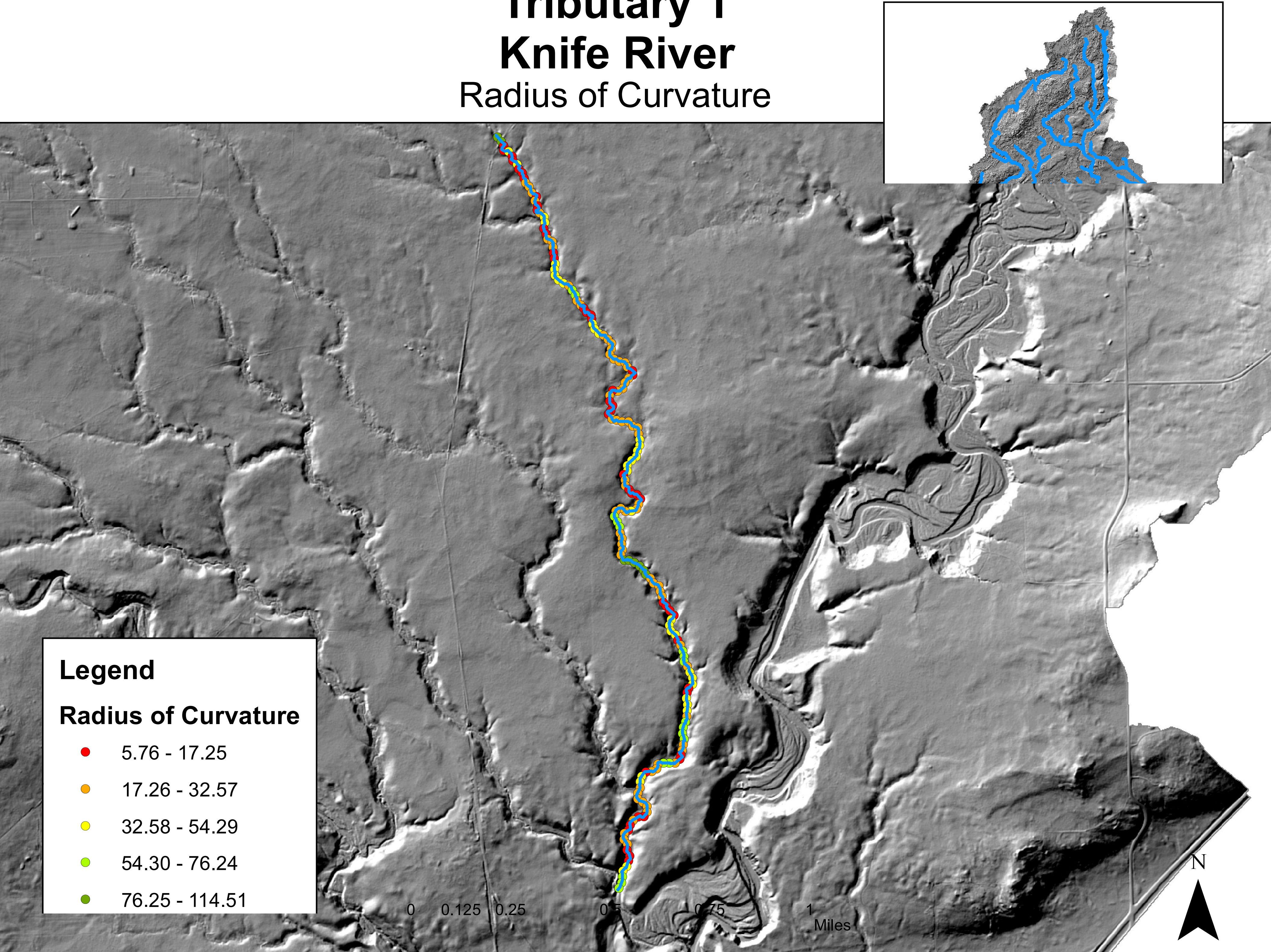
Stream Power Index



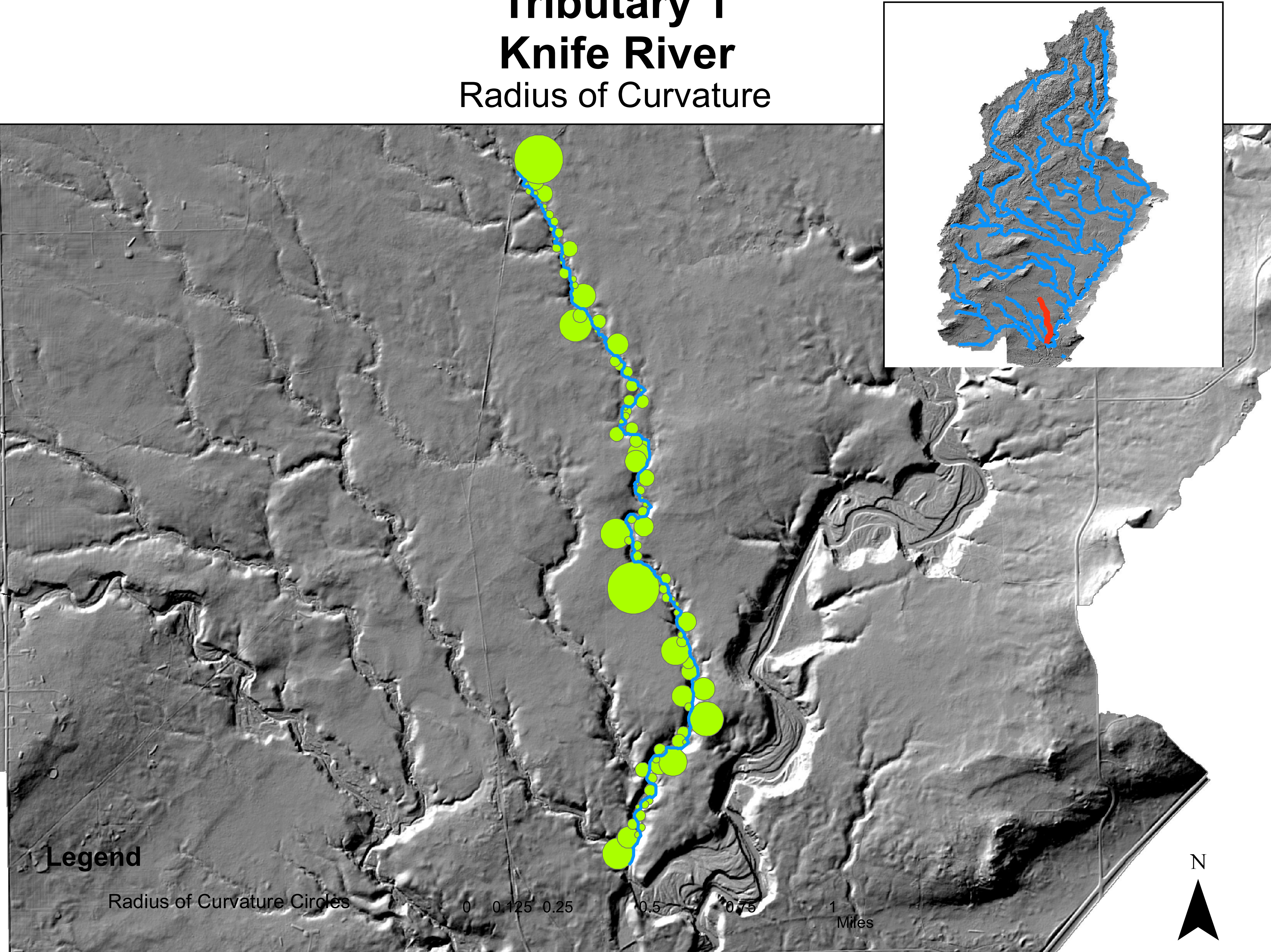
Tributary 1
Knife River
Bend Curvature



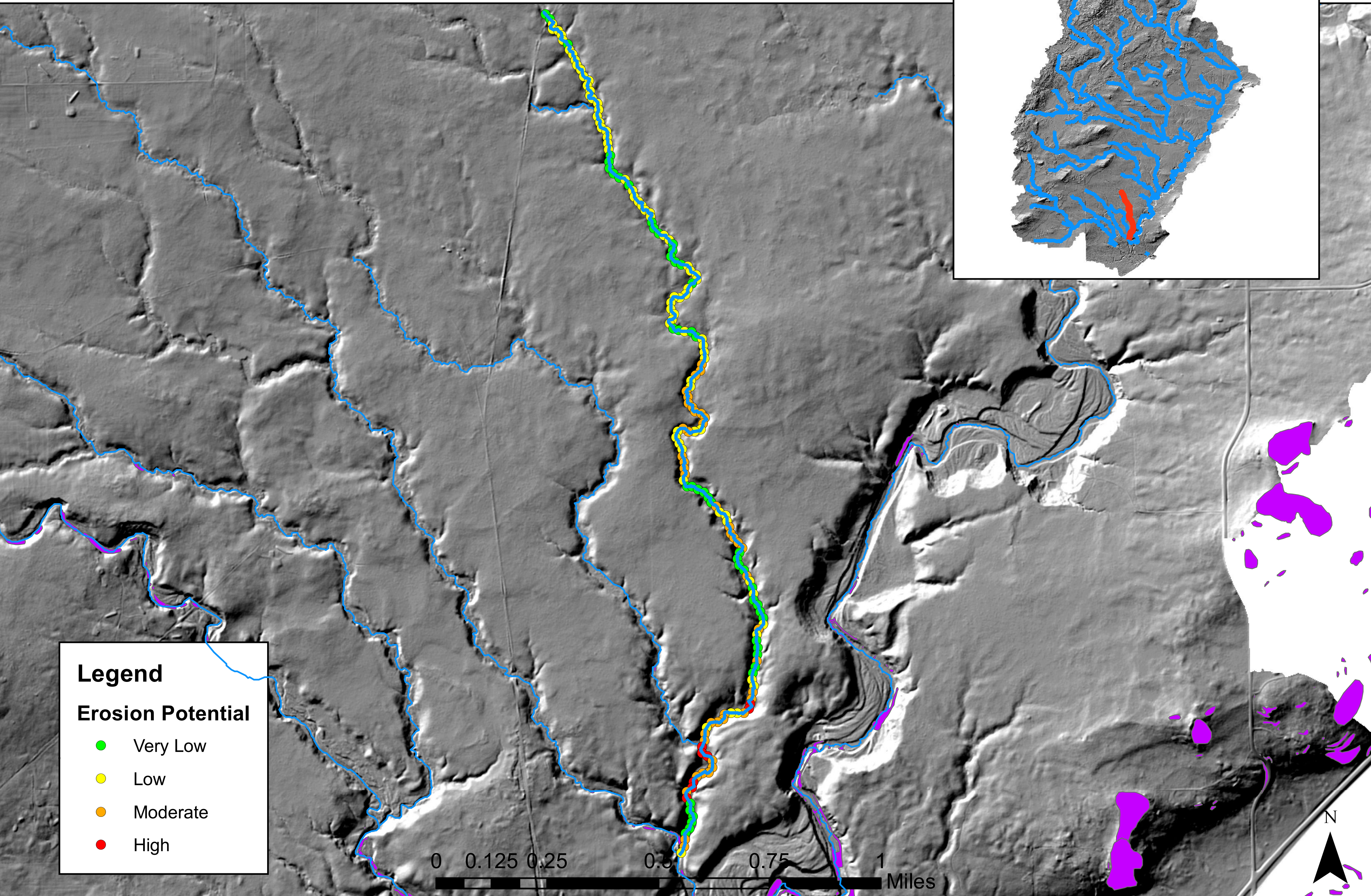
Tributary 1
Knife River
Radius of Curvature



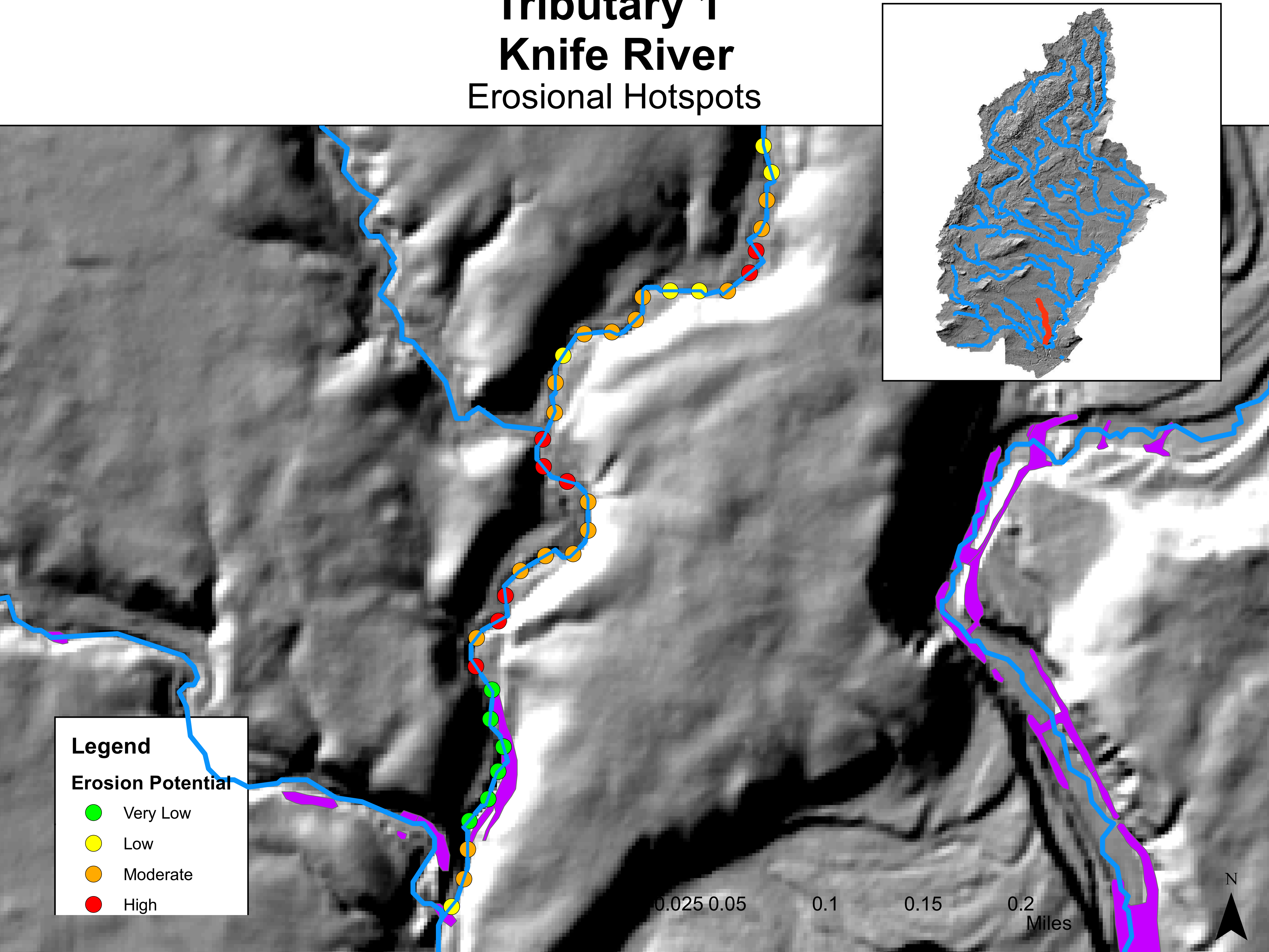
Tributary 1
Knife River
Radius of Curvature



Tributary 1
Knife River
Erosional Hotspots

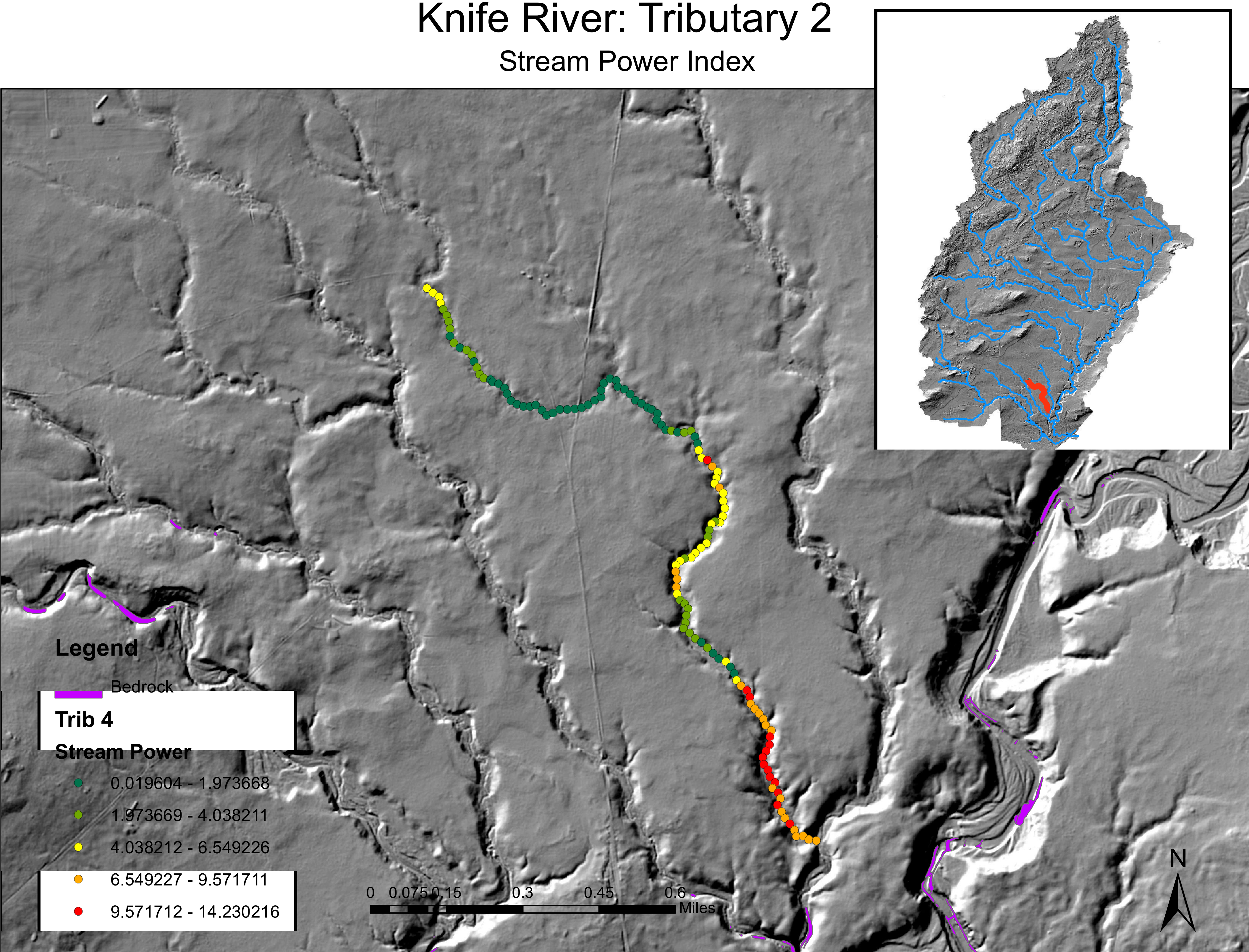


Tributary 1
Knife River
Erosional Hotspots

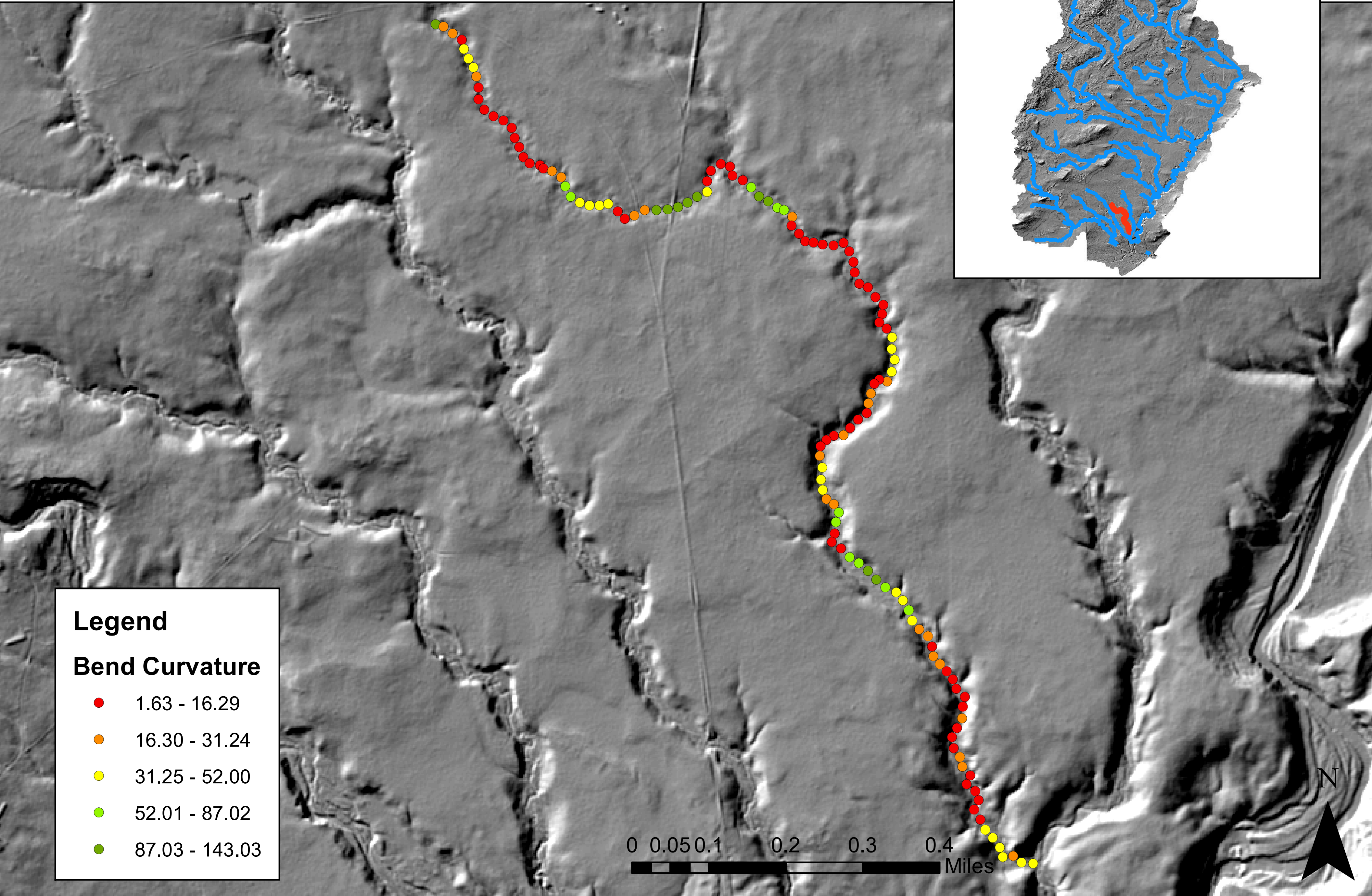


Knife River: Tributary 2

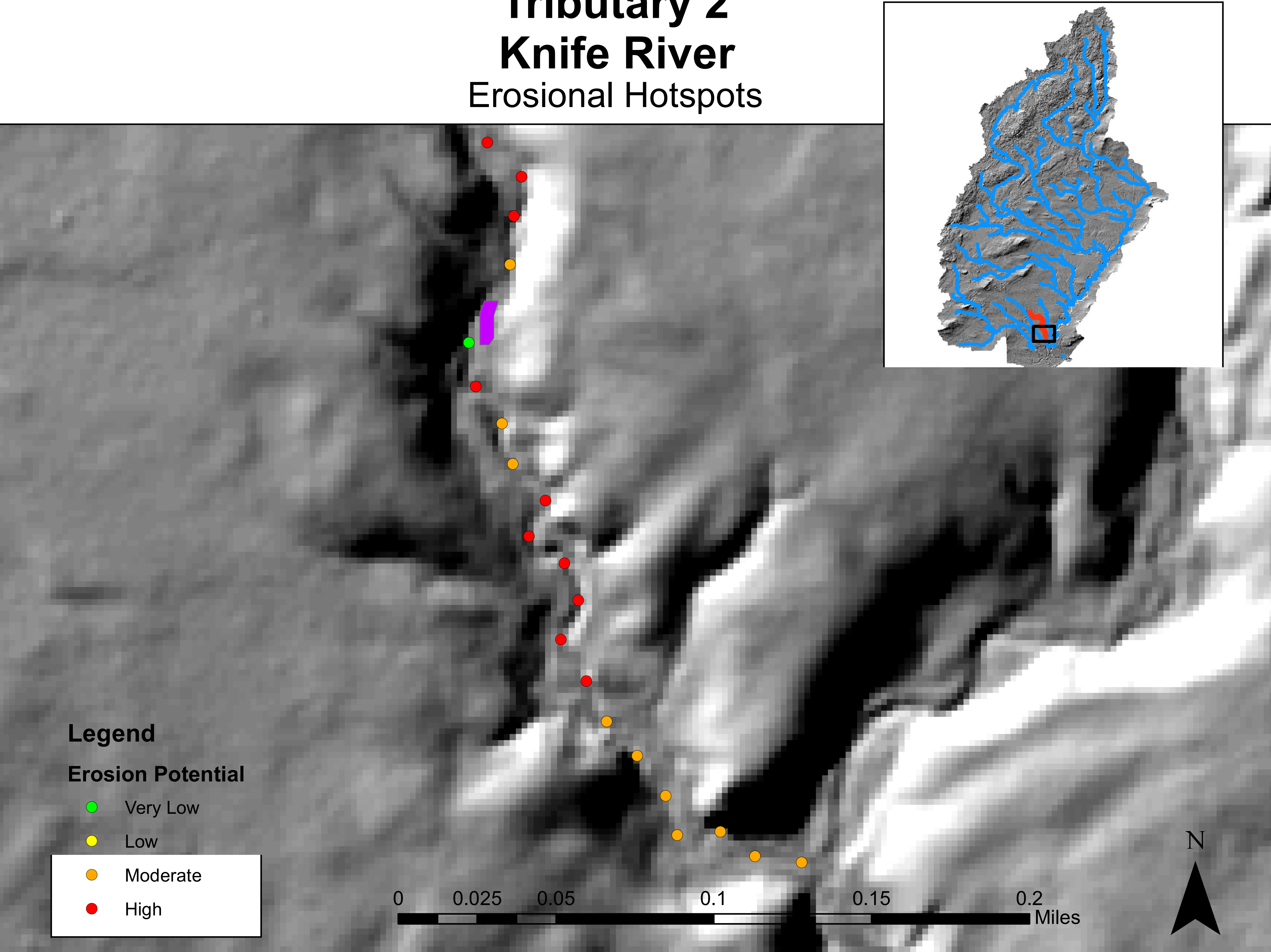
Stream Power Index



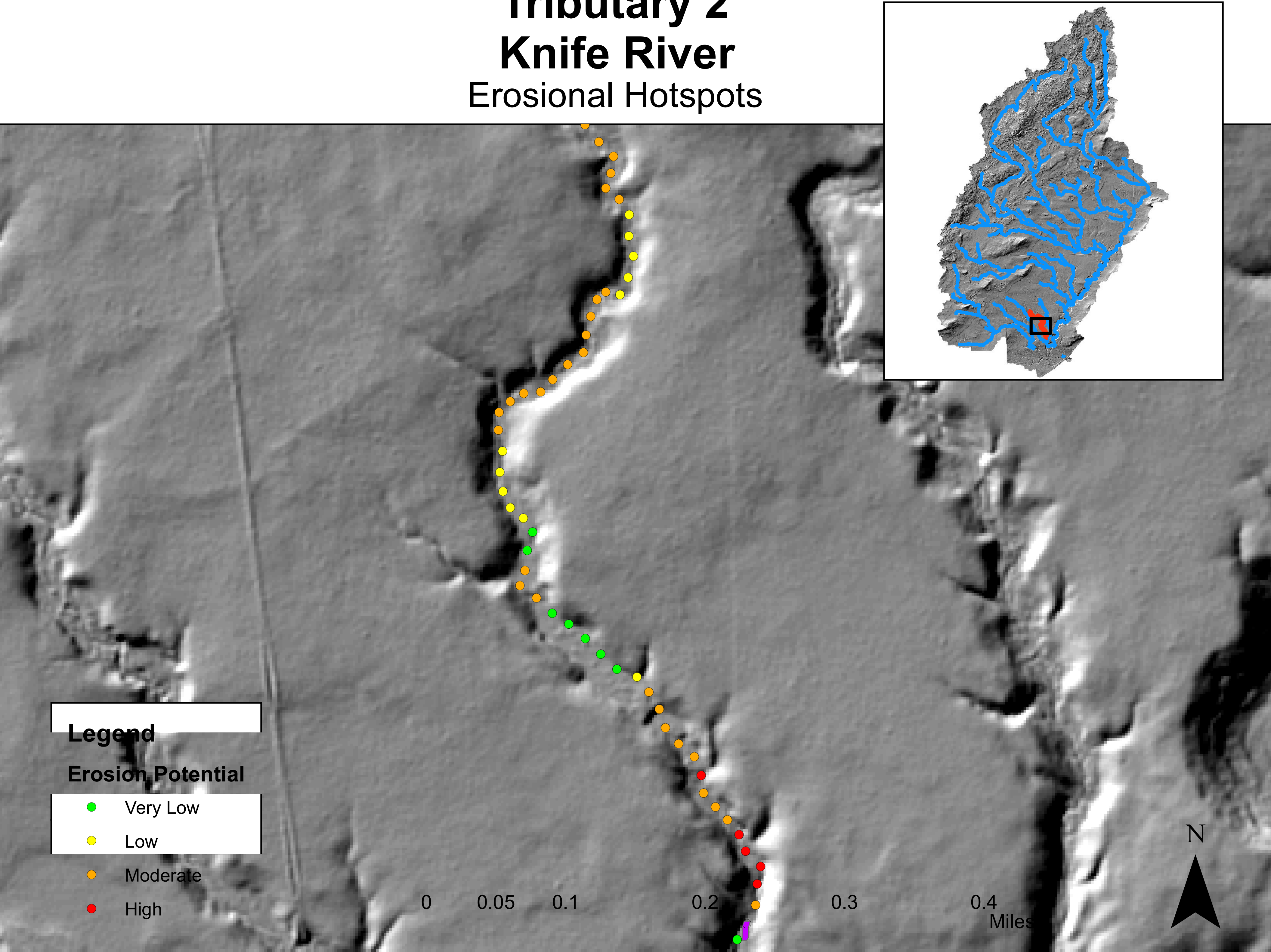
Tributary 2
Knife River
Bend Curvature



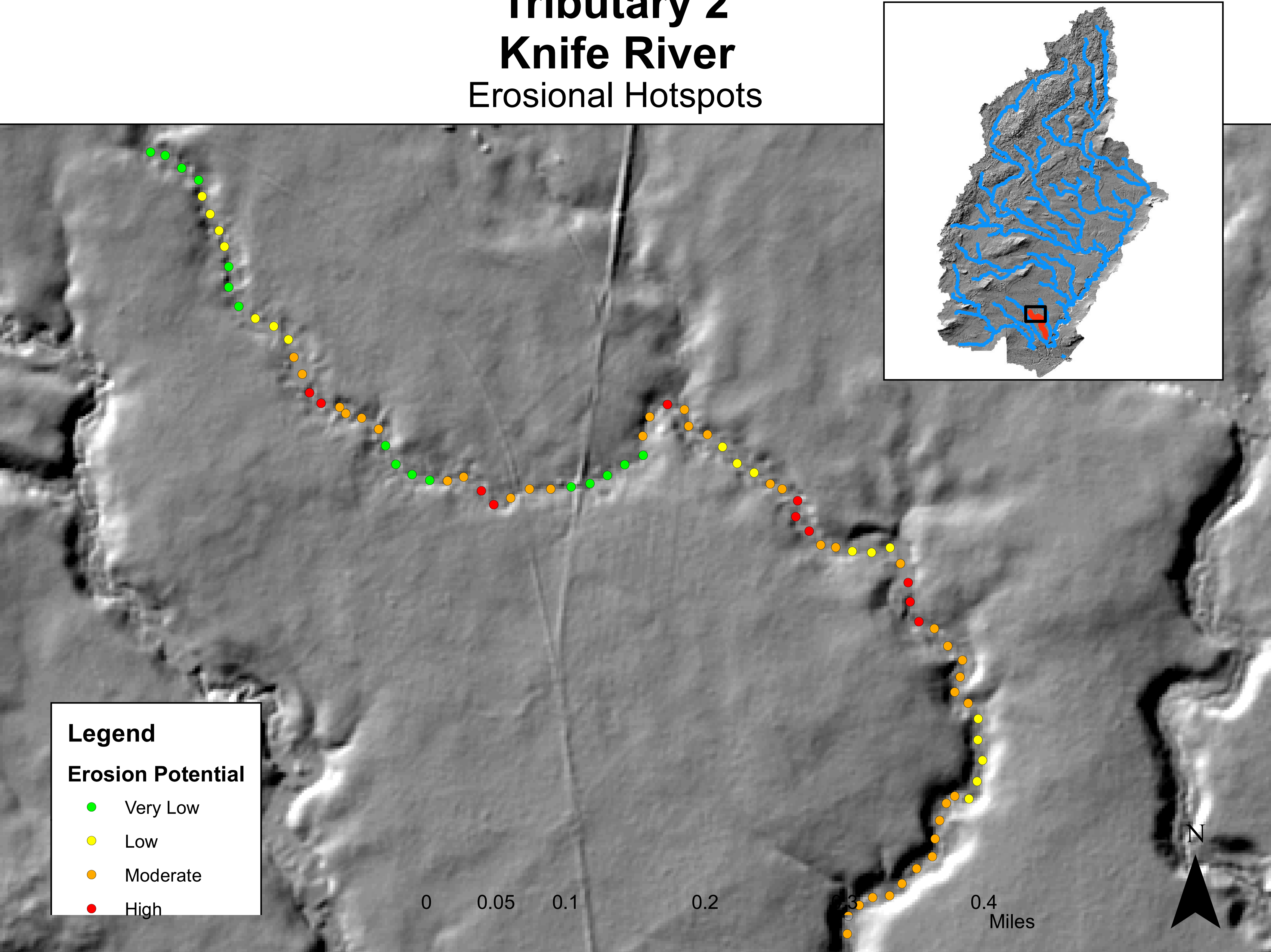
Tributary 2
Knife River
Erosional Hotspots



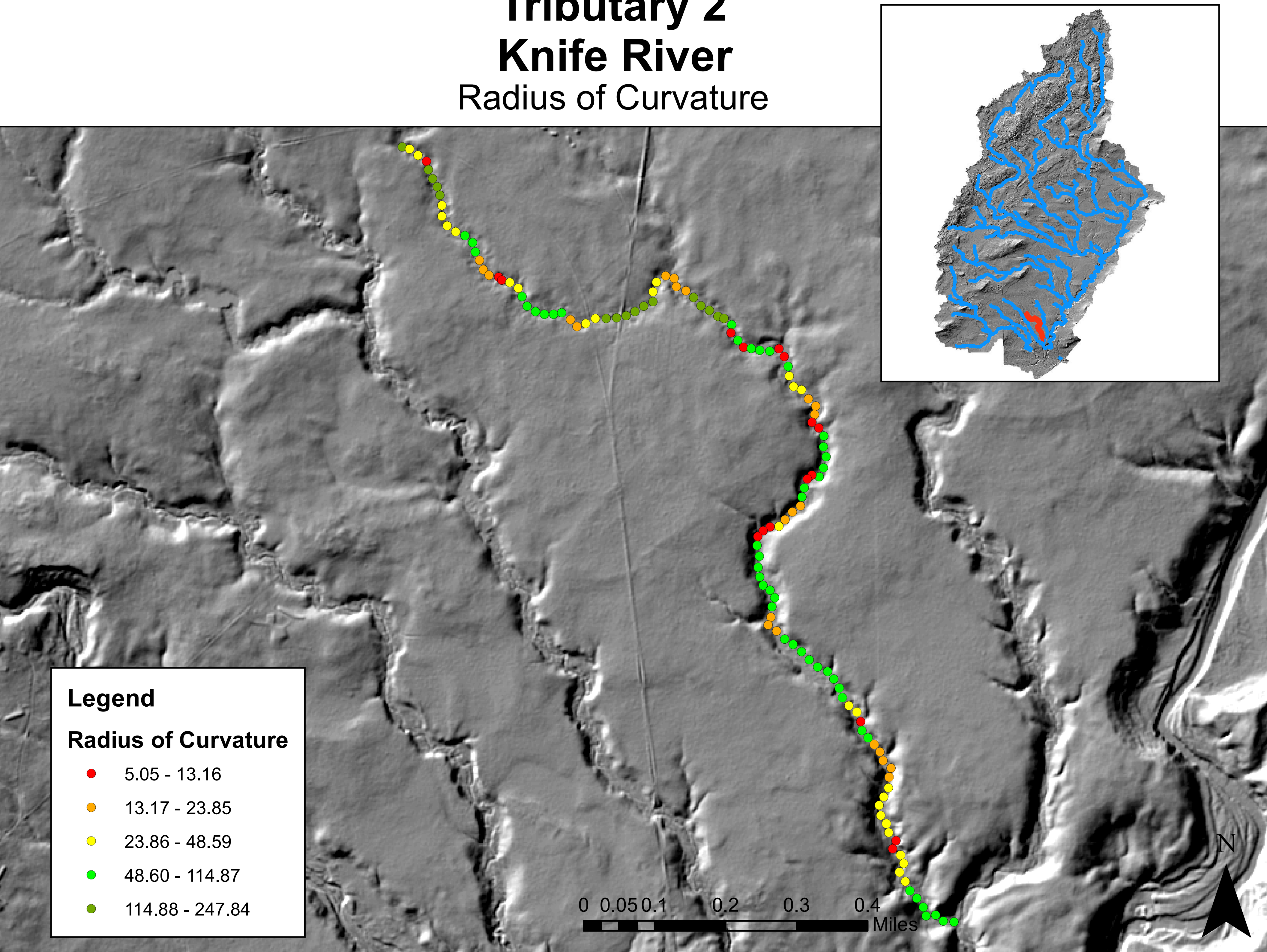
Tributary 2
Knife River
Erosional Hotspots



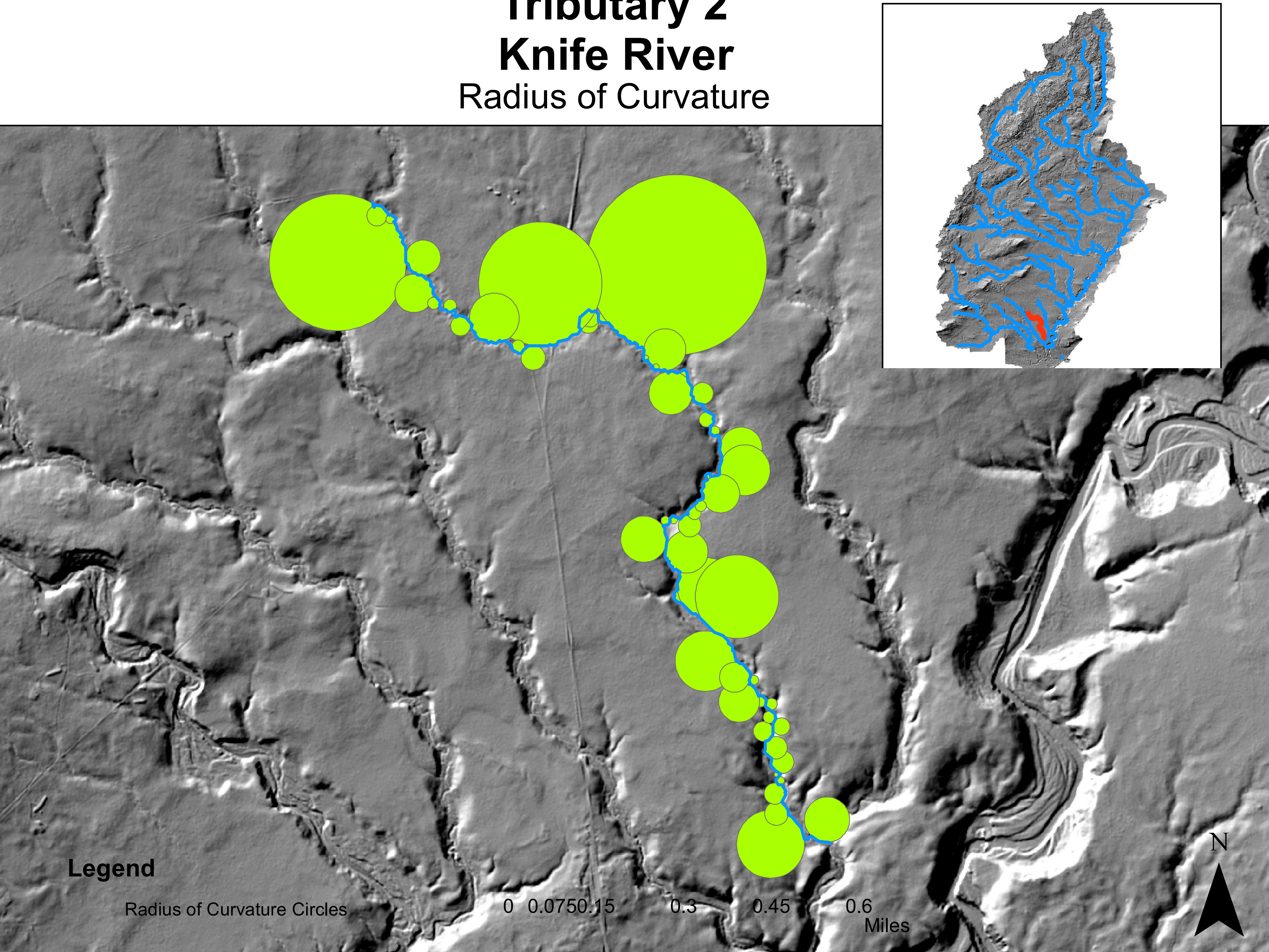
Tributary 2
Knife River
Erosional Hotspots



Tributary 2
Knife River
Radius of Curvature

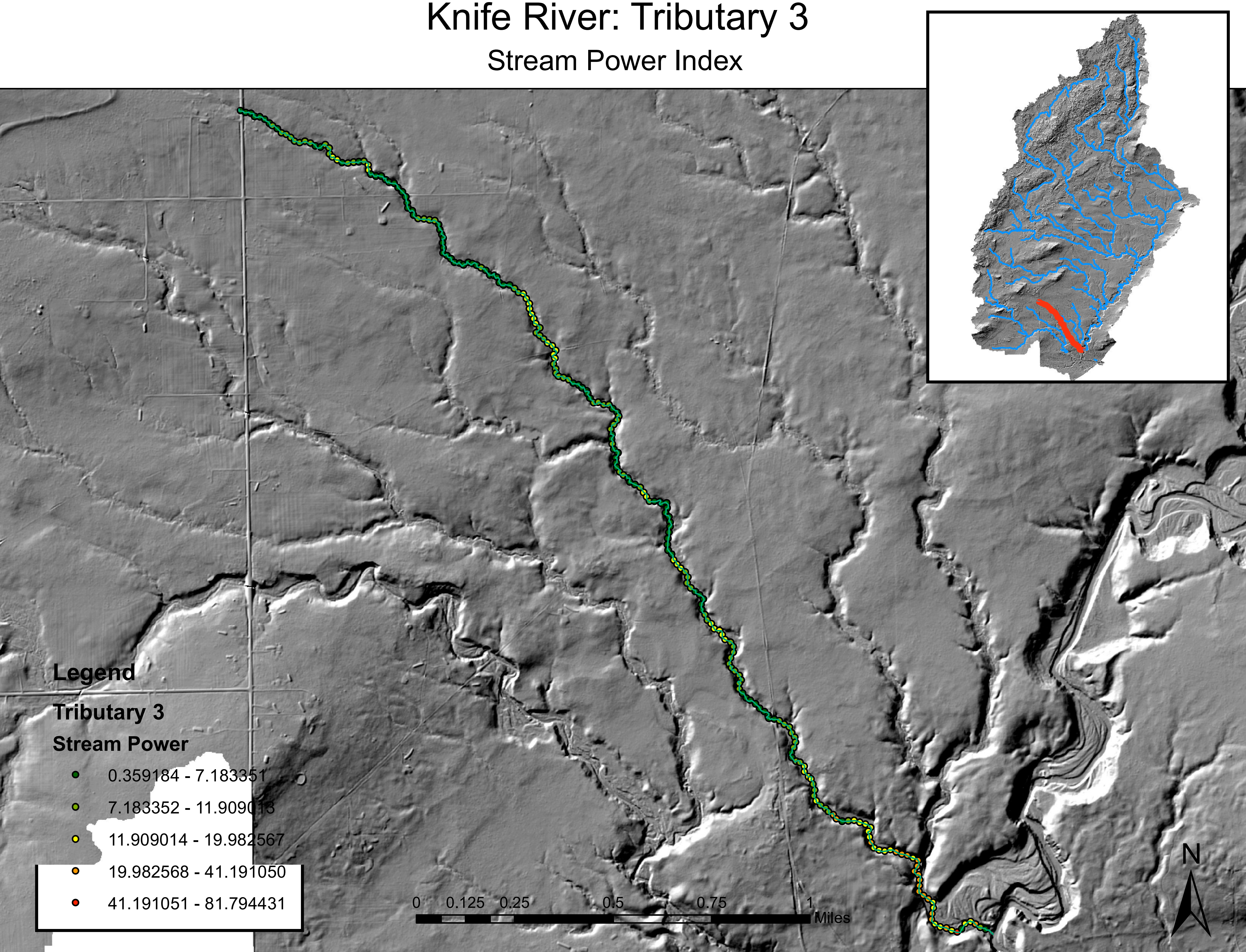


Tributary 2
Knife River
Radius of Curvature

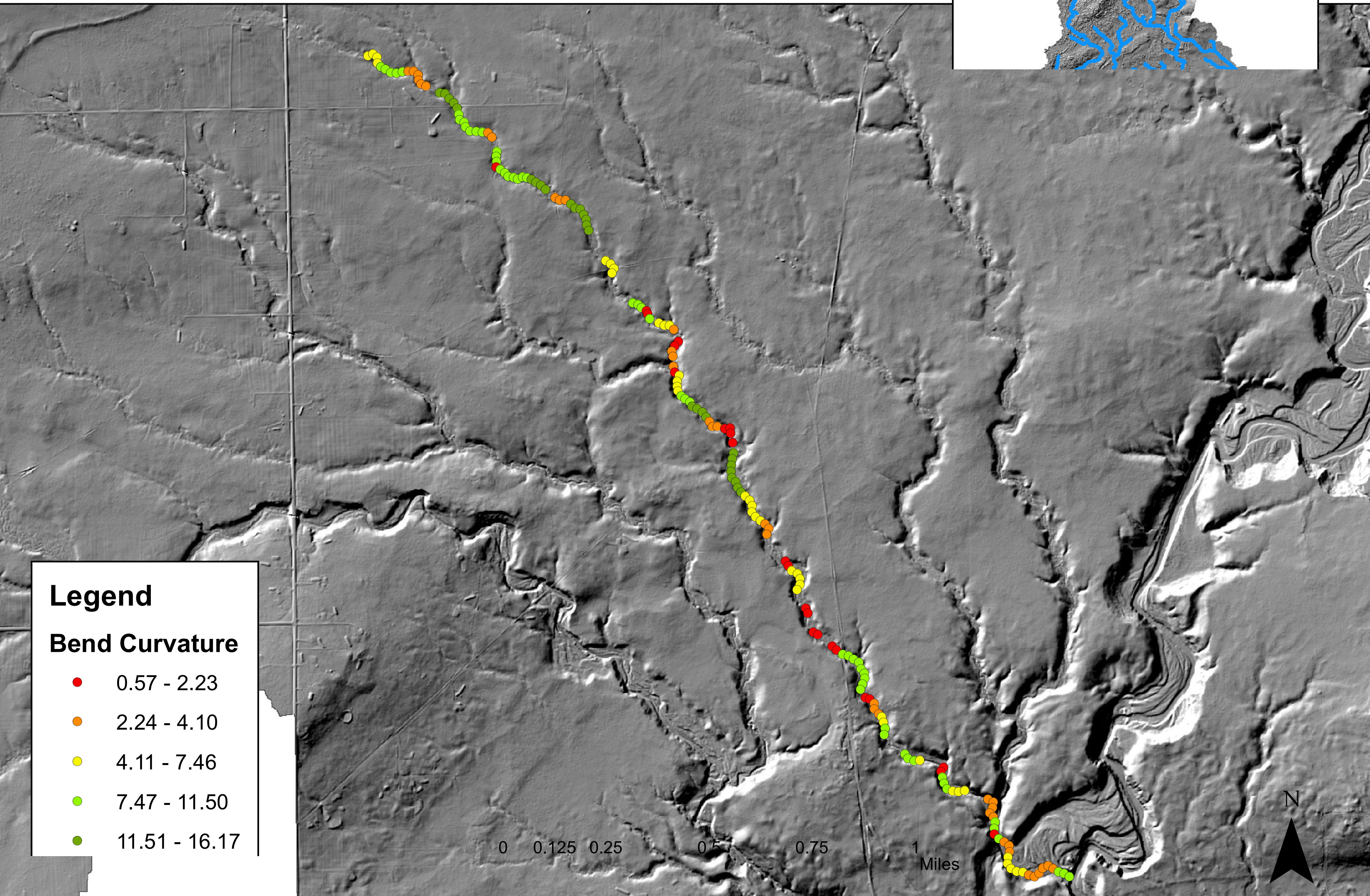


Knife River: Tributary 3

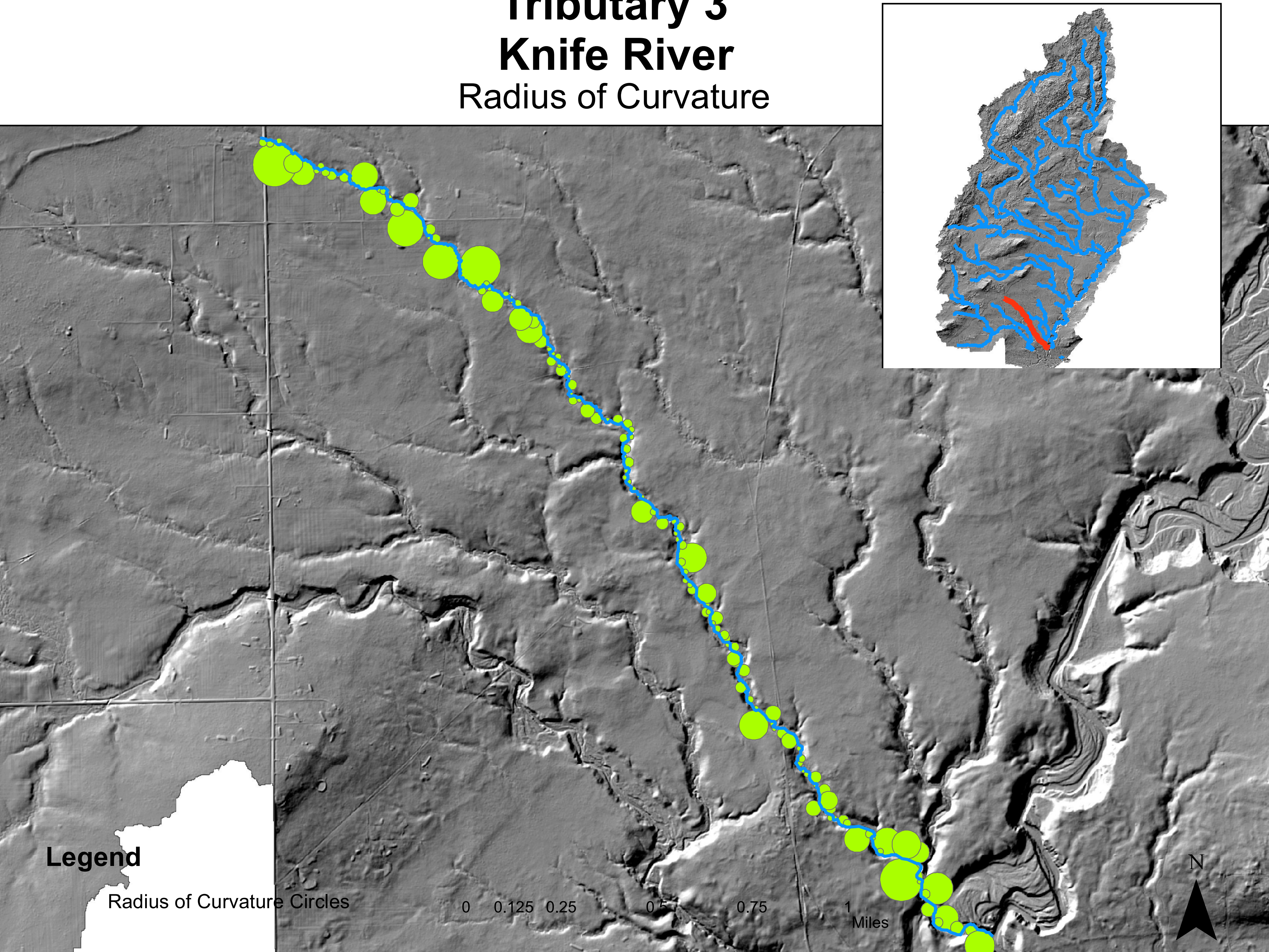
Stream Power Index



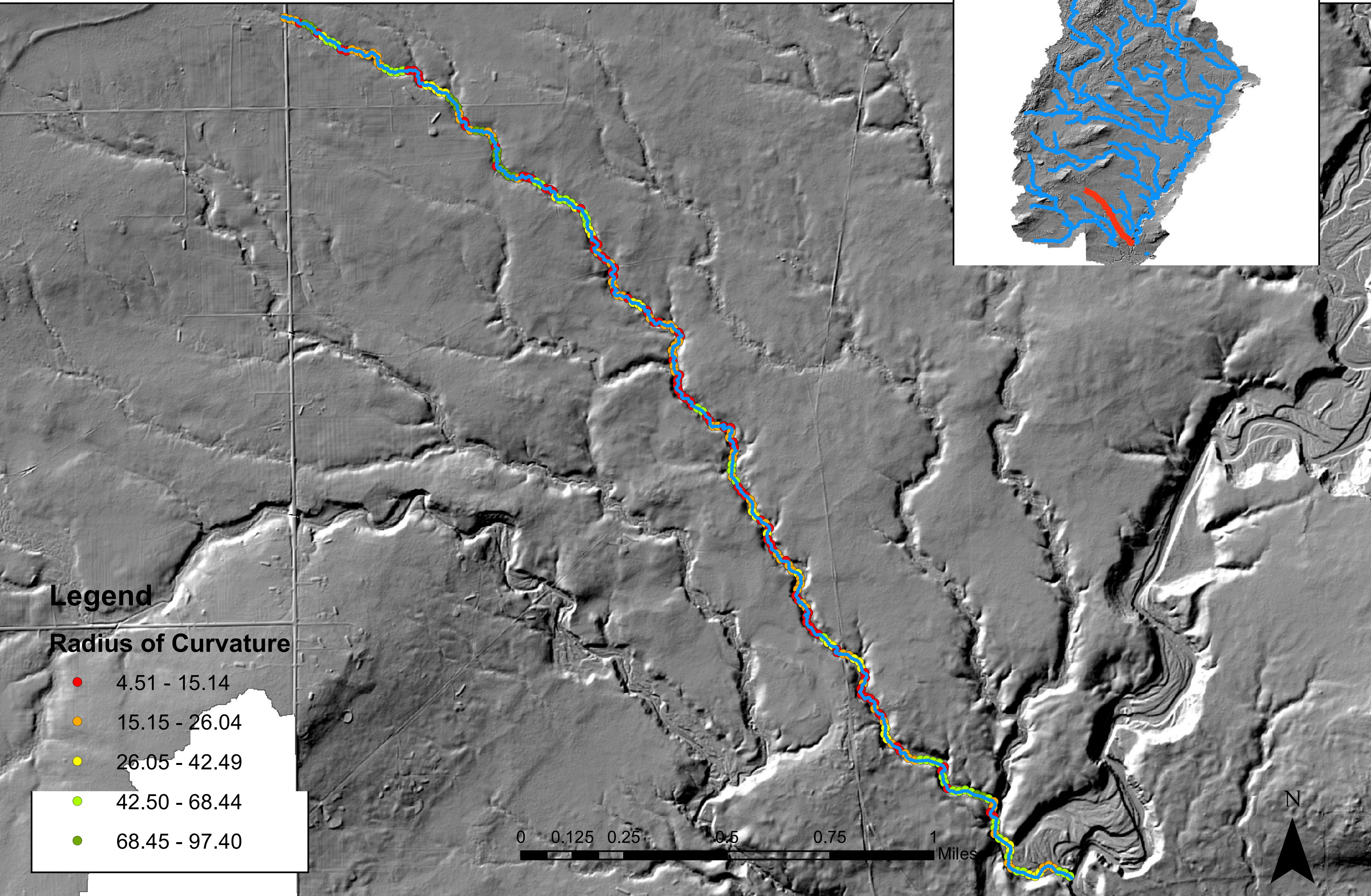
Tributary 3
Knife River
Bend Curvature



Tributary 3
Knife River
Radius of Curvature

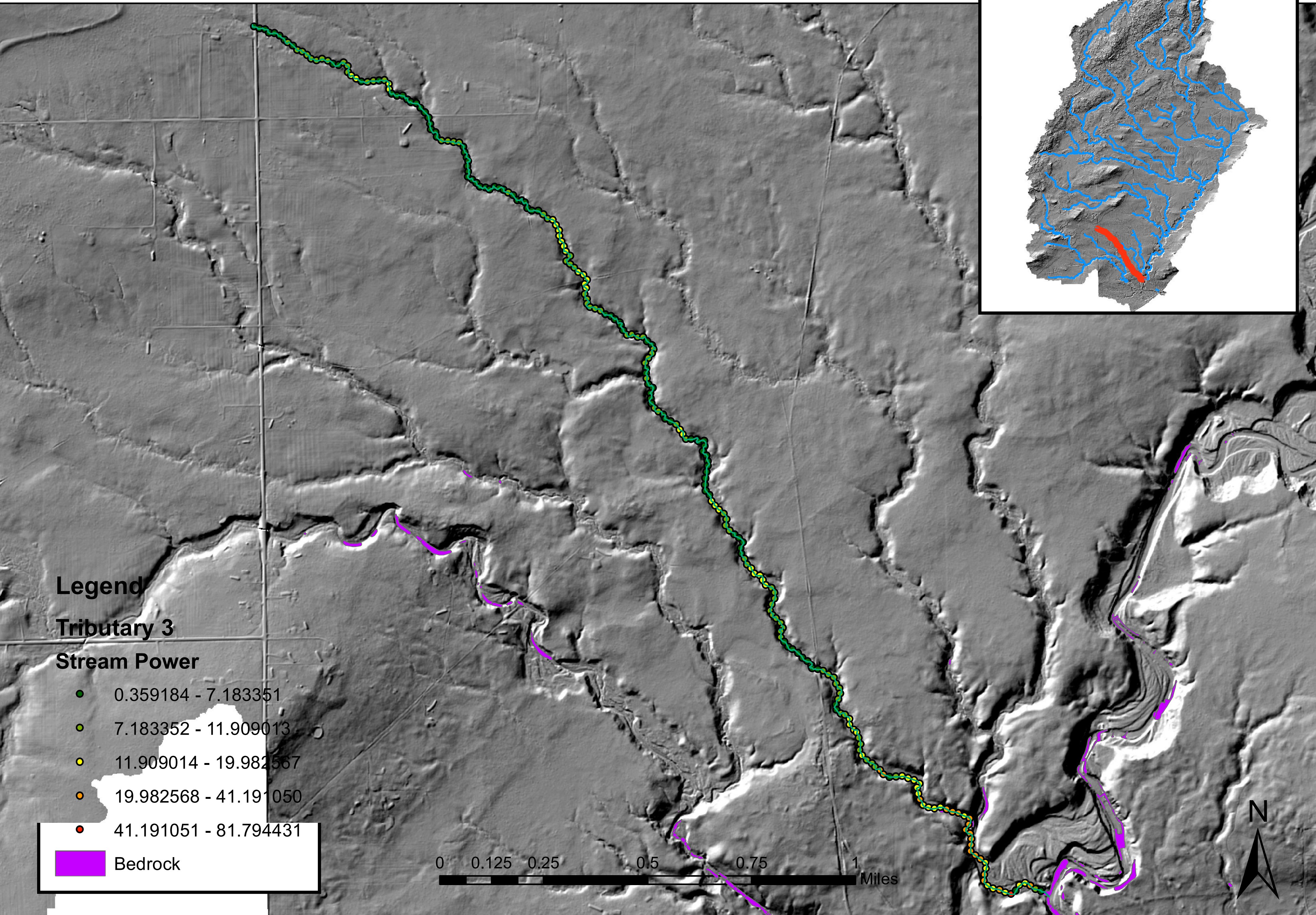


Tributary 3
Knife River
Radius of Curvature

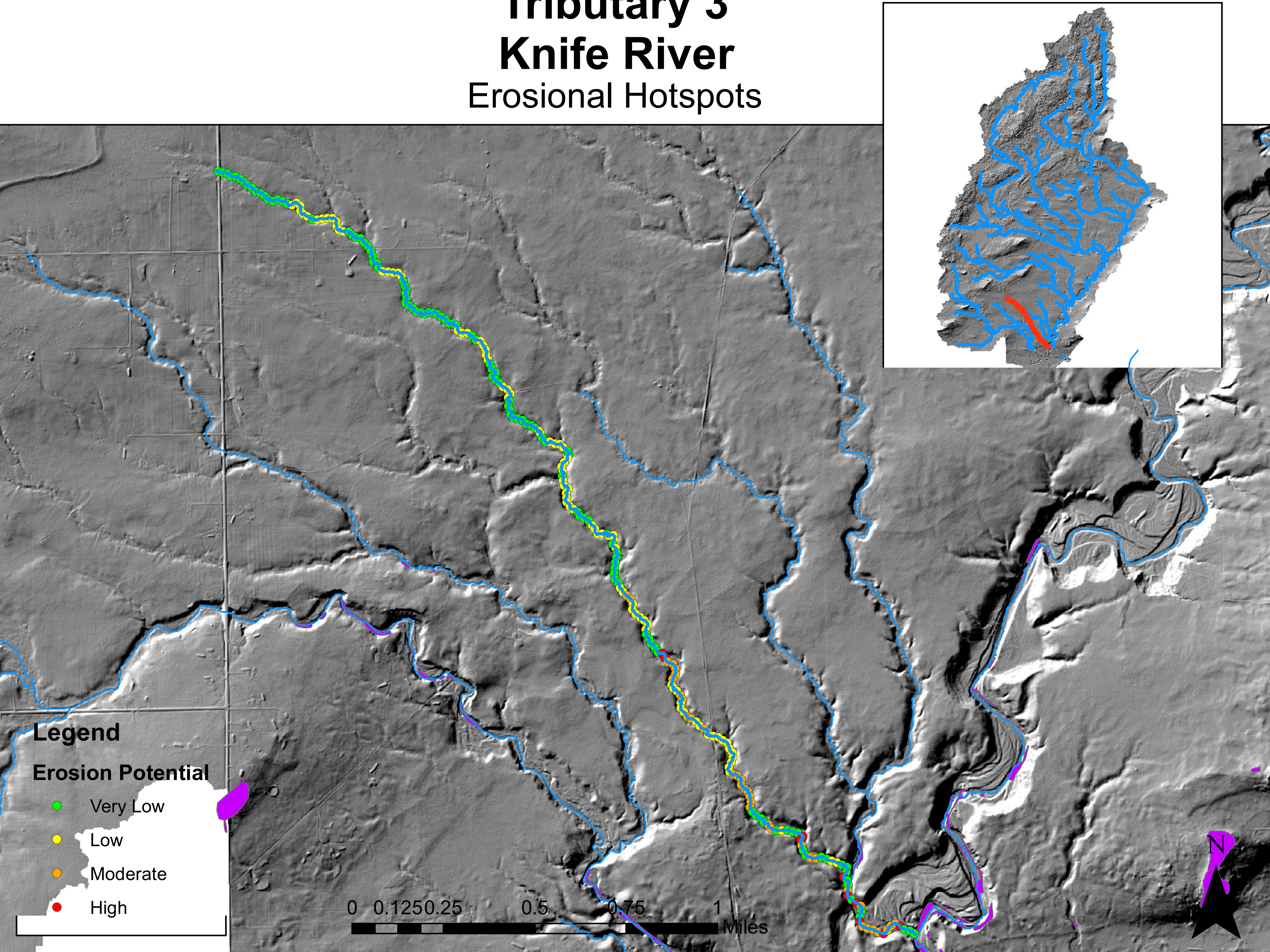


Knife River: Tributary 3

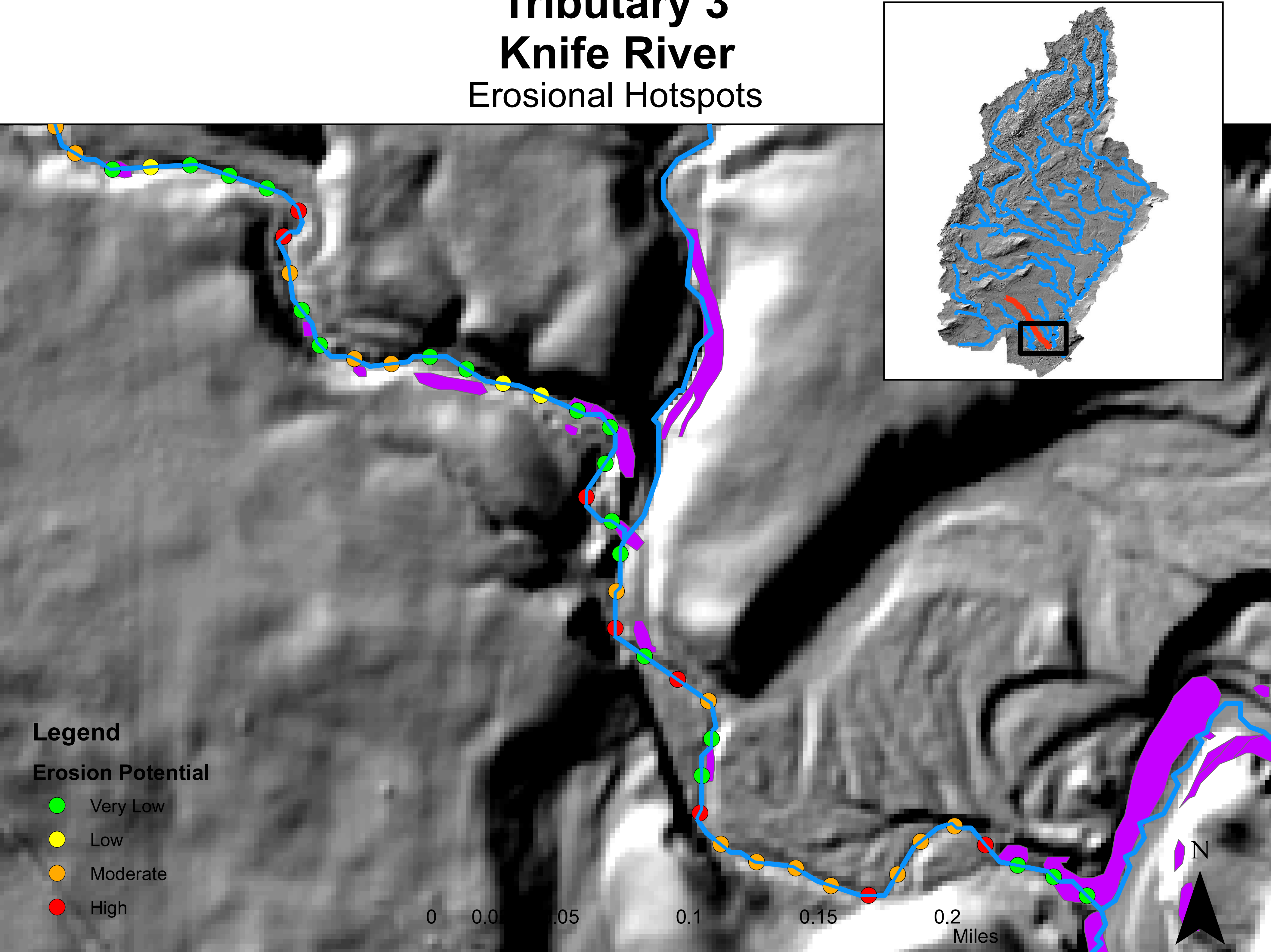
Stream Power Index



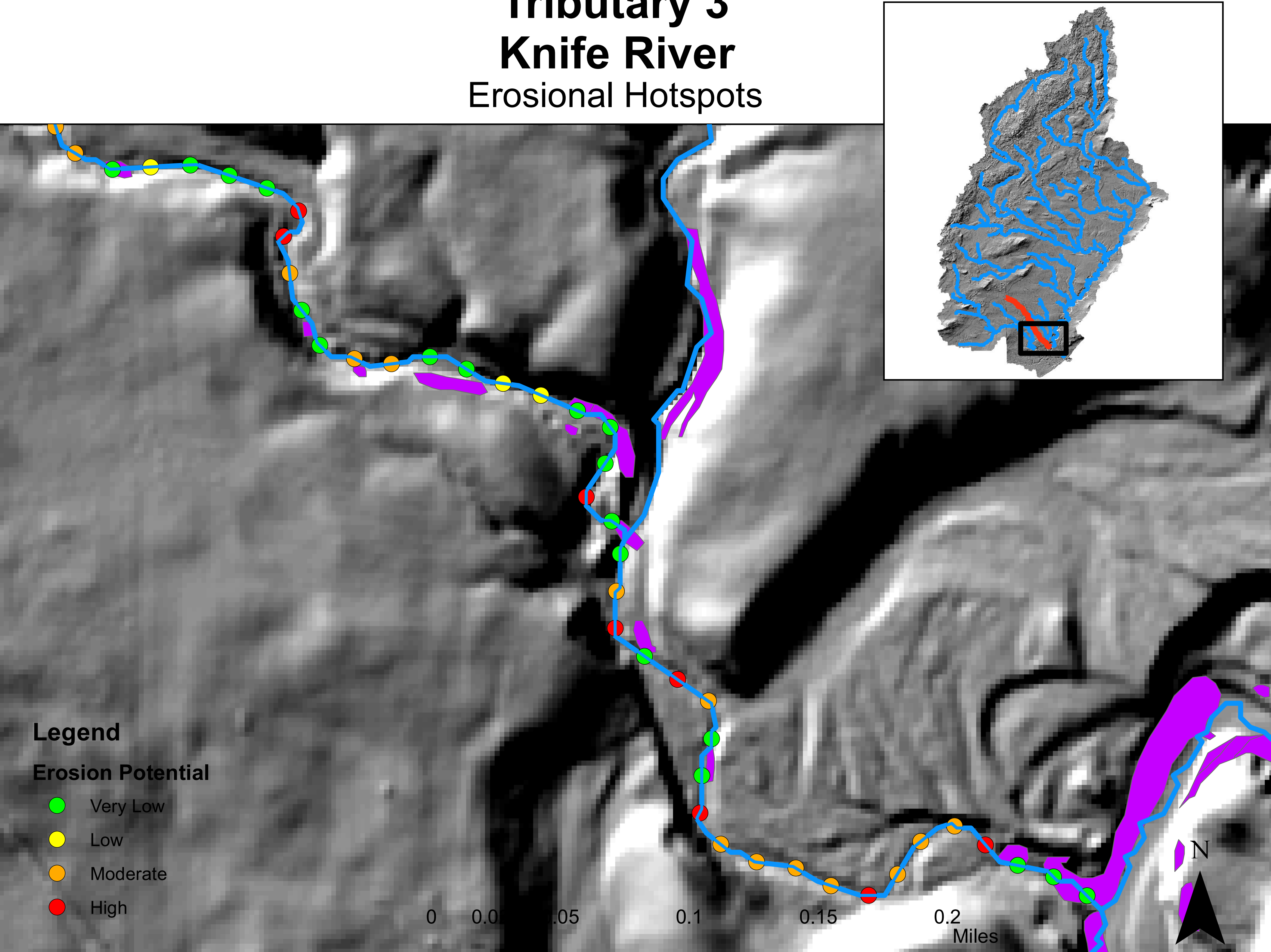
Tributary 3
Knife River
Erosional Hotspots



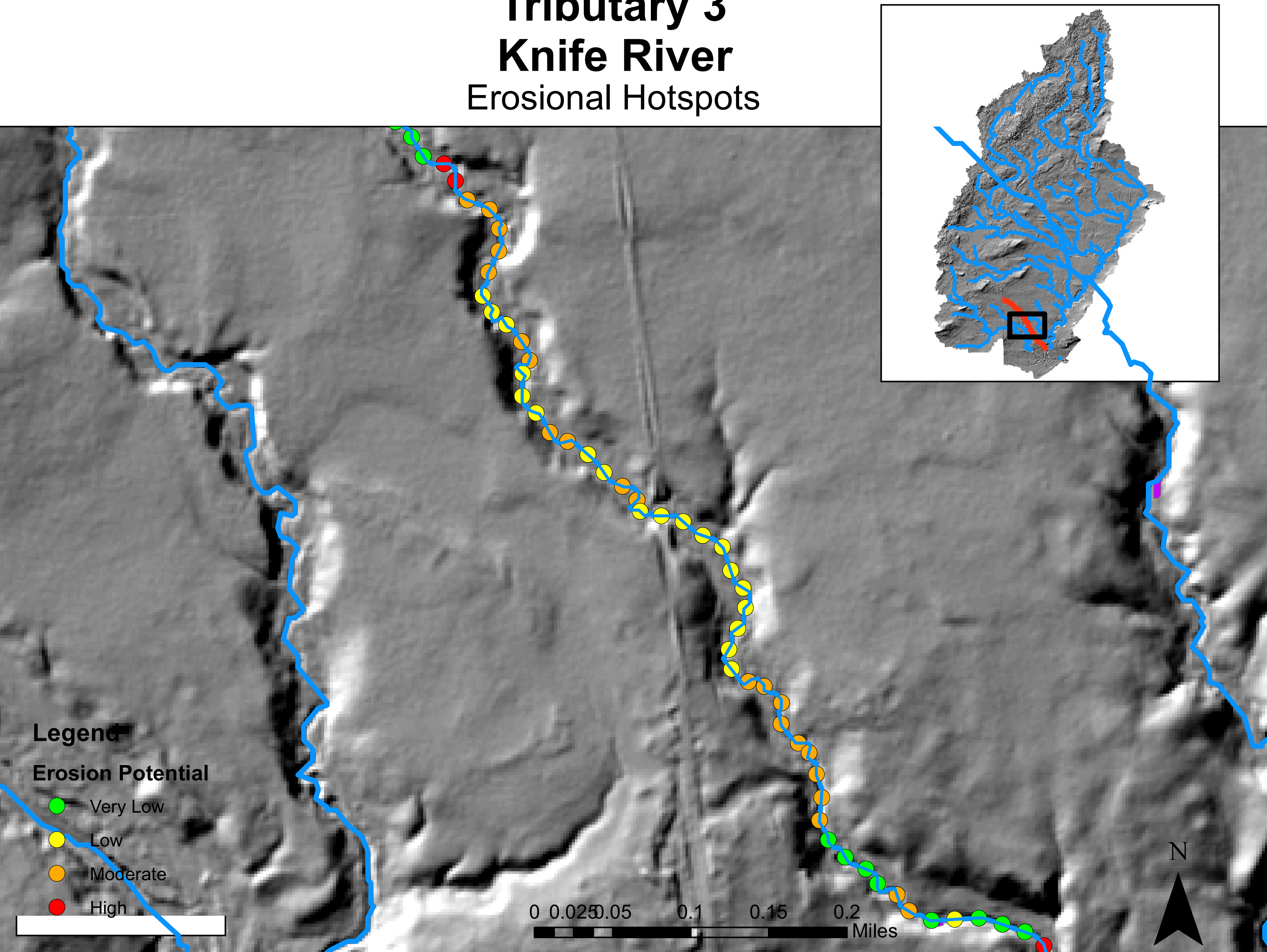
Tributary 3
Knife River
Erosional Hotspots



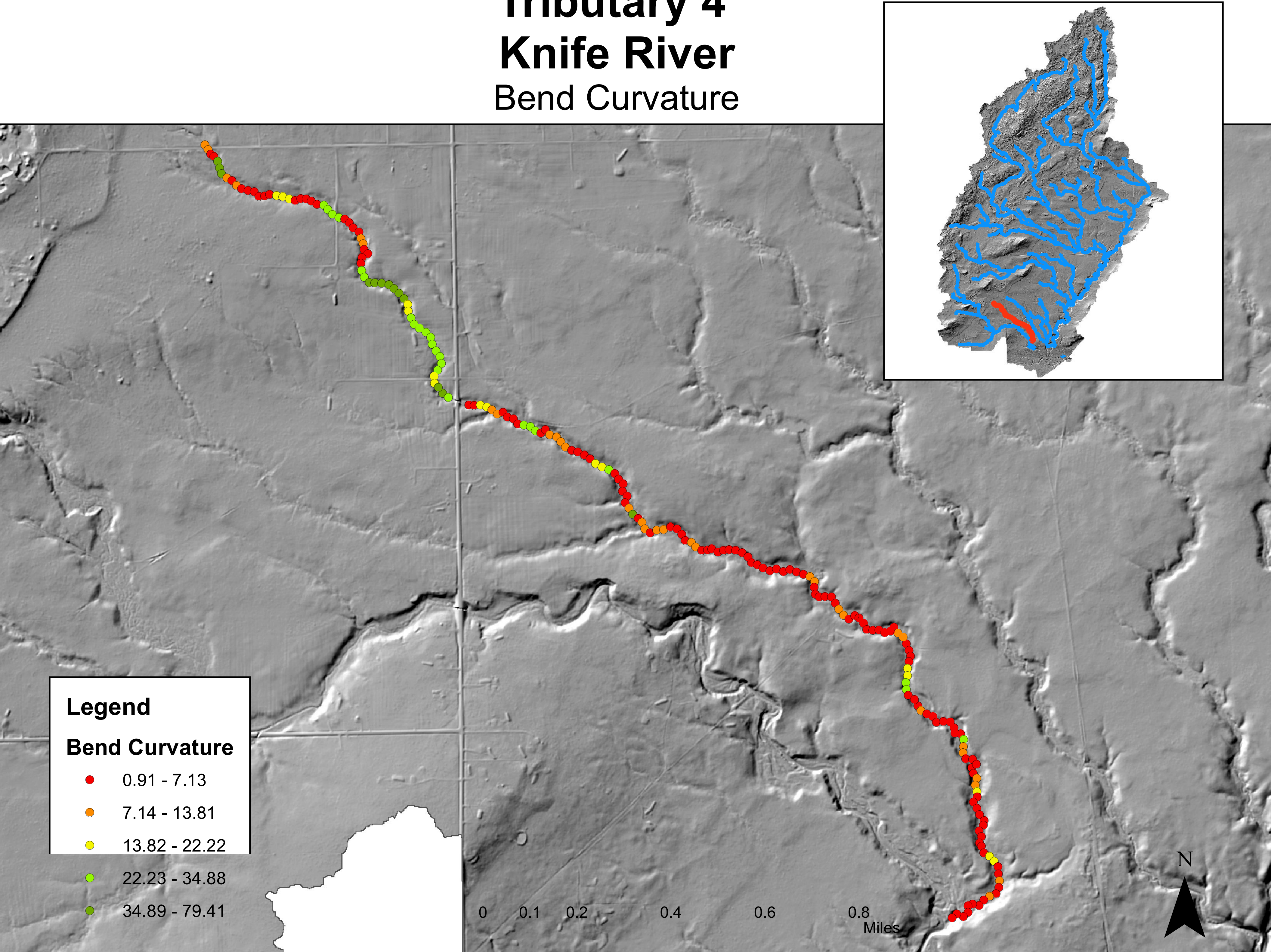
Tributary 3
Knife River
Erosional Hotspots



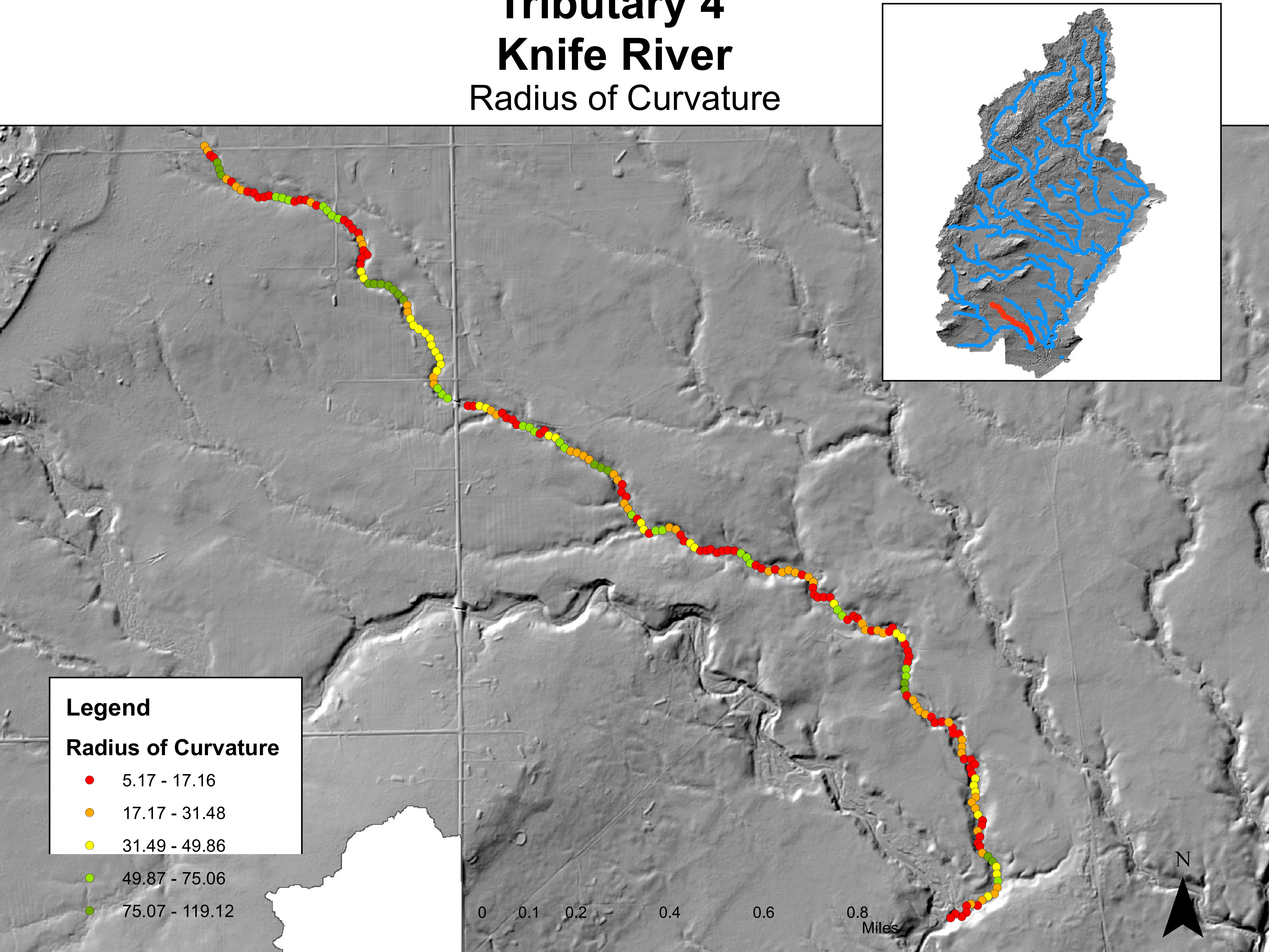
Tributary 3
Knife River
Erosional Hotspots



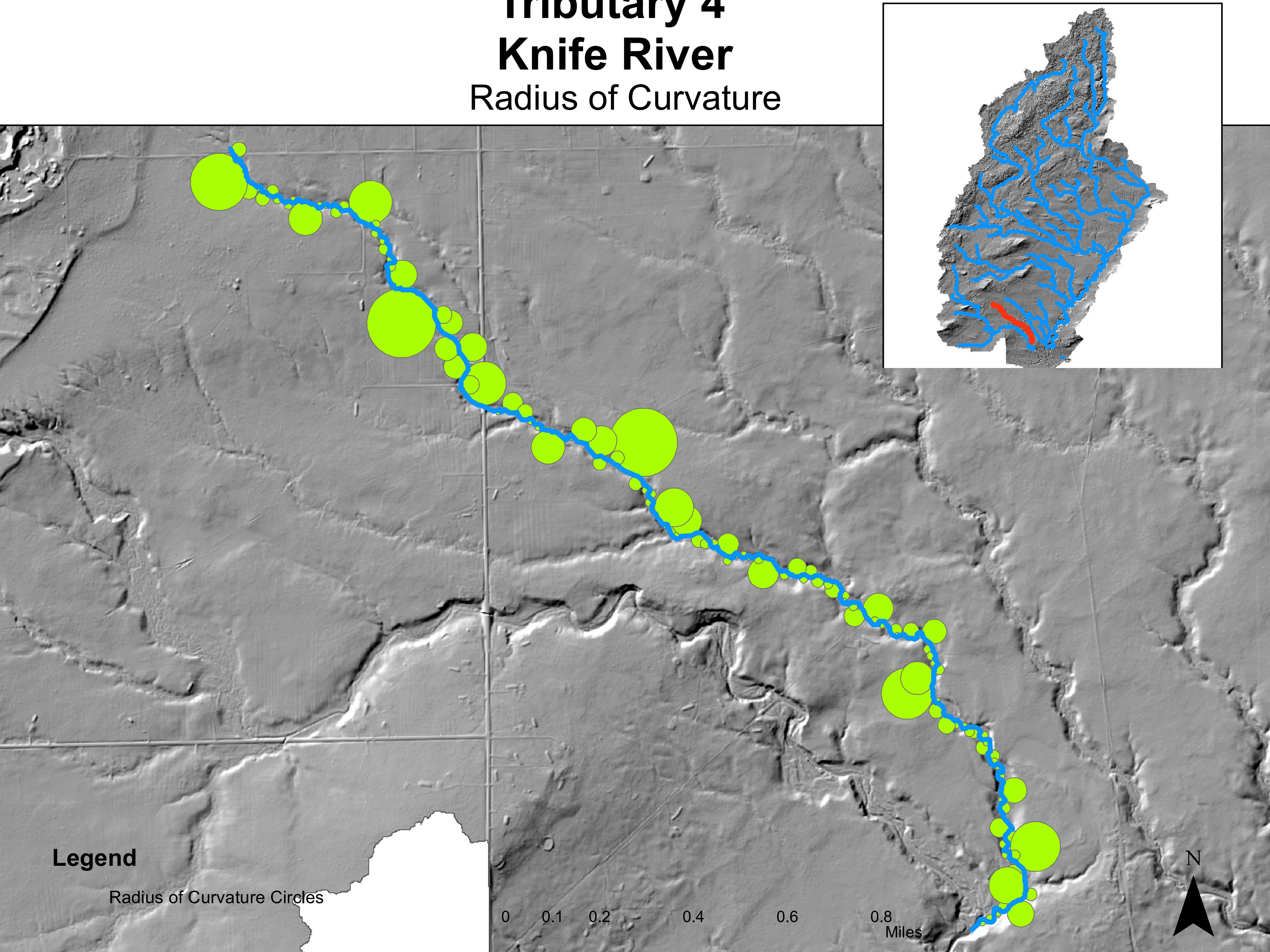
Tributary 4
Knife River
Bend Curvature



Tributary 4
Knife River
Radius of Curvature

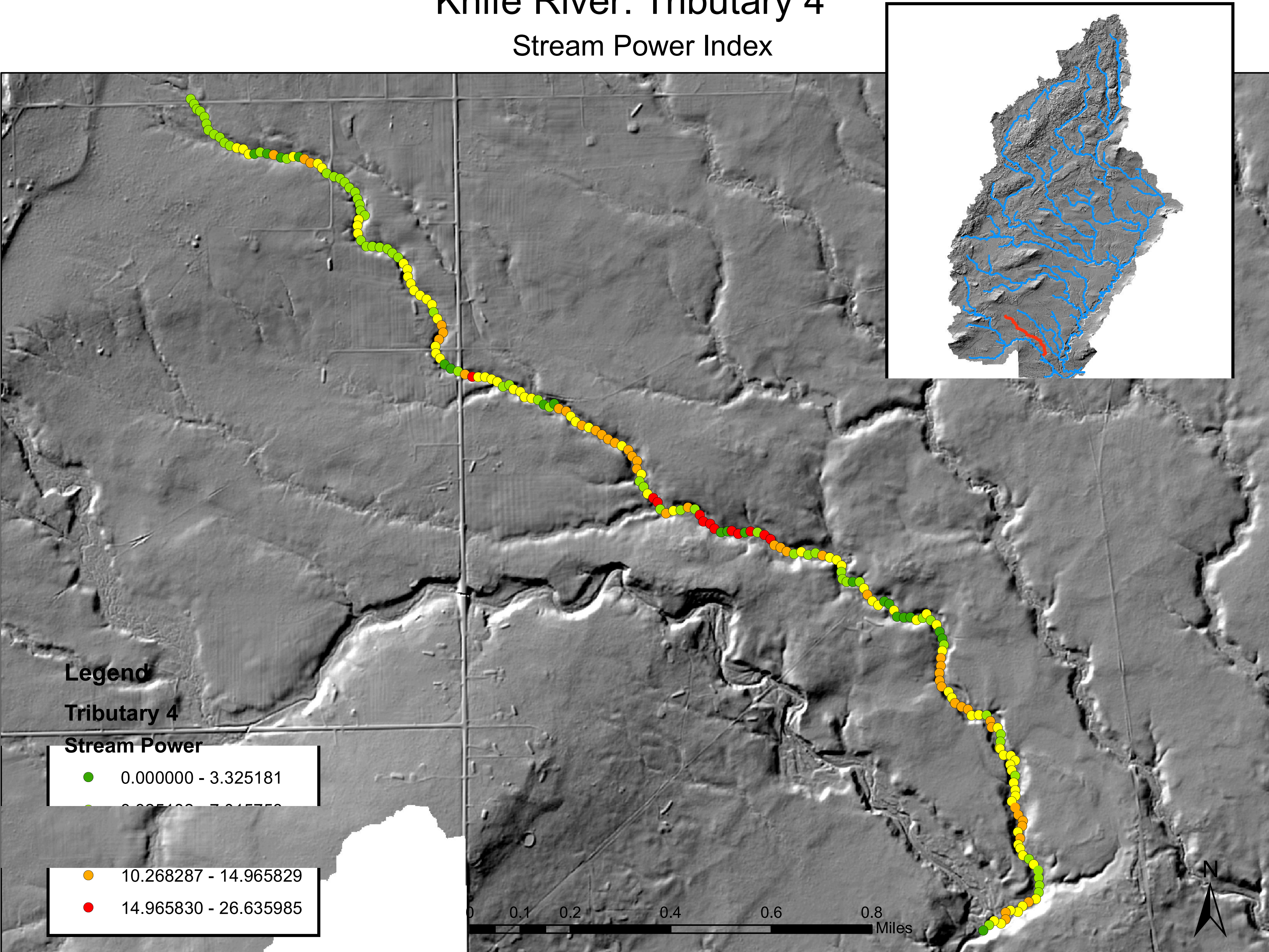


Tributary 4
Knife River
Radius of Curvature



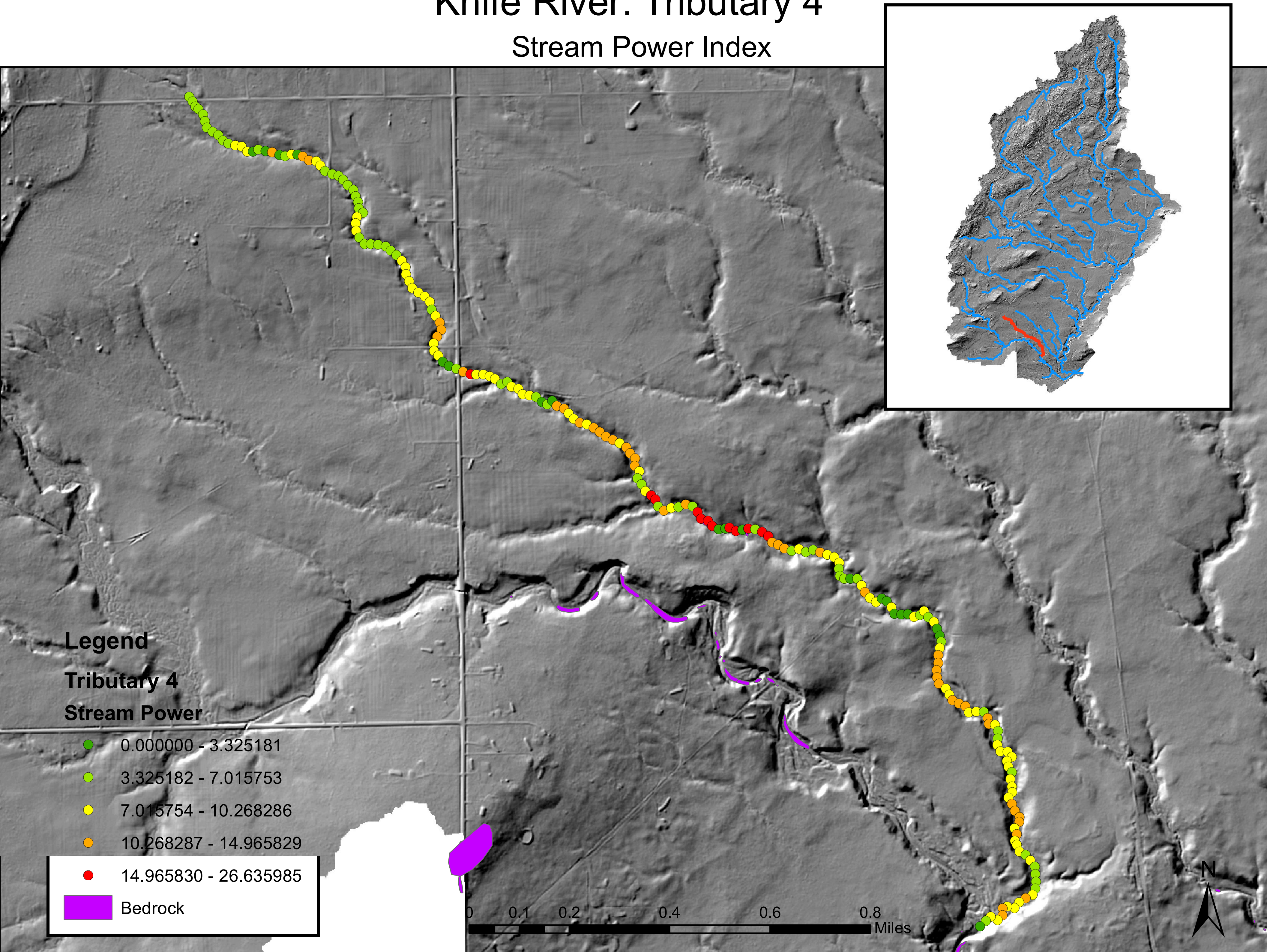
Knife River: Tributary 4

Stream Power Index

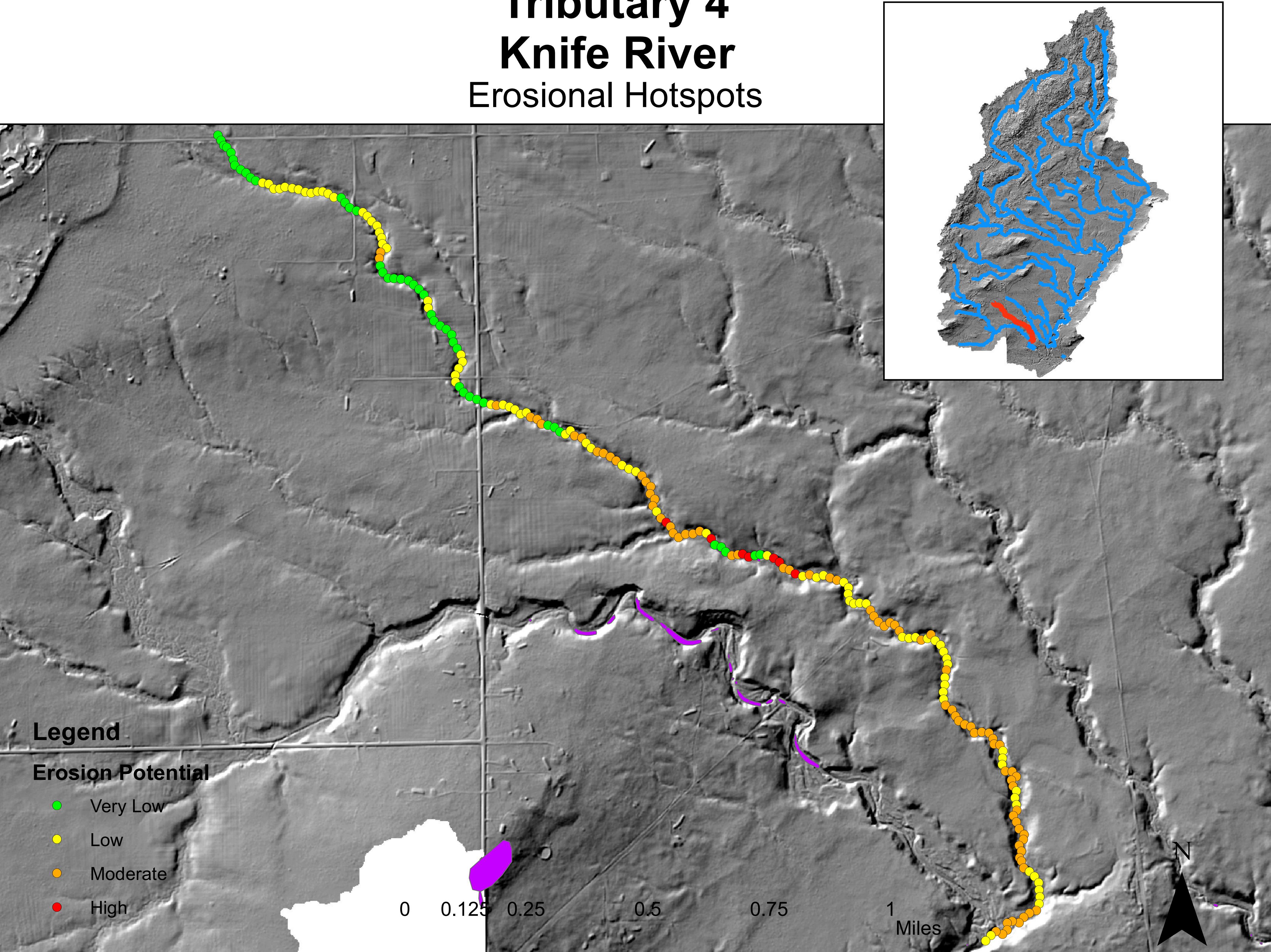


Knife River: Tributary 4

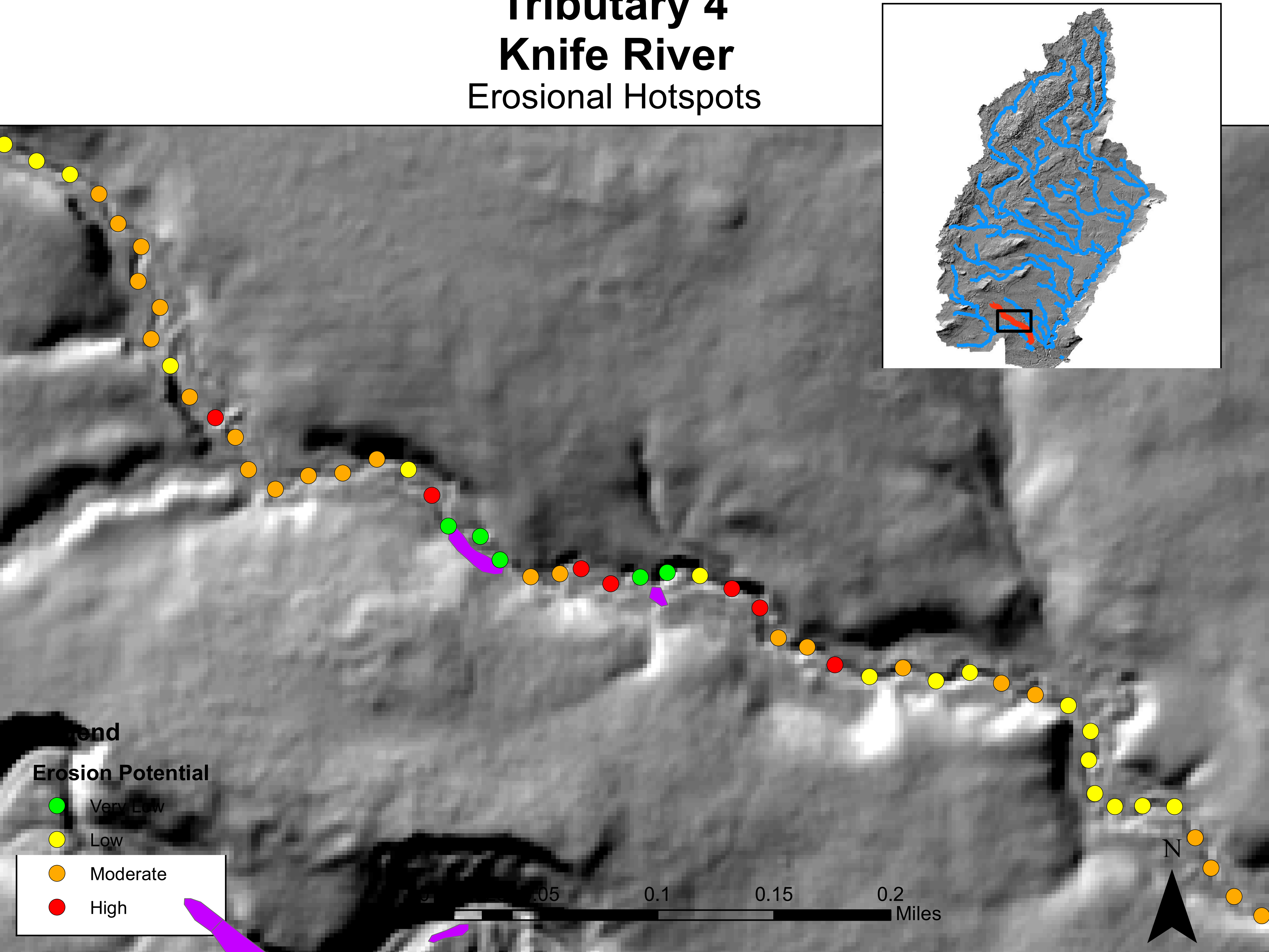
Stream Power Index

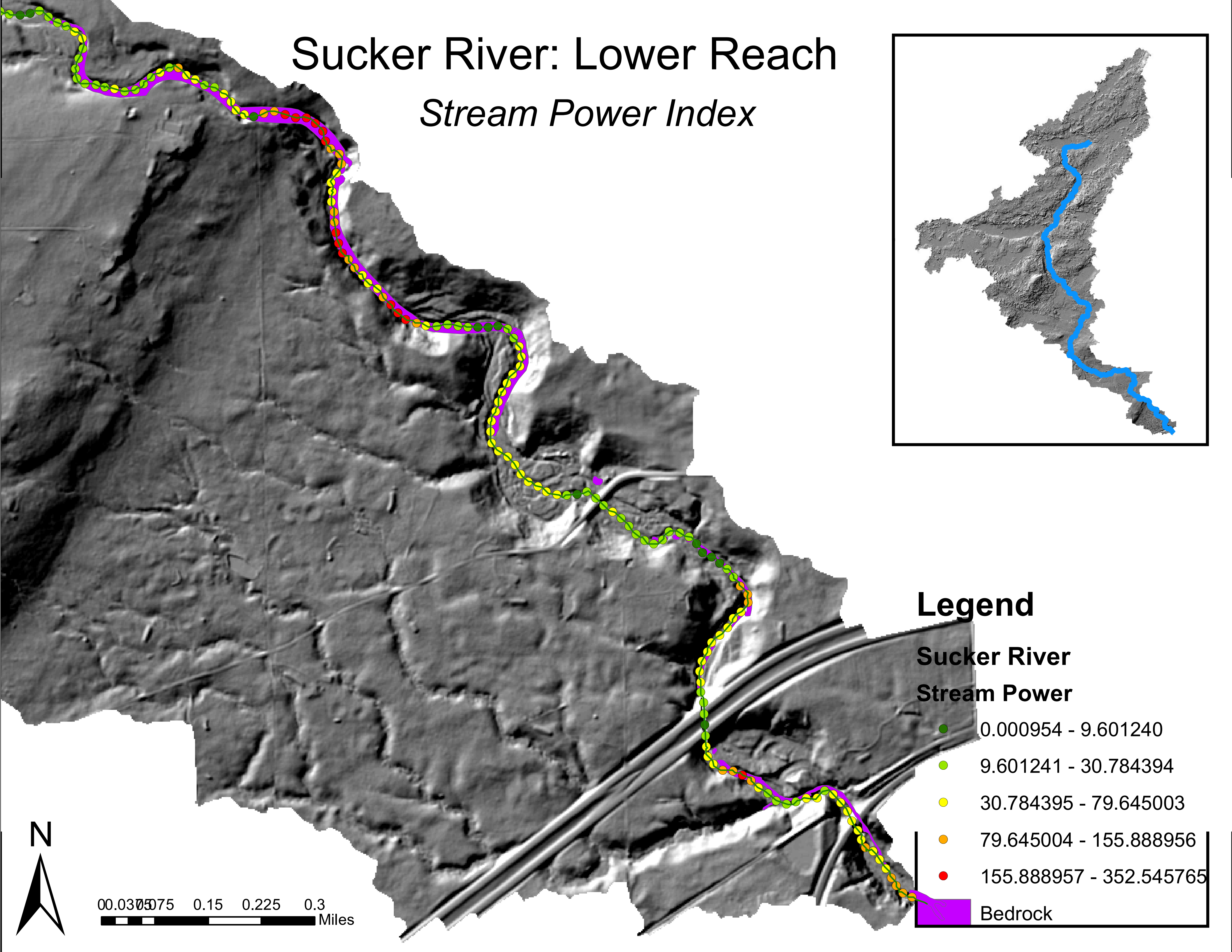


Tributary 4
Knife River
Erosional Hotspots



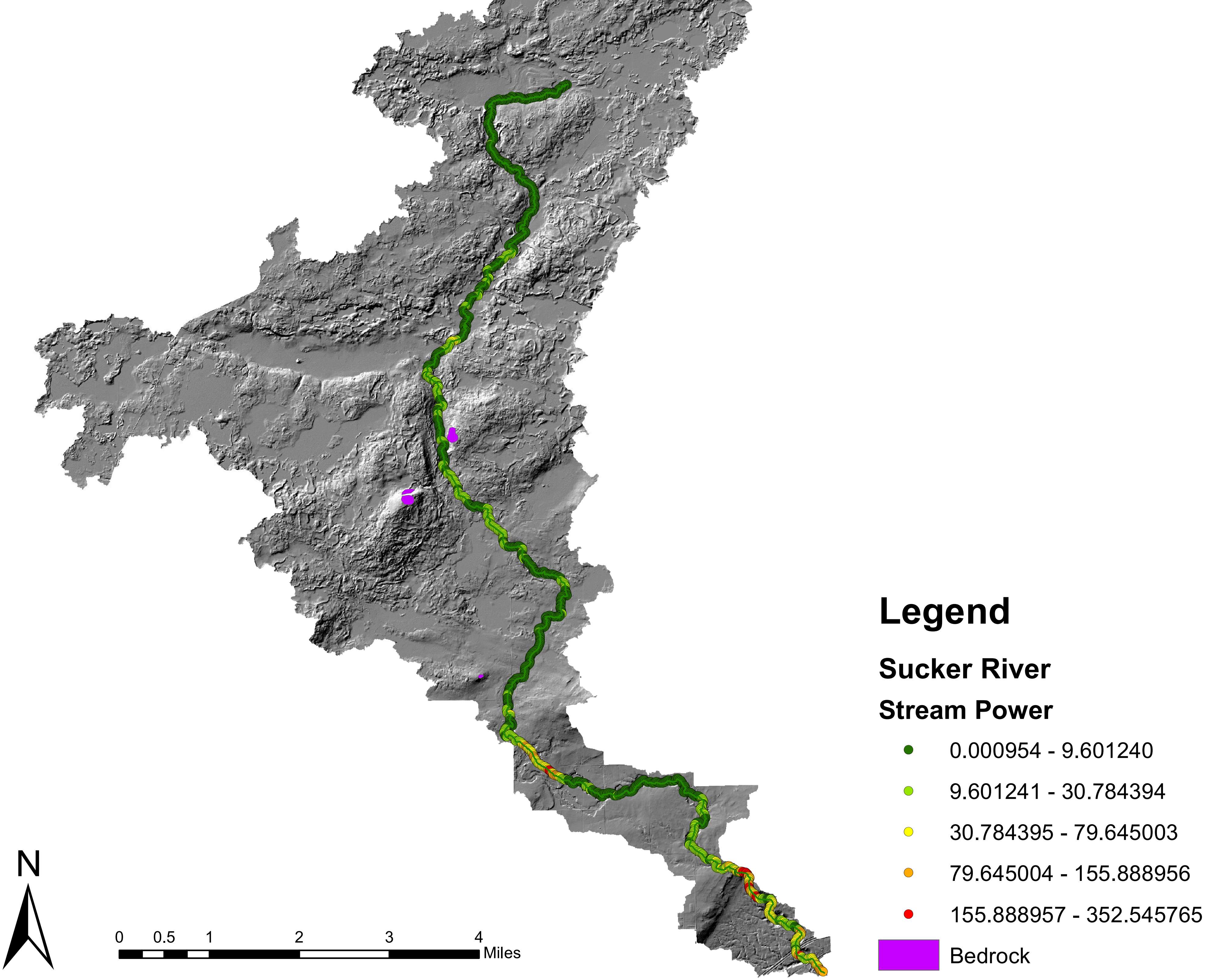
Tributary 4
Knife River
Erosional Hotspots

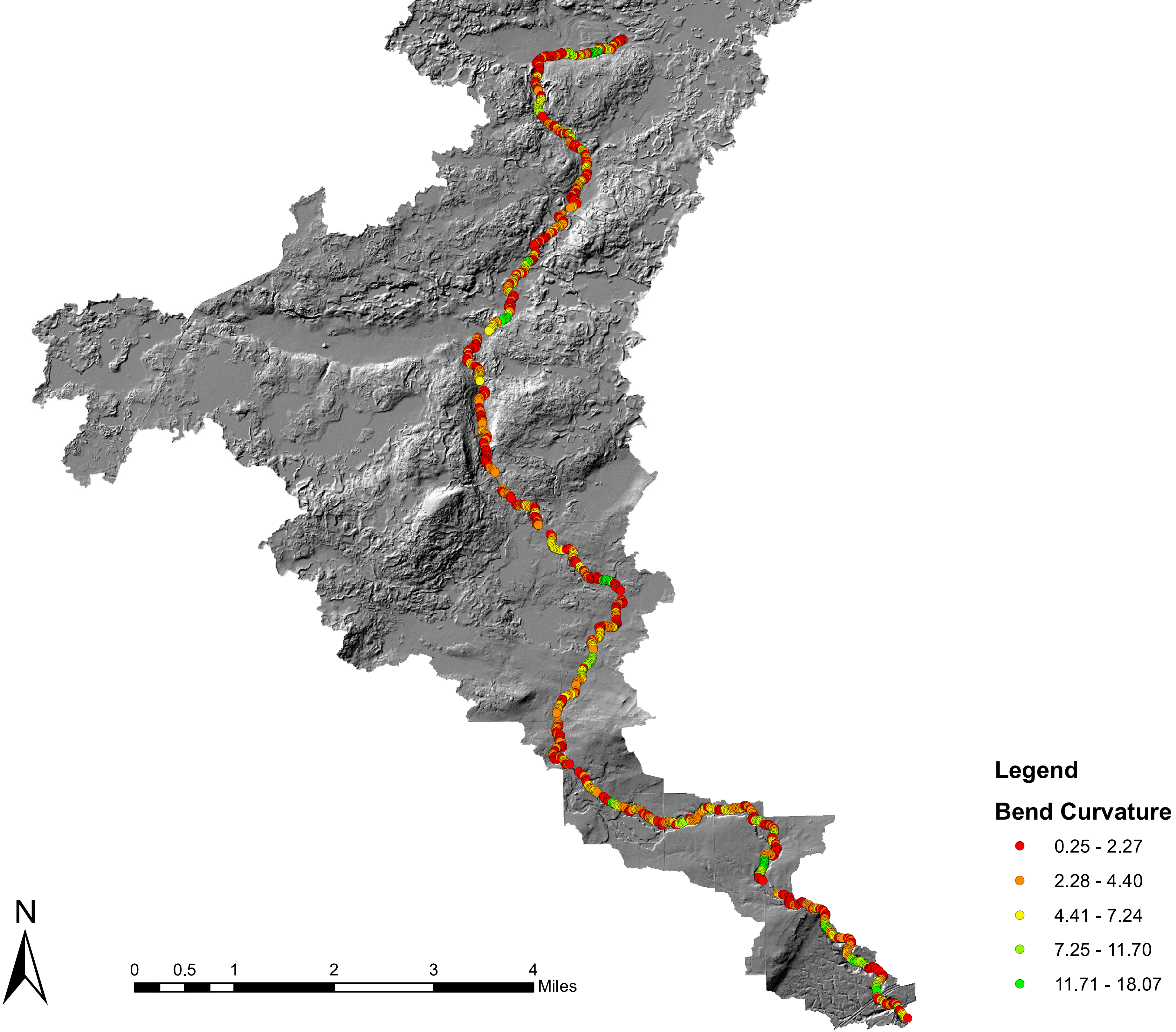


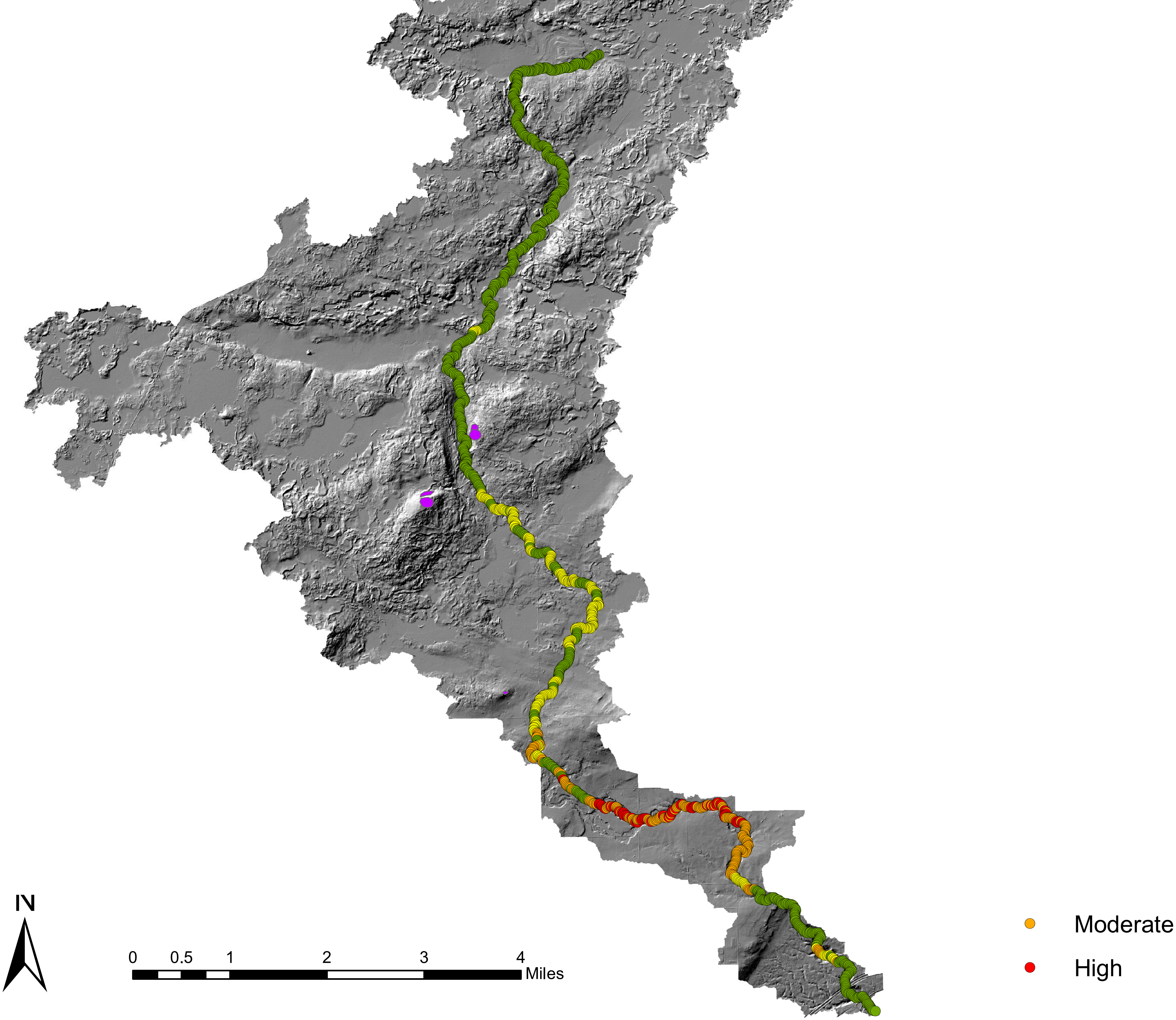


Sucker River: Lower Reach

Stream Power Index

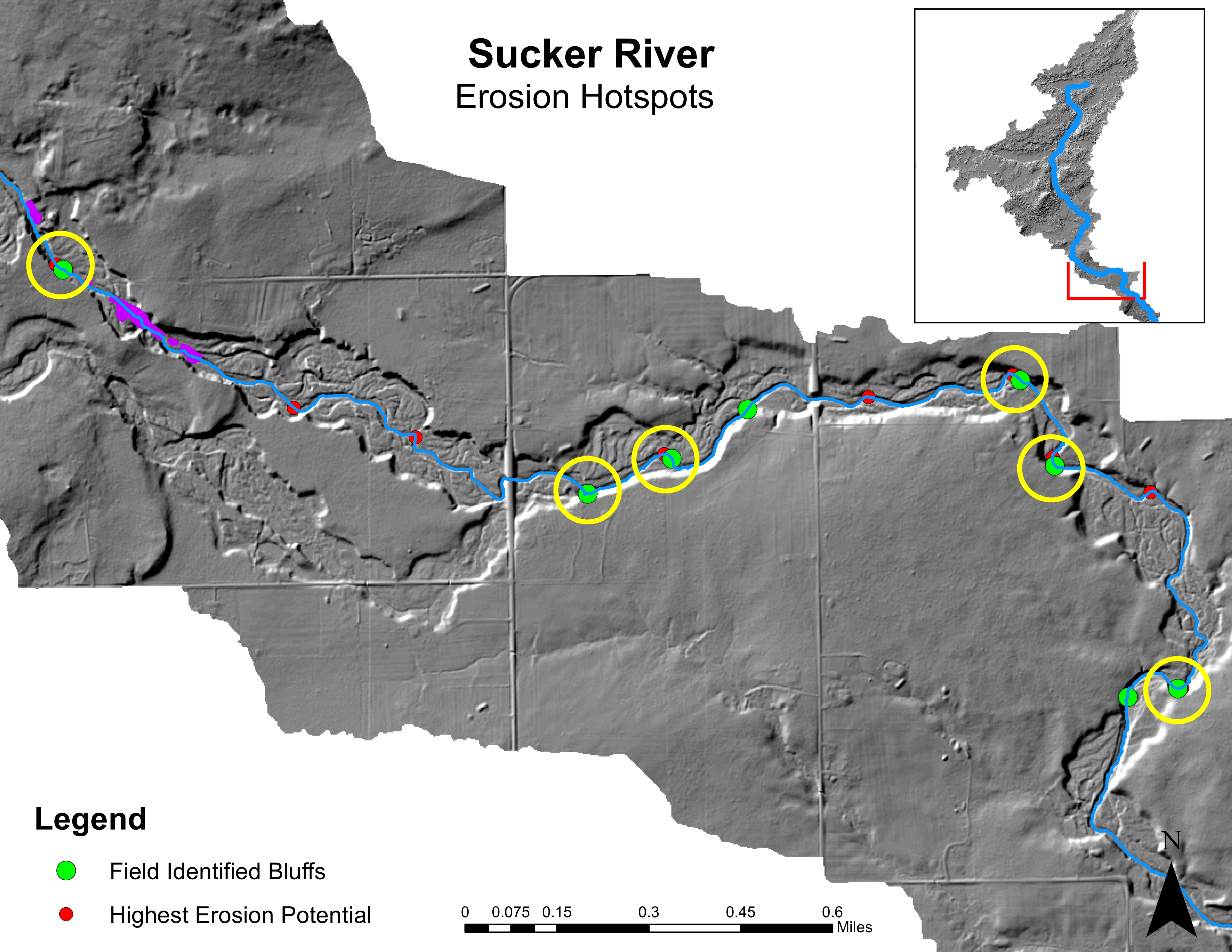

Legend
Sucker River
Stream Power
0.000954 - 9.601240
9.601241 - 30.784394
30.784395 - 79.645003
79.645004 - 155.888956
155.888957 - 352.545765
Bedrock
N
0
0.5
1
2
3
4
Miles

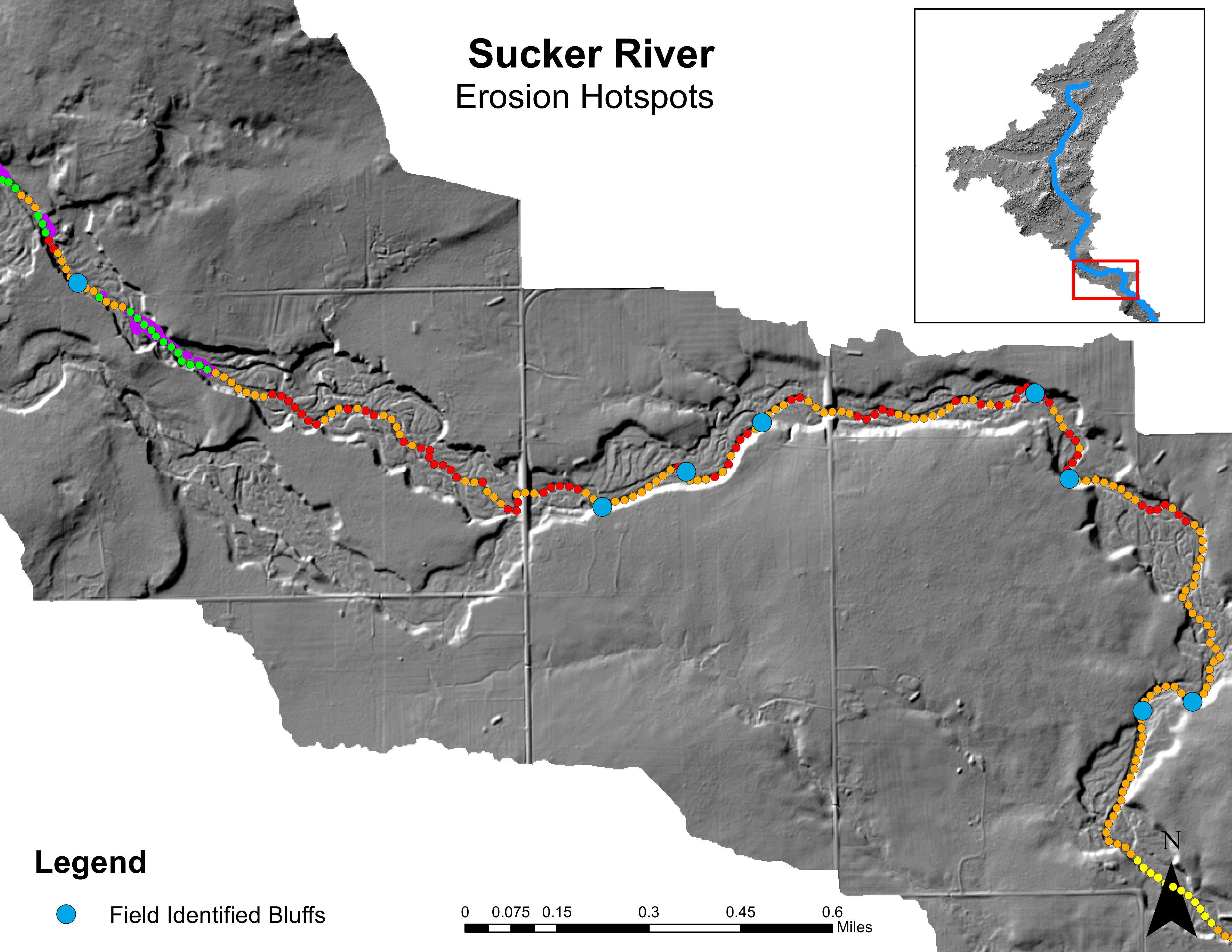

Legend
Bend Curvature
0.25 - 2.27
2.28 - 4.40
4.41 - 7.24
7.25 - 11.70
11.71 - 18.07
N
0
0.5
1
2
3
4
Miles

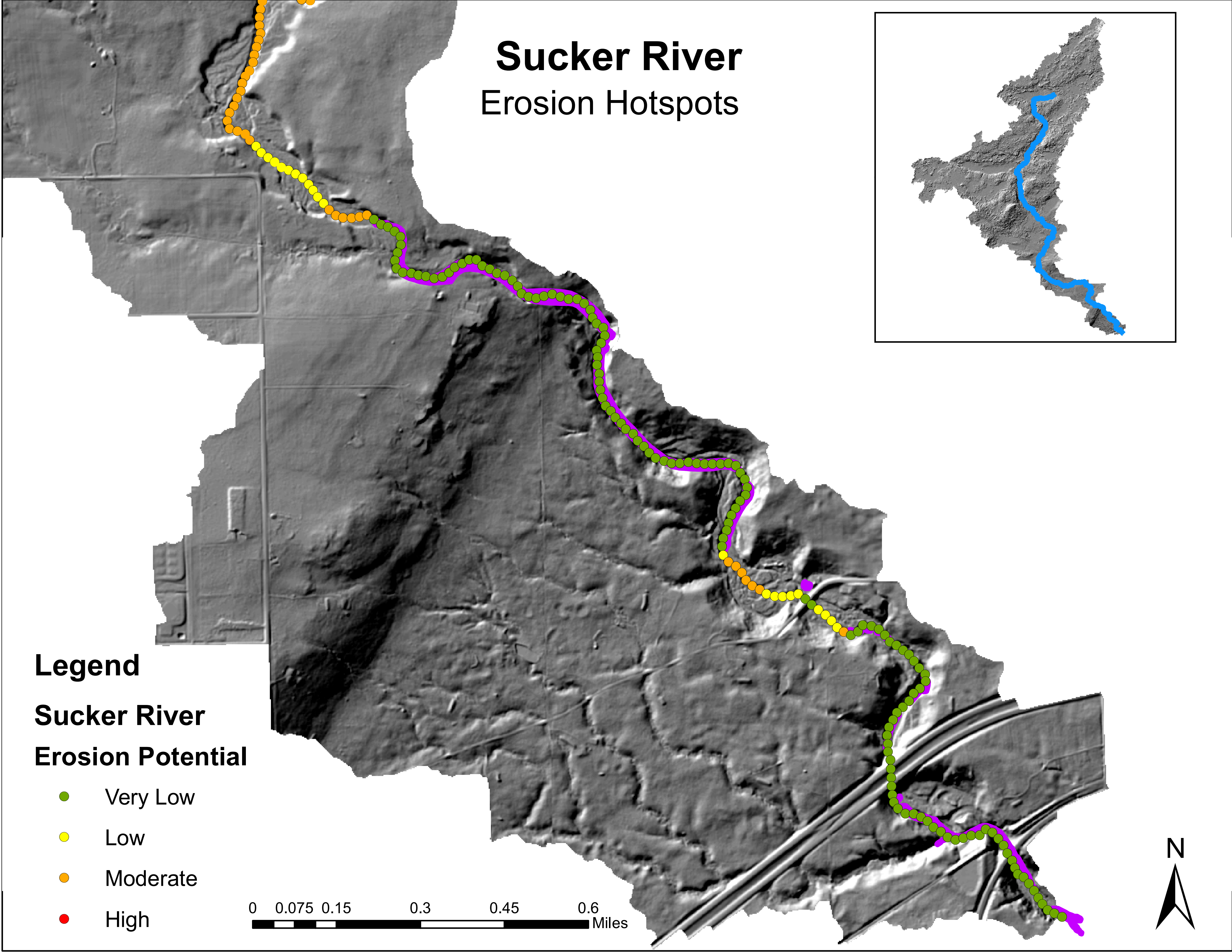

N
0
0.5
1
2
3
4
Miles
Moderate
High

Sucker River

Erosion Hotspots




Sucker River
Erosion Hotspots
Legend
● Field Identified Bluffs
0
0.075
0.15
0.3
0.45
0.6
Miles
N

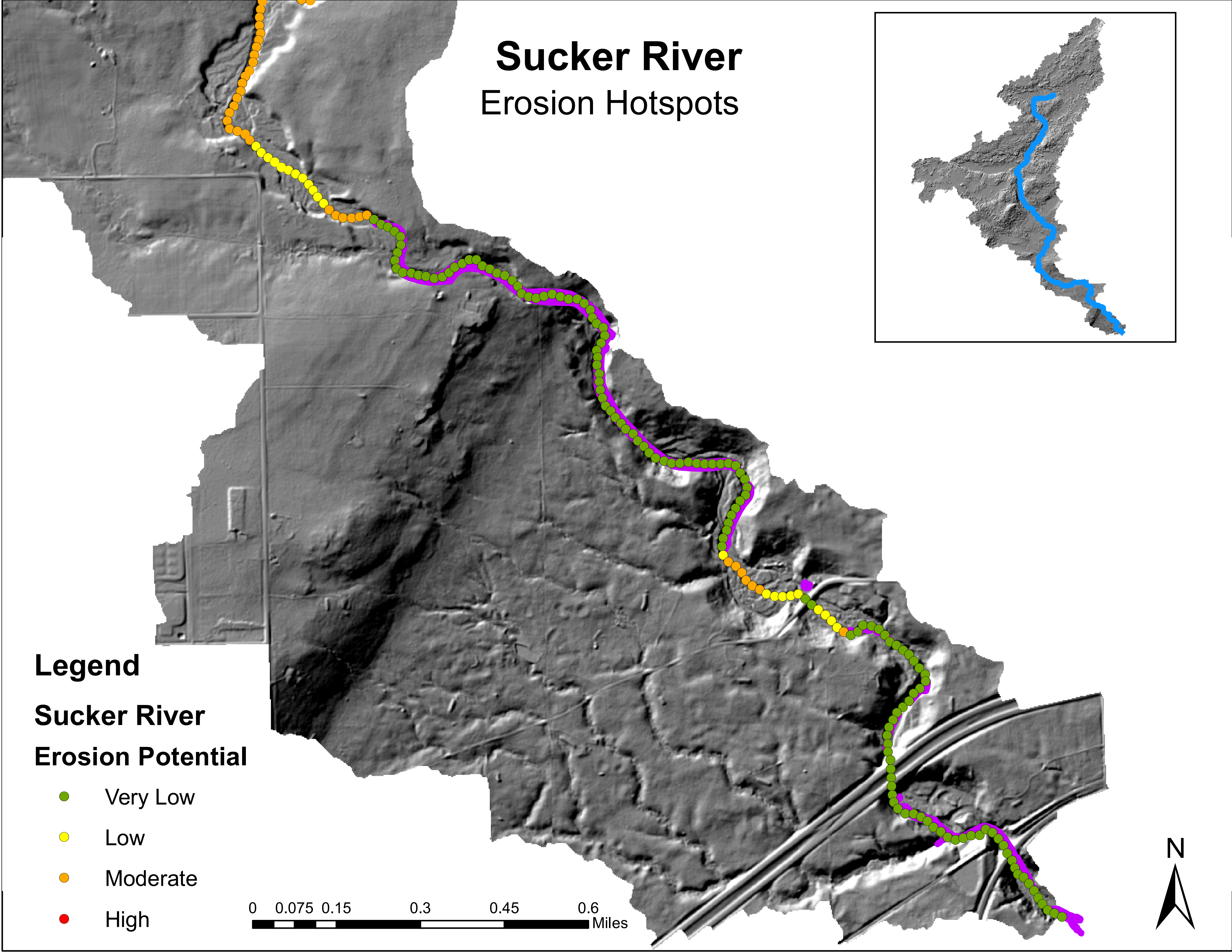


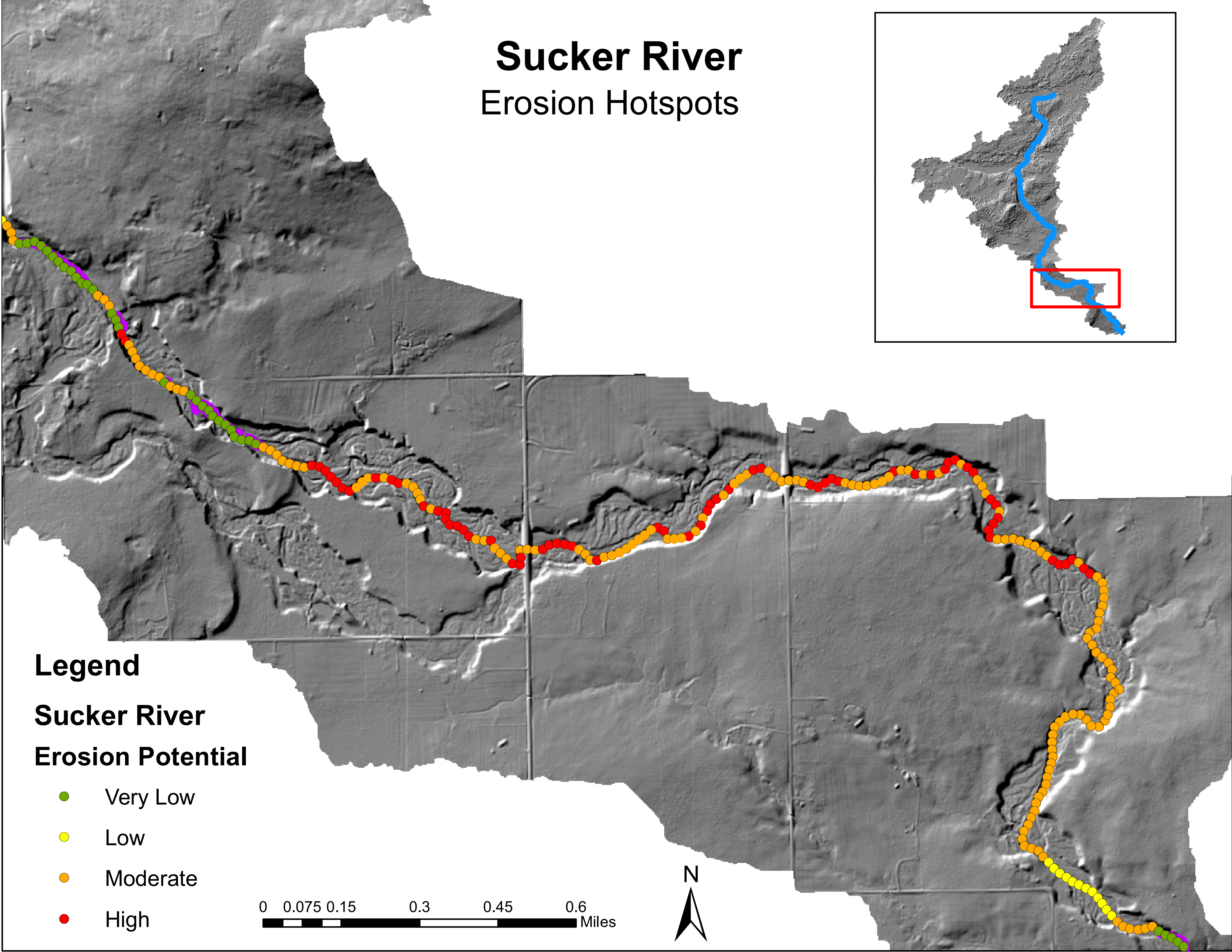
Sucker River

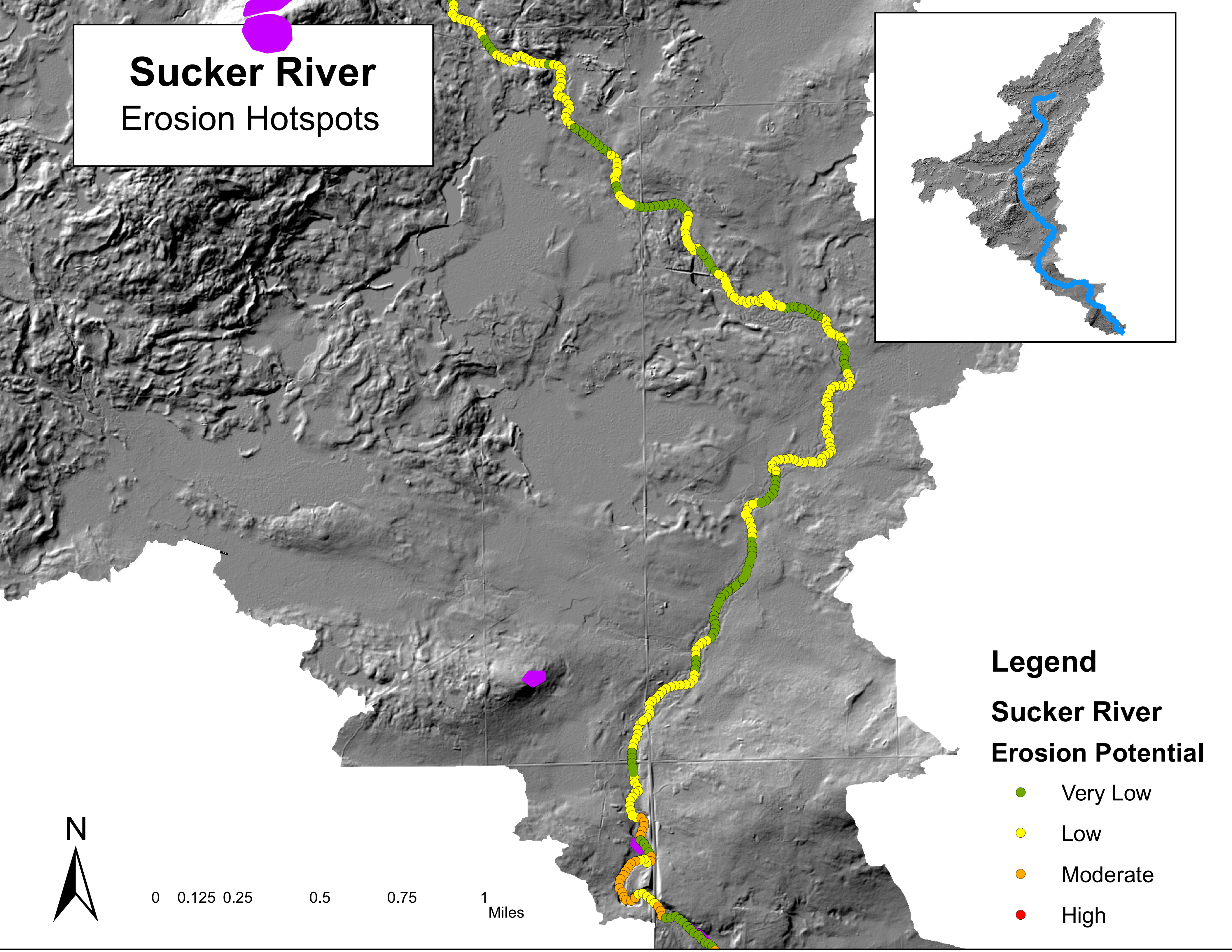
Erosion Hotspots

Sucker River

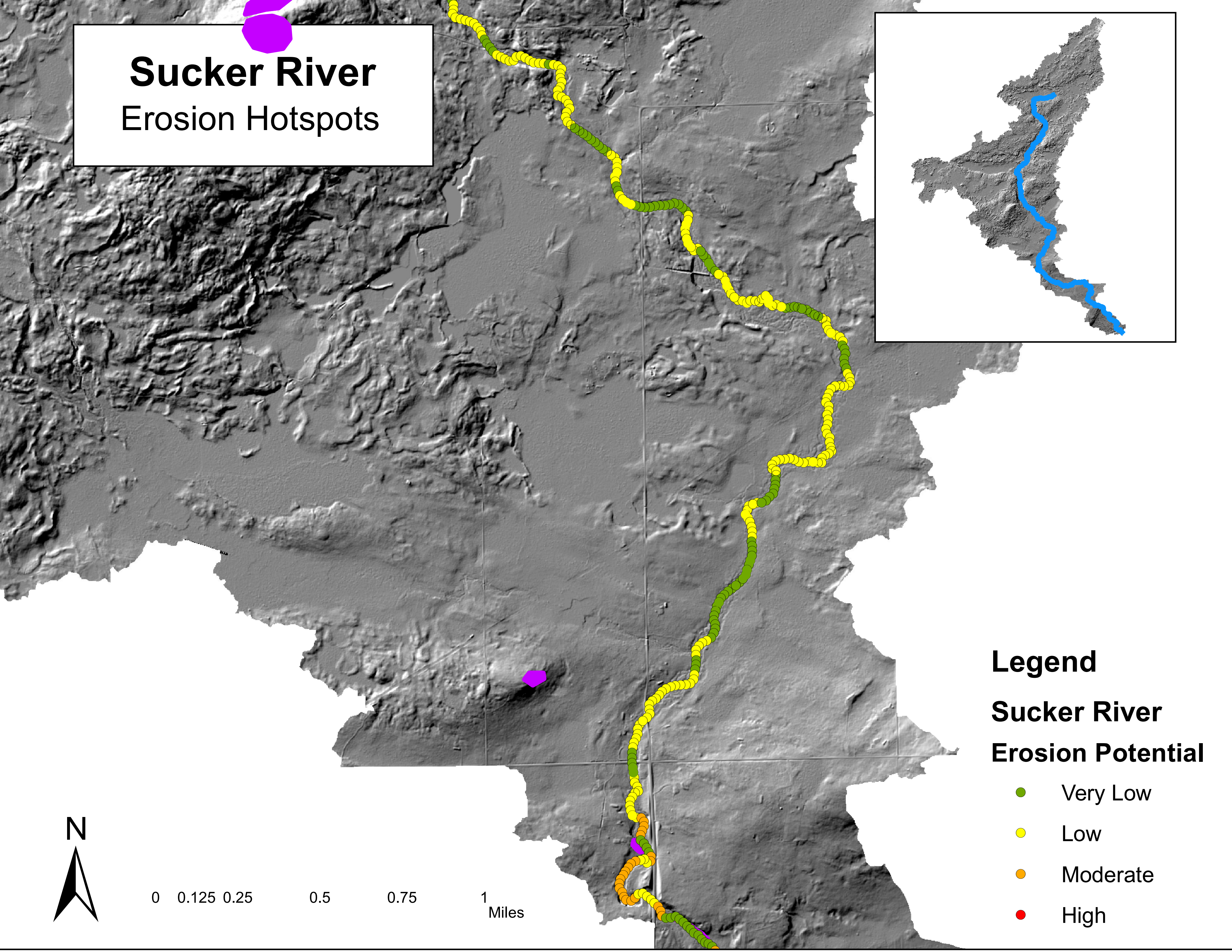
Erosion Hotspots

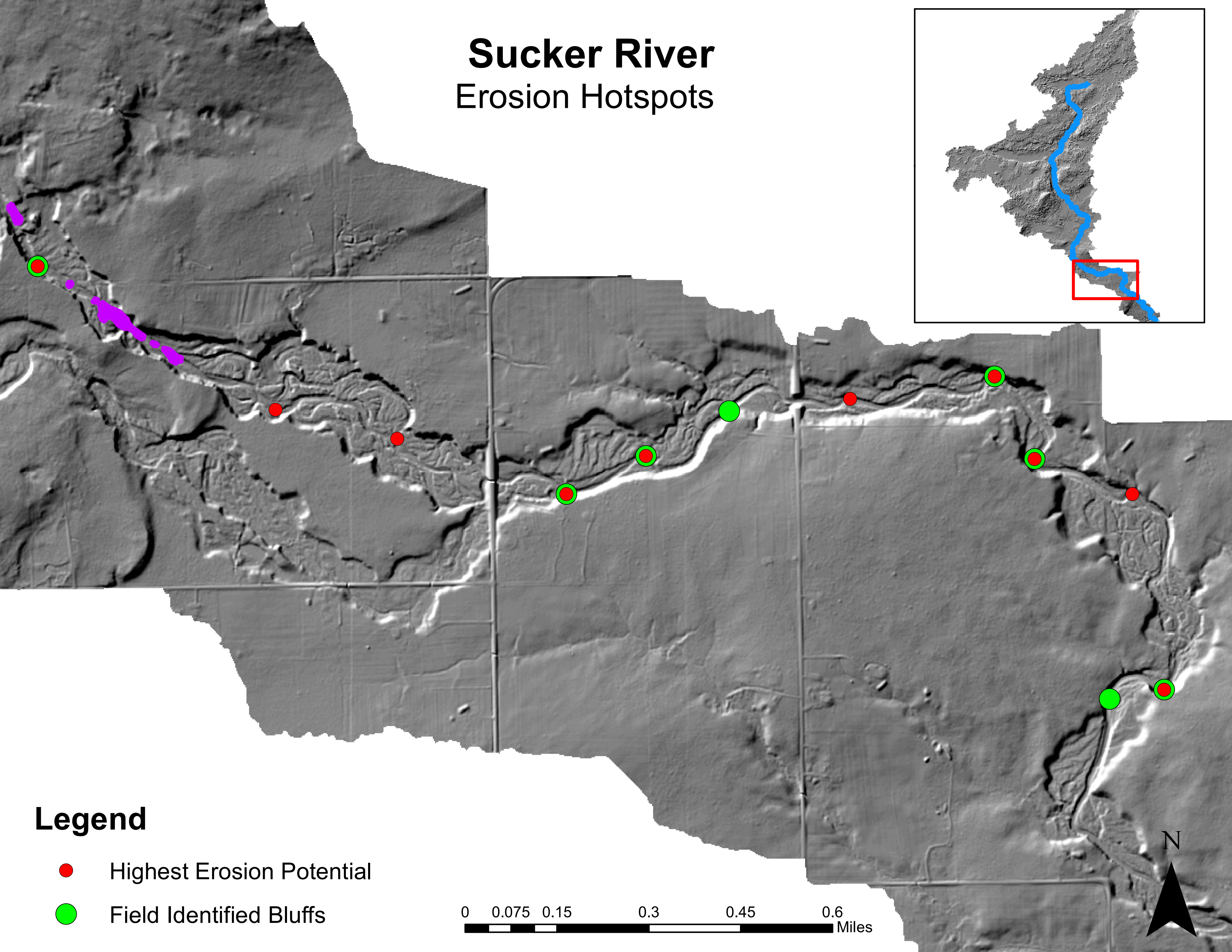



Sucker River
Erosion Hotspots
Legend
Sucker River
Erosion Potential
● Very Low
● Low
● Moderate
● High
0
0.075
0.15
0.3
0.45
0.6
Miles
N



Sucker River
Erosion Hotspots


Sucker River
Erosion Hotspots
Legend
Sucker River
Erosion Potential
● Very Low
● Low
● Moderate
● High
N
0
0.125
0.25
0.5
0.75
1
Miles

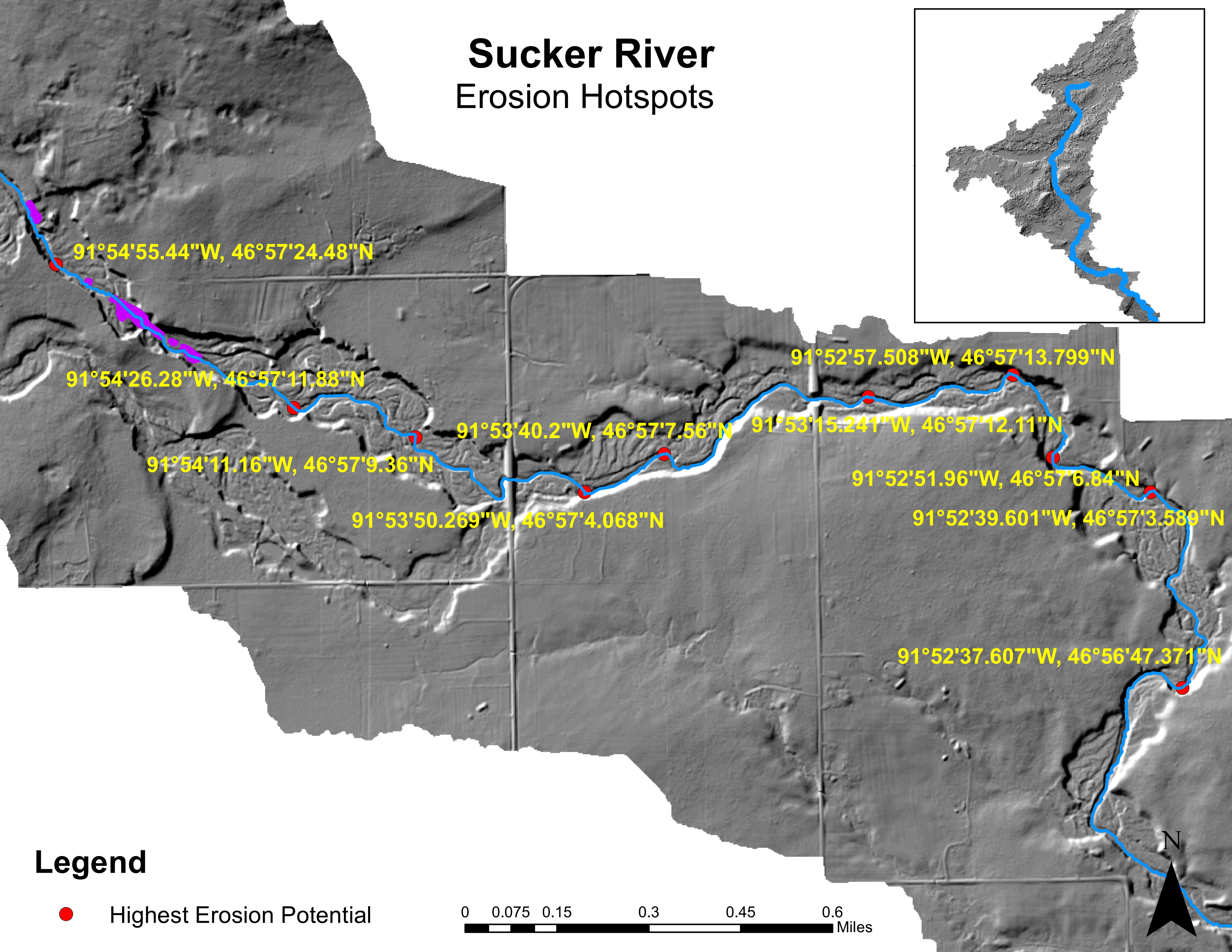


Sucker River

Erosion Hotspots

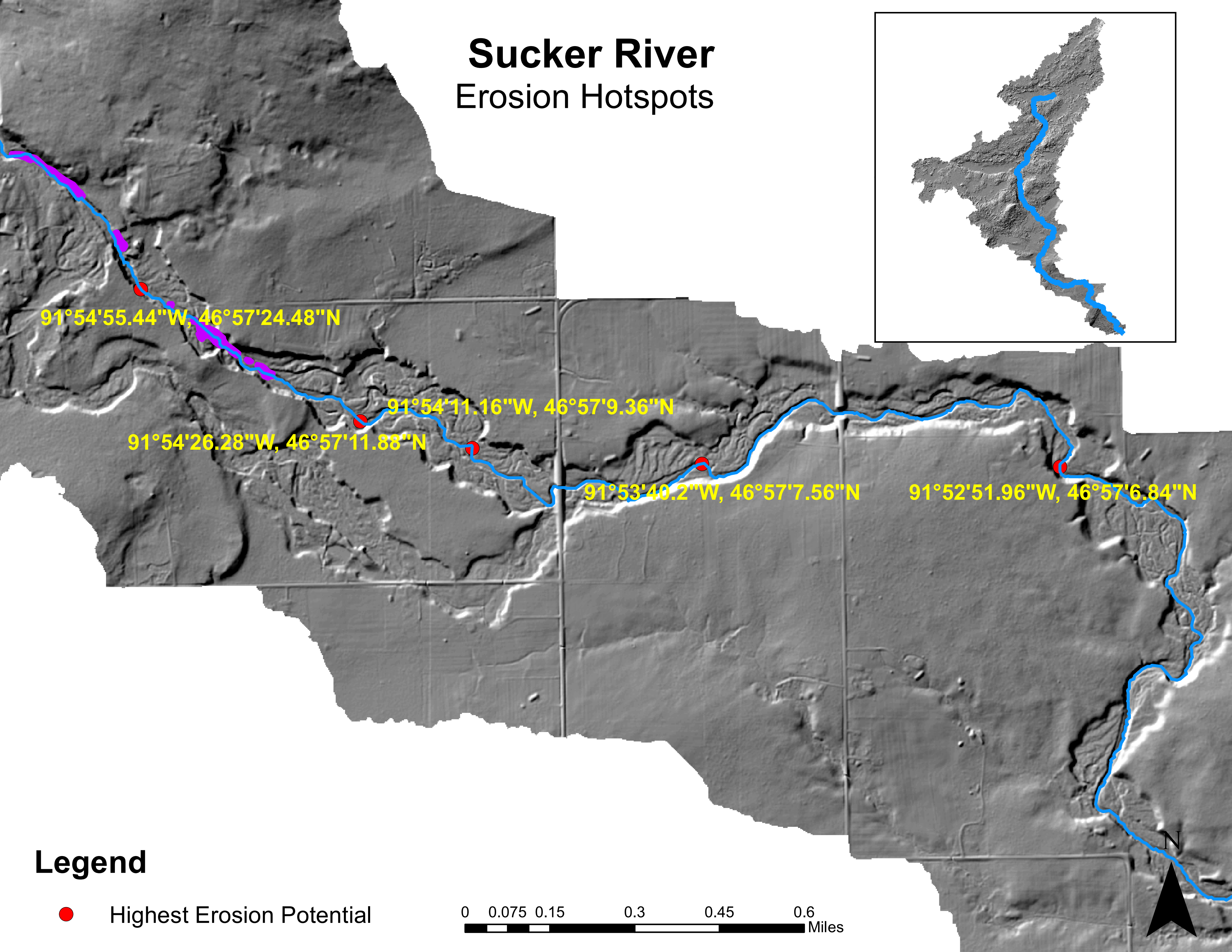
Sucker River

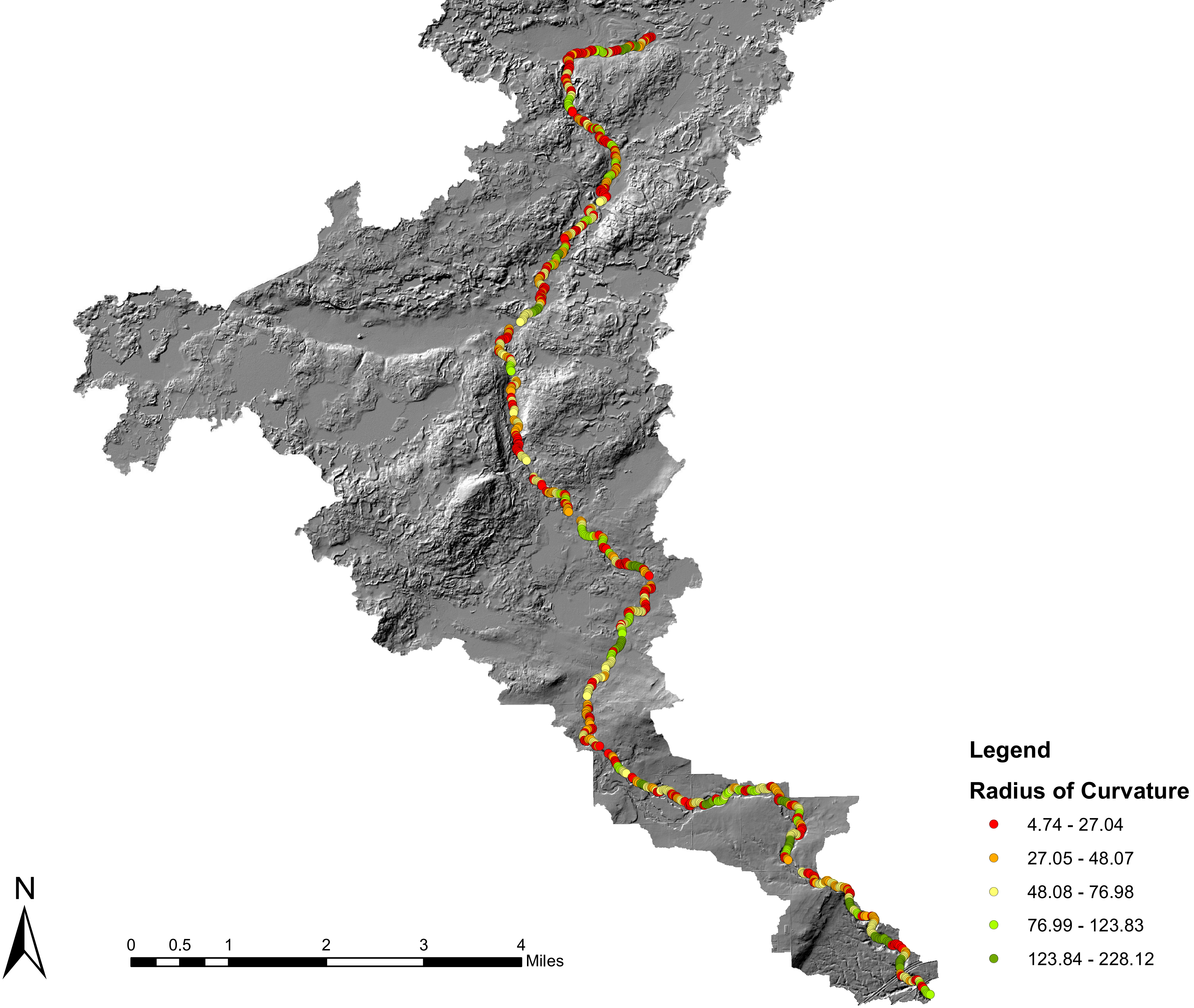
Erosion Hotspots

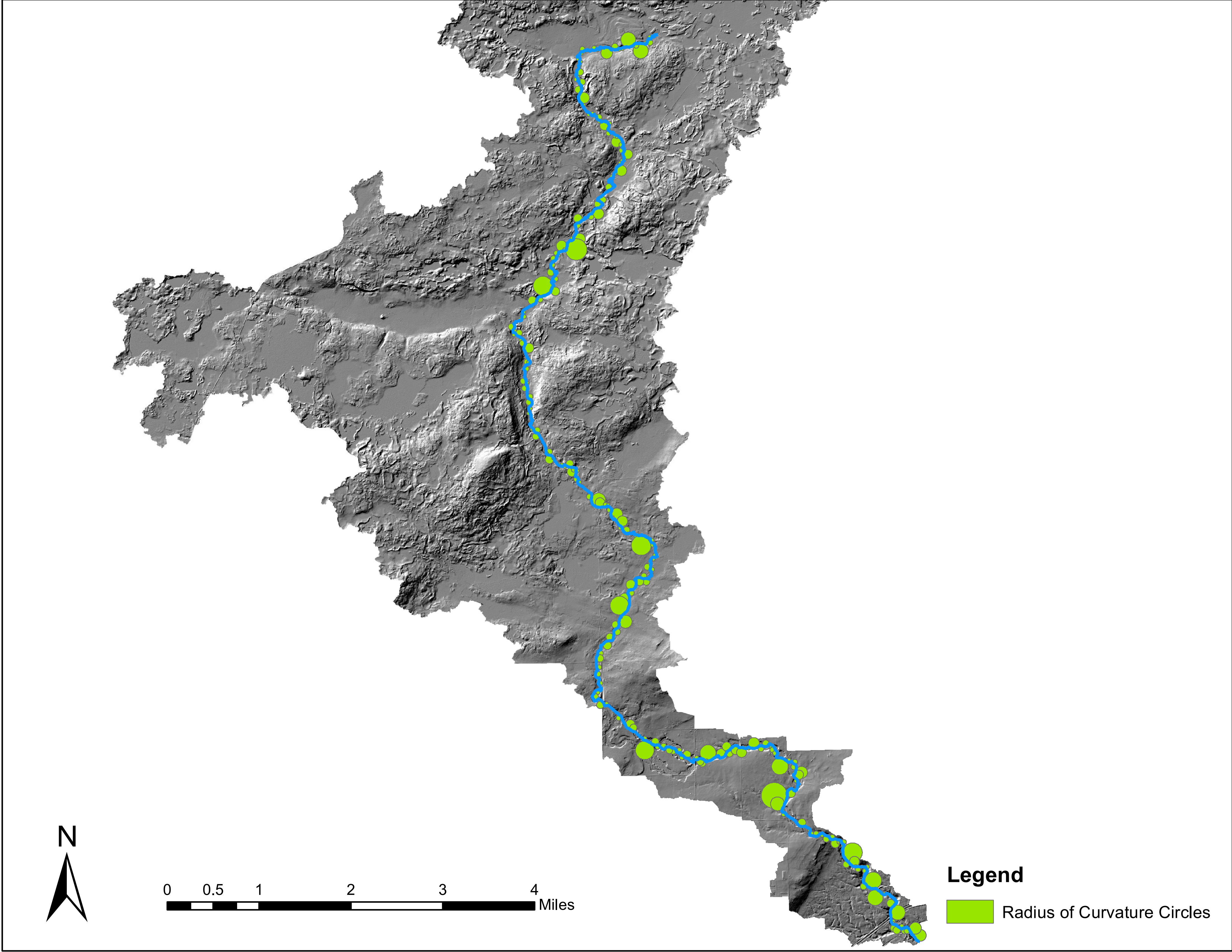


Sucker River

Erosion Hotspots



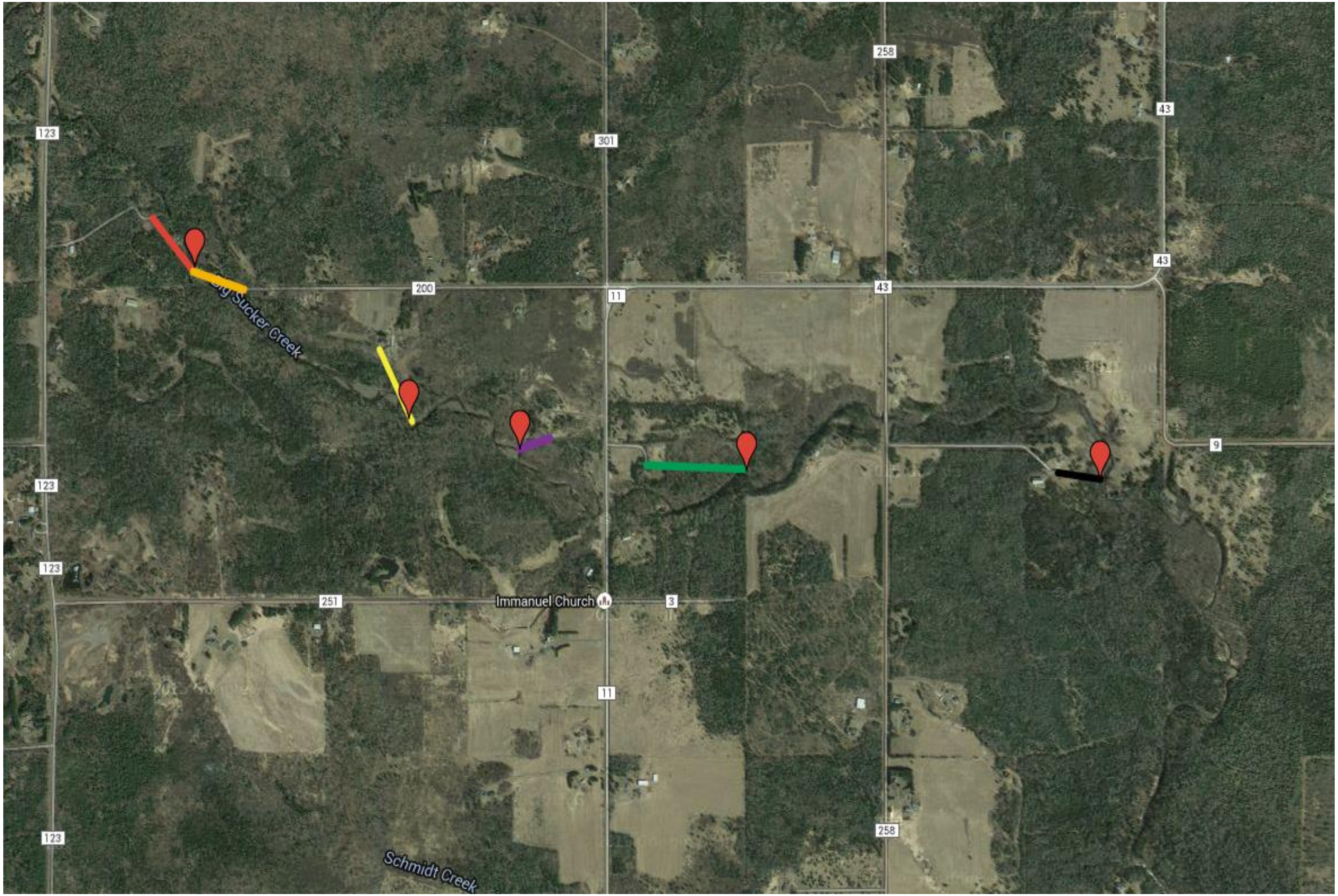

Legend
Radius of Curvature
● 4.74 - 27.04
● 27.05 - 48.07
● 48.08 - 76.98
● 76.99 - 123.83
● 123.84 - 228.12
N
0
0.5
1
2
3
4
Miles

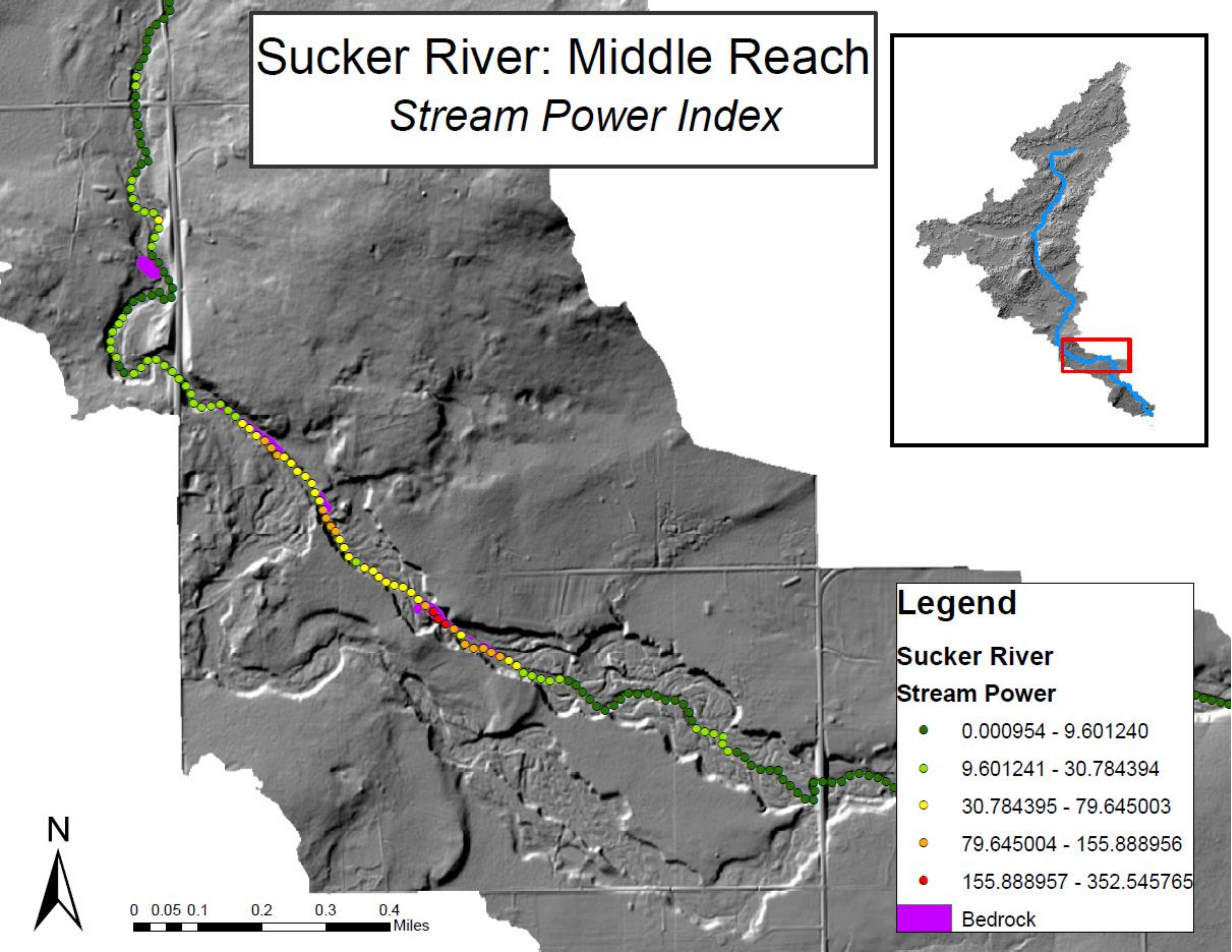

N
0
0.5
1
2
3
4
Miles
Legend
🟩 Radius of Curvature Circles

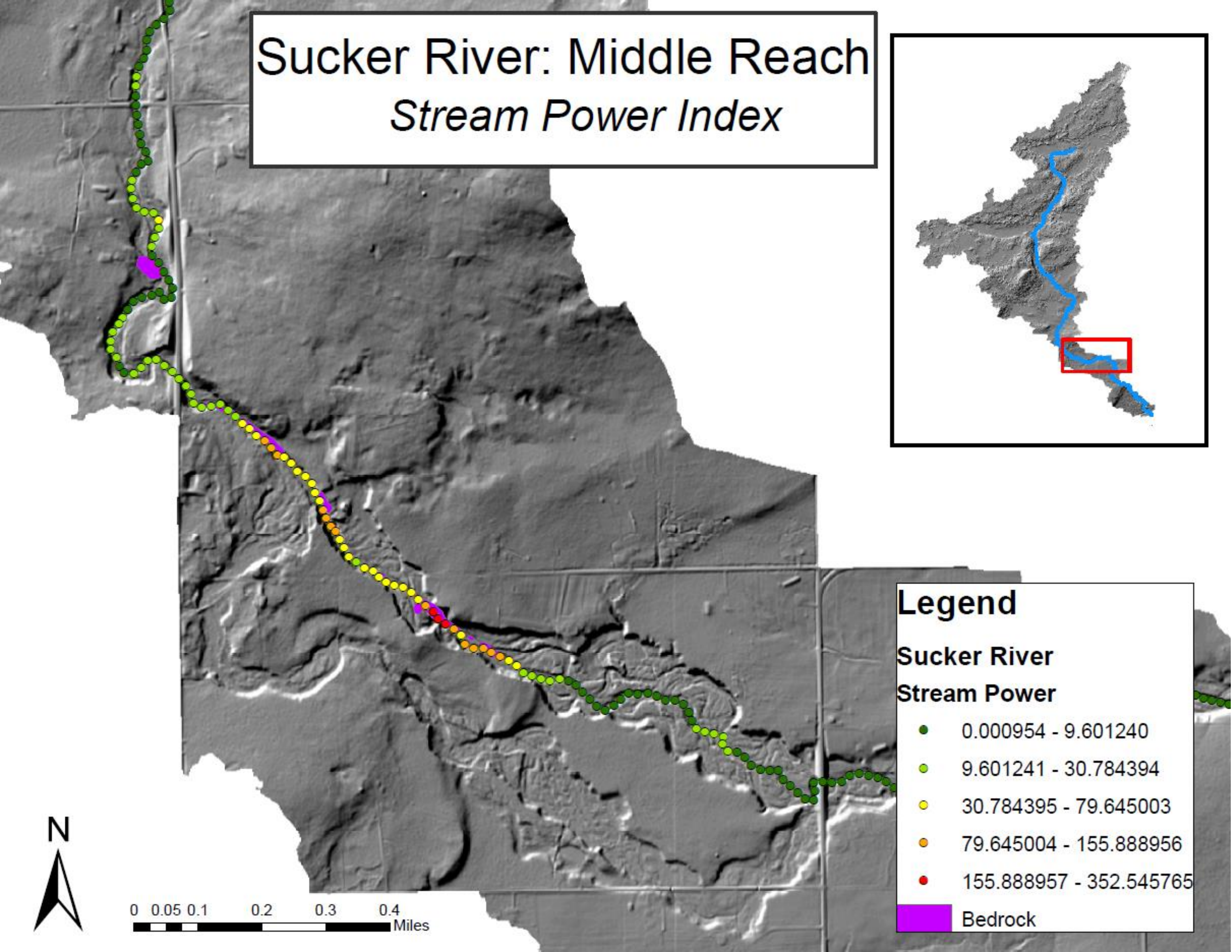
Sucker River

Erosion Hotspots

- 46.9568, -91.91539
- 46.9533, -91.90729
- 46.9526, -91.9031
- 46.95209, -91.8945
- 46.95189, -91.8811
- 580 ft
- 500 ft
- 680 ft
- 300 ft
- 900 ft
- 400 ft




Sucker River: Middle Reach
Stream Power Index
Legend
Sucker River
Stream Power
● 0.000954 - 9.601240
● 9.601241 - 30.784394
● 30.784395 - 79.645003
● 79.645004 - 155.888956
● 155.888957 - 352.545765
▬ Bedrock
N
0 0.05 0.1 0.2 0.3 0.4
Miles

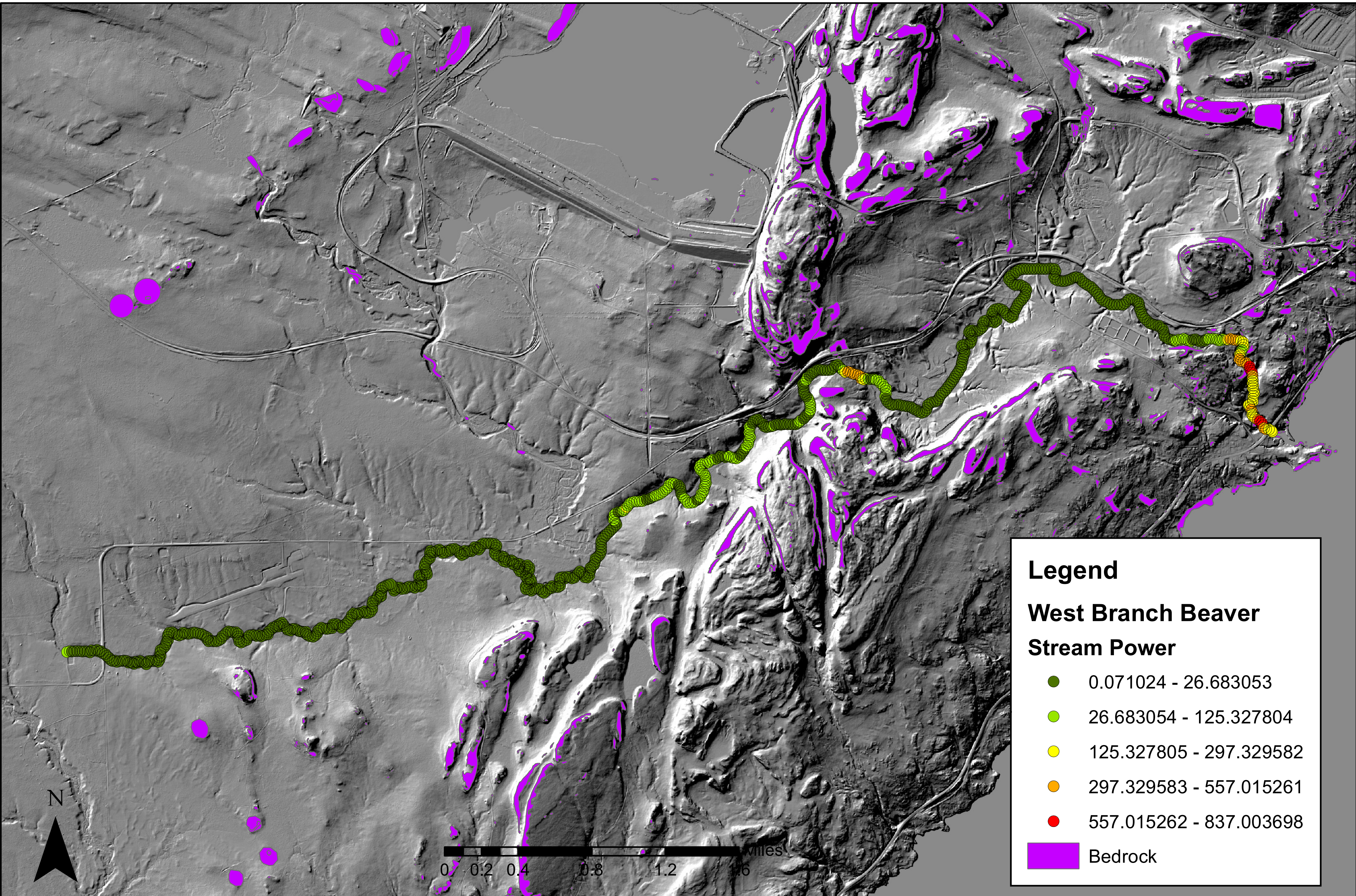


Sucker River: Middle Reach

Stream Power Index

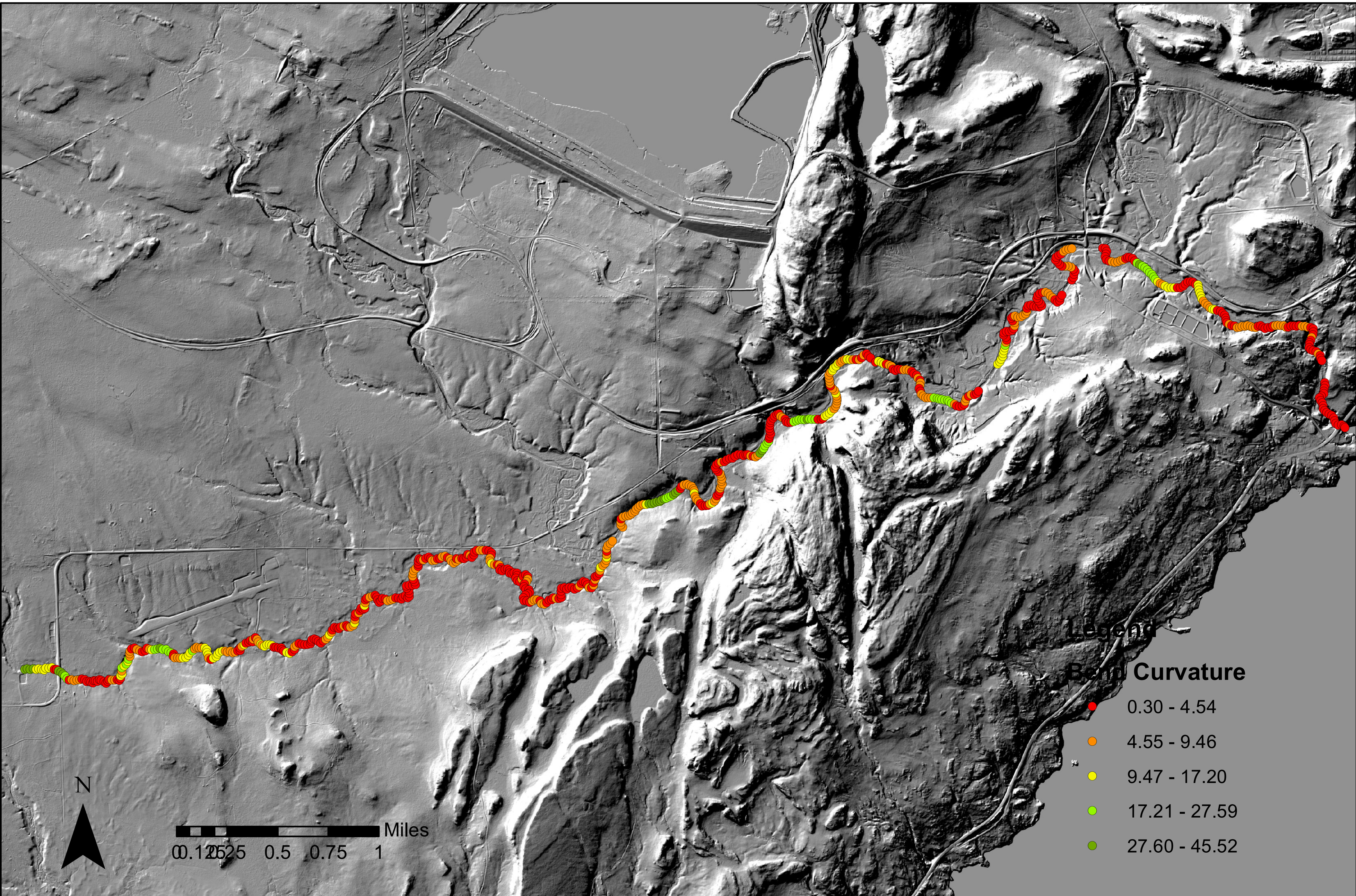
West Branch Beaver River

Stream Power Index



West Branch Beaver River

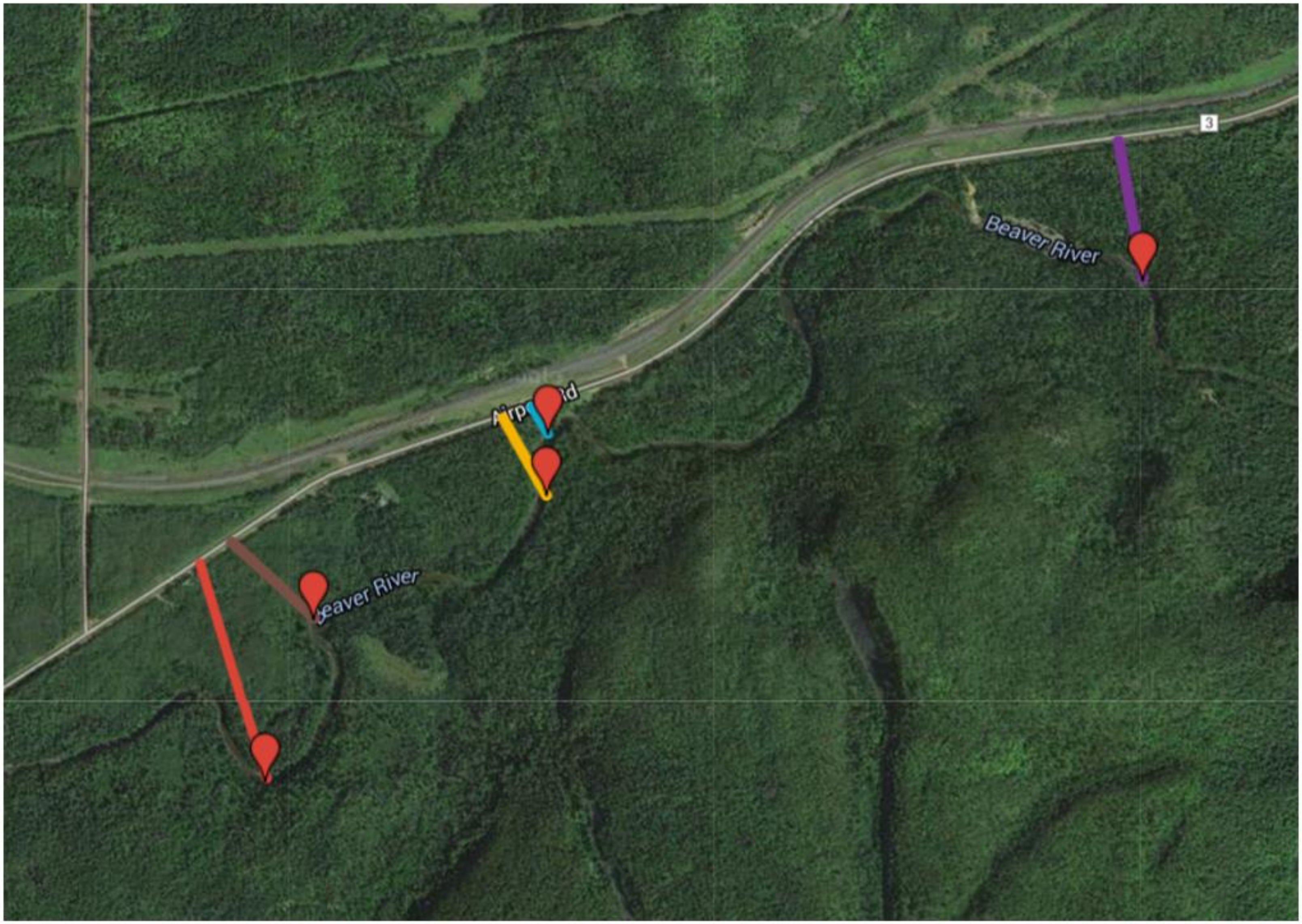
Bend Curvature



West Beaver

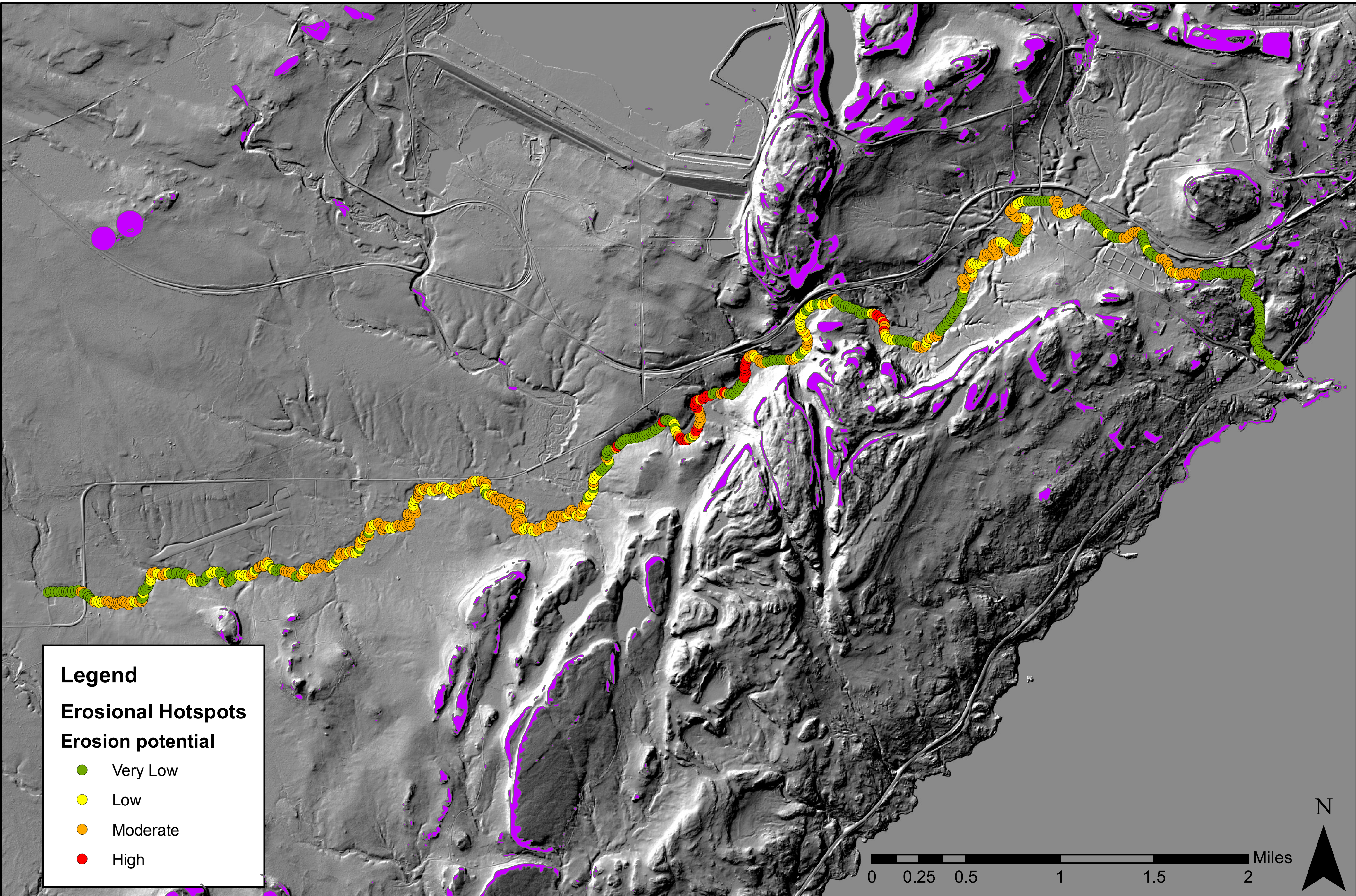
Erosion Hotspots

- 47.2645, -91.34028
- 47.26169, -91.35563
- 47.26058, -91.35568
- 47.25833, -91.36168
- 47.25541, -91.36292
- 920 ft
- 220 ft
- 580 ft
- 720 ft
- 1450 ft



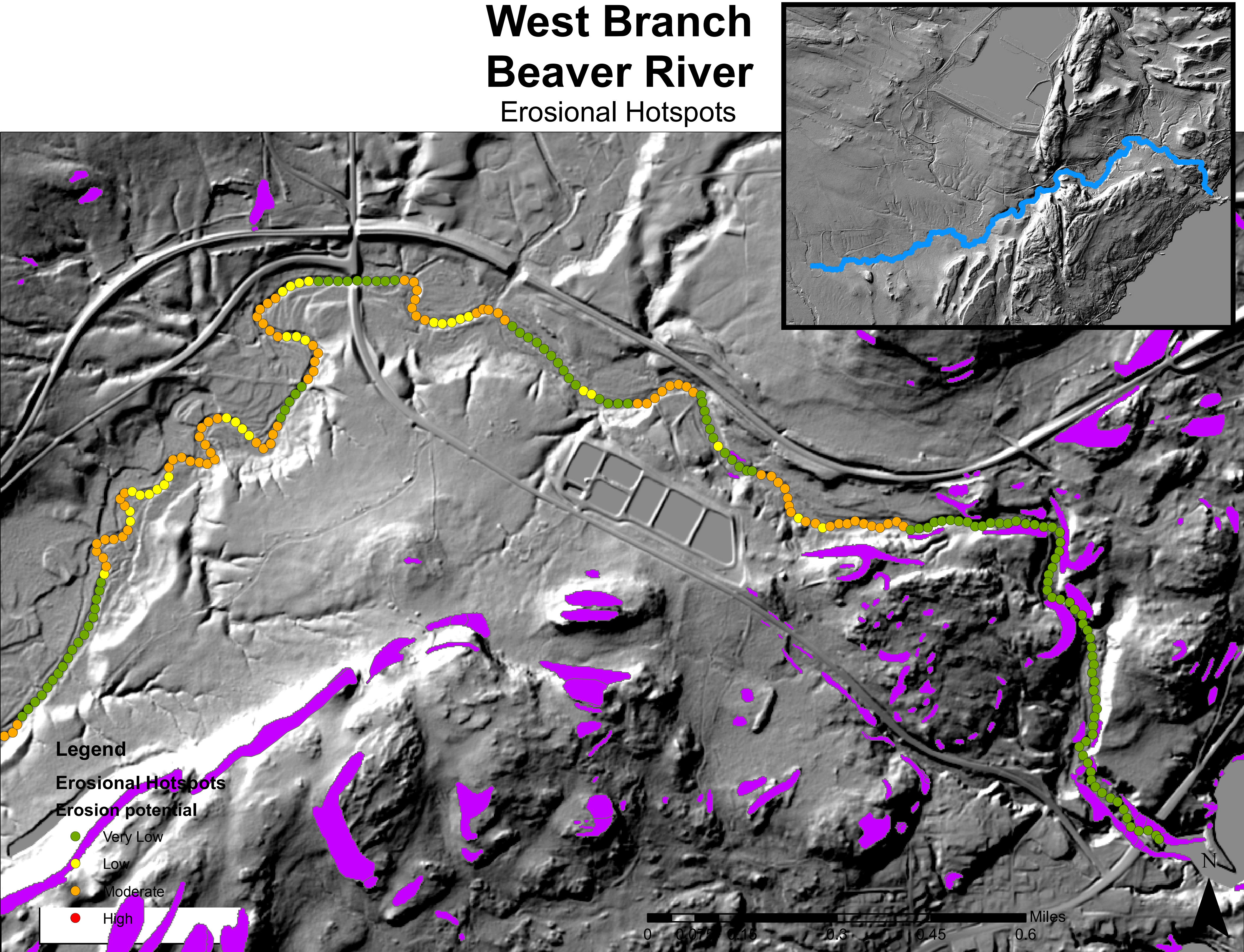
West Branch Beaver River

Erosional Hotspots



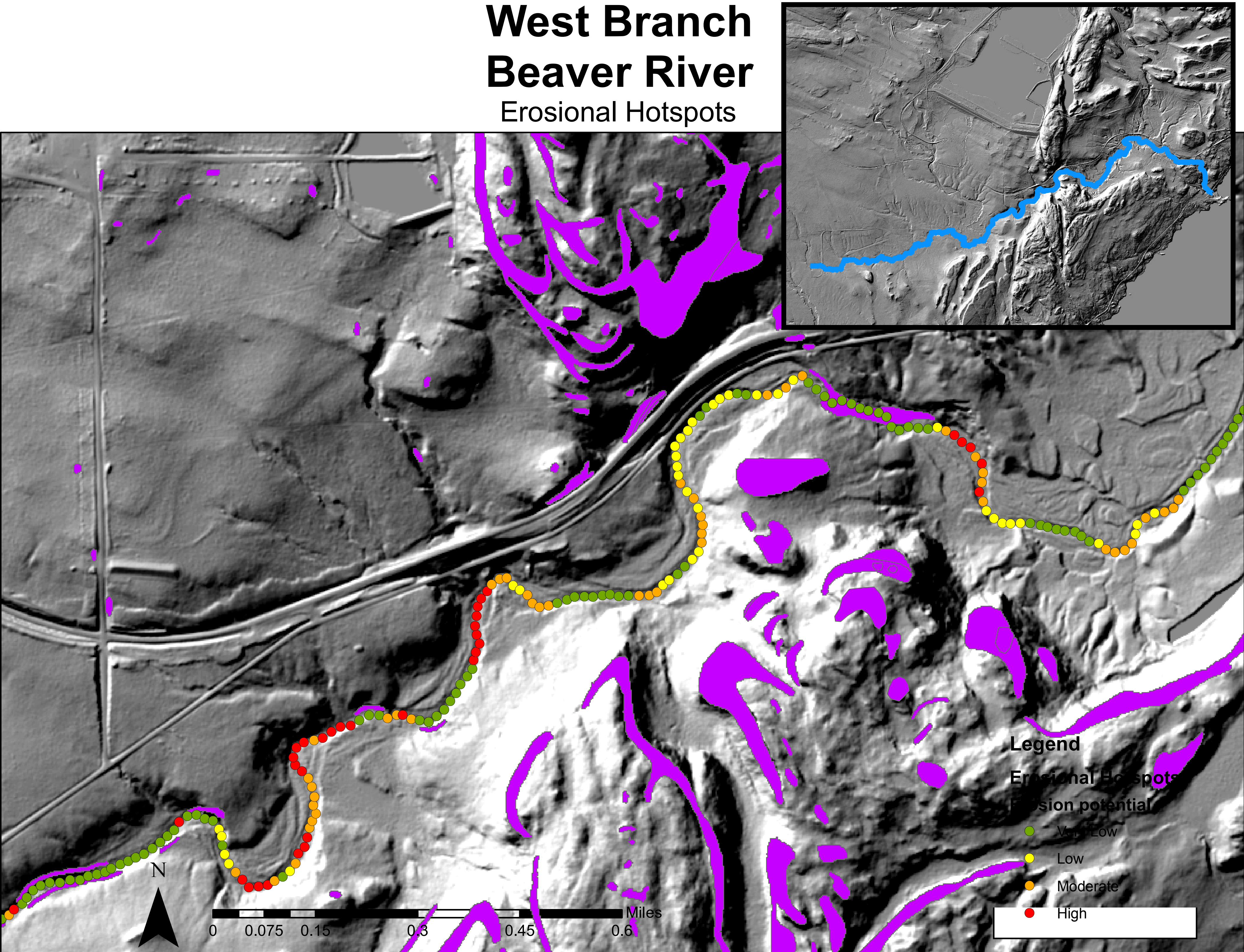
West Branch Beaver River

Erosional Hotspots



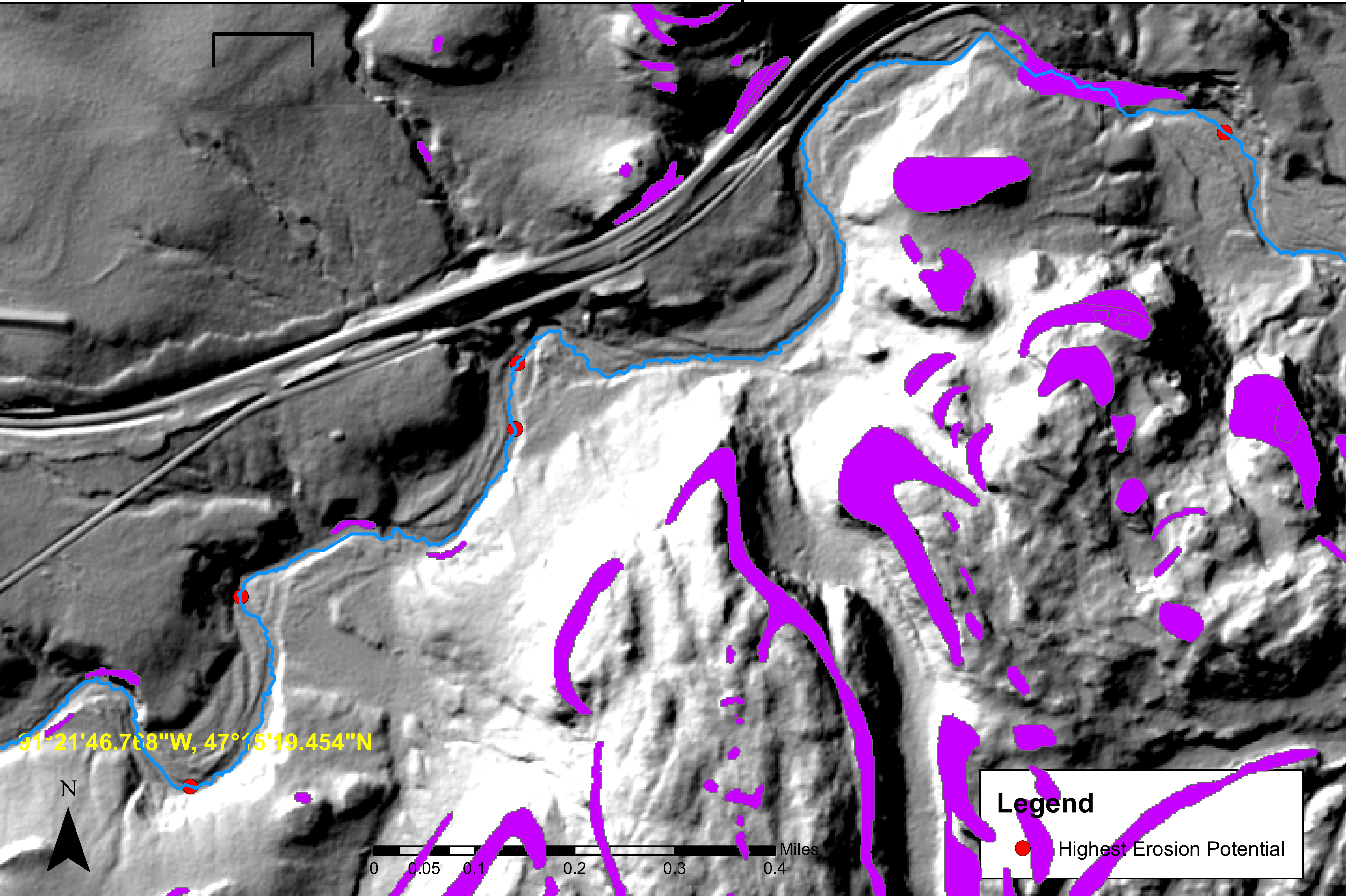
West Branch Beaver River

Erosional Hotspots



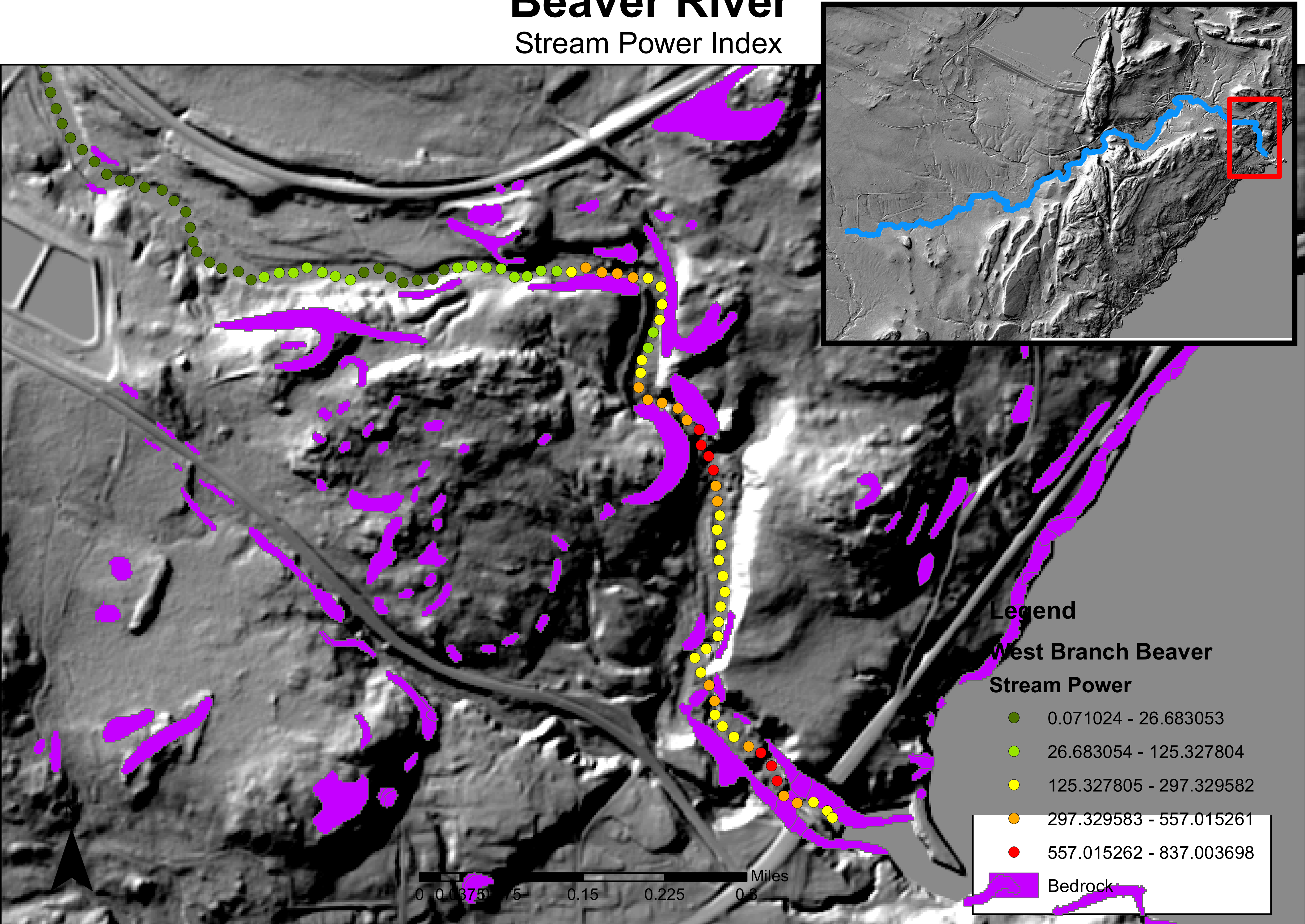
West Branch Beaver River

Erosional Hotspots



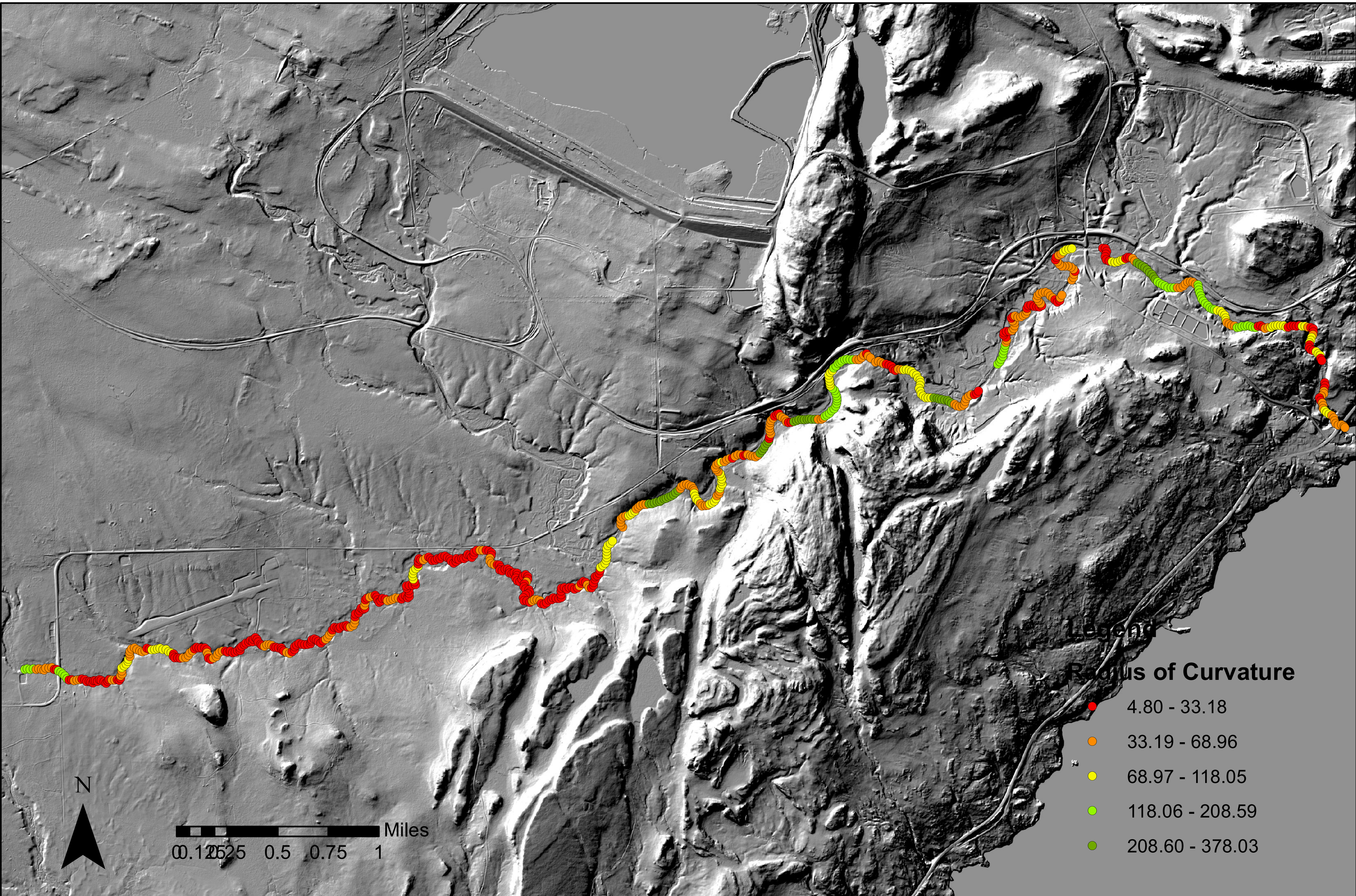
West Branch Beaver River

Stream Power Index



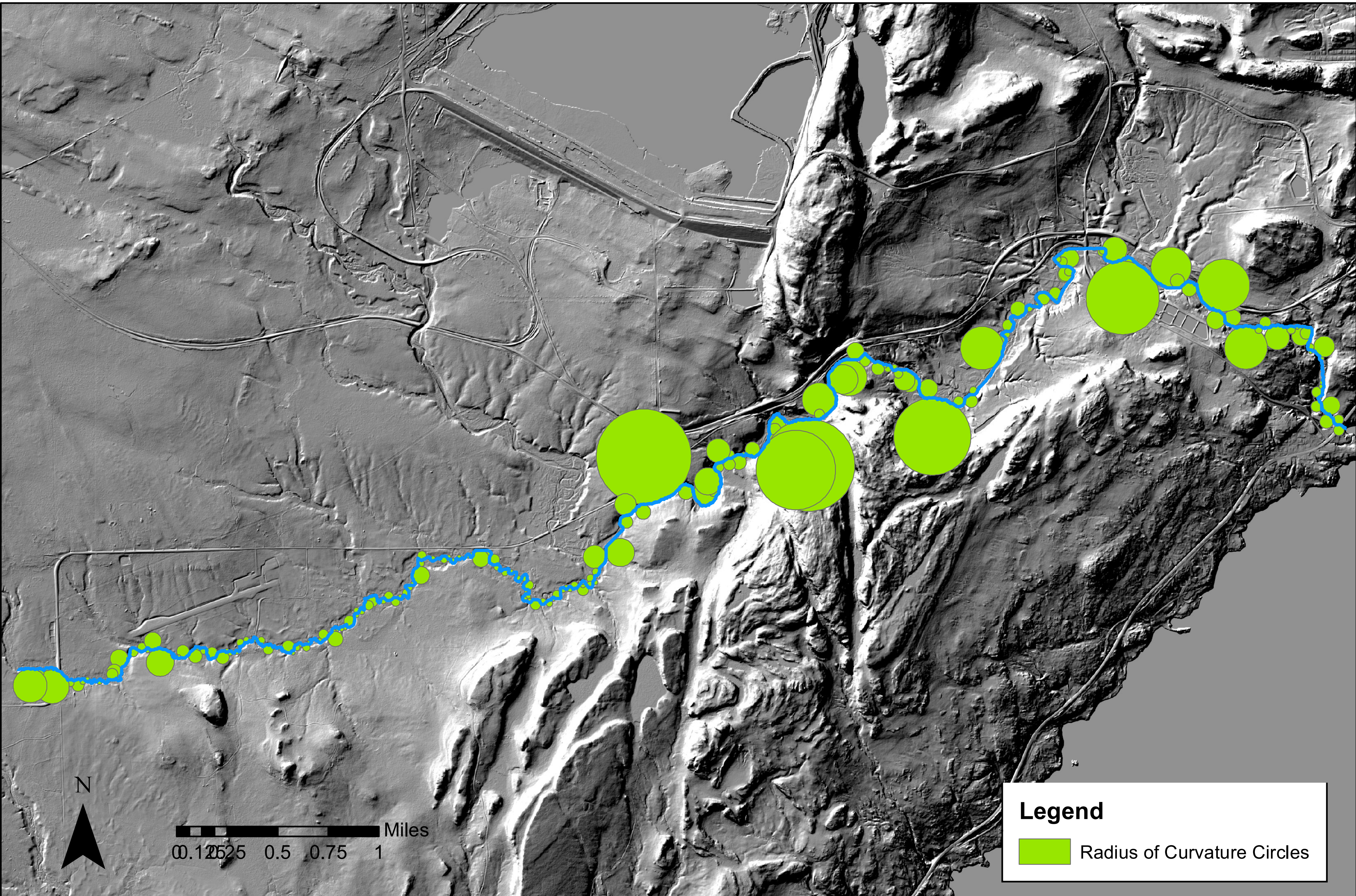
West Branch Beaver River

Radius of Curvature



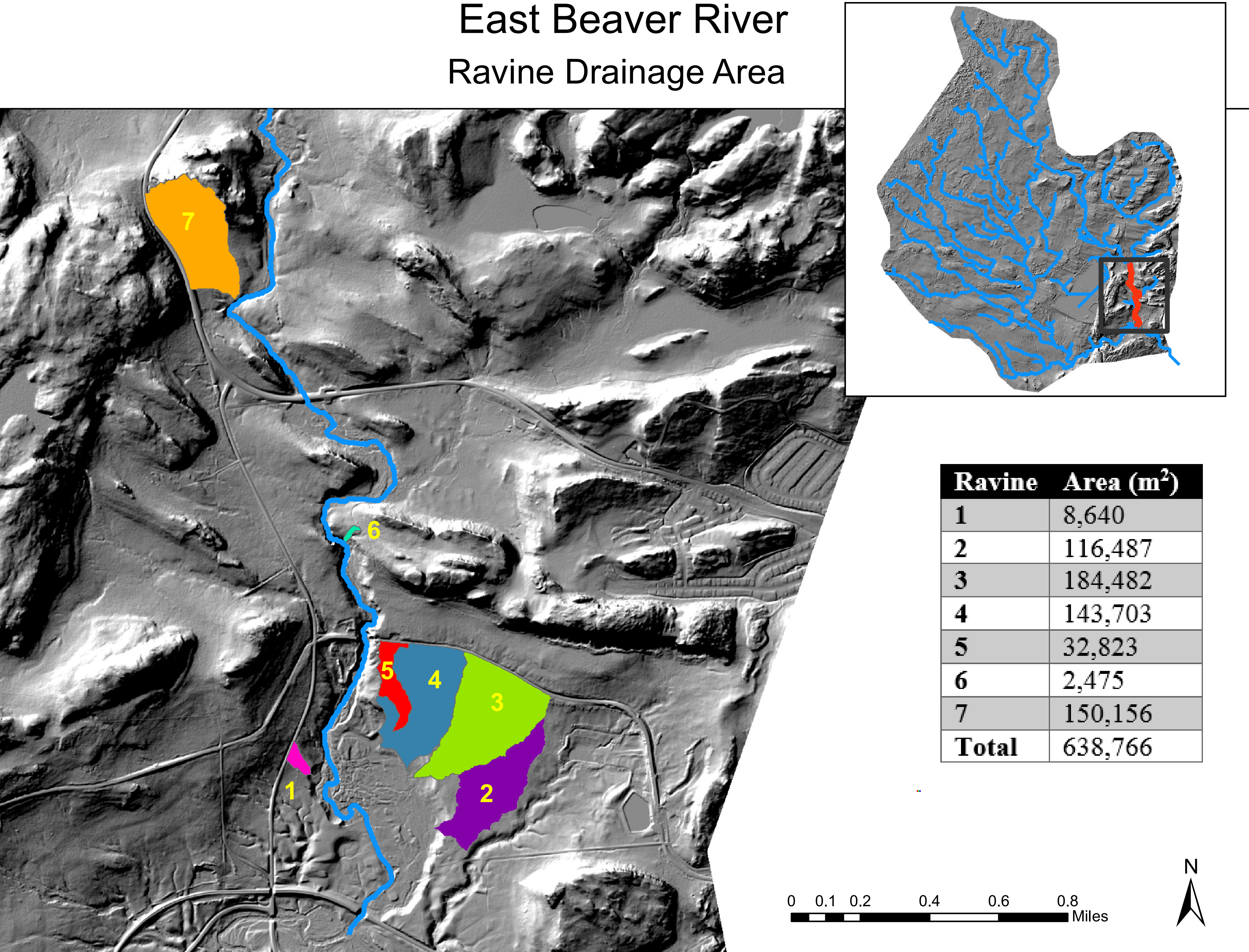
West Branch Beaver River

Radius of Curvature



East Beaver River

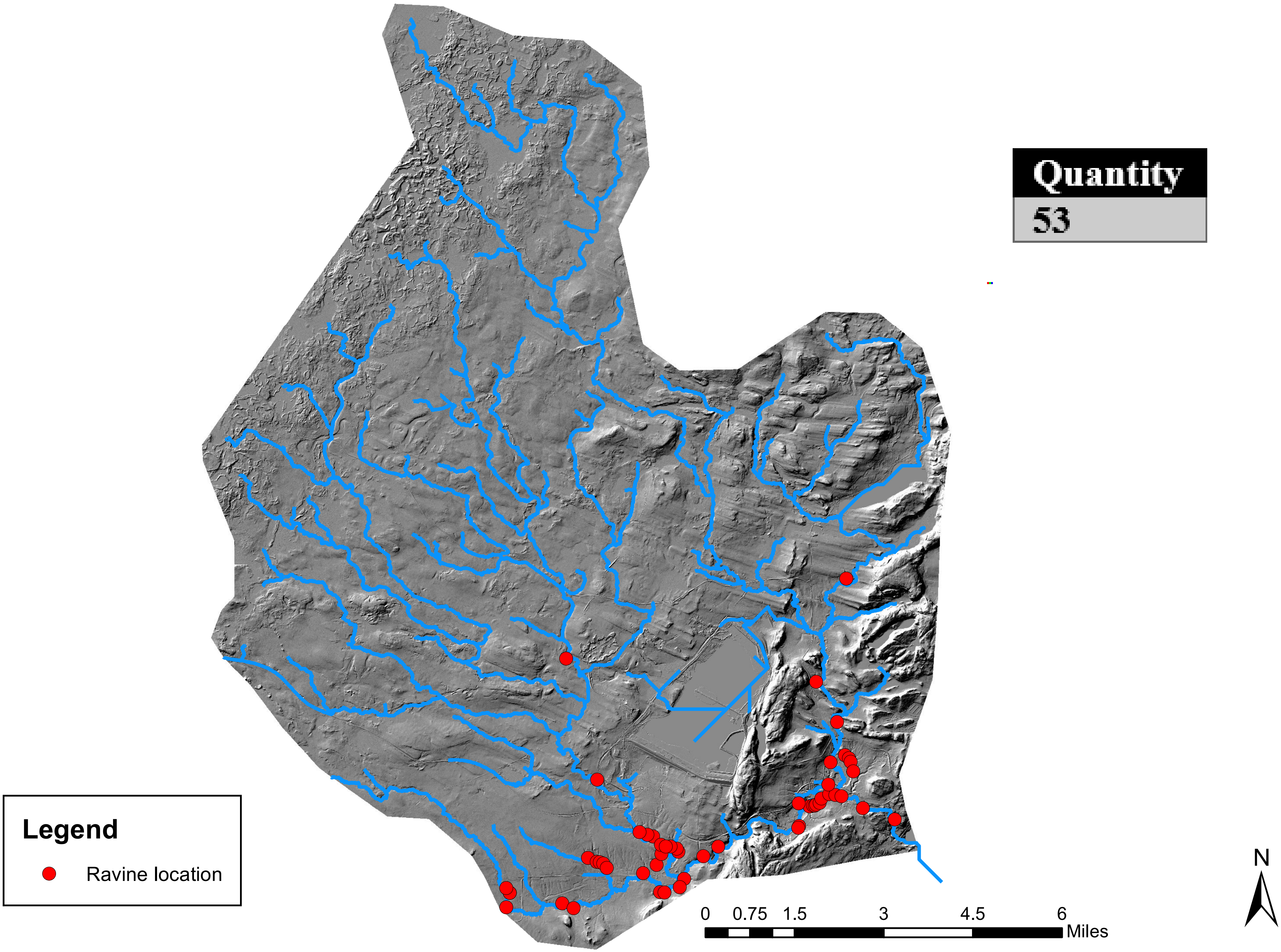
Ravine Drainage Area



Ravine	Area (m^2)
1	8,640
2	116,487
3	184,482
4	143,703
5	32,823
6	2,475
7	150,156
Total	638,766

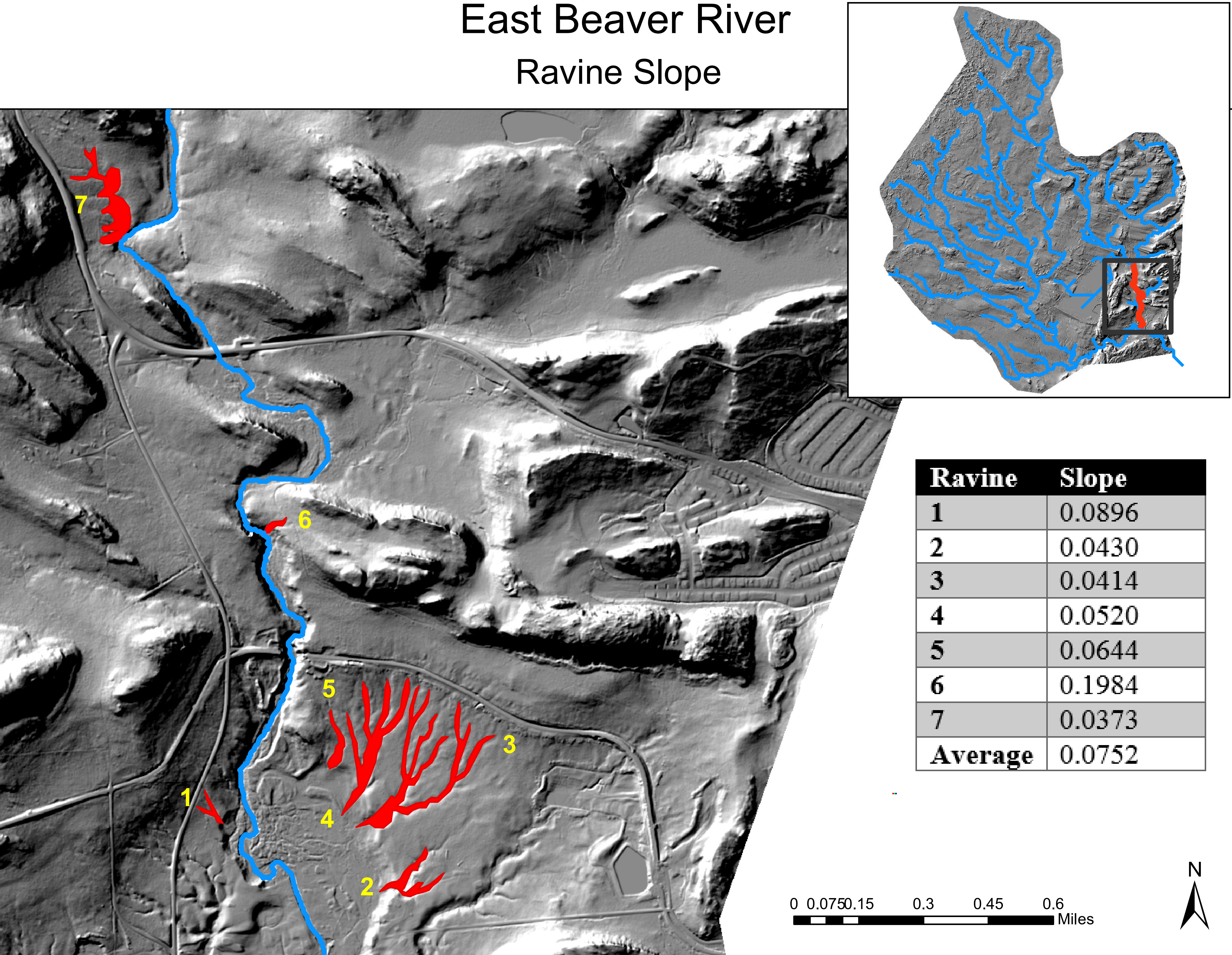
Beaver River

Ravine Locations



East Beaver River

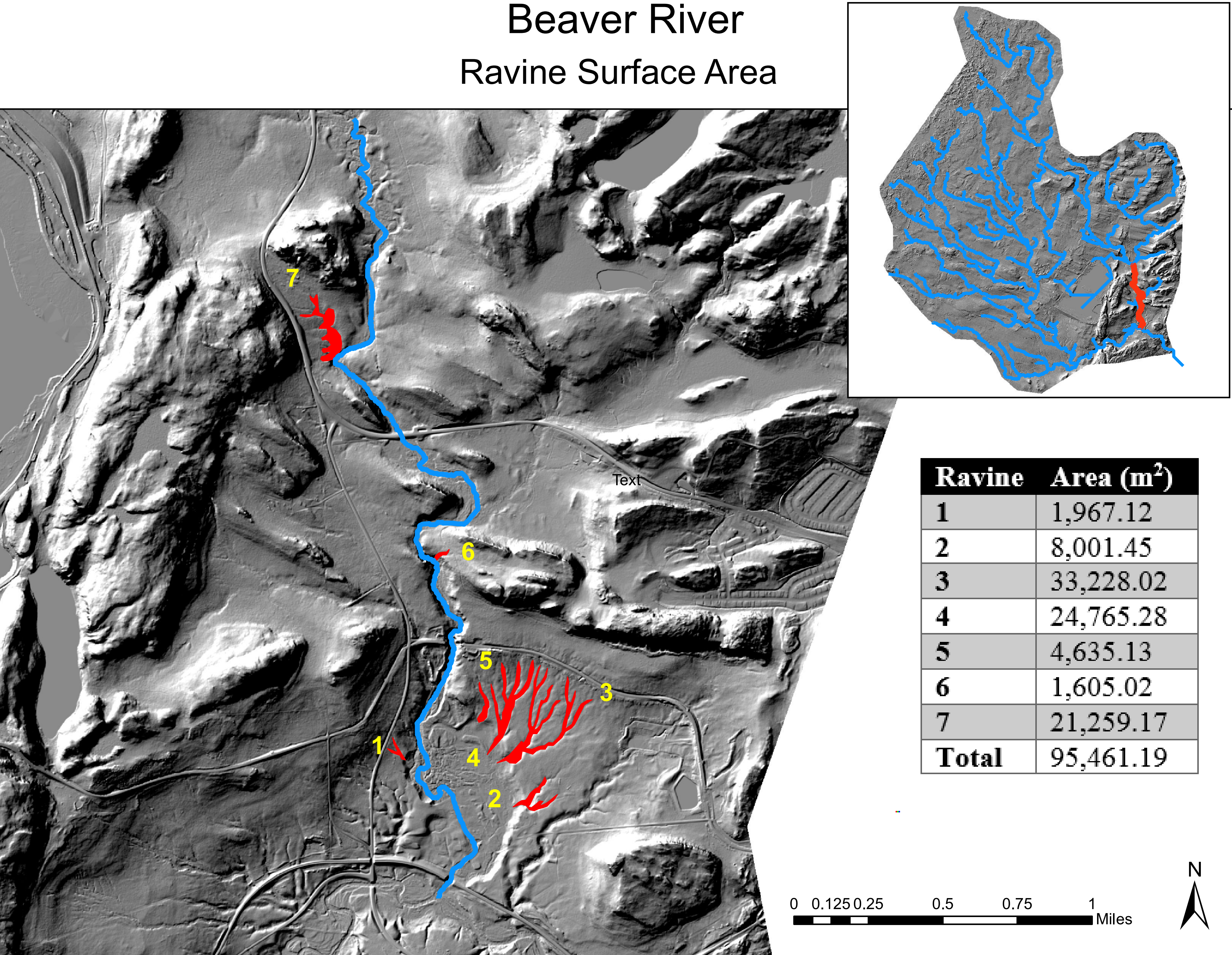
Ravine Slope



Ravine	Slope
1	0.0896
2	0.0430
3	0.0414
4	0.0520
5	0.0644
6	0.1984
7	0.0373
Average	0.0752

Beaver River

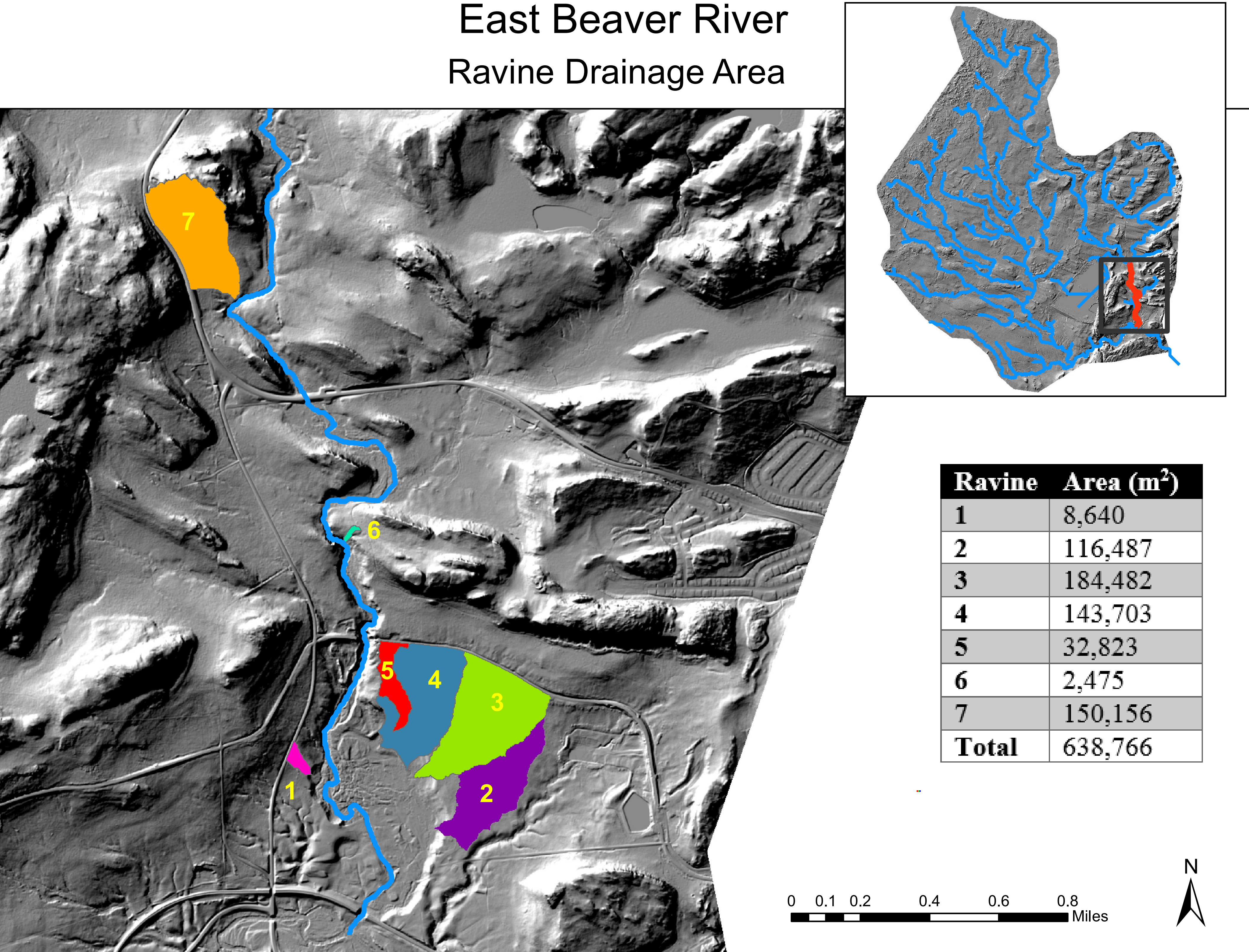
Ravine Surface Area



Ravine	Area (m^2)
1	1,967.12
2	8,001.45
3	33,228.02
4	24,765.28
5	4,635.13
6	1,605.02
7	21,259.17
Total	95,461.19

East Beaver River

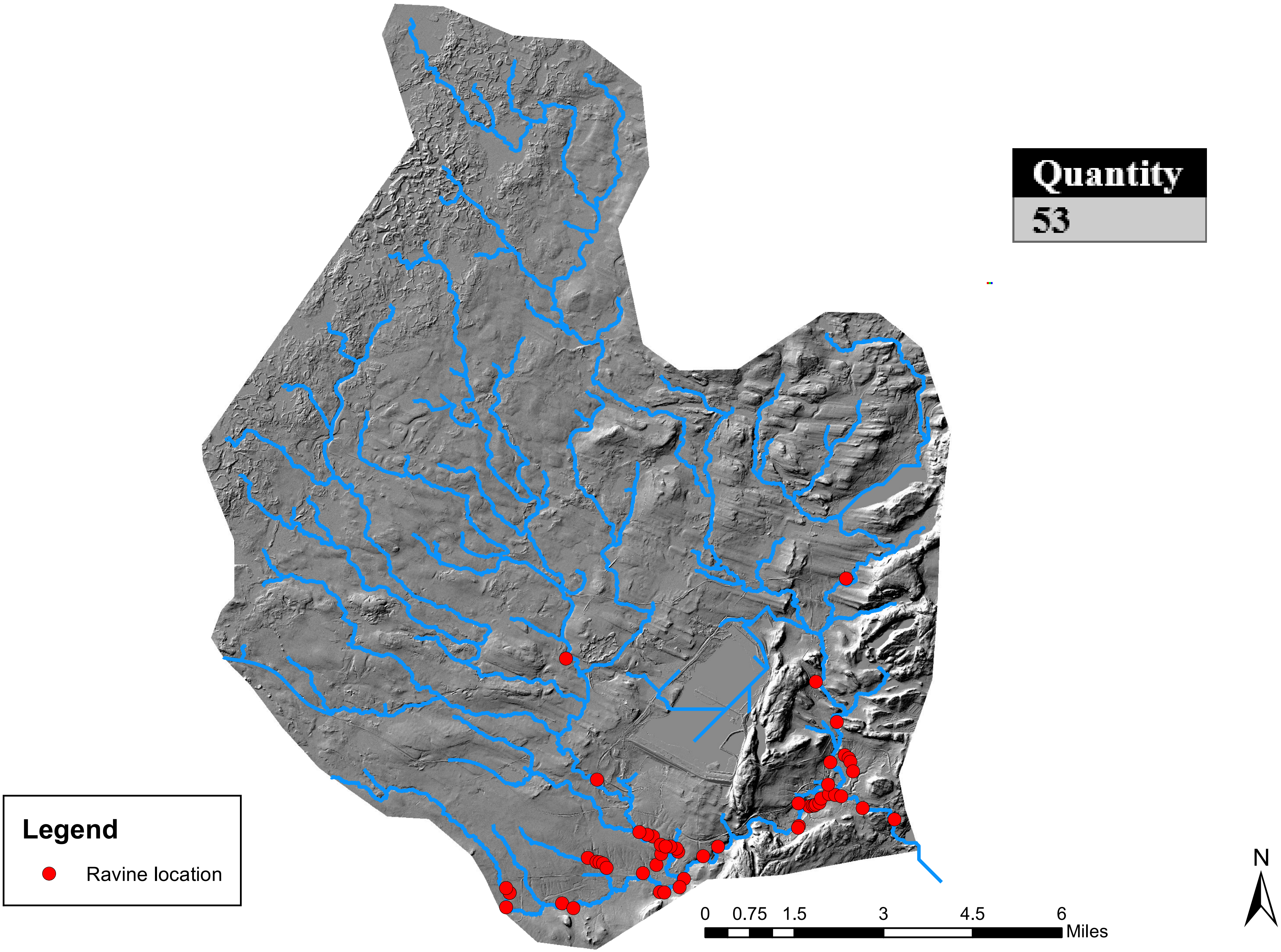
Ravine Drainage Area



Ravine	Area (m^2)
1	8,640
2	116,487
3	184,482
4	143,703
5	32,823
6	2,475
7	150,156
Total	638,766

Beaver River

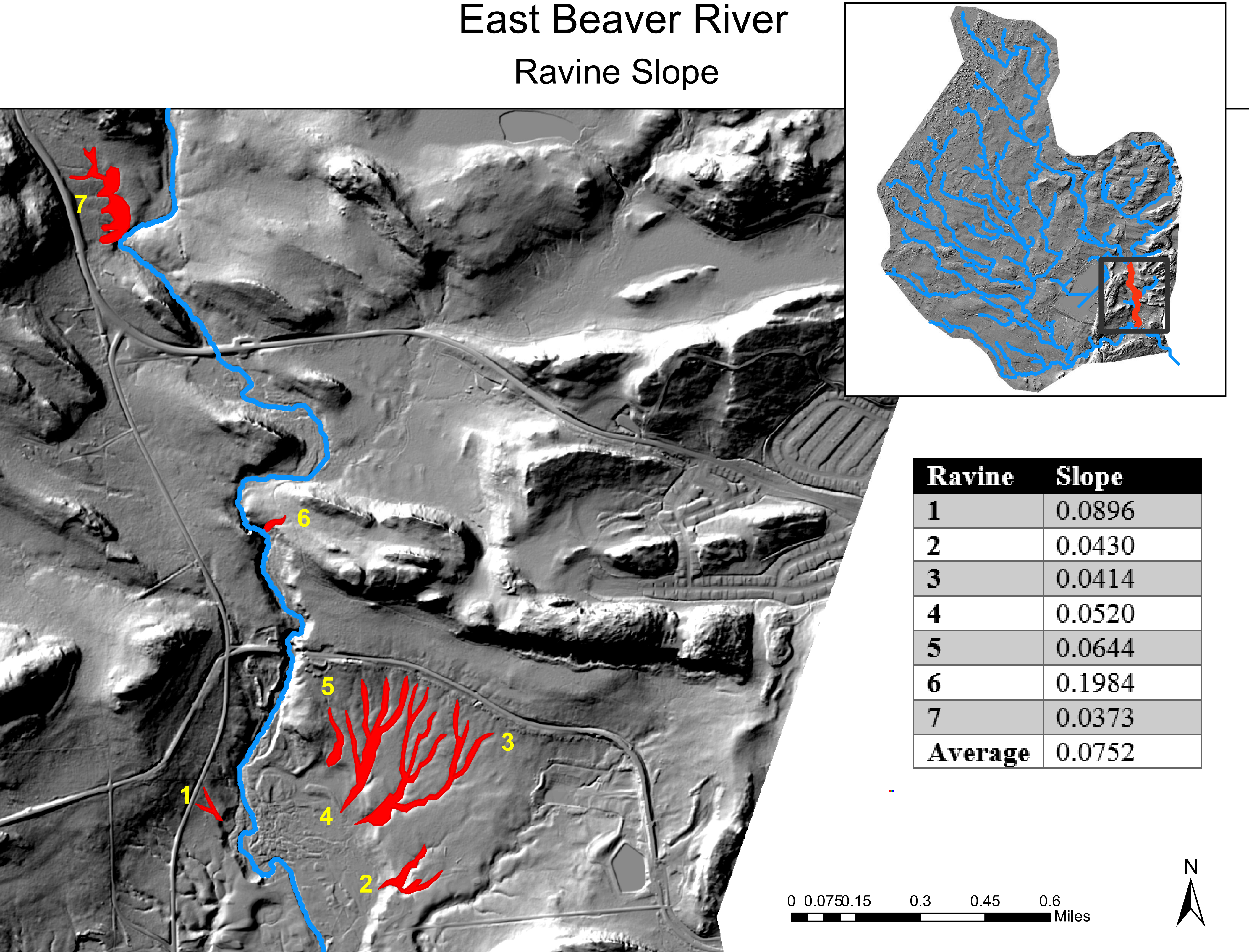
Ravine Locations



Quantity
53

East Beaver River

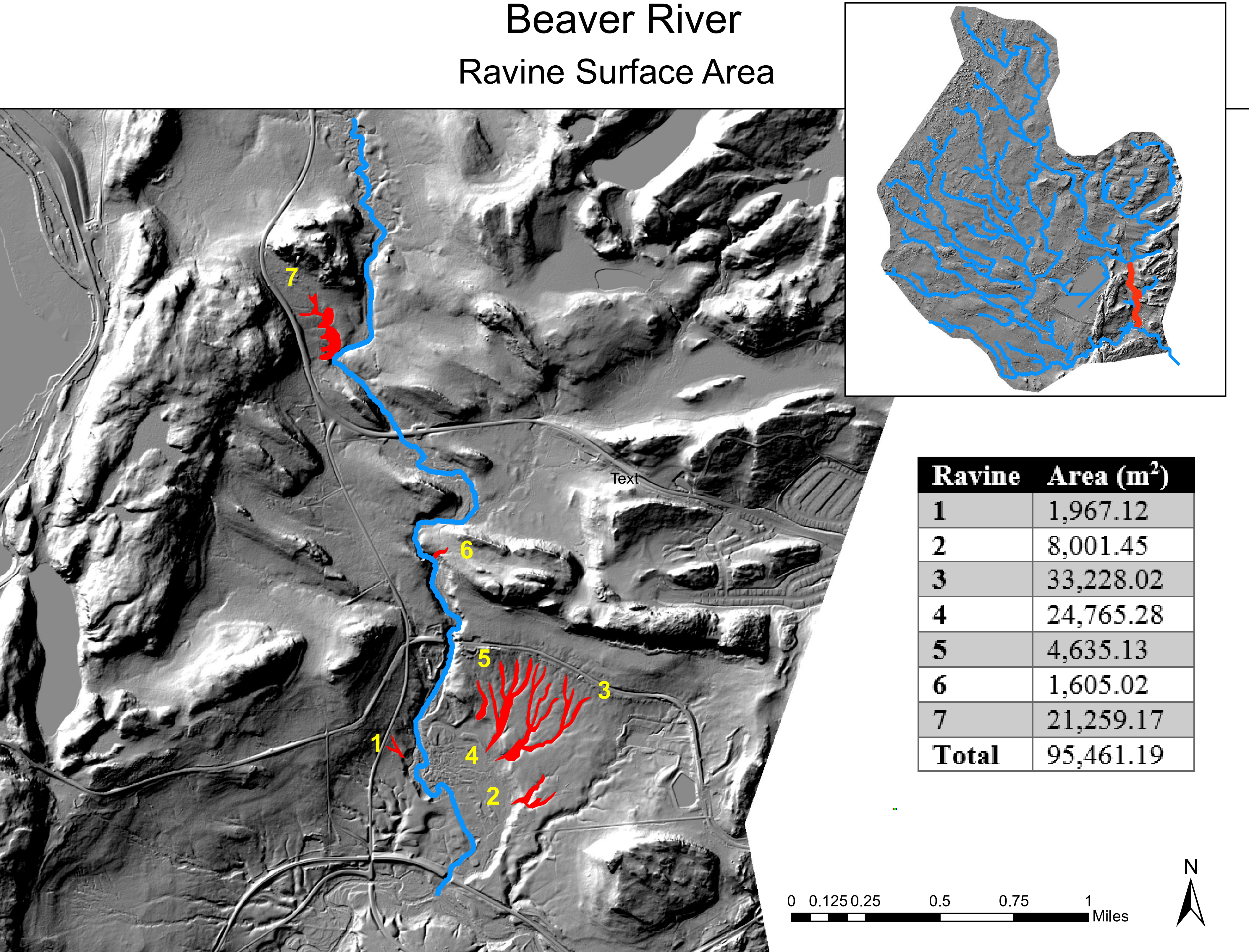
Ravine Slope



Ravine	Slope
1	0.0896
2	0.0430
3	0.0414
4	0.0520
5	0.0644
6	0.1984
7	0.0373
Average	0.0752

Beaver River

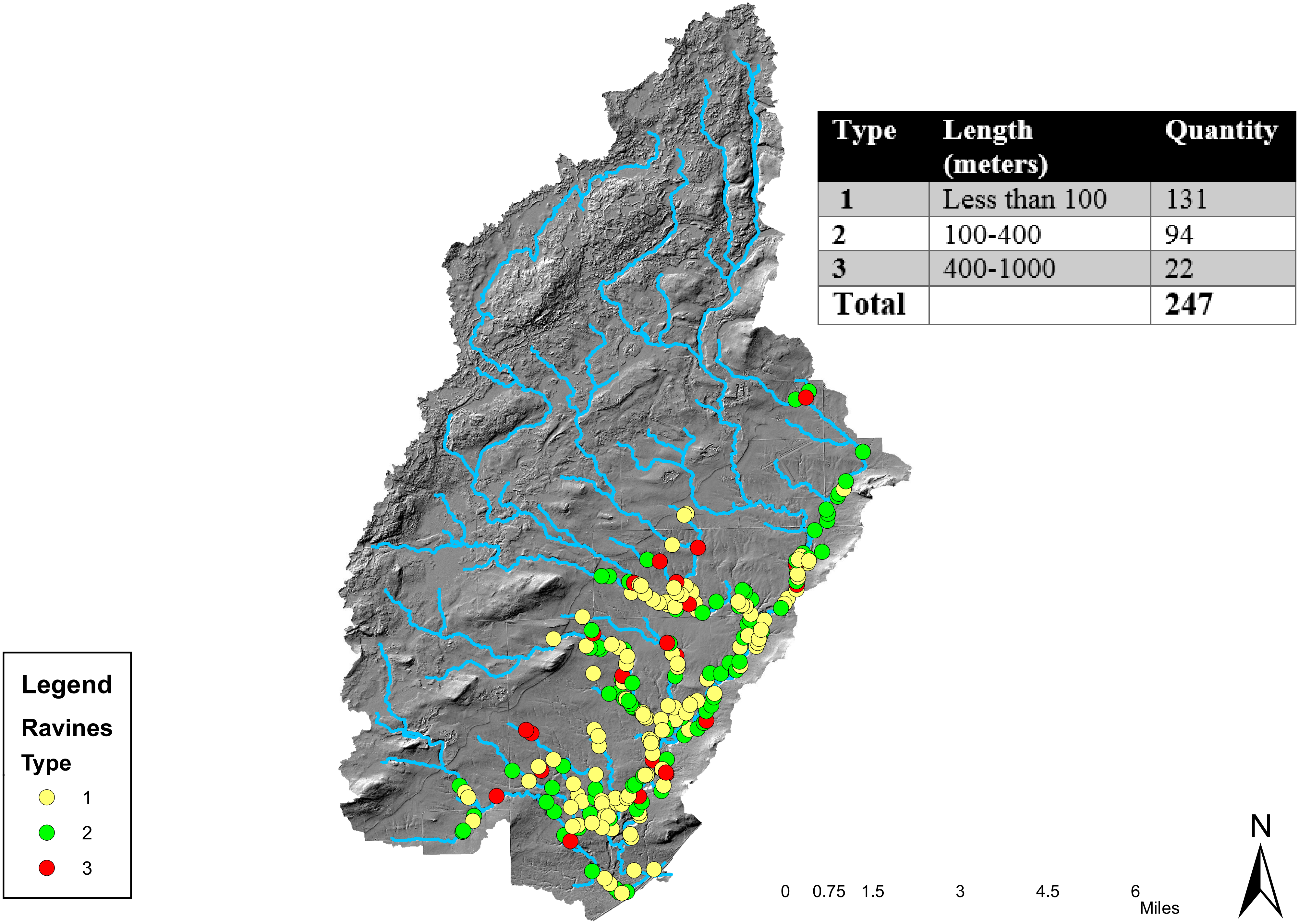
Ravine Surface Area



Ravine	Area (m^2)
1	1,967.12
2	8,001.45
3	33,228.02
4	24,765.28
5	4,635.13
6	1,605.02
7	21,259.17
Total	95,461.19

Knife River

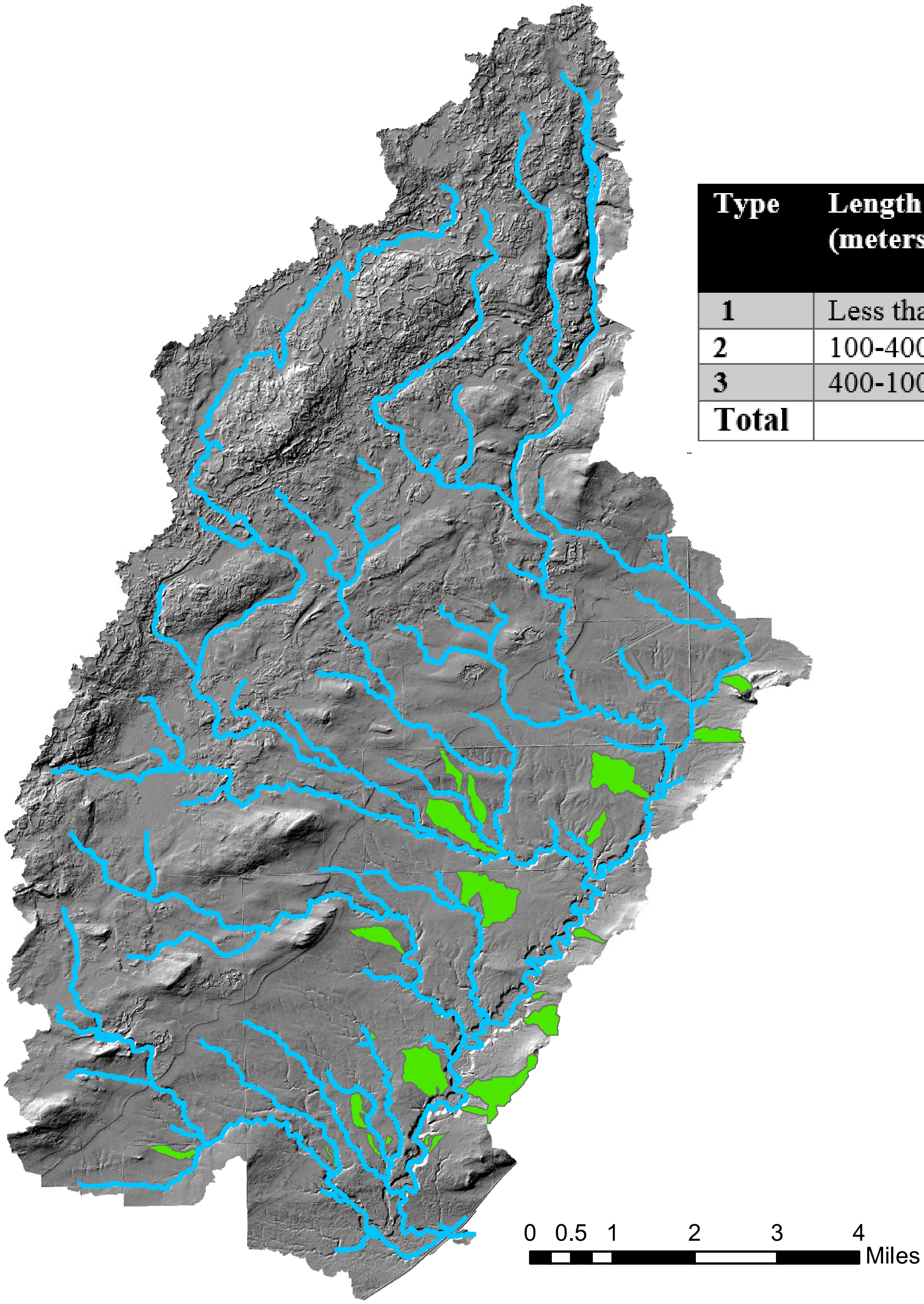
Ravine Locations



Type	Length (meters)	Quantity
1	Less than 100	131
2	100-400	94
3	400-1000	22
Total		**247**

Knife River

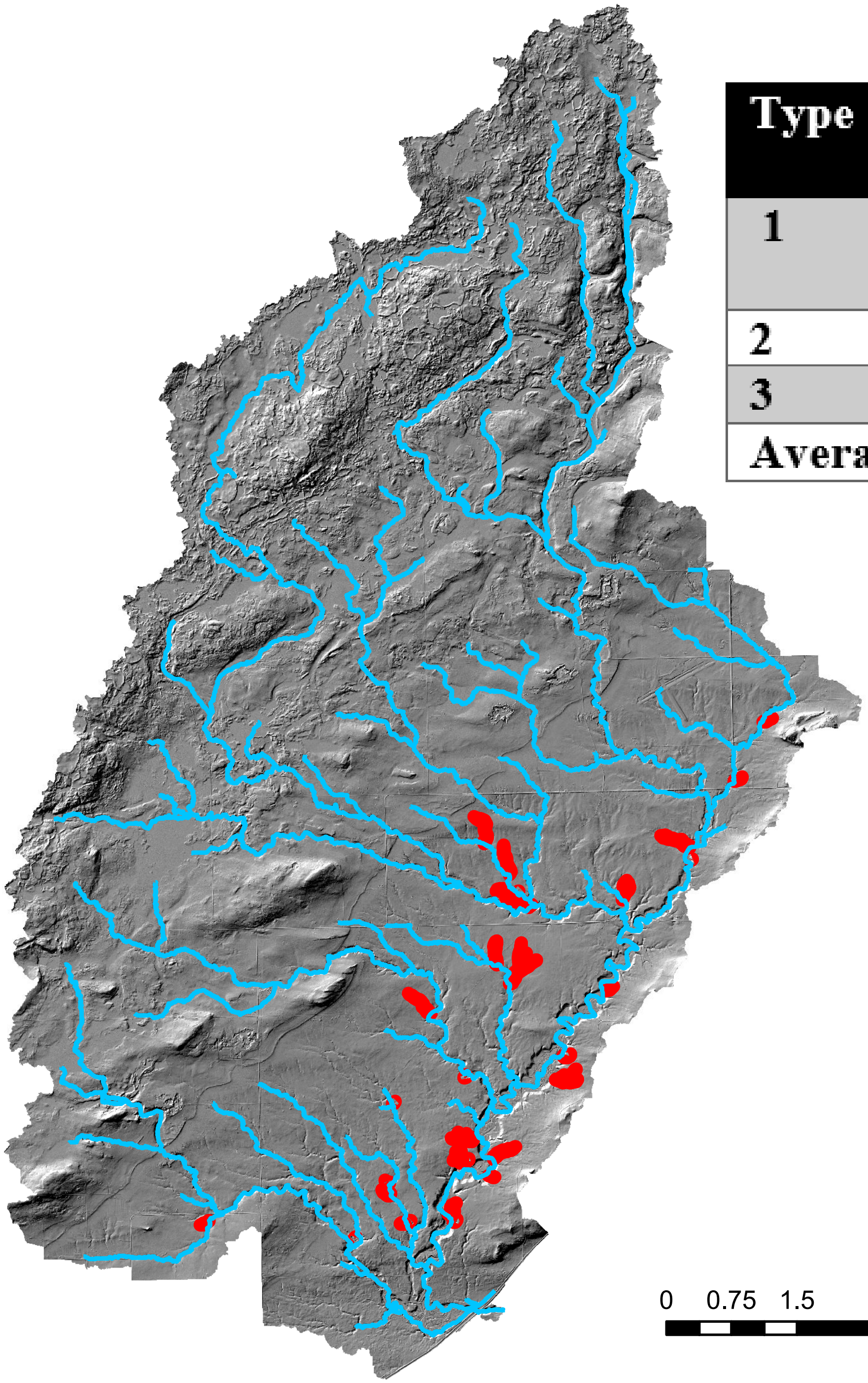
Ravine Drainage Area



Type	Length (meters)	Quantity	Average Drainage Area (m^2)	Total Drainage Area (m^2)
1	Less than 100	131	32,977	4,319,935
2	100-400	94	111,477	10,478,810
3	400-1000	22	328,602	7,229,240
Total		**247**		**22,027,984**

Knife River

Ravine Slope

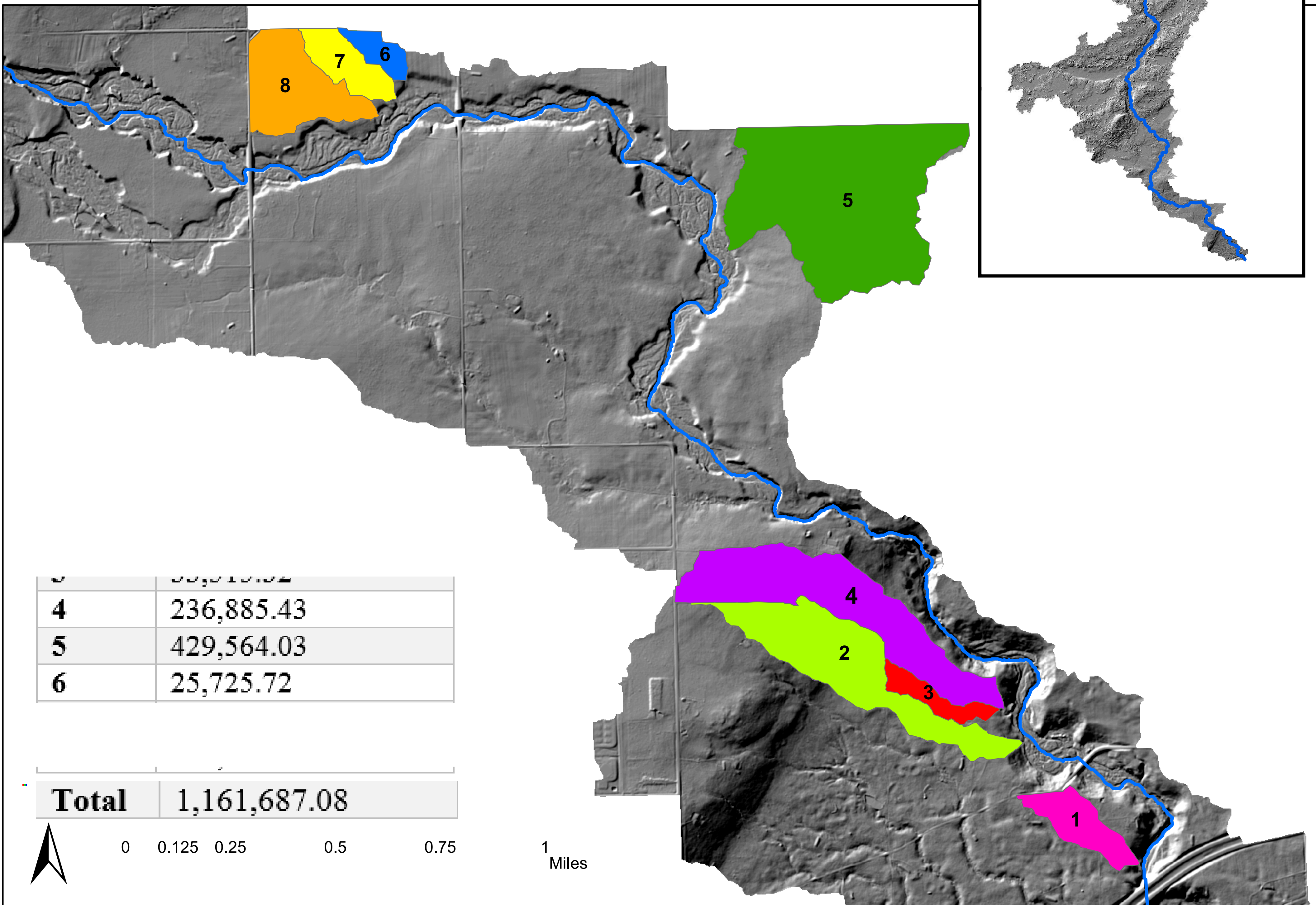


Type	Length (meters)	Average Slope
1	Less than 100	.025
2	100-400	.027
3	400-1000	.047
Average		**.033**

Legend

🟥 Sampled Ravines

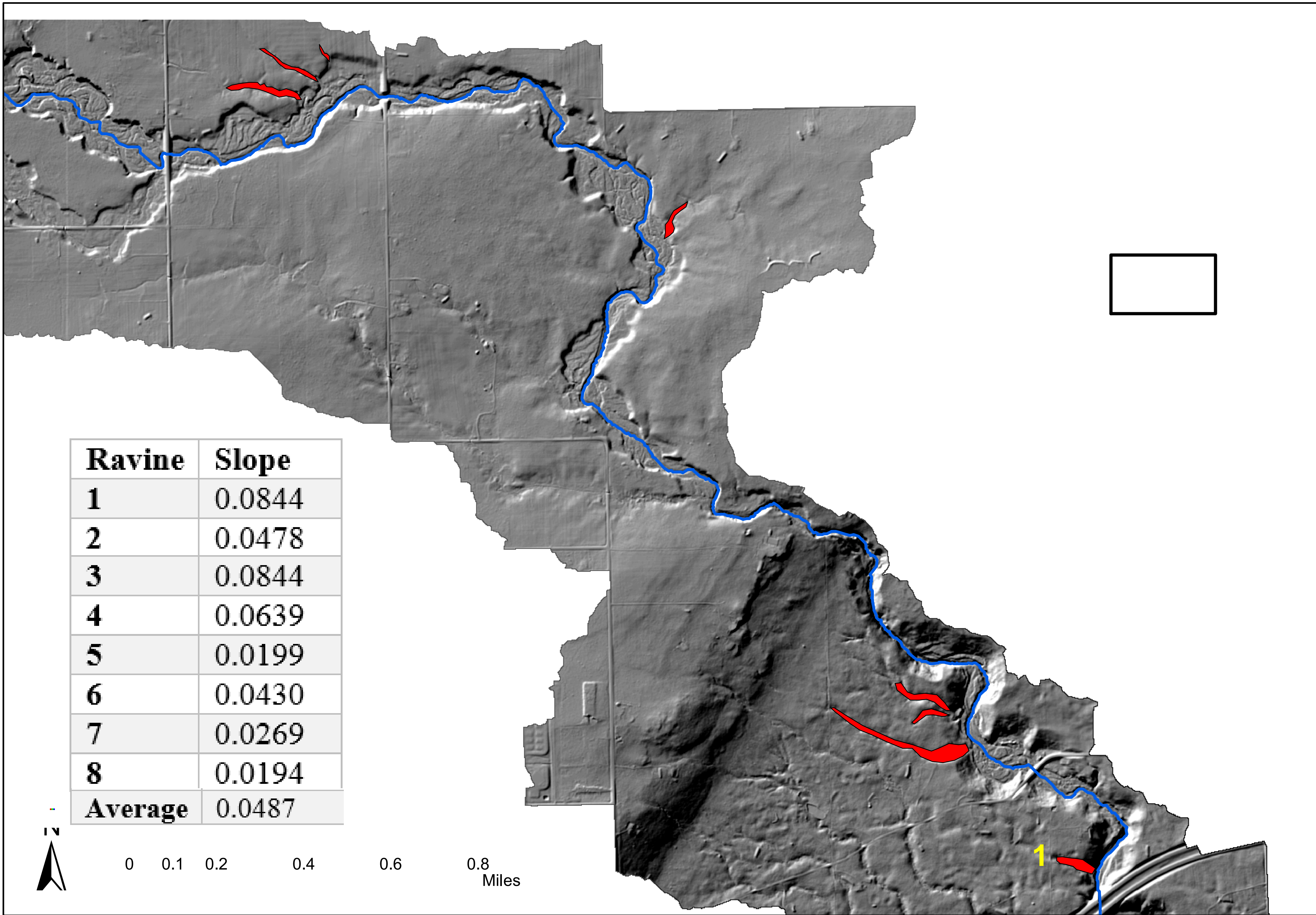
Sucker River
Drainage Area



[illegible]	[illegible]
4	236,885.43
5	429,564.03
6	25,725.72
Total	1,161,687.08

Sucker River

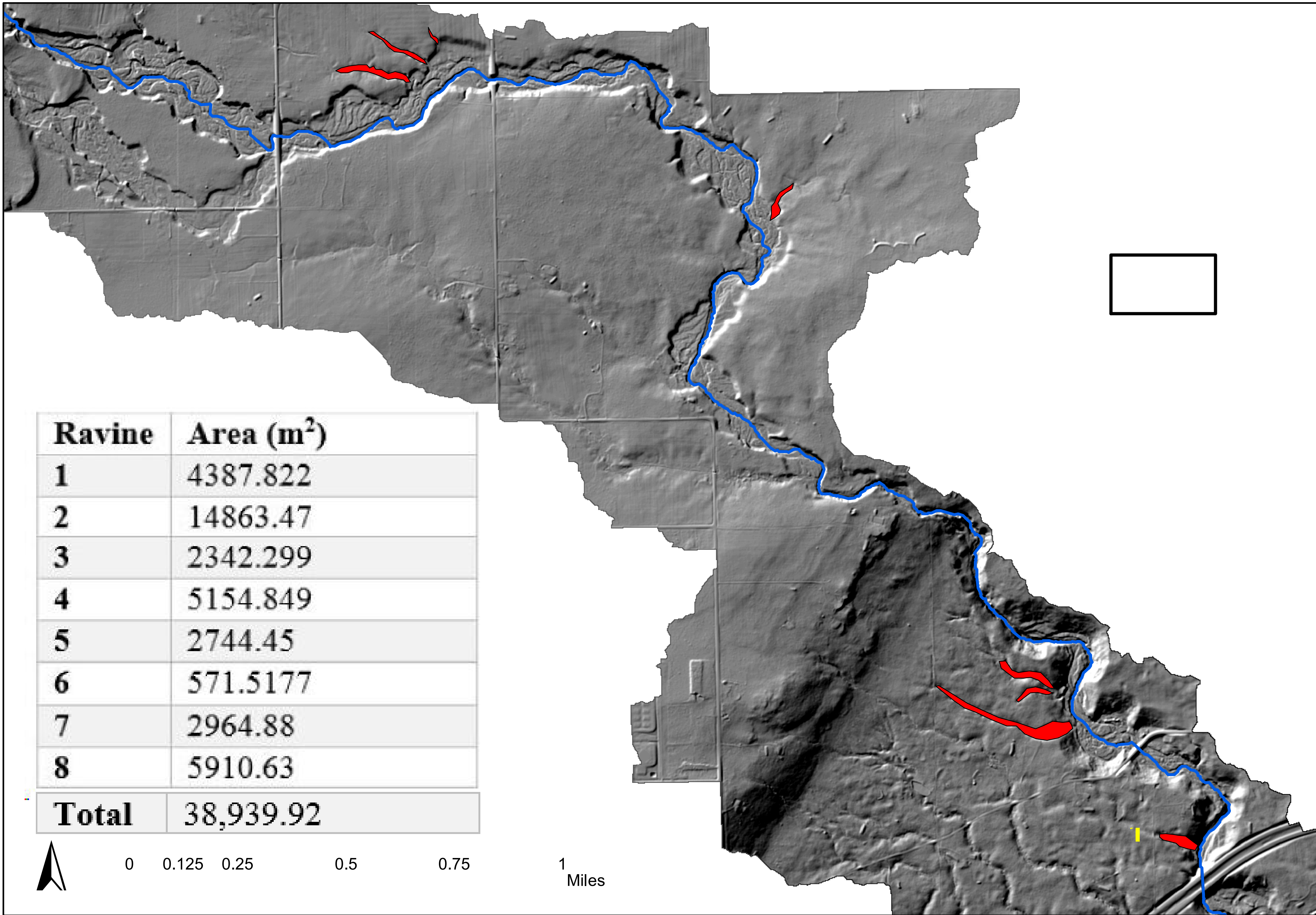
Slope



Ravine	Slope
1	0.0844
2	0.0478
3	0.0844
4	0.0639
5	0.0199
6	0.0430
7	0.0269
8	0.0194
Average	0.0487

Sucker River

Ravine Area

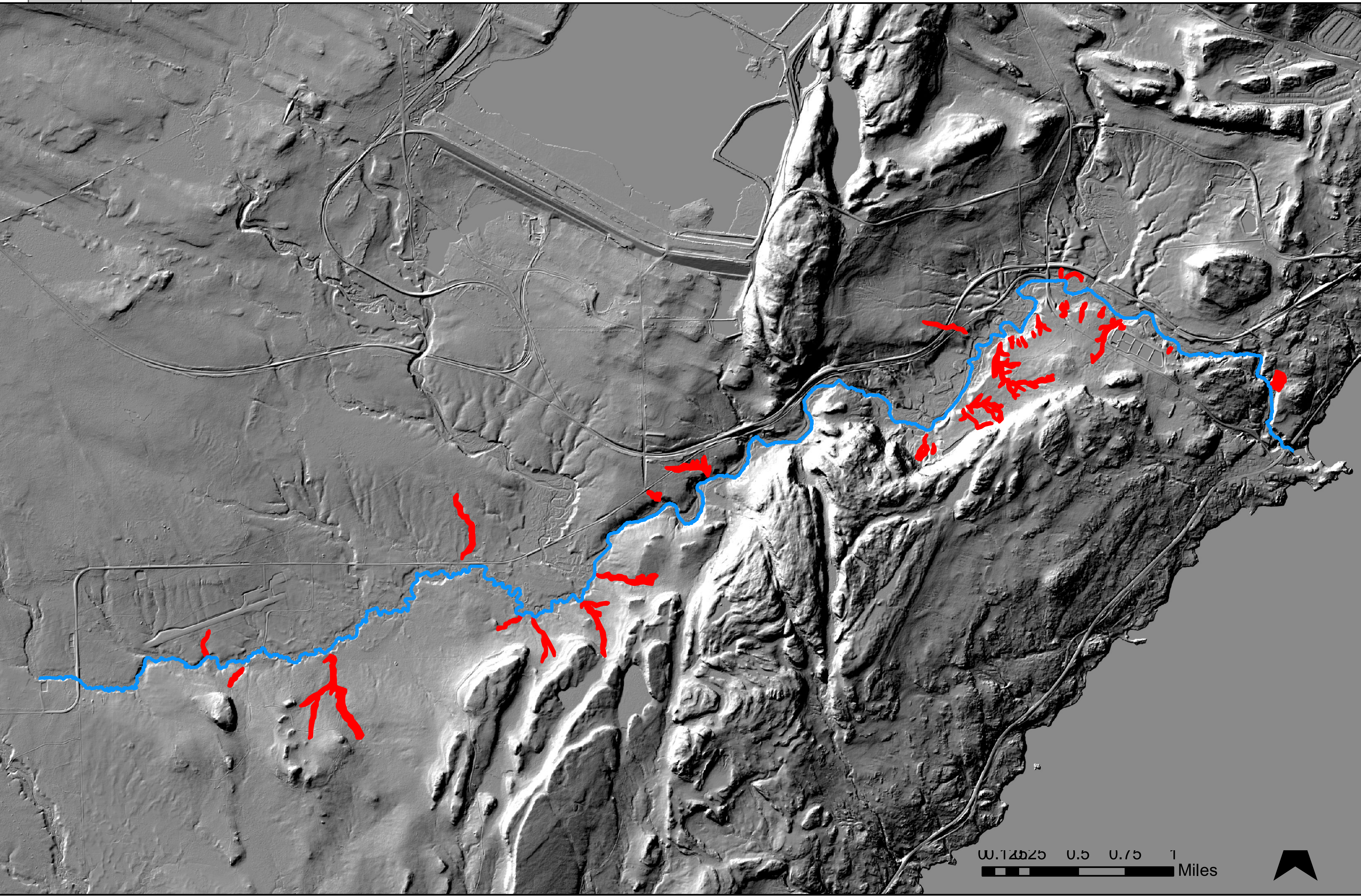


Ravine	Area (m^2)
1	4387.822
2	14863.47
3	2342.299
4	5154.849
5	2744.45
6	571.5177
7	2964.88
8	5910.63
Total	38,939.92

Ravine	Slope
1	.024
2	.040
3	.012
4	.023
5	.022

West Branch Beaver River

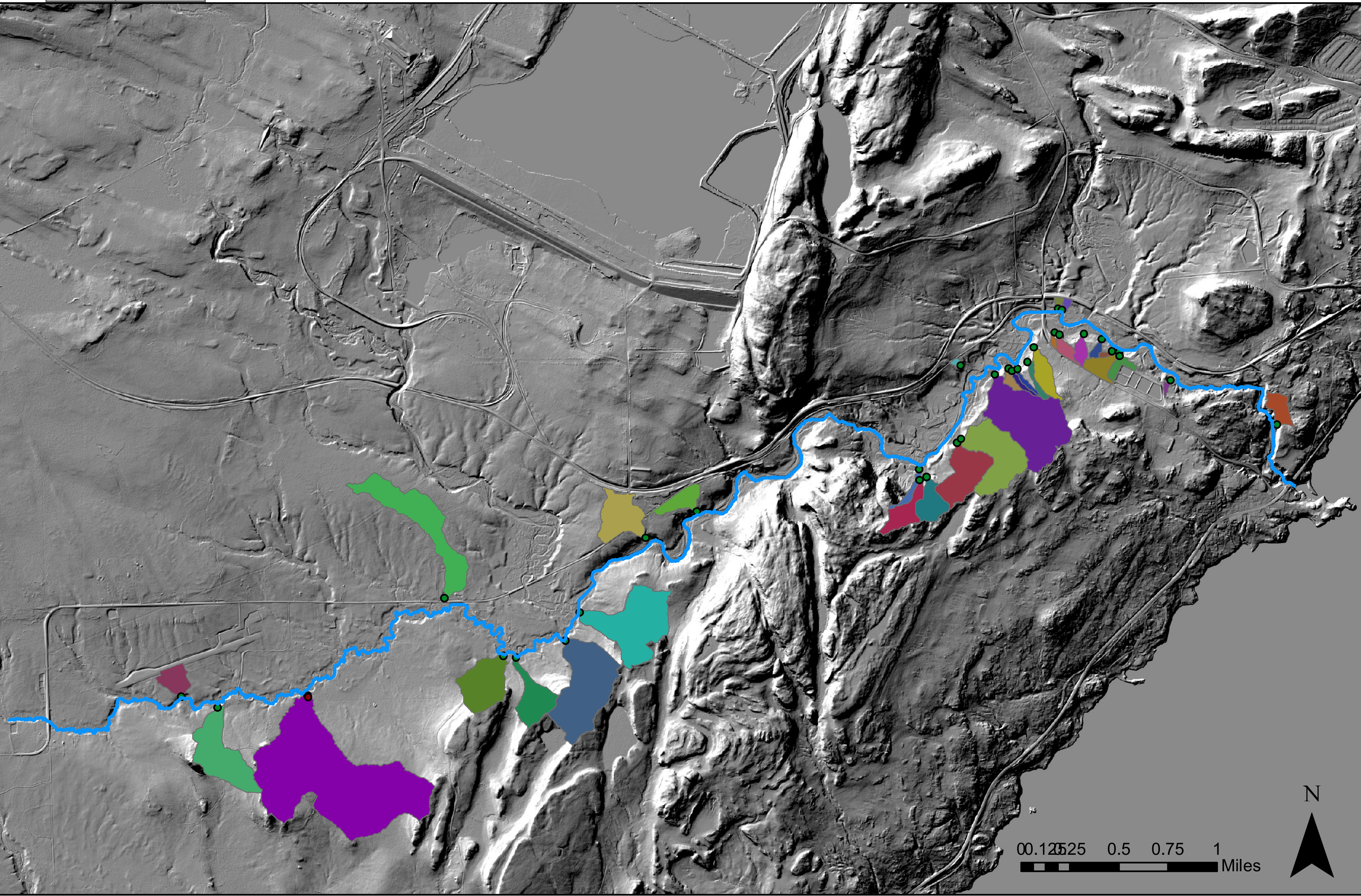
Slope



Ravine	Area (m^2)
1	47,916
2	178,389
3	866,916
4	237,303
5	134,397

West Branch Beaver River

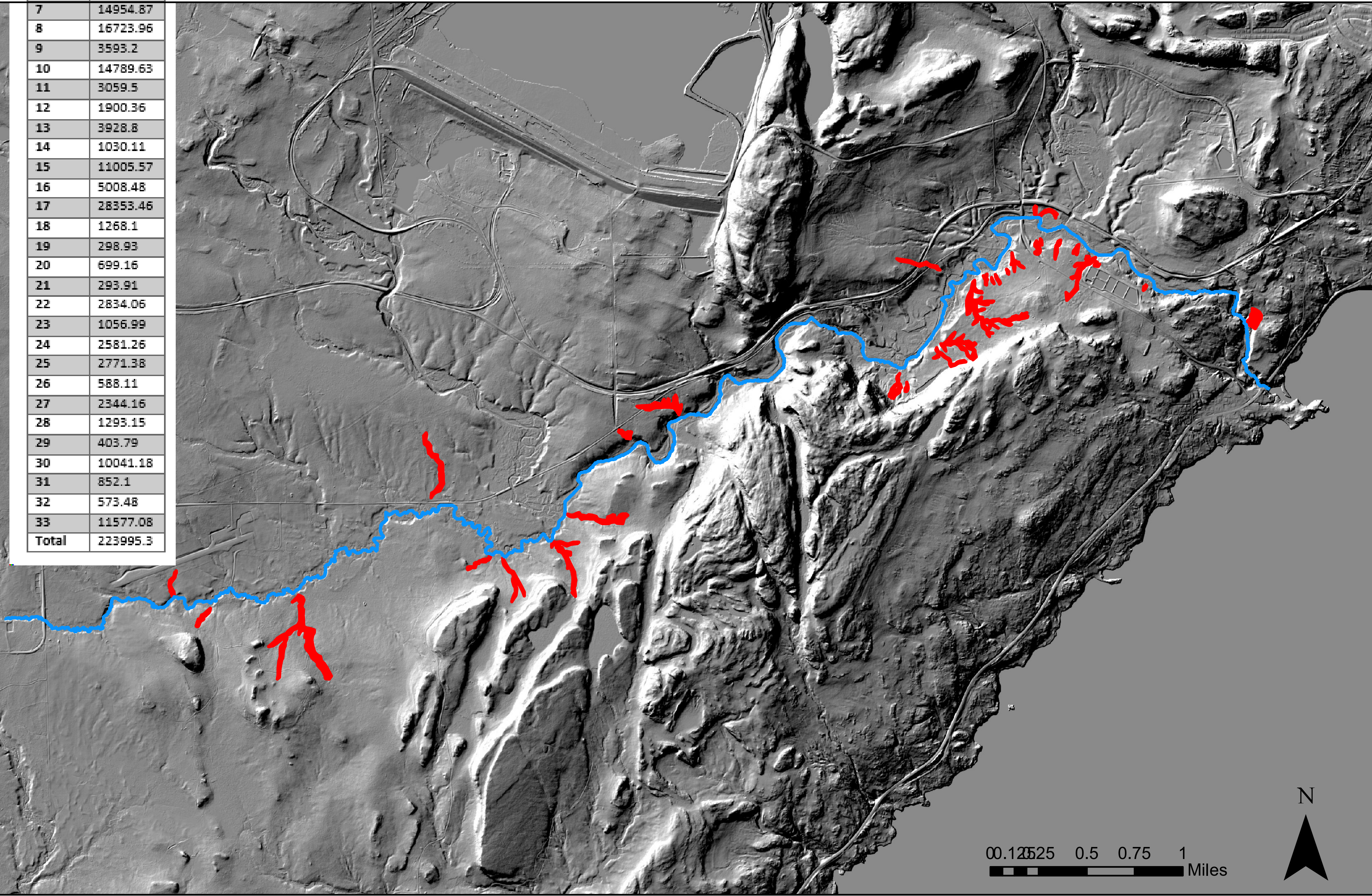
Ravine Drainage Area



West Branch Beaver River

Surface Area

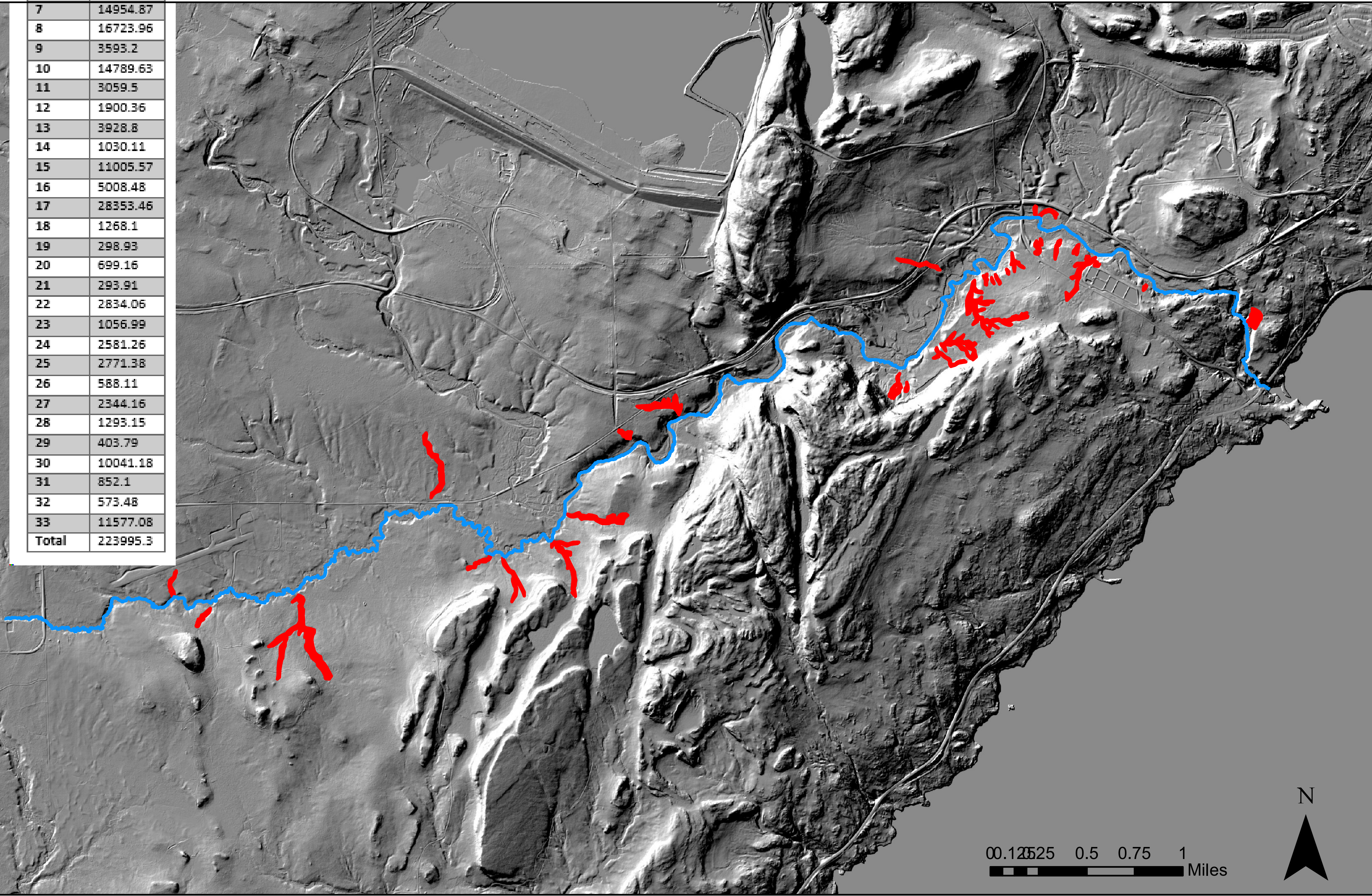
Ravine	Area (m^2)
1	3508.71
2	3788.8
3	48162.19
4	14301.46
5	3019.72
6	7389.62
7	14954.87
8	16723.96
9	3593.2
10	14789.63
11	3059.5
12	1900.36
13	3928.8
14	1030.11
15	11005.57
16	5008.48
17	28353.46
18	1268.1
19	298.93
20	699.16
21	293.91
22	2834.06
23	1056.99
24	2581.26
25	2771.38
26	588.11
27	2344.16
28	1293.15
29	403.79
30	10041.18
31	852.1
32	573.48
33	11577.08
Total	223995.3



West Branch Beaver River

Surface Area

Ravine	Area (m^2)
1	3508.71
2	3788.8
3	48162.19
4	14301.46
5	3019.72
6	7389.62
7	14954.87
8	16723.96
9	3593.2
10	14789.63
11	3059.5
12	1900.36
13	3928.8
14	1030.11
15	11005.57
16	5008.48
17	28353.46
18	1268.1
19	298.93
20	699.16
21	293.91
22	2834.06
23	1056.99
24	2581.26
25	2771.38
26	588.11
27	2344.16
28	1293.15
29	403.79
30	10041.18
31	852.1
32	573.48
33	11577.08
Total	223995.3



Appendix E: Ravine erosion assessment with WEPP and GIS

Purpose

To assess the contribution of ravines to sediment load in several watersheds along the North Shore of Lake Superior using the Watershed Erosion Prediction Project (WEPP) model and GIS data focusing on the Kinfe River where the greatest area of ravines was found.

Background

Ravine and gully erosion are common sources of sediment to rivers. Factors that promote gully and ravine formation include removal of vegetation, changes to land use or land-cover that promote increased runoff, and steep changes in slope. Gullies are most commonly formed in bare soil after storm events in farmland (Cruse et al. 2006), construction sites or other areas of unvegetated soil. Ravines are vegetated areas (usually forest) that were formerly gullies but were too steep or large for any agricultural activity so they became re-vegetated by natural cover. In Minnesota ravines are common along steep slopes bordering elevation drops such as those areas bordering the Minnesota River valley and the North Shore of Lake Superior. On the Lake Superior North Shore streams ravines appear to be most common where land–use has accelerated runoff from vegetation clearance for example on the ski hill located in Lutsen, Minnesota (Hansen et al. 2010). They are also present in watersheds with abundant clay soil near the surface mostly in the Knife, Beaver and Gooseberry River watersheds in northeastern Minnesota.

Questions

The research questions addressed in this study included the following:

- What is the geographic extent of ravines in the Beaver, Knife and Sucker watersheds of the Lake Superior North Shore?
- What is the predicted sediment contribution from ravine erosion using the WEPP model on slopes with different characteristics?
- How do physical variables (slope length, shape and soils) and vegetation characteristics influence ravine erosion rates on the North Shore?

Methods

Ravine areas were delineated by Hall (2016) in each of the three watersheds using GIS as described in the methods section of the main report. Maps were made showing the drainage area, surface area, and slope of each ravine in the Sucker River, Knife River, and Beaver River watersheds (see Appendix D).

Modeling work focused on the Knife River watershed since it contained approximately 89% of the total ravine surface area within the study area (defined as the Beaver, Knife and Sucker River watersheds).Sediment contributions from ravines were thought to be minimal from the Beaver and Sucker watersheds. Ravines with representative conditions for the watershed as determined from the GIS analysis were used to model hillslopes along Knife River just north of Hwy 61 near Two Harbors. The Watershed Erosion Prediction Project (WEPP) model was used to simulate erosion rates given typical conditions for ravines along the Lake Superior North Shore, focusing on the Knife River. WEPP is a hillslope hydrology and erosion model intended for use in smaller watersheds, typically < 1 square mile in area (Flanagan and Nearing 1995). WEPP input variables include climate, soil type, hillslope shape and gradient, vegetation cover. Since the climate doesn't vary substantially between locations in our study the main variables that affect erosion and runoff rates are soil type, slope and vegetation type. WEPP output includes predictions of annual runoff, sediment erosion and deposition. These outputs can be calculated at different points along the hillslope and for different storms as well. For this study the average hillslope erosion rate and the maximum are presented for each slope in the results

Eight model simulations were run using different hillslope conditions as described in Table 1. The same climate file was used for each run and convex hill shape. Low slope, moderate and steep slopes were input using slope ranges obverted from GIS and Lidar data. Slope lengths were used based on observed GIS data as well. The soil profile was comprised of a shallow loamy layer on top of a clay subsoil, similar to the Cuttre soils series common in the Knife River and North Shore area.

Table 1:WEPP model simulations runs and input parameters

Model run name	Climate file	Land cover	Hillslope properties (shape, slope and length)	Soil profile
1.Low slope, forest	Two Harbors, MN	forest	Convex, 3%, 300 feet	Clay in subsoil
2.Low slope, grass	Two Harbors, MN	grass	Convex, 3%, 300 feet	Clay in subsoil
3.Mod slope, forest	Two Harbors, MN	forest	Convex, 6%, 300 feet	Clay in subsoil
4.Mod slope, grass	Two Harbors, MN	grass	Convex, 6%, 300 feet	Clay in subsoil
5.Steep slope, forest	Two Harbors, MN	forest	Convex, 12%, 300 feet	Clay in subsoil
6.Steep slope, grass	Two Harbors, MN	grass	Convex, 12%, 300 feet	Clay in subsoil
7. Mod long slope, forest	Two Harbors, MN	forest	Convex, 6%, 600 feet	Clay in subsoil
8.Mod long slope, grass	Two Harbors, MN	grass	Convex, 6%, 600 feet	Clay in subsoil

Scaling-up WEPP model results to the entire watershed

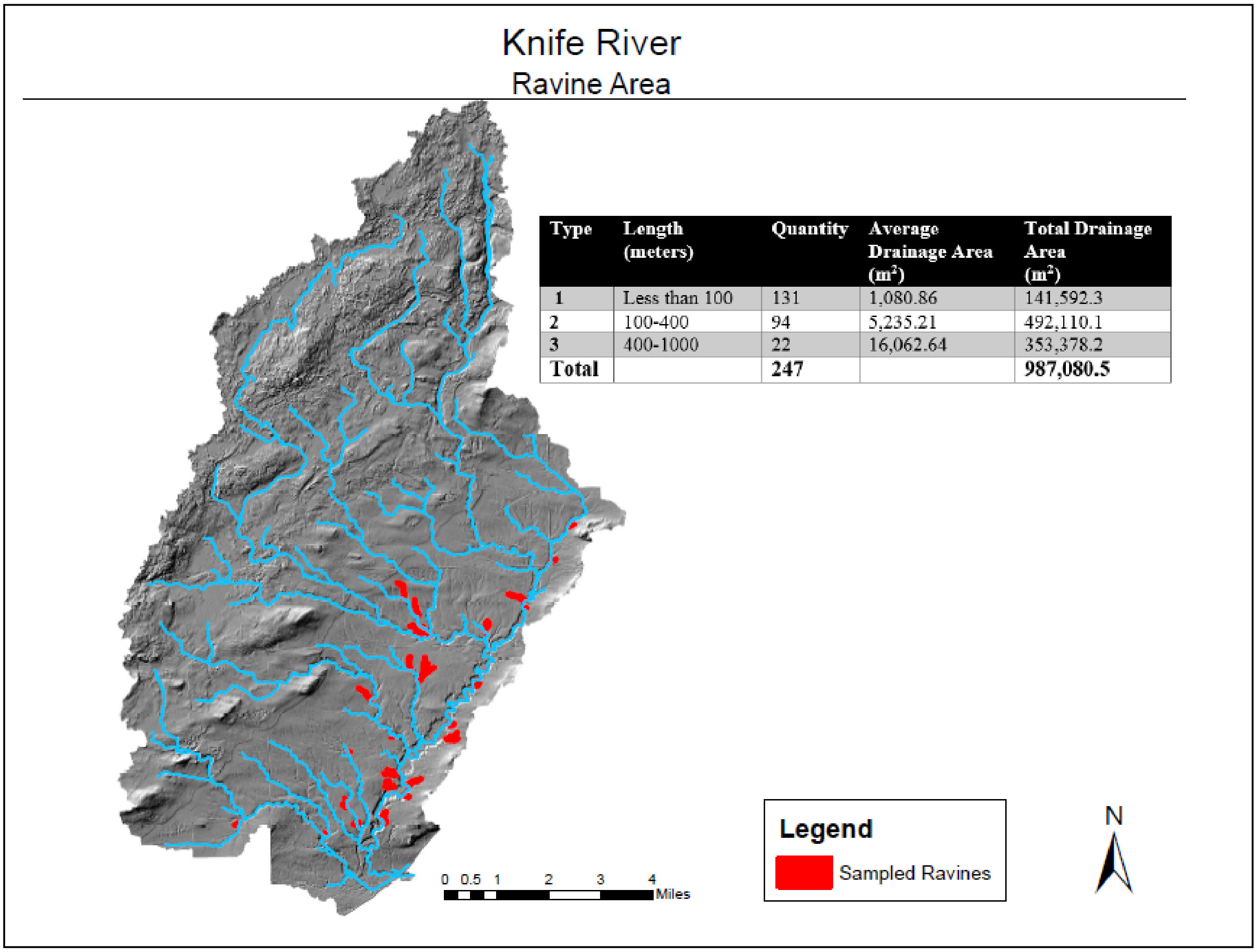
Representative reaches of ravines using slopes obtained from Lidar were used to model erosion in WEPP. For the purpose of estimating total sediment load from ravine erosion the area of ravines in different slope categories was determined. The area of each ravine slope class in each watershed was then calculated and scaled up to the entire ravine area in each watershed (table 3). Average erosion rates for different ravine slope categories were then applied to similar ravine types of the entire watershed. The minimum and maximum soil loss rates from the different scenarios are listed in the results section as well.

Results

Ravines were most common in the Knife River watershed with 247 ravines delineated in GIS totaling 98.7 ha in area. The East Beaver had 7 ravines totaling 9.5 ha while the West Beaver had 33 ravines and the Sucker watershed had 8 ravines totaling 3.9 ha. Average ravine slopes were steepest in the East Beaver at 7.5% with the Sucker averaging 4.9% and the Knife the lowest at 3.3% (Table 2).

Table 2. Physical characteristics of ravines in three watersheds in the North Shore of Lake Superior study area from GIS analysis. Leah Hall (2016) thesis

	# of ravines	Ravine Area (ha)	Slope (avg., range)	Ravine drainage area (total) ha	
East Beaver	7	9.5	7.5% (3.7 – 19.8%)	65	
West Beaver	33	Not available	Not available	326	
Knife	247	98.7	3.3% (2.0-12.5%)	2200	
Sucker	8	3.9	4.9% (1.9 – 8.4%)	116	



Type	Length (meters)	Quantity	Average Drainage Area (m^2)	Total Drainage Area (m^2)
1	Less than 100	131	1,080.86	141,592.3
2	100-400	94	5,235.21	492,110.1
3	400-1000	22	16,062.64	353,378.2
Total		**247**		**987,080.5**

Figure 2. Ravine area in the Knife River watershed delineated in GIS. Note 1,000 m^2 = 1 hectare.

Physical characteristics of ravines

Most of the ravines were convex in shape with increasing drainage area, slope and bank height as they descended down to the elevation of the main river valleys. The progression from relatively flat swales to more deeply entrenched channels is shown in Figures 3 – 5. .Ravines were most commonly observed in clay soil types such as the Cuttre soil series which is common in the Knife River watershed (See appendix B for a description of this soil series).

Figure 3. A shallow ravine with a lower slope in the project area near the north shore of Lake Superior.

Figure 4. Ravine that has cut down somewhat with moderate slope

Figure 5.A steeper portion of ravine located on the downstream end. Note that the downstream locations are typically forested rather than open, reducing the probable erosion rates. The highest erosion rates were predicted for the steeper, downstream ends.

The WEPP Model results are summarized in Table 4 showing runoff and soil loss generated from storm events over a 50 year simulated time period using the Two Harbors climate file. The average annual precipitation was 32.8 inches/year, occurring as snow and rainfall. Most flow through the ravines was predicted to occur as storm water runoff (2.95 – 4.01 inches) with less snowmelt runoff (0.44-2.23 inches).Snowmelt was considerably less under forested conditions. Predicted total annual runoff ranged from 4.3 – 5.34 inches/year with the higher amounts coming from the grass slopes. Average annual soil loss (eroded soil from the hill slope) was 0.18 to 4.56 tons/acre/year with the lowest occurring on low to moderate slope with forest cover. The highest rate was found on the steep, grass slopes. Maximum soil loss rates were considerably higher at a point on the grass hillslopes with 10.2 and 16.7 tons/acre/year for model runs #6 and #8. Annual sediment yield (the amount carried off the hillslope) was the same as sediment loss indicating no deposition was occurring given the convex hill shape.

Table 4. WEPP modeling results

Model Run(see table 1 for inputs)	**Average annual precipitation**	**snowmelt runoff (annual)**	**Storm water runoff (annual)**	**Total runoff (annual)**	**Average annual soil loss***	**Average annual sediment yield***	**Max soil loss rate (at one point on hillslope)**
Units	Inches	Inches/year	Inches/year	Inches/year	(tons/acre/yr)	(tons/acre/yr	(tons/acre/yr)
1.Low slope, forest	32.8	0.45	3.85	4.3	0.18	0.18	0.18
2.Low slope, grass	32.8	2.19	2.95	5.14	0.28	0.28	0.28
3.Mod slope, forest	32.8	0.45	3.85	4.3	0.19	0.19	0.19

4.Mod slope, grass	32.8	2.18	3.01	5.19	1.27	1.27	5.9
5.Steep slope, forest	32.8	0.44	4.01	4.45	0.22	0.22	0.5
6.Steep slope, grass	32.8	2.24	3.1	5.34	4.56	4.56	16.7
7. Mod long slope, forest	32.8	0.44	3.89	4.33	0.19	0.19	0.19
8.Mod long slope, grass	32.8	2.23	3.05	5.28	2.73	2.73	10.2

The results scaled up to the entire Knife River watershed are presented in Table 5.

Table 5. Scaled up sediment estimates using modeled sediment loads and ravine areas from GIS for the Knife River

Ravine category by slope class	Ravine area (ha) within each category (estimated)	Ravine Erosion rate(tons/ac/yr) (WEPP model)	Range of modeled ravine erosion rates (tons/ac/yr)	Total Erosion (tons/year) for entire watershed: average rate (min, max)
low slope (3%)	50.2	0.22	0.18 – 0.28	26.6 (21.8 – 33.9)
moderate slope (6%)	32.3	0.5	0.19 - 2.73	39.9(15.2 – 218.1)
steep slope (12%)	16.5	1.46	0.22 -4.56	59.5 (7.3 -185.8)
Total	99.0	n/a	0.18 – 4.56	126.1 (44.3 – 437.8)

Discussion

The modeled ravine erosion total was 126 tons/year using the average rates from each slope category with a range from 44 to 438 tons/year depending on slope, length, and land-cover. The value of 126 tons/year is small compared to that measured for bluffs which were approximately 1800 tons/year and 600—700 tons/year predicted for stream banks.

The input parameters for WEPP (Table 3) influenced results in a variety of ways. Climate was the same for each model run. There was substantially more (5 times) snowmelt runoff predicted for the grass hill slopes compared to forest presumably due to the timing of melting and rain-on-snow events. The land cover, forest or grass produced the greatest difference with no forested ravines exceeding 0.5 t/ac/yr and averaging between 0.18 – 0.22 t/ac/yr. Grasses averaged about 20 times more sediment yield primarily because of the increased runoff and erosive forces generated in the lower parts of the ravine. Forests have greater interception and transpiration over time scales of months to years.

Hillslope characteristics that affected erosion rates included hillslope shape, slope and length. Most of the slopes were convex which produces higher sediment yields than concave because there are no depositional surfaces along the hillslope and erosional forces progressively increase moving downhill. Some of the slopes were probably S-shaped but they were not modeled in this study. Slope angle increased erosion but the model was less sensitive to this than land cover and slope length. Slope length approximately doubled sediment erosion rates going from 300 feet (the average ravine length for the Knife River) to 600 foot slope length.

Not all sediment eroded from ravines is carried to the outlet streams due to lack of flow in intermittent streams. Due to their small drainage area and lack of baseflow ravines generally only flow after storm events. In contrast the bluffs along the Knife River have a much higher sediment delivery ratio. Another factor limiting sediment production from the North Shore ravines is the lack of steep, bare side slopes. Most of the ravines are more like grass or forested swales that are not very entrenched as shown in Figure 3.

Conclusion

Currently ravines do not appear to be a major source of sediment to the Knife River though predicted contributions did range from approximately 44 to 440 tons/year. In terms of management, dramatic changes to land use could accelerate erosion in gullies particularly deforestation and development on steep or long slopes directly above ravines. The maximum rates of soil loss predicted were quite high (up to 16.7 tons/acre/year) indicating that ravines do have potential to contribute large amounts of sediment to North Shore streams if changes to land-use and hydrology occurred. This has been the case in other parts of the Midwest including the Minnesota River where hydrology and land-use have been highly altered, suggesting that land-use management should preserve forest cover and water storage whenever possible in areas with ravines.

References

Cruse, R., Flanagan, D., Frankenberger, J., Gelder, B., Herzmann, D., James, D., ... & Todey, D. (2006). Daily estimates of rainfall, water runoff, and soil erosion in Iowa. *Journal of soil and water conservation*, *61*(4), 191-199.

Flanagan, D.C. and M.A. Nearing (eds.). 1995. U.S. Department of Agriculture (USDA) Water Erosion Prediction Project: Hillslope profile and watershed model documentation. National Soil Erosion Research Laboratory (NSERL) Report No. 10. USDA Agricultura

Streambank erosion estimates for the main channel of the Knife River, North Shore of Lake Superior

Introduction

Streambank erosion is a naturally occurring process that contributes sediment to rivers. Most streambank erosion occurs at high flows, typically greater than the 1 year recurrence interval flow. While much of that sediment may be deposited on point bars or floodplains some sediment may deposit on the bed or become suspended contributing to high turbidity values negatively impacting aquatic life in the stream. Therefore there is an interest by natural resource managers in understanding the sediment contributions from stream bank erosion.

Methods

One approach to predict rates of stream bank erosion is the BANCS method which utilizes estimates of bank erodibility and erosive force in-stream to forecast annual rates of lateral bank retreat (Rosgen 2001). The method uses a bank erosion hazard index (BEHI) worksheet to measure bank height, bank angle, bank full height, vegetation coverage, root depth and root density. Stream erosive force is estimated using different field or GIS measurements to obtain a near bank stress (NBS) value. The two values are then plotted to obtain an annual average estimate of streambank erosion in feet/year.

Lake County SWCD surveyed two reaches of the Knife River in northeastern Minnesota along both the left and right bank with 110 and 111 worksheet estimates made along each respective side of the river in 2013. This data was used to calculate annual average bank erosion rates using the BANCS relationships developed by Rosgen (2001). Using the estimated annual average erosion from the BANCS graphs and a bulk density of 1.3 tons/yd^3, a mass in tons was calculated. In total, Lake County SWCD surveyed 9 miles of the total 23.9 miles listed as the length of the Knife River or 38% of the total length. Banks greater than 10 feet (3.0 m) were excluded from the calculation and classified as bluffs. The erosion estimated from the bluffs was then used in the bank : bluff erosion ratio used to obtain another estimate of sediment loading from stream banks.

University of Minnesota staff used the Lake County SWCD calculations scaled up to the entire length of the Knife River and applied the percentage of fine sediment to predict contribution to suspended load. Using soil particle size distribution data, the percent fine sediment was calculated and classified as suspended sediment load. The coarse sand was assumed to primarily deposit locally in the channel or floodplain and thus not contribute to downstream turbidity and sediment load estimates.

A second approach for estimating total stream bank erosion was utilizing the ratio of bluff to bank erosion from BANCS data sheets. This has the advantage of utilizing the same methodology for both bluff and bank erosion so that if the total erosion predictions are inaccurate, the ratio of the two may be more accurate.

Results

The summary of the Lake County SWCD BANCS estimates of annual average bank erosion are presented in Table 1 below. The raw data is listed in Table 2 at the end of this section. Most (82%) of the stream banks had very low to low BEHI scores and 88% had low or very low NBS scores. The BANCS equations predicted a total of 1,746 tons/year annual average bank erosion. Scaling up the calculations to the entire 23.9-mile length of the Knife River yields a value of 4,636 tons/year predicted gross erosion.

Using particle size data from the soil survey in areas adjacent to the river, 56% of the sediment was estimated to be fine (silt / clay). Assuming the fine sediment is transported downstream while the sand is deposited locally, the fraction of total gross erosion predicted to be transported downstream was 2,862 tons/year.

Table 1. Stream bank erosion predictions for the Knife river

Knife River	**Result**	**units**	**notes**
% stream banks with very low to low bank erosion hazard index (BEHI)	78%	percent	From BANCS field survey sheets
% stream banks with moderate to high BEHI	22%	percent	From BANCS field survey sheets
% stream banks with very low to low near bank shear stress (NBSS)	70%	percent	From BANCS field survey sheets
% stream banks with moderate to high NBSS	30%	percent	From BANCS field survey sheets
Annual gross stream bank erosion estimate – stream banks in surveyed reach or 9 miles	1924	Mass (tons)	Predicted by BANCS
Annual gross streambank erosion estimate – scaled-up to whole river length of 23.9 miles	5110	Mass (tons)	Predicted by BANCS
Sediment load estimated to be transported downstream (fine sediment; silt and clay)	2862	Mass (tons)	Predicted by BANCS
Estimated contribution of banks to suspended load using the bluff:bank ratio method	672-711	Mass (tons)	Using TSS load data from Knife River and bluff:bank erosion ratios from BANCS sheets

The ratio of bluff to bank gross erosion from the Lake County BANCS data sheets was found to be 0.51 : 0.49 (bluffs : banks) assuming that banks greater than 10 feet were actually bluffs, not accounting for the fraction of fine sediment. When accounting for the fraction of fine sediments, using 56% fine sediment for streambanks and 90% fine sediment for bluffs, the ratio of bluff to bank contribution to suspended load would be 0.63 : 0.37.

The bluffs which are thought to be the major source of sediment in the north shore streams were estimated to comprise 73% of the total sediment load in the Knife River (Table 5 of main report). Since the total measured TSS load in the Knife River ranged from 1,259 to 4,614 tons/year between 2001 and 2013 and averaged 2,489 tons per year, the bluff contribution would be equivalent to 1,817 tons/year from bluff erosion on average.

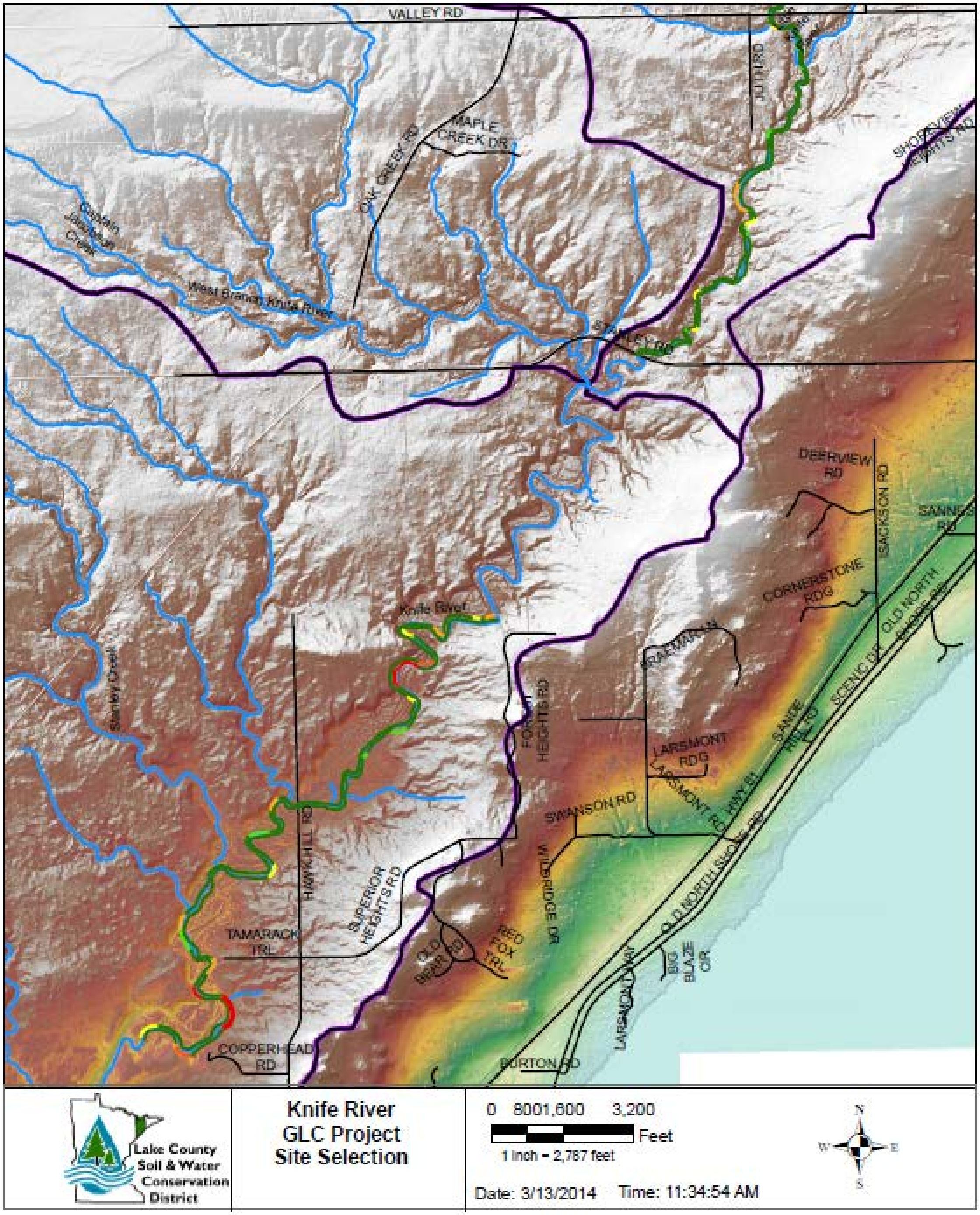


Figure 1. Sample locations for BANCS analysis done by Lake County SWCD in 2013. Surveyed reaches are highlighted in green.

Discussion

The gross erosion estimates of bank erosion (5,110 tons/year) are likely overestimates due to the use of BANCS graphs that aren't specific to the North Shore of Minnesota. Secondly the qualitative description of the BEHI and NBS scores described 78% of BEHI scores and 70% of NBSS scores to very low or low, indicating there was not much observational evidence for large sediment contributions from stream banks. However given the long linear extent of streambanks (23.9 miles on the main stem of the Knife River) even slight increases in bank erosion could lead to large sediment load increases in the range of hundreds to thousands of tons/year. Therefore a more reasonable estimate of net stream bank contribution to suspended load might be the 672 - 711 tons/year estimate obtained using the bank : bluff erosion ratio and measured TSS data from the Knife River.

Another issue with the BANCS methodology is that the sediment loading estimates are based upon annual average erosion rates from small frequent floods. However the 2012 flood along the North Shore was more than two times the previous high at 25,500 cfs on the Knife River at the USGS Two Harbors stream gauge in 40 years of record. This event likely eroded many times the annual average mass of sediment. This appeared to be the case for the bluffs surveyed in this project and is likely applicable to the stream banks. However further research is needed to confirm actual rates of stream bank erosion using repeat surveys with LiDAR scans and/or field surveys. This would help to corroborate the BANCS predictions.

References

Rosgen, D.L., 2001, March. A practical method of computing streambank erosion rate. In *Proceedings of 7th Federal Interagency Sedimentation Conference, March, Reno Nevada*.