Lake Superior Streams Sediment Assessment: Phase I

A report prepared for the Minnesota Pollution Control Agency

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CLEAN WATER LAND & LEGACY AMENDMENT

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EXECUTIVE SUMMARY

Under the Clean Water Act, states are required to monitor their water bodies for water quality impairments. While Minnesota's North Shore has relatively little development as compared to other areas of the state, degraded stream health does still exist. At present, 12 of Minnesota's major tributaries draining to Lake Superior are impaired for turbidity, mercury and chlorides as well as low dissolved oxygen, lack of cold water assemblages and pH. Turbidity and excess sediments are the leading causes of water quality impairments throughout the United States and turbidity is identified as an impairment on 10 of the 12 streams impaired along the North Shore. These turbidity impaired streams include the Knife, Poplar, Beaver, Flute Reed, French, Lester, Talmadge and Big Sucker Rivers as well as Amity and Skunk Creeks. Excessive turbidity in these streams is largely dependent on elevated suspended sediment levels. These sediments are delivered to streams from upland sources of erosion as well as instream erosion of channel banks and bluffs.

Excessive sediment levels in Minnesota's North Shore streams are of concern due to their potential impact on the health of aquatic organisms, the fact that sediments carry nutrients to water bodies causing eutrophication of waters, and because these sediments can be transported to Lake Superior where sedimentation can reduce depths in harbors and shipping canals. Due to these effects, erosion and sediment transport from Lake Superior tributary streams are being studied and modeled by federal, state and local agencies in order to manage impacts to receiving water bodies. The US Army Corps of Engineers (USACE) is developing sediment transport models for Great Lakes tributary streams, including one North Shore stream, the Knife River. Total Maximum Daily Load (TMDL) studies for excessive turbidity have been completed for the Knife and Poplar Rivers. Many more local monitoring and management efforts are active along other North Shore streams; however, a comprehensive study of the major causes of erosion and sediment transport, excessive turbidity levels and their impacts on North Shore streams has not yet been conducted.

This report details the first of a two part effort outlined in the Lake Superior Streams Sediment Assessment work plan to begin developing an ecological systems understanding of sediment loading and its impacts on stream health along Minnesota's North Shore. This initial assessment focused on characterizing the landscape of the North Shore as well as collecting and organizing available water quality data and data on aquatic organism health. This assessment also used GIS based tools to identify reference and degraded areas along the North Shore. Aerial flyovers and field studies were also used to expand upon GIS findings and to further characterize stability and erosion hazard along North Shore streams.

Initial findings show wide variability in stream turbidity levels with some of the greatest suspended sediment loads occurring in the spring of the year. As identified by the Knife River TMDL study, turbidity levels in the stream were on average twice as high as state water quality standards though turbidity levels exceeding 16 times the standard were documented. With respect to aquatic organism health across the North Shore, fish and macroinvertebrate species were found to have "Good", if not "Fair", overall health and diversity as defined by metrics of the Index of Biologic Integrity.

Using a GIS based analysis tool, anthropogenic factors such as population density, road density, land cover in crops and developed land cover were evaluated for their spatial distribution and magnitudes. Results showed that potential impacts from these variables were most highly concentrated around the more urbanized areas of Duluth and Two Harbors near the Lake Superior Shore. While the magnitude of potential stress associated with road density was overall quite low, roads were the most widespread

anthropogenic stressor and therefore have the greatest potential to impact water quality across the entire area of the North Shore. A detailed field analysis further identified that roads can increase catchment drainage density and can promote erosion from and along roads. Additionally, road-stream crossing were found to have destabilizing effects on streambanks both upstream and downstream of the road crossings.

Using an additional GIS based tool, natural variables were also assessed for their potential to impact water quality. Examples of these variables include stream channel and near channel slopes, sediment erosion factors, wetland area and tree canopy coverage. Accumulated effects of such variables demonstrate that areas with the greatest potential to impact water quality occur along channel mainstems, with stress potential trending positively with stream order.

Stream channel characteristics assessed by aerial photograph analysis identified stream reaches with high potential for channel erosion and those which have increased stability as a result of bedrock controls. A group of 33 sites was also field assessed for channel stability using Rosgen's modified Pfankuch assessment; approximately ~42% of those sites were considered to have "Good" stability, ~27% "Fair" stability and ~31% "Poor" stability.

Follow-up work to a separate study, the Lower Poplar River Sediment Source Assessment project, was also summarized here and the full report is included as an appendix at the end of this document. This effort used LiDAR data to identify preferential flow pathways throughout the watershed where gully and ravine erosion are likely to be present. Furthermore, a WEPP model was designed to evaluate sheet erosion from both hillslopes and throughout the Lower Poplar River watershed. While land use in this area is primarily forested, there are resort developments with associated ski runs, hiking trails, and a golf course complex, along with townhome, single residential home subdivision developments and a road network for access. WEPP modeling identified the largest soil losses due to sheet erosion as coming from the ski slopes.

ACRONYMS

BEHI	Bank Erosion Hazard Index
CL	Confidence Limit
CWA	Clean Water Act
CZMA	Coastal Zone Management Area
DEM	Digital Elevation Model
DNR	Department of Natural Resources
EDA	Environmental Data Access
F-IBI	Fish Index of Biologic Integrity
FNMU	Formazin Nephelometric Multibeam Unit
FNU	Formazin Nephelometric Unit
GIS	Geographic Information Systems
GP	Glide/Pool
IBI	Index of Biologic Integrity
LCCP	Land Cover in Crop Production
LCDV	Land Cover Developed
LiDAR	Light Detection and Ranging
M-IBI	Macroinvertebrate Index of Biologic Integrity
MnDOT	Minnesota Department of Transportation
MPCA	Minnesota Pollution Control Agency
NHD	National Hydrography Dataset
NLCD	National Land Cover Dataset
NPDES	National Pollution Discharge Elimination System
NRCS	Natural Resources Conservation Service
NRMP	Normalized Population Density
NRRI	Natural Resources Research Institute
NTRU	Nephelometric Turbidity Ratio Unit
NTU	Nephelometric Turbidity Unit
RDI	Road Density Index
RGA	Rapid Geomorphic Assessments
RII	Road Impact Index
RLA	Reconnaissance Level Assessments
RR	Riffle/Run
SGP	Short Grass Prairie
SPI	Stream Power Index
SSSF	Shallow Subsurface Stormflow
STATSGO	State Soil Geographic Database
SUMREL	Sum of Relative Scores
TDS	Total Dissolved Solids
TDVS	Total Dissolved Volatile Solids
TGP	Tall Grass Prairie
TIGER	Topographically Integrated Geographic Encoding and Referencing
TMDL	Total Maximum Daily Load
TS	Total Solids
TSVS	Total Suspended Volatile Solids
TSS	Total Suspended Solids
TVS	Total Volatile Solids
UMN	University of Minnesota
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
W/D	Width to Depth Ratio
WEPP	Water Erosion Prediction Project

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1.0 BACKGROUND

Located along the easternmost edge of the Laurentian Mixed Forest, the Minnesota North Shore spans approximately 2,211 square miles and encompasses both the Lake Superior North (04010101) and Lake Superior South (04010102) 8-digit HUC watersheds (Figure 1). Topography along the North Shore is quite variable. Elevations range from approximately 2,300 ft. above mean sea level down to approximately 600 ft. at Lake Superior (Figure 2). Elevation changes are greatest along the steep peaks and ridges near the shore of Lake Superior; whereas, upland areas experience more level and gently rolling terrains. Due to the variability in elevation of this landscape, Lake Superior tributary streams are some of the most variable in the state with gently meandering low relief streams as well as cascading rivers and waterfalls.

Catchment areas drained by some of the larger Lake Superior tributaries are illustrated in Figure 3. The size distribution of these catchments is shown in Figure 4. Catchment areas greater than $50mi^2$ include the Lester, Gooseberry, Cross, Devil's Track, Knife, Manitou, Cascade, Poplar, Beaver, Baptism, Temperance, Brule and Pigeon River catchments. Together they span an area that covers approximately 70% of the North Shore. Characteristics of each catchment are summarized in Table 1.

2.0 COMPILATION AND ASSESSMENT OF EXISTING DATA

In accordance with Task 2a of this project, Reconnaissance Level Assessments (RLAs) were conducted for the North Shore. These assessments focused on collection and preliminary assessment of existing data relating to landscape characteristics and stream health.

2.1 LAND COVER

Land cover across the North Shore is predominantly forested with nearly 85.7% of the area covered by deciduous, evergreen and mixed forests (Figure 5). Open water areas and wetlands cover 4.9% and 3.1% of the area, respectively, while developed lands, which are concentrated primarily around the urbanized Duluth area, cover just over 1.7% of the North Shore area. Other land uses in this area are comprised of shrub, grassland, pasture, cultivated crops and barren land (Table 2).

2.2 GEOLOGY AND SOILS

Soils along the North Shore are comprised largely of glacial tills. The Rainy lobe glacial advance brought with it a brown, sandy till consisting of basalt, gabbro and other rocks from the North East. The Superior lobe deposited red sandstone, shale and agates which together formed tills distinctly red in color (MGS, 1997). Soils in other parts of the North Shore are the result of igneous basalt scoured uplands (Table 3).

At present, comprehensive spatial soils data are not available for the entirety of the North Shore though some detailed quadrangle maps, which were generated by the Minnesota Geological Survey for areas between the French River and Castle Danger, do exist (see Appendix A; Hobbs, 2002, 2003a, 2003b, 2004, 2009). The most recent comprehensive assessment of soils across the North Shore dates back to the 1980 survey by Cummins and Grigal (1980). This survey delineated soil boundaries by considering landscape relief with other soil forming factors such as climate, parent material and vegetation. The soils delineated by this process include organic soils as well as those soils formed in red clayey sediments, in thin tills over bedrock, in gray/brown sandy and gravelly sediments and in mixed sediments from the Rainy and Superior Lobes (Table 4). The spatial distribution of soils across the North Shore based on the Cummins and Grigal survey is shown in Figure 6.

The breakdown of soils common across the North Shore and large Lake Superior tributary catchments (>50mi2) are shown in Figure 7. Soils formed in thin tills over bedrock (brown and red tills, brown stony tills and gray lacustrine deposits) are the most common soil types covering nearly 60% of the area of the North Shore. Soils formed in brown sandy and gravelly sediments (brown till, stony brown till and some red outwash) constitute approximately 20% of the soils by area, while soils formed in red clayey sediments (red lacustrine sediments) or those formed in mixed sediments from the Rainy and Superior Lobes (red stony tills) each cover nearly 10% of the North Shore. Minor areas along the North Shore are covered by organic soils according to the 1980 soils survey.

The Pigeon River catchment is comprised predominately of soils formed in thin tills over bedrock (~95% by area; brown tills). This is in contrast to the Manitou River catchment which has the lowest percent of soils formed in thin tills over bedrock (~25% by area) but the highest percentage by area of soils formed in sandy and gravely sediments (~55% by area). The Knife River catchment has the largest percent of clayey red lacustrine sediments (28%) while the Beaver and Gooseberry River catchment have red lacustrine sediments covering 14% and 17% of their catchment areas, respectively. The remaining catchments have less than 5% red lacustrine sediments by area. Figures illustrating the spatial distribution of these soil types across large Lake Superior tributary catchments (>50mi^2) are provided in Appendix B.

2.3 STREAM CHARACTERISTICS

Streams along the North Shore have some of the most variable relief and classification types in Minnesota. While much of Minnesota has low relief streams and rivers, some North Shore streams experience substantial topographic changes resulting in cascades and waterfalls. North Shore streams are also unique in that they can either meander through relatively erodible soils or be channeled through armored sections or over bedrock outcroppings. Streams in the headwaters are lacustrine flowages between wetlands and/or lakes. Unit stream power is very low compared to typical watersheds where unit stream power is strong near the headwaters and becomes less strong in large flat valleys; the Mississippi River is a classic example. The strongest unit stream power in many North Shore streams occurs within a mile or two of the outlet into Lake Superior. This feature drives a number of physical, biological and chemical attributes. Physically, waterfalls limit fish passage and, biologically, only selected species can survive in turbid high velocity water. Chemically, low oxygen water displaced from an upland wetland becomes enriched in oxygen with the passage over rocks and falls. Though some of these attributes can be found in other Minnesota streams, the combination of gradient, that is, no-flow (lacustrine) to extremely high flow near the mouth (no sediment deposition) is unique to North Shore streams in Minnesota. These features will require a tailored management approach to insure a sustainable future for vulnerable stream systems.

2.3.1 Aerial photograph collection and erosion assessment

As part of the project’s effort to efficiently document stream characteristics along select waters, aerial photographs were collected along mainstem reaches of the Brule, Temperance and Knife Rivers. These photographs were taken during leaf off in the Spring of 2010 by flyover surveys conducted by the MPCA (Task 2c). These photos were used to identify many eroding bluff features along the mainstem of channels. Descriptions of the eroding bluff features and their locations along the surveyed streams are presented in Appendix C.

2.3.2 Evaluation of stability, channel armoring and bedrock controls

In addition to detecting actively eroding features, these aerial photographs of the Knife, Temperance and Brule Rivers were also used to evaluate bankfull channel dimensions along the rivers. These bankfull dimensions were used to predict channel stability. In the absence of armoring or bedrock controls, bankfull widths tend to increase with increases in contributing catchment area. As a result, the widest part of the stream is often the channel mouth. In contrast, the presence of stabilizing bedrock controls or channel armoring can inhibit channel widening. These areas are represented by sudden decreases in channel widths and lower overall correlations between channel widths and contributing catchment area.

Examples of the effects of bedrock controls on bankfull channel widths are illustrated in Figure 8. On Lake Superior tributary streams such as the Brule and Temperance Rivers, channel widths tend to decrease suddenly where bedrock controls and armored channel banks are present. Bankfull widths increase, again, as the channel passes through more erodible soils. In contrast, the Knife River, which meanders through more erodible clayey lacustrine sediments, has fewer bedrock controls and a stronger overall correlation between the width of the channel and contributing catchment area. As one might predict, the lower part of the Knife River is more susceptible to bank and bluff erosion than the Brule and Temperance Rivers.

2.4 STREAM FLOW DATA

Streamflow data is a critical component for calculating pollutant loads in streams. Flow records can also be useful for performing hydrologic analyses or evaluating long-term streamflow trends. All streamflow gaging stations that are or have been operational along the North Shore were identified and are reported in Table 5. Data from these stations have been collected and maintained by the NRRI, the USGS and the DNR/MPCA. GIS layers containing gage station information and streamflow data are provided in Appendix D.

The earliest long-term gaging stations installed on streams along the North Shore include those on the Poplar River (October, 1912), the Pigeon River (June, 1921), and the Baptism River (August, 1928). Figure 9 highlights the 14 Lake Superior tributaries (with catchment areas >10mi^2 in size) and the timelines for which these streams have been monitored for flows. It is of note that only six are continuously gaged today (Pigeon, Brule, Poplar, Baptism, Amity and Knife Rivers). Consequently, long-term streamflow records are limited for Lake Superior tributaries on the North Shore.

As streamflow data are limited, discharge relationships were evaluated for streams in neighboring catchments as a means to extrapolate missing streamflow records. Relationships between mean daily discharges for nearby Lake Superior tributaries are shown in Appendix E. From these data it appears that strong relationships exist between many North Shore streams.

2.5 SEDIMENT RELATED WATER QUALITY DATA

All available water quality data were compiled for submission with this report. Although sediment related data are of particular interest in this study, all water chemistry data were collected and organized due to its potential importance in identifying biological stressors and assessing overall stream health in subsequent tasks. The locations of all TSS, transparency and turbidity water quality monitoring stations are illustrated in Figures 10 and 11. Timelines of data collection for TSS, turbidity and transparency as well as sample levels are provided in Appendix F. The MPCA's online Environmental Data Access (EDA) provided the largest collection of water quality data for the North Shore though the NRRI's Lake Superior Streams website also provides substantial chemistry data for Duluth area streams. Georeferenced water quality data were submitted with this report (see Appendix D).

2.5.1 Sediment related water quality parameters

A number of sediment related parameters are available from water quality monitoring stations along the North Shore. These parameters include turbidity, transparency, total suspended solids, total volatile solids, total dissolved solids, and total solids. A description of each sediment related parameter is provided below though turbidity, transparency and total suspended solids are likely to be the most relevant data to this study.

Turbidity is the cloudiness or haziness of water and can be impacted by a variety of factors including sediments, organic and inorganic material, soluble organic compounds and microbes (MPCA, 2008). Turbidity is measured by passing light through water and measuring the extent to which the light is scattered. While often reported in Nephelometric Turbidity Units (NTUs), turbidity can take on a variety of units (NTUs, NTRUs, FNUs, and FNUMs) which result from differences in measurement methods such as the wavelengths of light and the direction at which it is applied through a water column (see Table 6). Due to variation in light scattering, it can be difficult to compare data between these methods. Turbidity data collected along the North Shore are reported in variable units (NTUs, NTRUs, FNUs, or without units). At present, the state of Minnesota uses turbidity as its metric to assess sediment related stream impairments. The State's numeric water quality standards are 10NTUs or 25NTUs for Class 2A and Class 2B waters, respectively.

Transparency is also a measurement used to examine water quality impacted by sediments. This parameter expresses how clear water is and is defined by the depth to which light penetrates water (depth in centimeters).

Total Suspended Solids (TSS) are particles sampled from the water column which can be removed by filtration. Under the Clean Water Act (CWA), TSS is considered a conventional pollutant. In contrast to TSS, **Total Dissolved Solids (TDS)** are operationally defined as material that can pass through a 2um pore filter. These materials constitute both organic and inorganic substances in water. **Total Solids (TS)** represent the sum of total dissolved (TDS) and TSS in water. TS, like TSS and TDS, are reported in mg/l. **Total Volatile Solids (TVS)** represents the fraction of TS comprised of organic compounds of plant or animal origin. TVS constituent material can be removed by biologic processing (eg. enzymatic or microbial degradation, etc.).

As sediment related data collection is highly variable across the North Shore, relationships between various parameters may prove useful to establish more robust datasets. At a regional and local scale, transparency, TSS and turbidity are often highly correlated. Figure 12 demonstrates the relationship between transparency and TSS along North Shore Streams. Transparency decreases rapidly with increases in TSS and quickly levels out, a typical trend for transparency and TSS relationships. While there is a more robust dataset for the Lake Superior South watershed compared to the Lake Superior North watershed, overall relationships appear to be similar. For the entirety of the North Shore as well as for the individual 8-digit HUC watersheds, transparency and TSS relationships appear to be quite strong with R^2 values ranging from 0.59 to 0.64.

Water quality data reported to the MPCA come from a variety of resources including the DNR, USGS, MPCA, and NRRI. Due to inconsistencies in water quality data observations and before further analysis, all turbidity data analyzed will need to be confirmed for unit accuracy through personal contact with personnel from reporting agencies before further analysis. An example of the type of inconsistencies identified includes times when turbidity units are represented by Nephelometric Turbidity Unit (NTU), but were actually recorded as Nephelometric Turbidity Ratio Unit (NTRU) or Formazin Turbidity Unit (FTU). In some instances turbidity units are not specified.

2.6 TURBIDITY TOTAL MAXIMUM DAILY LOAD (TMDL) STUDIES

To date, two turbidity TMDL studies have been completed for the Knife and Poplar Rivers. The Knife River was placed on the 303d list of Impaired Waters in 1998 due to excessive turbidity levels. During the TMDL data collection phase from 2004 to 2006, 64 grab samples were collected to evaluate turbidity levels. On average, turbidity levels were about twice the numeric water quality standard of 10 NTUs. The maximum exceedance documented during this study was approximately 16 times the state's water quality standard; this exceedance was recorded during the summer of 2005.

In addition to turbidity, collected water samples were also assessed for TSS. TSS levels correlating with 10 NTUs were found to be either 15-18mg/L at the upper part of the watershed or 4-5mg/L near the channel confluence with Lake Superior where red clayey soils are more common. These data highlight the local variability possible for turbidity-TSS relationships.

In 2004, the lower 2.73 mile section of the Lower Poplar River was also placed on the 303d list of impaired waters for excessive turbidity. A number of studies have been completed on this impaired reach and the "Poplar River Turbidity Assessment" (RTI, 2008) identified that the highest exceedances occur at the higher flows. This study also revealed that over half of the annual sediment loads were transported during spring time. TSS and turbidity relationships developed for the Poplar River identified a 12mg/L TSS surrogate for the 10NTU turbidity standard.

2.7 BIOLOGICAL DATA – INDEX OF BIOLOGIC INTEGRITY (IBI)

The Index of Biologic Integrity is a tool used to assess overall stream health through biosurveillance of fish and macroinvertebrate community structure. IBI scoring thresholds and confidence limits are developed from reference water bodies and take into account the natural variability of biological community structure within a specific stream class. As a result, IBI scores can be compared between streams across the state. Along Minnesota's North Shore, stream classes for Fish IBI (F-IBI) surveys include Northern, Northern Coldwater, Northern Headwater, and Low Gradient Streams. For Macroinvertebrate IBI (M-IBI) surveys, classes are delineated by Northern Coldwater Streams, Northern Forest Rivers, and the Riffle/Run (RR) Habitats or Glide/Pool (GP) Habitats of Northern Forest Streams.

IBI scores that fall within the upper and lower confidence limits (CL) of community specific threshold scores designate overall stream health as "Fair". Stream health is considered "Good" when IBI scores are above the upper CL and "Poor" when IBI scores fall below the lower CL for each stream class. IBI scores can range from 0-100 with 100 indicating the best possible stream health based on biologic community structure.

Fish and macroinvertebrate IBI rating scores for sites surveyed along the North Shore since 1997 are provided in Figure 13. Preliminary assessment of the data demonstrates that stream health, as assessed by IBI score, is considered "Good" for a majority of the streams and rivers sampled along the North Shore. It is difficult to comment on trends in stream health by stream class, as F-IBI and M-IBI surveys were conducted mostly in Northern Coldwater Streams. Streams considered to have "Poor" health according to both F- and M-IBI surveys include the Beaver and Knife Rivers as well as Chester and Tischer Creeks. All data have been included in a GIS Geodatabase and were submitted with this report.

3.0 ANTHROPOGENIC STRESSOR ANALYSIS TO IDENTIFY DEGRADED AND REFERENCE CATCHMENTS

Human activity can stress landscapes and have deleterious effects on water quality. The following presents an assessment of the relative extent and spatial distribution of anthropogenic stress along the Minnesota North Shore and reveals potential factors impacting turbidity in this region. This assessment also fulfills components of Task 2b of the Lake Superior Streams Sediment Assessment project.

3.1 GIS BASED ANTHROPOGENIC STRESSOR TOOL

To investigate anthropogenic stress along the North Shore, this study employed a scalable GIS based anthropogenic stressor tool developed for the Lake Superior Basin by the Natural Resource Research Institute (NRRI) at the University of Minnesota Duluth (Host et al., 2010). The tool was developed using high resolution (10m) Digital Elevation Model (DEM) terrain data to delineate the catchments and subcatchments of the Lake Superior basin. Stressor gradients within each delineated subcatchments were determined for land cover, population density, and road density using the National Land Cover Database, US Census data, and TIGER line data, respectively (Table 7). Additionally, point source discharge data were determined for larger Lake Superior tributary catchment using NPDES point source discharge permit records. All stressor data used by the NRRI to develop the tool are publically available. Further information on the development and use of this tool can be found in the 2010 NRRI report in Appendix G.

To address the relative impact of various stressors, the NRRI performed a series of transformations, standardizations and normalizations to both density and percent cover values for anthropogenic stressors within each subcatchment (Host et al., 2010). The resulting values for each stressor variable were then added and again normalized to the entire area of the North Shore to derive a sum of relative scores, or a "SUMREL" composite score. This standardization process allows for comparison of SUMREL scores between catchments, or subcatchment areas, that are variable in size. Point source discharge data were only considered for larger catchment areas (for the purpose of this study, those catchments delineated with areas greater than 10mi^2). Normalized SUMREL composite scores have values ranging from 0.0 to 1.0, with 1.0 indicating the highest level of potential stress. The GIS layers used in this study were accessed online through the UMN NRRI website (http://www.nrri.umn.edu/lsgis2) and consisted of delineated catchment and subcatchment boundaries with corresponding anthropogenic stressor scores.

3.2 DEFINING ANTHROPOGENIC STRESS

Composite SUMREL scores were investigated for subcatchments delineated along the North Shore (NRRI, 2010) as well as the larger Lake Superior tributary catchments with areas greater than 10mi^2. For the purpose of this study, catchments and subcatchments were considered to have a "reference" condition if the composite SUMREL scores were between 0.0-0.3, or to be "degraded" by anthropogenic stressors if SUMREL scores fell between 0.7-1.0 (Host et al., 2010). All SUMREL scores between 0.3-0.7 were considered to represent intermediate conditions.

3.3 SUBCATCHMENT LEVEL SUMREL ANALYSIS

SUMREL composite scores were evaluated at the subcatchment level according to procedures outlined by the NRRI (Host et al., 2010). Their SUMREL scores were derived without consideration of point source discharge variables. This approach was suggested by the NRRI as point source discharge is a stressor variable seldom encountered at the subcatchment level.

Most subcatchments across the North Shore have composite SUMREL scores below 0.3 and therefore are predicted to have "reference" conditions (Figure 14). The median subcatchment composite SUMREL score is 0.012 though scores upwards of 1.0, which qualify subcatchments as "degraded", are found in subcatchments in the urbanized Duluth area. Road density appears to be the most influential variable raising SUMREL scores across most of the North Shore. This is evident in Table 8 as the median and mean road density index (RDI) scores for subcatchments of major Lake Superior tributary catchments tend to be higher than scores for population density (NRMP), percent land cover developed (LCDV) and percent land in agricultural crop production (LCCP). Subcatchments with the highest SUMREL scores are primarily the result of a combination of high road densities, high population densities and increased levels of development.

3.4 CATCHMENT LEVEL SUMREL ANALYSIS

Lake Superior tributary catchments with areas greater than $10mi^2$ were investigated in the catchment level analysis. When SUMREL stressor scores were evaluated using the same four stressor variables (RDI, NRMP, LCDV, LCCP) at this catchment scale, each catchment, with the exception of the "degraded" Lester River area, appeared to have a "reference" condition (Figure 15). However, when the point source discharge variable are included in the calculations of SUMREL scores, no catchments are identified as having "reference" conditions (Figure 16). These data reflect similar findings by the NRRI (Figure 17).

The SUMREL composite scores derived using the point source discharge stressor variable, are much higher than those derived without it (Table 9). Although concentrated in small areas along streams, often near catchment outlets, the point source discharge variables have high potential to inflate catchment wide SUMREL scores. Accordingly, care should be taken when interpreting catchment health based on the influence of the point source discharge variables.

3.5 PREDICTION OF TURBIDITY IMPAIRED LAKE SUPERIOR STREAM CATCHMENTS

It is difficult to comment on the ability of the anthropogenic stressor variables to predict the likelihood of turbidity impairments within Lake Superior catchments. This is in part due to differences in water quality and streamflow data available for the Lake Superior tributary catchments. As illustrated in Figure 18, only one catchment encompassing a turbidity impaired stream was identified as "degraded" using the SUMREL anthropogenic stressor tool (Lester River & Amity Creek catchment; SUMREL scores between 0.7-1.0). The Knife and Beaver River catchments, which are designated by the state as impaired for turbidity, also had SUMREL scores very near degraded conditions when point source discharge variables were considered (SUMREL scores between 0.6-0.7). In contrast, the turbidity impaired Poplar and Flute Reed River catchments have SUMREL scores within the range of 0.4-0.5, which categorizes them as having intermediate, not necessarily degraded conditions. This may suggest that SUMREL scores that account for all of the five anthropogenic stressor variables, and result in "degraded" conditions, could extend below 0.7 for the North Shore. It may be difficult to determine what the appropriate range of SUMREL scores for "degraded" conditions is as many streams which are not designated as impaired (for example the Manitou, Baptism, and Devil's Track River catchments) have SUMREL scores between 0.4-0.7 (0.4-1.0 accounts for the range of SUMREL scores assigned to catchments with known turbidity impairments). It is unlikely that modifying our definitions of a "degraded" catchment from 0.7-1.0 to some wider range would more accurately capture "degraded" areas.

When SUMREL scores are derived with the exclusion of point source discharge data, all large Lake Superior tributary catchments, with the exception of the Lester River catchment, are considered to have a “reference” condition (SUMREL composite scores less than 0.3). Based on these findings using anthropogenic stressor data, it is difficult to identify degraded and reference condition catchment areas for turbidity impaired waters in this study. That being said, this anthropogenic stressor tool does reveal that spatially, roads are the anthropogenic variable with the greatest potential to impact water quality over the area of the North Shore.

4.0 EVALUATION OF NATURAL VARIABLES AND THEIR ACCUMULATED POTENTIAL FOR WATER QUALITY IMPACTS

As anthropogenic factors did not appear to be the only variable impacting sediment loading along North Shore streams, natural variables were also considered. To evaluate the potential impact of natural variables on water quality of North Shore streams, a similar GIS based analysis tool developed by the NRRI was used (http://gisdata.nrri.umn.edu/geonetwork/). In addition to evaluating anthropogenic variables (nrmp, rdn, lccp, lcdv), this tool considered natural variables such as stream slope, stream context, stream-road intersections, percent canopy coverage, percent wetlands, stream channel and stream context sedimentary erosion potential (from STATSGO data) and stream channel and stream context KFFACT (from STATSGO data). For a list of each variable see Table 10. The “stream context” is a term coined by the NRRI to describe the area around the stream, or essentially the stream banks (approximately 100m on each side of the stream). KFFACT is a soil erodibility factor found in STATSGO soils data that “quantifies the susceptibility of soil particles to detachment and movement by water” (Brown, 2011).

Individual variable scores derived for each of the natural variables were compared between subcatchments along the North Shore. This tool also calculated “accumulated” stressor scores for each subcatchment based on scores for that area, as well as from each upstream subcatchment. In order to locate “reference” and “degraded” locations, overall subcatchment level SUMREL scores were re-calculated using these natural variables in addition to the anthropogenic variables previously assessed. For more information on the development of this tool see the 2011 NRRI Report in Appendix H.

4.1 ANALYSIS OF INDIVIDUAL NATURAL VARIABLES

Stream slopes (stmslp) and bank slopes (bnkslp) were assessed for each subcatchment along the North Shore. Stream slopes are greater in some of the more Northern catchments as well as along the Lake Superior shore while accumulated variable scores are highest near the channel confluences (Figure 19). Accumulated scores are notably higher and impact longer stream reaches on the Brule River as compared to any other North Shore stream (Figure 20). Bank slopes are steeper among the more northern catchments like the Pigeon and Brule rivers as well as along areas very near the edge of Lake Superior (Figure 21). When accumulated bank slopes (a_bnkslp) were considered, their scores and potential stress appeared to be highest along the main channels of the rivers (Figure 22). As one might expect, the Pigeon and Brule rivers, which have the greatest number of subcatchments with higher stream context scores, also have some of the greatest accumulated variable scores.

Mean STATSGO sedimentary erosion potential, for both in the stream channel (ssedero) and along the channel banks (bsedero) shows low to intermediate values for much of the North Shore (Figure 23 and 24, respectively). Near reference level scores are found primarily in the Caribou, Two Island, Brule and Pigeon River catchments. Accumulated scores for sedimentary erosion potential are highest along the stream channels. Higher accumulated stressor scores trend with higher stream orders (Figures 25-26).

Mean STATSGO KFFACT values for the stream and bank areas are high where the sedimentary erosion potentials are elevated (Figure 27 and 28). Accumulated potential stress associated with the KFFACT variable is focused along the mainstems of the stream channels (Figure 29 and 30).

Though it can vary throughout the season, the percent canopy cover is quite elevated across most of the North Shore. Areas with the highest percent canopy cover include many subcatchments further up the North Shore (Figure 30). Accumulated percent canopy cover scores are also quite high across most of the North Shore (Figure 31). Wetland coverage was also elevated across the North Shore though the proportion of wetlands notably increases as one moves upland and inland (Figure 32). Unlike many of the natural variables assessed with this tool, accumulated benefits associated with wetland features does not appear to concentrate along stream channels but instead appears to remain in the upland and inland areas (Figure 33). These data may suggest that many of the upland wetland areas are relatively disconnected from downstream catchments.

4.2 ACCUMULATIVE IMPACT OF SUBCATCHMENT LEVEL ANTHROPOGENIC STRESSOR SCORES

Of the anthropogenic variables previously analyzed (rdn, nmrp, lccp, lcdv), the extent and spatial distribution of their stressor scores did not appear to differ when accumulated stress was evaluated (Figures 34-38). This is in contrast to the effects of accumulated stress when road-stream intersections were assessed using this revised tool. While the number of road-stream intersections was quite low in subcatchments across most of the North Shore, accumulated effects of these road-stream crossings elevated scores along the main channels (Figures 39 and 40).

4.3 REVISED SUMREL SCORES

Using scores associated with the natural variables, in addition to the anthropogenic stressor variables, revised SUMREL scores were calculated for subcatchments across the North Shore (Figure 41). At this scale, the data show that potential stress is higher along the lower half of the North Shore and in areas closer to the Lake Superior shore. The magnitude and distribution of these stressor scores appear to correlate most closely with the bkffact variable. When accumulated SUMREL stressor scores were evaluated, there were intermediate scores across much of the North Shore, with lower, “reference” condition SUMREL scores (0.0-0.3) found in the upper parts of the Temperance, Brule and Pigeon catchments (Figure 42). The “degraded” (0.7-1.0) or nearly degraded SUMREL scores were concentrated along the river channels with higher scores trending with higher order streams. Figure 43 demonstrates how higher accumulated SUMREL scores are concentrated along the higher order streams.

Together, these data demonstrate that many variables, both natural and anthropogenic in nature, have the ability to impact water quality along the North Shore. When evaluated together, the SUMREL scores derived with the NRRI’s GIS based stressor tool appear to be most dependent on the soil erodibility factors from the STATSGO soils data. When SUMREL scores are assessed for their accumulative effects, scores are highest along the main channels of streams where overland flows are channeled to. Higher SUMREL scores are again associated with higher stream order. More detailed SSURGO soils data, expected to be available within the next few years, will be very useful for refining our spatial understanding of degraded and reference areas along the North Shore.

5.0 FIELD VERIFICATION OF RLA RESULTS

In accordance with Task 3 of the Lake Superior Streams Sediment Assessment project, field efforts were completed to validate RLA findings. This includes assessments of stream stability and erosion hazard within catchments and subcatchments determined to have higher SUMREL scores. Additionally, comparisons of bank material were made to available soils data. The results are presented below.

5.1 STREAM STABILITY AND IN-CHANNEL EROSION

As outlined in Task 3a of the Lake Superior Streams Sediment Assessment, stream channel stability was also assessed to validate the ability of the GIS based anthropogenic stressor tool to identify areas of degraded stream health and instability. The Modified Pfankuch assessment used to assess stream stability is dependent on Rosgen's stream channel classification and physical characteristics of both channel banks and channel bottom. Erosion hazard at sites is dependent on physical characteristics of the channel banks alone. A total of 33 sites were assessed for channel stability and erosion hazard in this study.

5.1.1 Field site selection

Due to time constraints, field sites were selected and surveyed by the UMN team prior to the completion of RLA assessments and development of the NRRI's GIS based natural and anthropogenic stressor tools. In total, 33 sites were selected for field assessments along the Knife, Silver, Stewart, Crow, Encampment, Beaver, Temperance and Flute Reed Rivers. The selected sites were ultimately chosen along the length of streams to capture the variability in slope, topography, soils and stream order. Due to the rugged terrain across much of the North Shore, and to facilitate ease of access, field sites were limited to stream reaches near road crossings. Sites were not surveyed close to Lake Superior because channels nearer the lake are confined by bedrock outcrops and are therefore predictably stable.

5.1.2 Stream channel classification

The Rosgen Stream Classification system (Rosgen, 1996) employed in this study is commonly used by geomorphologists to determine stream types in order to evaluate channel stability. Rosgen's classification system considers channel and valley metrics to designate stream categories (A - G) and further observation of dominant channel material is also used to place the channel types into 6 further delineation classes (see Figure 44).

Both Rosgen Level I and Level II surveys were conducted during our field efforts (Table 10). Level II surveys involved the measurement of stream channel cross-sections to identify the average bankfull height, bankfull width, and floodprone width. Longitudinal surveys were made to determine channel slopes and pebble counts determined dominant channel bed material. Mecklenberg database templates were used to summarize these field measurements for 7 Level II sites and are included in Appendix I. It is important to note that four of these sites located on the Knife, Beaver and Encampment Rivers were previously surveyed in 1997 (Taylor et al., 1998, unpublished data) though comparisons between the data will not be discussed in this report.

To substantially increase the number of sites investigated along the North Shore, a large number of rapid Level I surveys (26 in total) were conducted in addition to the Level II surveys. To reduce field survey times, the Level I surveys relied upon visual estimation of dominant channel bed material rather than using pebble counts. No longitudinal profiles were made and floodprone widths were determined remotely following field visits. Both GoogleMaps and LiDAR terrain data (1m resolution) were used to remotely determine floodprone widths and associated entrenchment ratios at these sites. Bankfull widths and average depths were measured in the field. Bankfull indicators used included elevations of bench leveling, point bar elevations, visible water stains and transitions in vegetative material. All field metrics used to determine channel types are included in Table 10.

Although many channels were easily assigned a stream classification (A-G), some sites proved challenging to categorize. These challenges resulted from the potential error and variability associated with offsite assessments of floodprone widths, variability of channel characteristics observed along investigated reaches, and channel metrics which placed streams into a mix of categories or in between categories. A combination of channel metrics, photograph analysis and best judgment from experienced field technicians was used to assign stream types at such challenge sites.

Stream channel classification results are summarized in Table 11. Of the 33 sites assessed during the field campaign, channels having B2, B3, E3 and C4 type characteristics were the most commonly observed channel sites (6 sites each), though C2, C3, and E4 type channel characteristics were also repeatedly encountered. E2 and E5 stream types were each found at a single site. It is of note that channel material was highly variable at many of the sites surveyed in this study.

These data may not be surprising as E and C-type channels are the channel types most common to Minnesota. The armored channels and steeper gradients along Lake Superior form the landscape which shapes B-type channels like those encountered in the study. A-type channels are also present at waterfall locations along the North Shore though none were assessed in this study.

Spatially, E- and C-type channels were widespread across the North Shore (Figure 45). Sites classified as having B-type channels were more centrally located though this may be the consequence of the relatively limited number of sites evaluated. No trends were apparent when sites were classified by channel material.

5.1.3 Ranking of channels by stability and erosion hazard

Stream stability was assessed based on channel classifications at each Level I and II site using both Rosgen's modified Pfankuch stability assessment and the Bank Erosion Hazard Index (BEHI). Pfankuch stability assessments consider characteristics of the upper and lower banks as well as the channel bottom to rate stability associated with each stream class. Numeric scores derived using the Pfankuch stability assessment worksheet are then translated into an adjective stability rating of either "Good", "Fair" or "Poor" based on stream type. In contrast to Pfankuch, BEHI considers only streambank characteristics to identify the potential hazard for erosion and direct sediment loading to streams. However, similar to the Pfankuch assessment, BEHI also assigns an adjective rating score to each site. These ratings identify the erosion hazard as "Low", "Moderate", "High", "Very High" or "Extreme". Example of field forms used to collect Pfankuch and BEHI metrics are included in Appendix J.

Of the sites assessed in this study, 14 sites (over 40%) were considered to have "Good" stability based on Pfankuch assessments. Nine sites had "Fair" ratings and four sites had "Poor" ratings (Table 11). Four sites had intermediate stability ratings based on transitional channel classifications. For example, the Pfankuch score of 64 for the Stanley Creek (ST1) E3-4-type channel could have either a "Good" or "Fair" stability rating. Stability of each site as determined by the Pfankuch stability ratings are illustrated in Figure 46.

With respect to bank erosion hazard (BEHI), 13 sites had a "Low" erosion hazard, 17 sites were ranked as "Moderate", two sites were ranked as "High" and only one site was ranked "Very High" (Table 11). None of the sites investigated were considered to have "Extreme" erosion potential. Although a number of eroding bluffs with more severe erosion hazard and higher BEHI scores are known to occur along some North Shore streams, only one of those sites was field evaluated in this study. All sites and their adjective BEHI ratings are illustrated in Figure 47.

5.1.4 BANK AND BLUFF SOILS ASSESSMENT

The available soils data along the North Shore is quite generalized and the published quaternary geology mapping of the North Shore has only progressed as far as Castle Danger. Beyond Castle Danger, published maps are not accurate enough to describe local variability in geomorphic conditions that would impact erosion potential of stream channels. Furthermore, soils data is also limited to broad categories. To compare existing soils data to actual field conditions, soil samples were collected from streambanks and bluffs along North Shore streams and were analyzed in the lab by hydrometer and sieve analysis. Sites sampled had a wide range of distribution of particles sizes (Table 12). Of particular note was the high clay content of the sample taken from the Knife River bluff. This sample was collected from a location that overlaps with the broad area delineated as having predominantly red lacustrine sediments.

6.0 FIELD ASSESSMENT OF ROAD IMPACTS ON SEDIMENT SUPPLY

Although anthropogenic stress as determined by SUMREL scores was very low for most subcatchments of the North Shore, SUMREL scores were elevated in most subcatchments due to the presence and density of roads. To address the potential impact of roads on sediment delivery to Lake Superior tributaries, we examined the extent and hydrologic connectivity of roads and streams, the contribution of roadside erosion on sediment availability and the localized effects of stream-road crossings on stream channel stability. Due to the high density of roads and impervious surfaces around the City of Duluth, our analysis was directed at North Shore catchments outside of this urbanized area. The following presents a summary of the study findings (see Appendix K for the full report).

6.1 ROAD-STREAM CONNECTIVITY ANALYSIS

Within the transportation network high risk areas for increased sediment and fluvial conveyance exists for roads in close proximity to streams, especially roads draining to ditches which drain directly to streams. This is especially true for all road-stream crossings which serve as a direct connection of roads to streams (Croke et al., 2005). –Dutton, 2012.

GIS analysis of stream-road layers was conducted to examine the impact of roads on channel network extension. As with methods outlined by Miller (2010), this study quantified channel network extensions resulting from the proximity of roads to streams, in addition to the areas in which they intersect. To do this, a modified roads layer was developed which consisted of a MnDOT roads base layer and a US Forest Service (Superior National Forest) roads layer. The modified layer was overlaid with buffered stream layers (USGS NHD hydrography layer, 30m resolution) to evaluate roads within close proximity to streams. Stream buffer widths used to determine proximity were 10, 50 and 100-ft, to account for St. Louis County setback requirements (Dutton, 2012). The length of road intersecting these layers was considered an extension of the stream network and was added to existing stream lengths to evaluate changes in drainage density.

In total, 1346 stream-road intersections were identified using the GIS analysis and over 3485 miles of roads were found to be within 100ft of North Shore streams (Table 13). Together, the intersection of these features and their proximity to one another resulted in a drainage density increase of 1.5% when channels were buffered at 10ft widths and upwards of 9.5% when streams were buffered at 100ft widths.

To verify these increases in drainage density, channel network extensions were also measured in the field. Sites at stream-road crossings were selected at random from six control and impaired study catchments. Turbidity impaired catchments selected in this study include the Beaver, Flute Reed and Knife River catchments while control, or unimpaired waters included the Baptism, Brule and Temperance River catchments. It's important to note that these catchments all had similar land cover types (the exception being the large open water area in the Brule River catchment) and geomorphic associations representative of the greater North Shore.

A total of 54 sites, or 4% of all road-stream intersections identified by GIS, were selected for field verification of channel network extensions (Figure 48). Lengths of road within varying proximities of nearby streams (10, 50, and 100ft) were directly measured in the field. Similar to drainage density increases identified by GIS layers, drainage densities were found to increase by ~1.0% to 6.9% (corresponding to buffer widths of 10 and 100ft, respectively). These results suggest that road-stream linkages increase drainage densities in North Shore catchments and that estimates made using GIS reasonably match measurements made in the field.

6.2 ROADSIDE EROSION

Roads themselves erode over time and have the potential to transport sediments to nearby streams. To assess the extent to which roads act as sediment sources along the North Shore, the 54 road-stream intersections identified in section 5.1 were examined for the presence of active erosion (rill, gully or mass erosion) and volumes of sediment loss.

In this study rill erosion was characterized by features with continuous widths of 0.5–2in and depths of 0.25–2in while gullies were identified from features having discontinuous widths greater than 0.5in and depths less than 50in. "Mass erosion was characterized as a feature larger than a gully in which bank failure was observed" (Dutton, 2012). Sites were also assessed for road surface type and local landscape characteristics to explore variables that might predict the presence and degree of erosion.

In total, 35 of the 54 sites were impacted by observable erosion. This erosion occurred along paved, gravel and native soil roads and took on the form of rill gully and mass erosion. Rill, gully and mass erosion was encountered at 50%, 32% and 2% of sites with active erosion, respectively. By road surface type, 61% of paved roads, 65% of gravel roads, and 78% of native soil roads assessed in this study were found to be actively eroding.

To determine the volume of soil loss, erosive features were measured directly with a ruler and trundle wheel. In total, 93m^3 of sediment were found to have eroded from the sites with a majority of the erosion observed from the road shoulder alongside paved surfaces (54m^3). Controlling for extreme values, the greatest sediment losses occurred along paved roads on Superior Lobe glacial till in impaired catchments. On average, 1.7m^3 of sediment was lost from each site with median sediment losses of 0.005m^3. Scaling these sediment loss volumes from the 54 road crossings to the entire North Shore (1346 sites), erosion volumes are estimated to be upwards of 2,300m^3. If outliers are excluded, volumes of eroded sediment might be closer to 348m^3. These data represent a snap shot in time as each site was assessed only once during the summer of 2010. It is of note that the initiation of rill or gully erosion can lead to the expansion of erosion features as well as increased sediment loading over time.

Predictive modeling was also performed to identify factors that best predicted the erosion observed along the surveyed roads. Variables investigated include traffic intensity, road segment dimensions (length, width and area), vegetation type, k factor, impairment designation (impaired or not), hillslope position, geomorphic association, shoulder material, road supply and stream order. Determining traffic intensity was difficult as individual field visits were short for each site; therefore traffic intensity was given a binary indicator of "0" if roads were closed and vegetated or "1" if roads were operational. Significance for all comparisons was determined by p>0.05. The results of predictive modeling indicate that traffic, soil K-factor, impairment status, and hillslope position were the best predictors of the presence of erosion though they are not statistically significant. However, the width of road shoulder material (sediment supply) and hillslope position best determined erosion volumes and are statistically significant (p=0.009 and 0.045, respectively).

6.3 ROAD-STREAM CROSSING IMPACT ON CHANNEL STABILITY

While roads can impact stream connectivity and have the potential to transport eroded sediments to nearby waters, road-stream crossings also have the potential to impact channel stability resulting in increased sediment supply from within the stream. To address road impacts on local stream stability, channel segments, both upstream and downstream of road crossings, were evaluated for stability.

In total seven sites, or 14 segments, were selected for analysis (*Beaverx01, Brule28, Flute Reed, Knife32, Nicado, Temp16*, and *Temp17*), the locations of which are illustrated in Figure 48. These locations were selected from the road survey database based on ability to be accessed and surveyed, vegetative coverage condition and bridge or culvert conditions. The sites ranged from 1st to 4th order streams and drained catchments ranging in size from 0.5 to 147.7 square miles. Land cover was similar between catchments, with forested cover ranging from 83-97%, developed land ranging from 0.1-2.2% and wetland area ranging from 0-8.1% (Table 14).

To assess channel stability, each stream segment was first channel typed using Rosgen Level I and II channel surveys. Cross sectional profiles, longitudinal profiles, bankfull elevations, W/D ratios and dominant channel material were determined from field measurements. Aerial photos accessed from the MN Geospatial Information Office (2011) and GoogleEarth™ were used to determine entrenchment ratios where cross sectional profiles did not capture floodplain widths. Aerial photos were also used to evaluate sinuosity and alterations in channel morphology. Channel alteration was assessed using photos from 1991, 2003, 2009, and 2010 (accessed online from MN Geo, 2011). Statistics were completed using the Mann-Whitney-Wilcoxon test (p>0.05).

Of the 14 stream segments assessed, channel types included B, C and E-type channels. Channel types at upstream to downstream locations at the investigated road-stream crossings included E → C and B → B type channels at 2 sites and B → C, C → B, and C → B at a single site each (Table 15).

Channel stability was assessed at each site using the Modified Pfankuch stability assessment. As previously described, the Modified Pfankuch stability assessment assigns a stability ranking ("Good", "Fair" or "Poor") to streams based on characteristics of the upper and lower banks as well as characteristics of the channel bottom. At three of the seven sites, the stream segment downstream of the road crossing was found to have an overall reduced stability compared to the upstream segment of stream (Table 15). For example, upstream segments of the road crossing at *Beaverx01* had "Good" stability while the downstream segment had only "Fair" stability. In contrast, stability was improved downstream of the road crossing at the *Nicado* and *Flute Reed* sites. Overall stability rankings remained "Good", or stable, at both upstream and downstream segments at *Temp16* and *Temp17*.

Factors contributing to more degraded conditions downstream of the road crossing were the result of scouring of the channel bed, deposition on the lower banks and mass erosion of the upper banks at 57% of the sites assessed (see Appendix I for factors assessed in the Modified Pfankuch stability assessment). Streams downstream of road crossings were also more degraded due to steeper slopes of the upper bank and consolidation of channel substrates at 43% of the sites. Factors influencing more stable conditions at downstream segments included more uniform size of channel substrates, higher rock angularity and reduced debris jam potential (29% of sites).

Factors scoring similarly at upstream and downstream segments included rock angularity, and debris jam potential for 75% of the sites, bottom substrate distribution for 62.5% of the sites, and lower bank cutting, bank rock content, obstructions to flow and vegetative protection of the upper bank for 50% of the sites. Detailed stream surveys and stability analyses for each site are provided in Appendix K.

General observations from the field reveal that aggradation of sediments and debris jams upstream of road crossings appear to contribute to backwater conditions (*Nicado* and *Beaverx01*). Channel alterations detected using historical aerial images identified meander pattern change at the Brule and Knife rivers which directed channel flows at downstream streambanks. Field observations also identified increased runoff pathways from roads to streams at the culvert locations. At these locations increased sediment deposition was apparent on riprap and channel boulders.

7.0 LOWER POPLAR RIVER WATERSHED SEDIMENT SOURCE ASSESSMENT

The University of Minnesota's Lower Poplar River Watershed[4] Sediment Source Assessment study commenced in 2009 following the Lower Poplar River's 2004 listing as a turbidity impaired stream reach. The findings of this study expand upon and refine quantitative estimates of soil erosion from two previous studies (RTI, 2008 and NAWE, 2005) investigating sediment sources in the Lower Poplar River Watershed. Below is a summary of the methods and findings from the University of Minnesota's assessment of soil loss and sediment transport caused by sheet erosion, mass wasting at slumps, ravine erosion, erosion from roads and trails and erosion from streambanks and channel bottoms. Additional details can be found in the full report provided in Appendix J.

7.1 SHEET EROSION

Sheet erosion from hillslopes is heavily driven by rainfall and snowmelt events and can be dependent on surface runoff, shallow subsurface stormflow (SSSF) and groundwater discharge (reviewed in Nieber, 2013). In the Lower Poplar River Watershed (Figure 49), due to the predominance of near surface and exposed bedrock, the contributions of groundwater and SSSF are relatively minimal. Direct surface runoff generated from rainfall and snowmelt events is therefore the predominant driver of soil erosion from upland slopes.

[4] To be consistent with terminology of the "Lower Poplar River Watershed Sediment Assessment" report, the term "watershed" will replace the use of the term "catchment" (Lake Superior tributary *catchment*) in Section 7 of this report.

Surface runoff is generated when the rate of water applied to a surface exceeds the infiltration capacity of the soil or when subsurface flows saturate the soil profile and prevent infiltration. These are known as Hortonian and Dunne mechanisms, respectfully. Dunne mechanisms dominate in areas where the upper soil layers have high hydraulic conductivities and the downward movement of water is restricted by low conductivity layers of soil or bedrock. Hortonian mechanisms of surface runoff generation dominate where soils become saturated quickly, where vegetation is sparse and where the soil surface is very disturbed. Hortonian mechanisms are also significant during winter and spring snowmelt periods when the soil is frozen and soil hydraulic conductivities are drastically reduced.

The angle of slopes and their lengths can also play a crucial role in affecting the erosive power of overland flows. Physical obstructions on the landscape that impede surface runoff have the potential to slow overland flows and reduce sheet erosion.

Vegetation type and density can also have significant impacts on surface runoff throughout the year. Live vegetation and plant litter intercept rainfall and prevent compaction of the soil surface. Deep and extensive plant root networks promote infiltration by forming macropores through which infiltrating water is routed. These roots also play an important role in removing water from the soil profile during transpiration. Plants and plant litter can further function to insulate soils and reduce freezing of the soil profile.

7.1.1 Lower Poplar River landscape characteristics

A variety of land uses and land cover types are present across the Lower Poplar River Watershed. The terrain, vegetation and soil types characteristic of these areas all impact the magnitude of overland flows and soil erosion from hillslopes. Land use and vegetation present throughout the Lower Poplar River Watershed include forested areas (including upland and lowland deciduous and conifer forests), golf course areas (with short grass or lawn-grass), ski runs (areas defined as having shrub or grasslands modeled as either Tall Grass Prairies (TGP) and Short Grass Prairies (SGP) by the WEPP model), developed areas (resort areas with large areas of impervious pavements and little vegetation), slumps (unvegetated and exposed bluffs along the river channel), ravines (deep eroding features along hillslopes), and roads.

7.1.2 WEPP Modeling

WEPP Modeling accounts for runoff hydrology along hillslopes, sheet erosion and the transport of eroded sediments to streams. This model, which can simulate surface runoff caused by both Hortonian and Dunne mechanisms of overland flow, was used to quantify sheet erosion from both hillslopes and slumps in this study. The period of investigation ranged from 2001 through 2005. To accurately model for the erosive effects of overland flows during this period, the WEPP Model required soil, vegetation, terrain, and climate data to derive water balances as well as thermal balances within the soil profile. Figure 50 illustrates the water balance accounted for by the WEPP model. Due to the specificity of this model, surface runoff generating processes and soil erosion can be quantified from individual hillslopes and modeling of sediment transport processes determines the amount of sediment transported to streams.

A preprocessing tool known as GeoWEPP was used to delineate the watershed and hillslopes using 30m DEM data. The watershed and individual hillslope boundaries are illustrated in Figures 51 and 52, respectively. Land use types of the various hillslopes are highlighted in Figure 53. Vegetation type and characteristics were estimated from land cover data (NLCD, 2006). Spatial soils data (soil thickness, texture, field capacity, wilting point, hydraulic conductivity, soil erosivity, and soil critical shear strength) were obtained from both the Natural Resources Conservation Service (NRCS - STASTGO) and the Coastal Zone Management Area (CZMA) database. Parameters specific to the study area used in the WEPP model are provided in Appendix L.

7.1.3 Hillslope Erosion

Based on water balance and thermal balance data, the WEPP model predicted that Dunne mechanisms of overland flow dominate during the summer months along the North Shore while Hortonian mechanisms of overland flow are more important during winter and spring months when infiltration is limited in frozen soils. Annual estimates of soil erosion from hillslopes with various land use types are presented in Table 16. Although ski slopes cover only 15% of the Lower Poplar River watershed by area, WEPP modeling predicts that these areas contribute some of the highest sediment loads to the Lower Poplar River (~575 tons/yr assuming SGP). This is drastically higher than the sediment loads from forested areas or the golf courses (6 tons/yr each) and is still higher than the 312 tons/yr estimated to originate from ravines.

Due to the high rates of soil erosion from the ski slopes, various scenarios were run to evaluate factors impacting soil erosion magnitudes from hillslopes. The first factor investigated was vegetative type. When model simulations were modified, assuming TGP vegetation type instead of SGP, annual sediment contributions were reduced from 575 tons/yr to 143 tons/yr. This suggests that vegetation type and management along ski slopes in the Lower Poplar River watershed can have a dramatic effect on hillslope soil erosion.

Artificial snow, which is added to the ski slopes in the Lutsen Mountain ski area, also has the potential to impact surface runoff volumes and subsequently soil erosion. Records indicate that approximately 70 million gallons of water, roughly equivalent to 12” of snow depth, are applied to the ski slopes within the study area annually. The WEPP model was used to model the impact of these increased artificial snow depths on soil erosion from an individual ski hillslope during the study period. Model results indicate that in general, soil erosion increases with increased applications of artificial snow to the hillslopes. The degree by which this occurs is influenced by the type of vegetative cover (Table 17).

Slope lengths are also known to influence the erosive power of overland flows and consequently soil erosion from hillslopes. Along ski slopes at Lutsen Mountain, features such as water bars have been installed as Best Management Practices to obstruct overland flows, reduce slope lengths and mitigate soil erosion, thus functioning similarly to terraces on agricultural fields. To investigate the impact of such water bars, WEPP evaluated soil erosion from a 680ft hillslope with a 35% slope assuming a 50% reduction in length. Results indicate drastic reductions in soil loss when slope lengths are decreased (Table 17). At the time of this study, the number and locations of water bars along Lutsen Mountain ski slopes was unknown. Mapping of these features will be useful for refined estimates of soil erosion from ski slopes.

7.2 EROSION FROM SLUMPS

Exposed slumps are present along the Lower Poplar River and have the potential to contribute large sediment loads directly to streams by either sheet erosion or mass wasting. The locations of these slumps are presented in Figure 54. Together their surface area spans 4.6 acres, has relatively bare soils and average slopes of 70%.

Using the WEPP model, soil erosion by hillslope processes from these slumps was estimated to be 284 tons/yr. Sediment loading from mass wasting was assessed using methods outlined by Sekely et al. (2002) which predicted sediment loading values that were higher than sediment loads determined to originate from all sediment sources in the watershed, thus indicating these estimates to be unreasonable. In order for mass wasting to occur, the river must rise to levels above the armored channels and come into contact with the toe of the slump slope then remove soil to destabilize the bank. Hydrologic assessments identified that river stage during the study period was rarely high enough to erode soils from the toe of the slope at the slump sites. Therefore mass wasting of soil at slump sites is predicted to have contributed minimal sediment loads to the Lower Poplar River since 2008.

7.3 STREAMBANKS AND CHANNEL BOTTOMS

Geomorphic surveys were conducted along the Lower Poplar River channel. The channel banks and channel bottom were found to be heavily armored with large rock and cobble. Due to this armoring it did not appear that there is high potential for downcutting and soil erosion from within the Lower Poplar River channel.

7.4 EROSION FROM RAVINES

Three major ravines are present in the Lower Poplar River watershed. The locations of these features are shown in Figure 55 and their dimensions are summarized in Table 18. The Brule ravine (155 acres) historically received runoff from the ski slopes of Eagle Mountain. In 2006, a flow diversion was constructed to divert hillslope runoff past the ravine. This ravine has since been revegetated and erosion from this area has been drastically reduced. The Ullr ravine is an actively developing ravine. At present, it spans 4.6 acres though development upstream contributes an additional 22 acres directing flows towards the ravine. It is unclear as to when down cutting of the Brule and Ullr ravines began. The Moose Mountain ravine (232 acres) is a feature that has been apparent on the landscape at least as far back as 1860 and all upland contributing area to this ravine is forested. The sediment contribution from these three ravines is estimated to be 243 tons/yr.

7.5 EROSION ALONG ROADS

Sediments eroded from roads in the Lower Poplar River watershed could not be modeled by WEPP. Instead, methods outlined in Rosgen (2007) were used. This approach determines sediment yields by accounting for the Road Impact Index (RII). This index is calculated by considering the area of a subwatershed that contains roads, the area of surface disturbance, the number of stream crossings and the position of the road relative to the stream. Additional factors include road slopes, age of the road, road surfacing, presence vegetation or protection lining ditched, vegetative cover on the disturbed soil areas and the presence of unstable terrain associated with mass erosion. These parameters are input into a spreadsheet to derive sediment load values. Altogether, roads are estimated to contribute just over 35 tons of sediment per year.

8.0 TERRAIN ANALYSIS FOR HYROLOGIC PATHWAYS

In accordance with Task 6 of the Lake Superior Sediment Assessment project, a terrain analysis was conducted using high resolution (3m) LiDAR data to identify locations across the lower Poplar River watershed landscape where overland flows are concentrated. These areas have the potential to be eroded by concentrated overland flows and are locations where gullies and ravines commonly form.

To identify these areas in the lower Poplar River watershed, the Stream Power Index (SPI) was calculated from the LiDAR data in ArcGIS. Stream Power Index is a metric that considers slopes and upland contributing areas to define the likelihood of preferential flow paths over the land. SPI values are calculated for each raster cell in the Lower Poplar River watershed using the upslope contributing area for a gridded cell (α; in square meters per meter cell) and the slope (β; in degrees) (see Equation 1). The range of SPI scores that results are watershed specific and so the highest watershed specific scores are often used to identify areas with the greatest potential to transport overland flows. For the purposes of this study the 98th percentile of watershed specific SPI scores, or the top 2% of SPI scores, were used to highlight preferential flow paths. These areas are shown in red in Figure 56. The preferential flow pathways or areas with high potential for erosion identified by Hansen et al. (2010) are coincident with the pathways delineated by high SPI values (refer to Section 7.4 above).

Equation 1: $$log\ e^{\left(\frac{a}{tan\beta}\right)}$$

It is important to note that such GIS based SPI analyses evaluate the spatial extent over which there is potential for erosion. Local erodibility of the soil and land use conditions, are important factors which are not accounted for in the calculation of SPI values. These factors can impact whether active erosion occurs or not and additional soil properties that promote infiltration and reduce overland flows may have additional impacts that are not readily identifiable in the SPI analysis. Similarly, vegetation can slow and/or intercept overland flows, thus reducing stream power. It is important to note that the displayed SPI values in this analysis do not account for possible interruptions of flow pathways by roads or trails and the culverts that underlay them. Accounting for such culvert features in the terrain data may have a significant effect on the distribution of SPI values.

9.0 CONCLUSIONS AND FUTURE DIRECTIONS

This report provides the first of a two part study to develop an ecological systems understanding of the natural variability and anthropogenic factors impacting North Shore sediment related impairments. It explores sediment sources, mechanisms of sediment delivery to streams, and impacts to overall stream health. Throughout this effort, data were gathered to provide the initial characterization of the North Shore and stream health. The data collected included water quality data, soils data, streamflow records, aerial imagery and GIS based natural and anthropogenic stressor tools.

Available water quality data for turbidity along the North Shore is limited; however, more data related to TSS and transparency is available and may provide greater insight into sediment related water quality impairments. At present, numeric state water quality standards for turbidity in North Shore Class 2a streams are set at 10 NTUs. Initial case studies of TSS-turbidity relationships along the Knife and Poplar Rivers expose variability in TSS equivalents to the water quality standard at both the stream and reach level. These findings highlight the variability of natural sediment characteristics along the North Shore, and the innate potential for water quality impairments along streams.

Understanding the impact of various soil types on sediment impairments along North Shore streams is limited by the fact that the most recent comprehensive soils data date back to 1980. While these data do predict rough boundaries of North Shore soils, refined soil survey data, which is anticipated to be available within the next few years, will be necessary for high accuracy mapping of areas with elevated potential for upland and in-channel soil erosion.

Streamflow data is also necessary to evaluate sediment stressors, to predict the potential for in-channel erosion, to evaluate long-term flow trends and to evaluate biological health. Streamflow data along the

North Shore is limited, though strong relationships were identified between neighboring streams. It will be important to maintain existing long-term gaging stations and to strategically introduce additional stations at catchments of interest when and where funding becomes available.

Aerial imagery collected along the Brule, Temperance and Knife Rivers did allow for identification of areas where there is higher potential for in-channel erosion and where channel armoring and bedrock outcrops exert more stabilizing controls on the stream. In general, bankfull widths of streams tend to positively correlate with upstream contributing area. Such relationships were more prominent for the Knife River which has more highly erodible channel banks and more numerous bluffs. In contrast, less strong relationships were observed on the Brule and Temperance Rivers where channel armoring and bedrock channel bottoms are more common. Such assessments of other North Shore streams might highlight those rivers, or river reaches, with less channel armoring and lower overall stability.

Together, these observations of natural landscape characteristics along the North Shore suggest a high capacity of natural variables to influence the locations of sediment sources and their erosion potential. While current water quality standards require one numeric goal, it may be unlikely that all North Shore streams or stream segments can be held to equal standards. For example, stream segments that meander through lacustrine sediments, or segments located downstream from such locations, are likely to have higher potentials for turbid waters than reaches running through sandier soils or bedrock. Future efforts to enhance channel characterization to identify erosion risk will be critical to evaluate stream and segment specific impairment potentials.

A GIS based stressor tool, designed to take into consideration both natural and anthropogenic variables was used to highlight both reference areas as well as areas with high potential to impact water quality. Conditions of individual subcatchments as well as accumulated stress of a subcatchment based on upstream contributing areas were evaluated. In general, subcatchment areas with the greatest potential to impact water quality mapped to areas where the STATSGO kffact erodibility factors were high. Based on accumulated potential stress, degraded areas were highest along stream channels; higher potential stress correlated with higher stream orders. This trend was found with variables assessed independently or with each variable assessed together to assess overall SUMREL scores.

Anthropogenic stressor variables were also assessed independently of the natural variables. Population density, road density, land in cover crops and land developed were considered to evaluate the extent and magnitude of anthropogenic stress. Nearly all subcatchments outside of urbanized areas along the North Shore were identified as having reference conditions. Consequently, it was difficult to identify areas with high potential for soil erosion or sediment related stream impairments based on these variables alone. That being said, this anthropogenic assessment tool did suggest that roads are the variable having the largest potential to inflict the most widespread anthropogenic stress across the North Shore.

Based on these findings, further analyses were conducted to identify the mechanisms by which roads might impact soil erosion and sediment loading to streams. Roads were found to increase the drainage density of channel networks and efficiently convey overland flows to streams. These overland flows have the potential to carry high sediment loads to streams. Construction, maintenance and use of roads were also identified as factors influencing road and roadside erosion.

While upland erosion from roads presents one potential source of sediments to streams, in-channel erosion was also identified as a major sediment source. During field investigations, culverts and bridges at stream-road crossing were determined to impact stream instability and bank erosion both downstream and upstream of the crossings.

To further evaluate stream stability and its relationship to GIS derived SUMREL scores along the North Shore, a field campaign was conducted in which 33 sites were assessed for Rosgen channel types, bank erosion hazard (Rosgen's BEHI assessment) and channel stability (Rosgen's Modified Pfankuch stability assessment). A range of Rosgen channel types (E, C and B-type channels) were identified with varying levels of stability and erosion hazard. There did not appear to be any correlation between channel type, stability rating, erosion hazard and accumulated SUMREL stressor scores. Although the SUMREL stressor analysis tool highlights subcatchment areas with higher likelihoods for degraded conditions, it does not appear that this scale will allow for identification of site specific erosion hazard and channel instability.

Based on field site observations and comparison with aerial photographs, it appears that better data related to the various till layers, their composition, position, and extent of contact with streams may be critical components necessary to predict or model sediment loading to Lake Superior tributary streams. Such factors, which can influence channel type, channel stability and erosion hazard, are illustrated in Figure 57. This aerial image shows the West Branch of the Beaver River and two sites that were surveyed as part of this project (BR4 and BR5). While Pfankuch stability ratings are "Fair" at both sites, the BR5 site has a "High" BEHI ranking and the BR4 site has a "Low" BEHI ranking. The BR5 site is characterized as a C4 stream with higher erosion hazard, high sinuosity, low slope, gravel bed materials and a wide floodplain. In contrast, the less erosion prone BR4 site is characterized as a B2 channel with low sinuosity, a narrow floodplain, cobble bed materials and a higher channel gradient. The B2 river reach flows through coarser glacial tills while the C4 river reach meanders through an erosion prone old lake bed dominated by fine lake clays (Figure 58). There are a number of such small lake beds mixed in with the glacial till landscape of the North Shore. In fact, three of our field survey sites were located in similar landscapes. All three exhibited low stability scores, high bank erosion potential and had lake clays exposed in scour pools and in the lower banks. This type of image analysis may prove useful for identifying other locations with high potential for bank erosion and sediment loading to streams.

A case study analysis of soil erosion from the Lower Poplar River catchment was also completed for this study. Modeling of sheet erosion from this area suggested the ski slopes on the Lower Poplar River are the largest contributors of sediment to the turbidity impaired reach though erosion from ravines was also considered a significant sediment source. Vegetation management and other BMPs (like water bars, etc.) to manage water flow on slopes are key to mitigating soil erosion from these areas. LiDAR may provide high resolution evaluation of more critical slopes and locations where BMPs might provide the greatest overall benefits. While large slumps are present along the sides of the channel, mass wasting of these features was not expected to have greatly affected turbidity levels during the study period. This was because stream stage was not predicted to have been elevated for long enough times during the study period to have carried away sediment from the toe of the slope.

Newer LiDAR terrain data was also used in this case study to identify preferential flow pathways in upland areas which channel overland flows towards streams. These areas have the potential to receive substantial volumes of erosive overland flows and reveal areas where gully and ravine erosion are likely to occur. This high resolution data is providing many opportunities for land managers to precisely evaluate site specific features for mitigation of overland flows and upland soil erosion.

10. FUTURE NEEDS

Watershed management decisions along the Lake Superior shore face multiple challenges of reducing pollutant loading, maintaining water quality, restoring valuable habitat and supporting the needs of the communities. The backbone of these management decisions are the datasets this report has summarized. Interpretation of the data into meaningful management decisions, identifying data needs and executing efficient and affordable data acquisition is the challenge ahead.

To meet sediment related water quality goals along the North Shore, it appears that this challenge is in part complicated by understanding of natural variables and current water quality criteria. There is a need to develop a further understanding of the effects and interactions of natural and anthropogenic variables on water quality and to recognize that single criteria do not capture and explain how a stream system functions. Reliance on single numeric criteria in state water quality standards has constrained our ability to adequately identify, characterize, and address the multiple elements present in a system that affect water quality.

The current development of a Tiered Aquatic Life Use (TALU) framework by the MPCA will greatly improve the state's water quality standards by providing a framework incorporating the range of aquatic life conditions present in Minnesota's streams and rivers. It will aid in moving Minnesota's aquatic life standards from a "one-size-fits-all" approach to one that protects appropriately classified waters on their biological potential." (http://www.pca.state.mn.us/index.php/water/water-permits-and-rules/water-rulemaking/tiered-aquatic-life-use-talu-framework.html)

Once the TALU framework is in place, a framework will be needed to identify, characterize, and better understand the key physical components (source, processes, pathways) affecting the habitat of a stream and subsequently the condition of the aquatic life. Such a physical framework is needed to encompass the largely physical processes in watersheds that drive the physical (habitat) conditions in a stream or river including hydrology, fluvial geomorphology, and other watershed characteristics (geology, soils, topography, land cover/use, etc.)

It will be critical moving forward to assess the current datasets and determine which are suitable or useful in meeting the goals of North Shore sediment management. Furthermore, it will be key to identify the various watershed assessment tools that appropriately evaluate the unique landscape and land use features of the North Shore. With the data collection and organization completed with this project, current data collection locations and monitoring sites can be analyzed to see if they are numerous enough or are properly located to account for both natural and anthropogenic stressor on the North Shore. And while very useful data were generated from the SUMREL analyses and others, it will be crucial to re-evaluate reference and degraded subcatchment areas when the detailed soils data finally becomes available.

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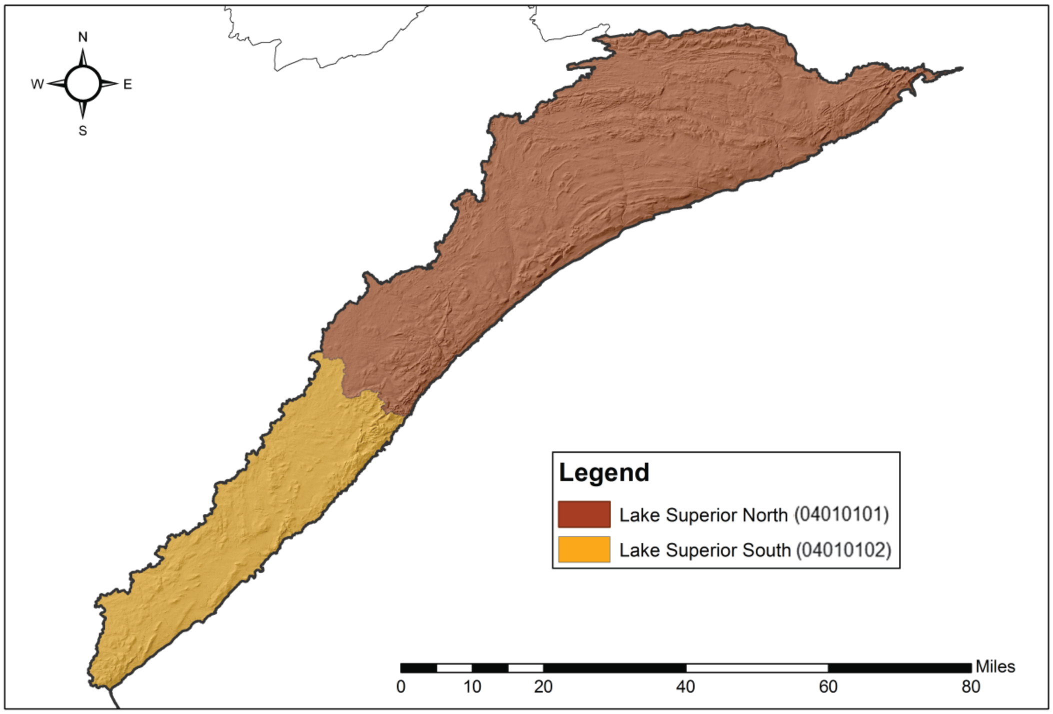
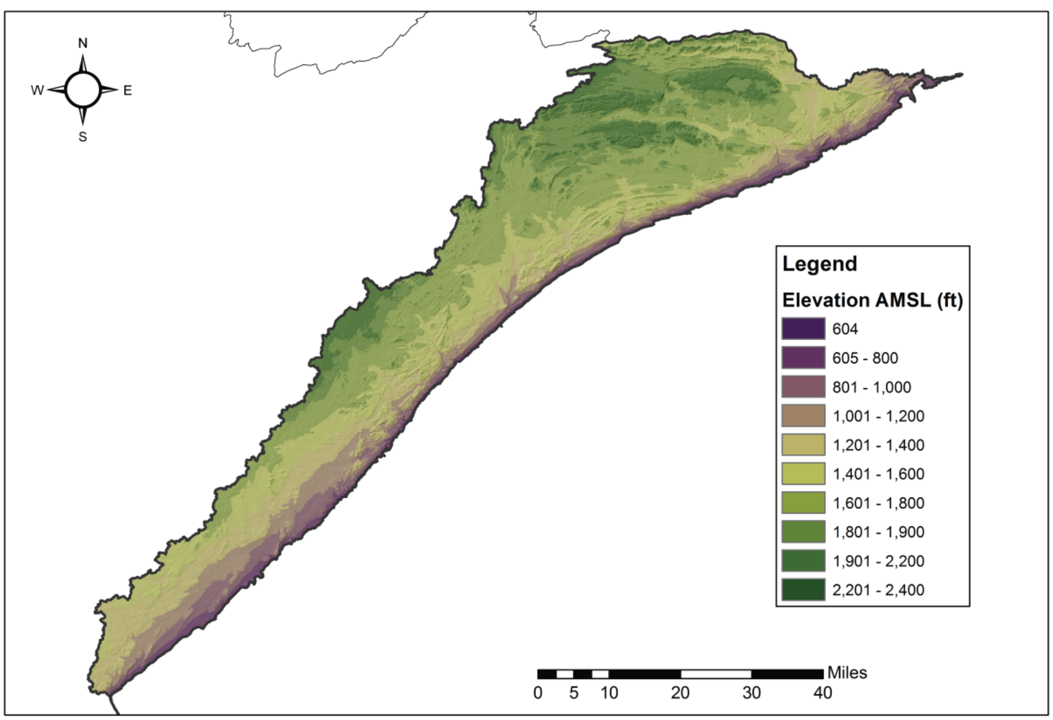


Figure 1. The Minnesota North Shore and the major 8-digit HUC watersheds that define its boundaries: Lake Superior North (04010101) and Lake Superior South (04010102) watersheds



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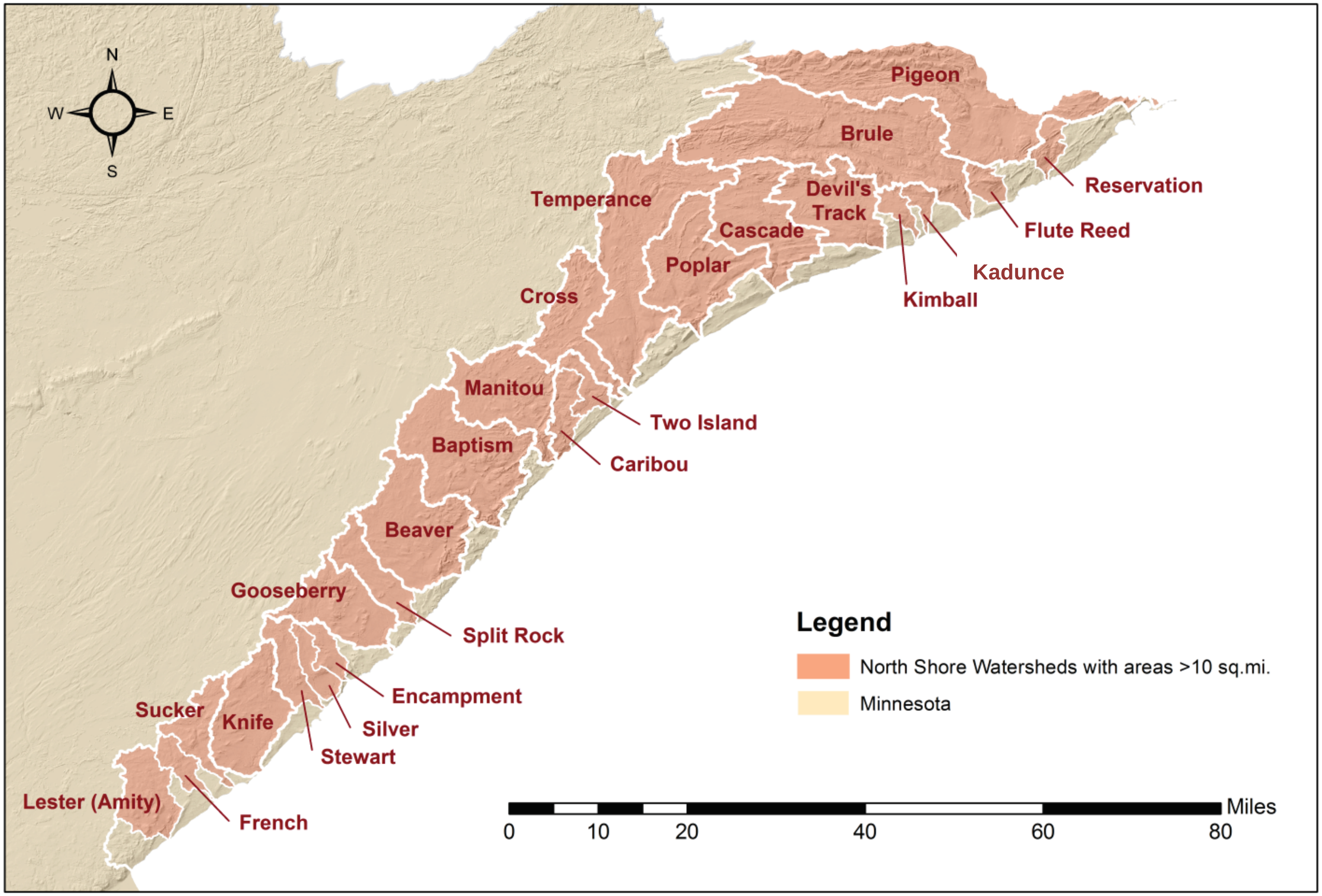

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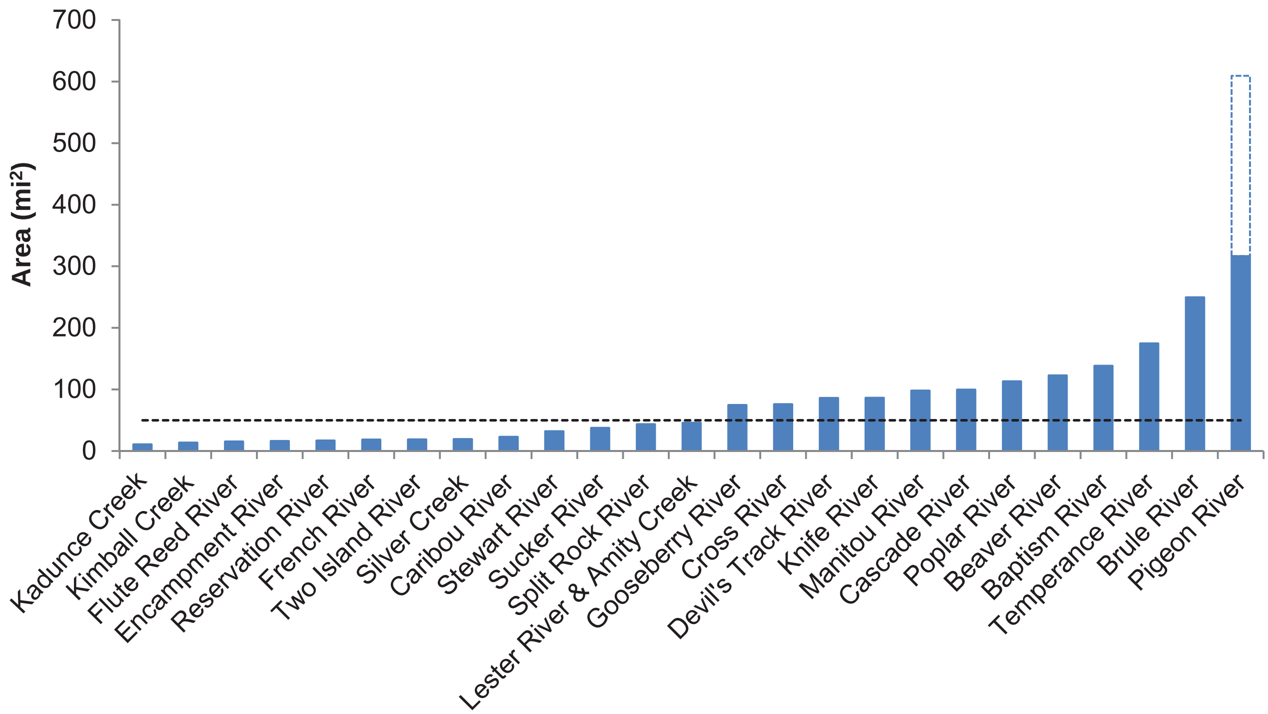

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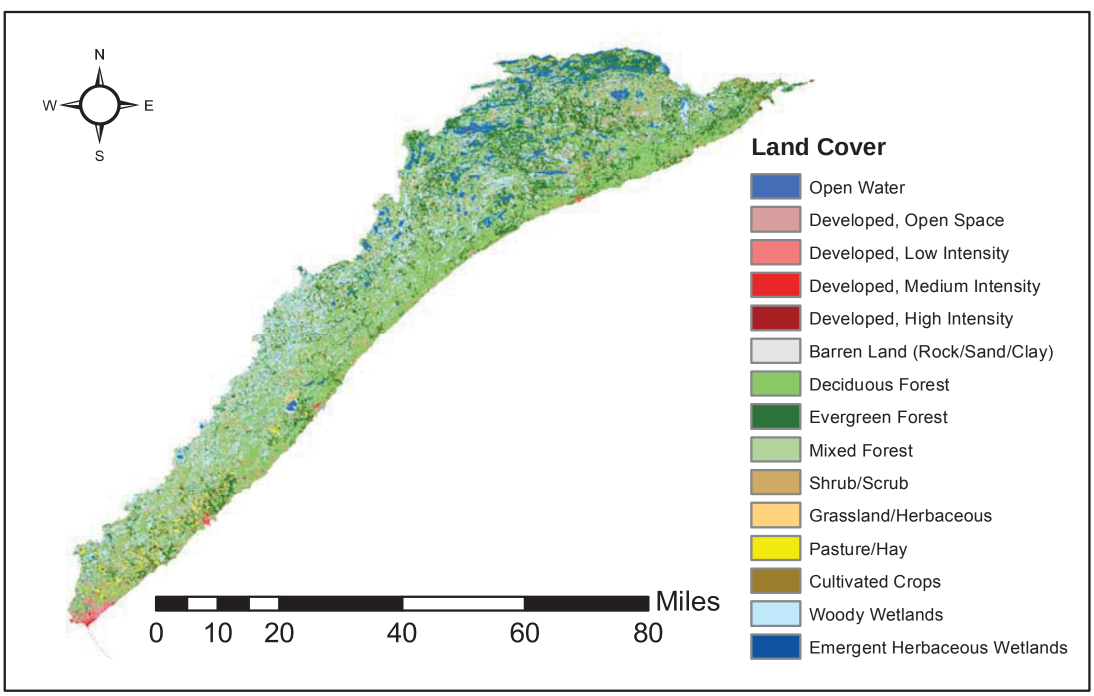

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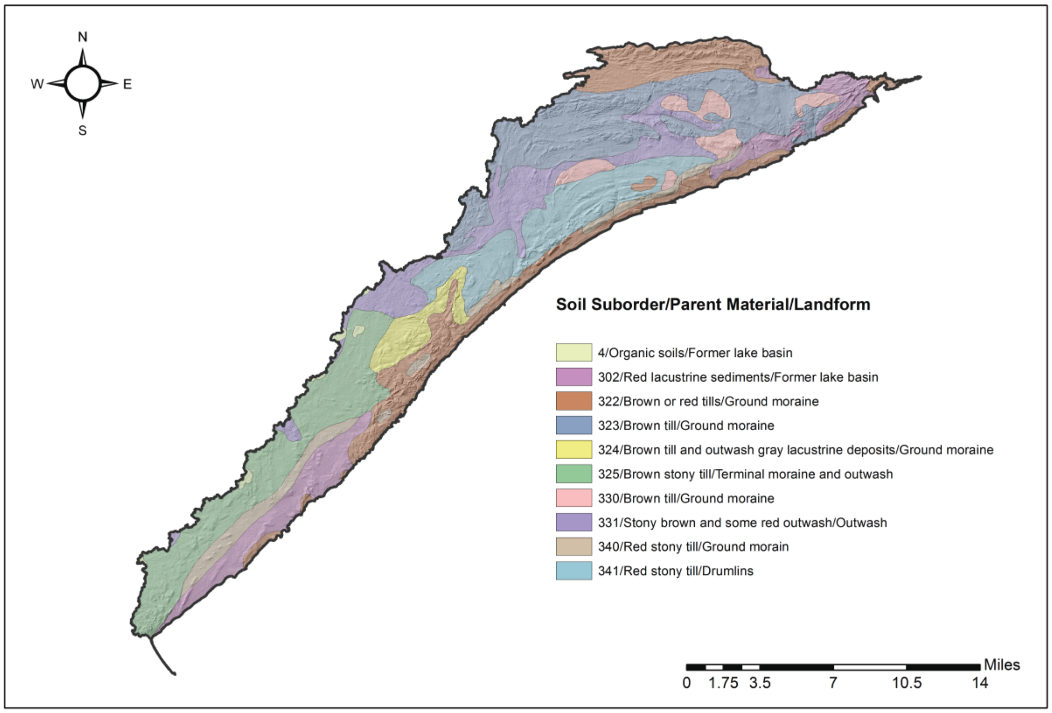

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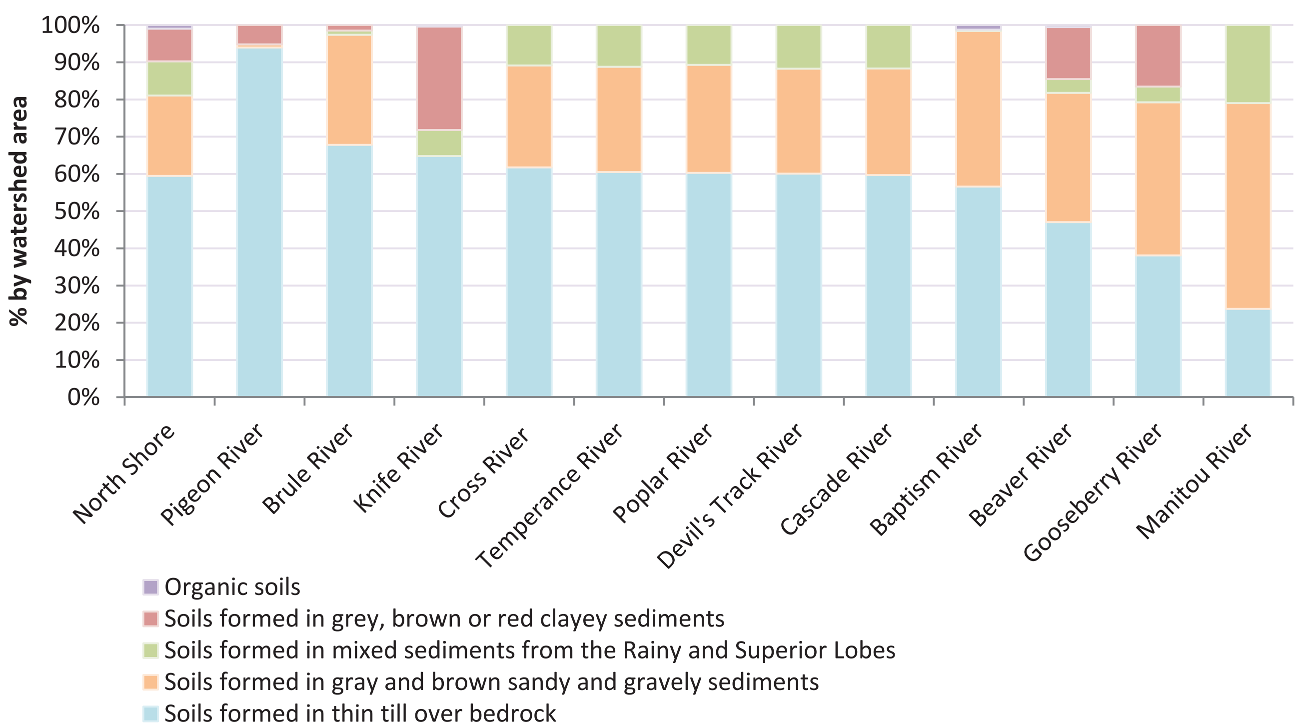

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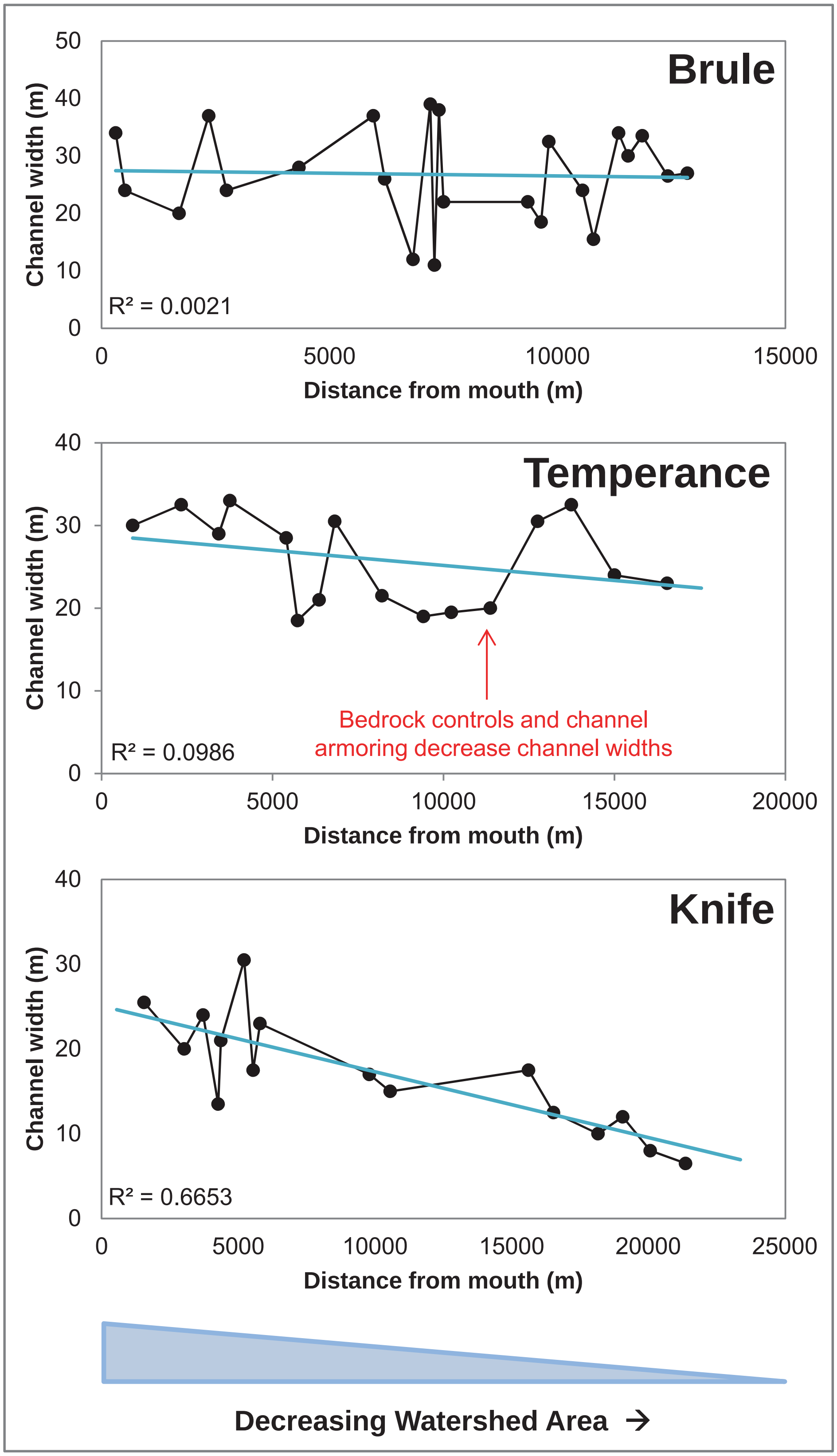

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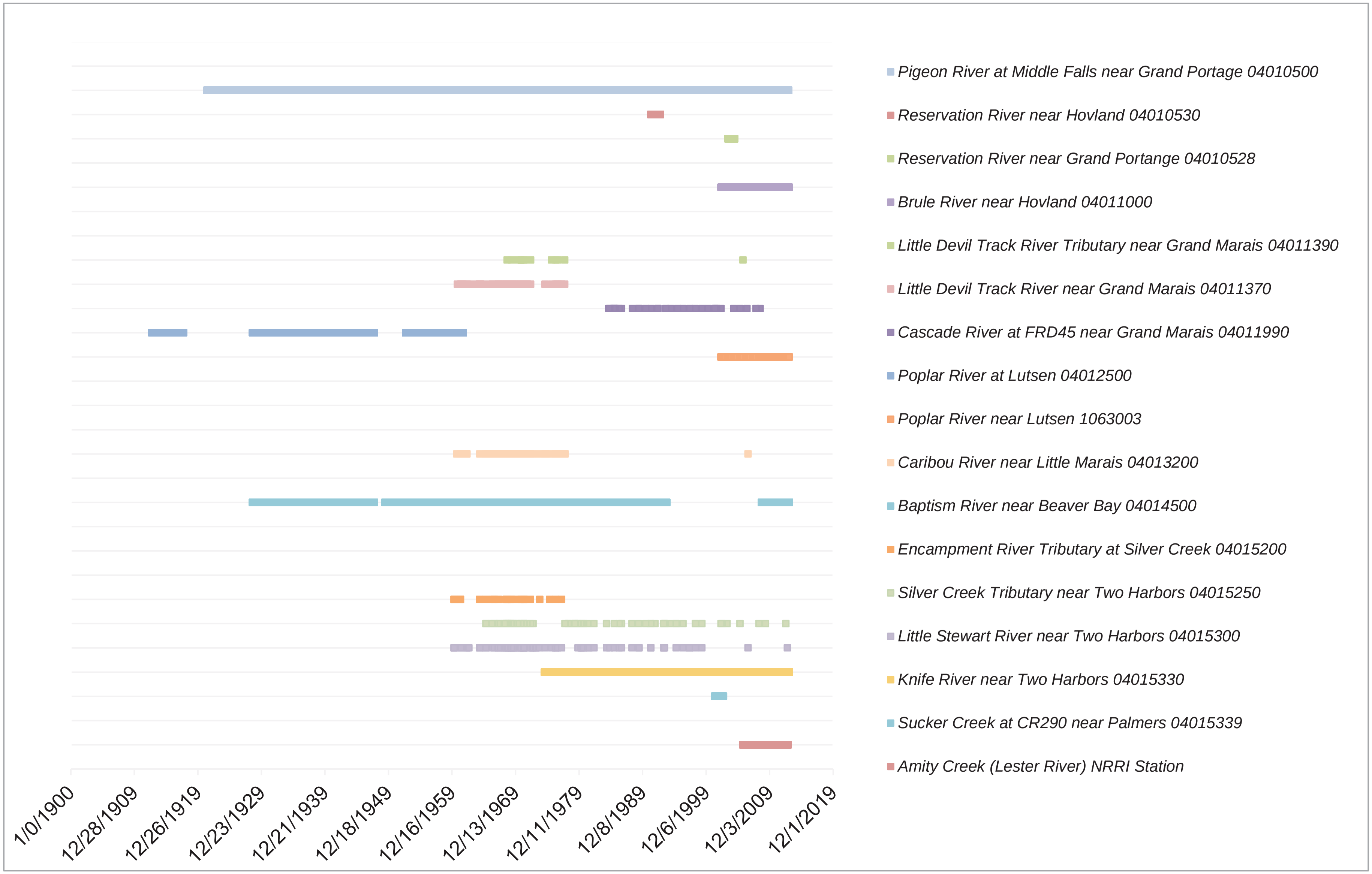

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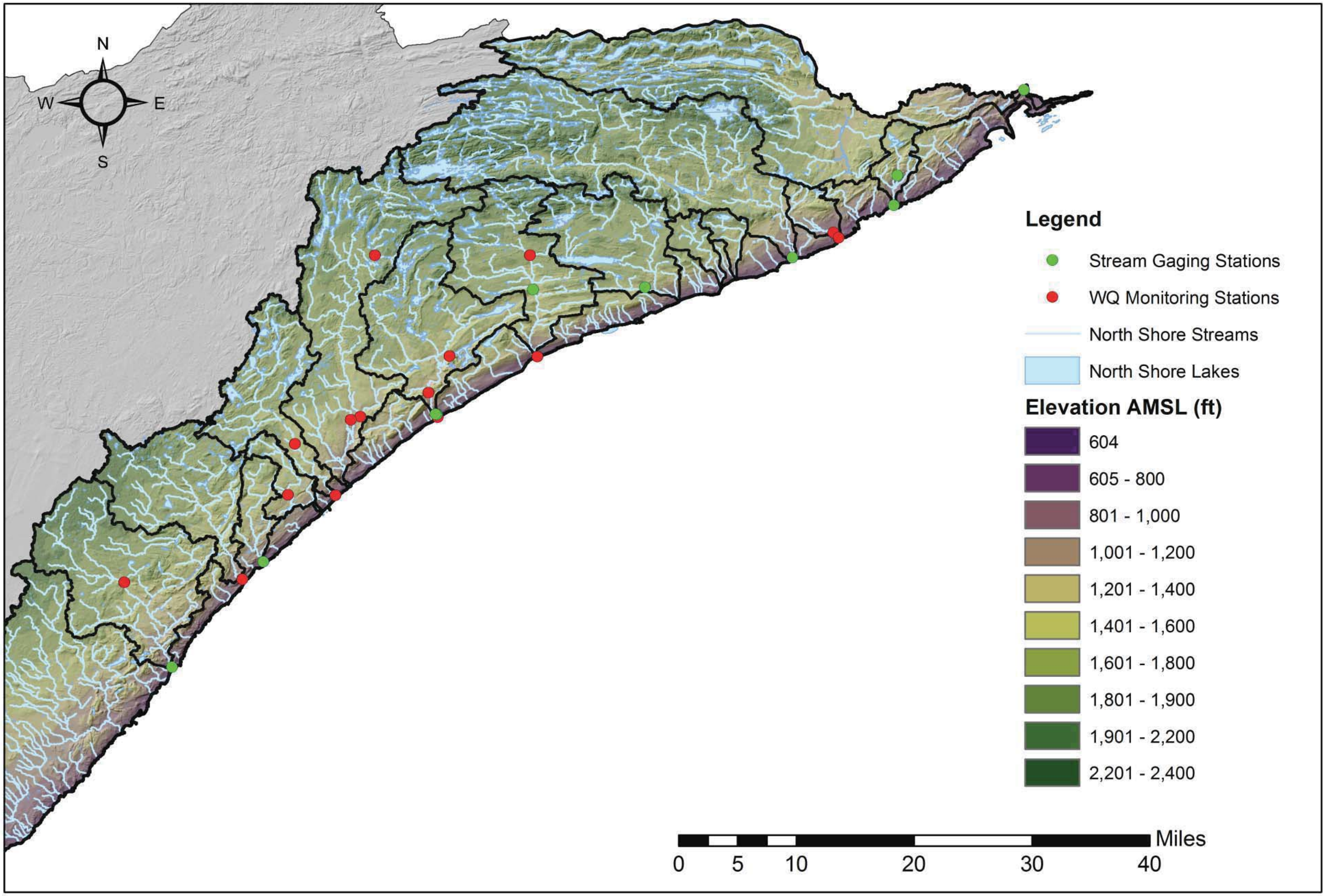

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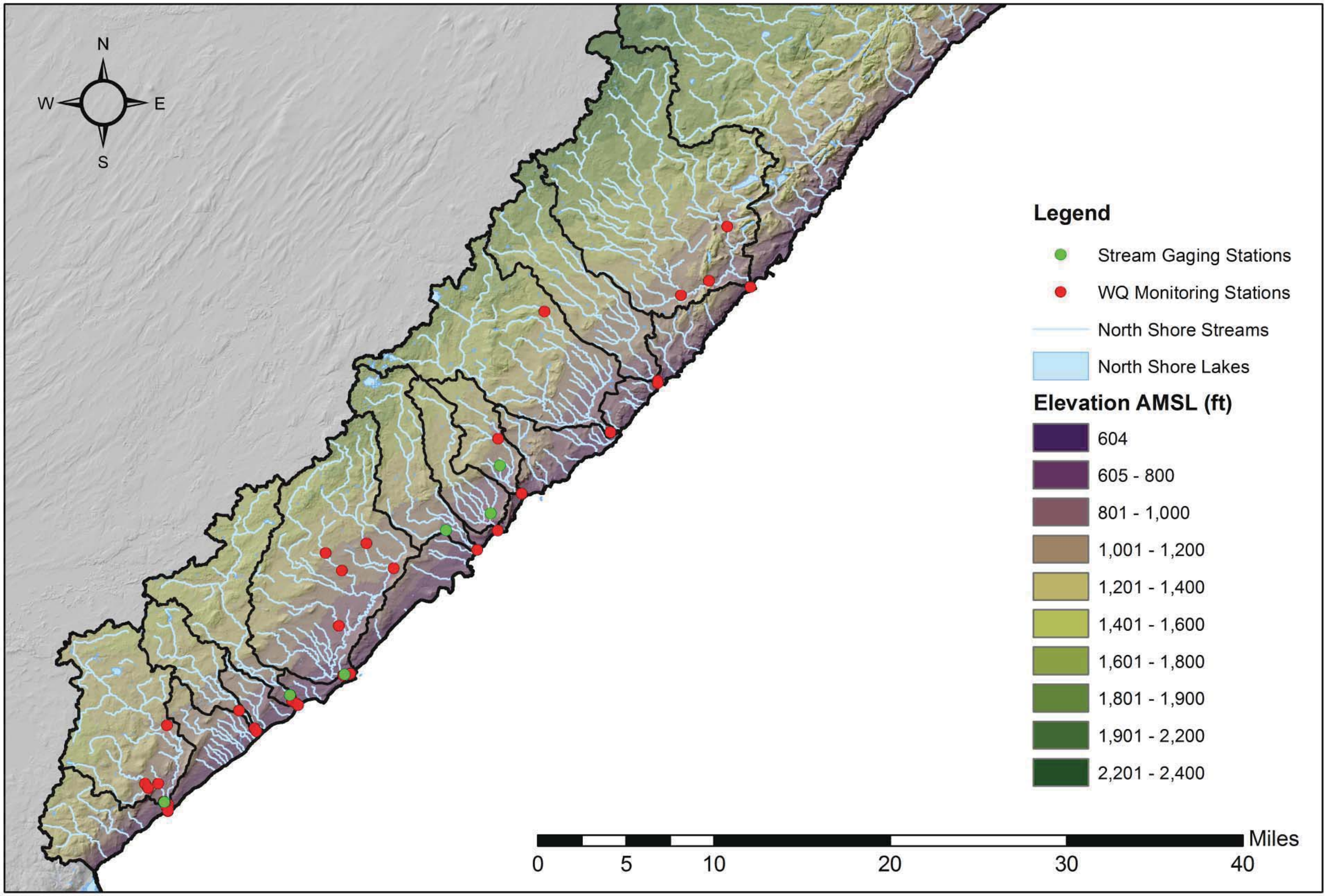

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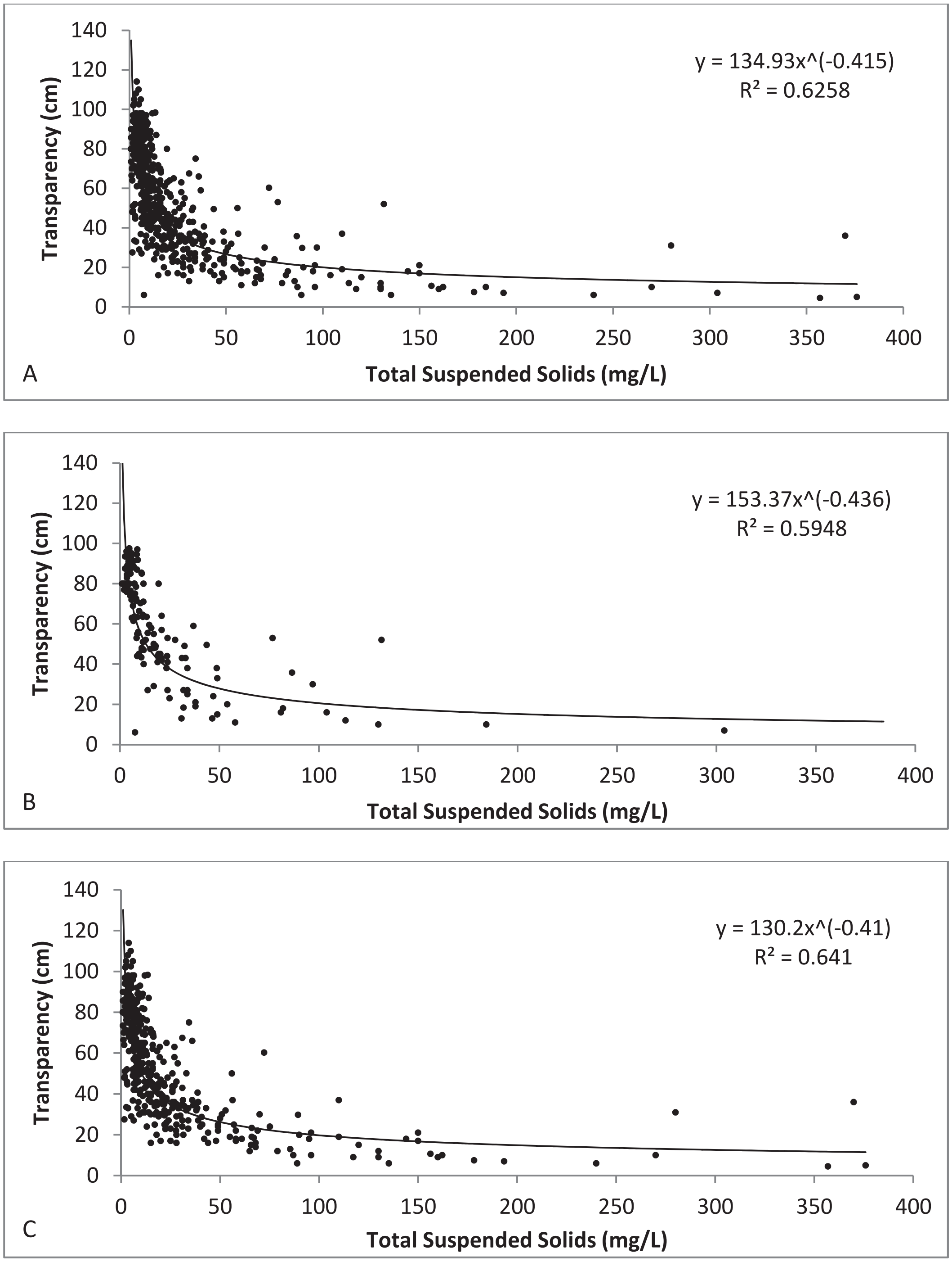

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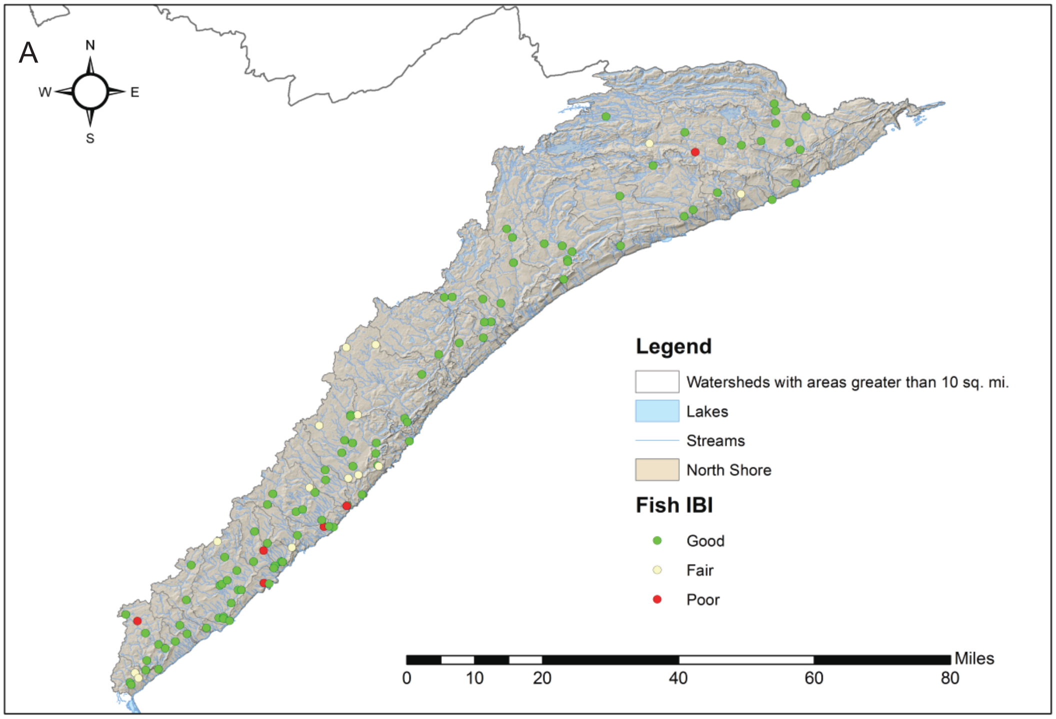

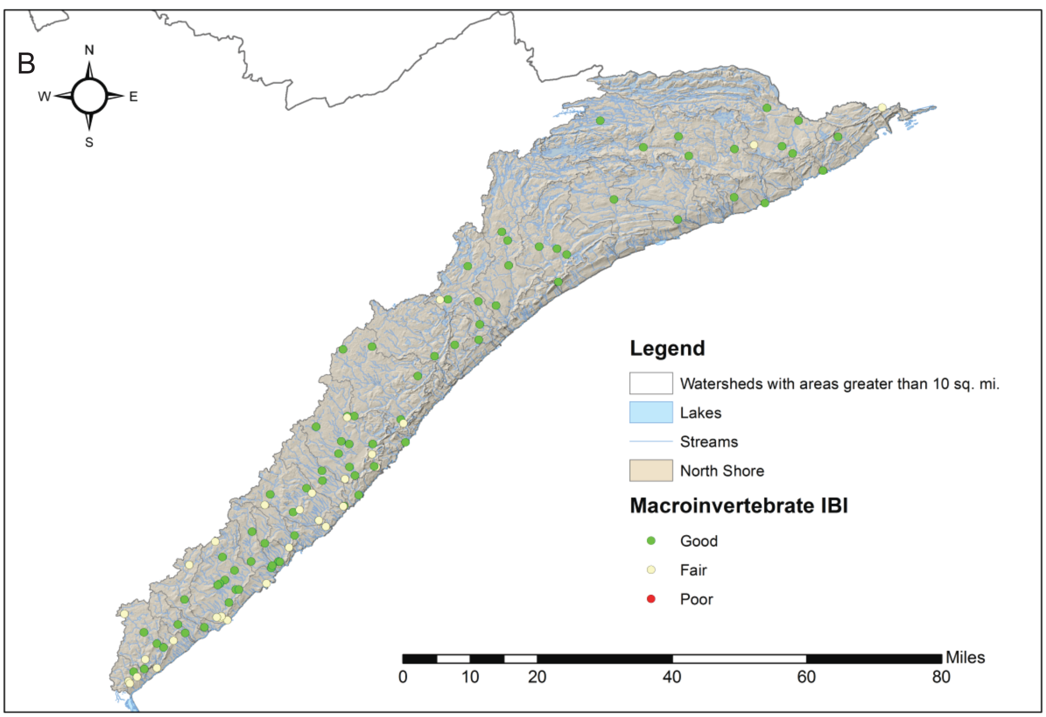

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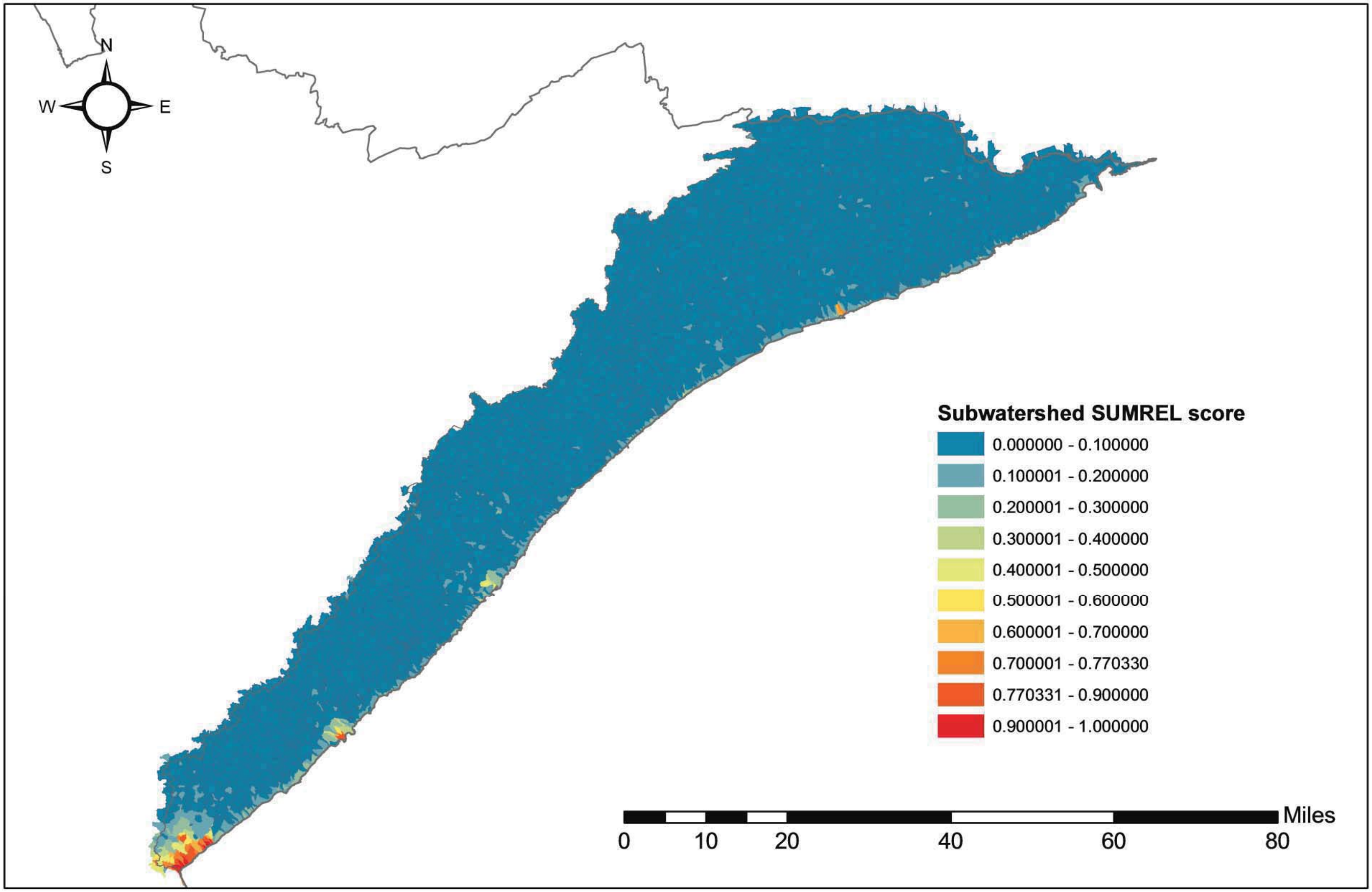

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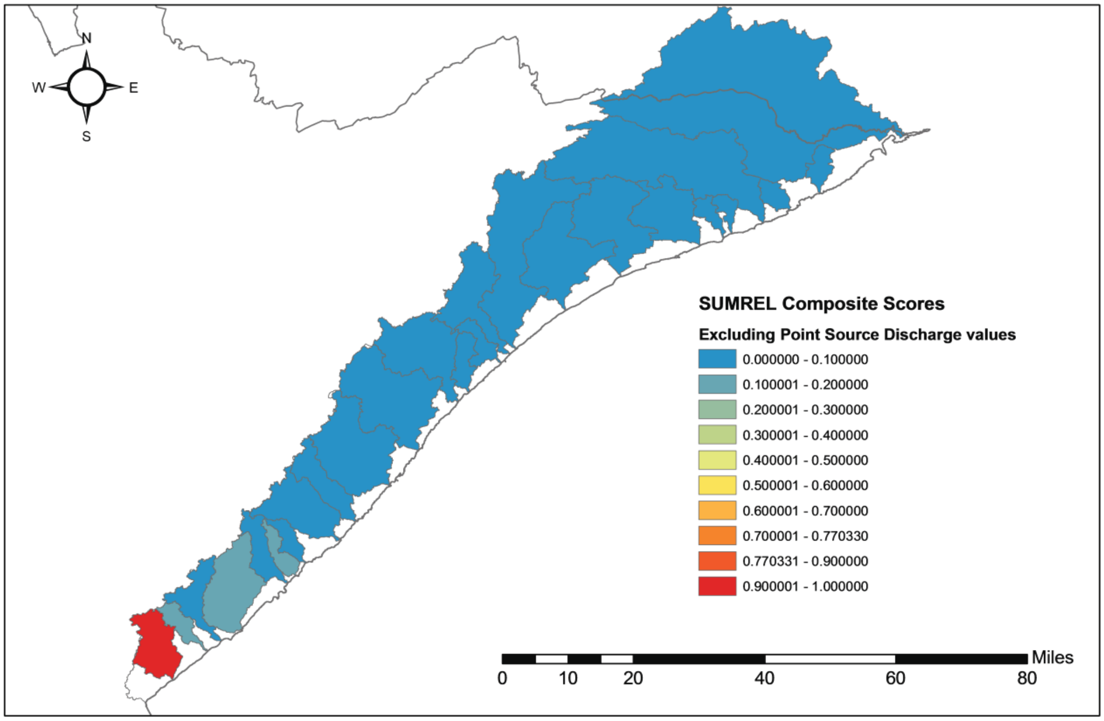

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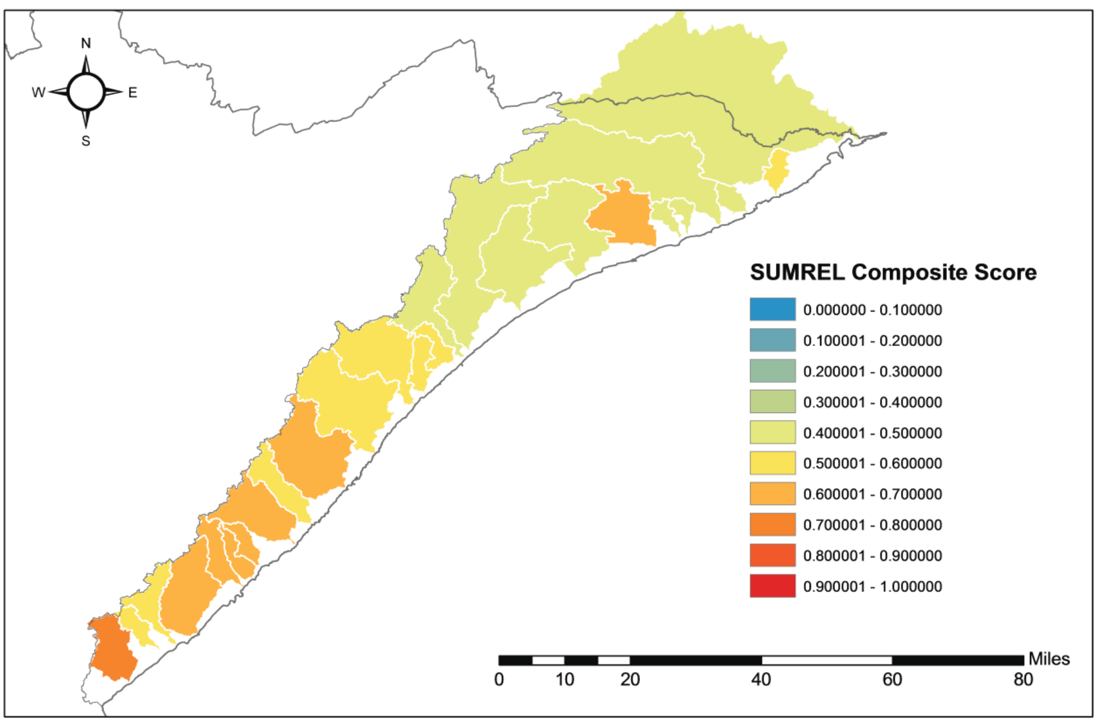

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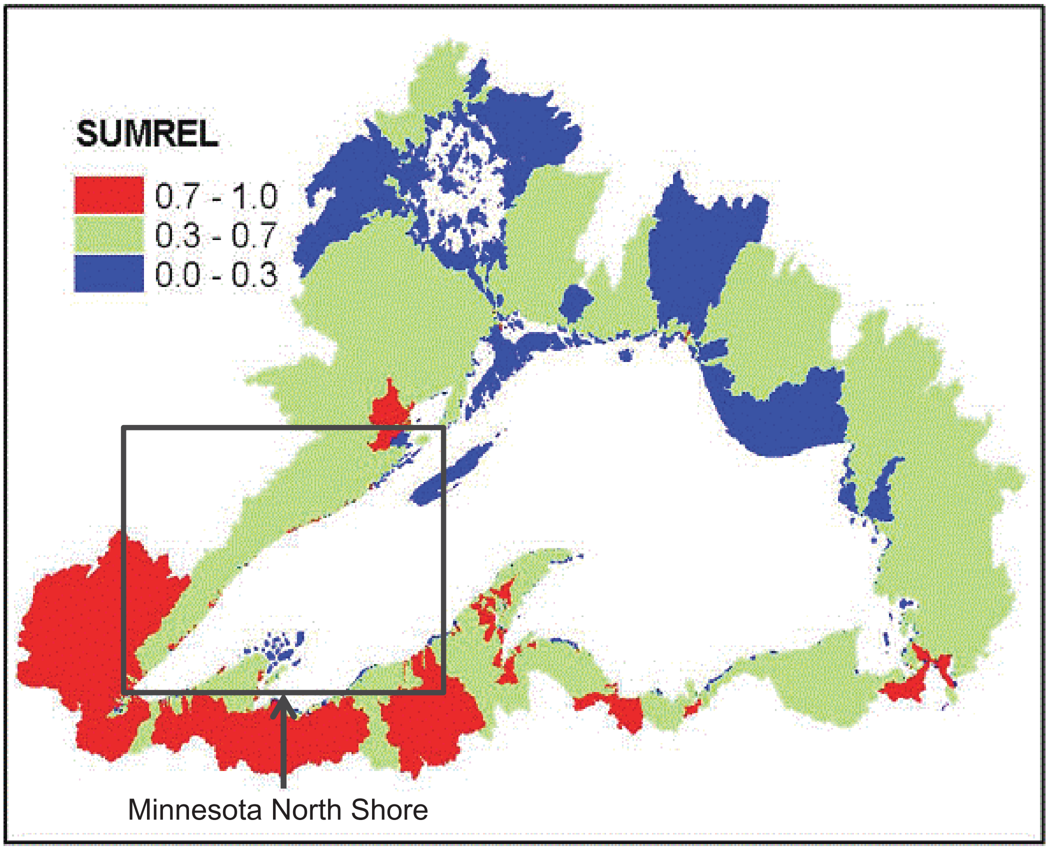

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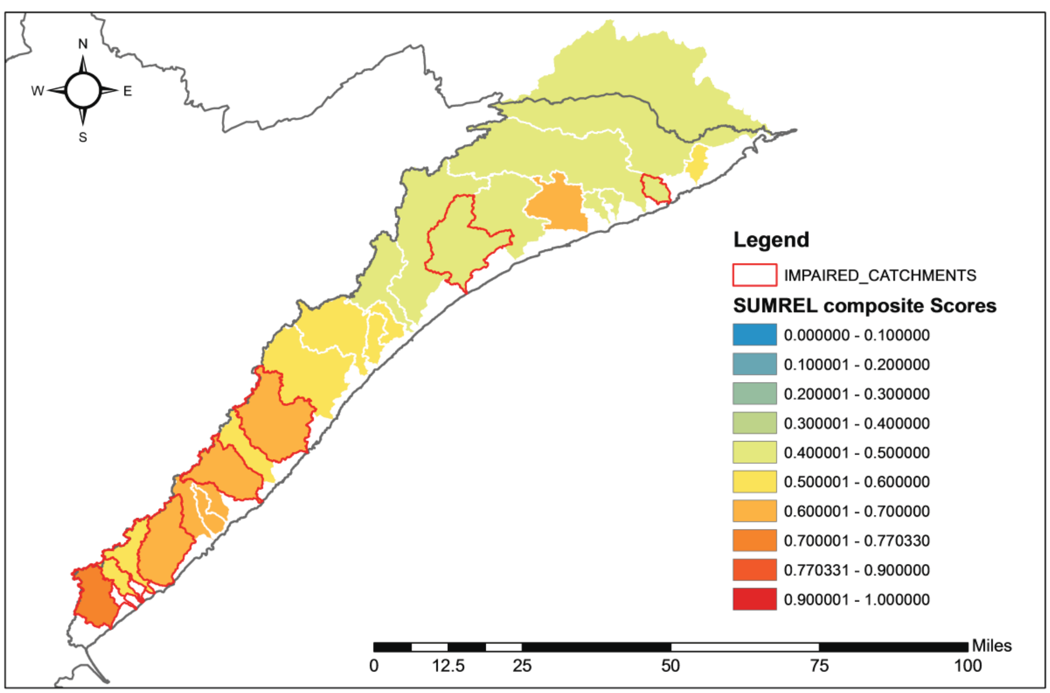

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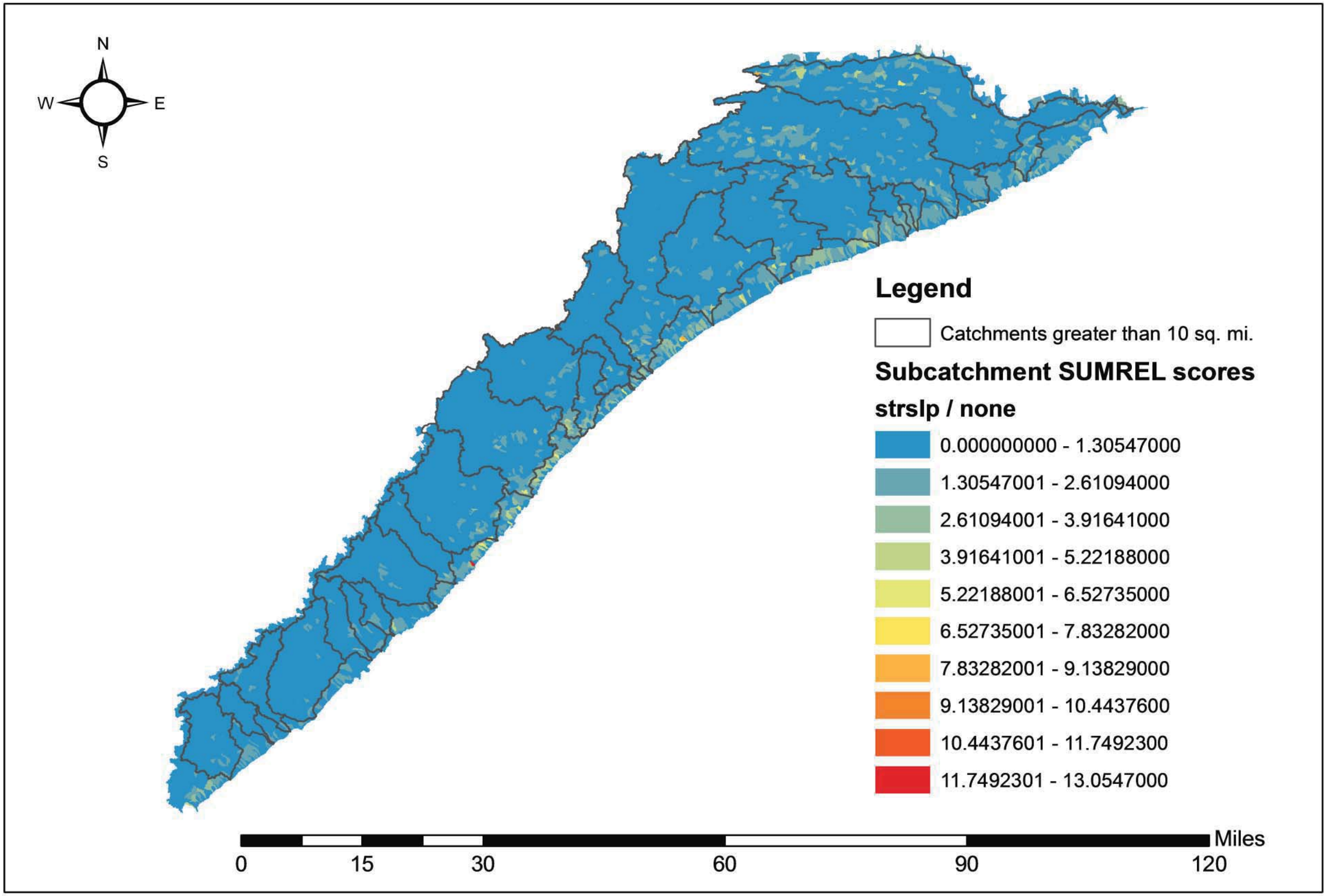

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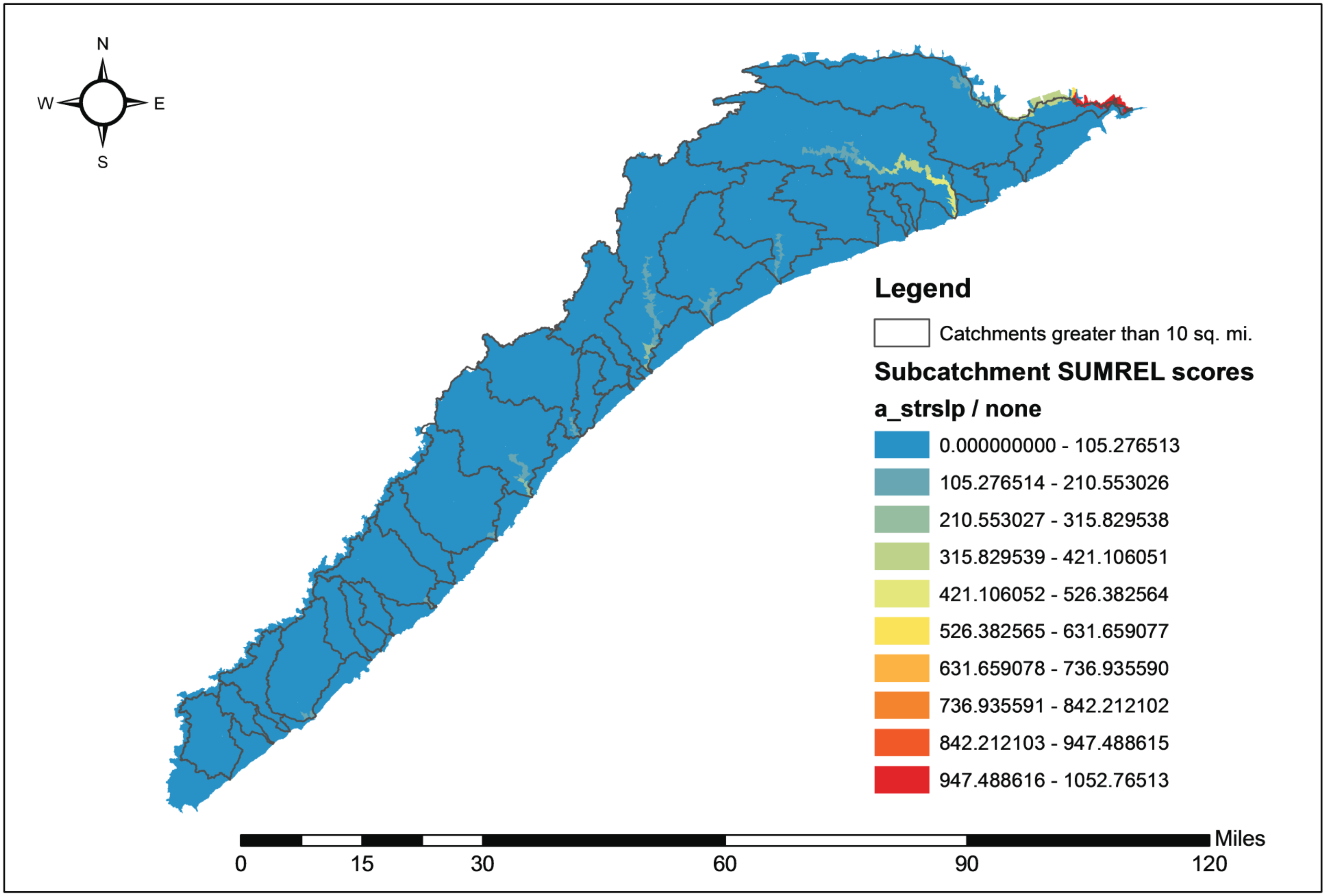

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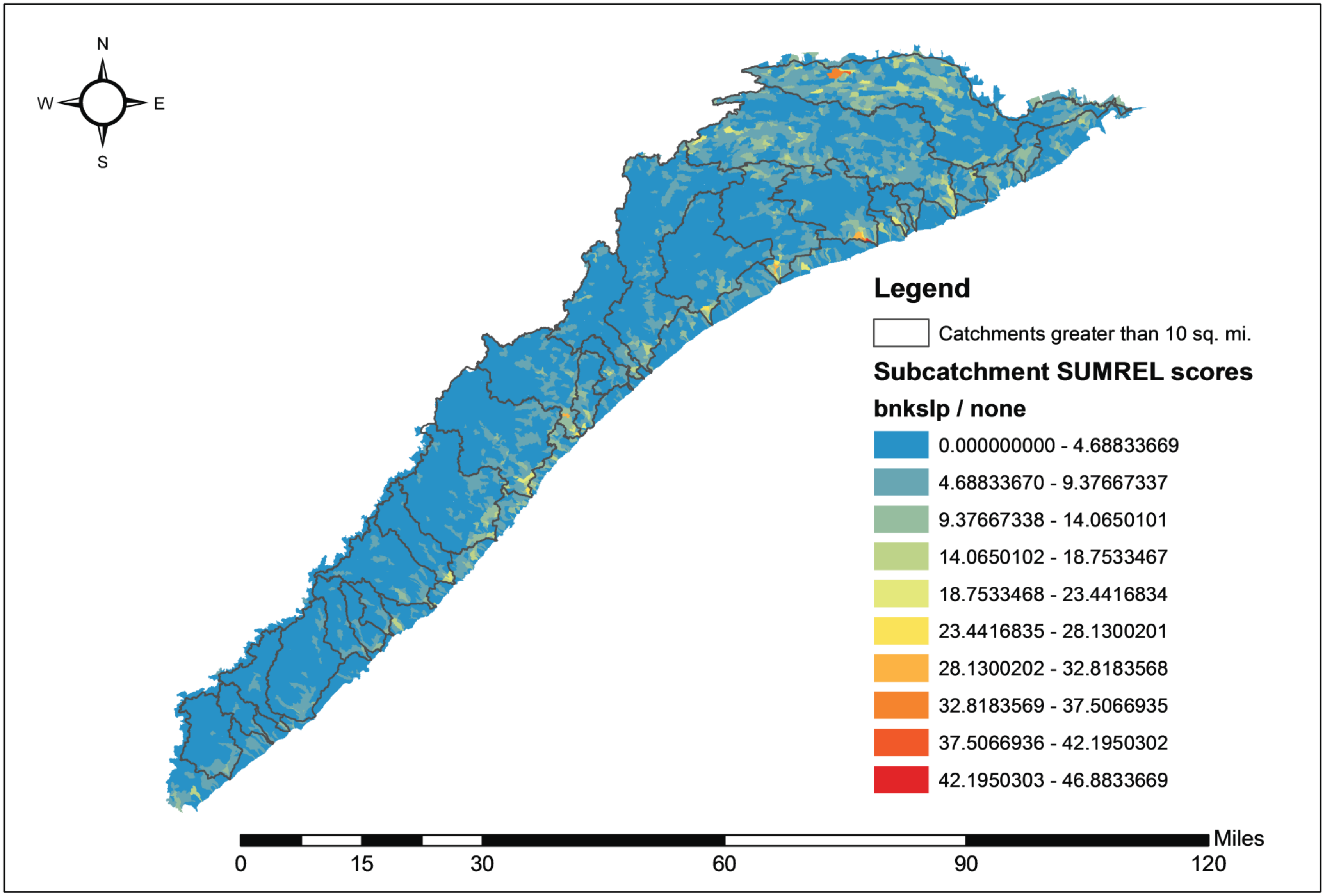

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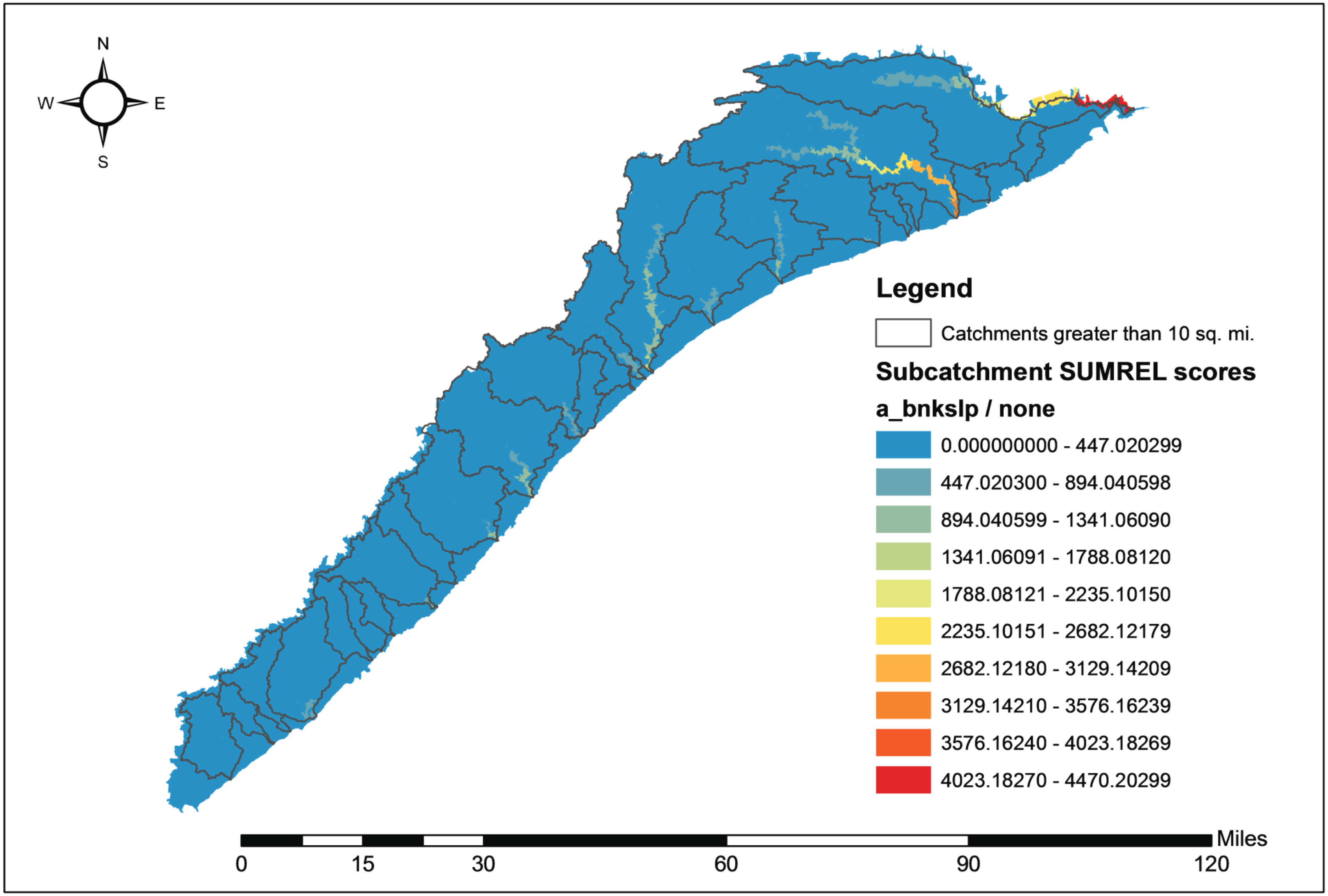

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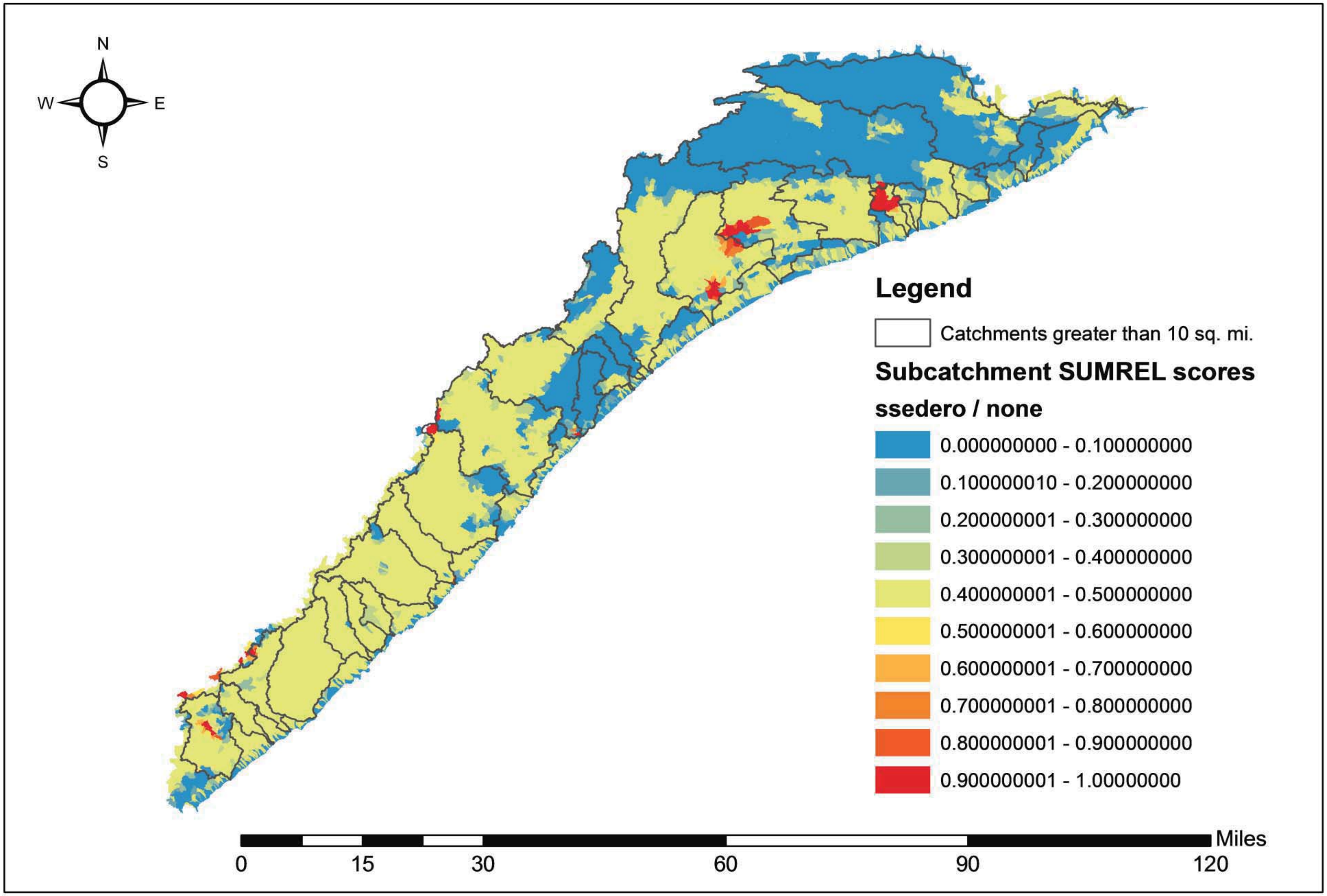

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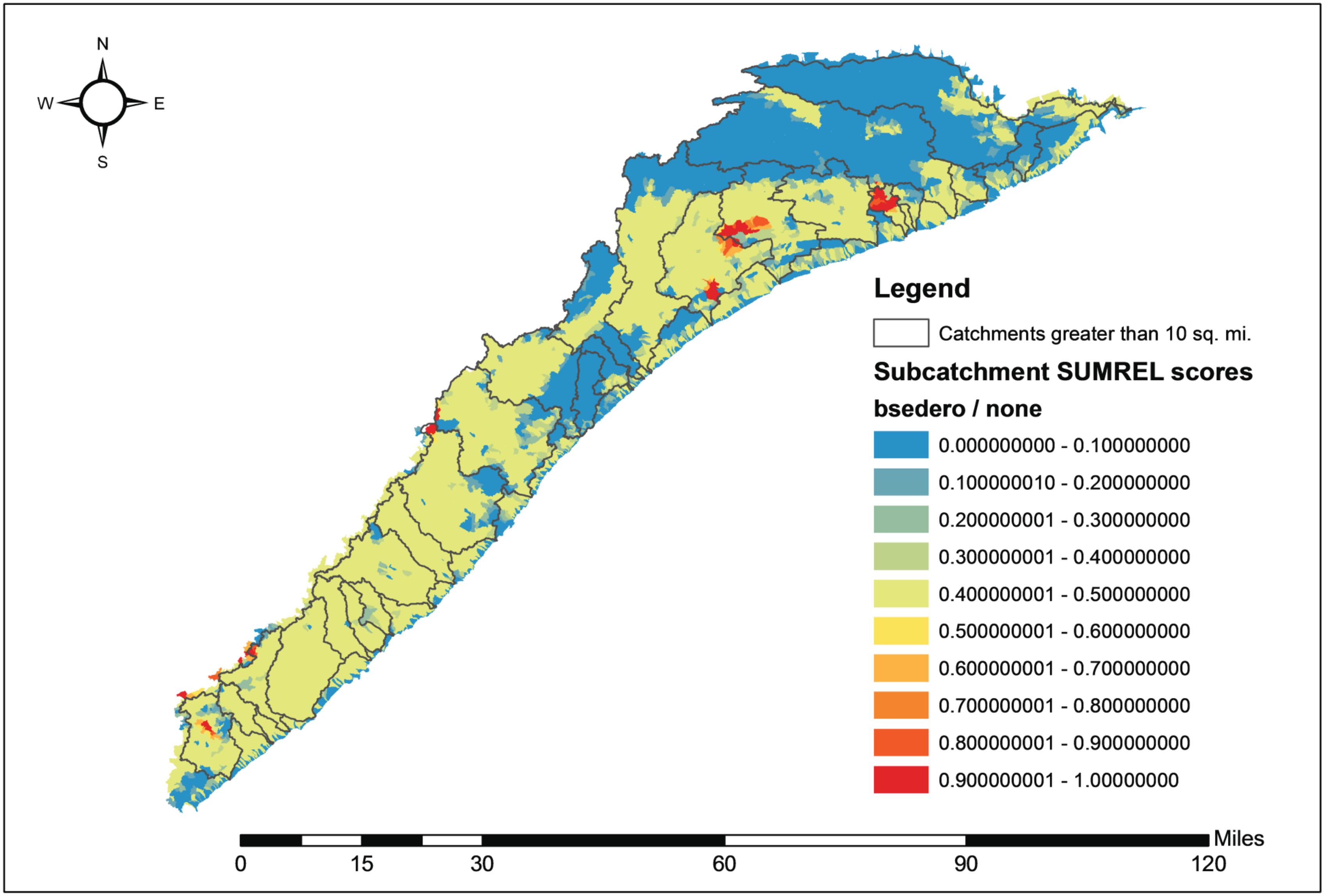

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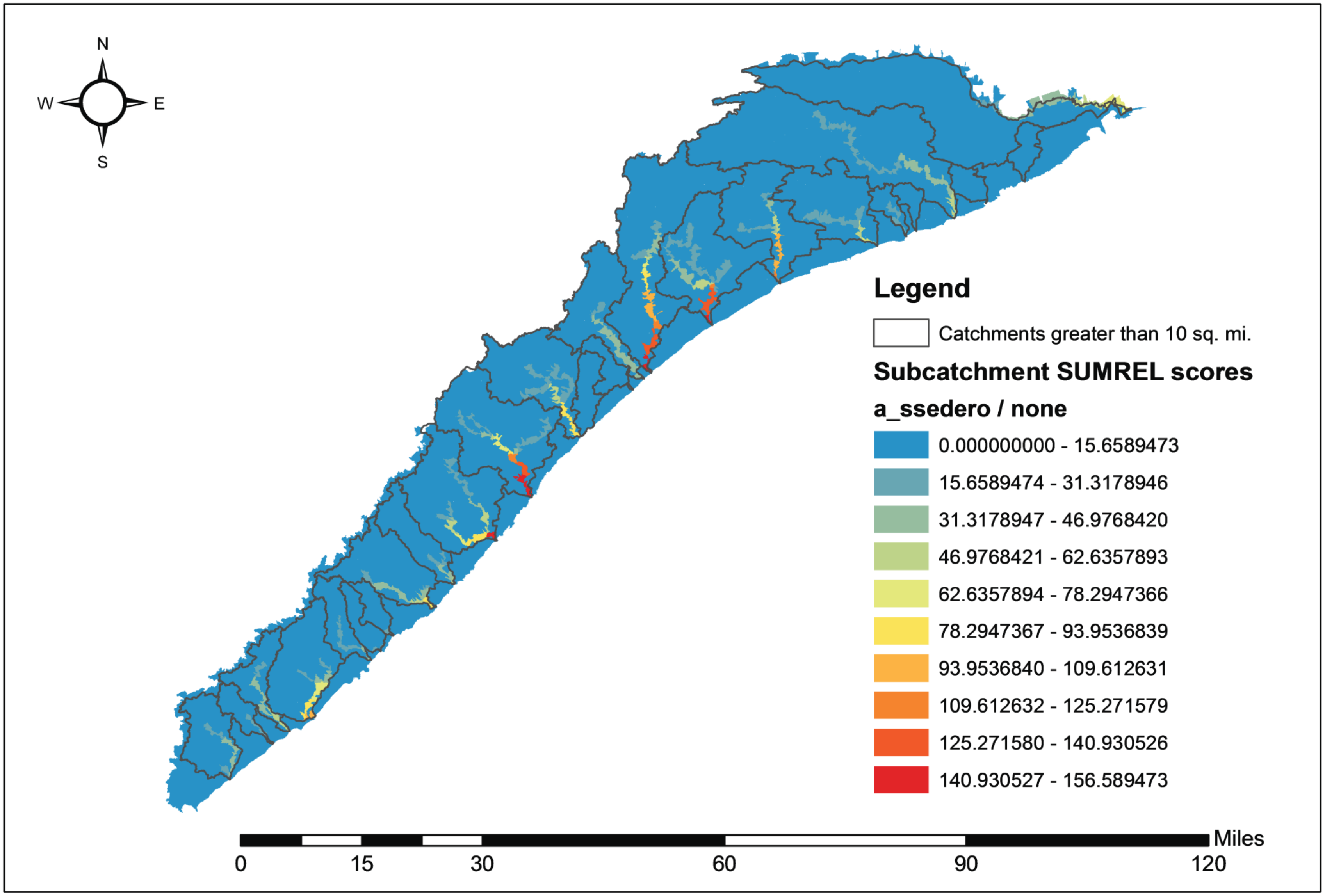

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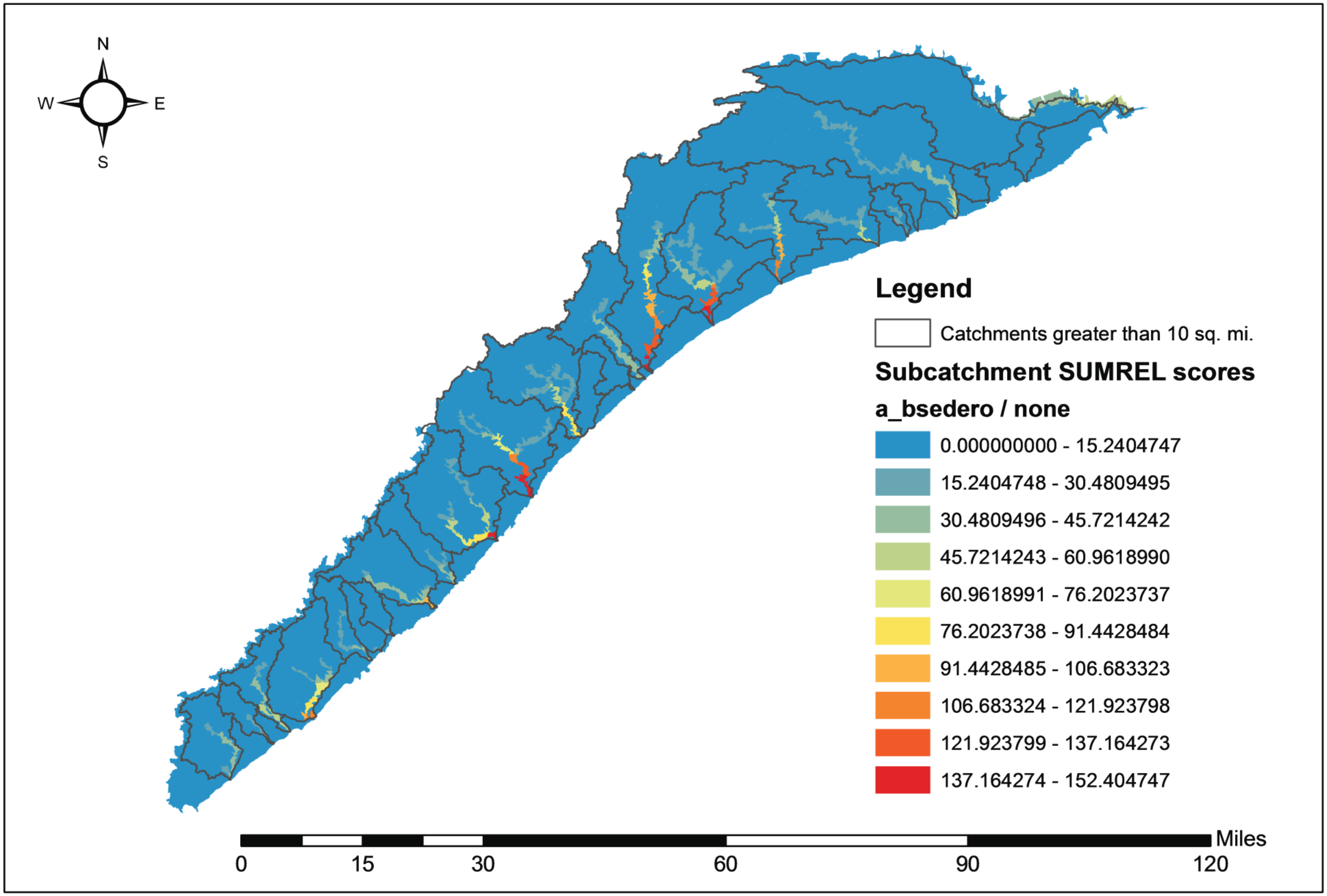

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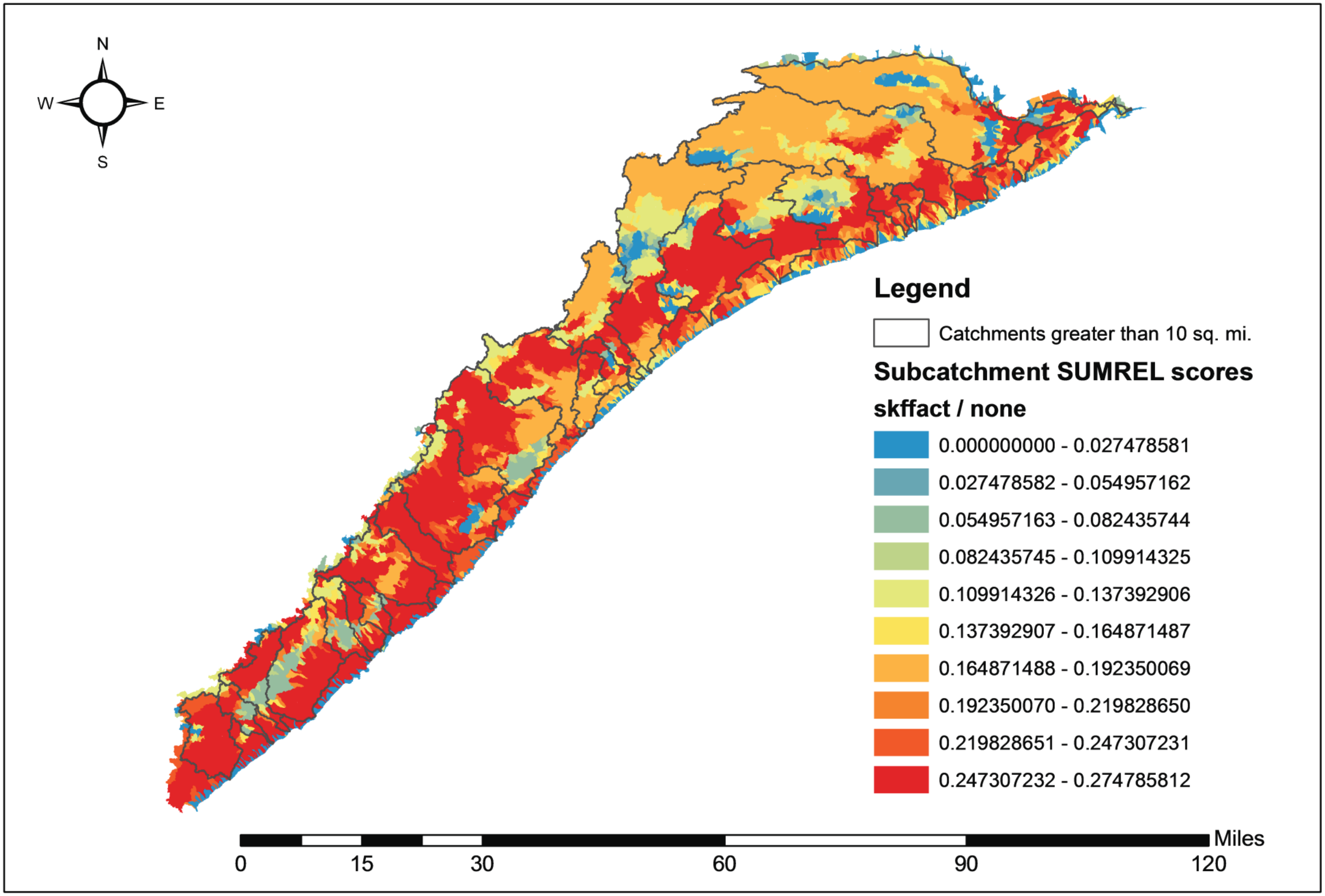


Figure 27. Mean STATSGO KFFACT values along the Minnesota North Shore.

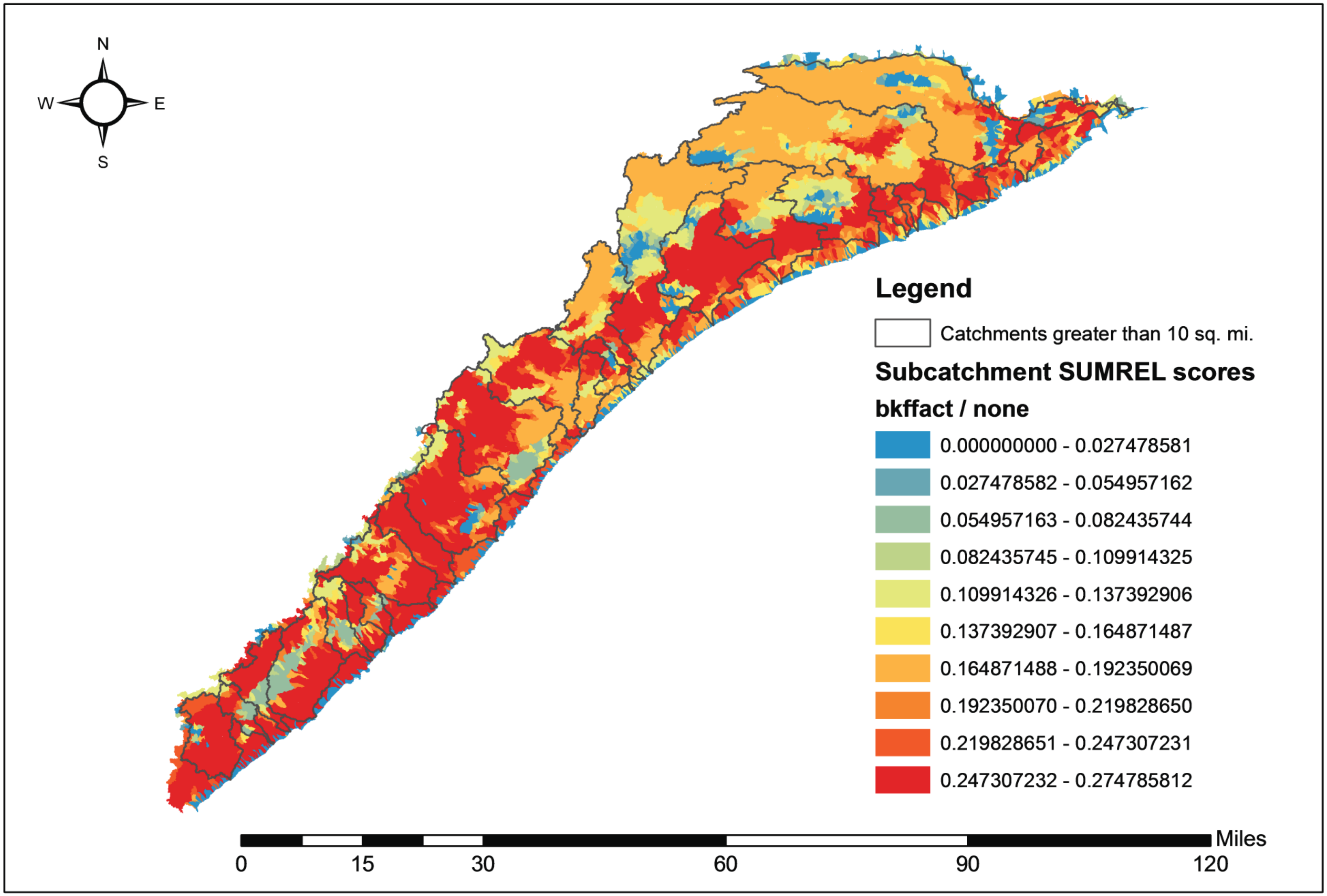


Figure 28. Bank STATSGO KFFACT values for subcatchments along the Minnesota North Shore.

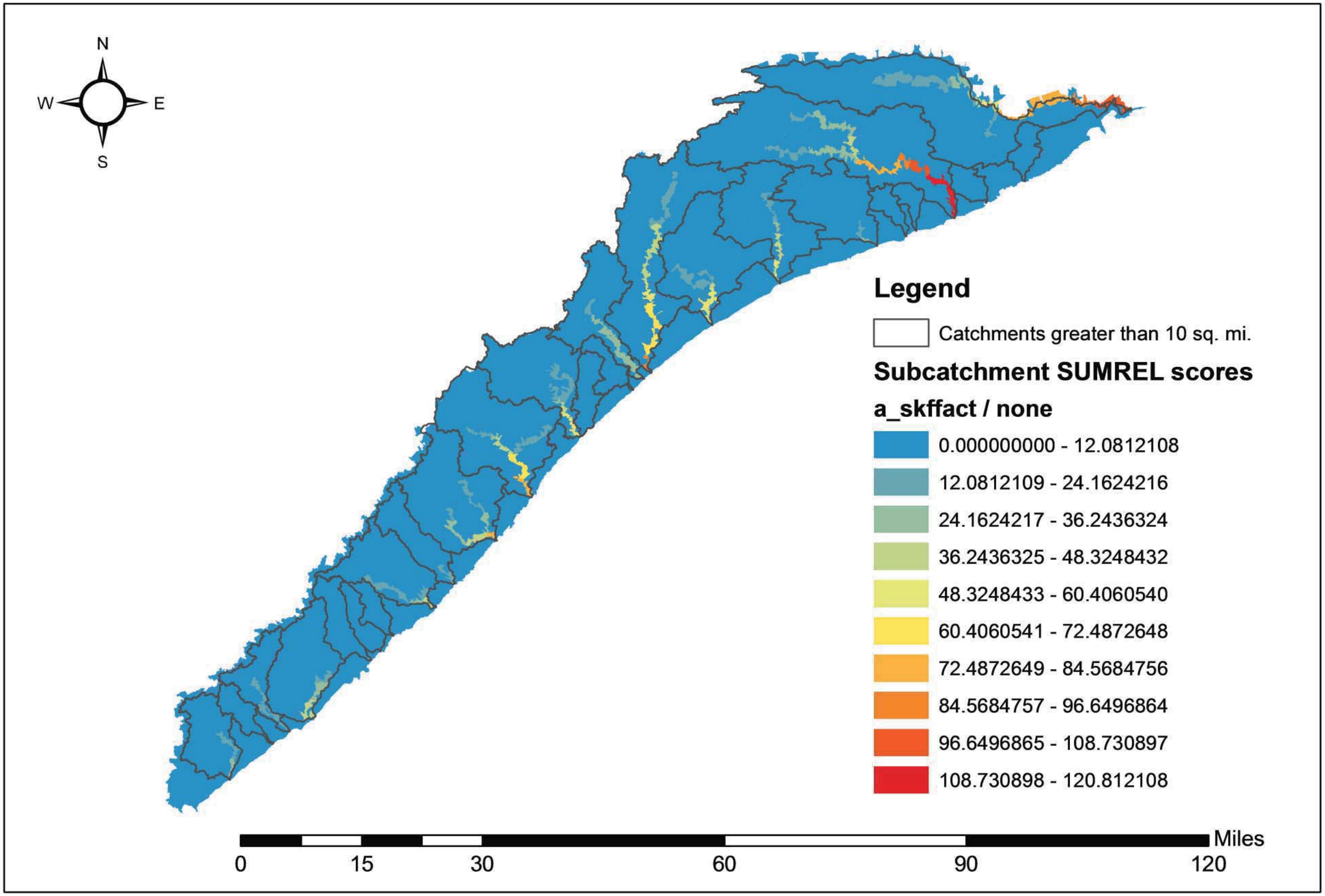


Figure 29. Accumulated mean STATSGO KFFACT values along the Minnesota North Shore.

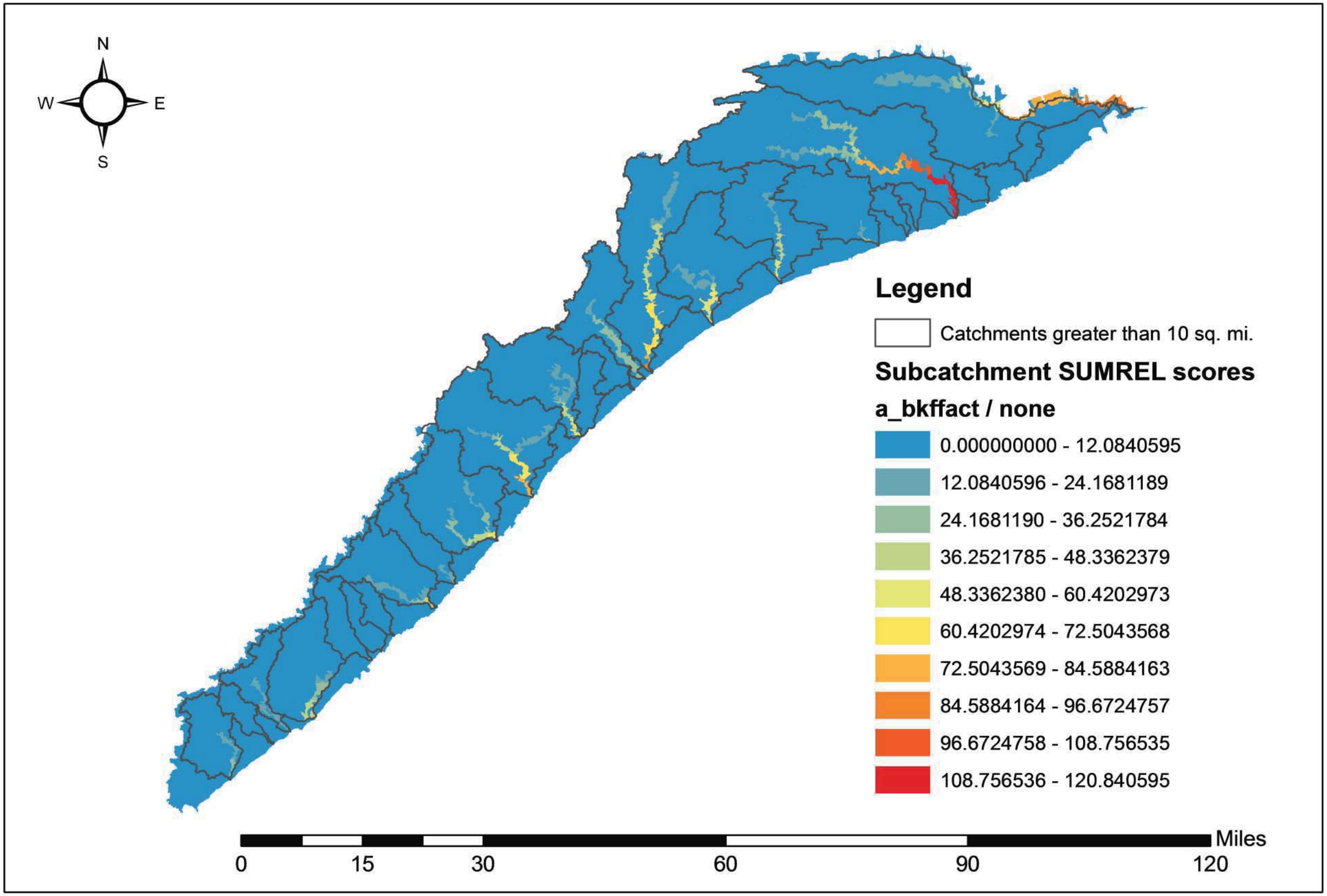


Figure 30. Accumulated bank STATSGO KFFACT values for subcatchments along the Minnesota North Shore.

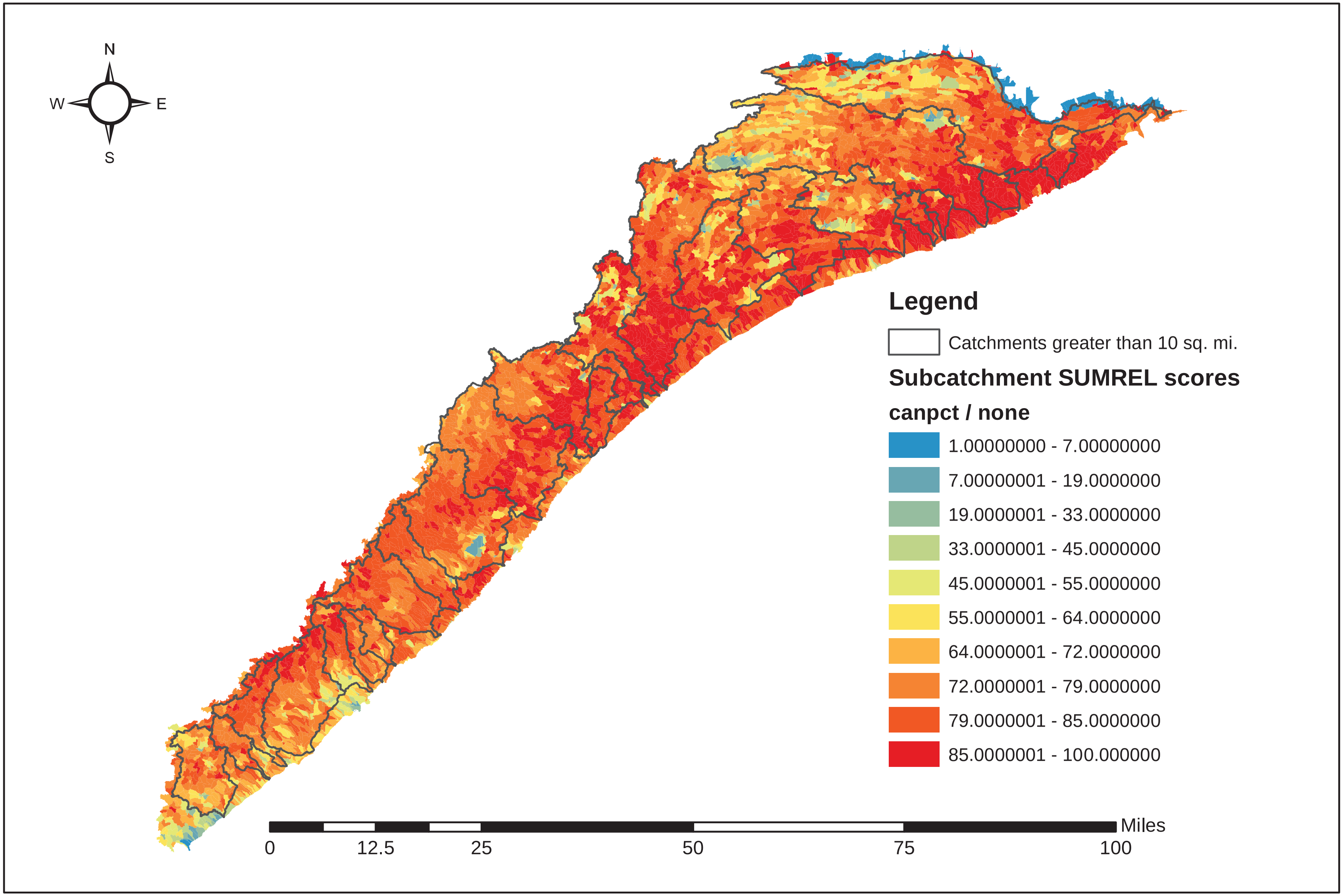


Figure 31. Percent canopy coverage values for subcatchments across the North Shore.

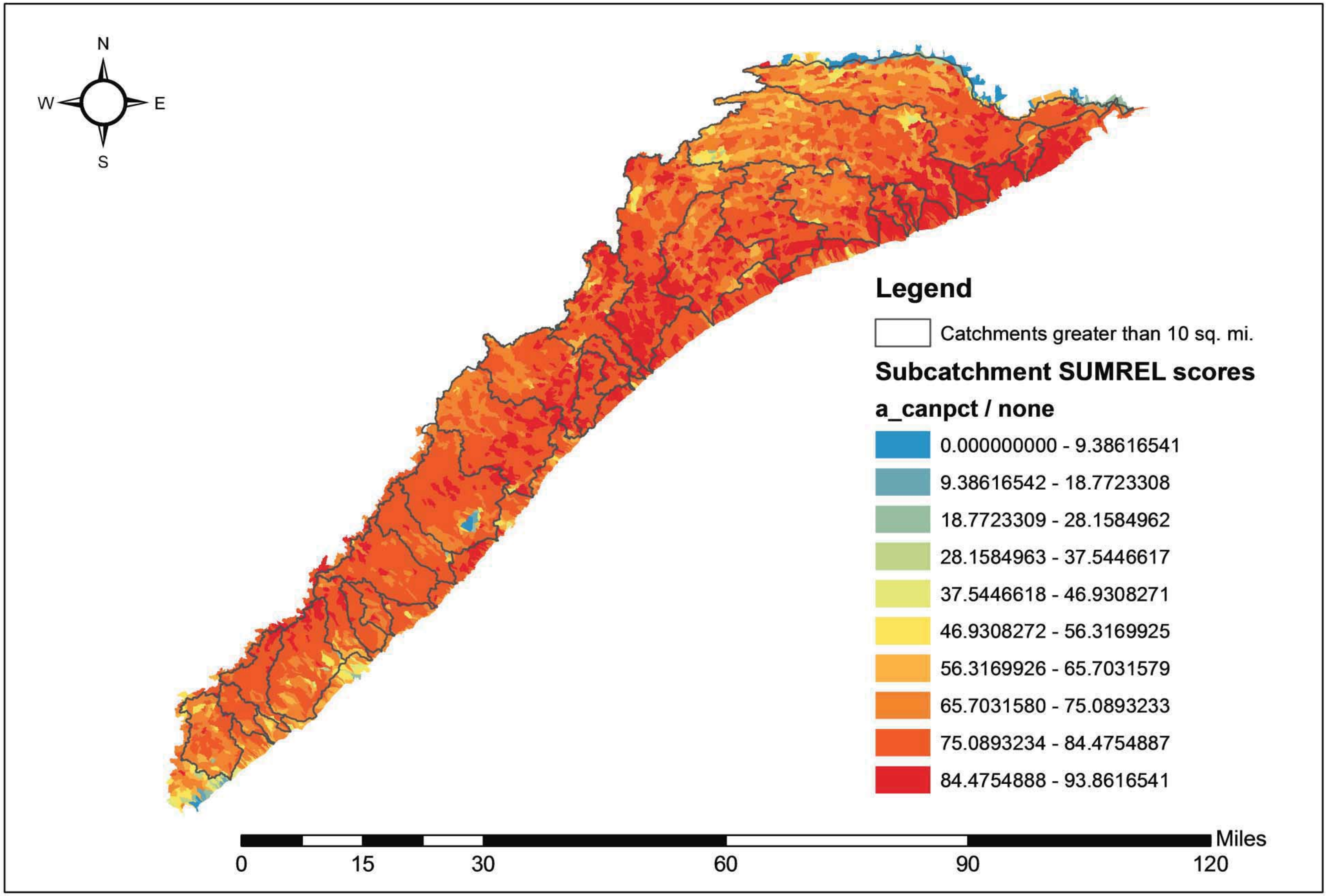


Figure 32. Accumulated percent canopy cover within subcatchments along the Minnesota North Shore.

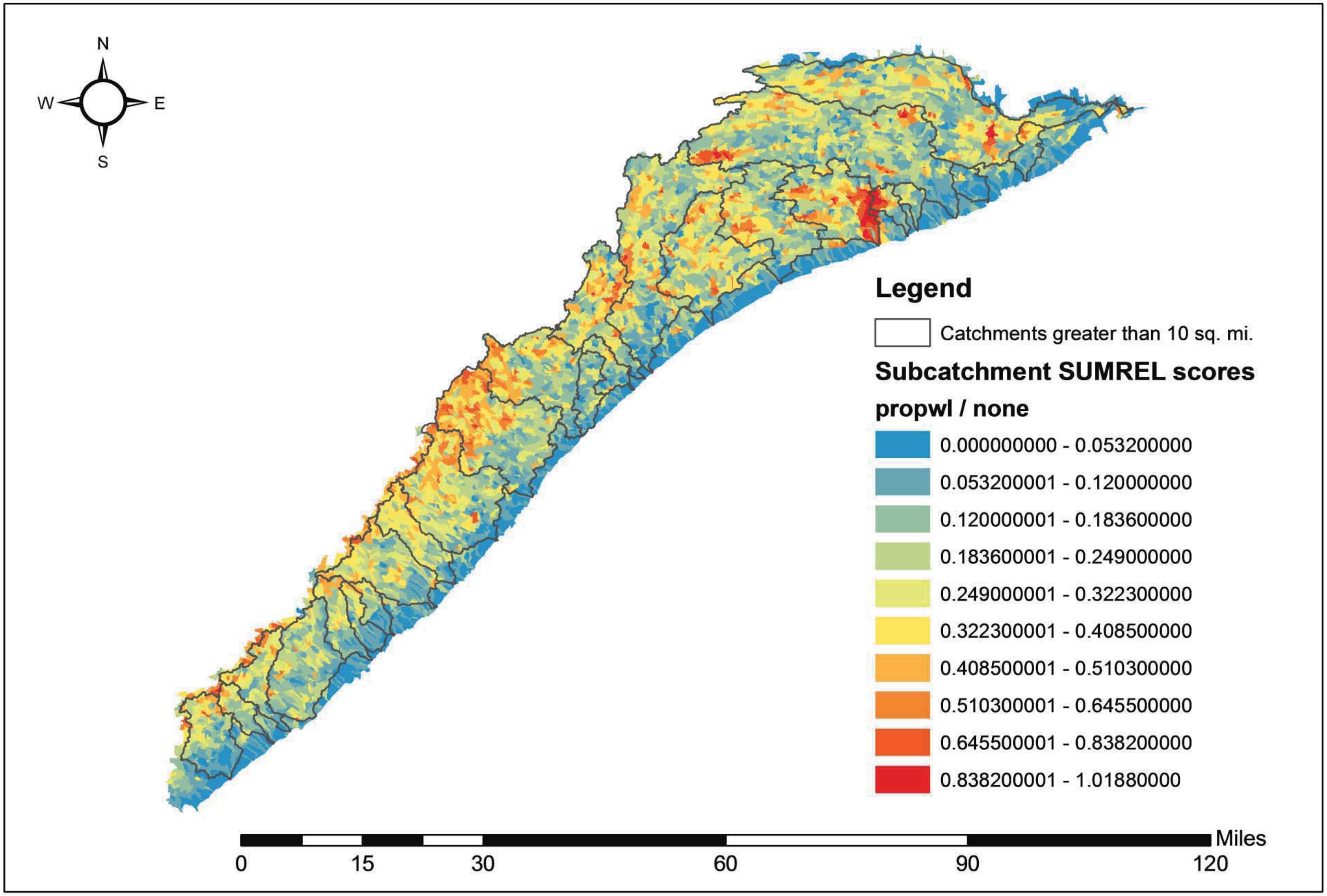


Figure 33. Proportion of wetlands per subcatchment along the Minnesota North Shore.

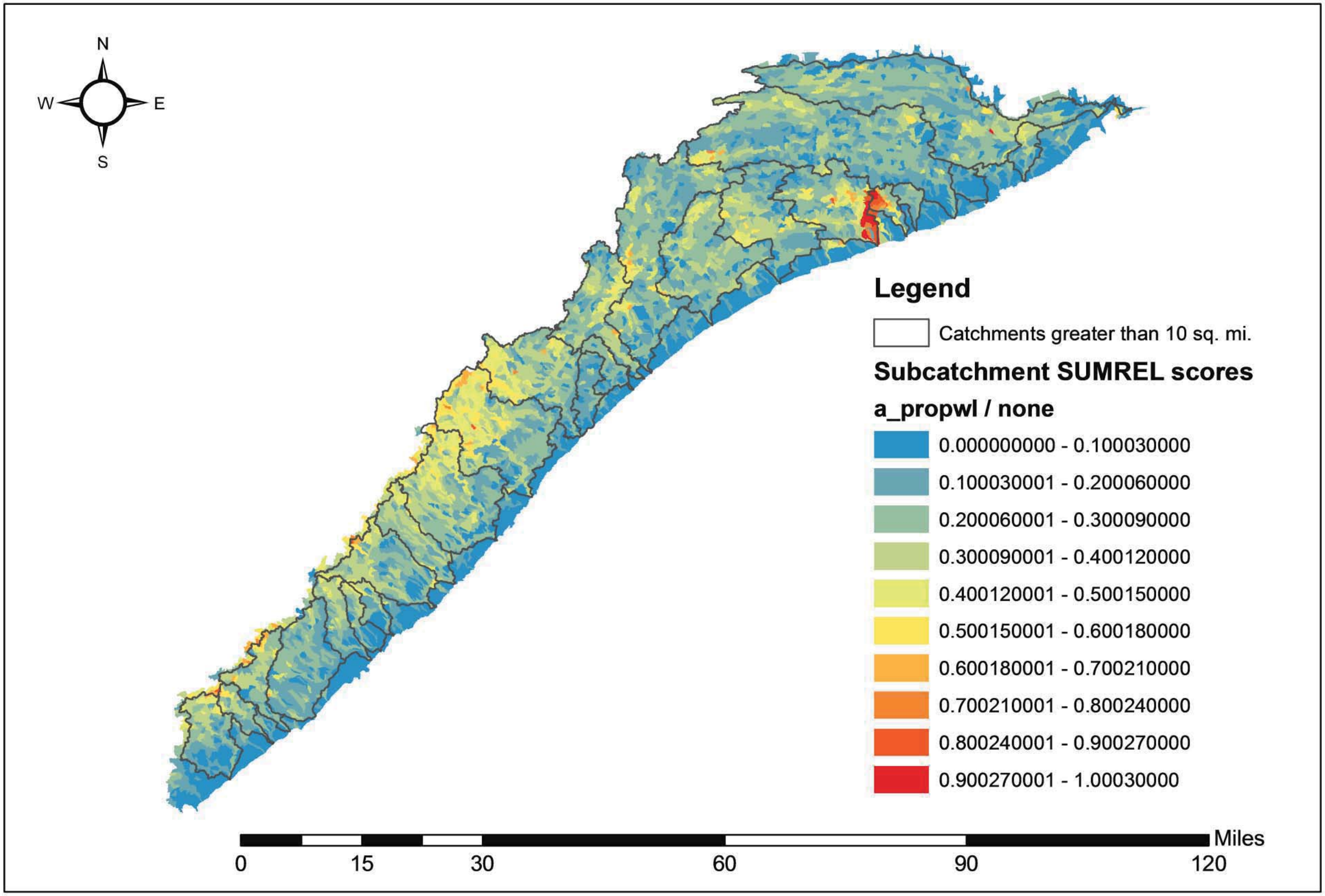


Figure 34. Accumulated effects of wetlands per subcatchment along the Minnesota North Shore.

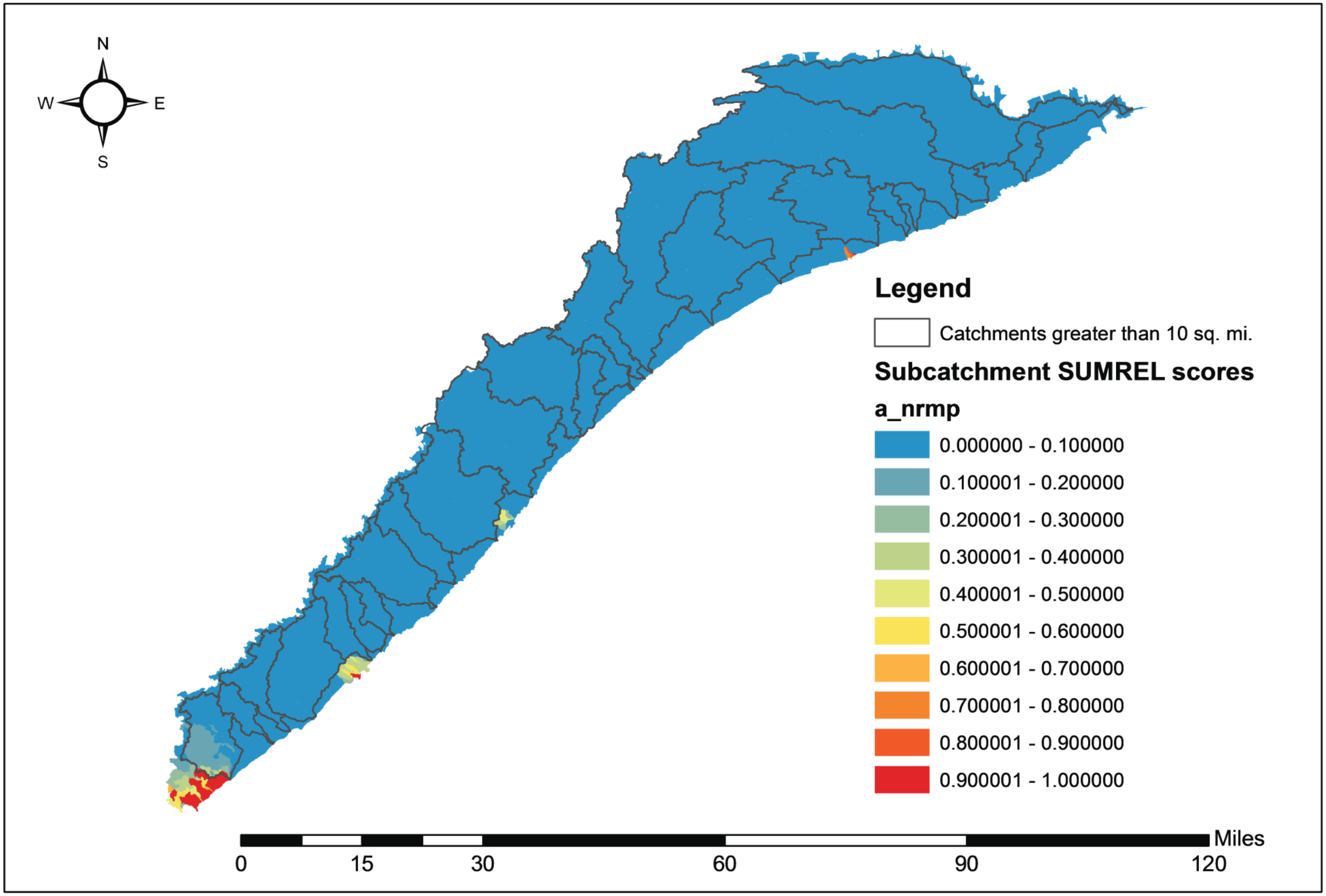


Figure 35. Accumulated normalized population density along the Minnesota North Shore.

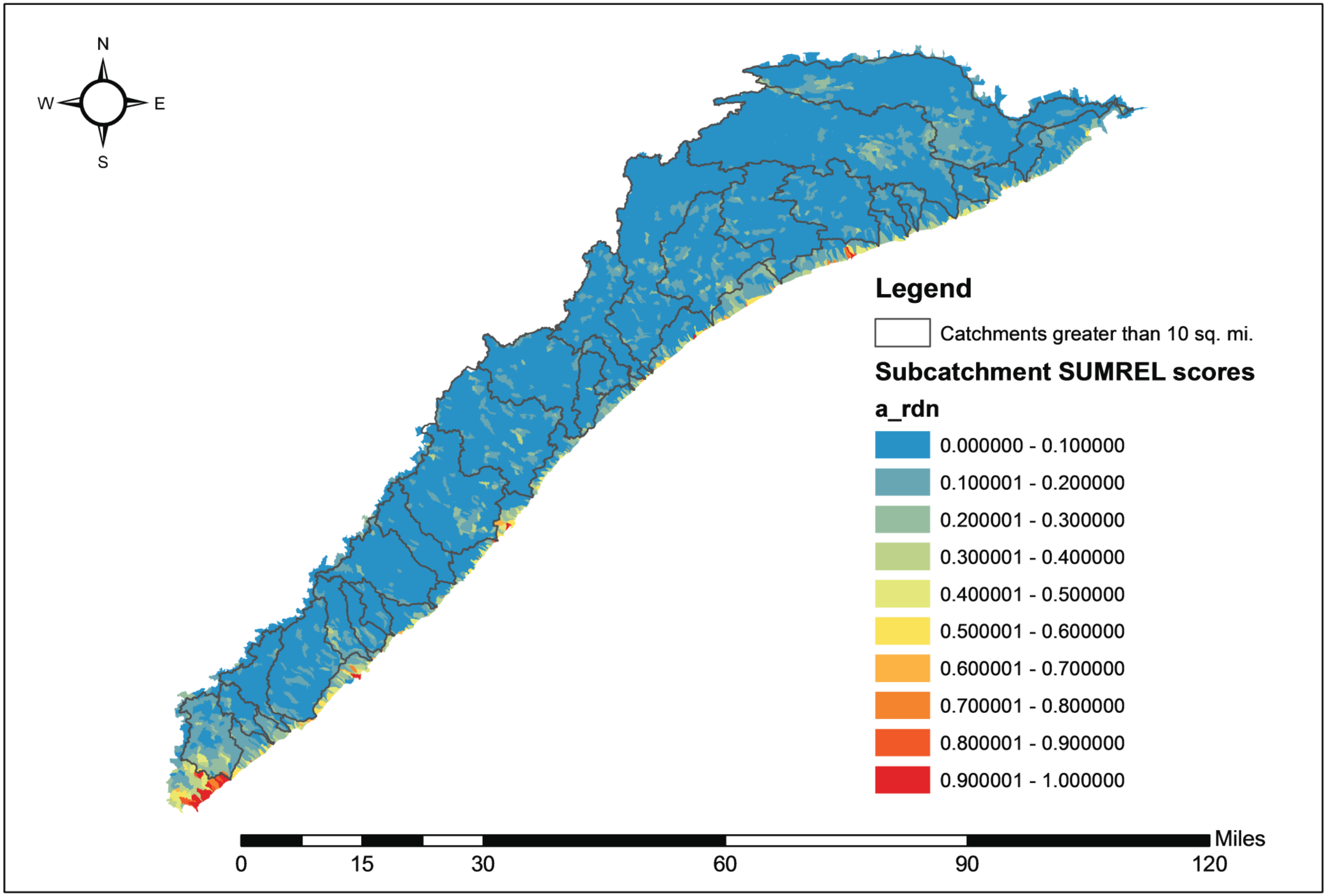


Figure 36. Accumulated road density network per subcatchment along the Minnesota North Shore.

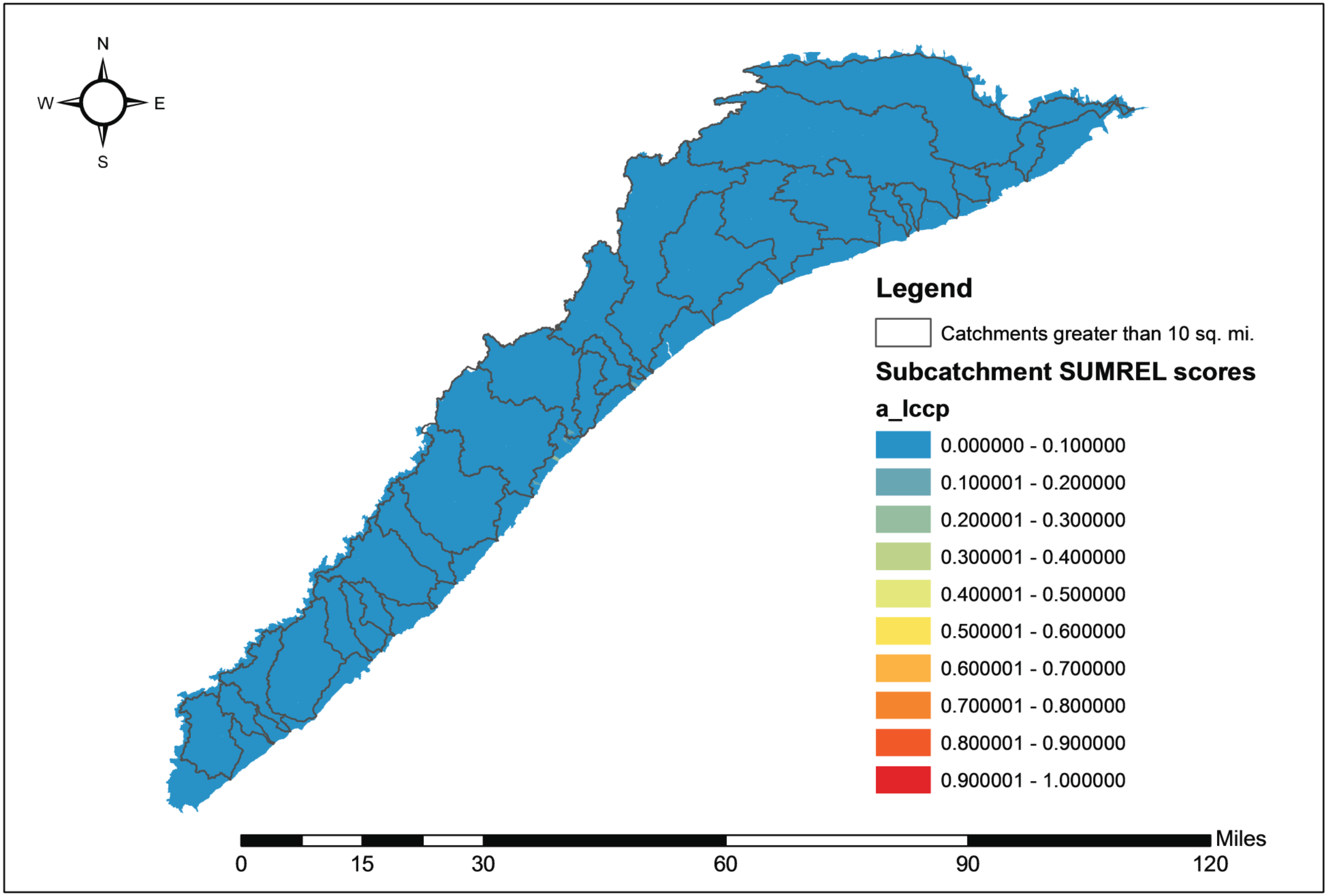


Figure 37. Accumulated land cover in crops along the Minnesota North Shore.

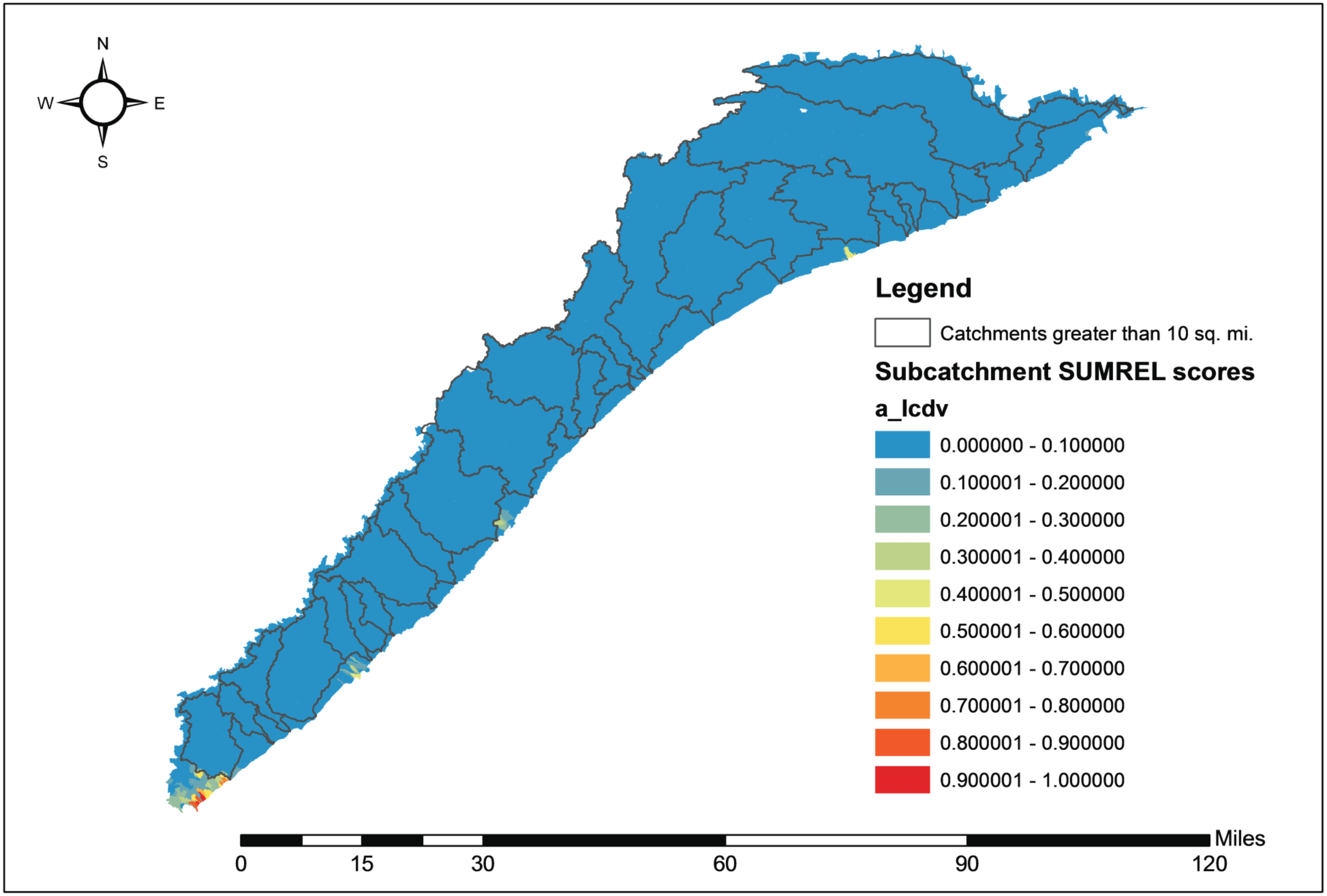


Figure 38. Accumulated land cover in development along the Minnesota North Shore.

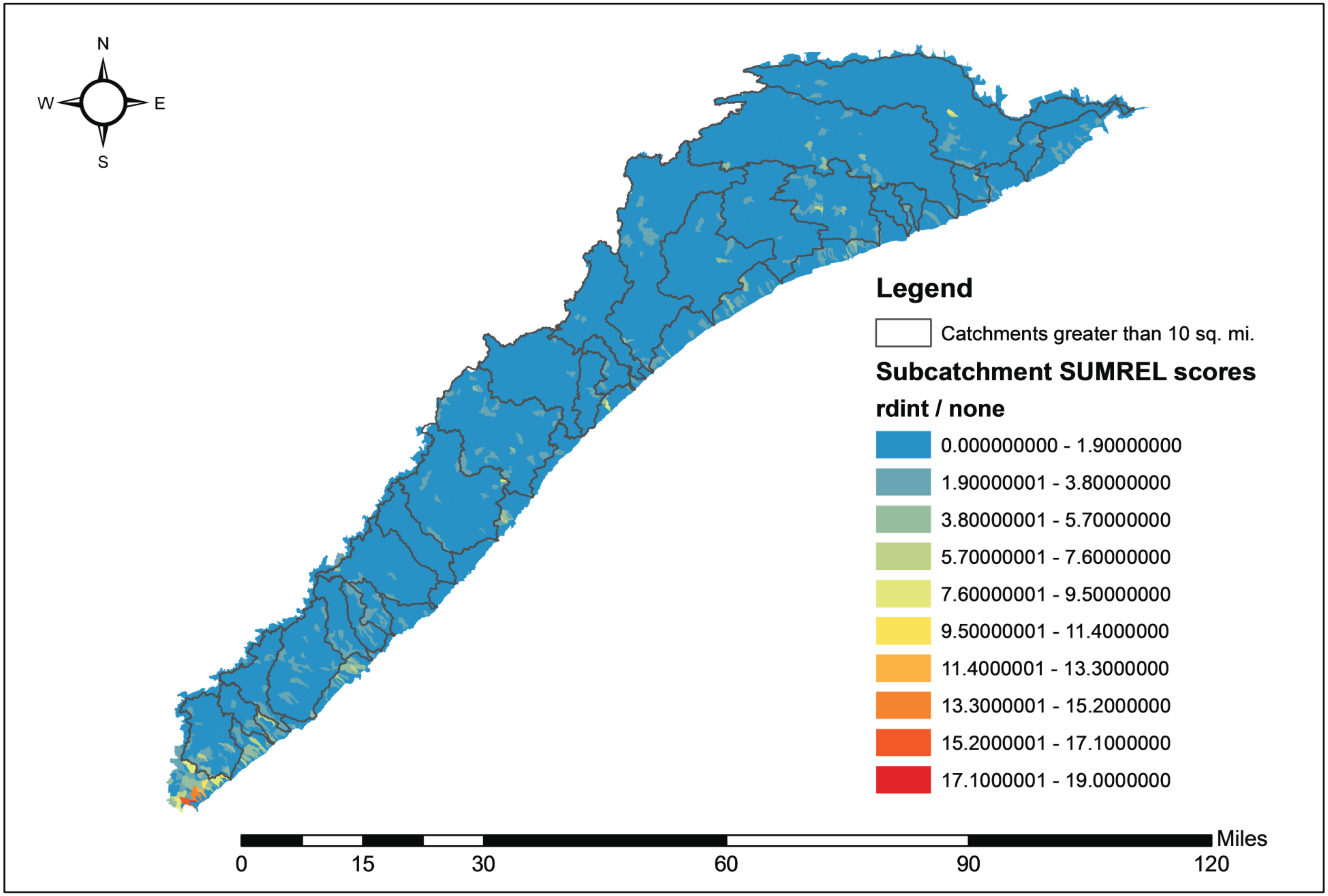


Figure 39. Road stream intersections per subcatchment along the Minnesota North Shore.

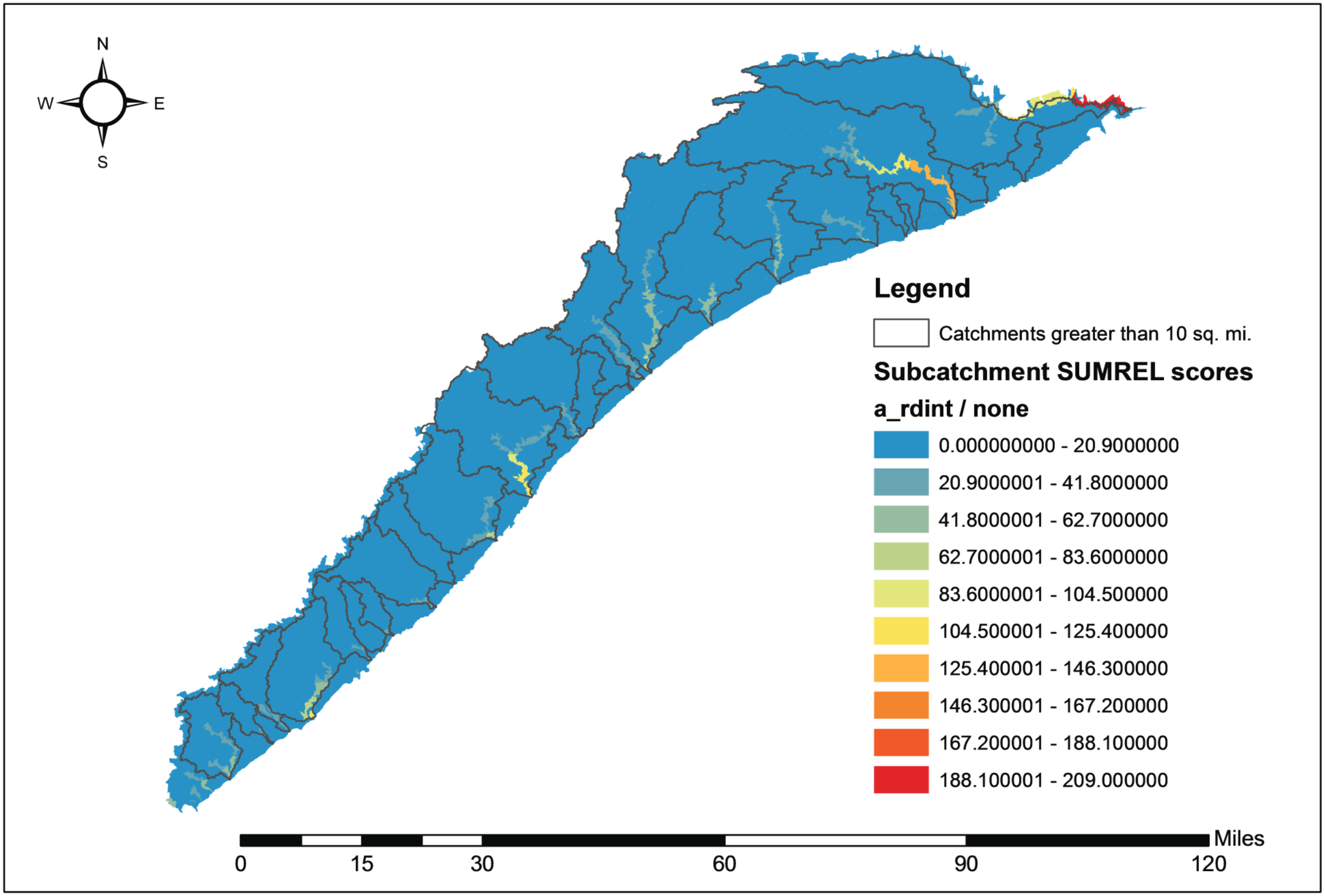


Figure 40. Accumulated road stream intersections per subcatchments along the Minnesota North Shore.

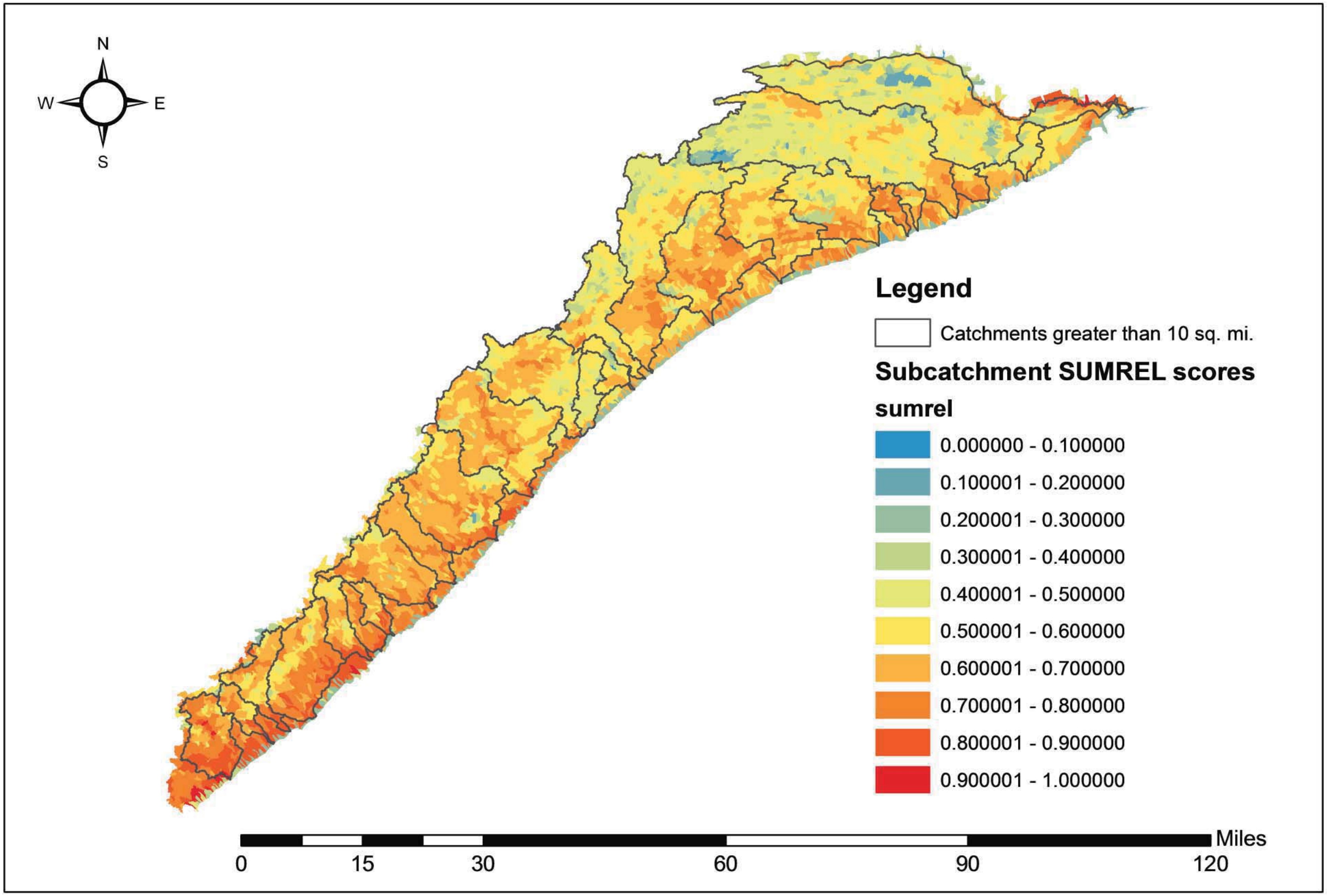


Figure 41. SUMREL stressor scores considering natural and anthropogenic variables along the Minnesota North Shore.

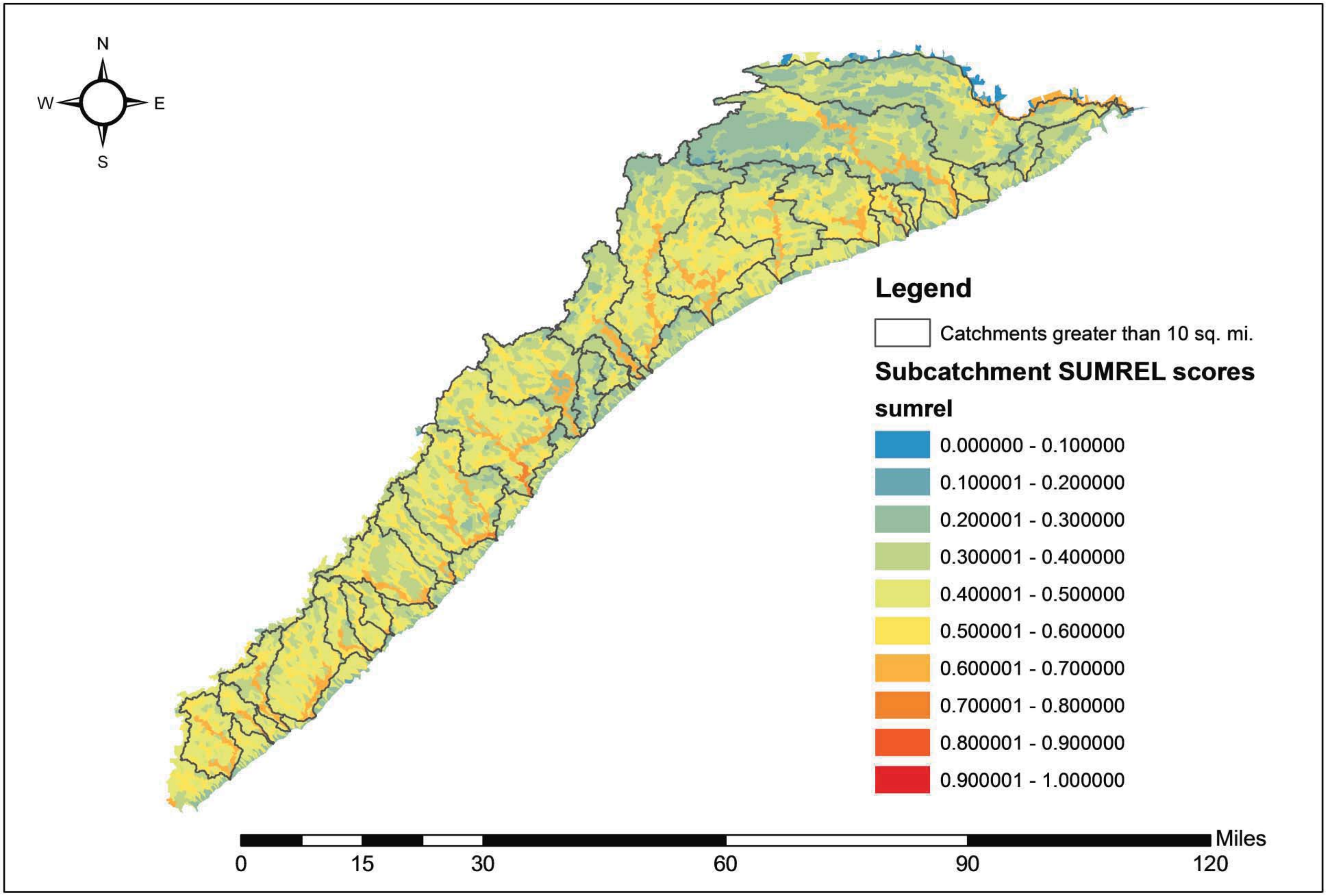


Figure 42. Accumulated SUMREL scores considering both natural and anthropogenic stressor variables along the Minnesota North Shore.

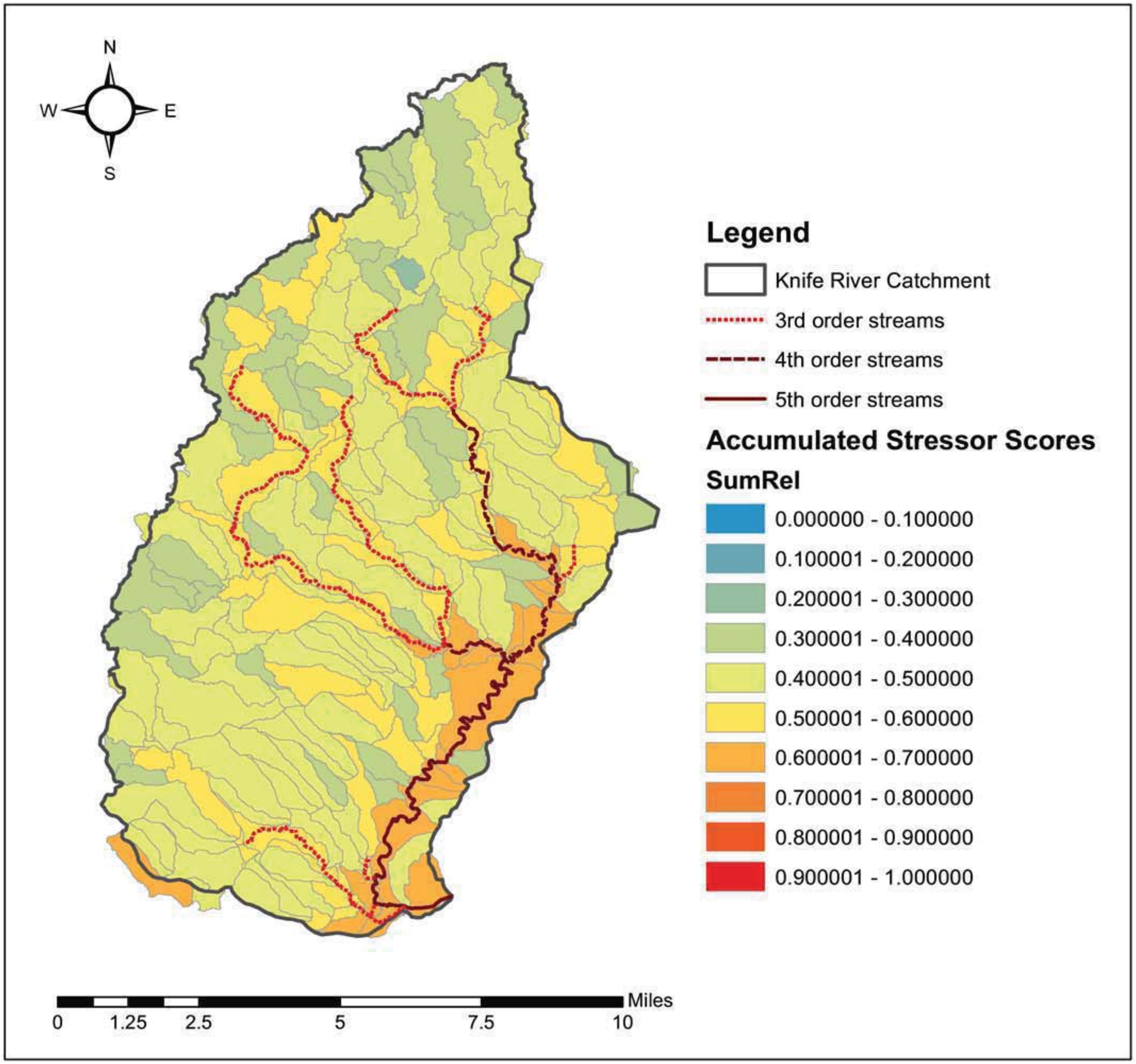


Figure 43. Comparison of accumulated SUMREL stressor scores to stream order in the Knife River catchment.

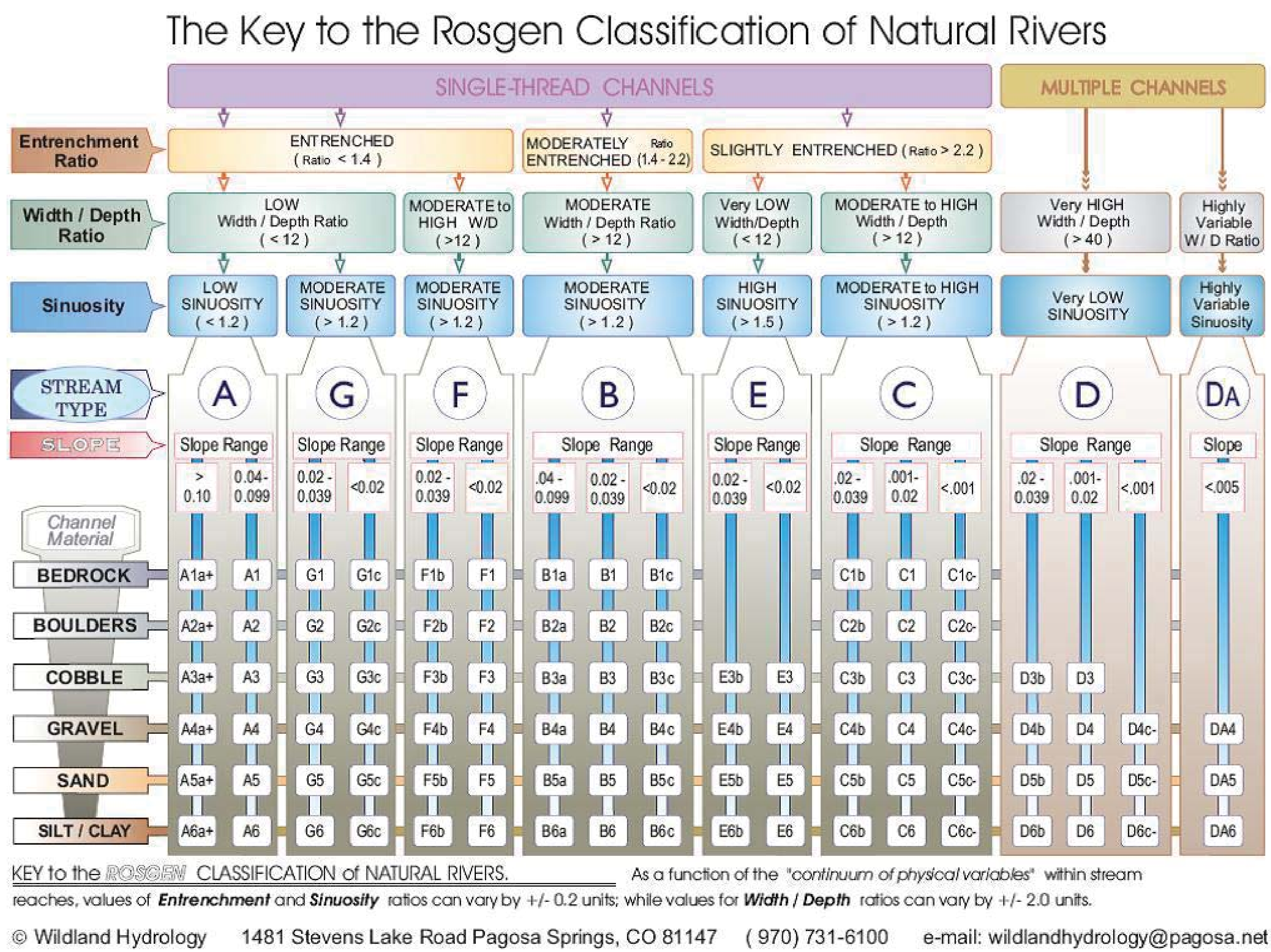


Figure 44. Rosgen’s Channel Classification System

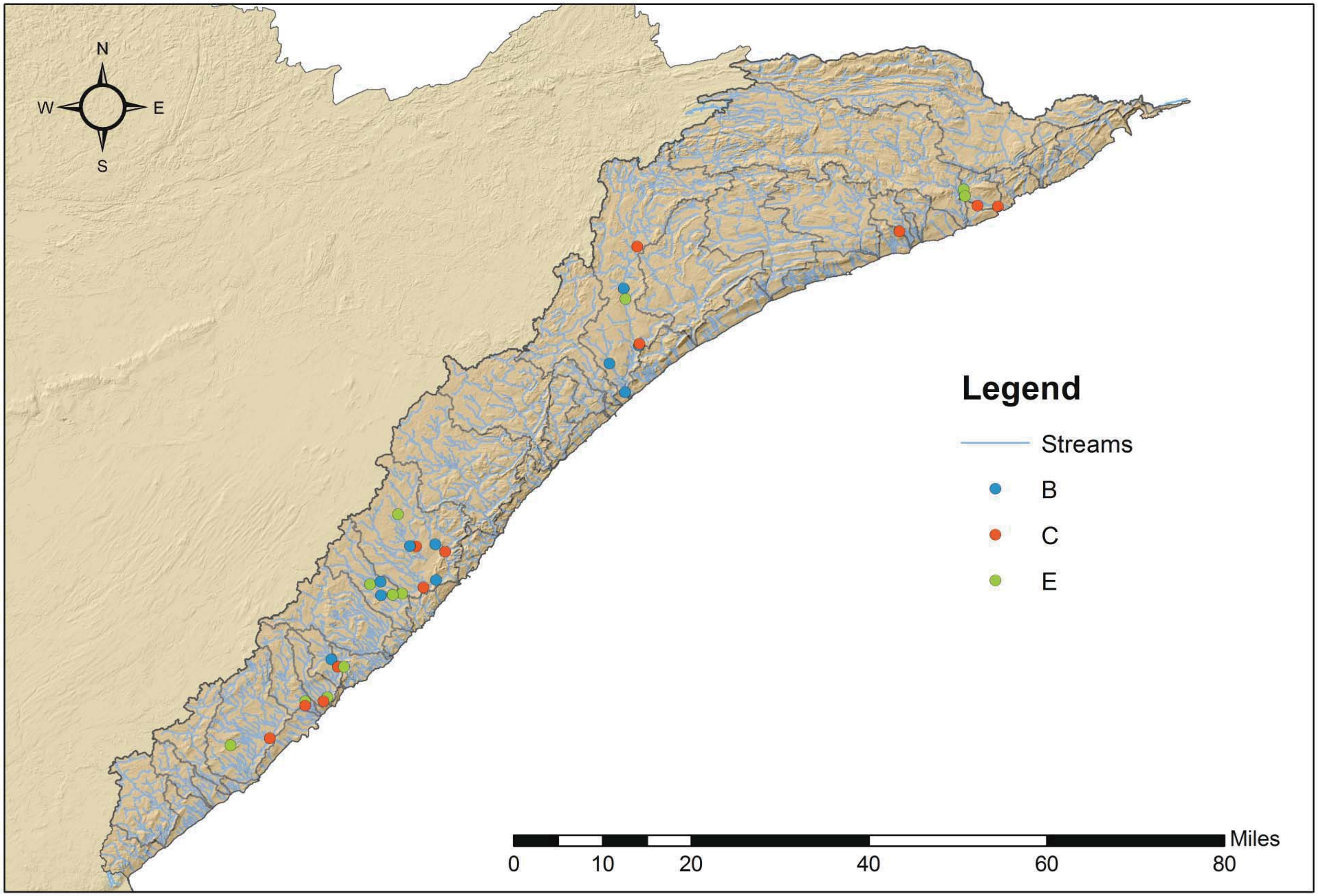


Figure 45. Channel Classifications for Level I and Level II field sites.

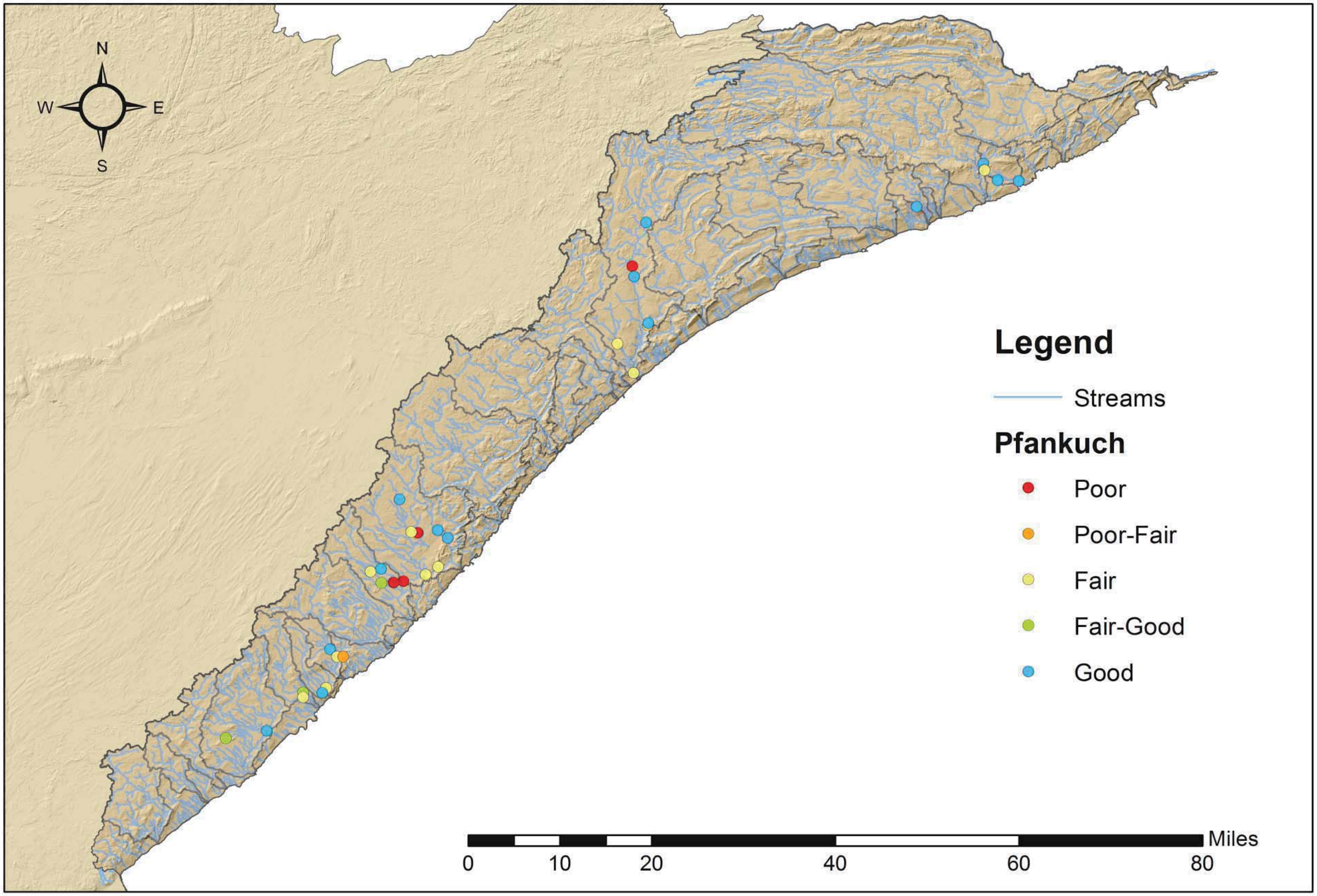


Figure 46. Pfankuch channel stability ratings defined at each of the Level I and Level II field sites.

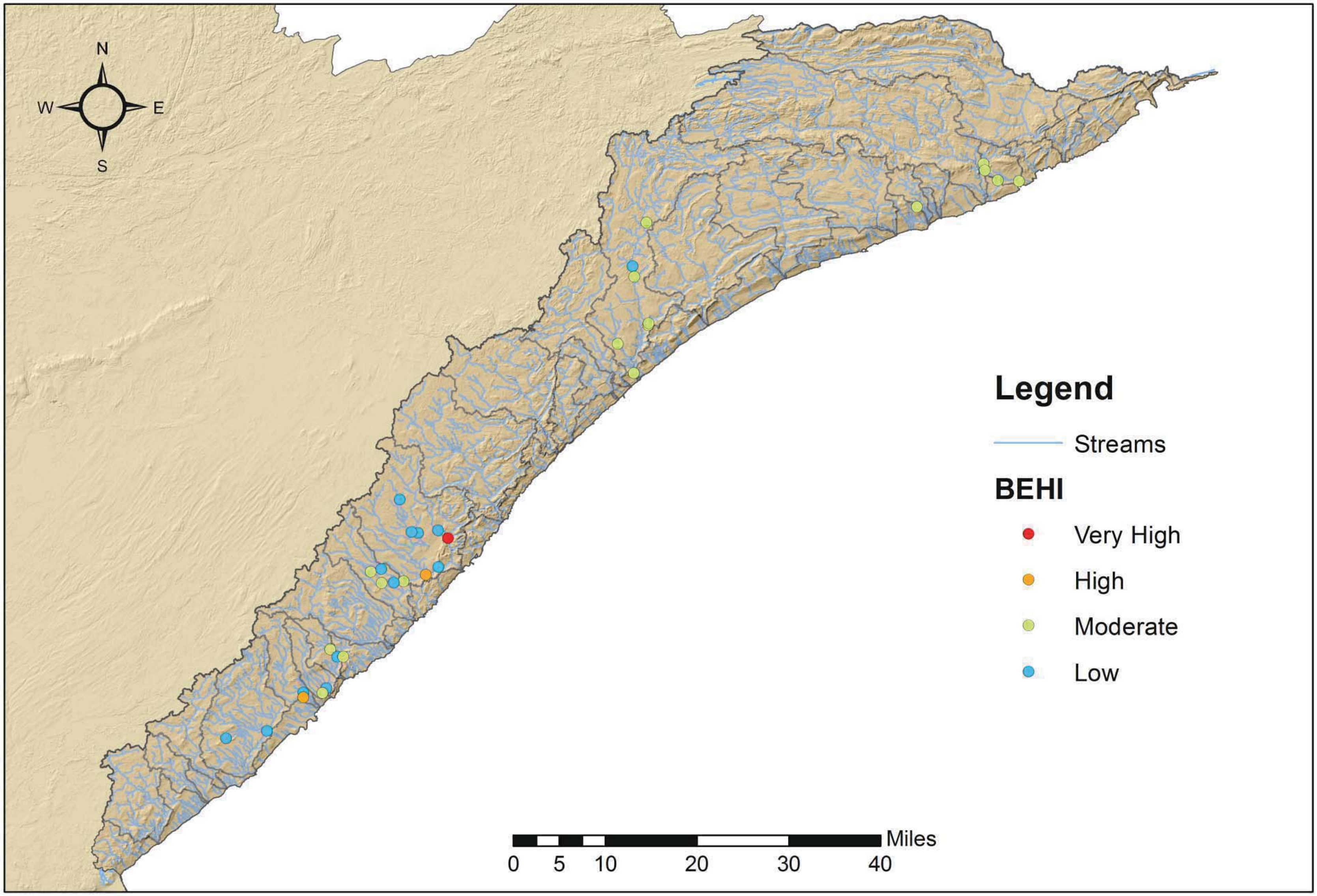


Figure 47. BEHI adjective ratings determined at each of the Level I and Level II field sites.

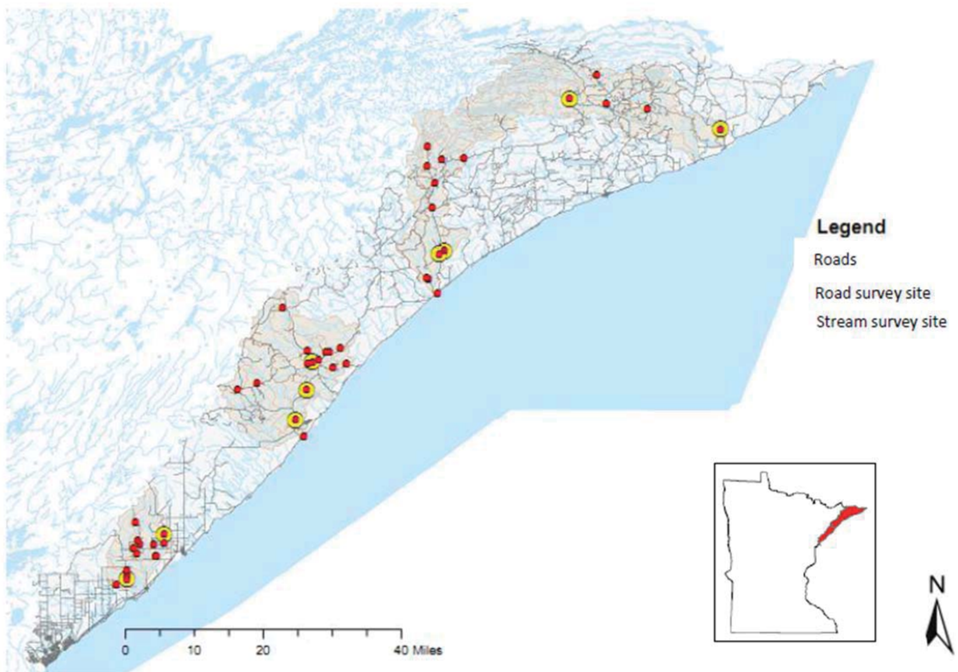


Figure 48. Road and stream survey sites. Red dots indicate the locations of the 54 road-stream crossings assessed in this study while the larger yellow circles highlight areas where surveys of channel stability were evaluated upstream and downstream of the road crossings. Figure taken from Dutton, 2012.

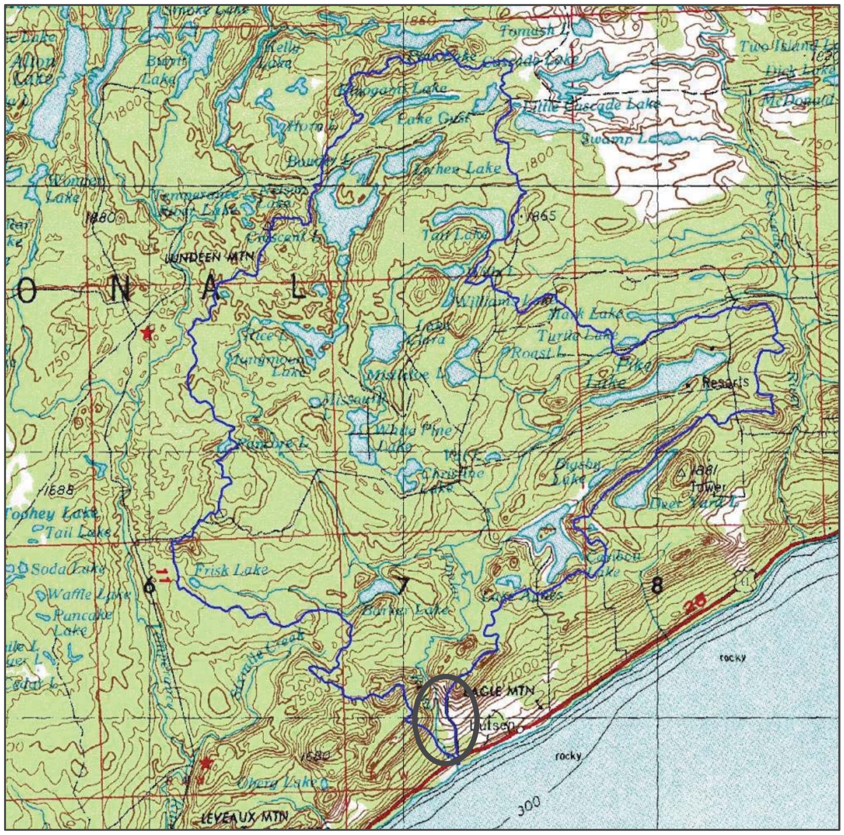


Figure 49. Topographic map with the outline of the Poplar River located along the north shore of Lake Superior. The red oval outlines the area of interest with regard to the turbidity impairment, that is, the Lower Poplar River watershed. (Figure 1 from Nieber, 2013).

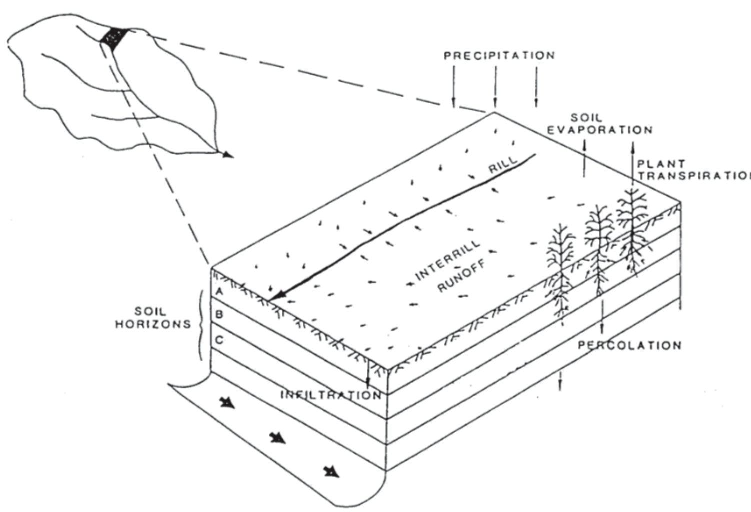


Figure 50. Illustration of the water balance components handled in the WEPP model hydrologic calculations. Vegetation interception and shallow subsurface flow are not shown here but they are included in the model calculations. (Figure 3 from Nieber, 2013).

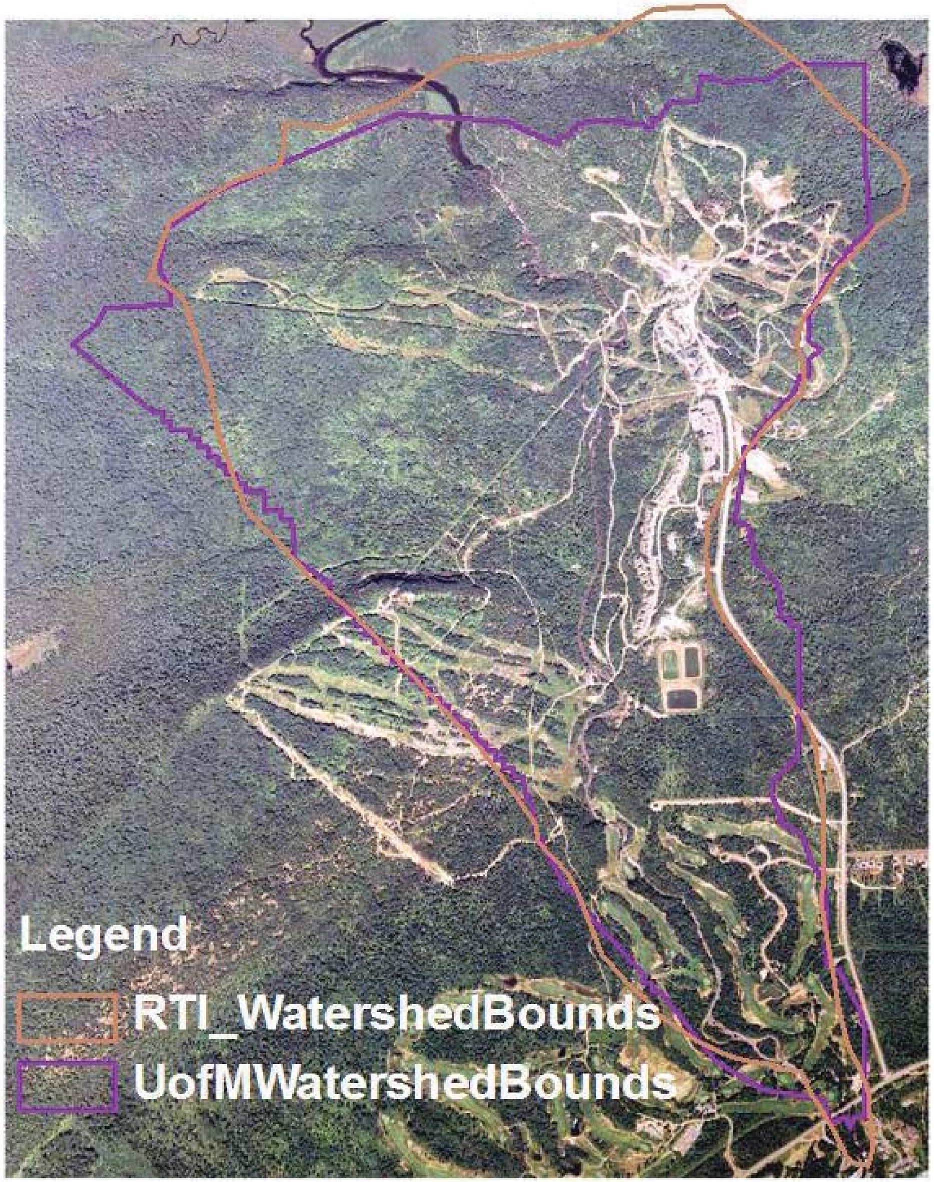


Figure 51. Watershed delineations for the Lower Poplar River watershed. One delineation is for the current effort (UofM) while the other one is for the RTI study (RTI, 2008). (Figure 9 from Nieber, 2013).

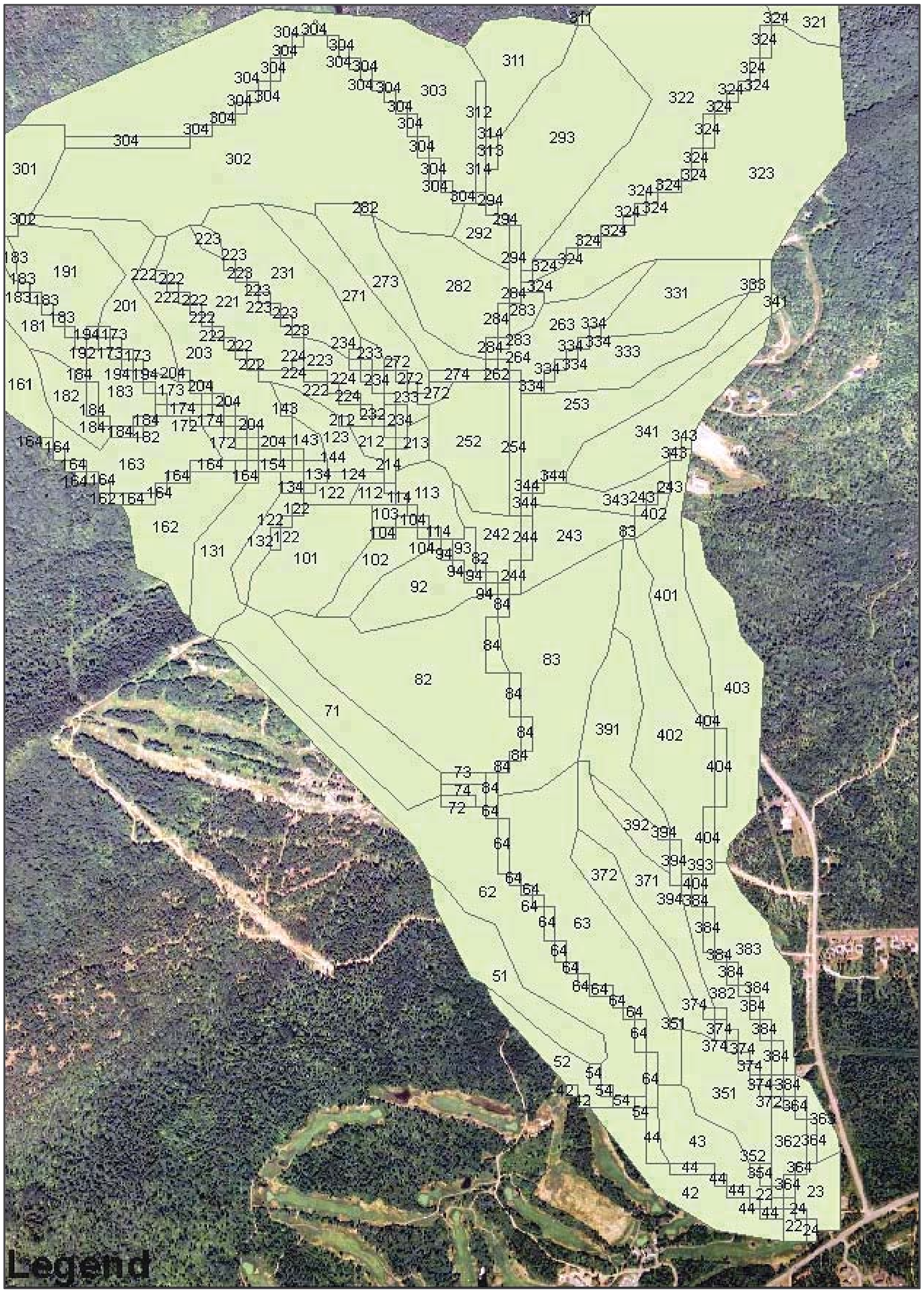


Figure 52. Delineated hillslopes and stream elements of the Lower Poplar River watershed. Individual hillslopes are assigned a unique number. The stream elements are identified by a linear sequence of elements that have the same number. Different stream segments are distinguished by the assigned numbers. (Figure 10 from Nieber, 2013).

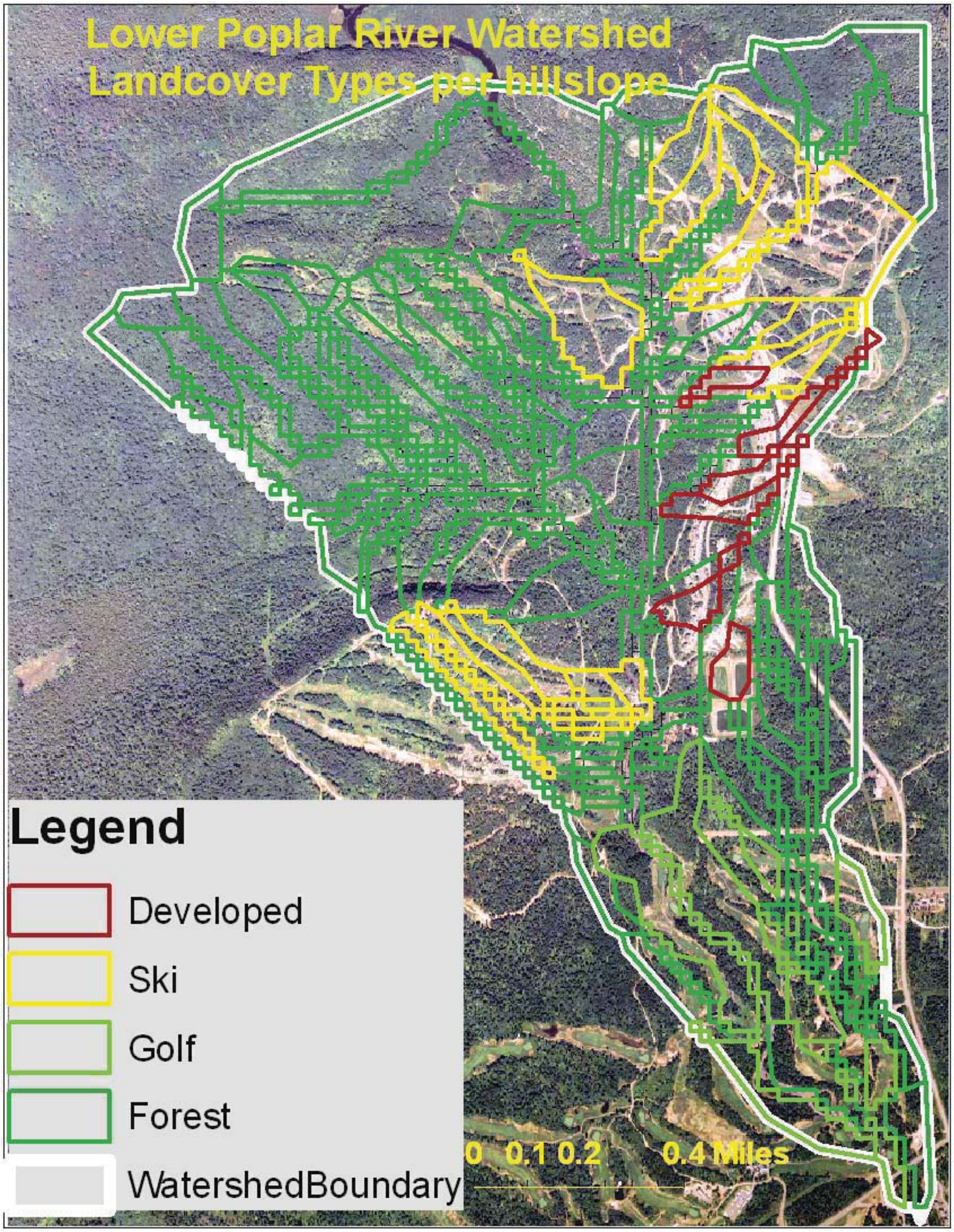


Figure 53. The land use and land cover classifications assigned to the hillslope elements for the WEPP model. (Figure 13 from Nieber, 2013).

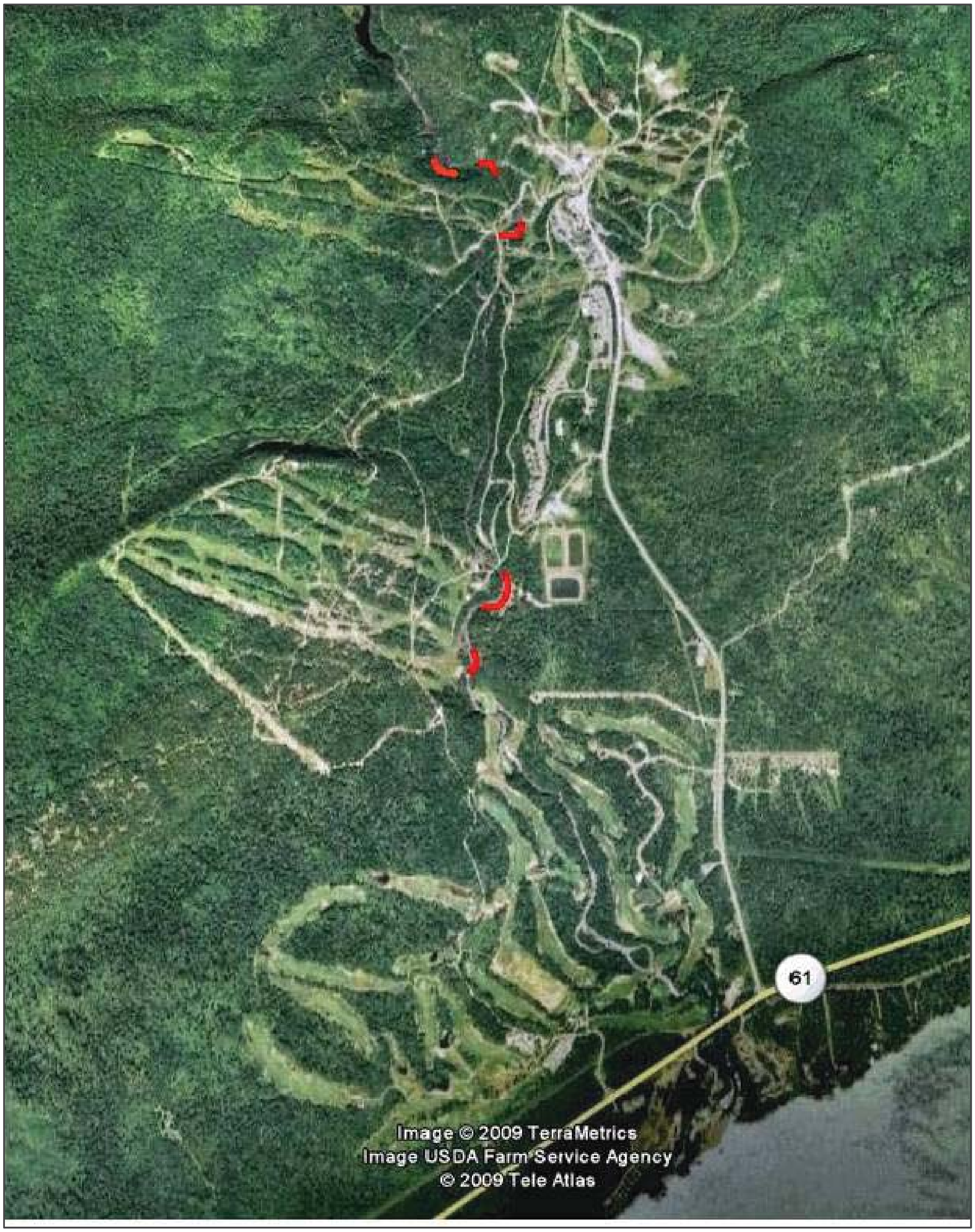


Figure 54. Location of slumps identified in the Lower Poplar River watershed. These slumps are indicated by the red areas along the Lower Poplar River. (Figure 12 from Nieber, 2013).

Figure 55. Illustration of the location of major ravines in the Lower Poplar River watershed. (a). Ullr ravine; (b). Brule ravine; (c). Moose Mountain ravine. Image is by courtesy of Google Maps. (Figure 24, Nieber 2013).

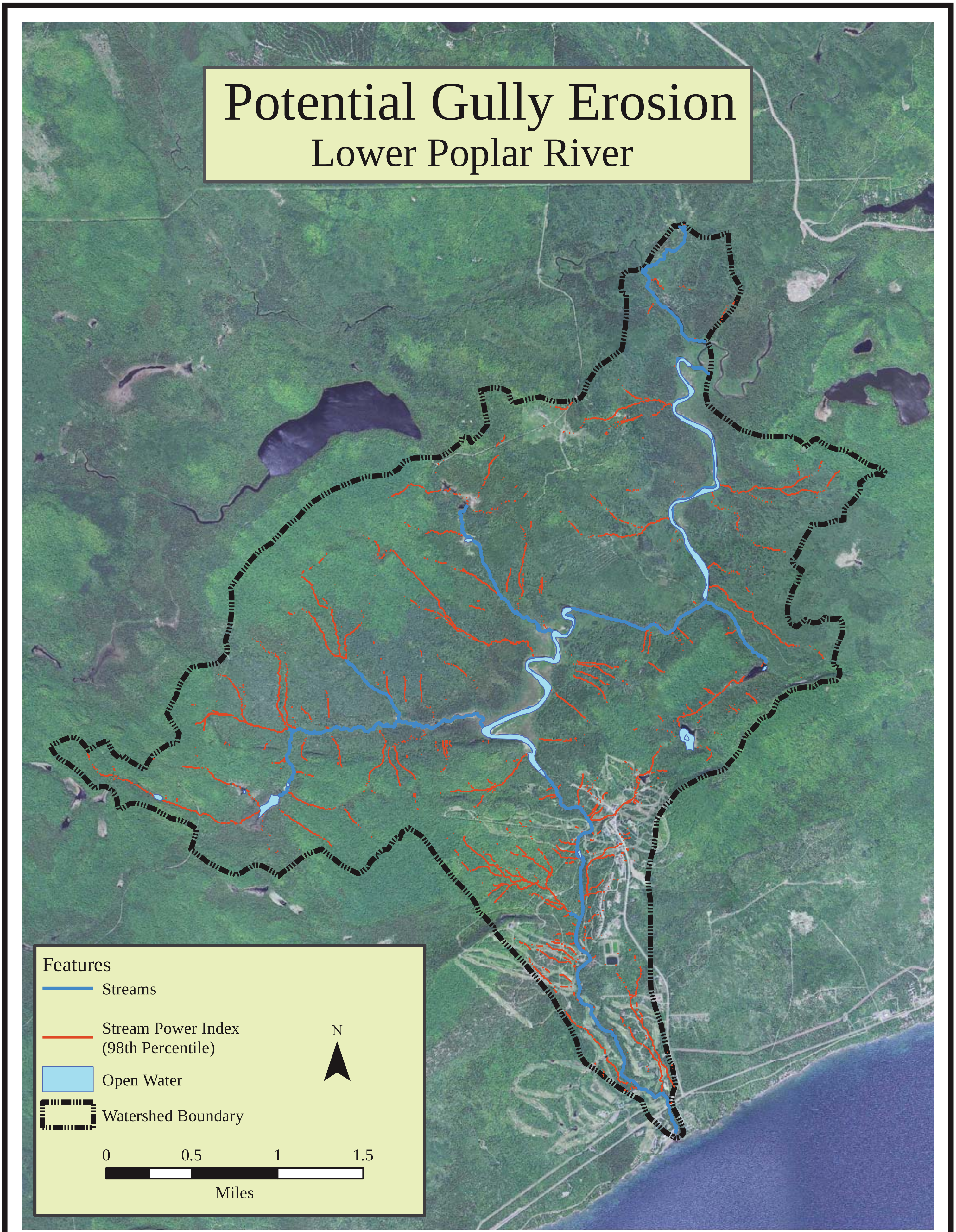


Figure 56. Potential gully locations as determined by SPI analysis.

Figure 57. Old lake bed and glacial till landscape.

Figure 58. Stream bank in an old lake bed C4 channel (the BR5 site).

TABLES

Table 1. Lake Superior tributary catchment characteristics.

CATCHMENT	AREA (MI^2) DNR	AREA (MI^2) NRRI	IMPAIRED STREAM	TURBIDITY IMPAIRED STREAM	TROUT STREAM	MPCA DESIGNATED PRIMARY TRIB	STREAM GAGING STATIONS	WQ MONITORING STATIONS (TSS)	WQ MONITORING STATIONS (Transparency)	WQ MONITORING STATIONS (TURB)
Kadunce Cr.	11.05	11.40			X				S000-864	
Kimball Cr.	13.74	13.75			X					
Flute Reed R.	15.48	15.43	X	X	X			S004-283	S003-903, S005-937, S004-856, S004-855, S004-283, S004-235	S004-235, S004-283, S004-855, S004-856, S005-937
Encampment R.	16.42	17.27			X		04015200	S003-979, S000-279	S003-979	
Reservation R.	17.12	18.07					04010528, 04010530			
French R.	18.65	18.91	X	X	X			S000-255, S006-280	S005-549, S001-754, S000-255	
Two Island R.	19.10	19.68			X	X		S006-285		
Silver Cr.	19.60	20.01			X			S003-991		
Caribou R.	23.10	22.77			X		04013200	S004-954, S006-275	S002-275, S004-954	S004-954
Stewart R.	32.13	32.45			X		04015300	S003-989		
Sucker R.	37.72	37.96	X	X	X	X	04015339	S000-264, S001-756, S003-978, S006-239	S005-547, S006-239	
Split Rock R.	43.72	43.83			X	X		S000-263, S006-235		
Lester R. & Amity Cr.	45.93	53.27	X	X	X	X	AMITY CR. (NRRI)	S000-258, S001-757, S006-281, S003-820, S003-977, S003-980, S004-950, S005-486, S006-291, S006-238	S001-757, S005-469, S005-488, S004-950, S005-400, S005-486, S004-720, S003-820, S004-731, S001-329, S000-258, S006-238	
Gooseberry R.	74.80	72.67			X			S000-256, S006-287	S000-256	
Cross R.	76.27	74.46			X	X		S000-254		
Devil's Track R.	86.18	75.92			X	X	04011390, 04011370			
Knife R.	86.48	86.91	X	X	X	X	04015300	S003-642, S003-668, S000-257, S006-282, S003-669, S003-670, S006-278, S006-240	S003-670, S003-668, S006-098, S006-240, S003-642, S003-669, S005-473, S003-838, S005-394, S000-257	S000-257
Manitou R.	98.12	99.13			X	X		S000-258		
Cascade R.	99.70	110.92			X	X		S000-253	S000-253	
Poplar R.	113.24	113.96	X	X	X	X	04012500, 1063003	S000-261, S004-406, S004-406	S004-406, S001-753, S000-261	
Beaver R.	123.01	122.08	X	X	X	X		S000-252, S006-234, S006-273, S006-277	S000-252, S006-234	
Baptism R.	138.39	137.43			X	X	04014500	S000-250, S006-290	S000-250	
Temperance R.	174.97	185.11			X	X		S000-265, S006-284		
Brule R.	249.76	265.06	X		X	X	04011000	S000-251	S000-251, S001-383, S003-904, S004-459	S003-904, S000-251
Pigeon R.	316.47	609.49				X	04010500	S000-260		

Table 2. Land cover across the North Shore. Data obtained from the 2001 National Land Cover Dataset. Table adapted from Dutton, 2012.

Type of Land Use	Definition	Percentage
Developed	Development ranging from 0-100%	1.7%
Forest	Deciduous, Evergreen, Mixed Forest	85.7%
Wetland	Woody and Emergent	3.1%
Open Water	Open water	4.9%
Other	Shrub, grassland, pasture, cultivated crops, barren land	4.6%

Table 3. Surficial geology as defined by glacial and parent material associations. Table adapted from Dutton, 2012.

Geomorphic Association	Sediment Association	% Total of North Shore
Fluvial	Alluvium (100)	0.0
Mines	Undifferentiated (101)	0.1
Organic Deposits	Peat (102)	1.2
Rainy Lobe	Till Plain (103)	2.8
	Ice Contact (104)	0.0
Scoured Bedrock Uplands	Igneous (105)	37.9
	Metamorphic (107)	4.7
	Undifferentiated (106)	2.1
St. Louis Lobe	Lacustrine (108)	0.0
Superior Lobe	Supraglacial Drift Complex (109)	9.2
	Ice Contact (110)	0.47
	Till Plain (111)	40.5
	Outwash (112)	0.98
Undifferentiated	Ice Contact (113)	0.0

Table 4. Soils summary for soil types delineated across the Minnesota North Shore by Cummins and Grigal, 1980.

Map symbol	Dominant Great Groups	Family Texture	Landform	Parent Material	Original Vegetation	Representative Series
Organic soils.						
004	Borohemists	Hemic	Lake plains and former lake basins, nearly level, <5ft local relief	----	Swamp Conifers	Moose Lake
Includes soils formed in red clayey sediments.						
302	Eutroboralfs Haplaquepts Glossoboralis	Very-fine Very-fine Fine-silty	Lake plain, nearly level, 0-10 ft. local relief	Red lacustrine sediments	White pine, spruce, fir, aspen-birch	Ontonagon Bergland Campia
Includes soils formed in thin till over bedrock.						
322	Udorthents Dystrochrepts Borohemists	Loamy Loamy Coarse-Loamy	Ground moraine over bedrock, 15-150 ft. local relief.	Brown or red till	White pine, aspen-birch	Quetico Insula Mesaba
323	Fragiochrepts Dystrochrepts Udorthents	Coarse-loamy Loamy Loamy	Ground moraine over bedrock, 20-75 ft. local relief	Brown till	Jack pine, white and red pine, aspen-birch	Conic Insula Quetico
324	Dystrochrepts Dystrochrepts Udorthents Eutroboralfs	Loamy Coarse-Loamy Sandy-skeletal Very-fine	Ground moraine over bedrock, 20-75ft. local relief	Brown till and outwash and gray lacustrine deposits	Jack pine, aspen-birch, white and red pine	Insula Mesaba Toivola Taylor
325	Fragiochrepts Udorthents Borohemists	Coarse-loamy Sandy-skeletal Hemic	Terminal moraine and outwash, 40-150 ft. local relief	Brown stony till	White pine, aspen-birch, borthern hardwoods	Ahmeek Toivola Mooselake
Soils formed in brown sandy and gravelly sediments.						
330	Fragiorthods Fragiochrepts Borohemists	Coarse-loamy Coarse-loamy Hemic	Ground moraine over bedrock, 5-25 ft. local relief	Brown till	White pine, aspen-birch	Iron River Ahmeek Greenwood
331	Udorthents Haplorthods Dystrochrepts	Sandy-skeletal Coarse loamy/sandy Coarse-loamy/sandy	Outwash, 20-50 ft. local relief	Stony brown and some red outwash	Red and white pine, aspen-birch, spruce-fir	Toivola Amasa Cloquet
Soils formed in mixed sediments from the Rainy and Superior Lobes.						
340	Eutroboralfs Glossaqualfs Borohemists	Fine-loamy Fine-loamy Hemic	Ground morain, 5-15 ft. local relief	Red stony till	Aspen-birch	Duluth Dusler Mooselake
341	Fragiochrepts Fragiaqualfs Borohemists	Coarse-loamy Coarse-loamy Hemic	Drumlins, 2-20 ft. local relief	Red stony till	White pine, aspen-birch, northern hardwoods	Ahmeek Ronneby Mooselake

Table 5. Streamflow gaging stations along the North Shore.

STATION ID	WATERSHED	LOCATION	LAT	LONG	PROVIDER	DATA TYPE	RECORDS BEGIN	MOST RECENT RECORD
04012500	POPLAR	POPLAR RIVER AT LUTSEN, MN	47.639722	-90.708611	USGS	CONTINUOUS	10/1/1912	7/12/1960
04010500	PIGEON	PIGEON RIVER AT MIDDLE FALLS NR GRAND PORTAGE MN	48.012222	-89.616111	USGS	CONTINUOUS	6/1/1921	present
04010510	GRAND PORTAGE	GRAND PORTAGE RIVER AT GRAND PORTAGE MN	47.963611	-89.683333	USGS	CONTINUOUS	5/13/1991	9/30/1992
04010528	RESERVATION	RESERVATION RIVER NEAR GRAND PORTAGE, MN	47.913611	-89.854167	USGS	CONTINUOUS	5/22/2003	8/13/2003
04010530	RESERVATION	RESERVATION RIVER NEAR HOVLAND MN	47.877222	-89.8625	USGS	CONTINUOUS	4/1/1991	1/21/1992
04014500	BAPTISM	BAPTISM RIVER NEAR BEAVER BAY, MN	47.3375	-91.200556	USGS	CONTINUOUS	8/1/1928	present
04015330	KNIFE	KNIFE RIVER NEAR TWO HARBORS, MN	46.946944	-91.792222	USGS	CONTINUOUS	7/1/1974	present
04011000	BRULE	BRULE RIVER NEAR HOVLAND, MN	47.81823	-90.0518	USGS	CONTINUOUS	4/5/2002	present
04015339	SUCKER	SUCKER CREEK AT COUNTY ROAD 290 NEAR PALMERS, MN	46.930611	-91.858111	USGS	CONTINUOUS	4/7/2001	9/23/2001
1063003	POPLAR	POPLAR RIVER NR LUTSEN, 0.2 MI US OF MN61	47.640194	-90.710778	DNR	CONTINUOUS	4/15/2002	present
04011370	DEVIL'S TRACK	LITTLE DEVIL TRACK R. NR GRAND MARAIS, MN	47.785833	90.328889	USGS	DISCONTINUOUS	6/23/1961	9/10/1977
04011390	DEVIL'S TRACK	LITTLE DEVIL TRACK R. TRIB. NR GRAND MARAIS, MN	47.788056	-90.322222	USGS	DISCONTINUOUS	8/18/1969	9/24/2005
04013100	SUGARLOAF	LAKE SUPERIOR TRIBUTARY NEAR TACONITE HARBOR, MN	47.487222	-90.988611	USGS	DISCONTINUOUS	4/17/1964	9/24/1977
04013400	CRYSTAL	LITTLE MARAIS RIVER NEAR LITTLE MARAIS, MN	47.416111	-91.102222	USGS	DISCONTINUOUS	5/9/2000	6/7/2008
04015370	TALMADGE	TALMADGE RIVER AT DULUTH, MN	46.888889	-91.9225	USGS	DISCONTINUOUS	7/1/1964	4/22/2008
04015070	SPLIT ROCK	LAKE SUPERIOR TRIBUTARY AT SPLIT ROCK STATE PARTK, MN	47.1925	-91.391389	USGS	DISCONTINUOUS	6/22/2000	4/15/2009
04011990	CASCADE	CASCADE RIVER AT FOREST RD 45 NEAR GRAND MARAIS, MN	47.79	-90.526389	USGS	DISCONTINUOUS	8/6/1985	6/8/2008
04015150	CROW	CROW CREEK NEAR SILVER CREEK, MN	47.141667	-91.577222	USGS	DISCONTINUOUS	4/19/1960	8/20/1975
04015200	ENCAMPMENT	ENCAMPMENT RIVER TRIBUTARY AT SILVER CREEK, MN	47.116944	-91.601111	USGS	DISCONTINUOUS	4/27/1960	3/15/1977
04015250	SILVER	SILVER CREEK TRIBUTARY NEAR TWO HARBORS, MN	47.077778	-91.613611	USGS	DISCONTINUOUS	4/27/1965	6/20/2012
04015300	STEWART	LITTLE STEWART RIVER NEAR TWO HARBORS, MN	47.064444	-91.6675	USGS	DISCONTINUOUS	4/13/1960	9/19/2012
04013200	CARIBOU	CARIBOU RIVER NEAR LITTLE MARAIS	47.464167	-91.030556	USGS	DISCONTINOUS	9/20/1960	7/10/2006
Amity Creek	AMITY	Do not distribute coordinate locations – NRRI request			NRRI	CONTINUOUS	9/15/2005	present
Tischer Creek	TISCHER	Do not distribute coordinate locations – NRRI request			NRRI	CONTINUOUS	6/13/2002	present
Chester Creek	CHESTER	Do not distribute coordinate locations – NRRI request			NRRI	CONTINUOUS	6/13/2002	present

Table 6. Turbidity units and differences in detection methods. Adapted from the data provided by the USGS:http://water.usgs.gov/owq/turbidity/TurbidityInfoSheet.pdf

Detector Geometry	**White, broadband. Wavelength range 400-680nm.**	**Infrared, monochromatic. Wavelength range: 780-900nm.**
	Single Illumination Beam Source	
90 degrees to incident beam; single detector	Nephelometric Turbidity Unit (NTU)	Formazin Nephelometric Unit (FNU)
90 degrees or other angles; multiple detectors, instrument algorithms use combination of detector readings and ratio techniques	Nephelometric Turbidity Ratio Unit (NTRU)	Formazin Nephelometric Ratio Unit (FNRU)
	Multiple Illumination Beam Light Source	
90 degrees and possibly other angles; multiple detectors, instrument algorithms use combination of detector readings	Nephelometric Turbidity Multibeam Unit (NTMU)	Formazin Nephelometric Multibeam Unit (FNMU)

Table 7. Datasets used to develop the NRRI's anthropogenic stressor tool. Table adapted from Host et al., 2010.

Data Set	**Source and attributes**	**Summarization methods**
Land use/land cover	USGS National Land Cover Dataset	Zonal summaries by sub-watershed
Population density	U.S. Census data	Census blocks converted to raster grids, summarized by sub-watershed
Road density	USGS Tiger Data	Sum of weighted road density summarized by sub-watershed
Point source discharge	NPDES permits (EPA)	Sum of weighted point source scores by watershed, adjusted for sub-watershed area

Table 8. Subcatchment level SUMREL scores. This table includes the minimum, maximum, median and average values.

	MINIMUM				MAXIMUM				MEDIAN				AVERAGE			
Catchment	**NRMP**	**RDN**	**LCCP**	**LCDV**	**NRMP**	**RDN**	**LCCP**	**LCDV**	**NRMP**	**RDN**	**LCCP**	**LCDV**	**NRMP**	**RDN**	**LCCP**	**LCDV**
Baptism River	0.00059	0	0	0	0.03891	1.00000	0.11989	0.08674	0.002596	0.036382	0	0	0.00482	0.07153	0.00096	0.00239
Beaver River	0.00260	0	0	0	0.03891	0.98789	0.03943	0.20531	0.002596	0.010836	0	0	0.00675	0.06988	0.00052	0.00554
Brule River	0.00188	0	0	0	0.00303	1.00000	0	0.09927	0.001876	0	0	0	0.00238	0.04979	0	0.00131
Caribou River	0.00178	0	0	0	0.00260	0.33523	0.01996	0.01641	0.002596	0	0	0	0.00242	0.03401	0.00065	0.00030
Carlson Creek	0.00303	0	0	0	0.00303	0.14388	0	0.01875	0.003031	0.062561	0	0	0.00303	0.05790	0	0.00312
Cascade River	0.00178	0	0	0	0.02309	0.43599	0	0.02201	0.001876	0	0	0	0.00659	0.04321	0	0.00016
Chester Creek	0.22578	0	0	0	1.00000	0.74334	0.02932	0.42030	0.350467	0.187212	0	0.077513	0.46536	0.30687	0.00293	0.14059
Cross River	0.00059	0	0	0	0.00260	0.39141	0	0.02393	0.00178	0.039002	0	0	0.00135	0.05584	0	0.00059
Crow Creek	0.00260	0	0	0	0.02902	0.95453	0	0.07642	0.002596	0.0568	0	0	0.00682	0.11349	0	0.00459
Deer Yard Creek	0.00178	0	0	0	0.00178	0.26731	0	0	0.00178	0.154491	0	0	0.00178	0.12625	0	0
Devil's Track River	0.00188	0	0	0	0.02309	0.54915	0.05132	0.13189	0.001876	0.029765	0	0	0.00609	0.06679	0.00090	0.00382
Encampment River	0.00260	0	0	0	0.02937	0.22637	0.02714	0.01276	0.002596	0.056341	0	0	0.01233	0.06571	0.00210	0.00121
Flute Reed River	0.00303	0	0	0	0.00303	0.85542	0	0.09354	0.003031	0.051249	0	0	0.00303	0.09810	0	0.00339
French River	0.00769	0	0	0	0.08220	0.38091	0.00317	0.02158	0.007694	0.057155	0	0	0.02267	0.08441	0.00006	0.00119
Gooseberry River	0.00259	0	0	0	0.00333	0.24983	0.01862	0.02152	0.002596	0	0	0	0.00268	0.03231	0.00024	0.00059
Grand Portage Creek	0.00303	0	0	0	0.00303	0.90422	0	0.13385	0.003031	0.052053	0	0	0.00303	0.15056	0	0.02028
Hollow Rock Creek	0.00303	0	0	0	0.00303	0.28406	0	0.01061	0.003031	0.087051	0	0	0.00303	0.09510	0	0.00064
Kadunce Creek	0.00303	0	0	0	0.00303	0.45241	0.00924	0	0.003031	0.074598	0	0	0.00303	0.07603	0.00032	0
Kimball Creek	0.00193	0	0	0	0.00303	0.37110	0	0.01168	0.003031	0.050347	0	0	0.00296	0.06247	0	0.00050
Knife River	0.00333	0	0	0	0.04309	0.64308	0.04256	0.06854	0.031661	0.042568	0	0	0.02353	0.06593	0.00091	0.00129
Lester River & Amity Creek	0.00769	0	0	0	1.00000	1.00000	0.16434	0.40684	0.086619	0.144071	0	0	0.14567	0.16217	0.00619	0.01158
Manitou River	0.00059	0	0	0	0.00260	0.26000	0.16382	0.02452	0.002596	0	0	0	0.00204	0.03223	0.00221	0.00039
Onion River	0.00178	0	0	0	0.00178	0.14131	0	0	0.00178	0	0	0	0.00178	0.03045	0	0
Pigeon River	0.00016	0	0	0	0.00691	1.00000	0.01682	0.13451	0.00016	0.033058	0	0	0.00127	0.07702	0.00001	0.00018
Poplar River	0.00177	0	0	0	0.00188	1.00000	0	0.09955	0.00178	0.044579	0	0	0.00179	0.07715	0	0.00085
Reservation River	0.00303	0	0	0	0.00303	0.19176	0.00463	0.01029	0.003031	0	0	0	0.00303	0.02690	0.00009	0.00035
Rosebush Creek	0.02107	0	0	0	0.02309	1.00000	0.02143	0.17821	0.023091	0.152993	0	0	0.02298	0.17527	0.00219	0.01173
Schmidt Creek	0.02455	0	0	0	0.08220	0.41798	0.05076	0.00937	0.082146	0.131502	0	0	0.06848	0.15091	0.00760	0.00111
Silver Creek	0.00333	0	0	0	0.02937	0.72947	0.00502	0.02389	0.029367	0.056637	0	0	0.01974	0.09698	0.00021	0.00232
Split Rock River	0.00260	0	0	0	0.03637	0.22443	0.01810	0.01173	0.002596	0	0	0	0.00580	0.03211	0.00037	0.00031
Stewart River	0.00333	0	0	0	0.02937	0.67376	0.02893	0.04460	0.003325	0.042987	0	0	0.00637	0.08405	0.00145	0.00297
Sucker River	0.00769	0	0	0	0.04075	0.25881	0.02556	0.00622	0.007694	0	0	0	0.01314	0.05340	0.00056	0.00018
Sugarloaf	0.00178	0	0	0	0.00178	0.10228	0.00000	0.00000	0.00178	0	0	0	0.00178	0.03409	0.00000	0.00000
Talmadge River	0.02823	0	0	0	0.09478	0.30917	0	0.02102	0.082202	0.136184	0	0	0.08107	0.14682	0	0.00193
Temperance River	0.00178	0	0	0	0.00188	0.34349	0	0.09775	0.00178	0	0	0	0.00181	0.03968	0	0.00166
Tischer Creek	0.11131	0.12066	0	0	1.00000	1.00000	0	0.57639	1	0.461759	0	0.111294	0.63473	0.55059	0	0.14588
Two Island River	0.00075	0	0	0	0.00260	0.41368	0.03459	0.01604	0.00178	0.035583	0	0	0.00176	0.05883	0.00204	0.00093

Table 9. Catchment level SUMREL scores with and without point source discharge (PSD) variable scores considered.

Catchment	SUMREL score (w/o PSD)	SUMREL score (w/ PSD)
Baptism River	0.02102	0.58438
Beaver River	0.0394	0.60762
Brule River	0.0072	0.44243
Caribou River	0.0079	0.52080
Cascade River	0.0400	0.40389
Cross River	0.0001	0.42790
Devil's Track River	0.0301	0.61945
Encampment River	0.0.087	0.62533
Flute Reed River	0.0120	0.46733
French River	0.1516	0.57089
Gooseberry River	0.0010	0.65110
Kadunce Creek	0.0120	0.40720
Kimball Creek	0.0115	0.42144
Knife River	0.1468	0.61161
Lester River & Amity Creek	1.0000	0.71255
Manitou River	0.0049	0.55923
Pigeon River	0.0000	0.49124
Poplar River	0.0031	0.42777
Reservation River	0.0120	0.50403
Silver Creek	0.1228	0.61782
Split Rock River	0.0271	0.52558
Stewart River	0.0255	0.63744
Sucker River	0.0781	0.54340
Temperance River	0.0031	0.43395
Two Island River	0.0031	0.59900

Table 10. Natural and anthropogenic variables used to determine SumRel stressor scores.

Attribute	Definition	Data Source
strslp	Stream slope in this subcatchment	10m LiDAR data
bkslp	Bank slope in this catchment or the slope of the "stream context"	10m LiDAR data
pctwl	Percent wetland in this subcatchment	National Wetlands Inventory
rdint	Road/ stream intersections in this subcatchment	2008 MNDoT roads, ArcHydro streams
canpct	Percent tree canopy	NLCD
skffact	Stream KFFACT (STATSGO)	STATSGO soils data
ssedero	Stream sedimentary erosion potential	STATSGO soils data
bkffact	Bank KFFACT (STATSGO)	STATSGO soils data
bsedero	Bank sedimentary erosion potential	STATSGO soils data
nrmp	Normalized population density	US Census data
rdn	road density	US TIGER data
lccp	Percent wetland in this subcatchment	USGS National Land Cover Dataset
lcdv	Road/ stream intersections in this subcatchment	USGS National Land Cover Dataset
a_bkffact	Accumulated bkffact	---
a_bsedero	Accumulated bsedero	---
a_canpct	Accumulated canpct	---
a_ssedero	Accumulated ssedero	---
a_skffact	Accumulated skffact	---
a_bnkslp	Accumulated bnkslp	---
a_strslp	Accumulated strslp	---
a_rdint	Accumulated rdint	---
a_pctwl	Accumulated pctwl	---

Table 11. Field surveyed sites and metrics used to determine channel classifications.

Level II Surveys								All metrics measured directly in the field			Floodprone width estimated using LiDAR data		
Catchment	**Site ID**	**Lat**	**Long**	**Bnkf Depth (FD)**	**Bnkf Width (FD)**	**Dominant channel material**	**W/D Ratio**	**Flood-prone Width**	**Entrench-ment Ratio**	**Stream Type**	**Flood-prone Width**	**Entrench-ment Ratio**	**Stream Type**
Kimball Creek	KB1	47.812203	-90.21022	1.52	17.7	Cobble/Gravel	11.64	200	11.30	C3-4	45.40	2.56	E3-4
Beaver River	BR1_Downstream	47.31091	-91.32529	2.2	29	Gravel	13.18	60	2.07	C4	186.00	6.41	C4
Beaver River	BR5_West_Branch	47.253731	-91.37912	1.9	29	Gravel	15.26	200	6.90	C4	174.00	6.00	C4
Beaver River	BR_East_Branch	47.323345	-91.34844	2.11	38.1	Cobble	18.06	60	1.57	B3c	148.56	3.90	C3
Encampment	Encampment	47.139	-91.603	1.1	19.8	Cobble	18.00	40	2.02	B3c	35.67	1.80	B3
Knife River	Knife River	47.011712	-91.75225	0.92	22.58	Gravel	24.54	52	2.30	C4	37.00	1.64	B4
Knife River	Stanley Creek	47.001417	-91.8471	1.35	9.2	Gravel	6.81	60	6.52	E3-4	117.40	12.76	E3-4
Level I surveys								**Floodprone widths estimated with GoogleMaps**			**Floodprone width estimated using LiDAR data**		
Catchment	**Site ID**	**Lat**	**Long**	**Bnkf Depth (FD)**	**Bnkf Width (FD)**	**Dominant channel material**	**W/D Ratio**	**Flood-prone Width**	**Entrench-ment Ratio**	**Stream Type**	**Flood-prone Width**	**Entrench-ment Ratio**	**Stream Type**
Flute Reed	FR1	47.87663	-90.05046	1.65	16.5	Boulder	10.00	95	5.76	E2	133.95	8.12	E2
Flute Reed	FR2	47.86614	-90.04817	2	14.5	Cobble	7.25	80	5.52	E3	115.67	7.98	E3
Flute Reed	FR3	47.84974	-90.01887	1.65	20.7	Gravel	12.55	95	4.59	C4	115.33	5.57	C4
Flute Reed	FR4	47.84673	-89.96916	2.2	27	Cobble	12.27	80	2.96	C3	66.00	2.44	C3
Temperance	TP1	47.639717	-90.84713	2	108	Boulder	54.00	200	1.85	B2	119.90	1.11	F2
Temperance	TP2	47.64253	-90.84643	2	25	Cobble	12.50	260	10.40	C3	144.00	5.76	C3
Temperance	TP3	47.733045	-90.88032	1.9	68	Boulder	35.79	220	3.24	B2	109.90	1.62	B2
Temperance	TP4	47.716415	-90.87696	1.3	10	Cobble	7.69	200	20.00	E3	273.33	27.33	E3
Temperance	TP5	47.801115	-90.84489	2.1	55	Boulder	26.19	300	5.45	C2	279.62	5.08	C2
Temperance	TP6	47.611619	-90.91965	2	32	Cobble	16.00	50	1.56	B3	70.90	2.22	B3
Temperance	TP7	47.564384	-90.88412	2.8	124	Cobble	44.29	220	1.77	B3	135.21	1.09	F3
Beaver River	BR2	47.320361	-91.39502	1.5	18.5	Boulder	12.33	97	5.24	C2	145.30	7.85	C2
Beaver River	BR3	47.321606	-91.40978	1.2	25	Boulder	20.83	53	2.12	B2	313.40	12.54	C2
Beaver River	BR4	47.265475	-91.34891	2	52.2	Boulder	26.10	99	1.90	B2	110.00	2.11	B2
Beaver River	BR6	47.24457	-91.43115	2.5	8.5	Sandy	3.40	122	14.35	E5	86.00	1.06	F5
Beaver River	BR7	47.373842	-91.4362	1.5	10	Cobble	6.67	151	15.10	E3	266.14	26.61	E3
Split Rock River	SR1	47.26053	-91.50644	1.8	16.5	Cobble	9.17	172	10.42	E3	87.93	5.33	E3
Split Rock River	SR2	47.242	-91.48106	2.2	22	Boulder/ Cobble	10.00	48	2.18	B2-3	89.45	4.07	E2-3
Split Rock River	SR3	47.242431	-91.45325	1.8	10	Gravel	5.56	87	8.70	E4	84.86	8.49	E4
Split Rock River	SR4	47.264325	-91.48127	2	23.5	Boulder/ Cobble	11.75	45.5	1.94	B2-3	236.70	10.07	E2-3
Encampment	EC1	47.126895	-91.58742	2.5	30	Boulder	12.00	98	3.27	C2	157.63	5.25	C2
Crow Creek	CC1	47.1269	-91.57317	1.8	14	Cobble/Gravel	7.78	59	4.21	E3-4	51.42	3.67	E3-4
Stewart River	ST1	47.071406	-91.66745	3	35	Boulder/ Cobble	11.67	275	7.86	E2-3	69.33	1.98	B2-3
Stewart River	ST2	47.064241	-91.66732	1.2	15.7	Cobble/Gravel	13.08	300	19.11	C4	48.67	3.10	C4
Silver Creek	SC1	47.077561	-91.61414	1.5	17	Cobble	11.33	152	8.94	E3	32.80	1.93	B3
Silver Creek	SC2	47.07075	-91.62287	2	26.2	Cobble	13.10	81	3.09	C3	68.10	2.60	C3

Table 12. Channel classifications and channel stability scores. Channel dependent stream stability is represented by Pfankuch rankings while erosion hazard is represented by BEHI rankings.

Site ID; Stream Name	Rosgen Channel Classification	Pfankuch		BEHI	
		Score	Rating	Score	Rating
KB1; Kimball Cr.	C3-4	59.0	Good	20.0	Moderate
BR1 Downstream; Beaver R.	C4	78.0	Good	40	Very High
BR5 West Branch; Beaver R.	C4	98.0	Fair	31.3	High
BR East Branch; Beaver R.	B3c	49.0	Good	16.6	Low
EC; Encampment R.	B3c	57.0	Good	18.3	Moderate
KN1; Knife R.	C4	54.0	Good	20.0	Low
SN1; Stanley Cr.	E3-4	64.0	Fair-Good	15.0	Low
FR1; Flute Reed R.	E2	63.0	Good	25.5	Moderate
FR2; Flute Reed R.	E3	78.5	Fair	25.5	Moderate
FR3; Flute Reed R.	C4	71.5	Good	26.0	Moderate
FR4; Flute Reed R.	C3	70.0	Good	26.5	Moderate
TP1; Temperance R.	B2	52.0	Good	25.0	Moderate
TP2; Temperance R.	C3	59.0	Good	21.0	Moderate
TP3; Temperance R.	B2	108.0	Poor	19.5	Low
TP4; Temperance R.	E3	52.0	Good	21.5	Moderate
TP5; Temperance R.	C2	44.0	Good	23.5	Moderate
TP6; Temperance R.	B3	72.0	Fair	27.0	Moderate
TP7; Temperance R.	B3	71.0	Fair	28.0	Moderate
BR2; Beaver R.	C2	81.5	Poor	15.8	Low
BR3; Beaver R.	B2	48.0	Fair	15.5	Low
BR4; Beaver R.	B2	50.0	Fair	18.8	Low
BR6; Beaver R.	E5	107.5	Poor	23.5	Moderate
BR7; Beaver R.	E3	54.0	Good	18.5	Low
SR1; Split Rock R.	E3	83.5	Fair	28.5	Moderate
SR2; Split Rock R.	B2-3	48.0	Fair-Good	23.0	Moderate
SR3; Split Rock R.	E4	112.0	Poor	19.5	Low
SR4; Split Rock R.	B2-3	41.5	Good	19.0	Low
EC1; Encampment R.	C2	57.0	Fair	19.0	Low
CC1; Crow Cr.	E3-4	94.0	Poor-Fair	28.0	Moderate
ST1; Stewart R.	B2-3	55.0	Fair-Good	16.0	Low
ST2; Stewart R.	C4	110.0	Fair	36.3	High
SC1; Silver Cr.	E3	83.0	Fair	16.0	Low
SC2; Silver Cr.	C3	62.0	Good	26.0	Moderate

Table 13. Soils data from field samples compared to soils delineated by Cummins and Grigal, 1980.

Stream	Particle size data from field sites.				Feature	Lat	Long	Soil ID	Soil Types
	% gravel	% sand	% silt	% clay					
Knife	0	10	10	70	Bluff	46.984516	-91.785715	302	Red lacustrine sediments
Gooseberry	2	26	69	3	Bluff	47.145664	-90.46893	302	Red lacustrine sediments
Caribou	15	25	37	23	Bluff	47.461217	-91.025971	322	Brown/red till
Temperance	20	42	37	1	Bluff 1	47.57255	-90.88034	322	Brown/red till
Temperance	11	45	40	4	Bluff 2	47.57255	-90.88034	322	Brown/red till
Heartbreak Cr.	15	25	57	3	Bluff 1	47.609305	-90.919442	341	Red stony till
Heartbreak Cr.	25	50	25	0	Bluff 2	47.60724	-90.91505	341	Red stony till
Heartbreak Cr.	0	40	58	2	Bluff 3	47.60736	-90.9118	341	Red stony till
Heartbreak Cr.	25	45	27	3	Till exposure - bank	47.602094	-90.907188	341	Red stony till
Temperance	42	54	2	2	Till	47.57255	-90.88034	322	Brown/red till
Flute/Reed	13	19	48	20	Streambank	47.847059	-89.966483	322	Brown/red till
Flute/Reed	3	29	65	3	Lower streambank	47.847059	-89.966483	322	Brown/red till
Crow Creek	3	7	68	22	Streambank	47.126715	-91.572284	302	Red lacustrine sediments
Gooseberry	2	56	25	17	Streambank	47.145664	-90.46893	302	Red lacustrine sediments
Average	12	34	41	12					

Table 14. Impacts of roads on drainage densities along the North Shore. Table adapted from Dutton, 2012.

	100ft buffer			**50ft buffer**			**10ft buffer**		
Catchment parameters	**NS**	**C**	**I**	**NS**	**C**	**I**	**NS**	**C**	**I**
Road length (mile)	301.5	57.0	20.7	136.7	30.8	10.3	46.0	11.5	3.9
Stream length	3485.0	881.0	425.7	3320.2	854.8	415.2	3229.5	835.5	408.9
Nearby road length (mile)	301.5	57.0	20.7	136.7	30.8	10.3	46.0	11.5	3.9
Drainage Density (mile/mile^2)	1.58	1.49	1.89	1.50	1.45	1.85	1.46	1.42	1.82
Effective Drainage density (mile/mile^2)	9.47	6.92	5.11	4.29	3.73	2.54	1.45	1.39	0.97

** N. Shore = North Shore Watershed of the North Shore watershed, Northern Minnesota, USA*

** C = Control Watersheds (Baptism, Brule, Temperance)*

** I = Impaired Watersheds (Beaver, Flute Reed, Knife)*

Methodology, modified Wemple (1996), Croke and Mockler (2001)

Table 15. Land use descriptions of watershed areas drained by surveyed sites. Table adapted from Dutton, 2012.

Site	Stream order	Area (sq.mi.)	Land use					
			Forest (all)	Open water	Development (all)	Shrub	Barren land, scrub, grassland, pasture/hay	Wetland
Knife 32	3	6.1	83.6	0.3	2.2	0.2	5.6	3.1
Nicado	2	3.0	97.3	0.3	0.1	1.6	0.3	0.4
Temp16	2	4.5	92.6	0.1	0.1	6.2	0.6	0.6
Brule28	4	4.7	83.5	5.4	0.2	7.2	0.1	3.5
Flute Reed	1	0.5	95.7	2.7	1.6	0.0	0.0	0.0
Beaverx01	3	52.3	84.5	5.8	1.1	3.4	2.1	3.1
Temp17	4	147.7	86.2	6.2	0.2	3.1	0.2	4.1

*Land use is reported by percent of total drainage area.

Table 16. Upstream and downstream channel stability results. Table adapted from Dutton, 2012.

Watershed	Upstream ➔		Downstream	
	Rosgen Stream Classification	Pfankuch Stability	Rosgen Stream Classification	Pfankuch Stability
Beaverx01	B3c	Good	C4	Fair
Brule28	C4	Good	B4c	Fair
Flute Reed	B4a	Poor	B4a	Fair
Knife32	B4c	Good	B4c C3	Poor
Nicado	E5	Fair	C3	Good
Temp16	E4b	Good	C4	Good
Temp17	C4	Good	C3	Good

Table 17. Soil erosion values from WEPP simulation (5-year) for the Lower Poplar River Watershed. (Table 2 from Nieber, 2013).

Watershed Method (WEPP) – 5-year results				
Land use	Area Under Cover Type (acres)	Proportion of area under cover	Soil Loss (ton/ac/yr)	Soil Loss Rate (ton/yr)
Developed	30.0	0.030	0.0	0.0
Forest	743.4	0.739	0.006	6
Golf	85.8	0.085	0.07	6
Ski	146.5	0.146	3.92[&&]	575[&&]
Upland channels or ravines	--	--	--	312
Total	1005.7	1.000	1.08[&]	1,092

Table 18. Mean annual sediment (tons/acre/year) delivered to the toe of the hillslope for various conditions of added artificial snow (given as depth of snow water equivalent), vegetative cover, and slope length. The vegetative cover is expressed by type, either short grass prairie (SGP) or tall grass prairie (TGP) and by leaf area index (LAI). The slope length used for nearly all of the calculations was 680 feet. (Adapted from Table 3 from Nieber, 2013).

Vegetative cover; Type, LAI	Snow water equivalent of artificial snow (inches)			
	0	10.8	20.9	31.5
SGP, 0.5	3.0	5.0	12.6	53.8
SGP, 2.0	0.32	0.97	1.3	3.5
SGP, 4.0	0.22	1.3	0.96	2.3
TGP, 0.5	2.7	4.6	11.2	47.3
TGP, 2.0	0.27	0.93	1.0	2.8
TGP, 4.0	0.23	0.86	0.77	1.93
SGP, 0.5 with half slope length (340 feet)	0.96	0.5	0.3	0.08
Percent reduction with 50% reduction in hillslope length	78%	90%	97.7%	>99%

Table 19. Morphological characteristics of major ravines within the Lower Poplar River watershed. (Table 5 from Nieber, 2013).

Ravine	Contributing area (acres)	Length (ft)	Mean longitudinal slope (%)	Mean cross-section (ft^2)	Sediment Produced (tons)
Ullr	4.6[&]	380	44	280	5,586
Brule	155[#]	200	47	188	1,974
Moose Mountain	232	3,500	10	44	8,085

[&]Some runoff from Brule had been diverted to this ravine making the effective contributing area about 22 acres.
[#]The installation of a tightline to bypass the ravine has reduced the contributing area to the ravine.

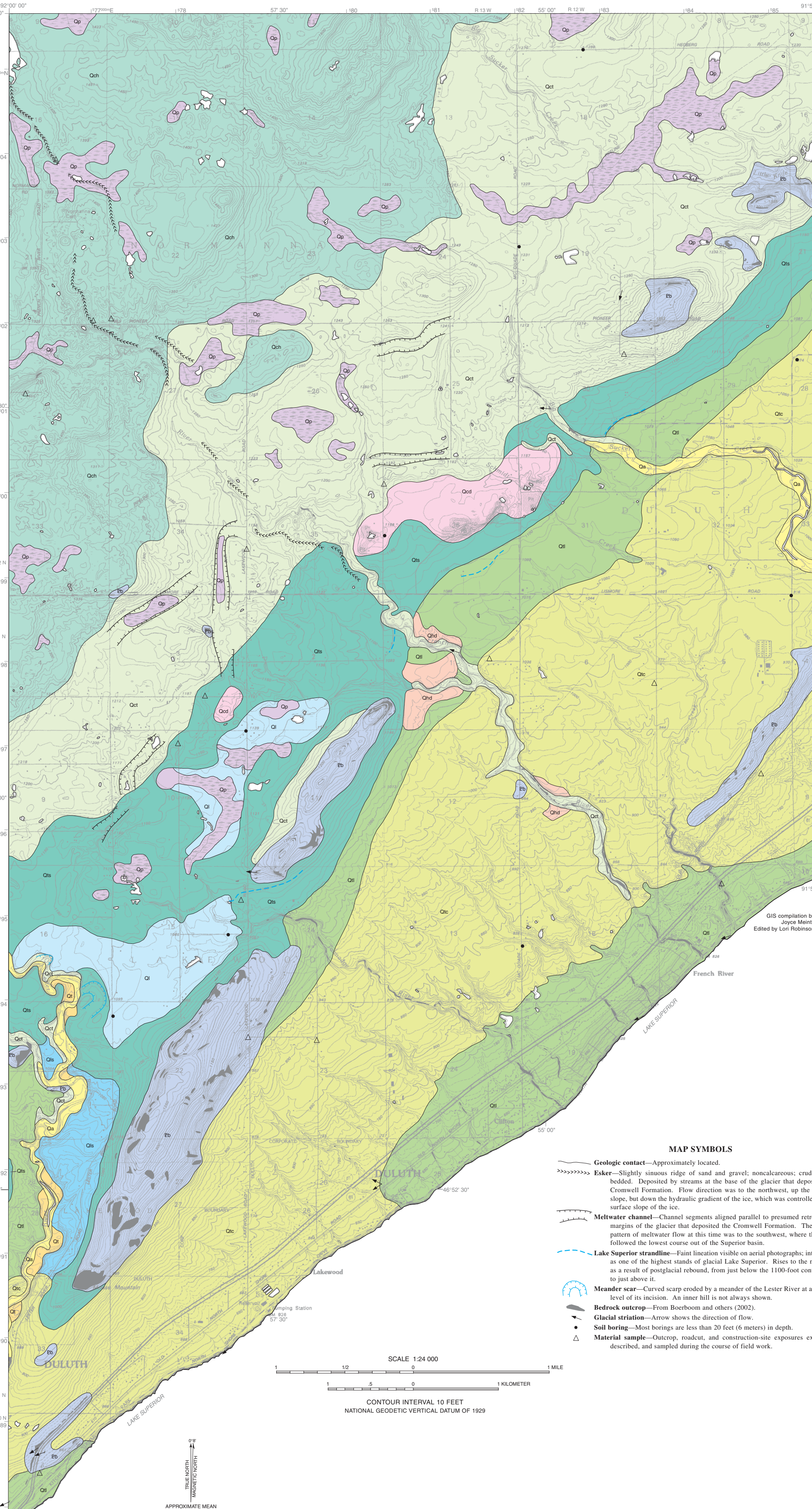
Table 20. Road Impact Index (RII). (Table 4 from Nieber, 2013).

Position in the watershed	Sub-watershed acres	Acres of roads	Number of crossings	Road Impact Index	Tons/ acre	Annual load Tons
Lower	25	2.27	3	0.27	12.6	28.59
Mid to Upper 1/3	249	15.7	3	0.19	0.42	6.66

Appendix A

UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
V.W. Chandler, Interim Director

Prepared and Published with the Support of
THE U.S GEOLOGICAL SURVEY AS PART OF THE 2001 STATE GEOLOGIC MAPPING PROGRAM ELEMENT (STATEMAP)
OF THE NATIONAL GEOLOGIC MAPPING PROGRAM

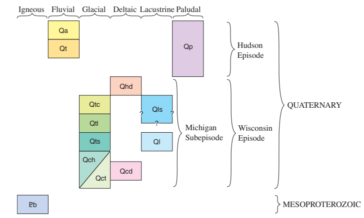


SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

TRUE NORTH
MAGNETIC NORTH
APPROXIMATE MEAN DECLINATION, 2002

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

QUATERNARY

HUDSON EPISODE*

Qp **Peat**—Partly-decayed organic debris accumulated in wetlands. Usually underlain by the same material that surrounds it.

Qa **Alluvium**—Sediment of modern streams. Channel sediment is mostly gravel, with a lesser amount of sand, over a lag of larger rocks. Little overbank sediment was observed, mostly sand and silt.

Qt **Older alluvium**—Stream sediment in low terraces along the Lester River; chiefly gravel.

WISCONSIN EPISODE: MICHIGAN SUBEPISODE

Fine-grained glacial sediment—Deposited by the Superior lobe within the Superior basin. These tills incorporate silt and clay deposited in the basin during recessions between advances.

Qtc ***Clay till***—Reddish-brown (2.5YR5/3 to 4/4) clay (Fig. 1); massive, calcareous. The upper meter is commonly leached; secondary carbonate nodules are common in the meter or two below the leached zone. Commonly contains more than 1 percent coarse-grained fragments (greater than 2 millimeters in diameter). In places, contains inclusions of brown (7.5YR4/3) to reddish-brown (5YR4/4) calcareous clay with few coarse-grained fragments. These inclusions are interpreted to reflect incorporation of gray Lake Agassiz clay, which was deposited in Lake Superior prior to the Marquette advance that deposited this till (Clayton, 1983). The average thickness is 3 to 4 meters, but is absent in a large area near Lake Superior, where the underlying clayey till (Qtl) forms the surface.

Qtl ***Clayey till***—Reddish-brown (5–2.5YR5/3 to 4/4) silty clay (Fig. 1); massive, slightly calcareous in places. Variable content of coarse-grained fragments, but generally more than 2 percent. The average thickness is about 3 meters, but a thickness of 15 meters was observed in a stream cut along the Lester River.

Qts ***Silty till***—Reddish-brown (mostly 5YR4/3 to 3/4) silt loam (Fig. 1); massive, noncalcareous. Variable content of coarse-grained fragments, averaging 4 to 5 percent. The average thickness is unlikely to be more than 2 meters.

Cromwell Formation (Wright and others, 1970)—Glacial and glacial meltwater sediment of the Superior lobe. Further defined as reddish-brown sandy to silty till containing fragments of red sandstone from the Superior basin, and associated sand and gravel. All the glacial sediments mapped at the surface in this area contain clasts chiefly of rocks of the Superior basin, including some red sandstone (although red felsite is more common). The fine-grained tills above are not included in the Cromwell Formation because they contain little sand. The formation is divided into two unsorted glacial facies and one stratified facies.

Qct ***Till, subglacial facies***—Reddish-brown (5YR5/4 to 4/4) rocky loam to sandy loam; compact, jointed, noncalcareous. Coarse-grained fragments average 12 percent. Topography is controlled chiefly by bedrock. The average thickness is about 3 meters.

Qch ***Till, supraglacial facies***—Reddish-brown (5YR5/4 to 4/4) rocky loam to sandy loam; noncalcareous. Less compact and jointed, and probably coarser on average than the subglacial till. Large-scale topography is controlled by bedrock, but small hummocks and hollows of about 3 meters relief were caused when ice melted from under supraglacial debris. Full thickness was not observed in the map area, and is probably variable; the average thickness is likely greater than 3 meters. Interpreted to be underlain by till of the subglacial facies (Qct), but this was not observed. Geomorphically, it forms part of the Highland moraine (Wright, 1972).

Qcd ***Ice-contact delta***—Sand and gravel mantled by till. Most particles are dark-gray and red; noncalcareous. Overall texture ranges from fine-grained sand to coarse-grained gravel, but individual beds have a narrower range, such as fine- to coarse-grained gravel. Sand and gravel beds are about 10-meters-thick. Most of the unit was likely derived from the glacier, which deposited it in small ice-marginal lakes. Overlain in most places by 1 to 3 meters of till of the Cromwell Formation (units Qct and Qch), which in turn is overlain in places by thin silty till (Qts).

Glaciolacustrine sediment—Sediment deposited in a glacial lake dammed by the Superior lobe. Each unit was deposited during a different phase of the lake, separated by one or more ice advances.

Qhd ***Delta sediment***—Chiefly sand. Deposited by the French River and its tributaries as they entered successively lower stages of glacial Lake Superior as the lake declined toward postglacial water levels. One- or 2-meters-thick over fine-grained glacial sediment.

Qls ***Laminated glacial lake sediment***—Reddish-brown (chiefly 2.5YR4/4) calcareous clay and silt. Finely laminated; contains little sand and few coarse-grained fragments. Deposited in a small glacial lake dammed between the Superior lobe and higher ground in the Lester River area. Associated either with the clay till (Qtc) or the clayey till (Qtl).

Ql ***Glacial lake sediment***—Reddish-brown to reddish-gray (typically 5YR4/3 to 4/4) calcareous silt and clay. Sand amounts to generally less than 10 percent (Fig. 1), and coarse-grained fragments are usually less than 1 percent. Typically unbedded, but horizontal beds and obscure color bands are present in places. Associated with the silty till (Qts).

MESOPROTEROZOIC

Ꞓb **Bedrock at or near the surface**—Dominated by mafic volcanic flows and diabase. The larger areas of this unit are diabase sills that form prominent ridges now tilted toward Lake Superior. The surface of the rock has been smoothed by glacial erosion and is relatively unweathered. Narrow areas of this unit along streams and the Lake Superior shoreline are shown as bedrock outcrop (see Map Symbols).

*Time–event classification follows Hansel and Johnson (1996).

MAP SYMBOLS

Geologic contact—Approximately located.

Esker—Slightly sinuous ridge of sand and gravel; noncalcareous; crudely flat-bedded. Deposited by streams at the base of the glacier that deposited the Cromwell Formation. Flow direction was to the northwest, up the regional slope, but down the hydraulic gradient of the ice, which was controlled by the surface slope of the ice.

Meltwater channel—Channel segments aligned parallel to presumed retreatal ice margins of the glacier that deposited the Cromwell Formation. The general pattern of meltwater flow at this time was to the southwest, where the water followed the lowest course out of the Superior basin.

Lake Superior strandline—Faint lineation visible on aerial photographs; interpreted as one of the highest stands of glacial Lake Superior. Rises to the northeast as a result of postglacial rebound, from just below the 1100-foot contour line to just above it.

Meander scar—Curved scarp eroded by a meander of the Lester River at an earlier level of its incision. An inner hill is not always shown.

Bedrock outcrop—From Boerboom and others (2002).

Glacial striation—Arrow shows the direction of flow.

Soil boring—Most borings are less than 20 feet (6 meters) in depth.

Material sample—Outcrop, roadcut, and construction-site exposures examined, described, and sampled during the course of field work.

REFERENCES

Boerboom, T.J., Green, J.C., and Jirsa, M.A., 2002, Bedrock geology of the French River, Lakewood, and Knife Lake quadrangles, St. Louis and Lake Counties, Minnesota: Minnesota Geological Survey Miscellaneous Map M-128, 2 pls., scale 1:24,000, W92°15'–92°30'/N46°37'30"–46°45'.

Clayton, L., 1983, Chronology of Lake Agassiz drainage to Lake Superior, *in* Teller, J.T., and Clayton, L., eds., Glacial Lake Agassiz: Geological Association of Canada Special Paper 26, p. 291-307.

Hansel, A.K., and Johnson, W.H., 1996, Wedron and Mason Groups: Lithostratigraphic reclassification of deposits in the Wisconsin Episode, Lake Michigan lobe area: Illinois State Geological Survey Bulletin 104, 115 p., 13 pls.

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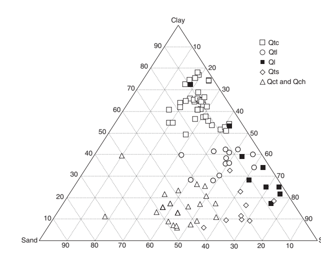

Figure 1. Texture of the less than 2 millimeter grain-size fraction of glacial and lacustrine sediment.

SURFICIAL GEOLOGY OF THE FRENCH RIVER AND LAKEWOOD QUADRANGLES, ST. LOUIS COUNTY, MINNESOTA

by

Howard C. Hobbs

2002

QUADRANGLE LOCATION

Base from U.S. Geological Survey French River and Lakewood 1:24,000 quadrangles, 1992.

Universal Transverse Mercator grid, zone 15
1983 North American Datum

Supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under assistance Award No. 01HQAG0099.

UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
V.W. Chandler, Interim Director

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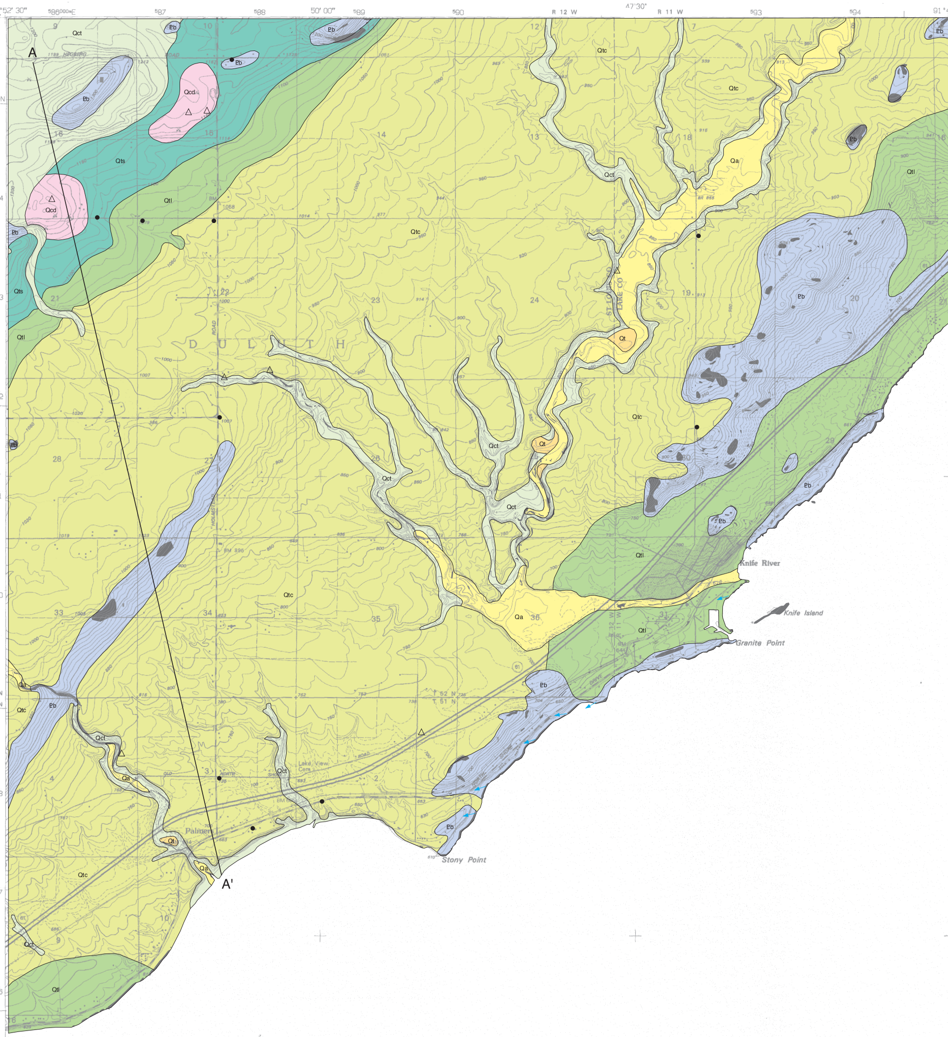


Base from U.S. Geological Survey Knife River 1:24,000 quadrangle, 1992.
Universal Transverse Mercator grid, zone 15
1983 North American Datum

APPROXIMATE MEAN DECLINATION, 2003

SCALE 1:24 000
1 1/2 0 1 MILE
1 .5 0 1 KILOMETER

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

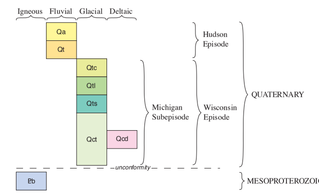
QUADRANGLE LOCATION

GIS compilation and cartography by R.S. Lively
Edited by Lori Robinson

SURFICIAL GEOLOGY OF THE KNIFE RIVER QUADRANGLE, ST. LOUIS AND LAKE COUNTIES, MINNESOTA

by
Howard C. Hobbs
2003

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

QUATERNARY

HUDSON EPISODE*

Qa **Alluvium**—Sediment of modern streams. Channel sediment is mostly gravel, with a lesser amount of sand, over a lag of larger rocks. Little overbank sediment was observed, mostly sand and silt.

Qt **Older alluvium**—Stream sediment in low terraces along the Knife River and Sucker Creek; chiefly gravel.

WISCONSIN EPISODE: MICHIGAN SUBEPISODE

Fine-grained glacial sediment—Deposited by the Superior lobe within the Superior basin. These tills incorporate silt and clay deposited in the basin during recessions between advances.

Qtc ***Clay till***—Reddish-brown (2.5YR5/3 to 4/4) clay (Fig. 1); massive, calcareous. The upper meter is commonly leached; secondary carbonate nodules are common in the meter or two below the leached zone. The majority of samples contain between 1 and 3 percent coarse-grained fragments. In places, contains inclusions of brown (7.5YR4/3) to reddish-brown (5YR4/4) calcareous clay with few coarse-grained fragments. These inclusions are interpreted to reflect incorporation of gray Lake Agassiz clay, which was deposited in Lake Superior prior to the Marquette advance that deposited this till (Clayton, 1983). The average thickness is 10 to 13 feet (3 to 4 meters) but the unit is absent in some areas near Lake Superior, where the underlying clayey till (Qtl) forms the surface.

Qtl ***Clayey till***—Reddish-brown (5–2.5YR5/3 to 4/4) silty clay (Fig. 1); massive, slightly calcareous in places. About half the samples contain more than 3 percent coarse-grained fragments, but only one third contain more than 5 percent. The average thickness is about 10 feet (3 meters).

Qts ***Silty till***—Reddish-brown (mostly 5YR4/3 to 3/4) silt loam (Fig. 1); massive, generally noncalcareous. About half the samples contain more than 6 percent coarse-grained fragments, but very few contain more than 12 percent. The average thickness is unlikely to be more than 7 feet (2 meters).

Cromwell Formation (Wright and others, 1970)—Glacial and glacial meltwater sediment of the Superior lobe. Defined as reddish-brown sandy to silty till containing fragments of red sandstone from the Superior basin, and associated sand and gravel. In this area, the clasts of the Cromwell Formation are mostly rocks of the Superior basin. Red sandstone is present, but North Shore Volcanic Group and Duluth Complex rocks are more common. The fine-grained tills described above are not included in this formation because they contain too little sand. The Cromwell Formation on this map is divided into an unsorted subglacial facies (Qct) and a stratified facies (Qcd).

Qct ***Till, subglacial facies***—Reddish-brown (5YR5/4 to 4/4) rocky loam to sandy loam; compact, jointed, noncalcareous. Coarse-grained fragments range from less than 1 to 45 percent, but average about 12 percent. Topography is controlled chiefly by bedrock. The average thickness is about 10 feet (3 meters).

Qcd ***Ice-contact delta sediment***—Sand and gravel. Most particles are dark-gray and red; noncalcareous. Overall texture ranges from fine-grained sand to coarse-grained gravel, but individual beds have a narrower range, such as fine- to coarse-grained gravel. Unit is about 10 meters thick. Most of the unit was likely derived from the glacier, which deposited it in small ice-marginal lakes. Overlain in most places by 3 to 10 feet (1 to 3 meters) of till of the Cromwell Formation (Qct), which in turn is overlain in places by thin silty till (Qts). This stratigraphic relationship suggests that the deltas formed during a recessional phase of the Superior lobe before its advance to the Highland moraine (Wright, 1972).

MESOPROTEROZOIC

Ɛb **Bedrock at or near the surface**—Dominated by mafic volcanic flows and diabase. The larger areas of this unit are diabase sills that are now tilted toward Lake Superior and form prominent ridges. The surface of the rock has been smoothed by glacial erosion and is relatively unweathered. Narrow areas of this unit along streams and the Lake Superior shoreline are shown as bedrock outcrop.

*Time-event classification follows Hansel and Johnson (1996).

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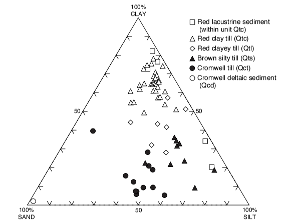

Figure 1. Texture of surficial units.

MAP SYMBOLS

Geologic contact—Approximately located.

Bedrock outcrop—Mapped by Boerboom and others (2002).

Glacial striation—Arrow shows the direction of flow.

Soil boring—Most borings are less than 20 feet (6 meters) in depth.

Material sample—Outcrop, roadcut, and construction-site exposures examined, described, and sampled during the course of field work.

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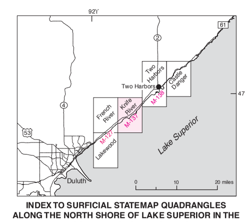
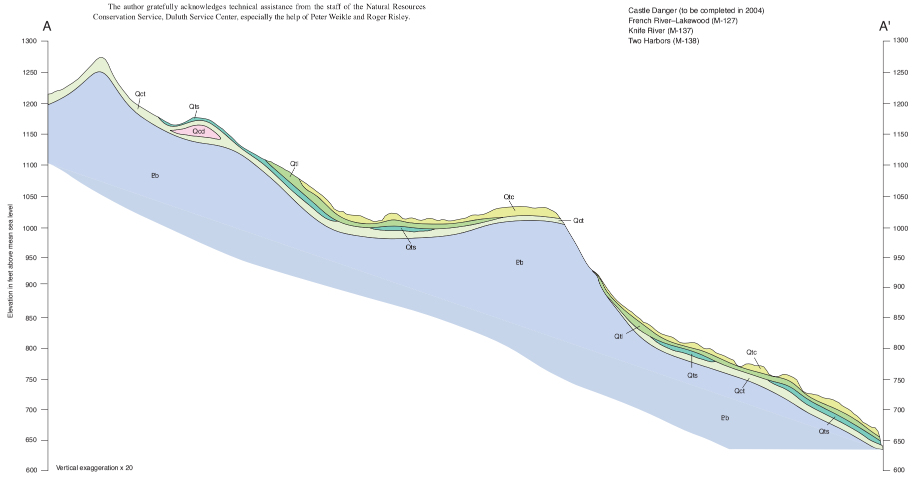


INDEX TO SURFICIAL STATEMAP QUADRANGLES ALONG THE NORTH SHORE OF LAKE SUPERIOR IN THE MISCELLANEOUS MAP SERIES

Castle Danger (to be completed in 2004)
French River–Lakewood (M-127)
Knife River (M-137)
Two Harbors (M-138)



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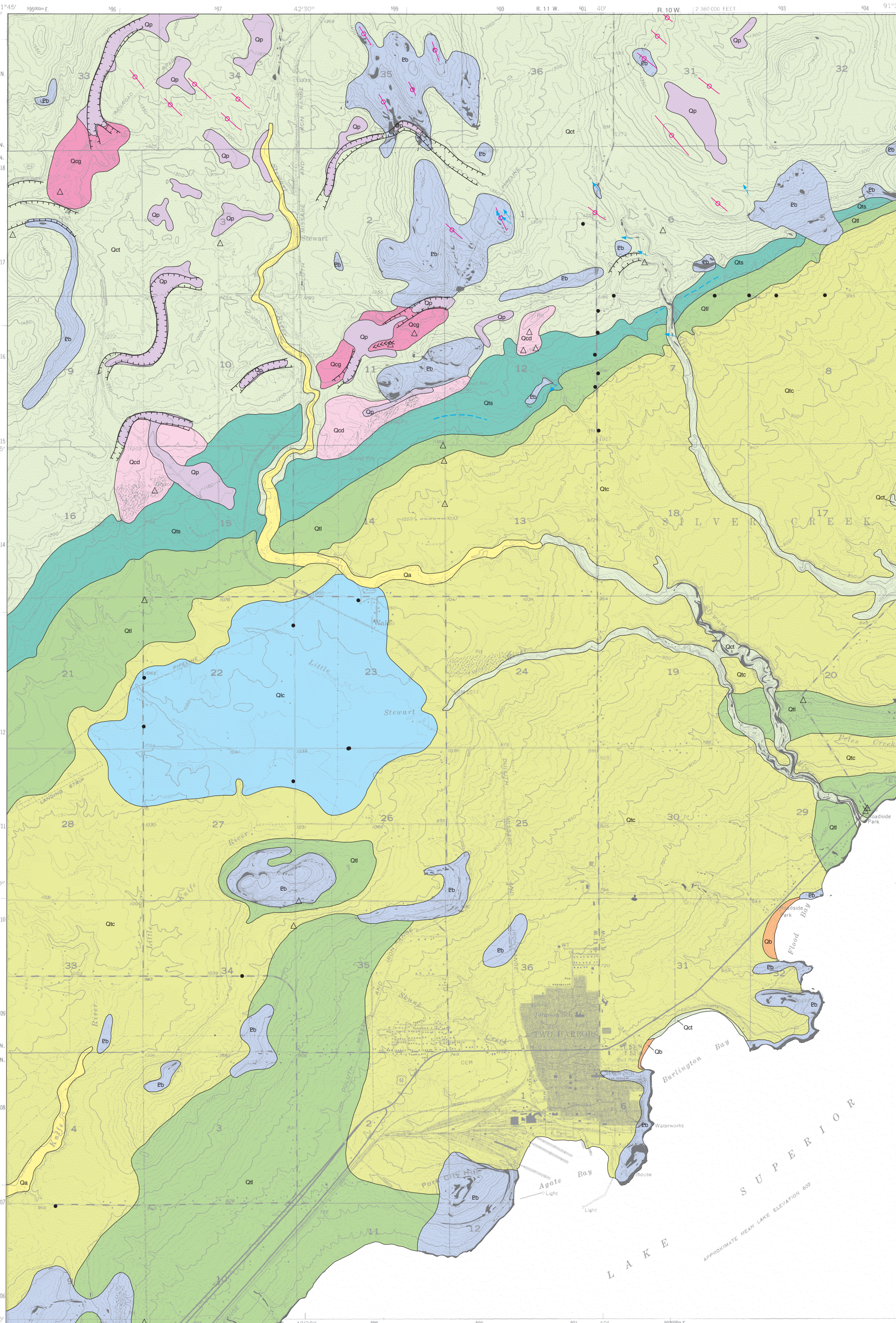
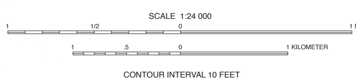
OF THE NATIONAL GEOLOGIC MAPPING PROGRAM

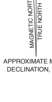
MISCELLANEOUS MAP SERIES
MAP M-138
Surficial Geology, Two Harbors Quadrangle



GIS compilation and cartography by R.S. Lively
Edited by Lori Robinson



CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



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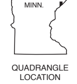


QUADRANGLE LOCATION

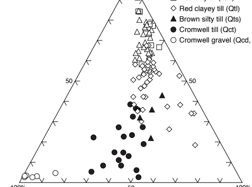


Figure 1. Texture of surficial units.

Base from U.S. Geological Survey Two Harbors 1:24,000 quadrangle, 1957, revised 1969.

Universal Transverse Mercator grid, zone 15
1983 North American Datum

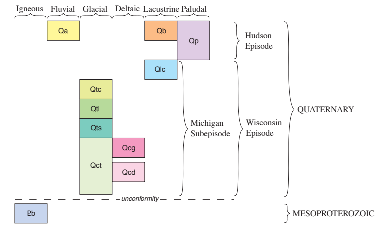
SURFICIAL GEOLOGY OF THE TWO HARBORS QUADRANGLE, LAKE COUNTY, MINNESOTA

by

Howard C. Hobbs

2003

CORRELATION OF MAP UNITS



DESCRIPTION OF MAP UNITS

QUATERNARY

HUDSON EPISODE*

Qp **Peat**—Partly-decayed organic debris accumulated in wetlands. Usually underlain by the same material that surrounds it.

Qa **Alluvium**—Sediment of modern streams. Channel sediment is mostly gravel, with a lesser amount of sand, over a lag of larger rocks. Little overbank sediment was observed, mostly sand and silt.

Qb **Modern beach deposit**—Clean, rounded, sorted gravel on the shore of Lake Superior.

WISCONSIN EPISODE: MICHIGAN SUBEPISODE

Glaciolacustrine sediment—Sediment deposited in a glacial lake dammed by the Superior lobe.

Qlc ***Glacial lake clay***—Reddish-brown (2.5YR4/4 or 4/3) clay. Typically unbedded. Sand is generally less than 10 percent (Fig. 1), and coarse-grained fragments (greater than 2 millimeters in diameter) are usually less than 1 percent. Thickness is 3 to 5 feet (1 to 1.5 meters) over clay till (Qtc) on a flat lake plain; contact is obscure, and is recognized in the field by a lack of pebbles in the lacustrine sediment.

Fine-grained glacial sediment—Deposited by the Superior lobe within the Superior basin. These tills incorporate silt and clay deposited in Lake Superior during recessions between advances. Clast composition is similar to that of the Cromwell Formation (described below), except that about half of the samples from Qtc and about one third of the samples from Qtl contain one to a few fragments of Paleozoic carbonate grains in the 1 to 2 millimeter fraction. Very few samples of Qts contain any Paleozoic carbonate.

Qtc ***Clay till***—Reddish-brown (2.5YR5/3 to 4/4) clay (Fig. 1); massive, calcareous. The upper meter is commonly leached; secondary carbonate nodules are common in the meter or two below the leached zone. The majority of samples contain between 1 and 3 percent coarse-grained fragments. In places, contains inclusions of brown (7.5YR4/3) to reddish-brown (5YR4/4) calcareous clay with few coarse-grained fragments. These inclusions are interpreted to reflect incorporation of gray Lake Agassiz clay, which was deposited in Lake Superior prior to the Marquette advance that deposited this till (Clayton, 1983). The average thickness is 10 to 13 feet (3 to 4 meters), but is absent in a large area near Lake Superior, where the underlying clayey till (Qtl) forms the surface.

Qtl ***Clayey till***—Reddish-brown (5–2.5YR5/3 to 4/4) silty clay (Fig. 1); massive, slightly calcareous in places. About half the samples contain more than 3 percent coarse-grained fragments, but only one third contain more than 5 percent. The average thickness is about 3 meters.

Qts ***Silty till***—Reddish-brown (mostly 5YR4/3 to 3/4) silt loam (Fig. 1); massive, noncalcareous. About half the samples contain more than 6 percent coarse-grained fragments, but very few contain more than 12 percent. The average thickness is unlikely to be more than 7 feet (2 meters). Appears to be more patchy than the tills described above.

Cromwell Formation (Wright and others, 1970)—Glacial and glacial meltwater sediment of the Superior lobe. Defined as reddish-brown sandy to silty till containing fragments of red sandstone from the Superior basin, and associated sand and gravel. In this area, the clasts of the Cromwell Formation are mostly rocks of the Superior basin. Red sandstone is present, but North Shore Volcanic Group and Duluth Complex rocks are more common. The fine-grained tills described above are not included in the Cromwell Formation because they contain too little sand. On this quadrangle, the formation is divided into an unsorted glacial facies (Qct) and two stratified facies (Qcd and Qcg).

Qct ***Till, subglacial facies***—Reddish-brown (5YR5/4 to 4/4) rocky loam to sandy loam; compact, jointed, noncalcareous. Coarse-grained fragments range from less than 1 to 45 percent, but average about 12 percent. Topography is controlled chiefly by bedrock. The average thickness is about 10 feet (3 meters).

Qcg ***Glaciofluvial gravel***—Gravel and sand. Overall texture ranges from fine-grained sand to coarse-grained gravel, but individual beds have a narrower range, such as fine- to coarse-grained gravel. Trough cross-bedding is common; in places the bedding is flat and obscure. Unit occupies the elevation range between 1,200 to 1,260 feet in one place, and 1,290 to 1,370 feet in another. The lower area includes an esker and an adjacent area with hummocky topography where the gravel is interfingered with till of the Cromwell Formation. The upper area appears to be a fan associated with a meltwater channel. Meltwater channels are expected to contain thin glaciofluvial gravel in places, but most of them are now covered with peat (Qp). Most of the sediment was likely deposited in small ice-marginal lakes.

Qcd ***Ice-contact delta sediment***—Sandy gravel similar to unit Qcg above, but finer-grained on average and lower in elevation (elevation ranges from 1,160 to 1,210 feet). Foreset beds were observed in places. Unit is about 33 feet (10 meters) thick. Overlain in most places by 3 to 10 feet (1 to 3 meters) of till of the Cromwell Formation (Qct), which in turn is overlain in places by thin silty till (Qts). This stratigraphic relationship suggests that the deltas formed during a recessional phase of the Superior lobe before its advance to the Highland moraine (Wright, 1972).

MESOPROTEROZOIC

Pb **Bedrock at or near the surface**—Dominated by mafic volcanic flows and diabase. The larger areas of this unit are diabase sills that are now tilted toward Lake Superior and form prominent ridges. The surface of the rock has been smoothed by glacial erosion and is relatively unweathered. Narrow areas of this unit along streams and the Lake Superior shoreline are shown as bedrock outcrop.

*Time–event classification follows Hansel and Johnson (1996).

MAP SYMBOLS

Geologic contact—Approximately located.

Meltwater channel—Channel segments aligned parallel to presumed retreatal ice margins of the glacier that deposited the Cromwell Formation. The general pattern of meltwater flow at this time was to the southwest, where the water followed the lowest course out of the Superior basin.

Lake Superior strandline—Faint lineation visible on aerial photographs; interpreted as one of the highest stands of glacial Lake Superior. Present sporadically, just above the 1100-foot contour line.

Esker—Coarse-grained meltwater sediment deposited in a tunnel under the ice. Contains gravel and boulders.

Bedrock outcrop—Mapped by Boerboom and others (2003).

Glacial striation—Arrow shows the direction of flow.

Flutes—Streamlined landforms, composed mostly of bedrock but mantled by till; shaped by ice flowing out of the Superior basin. Named the Highland Flutes by Wright (1972, p. 531.)

Soil boring—Most borings are less than 20 feet (6 meters) in depth.

Material sample—Outcrop, roadcut, and construction-site exposures examined, described, and sampled during the course of field work.

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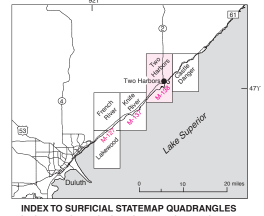

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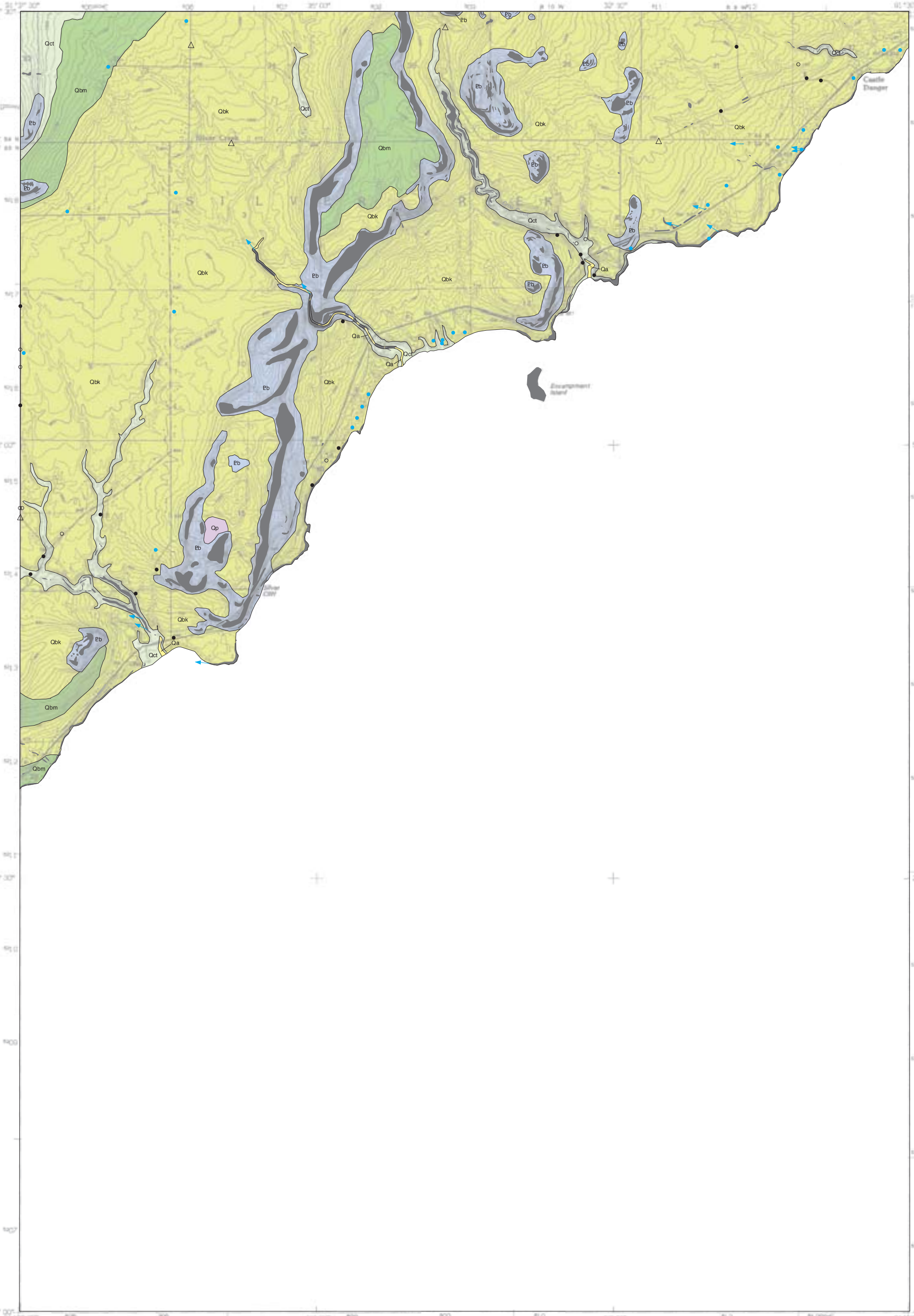
Castle Danger (to be completed in 2004)
French River–Lakewood (M-127)
Knife River (M-137)
Two Harbors (M-138)

UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

Prepared and Published with the Support of
THE U.S. GEOLOGICAL SURVEY AS PART OF THE 2003 STATE GEOLOGIC MAPPING PROGRAM ELEMENT (STATEMAP)
OF THE NATIONAL GEOLOGIC MAPPING PROGRAM



Base from U.S. Geological Survey Castle Danger 1:24,000 quadrangle, 1992.
Universal Transverse Mercator grid, zone 15
1983 North American Datum

APPROXIMATE MEAN DECLINATION, 2004

SCALE 1:24 000

CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

QUADRANGLE LOCATION

GIS compilation by Howard Hobbs and R.S. Lively
Edited by Lori Robinson

SURFICIAL GEOLOGY OF THE CASTLE DANGER QUADRANGLE, LAKE COUNTY, MINNESOTA

by

Howard C. Hobbs
2004

CORRELATION OF MAP UNITS

Igneous	Fluvial	Paludal	Glacial			
	Qa	Qp		Hudson Episode		QUATERNARY
			Qbk	Michigan Subepisode	Wisconsin Episode	QUATERNARY
			Qbm	Michigan Subepisode	Wisconsin Episode	QUATERNARY
			Qct	Michigan Subepisode	Wisconsin Episode	QUATERNARY
— unconformity —						
Ɛb						MESOPROTEROZOIC

MAP SYMBOLS

Geologic contact—Approximately located.

Bedrock outcrop—Mapped by Boerboom and others (2003).

Glacial striation—Arrow shows the direction of flow—from Boerboom and others (2003).

△ Soil boring—Most borings are less than 20 feet (6 meters) deep.

● Material sample—Outcrop, roadcut, or construction-site exposures examined, described, and sampled during the course of fieldwork.

○ Material description—Outcrop, roadcut, or construction-site exposures examined but not sampled.

● Record of water-well construction—Location of a water well for which there is a log prepared by a well driller.

DESCRIPTION OF MAP UNITS

QUATERNARY

HUDSON EPISODE*

Qp **Peat**—Partly decayed organic debris accumulated in wetlands. Typically underlain by the same material that surrounds it.

Qa **Alluvium**—Sediment of modern streams. Channel sediment is mostly gravel, with a lesser amount of sand, over a lag of larger rocks. Little overbank sediment was observed, mostly sand and silt. Although common in nearly all streams, most alluvium on this quadrangle is too narrow to map at this scale.

WISCONSIN EPISODE: MICHIGAN SUBEPISODE

Glacial deposits

All the sediment of the Wisconsin Episode on this map was deposited by or in front of the Superior lobe, which advanced from the northeast to the southwest through the Lake Superior basin (Wright, 1972). The rock clasts within the glacial deposits are chiefly derived from bedrock in the Superior basin. The bottom of the lake basin is composed of Precambrian red clastic sedimentary rocks: sandstone, siltstone, and shale. All of these are relatively soft and easily eroded. The northwest side of the basin (known locally as the North Shore) is composed of a variety of Precambrian igneous rocks of the North Shore Volcanic Group and the Duluth Complex: red and black basalt, red rhyolite, and dark gray to black gabbro and diabase. The igneous rocks occur as visible clasts over a wide range of sizes, from sand to boulders. Red sandstone and siltstone occur as granules to cobble-sized clasts, but are also broken down into their constituent grains. Shale is almost never seen as a clast, but breaks down to clay.

Clasts in the 1-2 millimeter fraction (very coarse-grained sand) were examined for their rock types. Samples from the Cromwell Formation (described below) contain only a few grains from outside the Superior basin, presumably from the Archean rocks of the Canadian Shield up-ice from the basin. These grains are predominantly granitic—quartz and felsic feldspar. Paleozoic carbonate grains are extremely rare. Some samples from the Barnum Formation contain a similar clast assemblage, but about half of the samples from unit Qbk and one third of the samples from unit Qbm contain a few Paleozoic carbonate grains. The samples that contain primary carbonate grains also contain a higher proportion of granitic grains, which suggests a common source outside the Superior basin (because the Barnum Formation is calcareous in the fine-grained fraction, many samples contain grains of secondary carbonate).

Most of the relief on the North Shore (other than the general slope toward the lake) results from differential erosion of the bedrock, probably during many glaciations. Diabase sills are especially resistant and typically stand out as ridges. All of the till sheets in the area are thin compared to the bedrock relief, and are draped over the bedrock topography. Thickness is greatest over bedrock lows and least over bedrock highs. There are no moraines or other constructional landforms.

Total drift thickness measured in water wells is typically 20 to 30 feet (6 to 9 meters), but there is an area of thicker drift along the shore on either side of the mouth of the Encampment River where depths can reach over 70 feet (21 meters). Bedrock outcrops are conspicuously absent from this part of the shoreline. Most of the modern stream valleys appear to have been cut by the streams that occupy them, typically through the soft Barnum Formation and into the Cromwell Formation and underlying bedrock. However, some of the deeper valleys appear to have existed before the last glaciation. The Crow Creek valley, for example, is much deeper than the average thickness of drift, yet till is exposed in several places near the bottom.

Barnum Formation (Wright and others, 1970)—Composed chiefly of silt and clay; stratified silt and clay were deposited together in proglacial lakes fronting the Superior lobe during recessions between glacial readvances, and unstratified silt and clay diamictons were deposited by readvances that incorporated these stratified sediments. On this quadrangle, the glaciolacustrine sediments are thin and generally buried under the upper till (Qbk).

Qbk ***Clay till***—Reddish-brown (2.5YR5/3 to 4/4) clay (Fig. 1); massive, calcareous. The upper few feet (1 meter) are commonly leached; secondary carbonate nodules are common several feet (1 to 2 meters) below the leached zone. The majority of samples contain between 1 and 3 percent coarse-grained fragments. The extremely clayey texture of this till, even compared with the underlying clayey till (unit Qbm), is thought to reflect incorporation of gray Lake Agassiz clay, which was deposited in Lake Superior prior to the Marquette advance that deposited this till (Clayton, 1983). Generally, the mixing of overridden lake sediment into the till is thorough enough to make the till visually homogeneous, but in places the till contains inclusions of brown (7.5YR 4/3) to reddish-brown (5YR4/4) calcareous clay with few coarse-grained fragments. These colors are not as red as typical Superior lobe glaciolacustrine clay (2.5YR4/4). The average thickness of this till is 10 to 13 feet (3 to 4 meters), but thicknesses up to 23 feet (7 meters) have been observed. The till is absent (presumably eroded) in a small area near Lake Superior where the underlying clayey till (unit Qbm) forms the surface. This till was deposited by a glacier whose ice margin was about 1,100 feet (335 meters) in elevation in this area. Above 1,100 feet (335 meters), one of the underlying tills generally forms the surface.

Qbm ***Clayey till***—Reddish-brown (5-2.5YR5/3 to 4/4) silty clay (Fig. 1); massive, calcareous. About half the samples contain more than 3 percent coarse-grained fragments, but only one third contain more than 5 percent. The average thickness is about 10 feet (3 meters). The clayey nature of this till is interpreted as a result of the Superior lobe incorporating glaciolacustrine sediment as it readvanced through the Superior basin. This sediment was derived primarily from meltwater of the Superior lobe, perhaps supplemented by clay from glacial Lake Aitkin-Upham, which overflowed into the Superior basin by way of the St. Louis River (Hobbs, 1983). The margin of the glacier that deposited this till was about 1,180 feet (360 meters) in elevation, so the unit generally forms the surface till between 1,100 and 1,180 feet (335 and 360 meters), below which it is buried by the clay till (unit Qbk). The clayey till forms the surface till at lower elevations where the upper till has been eroded. It is exposed in places along the sides of stream valleys, but is too narrow to map at this scale.

Cromwell Formation (Wright and others, 1970)—Defined as reddish-brown, sandy to silty till and associated meltwater sediment containing fragments of red sandstone from the Superior basin. Red sandstone is present in most samples, but North Shore Volcanic Group and Duluth Complex rocks are more common. Tills of the Cromwell Formation (only one of which is mapped here) contain more sand than tills of the Barnum Formation.

Qct ***Till***—Reddish-brown (5YR5/4 to 4/4) rocky loam to sandy loam; compact, jointed. Noncalcareous where exposed at the surface, but deep cuts reveal calcareous Cromwell till in places, especially where protected from leaching by calcareous till of the Barnum Formation. Coarse-grained fragments range from less than 1 to 45 percent of the total, and average about 12 percent. The average thickness is about 10 feet (3 meters). Sediments under the Cromwell till are thin and patchy, and not observed at the surface. The Cromwell till underlies the Barnum Formation almost everywhere the latter is mapped, but only occurs at the surface in two geomorphic settings: it is the surface till above the depositional limit of the Barnum Formation, which in this area is about 1,180 feet (360 meters) in elevation; and it is mapped in stream valleys and in places along the Lake Superior shoreline where the softer, clayey tills of the Barnum Formation have been removed by erosion. In the latter setting, bedrock outcrops are common.

MESOPROTEROZOIC

Ɛb **Bedrock at or near the surface**—Dominated by mafic volcanic flows and diabase. The larger areas of this unit are diabase sills that are now tilted toward Lake Superior and form prominent ridges. The surface of the rock has been smoothed by glacial erosion and is relatively unweathered in most places. Narrow areas of this unit along streams and the Lake Superior shoreline are shown by bedrock outcrop (see Map Symbols).

Note on correlation with adjacent surficial geology maps

Units Qbk and Qbm on this map are equivalent to units Qtc and Qtl, respectively, on the surficial geologic maps of the adjacent Two Harbors (Hobbs, 2003b), Knife River (Hobbs, 2003a), and French River and Lakewood quadrangles (Hobbs, 2002). This change was made in order to group the map units as lithostratigraphic units. The upper elevations of the tills of the Barnum Formation generally rise to the northeast, although they also show local dips. The overall rise is expected, both because each ice sheet must have had a slope in order for the ice to flow, and because differential postglacial rebound warps originally flat lines, such as strandlines. The local dips are generally correlated with steeper slopes where the surface till may have eroded from its original maximum position.

The Barnum Formation ice margins cannot be accessed by roads on the Castle Danger quadrangle, so the elevations of these margins were interpolated from data points on adjacent quadrangles, especially the Two Harbors NE quadrangle directly to the north.

*Time–event classification follows Hansel and Johnson (1996).

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Wright, H.E., Jr., Mattson, L.A., and Thomas, J.A., 1970, Geology of the Cloquet quadrangle: Minnesota Geological Survey GM-3, 30 p., 1 pl., scale 1:24,000.

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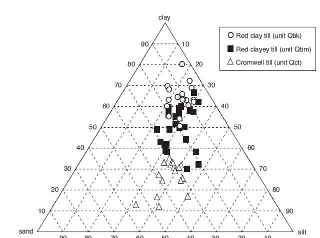
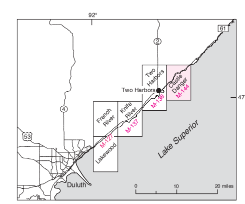


Figure 1. Matrix textures of glacial tills.



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French River–Lakewood (M-127)
Knife River (M-137)
Two Harbors (M-138)

UNIVERSITY OF MINNESOTA
MINNESOTA GEOLOGICAL SURVEY
Harvey Thorleifson, Director

Prepared and Published with the Support of
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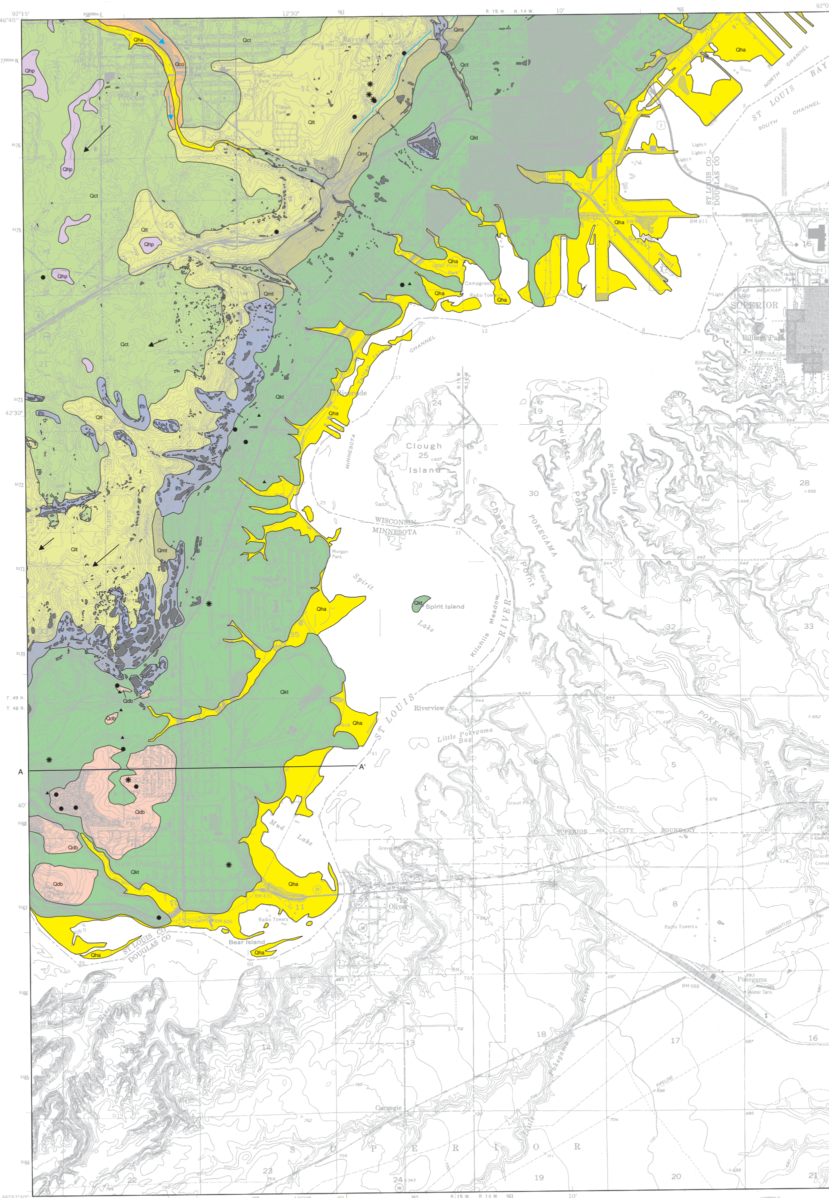
OF THE NATIONAL GEOLOGIC MAPPING PROGRAM

MISCELLANEOUS MAP SERIES
MAP M-188
Surficial Geology, West Duluth Quadrangle

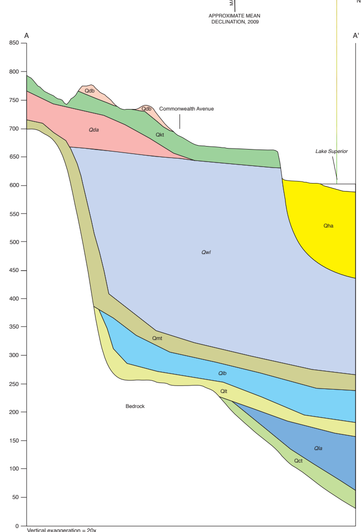


Base from U.S. Geological Survey West Duluth 1:24,000 quadrangle, 1997.
Universal Transverse Mercator grid, zone 15
1983 North American Datum

SCALE 1:24 000
CONTOUR INTERVAL 10 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

GIS compilation by R.S. Lively
Edited by Lori Robinson

QUADRANGLE LOCATION



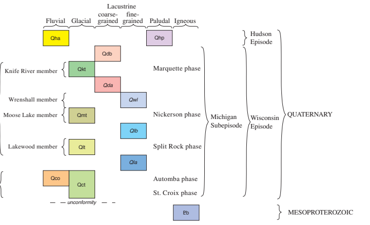
Vertical exaggeration = 20x

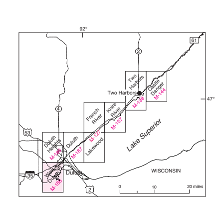
SURFICIAL GEOLOGY OF THE WEST DULUTH QUADRANGLE, ST. LOUIS COUNTY, MINNESOTA

By
Howard C. Hobbs

2009

CORRELATION OF MAP UNITS





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Duluth (M-187)
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West Duluth (M-188)

INTRODUCTION

The surficial geologic map units represent the materials expected to be encountered beneath the topsoil. Rock exposures without soil are shown as bedrock outcrop. Thin surficial layers that are chiefly restricted to the soil profile are not shown. Unit contact lines, descriptions, and map symbols were determined from observation and sampling of 23 natural, gravel pit, and construction exposures, and description and sampling of 7 Giddings probe auger borings during the 2008 field season. Auger borings ranged from 6 to 24 feet (2 to 7 meters) deep. Water well logs, shallow soil borings done in a Works Progress Administration project (various authors, 1940, 1941, and 1942), and St. Louis County soil map descriptions (Natural Resources Conservation Service, 2009) were also consulted.

Formation names are capitalized to show that they are formal lithostratigraphic units; member names are informal units at this time.

SUMMARY OF GLACIAL HISTORY

The Duluth area was glaciated many times in the Quaternary epoch, which comprises roughly the last 2 million years of Earth's history. During glacial periods, ice lobes emanated from the Laurentide ice sheet and advanced into the study area, mainly from the northeast. The lobe that followed the Lake Superior basin, and in large part created it, is called the Superior lobe. The basin is floored with Mesoproterozoic sedimentary rocks, which are soft compared to the surrounding igneous rocks. Differential erosion over many glaciations has greatly deepened the basin. The nearby Rainy lobe (named after Rainy Lake) also advanced from the northeast, but over the higher-elevation rocky terrain northwest of the Superior basin (Wright, 1972).

Glacial provenance refers to the general assemblage of rock fragments eroded from bedrock and sediment in the glacier's source area and deposited over the area covered by the ice. The specific composition of deposits varies from place to place. Superior provenance is recognized by rocks of the Keweenawan Supergroup, which consist of red sandstone and siltstone from the Lake Superior basin and igneous rocks on the northwestern side of the basin. The igneous rocks consist mostly of mafic rocks (basalt and gabbro) and red felsic rocks differentiated from the same source magma. However, Superior provenance also includes granites and metamorphic rocks from the Canadian Shield, and minor carbonate rocks, possibly from the Hudson Bay lowland. Most glacial deposits include locally-derived rocks and sediment in addition to the general provenance, but the Keweenawan Supergroup is the local bedrock in the Duluth area; thus the stone assemblage of the tills in this area is dominated by black and red rocks. The very coarse-grained sand fraction (1-2 millimeters) of many of the samples was classified and counted (Hobbs, 1998), and most samples contain more than 90 percent Keweenawan fragments. The matrix (less than 2 millimeters) of the tills is dominated by reddish sand, silt, and clay, derived chiefly from the red sedimentary rocks of the Lake Superior basin.

Sediment of Rainy provenance is dominated by igneous and metamorphic rocks of the Canadian Shield. However, the clast assemblage can locally include abundant Keweenawan igneous rock fragments over and near an outcrop area of Keweenawan igneous rocks, and in those places the assemblage of the Rainy lobe can be similar to the Superior lobe. But in the Rainy lobe, red sedimentary rocks are rare and the matrix is gray to brown rather than reddish-brown. All of the glacial sediment examined in surface samples and soil borings in the Duluth area had Superior clast assemblages; however, some Rainy-provenance sediment may lie hidden in the subsurface.

All of the examined glacial sediment in the Duluth area was deposited during the last glaciation, known as the Wisconsinan glaciation or Wisconsin Episode. Sediments from the early half of the glaciation have not been recognized, so only the late Wisconsinan, or Michigan Subepisode is shown on the correlation chart. Episode terminology is from Hansel and Johnson (1996). Evidence of pre-Wisconsin ice advances has been identified in adjacent regions (Knaeble, 2009), but it appears that in the mapped area these older deposits were partially or totally eroded and covered by later glaciations.

The first glacier to enter the area during the Michigan Subepisode was the combined Rainy and Superior lobes, which advanced as far as west-central Minnesota. Following the glacial maximum, both lobes retreated, but not as a single unit: the Rainy lobe retreated more quickly, and the Superior lobe expanded into areas that had been occupied by the Rainy lobe. The retreat of both lobes was punctuated by readvances, each less extensive than the previous one.

At least five distinct phases of Superior lobe advance and retreat resulted in a series of deposits grouped into the Barnum and Cromwell Formations. Ice of the first, or St. Croix phase, built the St. Croix moraine that extended from the Twin Cities through St. Cloud and into central Minnesota, and covered the area with red sandy till (Wright, 1972). There is some evidence of Superior-lobe ice beyond the St. Croix moraine, but it is not clear if this constitutes a separate phase. The ice margin then retreated into the Superior basin. At that position, meltwater from the ice collected in the depression between the ice and the side of the basin, forming a series of ice-marginal lakes, connected by meltwater channels. Deltas from these lakes are still preserved northeast of Duluth (Hobbs, 2002). A second advance, the Automba phase (Fig. 1; Wright, 1972), followed a more western and northern path than the St. Croix-phase ice as it flowed into areas once covered by the Rainy lobe. As a result, flow direction in the Duluth area switched about 90°, from southwest (parallel to the long axis of the Lake Superior basin) to northwest (spilling out of the basin). Both phases deposited till of the Cromwell Formation (unit Qct), but most if not all of the surface till was deposited in the Automba phase.

The ice then retreated into the Lake Superior basin again, perhaps as far back as Two Harbors, this time opening a larger lake. As ice readvanced for the third time, it incorporated lacustrine silt and clay, resulting in Lakewood till (unit Qlt) with a larger silt and clay content than till of the previous phases. This has been termed the Split Rock advance (Wright, 1972). Lakewood till forms a band along the upper slope of the Superior basin in the Duluth area. The ice surface was apparently not high enough to spill out of the basin as the Automba advance had done. But where the basin rim is lower to the southwest, the till extends as far as west-central Pine County (Fig. 1; assuming that unit Qsf of Knaeble and others, 2001 was deposited by this same advance).

The last three readvances incorporated significant amounts of glacial lake sediment. They have been grouped into the Barnum Formation, which is distinguished from the Cromwell Formation by its lower sand content (Wright and others, 1970). Compare the samples of the Cromwell Formation (unit Qct) with the samples of the Barnum Formation (units Qlt, Qmt, and Qkt) on Figure 2. Each advance deposited a finer-grained till than the previous advance.

After the ice of the Split Rock phase retreated, ice of the St. Louis sublobe advanced from the northwest into glacial Lakes Aitkin I and Upham I west and northwest of Duluth. Although ice of this advance did not reach the study area (Fig. 1), its meltwater affected the area indirectly. As St. Louis-sublobe ice melted, the lowland that it had filled became glacial Lake Aitkin-Upham II, which drained down the St. Louis River towards Lake Superior. Water from very high, early stages of proto-glacial Lake Agassiz overflowed into glacial Lake Aitkin-Upham II, and may have entered the Lake Superior basin at times when it was not filled with ice (Hobbs, 1983). Retreat from the Split Rock phase had opened up a larger Lake Superior than before. Its extent is not well known, but the lake must have been large enough and deep enough to accumulate a considerable amount of clay. The next advance, the Nickerson phase, deposited a clayey till (Moose Lake till, unit Qmt), which forms a band along the edge of the Lake Superior basin in the Duluth area inside and lower than the band of Lakewood till (unit Qlt). At the maximum extent, its ice blocked drainage coming down the St. Louis River and diverted flow south along the ice front, forming a series of drainage channels in Carlton County (generalized in Fig. 1). As ice retreated east, meltwater eventually flowed into glacial Lake Superior (Knaeble and Hobbs, 2009).

The Portage outlet near Moose Lake in Carlton County and the Brule outlet to the east in Wisconsin may initially have been open simultaneously to control the lake level. Eventually the Brule outlet cut down to a lower level and the Portage outlet was abandoned (Clayton, 1984; Farrand and Drexler, 1985; Carney, 1996). This level has been called glacial Lake Duluth, but here it is called the Duluth phase of glacial Lake Superior because it is merely a different level of a lake in the same basin. The only distinct strandline in the Duluth area is a wave-cut bench at the Duluth level. The break in slope is about 1,070 feet (326 meters) elevation. As the retreating ice uncovered lower ground on the Upper Peninsula of Michigan, the lake drained through lower outlets and created a series of stages below the Duluth level. Water coming down the St. Louis River cut into the earlier lake sediments and built a sandy delta in the Fond du Lac–New Duluth area, when the lake was still higher than its current level. Other deltas may have been built farther out in the lake basin as the water dropped below its present level. As the ice melted out of the whole basin, glacial Lake Agassiz water began to spill out of its eastern side into Lake Nipigon, which then drained into Lake Superior. This event occurred while the water level was below its present level in the Duluth area.

In a final phase (Fig. 1) correlated with the Marquette phase in northern Michigan, Superior-lobe ice advanced at about 10,000 radiocarbon years before present (Clayton, 1984; Farrand and Drexler, 1985; Breckenridge, 2007). Like its predecessors, ice advanced into a proglacial lake and deposited a till finer-grained than the previous till (Knife River till, unit Qkt). The resulting till is so clayey that the author suspects that it includes some admixed glacial Lake Agassiz clay that had been deposited in Lake Superior during the previous recession. The Knife River till did not reach high enough on the basin walls to cover the Duluth strandline, but it may have obliterated lower wave-cut benches. Ice retreated rapidly from the region, leaving no identifiable evidence of subsequent lake sediment in the West Duluth quadrangle. Lack of lower strandlines cut into the Knife River till may reflect rapid retreat and drawdown of the lake; alternatively, it may indicate that the clay till was not firm enough to maintain a wave-cut notch.

Lake Superior continued to drop until it reached a level hundreds of feet below its current level in the Duluth area. It has undergone major fluctuations since then. Downward fluctuations were driven by erosion of outlet streams. Upward ones were driven by postglacial uplift of the outlets, including the Sault St. Marie outlet of Lake Superior, and of outlets from the lower Great Lakes, as the continent slowly rebounds from the weight of the former ice sheet. In the Duluth area, the lake has been below its current level for most of postglacial time, except for the Nipissing level in the mid-Holocene epoch, which was approximately equal to the current level (Farrand and Drexler, 1985). The St. Louis River has thus alternatively been a downcutting stream and a drowned valley, as it is today. The water is still rising in the Duluth area at the rate of about 2 centimeters per decade (Farrand and Drexler, 1985).

A bay-mouth bar or barrier beach (Minnesota Point) has been built across the St. Louis River estuary. Its sand was supplied by waves and longshore currents. It may be migrating landward as the lake level rises. Rices Point is believed to be a remnant of a similar bar formed during the Nipissing stage of the lake (C.E. Larsen, unpub. data).

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Jason Aronson, geology graduate student at the University of Minnesota Duluth, scouted potential sampling sites and performed preliminary descriptions and sampling. He operated the power auger on many of the soil borings. Howard Mooers, from the Department of Geological Sciences at the University of Minnesota Duluth, provided useful information. Roger Risley, soil scientist at the National Resources Conservation Service in Duluth, Minnesota shared information about soil and sediment correlation in the area. Thanks are extended to all landowners who gave permission to examine exposures on their property, especially Darren Saari of the Veit Landfill.

DESCRIPTION OF MAP UNITS

HUDSON EPISODE

Qhp **Peat and other organic sediments**—Partially decomposed plant matter with organic-rich silt and marl (calcareous silt and clay); dark gray to black, soft and compressible; deposited in bogs and swamps. Typically found in depressions formed by melting, buried, glacial ice.

Qha **Floodplain alluvium and disturbed sediment**—A dark upper horizon, generally less than 6 feet (2 meters) thick, consisting of unbedded or thinly interbedded silt, clay, sand, and organic material, including scattered wood and shell fragments, which overlie sand, gravel, and boulders. Interpreted to be overbank deposits accumulating on the modern floodplain. Channel sediment is too narrow to map separately. Streams flowing down the steep side of the Lake Superior basin generally do not have floodplains wide enough to map. In the coastal plain along Lake Superior, alluvium is much thicker; it has filled a deep valley cut by the St. Louis River when the level of Lake Superior was much lower. In the harbor area, much of the surface has been covered with fill, and the boundary between land and water is artificial. In places, contacts with other map units are scarps.

WISCONSIN EPISODE

Michigan Subepisode

Barnum Formation—Glacial sediment of Superior provenance deposited by Superior-lobe ice. Includes related deposits reworked by meltwater and gravity. Its members mapped in the West Duluth quadrangle, from oldest to youngest, are the Lakewood, Moose Lake, Wrenshall, and Knife River members. There are two unnamed members composed of lacustrine sediment between advances, and one of delta sand deposited after the last glacial retreat (correlation chart). The Barnum Formation is composed of a sequence of separate Superior-lobe ice advance phases (the Split Rock, Nickerson, and Marquette phases). In each phase, ice advanced into proglacial lakes, incorporated some of the underlying fine-grained lake sediment, and deposited a fine-grained till. Of the proglacial lake sediment units, only one, the Wrenshall, has been named as a member. Oxidized till color is generally reddish-brown. Higher clay content is associated with redder color. Clast types in Barnum Formation tills and their associated outwash are typical of Superior provenance. Carbonate fragments are present in trace amounts, increasing in abundance in the younger members. Fine-grained carbonate in the matrix increases even more notably from older to younger.

Qdb ***Unnamed member***—Delta sediment of fine- to very fine-grained silty sand and coarse-grained silt. Minor, red, clay beds; calcareous. Sand color ranges from 10YR 6/3 to 5/4 (pale brown to yellowish-brown). Bedding is obscure. This sediment is similar to the delta included in the Wrenshall member (Qda), but is stratigraphically above the Knife River member.

Knife River member—Glacial sediment deposited by re-advancing ice correlative to the Marquette phase advance in Michigan (Clayton, 1984; Farrand and Drexler, 1985; Carney, 1996; Breckenridge, 2007). Correlative with one or both of the Hanson Creek and Douglas members of the Miller Creek Formation (Johnson, 1983).

Qkt **Till deposits**—Unsorted sediment having a clay matrix texture (Fig. 2). The matrix color is reddish-brown (2.5YR 4/4) where oxidized and weak red (2.5YR 4/2) where unoxidized. Pebbles, cobbles, and boulders are uncommon to rare. Primary carbonate clasts are uncommon to rare, but the matrix of the till is very calcareous and secondary carbonate nodules are common. Carbonate leaching depth is less than 3 feet (1 meter). On steep slopes, till is discontinuous and generally less than 15 feet (5 meters) thick. On the Lake Superior coastal plain, it is thicker and may include unsorted mudflow sediment of the same general appearance, sloughed from the slopes above.

Wrenshall member—Lacustrine deposits of glacial Lake Superior, stratigraphically beneath the Knife River Member.

Qda **Deltaic sand deposits** (shown only on cross section)—Brown to red-brown, medium-grained sand to silty, very fine-grained sand; moderately-well to well sorted. Bedding is generally horizontal. Coarse-grained clasts are absent or very rare. Deposited by the St. Louis River as it entered glacial Lake Superior after it had declined considerably from the Duluth level, but was still above its present level.

Qwl **Off-shore silt and clay lake deposits** (shown only on cross section)—Texture ranges from massive, almost pure clay, to alternating clay-rich and silt-rich laminated beds. Thin, very fine- and fine-grained sand layers occur locally. Clay layers are typically red but in places are dark gray. Silt layers are gray and may contain very fine-grained sand. Moderately to slightly calcareous. Pebbles and cobbles are rare and are interpreted to be dropstones. Description is based on observations in Carlton County (Knaeble and Hobbs, 2009), outside the study area, and on soil borings taken at the Veit landfill (Crowl, 2002).

Moose Lake member—Glacial sediment deposited by re-advancing ice associated with the Nickerson phase of the Superior lobe (Wright and others, 1970; Wright, 1972).

Qmt **Till deposits**—Chiefly unsorted sediment commonly having a clay loam to silty clay loam matrix texture (Fig. 2). The matrix color is reddish-brown (2.5YR 4/4 to 5YR 4/4) where oxidized and dark reddish-gray (5YR 4/2) where unoxidized. Pebbles, cobbles, and boulders vary from rare to common, but the unit typically has few clasts, most of which are small. Carbonate leaching depth is commonly less than 5 feet (1.5 meters). Unit tends to be thin and discontinuous on steep slopes.

Qlb ***Unnamed member*** (shown only on cross section)—Lacustrine sediment, not observed or sampled. Hypothesized to be present to account for the texture of the overlying Moose Lake member till. Based on this hypothesis, the sediment should be low in sand, and contain subequal amounts of silt and clay.

Lakewood member—Glacial sediment deposited by re-advancing ice associated with the Split Rock phase of the Superior lobe (Wright and others, 1970; Wright, 1972).

Qlt **Till deposits**—Chiefly unsorted sediment, commonly having a loam to silt loam matrix texture (Fig. 2). The matrix color is reddish-brown (5YR 4/4) where oxidized and dark reddish-gray (5YR 4/2) where unoxidized. Pebbles, cobbles, and boulders vary from rare to abundant, but typically clasts are common. Carbonate leaching is typically from 5 to 10 feet (1.5 to 3 meters). Areas of sandy Cromwell Formation till are present at the surface within the mapped area, where the Lakewood member deposits are thin or absent due to lack of deposition or subsequent erosion.

Qla ***Unnamed member*** (shown only on cross section)—Lacustrine sediment, not observed or sampled. Hypothesized to be present to account for the texture of the overlying Lakewood member till. Based on this hypothesis, the sediment should be low in sand, and contain more silt than clay.

Cromwell Formation—Glacial sediment of Superior provenance deposited by the Superior lobe. Includes related deposits reworked by meltwater and gravity. This formation is comprised of deposits related to two phases of the Superior lobe: the St. Croix phase and the Automba phase re-advance. Based on data from adjacent areas, till of the Automba phase generally contains less sand, more silt, and slightly more clay than St. Croix-phase till. The difference is not distinct or consistent enough to define separate members. The materials on this map assigned to the Cromwell Formation are considered to be deposits of the Automba phase, yet in a few places St. Croix-phase deposits may be at the surface, where erosion stripped away the overlying Automba-phase materials. Some Cromwell Formation deposits are covered by thin, unmapped loess.

Qco **Outwash deposits**—Fine- to coarse-grained sand and fine- to coarse-grained gravel; moderately to moderately-well sorted; generally stratified; carbonate typically is leached to the full depth of exposures. Deposited by meltwater from Automba-phase ice. Deposited in a valley still in use by modern drainage.

Qct **Till deposits**—Chiefly unsorted sediment having a loam, sandy loam, or silt loam matrix texture (Fig. 2). The matrix color is brown to reddish-brown (5YR to 7.5YR 4/4) where oxidized and dark reddish-gray (5YR 4/2) where unoxidized. Pebbles, cobbles, and boulders are uncommon to abundant, but coarse-grained fragments are generally common enough to make digging and drilling difficult. In places unit may include small bodies of bedded sediment at or near the surface. Carbonate leaching is generally greater than 10 feet (3 meters). Unleached till is only slightly to moderately calcareous.

MESOPROTEROZOIC

Pb **Shallow to bedrock**—Quaternary sediment cover is thin, and the surface topography is dominated by the bedrock topography. The average thickness of Quaternary sediment is about 5 feet (1.5 meters), but ranges from 0 to about 10 feet (3 meters), due to the irregularity of the bedrock surface. A fringe of shallow bedrock surrounds every bedrock outcrop, but is mapped only where it occupies a substantial area.

MAP SYMBOLS

Geologic contact—Approximately located.

Bedrock outcrop—Undivided; from Miller and Green (2008).

Flute—A streamlined hill or ridge formed at the base of moving ice and commonly surfaced by subglacial sediment. Related to the Highland Flutes of Wright (1972), which are described as partly cored by bedrock. Arrow shows the inferred direction of ice movement; the length of the arrow is approximately equivalent to flute length. The flutes are interpreted to have been formed by ice of the St. Croix phase.

Flow direction of a meltwater stream—Occurs in sand and gravel deposits. The arrow points in the general direction that glacial meltwater once flowed, if known.

Glacial lake strandline, Duluth level—Formed by waves in glacial Lake Superior when the water level was about 470 feet (143 meters) above the modern Lake Superior level. Consists of a tread and a riser cut into the side of the Lake Superior basin. There is no sandy beach. Instead, the tread of the strandline is a narrow shelf covered with cobbles and boulders.

Buried sand and gravel deposits (inferred)—Areas where sand and gravel is covered by till. One body is covered by till of the Lakewood member; the other is covered by till of the Moose Lake and Knife River members. These may represent deltas built by meltwater into glacial Lake Superior when its level was much higher than it is today.

Location of soil boring with samples—Maximum depth 24 feet (7 meters).

Location of material sample—Texture analysis and description.

Location of material observation—Description but no sample.

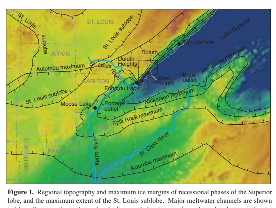

Figure 1. Regional topography and maximum ice margins of recessional phases of the Superior lobe, and the maximum extent of the St. Louis sublobe. Major meltwater channels are shown in blue. Topography is shown by shading, and elevation is shown by color: brown indicates the highest elevations and dark blue indicates the lowest (the surface of Lake Superior).

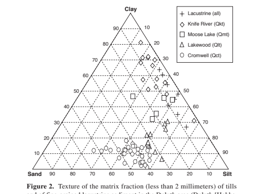

Figure 2. Texture of the matrix fraction (less than 2 millimeters) of tills and of fine-grained lacustrine sediment in the Duluth area (Duluth [Hobbs, 2009a], Duluth Heights [Hobbs, 2009b], and West Duluth quadrangles). Lacustrine samples are from Barnum Formation units Qll (not shown on the West Duluth quadrangle) and Qwl, and a lacustrine inclusion in unit Qkt. Lacustrine samples are shown regardless of member in order to show the range of lacustrine textures, and to demonstrate that adding various amounts of such sediment to sediment of Cromwell Formation texture can produce till textures that are seen in the Barnum Formation.

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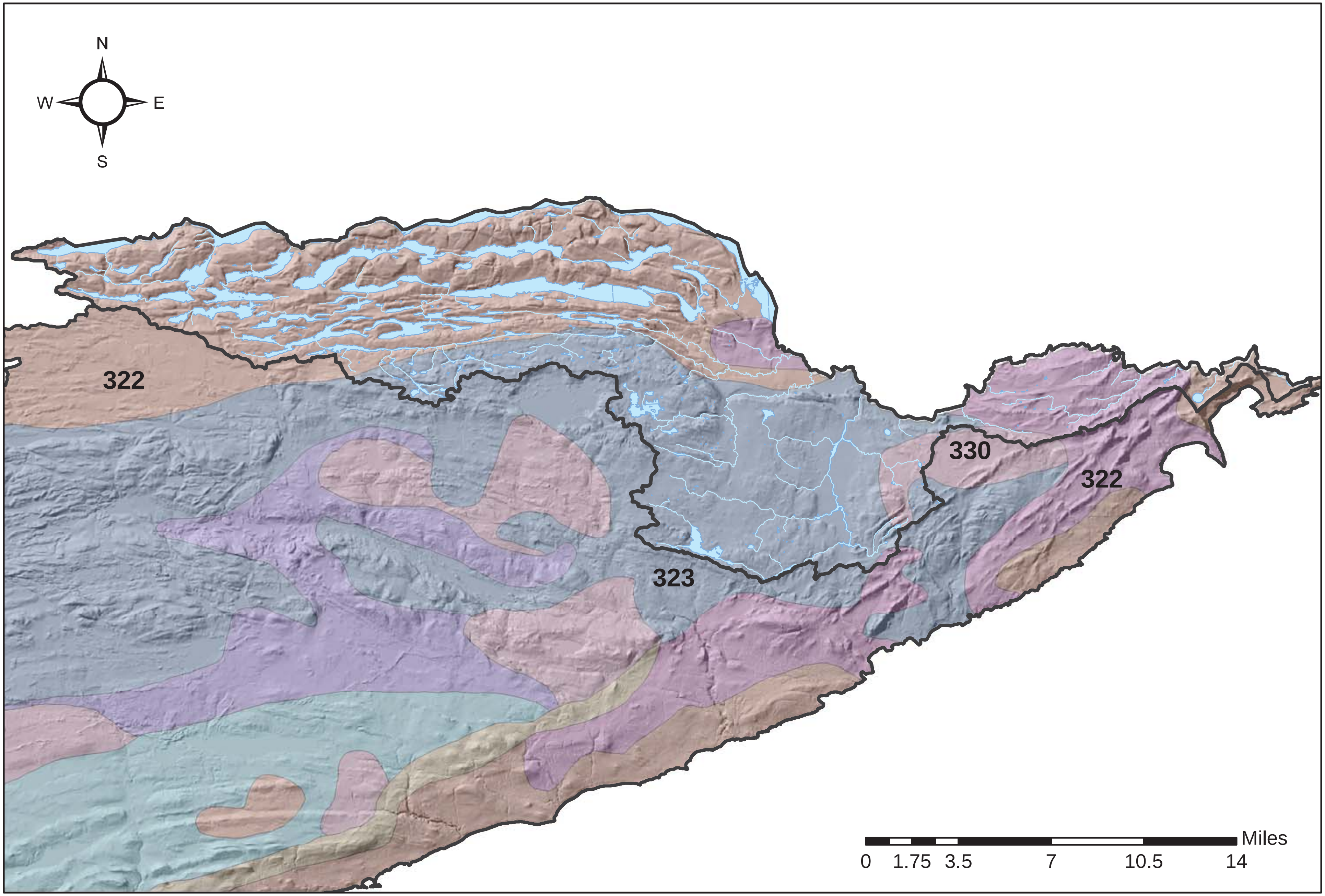
Appendix B

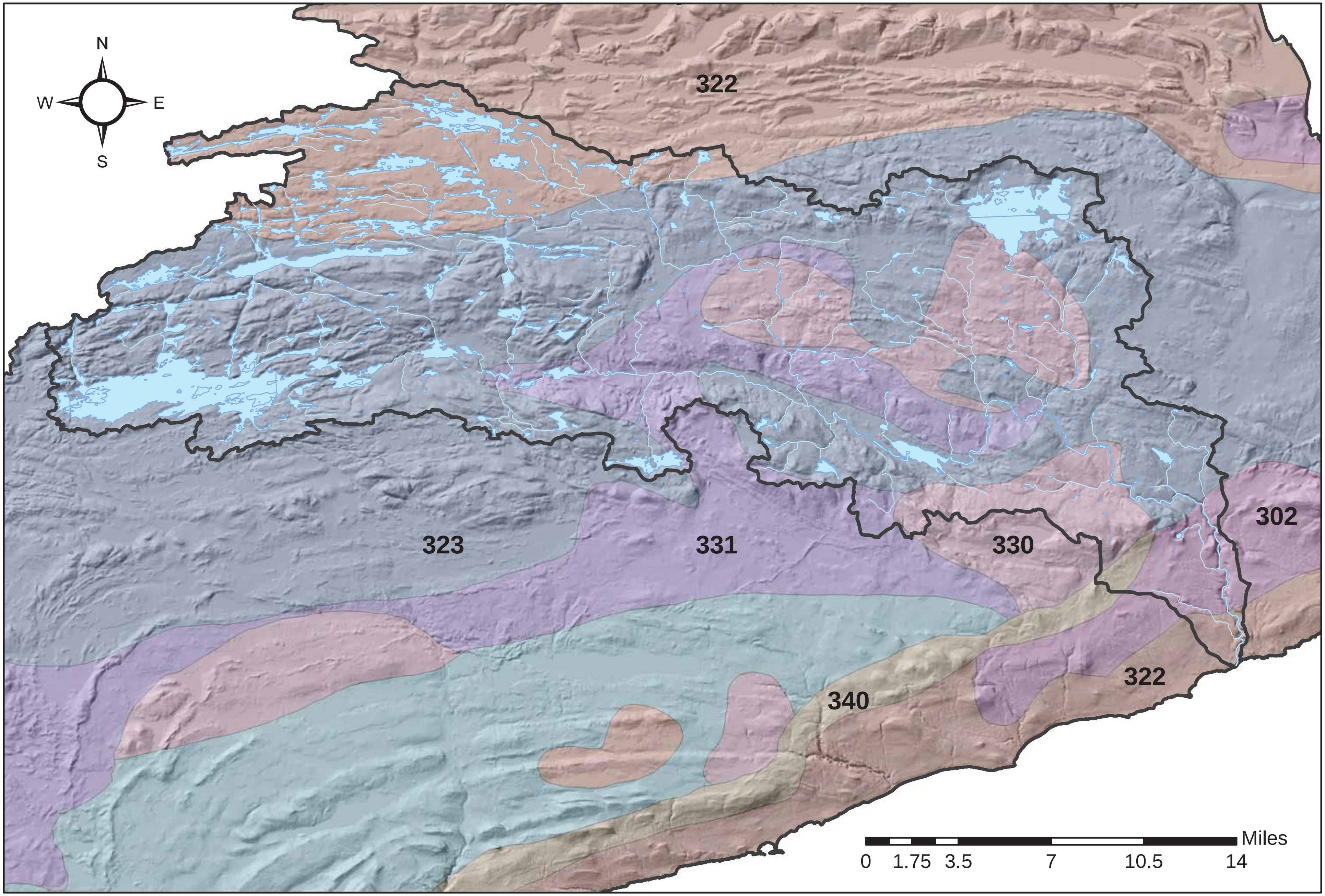
Legend

Soil Suborder/Parent Material/Landform

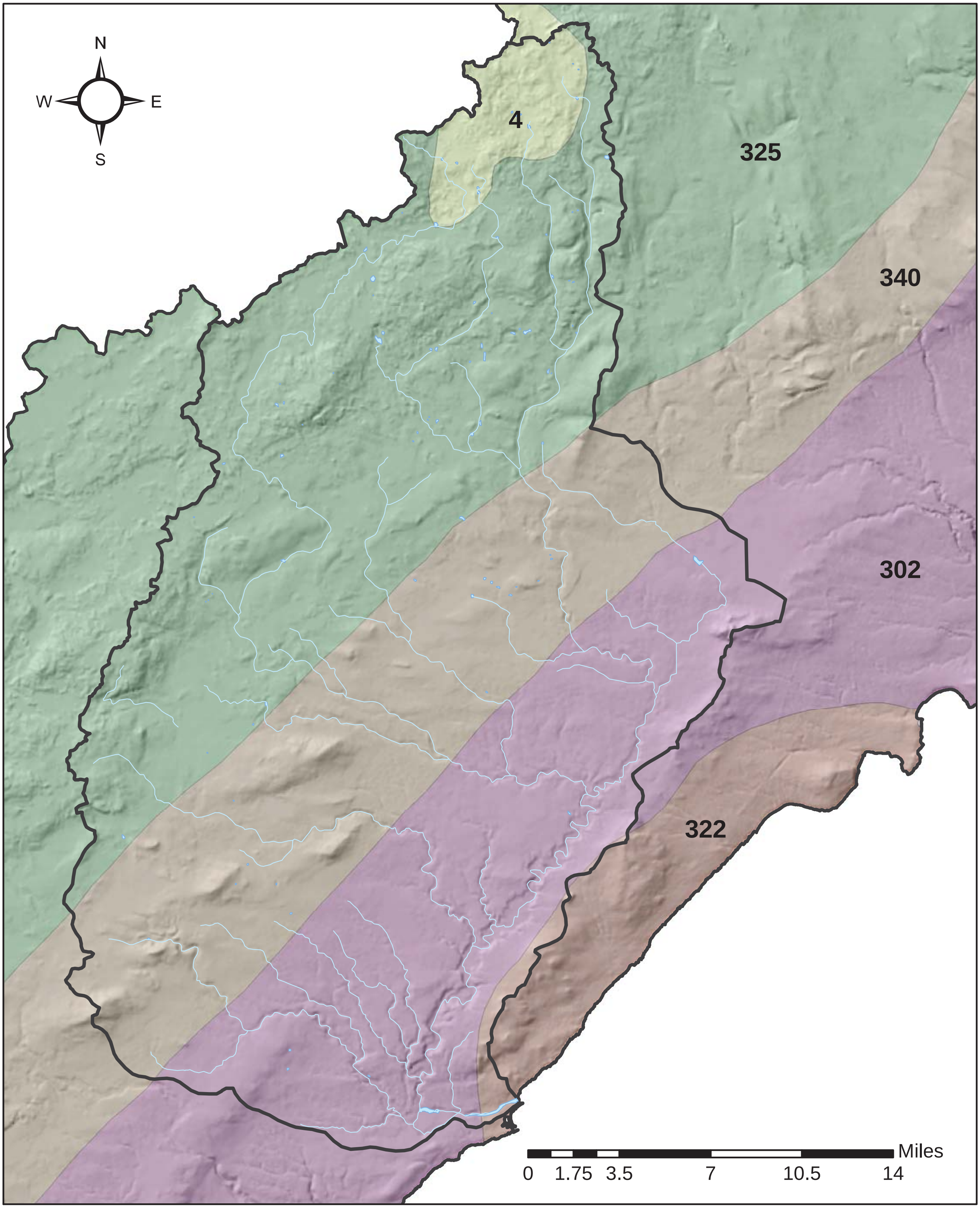
- 4/Organic Soils/Former lake basin
- 302/Red lacustrine sediments/Former lake basin
- 322/Brown or red tills/Ground moraine
- 323/Brown till/Ground moraine
- 324/Brown till and outwash gray lacustrine depsoits/Ground moraine
- 325/Brown stony till/Terminal moraine and outwash
- 330/Brown till/Ground moraine
- 331/Stony brown and some red outwash/Outwash
- 340/Red Stony till/Ground moraine
- 341/Red stony till/Drumlins



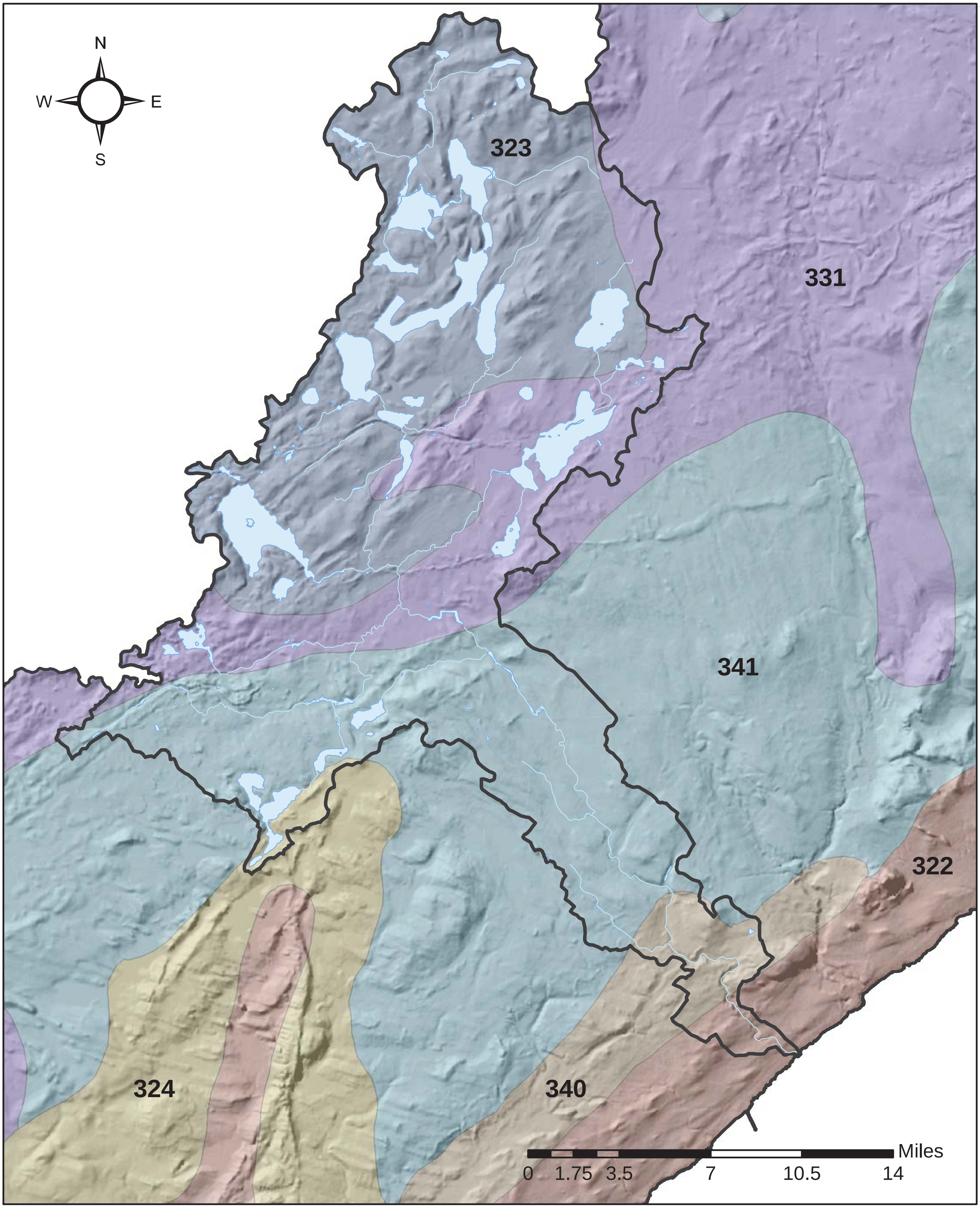
Pigeon River Watershed Soils (Cummins and Grigal, 1980).



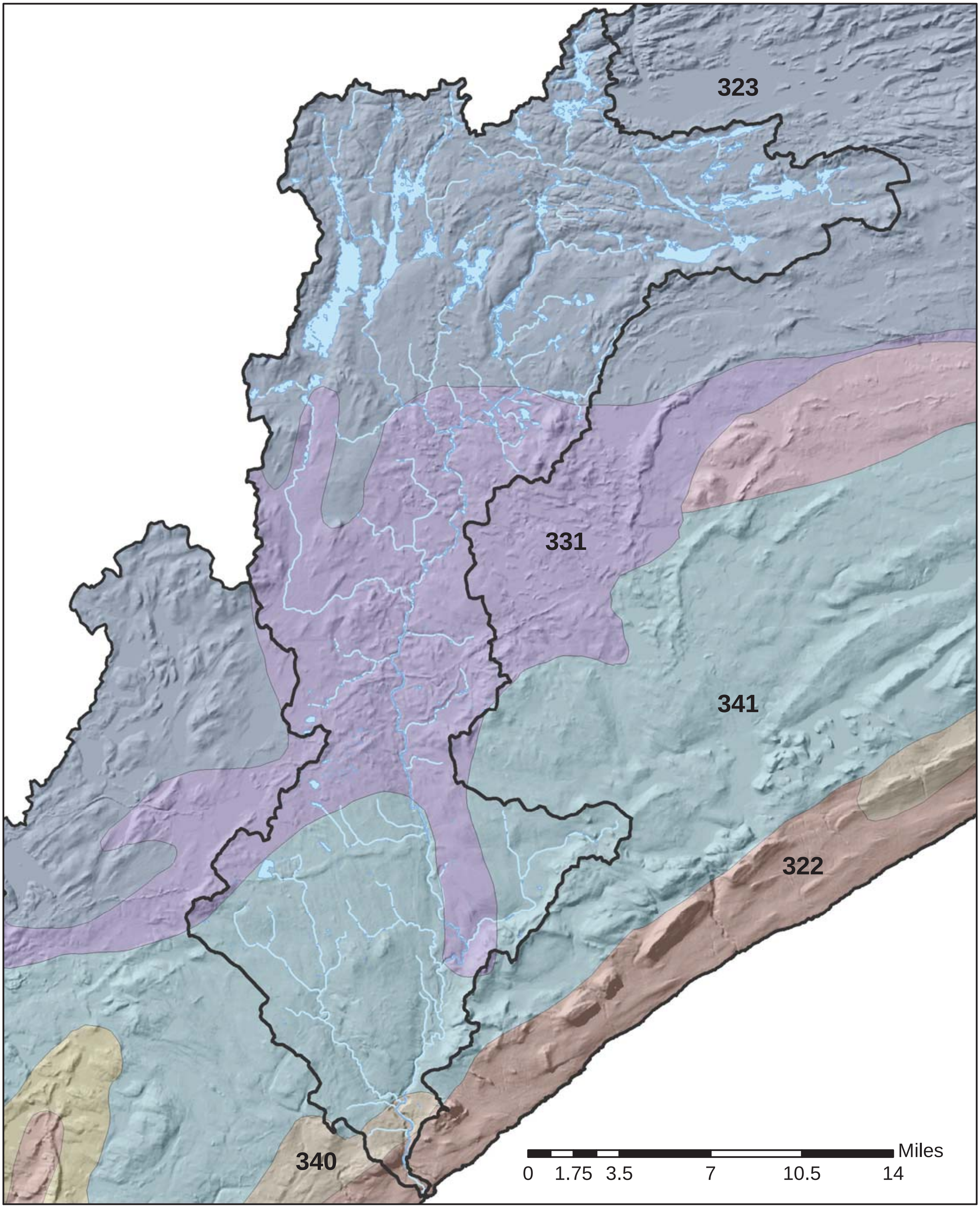
Brule River Catchment Soils (Cummings and Grigal, 19809).



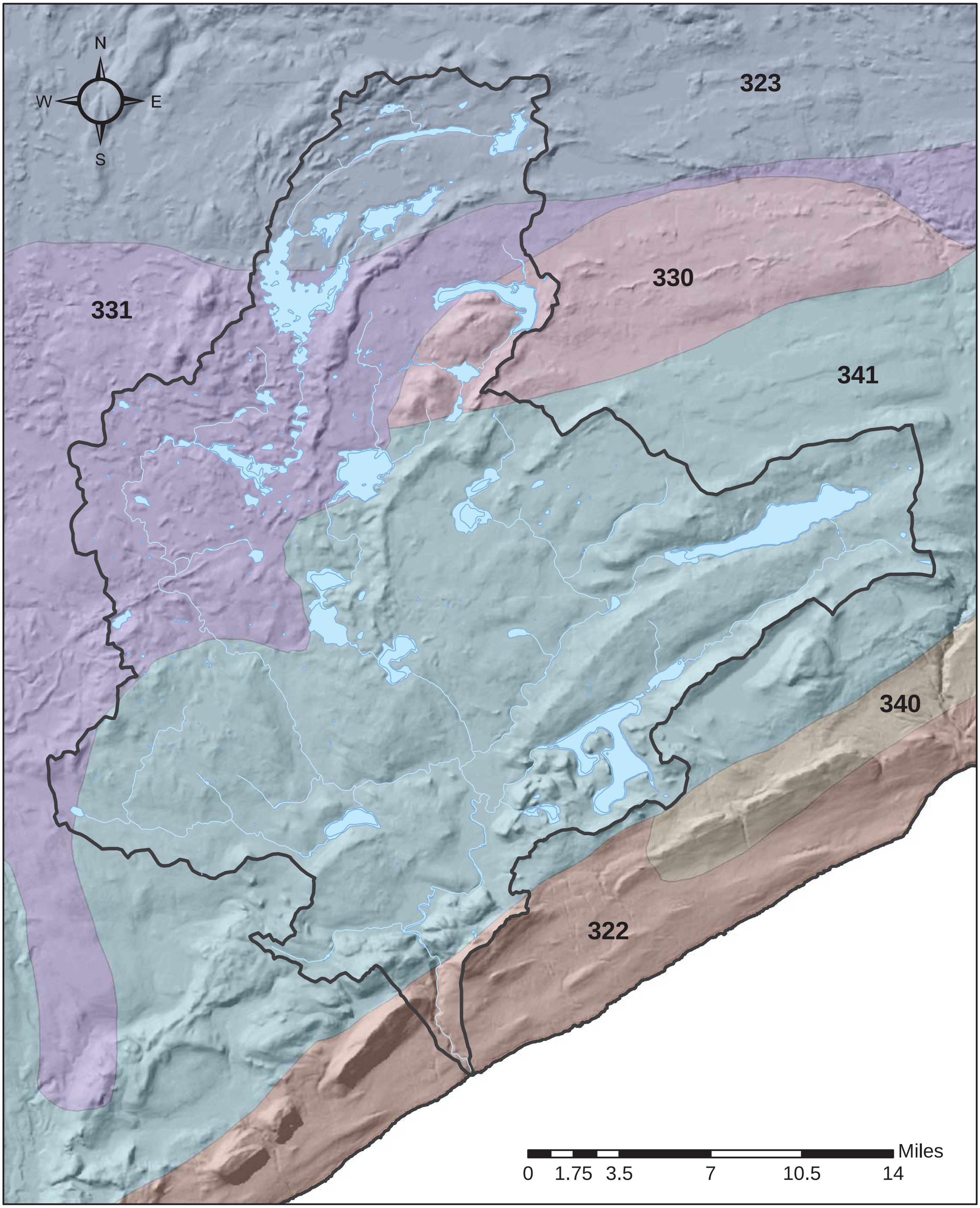
Knife River Catchment Soils (Cummins and Grigal, 1980).



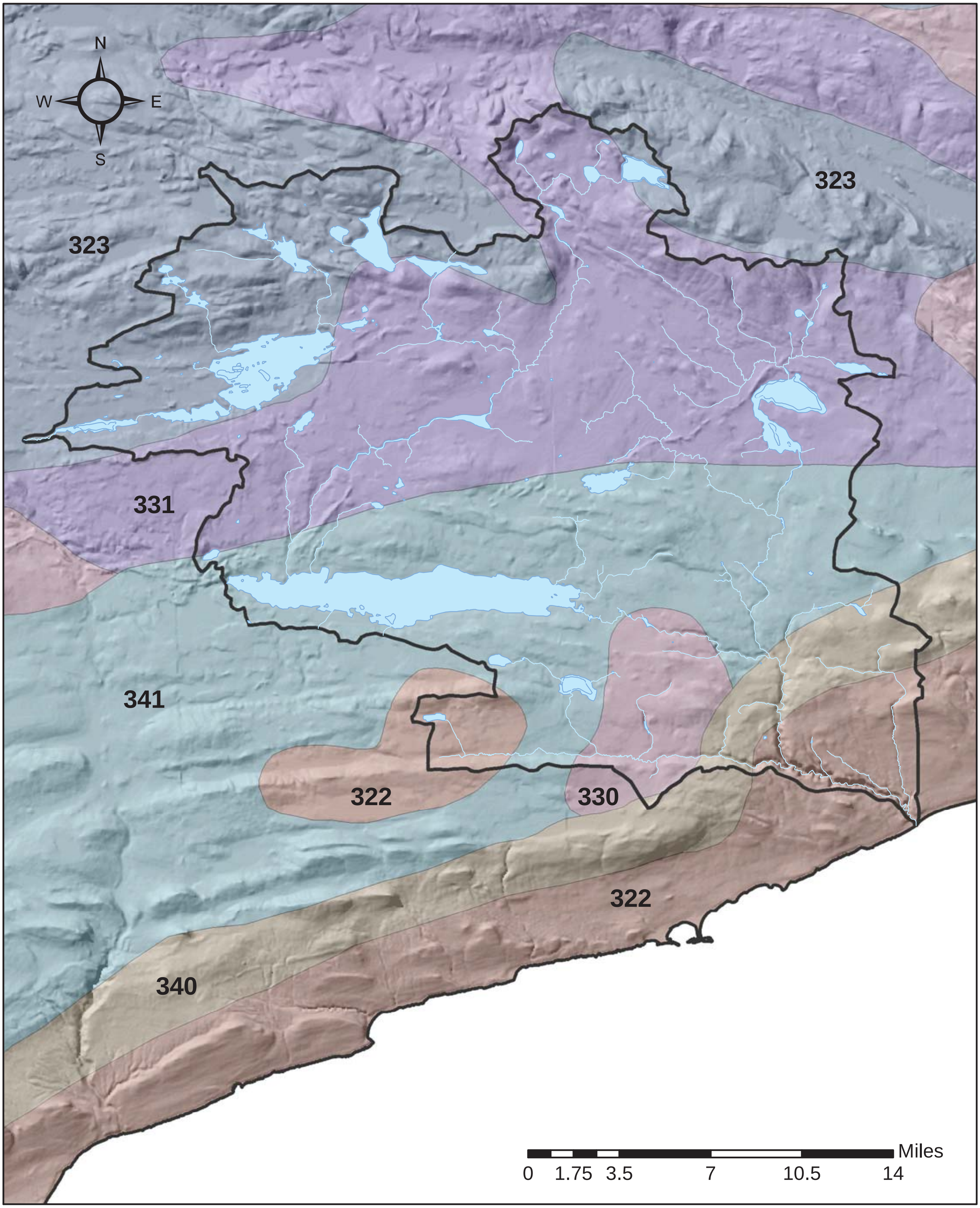
Cross River Catchment Soils (Cummins and Grigal, 1980).



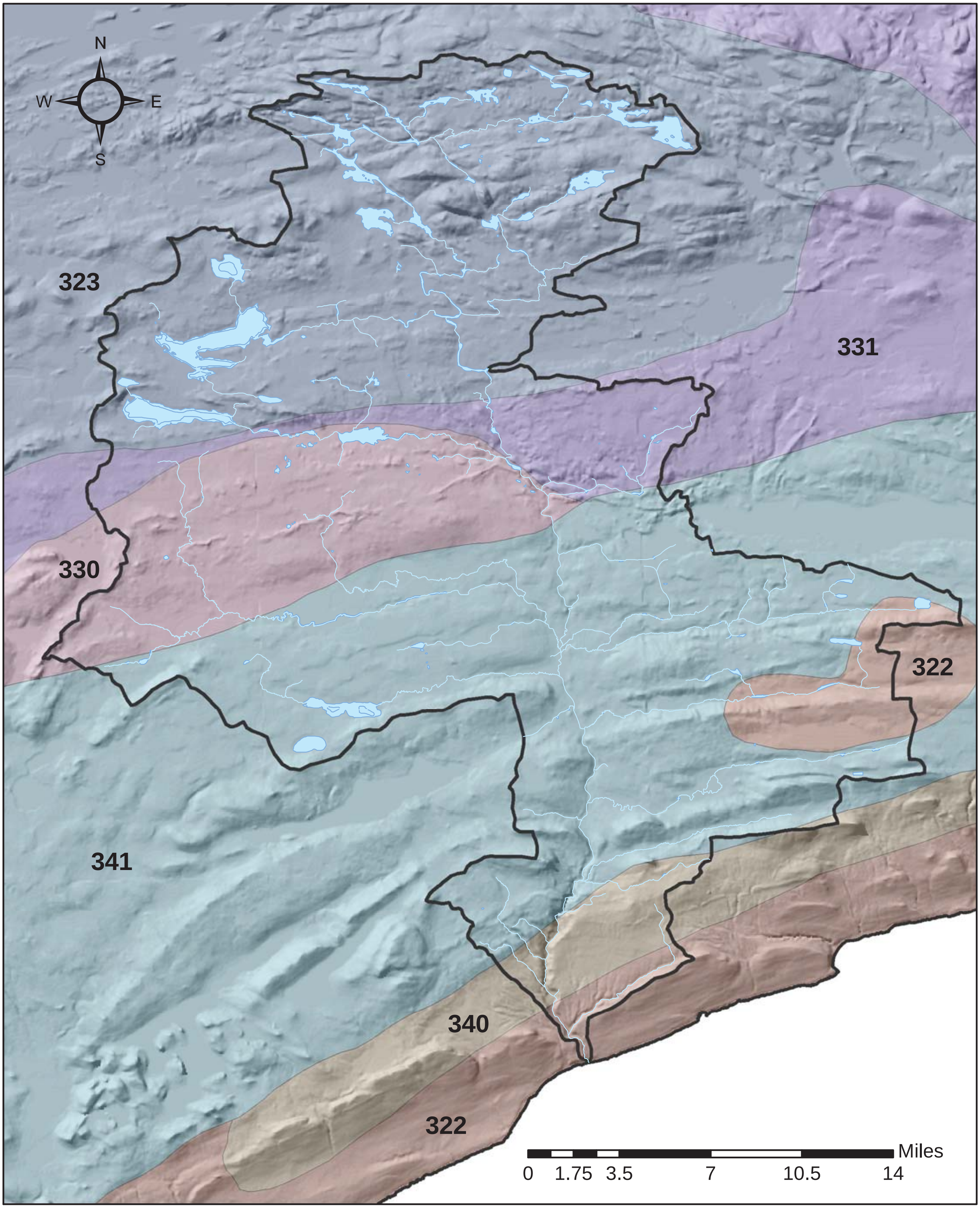
Temperance River Catchment Soils (Cummins and Grigal, 1980).



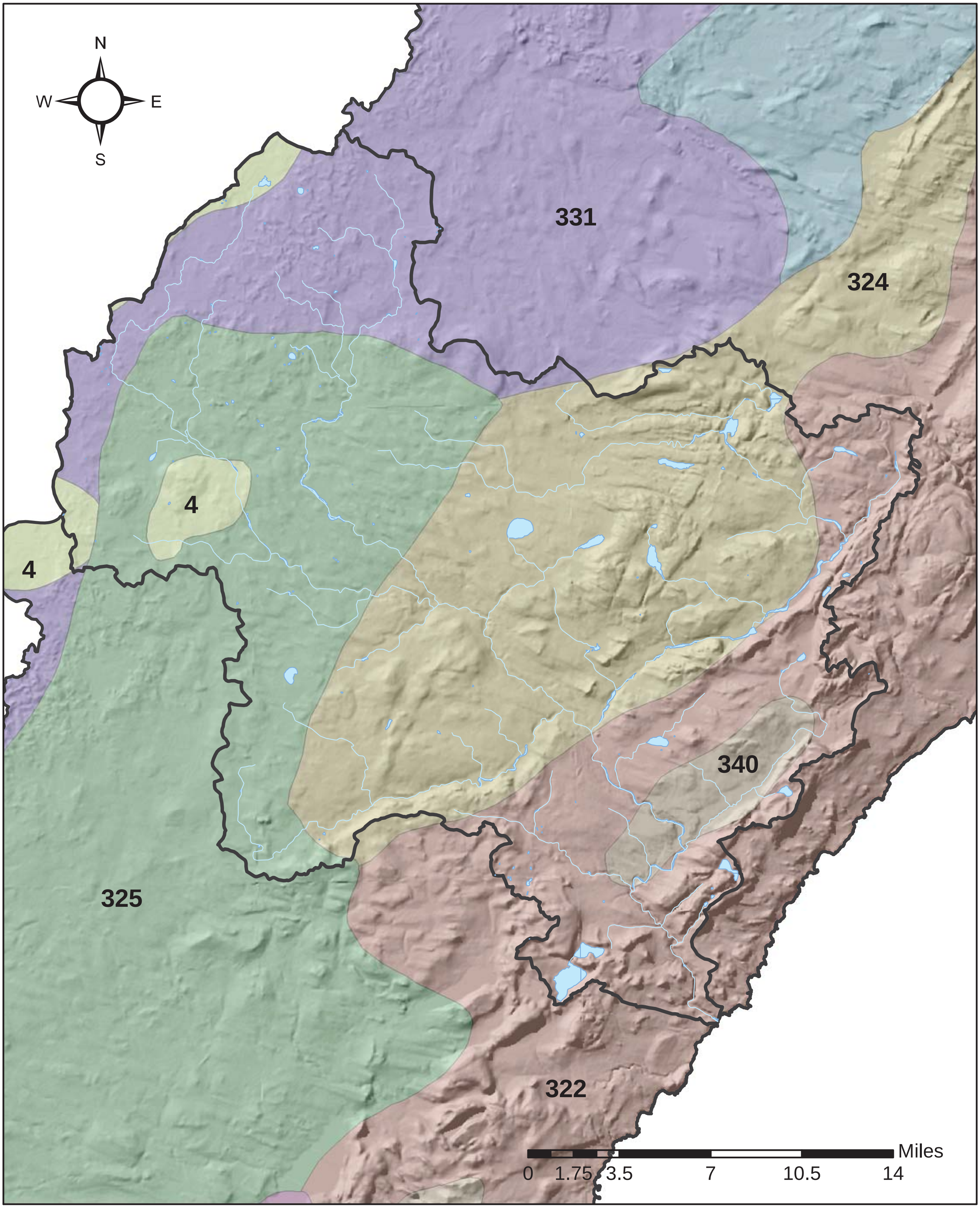
Poplar River Catchment Soils (Cummins and Grigal, 1980).



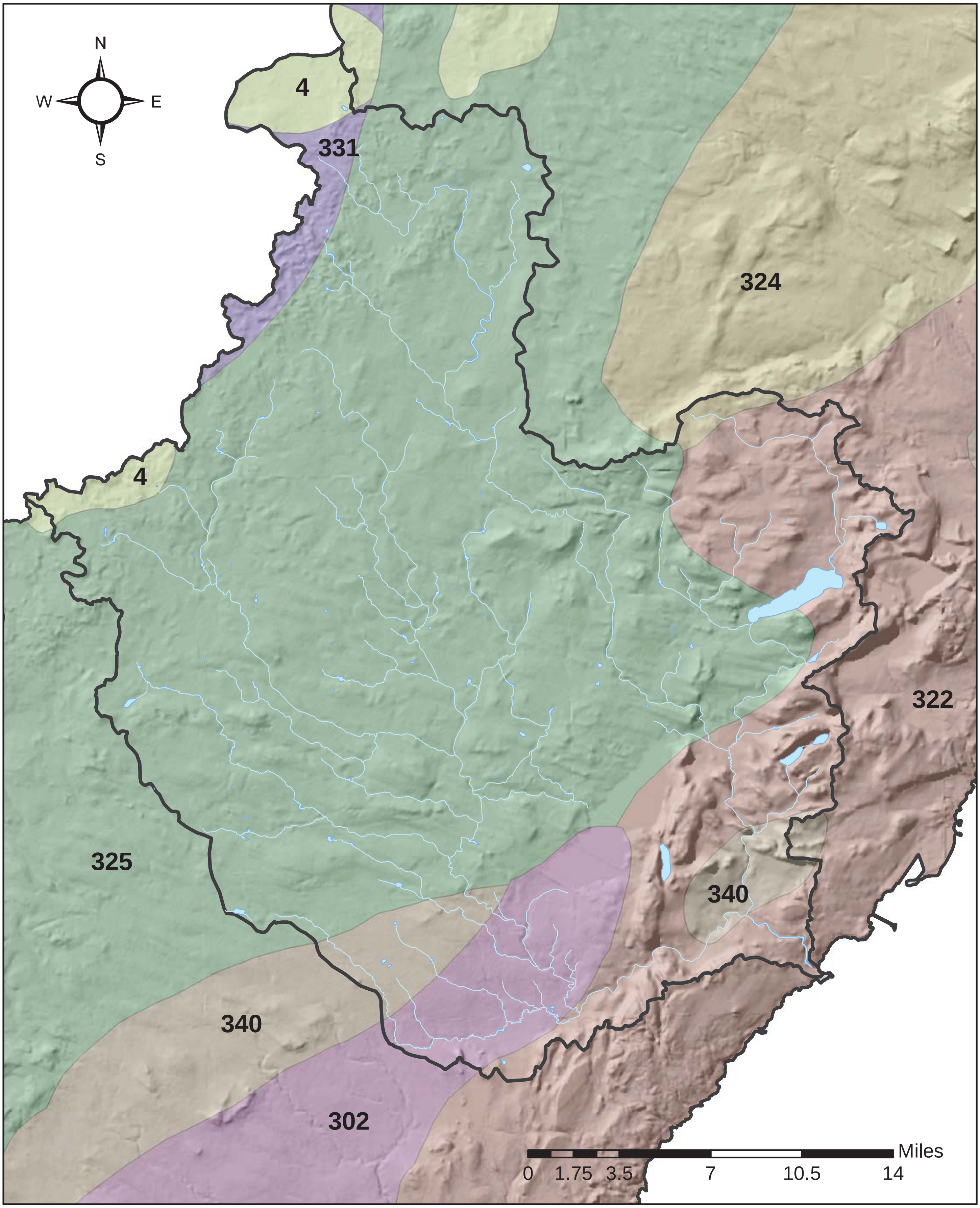
Devil's Track River Catchment Soils (Cummins and Grigal, 1980).



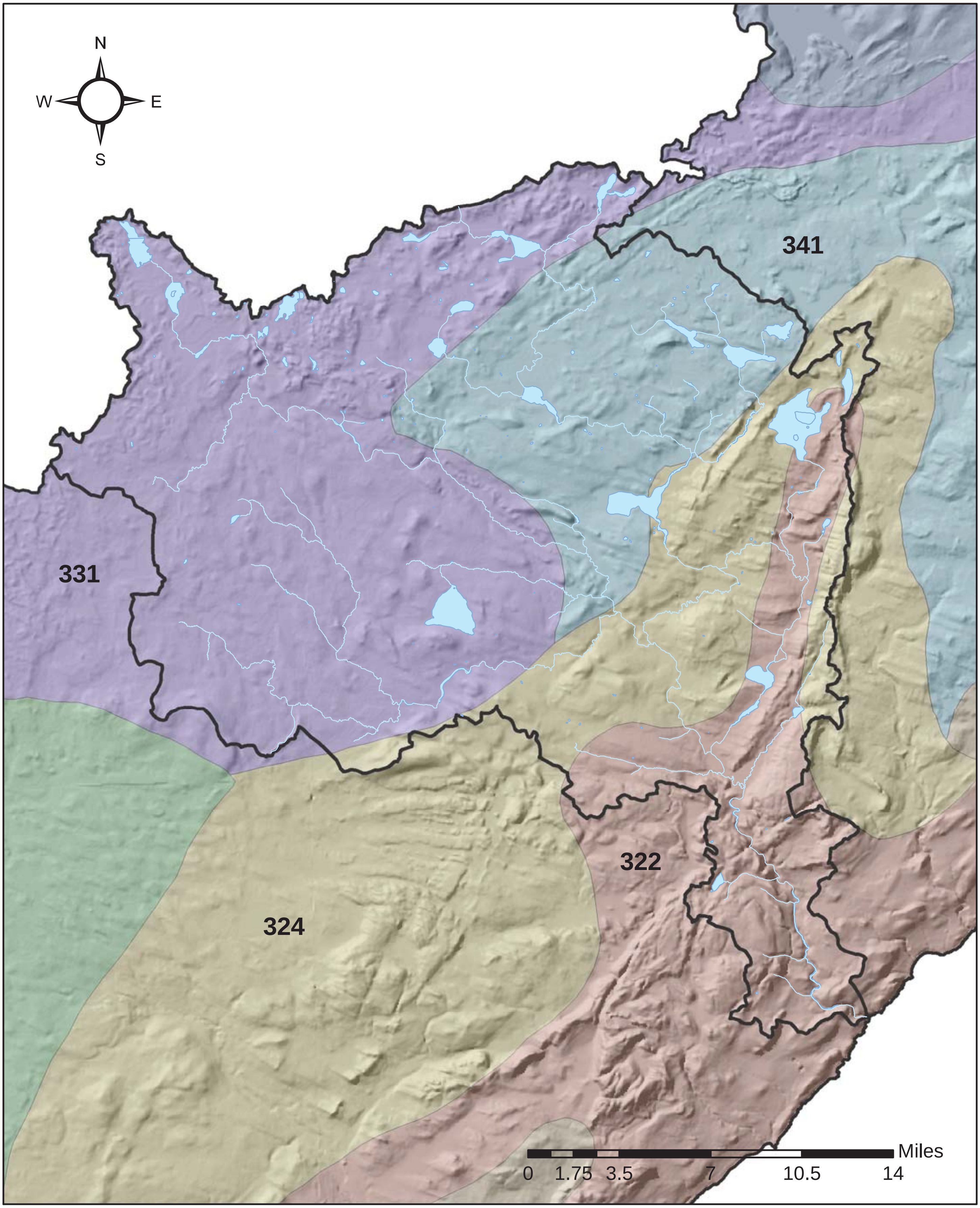
Cascade River Soils (Cummins and Grigal, 1980).



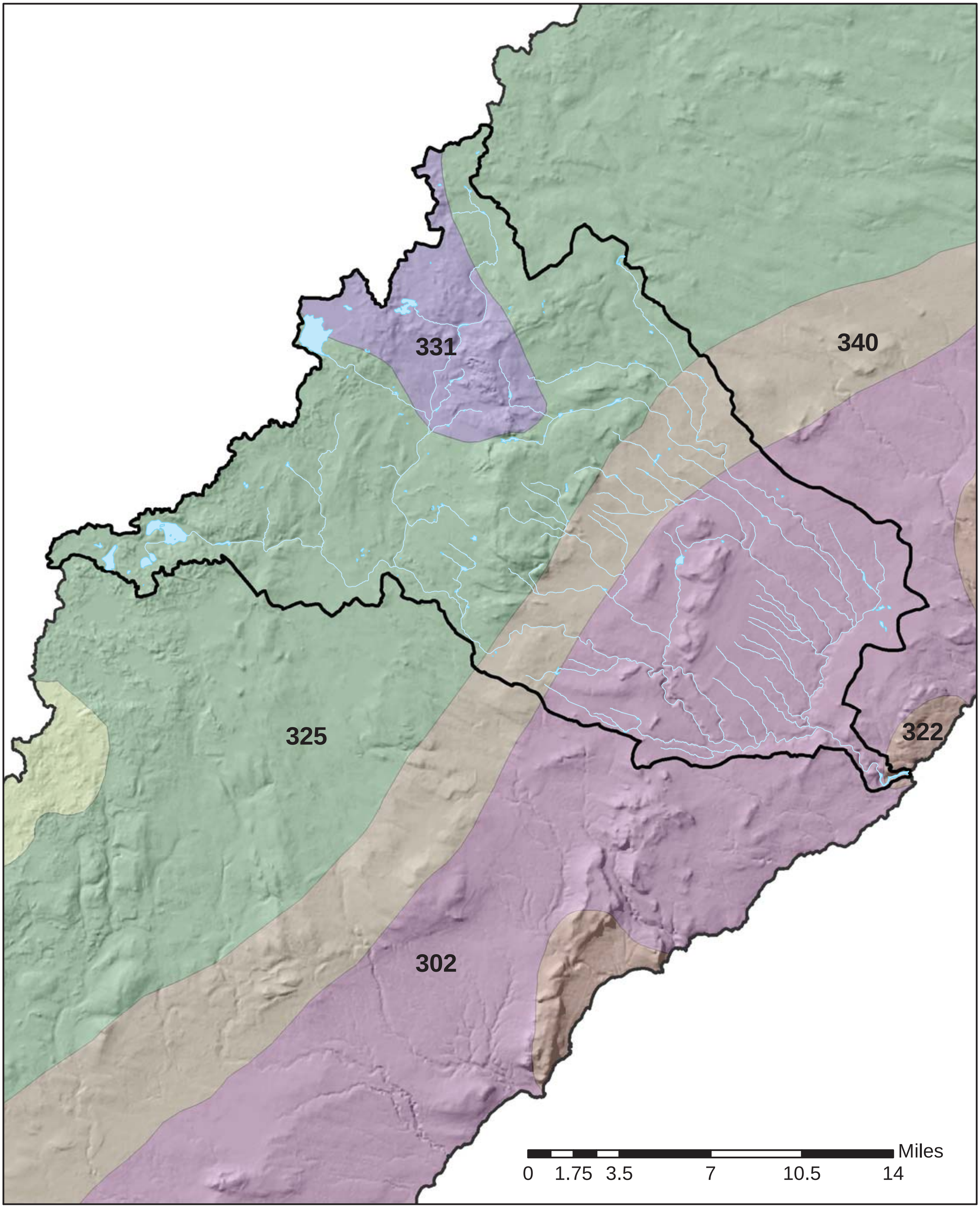
Baptism River Catchment Soils (Cummins and Grigal, 1980).



Beaver River Catchment Soils (Cummins and Grigal, 1980).



Manitou River Catchment Soils (Cummins and Grigal, 1980).



Gooseberry River Catchment Soils (Cummins and Grigal, 1980).

Appendix C

Aerial Photo Analysis of possible Bluff/Bank erosion locations along the Poplar River

- 90°42'42.826"W 47°38'27.115"N and 90°42'39.506"W 47°38'25.548"N
  - Two bluffs, connected and going in different direction
  - Easily assessable – right by golf course
  - Snowmobile trail crosses river there
- 90°42'50.596"W 47°38'29.425"N
  - Also on golf course
- 90°42'48.703"W 47°38'33.146"N
  - At a stop where there is no buffer between golf course and river
- 90°43'6.11"W 47°38'57.038"N
  - A little less than 100 meters upstream from the end of the golf course
- 90°43'1.2"W 47°39'3.892"N
  - Right below the wastewater treatment plant
  - About 300 meters upstream from the last point
  - “Mega slope”
  - Across from ski slopes
- 90°43'5.814"W 47°39'31.08"N and 90°43'5.868"W 47°39'32.254"N
  - Right after the river splits and comes back together
  - Two/three bluffs or sandbars
  - 1.5 miles from 61 on turn off of Ski Hill Rd.
  - Less than ¼ mile from road

Aerial Photo Analysis of possible Bluff/Bank erosion locations along the Temperance River

Note: In the River closest to Lake Superior, it is mostly bedrock, with a couple of stretches where the river widens and looks to be sandy.

- 1st sandy stretch
  - 90°52'46.985"W 47°33'35.569"N
  - is accessible by trail
  - Come up from 61
  - Park at stop on Temperance Rd and hike down.
- 2nd is right next to road
  - 90°52'58.015"W 47°34'4.465"N
  - 1.1 miles up Temperance Rd.
  - Could road be affecting runoff?
  - Continues for awhile around next bend, which veers away from road
  - Could be worthwhile to check out the section that veers away from the road
    - 90°52'50.661"W 47°34'19.738"N
    - 90°52'50.065"W 47°34'34.702"N
    - Has a lot of exposed sand and rock
    - Possible changing channel

After travelling about a mile up from the shore of Lake Superior, the river seems to not be in bedrock at all. There are a lot of exposed sand and/or rocky banks. Provided below is only an in depth description of bluffs or areas of bank erosion with high potential for sediment loading.

- 90°53'16.351"W 47°35'3.787"N
  - The stream channel is shifting
  - The channel splits before the bend
  - Reconnects after bend
  - The smaller part goes on the outer part of the bend
- 90°52'18.846"W 47°36'21.491"N
  - Bridge on trail
- 90°52'3.542"W 47°36'29.629"N
  - Large bluff
  - Easiest access may be using snowmobile trail – a little over a mile hike to the river and then walking along river from the bridge - about 676 meters
  - Other possibility: Walking through the bush from road, and walking along river from north
  - There is a set of three or so sandy bluffs right around here.
- 90°51'52.12"W 47°36'46.272"N
  - Another potential bluff
  - Upstream, it splits into multiple channels, this is where it comes together
  - Soil type changing?
  - Changing valley type?
  - Interesting to see how the land is coping
  - Might be hard to get here
    - Trail that goes along river seems to loop right along that point
    - 3.7 miles up the Sawbill trail and then walk through forest 186 meters to river
- 90°51'48.819"W 47°37'4.479"N

    - Entrance of tributary
    - Possible bluff
        - Not very far from the last site – maybe 100 meters
- 90°51'44.562"W 47°37'10.028"N
    - Another spot where the river splits and comes back together
        - This one is much smaller of a distance before they come back together
        - A little less than 300 meters from the road
- 90°50'56.356"W 47°38'31.673"N
    - Small bluff
    - Fairly close to the bridge

Aerial Photo Analysis of possible Bluff/Bank erosion locations along the Knife River

Note: There appears to be a “bluff” on every curve of this river.

- 91°47'57.072"W 46°56'51.368"N
  - Bluff - 160 meters from Hwy 61
  - Two more potential bluffs within 380 meters of spot
- 91°48'17.501"W 46°56'54.316"N
  - Large bluff on sharp curve
  - 230 meters from last point
  - Housing development could contribute to bluff presence
    - 91°48'18.159"W 46°57'7.506"N
    - Location of large field
    - 250 meters away from bluff (other parts of river are closer)
- 91°48'22.273"W 46°57'10.972"N
  - Right next to Co Rd. 255 – road could be impacting bluff
- 91°47'55.81"W 46°58'8.261"N
  - Take Co. Rd. 102 past Blueberry Ridge
  - From 61 go a total of 0.9 miles
  - Turn left and go 0.4 miles
  - Bluff is 750 meters from end of road (then turns into a private driveway)
- 91°47'55.814"W 46°58'8.275"N
  - Bluff
- 91°47'42.341"W 46°58'7.891"N & 91°47'23.882"W 46°58'14.635"N
  - Two large red colored bluffs
  - One on the upstream side of house (has had a total station there)
  - One on the downstream side of house
    - Small pond at top of bluff
  - Largest bluffs yet on the Knife
- 91°47'36.612"W 46°58'21.336"N
  - Smaller red colored bluff
- 91°47'29.795"W 46°58'27.143"N & 91°47'33.196"W 46°58'29.002"N & 91°47'35.579"W 46°58'30.206"N
  - Series of 3 bluffs, housing development above
  - Pond above
  - Very turbid tributary coming in
- 91°47'8.597"W 46°59'4.048"N
  - House built right on top of bluff
  - Turbid tributary coming in upstream <100 meters
  - <200 meters from road.
  - Driveway leads right to bluff

    - Large field also right above bluff
- 91°46'21.357"W 46°59'24.894"N
- 91°46'30.591"W 46°59'31.684"N
    - Mega-bluff
    - Longest bluff yet
    - Take Co Rd 102 2.2 miles up, continue on road and bluff is 700 meters east through forest

Appendix D

GEODATABASE: MN_NORTH_SHORE.gdb

- lsn_04010102.shp
    - Lake Superior North major 8-digit HUC watershed (04010102). Accessed online from the DNR Data Deli: “DNR Watersheds - DNR Level 04 - HUC 08 – Majors”.
- lss_04010101.shp
    - Lake Superior South major 8-digit HUC watershed (04010101). Accessed online from the DNR Data Deli: “DNR Watersheds - DNR Level 04 - HUC 08 – Majors”.
- ns_outline.shp
    - This file was generated from the Lake Superior North and South major watershed files and forms the boundaries of the North Shore.
- ns_subwatersheds.shp
    - Accessed online from the DNR Data Deli: “DNR Watersheds – DNR Level 07 – Minors”.
- ns_streams.shp
    - Accessed online from the DNR Data Deli: “Streams with Strahler Stream Order”..
- ns_trout_streams.shp
    - Accessed online from the DNR Data Deli: “Minnesota Trout Streams”.
- ns_lakes.shp
    - Accessed online from the DNR Data Deli: “DNR 24K Lakes”.
- ns_wetlands.shp
    - Accessed online from the DNR Data Deli: “DNR 100K Wetlands”.
- presettlement_veg.shp
    - Accessed online from the DNR Data Deli: “Presettlement Vegetation”.
- ns_nlcd_2006.img
    - Accessed online from the National Land Cover Database: “NLCD2006 Land Cover”.
- ns_soil_cummins_grigal.shp
    - Accessed online from the DNR Data Deli: “Soils and Land Surfaces in Minnesota (Cummins and Grigal)”.
- ns_bedrock.shp
    - Accessed online from MN Geo: “Bedrock Geology”.
- ns_geomorph.shp
    - Accessed online from the DNR Data Deli: “Geomorphology of Minnesota”.
- ns_roads.shp
    - Accessed online from the DNR Data Deli: “DOT Basemap Roads – All Types”.
- ns_quaternary.shp
    - Accessed online from MN Geo: “Quaternary Geology”.
- minnesota_boundary.shp
    - Accessed online from the DNR Data Deli: “Streams with Strahler Stream Order”.
- county_boundaries.shp
    - Accessed online from the DNR Data Deli: “Minnesota County Boundaries”.
- ns_DEM.tiff

    - 30m DEM of the North Shore. Accessed online from MN Geo “Digital Elevation Model (DEM) of Minnesota: statewide, 1:24:000, Level 2, raster”.
- statsgo.shp
    - Soil data accessed online from the Natural Resources Conservation Service (NRCS).

GEODATABASE: NS_WATERSHEDS.gdb

- This Geodatabase file contains shapefiles of North Shore watersheds. These watershed files are comprised of the DNR Minor 07 watersheds delineated by the DNR.

GEODATABASE: UMN_CHANNEL_SURVEYS.gdb

- surveyed_channels_33.shp
    - Georeferenced sites with channel survey information (field data, remote measurements, pfankuch and behi scores/ratings.

GEODATABASE: STREAMS_DATA.gdb

- F_IBI.shp
    - FISH IBI data obtained from MPCA.
- M-IBI.shp
    - MACROINVERTEBRATE IBI Data obtained from MPCA.
- ns_streamflow_stations.shp
    - Streamflow station information and flow data
- all_wq_monitoring_stations.shp
    - Includes all available water quality data. Turbidity, TSS and Transparency data can be easily selected from this large dataset.

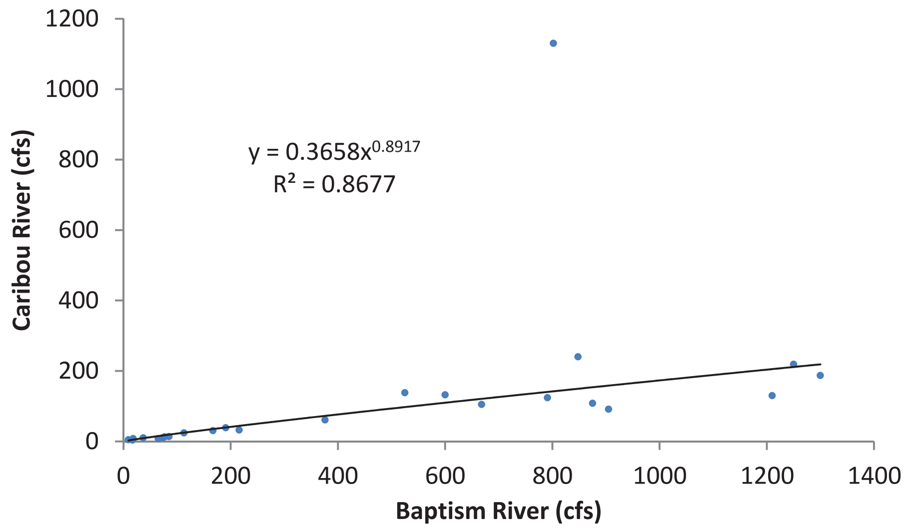
GEODATABASE: SUMREL.gdb

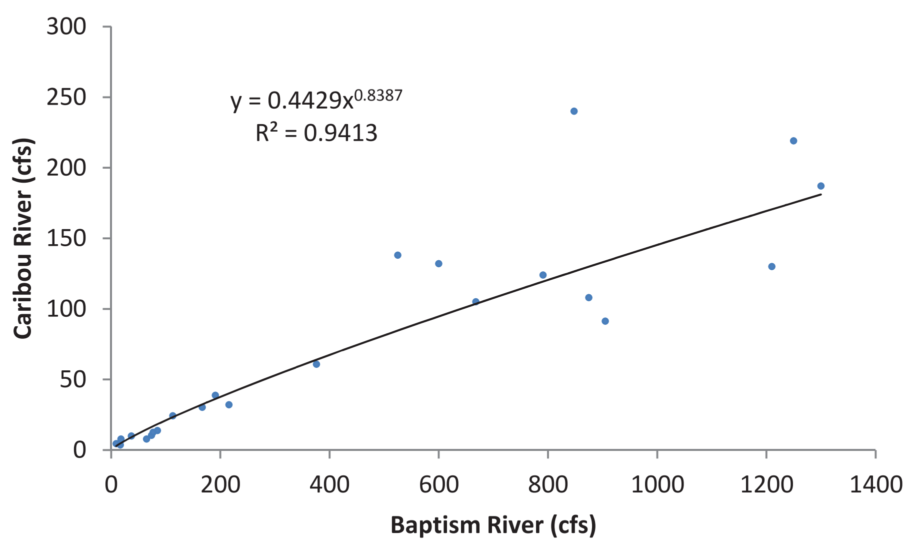
- clipped_streams_knife.shp
    - Knife River Streams.
- knife_dis.shp
    - Knife River Watershed
- knife_SUMREL.shp
    - Clipped watershed used to evaluate SUMREL score relationships to in-channel erosion.
- ns_sumrels_wshds.shp
    - File containing watersheds delineated by the NRRI and corresponding SUMREL anthropogenic stressor scores.

- subwatershed_sumrel.shp
    - File containing sub-watersheds delineated by the NRRI and SUMREL anthropogenic stressor scores.
- surveyed_channels_33.shp

Appendix E

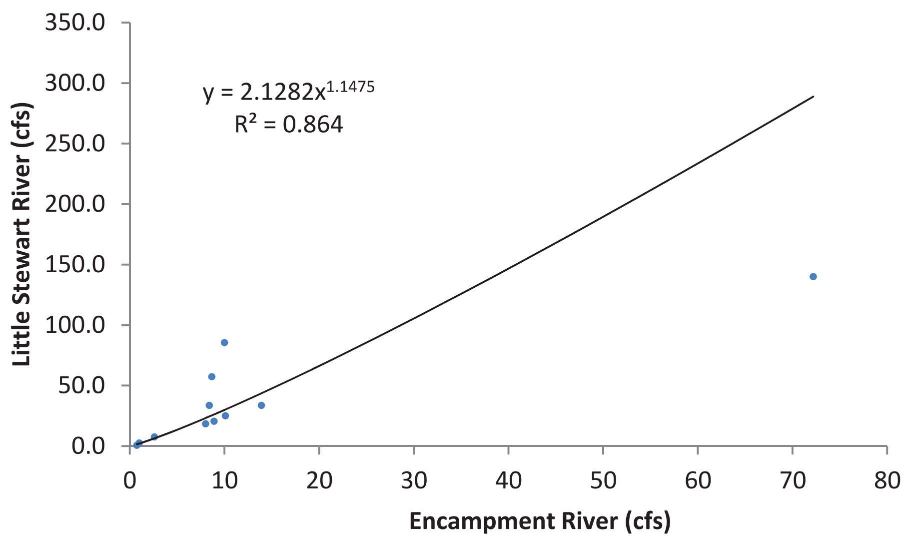
Mean daily discharge relationships

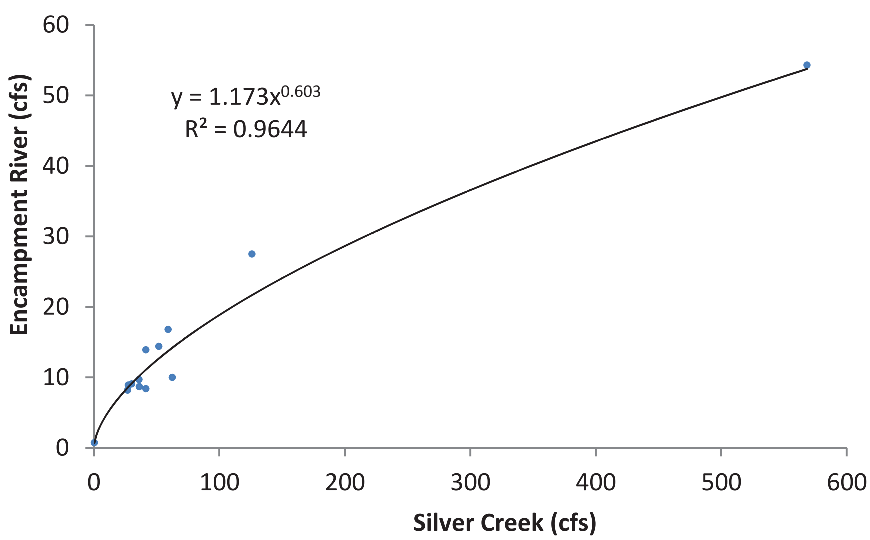




Regression relationship between stream gaging stations 04013200 on the Caribou River and 04014500 on the Baptism River. The top graph displays all available data. The bottom graph displays all data with the exception of the outlier point.

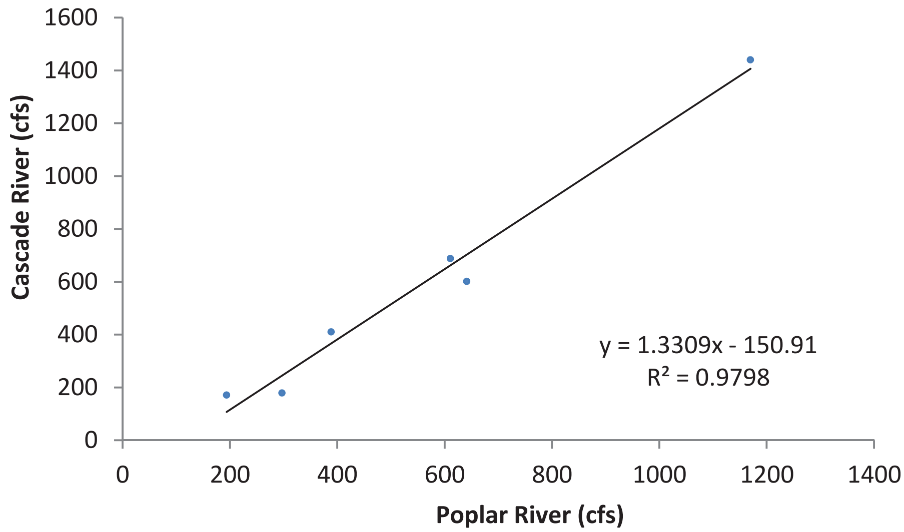
Mean daily discharge relationships



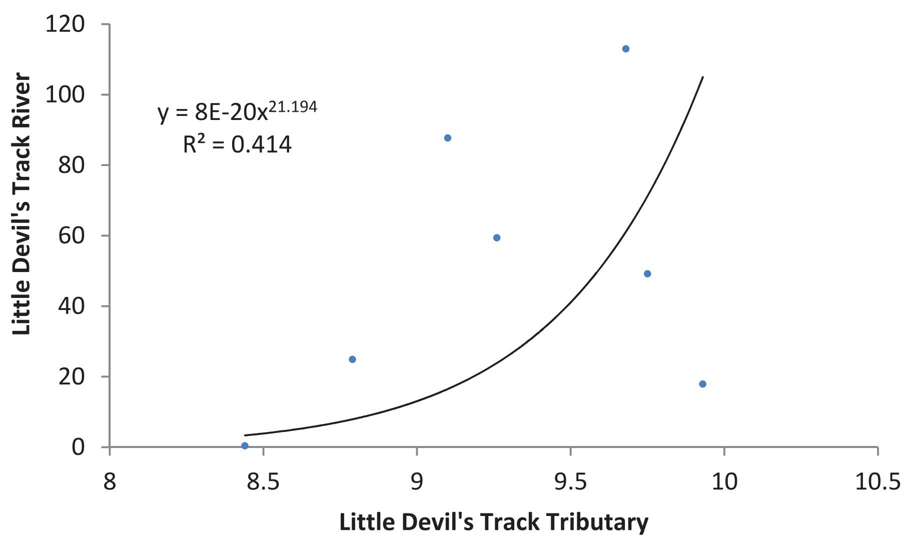


Regression relationship between the Encampment River stream gaging station (04015200) and both the Little Stewart River (04015300) and Silver Creek (04015250) gaging stations.

Mean daily discharge relationships

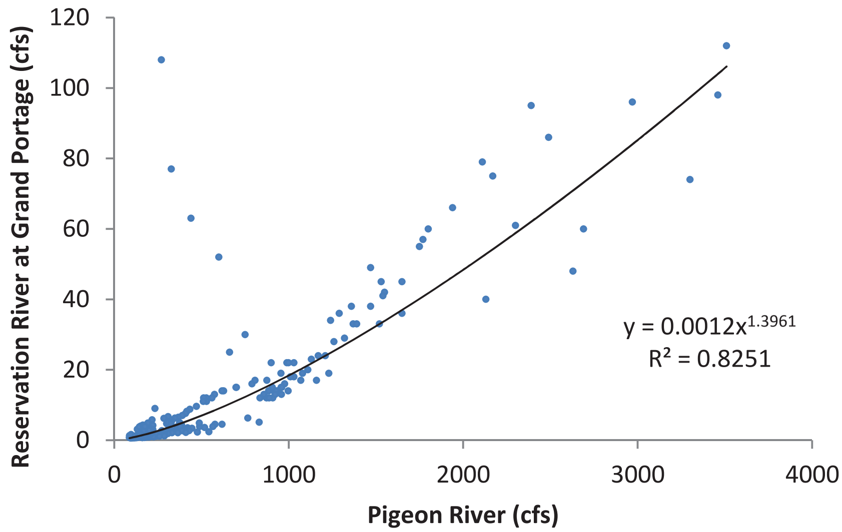


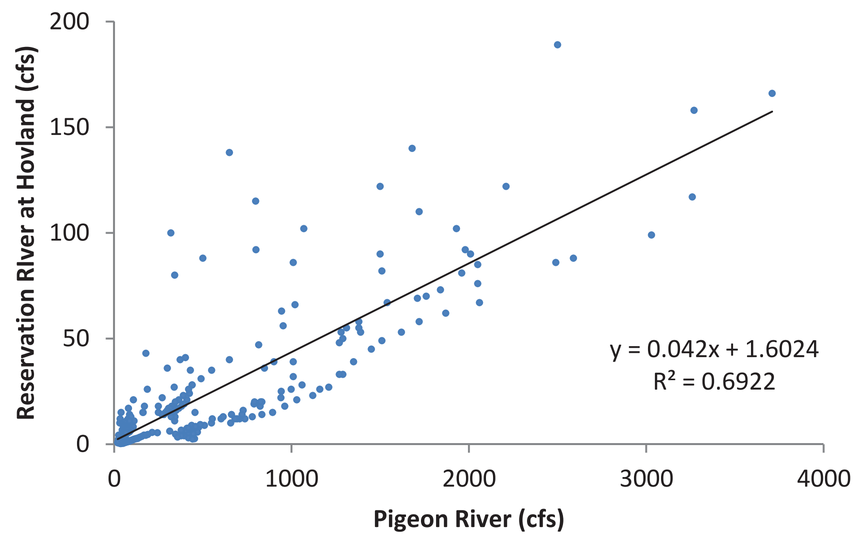
Regression relationship between the Poplar River (station 04012500) and Cascade River (station 04011990).



Regression relationship between the two gaging stations on the Little Devil’s Track River (mainstem station 04011370 and tributary station 04011390).

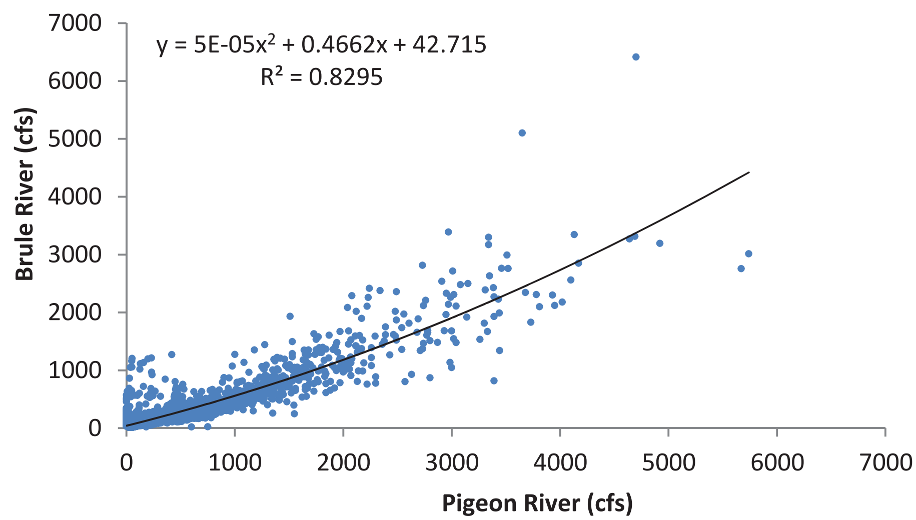
Mean daily discharge relationships



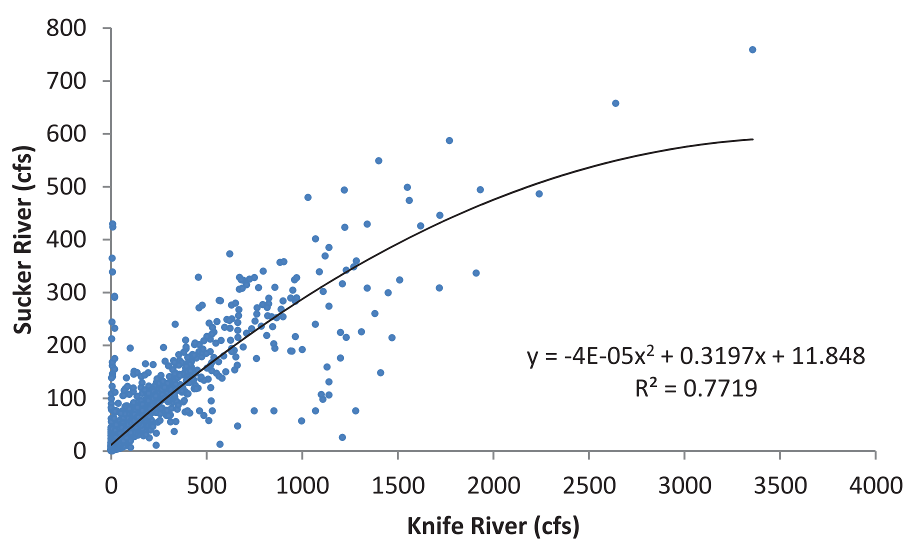


Regression relationship between the Pigeon River (station 04010500) and each of the gaging stations on the Reservation River (station 04010528 near Grand Portage and station 04010530 near Hovland).

Mean daily discharge relationships

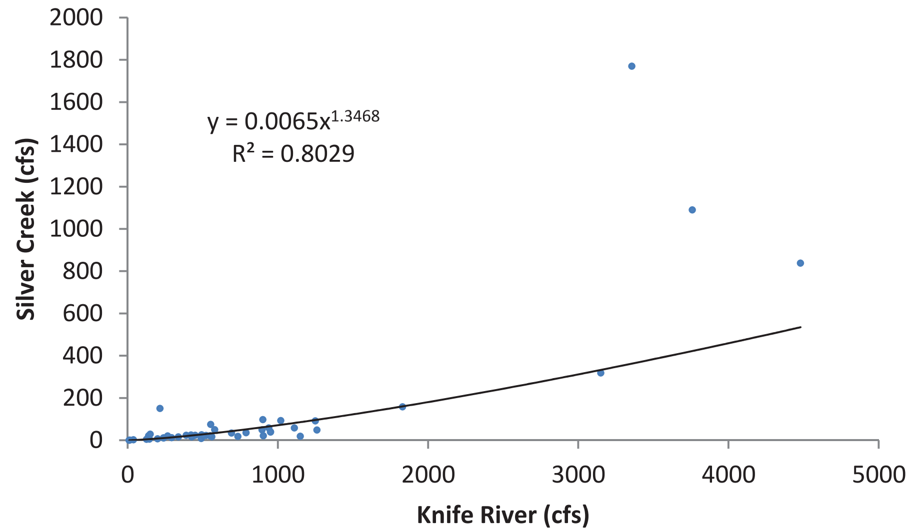


Regression relationship between the Pigeon River (station 04010500) and the Brule River (station 04011000).

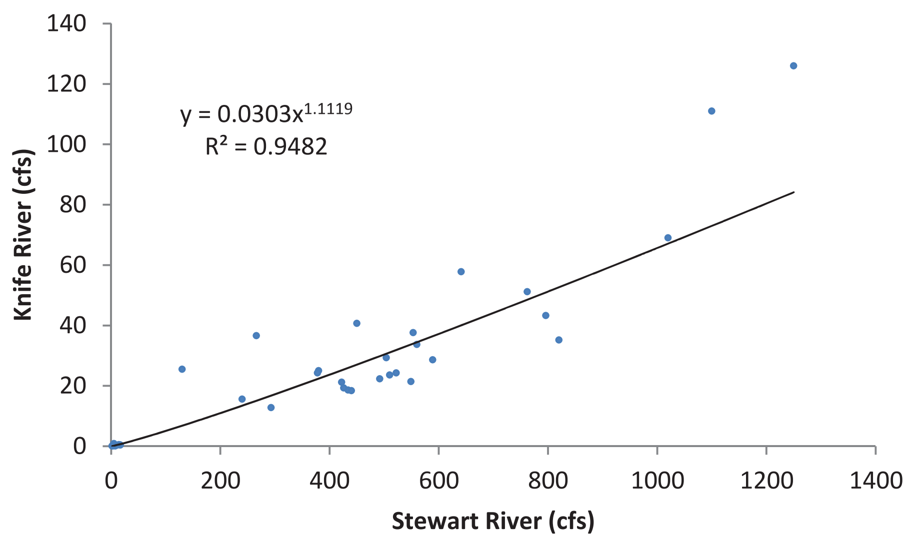


Regression relationship between the Sucker River (station 04015339) and the Knife River (station 04015330).

Mean daily discharge relationships

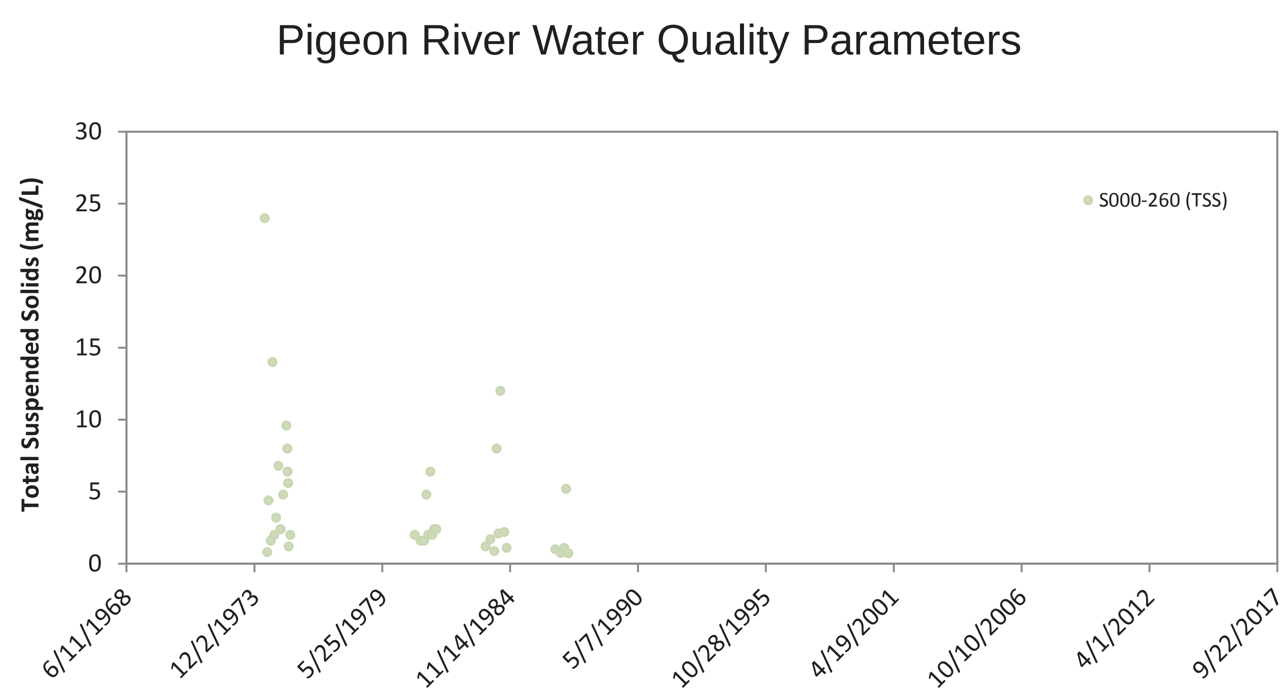


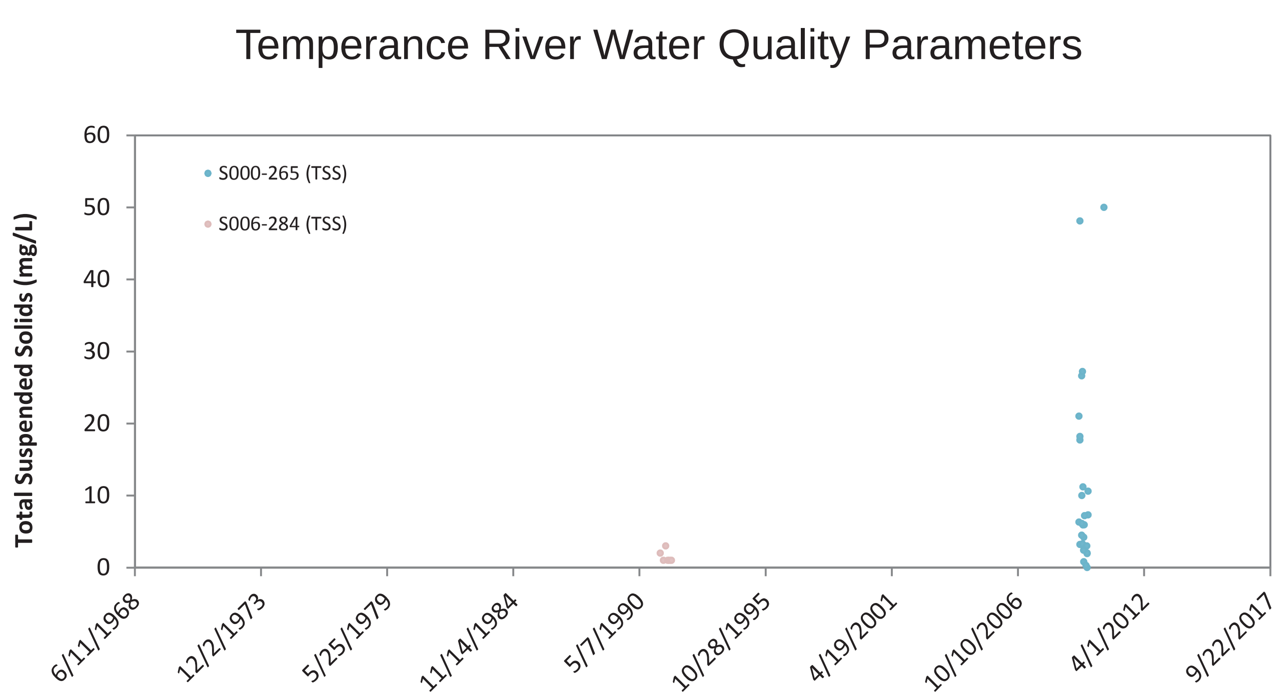
Regression relationship between the Silver Creek (station 04015250) and the Knife River (station 04015330).



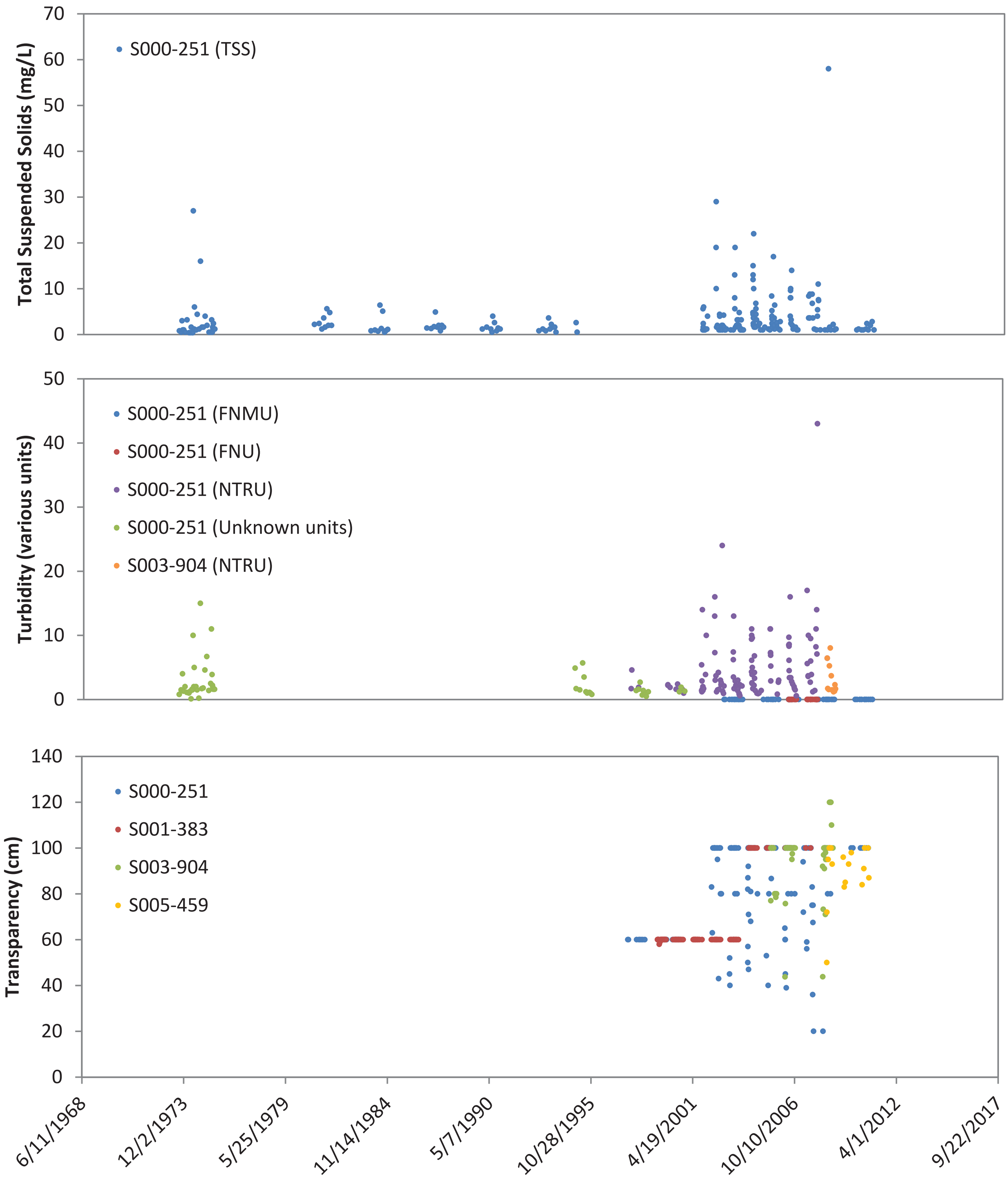
Regression relationship between the Knife River (station 04015330) and the Little Stewart River (station 04015300).

Appendix F

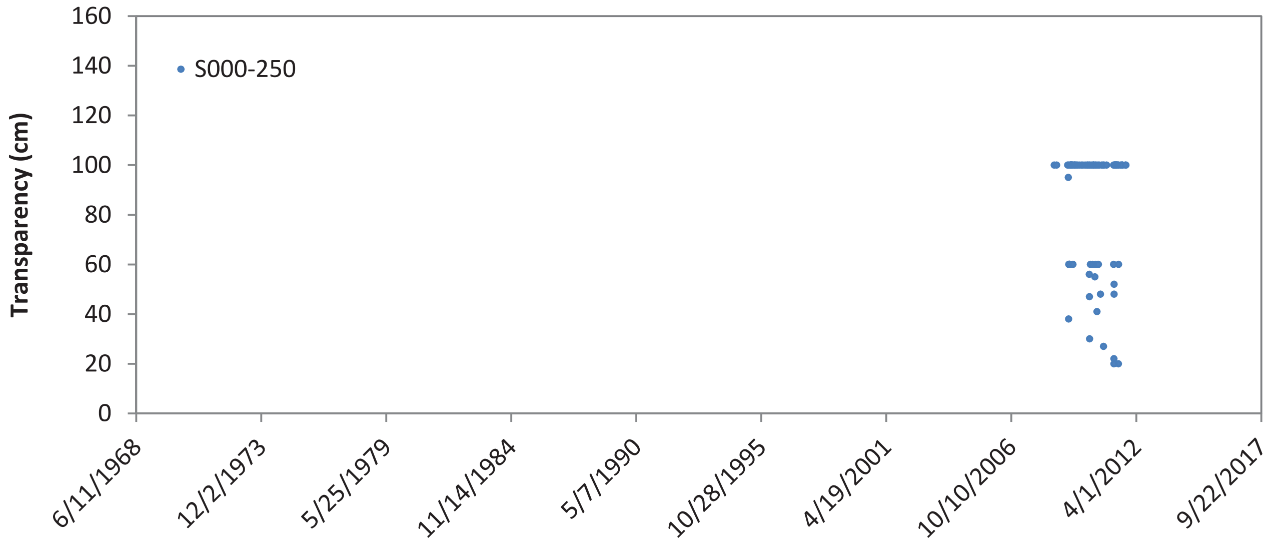

Pigeon River Water Quality Parameters
Total Suspended Solids (mg/L)
0
5
10
15
20
25
30
S000-260 (TSS)
6/11/1968
12/2/1973
5/25/1979
11/14/1984
5/7/1990
10/28/1995
4/19/2001
10/10/2006
4/1/2012
9/22/2017

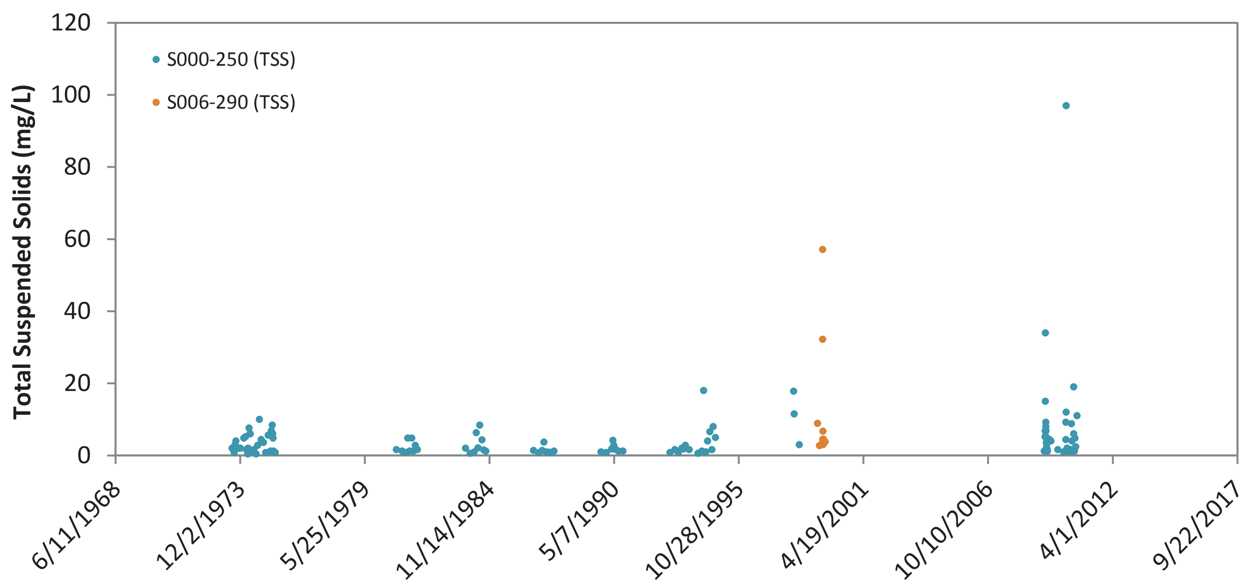

Temperance River Water Quality Parameters
Total Suspended Solids (mg/L)
0
10
20
30
40
50
60
S000-265 (TSS)
S006-284 (TSS)
6/11/1968
12/2/1973
5/25/1979
11/14/1984
5/7/1990
10/28/1995
4/19/2001
10/10/2006
4/1/2012
9/22/2017

Brule River Water Quality Parameters

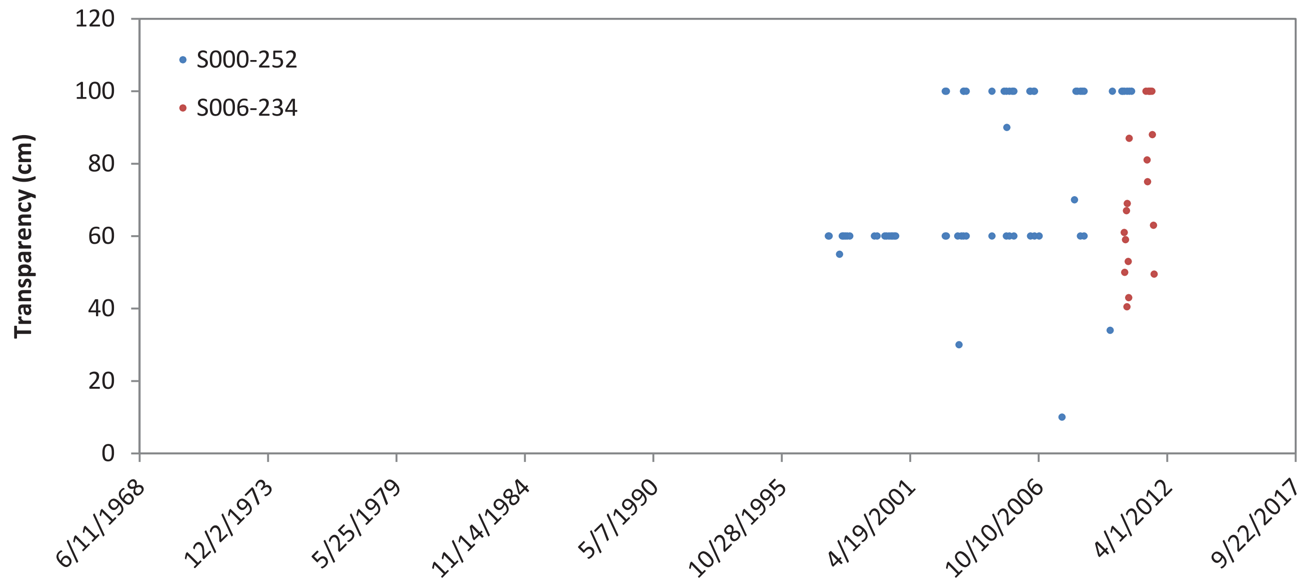


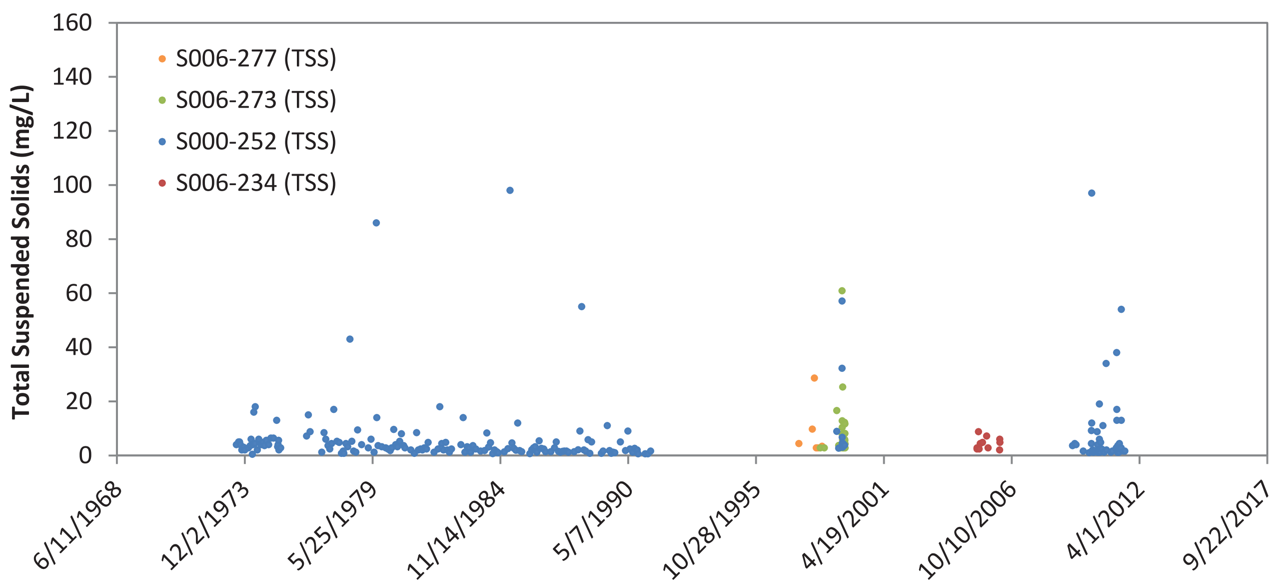
Baptism River Water Quality Parameters



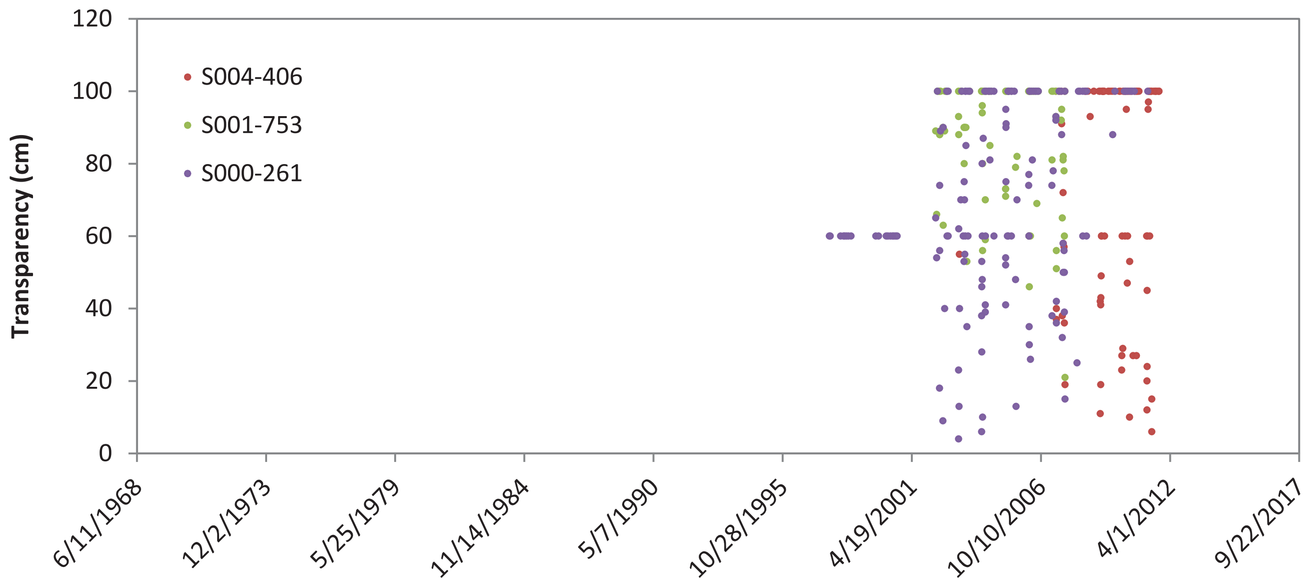


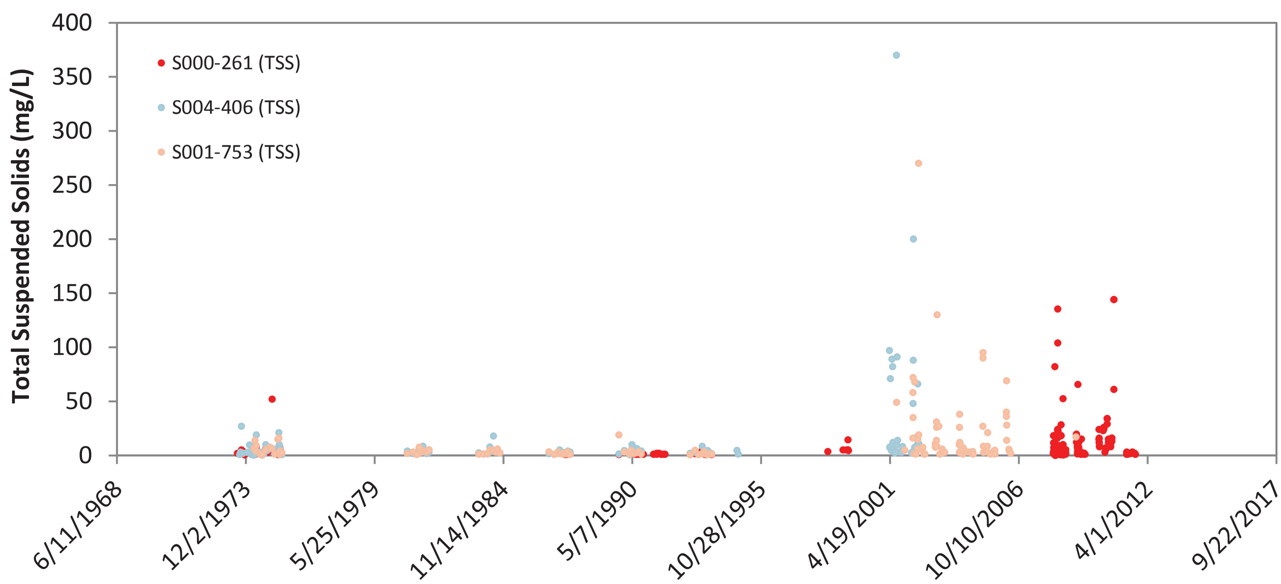
Beaver River Water Quality Parameters



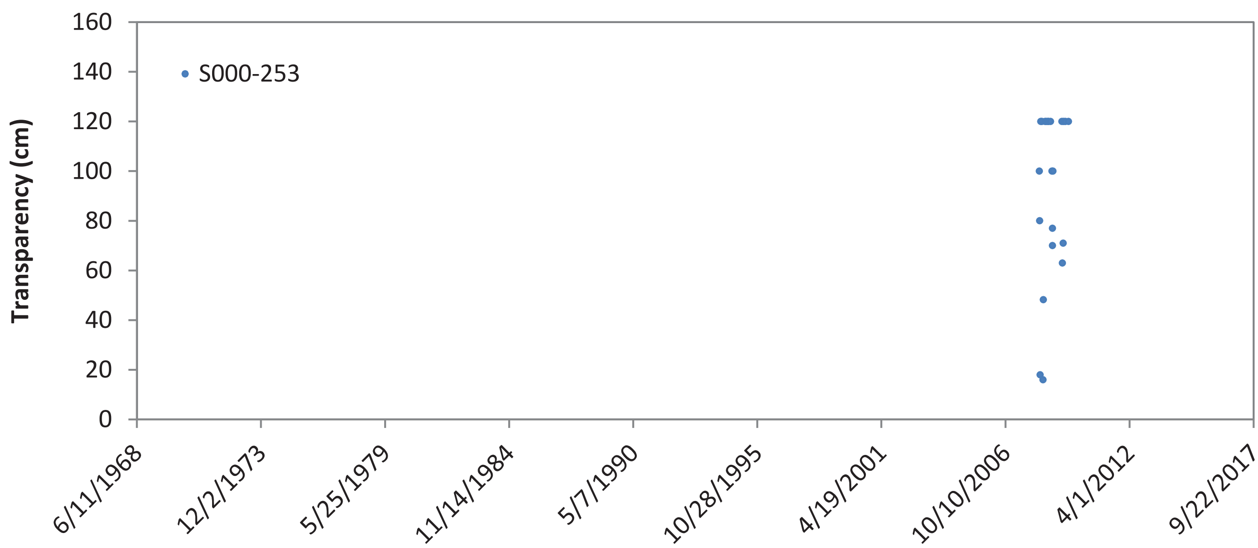


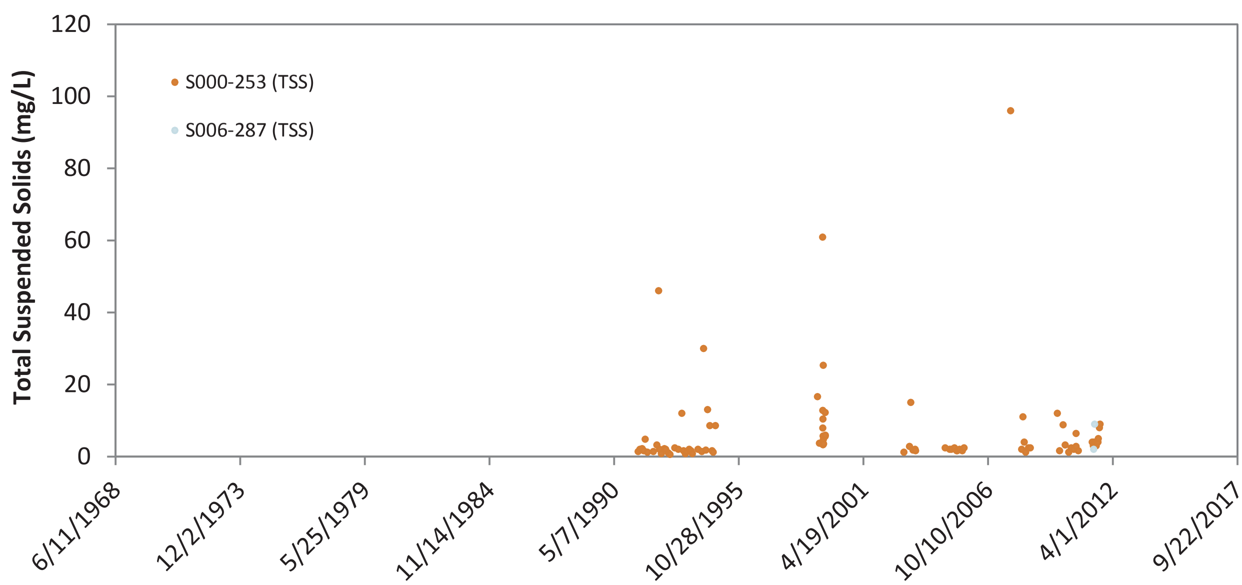
Poplar River Water Quality Parameters



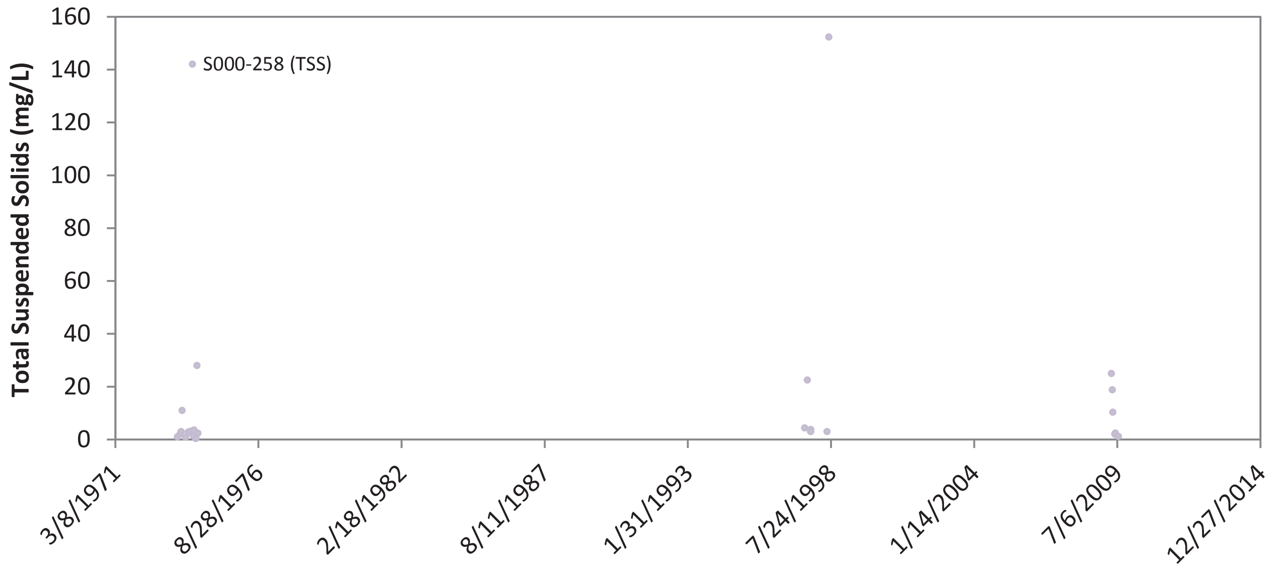


Cascade River Water Quality Parameters

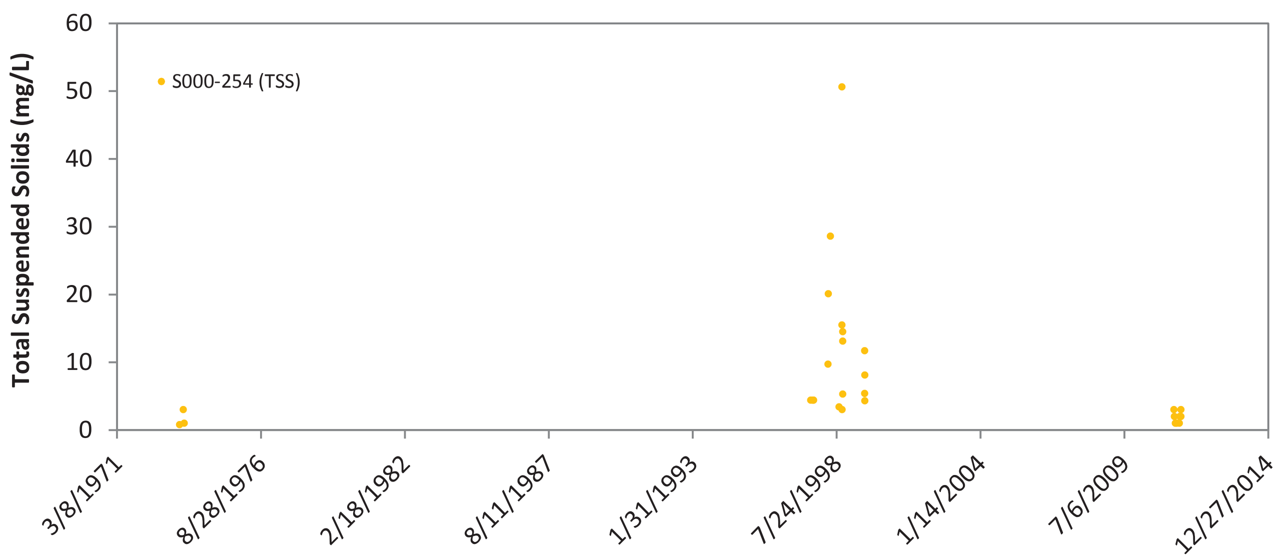




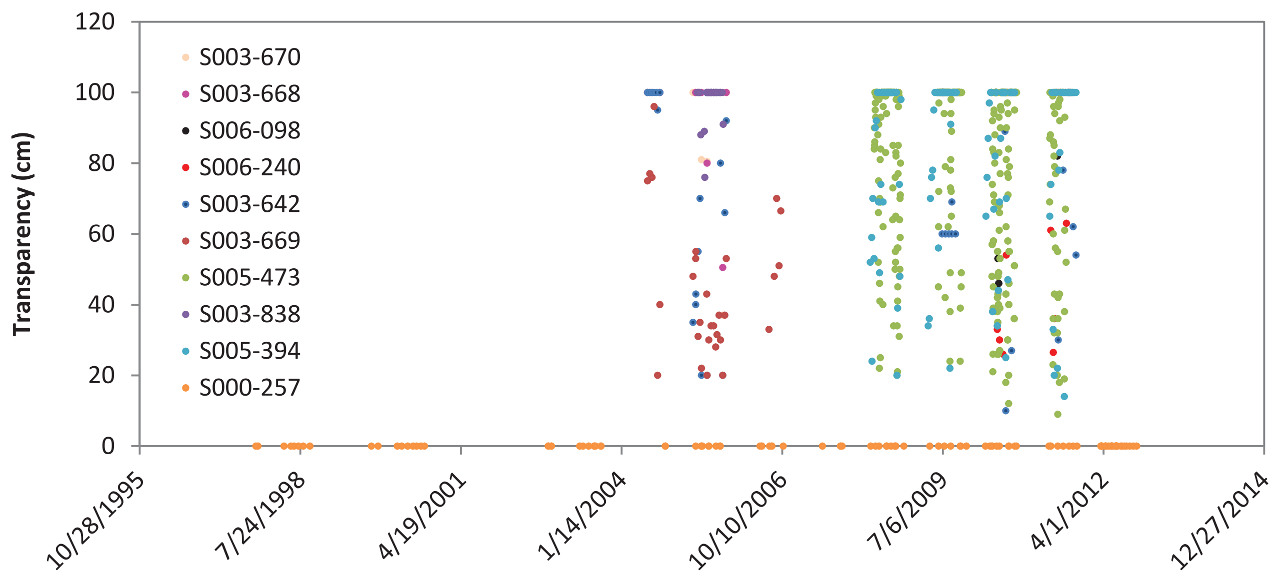
Manitou River Water Quality Parameters

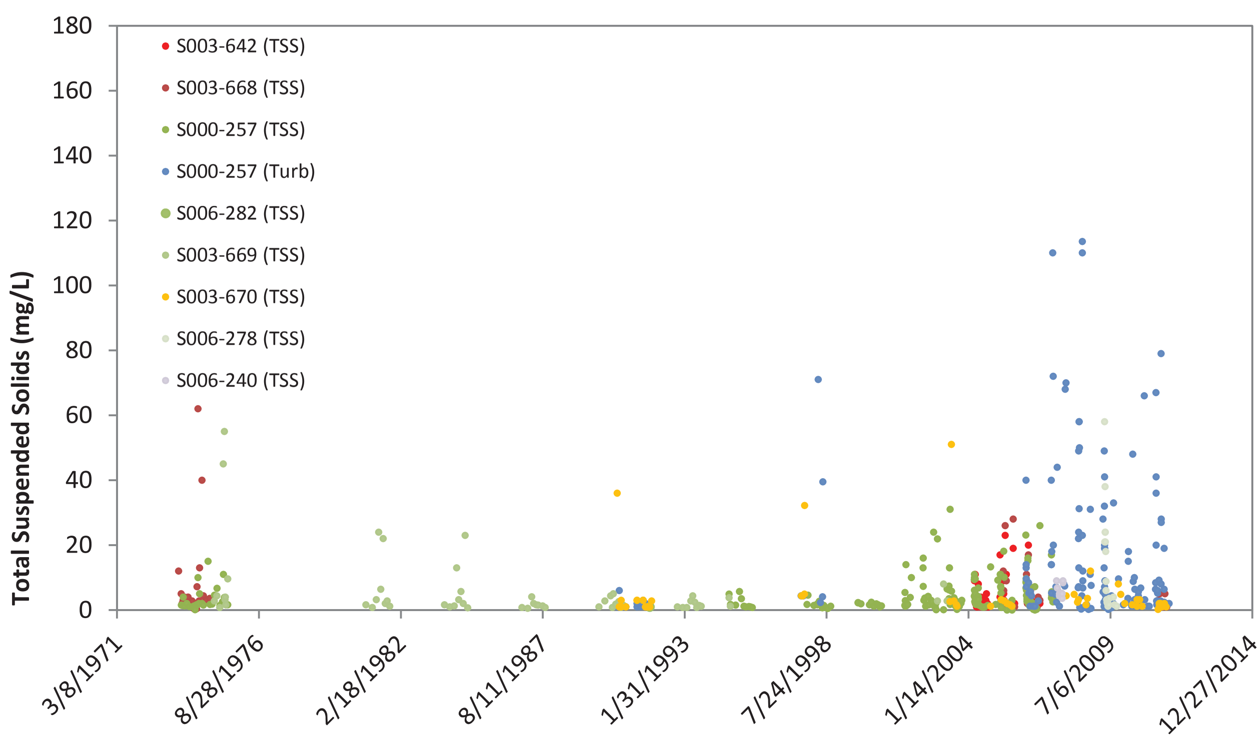


Cross River Water Quality Parameters

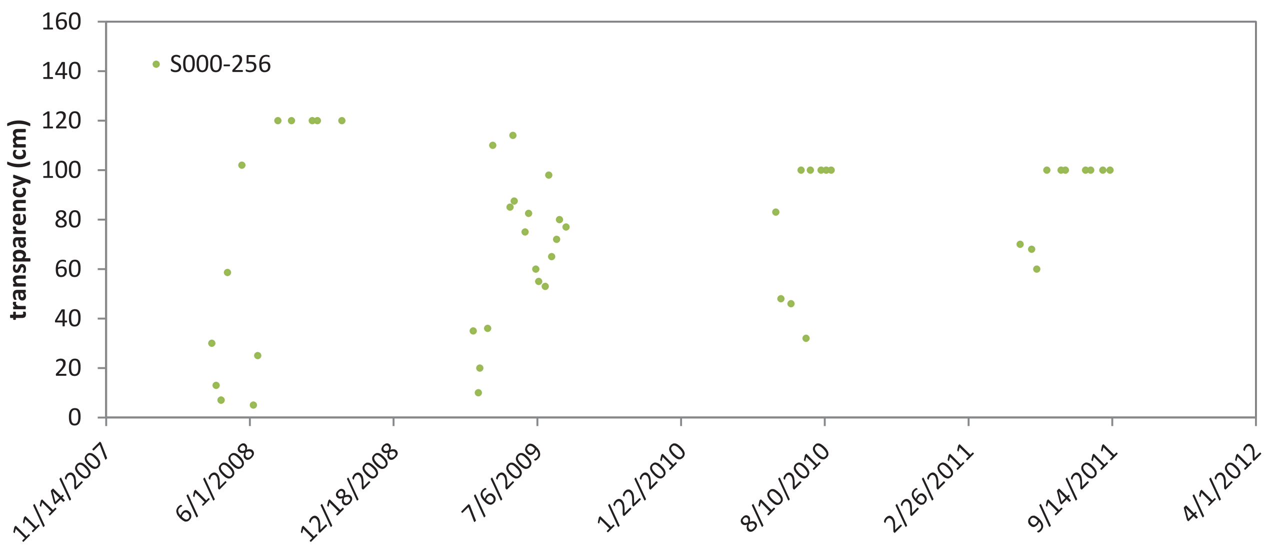


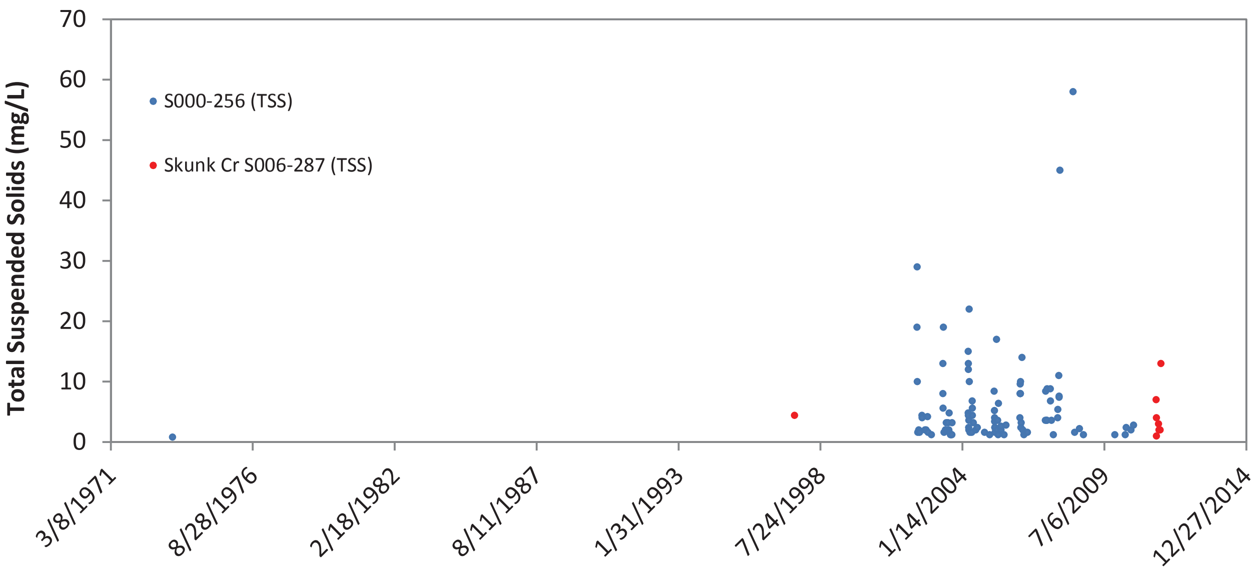
Knife River Water Quality Parameters



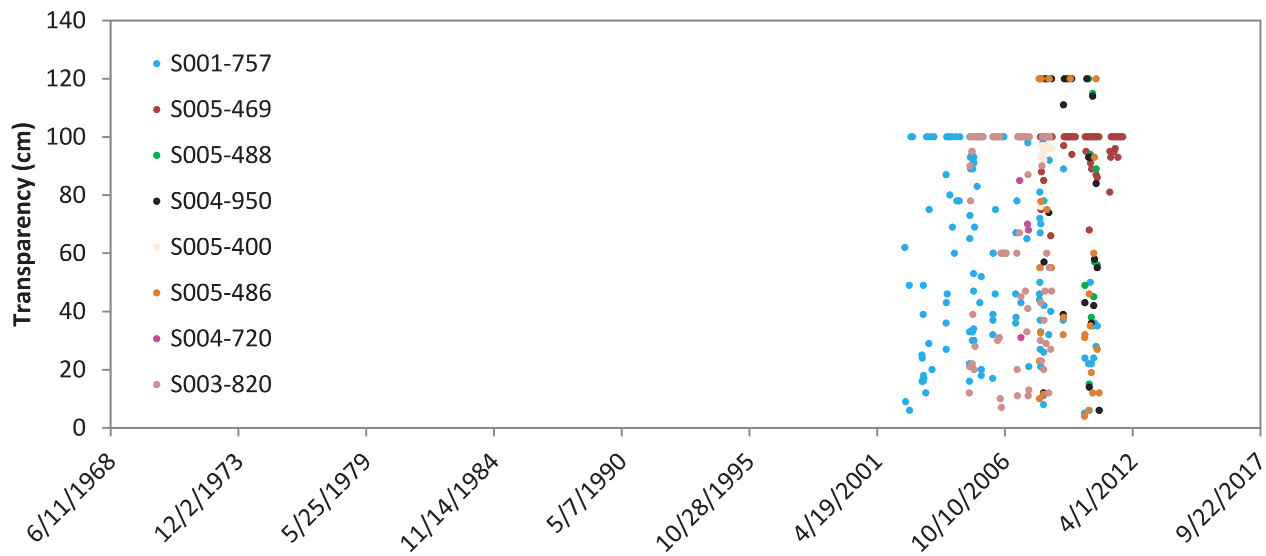


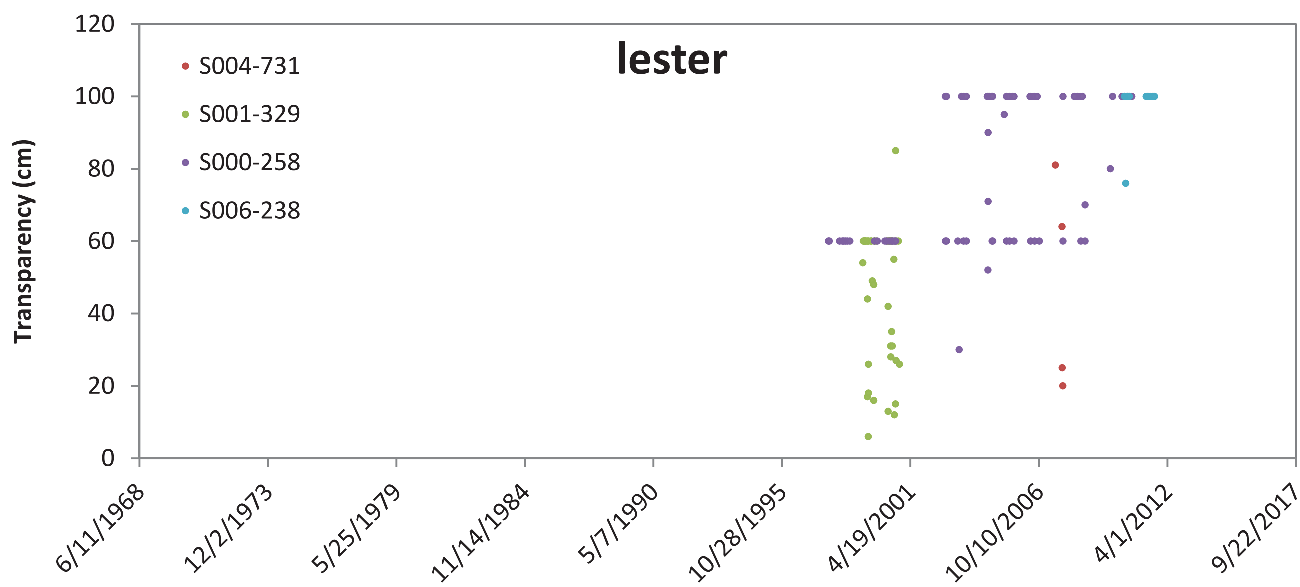
Gooseberry River Water Quality Parameters

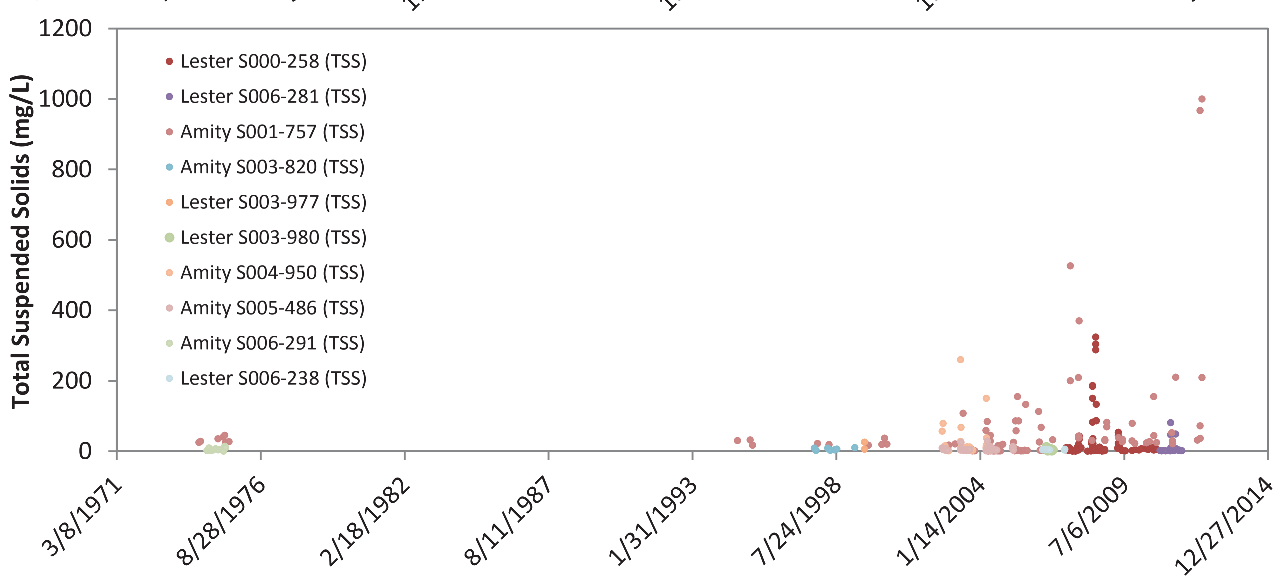




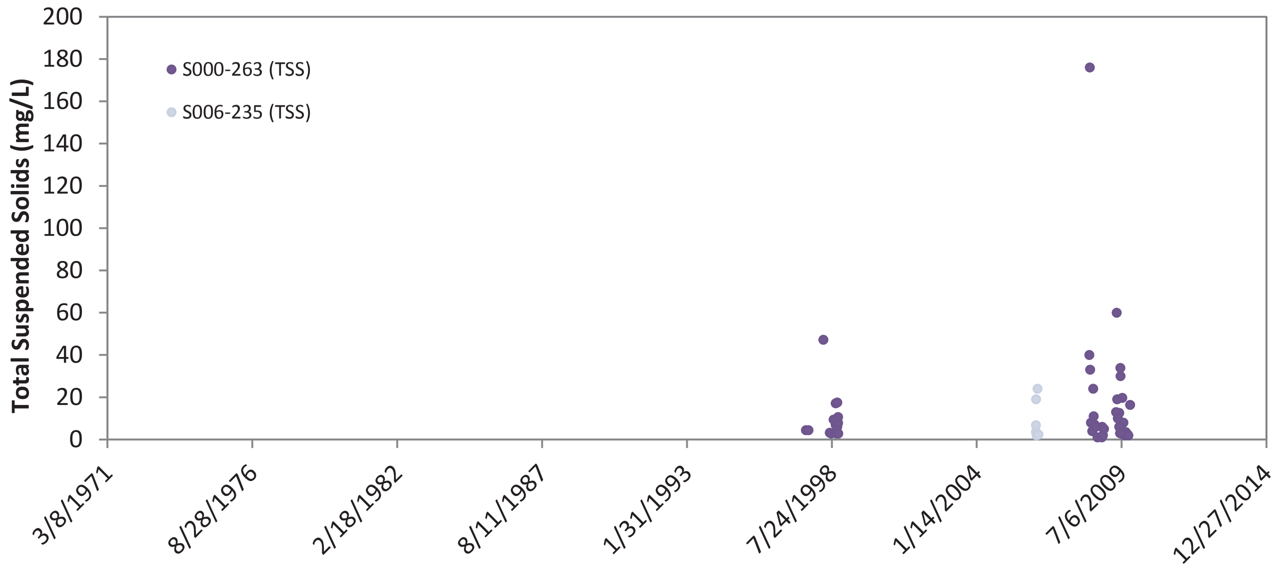
Lester & Amity River Water Quality Parameters



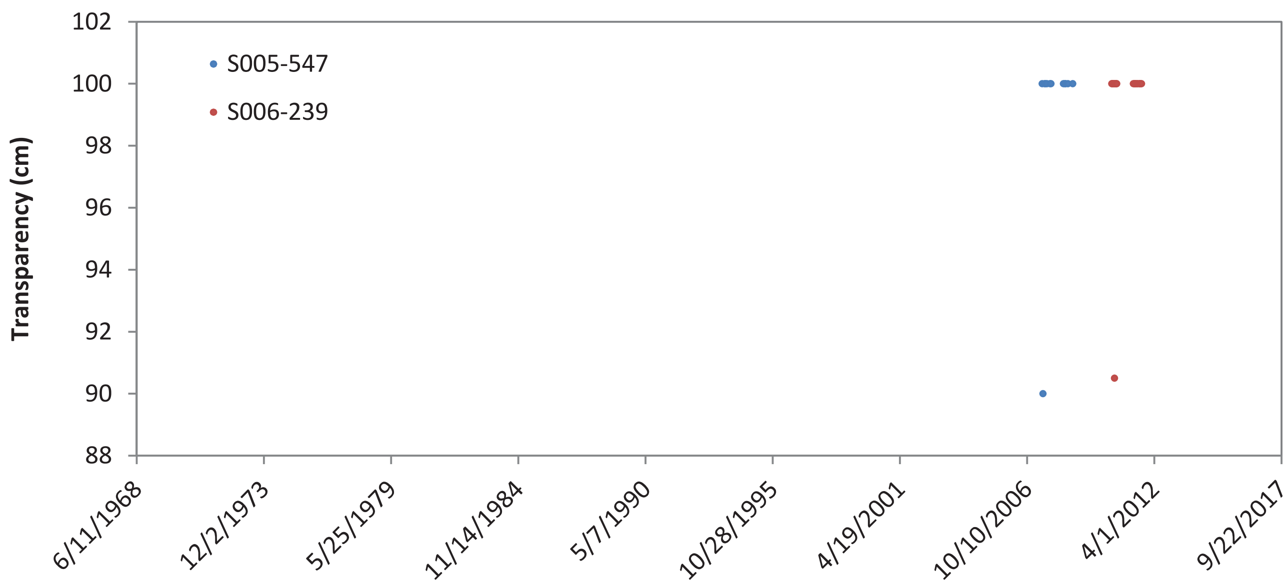


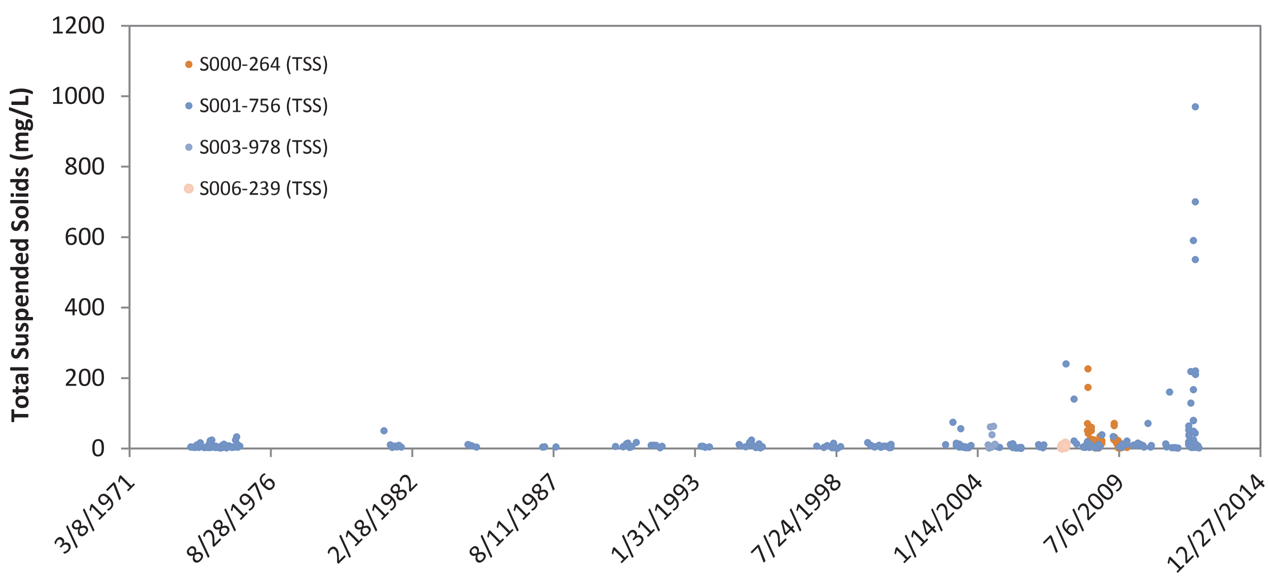


Split Rock River Water Quality Parameters

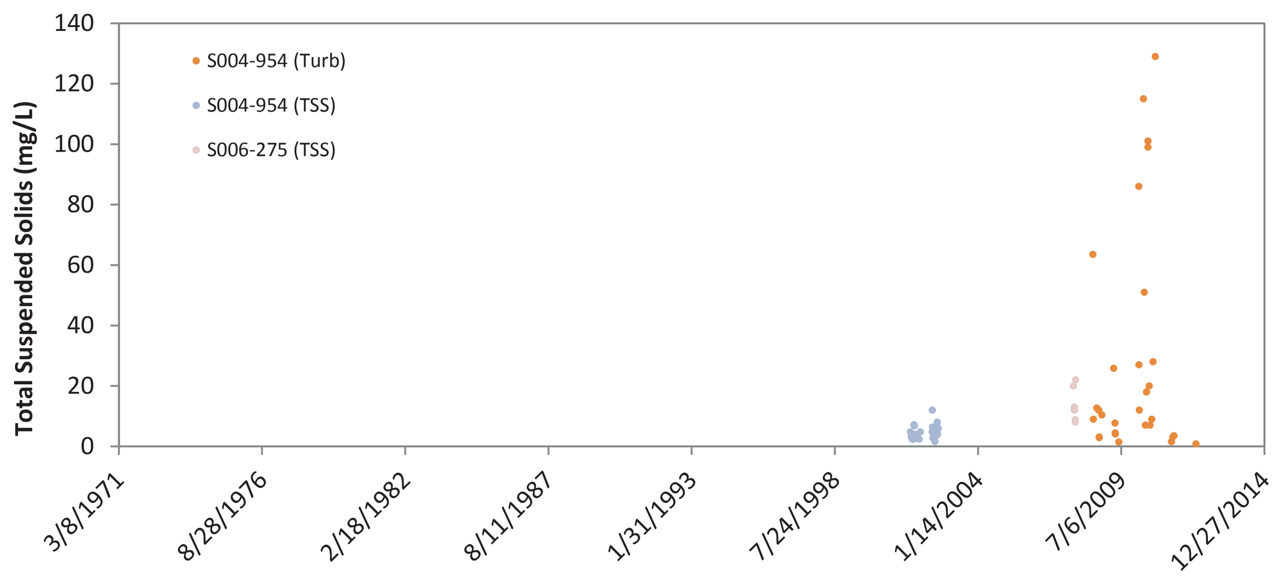


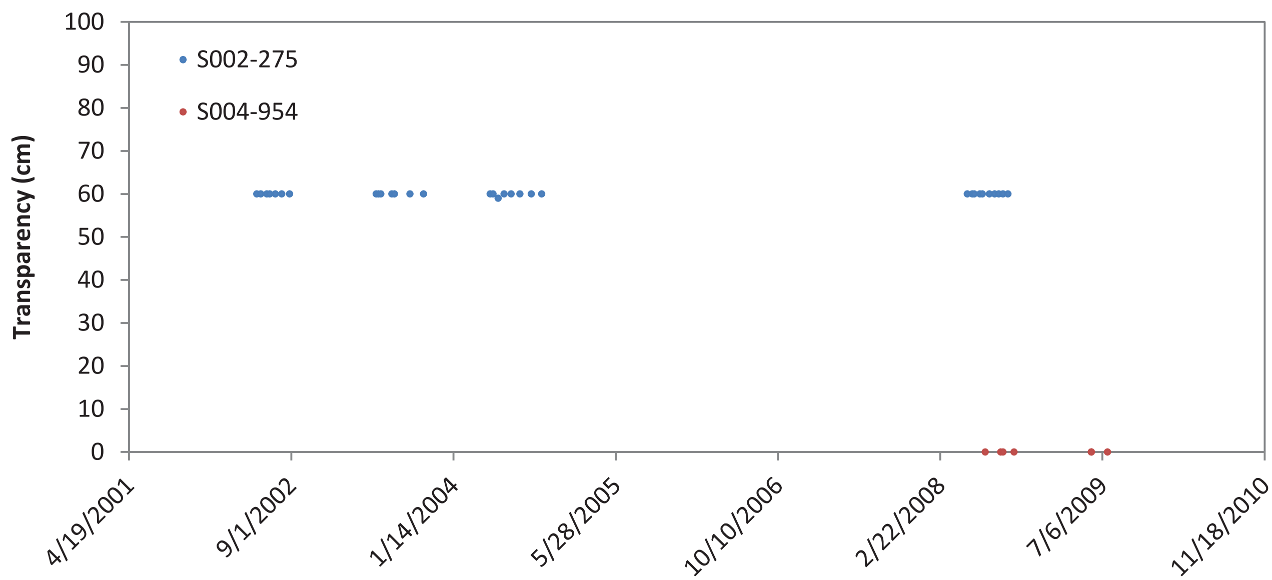
Sucker River Water Quality Parameters



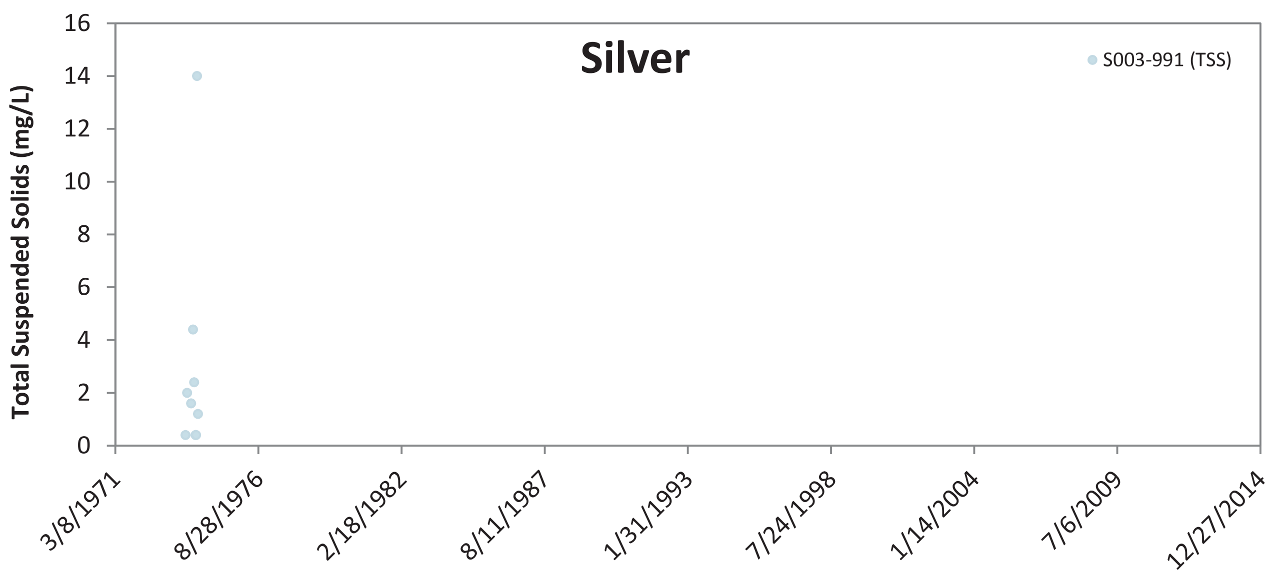


Caribou River Water Quality Parameters

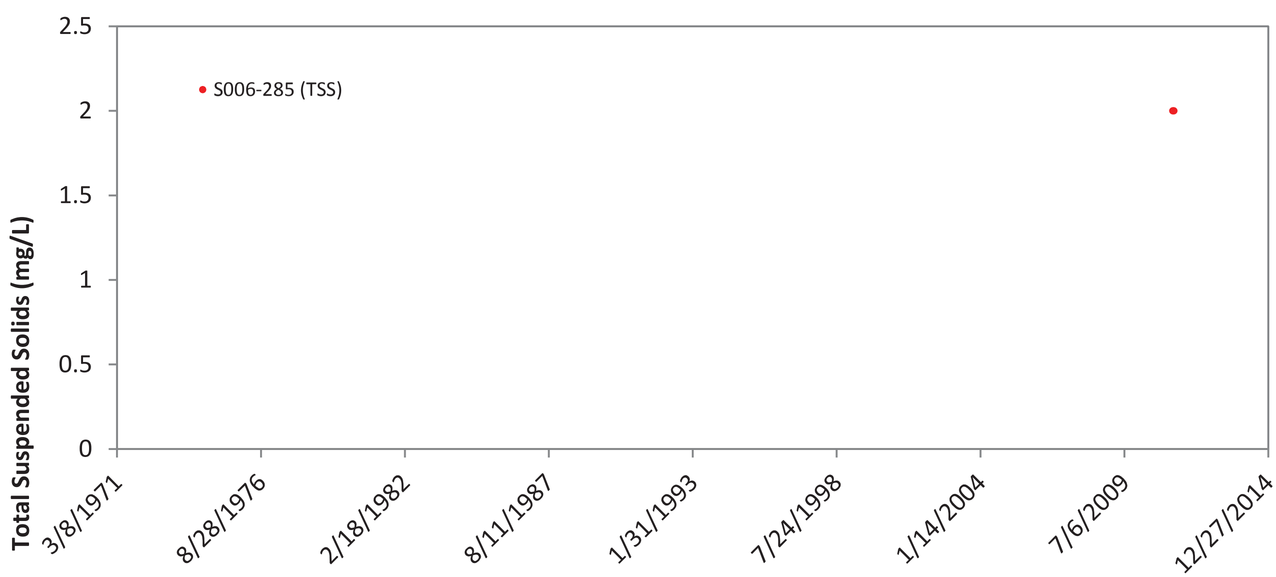




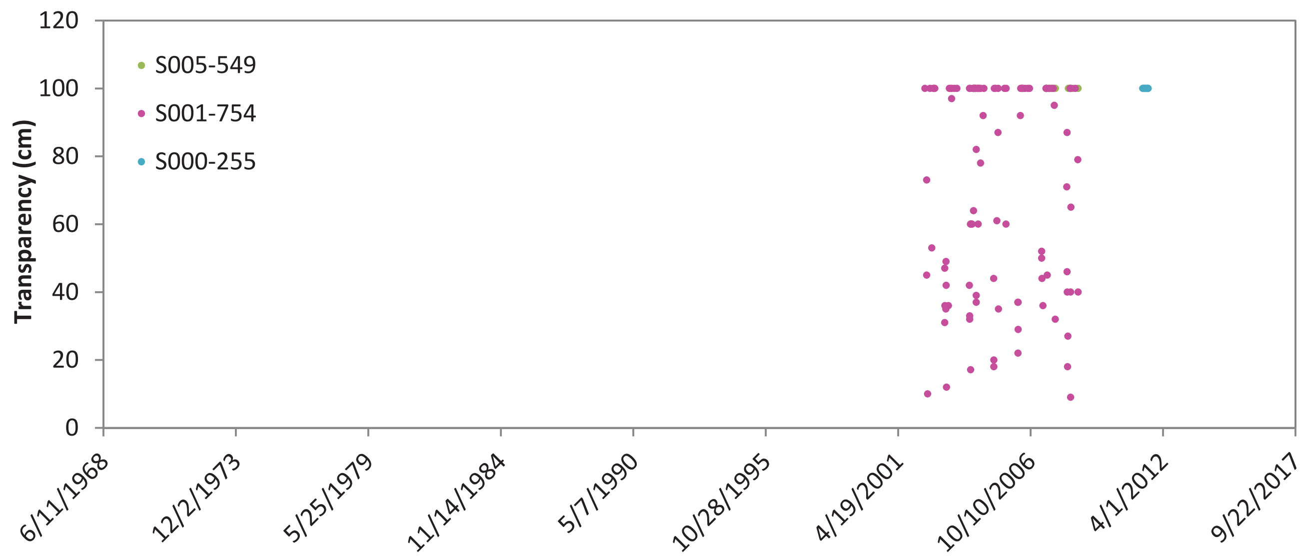
Silver River Water Quality Parameters

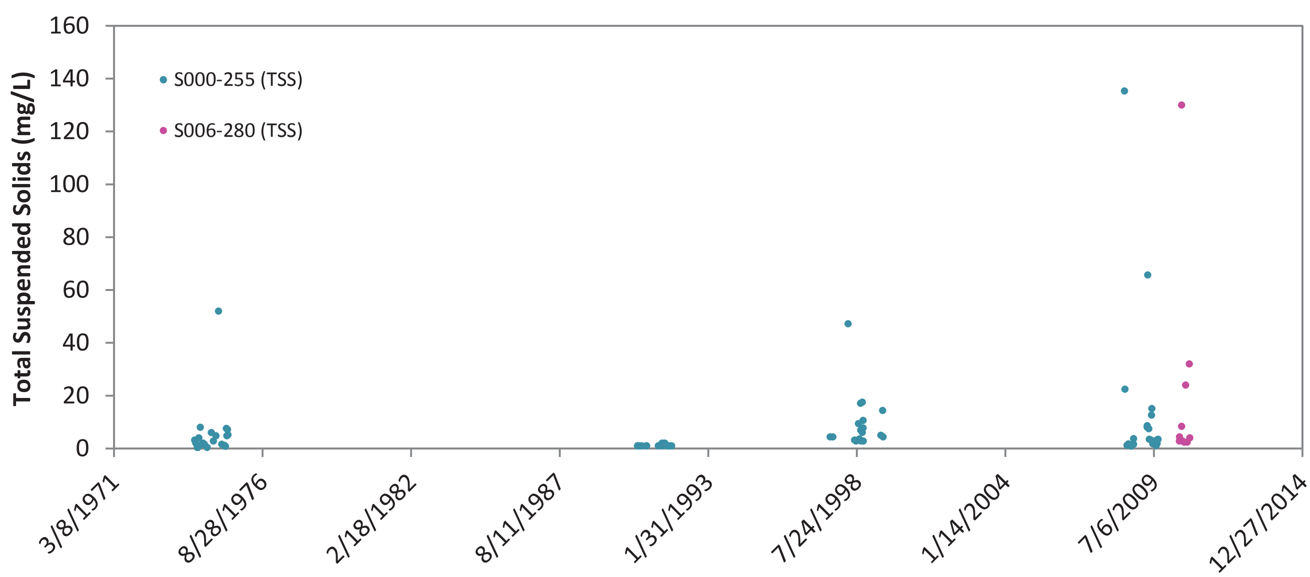


Two Island River Water Quality Parameters

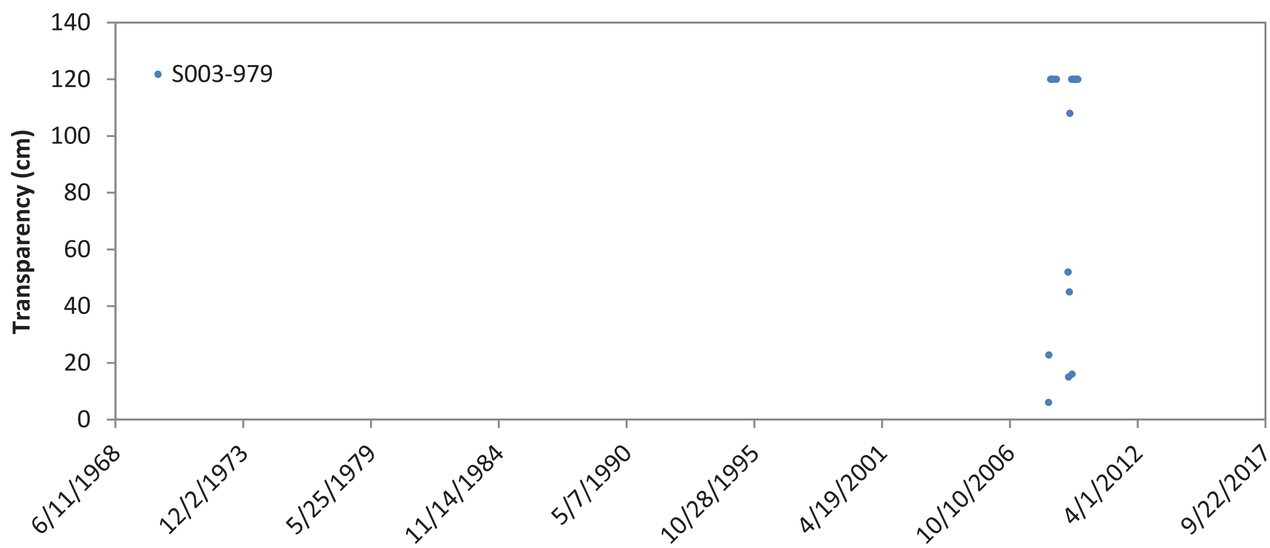


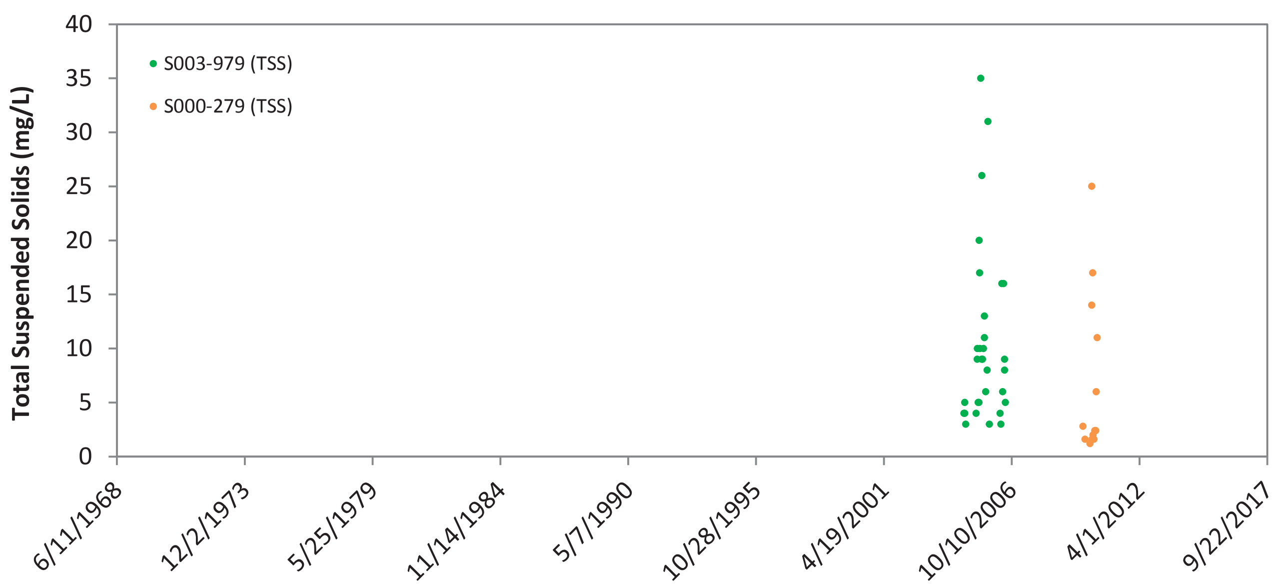
French River Water Quality Parameters



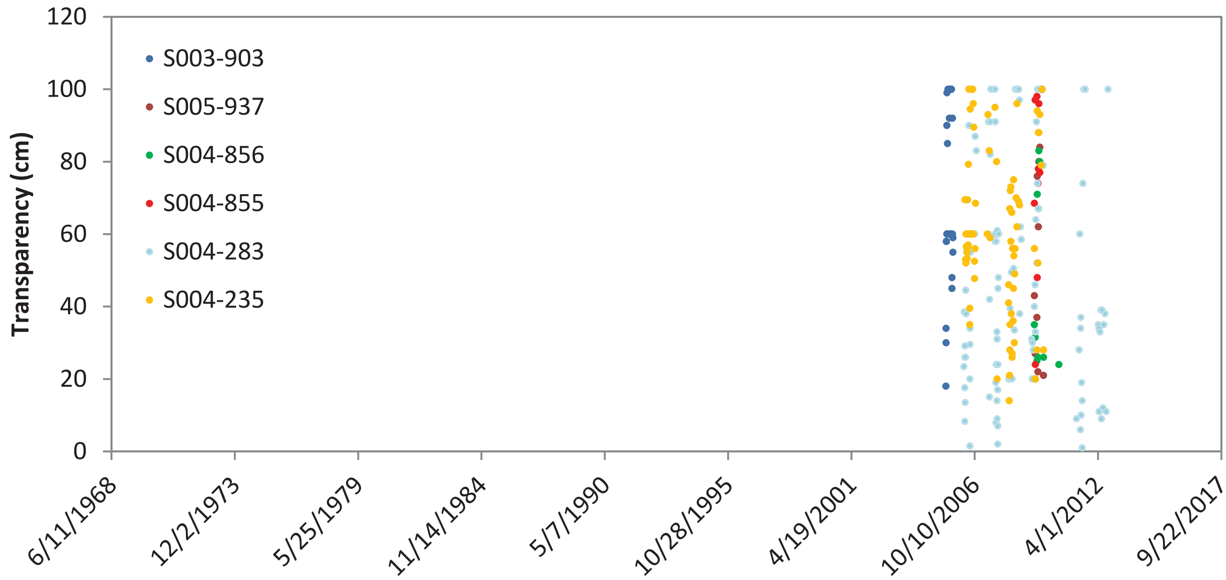


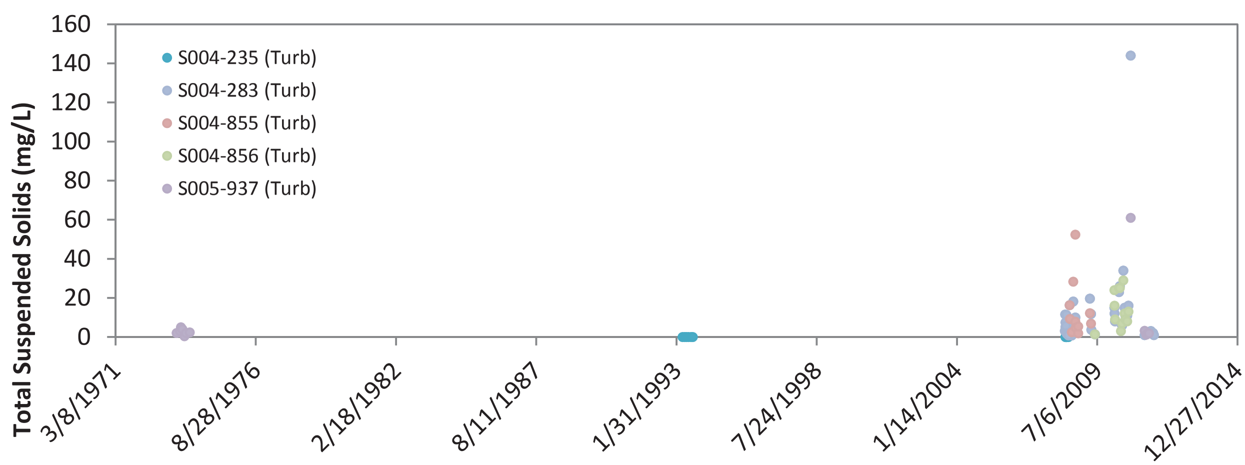
Encampment River Water Quality Parameters

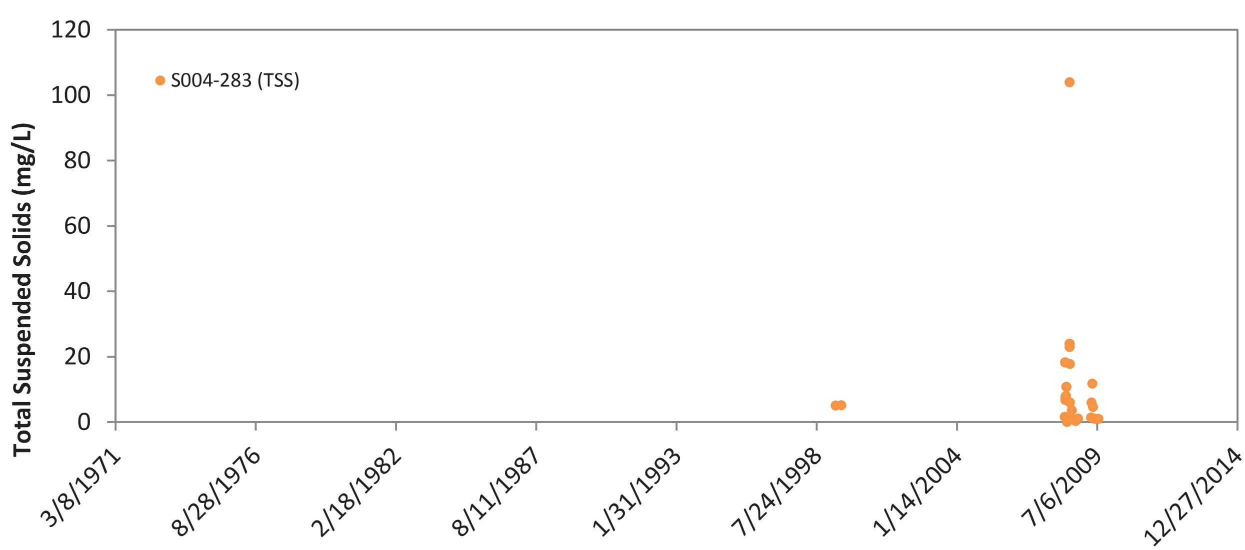




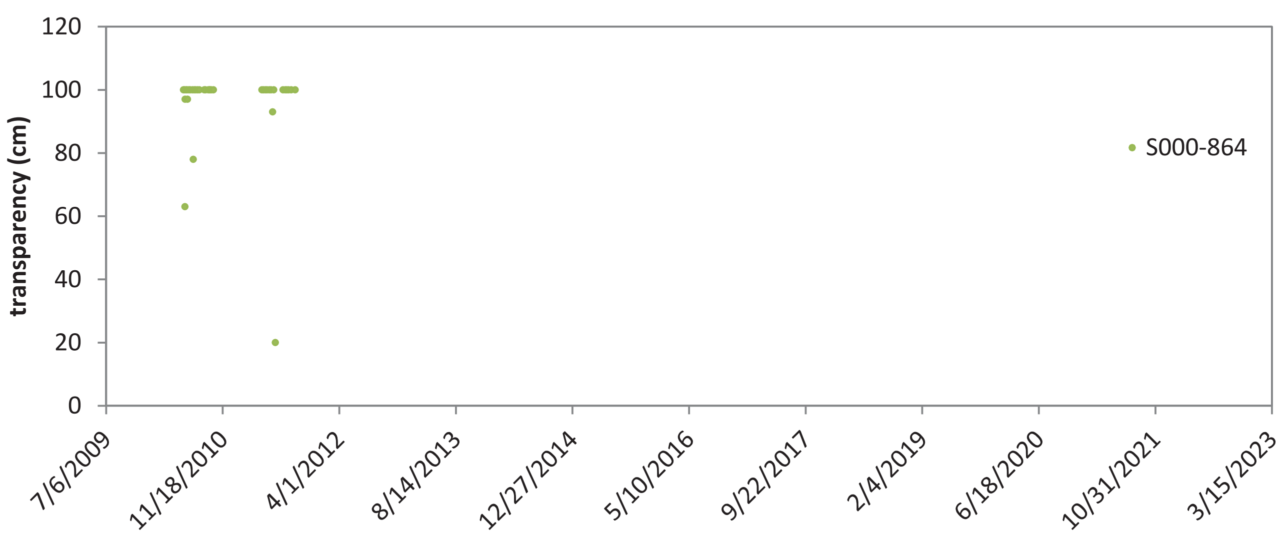
Flute Reed River Water Quality Parameters



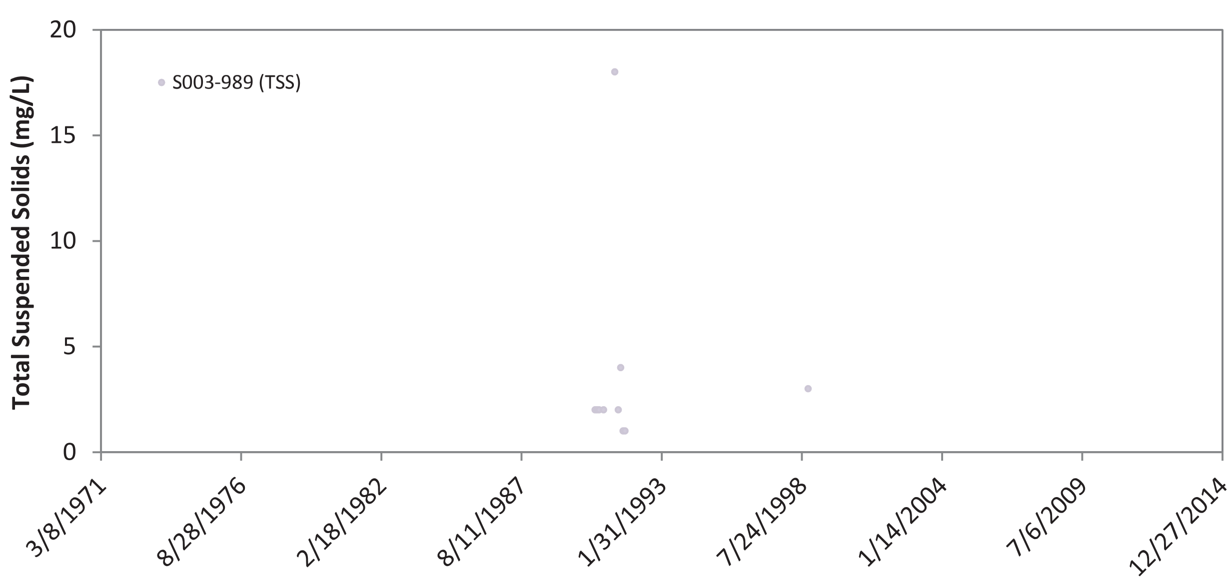




Kandunce River Water Quality Parameters



Stewart River Water Quality Parameters



Appendix G

PRIORITIZED MONITORING FOR THE LAKE SUPERIOR BASIN
(Grant number: GL00E28801-0)

FINAL REPORT

January 2010

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ABSTRACT

This project quantifies the gradient of environmental stressors within the Lake Superior basin at a fine spatial resolution, and uses this gradient to develop a monitoring framework that will support individual agency and ongoing binational cooperative monitoring efforts across the basin. Key elements of the project include development of high-resolution watersheds throughout the basin, summarization of the major point and non-point stressors within these watersheds, and creation of tools for scaling the watersheds and stressor summaries. These data and tools allow identification of reference and degraded sites, and promote development of statistically defensible monitoring designs that will work within and across agency monitoring efforts.

BACKGROUND

Lake Superior, headwaters to the largest freshwater system in the world, faces increasing risk from human activities coupled with global climatic change. Human-induced stressors affecting Lake Superior are many, including biological factors such as invasive species and the rapid spread of diseases (e.g. Viral Hemorrhagic Septicemia), chemical inputs from point and non-point sources, and physical changes ranging from shoreline alteration to effects of land use change in the watersheds. These stressors interact and are operating under changing temperature and precipitation regimes, providing challenges to both monitoring and remediation activities. In addition, the gradient of ecological health across Lake Superior is large, ranging from the Area of Concern in the Duluth-Superior harbor to pristine waters from sparsely populated boreal watersheds. As a result, balancing human activities and funding between protection and restoration to sustain Lake Superior ecosystems presents formidable challenges.

One of the challenges for large lake systems is the development of monitoring programs that 1) effectively identify trends in habitat improvement or degradation, and 2) can be coordinated across the multiple management agencies (Lake Superior Binational Program 2006; Chapter 3). A foremost issue in habitat monitoring is how to distribute a limited number of samples so they are truly representative of a target population and identify trends in biotic and abiotic response variables. Devising a statistically robust monitoring scheme requires an *a priori* understanding of i) the fundamental units for sampling, and ii) the gradient or range of environmental stressors impacting these units (Host *et al.* 2005,Danz *et al.* 2005a). Understanding stressor gradients is particularly challenging in that they comprise multiple and often intercorrelated factors; these include a variety of point source discharges (NPDES sites, toxic release inventory sites, mines, power plants), stresses related to human populations (road and population densities), and non-point sources related to composition and changes in land use, land cover, atmospheric deposition and landscape pattern. Yet understanding how stressors are distributed among watersheds is critical for both monitoring and restoration.

The goal of this project was to develop data and tools to quantify the gradient of anthropogenic stress in Lake Superior watersheds. The maps, decision tools and data from this effort will permit resource managers and decision makers across the basin to make more informed decisions on prioritizing watersheds for monitoring and restoration efforts.

Given this overall goal, the specific objectives for this project were to:

1) create a scalable system of fine-resolution, hierarchically nested watersheds across the Lake Superior basin;
2) quantify the natural environmental and human disturbance gradients for fine-scale watersheds;
3) use these gradients to provide supporting data for intra- and cross-agency monitoring and sampling designs;
4) identify reference (least impacted) and degraded watersheds and coastal regions within the Lake Superior basin;
5) develop tools that allow users to scale data appropriate to their sample domain and response variables;
6) disseminate project outputs via an updated LSDSS website.

METHODS and RESULTS

Objective 1: Create a scalable system of fine-resolution, hierarchically nested watersheds across the Lake Superior basin.

We used ArcHydro, a data model developed by ESRI (Maidment & Morehouse 2002), designed to manage and process watershed delineations and watershed summary information. Using flow direction and flow accumulation grids derived from elevation maps, stream networks were identified based on a minimum flow accumulation threshold. This allows for selectively delineating streams at either broad scales or very fine scales. Once the stream networks were delineated, flow direction was used to delineate the contributing area or sub-catchment for each stream reach between stream confluences (Hollenhorst *et al.* 2007).

The watershed delineation was based on a 10 m Digital Elevation Model (DEM) for the U.S. side of the Lake Superior basin, and 20 m DEMs on the Canadian side. Drainage enforcement, the process of removing spurious ‘sink’ data points from the DEM, was done using stream data from the National Hydrologic Data (NHD) for the U.S. portion of the basin and the Water Virtual Flow Seamless Provincial Data Set for the Canadian basin.

The ArcHydro model maintains hydrologic continuity, by assigning a unique “Hydro-ID” to each subcatchment, and identifying a downstream Hydro-ID for the next downsteam catchment. These attributes are also transferred to the corresponding stream reach and pour points. Because of this “nextdown” ID, it is possible, to accumulate information as the streams flow down the drainage network. For example, area-weighted means of relative values associated with each catchment (i.e. proportion or density) can be accumulated down the network.

The ArcHydro procedure resulted in the delineation of approximately 131,000 subcatchments in the Lake Superior basin (Figure 1). The average size of each subcatchment was 93 ha (230 ac). Subcatchments were combined based on their Hydro-IDs to identify watersheds emptying into Lake Superior. Approximately 7,000 Lake Superior tributary watersheds (hereafter referred to as simply ‘watersheds’) and the adjacent coastal areas that drain directly into the lake (interfluves)

Figure 1. Subcatchments of the Lake Superior basin.

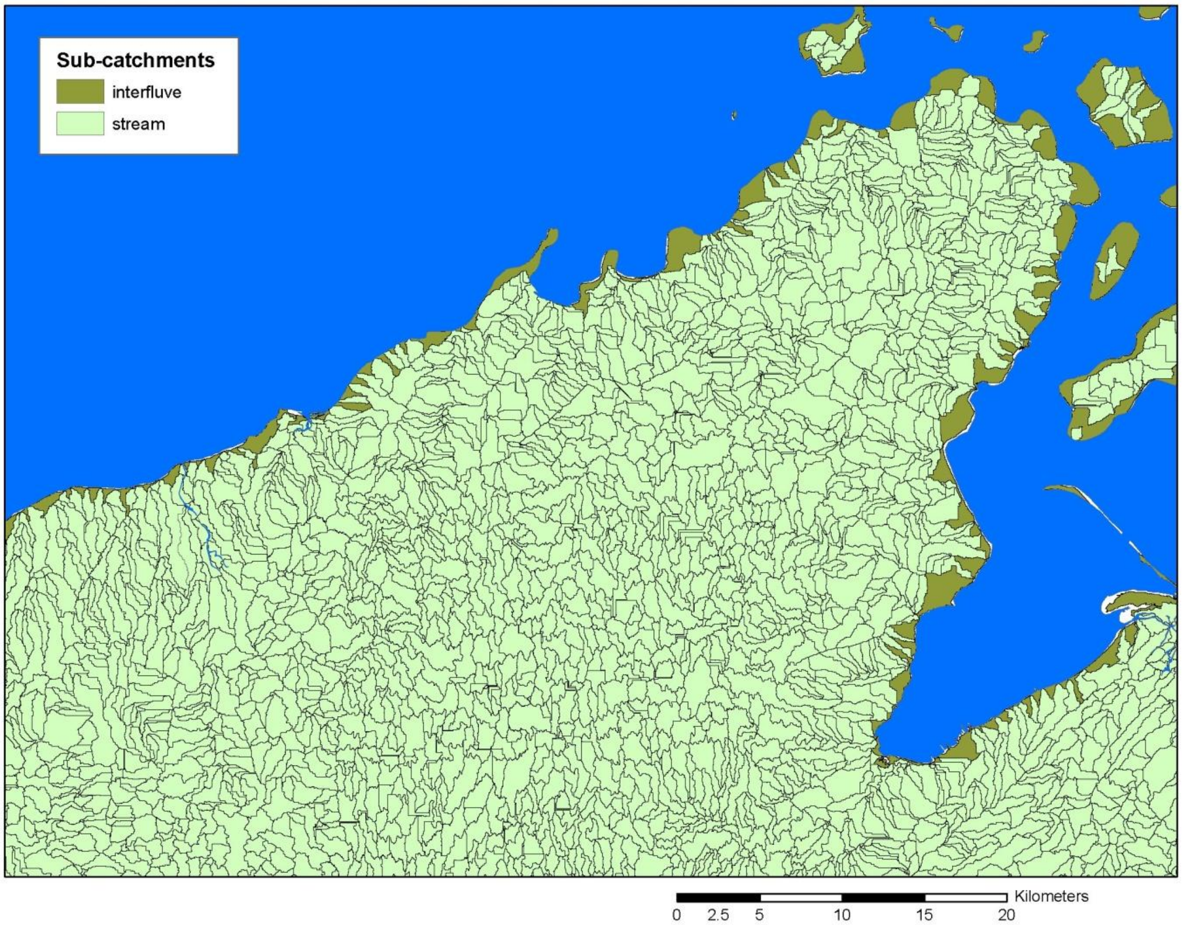

Figure 2. Detail of subcatchments for an area of the Bayfield Peninsula, WI.

were identified. (Figure 2). The GIS shapefiles for the watersheds and subcatchments can be downloaded at www.nrri.umn.edu/lsgis2 or viewed at http://gisdata.nrri.umn.edu/geomoose/GLNPO.html.

Evaluation

We evaluated the ArcHydro delineation of watersheds on the U.S. side of the basin by overlaying the fine-scale watersheds with stream reaches from the National Hydrologic Database, and observing the correspondence between stream confluences in the NHD and the pour points of individual watersheds. We also overlaid selected ArcHydro linework on 1:24,000 Digital Raster Graphics and compared watershed boundaries with topography from the DRG.

Objective 2: Quantify the natural environmental and human disturbance gradients for fine-scale watersheds.

The source data identified for this analysis were derived from the Great Lakes Environmental Indicators project (Danz *et al.* 2005a,Danz *et al.* 2005b), which identified stressor gradients for watersheds of the Great Lakes basin, and Host et al. (2005), who developed *a priori* analyses for identifying reference conditions. Spatial data from the Canadian side of the basin were first acquired and "harmonized" with U.S. data during the Lake Erie Habitat Mapping project (PIs Johnson, Ciborowski, Hollenhorst and Mackey). Data were selected because they provide comprehensive coverage of a broad geographic region, exist at appropriate temporal and spatial scales for the proposed analysis, and have strong impacts on the structure, function and composition of the ecological communities that comprise the basin.

Anthropogenic stress was quantified using a suite of publicly-available U.S. and Canadian spatial databases (Table 1). Digital spatial data were obtained from existing, publically available data sources with well-established and independently approved federal, state or provincial data sources with in-house quality assurance programs. U.S. land cover was derived from the National Land Cover Database (Vogelmann *et al.* 1998) and Canadian land cover from the Ontario Land Cover Database (Spectranalysis 2004). Both of these land cover datasets were derived from 30 m Landsat Thematic Mapper satellite data, and use similar land classification schemes. Land cover data were used to calculated % agricultural and residential land use by area for each subcatchment. U.S. and Canadian population densities were derived 2000 U.S. Census and the 2001 Census of Canada, respectively. U.S. Census blocks and Canadian Census Divisions were gridded to 30 m pixels and summarized by subcatchment.

Table 1. Anthropogenic stressor data sets, characteristics, and summarization methods.

Data set	Source and attributes	Summarization methods
Land use/land cover	USGS National Land Cover Dataset Land Information Ontario Ontario Land Cover Database	Zonal summaries by subcatchment
Population density	U.S. Census data Statistics Canada 2001 Census of Canada	Census blocks converted to raster grids, summarized by subcatchment
Point source discharge	NPDES permits (EPA); Canadian Hazards Atlas	Sum of weighted point source scores by watershed, adjusted for subcatchment area
Road density	USGS Tiger Data MNR Road Segment Dataset	Sum of weighted road density summarized by subcatchment

A road density index (km/km^2) was calculated from U.S. Census TIGER line files (U.S. Census Bureau 2002) and the MNR Road Segment dataset. Roads were weighted based on size, with arterials, collectors and local roads receiving lower weights than expressways and limited access highways (typically 4-lane roads; Table 2). The density index was calculated as total weighted road length / subcatchment area.

Table 2. Road class weights for U.S. and Canadian highway systems.

Nation	Road Class	Description	Weight
Canada	Arterial	Arterial	1
Canada	Collector	Collector	1
Canada	Expressway / Highway	Expressway / Highway	2
Canada	Local / Strata	Local / Strata	1
Canada	Local / Street	Local / Street	1
Canada	Local / Unknown	Local / Unknown	1
Canada	Ramp	Ramp	3
Canada	Resource / Recreation	Resource / Recreation	1
Canada	Service	Service	1
Canada	Winter	Winter	1
U.S.	0	Limited Access	2
U.S.	1	Limited Access	2
U.S.	2	Highway	2
U.S.	3	Major Road	1
U.S.	4	Local Road	1
U.S.	5	Minor Road	1
U.S.	6	Other Road	1
U.S.	7	Ramp	3
U.S.	8	Ferry	0
U.S.	9	Pedestrian Way	0

U.S. point source data were obtained from the National Pollutant Discharge Elimination System permit system database, which includes industrial, municipal and other facilities that discharge pollutants into U.S. waters. Canadian point source data was obtained from Environment Canada’s National Pollution Release Inventory.

Point sources were weighted based on the number and types of stressors potentially resulting from these sources. Stressors within the point source coverage included sewage, pathogens, PAHs, solvents, nutrients, salts and pharmaceuticals. A full listing of the stressors and their weights by SIC code is presented in Appendix I.

Stressor transformations and summaries

We evaluated a number of normalizing transformations for each variable, including log, ln, and arcsine transformations. The use of high-resolution watersheds resulted in a large number of zeros (i.e. non-occurrence of the stressor) for many of the variables. The best results were obtained using a $\log_{10}$ transformation of non-zero values (Appendix II). Each of the variables’ data values (x) were transformed to $\log_{10}$ (x), using the minimum non-zero value of x to replace zero values. These transformed (x') values were then standardized, $(x'-\mu)/\sigma$, with μ and σ being the mean and standard deviation for all x', respectively. These standardized values (x") were then normalized, (x"-min)/(max-min), with min and max being the minimum and maximum for all x", respectively. Finally the five “x'” values for each variable in each watershed were summed and the summed values normalized again to give a single number – SUMREL - for each watershed. SUMREL ranges from 0.0-1.0, with 1.0 representing the maximum composite stress within a geographic coverage of interest. Note that this design allows stressor scores to be calculated for any given spatial extent – from local watersheds to an ecoregion, lake, or basin.

EPA secondary data disclaimer: "The data have been reviewed by the project advisors and included in the project report. Approval does not signify that all of the data necessarily meet standard quality assurance criteria, but the data is of sufficient quality to support its intended use."

Objective 3: Provide supporting data for intra- and cross-agency monitoring and sampling designs using these gradients

The SUMREL raw data, scores and GIS coverages are available on the Exploring Lake Superior website, *www.nrri.umn.edu/lsgis2*, described in further detail below. We have presented the stressor gradient work at numerous professional and informal meetings with the Lake Superior LaMPs, the Wisconsin and Minnesota Departments of Natural Resources, the MN Board of Soil and Water Resources, and other agencies. In addition, we presented this material at the planning workshop for the Lake Superior Intensive year of sampling (CSMI) in Duluth MN in April 2009.

Objective 4: Identify reference (least impacted) and degraded watersheds and coastal regions within the Lake Superior basin.

The SUMREL scores calculated in Objective 2 were used to generate maps of stressors across the Lake Superior basin (Figure 3). When SUMREL scores were calculated for the entire Lake Superior basin, we found that the sparsely populated Canadian watersheds have relatively low stressor index scores, while the urban areas of Duluth and Thunder Bay and south shore of Lake Superior have higher scores. Islands, including Isle Royale, the Apostle Islands, and the islands of Lake Nipigon have low values for road density, population, and agriculture, and so also have low stressor scores.

Reference areas, representations of the ‘least-disturbed’ watersheds or ecosystems, are typically defined as systems within the upper 10^{th} or 25^{th} percentiles of the population with respect to levels of disturbance (Davis & Simon 1995). Figure 4 shows how the ‘tails’ of the stressor gradient – reference and degraded sites- are distributed using SUMREL thresholds of 10, 20 and 30%. The 10% cutoff identifies Isle Royale, the Apostles, and a number of Canadian coastal interfluves as reference sites, and urban sites in Duluth and Thunder Bay as degraded. The 20% cutoff includes Lake Nipigon islands and coast, and much of the Canadian north shore as reference, and adds several urban watersheds as degraded. The 30% cutoff considerably increases the land area in both reference and degraded categories, including the large St. Louis River watershed and many south shore watersheds as in the degraded category.

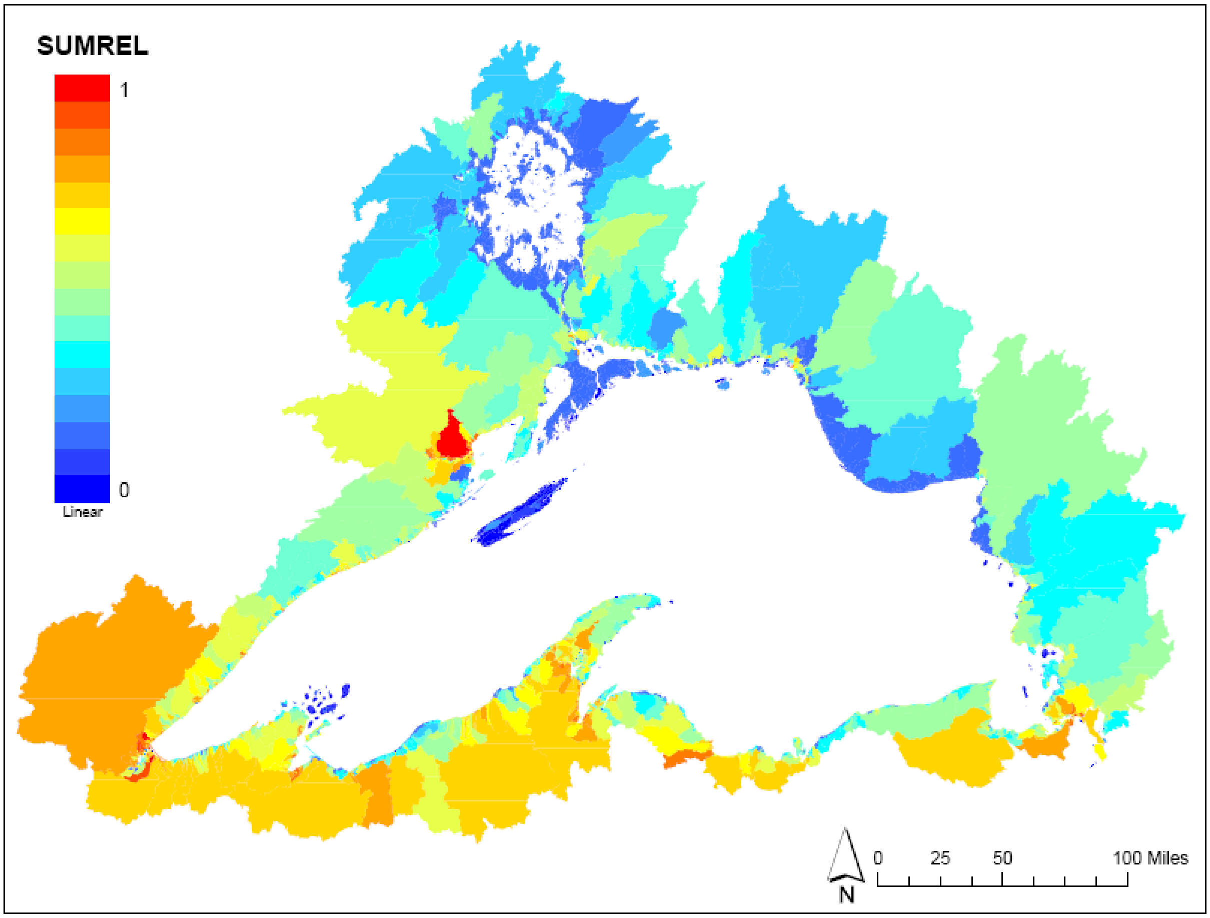

Figure 3. SUMREL stressor scores, summarized for Lake Superior tributary watersheds and interfluves. Red indicates higher stress based on the composite stressor index.

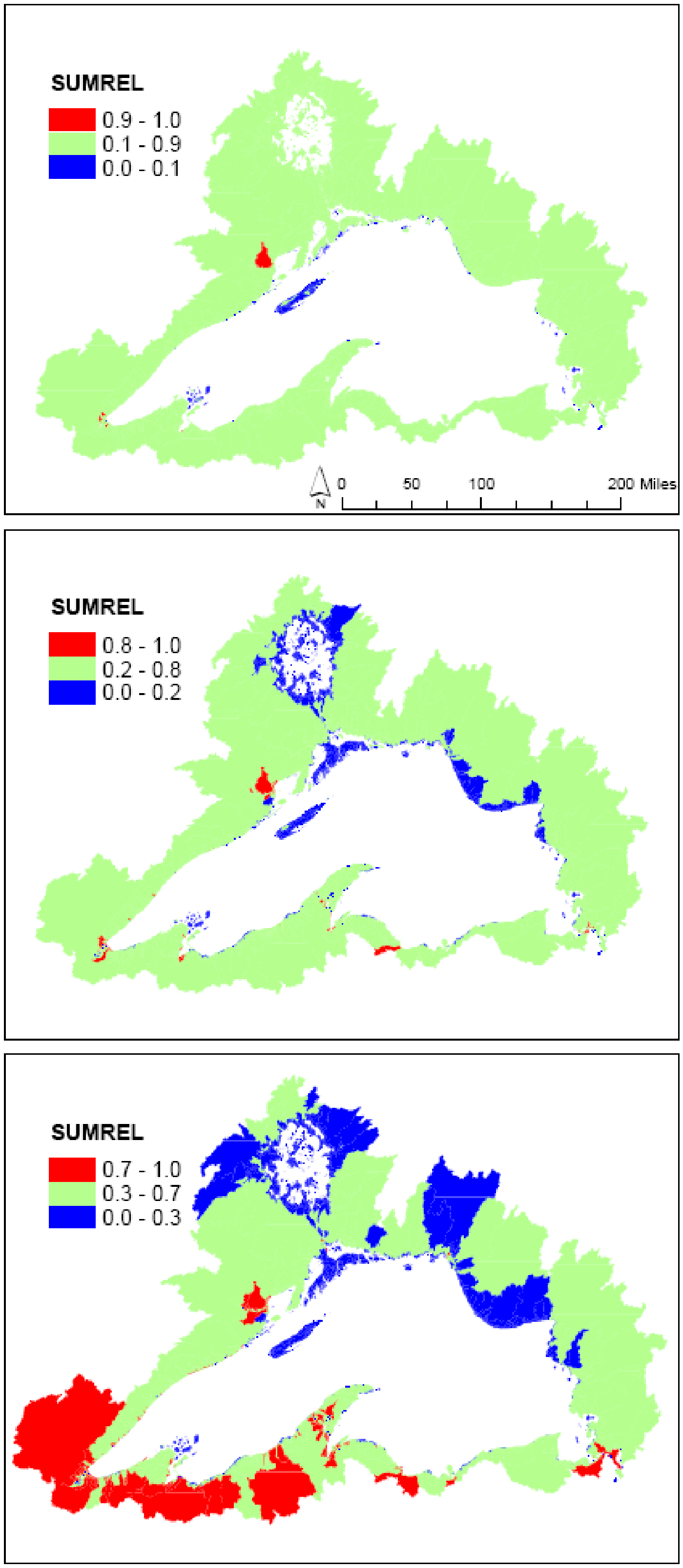

Figure 4. Reference (blue) and degraded watersheds, using 10th, 20th, and 30th percentiles of the SUMREL scores.

One of the key issues addressed in the Great Lakes Environmental Indicators (GLEI) project was identification of the appropriate extent for calculating a stressor gradient (Brazner *et al.* 2007). For example, across the Great Lakes basin, watersheds of the Erie and Ontario basin have much higher stressor scores than those of the Lake Superior basin, confounding an interpretation of reference condition. The Lake Superior basin itself has a broad range of watershed conditions. For this reason, we provide the ability to calculate SUMREL scores for user-defined extents, such as ecoregions or HUC watersheds. Figure 5 shows an example of stressor scores rescaled to three HUCs (St. Louis, Cloquet, and Beaver-Lester) along Lake Superior's north shore.

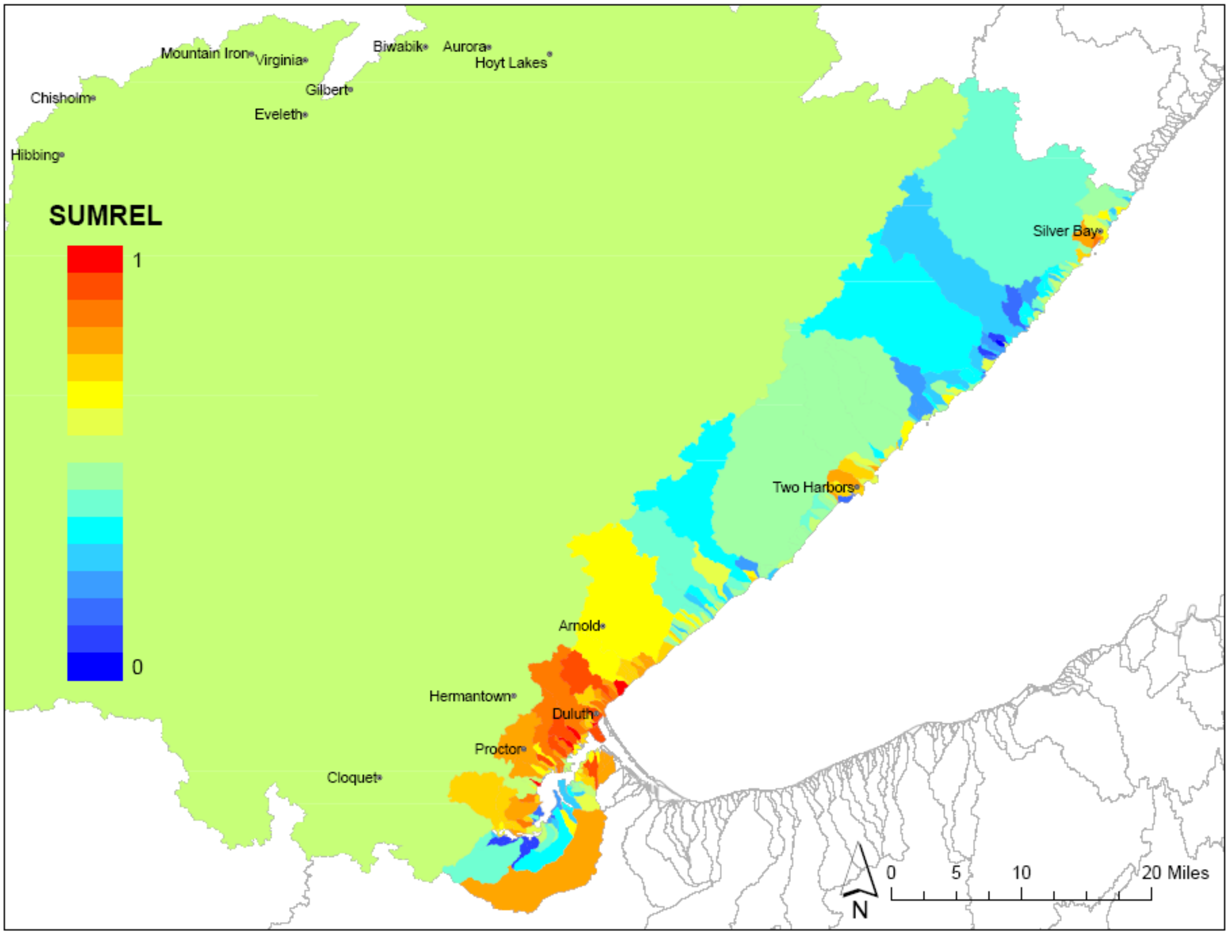

Figure 5. SUMREL scores rescaled to the St. Louis, Cloquet, and Beaver-Lester HUC watersheds.

Evaluation

Stressor gradient SUMREL scores were modified from methods from Host et al 2005. The SAS code used as the basis for the current work was originally developed under EPA Grant R828777: "Protocols for Selecting Classification and Reference Conditions" and was written as a generalized and transportable routine for calculating stressor scores for watersheds. The code contained subroutines for all data transformations and summaries, and had been used to identify reference sites in the St. Louis River AOC and the Lester-Amity watershed on Lake Superior's north shore. The transformation and summary routines were rewritten in the statistical language

R script to more readily integrate with GIS software. To verify the equations, the routines were also translated into Python - identical results were obtained with both routines.

Objective 5. Develop tools that allow users to scale data appropriate to their sample domain and response variables

We developed an online Interactive Stressor Viewer application allowing users to specify a spatial extent for summarizing the individual and composites stressors developed in Objective 2. The application uses GeoMOOSE as a platform for accessing map data. GeoMOOSE is an open-source Javascript framework for delivering cartographic data to a standard Internet browser (*www.GeoMOOSE.org*).

The application allows the user to view basemaps (low and high resolution watersheds, streams, shorelines), along with individual and composite stressors (Figure 6).

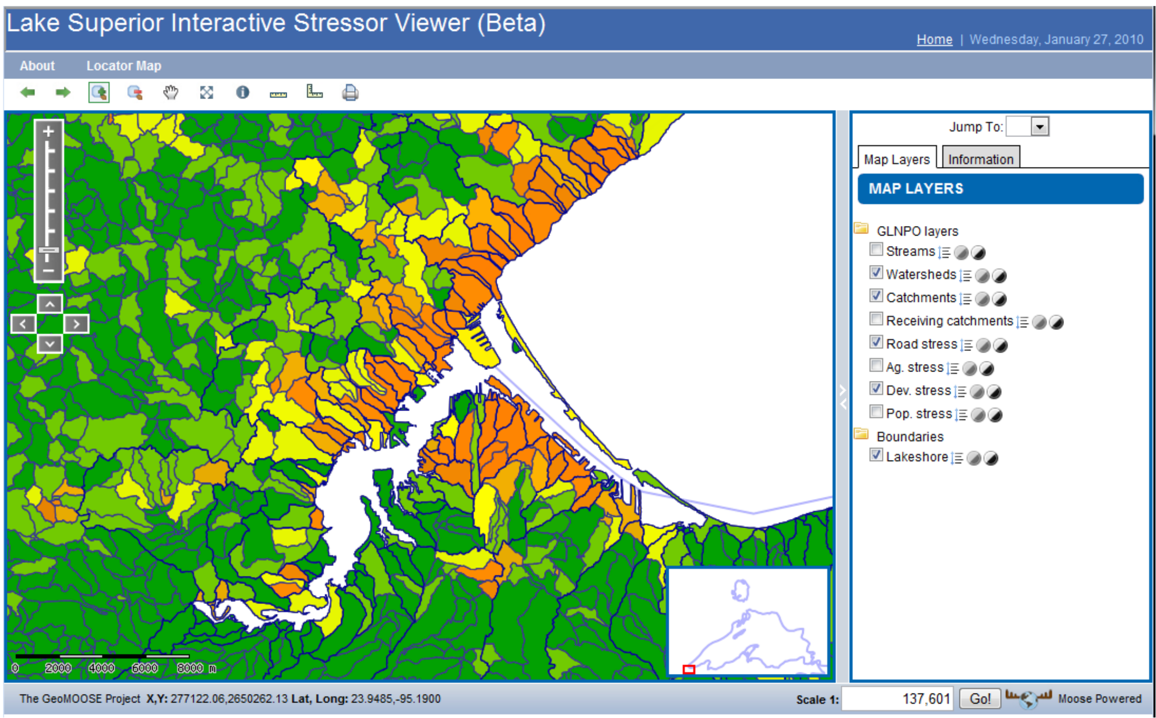

Figure 6. Screen capture of ISV tool, showing distribution of road density in the Duluth-Superior area; orange colors indicate higher road densities.

The user can select various layers to display on the map including:

- Streams: Streams used in the generation of the subcatchment network
- Watersheds: Watersheds combining one or more subcatchments
- Subcatchments: High resolution catchments
- Receiving catchments: Subcatchments which receive flow from uphill subcatchments.
- Road stress index: Color coded road stress levels
- Agricultural stress index: Color coded % agriculture (from NLCD and OLCD)

- Development stress index: Color coded % residential land use (from NLCD and OLCD)
- Pop. stress: Color coded population levels (from U.S. census; Census of Canada)

The ISV also has a unique information tool – it allows a user to click on an individual catchment and retrieve information on the stressor types and magnitudes associated with that particular catchment. The tool identifies the subcatchment at the point where the user clicked (red), the set of upstream subcatchments which drain into the selected subcatchment (green), and the set of downstream subcatchments which lead to the lake (blue) (Figure 7). The ISV also displays subcatchment counts, area, percent agricultural land cover, percent developed land cover, population, and a weighted road index. These variables are summarized for the selected catchment, as well as all upstream, downstream, and combined catchments. Graphical indicators show the relative intensity of each of these factors. The application generates a simple visualization comparing the magnitude of each stressor relative to other catchments within the Lake Superior basin.

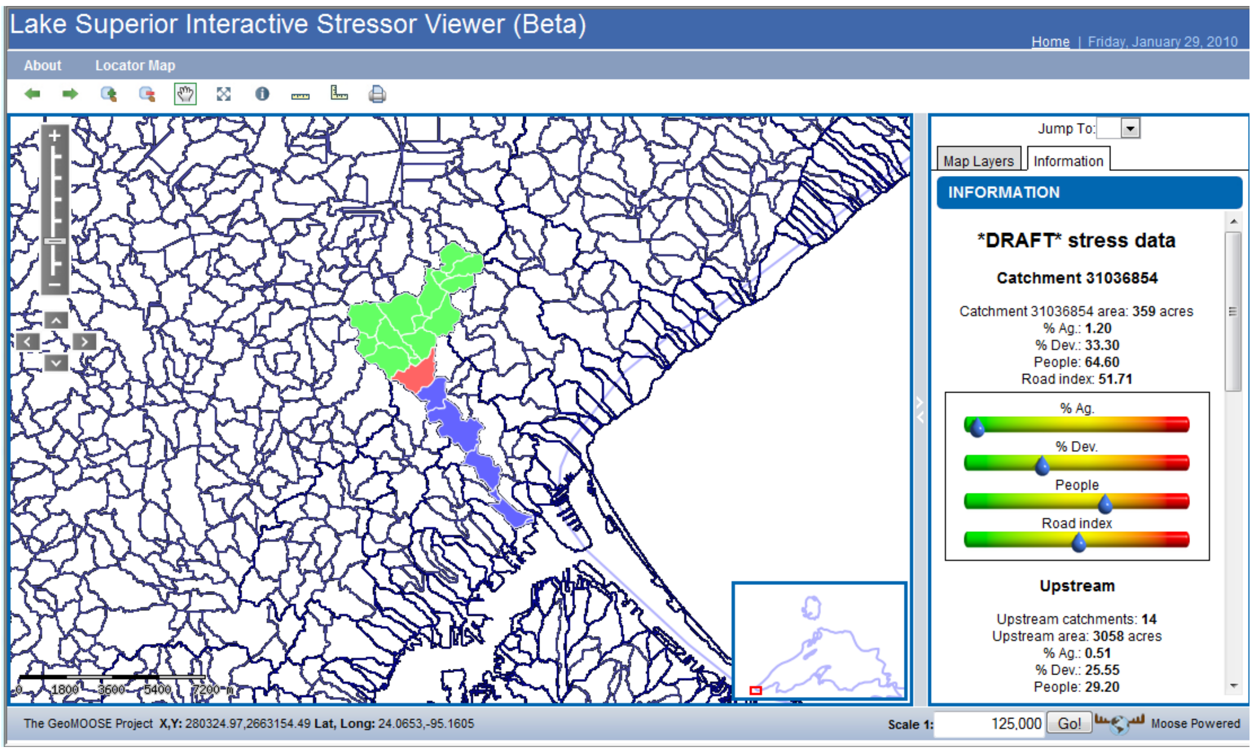

Figure 7. Tool for visualizing relative stressor data for a target catchment (red), as well as a summary of upstream (green) and downstream (blue) catchments.

Objective 6: Disseminate project outputs via an updated LSDSS website

The Lake Superior Decision Support Project was an early effort to develop GIS-based decision support applications focused on the Lake Superior basin. Funded by the USEPA Region 5 Coastal Environmental Management Grant Program through the Minnesota Department of Natural Resources, the project created synoptic databases of fundamental natural resource and infrastructure layers on the U.S. and Canadian sides of the Lake Superior basin. The website was designed for a wide audience, including local governments, regional planning agencies, resource management groups, educational and interpretive organizations and individual citizens. The primary goal of the project was to provide users with practical tools they can apply to local land and resource decisions in a context of basin-wide objectives for long-term sustainability and stewardship. A second goal was to provide tools to interpretive and educational institutions to foster public awareness and support of GIS-based land use decision support.

The final LSDSS website comprised downloadable shape files, data viewers using Internet Map Server and Google Earth, images, and FGDC-compliant metadata. Several dozen synoptic data sets were developed, including bathymetry, elevation, climate, land use, hydrography, presettlement vegetation, and numerous others. It also included a pilot project that provided a stormwater model of the Miller Creek watershed in Duluth, MN, along with a Land Use Planning Primer developed in cooperation with the Center for Rural Design at the University of Minnesota.

The project ran from 1999 through 2002, with additional funding to add the second revision of the Lake Superior Binational Program's Important Habitat Sites and Areas in 2006. The Important Habitat map was created by the Lake Superior Binational Program's Habitat Committee. The map “Important Habitat Conditions in the Lake Superior Basin” was included in the Lake Superior Lakewide Management Plan (LaMP) 2000 as a revision to the original Important Habitat Map published in 1996. The present version represents the second revision of the map and its accompanying habitat site information databases. It includes area data derived from federal, provincial, state and tribal natural resource agencies, published literature, and local knowledge. The map added several new layers, including: Lake Trout Important Habitat, Lake Whitefish Important Habitat, and Minnesota County Significant Biodiversity Areas. Support for adding the Important Habitat map to the Lake Superior Decision Support website was provided by the Canada-Ontario Agreement through the Great Lakes Binational Program.

The current “Explore Lake Superior” website replaces LSDSS, whose data content is replicated on these Supporting Data pages (Figure 8). To the degree possible, the files have been updated. For historical interest, we have retained an archival copy of the original LSDSS website.

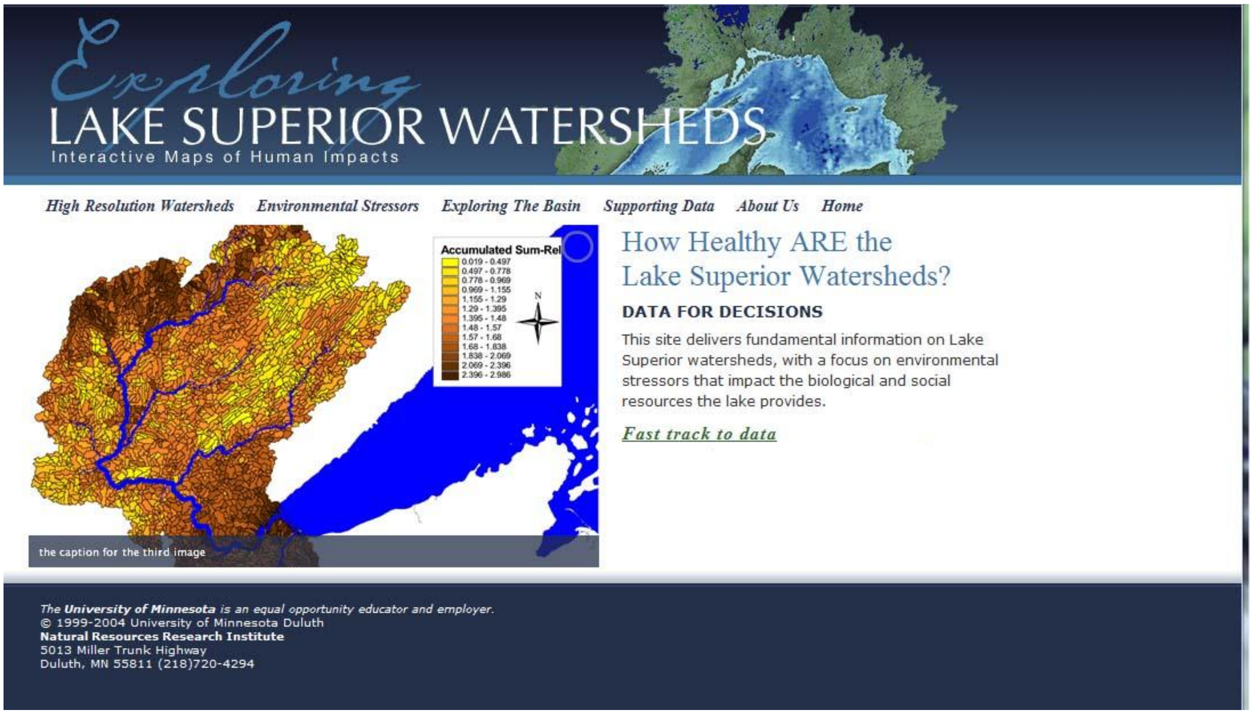

Figure 8. Homepage for "Exploring Lake Superior Watersheds"

The “Exploring Lake Superior Watershed’s” site can be found at *www.nrri.umn.edu/lsgis2*

Summary

This project achieved several important objectives that will inform upcoming efforts related to the Cooperative Science and Monitoring Initiative (CSMI), the upcoming coastal wetland monitoring program, the EPA’s Coastal Assessment, and other ongoing or proposed efforts in the basin. First, data encompassing the entire Lake Superior Basin were assembled in one location, and the spatial data were “harmonized” to enable mapping and analysis across the basin. This process involved cross-walking the unique classification systems for each of the data sets in the U.S. and Canada, and placing these in a common geographic coordinate system. Next, delineation of highly resolved subcatchments within the basin’s tributary watersheds will enable managers and decision-makers to identify: 1) specific tributaries that account for disturbances in the coastal and nearshore zone of the lakes, and 2) specific locations within the tributary, as well as specific stressor types that may potentially result in impairments to that part of the river system. Identification of the location and magnitude of point and nonpoint source stressors will also permit identification of both reference and degraded conditions which will inform the process of prioritizing restoration and protection efforts. Furthermore, identification of “least impacted” areas within a watershed can serve as a benchmark for restoration efforts. Lastly, the development of tools to identify the stress gradient over a user-specified region (e.g., HUC, basin), can inform the design of future monitoring and assessment programs. Upcoming sampling in the Lake Superior Basin will benefit from the data and tools provided by this effort.

Acknowledgements

This work was funded by a grant from the Great Lakes National Program Office, Grant number: GL00E28801-0. Dr. Jan Ciborowski at the University of Windsor provided valuable insights throughout the development of the stressor gradient approach. Ms. Jane Reed created the design of the "Explore Lake Superior" website, and Mr. Gerald Sjerven served as website administrator.

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Appendix I. Weightings for individual component stressors of point source types and composite scores for NPDES sic2 codes.

sic2	sic2d	sewerage	pathogens	PAHs	hydro-carbons	metals	solvents	nutrients	particu-lates	salts	chlorinate	physical damage	pharma-ceuticals	**composite score**
4952	SEWERAGE SYSTEMS	1	1	0	3	3	3	2	0	0	3	0	3	**19**
2911	PETROLEUM REFINING	0	0	3	3	3	3	2	0	0	0	1	0	**15**
2999	PROD OF PETROLEUM & COAL, NEC	0	0	3	3	3	0	2	2	0	0	1	0	**14**
1381	DRILLING OIL AND GAS WELLS	0	0	3	3	0	3	0	2	0	0	1	0	**12**
3519	INTERNAL COMBUSTION ENGINES,	0	0	3	3	3	3	0	0	0	0	0	0	**12**
3523	FARM MACHINERY AND EQUIPMENT	0	0	3	3	3	3	0	0	0	0	0	0	**12**
3524	LAWN AND GARDEN EQUIPMENT	0	0	3	3	3	3	0	0	0	0	0	0	**12**
3531	CONSTRUCTION MACHINERY	0	0	3	3	3	3	0	0	0	0	0	0	**12**
3537	INDUSTRIAL TRUCKS AND TRACTORS	0	0	3	3	3	3	0	0	0	0	0	0	**12**
2411	LOGGING CAMPS/LOGGING CONTRACT	0	0	3	3	0	0	2	2	0	0	1	0	**11**
7349	BUILDING MAINTNENANCE SERVICE	0	0	0	3	0	3	0	0	2	3	0	0	**11**
2611	PULP MILLS	0	0	0	3	0	0	2	2	0	3	0	0	**10**
2621	PAPER MILLS	0	0	0	3	0	0	2	2	0	3	0	0	**10**
2631	PAPERBOARD MILLS	0	0	0	3	0	0	2	2	0	3	0	0	**10**
1221	BITUMINOUS COAL & LIG, SURFACE	0	0	3	3	0	0	0	2	0	0	1	0	**9**
1622	BRIDGE, TUNNEL & ELEV HWY CONS	0	0	3	3	0	0	0	2	0	0	1	0	**9**
1629	HEAVY CONSTRUCTION, NEC	0	0	3	0	3	0	0	2	0	0	1	0	**9**
1711	PLUMB, HEAT & AIR CONDITIONING	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2491	WOOD PRESERVING	0	0	0	3	0	3	0	0	0	3	0	0	**9**
2514	METAL HOUSEHOLD FURNITURE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2515	MATTRESSES AND BEDSPRINGS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2522	METAL OFFICE FURNITURE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2531	PUBLIC BUILDING/RELATED FURNIT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2542	METAL PARTI,SHELF,LOCKERS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
2869	INDUST. ORGANIC CHEMICALS NEC	0	0	0	3	0	3	0	0	0	3	0	0	**9**
3061	MECHANICAL RUBBER GOODS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3264	PORCELAIN ELECTRICAL SUPPLIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3313	ELECTROMETALLURGICAL PRODUCTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3322	MALLEABLE IRON FOUNDRIES	0	0	3	0	3	3	0	0	0	0	0	0	**9**
3357	DRAW/INSULAT OF NONFERROUS WIR	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3423	HAND AND EDGE TOOLS, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3429	HARDWARE, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3448	PREFABRICATED METAL BUILDINGS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3449	MISC. STRUCTUAL METAL WORK	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3451	SCREW MACHINE PRODUCTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3452	BOLTS, NUTS, RIVETS & WASHERS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3491	INDUSTRIAL VALVES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3492	FLUID POWER VALVES & HOSE FITT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3496	MISC. FABRICATED WIRE PRODUCTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3532	MINING MACHINERY	0	0	3	0	3	3	0	0	0	0	0	0	**9**
3535	CONVEYORS & CONVEYING EQUIPMEN	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3536	CRANES/HOISTS/MONORAIL SYSTEMS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3541	MACHINE TOOLS, METAL CUTTING	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3544	SPECIAL DIES/TOOLS/JIGS & FIXT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3546	POWER DRIVEN HAND TOOLS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3548	WELDING APPARATUS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3554	PAPER INDUSTRIES MACHINERY	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3559	SPECIAL INDUSTRY MACHINERY,NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3561	PUMPS AND PUMPING EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3562	BALL AND ROLLER BEARINGS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3565	PACKAGING MACHINERY	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3566	SPEED CHANGERS, DRIVES & GEARS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3567	INDUSTRIAL FURNACES AND OVENS	0	0	3	0	3	3	0	0	0	0	0	0	**9**
3569	GENERAL INDUSTRIAL MACHINERY	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3579	OFFICE MACHINES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3582	COMMERCIAL LAUNDRY EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3585	REFRIGERATION & HEATING EQUIP	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3589	SERVICE INDUSTRY MACHINERY	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3592	CARBURETORS,PISTONS,RINGS,VALV	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3593	FLUID POWER CYLINDERS & ACTUAT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3612	TRANSFORMERS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3621	MOTORS AND GENERATORS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3625	RELAYS AND INDUSTRIAL CONTROLS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3629	ELECTRICAL INDUSTRIAL APPARATS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3631	HOUSEHOLD COOKING EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3632	HOUSEHOLD REFRIG. & FREEZERS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3633	HOUSEHOLD LAUNDRY EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3634	ELECTRIC HOUSEWARES AND FANS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3635	HOUSEHOLD VACUUM CLEANERS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3639	HOUSEHOLD APPLIANCES, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3641	ELECTRIC LAMPS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3646	COMMERCIAL LIGHTING FIXTURES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3661	TELEPHONE/TELEGRAPH APPARATUS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3671	ELECTRON TUBES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3672	PRINTED CIRCUT BOARD	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3674	SEMICONDUCTORS & RELATED DEVIC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3677	ELEC COILS, TRANSF. & INDUCTOR	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3679	ELECTRONIC COMPONENTS, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3691	STORAGE BATTERIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3694	ELEC EQUIP FOR INT COMBUS ENGI	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3699	ELEC MACHINERY,EQUIP & SUPPLIE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3711	MOTOR VEHICLES & CAR BODIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3713	TRUCK & BUS BODIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3714	MOTOR VEHICLE PARTS & ACCESSOR	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3721	AIRCRAFT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3728	AIRCRAFT PARTS AND EQUIP, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3731	SHIP BUILDING AND REPAIRING	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3732	BOAT BUILDING AND REPAIRING	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3743	RAILROAD EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3751	MOTORCYCLES, BICYCLES AND PART	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3764	SPACE PROPULSION UNITS & PARTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3795	TANKS AND TANK COMPONENTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3799	TRANSPORTATION EQUIPMENT, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3812	SEARCH & NAVIGATION EQUIPMENT	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3822	ENVIRONMENTAL CONTROLS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3824	FLUID METERS & COUNTING DEVICE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3825	INSTRUMENTS TO MEASURE ELECTRI	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3829	MEASURING & CONTROLLING DEVICE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3841	SURGICAL & MEDICAL INSTRUMENTS	0	0	0	3	3	3	0	0	0	0	0	0	**9**

Appendix I. Weightings for individual component stressors of point source types and composite scores for NPDES sic2 codes.

sic2	sic2d	sewerage	pathogens	PAHs	hydro-carbons	metals	solvents	nutrients	particu-lates	salts	chlorinate	physical damage	pharma-ceuticals	**composite score**
3842	SURGICAL APPLIANCES & SUPPLIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3861	PHOTOGRAPHIC EQUIP & SUPPLIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3993	SIGNS AND ADVERTISING DISPLAYS	0	0	0	3	3	3	0	0	0	0	0	0	**9**
3999	MANUFACTURING INDUSTRIES, NEC	0	0	0	3	3	3	0	0	0	0	0	0	**9**
5051	METAL SERVICE CENTERS & OFFICE	0	0	0	3	3	3	0	0	0	0	0	0	**9**
5541	GASOLINE SERVICE STATIONS	0	0	3	3	0	3	0	0	0	0	0	0	**9**
7384	PHOTOFINISHING LABORATORIES	0	0	0	3	3	3	0	0	0	0	0	0	**9**
7692	WELDING REPAIR	0	0	0	3	3	3	0	0	0	0	0	0	**9**
1389	OIL AND & FIELD SERVICES, NEC	0	0	3	3	0	0	0	2	0	0	0	0	**8**
2221	BROAD WOVEN FABRIC MILLS, SYNT	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2396	AUTOMOTIVE TRIMMINGS, APPAREL	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2431	MILLWORK	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2493	RECONSTITUTED WOOD PRODUCTS	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2591	DRAPE HARDWARE/WINDOW BLINDS	0	0	0	0	3	3	0	2	0	0	0	0	**8**
2653	CORRUGATED/SOLID FIBER BOXES	0	0	0	3	0	0	0	2	0	3	0	0	**8**
2657	FOLDING PAPERBOARD BOXES	0	0	0	3	0	0	0	2	0	3	0	0	**8**
2676	SANITARY PAPER PRODUCTS	0	0	0	3	0	0	0	2	0	3	0	0	**8**
2679	CONV PAPER & PAPERBRD PRODUCTS	0	0	0	3	0	0	0	2	0	3	0	0	**8**
2711	NEWSPAPERS: PUBLISHING & PRINT	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2731	BOOKS: PUBLISHING & PRINTING	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2732	BOOK PRINTING	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2752	COMMERCIAL PRINT, LITHOGRAPHIC	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2754	COMMERCIAL PRINTING, GRAVURE	0	0	0	3	0	3	0	2	0	0	0	0	**8**
2952	ASPHALT FELT AND COATINGS	0	0	3	3	0	0	0	2	0	0	0	0	**8**
3949	SPORTING & ATHLETIC GOODS, NEC	0	0	0	3	0	3	0	2	0	0	0	0	**8**
4111	LOCAL AND SUBURBAN TRANSIT	0	0	3	3	0	0	0	0	2	0	0	0	**8**
4493	MARINAS	0	0	3	3	0	0	2	0	0	0	0	0	**8**
4581	AIRPORTS, FLYING FIELDS & SER	0	0	3	3	0	0	0	0	2	0	0	0	**8**
7948	RACING, INCLUDING TRACK OPERA	0	0	3	3	0	0	0	2	0	0	0	0	**8**
8731	COMMERCIAL PHYSICAL RESEARCH	0	0	0	0	3	3	0	2	0	0	0	0	**8**
1311	CRUDE PETROLEUM & NATURAL GAS	0	0	3	3	0	0	0	0	0	0	1	0	**7**
4612	CRUDE PETROLEUM PIPELINES	0	0	3	3	0	0	0	0	0	0	1	0	**7**
4613	REFINED PETROLEUM PIPELINE	0	0	3	3	0	0	0	0	0	0	1	0	**7**
4619	PIPELINES, NEC	0	0	3	3	0	0	0	0	0	0	1	0	**7**
4959	SANITARY SERVICES, NEC	1	1	0	0	0	3	2	0	0	0	0	0	**7**
7011	HOTELS AND MOTELS	0	0	0	0	0	3	2	0	2	0	0	0	**7**
7542	CAR WASHES	0	0	0	0	0	3	2	0	2	0	0	0	**7**
7992	PUBLIC GOLF COURSES	0	0	0	0	0	0	2	2	0	3	0	0	**7**
8011	OFFICES & CLINICS OF MED DOCT	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8051	SKILLED NURSING CARE FACILITIE	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8052	INTERMEDIATE CARE FACILITIES	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8062	GEN. MEDICAL/SURGICAL HOSPITAL	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8063	PSYCHIATRIC HOSPITALS	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8069	SPECIALTY HOSPITALS	0	0	0	0	0	0	2	2	0	0	0	3	**7**
8361	RESIDENTIAL CARE	0	0	0	0	0	0	2	2	0	0	0	3	**7**
9511	AIR & WATER RES & SOL WSTE MGT	0	0	0	0	0	0	2	2	0	0	0	3	**7**
9631	REG & ADM OF COMMS, ELEC, GAS	0	0	0	3	0	0	2	2	0	0	0	0	**7**
241	DAIRY FARMS	0	1	0	0	0	0	2	0	0	0	0	3	**6**
253	TURKEY AND TURKEY EGGS	0	1	0	0	0	0	2	0	0	0	0	3	**6**
254	POULTRY HATCHERIES	0	1	0	0	0	0	2	0	0	0	0	3	**6**
259	POULTRY AND EGGS, NEC	0	1	0	0	0	0	2	0	0	0	0	3	**6**
271	FUR-BEARING ANIMALS & RABBITS	0	1	0	0	0	0	2	0	0	0	0	3	**6**
273	ANIMAL AQUACULTURE	0	1	0	0	0	0	2	0	0	0	0	3	**6**
921	FISH HATCHERIES AND PRESERVES	0	1	0	0	0	0	2	0	0	0	0	3	**6**
1011	IRON ORES	0	0	0	0	3	0	0	2	0	0	1	0	**6**
1021	COPPER ORES	0	0	0	0	3	0	0	2	0	0	1	0	**6**
1081	METAL MINING SERVICES	0	0	0	0	3	0	0	2	0	0	1	0	**6**
2295	COATED FABRICS, NOT RUBBERIZED	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2434	WOOD KITCHEN CABINETS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2511	WOOD HOUSEHOLD FURN, EXC UPHOL	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2521	WOOD OFFICE FURNITURE	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2671	COATED & LAMINATED PACKAGING	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2759	COMMERCIAL PRINTING, NEC	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2819	INDUSTRIAL INORGANIC CHEMICALS	0	0	0	0	3	0	0	0	0	3	0	0	**6**
2821	PLSTC MAT./SYN RESINS/NV ELAST	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2822	SYN RUBBER (VULCAN ELASTOMERS)	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2851	PAINTS/VARNISH/LACQUERS/ENAMEL	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2865	CYCLIC CRUDES INTERM., DYES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2879	PESTICIDES & AGRICULTURAL CHEM	0	0	0	3	0	0	0	0	0	3	0	0	**6**
2891	ADHESIVES AND SEALANTS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2892	EXPLOSIVES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
2893	PRINTING INK	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2899	CHEMICALS & CHEM PREP, NEC	0	0	0	3	0	3	0	0	0	0	0	0	**6**
2992	LUBRICATING OILS AND GREASES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
3011	TIRES AND INNER TUBES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3052	RUBBER & PLASTICS HOSE & BELT	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3053	GASKETS, PACKING & SEALING DEV	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3069	FABRICATED RUBBER PRODUCTS,NEC	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3081	UNSUPPORTED PLSTICS FILM/SHEET	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3089	PLASTICS PRODUCTS, NEC	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3131	BOOT & SHOE CUT STOCK & FINDNG	0	0	0	3	0	3	0	0	0	0	0	0	**6**
3291	ABRASIVE PRODUCTS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3296	MINERAL WOOL	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3312	BLAST FURN/STEEL WORKS/ROLLING	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3315	STEEL WIRE DRAW & STEEL NAILS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3316	COLD ROLLED STEEL SHEET/STRIP	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3317	STEEL PIPE AND TUBES	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3321	GRAY IRON FOUNDRIES	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3324	STEEL INVESTMENT FOUNDRIES	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3325	STEEL FOUNDRIES, NEC	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3339	PRMRY SMELT/NONFERROUS METALS	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3341	2NDARY SMELT/NONFERROUS METALS	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3369	NONFERROUS FOUNDRIES, EXC ALUM	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3399	PRIMARY METAL PRODUCTS, NEC	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3411	METAL CANS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3412	METAL BARRELS, DRUMS AND PAILS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3431	METAL SANITARY WARE	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3432	PLUMB FIXTURE FITTINGS & TRIM	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3441	FABRICATED STRUCTURAL METAL	0	0	0	0	3	3	0	0	0	0	0	0	**6**

Appendix I. Weightings for individual component stressors of point source types and composite scores for NPDES sic2 codes.

sic2	sic2d	sewerage	pathogens	PAHs	hydro-carbons	metals	solvents	nutrients	particu-lates	salts	chlorinate	physical damage	pharma-ceuticals	**composite score**
3444	SHEET METAL WORK	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3446	ARCHITECTURAL METAL WORK	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3462	IRON AND STEEL FORGINGS	0	0	3	0	3	0	0	0	0	0	0	0	**6**
3465	AUTOMOTIVE STAMPINGS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3469	METAL STAMPINGS, NEC	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3471	PLATING AND POLISHING	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3479	METAL COATING & ALLIED SERVIC	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3493	STEEL SPRINGS, EXCEPT WIRE	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3495	WIRE SPRINGS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3498	FABRICATED PIPE AND FITTINGS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3499	FABRICATED METAL PRODUCTS NEC	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3542	MACHINE TOOLS, METAL FORMING	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3545	MACHINE TOOL ACCESSORIES	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3563	AIR AND GAS COMPRESSORS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3564	BLOWER AND FANS	0	0	0	0	3	3	0	0	0	0	0	0	**6**
3991	BROOMS AND BRUSHES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
4011	RAILROADS, LINE HAUL OPERATING	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4013	RAILROAD SWTCHING & TERM ESTAB	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4151	SCHOOL BUSES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4212	LOCAL TRUCKING WITHOUT STORAGE	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4213	TRUCKING, EXCEPT LOCAL	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4231	TRUCKING TERMINAL FACILITIES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4432	FREIGHT TRANSP ON THE GR LAKES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4499	WATER TRANSPORTATION SERIVCES	0	0	3	3	0	0	0	0	0	0	0	0	**6**
4961	STEAM & AIR-CONDITIONING SUP	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5043	PHOTOGRAPHIC EQUIP & SUPPLIES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5052	COAL & OTHER MINERALS & ORES	0	0	0	3	0	0	0	2	0	0	1	0	**6**
5063	ELECTRICAL APPARATUS AND EQUIP	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5083	FARM & GARDEN MACHINE & EQUIP	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5085	INDUSTRIAL SUPPLIES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5087	SERVICE ESTABLISH EQUIP & SUPP	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5092	TOYS & HOBBY GOODS & SUPPLIES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5093	SCRAP & WASTE MATERIALS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5144	POULTRY AND POULTRY PRODUCTS	1	1	0	0	0	0	2	2	0	0	0	0	**6**
5169	CHEMICALS AND ALLIED PRODUCTS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5171	PETROLEUM BULK STATIONS & TERM	0	0	3	3	0	0	0	0	0	0	0	0	**6**
5172	PETROL & PET PROD WHOLESALERS	0	0	3	3	0	0	0	0	0	0	0	0	**6**
5192	BOOKS, PERIODICALS & NEWSPAPER	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5511	MOTOR VEH. DEALERS (NEW/USED)	0	0	0	3	0	3	0	0	0	0	0	0	**6**
5551	BOAT DEALERS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
7533	AUTO EXHAUST SYSTEM REP SHOPS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
7538	GENERAL AUTO REPAIR SHOPS	0	0	0	3	0	3	0	0	0	0	0	0	**6**
7539	AUTOMOTIVE REPAIR SHOPS, NEC	0	0	0	3	0	3	0	0	0	0	0	0	**6**
7549	AUTO SERV, EXC REP & CARWASHES	0	0	0	3	0	3	0	0	0	0	0	0	**6**
7699	REPAIR SHOPS & RELATED SERVICE	0	0	0	3	0	3	0	0	0	0	0	0	**6**
8221	COLLEGES, UNIV & PROF SCHOOLS	0	0	0	0	0	0	2	2	2	0	0	0	**6**
8734	COMMERCIAL TESTING LABORATORY	0	0	0	3	0	3	0	0	0	0	0	0	**6**
9621	REG & ADMIN OF TRANS PROGRAMS	0	0	0	0	0	0	2	2	2	0	0	0	**6**
175	DECIDUOUS TREE FRUITS	0	0	0	0	0	0	2	0	0	3	0	0	**5**
721	CROP PLANTING & PROTECTION	0	0	0	0	0	0	2	0	0	3	0	0	**5**
723	CROP PREP SERVICES FOR MARKET	0	0	0	3	0	0	2	0	0	0	0	0	**5**
831	FOREST PRODUCTS	0	0	0	3	0	0	0	2	0	0	0	0	**5**
1479	CHEM & FERT MINERA MINING, NEC	0	0	0	0	0	0	2	2	0	0	1	0	**5**
1531	OPERATIVE BUILDERS	0	0	0	0	3	0	0	2	0	0	0	0	**5**
1541	GEN CONTRACT-INDUST. BLDGS.	0	0	0	0	3	0	0	2	0	0	0	0	**5**
2048	PREP FEEDS & INGRED FOR ANIMA	0	0	0	3	0	0	2	0	0	0	0	0	**5**
2231	BROAD WOVEN FABRIC MILLS, WOOL	0	0	0	0	0	3	0	2	0	0	0	0	**5**
2253	KNIT OUTERWEAR MILLS	0	0	0	0	0	3	0	2	0	0	0	0	**5**
2299	TEXTILE GOODS, NEC	0	0	0	0	0	3	0	2	0	0	0	0	**5**
2426	HARDWOOD DIMEN & FLOORING MILL	0	0	0	3	0	0	0	2	0	0	0	0	**5**
2435	HARDWOOD VENEER AND PLYWOOD	0	0	0	3	0	0	0	2	0	0	0	0	**5**
2452	PREFAB WOOD BLDGS & COMPONENTS	0	0	0	3	0	0	0	2	0	0	0	0	**5**
2655	FIBER CANS, TUBES,DRUMS & PROD	0	0	0	3	0	0	0	2	0	0	0	0	**5**
2816	INORGANIC PIGMENTS	0	0	0	0	0	3	0	2	0	0	0	0	**5**
2841	SOAP/DETERG EXC SPECIAL CLEANR	0	0	0	0	0	3	2	0	0	0	0	0	**5**
2844	PERFUMES,COSMETICS,TOILET PREP	0	0	0	0	0	3	2	0	0	0	0	0	**5**
2861	GUM AND WOOD CHEMICALS	0	0	0	0	0	3	0	2	0	0	0	0	**5**
2951	PAVING MIXTURES AND BLOCKS	0	0	0	3	0	0	0	2	0	0	0	0	**5**
3161	LUGGAGE	0	0	0	3	0	0	0	2	0	0	0	0	**5**
3172	PERSONAL LEATHER GOODS,EXC HAN	0	0	0	0	0	3	2	0	0	0	0	0	**5**
3274	LIME	0	0	0	0	0	0	2	2	0	0	1	0	**5**
4789	TRANSPORTATION SERVICES, NEC	0	0	0	3	0	0	0	0	2	0	0	0	**5**
5531	AUTO AND HOME SUPPLY STORES	0	0	0	0	0	3	2	0	0	0	0	0	**5**
5712	FURNITURE STORES	0	0	0	3	0	0	2	0	0	0	0	0	**5**
7033	REC VEHICLE PARKS & CAMPSITES	0	0	0	3	0	0	2	0	0	0	0	0	**5**
7211	POWER LAUNDRIES, RES & COMMERC	0	0	0	0	0	3	2	0	0	0	0	0	**5**
7215	COIN-OPERATED LAUNDRIES/DRYCLE	0	0	0	0	0	3	2	0	0	0	0	0	**5**
7218	INDUSTRIAL LAUNDERERS	0	0	0	0	0	3	2	0	0	0	0	0	**5**
7219	LAUNDRY & GARMENT SERVICES,NEC	0	0	0	0	0	3	2	0	0	0	0	0	**5**
2041	FLOUR & OTHER GRAIN MILL PROD	0	0	0	0	0	0	2	2	0	0	0	0	**4**
2043	CEREAL BREAKFAST FOODS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
2045	BLENDED AND PREPARED FLOUR	0	0	0	0	0	0	2	2	0	0	0	0	**4**
2046	WET CORN MILLING	0	0	0	0	0	0	2	2	0	0	0	0	**4**
2063	BEET SUGAR	0	0	0	0	0	0	2	2	0	0	0	0	**4**
2076	VEG. OIL MILLS, EXCEPT CORN	0	0	0	0	0	0	2	2	0	0	0	0	**4**
4225	GENERAL WAREHOUSING & STORAGE	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4226	SPECIAL WAREHOUSING & STORAGE	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4741	RENTAL OF RAILROAD CARS	0	0	0	0	0	0	0	2	2	0	0	0	**4**
4922	NATURAL GAS TRANSMISSION	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4923	NAT GAS TRANSMISSION & DISTRIB	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4924	NATURAL GAS DISTRIBUTION	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4925	MIXED,MANUFAC,OR LIQ GAS PROD	0	0	0	3	0	0	0	0	0	0	1	0	**4**
4939	COMBINATION UTILITIES, NEC	0	0	0	3	0	0	0	0	0	0	1	0	**4**
7832	MOTION PIC THEA., EX DRIVE-IN	0	0	0	0	0	0	2	2	0	0	0	0	**4**
7933	BOWLING CENTERS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
7941	PROF SPORTS CLUBS & PROMOTERS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
7991	PHYSICAL FITNESS FACILITIES	0	0	0	0	0	0	2	2	0	0	0	0	**4**
7996	AMUSEMENT PARKS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
7999	AMUSEMENT AND RECREATION, NEC	0	0	0	0	0	0	2	2	0	0	0	0	**4**

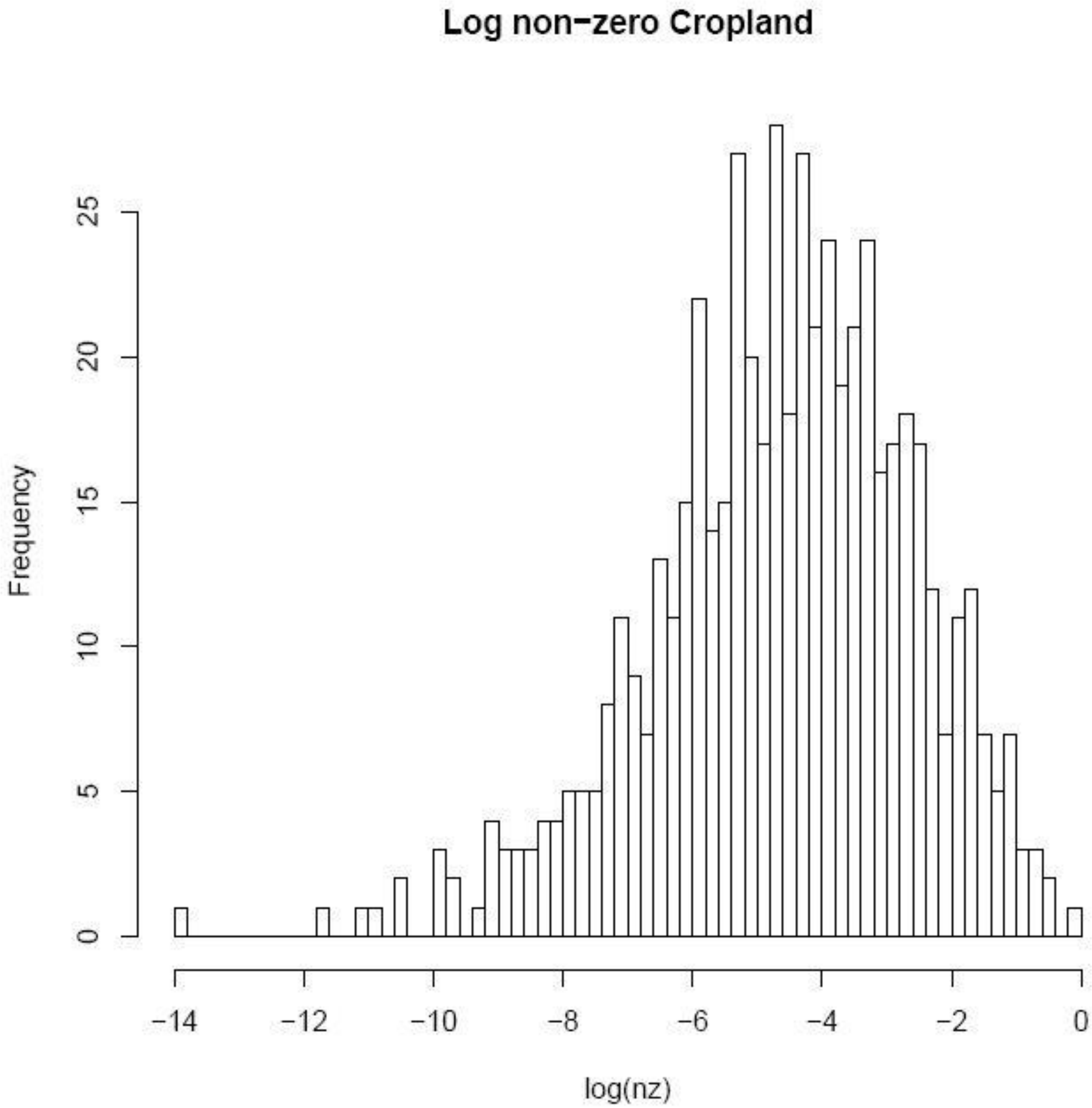
Appendix I. Weightings for individual component stressors of point source types and composite scores for NPDES sic2 codes.

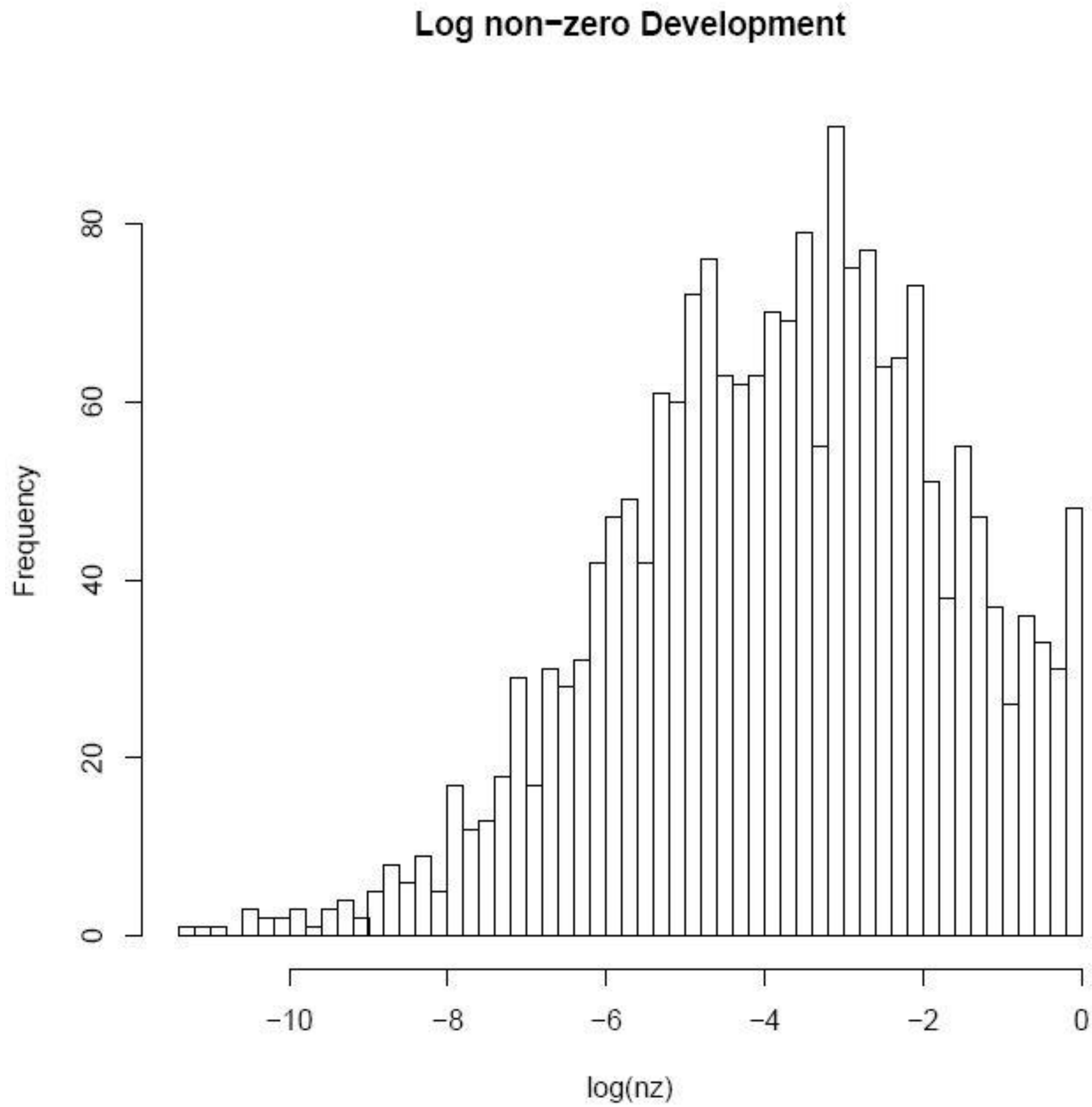
sic2	sic2d	sewerage	pathogens	PAHs	hydro-carbons	metals	solvents	nutrients	particu-lates	salts	chlorinate	physical damage	pharma-ceuticals	**composite score**
8099	HEALTH & ALLIED SERVICES, NEC	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8211	ELEMENTARY & SECONDARY SCHOOLS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8249	VOCATIONAL SCHOOLS, NEC	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8412	MUSEUMS AND ART GALLERIES	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8611	BUSINESS ASSOCIATIONS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8661	RELIGIOUS ORGANIZATIONS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8699	MEMBERSHIP ORGANIZATIONS, NEC	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8711	ENGINEERING SERVICES	0	0	0	0	0	0	2	2	0	0	0	0	**4**
8811	PRIVATE HOUSEHOLDS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
9111	EXECUTIVE OFFICES	0	0	0	0	0	0	2	2	0	0	0	0	**4**
9121	LEGISLATIVE BODIES	0	0	0	0	0	0	2	2	0	0	0	0	**4**
9199	GENERAL GOVERNMENT, NEC	0	0	0	0	0	0	2	2	0	0	0	0	**4**
9223	CORRECTIONAL INSTITUTIONS	0	0	0	0	0	0	2	2	0	0	0	0	**4**
9711	NATIONAL SECURITY	0	0	0	0	0	0	2	2	0	0	0	0	**4**
751	LIVESTOCK SERVICES, EXCEPT VET	0	1	0	0	0	0	2	0	0	0	0	0	**3**
912	FINFISH	0	1	0	0	0	0	2	0	0	0	0	0	**3**
1429	CRUSHED AND BROKEN STONE, NEC	0	0	0	0	0	0	0	2	0	0	1	0	**3**
1442	CONSTRUCTION SAND AND GRAVEL	0	0	0	0	0	0	0	2	0	0	1	0	**3**
1499	MISC NONMETAL MINERALS, NEC	0	0	0	0	0	0	0	2	0	0	1	0	**3**
2011	MEAT PACKING PLANTS	0	1	0	0	0	0	2	0	0	0	0	0	**3**
2013	SAUSAGES & PREPARED MEAT PROD	0	1	0	0	0	0	2	0	0	0	0	0	**3**
2015	POULTRY SLAUGHTERING & PROCESS	0	1	0	0	0	0	2	0	0	0	0	0	**3**
2656	SANITARY FOOD CONTAINERS	0	0	0	3	0	0	0	0	0	0	0	0	**3**
2678	STATIONERY,TABLETS & REL PROD	0	0	0	3	0	0	0	0	0	0	0	0	**3**
2812	ALKALIES AND CHLORINE	0	0	0	0	0	0	0	0	0	3	0	0	**3**
2813	INDUSTRIAL GASES	0	0	0	3	0	0	0	0	0	0	0	0	**3**
2824	SYN ORG FIBERS,EXCEPT CELLULOS	0	0	0	3	0	0	0	0	0	0	0	0	**3**
2833	MEDICINAL CHEM/BOTANICAL PRODU	0	0	0	0	0	0	0	0	0	0	0	3	**3**
2834	PHARMACEUTICAL PREPARATIONS	0	0	0	0	0	0	0	0	0	0	0	3	**3**
2835	DIAGNOSTIC SUBSTANCES	0	0	0	0	0	0	0	0	0	0	0	3	**3**
2842	SPECIALTY CLEANING, POLISHING	0	0	0	0	0	3	0	0	0	0	0	0	**3**
2843	SURF ACTIVE AGENT, FIN AGENTS	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3111	LEATHER TANNING AND FINISHING	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3211	FLAT GLASS	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3221	GLASS CONTAINERS	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3229	PRESSED & BLOWN GLASS & GWARE	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3231	GLASS PROD MADE OF PURCH. GLAS	0	0	0	0	0	3	0	0	0	0	0	0	**3**
3275	GYPSUM PRODUCTS	0	0	0	0	0	0	0	2	0	0	1	0	**3**
3281	CUT STONE & STONE PRODUCTS	0	0	0	0	0	0	0	2	0	0	1	0	**3**
3295	MINE & EARTHS, GROUND OR TREAT	0	0	0	0	0	0	0	2	0	0	1	0	**3**
3299	NONMETALLIC MINERAL PROD, NEC	0	0	0	0	0	0	0	2	0	0	1	0	**3**
3351	ROLL/DRAW/EXTRUDING OF COPPER	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3354	ALUMINUM EXTRUDED PRODUCTS	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3355	ALUMINUM ROLLING & DRAWING NEC	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3356	ROLL, DRAW & EXTRUD NONFERROUS	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3364	NONFERROUS DIE CAST, EXC. ALUM	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3365	ALUMINUM FOUNDRIES	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3398	METAL HEAT TREATING	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3443	FAB PLATE WORK (BOILER SHOPS)	0	0	0	0	3	0	0	0	0	0	0	0	**3**
3466	CROWNS AND CLOSURES	0	0	0	0	3	0	0	0	0	0	0	0	**3**
4221	FARM PROD WAREHOUSING & STORAG	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4222	REFRIGERTAED WAREHOUSING & STO	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4491	MARINE CARGO HANDLING	0	0	3	0	0	0	0	0	0	0	0	0	**3**
4783	PACKING AND CRATING	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4911	ELECTRICAL SERVICES	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4931	ELEC & OTHER SERVICES COMBINED	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4932	GAS & OTHER SERVICES COMBINED	0	0	0	3	0	0	0	0	0	0	0	0	**3**
4941	WATER SUPPLY	0	0	0	0	0	0	0	0	0	3	0	0	**3**
5045	COMPUTERS, PERIPHERALS, & SOFT	0	0	0	0	3	0	0	0	0	0	0	0	**3**
5112	STATIONERY AND OFFICE SUPPLIES	0	0	0	3	0	0	0	0	0	0	0	0	**3**
6553	CEMETERY SUBDIVIDERS & DEVELOP	0	0	0	0	0	0	2	0	0	0	1	0	**3**
7819	SERV. ALLIED TO MOTION PICTURE	0	0	0	0	0	3	0	0	0	0	0	0	**3**
161	VEGETABLES AND MELONS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
182	FOOD CROPS GROWN UNDER COVER	0	0	0	0	0	0	2	0	0	0	0	0	**2**
1422	CRUSHED AND BROKEN LIMESTONE	0	0	0	0	0	0	0	2	0	0	0	0	**2**
1446	INDUSTRIAL SAND	0	0	0	0	0	0	0	2	0	0	0	0	**2**
1521	CONTRACTORS-SINGLE FAMILY HOUS	0	0	0	0	0	0	0	2	0	0	0	0	**2**
1751	CARPENTRY WORK	0	0	0	0	0	0	0	2	0	0	0	0	**2**
1794	EXCAVATION WORK	0	0	0	0	0	0	0	2	0	0	0	0	**2**
2021	CREAMERY BUTTER	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2022	CHEESE, NATURAL AND PROCESSED	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2023	CONDENSED AND EVAPORATED MILK	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2024	ICE CREAM AND FROZEN DESSERTS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2026	FLUID MILK	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2033	CANNED FRUITS, VEG, PRES, JAM	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2034	DEHYDRATED FRUITS, VEG, SOUPS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2035	PICKLED FRTS & VEG. SAUCES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2037	FROZEN FRTS, FRT JUICES & VEG	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2038	FROZEN SPECIALTIES, NEC	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2047	DOG AND CAT FOOD	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2051	BREAD & OTHER BAKERY PRODUCTS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2052	COOKIES AND CRACKERS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2053	FROZEN BAKERY PRODUCTS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2061	CANE SUGAR, EXCEPT REFINE ONLY	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2066	CHOCOLATE AND COCOA PRODUCTS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2075	SOYBEAN OIL MILLS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2077	ANIMAL AND MARINE FATS & OILS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2082	MALT BEVERAGES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2083	MALT	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2084	WINES, BRANDY & BRANDY SPIRIT	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2085	DIST, RECTIFIED & BLENDED LIQ	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2086	BOT & CAN SOFT DRNK & CARB WA	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2091	CANNED & CURED FISH & SEAFOOD	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2092	FRE OR FROZ PCK FISH, SEAFOOD	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2099	FOOD PREPARATIONS, NEC	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2451	MOBILE HOMES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2873	NITROGEN FERTILIZERS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
2874	PHOSPHATIC FERTILIZERS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
3241	CEMENT, HYDRAULIC	0	0	0	0	0	0	0	2	0	0	0	0	**2**

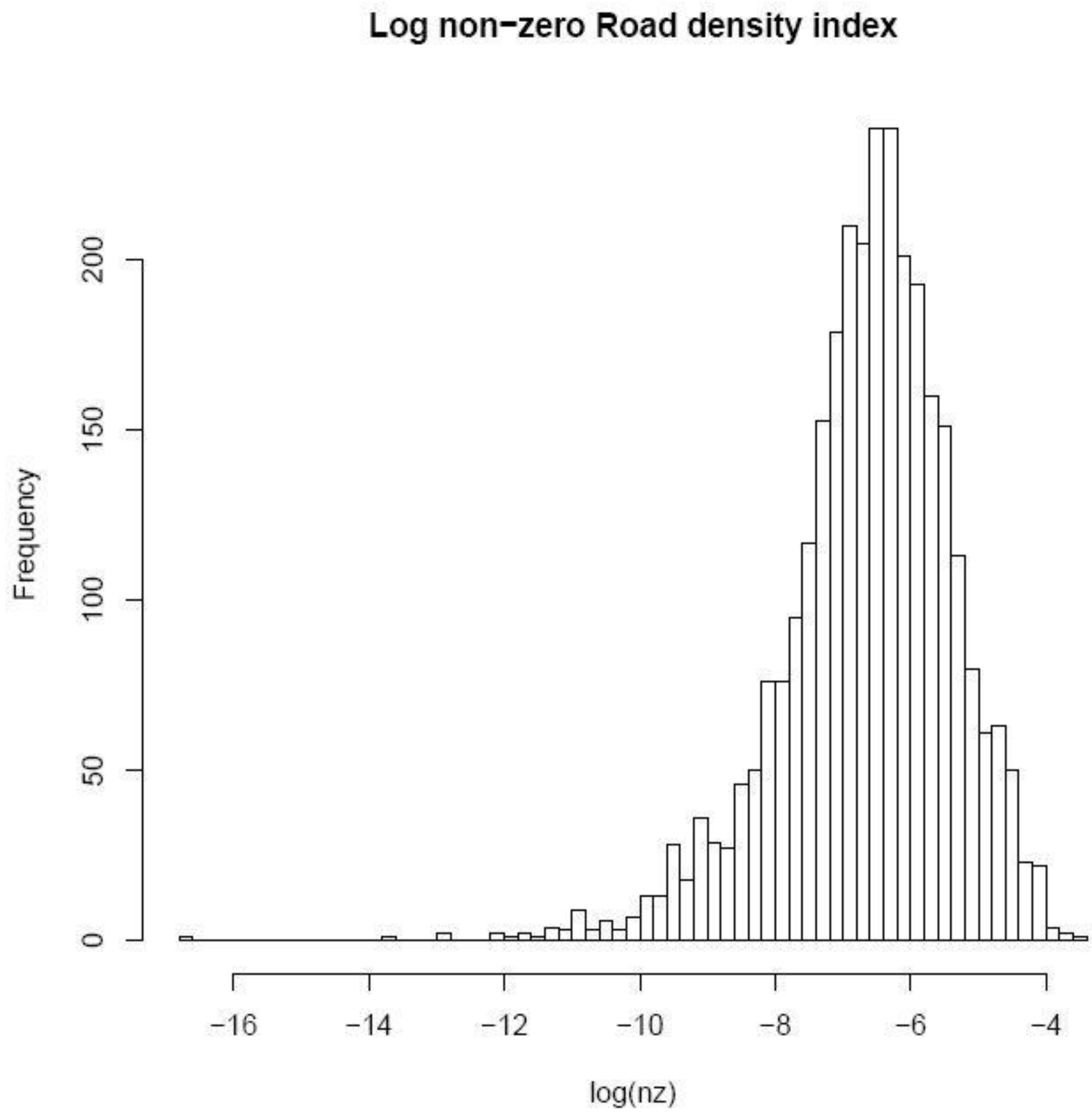
Appendix I. Weightings for individual component stressors of point source types and composite scores for NPDES sic2 codes.

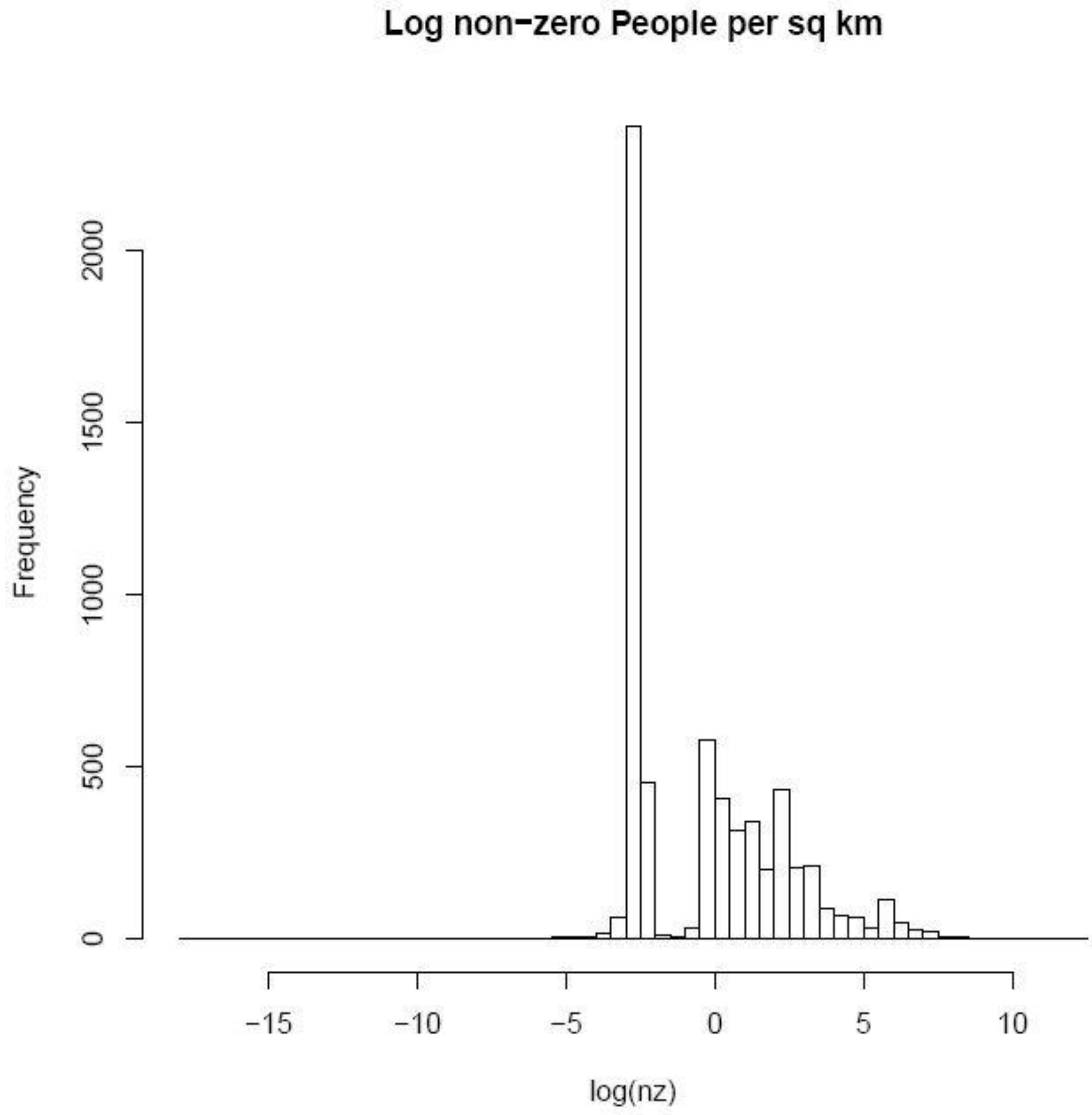
sic2	sic2d	sewerage	pathogens	PAHs	hydro-carbons	metals	solvents	nutrients	particu-lates	salts	chlorinate	physical damage	pharma-ceuticals	**composite score**
3251	BRICK AND STRUCTURAL CLAY TILE	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3253	CERAMIC WALL AND FLOOR TILE	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3255	CLAY REFRACTORIES	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3262	VIT CHINA TABLE & KTCHN ARTICL	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3263	FINE EARTHENWARE	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3269	POTTERY PRODUCTS, NEC	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3271	CONCRETE BLOCK & BRICK	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3272	CONCRETE PROD EXC BLCK & BRICK	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3273	READY-MIXED CONCRETE	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3292	ASBESTOS PRODUCTS	0	0	0	0	0	0	0	2	0	0	0	0	**2**
3297	NONCLAY REFRACTORIES	0	0	0	0	0	0	0	2	0	0	0	0	**2**
4785	INSPECTION & FIXED FACILITIE	0	0	0	0	0	0	2	0	0	0	0	0	**2**
4953	REFUSE SYSTEMS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5032	BRICK, STONE & RELAT MATERIALS	0	0	0	0	0	0	0	2	0	0	0	0	**2**
5141	GROCERIES, GENERAL LINE	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5142	PACKAGED FROZEN FOODS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5143	DAIRY PROD, EXC DRIED & CANNED	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5149	GROCERIES & RELATED PRODUCTS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5153	GRAIN AND FIELD BEANS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5159	FARM-PRODUCT RAW MATERIALS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5211	LUMBER & BUILD MATERIAL DEALER	0	0	0	0	0	0	0	2	0	0	0	0	**2**
5311	DEPARTMENT STORES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5399	MISCELLANEOUS GENERAL STORES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5411	GROCERY STORES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5451	DAIRY PRODUCTS STORES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5461	RETAIL BAKERIES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5499	MISCELLANEOUS FOOD STORES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5812	EATING PLACES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
5961	CATALOG AND MAIL-ORDER HOUSES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6021	NATIONAL COMMERCIAL BANKS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6311	LIFE INSURANCE	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6512	OPER OF NONRESIDENTIAL BLDGS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6513	OPERATORS OF APART BUILDINGS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6514	OPER OF DWELL OTHER THAN APART	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6515	OPER OF RES MOBILE HOME SITES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6552	LAND SUBDIVIDERS & DEV, EX CEM	0	0	0	0	0	0	2	0	0	0	0	0	**2**
6719	HOLDING COMPANIES, NEC	0	0	0	0	0	0	2	0	0	0	0	0	**2**
7032	SPORTING & RECREATIONAL CAMPS	0	0	0	0	0	0	2	0	0	0	0	0	**2**
7377	COMPUTER RENTAL AND LEASING	0	0	0	0	0	0	2	0	0	0	0	0	**2**
7389	BUSINESS SERVICES, NEC	0	0	0	0	0	0	2	0	0	0	0	0	**2**
8732	COMMERCIAL NONPHYSICAL RESEAR	0	0	0	0	0	0	2	0	0	0	0	0	**2**
8741	MANAGEMENT SERVICES	0	0	0	0	0	0	2	0	0	0	0	0	**2**
9229	PUBLIC ORDER AND SAFETY, NEC	0	0	0	0	0	0	0	2	0	0	0	0	**2**
9411	ADMINISTRATION OF EDUCAT PROG	0	0	0	0	0	0	0	2	0	0	0	0	**2**
9512	LAND, MIN, WILDLIFE/FOREST CON	0	0	0	0	0	0	0	2	0	0	0	0	**2**
9999	NONCLASSIFIABLE ESTABLISHMENTS	0	0	0	0	0	0	0	2	0	0	0	0	**2**
8999	SERVICES, NEC	0	0	0	0	0	0	0	0	0	0	1	0	**1**

Appendix II – Distributions of transformed stressor values

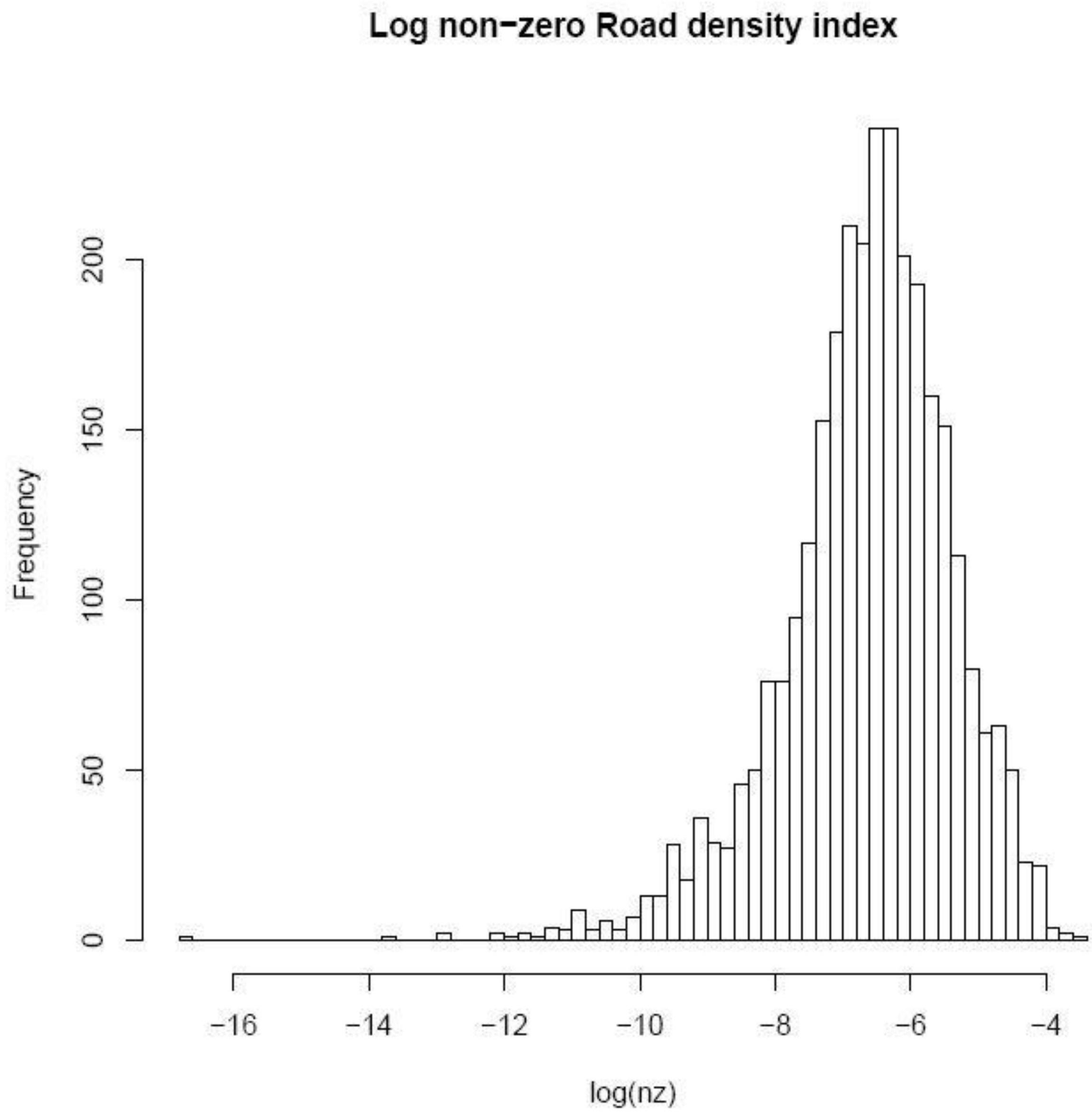



Log non−zero Development
Frequency
0
20
40
60
80
−10
−8
−6
−4
−2
0
log(nz)


Log non−zero Road density index
Frequency
0
50
100
150
200
−16
−14
−12
−10
−8
−6
−4
log(nz)



Log non−zero People per sq km
Frequency
0
500
1000
1500
2000
−15
−10
−5
0
5
10
log(nz)


Log non−zero Road density index
Frequency
0
50
100
150
200
−16
−14
−12
−10
−8
−6
−4
log(nz)

Appendix H

Lake Superior Streams Sediment Assessment

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Date: 7-25-2011
NRRI-tech-rep: NRRI/TR-2011/35
Prepared for: MPCA

Contents

Task 1 - Watershed boundaries

130921 subcatchments were delineated for the Lake Superior basin for another project [GLNPO, 2008]. Quoting from that site:

> We used ArcHydro, a data model developed by ESRI, designed to manage and process watershed delineations and watershed summary information. Using flow direction and flow accumulation grids derived from elevation maps, stream networks were identified based on a minimum flow accumulation threshold. This allows for selectively delineating streams at either broad scales or very fine scales. Once the stream networks were delineated, flow direction was used to delineate the contributing area or sub-catchment for each stream reach between stream confluences (Hollenhorst et al. 2007).
>
> The watershed delineation was based on a 10 m Digital Elevation Model (DEM) for the U.S. side of the Lake Superior basin, and 20 m DEMs on the Canadian side. Drainage enforcement, the process of removing spurious ‘sink’ data points from the DEM, was done using stream data from the National Hydrologic Data (NHD) for the U.S. portion of the basin and the Water Virtual Flow Seamless Provincial Data Set for the Canadian basin.
>
> The ArcHydro model maintains hydrologic continuity, by assigning a unique “Hydro-ID” to each subcatchment, and identifying a downstream hydro-id for the next downstream catchment. These attributes are also transferred to the corresponding stream reach and pour points. Because of this “nextdown” id, it is possible, to accumulate information as the streams flow down the drainage network. For example, area-weighted means of relative values associated with each catchment (i.e. proportion or density) can be accumulated down the network.

For this work, the attributes referred to above as ’Hydro-ID’ and ’nextdown’ are named ’atom_id’ and ’down_id’ respectively. 18282 of these subcatchments were extracted and projected to UTM zone 15N. These subcatchments cover all watersheds draining into Lake Superior between between the Nemadji, in Wisconsin, and the Pigeon, on the US / Canada border, inclusive. When subcatchments were merged according to their network connectivity, 666 watersheds were identified for the study region.

Comparison with NRCS/USGS Watershed Boundary Dataset (WBD) 12 digit watersheds

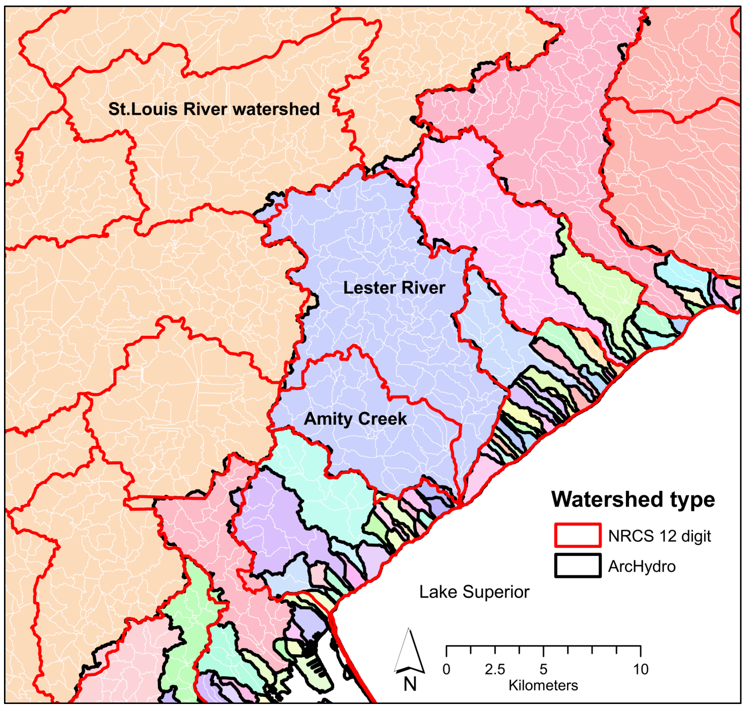


Figure 1: Comparison of ArcHydro and NRCS/USGS 12 digit watersheds, background shows ArcHydro subcatchments colored by ArcHydro watershed.

source	**number**	**min. area ha**	**max. area ha**	**mean area ha**
ArcHydro sub-catchments	18282	N/A	980	97.7
ArcHydro water-sheds	666	0.16	917850	2681
NRCS WBD-12	211	2781.8	16643	7954

(N/A: The ArcHydro subcatchment data includes very small units which meet the accumulation threshold criteria it uses)

Comparison of the areas of the two watershed products is not meaningful, because of differences in the definition of a watershed. ArcHydro considers both very large (St. Louis River) and very small areas which drain directly to to lake to be watersheds, whereas the NRCS/USGS 12 digit product targets units of a particular area.

Comparison of watershed boundaries, in those places where they'd be expected to coincide, shows differences which are unlikely to significantly impact the use of the ArcHydro product as a stress index generation tool. These differences may arise from inaccuracies in the Digital Elevation Model (DEM) used to generate the ArcHydro subcatchments. There may also be inaccuracies in the NRCS/USGS WBD-12 boundaries.

Size frequencies for watersheds and subcatchments

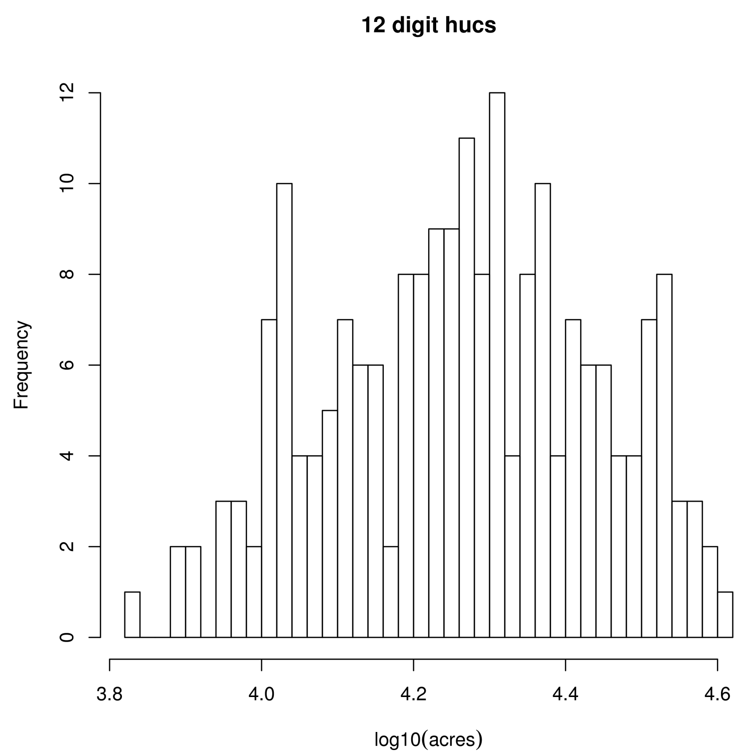


Figure 2: Size distribution for 12 digit HUCs in the study area

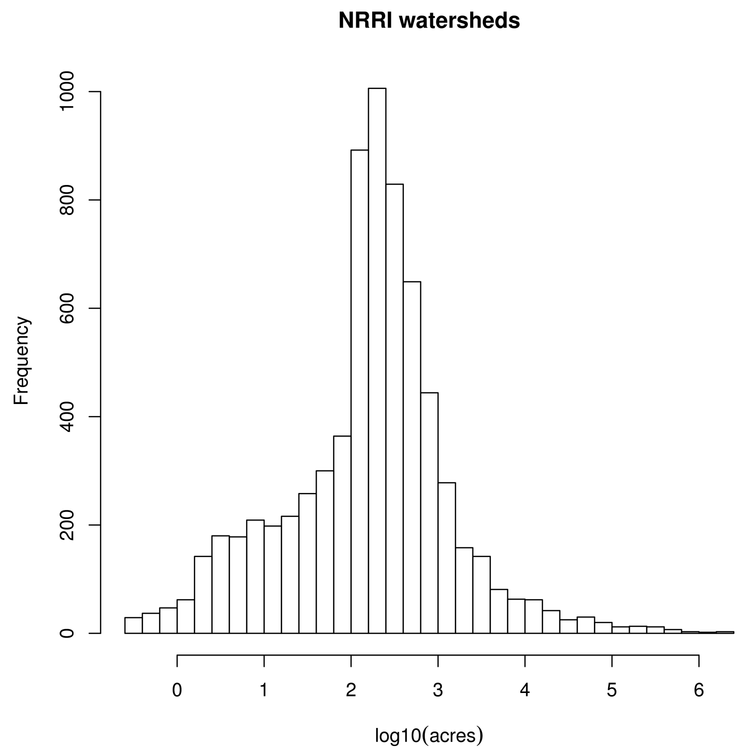


Figure 3: Size distribution for ArcHydro watersheds in the study area

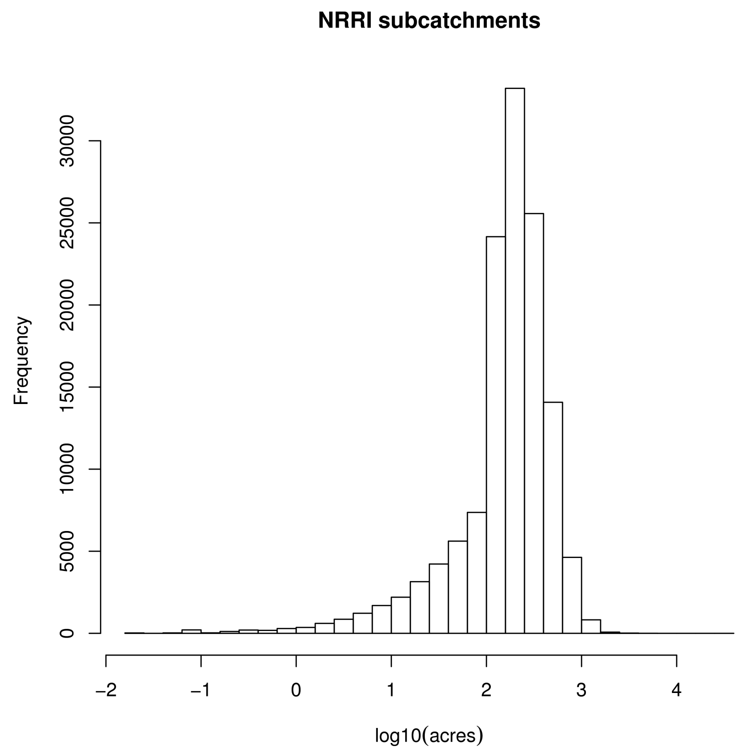


Figure 4: Size distribution for ArcHydro subcatchments in the study area

Task 2 - Relevant data layers

The lack of high resolution SSURGO soils data for the NE MN region continues to be a significant data gap for analyses such as this one.

Definition: "stream context"

Within this document the term "stream context" is used to refer to the area surrounding a stream approximately 100 m either side of the stream. The analysis of near stream slope and soil characteristics in this area is described in more detail in Task 3, but the term is defined here as it is used to describe the scale of some data layers...

From the GLNPO Lake Superior wide ArcHydro project

Population density Area weighted from census blocks into the ArcHydro subcatchments. 2000 era census data was used for both US and Canadian subcatchments. Canadian census data tends to use larger census blocks which appear as a lower density population over a wider area.

Point source pollution releases Count within ArcHydro subcatchments, NPDES permits (EPA), Canadian Hazards Atlas

Road density Length per unit area within ArcHydro subcatchments

Percent urban By ArcHydro subcatchment, 2001 NLCD, Land Information Ontario Ontario Land Cover Database

Percent agricultural By ArcHydro subcatchment, 2001 NLCD ,Land Information Ontario Ontario Land Cover Database

Added for this project, at the ArcHydro subcatchment level

Stream / road intersections Count within ArcHydro subcatchments, 2008 MNDoT roads, ArcHydro streams

Percent canopy coverage From NLCD

Percent wetland Percent of subcatchment in a National Wetland Inventory class other than 'U', upland.

Percent impervious From NLCD

Stream channel slope See Task 3, from 10m digital elevation data

Stream context slope See Task 3, from 10m digital elevation data

Stream channel sedimentary erosion potential From the State Soil Geographic Database (STATSGO)

Stream context sedimentary erosion potential From STATSGO

Stream channel KFFACT From STATSGO

Stream context KFFACT From STATSGO

Task 3 - Develop methodology

Methods were primarily an application of the "SumRel" combined stressor index described in [GLNPO, 2008] and [Host et al., 2011] with special treatment of stream channel and stream context slope and erosion risk factors. The layers described in Task 2 - Relevant data layers were simple "proportion of subcatchment" or "number within subcatchment" (point source pollution and road / stream intersections), with the exception of the "stream channel" and "stream context" variables, which were the product of a geomorphic analysis method developed for this project.

Geomorphic analysis for stream variables

The ArcHydro modeling process [GLNPO, 2008] generates a network of stream reaches based on the cells in a Digital Elevation Model (DEM) which exceed a certain flow accumulation threshold. "Reaches" in this case refer to the undivided sections of the stream network between stream confluences. These reaches are used to generate the subcatchment polygons, by mapping the part of the DEM which slopes towards the stream. These reach lines where used to characterize the slope of the stream channel and stream context and the distribution of soil types in the stream channel and stream context, although as noted elsewhere soil data resolution is low.

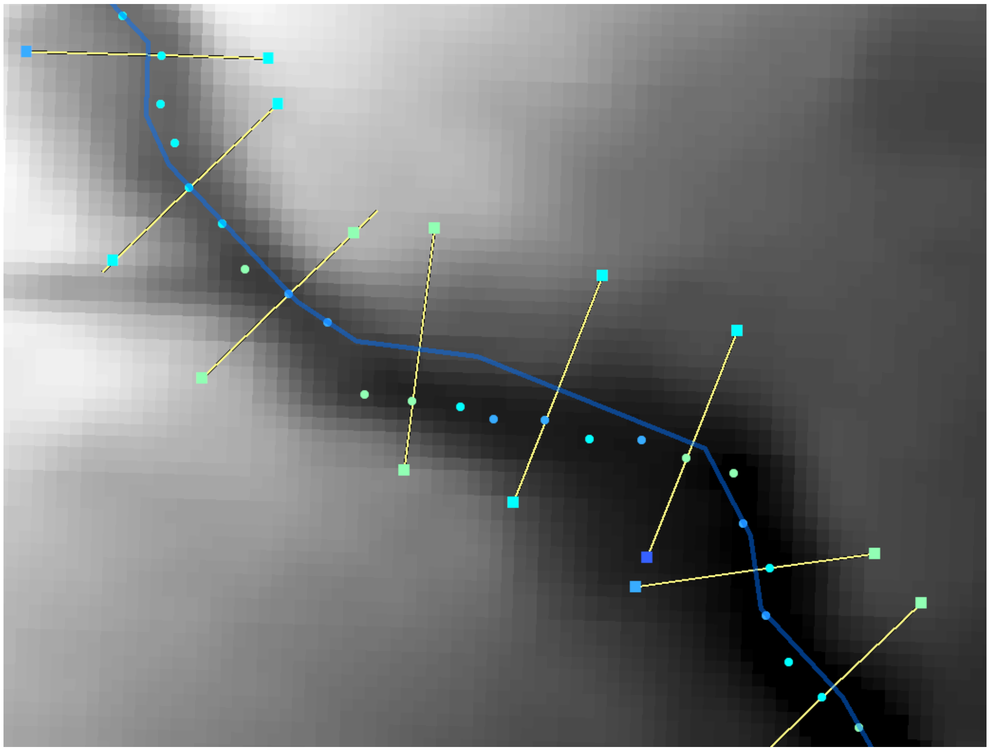


Figure 5: Image above illustrates how the stream reach line can be used to analyze the stream channel and stream context:

- points are located along the stream reach at 20 m increments and a line perpendicular to the stream (normal) is drawn through the points 100 m either side of the reach (only every third normal shown above)
- the normal is divided into 10 m increments and the ground height measured from the DEM for each point
- the point representing the stream channel is corrected by allowing it to move downhill to the lowest point on the normal (i.e. it is not moved to a lower point on the normal if that point is separated from the channel point by higher DEM cells)
- stream channel slope is estimated for each stream channel point from the horizontal and vertical distance to its upstream point
- from the corrected stream channel point the highest point on the normal in both directions is located to generate a pair of stream context points, and the stream context slope is estimated for each of these from the horizontal and vertical distance to its stream channel point
- for each subcatchment many stream channel slope and stream context slope measurements are made, the mean value is assigned to the subcatchment. The STATSGO KFACT

and erosion potential values are also extracted for each channel and stream context point, and the mean for each group assigned to the subcatchment.

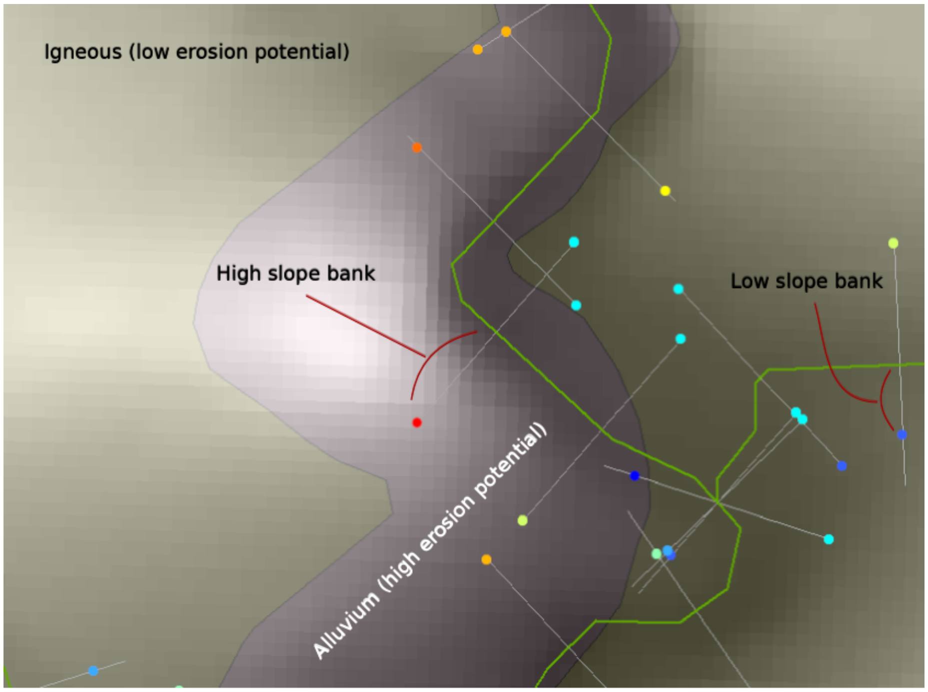


Figure 6: Stream context points measuring slope and erosion potential.

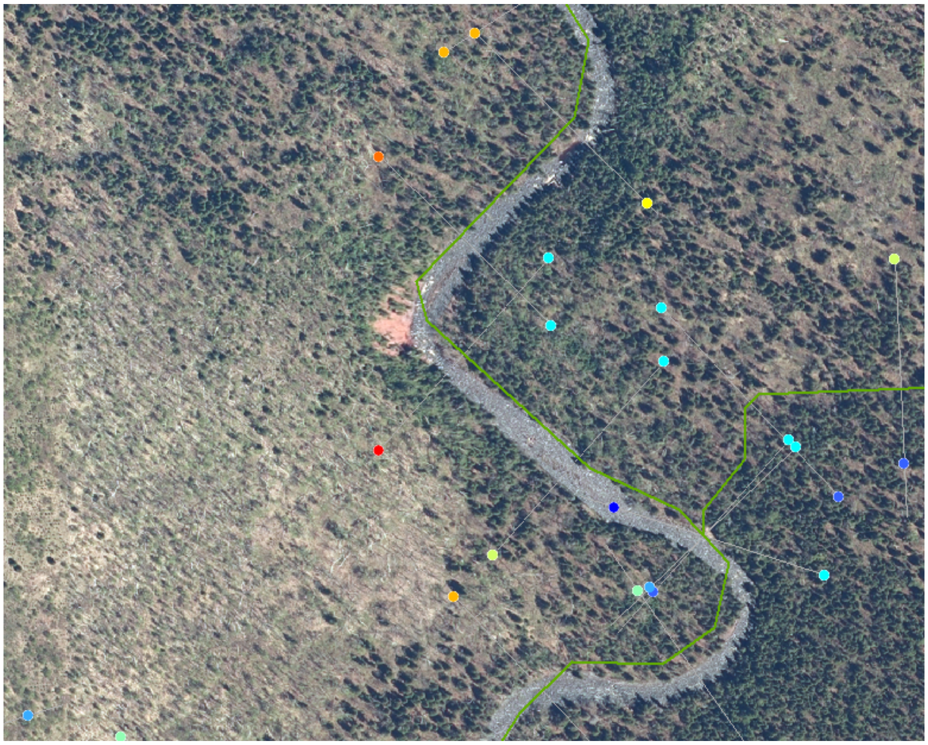
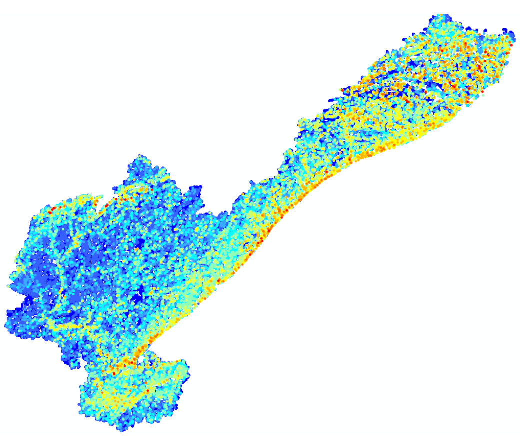
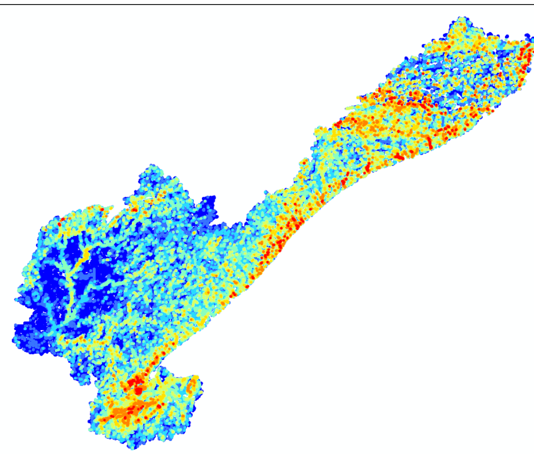


Figure 7: Slump in area indicated as high risk by stream context point methodology.

Table 1: Stream slope (left) and bank slope points for the study area, showing low (blue) to high (red) slope.

Task 4 - Identify reference watersheds

The SumRel combined stressor index provides a single value for a set of stressors to allow rapid identification of areas which deserve more detailed examination, either as hot-spots of combined stress, or reference areas with low overall stress. SumRel values are normalized into a zero to one range, and are calculated as follows (from http://www.nrri.umn.edu/lsgis2/stressors/summary.html):

> We evaluated a number of normalizing transformations for each variable, including log, ln, and arcsine transformations. The use of high-resolution watersheds resulted in a large number of zeros (i.e. non-occurrence of the stressor) for many of the variables. The best results were obtained using a log10 transformation of non-zero values. Each of the five variables data values (x) were transformed to log10 (x), using the minimum non-zero value of x to replace zero values. These transformed (x') values were then standardized, (x'-μ)/σ, with μ and σ being the mean and standard-deviation for all x', respectively. These standardized values (x") were then normalized, (x"-min)/(max-min), with min and max being the minimum and maximum for all x", respectively. Finally the five x" values for each variable in each watershed were summed and the summed values normalized again to give a single number - SUMREL - for each watershed. SUMREL ranges from 0.0-1.0, with 1.0 representing the maximum composite stress within a geographic coverage of interest. Note that this design allows stressor scores to be calculated for any given spatial extent – from local watersheds to an ecoregion, lake, or basin.

SumRel may be calculated either with local variables (the measure of that variable for the local subcatchment only), or "accumulated" variables - the value of a variable for the entire upstream drainage of a subcatchment. Care must be taken to apply necessary area weighting when determining combined values for proportions like percent wetland.

For this project both local and accumulated SumRel scores were calculated; the local version identifying potential sediment generation hotspots on the landscape, and the accumulated version indicating which watersheds or stream reaches might be under particularly high (or low) levels of sediment generation risk.

Variable	**Local SumRel transform**	**Accumulated SumRel transform**	**Description**
strslp	zLog	absent	The mean of stream channel point slopes for each subcatchment.
bnkslp	zLog	absent	The mean of stream context point slopes for each subcatchment.

... continued on next page

Variable	Local SumRel transform	Accumulated SumRel transform	Description
pctwl	-identity	-identity	The percent of each subcatchment covered by NWI wetland.
rdint	identity	identity	The number of stream / road intersections for each subcatchment.
canpct	-zLog	-identity	Percent forest canopy for each subcatchment.
accam2	zLog	zLog	Upstream area for the subcatchment (this value was "accumulated" for both the local and accumulated SumRel scores).
skffact	identity	zLog	Mean STATSGO KFFACT value for each stream channel point in the subcatchment.
ssedero	identity	zLog	Mean STATSGO sediment erosion value for each stream channel point in the subcatchment.
bkffact	identity	zLog	Mean STATSGO KFFACT value for each stream context point in the subcatchment.
bsedero	identity	zLog	Mean STATSGO sediment erosion value for each stream context point in the subcatchment.
imp	zLog	zLog	Percent impervious cover for the subcatchment.
ppsk	zLog	zLog	Population density (people per sq. km) for the subcatchment.

Transforms applied were: *zLog* - $\log_{10}$ of value, or minimum non-zero value in place of zero values; *identity* - no transformation; *absent* - variable was not used for accumulated SumRel. Transformations preceded by '-' indicate that the parameter is thought to decrease sediment generation risk as it increases. There parameters are handled in the SumRel calculation by subtracting their normalized (0-1) value from 1. Slope variables were excluded from the accumulated SumRel scores as the effect of slope is somewhat local, at least in terms of local sediment generation.

Visualization of individual variables

The following sequence of figures illustrates the variables selected for the analysis in Local and Accumulated views, in either $\log_{10}$ or linear scale, depending on which scale best shows the structure of the data. Green to red gradient shows low to high values for the variable, not necessarily low to high sediment generation risk. All of these images can be made with the data included in this report. Some variable were not available in Canada or Wisconsin, and this is reflected in their visualization.

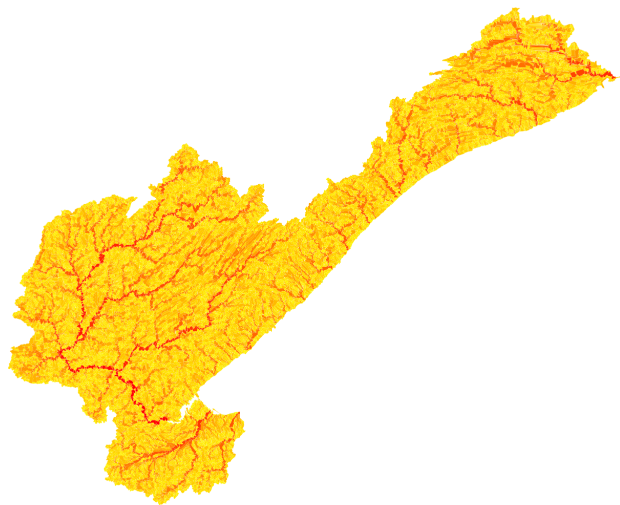


Figure 8: Accumulated drainage area, ~ stream power (log10)

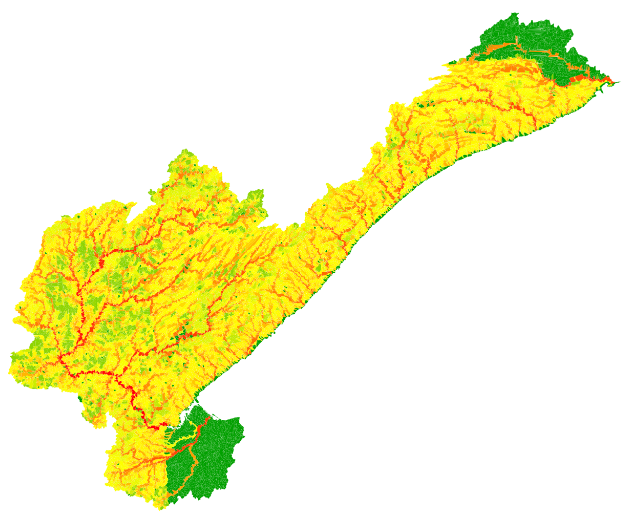


Figure 9: Accumulated bank erodability, KFFACT (log10)

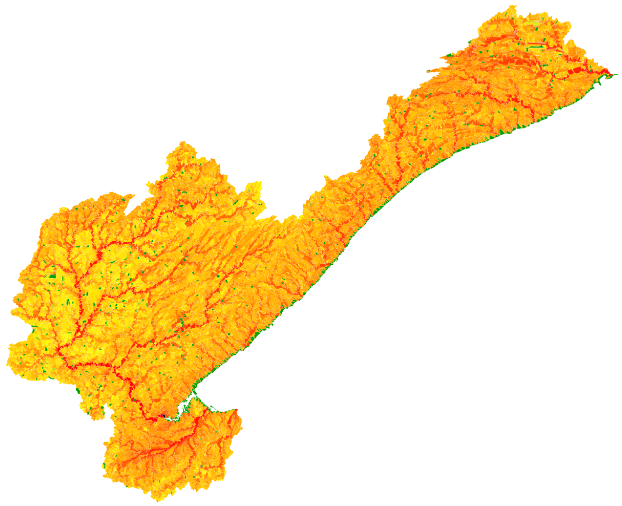


Figure 10: Accumulated bank slope (log10)

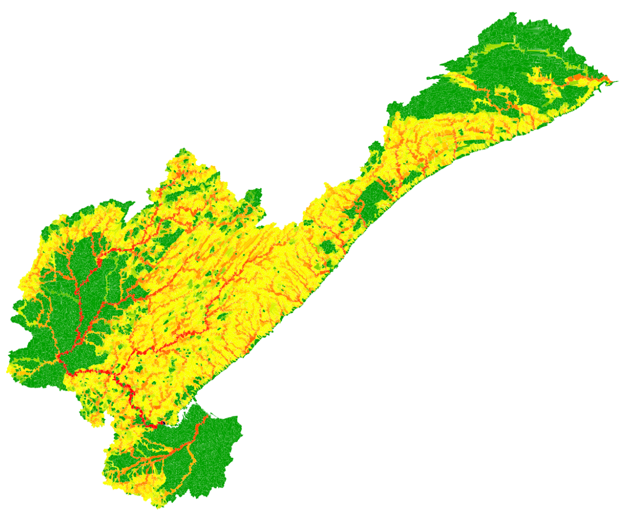


Figure 11: Accumulated bank erodability, Sed. assoc (log10)

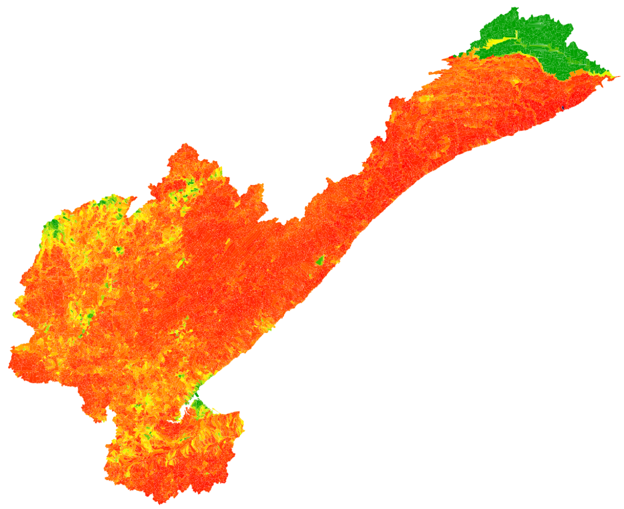


Figure 12: Accumulated canopy percent (linear)

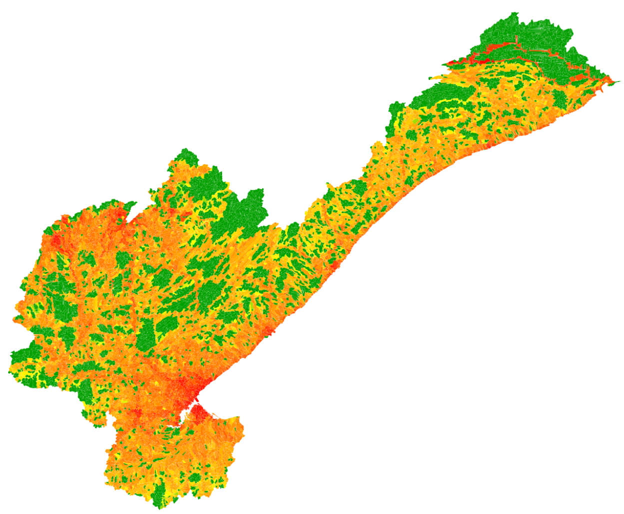


Figure 13: Accumulated imperviousness (log10)

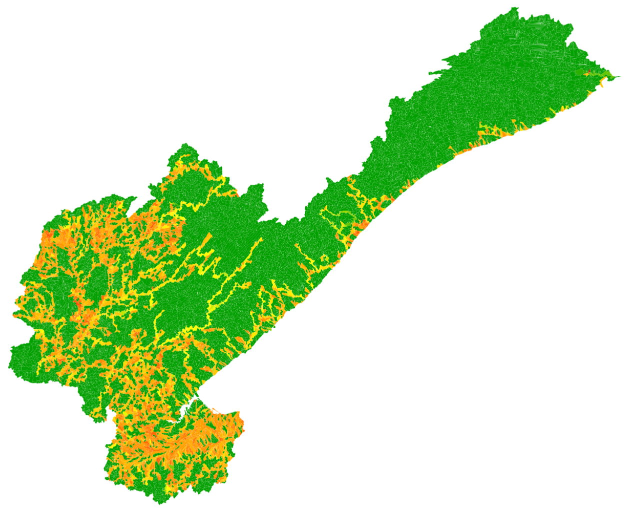


Figure 14: Accumulated crop proportion (log10)

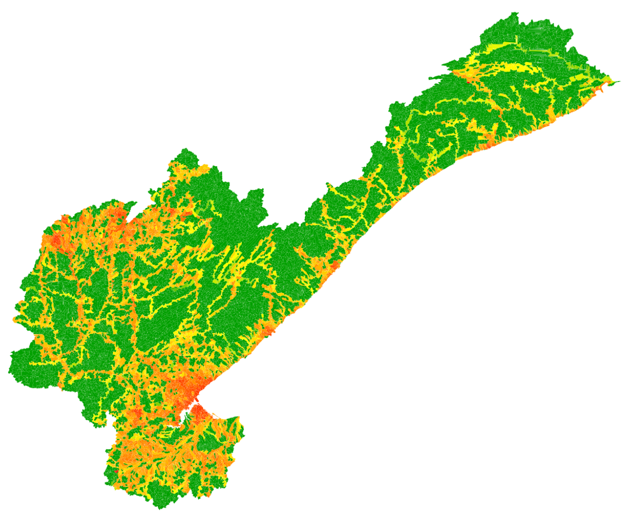


Figure 15: Accumulated dev. proportion (log10)

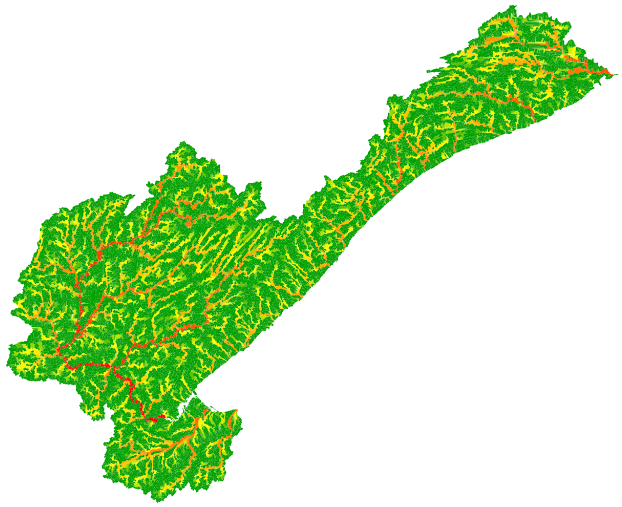


Figure 16: Accumulated steps to lake (log10)

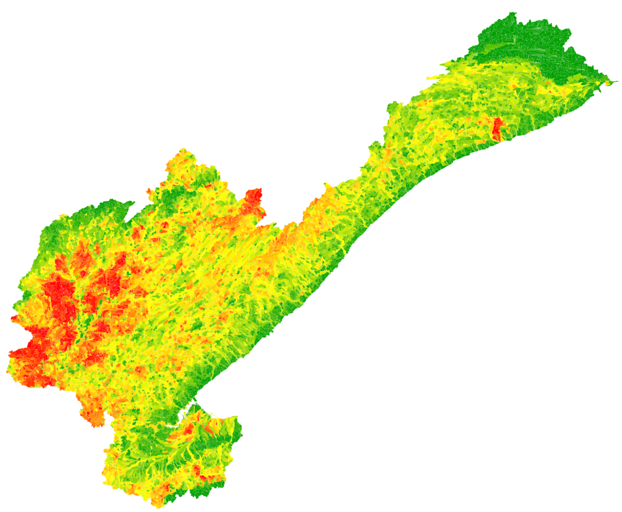


Figure 17: Accumulated percent wetland (linear)

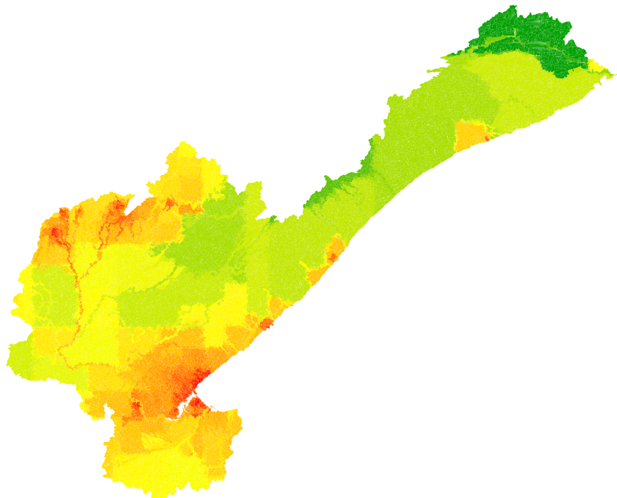


Figure 18: Accumulated people per sq. km (log10)

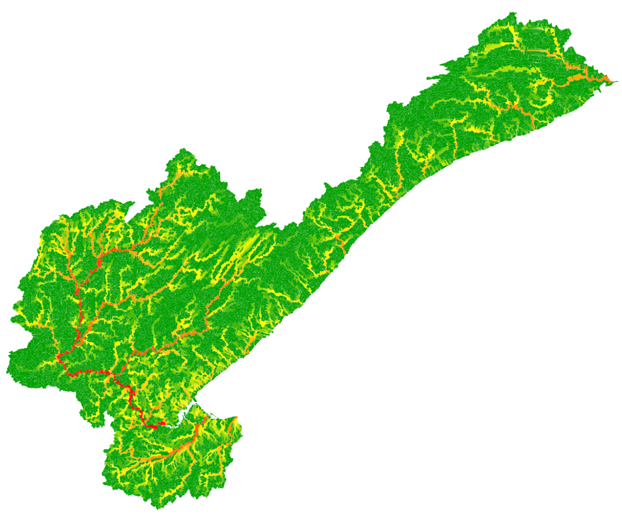


Figure 19: Accumulated road intersections (log10)

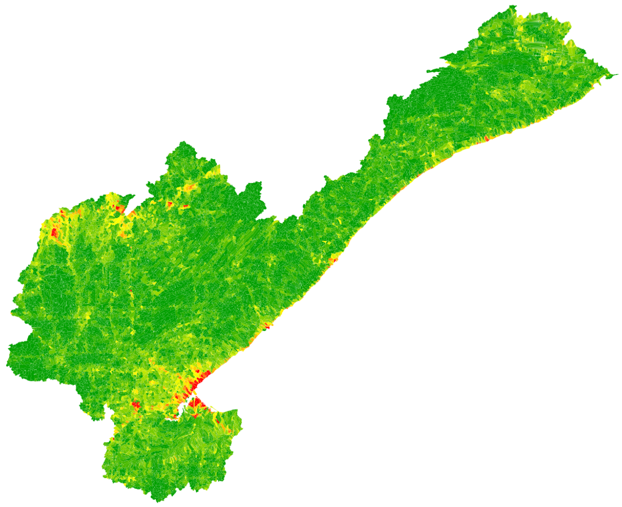


Figure 20: Accumulated road density (linear)

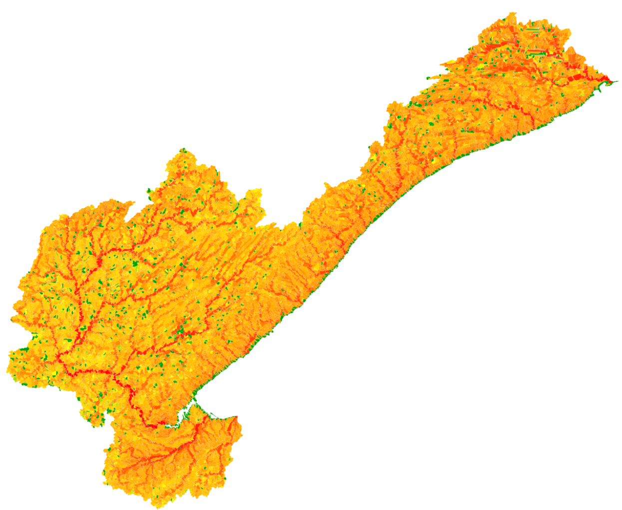


Figure 21: Accumulated stream slope (log10)

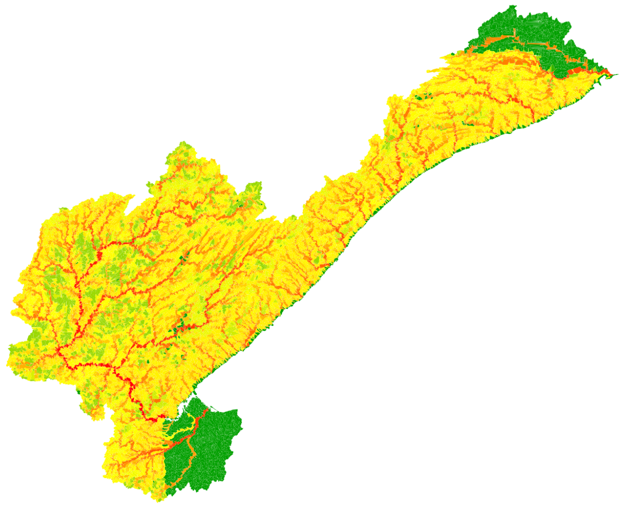


Figure 22: Accumulated stream erodability, KFFACT (log10)

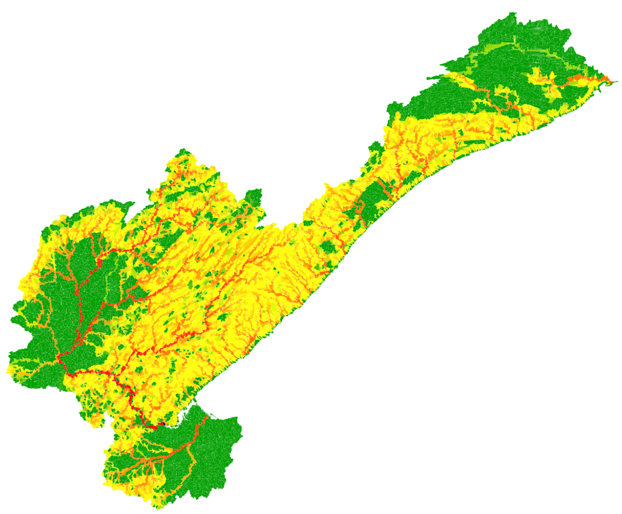


Figure 23: Accumulated stream erodability, Sed. assoc (log10)

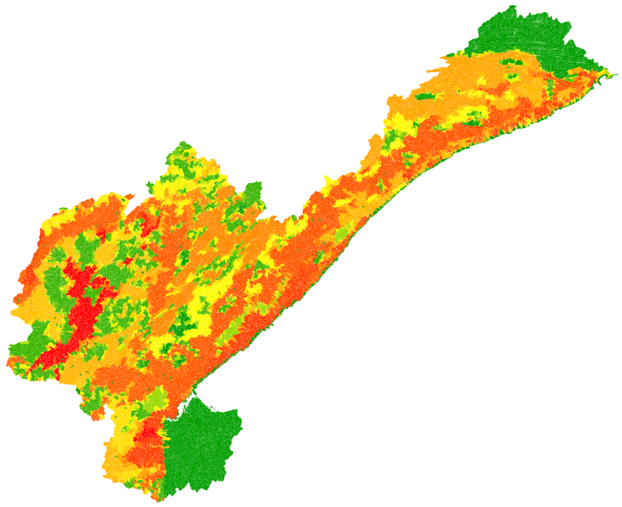


Figure 24: Local bank erodability, KFFACT (linear)

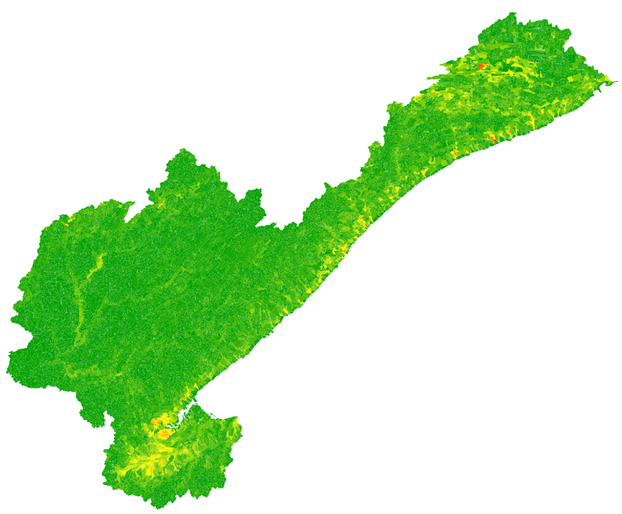


Figure 25: Local bank slope (linear)

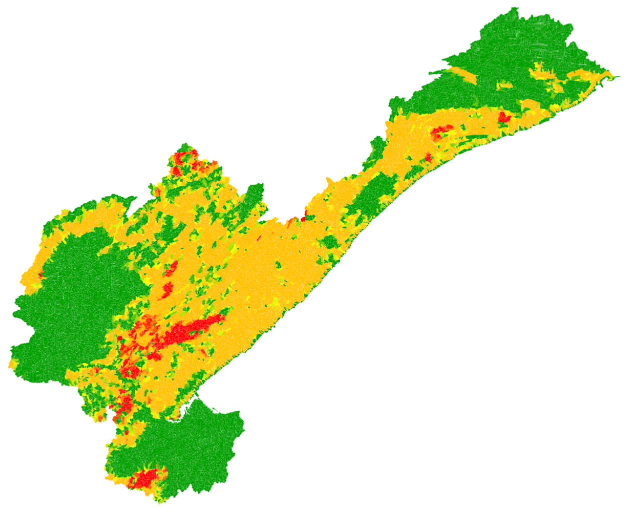


Figure 26: Local bank erodability, Sed. assoc (linear)

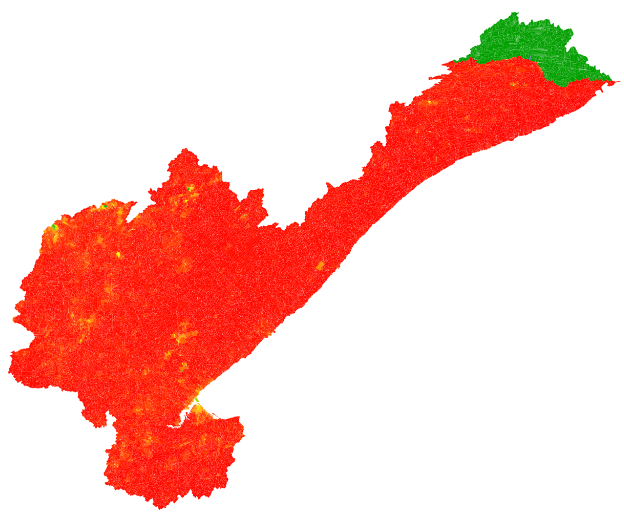


Figure 27: Local canopy percent (log10)

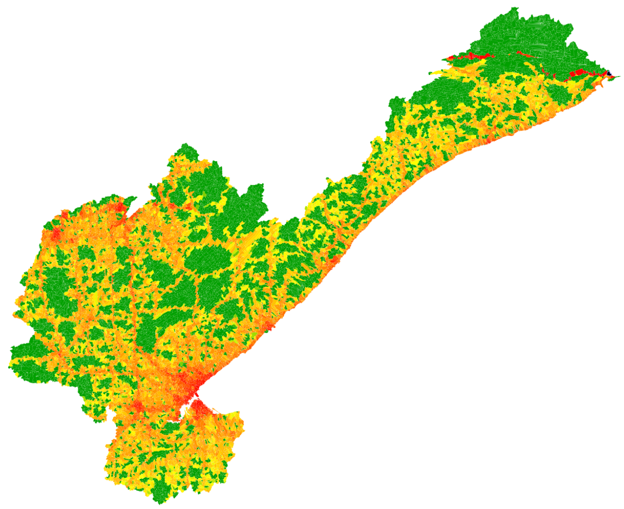


Figure 28: Local imperviousness (log10)

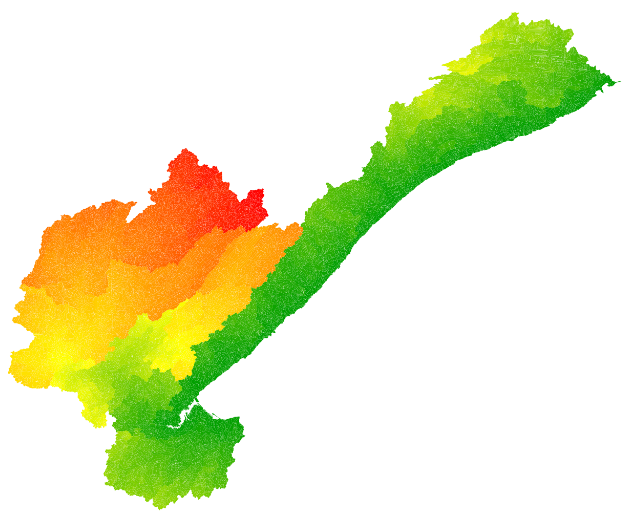


Figure 29: Local Steps to lake (linear)

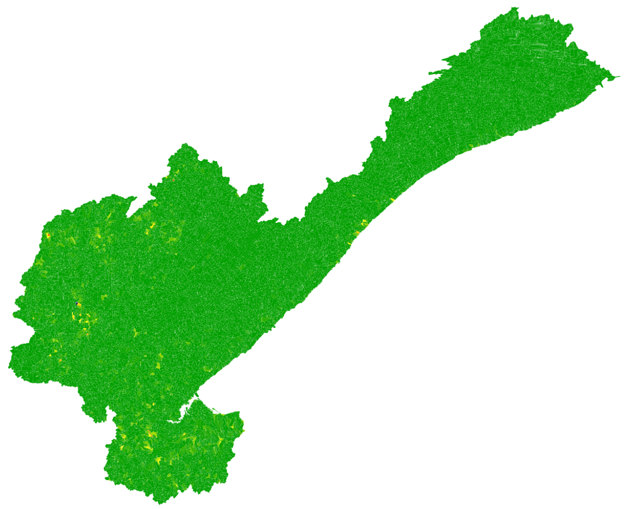


Figure 30: Local crops (linear)

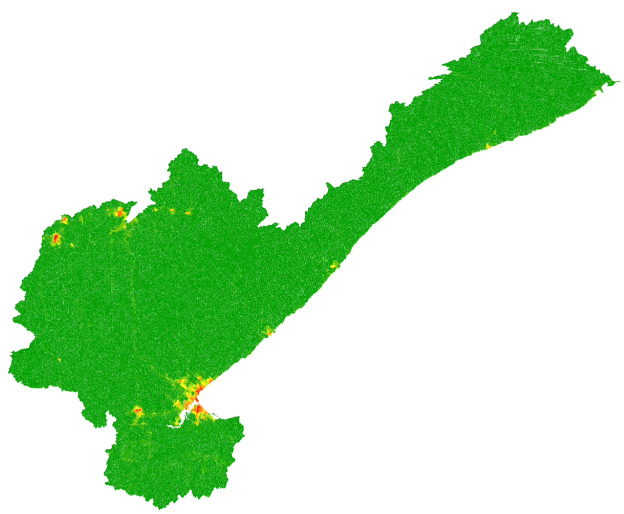


Figure 31: Local dev. (linear)

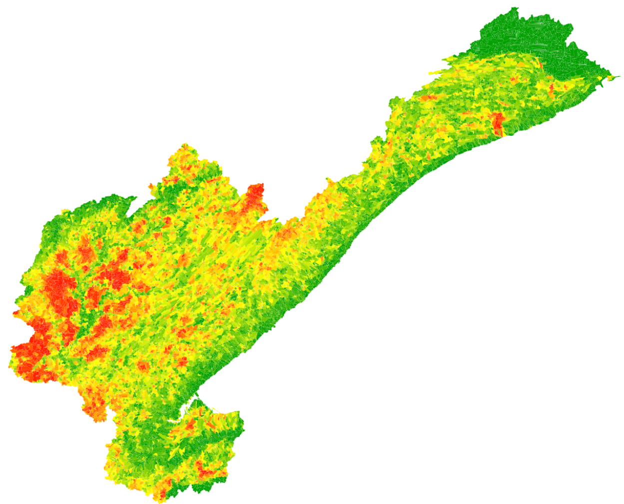


Figure 32: Local percent wetland (linear)

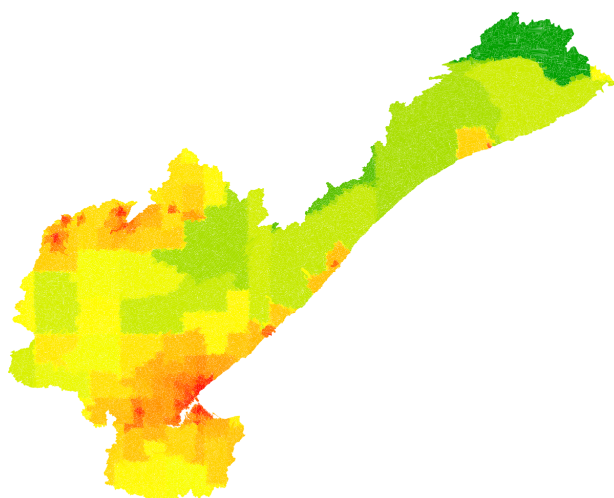


Figure 33: Local people per sq. km (log10)

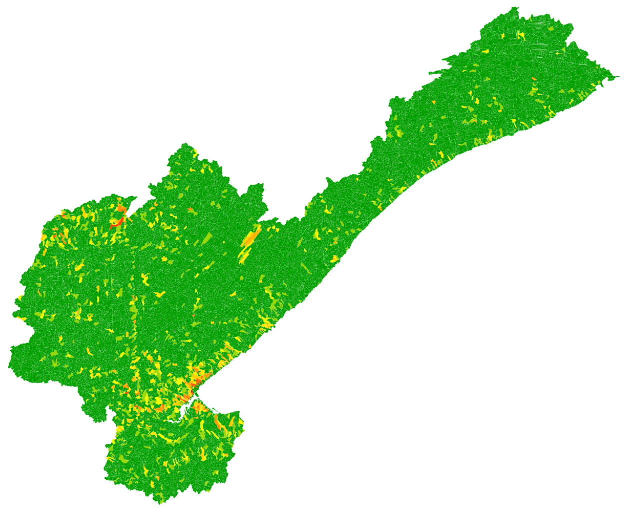


Figure 34: Local road intersections (log10)

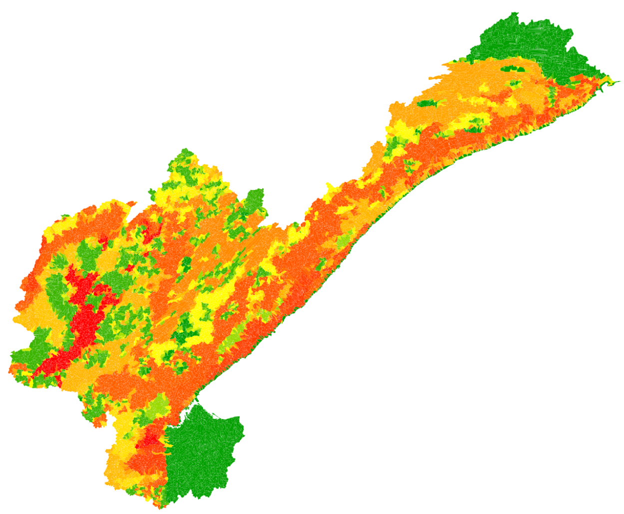


Figure 35: Local stream erodability, KFFACT (linear)

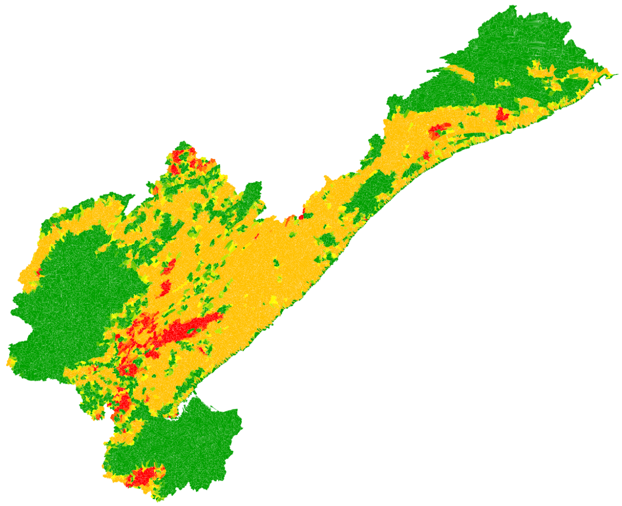


Figure 36: Local stream erodability, Sed. assoc (linear)

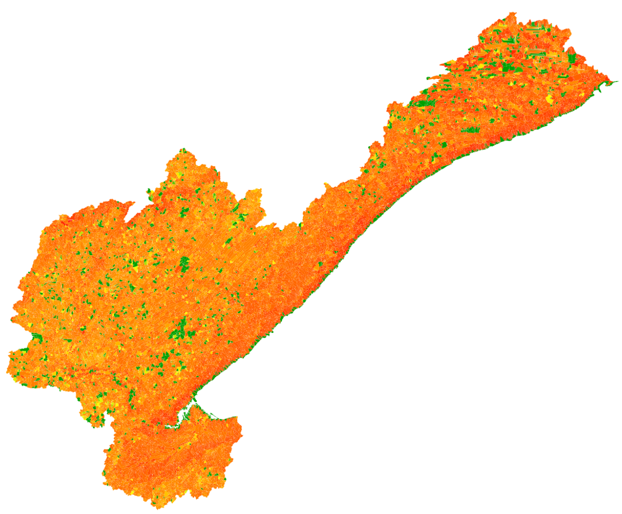


Figure 37: Local stream slope (log10)

SumRel maps

The following maps, generated from the data included with this report, show SumRel scores for ArcHydro subcatchments generated with accumulated and local risk parameters, respectively. Inevitably the accumulated form reflects flow accumulation, so at this scale the local form is probably more informative.

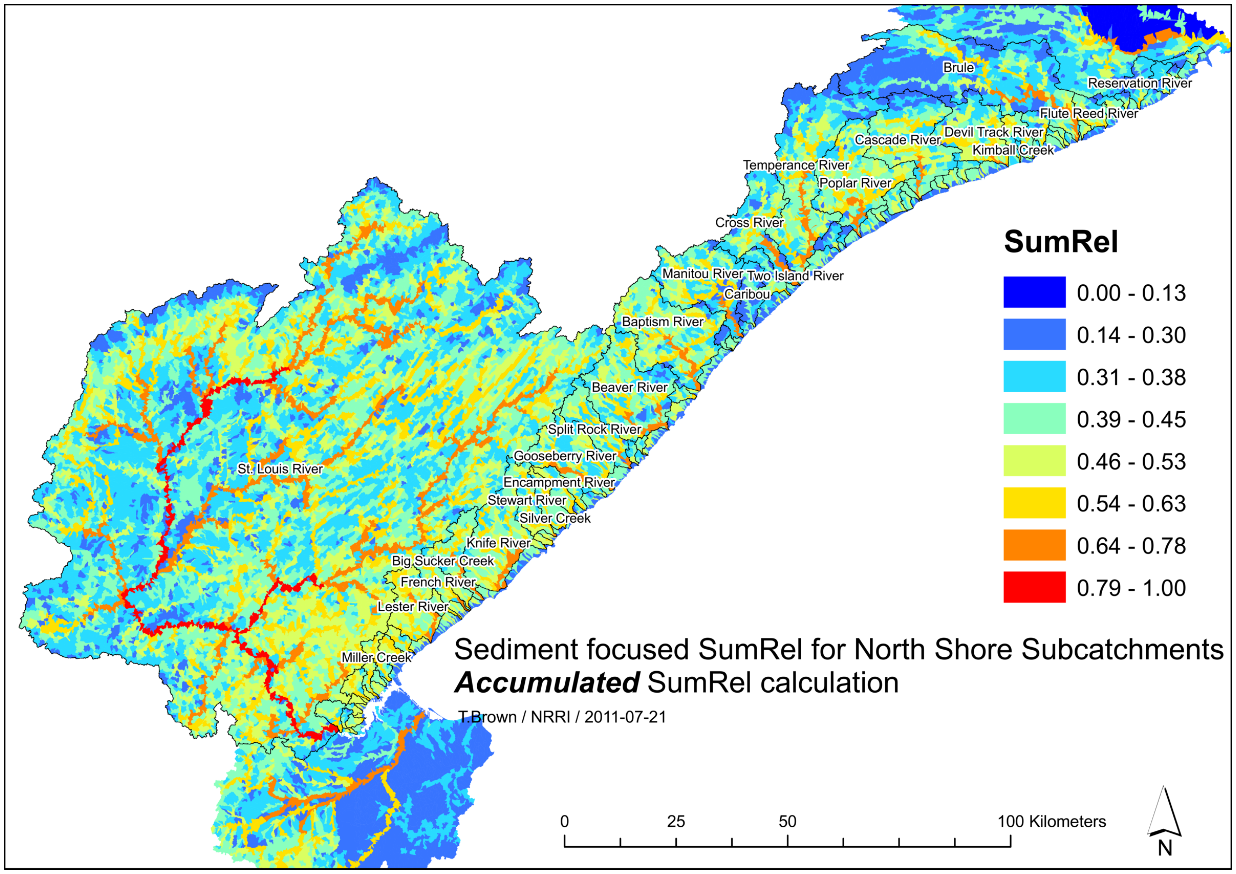


Figure 38: SumRel scores based on accumulated sediment risk variables

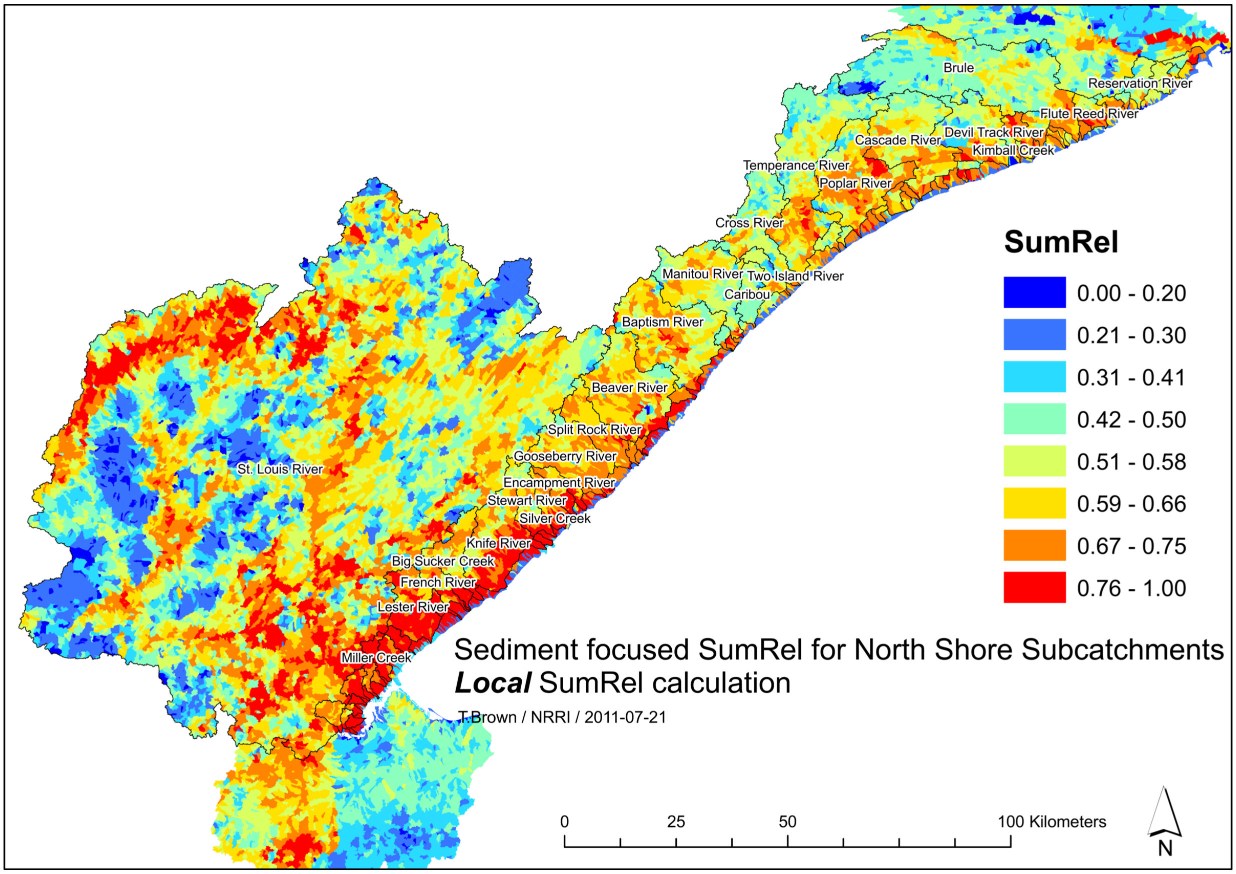


Figure 39: SumRel scores based on local sediment risk variables

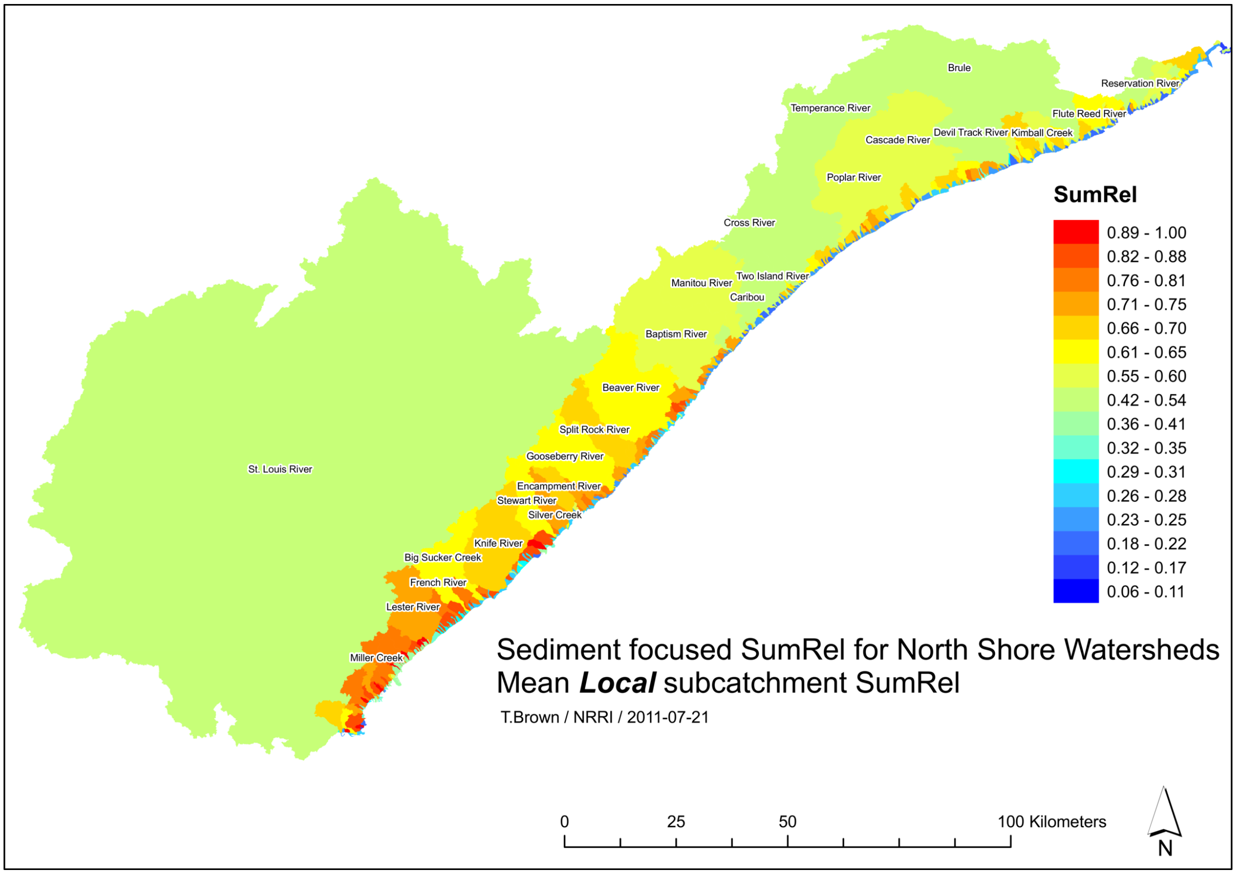


Figure 40: Mean SumRel scores by watershed, based on subcatchment local SumRel scores.

Finally, in the figure above, when viewed at the watershed scale, the mean local subcatchment SumRel shows several interesting spatial patterns. Watersheds can be grouped in four size ranges, (1) the Saint Louis River, (2) larger watersheds (Lester, Gooseberry, Knife, Baptism, etc.), (3) medium sized watersheds, and (4) small watersheds.

The Saint Louis River (1) has, on average, an intermediate sediment generation risk. The large (2) watersheds show a trend of decreasing risk moving up the shore. The medium watersheds (3) show a similar pattern, although their risk is generally higher, reflecting their proximity to the coast and the stressors found there. The smallest watersheds (4) often show low levels of stress, reflecting their small size and consequent tendency to contain few risk factors. The pattern of greater stress in the southern part of the shore is repeated.

Task 5 - Final report / data delivery

The following inputs and outputs for the preceding analyses are included with this report:

`subcatchments_acc.shp` This shapefile contains 18282 subcatchments with the following attributes:

a_* The accumulated form of of one of the attributes listed below

accsumrel SumRel calculated from accumulated parameters

area_m2 Area in square meters of the subcatchment

atom_id The subcatchments unique ID

bkffact The mean STATSGO KFFACT value for the stream context points

bnkslp The mean slope value for the stream context points

bsedero The mean STATSGO sedimentary erosion risk for the stream context points

canpct Percent of subcatchment under tree canopy

down_id atom_id of the immediate downstream subcatchment, < 1 indicates drains to lake

drainsto atom_id of the final downstream subcatchment before the lake

imp Percent imperviousness for the subcatchment

lakehops Number of subcatchments below this one before the lake

lccp Percent of subcatchment in crop landcover (NLCD)

lcdv Percent of subcatchment in developed landcover (NLCD)

locsumrel SumRel calculated from local variables

pctwl Percent of subcatchment in wetland

perim_m Perimeter of subcatchment (m)

ppsk People per square kilometer in subcatchment

rdint Road / stream intersections in subcatchment

skffact The mean STATSGO KFFACT value for the stream channel points

ssedero The mean STATSGO sedimentary erosion risk for the stream channel points

strslp The mean slope value for the stream channel points

uplinks The number of subcatchments draining into this one, usually 0, 1, or 2, but can be 3 or 4

watershed_ A watershed containing this subcatchment. Equivalent to the drainsto value, but more convenient (shorter) numbers

Other attributes present in this shapefile should be ignored.

mpcaaoistr_utm.shp Stream lines for each subcatchment from ArcHydro. The field `atom_id` links these lines to the subcatchment, other fields should be ignored.

streampnts_geol2.shp The stream channel points used for characterizing stream channel slope and STATSGO parameters. Fields of interest are `lat_dist` and `vert_dist`, $\frac{vert\_dist}{lat\_dist}$ is the slope of the stream channel around the point. Other fields can be ignored.

bankpnts_utm.shp The stream context points used for characterizing stream context slope and STATSGO parameters. Fields of interest are `lat_dist` and `vert_dist`, $\frac{vert\_dist}{lat\_dist}$ is the slope of the stream context around the point. Other fields can be ignored.

nsstr.kml As shown below, this KML file acts as an index to a set of KML files representing each stream modeled by ArcHydro along the north shore - it can be viewed in GoogleEarth. To load the KML visualization of a particular stream, click the yellow push-pin icon for that stream, then right click the `load stream` link in the popup balloon, and select “Open Link”.

Blue stream reaches have lower slopes, orange have higher slopes. The particular slope is reported when the stream reach is clicked.

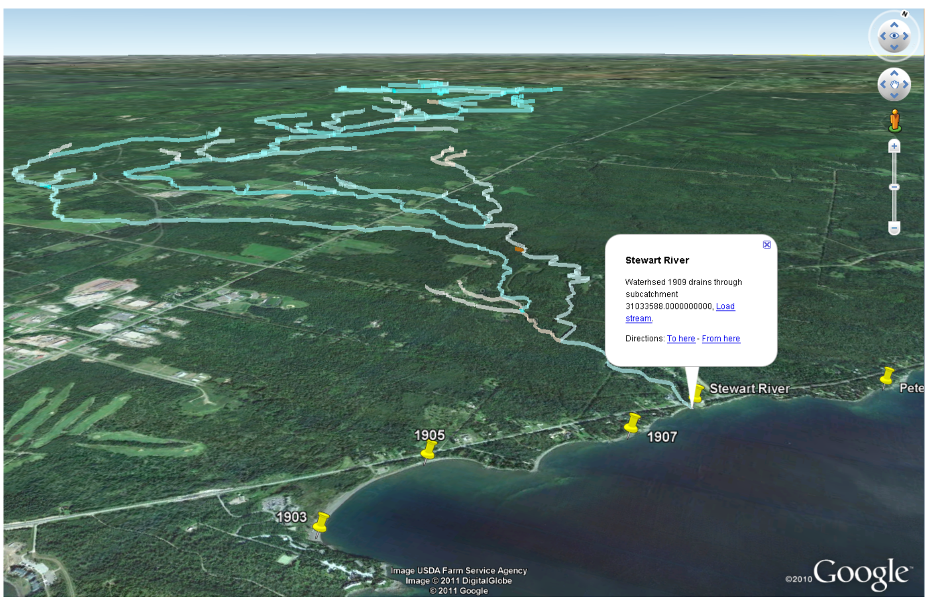


Figure 41: GoogleEarth visualization of streams through the `nsstr.kml` index file.

References

[GLNPO, 2008] GLNPO (2008). High resolution subcatchment characterization of the lake superior basin. http://www.nrri.umn.edu/lsgis2/.

[Host et al., 2011] Host, G. E., Brown, T. N., Johnson, L. B., & Ciborowski, J. J. H. (2011). High-resolution assessment and visualization of environmental stressors in the lake superior basin. *Aquatic Ecosystem Health and Management, in press*.

Appendix I

Mecklenberg Database Summary Forms

Reference Reach	Hints
Stream:	Beaver River, BR1_Downstream
Watershed:	Beaver River Watershed
Location:	North of Beaver Bay MN 5 miles
Latitude:	47.31091
Longitude:	-91.325
County:	Lake
Date:	September 30, 2010
Observers:	Brad Hansen, Sara Johnson
Channel Type:	C4
Drainage Area (sq mi):	
Notes:	BEHI= 40 Pfankuch=78

Dimension

		typical	min	max
Size:	x-area bankfull	62.4	---	---
	width bankfull	29.0	---	---
	mean depth	2.2	---	---
Ratios:	Width/Depth Ratio	13.5	---	---
	Entrenchment Ratio	6.9	---	---
	Riffle Max Depth Ratio	1.2	---	---
	Bank Height Ratio	---		

Hydraulics:	riffle	pool	run
discharge rate, Q (cfs)	---	---	---
velocity (ft/sec)	---	---	---
relative roughness	16.7	---	---

Pattern

	typical	min	max
Sinuosity	---		

Channel Materials

	total	riffle	pool	run	glide	bar sample
D16	1.963	---	---	---	---	---
D35	8.60	---	---	---	---	---
D50	13.1	---	---	---	---	---
D84	39.3	---	---	---	---	---
D95	57.8	---	---	---	---	---
Largest Bar						0
% Silt/Clay	1%	---	---	---	---	---
% Sand	15%	---	---	---	---	---
% Gravel	81%	---	---	---	---	---
% Cobble	3%	---	---	---	---	---
% Boulder	0%	---	---	---	---	---
% Bedrock	0%	---	---	---	---	

Reference Reach	Hints
Stream:	Beaver River, East Branch (U/S site)
Watershed:	Beaver River Watershed
Location:	North of Beaver Bay 6 miles
Latitude:	47.323
Longitude:	-91.348
County:	Lake
Date:	September 30, 2010
Observers:	Brad Hansen, Sara Johnson
Channel Type:	B3c
Drainage Area (sq mi):	
Notes:	BEHI = 16.6 Pfankuch = 49

Dimension

		typical	min	max
Size:	x-area bankfull	80.3	---	---
	width bankfull	38.1	---	---
	mean depth	2.1	---	---
Ratios:	Width/Depth Ratio	18.0	---	---
	Entrenchment Ratio	1.6	---	---
	Riffle Max Depth Ratio	1.2	---	---
	Bank Height Ratio	1.0		
Hydraulics:		riffle	pool	run
	discharge rate, Q (cfs)	439.0	439.0	439.0
	velocity (ft/sec)	5.5	---	---
	relative roughness	---	---	---

Pattern

	typical	min	max
Sinuosity	---		

Channel Materials

	total	riffle	pool	run	glide	bar sample
D16	1.963	---	---	---	---	---
D35	8.60	---	---	---	---	---
D50	13.1	---	---	---	---	---
D84	39.3	---	---	---	---	---
D95	57.8	---	---	---	---	---
Largest Bar						0
% Silt/Clay	1%	---	---	---	---	---
% Sand	15%	---	---	---	---	---
% Gravel	81%	---	---	---	---	---
% Cobble	3%	---	---	---	---	---
% Boulder	0%	---	---	---	---	---
% Bedrock	0%	---	---	---	---	

Reference Reach	Hints

Stream:	**Beaver River, BR5_West Branch**
Watershed:	**Beaver River Watershed**
Location:	**Co. Rd. 3**
Latitude:	**47.2540**
Longitude:	**-91.3790**
County:	**Lake**
Date:	**September 14, 2010**
Observers:	**Brad Hansen, Danielle Dutton**
Channel Type:	**C4**
Drainage Area (sq mi):	
Notes:	BEHI=31 Pfankuck=98

Dimension

		typical	min	max
Size:	x-area bankfull	54.2	---	---
	width bankfull	29.0	---	---
	mean depth	1.9	---	---
Ratios:	Width/Depth Ratio	15.5	---	---
	Entrenchment Ratio	6.9	---	---
	Riffle Max Depth Ratio	1.4	---	---
	Bank Height Ratio	1.3		

Hydraulics:	riffle	pool	run
discharge rate, Q (cfs)	---	---	---
velocity (ft/sec)	---	---	---
relative roughness	11.8	---	---

Pattern

	typical	min	max
Sinuosity	---		

Channel Materials

	total	riffle	pool	run	glide	bar sample
D16	0.688	0.000	0.000	0.0	0.0	---
D35	7.74	0.00	0.00	0	0	---
D50	16.3	0.0	0.0	0	0	---
D84	48.2	0	0	0	0	---
D95	90.5	0	0	0	0	---
Largest Bar						0
% Silt/Clay	3%	---	---	---	---	---
% Sand	21%	---	---	---	---	---
% Gravel	65%	---	---	---	---	---
% Cobble	9%	---	---	---	---	---
% Boulder	2%	---	---	---	---	---
% Bedrock	0%	---	---	---	---	

Mecklenberg Database Summary Forms

Reference Reach | Hints

Stream:	**Encampment River (EC2)**
Watershed:	**Encampment River Watershed**
Location:	**Upstream road culvert. TWSHIP 34 or Clark road**
Latitude:	**47.139**
Longitude:	**-91.603**
County:	**Lake**
Date:	**September 14, 2010**
Observers:	**Brad Hansen, Danielle Dutton**
Channel Type:	**B3c**
Drainage Area (sq mi):	
Notes:	BEHI=18 Pfankuch=57

Dimension

		typical	min	max
Size:	x-area bankfull	22.6	---	---
	width bankfull	19.9	---	---
	mean depth	1.1	---	---
Ratios:	Width/Depth Ratio	17.4	---	---
	Entrenchment Ratio	2.5	---	---
	Riffle Max Depth Ratio	1.5	---	---
	Bank Height Ratio	0.8		

Hydraulics:	riffle	pool	run
discharge rate, Q (cfs)	---	---	---
velocity (ft/sec)	---	---	---
relative roughness	2.1	---	---

Pattern

	typical	min	max
Sinuosity	---		

Channel Materials

	total	riffle	pool	run	glide	bar sample
D16	12.309	0.000	0.000	0.0	0.0	---
D35	44.37	0.00	0.00	0	0	---
D50	78.8	0.0	0.0	0	0	---
D84	166.7	0	0	0	0	---
D95	252.3	0	0	0	0	---
Largest Bar						0
% Silt/Clay	4%	---	---	---	---	---
% Sand	6%	---	---	---	---	---
% Gravel	31%	---	---	---	---	---
% Cobble	49%	---	---	---	---	---
% Boulder	4%	---	---	---	---	---
% Bedrock	6%	---	---	---	---	

Mecklenberg Database Summary Forms

Reference Reach	Hints
Stream:	Knife River (KN1)
Watershed:	Knife River Watershed
Location:	5 miles west of Two Harbors
Latitude:	47.012
Longitude:	-91.752
County:	Lake
Date:	September 29, 2010
Observers:	Brad Hansen, Sara Johnson, Danielle Dutton
Channel Type:	C4
Drainage Area (sq mi):	
Notes:	BEHI score = 20 Pfankuch = 54

Dimension

		typical	min	max
Size:	x-area bankfull	20.8	---	---
	width bankfull	22.6	---	---
	mean depth	0.9	---	---
Ratios:	Width/Depth Ratio	24.5	---	---
	Entrenchment Ratio	2.3	---	---
	Riffle Max Depth Ratio	2.0	---	---
	Bank Height Ratio	---		
Hydraulics:		riffle	pool	run
	discharge rate, Q (cfs)	114.5	---	---
	velocity (ft/sec)	5.5	---	---
	relative roughness	5.9	---	---

Pattern

	typical	min	max
Sinuosity	1.5		

Channel Materials

	total	riffle	pool	run	glide	bar sample
D16	1.959	0.000	0.000	---	0.0	---
D35	8.58	0.00	0.00	---	0	---
D50	17.3	0.0	0.0	---	0	---
D84	47.6	0	0	---	0	---
D95	93.8	0	0	---	0	---
Largest Bar						0
% Silt/Clay	1%	---	---	---	---	---
% Sand	15%	---	---	---	---	---
% Gravel	74%	---	---	---	---	---
% Cobble	10%	---	---	---	---	---
% Boulder	0%	---	---	---	---	---
% Bedrock	0%	---	---	---	---	

Mecklenberg Database Summary Forms

Reference Reach	Hints
Stream:	Stanley Creek (SN1)
Watershed:	Knife River Watershed
Location:	South west of Two Harbors 10 miles
Latitude:	47.001
Longitude:	-91.847
County:	St. Louis
Date:	September 30, 2010
Observers:	Brad Hansen
Channel Type:	E3-4
Drainage Area (sq mi):	
Notes:	BEHI = 15 Pfankuch 64

Dimension

		typical	min	max
Size:	x-area bankfull	12.4	---	---
	width bankfull	9.2	---	---
	mean depth	1.3	---	---
Ratios:	Width/Depth Ratio	6.8	---	---
	Entrenchment Ratio	6.5	---	---
	Riffle Max Depth Ratio	1.4	---	---
	Bank Height Ratio	---		

Hydraulics:	riffle	pool	run
discharge rate, Q (cfs)	56.2	56.2	56.2
velocity (ft/sec)	4.5	---	---
relative roughness	3.9	---	---

Pattern

	typical	min	max
Sinuosity	---		

Channel Materials

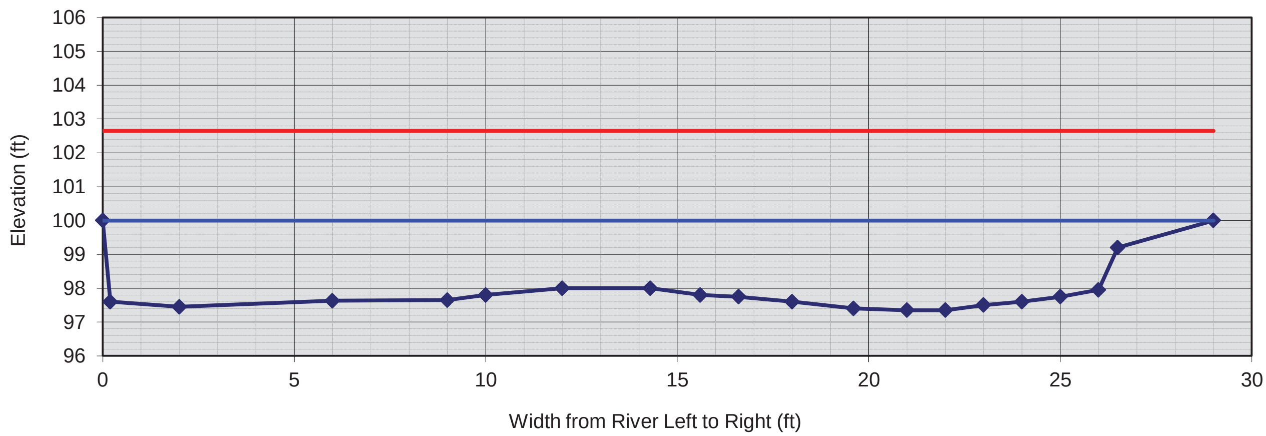
	total	riffle	pool	run	glide	bar sample
D16	0.264	0.000	0.000	---	---	0.2
D35	11.42	0.00	0.00	---	---	4
D50	28.2	0.0	0.0	---	---	10
D84	104.3	0	0	---	---	28
D95	230.3	0	0	---	---	86
Largest Bar						0
% Silt/Clay	0%	---	---	---	---	4%
% Sand	27%	---	---	---	---	26%
% Gravel	38%	---	---	---	---	61%
% Cobble	31%	---	---	---	---	4%
% Boulder	4%	---	---	---	---	4%
% Bedrock	0%	---	---	---	---	

Cross sectional surveys - Level II Sites

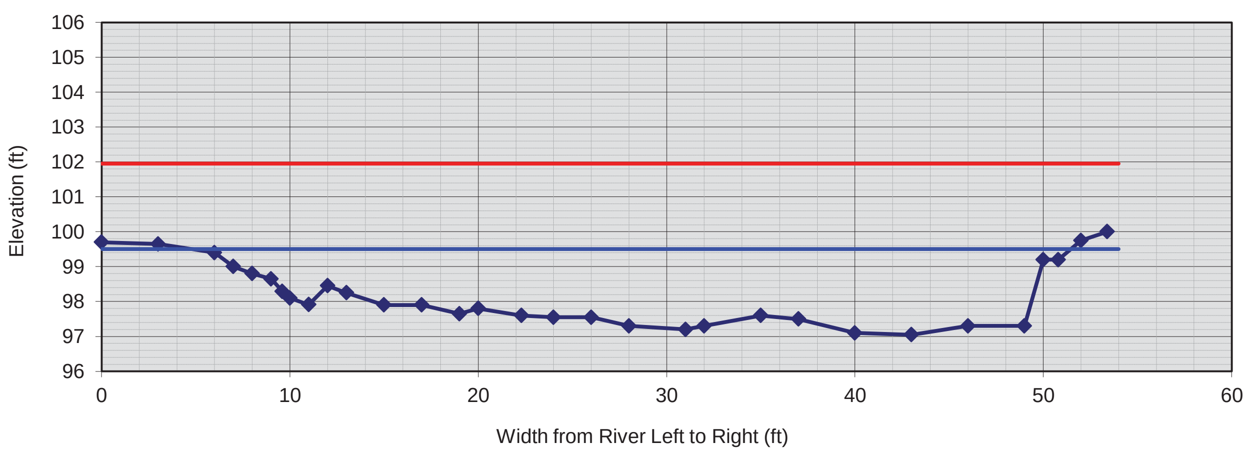
Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

Cross Sections: Beaver River, BR1_Downstream

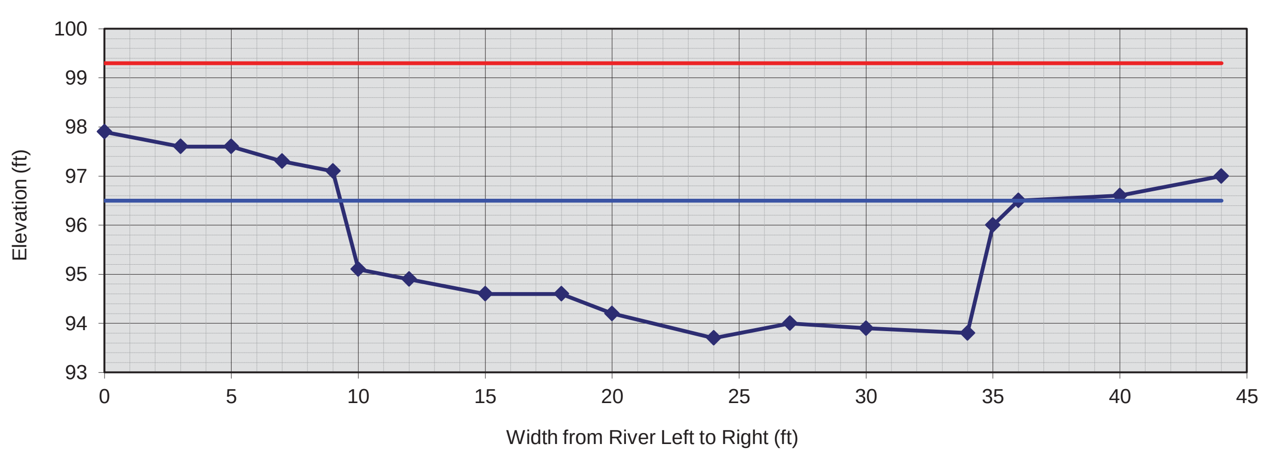
Section 1: Riffle Beaver



Section 2: Riffle Beaver



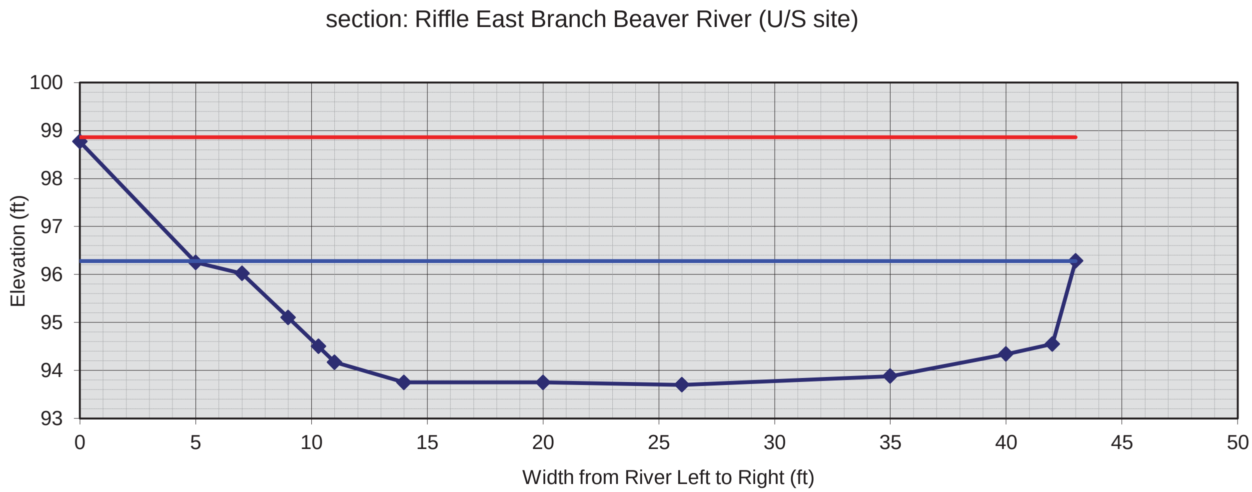
Section 3: Riffle Beaver

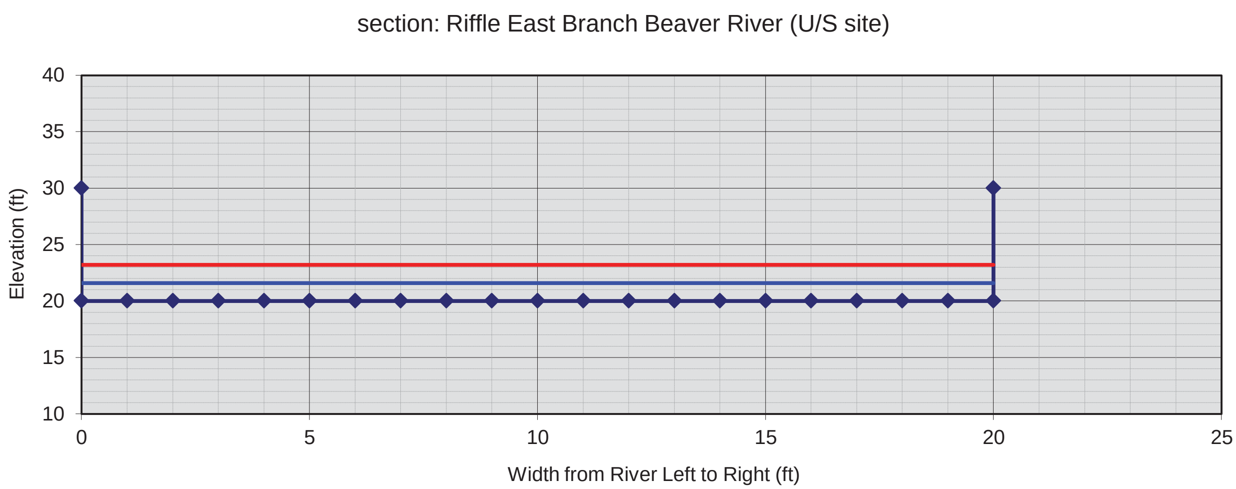


Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

Cross Sections: Beaver River, BR_East Branch

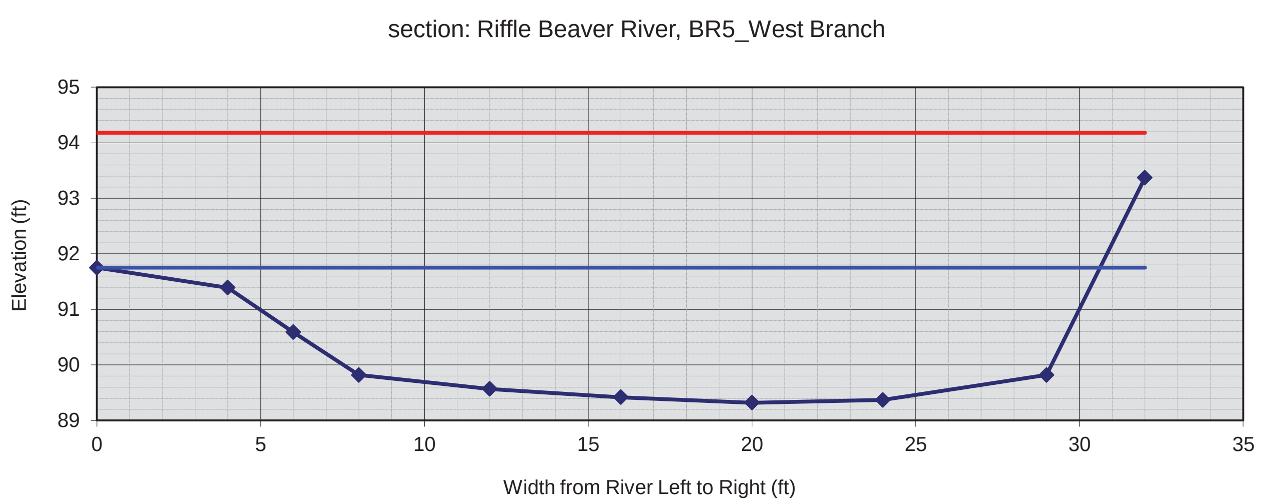


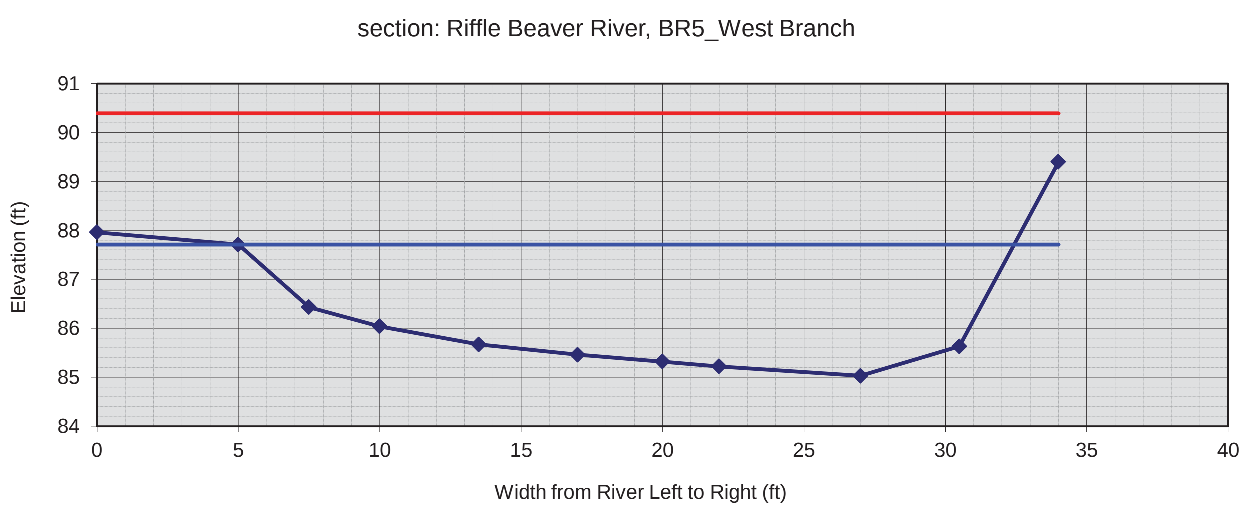


Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

Cross Sections: Beaver River, BR5_West Branch

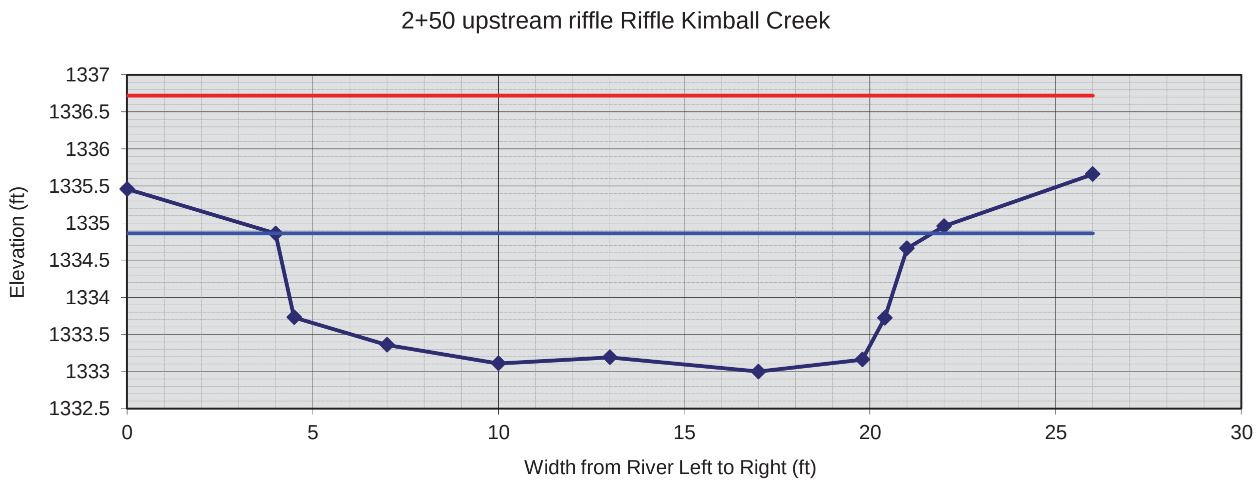




Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

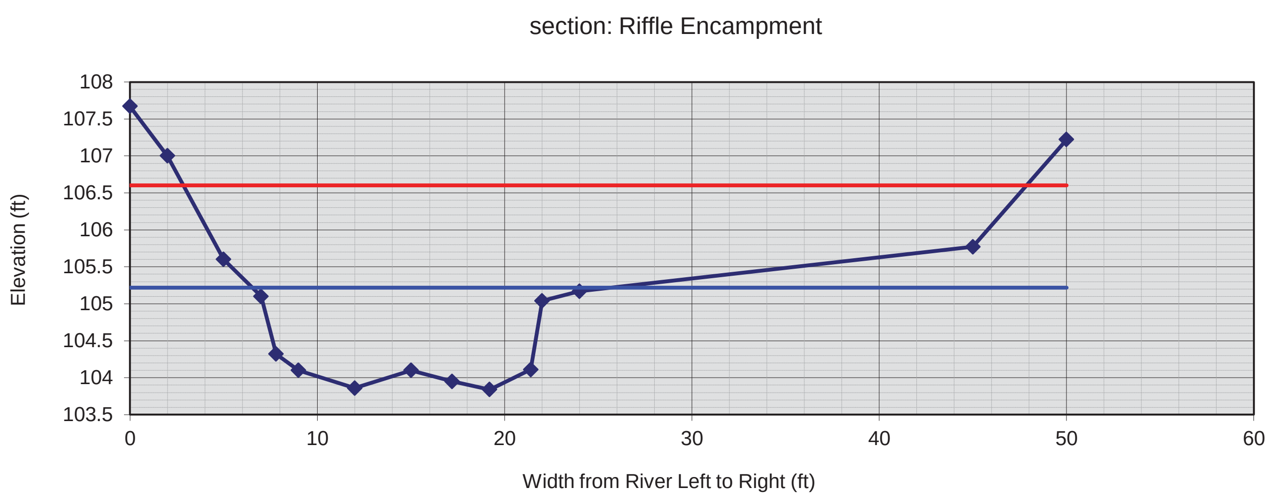
Cross Section: Kimball Creek

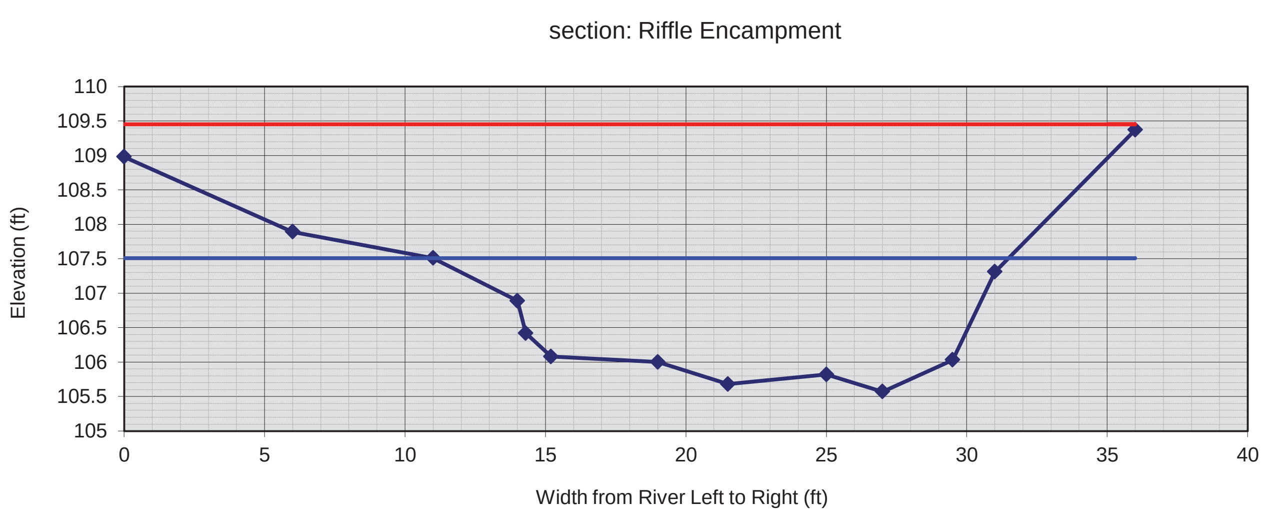


Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

Cross Sections: Encampment River

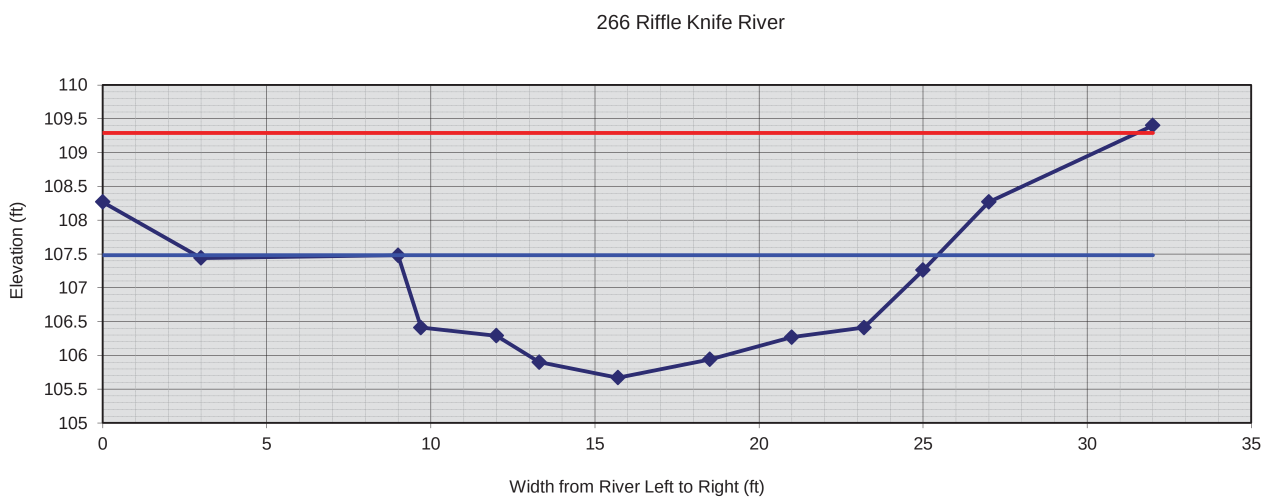


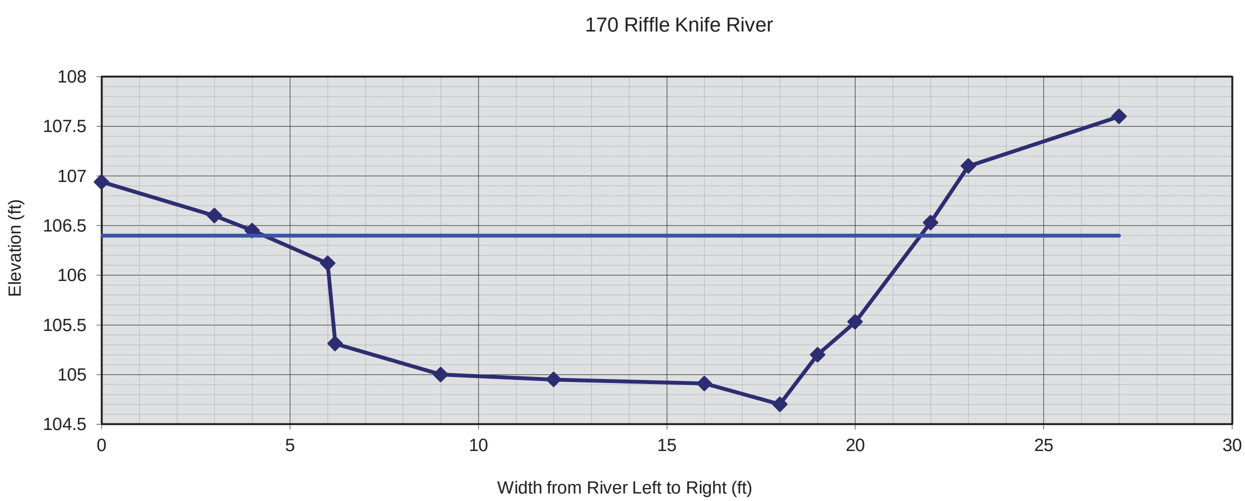


Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

Cross Sections: Knife River, KN1

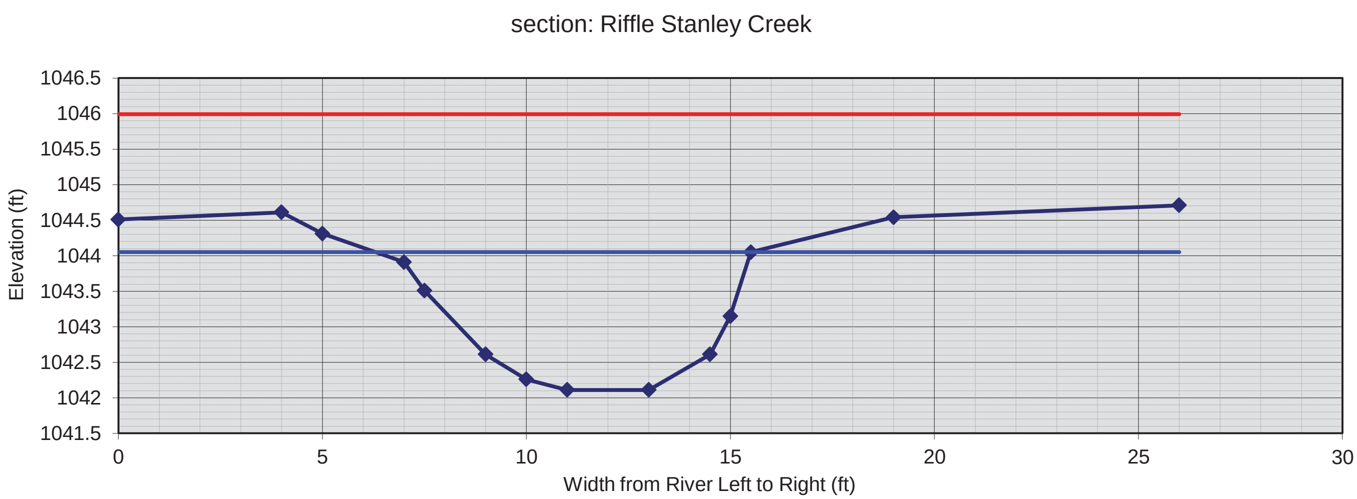




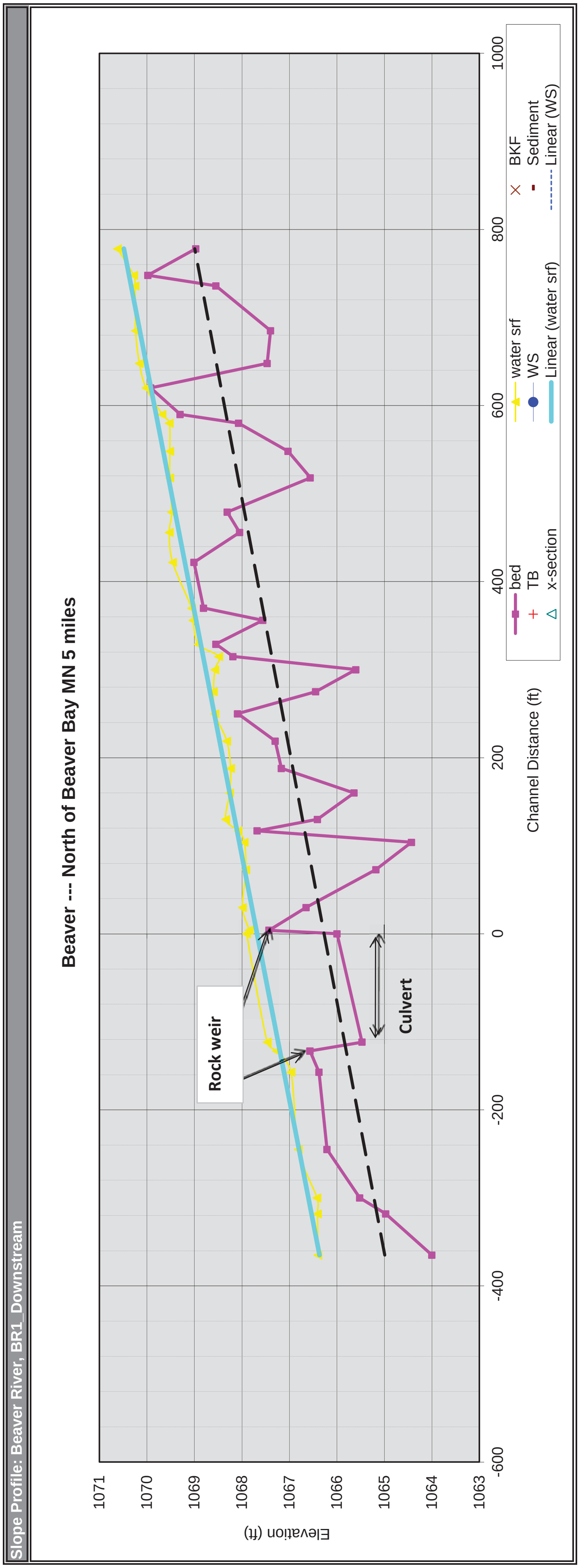
Cross sectional surveys - Level II Sites

Dark Blue - Cross sectional profile **Light Blue** - Bankfull Height **Red** - Floodprone Height

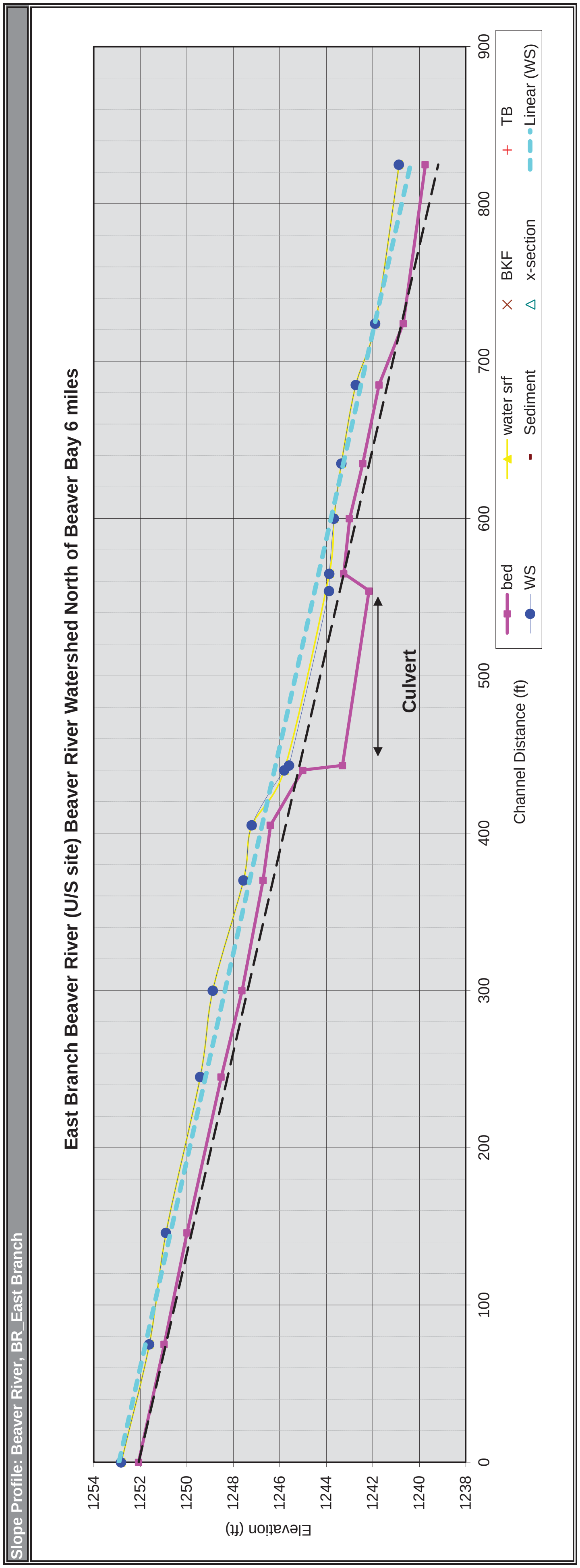
Cross Section: Stanley Creek, SN1



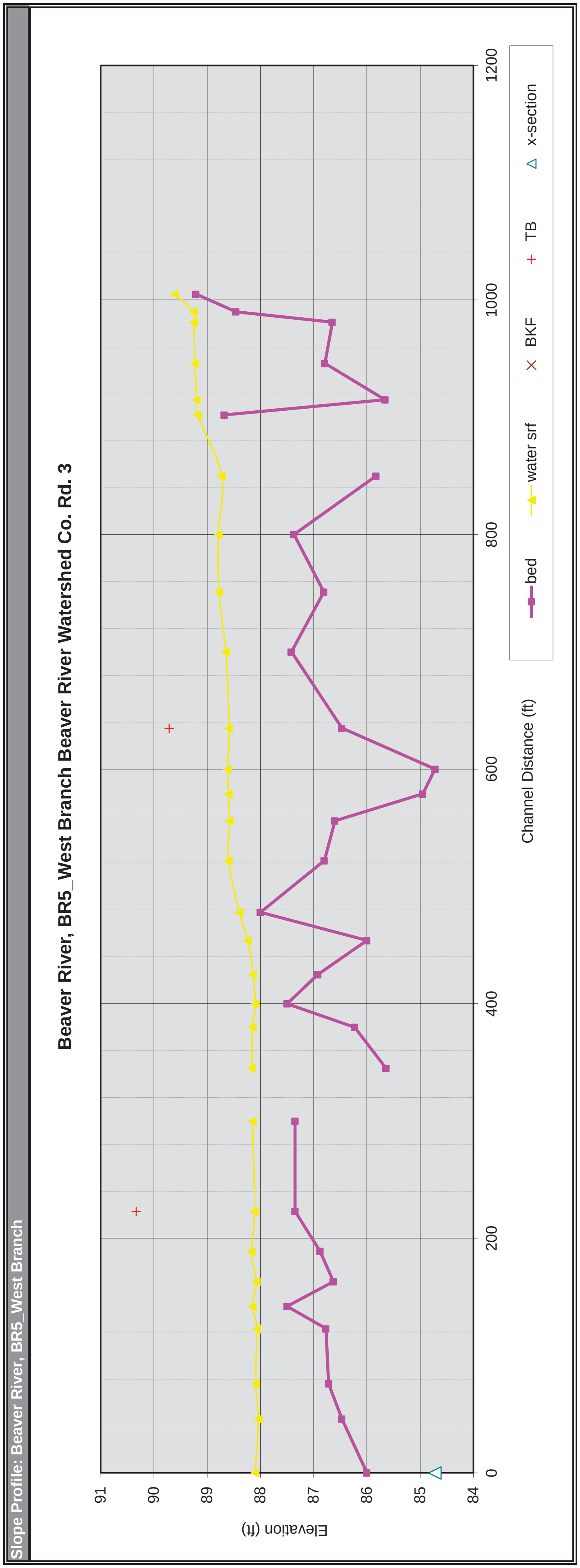
Longitudinal Site Surveys



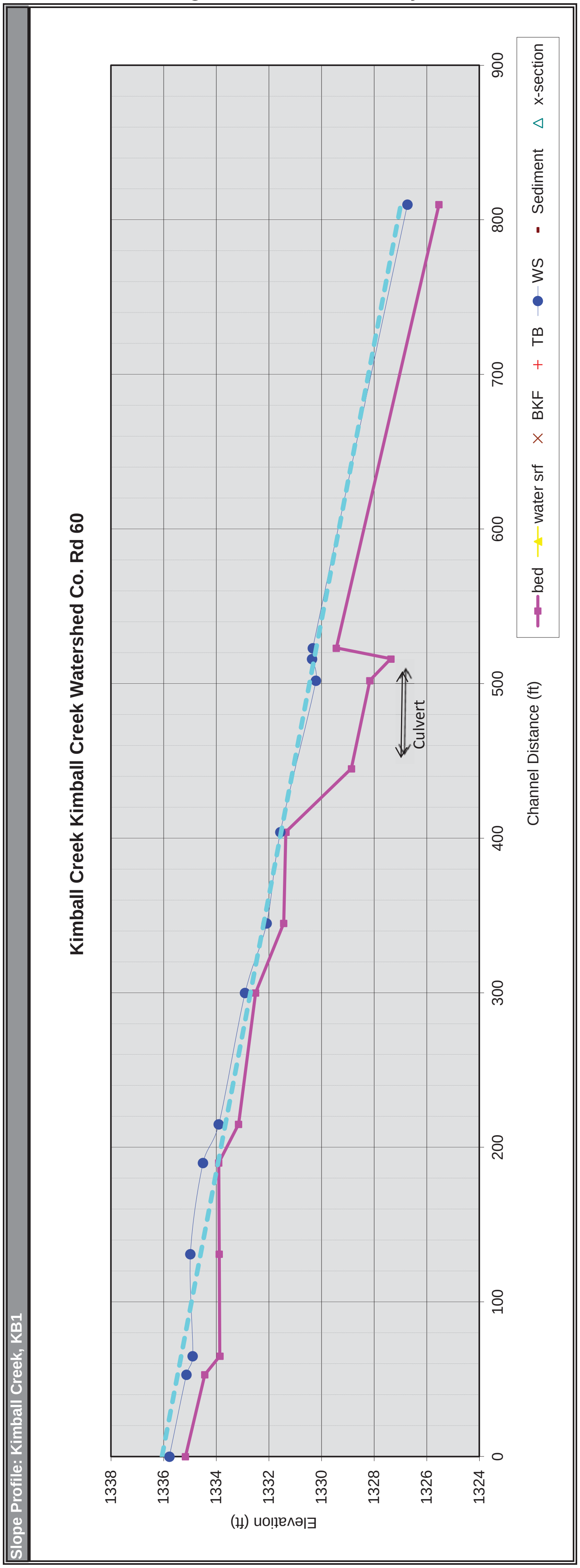
Longitudinal Site Surveys



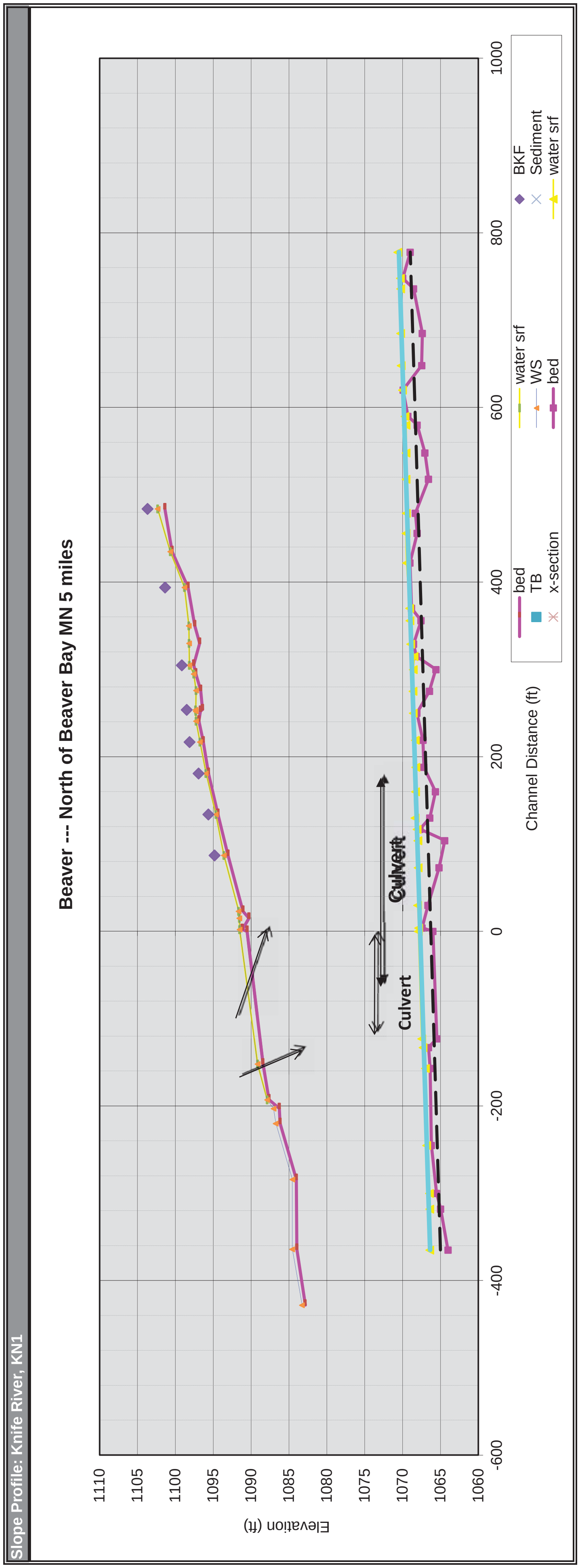
Longitudinal Site Surveys



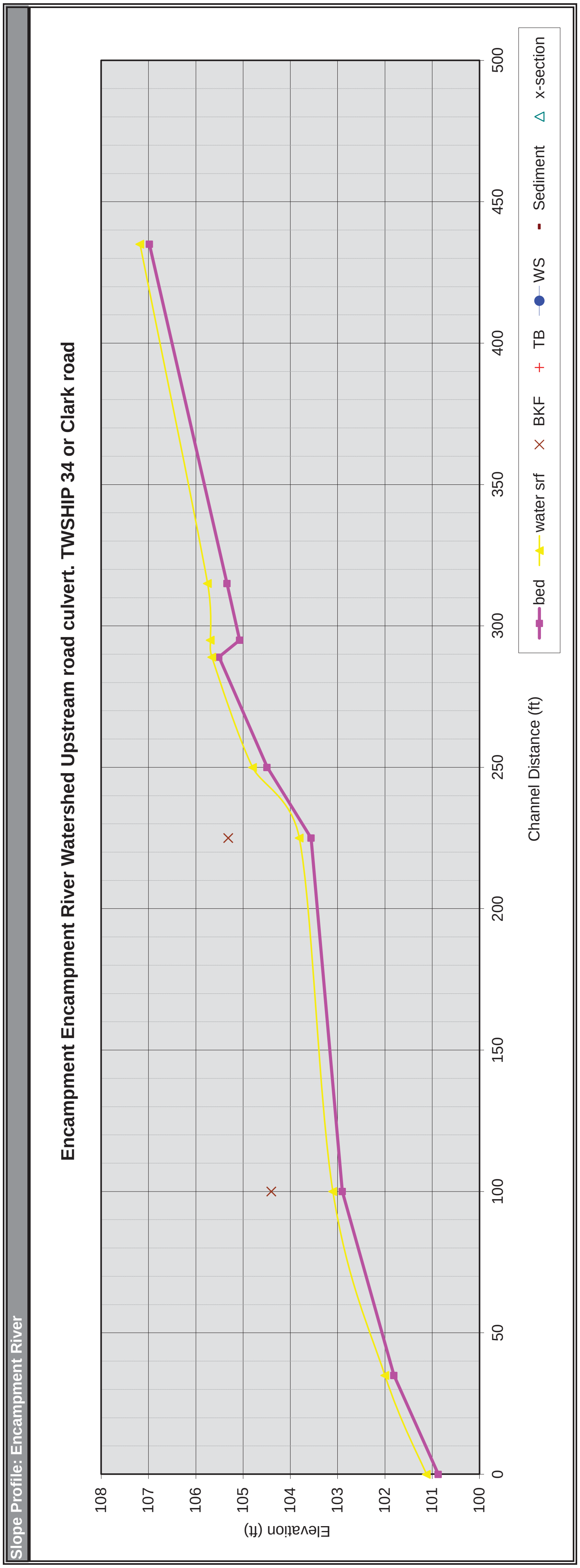
Longitudinal Site Surveys



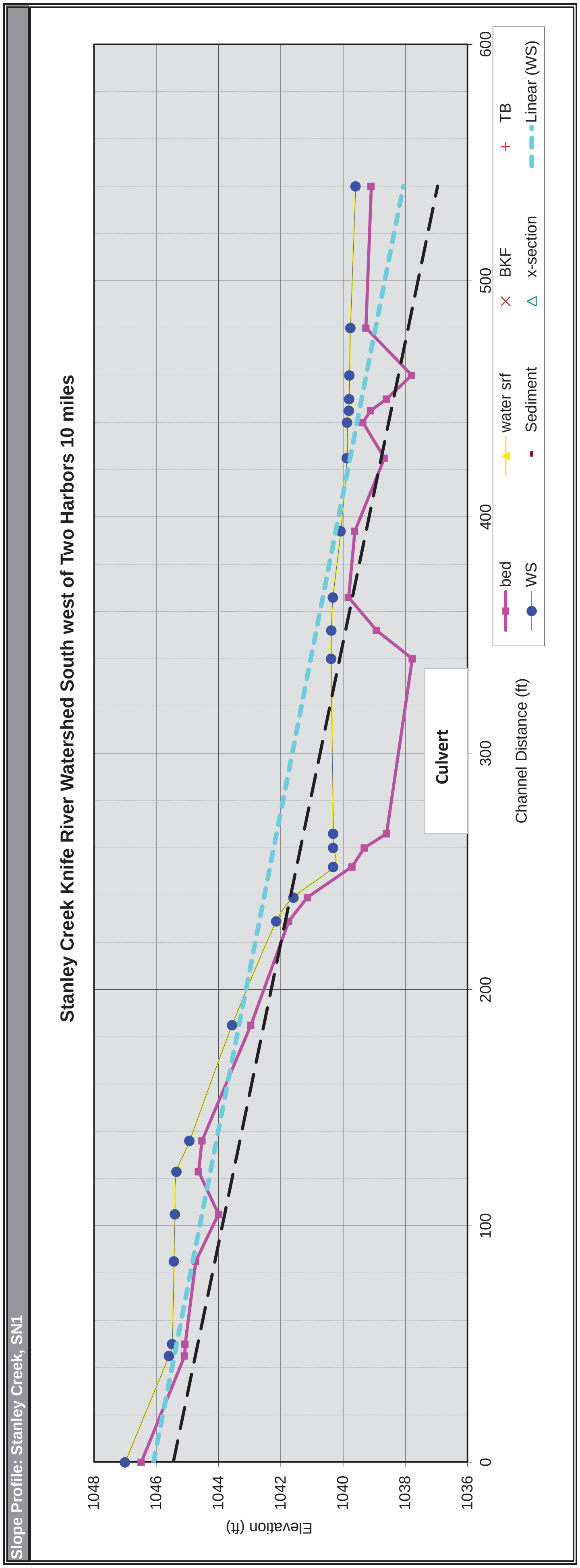
Longitudinal Site Surveys



Longitudinal Site Surveys



Longitudinal Site Surveys



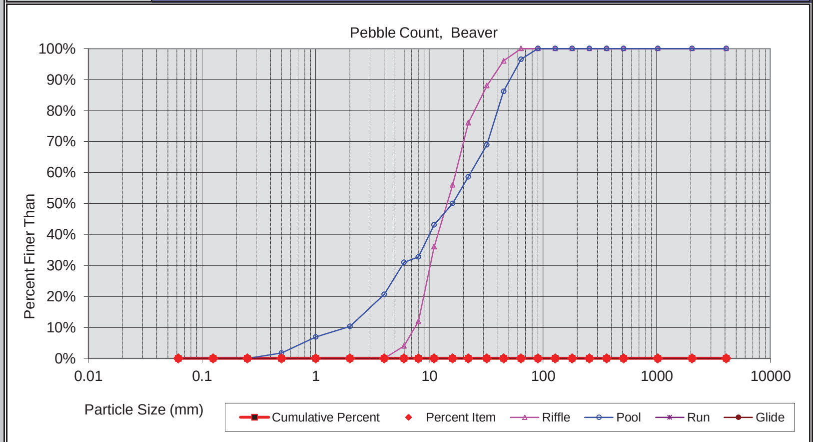
Pebble Count Data Summary

Weighted Pebble Count

Percent Riffle:		Percent Run:	
Percent Pool:		Percent Glide:	

	Beaver River, BR1_Downstream
	Beaver River Watershed
	North of Beaver Bay MN 5 miles
Note:	

Material	Size Range (mm)		Total #
silt/clay	0	0.062	0.0
very fine sand	0.062	0.13	0.0
fine sand	0.13	0.25	0.0
medium sand	0.25	0.5	0.0
coarse sand	0.5	1	0.0
very coarse sand	1	2	0.0
very fine gravel	2	4	0.0
fine gravel	4	6	0.0
fine gravel	6	8	0.0
medium gravel	8	11	0.0
medium gravel	11	16	0.0
coarse gravel	16	22	0.0
coarse gravel	22	32	0.0
very coarse gravel	32	45	0.0
very coarse gravel	45	64	0.0
small cobble	64	90	0.0
medium cobble	90	128	0.0
large cobble	128	180	0.0
very large cobble	180	256	0.0
small boulder	256	362	0.0
small boulder	362	512	0.0
medium boulder	512	1024	0.0
large boulder	1024	2048	0.0
very large boulder	2048	4096	0.0
bedrock			0.0
Weighted Count:			0
True Total Particle Count:			83



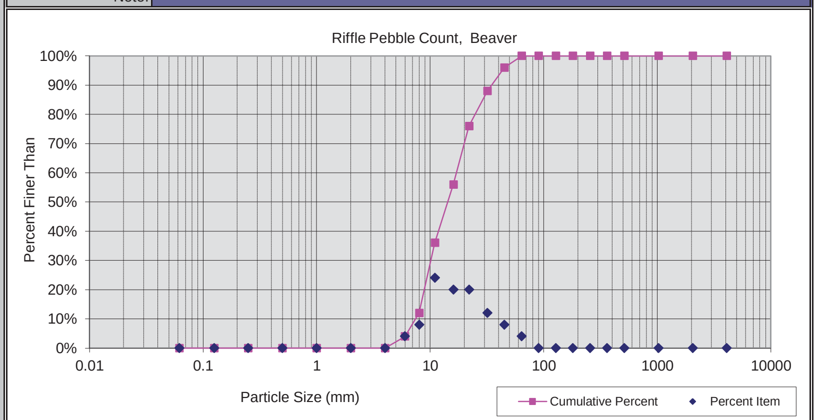
Size percent less than (mm)				
D16	D35	D50	D84	D95
0.000	0.00	0.0	0	0

Percent by substrate type					
silt/clay	sand	gravel	cobble	boulder	bedrock
---	---	---	---	---	---

Riffle Pebble Count

	Beaver River, BR1_Downstream
	Beaver River Watershed
	North of Beaver Bay MN 5 miles
Note:	

Material	Size Range (mm)		Count
silt/clay	0	0.062	0
very fine sand	0.062	0.13	0
fine sand	0.13	0.25	0
medium sand	0.25	0.5	0
coarse sand	0.5	1	0
very coarse sand	1	2	0
very fine gravel	2	4	0
fine gravel	4	6	1
fine gravel	6	8	2
medium gravel	8	11	6
medium gravel	11	16	5
coarse gravel	16	22	5
coarse gravel	22	32	3
very coarse gravel	32	45	2
very coarse gravel	45	64	1
small cobble	64	90	
medium cobble	90	128	
large cobble	128	180	
very large cobble	180	256	
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			25



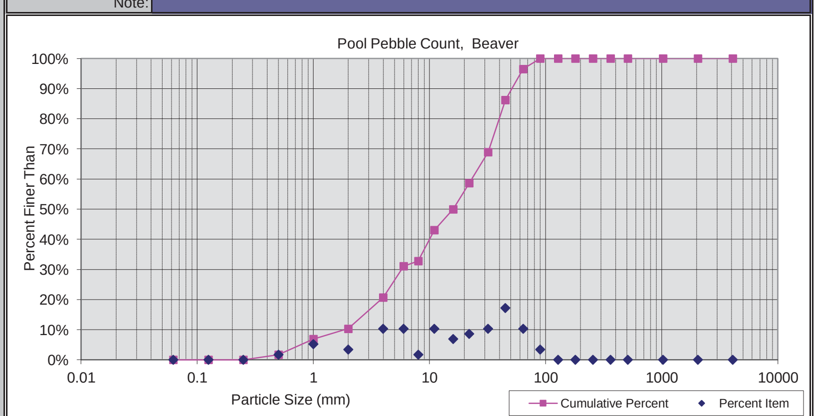
Size percent less than (mm)				
D16	D35	D50	D84	D95
8.436	10.86	14.3	28	43

Percent by substrate type					
silt/clay	sand	gravel	cobble	boulder	bedrock
0%	0%	100%	0%	0%	0%

Pool Pebble Count

	Beaver River, BR1_Downstream
	Beaver River Watershed
	North of Beaver Bay MN 5 miles
Note:	

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	
fine sand	0.13	0.25	
medium sand	0.25	0.5	1
coarse sand	0.5	1	3
very coarse sand	1	2	2
very fine gravel	2	4	6
fine gravel	4	6	6
fine gravel	6	8	1
medium gravel	8	11	6
medium gravel	11	16	4
coarse gravel	16	22	5
coarse gravel	22	32	6
very coarse gravel	32	45	10
very coarse gravel	45	64	6
small cobble	64	90	2
medium cobble	90	128	
large cobble	128	180	
very large cobble	180	256	
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			58



Size percent less than (mm)				
D16	D35	D50	D84	D95
2.921	8.57	16.0	43	61

Percent by substrate type					
silt/clay	sand	gravel	cobble	boulder	bedrock
0%	10%	86%	3%	0%	0%

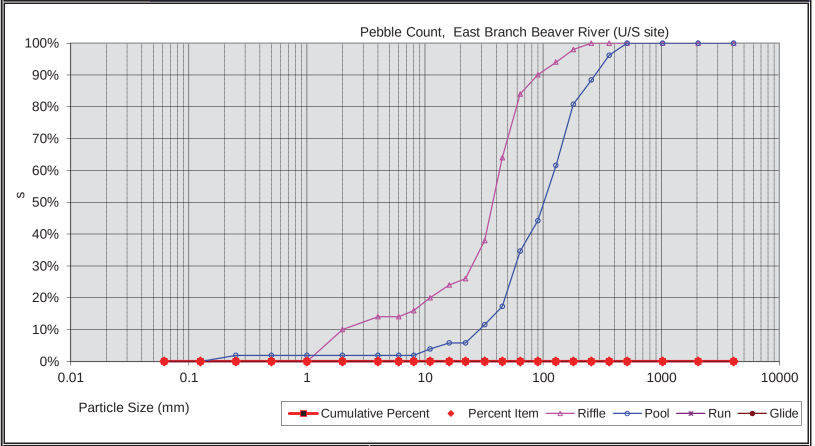
Pebble Count Data Summary

Weighted Pebble Count

Percent Riffle:		Percent Run:	
Percent Pool:		Percent Glide:	

Material	Size Range (mm)		Total #
silt/clay	0	0.062	0.0
very fine sand	0.062	0.13	0.0
fine sand	0.13	0.25	0.0
medium sand	0.25	0.5	0.0
coarse sand	0.5	1	0.0
very coarse sand	1	2	0.0
very fine gravel	2	4	0.0
fine gravel	4	6	0.0
fine gravel	6	8	0.0
medium gravel	8	11	0.0
medium gravel	11	16	0.0
coarse gravel	16	22	0.0
coarse gravel	22	32	0.0
very coarse gravel	32	45	0.0
very coarse gravel	45	64	0.0
small cobble	64	90	0.0
medium cobble	90	128	0.0
large cobble	128	180	0.0
very large cobble	180	256	0.0
small boulder	256	362	0.0
small boulder	362	512	0.0
medium boulder	512	1024	0.0
large boulder	1024	2048	0.0
very large boulder	2048	4096	0.0
bedrock			0.0
		Weighted Count:	0
		True Total Particle Count:	102

East Branch Beaver River (U/S site)
Beaver River Watershed
North of Beaver Bay 6 miles
Note:

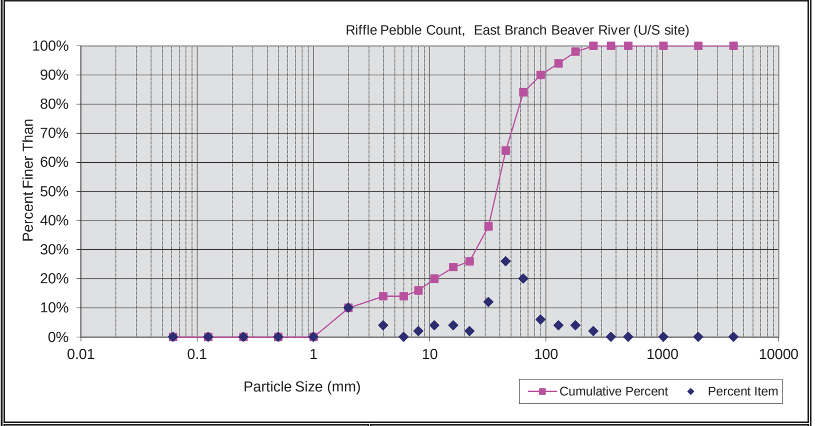


Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
0.000	0.00	0.0	0	0	---	---	---	---	---	---

Riffle Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	
fine sand	0.13	0.25	
medium sand	0.25	0.5	
coarse sand	0.5	1	
very coarse sand	1	2	5
very fine gravel	2	4	2
fine gravel	4	6	
fine gravel	6	8	1
medium gravel	8	11	2
medium gravel	11	16	2
coarse gravel	16	22	1
coarse gravel	22	32	6
very coarse gravel	32	45	13
very coarse gravel	45	64	10
small cobble	64	90	3
medium cobble	90	128	2
large cobble	128	180	2
very large cobble	180	256	1
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
		Total Particle Count:	50

East Branch Beaver River (U/S site)
Beaver River Watershed
North of Beaver Bay 6 miles
Note: IN CULVERT,10 TAKEN ACROSS THE CROSS SECTION EVERY 10 FEET

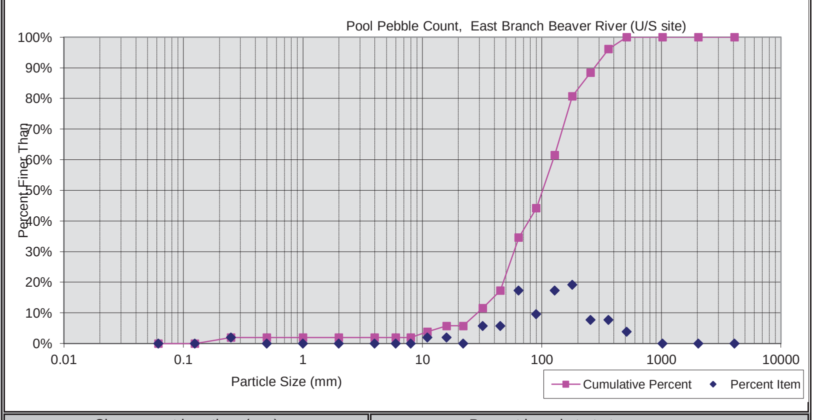


Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
8.000	29.14	37.5	64	139	0%	10%	74%	16%	0%	0%

Pool Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	
fine sand	0.13	0.25	1
medium sand	0.25	0.5	
coarse sand	0.5	1	
very coarse sand	1	2	
very fine gravel	2	4	
fine gravel	4	6	
fine gravel	6	8	
medium gravel	8	11	1
medium gravel	11	16	1
coarse gravel	16	22	
coarse gravel	22	32	3
very coarse gravel	32	45	3
very coarse gravel	45	64	9
small cobble	64	90	5
medium cobble	90	128	9
large cobble	128	180	10
very large cobble	180	256	4
small boulder	256	362	4
small boulder	362	512	2
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
		Total Particle Count:	52

East Branch Beaver River (U/S site)
Beaver River Watershed
North of Beaver Bay 6 miles
Note: DOWNSTREAM OF THE CULVERT Channel



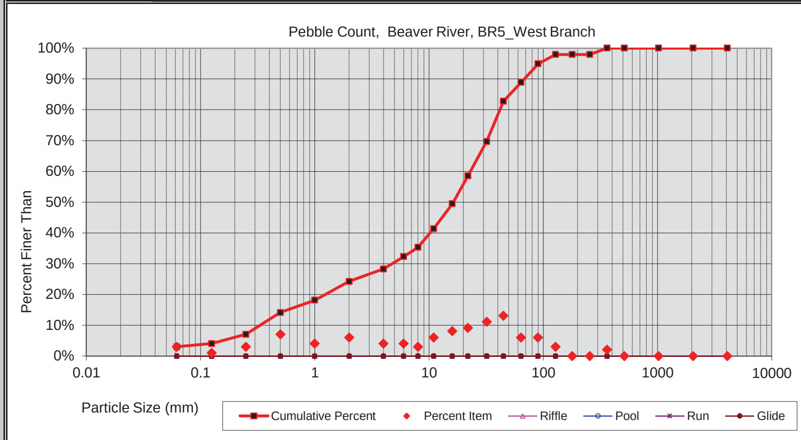
Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
41.654	64.88	101.2	209	344	0%	2%	33%	54%	12%	0%

Pebble Count Data Summary

Weighted Pebble Count			
Percent Riffle:		Percent Run:	
Percent Pool:		Percent Glide:	

Material	Size Range (mm)		Total #
silt/clay	0	0.062	3.0
very fine sand	0.062	0.13	1.0
fine sand	0.13	0.25	3.0
medium sand	0.25	0.5	7.0
coarse sand	0.5	1	4.0
very coarse sand	1	2	6.0
very fine gravel	2	4	4.0
fine gravel	4	6	4.0
fine gravel	6	8	3.0
medium gravel	8	11	6.0
medium gravel	11	16	8.0
coarse gravel	16	22	9.0
coarse gravel	22	32	11.0
very coarse gravel	32	45	13.0
very coarse gravel	45	64	6.0
small cobble	64	90	6.0
medium cobble	90	128	3.0
large cobble	128	180	0.0
very large cobble	180	256	0.0
small boulder	256	362	2.0
small boulder	362	512	0.0
medium boulder	512	1024	0.0
large boulder	1024	2048	0.0
very large boulder	2048	4096	0.0
bedrock			0.0
Weighted Count:			99
True Total Particle Count:			0

	Beaver River, BR5_West Branch
	Beaver River Watershed
	Co. Rd. 3
Note:	



Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
0.688	7.74	16.3	48	91	3%	21%	65%	9%	2%	0%

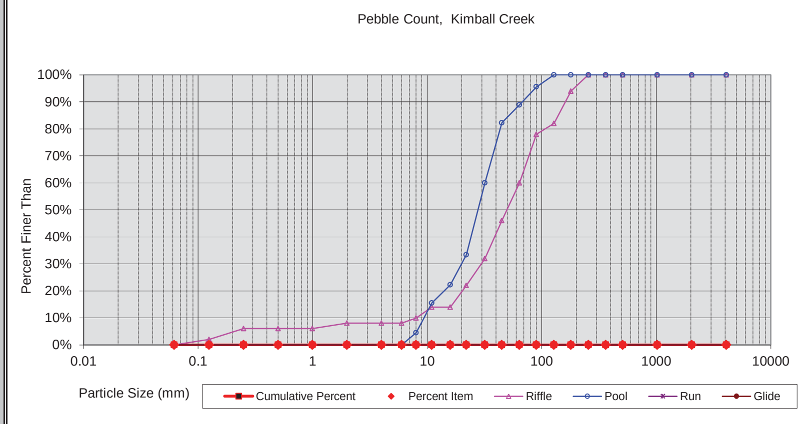
Pebble Count Data Summary

Weighted Pebble Count

Percent Riffle:		Percent Run:	
Percent Pool:		Percent Glide:	

Material	Size Range (mm)		Total #
silt/clay	0	0.062	0.0
very fine sand	0.062	0.13	0.0
fine sand	0.13	0.25	0.0
medium sand	0.25	0.5	0.0
coarse sand	0.5	1	0.0
very coarse sand	1	2	0.0
very fine gravel	2	4	0.0
fine gravel	4	6	0.0
fine gravel	6	8	0.0
medium gravel	8	11	0.0
medium gravel	11	16	0.0
coarse gravel	16	22	0.0
coarse gravel	22	32	0.0
very coarse gravel	32	45	0.0
very coarse gravel	45	64	0.0
small cobble	64	90	0.0
medium cobble	90	128	0.0
large cobble	128	180	0.0
very large cobble	180	256	0.0
small boulder	256	362	0.0
small boulder	362	512	0.0
medium boulder	512	1024	0.0
large boulder	1024	2048	0.0
very large boulder	2048	4096	0.0
bedrock			0.0
Weighted Count:			0
True Total Particle Count:			95

	Kimball Creek
	Kimball Creek Watershed
	Co. Rd 60
Note:	

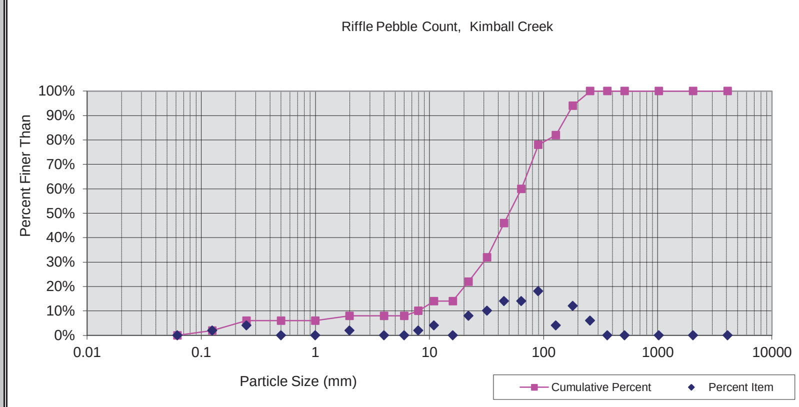


Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
0.000	0.00	0.0	0	0	---	---	---	---	---	---

Riffle Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	1
fine sand	0.13	0.25	2
medium sand	0.25	0.5	
coarse sand	0.5	1	
very coarse sand	1	2	1
very fine gravel	2	4	
fine gravel	4	6	
fine gravel	6	8	1
medium gravel	8	11	2
medium gravel	11	16	
coarse gravel	16	22	4
coarse gravel	22	32	5
very coarse gravel	32	45	7
very coarse gravel	45	64	7
small cobble	64	90	9
medium cobble	90	128	2
large cobble	128	180	6
very large cobble	180	256	3
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			50

	Kimball Creek
	Kimball Creek Watershed
	Co. Rd 60
Note:	Riffle upstream

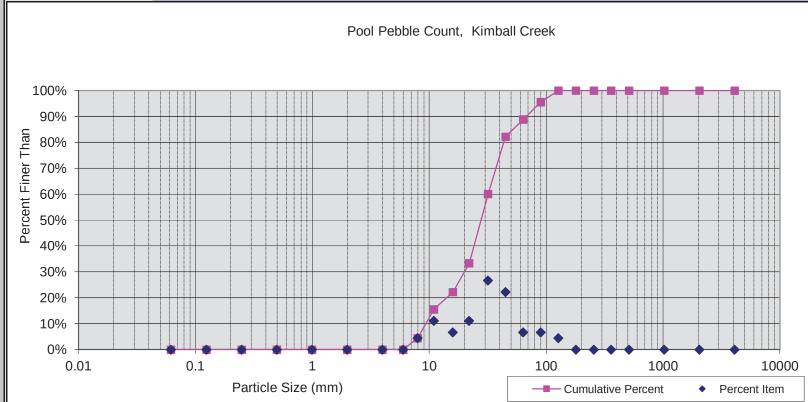


Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
17.326	34.43	49.8	135	191	0%	8%	52%	40%	0%	0%

Pool Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	
fine sand	0.13	0.25	
medium sand	0.25	0.5	
coarse sand	0.5	1	
very coarse sand	1	2	
very fine gravel	2	4	
fine gravel	4	6	
fine gravel	6	8	2
medium gravel	8	11	5
medium gravel	11	16	3
coarse gravel	16	22	5
coarse gravel	22	32	12
very coarse gravel	32	45	10
very coarse gravel	45	64	3
small cobble	64	90	3
medium cobble	90	128	2
large cobble	128	180	
very large cobble	180	256	
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			45

	Kimball Creek
	Kimball Creek Watershed
	Co. Rd 60
Note:	In culvert count



Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
11.278	22.52	27.8	49	87	0%	0%	89%	11%	0%	0%

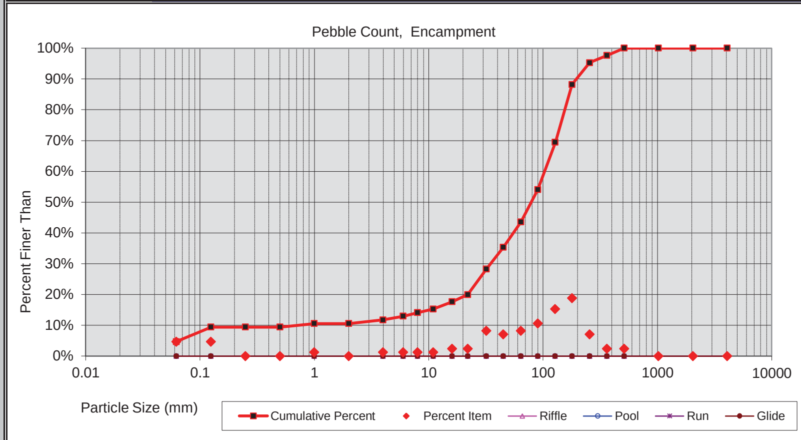
Pebble Count Data Summary

Weighted Pebble Count

Percent Riffle:		Percent Run:	
Percent Pool:		Percent Glide:	

Material	Size Range (mm)		Total #
silt/clay	0	0.062	4.0
very fine sand	0.062	0.13	4.0
fine sand	0.13	0.25	0.0
medium sand	0.25	0.5	0.0
coarse sand	0.5	1	1.0
very coarse sand	1	2	0.0
very fine gravel	2	4	1.0
fine gravel	4	6	1.0
fine gravel	6	8	1.0
medium gravel	8	11	1.0
medium gravel	11	16	2.0
coarse gravel	16	22	2.0
coarse gravel	22	32	7.0
very coarse gravel	32	45	6.0
very coarse gravel	45	64	7.0
small cobble	64	90	9.0
medium cobble	90	128	13.0
large cobble	128	180	16.0
very large cobble	180	256	6.0
small boulder	256	362	2.0
small boulder	362	512	2.0
medium boulder	512	1024	0.0
large boulder	1024	2048	0.0
very large boulder	2048	4096	0.0
bedrock			5.0
Weighted Count:			90
True Total Particle Count:			0

	Encampment
	Encampment River Watershed
	Upstream road culvert. TWSHIP 34 or Clark road
Note:	



Size percent less than (mm)				
D16	D35	D50	D84	D95
12.309	44.37	78.8	167	252

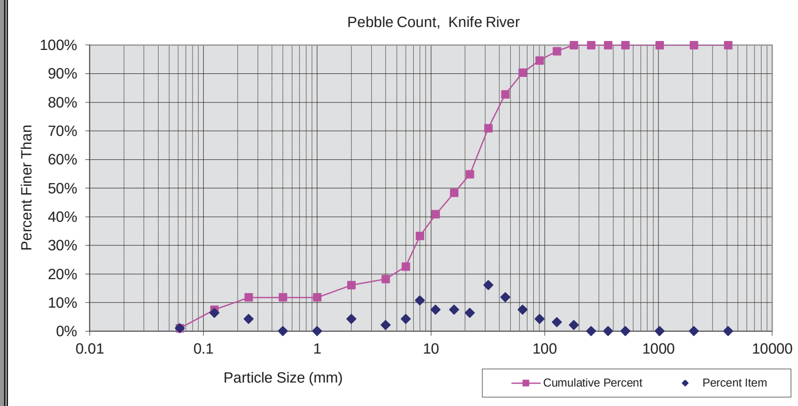
Percent by substrate type					
silt/clay	sand	gravel	cobble	boulder	bedrock
4%	6%	31%	49%	4%	6%

Pebble Count Data Summary

Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	1
very fine sand	0.062	0.13	6
fine sand	0.13	0.25	4
medium sand	0.25	0.5	
coarse sand	0.5	1	
very coarse sand	1	2	4
very fine gravel	2	4	2
fine gravel	4	6	4
fine gravel	6	8	10
medium gravel	8	11	7
medium gravel	11	16	7
coarse gravel	16	22	6
coarse gravel	22	32	15
very coarse gravel	32	45	11
very coarse gravel	45	64	7
small cobble	64	90	4
medium cobble	90	128	3
large cobble	128	180	2
very large cobble	180	256	
small boulder	256	362	
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			93

	Knife River
	Knife River Watershed
	5 miles west of Two Harbors
Note:	



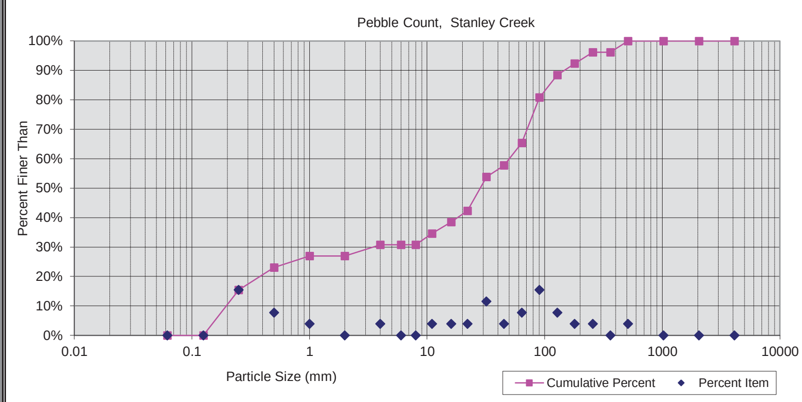
Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
1.959	8.58	17.3	48	94	1%	15%	74%	10%	0%	0%

Pebble Count Data Summary

Pebble Count

Material	Size Range (mm)		Count
silt/clay	0	0.062	
very fine sand	0.062	0.13	
fine sand	0.13	0.25	4
medium sand	0.25	0.5	2
coarse sand	0.5	1	1
very coarse sand	1	2	
very fine gravel	2	4	1
fine gravel	4	6	
fine gravel	6	8	
medium gravel	8	11	1
medium gravel	11	16	1
coarse gravel	16	22	1
coarse gravel	22	32	3
very coarse gravel	32	45	1
very coarse gravel	45	64	2
small cobble	64	90	4
medium cobble	90	128	2
large cobble	128	180	1
very large cobble	180	256	1
small boulder	256	362	
small boulder	362	512	1
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
bedrock			
Total Particle Count:			26

	Stanley Creek
	Knife River Watershed
	South west of Two Harbors 10 miles
Note:	**upstream section**

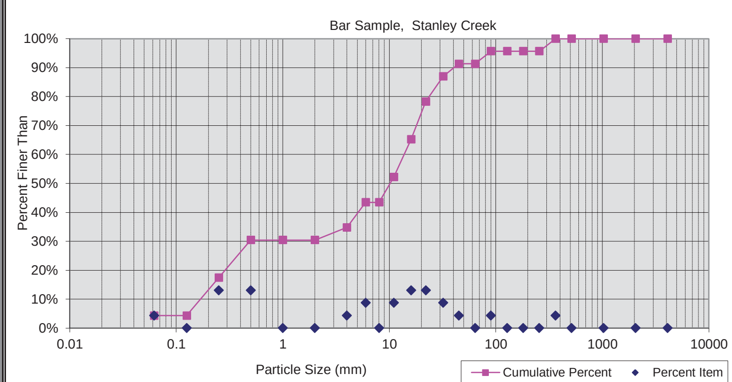


Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
0.264	11.42	28.2	104	230	0%	27%	38%	31%	4%	0%

Bar Sample

Material	Size Range (mm)		Count
silt/clay	0	0.062	1
very fine sand	0.062	0.13	
fine sand	0.13	0.25	3
medium sand	0.25	0.5	3
coarse sand	0.5	1	
very coarse sand	1	2	
very fine gravel	2	4	1
fine gravel	4	6	2
fine gravel	6	8	
medium gravel	8	11	2
medium gravel	11	16	3
coarse gravel	16	22	3
coarse gravel	22	32	2
very coarse gravel	32	45	1
very coarse gravel	45	64	
small cobble	64	90	1
medium cobble	90	128	
large cobble	128	180	
very large cobble	180	256	
small boulder	256	362	1
small boulder	362	512	
medium boulder	512	1024	
large boulder	1024	2048	
very large boulder	2048	4096	
Total Particle Count:			23

	Stanley Creek
	Knife River Watershed
	South west of Two Harbors 10 miles
Note:	**downstream section**



Size percent less than (mm)					Percent by substrate type				
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder
0.232	4.04	10.2	28	86	4%	26%	61%	4%	4%

Appendix H

Worksheet 5-15. Pfankuch (1975) channel stability rating procedure, as modified by Rosgen (1996, 2001b).

Stream: Location: Valley Type: Observers: Date:

Location	Key	Category	Excellent Description	Rating	Good Description	Rating	Fair Description	Rating	Poor Description	Rating
Upper Banks	1	Landform slope	Bank slope gradient <30%.	2	Bank slope gradient 30–40%.	4	Bank slope gradient 40–60%.	6	Bank slope gradient > 60%.	8
	2	Mass erosion	No evidence of past or future mass erosion.	3	Infrequent. Mostly healed over. Low future potential.	6	Frequent or large, causing sediment nearly yearlong.	9	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	12
	3	Debris jam potential	Essentially absent from immediate channel area.	2	Present, but mostly small twigs and limbs.	4	Moderate to heavy amounts, mostly larger sizes.	6	Moderate to heavy amounts, predominantly larger sizes.	8
	4	Vegetative bank protection	> 90% plant density. Vigor and variety suggest a deep, dense soil-binding root mass.	3	70–90% density. Fewer species or less vigor suggest less dense or deep root mass.	6	50–70% density. Lower vigor & fewer species from a shallow, discontinuous root mass.	9	<50% density plus fewer species & less vigor indicating poor, discontinuous & shallow root mass.	12
Lower Banks	5	Channel capacity	Bank heights sufficient to contain the bankfull stage. Width/depth ratio departure from reference width/depth ratio = 1.0. Bank-Height Ratio (BHR) = 1.0.	1	Bankfull stage is contained within banks. Width/depth ratio departure from reference width/depth ratio = 1.0–1.2. Bank Height Ratio (BHR) = 1.0–1.1.	2	Bankfull stage is not contained. Width/depth ratio departure from reference width/depth ratio = 1.2–1.4. Bank-Height Ratio (BHR) = 1.1–1.3.	3	Bankfull stage is not contained; overbank flows are common with flows less than bankfull. Width/depth ratio departure from reference width/depth ratio >1.4. Bank-Height Ratio (BHR) >1.3.	4
	6	Bank rock content	> 65% with large angular boulders. 12"+ common.	2	40–65%. Mostly boulders & small cobbles 6–12".	4	20–40%. Most in the 3–6" diameter class.	6	<20% rock fragments of gravel sizes, 1–3" or less.	8
	7	Obstructions to flow	Rocks and logs firmly imbedded. Flow pattern w/o cutting or deposition. Stable bed.	2	Some present causing erosive cross currents and minor pool filling. Obstructions fewer and less firm.	4	Moderately frequent, unstable obstructions move with high flows causing bank cutting and pool filling.	6	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	8
	8	Cutting	Little or none. Infrequent raw banks <6".	4	Some, intermittently at out-curves and constrictions. Raw banks may be up to12".	6	Significant. Cuts 12–24" high. Root mat overhangs and sloughing evident.	12	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	16
	9	Deposition	Little or no enlargement of channel or point bars.	4	Some new bar increase, mostly from coarse gravel.	8	Moderate depostion of new gravel and coarse sand on old and some new bars.	12	Extensive deposit of predominantly fine particles. Accelerated bar development.	16
Bottom	10	Rock angularity	Sharp edges and corners. Plane surfaces rough.	1	Rounded corners and edges. Surfaces smooth and flat.	2	Corners and edges well rounded in 2 dimensions.	3	Well rounded in all dimensions, surfaces smooth.	4
	11	Brightness	Surfaces dull, dark or stained. Generally not bright.	1	Mostly dull, but may have <35% bright surfaces.	2	Mixture dull and bright, i.e., 35–65% mixture range.	3	Predominantly bright, > 65%, exposed or scoured surfaces.	4
	12	Consolidation of particles	Assorted sizes tightly packed or overlapping.	2	Moderately packed with some overlapping.	4	Mostly loose assortment with no apparent overlap.	6	No packing evident. Loose assortment, easily moved.	8
	13	Bottom size distribution	No size change evident. Stable material 80–100%.	4	Distribution shift light. Stable material 50–80%.	8	Moderate change in sizes. Stable materials 20–50%.	12	Marked distribution change. Stable materials 0–20%.	16
	14	Scouring & deposition	<5% of bottom affected by scour or deposition.	6	5–30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	12	30–50% affected. Deposits and scour at obstructions, constrictions & bends. Some filling of pools.	18	More than 50% of the bottom in a state of flux or change nearly yearlong.	24
	15	Aquatic vegetation	Abundant growth moss-like, dark green perennial. In swift water too.	1	Common. Algae forms in low velocity and pool areas. Moss here too.	2	Present but spotty, mostly in backwater. Seasonal algae growth makes rocks slick.	3	Perennial types scarce or absent. Yellow-green, short-term bloom may be present.	4
			Excellent Total =		Good Total =		Fair Total =		Poor Total =	

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

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

Grand Total =	
Existing Stream Type =	
*Potential Stream Type =	
Modified Channel Stability Rating =	

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

Worksheet 5-16. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-15** with BEHI variables to determine BEHI score.

Stream:		Location:
Station:		Observers:
Date:	Stream Type:	Valley Type:

BEHI Score (Fig. 5-15)

Study Bank Height / Bankfull Height (C)

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

Root Depth / Study Bank Height (E)

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

Weighted Root Density (G)

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

Bank Angle (H)

Bank Angle as *Degrees* =	(H)	

Surface Protection (I)

Surface Protection as % =	(I)	

Bank Material Adjustment:

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

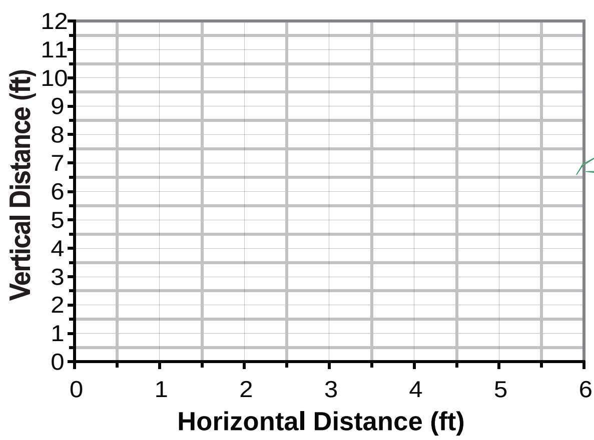
Bank Material Adjustment

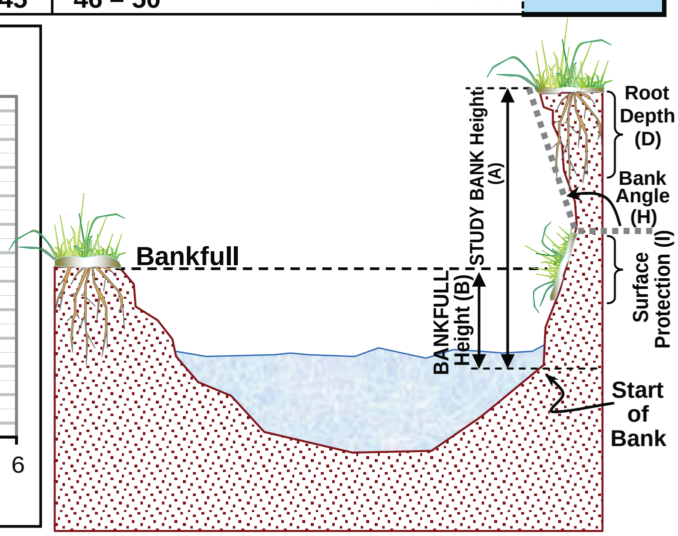
Stratification Adjustment

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

Very Low	Low	Moderate	High	Very High	Extreme	**Adjective Rating** and **Total Score**
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50	

Bank Sketch





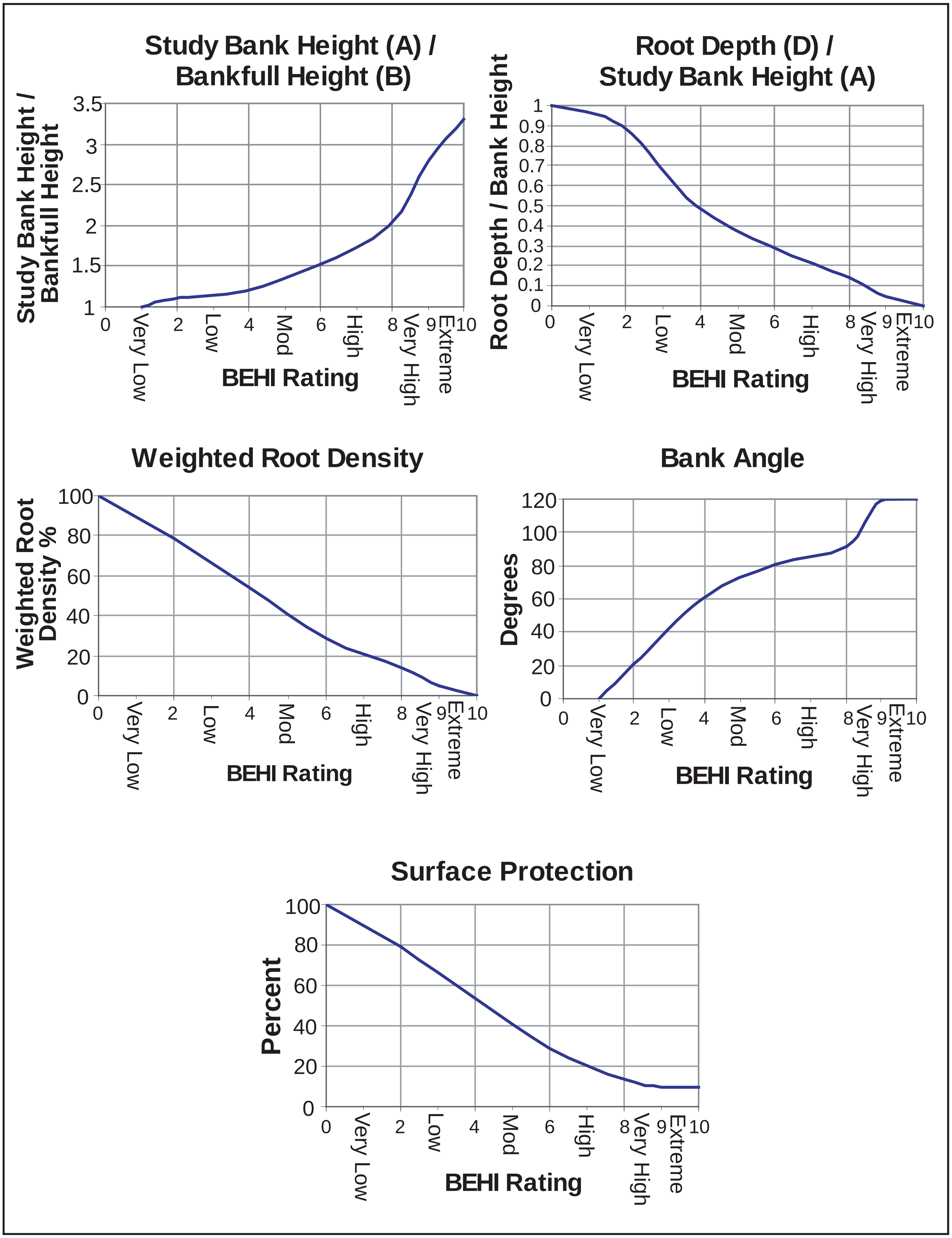


Figure 5-15. Streambank erodibility criteria showing conversion of measured ratios and bank variables to a BEHI rating (Rosgen, 1996, 2001a). Use **Worksheet 5-16** variables to determine BEHI score.

Appendix I

Factors influencing roadside erosion and in-stream geomorphic stability at road-stream crossings for selected watersheds, North Shore, Minnesota, USA.

Patricia Danielle Dutton

Error! No sequence specified.

University of Minnesota – Twin Cities

<u>**Co-Advisors and Committee**</u>

Kenneth Brooks

Joseph Magner

John Nieber

Dedication

I would like to dedicate this work to all of those who've supported this arduous process. With gratitude, I thank my family, and the amazing community of friends and colleagues that I have formed these years at the University of Minnesota. To the field assistants that made this happen, particularly Cristina Lopez-Barrios, thank you. To the family that has become my family, you've truly contributed to my sanity and happiness during this process, for your endless authenticity and passion for life I thank you - Britta, Jean, Gabe, and Laura. And, to one person in particular, you are an intellectual match; an encouraging positive force and an ever present supporter (despite my prolonging-procrastination) and an endless strength. For that I thank you Joe Shannon, I owe you.

To my advisors Ken Brooks, Joe Magner and John Nieber, I appreciate your diligent support and kindness, thanks for taking a chance on an east coast ex-chemistry major. Your harrowing tales of hydrology on a shoe string will forever stay in my heart, I will reflect fondly on my experience for years to come.

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Abstract

Currently, 8 major watersheds in Minnesota's North Shore exceed state water quality standards for turbidity (10 NTU) a surrogate for total suspended solids. In this region, recent anthropogenic disturbances can be attributed to roadway construction and maintenance. The presence of roadways can pose a serious threat to ecosystem functions, altering local and landscape hydrology, fragmenting riparian areas, and delivering chemical pollutants and suspended sediments to nearby waterways via surface runoff and seepage.

This study examined the current extent of hydrologic connectivity between roads and streams, by investigating roadside erosion for select sub-watersheds within the North Shore watershed of Minnesota, USA. Surveys were conducted at 54 road-stream crossings along 12.2 km of roadways in the summer of 2010. A Road-stream connectivity analysis found roads increase the drainage density of North Shore watersheds by approx. 1.45-9.47%. Measureable erosion was observed at 64.8% of survey sites (gully, or rill) totaling 93.26 m^3, with an average loss per site of 1.73 m^3, or 7.65 m^3/km. Traffic intensity, road construction, parent material, stream order, soil k factor, hillslope gradient best predicted erosion for this dataset using logistic regression at local and watershed wide scales.

The effect road-stream crossings as a localized stress on stream stability was also examined at seven sites, using Rosgen level I classification and Pfankuch stability metrics. This qualitative analysis of stream stability upstream and downstream of road-stream crossing structures indicated study road-stream crossings are causing localized instability. Assessments indicated stream segments are negatively impacted both upstream and downstream of crossing structures.

Introduction

Roadways are often a lasting land use legacy within watersheds. However, impervious surfaces can severely alter local and landscape hydrologic interactions, increasing surface runoff which may increase local sediment detachment rates, and lead to higher peak stream flows in frequency, duration and magnitude (Dunne & Leopold, 1978, Harr et al., 1975, Jones & Grant, 1996, Coleman et al., 2005). In many cases roads and development increase runoff efficiency leading to destabilization of slopes, increased sediment losses and decreased water quality (Johnson & Beschta, 1980, Reid & Dunne, 1984, Luce & Wemple, 2001, Luce & Black, 1999, Lane et al., 2006). Within the literature, roads in forested landscapes have been shown to contribute to increased runoff efficiency and sediment production through the formation of local erosion processes such as gully or rills, or in some cases mass erosion. Past forest road studies indicate traffic (Reid & Dunne, 1984, Sheridan *et al.*, 2006, McCaffery *et al.*, 2007), road surface type, position and construction (Booth & Jackson, 1997, Luce & Wemple, 2001, Wemple *et al.*, 1996, Wemple & Jones, 2003), hillslope gradient and contributing area (Montgomery, 1994 Wemple *et al.*, 1996 Croke & Mockler, 2001, Poesen *et al.*, 2003, Takken *et al.*, 2008), resident surficial geology and topography (Sugden & Woods, 2007), are driving factors lending to increased runoff and road induced sediment production.

Understanding the extent and origin of water quality impairments is a pressing issue for land managers tasked with responding to those impairments. Currently, 5 of the 10 major watersheds in Minnesota's North Shore along Lake Superior are exceeding state water quality standards for turbidity (10 NTU), a surrogate for total suspended solids. These streams are classified as "impaired" for turbidity on the EPA 303(d) list. Prolonged turbidity can have deleterious effects on stream biotic integrity (Warren & Pardew, 1998 Avolio, 2003). Increased sediment supply to streams can trigger a morphological response reducing sediment carrying capacity, resulting in aggradation of fine sediments and channel materials, in time altering stream bed slope (Lisle, 1982, Booth & Jackson, 1997, Bledsoe & Watson, 2001, Goode & Wohl, 2007, McCaffery *et al.*, 2007). Although extensive evaluations of water quality have been conducted along North Shore and South Shore-Lake Superior watersheds, concerning the extent of geotechnical failure of hillslopes (Nieber *et al.*, 2008, Hansen *et al.*, 2009), historical land use and forest conversion on water quality (Detenbeck *et al.*, 2004, Detenbeck *et al.*, 2005); the extent of road-connectivity and effect on water resources within the North Shore Minnesota is still unknown.

Within the transportation network high risk areas for increased sediment and fluvial conveyance exists for roads in close proximity to streams, especially roads draining to ditches which drain directly to streams. This is especially true for all road-stream crossings which serve as a direct connection of roads to streams (Croke *et al.*, 2005). This study examines local effects of roads on North Shore waters by examining channel network extension, sediment availability and in-stream geomorphic stability at road-stream crossings.

Chapter 1 investigates the extent of road connectivity at the watershed and local level; examining the various scales in which roads may act as an extension to the stream network. An additional investigation examines roadside erosion and sediment source availability to neighboring waterways (streams, lakes, wetlands); quantified and characterized by major factors such as water quality and geomorphic associations. This investigation also draws comparisons between turbidity impaired watersheds and non-turbidity impaired watersheds to best evaluate a causal link between road side sediment contributions to streams and known water quality impairments. Chapter 2 considers the in-stream costs of local development by qualitatively analyzing in-stream stability at stream segments above and below road-stream crossings using Rosgen level I and Pfankuch stability assessments.

Study site background

North Shore watershed – North Shore streams

Land uses

The portion of the Lake Superior watershed in Minnesota that drains North Shore streams is 2,211 sq miles. The predominant land use for the watershed is coniferous and deciduous forest (85.7%), with 1.7% developed, 3.1% wetland, and 4.9% open water (Tables

Table 1) (USGS, 2001). Approximately 65% of the watershed is part of the Superior National Forest accounting for the largest land use, with 13% of state lands managed by the Minnesota DNR within the national forest boundary, 2.2% of lands are outside of Superior National Forest boundaries.

Soil type

Soils within the North Shore watershed are variable due to past glacial activity. Soil texture derived from the USDA NRCS State Soil Geographic Database (STATSGO) describes deposits of thick silty clay loam (12.1%), loam (33.8%), to thin soils of gravelly silt and sandy loam (Table 2) (NRCS, 2011).

Geomorphic Association

The landform topography and surficial geology (aggregated and coined as "geomorphic associations" within this report) of the watershed were derived from a geomorphology map developed by the University of Minnesota at Duluth in 1997 at a 1:100,000 scale derived from NHAP air photos (1:80,000), and USGS 1:100,000 and 1:24,000 scale topographic maps and other sources for development of level 4 Ecological Classification; accessed through the DNR GIS spatial database (Minnesota DNR Data Deli, 2011). This data layer illustrates the glacial terrain of the North Shore watershed, giving clues towards the age and underlying stratigraphy of the watershed. Topographically, much of the watershed is considered to have gentle to undulating rolling terrain (63%) and steep gradient with abrupt peaks and ridges (24%). Surficial geology is defined as sediment deposits left by glacial activity related to the Rainy Lobe 2.8%, Superior Lobe 51.1%, along with exposed or thin layered igneous basalt scoured bedrock 44.7 % (

Tables

Table 1. Average land uses for North Shore watershed

Type of Land Use	*Definition*	Percentage
Developed	*(Development ranging from 0-100%)*	1.7%
Forest*	*(Deciduous, Evergreen, Mixed Forest)*	85.7%
Wetland	*(Woody and Emergent)*	3.1%
Open Water	*(Open water)*	4.9%
Other	*Shrub, grassland, pasture, cultivated crops, barren land*	4.6%

Forest* : Trees greater than 5 m tall, in a forest occupying greater than 20 % total vegetation were considered for count.

).

Parent material and Stratigraphy

Predominant bedrock material for the North Shore was investigated using bedrock data obtained from the USGS (USGS 2004). Predominantly bedrock is aged from the Middle Proterozoic period, with a small portion dating to the Early Proterozoic period. The Proterozoic era began approximately 2.5 billion years ago and ended 543 million years ago. With evidence of material dating to the Archaean era northwest of the North Shore watershed, this material would be much older dating between 3.8 – 2.5 billion years ago. The USGS bedrock data describes the predominant type of rock within the North Shore watershed as basalt (43.15%), gabbro (35.13%) and granite (10.03%). Common rock types (predominant and secondary combinations) are basalt/rhyolite (35.8%), gabbro/troctolite (32.19%), granite (10.03%) (USGS 2004).

Watershed fluvial characterizations

A majority of sub-watersheds with the North Shore-Lake Superior watershed can be characterized generically as having an upper watershed residing on a low gradient landform (< 10%) with wide gently sloping valleys. These upper watersheds stereotypically have high storage areas composed of wetlands, lakes and small first and second order streams. The topography shifts to a high gradient landform controlled by the underlying bedrock as streams continue towards their watershed confluence with Lake Superior. This abrupt change in gradient occurs at different locations along the shore, for a majority of sub-watersheds this occurs within the last few miles of stream length. The landform in these locations is often characterized by narrow confined valleys, where streams have a high stream power capable of carrying a much larger bedload, (Hyndman & Hyndman, 2005). Discontinuities to this characterization are in watersheds which may have resulted from more frequent glacial advance and retreat (Personal communiqué with Howard Hobbs of Minnesota Geological Society).

These characteristics apply loosely to "major" streams (Stahler order 3-4), within the North Shore watershed; discounting near shore streams (1st-2nd order streams) (Figure 1). Due to the dynamic nature for which the North Shore landform was created, many small first order streams (either groundwater seeps, or ephemeral pathways) reside near shore to Lake Superior. First order streams respond to precipitation events at a rapid rate in comparison to larger neighboring streams (Hyndman & Hyndman, 2005). This type of response in combination with the steep bedrock controlled gradient of the North Shore often creates "flashy" turbulent discharges which have the capacity to carry high sediment loads per unit area. Near shore first order streams were not investigated in this study as they generally lie outside of the bounds of major sub-watershed distinctions. However, it is likely that these streams interplay with road design, and maintenance; especially after large precipitation events.

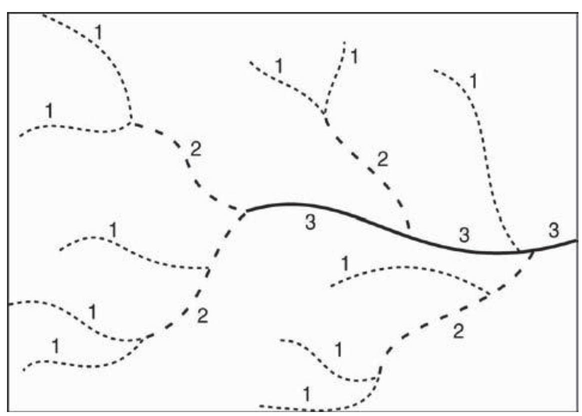


Figure 1. Stahler stream ordering (Ward et al., 2008)

Study watersheds

Due to the immense size of the North Shore watershed it was not feasible to conduct a study consisting of the entire area, a subset of six watersheds were chosen for this study. Some watersheds were chosen due to their current designation as an impaired waterway for turbidity on the EPA's 303d "impaired waters" list, others were chosen due to inclusion in a larger project to study current fluvial geomorphic attributes of North Shore waters. A key attribute for this study was to study areas *outside* of the urbanized watersheds which compose the Duluth, MN area. The assumption being, these watersheds have higher road densities and impervious surfaces, with a greater traffic intensity which could skew results when compared to more outlying less inhabited areas.

Watersheds studied were the Baptism, Beaver, Brule, Flute Reed, Knife and Temperance rivers. Watershed areas ranged from 15 miles^2 (40.09 km^2) to over 200 miles^2(686.97 km^2). Average precipitation for the watershed is estimated to be ~32 inches (Table 2. STATSGO data for the North Shore watershed for depth to restrictive layer and surface texture

Depth to Restrictive layer	Surface Texture	% Total of North Shore watershed
18	*Gravelly silt loam*	4.8%
77	*Gravelly sandy loam*	29.1%
201	*Fine sand*	0.0%
	Fine sandy loam	9.1%
	Loam	33.8%
	Mucky peat	2.3%
	Sandy loam	0.0%
	Silt loam	3.2%
	Silty clay	1.7%
	Silty clay loam	12.1%
	Very fine sandy loam	3.0%
	(blank)	0.8%

Table 3. Surficial geology as defined by glacial and parent material associations

Geomorphic Association	*Sediment Association*	*% of total*
Fluvial	Alluvium	0.0%
Mines	Undifferentiated	0.1%
Organic Deposits	Peat	1.2%
Rainy Lobe	Ice Contact	0.0%
	Till Plain	2.8%
Scoured Bedrock Uplands	Igneous	37.9%
	Metamorphic	4.7%
	Undifferentiated	2.1%
St. Louis Lobe	Lacustrine	0.0%
Superior Lobe	Ice Contact	0.5%

	Outwash	1.0%
	Supraglacial Drift Complex	9.2%
	Till Plain	40.5%
Undifferentiated	Ice Contact	0.0%

Table 4, area weighted theissen polygons for select study watersheds). Major watershed geomorphic associations range from 8 – 86% scoured bedrock uplands, 6 – 92% Superior Lobe (Table 5). Land uses are similar between study watersheds, predominately forested watersheds (80 – 90%) with low development (0.236 – 2%). A noted exception is with the Brule watershed, which has twice as much open water as any other study watershed (

Table 6). Other study characteristics include, stream density ranging from 1.16 – 2.11 mile/mile^2, road density ranging from 0.62 – 1.21 mile/mile^2, and total road-stream crossings ranging from 18 – 89 (

Table 7).

Tables

Table 1. Average land uses for North Shore watershed

Type of Land Use	*Definition*	Percentage
Developed	*(Development ranging from 0-100%)*	1.7%
Forest*	*(Deciduous, Evergreen, Mixed Forest)*	85.7%
Wetland	*(Woody and Emergent)*	3.1%
Open Water	*(Open water)*	4.9%
Other	*Shrub, grassland, pasture, cultivated crops, barren land*	4.6%

Forest* : Trees greater than 5 m tall, in a forest occupying greater than 20 % total vegetation were considered for count.

Table 2. STATSGO data for the North Shore watershed for depth to restrictive layer and surface texture

Depth to Restrictive layer	Surface Texture	% Total of North Shore watershed
18	*Gravelly silt loam*	4.8%
77	*Gravelly sandy loam*	29.1%
201	*Fine sand*	0.0%
	Fine sandy loam	9.1%
	Loam	33.8%
	Mucky peat	2.3%
	Sandy loam	0.0%
	Silt loam	3.2%
	Silty clay	1.7%
	Silty clay loam	12.1%
	Very fine sandy loam	3.0%
	(blank)	0.8%

Table 3. Surficial geology as defined by glacial and parent material associations

Geomorphic Association	*Sediment Association*	*% of total*
Fluvial	Alluvium	0.0%
Mines	Undifferentiated	0.1%
Organic Deposits	Peat	1.2%
Rainy Lobe	Ice Contact	0.0%
	Till Plain	2.8%
Scoured Bedrock Uplands	Igneous	37.9%
	Metamorphic	4.7%
	Undifferentiated	2.1%
St. Louis Lobe	Lacustrine	0.0%
Superior Lobe	Ice Contact	0.5%
	Outwash	1.0%
	Supraglacial Drift Complex	9.2%
	Till Plain	40.5%
Undifferentiated	Ice Contact	0.0%

Table 4. Area weighted total precipitation for selected watersheds

Watershed	Watershed	Brimson	Grand	Grand	Isabella	Lutsen	Two	Two	Wolf	Avg

	area ($mile^2$)		Marais	Portage		3NNE	Harbors	Harbors - 7NW	Ridge	annual precip (in)
Baptism	140.53				6.11	0.48			26.59	33.19
Beaver	123.01	0.28						3.45	28.79	32.52
Brule	265.24		25.39			7.23				32.63
Flute Reed	15.48		24.66	7.47						32.13
Knife	86.48						22.95	9.47		32.41
Temperance	182.20					31.74				31.74

Table 5. Study watersheds geomorphic associations

Geomorphic Association	*Sedimentary Association*	*Baptism*	*Beaver*	*Brule*	*Flute Reed*	*Knife*	*Temperance*
Mines	*Undifferentiated*		1.42%				
Organic Deposits	*Peat*	3.14%	0.67%	0.34%			0.14%
Rainy Lobe	*Ice Contact*			0.03%			
	Till Plain		0.01%	7.55%			
Scoured Bedrock Uplands	*Igneous*	28.84%	19.13%	84.37%	48.90%	2.93%	44.36%
	Metamorphic			0.03%			
	Undifferentiated		0.23%	1.54%		5.17%	
Superior Lobe	*Ice Contact*			0.25%			0.25%
	Outwash	0.58%	1.26%	0.15%			
	Supraglacial Drift Complex	16.14%	15.21%			33.41%	
	Till Plain	51.30%	62.06%	5.74%	51.10%	58.49%	55.24%

Table 6. Land cover and land uses breakdown for study watersheds

Land Use	*Definition*	*Baptism*	*Beaver*	*Brule*	*Flute Reed*	*Knife*	*Temperance*
Developed	*(0-100%)*	0.937%	1.172%	0.292%	0.534%	2.216%	0.236%
Forest	*(Deciduous, Evergreen, Mixed Forest)*	88.224%	87.929%	81.312%	96.824%	86.750%	87.705%
Wetland	*(Woody and Emergent)*	4.048%	2.385%	3.338%	1.100%	3.832%	3.653%
Open Water		1.199%	2.838%	10.171%	1.024%	0.130%	5.248%
Other	*Shrub, grassland, pasture, cultivated crops, barren land*	5.592%	5.677%	4.886%	0.519%	7.073%	3.157%

Table 7. North Shore-Lake Superior watershed characteristic summary: total roads, road density, total road-stream crossings, percent imperviousness, total streams and stream density.

Watersheds	Watershed area (mile^2)	Total Road (mile)	Road Density (mile/mile^2)	Total Road-stream Crossings	Impervious %	Total Stream mile	Stream Density (mile/ mile^2)
Amity	16.68	60.92	3.65	47	6.89	33.41	2.00
Baptism	**138.22**	**85.7**	**0.62**	**52**	**1.44**	**182.68**	**1.32**
Beaver	**122.85**	**93.79**	**0.76**	**54**	**1.77**	**166.68**	**1.36**
Brule	**264.9**	**218.06**	**0.82**	**88**	**1.9**	**371.08**	**1.40**
Chester	6.72	33.2	4.94	29	9.94	11.42	1.70
Encampment	16.4	13.48	0.82	24	1.7	28.25	1.72
Flute Reed	**15.46**	**18.63**	**1.21**	**18**	**2.53**	**56.35***	**3.64**
French	18.63	24.08	1.29	26	2.54	33.09	1.78
Gooseberry	47.4	29.51	0.62	20	1.37	75.65	1.60
Knife	**86.37**	**79.06**	**0.92**	**89**	**1.82**	**182.28**	**2.11**
Lester	36.42	59.63	1.64	42	3.2	60.78	1.67
Little Sucker	3.68	15.92	4.32	20	9.63	8.78	2.38
Pigeon	270.35	116.25	0.43	44	0.98	253.51	0.94
Poplar	113.13	141.81	1.25	43	2.89	129.92	1.15
Skunk Creek	27.31	5.43	0.2	7	0.47	58.33	2.14

Sucker	37.67	24.71	0.66	19	1.38	48.54	1.29
Talmadge	5.91	13	2.2	15	4.21	9.83	1.66
Temperance	**184.1**	**147.44**	**0.8**	**41**	**1.78**	**270.25**	**1.47**
Tischer	7.26	55.59	7.65	42	14.91	11.15	1.54

Value defined by NHD stream layer and 10k stream-line (km) from 30 m DEM

Literature Review: Roads

Flood Frequency

The hydrologic effects of roadway construction on watershed processes have widely been studied (Leopold, 1973, Harr *et al.*, 1975, Booth, 1991). Watershed scale adjustments to the loss of vegetation, and compaction of soils has been shown to increase water yields due to decreased interception and altered evapotranspiration demands (Keppeler, 1998, Hilbert, 1967). Increased imperviousness decreases resident storage by decreasing infiltration and groundwater recharge, leading to a reduction of baseflows, creating greater runoff efficiencies.

Although increases in flood frequency may influence road induced sediment detachment to local water resources, it was not the focus of this evaluation. The remaining discussion will relate to the effects of roadway construction on sediment detachment and deposition.

Connectivity

Landform-catchment scale connectivity is related to hydrologic processes, Hortonian or saturated overland flow; and the variable source area concept. Hortonian overland flow (HOF) and saturated overland flow (SOF) are observed as infiltration excess, or sheet flow on impervious surfaces and in arid climates. The Variable Source Area concept (VSA) is common to humid regions, and is a hydrologic process that connects subsurface saturated hillslopes to stream channels. Typical discussions of runoff and connectivity are appreciated on a catchment scale for use in modeling and predictive forecasting. Yet the same components can be used on a local scale, by determination of the capacity of road delivery pathways.

This study investigates effects of sediment production at road-stream crossings by examining roadway connectivity to water resources on a watershed and local scale. Road connectivity can be considered the relationship between many climate and landscape factors: average precipitation and severity of storms, position of the road on the landscape and proximity to water resources; runoff potential and delivery pathways which are both considered aspects of road construction; and the ability of the riparian buffer area (adjacent to the road) to reduce sediment dispersal downslope (

Figure 2)(Bracken & Croke, 2007).

Local connectivity: Flowpaths and channel initiation

Flowpaths

Roadways can significantly alter local hydrologic processes, often delivering runoff to stream networks. An investigation of road runoff delivery pathways to nearby water resources illustrates the level of road-stream connectivity on a local scale. Runoff can be conveyed off of the road prism in two categorical ways, as a dispersive flow or a directed flow (Figure 3, Croke *et al.*, 2005). Dispersive runoff is considered a low energy flow often directed into a highly vegetated area such as a forest (Bracken & Croke, 2007). This type of runoff is often considered a low impact result of roads, in that streamflow is often re-infiltrated into a forested or vegetated buffer at a rapid rate due to dispersal of streamflow volume. Direct flowpaths result as streamflow energy is directed off of the road prism to a structured pathway or conduit (such as a ditch) which directs the flow to a stream or storage area. This type of runoff typically creates a direct roadway connection to streams, and may result in erosion occurrences as ephemeral flowpaths detach soil over time.

Connectivity of flowpaths to stream networks results in channel network extension if direct flowpaths are observed. LaMarche and Lettenmaier (2001) hypothesize flowpath processes at culvert locations by describing four potential ends runoff may have, ultimately two of which describe road-stream connectivity. This definition is incorporated into the road-stream site survey analysis.

Flowpath process and connectivity:

A. Re-infiltrate into the soil directly below a ditch relief culvert
B. Enter a stream directly at a stream crossing culvert
C. Re-infiltrate below a gully that does not extend to the stream channel
D. Enter a stream indirectly through the formation of a gully below a ditch relief culvert

- Cases A or C = road NOT connected to the stream network (at least through surface flow)
- Cases B or D = road network connected to the stream network, directly or indirectly (respectively)

Wemple (1996) evaluated road-stream connectivity as the sum of gully erosion length off of road prisms, and the sum of road segments directly linked to streams within a watershed area. Croke and Mockler (2001) employed a modified Wemple (1996) methodology to examine road-stream connectivity by examining roadway proximity to water resources. This method employed a categorical system to determine connectivity by examining the length of the erosion feature and its distance to the stream; determined at distances greater than 10 meters and less than 10 meters from the stream. This study employed the Croke and Mockler (2001) system of evaluation, but modified the approach to include categories used by Miller (2010), to examine road proximity to streams at distances of 3.04 m – 30.4m (10 – 100 ft) (Miller, 2010).

Erosion features

With low infiltration rates due to surfacing or compaction, roads persistently deliver overland flow to surfaces alongside roadways resulting in channel initiation and erosion. Detachment of sediment particles is likely to occur as a result of concentrated high energy flows that exceed critical shear stress of the soil (Horton, 1945, Poesen et al., 2003). Road related sediment transport can take many forms, from dispersive runoff flows that carry fine sediment (attributed to trafficking on gravel and native roads), and channelized flows leading to incised channels and landsliding (Figure 3). This study focused on rill and gully erosion.

To date there are many interpretations defining rill and gully processes, this study follows classifications by Poesen *et al.* (2003). Gullies can range in depth from 0.5 – 30 m (Poesen *et al.*, 2003), and are often classified as a “permanent” or “ephemeral” gully. This study evaluated ephemeral erosion defined at concentrated flowpaths at depths of less than 1.54 m (Poesen *et al.*, 2003).

Precipitation both in terms of rainfall intensity and volume can encourage rill and gully development. Poesen et al. (2003) cites “rain thresholds” of 7.5 mm as a lower limit for rilling, 14.5 mm for gullies extending to 22 mm of rain. Other observations cited within the literature review by Poesen et al. (2003), indicate rain on snow events can have a considerable effect on frozen/thawing soils, initiating ephemeral gullies (observed in Norway) (Oygarden (2003) cited in Poesen et al., 2003). Sullivan and Foote (1983), found water related erosion was most frequently observed along roadsides, accounting for 15,309 occurrences or 81.5% of the dataset. Precipitation intensity and duration were primary factors for sediment detachment, often dictating where sediment was deposited along a buffer.

Vegetative buffers

Vegetative buffers are key to reducing runoff flows and to the retention of sediment conveyed off of the road prism. The effectiveness of a buffer is directly related to the length and hillslope as well as to the roughness factor of the vegetation (Elliot *et al.*, 2009). An intensive roadside erosion investigation in the state of Minnesota in 1983 (17, 902 sites, 185,991 km (115,570 miles) of roadway), found a lack of vegetative cover was the “single most important cause of erosion” for their dataset (Sullivan & Foote, 1983). When hillslope surfaces are unvegetated sediment source contributions will increase. This is particularly evident after construction, in which unvegetated buffers act as a major source of sediment, continuing for 1 – 2 years (MacDonald & Coe, 2008).

For short duration storms the volume and potential energy of runoff may only entrain particles locally, depositing material along the road side (not considering the effect of vegetative roughness). Longer duration storms may carry particles further into the ditch bottom or beyond. Given a precipitation event of average intensity, a short buffer length (especially short buffers with shallow rooted vegetation) may not dissipate runoff energy in time to deposit materials along the buffer, providing an opportunity for material to deposit in a nearby waterbody (Elliot *et al.*, 2009).

Road characteristics

Road surfaces

Road surfaces can either act as a sediment source or as a conveyance of runoff influencing erosion nearby. Erodibility of a road surface (be it unsealed/native, gravel or paved) is highly correlated to the age of the road, timing of grading and maintenance, traffic (type and timing), surficial geology and buffer vegetation density (Ramos-Scharron & MacDonald, 2007).

Unsealed roads (or native-soil roads) are known to be prime contributors of sediment, often affecting water quality (Luce & Wemple, 2001, Ramos-Scharron & MacDonald, 2007). Unpaved roads have been shown to increase surface erosion by two or more orders of magnitude compared to adjacent undisturbed hillslopes in the Virgin Islands (Ramos-Scharron & MacDonald, 2007). Sugden and Woods (2007) acknowledge unsealed roads are sediment contributors but underscore the roll of parent material and soil type as controlling factors in observed erosion rates. Sugden and Woods (2007) studied twenty ~0.05 ha unsealed native road plots in western

Montana, finding unsealed roads yielded 0 – 96.9 Mg/ha/yr over 3 years (2002-2004). The experimental plots were tested on both fine textured glacial till and were 4 times more likely to erode than the plots on metamorphic parent material.

Generally gravel roads are considered a surface which will reduce roadside erosion when applied to unsealed roads as it acts as an "armor" protecting the native surface (Sugden & Woods, 2007). Gravel is less erosive to rain splash impact and reduces rut formation which in itself greatly reduces road erosion; increases hydraulic conductivity reducing runoff. However because gravel can also harbor fine sediments in between large coarse fragments; gravel roads can also become a fine sediment source (Sugden & Woods, 2007).

Grading

Road grading, reshapes unsealed and gravel roads. This is a necessary road maintenance procedure and an efficient way of reducing rills and ruts. If unsealed roads are not graded the road surface will "armor" or vegetate reducing loose sediment sometimes by 70 – 80% (Elliot *et al.*, 2009). Ramos-Scharron and MacDonald (2005) found upon grading the likelihood of erosion increases by 70% when compared to ungraded roads in the Virgin Islands. Sediment availability may increase as the amored layer is disturbed following an exponential decay as years in between grading increases (Sugden & Woods, 2007).

Traffic

Roads were developed for traffic, yet trafficking can greatly affect sediment transport and erosion rates along roads. Vehicle traffic (especially heavy vehicle traffic) can encourage rut development and deform the road surface. If vehicle traffic is seasonal or changes intensity this can break up the armored road surface creating a highly erodibile condition. For gravel roads aggregates are broken down when forced into the sub-grade, this can decrease hydraulic conductivity and increase runoff and erosion (Reid & Dunne, 1984). Increased traffic rates on gravel roads are reported to increase sediment concentration by 2.7 fold in Marysville Australia (Sheridan *et al.*, 2006), Ramos-Scharron and MacDonald (2005) found greater traffic levels increased the supply of fine material by 2 – 1000 times that of lower levels. Even temporary changes in usage can amount to large differences in road sediment losses, as noted by Reid and Dunne (1984) whom compared weekdays to weekends finding a 7.5 rate increase for weekends (Figure 6).

Figures

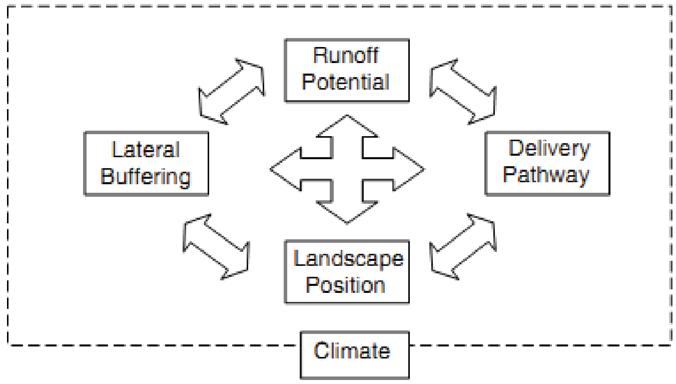


Figure 2. Components of catchment connectivity from Bracken & Croke (2007)

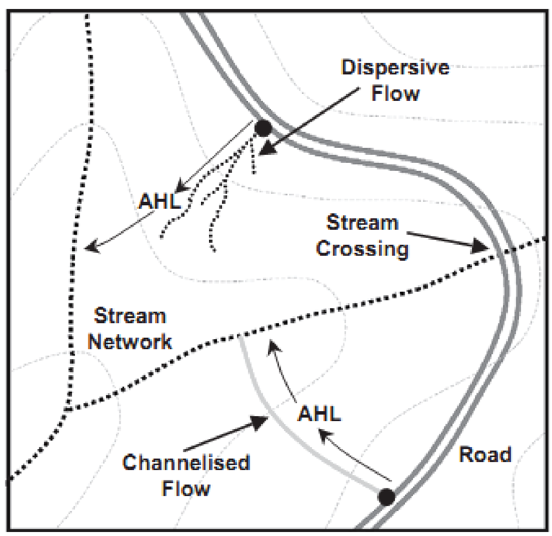


Figure 3. Examples of runoff pathways (from Croke *et al.*, 2005)

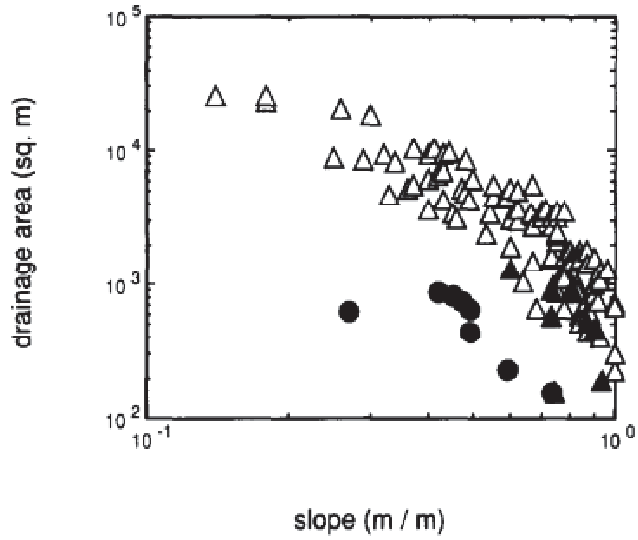


Figure 4. Channel initiation observed in both natural areas (open triangles) and as a result of roads (solid circles), along the Mettman Ridge, OR., (from Montgomery, 1994)

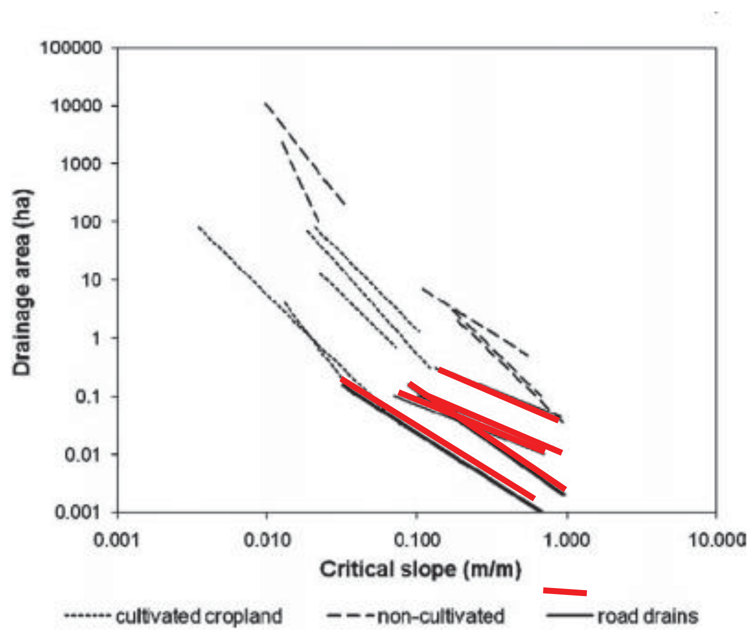


Figure 5. S-A thresholds for channel initiation in cultivated, non-cultivated lands (data created from Poesen *et al.*, 2003, Montgomery, 1994, Croke & Mockler, 2001, Takken *et al.*, 2008, taken from Takken *et al.*, 2008)

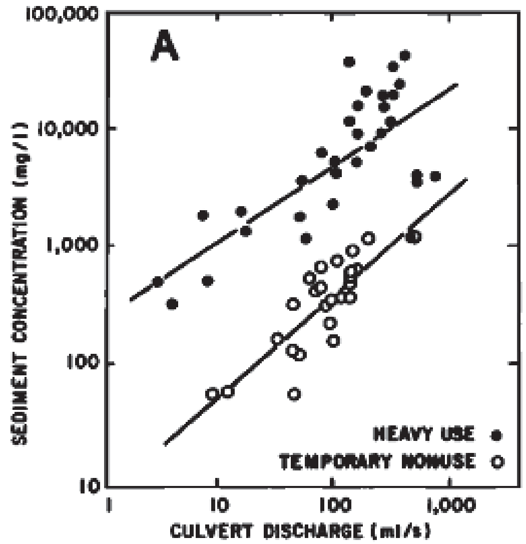


Figure 6. Sediment concentrations as a result of traffic usage (from Reid and Dunne 1984)

Chapter 1: Road Erosion

Outline of study approach:

Background: Major watershed level characteristics (sampling based on: Water Quality, Surficial geology attributes)

↓

Chapter 1: Road-stream crossing survey describing connectivity, current extent and magnitude of erosion.

↓

Chapter 2: In channel qualitative study of stream health, investigation of local development effects as an adverse stress on stream quality and stability.

Objective

This chapter explores the variability of observed erosion as it relates to site specific and watershed level factors. The results of observed sediment losses for road segments studied in the summer of 2010 are given in three parts. First road segments are described by their basic road attributes (length, area, slope and elevation). Secondly observed road erosion is quantified and characterized by major factors such as water quality and geomorphic associations, predictive modeling was executed utilizing measured field variables. Lastly, road segment variables such as road contributing area and road slope are used to predict channel initiation using the slope-area threshold.

Hypothesis

H1 – Geomorphic Association: *The frequency of road erosion will be highest for roads built upon scoured bedrock uplands, classified by the UMD-Geomorphology map.*

H2 - Surface: *The greatest sediment losses will occur alongside paved roads.*

H3 – Type of erosion: There will be a greater frequency of large scaled erosion (gully) rather than rills.

Methods

Identification of road survey locations

Road-stream crossing locations were estimated by intersecting the USGS NHD hydrography (30 m resolution) layer, and modified road layer consisting of MN DOT base road layer (digitized from USGS 1:24k mapping series, through the 2000 construction season) and a US Forest Service Superior National Forest (SNF) road layer (obtained from SNF hydrologist Marty Rye). Layers were buffered (5 m), intersected, extracted to points and then visually assessed to ensure road segments were not duplicated incurring an overestimation of road length. Points were then overlain with watersheds boundaries, elevation values (30m DEM), geomorphologic associations (Superior Lobe, scoured bedrock), and STATSGO soil texture, (Minnesota DNR Data Deli, 2011,NRCS, 2011) (Figure 7).

This dataset was sampled to represent geomorphic attributes of the North Shore – northern Lake Superior watershed, such that results could be scaled to estimate current sediment losses within the greater watershed (Table 8). Study watersheds were aggregated as "control" or "impaired" watersheds, and examined as two groups instead of individually by watershed. A total of 60 sites were originally chosen (30 for each study group [impaired, control watersheds]); however 54 survey sites were field verified and included in this study (Figure 8). This subset is estimated to describe 15.7% of North Shore watershed road-stream crossings. In order to capture the North Shore geomorphic variability it was not possible to equally sample primary geomorphic variables: superior lobe, and scoured bedrock uplands between the study watersheds.

***Watershed level connectivity:* Road-Stream direct linkages**

To evaluate total channel network extension due to roads, an analysis of road proximity to waterways was made combining an estimation method developed by Miller (2010), and direct road-stream linkage methods developed by Wemple (1996) and Croke and Mockler (2001). Road-stream connectivity was investigated using GIS data layers, a modified roads layer (MNDOT/USFS), USGS National Hydrography Dataset streamline layers, and MN DNR *lake-wetland* data layer, National wetlands inventory (NWI) polygons (24k) and MnDOT base-map lake delineations (Minnesota DNR Data Deli, 2011). Water resources were buffered at various scales (100 ft (30.5 m), 50 ft (15.2 m), < 10 ft (3.1 m)) simulating setback requirements in St. Louis County, then intersected with the roads layer. The sum of road length connected to streams was determined for each buffer distance.

All road segments found to intersect a stream layer at selected buffer widths, representing riparian corridor were considered an *extension of the stream network*. Drainage density was calculated as the combination of added road length and existing stream network within each riparian zone. In-field observations of direct road-stream connectivity were also incorporated into this analysis. All lengths are expressed in miles.

Road survey site direct connectivity

To evaluate road survey sample set channel extension and connectivity to water resources, distances from roadway to the crossing structure (culvert, bridge) were measured in the field and cross checked with digital aerial photography within ArcGIS ArcMap (La Marche & Lettenmaier, 2001). These distances represent the average total buffer length (average buffer length of both sides of the road prism) that lies between the roadway and the stream.

Field survey

Road survey methodology followed frameworks put forth by (Napper, 2008) and work by Montgomery, 1994, Wemple et al., 1996, Luce & Black, 1999, Croke & Mockler, 2001, Takken et al., 2008). Detailed assessments of road characteristics were evaluated at each road survey location, including: road segment length and width (measured three times at each location) using a trundle wheel, slope was measured using a clinometer, dominant road surface type (native, gravel (aggregate), paved), road design (inslope, outslope, crown, entrenched), percent vegetation on road, dominant soil texture of surrounding site, and evaluation of cutslope and fillslope percent vegetative cover. Roadside ditches were characterized using similar methodology to the road survey (Figure 10).

Erosion processes

Erosion volumes were determined by direct measurement of the feature using a ruler and trundle wheel. Each feature was mapped and described as a gully, rill or mass failure, then measured to characterize width (average of three measurements), depth (average of three measurements) and length (Figure 9). For this study, “rill” erosion was considered a feature with a constant width of 0.5 in – 2 in (1.3 cm – 5.1 cm) and a depth of 0.25 in – 2 in (0.6 cm - 5.1 cm), gully erosion was defined as a feature with a discontinuous width greater than 0.5 in (1.3 cm), with a depth less than 50 in (127 cm), mass erosion was characterized as a feature larger than a gully in which bank failure was observed (Figure 11). Characterization of erosion processes (gully, rill) is disputed within the literature, arguably the rill and gully dimensional characterizations used in this study are conservative when compared to other investigations (Croke & Mockler, 2001).

Statistical methodology – Roads

The road erosion dataset was primarily statistically analyzed using non-parametric tests and logistic regression using a presence/absence approach. All analysis was conducted using the statistical software, **R** (http://www.r-project.org/).

Kruskal-Wallis test

The non-parametric Kruskal-Wallis test was used to investigate significant differences between measured erosion volumes and key (categorical) variables (ie: watersheds, geomorphic association, road surface texture, traffic, stream order, watershed water quality (presence on EPA 303(d) listing), ditch vegetation type). The Kruskal-Wallis test is a ranked sums test where values (erosion volume) are ranked with the lowest value given a rank of #1 to the largest value receiving a rank of #n. Each value is replaced with a rank, and then returned to the respective categorical group and summed. If values are equal a tied ranking is given (Daniel, 1990).

Note on GIS Use

Much of the analysis and estimation of data pertaining to watershed, hydrography and road characteristics were completed using a GIS (Geographic Information System) ArcView 9.0. This was executed utilizing the buffer tool and the intersect tool, in the Proximity toolbox of ArcToolbox within ArcMap. All spatial data layers used were processed and projected to NAD 1983 UTM 15. Unless otherwise stated, data layers or aerial photography were retrieved from the Minnesota DNR Data Deli (http://deli.dnr.state.mn.us/), or the Minnesota Geospatial Information Office (http://www.mngeo.state.mn.us/). Digital Elevation Models (DEM), stream hydrography and historical photos (< 1991) were obtained from through the USGS map viewer (http://viewer.nationalmap.gov/viewer/). Detailed soils data (SSURGO) is not available at this time (2010-2011), thus STATSGO data was obtained through the USDA-NRCS soil data mart (http://soildatamart.nrcs.usda.gov/).

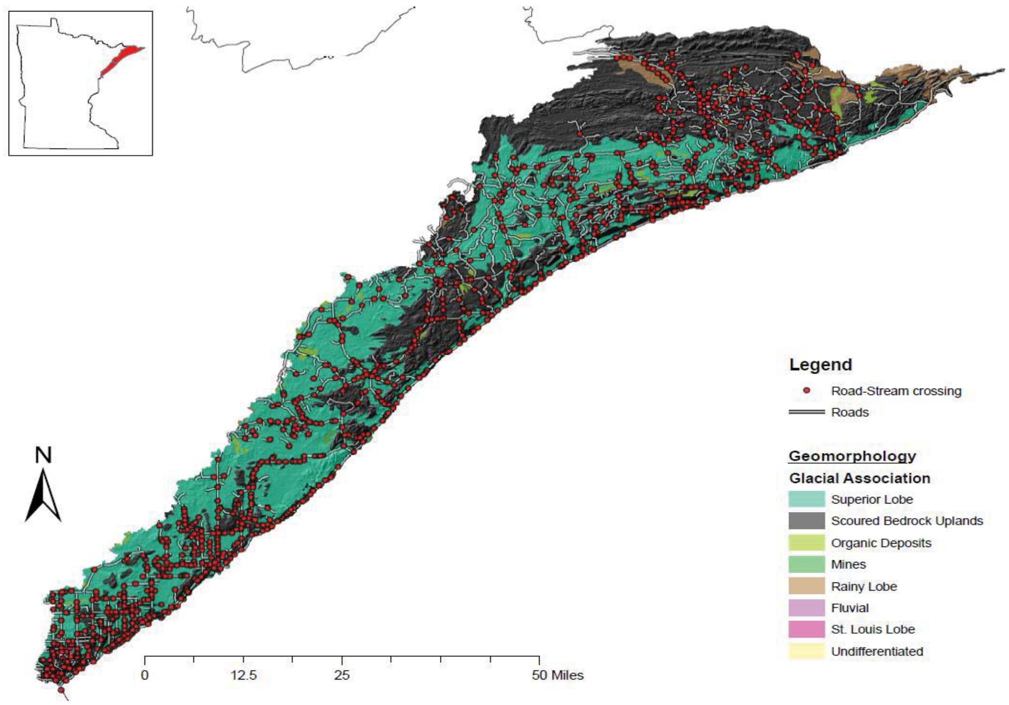


Figure 7. All crossings estimated using road and hydrography layers within GIS

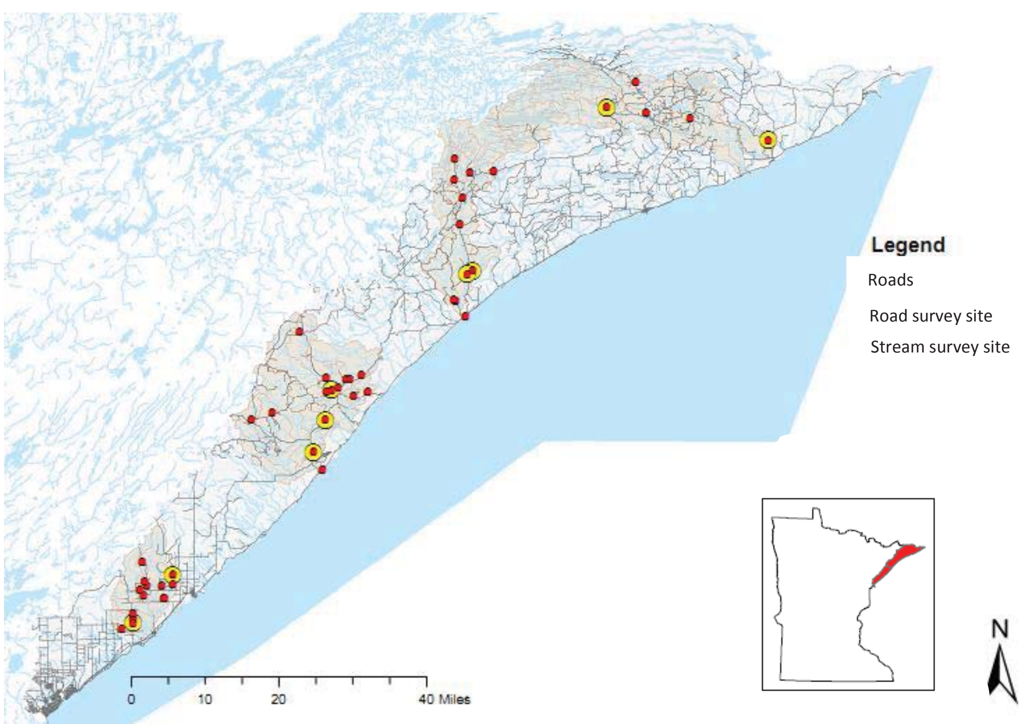


Figure 8. Road survey locations

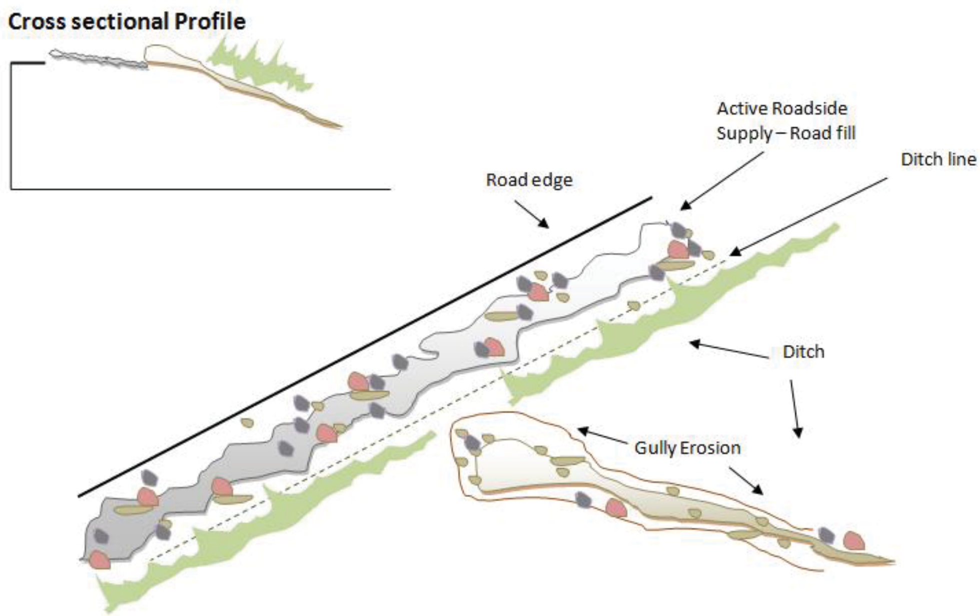


Figure 9. Field Survey Diagram and Cross Sectional Profile

Table 8. Sampling distribution

			Scoured Bedrock Uplands	Superior Lobe				Organic Deposits		Rainy Lobe	
	Total Crossings	Total # of crossings when sampled at 15%	*Igneous*	*Ice Contact*	*Outwash*	*Supraglacial Drift Complex*	*Till Plain*	*Peat*	*Till Plain*	*Metamorphic*	*Undifferentiated*
North Shore	1334	200	20.39%	0.52%	0.67%	10.72%	64.47%	0.75%	1.20%	0.82%	0.15%
Sample Set	333	54	24.02%	0.30%	0.30%	10.51%	60.66%	0.30%	3.90%	0.00%	0.00%
Impaired	153	27	4.58%	0.00%	0.00%	18.30%	77.12%	0.00%	0.00%	0.00%	0.00%
Control	180	27	40.56%	0.56%	0.56%	3.89%	46.67%	0.56%	7.22%	0.00%	0.00%

Results

Road-Stream direct linkages

Channel network extension and connectivity was evaluated as the percentage of the road network within 100 ft (30.48 m) of a stream at various scales. The results of this analysis indicate roads may increase stream drainages for the greater North Shore watershed by 1.45 – 9.47%. Estimations for study watersheds indicate roads increase drainage by 1.39 – 10.81%. Comparably these results are similar, suggesting by way of this analysis, the selected study watersheds may be a good representation of the total North Shore watershed.

The greatest increase in drainage density was found within the control watersheds for roads located 50-100 ft (15.24-30.48 m) (6.92%) from streams. This was true for the overall North Shore stream watershed (9.47%), and for control watersheds (5.11%) (**Error! Reference source not found.**). Considering all estimations, control watersheds were more likely to experience an increase in drainage density due to roadway proximity at various buffer widths, 100 ft (30.48 m) (control – 6.92%, impaired – 5.11%), 50 ft (15.24 m) (control – 3.73%, impaired - 2.54%), < 10 ft (3.04 m) (control – 1.39%, impaired – 0.97%). This trend however did not align with field survey observations, where impaired watersheds had the greatest increase in drainage density (0.99%) compared to control watersheds (0.53%).

Table 9. Road to stream linkages at buffer widths 100ft, 50ft, <10ft and with field observations

Catchment parameters	Unlinked network No road linkages			Roads linked to Streams at 100 ft (30.5 m)			Roads linked to Streams at 50 ft (15.2 m)			Roads linked to Streams at < 10 ft (3.1 m)			Observed characteristics	
	N. Shore	C	I	N. Shore	C	I	N. Shore	C	I	N. Shore	C	I	C	I
Road length (mile)	0.0	0.0	0.0	301.5	57.0	20.7	136.7	30.8	10.3	46.00	11.5	3.9	4.3	3.6
Gully length (mile)													7.8E-04	1.3E-02
Rill length (mile)													0.1	0.4
Total additional length	0.0	0.0	0.0	301.5	57.0	20.7	136.7	30.8	10.3	46.0	11.5	3.9	4.4	4.0
Stream Total drainage length (mile)	3183.5	824.0	405.0	3485.0	881.0	425.7	3320.2	854.8	415.2	3229.5	835.5	408.9	828.4	409.0
Stream Drainage density (mile/mile^2)	1.44	1.40	1.80	1.58	1.49	1.89	1.50	1.45	1.85	1.46	1.42	1.82	1.40	1.82
Increase in drainage density (%)	0.0	0.0	0.0	9.47	6.92	5.11	4.29	3.73	2.54	1.45	1.39	0.97	0.53	0.99

** N. Shore = North Shore Watershed of the North Shore watershed, Northern Minnesota, USA*

** C = Control Watersheds (Baptism, Brule, Temperance)*

** I = Impaired Watersheds (Beaver, Flute Reed, Knife)*

Methodology, modified Wemple (1996), Croke and Mockler (2001)

Road Survey Erosion

In the field, erosion was stratified by types, gully, rill and mass erosion. For this study, rill erosion was characterized as a feature with an approximate width of 0.5 in – 2 in (1.3 cm – 5.1 cm) and a depth 0.25 in – 2 in (0.64 cm – 5.1 cm), gully erosion was defined as a feature having a discontinuous width > 2 in (5.1 cm), with a depth > 0.5 in (1.3 cm), and mass erosion was considered any erosion occurring over a large area presumably a source of observed hillslope failure. Analysis of measurements taken in the field indicated 64.8% of the sample set had notable erosion (

Additional Tables

Table 110). Presence of an erosion type did not exclude other types, thus a site could have multiple types of erosion occurring.

Of the 12.2 km (7.58 miles) of road surveyed, and 54 road sites observed, 31.5% of sites were observed to have gully erosion, 50% of sites had rill erosion present, with 1 site or 1.8% of the sample set having mass erosion (

Table 12). The total sum of all observed erosion was 93.27 m^3 (3,293.7 ft^3) with an average per site loss of 1.73 m^3 (93.94 ft^3) or 7.65 m^3/km (434.50 ft^3/mile). The median of the sample set was 0.005 m^3(0.18 ft^3) the 3rd quartile was 0.15 m^3(0.53 ft^3) . Three of the sample sites exceeded this 3rd quartile value and were considered to be "outliers" within the dataset (volumes of 11.71 m^3, 13.8 m^3 and 52.36 m^3) (

Table 13). If excluding outliers the total sum of erosion observed was 14.79 m^3 (522.30 ft^3). Pertaining to road surface erosion, 60.71% of paved roads, 64.7% of gravel roads, and 77.7% of native roads surveyed had erosion. Sample sizes were not evenly distributed between road surface groups, which may have skewed the dataset (sites with erosion out of total: gravel: 11 out of 17, paved: 17 out of 28, native: 7 out of 9) (

Table 14).

When coupling the data with watershed wide characteristics (water quality and geomorphic attributes), the greatest sediment losses were found on paved surfaces in the control watersheds on Superior Lobe glacial till, resulting in a total eroded volume of 53.35 m^3 (1884.04 ft^3) (this value is inclusive of all sites). Controlling for outliers, total erosion was greatest along paved road sites in impaired watersheds on Superior Lobe glacial till at lower elevations (189 m – 323 m), with an eroded volume of 7.94 m^3(280.40 ft^3), with the least erosion occurring on native unsealed surfaces in control watersheds on Superior Lobe glacial till at higher elevations (522 m – 540 m) at 0.07 m^3 (2.47 ft^3) (

Table 13).

The total sum of erosion was greatest within control watersheds survey sites (2.83 m^3 or 55.81 m^3 including outliers) than for impaired watersheds sites (11.96 m^3 or 37.45 m^3) if including outliers). Excluding outliers, impaired watershed sites had the greatest average per site erosion (5.98 m^3 (211.18 ft^3)), compared to control watersheds (1.41 m^3 (49.79 ft^3)) (

Table 14).

By surface type, the greatest erosion occurred on paved roads in control watersheds (53.35 m^3 (1884.04 ft^3)), and paved roads in impaired watersheds (20.21 m^3(713.71 ft^3)); excluding outliers gravel and paved sites in impaired watersheds had the greatest per site average erosion at 2.72 m^3 (gravel), and 2.03 m^3 (paved) (

Table 14). Statistically analyzed using the Kruskal-Wallis ranked sums non-parametric test, there was only one difference in erosion occurrence between groups, with impaired watersheds sites found to be statistically dissimilar when compared to control watersheds for rill erosion, (alpha = 0.05, chi squared p value= 0.04285) (

Table 12).

Erosion observed by geomorphic associations was found to be greatest for Superior Lobe sites (65.05 m^3 (2297.22 ft^3)) compared to scoured bedrock upland parent material sites (28.21 m^3 (996.23 ft^3)), excluding outliers per site average erosion was lowest for scoured bedrock sites (2.77 m^3 (97.82 ft^3)), compared to Superior Lobe sites (4.63 m^3(163.51 ft^3)). Excluding outliers, the greatest erosion was found on Superior Lobe gravel (2.77 m^3 (97.82 ft^3)) and paved (1.32 m^3 (46.62 ft^3)) road survey sites and on gravel scoured bedrock sites (1.14 m^3 (40.26 ft^3)).

If observed sediment losses (65% of road survey sites, 93.27 m^3) were scaled from the 16% survey sampling distribution to represent the estimated 342 crossings within the study watersheds sample set, an eroded volume of 92.44 m^3 or 582.94 m^3 (if including outliers) is estimated to have occurred along roadsides at road-stream crossings within study watersheds (Table 10). This calculation assumes material may have been transported to nearby water bodies (stream, lakes, wetlands) or nearby riparian areas. With the limited dataset for this project and unequal sampling distribution in regards to geomorphic factors and characteristics, this limits the ability of the dataset to be scaled up to the North Shore watershed level as this project represents only 4% of the total watershed.

Table 10. Scaled erosion volume for North Shore Watershed

Type of observation	Definition	Total erosion (m^3)
Field Observations	All erosion (m^3)	93.27
	Excluding outliers (m^3)	14.79
North Shore Watershed	**Estimated crossings**	342
	Scaling factor (16%)	6.25
Estimated total erosion for North Shore watersheds	All erosion (m^3)	582.94
	Excluding outliers (m^3)	92.44

Predictive modeling

Using stepwise logistic regression and stepwise multiple linear regression watershed wide and road segment scale characteristics were tested to determine the best predictors of observed erosion. All models were tested at an alpha = 0.05, and by weighting AIC values to indicate the most explanatory relationship for the dataset.

Presence / Absence logistic regression – Road segment

The presence of erosion was modeled on a road segment scale, including variables such as: road dimension (width, length, area), hillslope angle, planar distance (roadside to stream), traffic and width of shoulder material. On a road segment wide basis, **traffic use** (0 indicating low use or minimum maintenance roads, 1 indicating medium or high traffic roads) (p= 0.1326, weighted AIC = 0.5924) (Table X).

Total volume of erosion multiple linear regression - Road segment

Investigating components driving erosion at a local scale, stepwise multiple linear regression tests were used to best predict the logarithm of observed total erosion using road segment site explanatory variables. The best predictor was the **width of shoulder materia**l, significant at an alpha=0.05, p value equal to 0.0097, weighted AIC=0.6371 (Table 15).

Presence / Absence logistic regression – Watershed wide

A stepwise logistic multiple regression test determined the best predictors for the occurrence of erosion at a watershed wide scale for the dataset. Watershed wide explanatory variables included surficial geology, watershed water quality association (impaired, control), Stahler stream order road surface type, soil k factor describing soil erodibility and soil texture (derived from NRCS STATSGO soil survey). When modeled, the most probable predictors of erosion (presence = 1, absence = 0) for the dataset were watershed water quality association (control, impaired) and soil k factor (p value = 0.1899, weighted AIC= 0.4849).

Total volume of erosion multiple linear regression

Stepwise multiple variable linear regression tests were used to predict the logarithm of observed total erosion as a volume using watershed wide explanatory variables. When modeled the best predictor was found to be 'contributing hillslope gradient' a factor grouping gradients at "10%", "10-25%" and "less than 10%" (Wemple & Jones, 2003). This relationship was found to be significant (alpha=0.05) with a p value equal to 0.0171, weighted AIC = 0.4973 (Table 15).

Additional Tables

Table 11. Total Observed Erosion in field (reflected as a % of erosion dataset, excluding non eroding sites)

			Geomorphic Association		Water Quality	
	Number of Sites	*% of Total sample*	*Scoured Bedrock Uplands*	*Superior Lobe*	*Control*	*Impaired*
% Observed Erosion	35	64.8%	76.9%	61.0%	59.3%	70.4%
% of Sites with Gully Erosion	17	31.5%	38.5%	29.3%	37.0%	25.9%
% of Sites with Rill Erosion	27	50.0%	61.5%	46.3%	37.0%	62.9%*
% of Sites with Mass Erosion	1	1.8%	7.7%	0.0%	0.0%	3.7%

**Statistically dissimilar when compared with control watersheds for rill erosion, chi squared p value = 0.04285*

Table 12. Road Characteristics for road survey sites grouped by Surface Type, Geomorphic association, and Water Quality status (average values)

Road Characteristics	*Gravel*	*Native*	*Paved*	*Scoured Bedrock Uplands*	*Superior Lobe*	*Control*	*Impaired*
# of road sites	17.00	9.00	28.00	13.00	41.00	27.00	27.00
Width (m)	5.72	5.59	9.01[a]	5.09	8.14*	7.97	6.83
Road length (m)	81.23	91.22	139.37 [a]	107.54	114.78	122.24*	103.83
Road area (m^2)	464.78	510.12	1255.18 [a]	547.83	933.82*	974.55*	709.66
Road slope average %)	0.03	0.05	0.03	0.04	0.03	0.04	0.04
Elevation (m)	448.06	464.78 [a]	354.39	465.00*	382.39	436.74*	367.81
Road to stream distance (ft)	3.29	1.98	5.94	3.80	4.65	3.33	5.56
Sediment in ditch (% occurrence)	0.76	0.78	0.82	0.92	0.76	0.67	0.93*

[a] Ranked the highest (A), and found to be statistically significantly different when tested with Kruskal Ranked Sums non-parametric approach (alpha = 0.05)

** Ranked the highest (A), and was found to be statistically significantly different than the other the opposing category when analyzed using a Mann-Whitney-Wilcoxon ranked sums non-parametric approach.*

Table 13. Total erosion by watershed group by volume (m^3)

Watershed group	# of sites with Erosion	# of Rills observed	# of Gullies observed	Total Erosion (m^3)	Average Total Erosion (m^3) (minus outliers)
Control	16	35	33	55.81	1.41
Impaired	19	127	33	37.45	5.98
Grand Total	35	162	66	93.26	7.40

Table 14. Total erosion by surface type by volume (m^3)

Road Surface	Water Quality	Geomorphic attribute	# of sites	Sum of total erosion	Sum of total (minus outliers)	Average erosion per site	Average erosion (minus outliers)
Gravel	*Control*	*Scoured Bedrock Uplands*	3	1.53	1.53	0.76	0.76
		Superior Lobe	8	0.64	0.64	0.19	0.19
	Impaired	*Scoured Bedrock Uplands*	4	0.42	0.42	0.38	0.38
		Superior Lobe	2	2.34	2.34	2.34	2.34
Native	*Control*	*Scoured Bedrock Uplands*	1	0.23	0.23	0.23	0.23
		Superior Lobe	5	0.07	0.07	0.07	0.07
	Impaired	*Scoured Bedrock Uplands*	1	13.77	0.00	13.77	0.52
		Superior Lobe	2	0.72	0.72	0.72	0.72
Paved	*Control*	*Scoured Bedrock Uplands*	1	0.00	0.00	0.00	0.00
		Superior Lobe	9	53.35	0.36	6.79	0.17
	Impaired	*Scoured Bedrock Uplands*	3	12.27	0.55	12.23	0.88
		Superior Lobe	15	7.93	7.93	1.14	1.14

Table 15. Erosion prediction model outputs

Road segment characteristics

Presence/Absence of erosion (Logistic regression)	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Erosion ~ Traffic	77.05	0	1.000	0.592	0.1326
Erosion ~ Traffic + Road length	78.46	-0.79	1.484	0.879	
Erosion ~ Traffic + Road length+Vegetation type (hillslope)	79.79	0.54	0.763	0.452	
Erosion ~ Traffic + Road length+Vegetation type (hillslope)+Rd. Area	81.4	2.15	0.341	0.202	

Volume prediction (Stepwise multiple linear regression)

Model stepwise regression	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Erosion Volume~ Width shoulder material (road supply)	79.25	0	1.000	0.592	0.009
Erosion Volume ~ Road supply + Vegetation type (hillslope)	80.91	1.66	0.436	0.258	
Erosion Volume ~ Road supply + Vegetation type (hillslope) + Rd. length	82.7	3.45	0.178	0.106	
Erosion Volume ~ Road supply + Vegetation type (hillslope)+ Rd. length + Rd. area	84.46	5.21	0.074	0.044	

Watershed wide characteristics

Presence/Absence of erosion (Logistic regression)	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Erosion ~ K factor + Water Quality group (impaired, control)	77.91	0.00	1.00	0.4849	0.1899
Erosion ~ K factor + Water Quality group + Traffic	78.69	0.78	0.68	0.3283	
Erosion ~ K factor + Water Quality group + Traffic + Stream order	80.45	2.54	0.28	0.1362	
Erosion ~ K factor + Water Quality grp + Traffic + Stream order+ Geomorphic Assoc.	82.43	4.52	0.10	0.0506	

Volume prediction (Stepwise multiple linear regression)	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Erosion Volume ~ Hillslope position	79.54	0.00	1.00	0.4973	0.0457
Erosion Volume ~ Hillslope position + Traffic	80.90	1.36	0.51	0.25	
Erosion Volume ~ Hillslope position + Traffic + Geomorphic Assoc.	81.56	2.02	0.36	0.18	
Erosion Volume ~ Hillslope position + Traffic + Geomorphic Assoc.+ K factor	83.47	3.93	0.14	0.07	

Discussion

Initial findings

With the approximate 2,339.5 miles (3,765.06 km) of roads and the estimated 1,346 stream crossings within the North Shore-Lake Superior watershed, stream interception of road sediments is likely occurring. Although the scale and rate of erosion is currently unknown, this study shed light on current sediment losses and road connectivity within select watersheds. This investigation evaluated channel network extension by way of road-side connectivity at 54 road-stream crossings within 6 watersheds. Observed sediment losses were compared between turbidity impaired watersheds and non-turbidity impaired watersheds to evaluate a causal link between road side sediment contributions to streams with known water quality impairments.

Initial findings of this study indicate, roads increase drainage density by approximately 1.45% – 9.47% within the North Shore watershed; and 5.11 – 6.92% within study watersheds. The extent of erosion observed at 54 field sites over 12.2 km (7.58 miles), indicated sediment losses totaling 93.27 m^3 (3,293.7 ft^3) or 7.65 m^3/km (434.5 ft^3/mile). When road characteristics such as contributing road area and hillslope gradient were modeled using the slope-area threshold (Montgomery, 1994). Without further investigation and monitoring it is unclear if the observed roadside erosion was a short term or long term scenario.

Observed erosion losses totaled 93.27 m^3 (if scaled to North Shore watershed: 92.44 m^3 or 582.94 m^3 (including outliers)). This value is considered a low estimate of road induced erosion when compared to sediment losses within the literature. It should be noted that a characterization of “low” is not known with certainty due to a lack of comparison data for this region. However to provide a point of context, a 1996 study by Wemple *et al.* (2001), calculated a net sediment loss of 13,080 m^3 (37.6 m^3/km) attributed to road prisms after a large preicpitation event (290 mm) in the western Cascade Range, OR; losses roughly 5 times that observed in this study.

Road-Stream connectivity

Roads are a large contributor of concentrated drainage and runoff, often draining runoff to ditches or stormwater drains which are designed to act as a conduit for conveying water in an efficient manner to nearby streams or waterbodies. The additive effect serves to increase road connectivity to streams, expanding the channel network (Montgomery, 1994, Booth & Jackson, 1997).

Investigating channel network extension by way of road-stream connectivity, roads within study watersheds were found to increase drainage density to streams by 5.11 – 6.92% at 100 ft (30.5 m), 2.54-3.73% at 50 ft (15.2 m) and 0.97-1.39% at 10 ft (3.1 m). Following MacDonald and Coe (2008) the likelihood of road related sediment conveyance to streams increases as road-stream distances decrease, less than 30 m therefore the minimum connectivity expected for study watersheds is 5.11-6.92% (30.5 m). Channel initiation processes observed in the field were incorporated into the investigation of road connectivity. On a per site level, gully processes were found to increase drainage area by 0.53-0.99%.

These values are lower than literature findings partly due to the limited observations of gully development observed in field (31% of sites, 6% of sites directly connected via gullying). It should be noted erosion observations were categorized at a smaller scale compared to the literature; with gullies categorized at depths greater than 5.1 cm (2.0 in). Comparably, Croke *et al* (2005) characterized channelization at depths greater than 30 cm (11.81 in), with observations less than 30 cm considered to be non-eroding or "dispersive" features. Gully lengths differed as well; average gully transport flow path was 0.73 m (2.39 ft), far less than the average gully plume length observed by Croke et al (2005) of 16 – 25 m (52.5 – 82 ft).

Although erosion characterizations were less than in other studies, it should be noted that 6% of study sites were directly connected via gullying. If this study were completed over time and monitored during and after precipitation events, this observation would surely increase. Compared to literature findings, the importance of large sample sets, and long term monitoring cannot be stressed enough, as it increases our ability to fully assess the situation at hand. For instance, a long term 30 year study at Cuttagee Creek, Australia estimated drainage density had increased by 6-10% due to gully initiation processes. Gullying accounted for 21-50% increase in drainage density at Lookout Creek and Blue River, OR Oregon (Wemple *et al.*, 1996). Croke and Mockler (2001) found 18% of 228 drains surveyed were directly connected to streams via gully development at Cuttagee Creek; and LaMarche and Lettenmairer (2001) found 24% of 1447 sites were fully connected to streams by gully formation (characterized at the base of culverts extending to the stream) in Deschutes River, WA.

Road characteristics

Many primary road variables such as surface material type were not known with certainty prior to sampling. Thus, sampling was not controlled for specific road characteristics (road with, segment length, road slope, road surface material, road age). The timing of resident channel formation is not known in entirety for the dataset, as sites were not actively monitored over a sufficient period of time to account for this. Roads within the North Shore were in place in the 1930s, and have undergone extensive redesign and reconstruction since then. Road age in combination with stratigraphy and elevation could create differing subsurface hydrology and differing contributing road area, as the road prism likely changed since first development.

The effect of road construction type was not fully investigated within this project. The dataset was overwhelmingly considered to have a "crown" if not an "at grade" construction type. But it goes without saying that the type of road can bear greatly on erosion efficiency. Elliot (2009) points out outsloping roads minimize surface erosion due to efficient dispersal of flow paths, whereas insloping roads transfer water to ditches, where erosion rates are greatly affected by the level of armoring and density of vegetation.

A key attribute not known with certainty for study road segments in addition to relative age was the timing and frequency of grading. Observations at some native and gravel road sites with roadway ruts may be an indication that grading and maintenance had not occurred in many years. This factor can greatly control sediment losses, in many cases the greatest losses occur on newly constructed roadways, tapering to negligible amounts with time (Elliot *et al.*, 2009). Sullivan and Foote (1983) confirmed this theory, as their study found older roads had higher frequencies of erosion, while newer roads had the greatest losses.

Cut and Fill slopes

A former study of roadside erosion throughout the state of Minnesota by Sullivan and Foot (1983), described St. Louis and Lake counties as having severe to slight-moderate road side erosion, with Cook county demonstrating minimal-slight erosion. The statewide finding of this report indicated cut and fill roads had the greatest soil losses, with fill type construction having the lowest losses. This project found sites with "fill" type and "cut and fill" type construction had the greatest losses within impaired watersheds on Superior Lobe glacial till along paved roads; these sites also incurred the highest frequency of erosion observations (frequency: *Fill* only: 13, *Cut and Fill*: 9). Within this study if evidence of erosion or plumes of deposition were observed it was mainly due to scarce vegetation rather than construction type. However this was not considered a large source of sediment with the majority (90%) of observations indicating fillslopes were fully vegetated between 80-100%.

Wemple et al., (2001) found road placement, condition, watershed geology and storm characteristics may have contributed greatly to sediment losses; variables indicated within this study to be major predictors of erosion. Although spatially, gully processes were not observed to be the dominant mode of road-stream connectivity, much of the observed erosion is estimated to result from increases in surface road runoff upon fillslopes (24% of sample set, cut/fill 17%, cutslopes 13%). Given the findings of Wemple et al (2001) road type, position and condition; hillslope vegetation, watershed geology, are all determinants of future sediment losses along roadsides, factors also augmented by severe weather.

Model predictions: Road survey site

Observed sediment losses were predicted using logistic regression at the road survey site and watershed level. This was to allow for possible separation of road specific and watershed specific factors.

Presence of Erosion: Traffic

Survey sites were visited once in the summer of 2010, with the assumption that observed traffic patterns may fluctuate by the hour, weekday and seasonally. To counteract possible bias, roads were given a binary indicator of "1" if in use or "0" if closed and vegetated. Using logistic regression the presence of erosion was best predicted at the road segment scale by traffic ($p=0.1326$, weighted AIC = 0.5924). Low levels of traffic had a negative relationship to the presence of erosion, therefore minimally trafficked roads were observed to have limited erosion observations. Sites considered "low traffic" or "closed" was 12 (22% of the dataset, with 15% of sites gravel or unsealed, 7% paved).

Erodibility of road material is likely to increase with increasing usage (high traffic levels) (Elliot *et al.*, 2009). For this project, the greatest frequency of erosion was noted along native and gravel roads, but not the greatest sediment losses. In comparison accelerated surface erosion was greatest along roadsides and ditches of impervious high use paved roads; (44% of sites were paved medium to high use road segments, 28% of sites were paved high use roads with erosion). In-field observations suggest impervious surfacing likely increased surface runoff to fillslopes consequently accelerating sediment detachment along roadsides. Notably 2 of the 3 “outliers” were located at heavily trafficked paved roads with large paved parking areas. These sites totaled an eroded volume of 64.71 m^3 or 69.3% of the total volume observed within this dataset.

Erosion by Volume: Width of Shoulder material

On a road segment scale, observed erosion was best predicted by the width of shoulder material (p=0.0097, weighted AIC=0.6371). The width of shoulder material characterized as roadside supply is shown to positively relate to erosion, thus as the shoulder material increases in width, erosion occurrences may also increase. This is assumed to be related to the large supply of erodible material which lies directly alongside the impervious road surface, composed of a material that is not armored and easily transportable. Sediment accumulation in ditches was observed to be similar in size and character to material originating from this shoulder material.

Watershed wide characteristics

Role of parent material

This project opted to additionally study possible connections between observed erosion and the underlying material of the road prism. Although many road sites had obviously undergone extensive redesigned with large well graded fillslopes with deviating road slopes comparable to the surrounding landscape; some sites were relatively undisturbed with minimal construction. It was at these sites that this project hypothesized greater erosion occurrences to occur on bedrock dominated landscapes, considered to have “thinner” soils, a characteristic that may limit infiltration on roadsides, and allow for greater seepage of groundwater (Wemple & Jones, 2003). However a study by Sugden and Woods (2007) suggest differently, underscoring the roll of parent material and soil type as controlling factors in observed road erosion rates.

Sugden and Woods (2007) studied twenty ~0.05 ha unsealed native road plots in western Montana, finding unsealed roads yielded 0 – 96.9 Mg/ha/yr over 3 years (2002-2004). The experimental plots were tested on both fine textured glacial till and metamorphic parent material, finding glacial till plots were 4 times more likely to erode than the plots on metamorphic parent material. The results of this study suggest, Superior lobe sites with an assumed highly erodible thick glacial deposit of material are more likely to erode than the areas defined as thin soil parent material scoured bedrock.

Unexpectedly sites with the greatest and least erosion were both present on Superior Lobe till. The lowest eroding sites may be influenced by glacial till material, however more than likely other factors are controlling the observed erosion; such as location, traffic, surface material and landform gradient. The lowest eroding sites were found on low traffic roads in low gradient landforms of the upper Brule and Temperance watersheds. It is presumed these sites on native unsealed roads, had the lowest erosion due to low traffic pressures and minimum maintenance, which may have armored the road surface from frequent sediment detachment. In comparison, the highest eroding sites were found at lower elevations on paved roads with greater traffic intensity.

Stream order

Stream order was found to negatively relate to observed erosion, this relationship was not significant (p= 0.4634). This relationship maybe skewed in that 46 of the sample sites occurred on low ordered streams (1st order- 21 sites, 2nd order - 14 sites, 3rd order- 11 sites) (Figure 12). Past studies indicate roads on 1st order streams may at times yield the greatest sediment within the watershed. Ramos-Scharron and MacDonald (2005) studied unpaved roadways in the U.S. Virgin Islands, on St. John in the eastern Caribbean which has a dry tropical environment. finding unpaved roads within first-order catchments yielded sediment five times greater than that of undisturbed catchments, with roads at a 2% slope producing 57 Mg ha^{-1} yr^{-1} of sediment per year.

Model predictions: Watershed wide scale

Presence of Erosion: Water Quality and K factor

The presence of erosion was best predicted by the watershed water quality grouping factor (impaired, control), and NRCS STATSGO derived K factor, describing soil erodibility at each site (p= 0.1899, weighted AIC= 0.4849). This relationship describes impaired watersheds as positively related to the presence of erosion, and a negative relationship to the K factor. Soils described by the K factor for this dataset are coarse to medium textured soils, with moderate k values (0.16 – 0.43). The negative K factor relationship suggests, lower k values such as soil high in clay or coarse textured sand are more likely to erode than silt or fine sandy loams. Without knowing the rate of erosion for the study sites, this relationship may be more of an indication of the effect of high runoff efficiencies of roadways in which concentrated flows due to road design may affect increases in erosion throughout time.

Erosion by volume: Hillslope contributions

On a watershed wide scale, observed erosion was best predicted by contributing hillslope gradient (p = 0.0171, weighted AIC = 0.49). Although a significant predictor, the weighted AIC suggests this factor may not be the *best* predictor. This significant positive relationship between contributing hillslope gradient to erosion is supported by findings from Wemple and Jones (2003), in which roads were found to be more likely to intercept subsurface flows from hillslopes, an influencing factor for channel initiation.

Wemple and Jones (2003) studied the interactions of roadways within predominantly forested systems in Oregon; finding intercepted subsurface flow was 95% of measured runoff from study road segments, with road surface runoff contributing far less at 1 – 7%. Wemple and Jones (2003) comment that rapid runoff response attributed to interception of subsurface flow is likely to occur as a function of the magnitude of precipitation events. During large events water tables are expected to rise to a level above the base of the road cut thereby increasing the likelihood of roadway interception. Other landform factors may influence roadway interception of subsurface flow such as antecedent moisture conditions of the site, the degree of road cut intersection of the soil profile; and the effect of parent material; finding **shallow soils** and short hillslopes were more likely to produce runoff.

The findings of Wemple and Jones (2003) may help to confirm results of this study. If survey sites are grouped by hillslope gradients “10%” and “10-25%”, the total volume of eroded material ranges between 12.13 - 14.32 m^3 (13% - 15% of observed erosion) on shallow soiled scoured bedrock parent material; and 0.11 – 55.82 (0.1 – 59.9%) on glacial till Superior lobe sites. Interestingly slopes “less than 10%” were found to be negatively related to total erosion; implying roads along low gradient landforms intercept less subsurface flow, suggesting road segments may receive less runoff resulting in low occurrences of erosion. The upper end of contributing hillslope gradient studied within this project (10 – 25%) can be considered low to moderate, especially when compared to western studies with hillslope gradients ranging between 25 -72% (Wemple & Jones, 2003). However it is entirely possible for a low gradient landform with high storage and conceivably a high water table to interact with roadways, with subsurface flow interception similarly occurring as indicated in western studies. This may depend upon road prism construction; if roads are flanked by wetlands or are placed at similar elevations to nearby lakes, with fillslopes or ditches sharing bank material an exchange of subsurface flow may occur. Because hillslope processes and subsurface interception was not a focus of this study, to validate this conclusion further investigation is necessary.

Error

Thus, this sample set may be exhibitive of the more persistent features on the landscape, subsequently overlooking the ephemeral additions which may occur during a precipitation event. Additionally, similar to Takken *et al.* (2008) and Montgomery (1994) environmental factors that were not controlled for, may have skewed model results due to the wide range of study including multiple watersheds with differing precipitation regimes, and at various elevations, road surface types, and soil type.

Conclusions and Future Work

This project investigated the extent of road-stream linkage, and road induced erosion. Measurable erosion was observed, however the estimated extent of current sediment losses was not observed to be occurring on a large enough scale to be considered a significant source of water quality impairment for North Shore watersheds. Although total sediment losses were low, the greatest probability for roadside erosion may be found on paved roads situated on Superior lobe glacial till, particularly within impaired watersheds The results of this exploratory research suggests the methodology and analysis employed are in line with literature supported theories concerning the hydrologic interaction of roads and resulting sediment transport. These findings suggest that relationships built upon findings from the Pacific Northwest, and southeastern Australia, region which is hydrologically dissimilar in many ways to Minnesota may be applicable for this region. The greatest limitation of this study is sample size, and the lack of repeated visits (monitoring). Future work could employ the methodologies of this project to further investigate the relation of sediment transport to geomorphic attributes.

Lastly, a confined subwatershed specific study would also allow for stronger relationships between observed erosion and road or watershed specific factors; along with supporting a clearer understanding of the influence of roads on channel stability.

Additional Figures

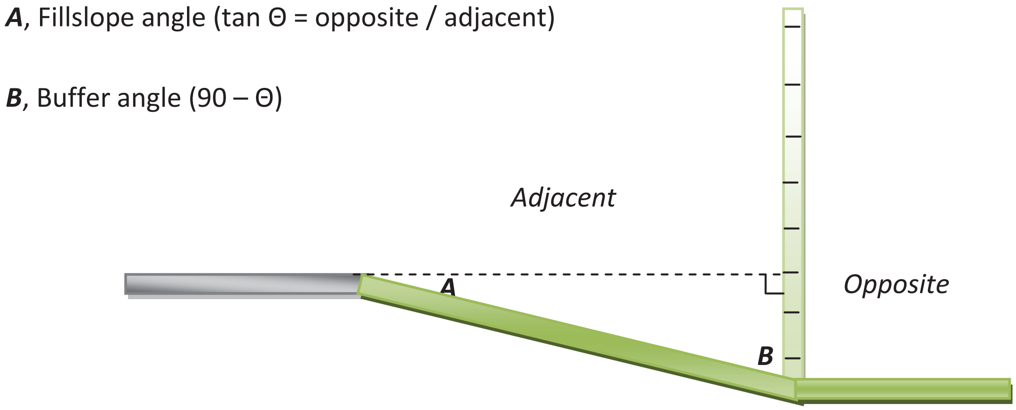


Figure 10. Depiction of ditch measurements and calculation of fillslope, and buffer slope angles

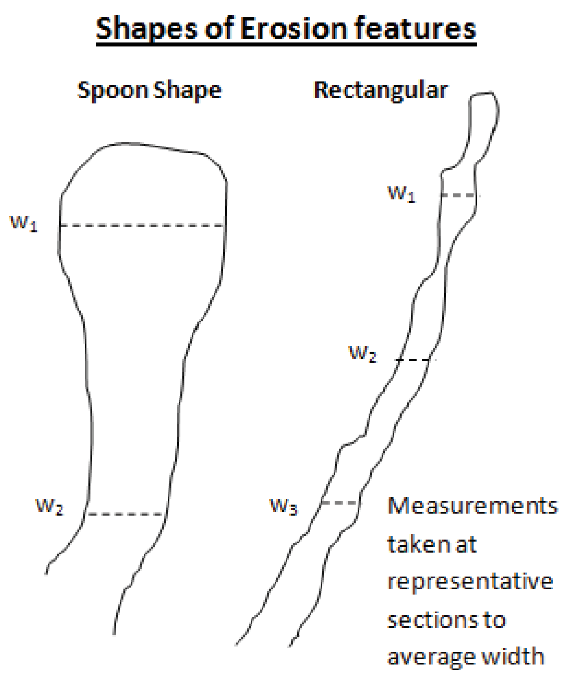
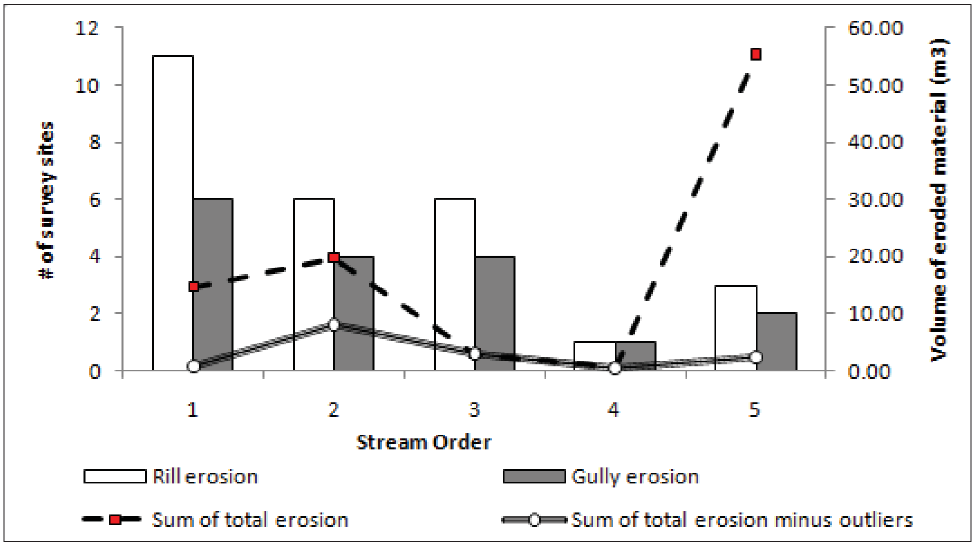


Figure 11. Depiction of measurement locations for erosion features



**Bars indicate number of survey sites per channel initiation process (primary y axis-left), total erosion measurements (line) (secondary y axis-right)*

Figure 12. Per site erosion occurrences as a function of stream order

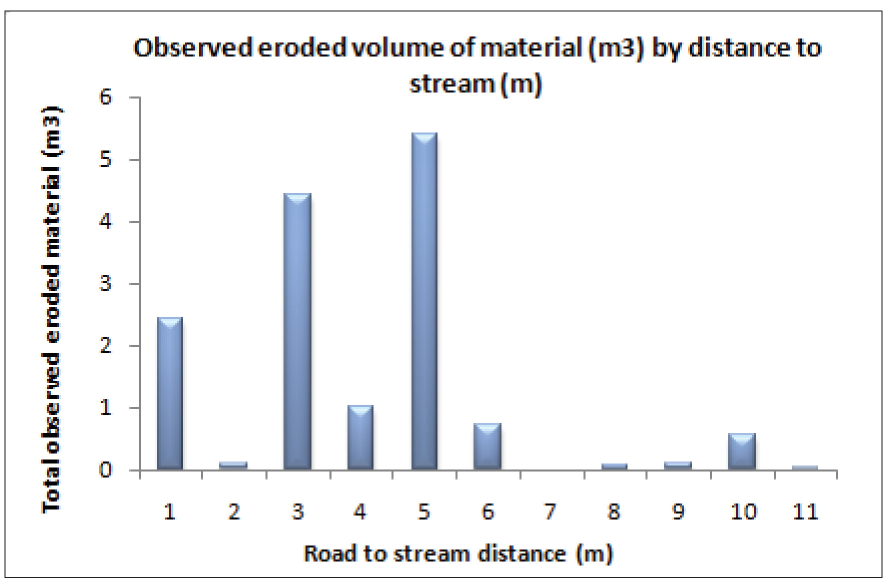


Figure 13. Total observed erosion (m3) by road to stream distance (m)

Chapter 2: Effect of Roads on Stream Geomorphology

Outline of study approach:

Background: Major watershed level characteristics (sampling based on: Water Quality, Surficial geology attributes)

Chapter 1: Road-stream crossing survey describing connectivity, current extent and magnitude of erosion.

Chapter 2: In channel qualitative study of stream health, investigation of local development effects as an adverse stress on stream quality and stability.

Objective

As a whole this project aimed to investigate the local effects of roads on North Shore waters. Chapter 1 investigated the extent of road connectivity on a broad scale, indicating roads are directly connected at various scales acting as an extension to the stream network. An additional investigation of roads as a sediment source to neighboring waterways (streams, lakes, wetlands), indicated roadside erosion was observable, however the estimated extent of sediment losses was not observed to be occurring at a large enough scale to be considered an active water quality impairment for north shore watersheds. Chapter 2 will consider in-stream stability at stream segments above and below road-stream crossings. This will describe the in-stream costs of local development.

Hypothesis

If stream reaches are directly affected by road development, reaches downstream of road-stream crossings will exhibit instability.

Empirical predictions of stream stability based on imperviousness

Local factors of increased imperviousness and constriction on stream stability have been widely studied, yet the long term watershed effect is not as clear. Some studies have sought **to empirically predict stream stability based on total imperviousness** (May *et al.*, 1997, Avolio, 2003, Short *et al.*, 2005,Cianfrani *et al.*, 2006). This has resulted in the creation of the Impervious Cover model (ICM) (Schueler, 1994). This model is used to detect stream health as a function of impervious cover (IC) for headwater streams with a subwatershed size of 5 – 50 km^2 (Schueler *et al.*, 2009). The ICM predicts stream health (combination of hydrologic and biologic uses) to *decline* with increased impervious cover additions (Figure 14). Conclusively this scale predicts subwatersheds with > 60% IC to be “non functioning” simply acting as conduits for flood waters (Schueler *et al.*, 2009); subwatersheds with 25% – 60% IC are “non supporting” in that they no longer support hydrologic, channel stability, habitat, water quality or biological diversity uses; subwatersheds with 10-25% are capable of supporting basic stream functions but are noted to be declining in health, and subwatershed with IC of < 10% (average ~7%) are sensitive to cover changes but are predicted to continue retention of good stream health with hydrologic, and biologic uses intact (Schueler *et al.*, 2009). The ICM is meant to act as a generalized predictive model with the caveat that stream subwatershed response can be highly variable based on local conditions (Bledsoe & Watson, 2001).

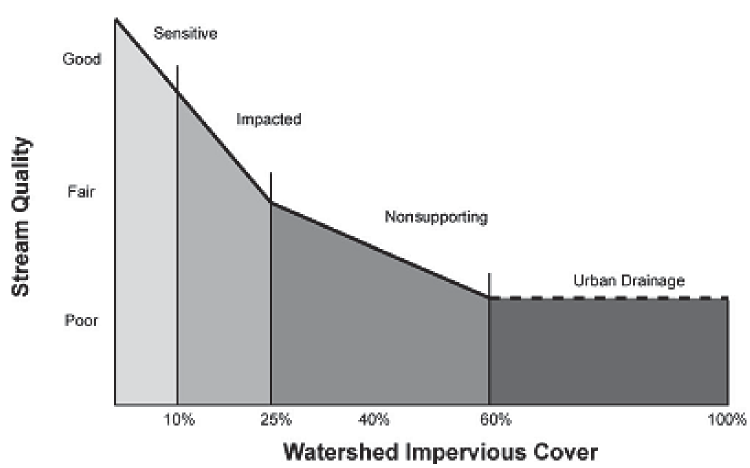


Figure 14. Impervious Cover Model (ICM) (Schueler et al 2009)

Channel stability in relation to local development/urbanization

Increased watershed development can directly affect stream stability (Schueler *et al.*, 2009, Booth & Jackson, 1997). The effects of land use conversion, particularly from development have been shown to directly affect channel stability. Stream morphological adjustments may occur as a result of development and road building. An increase in watershed imperviousness along with physical alterations of hydrologic flowpaths on a stream network may force an adjustment of **channel geometry** (May *et al.*, 1997, , Booth, 1991, Bledsoe & Watson, 2001 Hession *et al.*, 2003, Cianfrani *et al.*, 2006) this may include **channel enlargement** or **cross sectional area reduction** which may have a cascading effect on **sediment carrying and transport capability (**Lisle, 1982, Goode & Wohl, 2007, McCaffery *et al.*, 2007). Road-stream crossing structures have also been shown to **limit fish passage** and degrade **habitat** resulting in a lack of abundance of aquatic biota (Warren & Pardew, 1998, Booth, 1991, Klein, 1979, Alberti *et al.*, 2007, Khan & Colbo, 2008). A 2007 study found a relatively high correlation between aquatic IBI health and the number of stream crossings per subwatershed, with health decreasing as a function of increasing stream crossings (Figure 16) (Alberti *et al.*, 2007).

Studies have reasoned that although stream reach response to watershed development is highly variable, watersheds with less than **~10% imperviousness** are more affected at a local level (Booth & Jackson, 1997). Road and road-stream crossing development directly affects resident soil and riparian vegetative conditions. This occurs through initial disruption and fragmentation of continuous riparian zones (Luce & Wemple, 2001), with the compaction or paving over of soils and alterations of vegetative cover types. This alteration often spurs the replacement of deep rooted plants for shallow rooted grasses, thus changing the overall roughness and resistance needed to dissipate stream flow energy (Booth & Jackson, 1997).

Subwatershed sensitivity to impervious cover as indicated by stream channel instability is most likely related to storage (at pre-development conditions), connectivity and conveyance of impervious areas, compounded by the overarching magnitude and concentration of development over time (Bledsoe & Watson, 2001, Kang & Marston, 2006). Sensitivity to impervious development within subwatersheds occupying low levels of development (10-20%) can be particularly hinged on local factors related to characteristics of the area, such as: underlying geology, resident land use, riparian conditions, background channel entrenchment and sediment erodibility (Hammer, 1972, Bledsoe & Watson, 2001).

The duration of time between development and observed channel adjustments is particularly important to keep in mind. For example channel enlargement is *most likely to occur between 4-15 years after development*; with changes to channel geometry not expected to occur after 30 years of development within the subwatershed (Hammer, 1972). This is a result of the idea that a channel will counteract the changed hydrology of the subwatershed, recovering to a quasi-stable state. The caveat being, if the subwatershed urbanizes at a rate much greater than the expected channel recovery rate, the increased magnitude and frequency of peak flows may hinder channel morphology “recovery” for many more years than expected (Kang & Marston, 2006).

Effects of Impervious cover on resident hydrology

Road and impervious cover development alters resident hydrology through compaction of soils, leading to decreased infiltration, and increased runoff often resulting in Hortonian overland flows. The altered infiltration process and conveyance of water to a concentrated area ultimately affects local storage conditions (Dunne & Leopold, 1978). Additionally hillside road cuts can intercept subsurface flows, increasing road runoff, thereby increasing the probability of channel initiation and formation of new flow paths (Wemple & Jones, 2003).

Roads are a large contributor of concentrated drainage and runoff, often draining runoff to ditches or stormwater drains which are designed to act as a conduit for conveying water in an efficient manner to nearby streams or waterbodies. The additive effect serves to increase road connectivity to streams, expanding the channel network (Montgomery, 1994, Booth & Jackson, 1997).

The effects of sediment supplied by roads

Short term implications of roadway construction is often a largely available sediment supply that can be easily conveyed to nearby streams. The abundance of sediment can severely alter sediment delivery rates of the receiving stream. Hedrick *et al.* (2009) found the Sauerkraut Run (West Virginia) responded negatively to road crossing construction, affecting the channel form (width, depth) causing the stream to aggrade sediment due to the large supply, then degrade after the supply was dissipated, findings which corresponded to previous observations by Urban and Rhoades (2002) (cited in Hedrick *et al.*, 2009).

Road induced mass movement of coarse and fine sediment can occur outside of immediate construction or maintenance; most often occurring as a result of large precipitation events. MacDonald and Coe (2008) describe the consequences of road induced mass failures; "the episodic delivery of sediment can induce debris fans, valley terrace formation, channel avulsion, channel aggradation, substrate fining, channel widening and pool infilling." Often the morphological response to smaller scale sediment additions results in a similar process of reduced sediment carrying capacity. If prolonged this may compromise the streams ability to move material, resulting in aggradation of fine sediments and channel materials, in time altering stream bed slope.

There are many undesirable effects of crossing structures on channel morphology (which essentially act as a flow constriction); generally this can be summed as, 1) ***aggradation*** of materials (accumulation of sediment, debris), or ***degradation***, the lowering of a stream bed, increasing bank height. Often these processes can incur extensive deposition or erosion of material along stream banks and floodplains, even inducing local scour endangering the confidence of the structure itself (Rosgen, 2006). Not surprisingly the degree of morphologic influence a crossing structure can impart can be deleterious to aquatic habitat, and riparian vegetation.

Aggradation can be caused by a variety of factors, 1) a backwater effect caused by the crossing structure in the upstream of crossing structures as a result of flow constriction, in which stream flow volume exceeds the allowable volume of the structure to properly convey water or as due to a downstream constriction such as a debris jam; 2) migration of materials from an upstream source (Office of Bridge Development, 2007). Degradation can occur due to channel constriction which causes the stream to incise, lowering the streambed. This can occur due to "clear water" discharge, a result of storm drains; or base level shifts due to an altered hydraulic function (downstream channel constriction, channel modification such as straightening, or headcuts) (Rosgen, 2006).

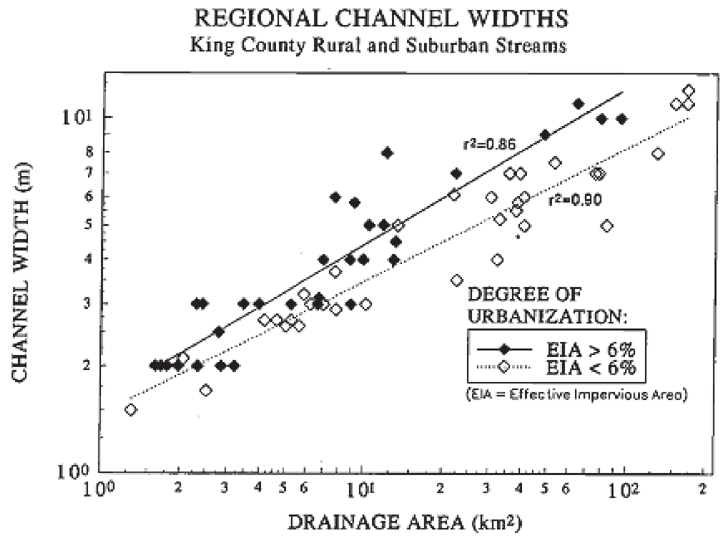


Figure 15. Channel widths as a function of contributing drainage area (Booth and Jackson 1997)

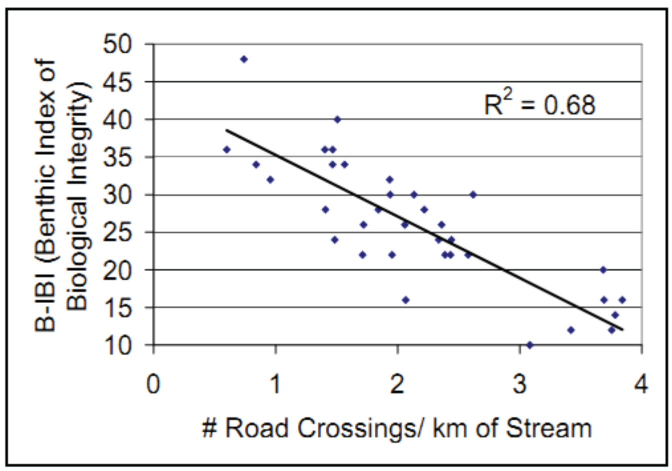


Figure 16. Relationship between stream ecological health and total number of road crossings per km upstream of sampling location (work of Alberti *et al.*, 2007, figure from Avolio, 2003).

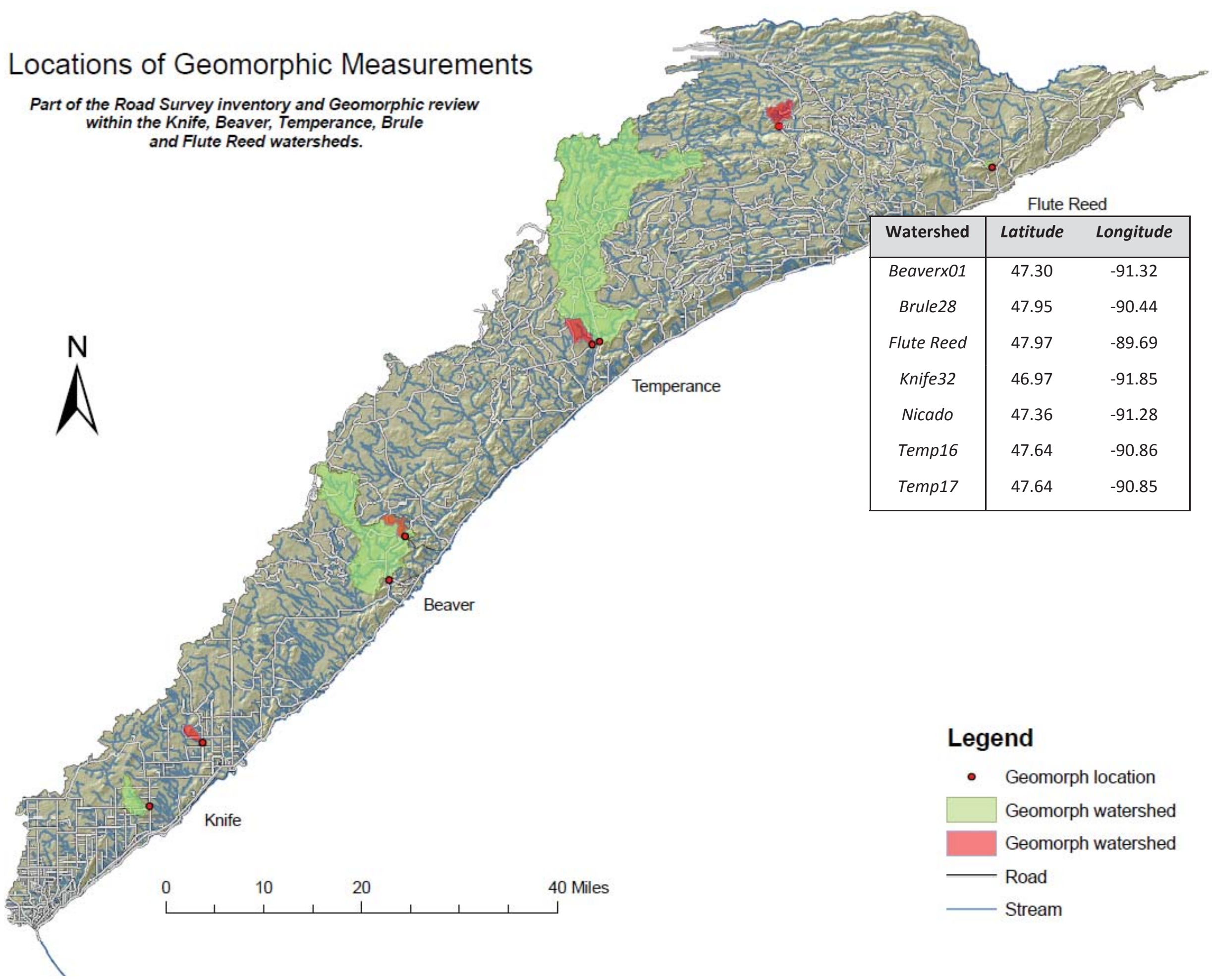
<u>Focus of this project</u>

This project characterized in-channel stability above and below road-stream crossing structures within subwatersheds at varying stages of development. Sites were located in watersheds considered “impaired” for turbidity exceedances by the state of Minnesota and the EPA. In addition sites were alternatively selected in watersheds that are not currently listed for turbidity impairments. Using stream surveying techniques, local stream stability was qualitatively assessed.

Methods

Site selection

Individual stream sites were chosen after a review of road site observations. Sites were chosen to include various road and erosion characteristics. This included road survey sites that had active erosion on site, and sites that did not show signs of erosion. Sites were also chosen due to road surface material type, culvert condition and ditch vegetation characteristics. Locations of geomorphic measurements and their corresponding watersheds are given in Figure 17. Sites were only chosen after an initial road survey, therefore a detailed sampling regime did not occur. Sites were studied in the fall of 2010, during the months of September and October.



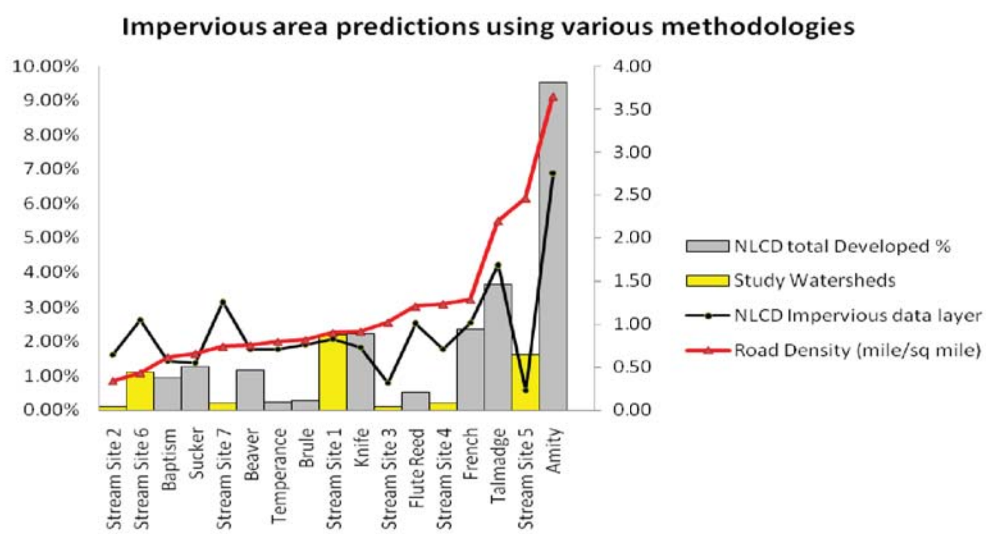
Watershed	*Latitude*	*Longitude*
Beaverx01	47.30	-91.32
Brule28	47.95	-90.44
Flute Reed	47.97	-89.69
Knife32	46.97	-91.85
Nicado	47.36	-91.28
Temp16	47.64	-90.86
Temp17	47.64	-90.85

Figure 17. Locations of Stream Geomorphic measurements and associated watershed drainage

The level of imperviousness

The level of imperviousness is an important watershed characteristic when studying stream stability (Schueler *et al.*, 2009). Initially the National Land Cover Database Imperviousness spatial layer was used to measure the level of imperviousness for each watershed. However upon comparison with 2009 MN DNR aerial photos, features indicated in the NLCD Impervious spatial layer were found to miscalculate roadways and development features, this is conceivably attributed to the age of the data layer which was created in 2001 (Figure 18).

To remedy this issue a full scale impervious surface investigation delineating impervious areas using aerial photos was not possible. May *et al.* (1997) found that calculated total imperviousness had a strong relationship to the road density (m/m^2) for the suburban Puget Sound, WA study area. Citing the work of May *et al.* (1997), road density was alternatively used as the sole impervious indicator for this project.



Note:

Site 1: Knife 32

Site 2: Nicado Creek

Site 3: Temperance 16

Site 4: Brule 28

Site 5: Flute Reed

Site 6: Beaver x01

Site 7: Temperance 7

Figure 18. Selected Lake Superior watershed characteristics: Development and open water.

Stream Geomorphology procedure

Stream geomorphology evaluations were conducted using a Rosgen level I and II type morphological evaluation of stream reaches, both upstream of the crossing and downstream of the crossing. The evaluation consisted of a stream type classification which included characterization of stream reach slope, bankfull elevation, bankfull width, cross sectional area, width to depth ratio, entrenchment ratio and dominant channel material (Rosgen, 1994). Additionally two different mechanisms to describe and assess channel stability were conducted; the modified Pfankuch channel stability assessment (Pfankuch, 1975, Rosgen, 2006) and the BEHI assessment of bank stability (Rosgen, 1996). All parameters collected were assembled to describe the behavior and possible response to bridge-culvert construction of the stream segment. General observations about the crossing structure were also recorded, and included size, type and age of structure, etc.

The Rosgen Level I and II procedures included:

- Cross sections at representative riffles (1-2 per upstream/downstream segment)
- Using data at cross sections - the width/depth ratio and bankfull elevation were calculated.
- Entrenchment ratios were obtained from aerial photos; only if the in-stream characterization did not fully characterize the floodplain width at each crossing.
- Longitudinal profiles (went through the crossing). Using longitudinal profiles the water slope and bed slope were extracted. Locations and frequency of riffle, pool, run, glide bed features were also calculated.
- Channel material assessment, conducted using the pebble count procedure (Woman, 1954, Rosgen, 1996) initially the stream segment was investigated on a reconnaissance level to coarsely define a riffle-pool ratio. Using this information, channel material was sampled using ten transects within the reach, spaced upon bed features proportional to the defined riffle-pool ratio. One hundred sampled were obtained for each segment (upstream, downstream) at each location (200 samples total for a stream crossing location).
- Plan form pattern to describe sinuosity was obtained by use of aerial photography (MN Geospatial Information Office, 2011).

- Channel stability assessment assessments were conducted for each stream segment (upstream, downstream):
- Modified Pfankuch stability (Pfankuch, 1975, Rosgen, 2006)
- BEHI (Rosgen, 2006)

**Examples of field forms used can be found in the Appendix, Appendices B: Field forms*

Data collected in-field was inputted into a Mecklenberg database template (Mecklenburg, 2006) in order to standardize reporting of morphological traits and hydraulic variables within sites.

For some streams a test of embeddedness was initially carried out following a Wisconsin DNR Fisheries manual which details an embeddedness procedure (WI DNR, 2002). The procedure involved using a rod to delicately insert into the streambed in order to define the depth of the active bed to the sub-pavement zone. By feeling for a change in resistance the user was able to describe this location, and measure the depth using a stadia rod. Each embeddedness sample was taken at the cross section locations in 4 equally spaced locations along the cross section with an additional measurement in the thalweg. Unknowing in preliminary field work procedural set up if embeddedness was a marked feature within North Shore streams the test was incorporated into our field sampling regime. However the test was consistently found to be inconclusive, thus a characterization of embeddedness for study streams was not notable enough for further review and analysis.

Sinuosity, review of aerial photos

Aerial photos were used extensively within this project. Frequently aerial photos helped to provide a current understanding of stream sinuosity, floodplain extent and vegetation condition. Historical photos were used to analyze former land use conditions and channel alterations nearest the crossing of interest.

Most typically the 2010 and 2009 DNR aerial imagery for the arrowhead region (MN Geospatial Information Office, 2011) were used for present day evaluations. If there was a question of terrain, the combination of aerial imagery and terrain supplied by Google Earth was used for individual site investigations. To investigate historical alterations to the crossing, an aerial photo analysis was conducted using readily available photos dated: 1991, 2003, 2009, 2010 (MN Geospatial Information Office, 2011). This type of investigation was used to measure the current sinuosity of stream segments and observe any possible change in stream channel morphology over time.

Statistical methodology – Stream survey

Stream morphological statistics were carried out in order to evaluate any differences that may reside between the upstream and downstream stream reach locations, Rosgen channel stream type and based upon Pfankuch stream stability scores of “Good” vs. “Fair” and “Poor” characterizations.

Tests for normality indicated the statistical sampling of the dataset would be best suited using the non-parametric ranked sums Mann-Whitney-Wilcoxon test. Similar to Student’s t-test, the Mann-Whitney-Wilcoxon test compares sample populations of two groups; however the Mann-Whitney-Wilcoxon test compares the summed rank instead of a measured value, and has no assumptions of normality. The test statistic (U) can be found using equation 10, the significance (p value) was computed using a chi-squared distribution set at an alpha of 0.05 (Daniel, 1990). The statistical procedure is the same as the Kruskal-Wallis test, but uses only two variables for comparison. The statistical mechanics and procedure of the ranked sums test were sufficiently described in the Statistical methodology – Road section, please refer to that section for further review.

$$U_1 = R_1 - \frac{n_1(n_1+1)}{2}$$ (***Eq. 10***)

R is the sum of the ranks, n being the sample size

Analysis was computed using the statistical package R, code and output is appended in *Appendix B: R code*. Sample code is given below to indicate the package and process necessary for computation.

Results

Seven road survey locations were chosen for a Rosgen stream classification (Level I, and Level II) along with a Pfankuch stream stability assessment. Stream survey locations were chosen from the road survey database based upon ability to survey and access, proximity to road, vegetative cover conditions, structure condition, or to proximity to a landform characteristic (ie: change in valley type). The resulting dataset of geomorphic evaluation sites was slimmed to a smaller than expected test group, due to time and weather constraints.

Geomorphic study reaches ranged from 1^{st} order to 4^{th} stream order, with watersheds draining 0.5 square miles to 147.7 square miles. Watershed land use consisted predominantly of a forested land use (83 – 97%, average 89%), with development from 0.1 – 2.2 %, average 0.79%; and open water and wetlands accounting for on average ~2.9% (Table 16, Figure 20). With land uses occurring similarly between surveyed watersheds, this allowed for a localized interpretation of stream stability.

Stream Classification

Stream classifications and stability assessments were conducted at both the upstream and downstream reach for each stream survey location (total 14 datasets). Rosgen (1996) classified stream types were found to be: B, C, E. Of the seven study sites, two types of "upstream -> downstream" stream type combinations were found, E -> C (2 study sites), B -> B (2 study sites), the remaining sites were not similar in combinations, B->C, C->B, C->C (Table 17).

Pfankuch stability assessments

Pfankuch stability scores were found to range from good to poor at both the upstream and downstream segments. Similarly to the Rosgen stream classifications, two combinations of upstream->downstream stability transitions were noted: good -> good (2 study sites), good -> fair (2 study sites), the remaining three sites were good -> poor, poor -> fair, fair -> good. When stability scores were analyzed between major stream types (B, C, E) no significance was found indicating trends within the sample set. Morphologic measurements are documented in the Appendix, *Appendix E: Stream Survey*.

For the dataset, upstream to downstream deviations were calculated. Between upstream and downstream reaches, 57.1% of sites were found to negatively deviate in quality for multiple categories, *bottom substrate* (scouring and deposition, aquatic vegetation*), lower* *banks* (deposition), *upper banks* (mass erosion). Additionally 42.9% of sites were found to negatively deviate in quality within the *upper banks* (landform slope), and *bottom substrate* (consolidation of particles).

Not all downstream sites negatively deviated in quality from the upstream reach; some sites were found to deviate *positively*. Of those observations, 28.6% of sites were found to improve conditions within the *bottom substrate* (bottom size distribution, rock angularity), and *upper banks* (debris jam potential). Additionally across the dataset, there were seven categorical instances in which a single downstream site positively improved (14.3% improvement).

There were many instances of neutral or null deviations for upstream to downstream quality. The greatest was found for the *bottom substrate* (rock angularity), and *upper banks* (debris jam potential) in which 75% of sites were observed to be neutral. Also, 62.5% of sites were found to maintain quality for bottom substrates (bottom size distribution), and 50% likely to maintain the lower banks (cutting, bank rock content, obstructions to flow), and in the upper banks (vegetative bank protection). *A detailed stream survey and stability analysis was completed for each site in the following section* (Table 17, Figure 20).

Table 16. Geomorph study watersheds, land cover and land uses, National Land Cover Database (2001)

	Forest (all)	Open Water	Development (all)	Shrub	Barren Land, Shrub, Grassland, Pasture/Hay	Wetland
Knife 32	83.6%	0.3%	2.2%	0.2%	5.6%	8.1%
Nicado Creek	97.3%	0.3%	0.1%	1.6%	0.3%	0.4%
Temperance 16	92.6%	0.1%	0.1%	6.2%	0.6%	0.6%
Brule 28	83.5%	5.4%	0.2%	7.2%	0.1%	3.5%
Flute Reed	95.7%	2.7%	1.6%	0.0%	0.0%	0.0%
Beaver x01	84.5%	5.8%	1.1%	3.4%	2.1%	3.1%
Temperance 17	86.2%	6.2%	0.2%	3.1%	0.2%	4.1%

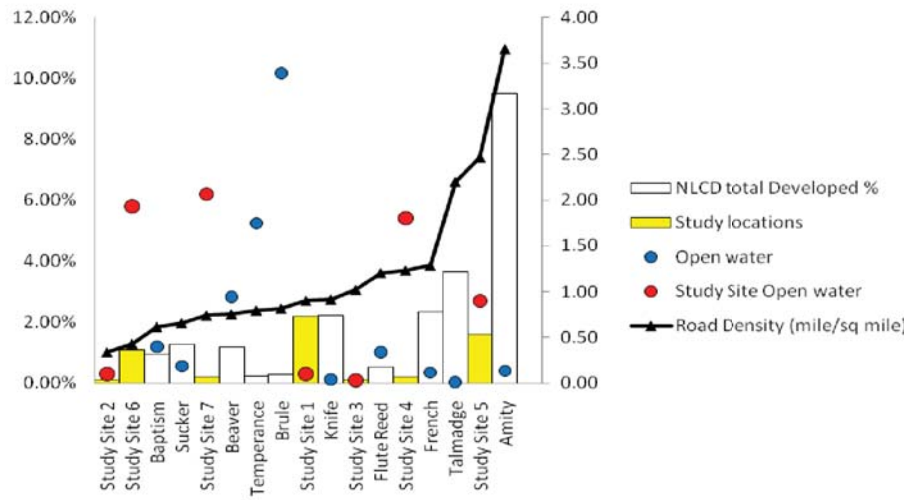


Figure 19. Watershed characteristics for geomorphic and road survey watersheds

Table 17. Stream survey characteristics and results

Watershed	*Stream Order*	Area (sq mile)	Upstream Rosgen Stream Classification	Upstream Pfankuch Stability	Downstream Rosgen Stream Classification	Downstream Pfankuch Stability
Beaverx01	3	52.3	B3c	Good - stable	C4	Fair
Brule28	4	4.7	C4	Good - stable	B4c	Fair
Flute Reed	1	0.5	B4a	Poor *unstable	B4a	Fair
Knife32	3	6.1	B4c	Good - stable	B4c	Poor *unstable
Nicado	2	3.0	E5	Fair	C3	Good - stable
Temp16	2	4.5	E4b	Good - stable	C4	Good - stable
Temp17	4	147.7	C4	Good - stable	C3	Good - stable

**** Material type: 3 - Large Cobble, 4 - Coarse Gravel, 5 - Coarse Sand***

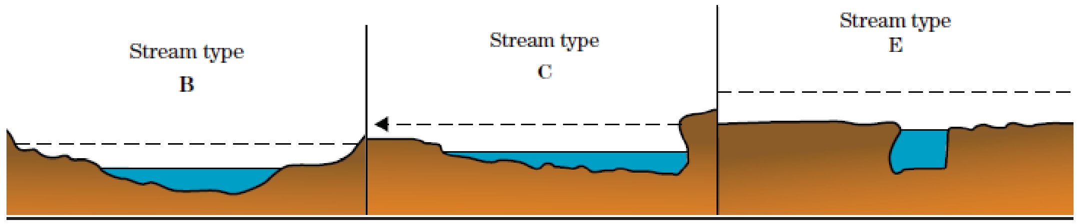


Figure 20. Stream types predominant in stream survey study (NRCS, 2007)

Aerial photo analysis (observations)

Historical aerial photos were qualitatively observed for distinct land use alterations nearest the stream survey locations. Photos accessed via the Minnesota Geospatial Information office and Land Management Information Center (LMIC*)* from 1991, 2003, and 2009 were used for this analysis. Brief descriptions of observations were made for each stream survey location.

Predominantly the aerial photo analysis indicated there was not an identifiable large scale change to the stream, land use, or crossing at each stream survey locations (Table 18). With the exception of 3 sites which had noticeable but minor changes observed. The three sites were the Flute Reed, Knife River site (#32), and the Nicado Creek location.

Describing the irregularities, for the Flute Reed location, there was notable expansion of the logging activity and staging area between 2003-2009 (in close proximity to roadway and stream). A noticeable change occurred in the crossing structure and meander pattern immediately upstream between 1991 and 2003 at the Knife River location. Lastly, the Nicado creek location had noticeable change in meandering upstream of the crossing between 1991-2003, with braiding occurring in some locations upstream by 2009.

The most notable land use change occurred at a nearby creek location in the Beaver watershed, in which three road survey locations were not present in 2003, but was evident in 2009. Describing increases in development by way of the forest road (presumably due to logging) that created the road survey sites B01, B02, B03 (Figure 21).

Table 18. Summary of observations for aerial photo analysis of photos 1991, 2003, 2009

Site ID	Land use change	Meander pattern change	Channelization	Changes to structure (replacement)	No Change
Brule 28					✓
Beaver x01					✓
Flute Reed	✓				✓
Knife 32		✓		✓	
Nicado		✓			
Temperance 16					✓
Temperance 17					✓

Figure 21. Comparison of land use change detected in Beaver watershed, road survey sites B01-B03 are found on the new road featured in the 2009 photo

Detailed Steam survey site analysis (upstream -> downstream)

Beaver x01: B3c -> C4

Pfankuch stability: Good -> Fair

**Site exhibited the effect of an abrupt change in valley type*

Beaver x01 is off of a paved road at the east branch of the Beaver River and county highway 5/Lake County highway 15, in Lake County. The site is characterized with dense forest cover and currently 3 box culverts. Upstream of the box culverts the stream type was found to be B3c, the downstream reach was characterized as C4. Observations in the field and a USGS 7.5 minute quadrangle, suggest a change in valley type is occurring. The sinuosity of the downstream reach changes dramatically, the slope decreases, the stream floodprone width increases, and the channel width decreases slightly. Dominant channel material type, D_{50}, was found to decrease from large cobble (upstream) to coarse gravel (downstream), the D_{84} decreased from small boulder to large cobble.

Brule 28: C4 -> B4c

<u>Pfankuch stability: Good -> Fair</u>

**Site was probably affected by road bed placement*

Brule 28 is off of a gravel road with an older corrugated culvert road-stream crossing on Fiddle Creek and Forest Road 325 & Lima Grade off of Gunflint Trail in Cook County. This stream runs parallel to the nearby roadbed for a few miles upstream and downstream. The valley widens allowing for a larger floodprone width upstream, then comparably downstream. Downstream the valley and creek narrows, where the stream eventually shares a bank with the fillslope of the road bed. This stream segment follows succession scenario 4, with the downstream occurring at a lower elevation as a type Bc (Rosgen, 2006). The Pfankuch stability indicated the downstream section had a stability rating of “Fair”, divergent from the upstream section of “Good”. Dominant channel material was maintained upstream to downstream with the D_{50} found to be coarse gravel, and the D_{84} changed from small boulder to large cobble.

Flute Reed: B4a -> B4a

<u>Pfankuch stability:</u> Poor-> Fair

**Effect of landuse or high flow event*

The Flute Reed site is off of a native surfaced road with a newly installed corrugated culvert on a 1st order unanamed tributary to the Flute Reed River and a Forest road (2nd left) off of Cook County rt 16/Arrowhead Trail, in Cook County. This site is on a minimum maintenance road with equipment and tracks to indicate it might be used for logging or staging. The site is unstable upstream, becoming more stable downstream. The stream channel upstream had obviously moved out of much older path (former path was dominated by mossy vegetation, and large boulders), the new path had un-vegetated sheared clay banks, with a gravel bed. Due to these observations which continued to become worse upstream, the stream was likely washed out by a large precipitation, the effect could have been exacerbated by upstream land uses. Downstream after a small section of instability the stream mirrored the unused stream path upstream, indicating it was relatively unaffected by upstream instability. The D_{50} material type was found to be the same upstream and downstream as coarse gravel, the D_{84} increased from medium gravel to large cobble downstream.

Knife 32: B4c -> B4c

Pfankuch stability: Good -> Poor

**Effect of surficial geology, culvert replacement/landowner land use*

Knife 32 is located off of a paved road at St Louis County Hwy 42/Holmestead Road and the Little Knife River, in St. Louis County. The site was found to have had a recent culvert replacement (2002), and local landowner land use effects which may have affected the downstream stability. Although the stream types stayed the same upstream and downstream, there were slight differences affecting stability between the two reaches. The Pfankuch stability assessment scored the upstream as “Good” and the downstream “Poor”, with primary poor observations describing an unstable stream bottom. In field observations indicated the upstream landowner previously constructed a pool for stocking fish by widening and dredging a section of the river, along this stretch there was a lack of riparian buffer, where landowner mows grass lawn to edge of stream. Additionally in-field observations of culvert, indicated predominant bank vegetation changed after culvert retrofitting from forested to grass, banks were rip rapped with larger boulders. In the downstream section, there were clues to instability, the bankfull width increased by 2ft, the max bankfull depth decreased by 1.1 ft as compared to the upstream. Observations in-field indicate two bankfull locations existed, a former and the present; with the former bankfull location similar to the upstream reference reach. The dominant channel materials D_{50}, increased from fine to very coarse gravel, and the D_{84} increased from medium gravel to small cobble.

Nicado: E5 -> C3

Pfankuch stability: Fair -> Good

**Effect of landform (wetland draining to lake), structure*

Nicado is located on Lax Lake Road and Nicado Creek in Lake County. The site is on a low gradient landform, with a grassy-shrub vegetative cover, with a wetland draining to Nicado creek which eventually empties into a lake. The site is on a paved road and has a corrugated culvert structure that is failing at the outlet. The outlet is bent closed, decreasing the volume of the pipe significantly. This section of Nicado is characterized as an E type stream upstream and a C type downstream of the culvert. This follows the channel succession type 1, E->C , which is considered to be a moderately unstable form (Rosgen, 2006). This suggests the channel is widening after the culvert, additionally the channel slope decreases in the downstream section which could be an affect of the low stream power due to the wetland contribution, failing structure, the C channel type, or the effect of the lake. Channel material changed dramatically from coarse sand to small cobble (D_{50}), and from very coarse gravel to medium boulder downstream (D_{84}). It is unclear to what extent the channel material composition upstream is affected by the competence of the structure, in which a disequilibrium is forced, where the stream cannot fully transport fine material.

Temperance 16: E4b -> C4

Pfankuch stability: Good -> Good

Temperance 16 is located off of a native surfaced road at the Blind Temperance River and 6 Hundred Rd (Just off of County Rd 2, in Cook County). The area is densly forested with a newer recessed culvert installed. The stream was characterized as E4b upstream, and C4 downstream. When referring to Rosgen (2006), the channel succession model indicates the upstream Eb should go first to a G type stream then to a B type stream, not C. However with if the stream type was considered E -> C, this would indicate a moderately unstable reach. Yet the Pfankuch stability assessment indicates the stream upstream and downstream is in “Good” condition. The channel material maintains a coarse gravel substrate upstream and downstream (D_{50}), with large cobble upstream and downstream (D_{84})

Temperance 17: C4 -> C3

Pfankuch stability: Good -> Good

Temperance 17 is located off of a gravel surfaced road at Six Mile Creek and 6 Hundred Rd (just off of Cook County Rd 2) in Cook County. The reaches both upstream and downstream were characterized as a C type stream. The Pfankuch stability assessment ranked of "Good" both upstream and downstream. The channels are slightly different with a decreasing slope downstream, and an increase of floodprone width, this may indicate a valley change. Channel material type D50increases from very coarse gravel, to small cobble, but maintains large cobble in both reaches for the D84.

Brief discussion of individual stream sites

The findings of this study suggest resident stream hydraulics were greatly affected by the crossing structure. This was true at the Nicado creek site (within the Beaver watershed). The crossing was severely impaired and crushed at the outlet, causing backwater conditions with noticeable aggradation immediately upstream of the culvert. The immediate effect of an ineffective structure was also noted at the Beaver River site (Bx01). This road-stream crossing resides at the junction of a transitioning valley type, whereby the upstream is a B type stream, with a narrower valley and channel, steep slopes producing much greater stream power and kinetic energy then the receiving downstream reach. Three box culverts were installed to convey streamflows, yet two of them were plugged with debris causing non-uniform flow to dissipate flows away from the structured outlet. This obstruction initially caused the channel to incise as flows lowered the stream bed slope. Once the two culverts became functionally inaccessible due to the lowered slope, backwater occurred at the useable culvert, leaving behind thick deposits of fine grained sediment.

Often the crossing structure itself can play a pivotal role in confinement and constriction of flows, this is particularly true for high streamflows (at flood stage), in which flows are restricted from dissipating energy to the floodplain due to culvert or bridge embankments (Hedrick *et al.*, 2009). Johnson (2002) studied the effect of channel constriction on bridge abutments; indicating the immediate product of constriction is scour, which can rapidly degrade a channel, causing stream bank erosion (or failure) due to increased shear stress and stream flow velocities. Although the Nicado and Beaver (Bx01) sites did not exhibit active stream bank erosion as an effect of constriction, it is entirely possible that this may occur in the future. More than likely the sites are affected by poorly operating or improperly sized structures.

Nicado and the Knife River sites (Knife 32) were found to have a change in meander pattern when analyzed by aerial photography between 1991-2009. This adjustment could be due to a variety of reasons, with most probable cause of channel avulsions due to the presence of the crossing structure. Whereas the Nicado site migration is more than likely attributed to environmentally charged factors related to the highly sinuous E type channel, and headwater stream location. The Knife River location (#32) was noted to have a shifted meander pattern, noteably characterized in later photos with a channelized stream reach. This is most likely the result of a restoration effort. This site resides on the little Knife River, and this stream crossing was impeding lateral migration resulting in extensive bank failure. Subsequent work and engineering went into an arched culvert with extensive rip-rapping with large boulders along the stream banks to encourage direction of flows away from the stream bank.

In the upper watershed of the expansive Brule River site Brule 28 was observed. This location was directly controlled by two factors: road placement and proximity, and valley transition. In the upper reaches of the site the stream meanders close to the road than off into a wider valley type, this is where the observed upstream reach occurred, accommodating a C type channel with a thick forest. Immediately downstream of the culvert the road fillslope shares a stream bank with the downstream reach. Although no damage or failure to the road was observed, the proximity of the road at this site extended far into the downstream reach. The deviation of vegetation and the obviously graded slope of the roadway indicate modifications that may have caused a poor stability assessment. The risk of stream bank failure is high as the downstream receiving channel may migrate or impinge on the road fillslope.

Discussion

> ***"Unless we can develop a more precise, process-based understanding of how altered landscapes produced degraded stream channels we probably will not achieve genuine protection without limiting the extent of development itself, a strategy that is being used with increasing frequency in this region's remaining resource-rich watersheds"***
>
> - ***(Booth and Jackson 1997, referring to King County, in Washington state)***

In a perfect world man could coexist without imparting effects on local waterways. Natural systems would maintain "stable conditions". For riverine or stream channels this would be defined as a time when the channel are neither aggrading nor degrading (Rosgen 1994). If a channel achieves this stability it will maintain a characteristic dimension, pattern, and profile dictated by underlying topographic and surficial deposits. Although this is not a perfect world, man has existed for many years within the Lake Superior watershed, with most recent emigrations occurring in the late 1850s.

Within North Shore watersheds a stable stream condition is occurring in many subwatersheds. Long term aggradation or degradation is typically an artifact of watershed scale modifications, attributed to a natural occurrence (event), or due to changes in land uses. Although many watersheds within the North Shore (outside of the Duluth area) have less than 10% impervious cover, the localized effects of land use change such as roads and road-stream crossing structures can be observed, at times departing deleterious effects on the natural course of the stream, causing a point of instability and potentially adversely affecting water quality by increasing sediment or channel instability. This project attempted to quantify the direct effects of roadways on North Shore streams by conducting a qualitative assessment at road-stream crossings; finding roadway crossings are in some locations causing localized instability.

Observed effects of road-stream crossing on stability of streams

Geomorphic rapid assessments of stream stability were undertaken in the North Shore watershed at seven North Shore stream sites. Sites were located in various watersheds under differing land uses, vegetation types, topography and surficial geology. Road-stream direct connections resulted in negative impacts on stream stability and quality (41.9%) when studied upstream of the crossing and immediately below the crossing.

Within this study, effects of road crossings observed upstream and downstream of the crossing suggest that the crossing itself is controlling certain aspects of the stream channel and modifying stability. The original hypothesis of this analysis was that streams would show a negative response to the crossing structure in the downstream reach. However it was found that streams responded negatively in both the downstream and upstream of the crossing. Using Pfankuch stability assessments for the seven sites, segments were compared using stream stability metrics of excellent, good, fair and poor. When upstream segments were compared to downstream segments, 1 out 7 segments declined in overall stream stability (Flute Reed). Individually declines were observed in the lowerbanks and stream bottoms. Categories with observed stream stability were in the upper and lower banks, notably improved scoring on deposition, mass erosion and bank cutting. When downstream segments were compared to upstream segments, 6 out of 7 segments declined in overall stream stability. Declines were observed across the board with the greatest declines in the upper, lower banks, notably bank cutting, increased deposition, mass erosion and declining landforms.

Of the seven road-stream crossings surveyed (in both the upstream and downstream direction), many observations were made concerning effects of land uses, vegetative components and interactions, and the effect of roads (in both proximity and concerning the structure). The predominant observed effects of road-stream connectivity at studied stream reaches were:

- Aggradation or degradation (upstream or downstream)
- Upstream aggradation (sign of backwater)
- Widening at structure, or along stream length departing from reference location
- Channel straightening
- Meander pattern change (aerial photo)
- Degrading embankments / rip rap
- Accumulation of debris
- Signs of washout or direct flowpaths from road to stream

- Proximity of roadway intruding on flood plain

Development affects processes on all scales from the watershed level to the reach scale. This project with a narrow subset of streams and reaches, was designed to detect effects of roadways on a segment and reach scale (in both the upstream and downstream reaches). This study focused on all aspects of road intrusions on local streams, from localized impacts of an altered riparian corridor, to channel alterations. Observations of downstream decline in bankfull width and depth compared to upstream, may explain the current sensitivity of the stream to the road crossing (Fitzpatrick *et al.*, 2006). Channel alterations such as stream segment straightening and the effects of road drainage and runoff; have forced stream segments in the Brule and Knife River to migrate into stream banks in order to maintain a natural sinuosity. At times large debris jams could not migrate through the crossing, causing channel constrictions, a result of this was observed stream aggradation of fine materials (Nicado, Beaver River (Bx01). A frequent observed effect of roads was found at all sites, with increased flow path generation derived from increased runoff conveyed from the road prism to the stream. This was most often observed along with accumulated sediment deposited on rip rap and boulders.

Common results of crossing structures were noted at the Nicado Creek site and the Beaver River site (Bx01). The crossing structure in both cases, was found to impede migration of the channel, confining and constricting flows, resulting in backwater upstream. This inevitably gave way to a process of aggradation and deposition of fine sediment, along with channel widening. In these cases in particular the crossing structure was a textbook example of channel confinement and resulting incision and instability (Hession *et al.*, 2003, Johnson, 2005).

As a whole with a limited sample set, the rapid assessment and one time observation do provide a small foray and interpretation of the dynamic equilibrium which might be occurring within the North Shore watershed. Of the seven sites evaluated, each were in subwatersheds with very low development, therefore the null hypothesis, that observed instability could be a result of natural variability and adjustment is highly likely. This is a main component and often referred to topic in many studies concerning stream geomorphology. The concept of natural variability has been underscored as a baseline component of all streams, regardless of stress related to extraneous variables such as development and land use conversion (Booth, 1991, Rosgen, 1996, Bledsoe & Watson, 2001, Coleman *et al.*, 2005,).

Effects of imperviousness

A general assumption associated to imperviousness is that positive stream health indicators decline with increased development (May *et al.*, 1997, Schueler *et al.*, 2009, Alberti *et al.*, 2007, Short *et al.*, 2005 , O'Driscoll *et al.*, 2009). This is a widely studied phenomenon, however direct effects of imperviousness are not yet conclusive. A textbook example of stream effects to increased development can be found in a recent study by Driscoll et al (2009). In this study, Driscoll et al (2009) studied stream responses to urbanization using an equal distribution of urban and rural stream segments within the coastal plains of North Carolina. Finding bankfull cross-sectional areas were 1.78 times greater for urban watersheds, with urban segments frequently incised, exhibiting a 3.4 greater cross sectional area than rural watersheds. Concluding watershed level imperviousness was a key variable in explanation of the altered channel dimension and enlargement.

To achieve a “threshold” between natural variability and “stress induced” alterations related to roads and effective impervious cover (IC) was not feasible within this study. Subwatershed imperviousness for this investigation ranged between 0.2 – 2.2% representing very low developed areas. The literature points to an impervious cover threshold between 7-10% per subwatershed (Schueler *et al.*, 2009), may result in “demonstrable, and probably irreversible, loss of aquatic-system function” (Booth & Jackson, 1997). Booth and Jackson (1997) caution, to dismiss the effect of development on stream instability below this threshold is “naïve” countering “changes imposed on the natural system are a continuum”. Therefore instability may occur in the lower scale of subwatershed development due to localized sensitivity to change.

There are studies which inconclusively relate stream instability to impervious cover (Short *et al.*, 2005). One study by Kang and Marston (2006) sought to define geomorphic changes within a subwatershed with a predominant forested rural upper watershed and a developing urbanized lower watershed in the Central Redbed Plains of Oklahoma. Finding between 90 stream reaches, there was no statistically significant difference in downstream geomorphic indices (mean bankfull depth, bankfull width, bankfull area and threshold grain size). The study cited effects of development were minimized due to geologic and vegetative driving factors such as bedrock resistance, cohesive substrates and riparian vegetation; as well as ecoregional differences between studied reaches. Although effects of roads and increased imperviousness were noted within this project, the underlying qualities and characteristics of many stream segments within the greater study watersheds, suggests extreme armoring of stream banks by bedrock, large cobbles and boulders, as well as old growth trees, may have mitigating in-stream effects on channel adjustments due to development (such as channel widening). This is a field observation and not validated by this study.

Geomorphic studies relating impacts of development can at times be inconclusive (as demonstrated previously). Unobserved stream adjustments may be due to manager misperceptions and/or causal interpretations; to remedy this increased knowledge of "normality" for individual systems prior to development is advocated. Institutional knowledge of local stream regimes will ultimately allow managers to counteract the impacts of stream instability as it relates to development, prior to the occurrence of extreme degradation.

Evaluation of hydrologic, geomorphic and aquatic changes over time can only be achieved through long term monitoring and pooled research between institutions. Evaluation of channel response over time requires multiple data points to fully capture the progression of channel change as a function of external stress and disturbances. Historically the North Shore watershed underwent multiple iterations of land use changes, stemming from intense land clearing and logging in the 1800s to present activities such as agriculture and increased imperviousness and urbanization. Yet our knowledge of stream channel response to historic land uses is fragmented and limited, as a long term data set is currently unavailable to justify current observations of stream instability and stress.

It is fair to note there are current efforts and undertakings to remedy this lack of knowledge, with the creation of monumented survey locations (e.g. USFS, DNR, MPCA, and EPA investigations). Yet these locations are not concentrated centrally within a specific region/watershed, but are spread apart within watersheds across the watershed. A need for long term monitoring and an integration of existing data sources by local state, academic and federal institutions would greatly serve long term forecasting for North Shore streams.

Note on methods

The Pfankuch assessment of channel stability and Rosgen channel classification at stream crossings, were very effective tools used to investigate the potential disruption of the roadway. This method was used and promoted by Johnson (2005) to assess road-stream crossing structures. Johnson (2005) modified the Pfankuch stream stability assessment to value local environmental factors which could negatively impact bridge stability. Johnson incorporated additional key lateral and vertical stability indicators such as bar development, bank soil texture and coherence and upstream distance to bridge from meander impact point and alignment. At the time of project design and planning this assessment was not known to the author, if known the additional parameters would have been incorporated into the study.

Future work

The author promotes further investigation, and refinement of an approach to fully quantify, the effect of roadways on stream morphology. Thoughts to do this would include, controlling for stream type and surficial geology when sampling, this would establish a baseline understanding of environmental controls, as well as to establish the true extent of road/stream connectivity. An observational snap shot in time does not support wide conclusions for the North Shore watershed, North Shore streams. Therefore a long term study using monumented survey locations, to monitor stream reach migration, erosion, suspended sediment and bed load under various precipitation events would be a decidedly better option.

For managers

To potentially minimize conveyance of runoff and flood peak flows, and therefore reduction of human induced stream channel instability may be to 1) limit watershed impervious area and road proximity to waterways, 2) counter imperviousness and development with riparian corridors; this will control runoff and allow for natural stream channel transition. Control of the riparian zone could be achieved by maintaining setbacks, and establishing (as well as regulating) buffer zones.

Chapter 1 and 2 Summary and Conclusions

Roadways are an implicit component of a community; they serve to transport people, and commodities. Yet this integration of transportation networks can alter watershed hydrologic functions and increase sediment availability. In the fall of 2010, road-stream crossings were investigated for erosion occurrences and stream stability, additional evaluations of effective conveyance and connectivity of the road to the stream channel were assessed.

Current connectivity as it relates to riparian corridor fragmentation was investigated using GIS, at buffer widths of 100ft, 50 ft, 10ft. Roads were found to increase drainage density to streams by 6.9 – 10.8% . The greatest increase in drainage density was found within the impaired watersheds for roads within the 100 ft riparian zone (10.81%). When compared to control watersheds, impaired watersheds were more likely to increase drainage density of the stream network at riparian buffer width 100 ft (10.81%), 50 ft (5.37%), < 10 ft (2.06%); although this was not a significant relationship ($p = 0.182$, $\alpha = 0.05$).

Field assessments of road characteristics at 54 road-stream crossings were conducted to quantify observable erosion. Road erosion was stratified by types, gully, rill and mass erosion, resulting in **64.8%** of survey sites exhibiting measureable erosion. Characteristics of erosion were not mutually exclusive, thus a site could have both if not all erosion types occurring. Erosion was varied throughout the dataset and skewed based upon surface type, position and characterization (water quality, surficial association). Of the 12.2 km of road surveyed, and 54 road sites observed, 31.5% of sites were observed to have gully erosion, 50% of sites had rill erosion present, and 1 site or 1.8% of the sample set had mass erosion. The sum of measured erosion total was 93.26 m^3 with an average per site loss of 1.73 m^3. The greatest probability for roadside erosion was found on paved roads situated on Superior Lobe glacial till, particularly within impaired watersheds.

Geomorphic rapid assessments of stream stability were undertaken in the North Shore watershed at seven North Shore stream sites. Sites were located in various watersheds under differing land uses, vegetation types, topography and surficial geology. Road-stream direct connections resulted negative impacts on stream stability and quality (41.9 % of the time) when studied upstream of the crossing and immediately below the crossing. Of the seven sites evaluated, each were in subwatersheds with very low development, therefore the null hypothesis, that observed instability could be a result of natural variability and adjustment is highly likely.

Within the transportation network high risk areas for increased sediment and fluvial conveyance exists for roads in close proximity to streams, this is especially true for all road-stream crossings which serve as a direct connection of roads to streams. Geomorphic in-stream assessments within this study indicate roadways may contribute to observed instability. There are many factors which may control this outcome, largely surficial geology, vegetative conditions, topographic discontinuities, land use variances. Long term monitoring may validate the effects of roads on water quality and instream stability observed within this study.

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Appendix

Appendix A. Field Forms

Field forms included in this appendix are what was used in this analysis for the Road and Stream portions of the study. The Pfankuch and BEHI stability sheets can be downloaded from the Rosgen, River Stability Field Guide (2008).

Road

- **Road Survey Evaluation**

Stream

- **Longitudinal Profile**
- **Cross Section**
- **Pebble Count**

Road Survey Evaluation and Stream Morphology Field Form

Name of Site (location) ____________________ *Site ID* ____________________

GPS ID Waypoint ____________ UTM: ____________

Date ____________________ Observers Name: ____________________

Weather ____________________

Road segment

***NOTE DIRECTION** of measurement (North, South, East, West) Note placement of width measurements, draw in erosional features, stream and drain point, not cutslope/fillslope*

A | B

Road side supply (ft) | *Road side supply (ft)*

C | D

Length of segment	______ *ft* *m*					
Width of segment	______ *ft* *m*	1)	2)	3)	4)	
Slope of segment	______ degree %	1)	2)	3)	4)	
Dominant Surface type	*Native (dirt)*	*Gravel (Aggregate)*	*Paved*			
Dominant Soil texture	*Sandy Loam*	*Silt Loam*	*Clay Loam*			
Road surface construction	*Inslope*	*Outslope*	*Crown*	*Entrenched*	*Turnpiked*	*User Created*
Vegetation (%), Type	______ %	*bare (no veg)*	*grass*	*mix*	*forested*	
Cutslope	***YES*** ***NO***	Vegetated______%				
Fillslope	***YES*** ***NO***	Vegetated______%				
Signs of erosion	***YES*** ***NO***		*Extent:* ______			
Road - Stream connectivity	*No flowpaths from road prism to stream*	*Direct flowpaths from road surface to ditch or stream*	*Average Length of flowpath* ______ ft m			
Gully	*Is there Rill development?*	YES NO				
Rills	*Is there Rill development?*	YES NO		*Average length of Rills*	*Max length of Rill*	

Notes:

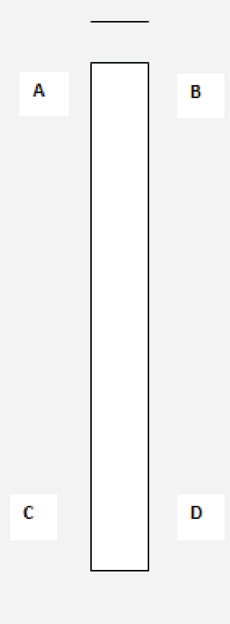
DRAW GULLIES, RILLS, etc

Road Survey Evaluation and Stream Morphology Field Form

Name of Site (location) ____________________ *Site ID* __________

Road side ditch

DRAW ARROWS TO INDICATE FLOW OF DITCHES, erosional features, flow paths, drain location, etc



Is there a Ditch?	*YES NO*					
Type of Ditch	*Lead off (outsloped to forest)*	*Linear (parallel to road)*		*1 ditch*	*both sides of road*	
Drain	*Is there a drain present?*	*YES NO*	*Diffuse or Point*	*Multiple:*		
Signs of erosion?	*YES NO*					
# of Gully / Rills? ________	*Is there a GULLY present?*	*YES NO*	*Rills?*	*YES NO*	Estimation of Z plane (for volume calcs)	
Extent of erosion	*Width*	____ *ft /m*	*Depth*	____ *ft /m*		____ *ft /m*
Vegetation (extent)	*%*	*Grass*	*Mix*	*Forested*		
Type of sediment in ditch	*Sediment type:*	*Road fill*	*Silt*	*Sand*	*Cobble*	*Boulder/ Bedrock*
Active Sediment source?	*YES NO*		*Notes:*			

Ditch measurements

	Total width	**Total height**	**Slope%cutslope**	**Distance for slope**
A				
B				
C				
D				

Road side culvert (or instream culvert)

Is there a Drain?	*YES NO*				
Type of Drain	*Box*	*Corrogated*	*Arched/ bottomless*		Bridge
Is the culvert perched?	*YES NO*	*Height above water level*	____________		*ft m*
Size of drain		*ft m*			

Notes:

Reach Average Pebble Count

Stream					Crew	
Site ID					Date	
Particle	**Millimeters**	**Size Class**	***Particle Tally***	**Total**	**Item %**	**%Cumulative**
Silt/Clay	**< 0.062**	**Sand**				
Very Fine	**0.062-0.125**					
Fine	**0.125 - 0.25**					
Medium	**0.25 - 0.5**					
Coarse	**0.5 - 1**					
Very Corase	**1 - 2**					
Very Fine	**2- 4**	**Gravel**				
Fine	**4 - 6**					
Fine	**6 -8**					
Medium	**8 - 12**					
Medium	**12 - 16**					
Coarse	**16 - 24**					
Coarse	**24 - 32**					
Very Coarse	**32 - 48**					
Very Coarse	**48 - 64**					
Small	**64 - 96**	**Cobble**				
Small	**96 - 128**					
Large	**128 - 192**					
Large	**192 - 256**					
Small	**256 - 384**	**Boulder**				
Small	**384 - 512**					
Medium	**512 - 1024**					
Large	**1024 - 2048**					
Very Large	**2048 - 4096**					
	> 4096	**Bedrock**				

Cross Section

Stream		Crew	
Site ID		Date	
Long Profile Station			

*All measurements begin on the left bank, facing downstream unless otherwise noted

Note	Distance (ft)	Elevation	Water Depth	Note

Notations	
Left	*L*
Right	*R*
Pin	*P*
Edge of Water	*EW*
Water Surface	*WS*
Active Channel	*AC*
Scour Line	*SL*
Bankfull	*BF*
Top of Bank	*TOB*
Monument	*MON*

Entrenchment	
Bankfull depth	
Bankfull Width	
2 x Bankfull depth	
Floodprone Width	
Entrenchment Ratio	

Longitudinal Profile

Stream		Crew	
Site ID		Date	

***All measurements area taken downstream unless otherwise noted**

Station	Backsight	Height of Instrument	Bed Surface Foresight	Water Surface Foresight	Bankfull Foresight	Top of Bank Foresight	Note

Appendix B. R code

R is a statistical package. It can be obtained at http://www.r-project.org/

Road erosion analysis – Logistic Regression

Basic R code methodology (example work flow)

```
# logistic model
g1<-glm(gully10 ~ 0 + wtshd + width, family=binomial)
summary(g1)
# odds-ratio, and confidence intervals
exp(cbind(coef(g1), confint(g1)))
# Diff between model and null Deviance, Degrees of freedom
between 2 models
cbind(g1$null.deviance- g1$deviance, g1$df.null-g1$df.residual)
# P Value
1-pchisq(g1$null.deviance- g1$deviance, g1$df.null-
g1$df.residual)
# Log Likelihood
logLik(g1)
```

Kruskal test results

```
kruskal(width, surf)
kruskal(rdlength, surf)
kruskal(rdarea, surf)
kruskal(elev, surf)

kruskal(rdlength, xgeo)
kruskal(rdarea, xgeo)

kruskal(totero, tex)
kruskal(totero, veg)
kruskal(totero, bin.slope)
```

Appendix C. Particle Size Distributions

Soil texturing occurred at each road survey location. Additional tests were taken to test the reliability of the field texturing. Using a bulk density probe samples were procured in the ditch to estimate the type of soil that is exported to nearby streams. Eventually these values along with field texturing were compared to the NRCS STATSGO soil database. Eventually upon analysis, field texturing was found to be correct when compared to STATSGO, 50% of the time. With the variance between field texturing and particle size distribution results, it became clear that the field texturing was too variable for characterizations. For use within this report and for within WEPP:Road, the STATSGO findings of soil type were used.

Methods

Soil texturing in field was conducted by in an area off of the roadway in the ditch, excluding areas of notable deposition from erosion or construction. Soil samples were taken using a bulk density probe. Locations for sampling excluded any noticeable deposition areas. These locations were chosen, as the intention was to get a sample of the most representative underlying material to characterize material which could be exported to the stream. The resulting sample material makeup was compared to the STATSGO soil texture data layer for comparison (NRCS 2011). This procedure was necessary to carry out due to the coarse nature of the STATSGO soil records, thus originally it was unclear if generalizations of resident soil texture could have been made without field verification.

All 14 samples collected in field were characterized following a particle size distribution procedure using a hydrometer and sieve type analysis (Clanton 2010) sieving of samples were completed using sieves sized: 16, 40, 80, 100, and 200.

Figure 22. Soil triangle (USDA)

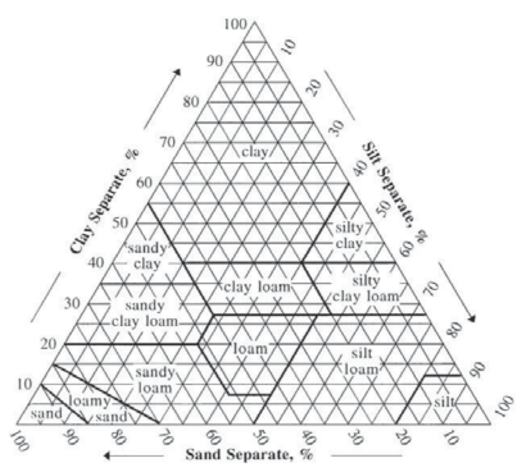


Table 19. Comparisons of soil characterizations using particle size analysis, field texturing, and STATSGO data

Watershed	Road site #	Sample label	Particle Size	Field texture	STATSGO	WEPP
Baptism	5	**B1**	Sand	Clay Loam	Loam	Loam
Beaver	xo1	**B21**	Sand	Sandy Loam	Gravelly Sandy Loam	Sandy Loam
Beaver	50	**B50**	Loamy Sand	NA	Gravelly Sandy Loam	Sandy Loam
Brule	28	**BR2**	Sand	Silt Loam	Fine Sandy loam	Sandy Loam
Beaver	Deb Taylor, rt 4	**BRT4**	Sandy Loam	-	-	-
Flute Reed	FR	**FR5**	Loamy Sand	Clay Loam	Loam	Loam
Flute Reed	FR	**FR6**	Loamy Sand	Clay Loam	Loam	Loam
Knife	45	**K1**	Silt Loam	Clay Loam	Silty Clay Loam	Silt Loam
Knife	32	**KF1**	Loamy Sand	Silt-Clay Loam	Silty Clay Loam	Loam
Beaver	506	**N2**	Sandy Loam	Clay	Mucky Peat/Loam	Silt Loam
Beaver	506	**RDFILL**	Sand	Sandy Loam	-	-
Temperance	16	**TP1**	Loamy Sand	Sandy Loam	Silt Loam	Loam
Temperance	16	**TP2**	Sand	Sandy Loam	Silt Loam	Loam
Temperance	17	**TP4**	Sandy Loam	Sandy Loam	Loam	Sandy Loam

Appendix D. Road Maintenance

Anna Heurth – DNR forests (Grand Marais)

Grading: Grading will greatly extend the life of a road segment. Graders bring material in from the sides of the road.

Resurfacing: Depends on how well they built the roads. In her experience of 3 years at this position they have not resurfaced a road yet. She is under the impression that a typical resurfacing schedule for a road is every 15-20 years – but this is entirely dependent upon funding. When done, about 4 inches of gravel will be put onto the roads. In the meanwhile, spot gravel maintenance will be done.

If roads are not graded correctly grass will grow, grading requires the operator to take gravel from the sides and spread it out, if they are taking 2" rather than 5" grass may grow in places where a ditch / vegetated area is not planned.

Bedrock is a constraint because it is hard to dig a good ditch line, a lot of blasting has occurred to get a ditch line, otherwise water flows directly over the road causing erosion problems. This is an issue because the costs are very high, designs are sometimes an issue as they don't always "get it right" and have to go back to the engineer to re-evaluate.

Traffic: System roads travelled more than minimum maintenance roads. Min. Maintenance roads will not be resurfaced.

Irish road (off of the Arrowhead trail) has some issues. This is mostly due to high traffic. The issues are not so much erosion related (wear and tear), but are related to culverts which can freeze and if not steamed will cause water to back up and flooding/washouts.

Notes: ("road manual" – could contact St Paul office to go in and check out the document, refer to Faulkner email)

Hire out most of their work.

Continuing education: rely on "road manual" (rules and regs. More than a manual). Have gone to a lot of classes pertaining to maintaining roads, protecting wetlands, have learned a lot from the old timers who have worked on road contracts for a number of years.

John Olsen – Superior National Forest (Civil Engineer)

Maintenance: Superior national forest on a somewhat fixed schedule for FR roads, but County roads in the SNF are County jurisdiction not SNF.

County has their own equipment and tends to work whenever conditions are good. SNF has to contract out.

Grading: Scheduled for 1 a month – dependent upon moisture conditions because need damp ground (soft) for grading. This can be a "hit or miss" component of scheduling, since it is so dependent on precipitation (ie: you need a lot of rain, 2 months of no rain means 2 months of no grading)

Plowing will move gravel to the ditch instead of keeping it on the road prism.

Can't cut below the washboard

Resurfacing will occur every 15-20 years, it is very expensive (must haul from gravel pits that are long distances apart), this will only occur if the % of fines that holds the gravel together is virtually gone. Frost will move surfacing out, plowing moves gravel, however generally on logging operations will plow to cut timber, or County maintenance.

Traffic: If looking at the maintenance numbering system (road class for FR roads) [1 – 5]:

3,4,5 : Higher standard main roads, crushed gravel, regular grading. Mowed every year with a 4-5ft strip; every 5-6 yrs roads have more intense maintenance "brushing" in which > 8 ft is cleared of (< 3inch) diameter material (this is to maintain a site distance for drivers, safety (no material in the road), keep animals and invasive species back).

1,2 : (1) is closed to public, no maintenance, a berm is in place that can be removed for logging. (2) Rarely get graded. It is open to the public, but is generally a 2 track logging road. Maintenance and brushing will occur to keep down material from growing down the center of the lane. Maintenance will generally only occur if there is an issue.

Russ – Cook County Highway Superivisor

Maintenance: 1/month roads are calcium chloride treated, this lengthens the time between gravel/grading schedules. This also reduces dust (which the public likes), helps on hard to maintain road sections such as steep hills that are prone to erosion (may washboard), becomes a safety issue.
Roads that are non-chloride treated will be graded 1 every 2 weeks but is weather dependent.
On gravel roads, last year they laid down 16,000 yards of phos 1 gravel, they hope to do 16,000 – 18,000 yrds every year for the next 10 years in order to catch up to the losses of erosion.
Mowing every summer at least twice, more aggressive brushing occurred this year (2010).
But they must deal with a variety of topography: ie: Cty rd 16 (Arrowhead trail) is clay based and relatively flat compared to the west end of the county. Gunflint trail – in the beginning of the trail the section is steep and paved, this causes a lot of erosion of the gravel shoulders. There is a move to pave these shoulders. The Caribou trail is having difficulties as it is close to the stream, a rock bouldering/wiring/concrete slurrying project will take place next year.
Will pave lower sections of shore line roads (roads that extend north from rt 61) to abate erosion. Looking to address culverts too.

They generally work across the whole county, try not to work on just once location in order to show the public that they are working on all parts not just a few.

Traffic: Classification system is somewhat similar to the MNDOT there has been a lot of movement from different classifications but generally a rule of thumb:
Single digit numbers are more travelled, the higher the number the lower the class. Ex: 23 and under are stat aided roads, 24 and higher are county tax payer supported.
There has been a shift in county development from farming to recreation, this has changed the usage of the roads and the traffic patterns.

Notes:
300 miles of roads in Cook County, 120 of which are paved roads, the remaining are gravel roads.

Projects currently:

Working to ditch roads that were not ditched properly in the past.

Appendix E. Stream Survey

Rosgen stream types, study watershed characteristics expanded summary of raw data

Table 20. Field work watersheds, geomorphic review – watershed characteristics

Upstream

Watershed	Area (sq mile)	Entrenchment ratio (+/- 0.2)	Width/Depth ratio (+/- 2)	Sinuosity (+/- 0.2)	LP H20 Surface slope	Material (D50)	Material Description
Beaverx01	52.32	1.8	83.6	1.3	0.0114	110	Large Cobble
Brule28	4.69	2.6	23.3	1.2	0.0125	21	Coarse Gravel
Flute Reed	0.50	1.9	21.4	1.11 (+ .2)	0.0627	17	Coarse Gravel
Knife32	6.07	2.0	11 (+ 2)	1.2	0.0148	6.2	Fine Gravel
Nicado	3.05	12.2	10.5	1.6	0.0002	0.57	Coarse Sand
Temp16	4.48	6.9	9.8	1.7	0.0277	54	Very Coarse Gravel
Temp17	147.72	2.8	62.9	1.2	0.0004	55	Very Coarse Gravel

Downstream

Watershed	Area (sq mile)	Entrenchment ratio (+/- 0.2)	Width/Depth ratio (+/- 2)	Sinuosity (+/- 0.2)	LP H20 Surface slope	Material (D50)	Material Description
Beaverx01	52.32	6.5	33.3	2.2	0.002	32	Coarse Gravel
Brule28	4.69	1.6	10.6 (+ 2)	1.09 (+ 0.2)	0.009	59	Very Coarse Gravel
Flute Reed	0.50	1.9	26.7	1.3	0.083	46	Very Coarse Gravel
Knife32	6.07	2.0	17.2	1.4	0.007	52	Very Coarse Gravel
Nicado	3.05	11.8	14.9	1.11 (+ 0.2)	0.002	110	Small Cobble
Temp16	4.48	5.6	15.3	1.5	0.013	24	Coarse Gravel
Temp17	147.72	6.2	87.3	2.2	0.003	83	Small Cobble

Table 21. Field work watersheds, channel stability analysis (Pfankuch, BEHI)

Upstream

Watershed	Rosgen Classification	Pfankuch	Pfankuch rating	BEHI score	BEHI rating
Beaverx01	B3c	43	Good - stable	5.7	Very Low
Brule28	C4	59.5	B4 -Good - stable	3.3	Very Low
Flute Reed	B4a	97	Poor *unstable	18.3	Low
Knife32	B4	56.5	Good - stable	19.8	Low-Mod
Nicado	E5	79	Fair	26.8	Moderate
Temp16	E4b	55	Good - stable	9	Very Low
Temp17	C4	56	E4 - Good - stable	4.7	Very Low

Downstream

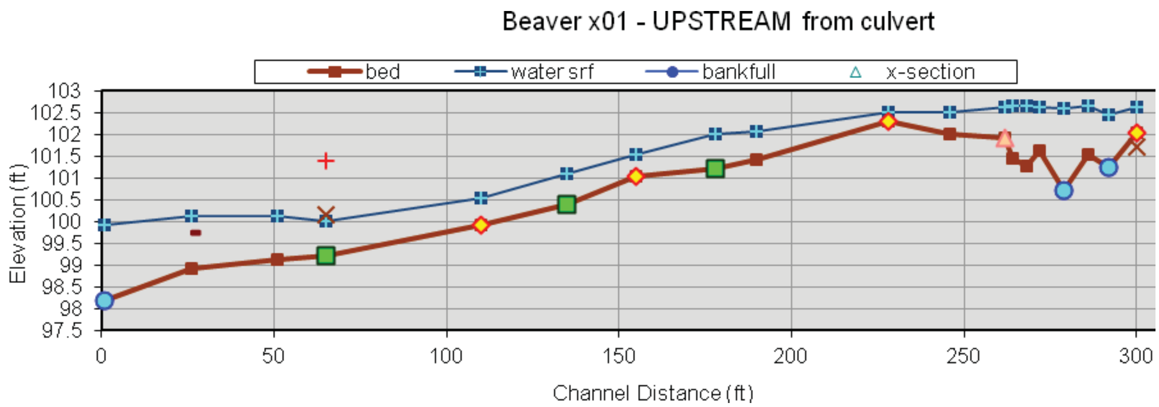
Watershed	Rosgen Classification	Pfankuch	Pfankuch rating	BEHI	BEHI rating
Beaverx01	C4	90.5	Fair	29.05	High/Moderate
Brule28	B4c	64	Fair	21.5	Moderate
Flute Reed	B4a	77	Fair	10.6	Low
Knife32	B4a	79	Poor *unstable	22.25	Moderate
Nicado	C3	64	Good - stable	27.7	Moderate
Temp16	C4	80	Good - stable	20.7	Moderate
Temp17	C3	58	Good - stable	9	Very low

Raw data from field survey

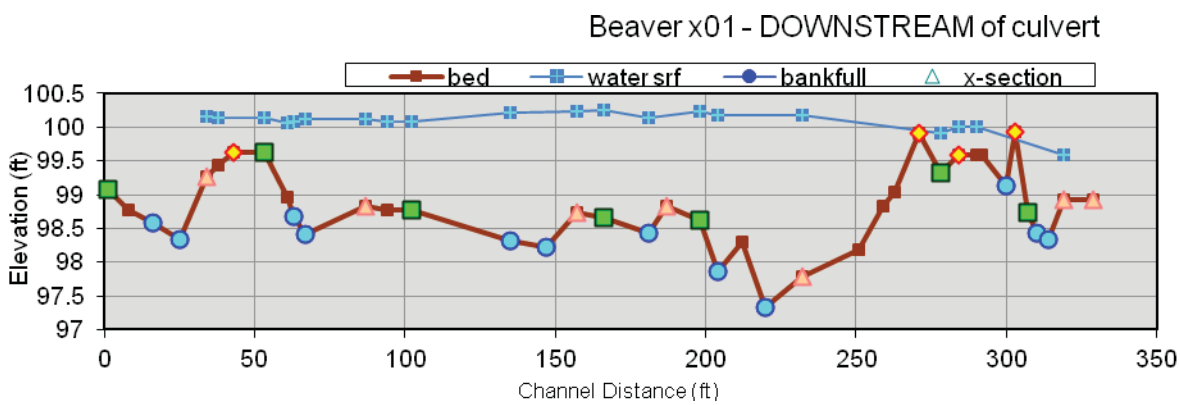
Beaver X01

Longitudinal profile

Upstream

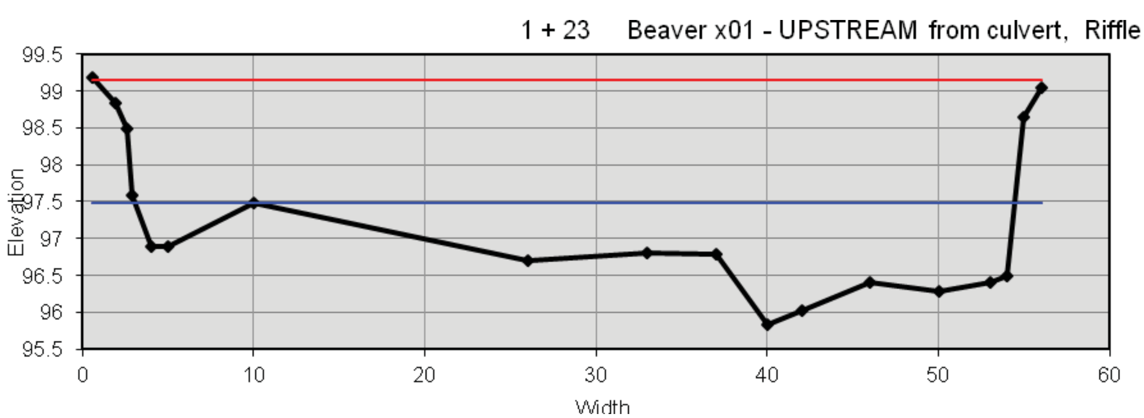


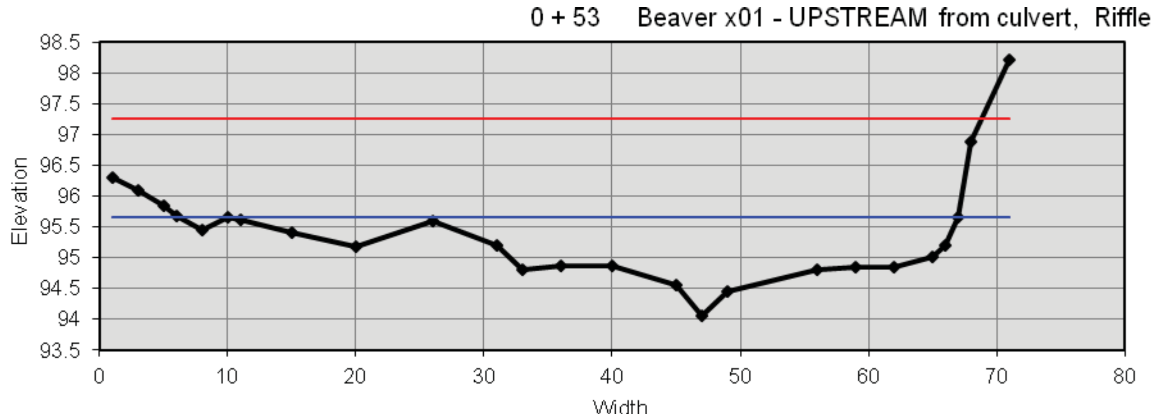
Downstream



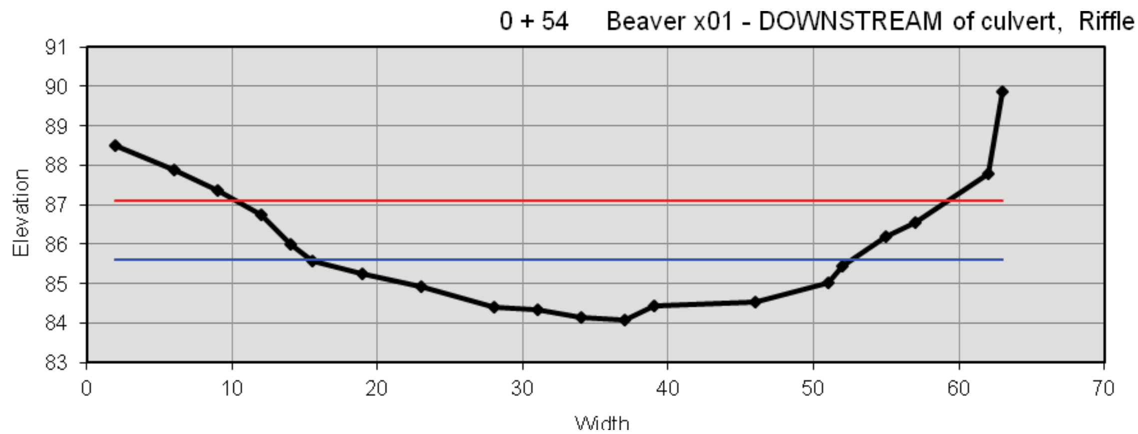
Cross Sections

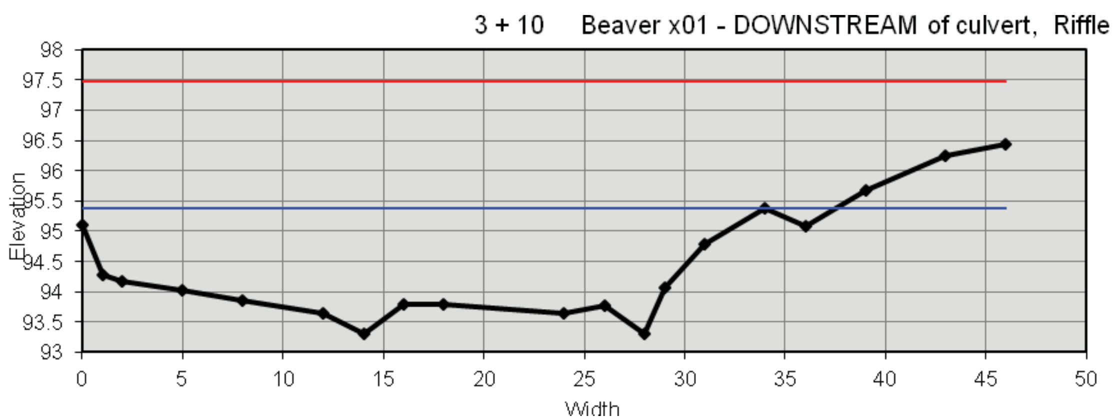
Upstream



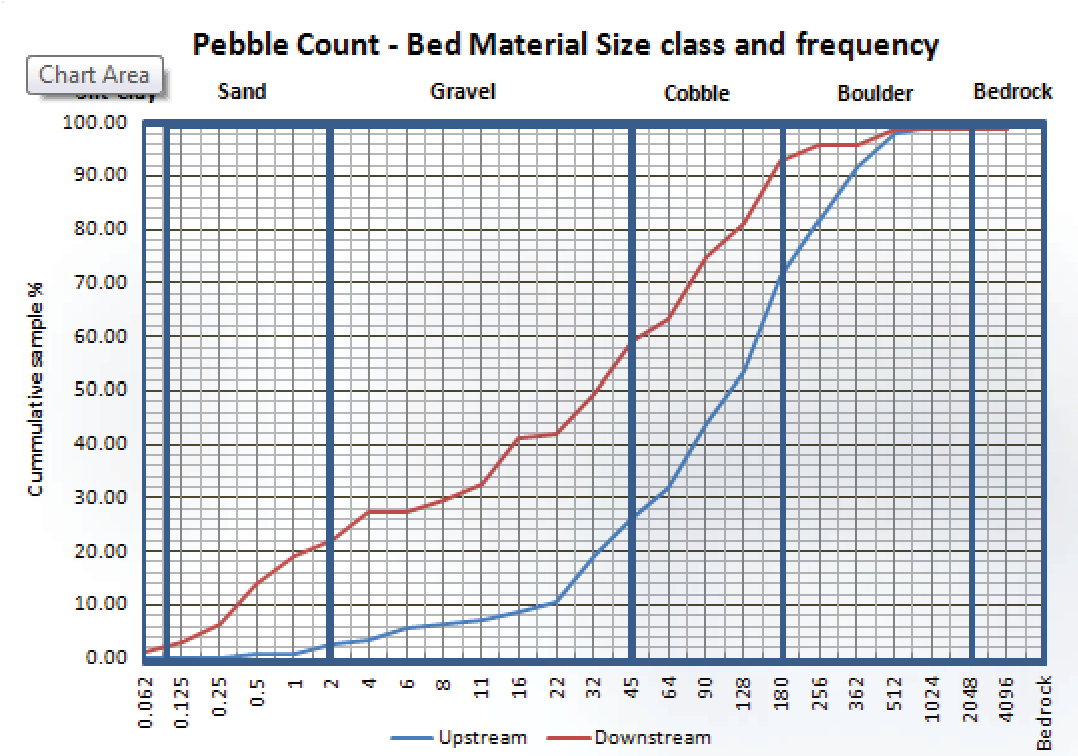

0 + 53 Beaver x01 - UPSTREAM from culvert, Riffle
Elevation
Width
98.5
98
97.5
97
96.5
96
95.5
95
94.5
94
93.5
0
10
20
30
40
50
60
70
80

Downstream


0 + 54 Beaver x01 - DOWNSTREAM of culvert, Riffle
Elevation
Width
91
90
89
88
87
86
85
84
83
0
10
20
30
40
50
60
70


3 + 10 Beaver x01 - DOWNSTREAM of culvert, Riffle
Elevation
Width
98
97.5
97
96.5
96
95.5
95
94.5
94
93.5
93
0
5
10
15
20
25
30
35
40
45
50

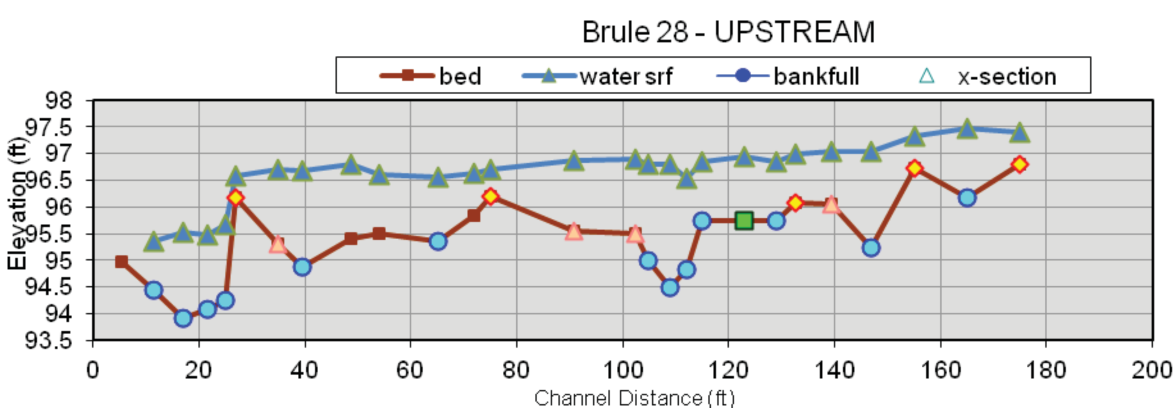
Material Composition



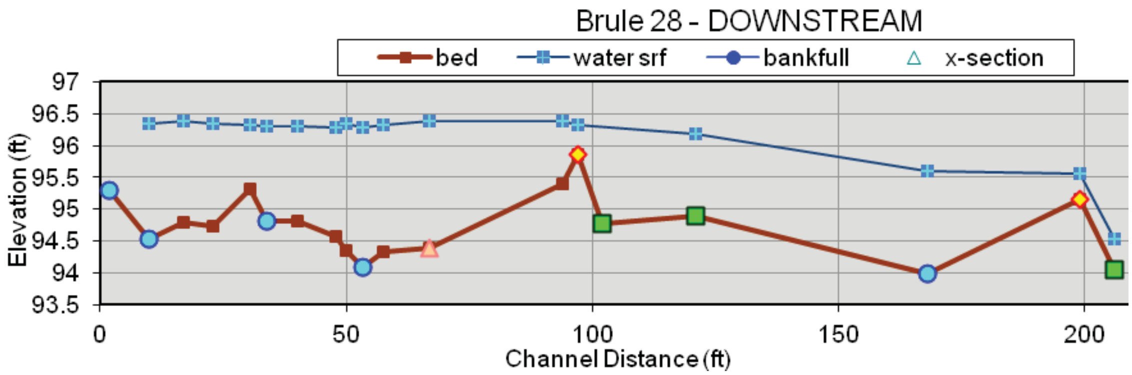
Brule 28

Longitudinal profile

Upstream

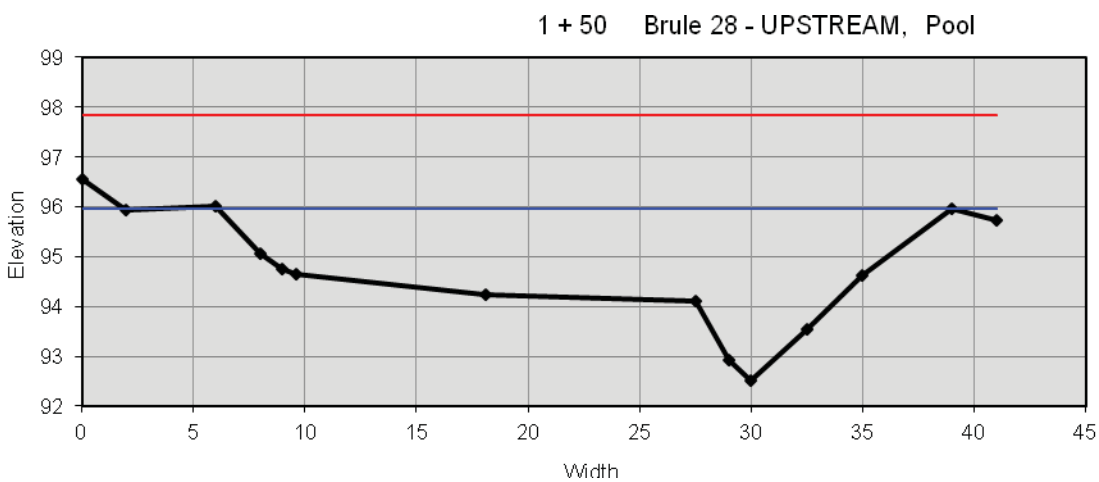


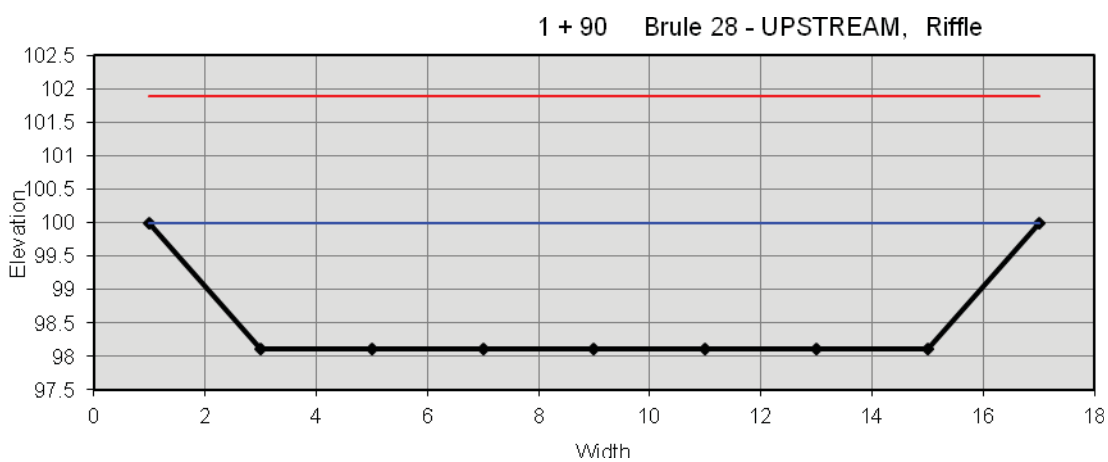
Downstream



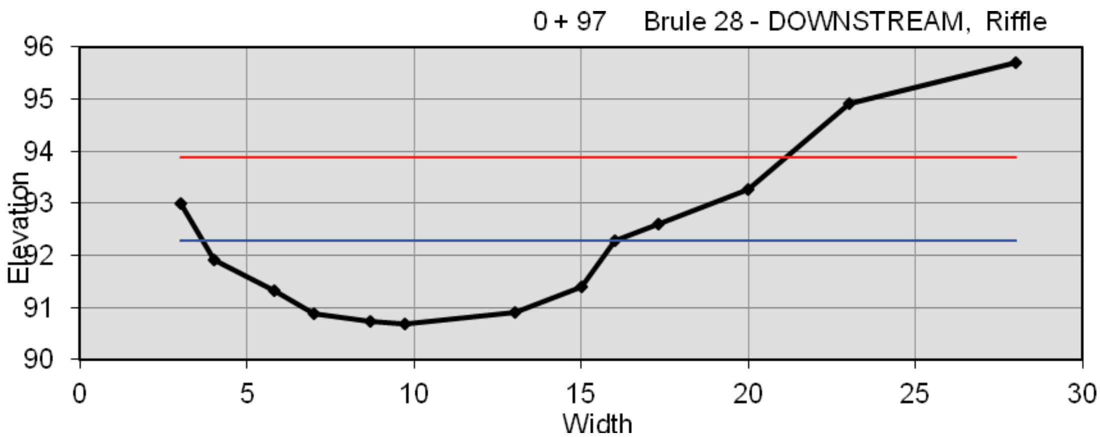
Cross Sections

Upstream

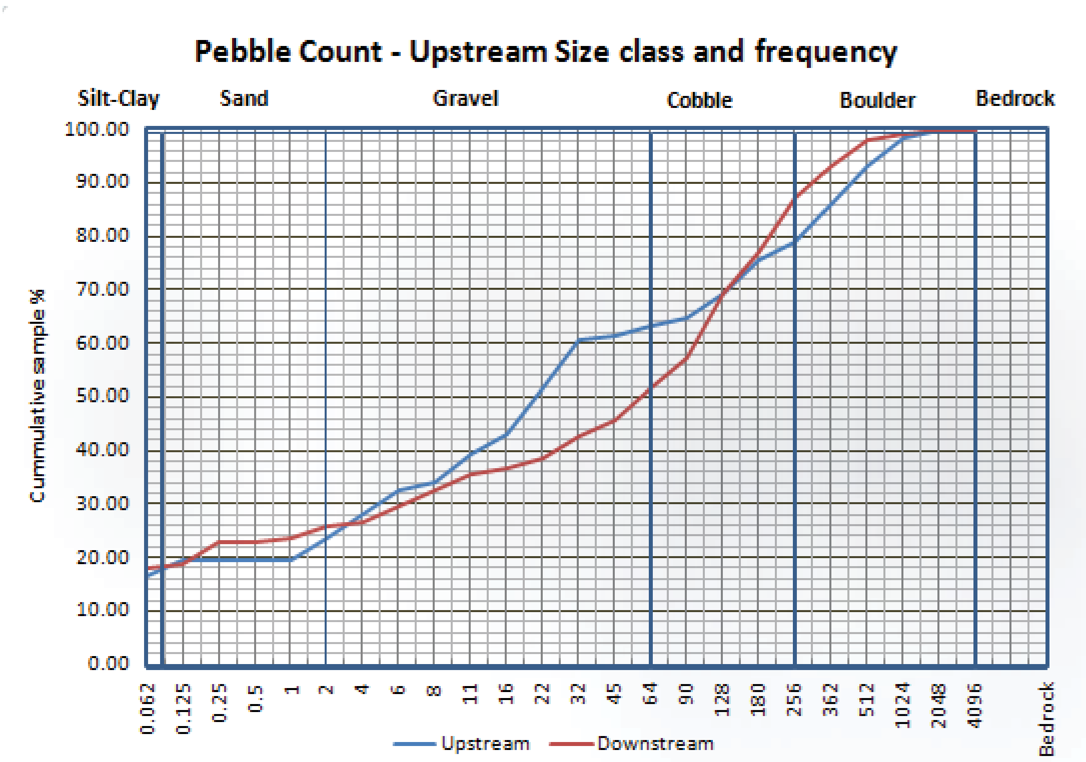




Downstream



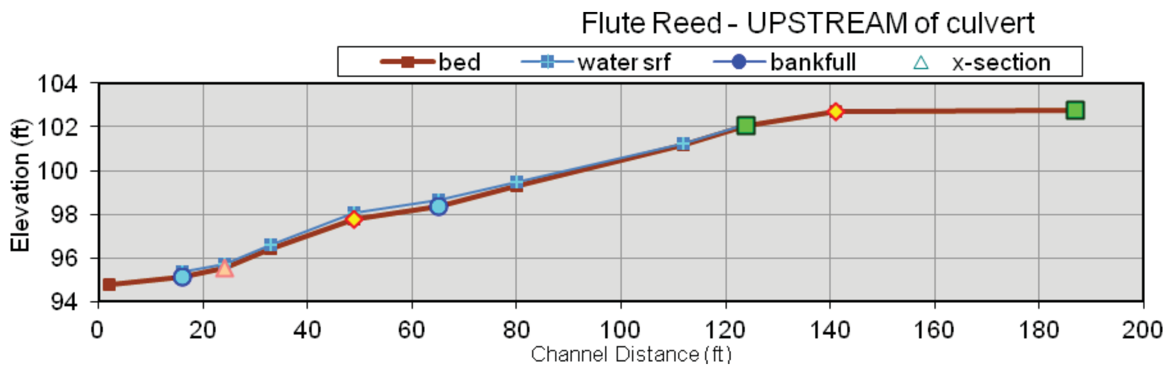
Material Composition



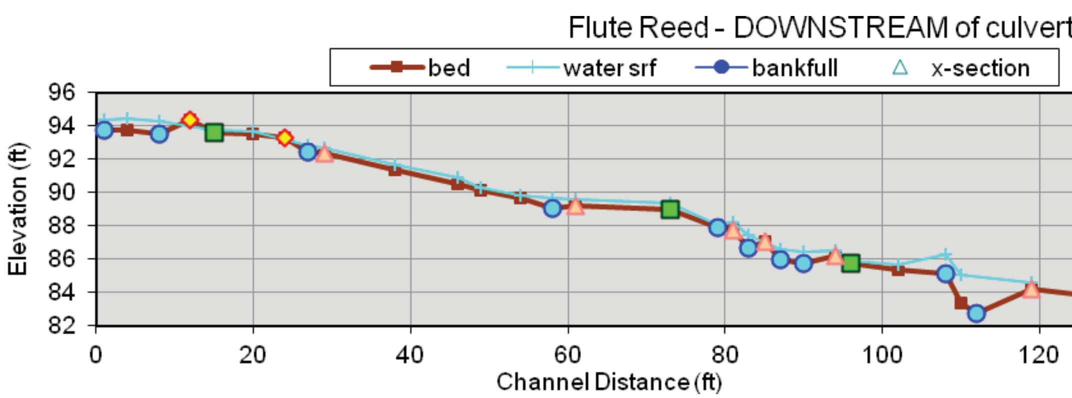
Flute Reed

Longitudinal profile

Upstream

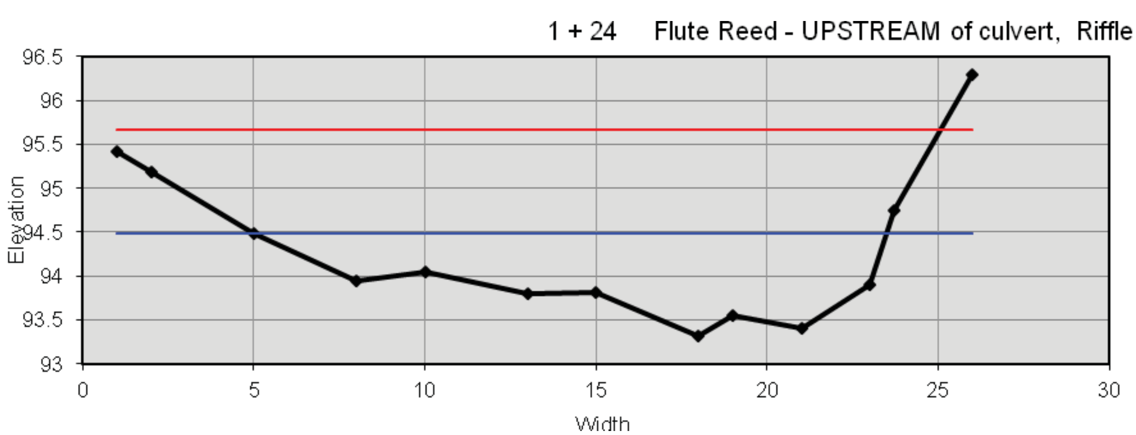


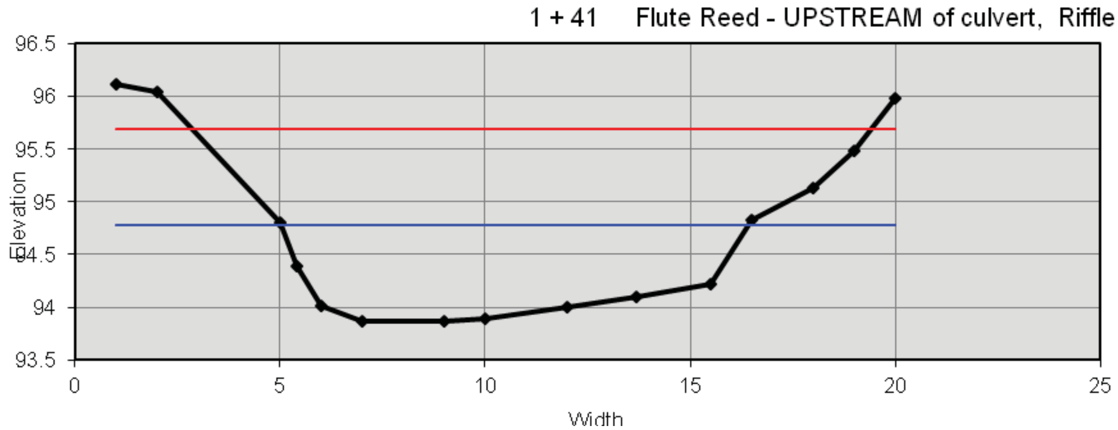
Downstream



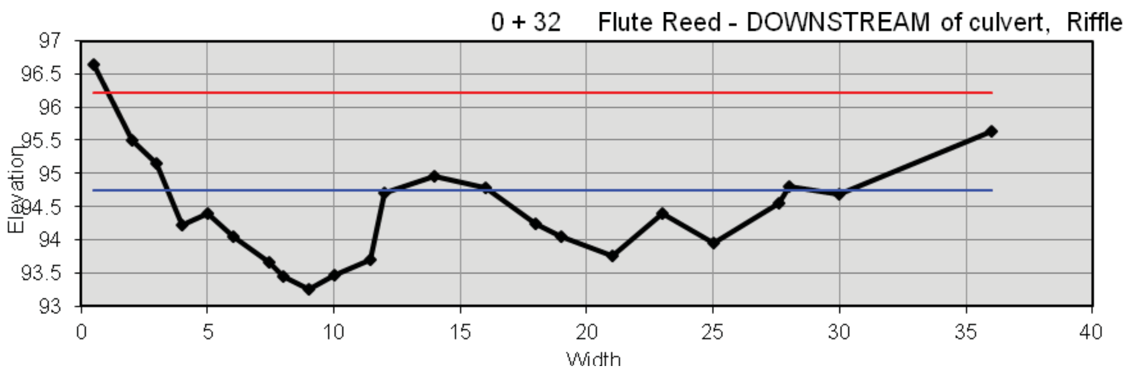
Cross Sections

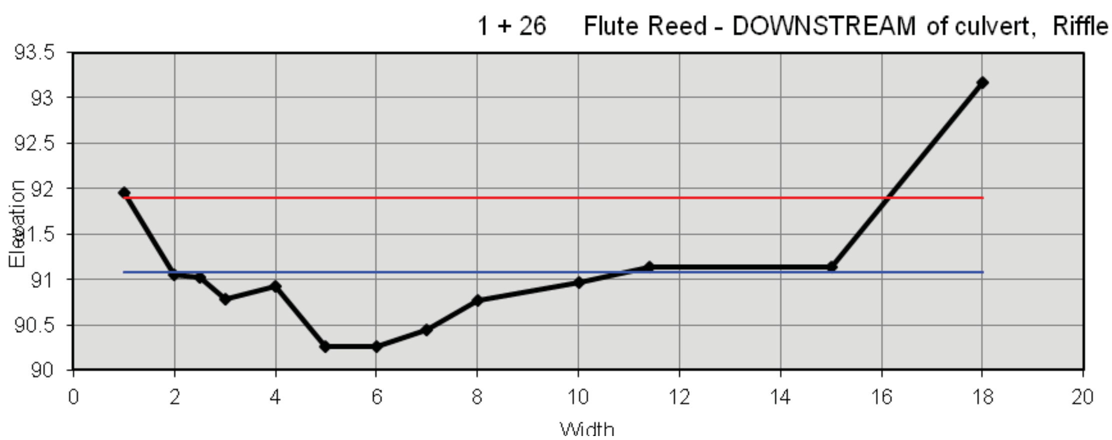
Upstream



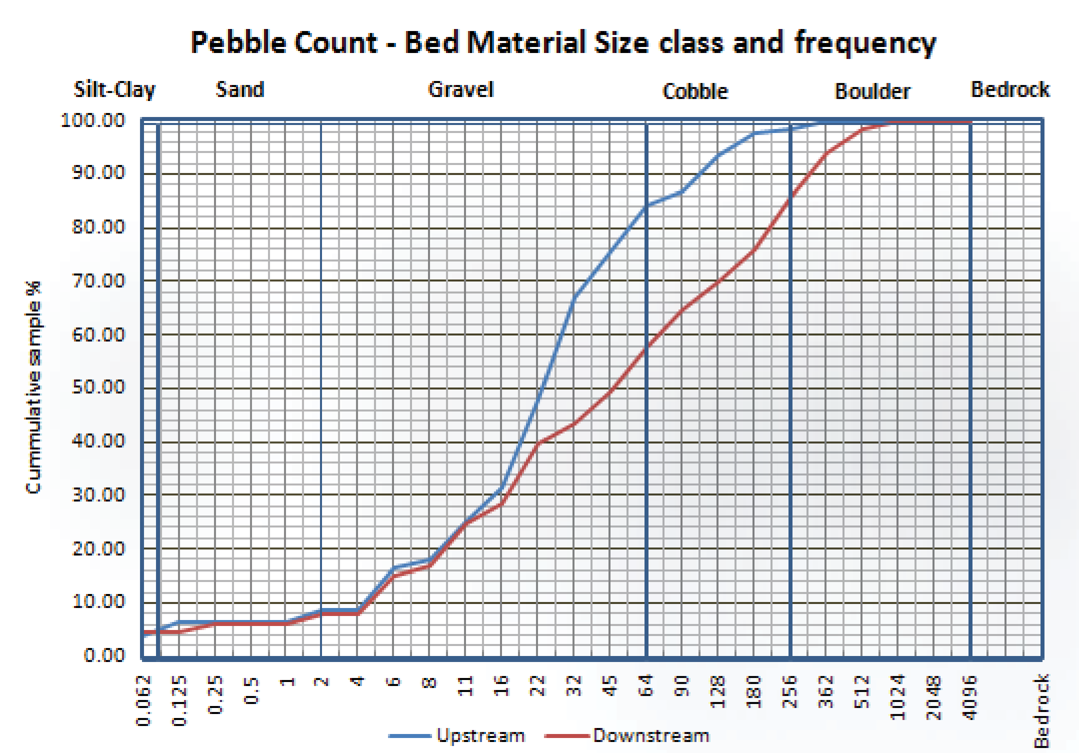

1 + 41 Flute Reed - UPSTREAM of culvert, Riffle
Elevation
Width

Downstream


0 + 32 Flute Reed - DOWNSTREAM of culvert, Riffle
Elevation
Width


1 + 26 Flute Reed - DOWNSTREAM of culvert, Riffle
Elevation
Width

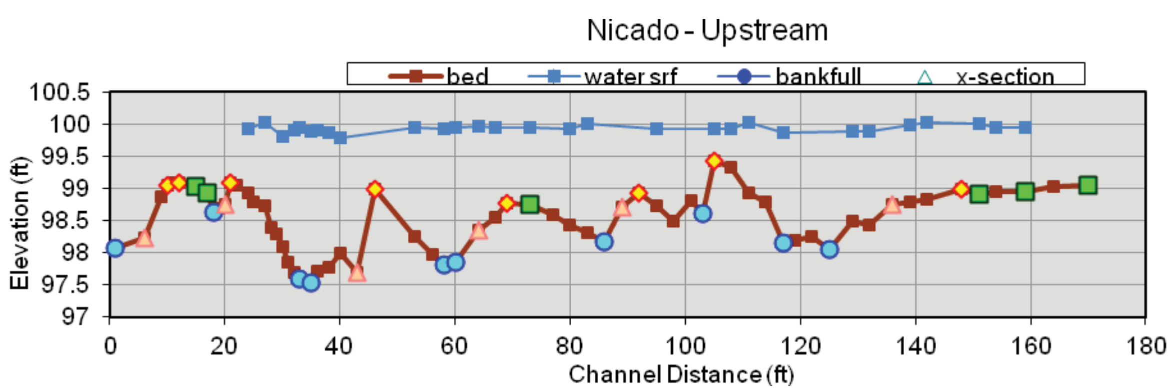
Material Composition



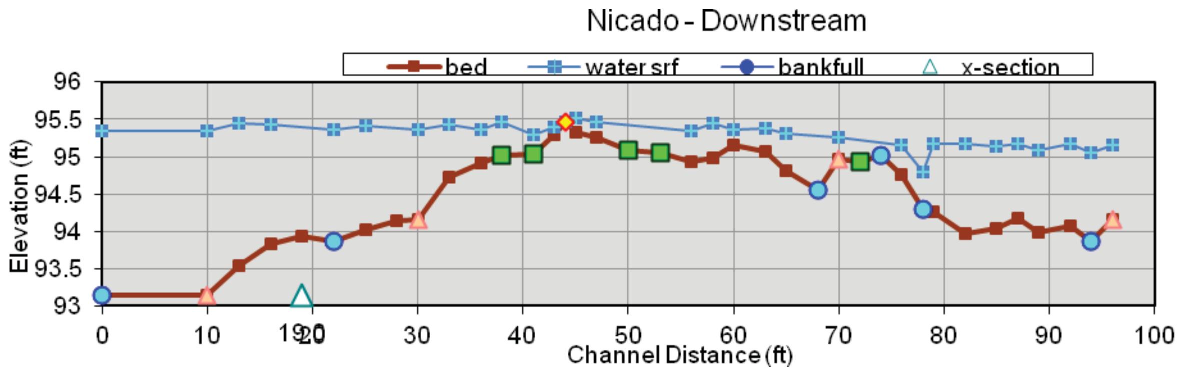
Nicado

Longitudinal profile

Upstream

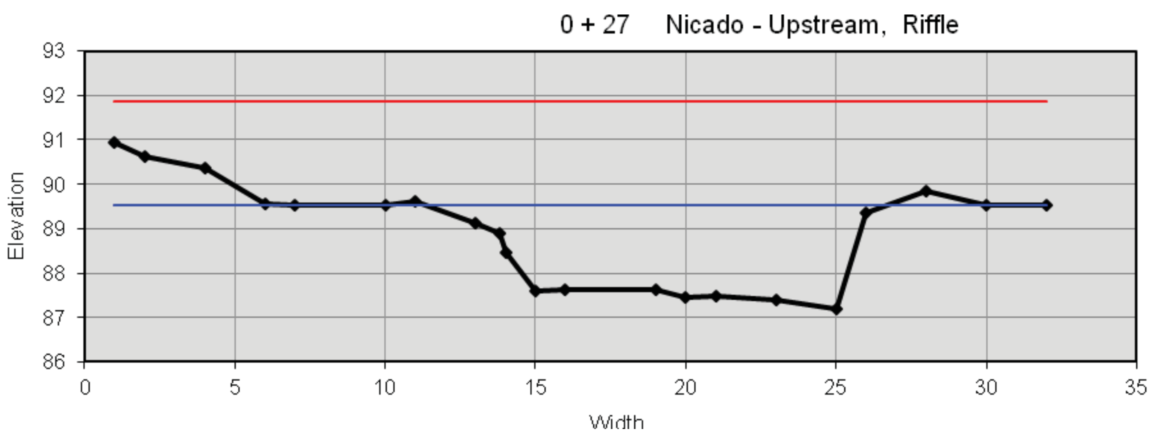


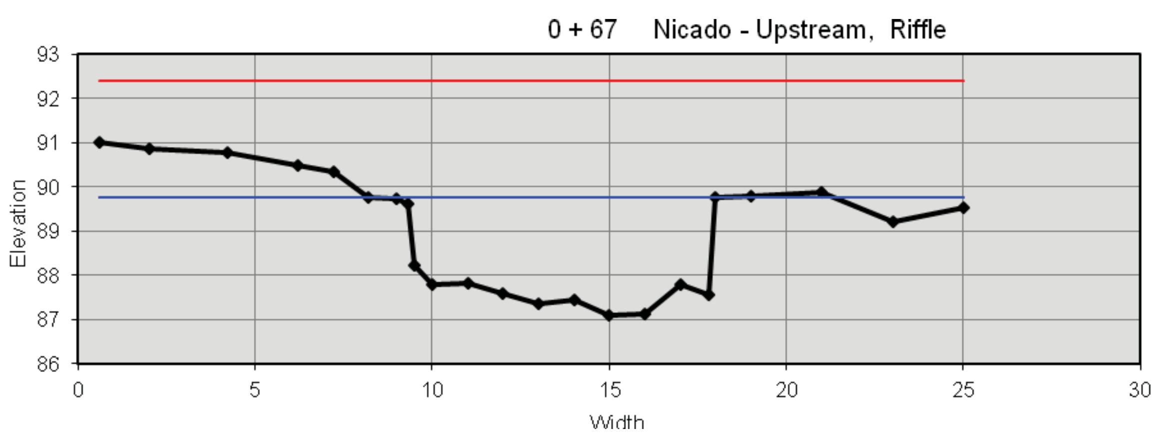
Downstream



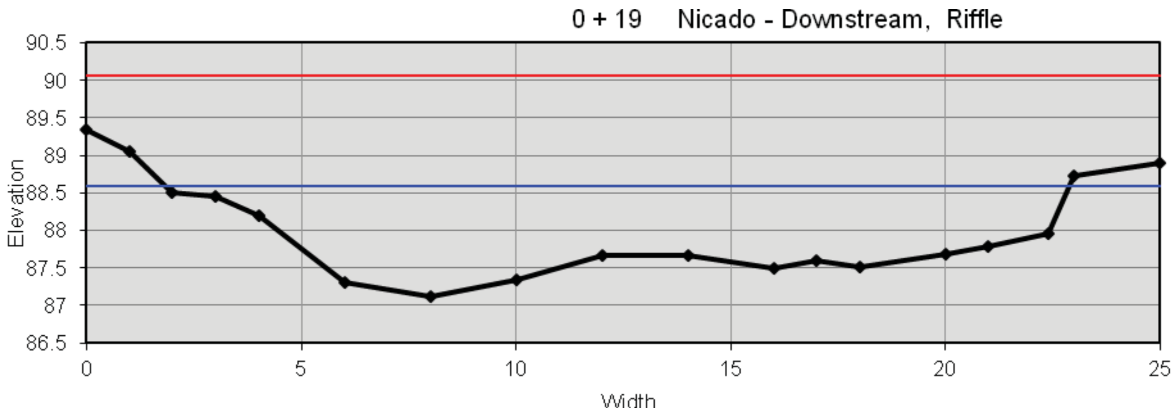
Cross Sections

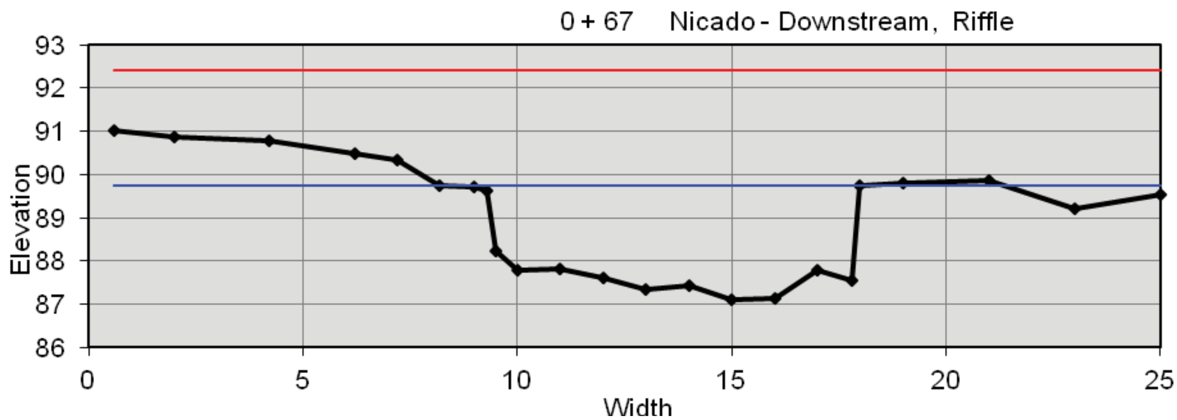
Upstream



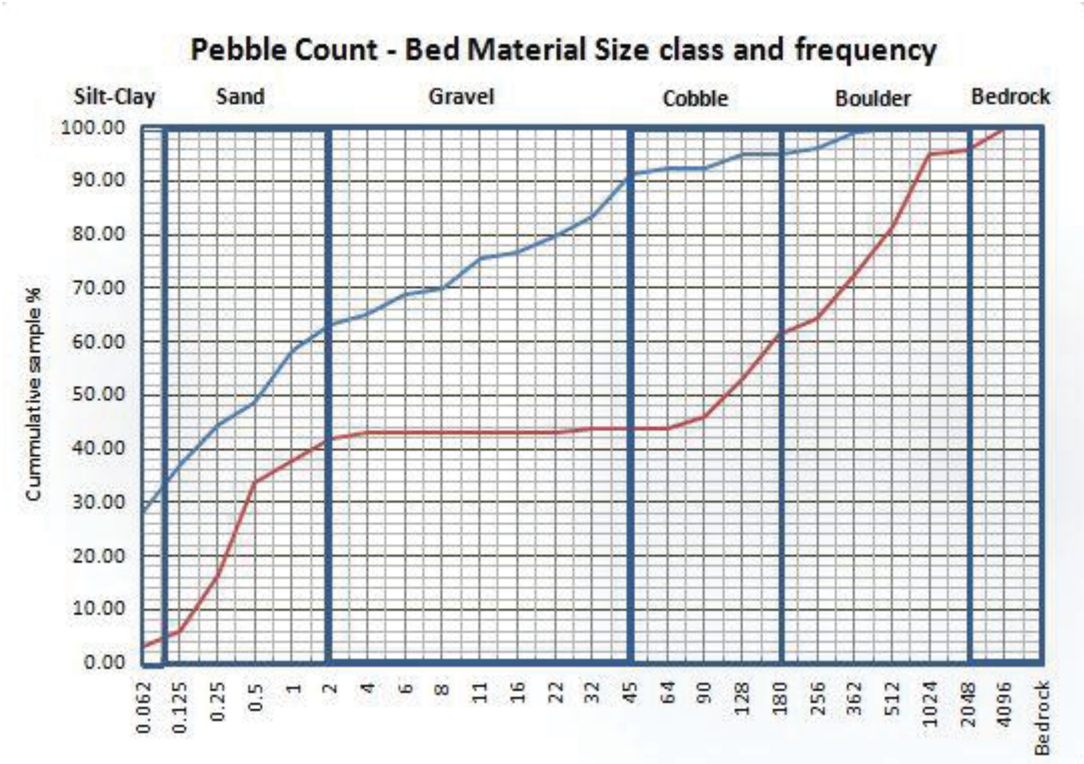


Downstream


0 + 19 Nicado - Downstream, Riffle
Elevation
Width
90.5
90
89.5
89
88.5
88
87.5
87
86.5
0
5
10
15
20
25


0 + 67 Nicado - Downstream, Riffle
Elevation
Width
93
92
91
90
89
88
87
86
0
5
10
15
20
25

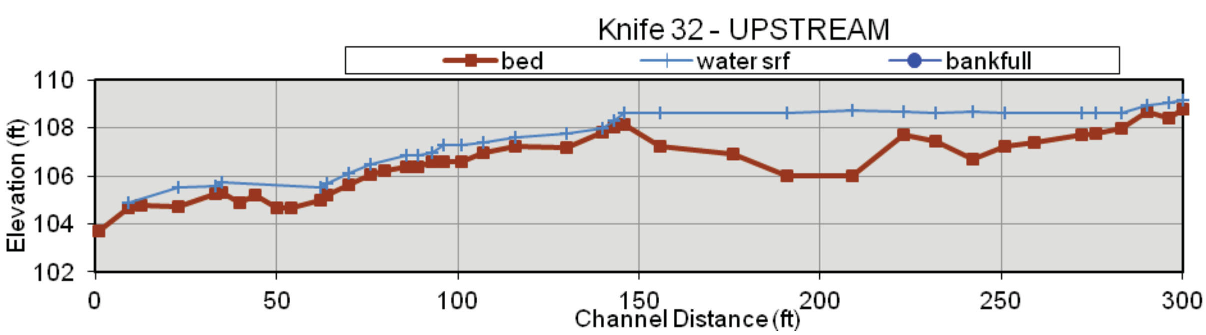
Material Composition



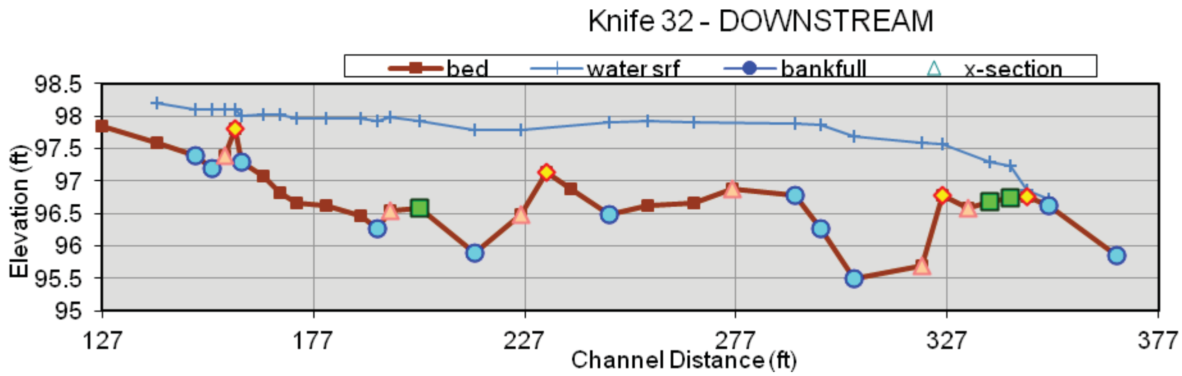
Knife 32

Longitudinal profile

Upstream

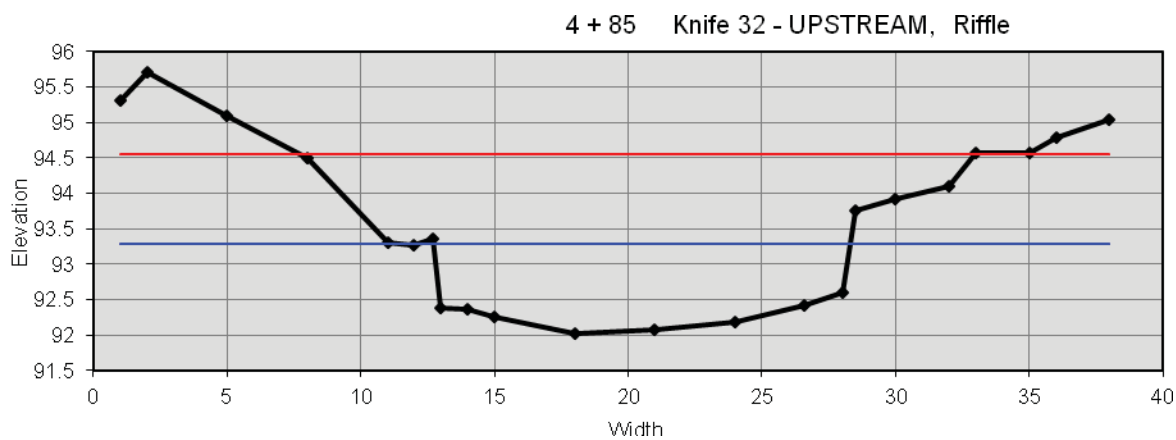


Downstream

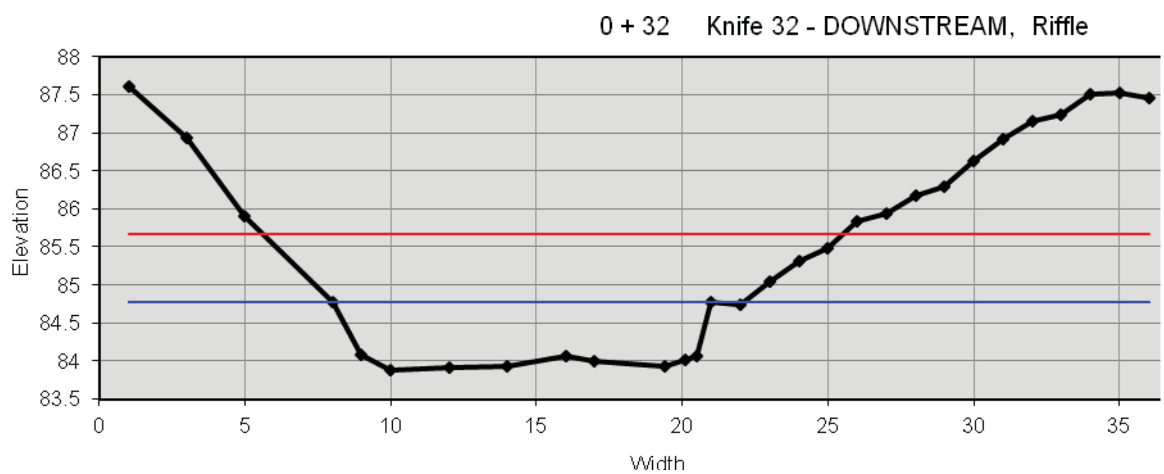


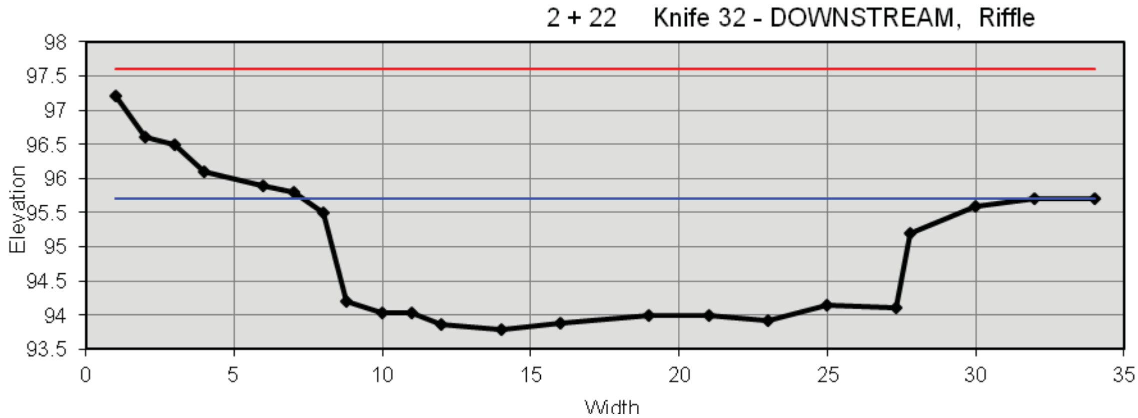
Cross Sections

Upstream

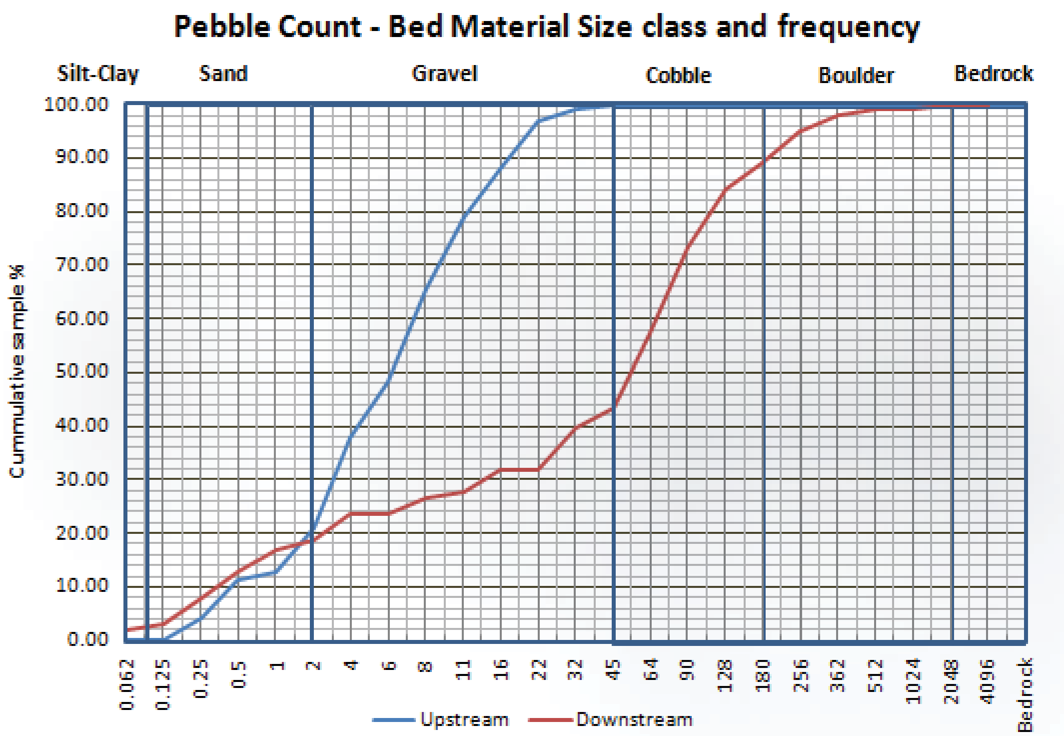


Downstream





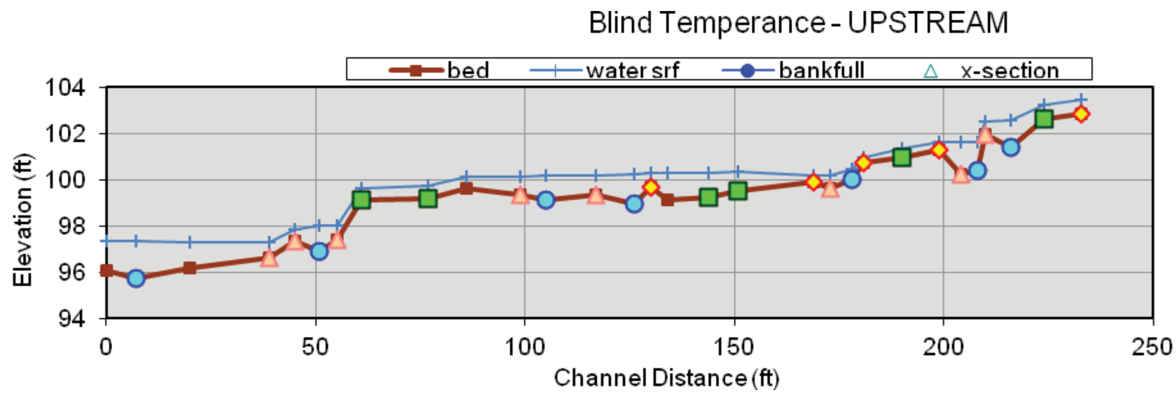
Material Composition



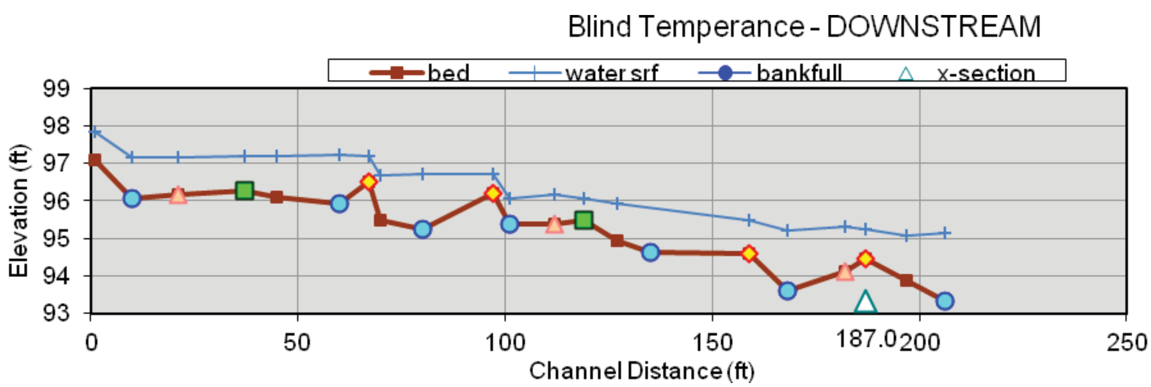
Temperance 16

Longitudinal profile

Upstream

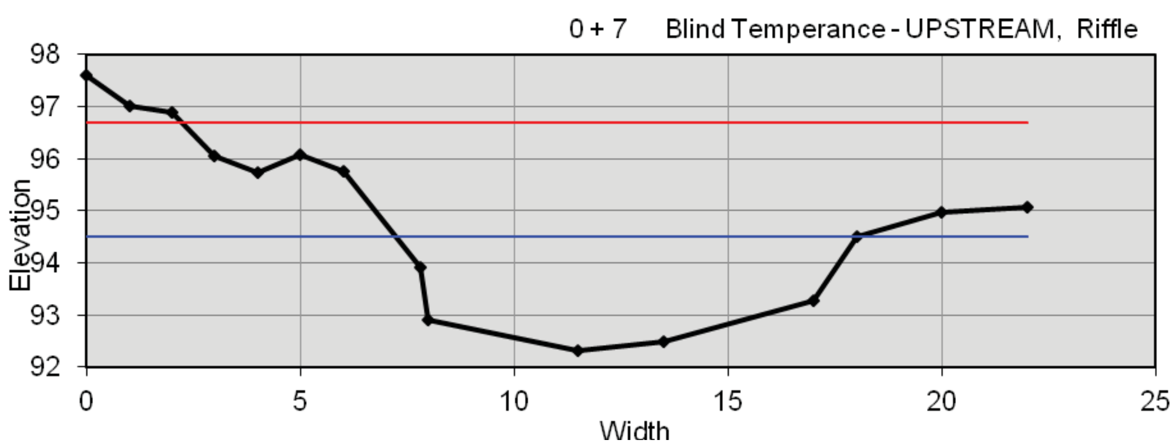


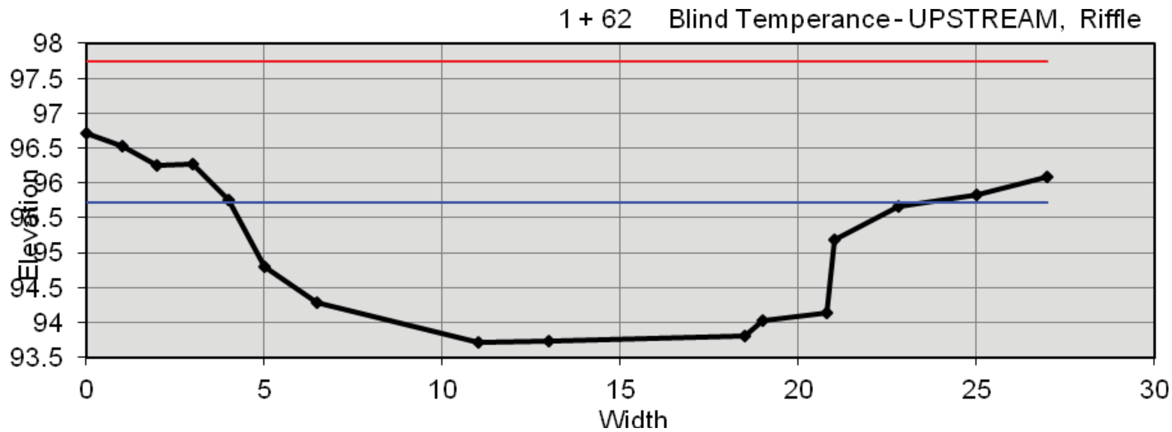
Downstream



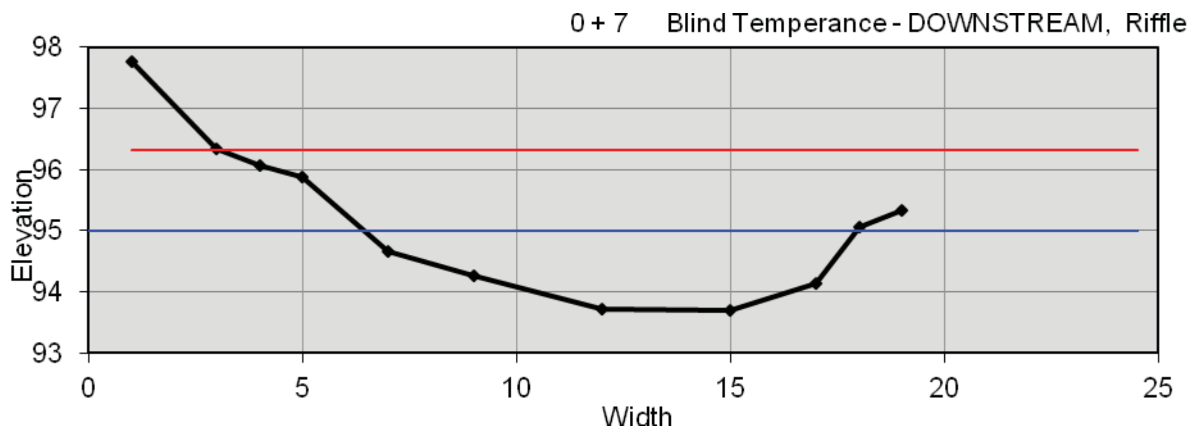
Cross Sections

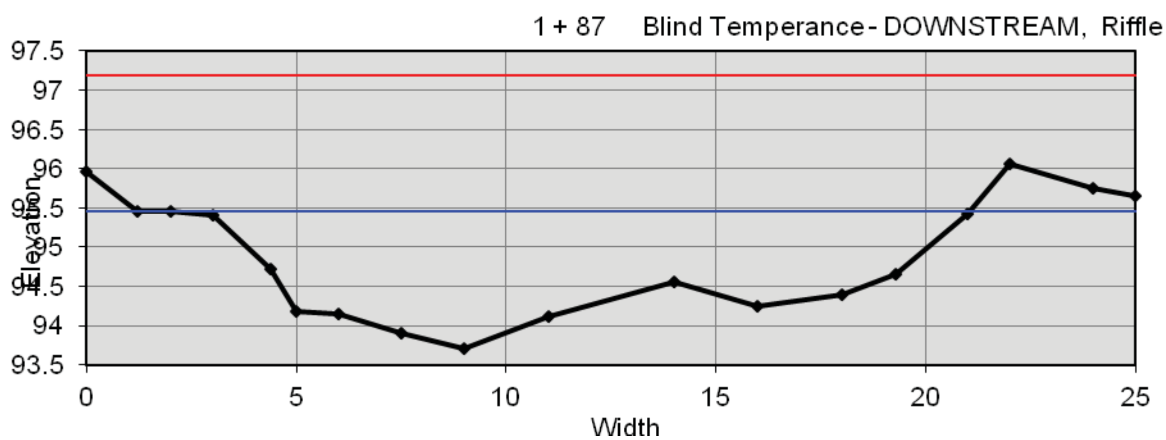
Upstream



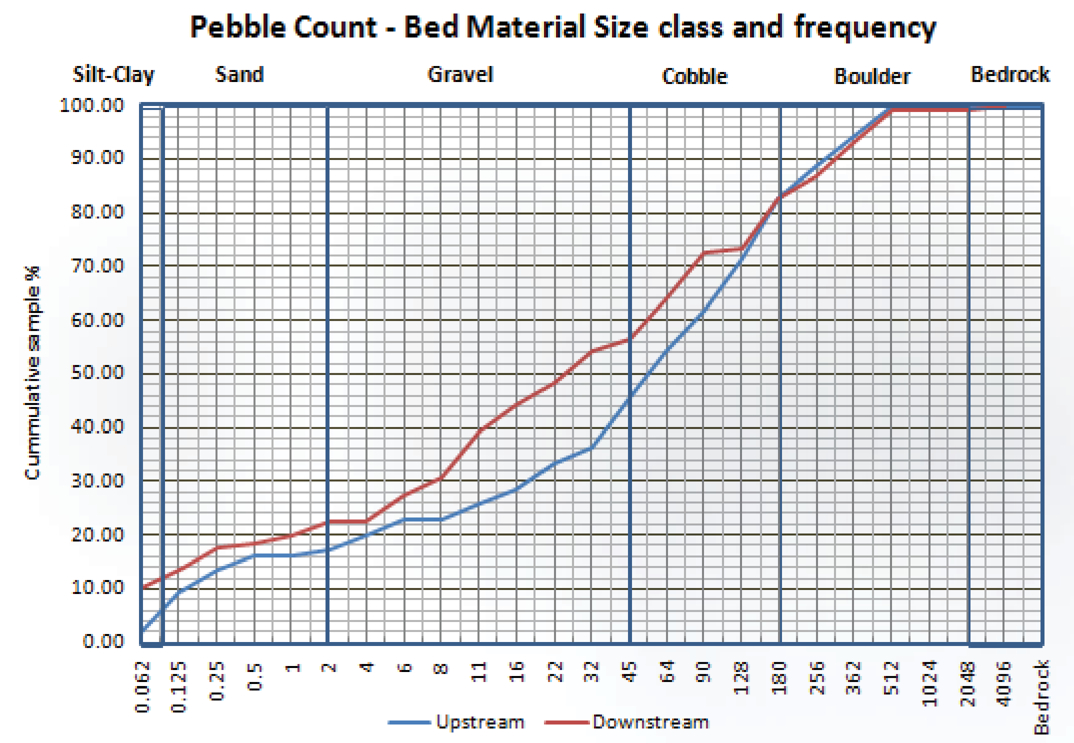

1 + 62 Blind Temperance - UPSTREAM, Riffle
Elevation
Width
98
97.5
97
96.5
96
95.5
95
94.5
94
93.5
0
5
10
15
20
25
30

Downstream


0 + 7 Blind Temperance - DOWNSTREAM, Riffle
Elevation
Width
98
97
96
95
94
93
0
5
10
15
20
25


1 + 87 Blind Temperance - DOWNSTREAM, Riffle
Elevation
Width
97.5
97
96.5
96
95.5
95
94.5
94
93.5
0
5
10
15
20
25

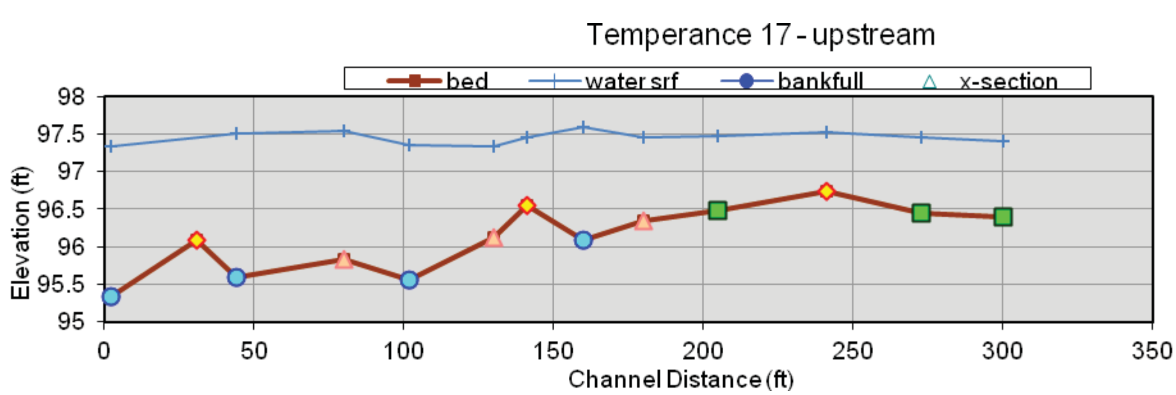
Material Composition



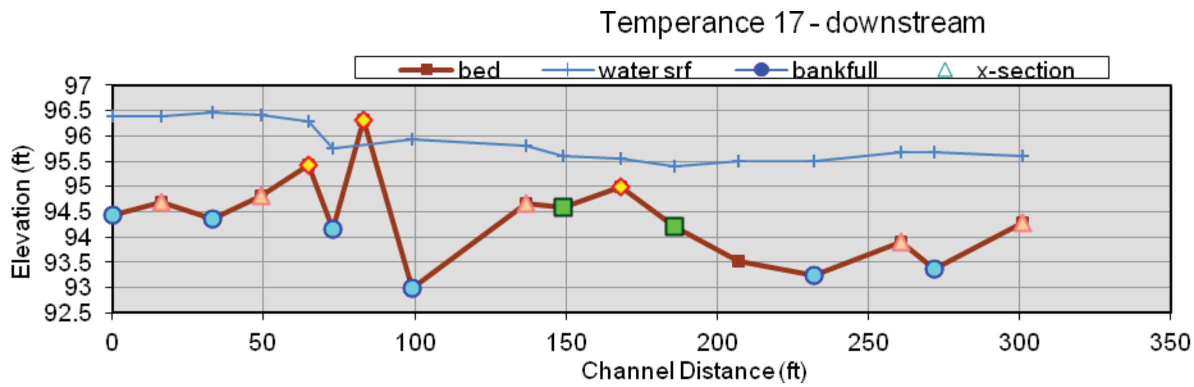
Temperance 17

Longitudinal profile

Upstream

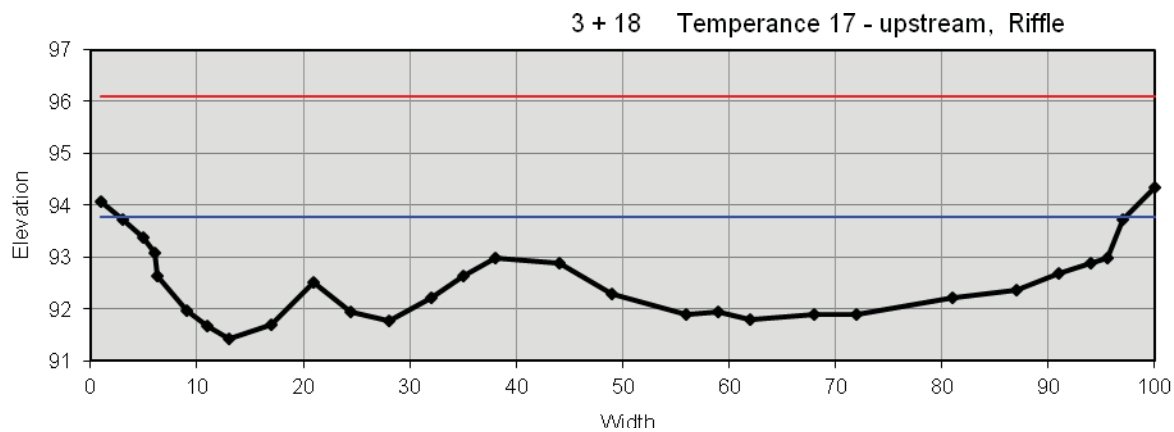


Downstream

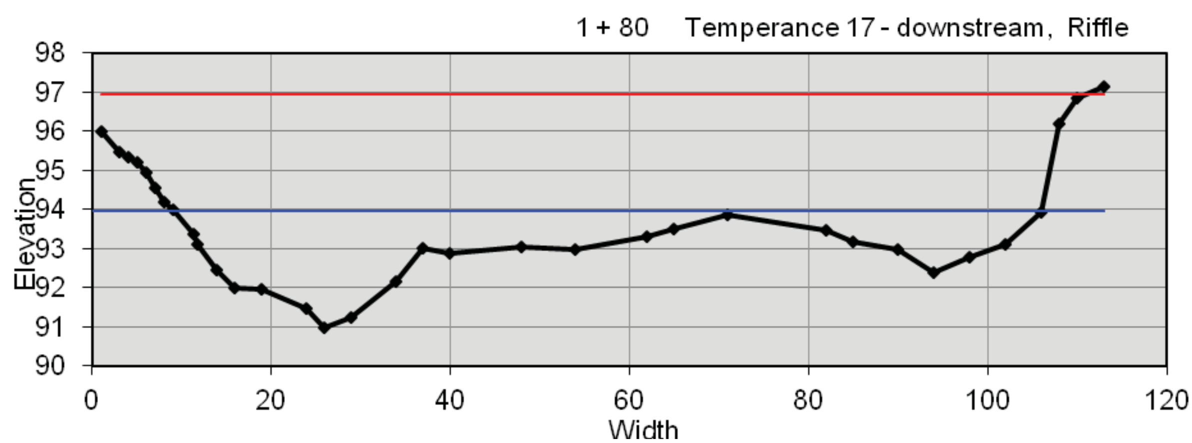


Cross Sections

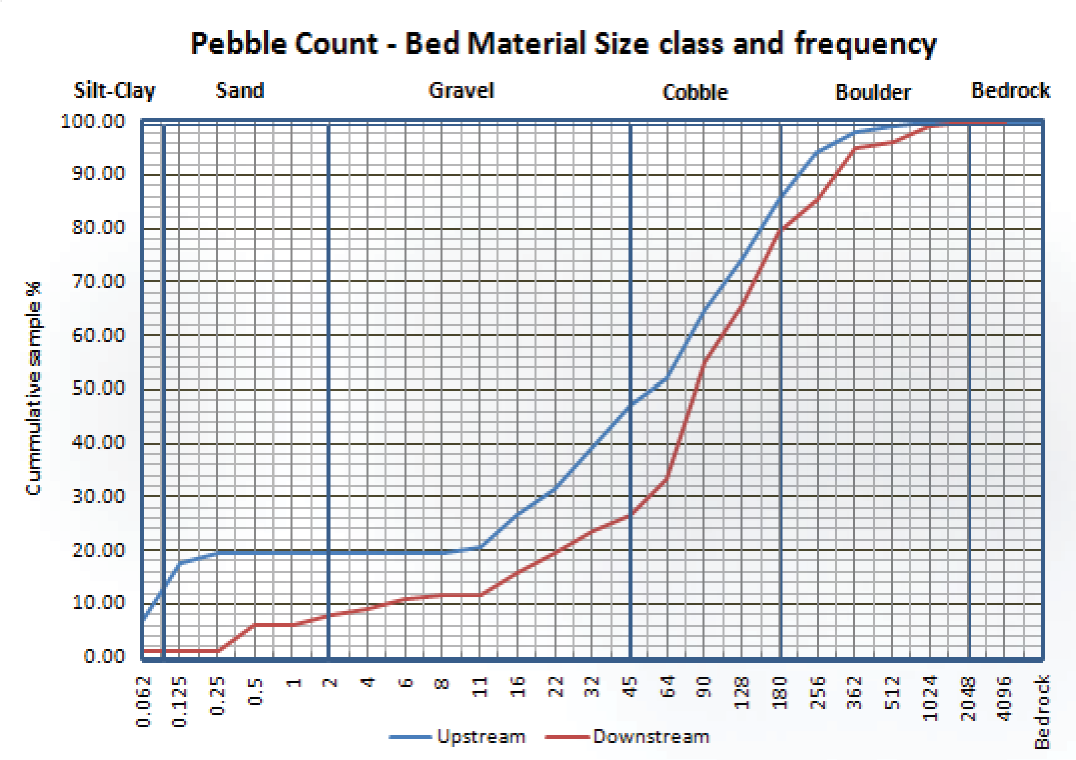
Upstream



Downstream



Material Composition


Pebble Count - Bed Material Size class and frequency
Silt-Clay
Sand
Gravel
Cobble
Boulder
Bedrock
Cummulative sample %
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
0.062
0.125
0.25
0.5
1
2
4
6
8
11
16
22
32
45
64
90
128
180
256
362
512
1024
2048
4096
Bedrock
Upstream
Downstream

Appendix F. Accuracy of Data layers

Air photos

Over-estimation of road-stream crossings is probable within this study. This error may have contributed to road survey site sampling error, and errors in estimation of watershed characteristics. The core data layers used are likely to have over/under estimations pertaining to hydrography or the road network. The hydrography data used was developed by the USGS National Hydrography Dataset (NHD) at a 1:24,000-scale; and road network digitized from older aerial photos or USGS quads (the MNDOT layer is current to the date January 1, 2002, with some properties as current as 1979); therefore these layers may not accurately describe the current dimension and path of the existing road and stream network. Figure 25 illustrates possible sampling error when road and stream networks were intersected, a tributary identified within the NHD hydrography layer is unidentified in image 1, but is counted as a road-stream crossing point.

This study openly assumes the data layers used, will best describe current conditions within the North Shore watershed. It is possible data layer errors became larger when road and stream networks were processed for purposes of this investigation; however manual investigations were undertaken to decrease multiple records within the road network and road-stream crossing database. Due to the scale of the investigation, it was infeasible to manually digitize road and stream networks.

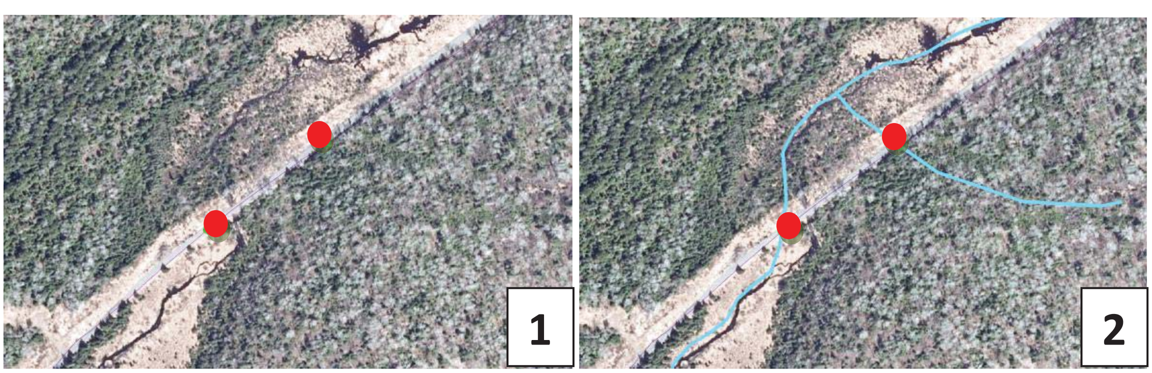


Figure 23

Appendix J

Lower Poplar River Watershed Sediment Source Assessment

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Caleb Arika

Bradley Hansen

Department of Bioproducts and Biosystems Engineering

University of Minnesota

Prepared for the Minnesota Pollution Control Agency

Karen Evens and Greg Johnson, Project Managers

Original submission, August 2011

Finalized February 2013

Introduction

In 2004 the reach of the Lower Poplar River (Figure 1) at Lutsen Minnesota was placed on the MPCA's impaired waters list for excessive turbidity. Monitoring of the Lower Poplar River for flow and turbidity was conducted from 2002 through 2006. Both upstream and downstream monitoring was conducted in an attempt to narrow down the source of the turbidity impairment. The monitoring data showed that the turbidity standards for aquatic life were exceeded at the lower monitoring station near the mouth of the Poplar River as it enters Lake Superior, but the standard was not exceeded at the upper station. This result indicates that the source(s) of the excessive sediment is (are) within the Lower Poplar River watershed.

In response to the turbidity impairment a study reported in RTI (RTI, 2008) was conducted to attempt to quantify the source(s) of the sediment producing the impairment. That report provided estimates of the amount of sediment generated from various sources within the Lower Poplar River watershed. Prior to the RTI study, there was also a study by North American Wetland Engineering (NAWE, 2005) which was intended to study the possible impacts of further proposed developments within the Lower Poplar River watershed, in particular the Ullr Mountain Planned Unit Development. The NAWE report also provided some estimates of sediment sources within the Lower Poplar River watershed. A third study was undertaken by the University of Minnesota (UofM) starting in 2009 to provide a better characterization of the runoff processes occurring in the watershed using additional field data and observations and more detailed applications of the WEPP model. A report by Hansen et al. (2010) reported on the results of the detailed field reconnaissance and analysis of archived field data and historical information. This report presents the results of the assessment of sediment sources using the findings of the first report and the additional WEPP modeling.

In the Lower Poplar River watershed sediment is generated from the following sources: sheet erosion from the land surface; erosion of streambanks and channel bottom; erosion of exposed slump surfaces; and erosion from downcutting in ravines. The sediment generated from the land surface by the sheet erosion process is associated with various land uses within the Lower Poplar River watershed, including forest (predominantly deciduous), ski slopes, golf course, developed areas (housing and commercial establishments), and roads. This report summarizes the results of an analysis to quantify the annual sediment load in the Lower Poplar River associated with each of these sources. A combination of methods was used to arrive at these estimates and the background for these methods along with estimated results will be presented in the following sections.

Analysis of sediment generated from sheet erosion

Modeling background

Erosion from upland areas is in the form of sheet and rill erosion, and gully erosion. The prediction of sheet and rill erosion has advanced significantly since the days of the Universal Soil Loss Equation (Wischmeier and Smith, 1960), an empirical equation for prediction of edge-of-field erosion. Today we have models such as the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995) which is a physically-based model that provides estimates of pointwise erosion in the field and also predicts the amount of eroded soil that actually is delivered to the point of interest/concern. The WEPP model, version 2010, was applied in the current project to estimate the local erosion in the Lower Poplar River watershed and to estimate the delivery of eroded soil to the outlet of the watershed.

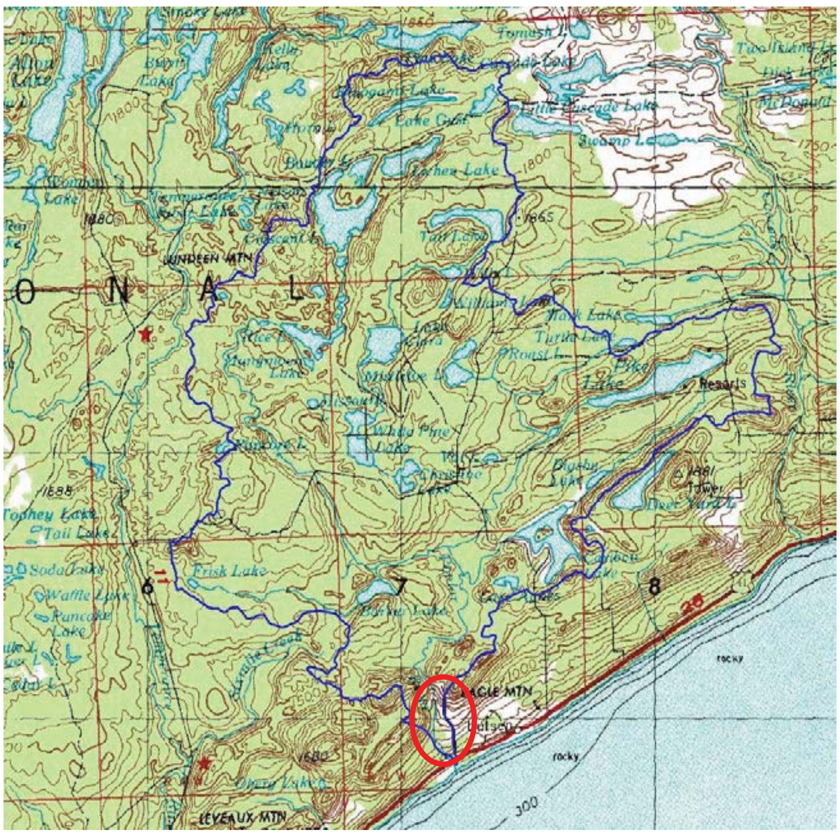

Figure 1. Topographic map with the outline of the Poplar River located along the north shore of Lake Superior. The red oval outlines the area of interest with regard to the turbidity impairment, that is, the Lower Poplar River watershed.

The WEPP model was developed to simulate the runoff hydrology of a landscape on the basis of individual hillslope units (see Figure 2a). It simulates the runoff generated on a hillslope in response to individual or series of rainfall/snowmelt events, and erosion associated with the runoff events is simulated simultaneously. Sediment generated at locations on the hillslope is transported by runoff water to downslope locations on the hillslope. The transported sediment can be deposited on lower portions of the hillslope, or else it is transported off the toe of the hillslope into an established stream channel.

Important properties of a hillslope that influence runoff generation, soil erosion, and sediment transport on a hillslope are the type of soil (soil thickness, texture, hydraulic conductivity), soil cover (vegetative type and vegetative density), surface slope, and soil erosivity. The WEPP model uses these properties as inputs to a system of physically-based equations for calculating surface runoff generation, evapotranspiration, soil particle detachment, and suspended sediment transport.

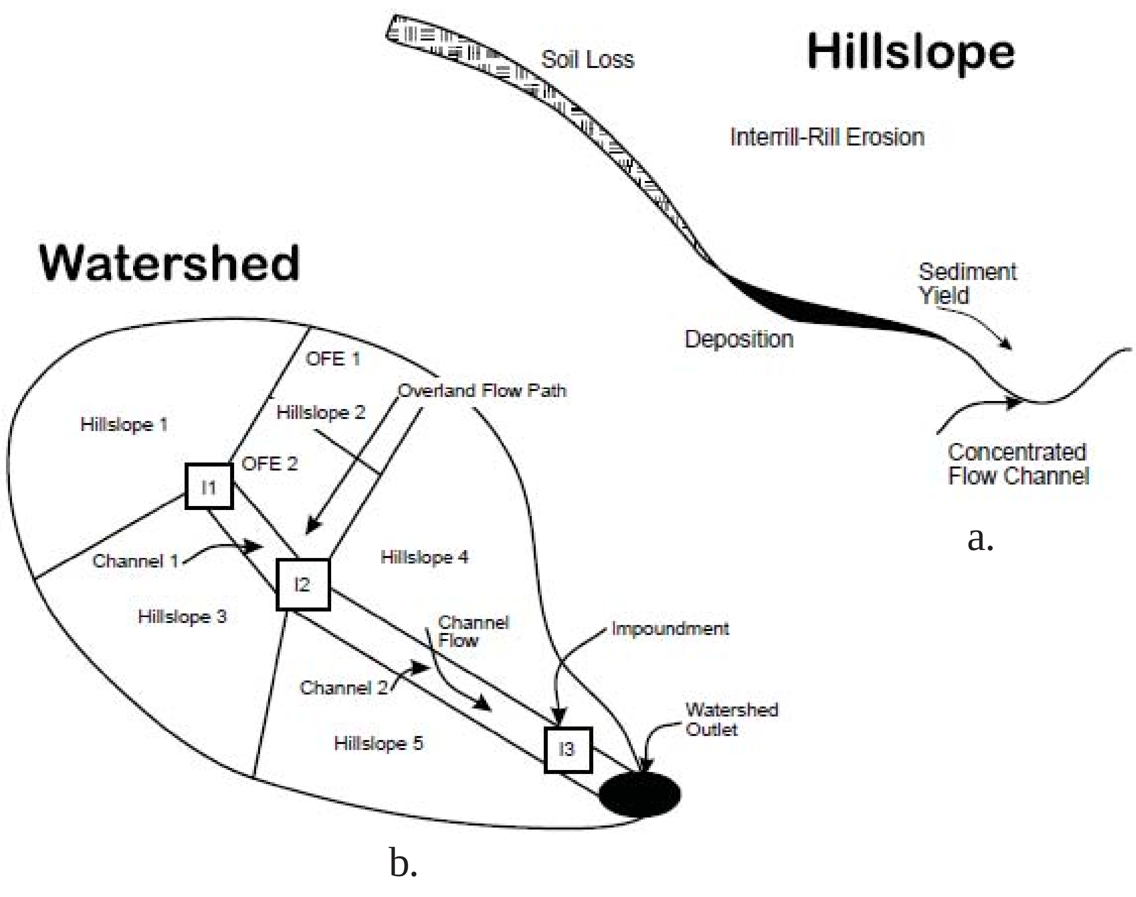

Figure 2. Illustration of the conceptual framework of the watershed version of the WEPP model. (a) The framework for the individual hillslope component and (b) the framework for the watershed. All hillslopes have a channel at the toe of the hillslope.

While the WEPP model can be applied to individual hillslopes, the watershed version of the model allows one to subdivide a watershed into a number of hillslope segments as shown in Figure 2b. The hydrology and sediment transport is then calculated for each of the segments, and the results are then combined through runoff routing and sediment transport routing to provide estimates of sediment delivery to the watershed outlet. The outlet of the watershed is the location where the sediment is monitored, and that is therefore the point of interest for the calculation of the sediment load by the WEPP model and matching with observed sediment load. However, since the WEPP model simulates the erosion and sediment transport on individual hillslopes, the resulting simulations also provide details of where the sediment is originating.

A useful tool for setting up (preprocessing) a WEPP model for a watershed is the GeoWEPP model (2008). This model serves as an ArcGIS interface between GIS data layers that are readily available for landscapes in the U.S., and the WEPP model. The GeoWEPP model was applied in the current project to prepare the input data for the WEPP model simulations. While the preparation of this input data would seem to be rather automatic using the GeoWEPP model, it will be mentioned later that a significant amount of modification of the prepared input data is necessary because of the changes in GIS databases over time, and due to the fact that manual interaction with the data is necessary to provide the most accurate representation of land surface conditions.

Water balance calculations in WEPP

The WEPP model conducts calculations of all of the significant water balance components associated with the terrestrial phase of the hydrologic cycle. It uses as input climatic/weather data either synthesized with stochastic methods or developed from direct observations. This input is then partitioned into the components of vegetation interception, infiltration, surface runoff, shallow subsurface flow, deep percolation, soil evaporation and plant transpiration. A schematic of the processes involved in the water balance for a single hillslope is presented in Figure 3. The fate of deep percolated water is not taken into account in the WEPP model; the percolated water is assumed to be lost from the watershed system. Some recent developments in the WEPP model point to the fact that a new version of WEPP will include baseflow from groundwater recharged by the percolated water.

Runoff generation processes

Possible processes of runoff generation in the landscape include surface runoff, shallow subsurface storm flow (SSSF), and groundwater discharge (Kirkby, 1978). While there are contributions to runoff from SSSF and groundwater discharge in the Lower Poplar River, those contributions are quite small in comparison to direct runoff from the land surface as a result of rainfall and snowmelt events. The SSSF and groundwater discharge components are small in this area because of shallow soil conditions (reduces the SSSF contribution), and the predominance of bedrock in the area leading to low availability of groundwater with regard to storm flows. We did not consider the contributions of SSSF or groundwater discharge to the generation of soil erosion within the Lower Poplar River, and instead focused on the direct surface runoff mechanism.

It is generally recognized that direct surface runoff can be generated by two mechanisms, the Hortonian mechanism which involves the exceedance of infiltration capacity of the soil at the soil surface, and the Dunne mechanism, also called saturated overland flow resulting from saturation of the soil profile due to downslope migration of soil moisture. The Hortonian mechanism generally occurs in the case where the vegetation is sparse and the surface of the soil is drastically disturbed, and thereby the surface hydraulic conductivity is significantly small, while the Dunne mechanism dominates when the soil has very high hydraulic conductivity at the surface and downward percolation of water is restricted by low conductivity layers of soil or bedrock.

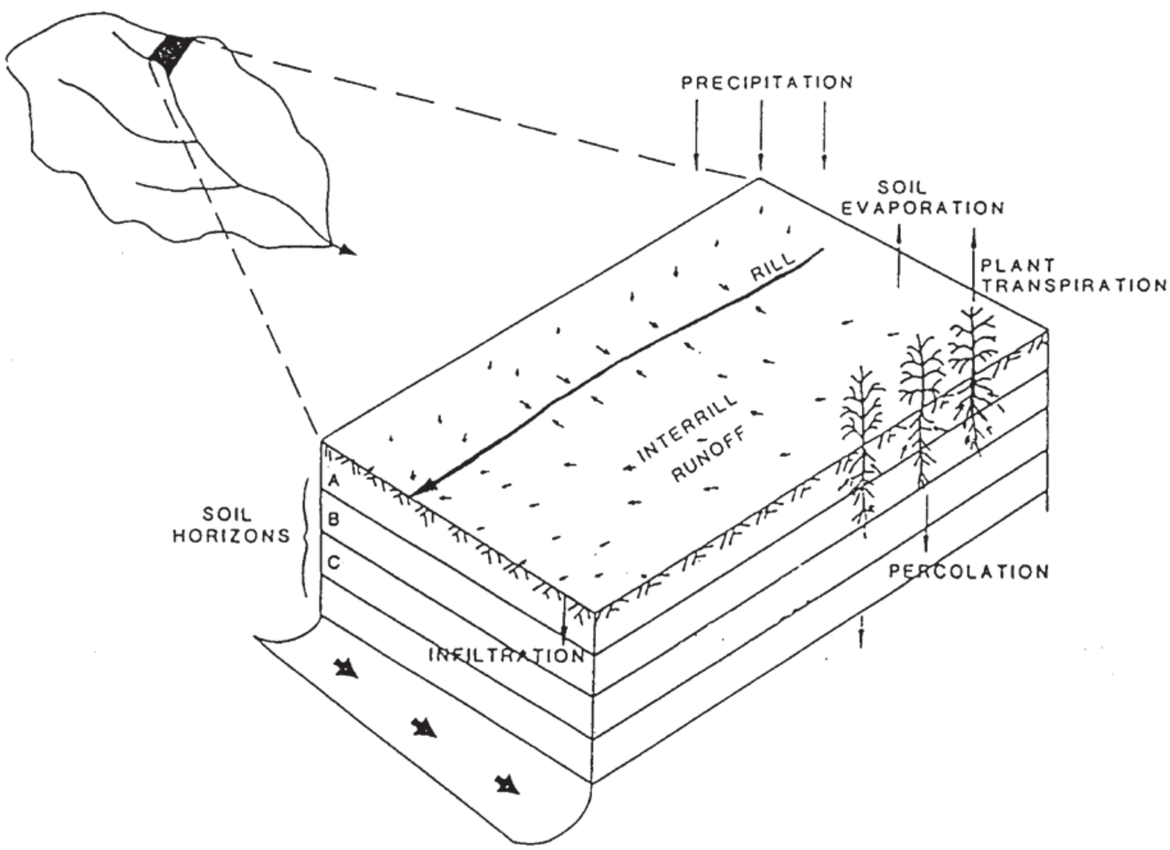

Figure 3. Illustration of the water balance components handled in the WEPP model hydrologic calculations. Vegetation interception and shallow subsurface flow are not shown here but they are included in the model calculations.

Measurements of saturated hydraulic conductivity in the forested areas of the Lower Poplar were determined to be upwards of 40 inches/hour, while on the ski slopes the conductivities were generally greater than 2 inches per hour. With hydraulic conductivities of this magnitude it requires an infrequent rainfall event of high intensity and long duration to produce surface runoff by the Hortonian mechanism. Runoff in these areas during the non-frozen period of the year then can only occur if the profile is susceptible to saturation as a result of a subsurface layer that restricts downward flow. Such restrictive layers do exist on many or all of the slopes since bedrock is shallow over most of the watershed (see discussion to follow with map analysis of bedrock depth), and even when bedrock is deeper the soils generally have denser soil layers at fairly shallow depth and these layers restrict downward percolation of water.

The condition where the Hortonian mechanism will be significant is during the winter and spring snowmelt period when the soil surface is frozen. Under the frozen condition the soil hydraulic conductivity is reduced drastically because water freezes in the soil pores, thereby blocking the pathways for water supplied by snowmelt and rain-on-snow at the soil surface. The degree of severity of this effect depends on how frozen the soil becomes over the winter, and the amount of moisture residing in the soil profile in the late fall just before freezing begins to occur. A wet profile will lead to very frozen soil and soil with very low surface hydraulic conductivity, and the surface will in effect not allow much water to infiltrate, while a dry soil will not have frozen water at all and the infiltration will then be high. Having a dry soil going into fall is very uncommon, and even during the winter some moisture can infiltrate into the soil during mid-winter thaw periods and then freeze to the point where hydraulic conductivity is drastically reduced. The amount of moisture present in the profile will be greatly affected by the fall rainfall amount, and also by the type of vegetation present on the surface. Healthy vegetation will tend to reduce the moisture in the profile going into the freezing period.

The WEPP model is able to simulate both the processes of Hortonian overland flow runoff generation and saturated overland flow generation. It does this by using mechanistically-based equations describing the two mechanisms. Hortonian overland flow is calculated by the well-known Green-Ampt methods (1911), while the saturated overland flow mechanism is calculated by using the Sloan and Moore (1984) approach to determining the zone of soil profile saturation.

The WEPP model accounts for the effect of freezing on the soil hydraulic conductivity as the model simulates the thermal energy balance of the soil profile and takes into effect the insulating properties of snow cover. The depth of freezing of the soil profile is calculated using the daily thermal energy balance at the soil surface (snow surface if snow is present) and the hydraulic conductivity of the soil is calculated to decrease exponentially with any increase in ice content of the soil. Experience with the model shows that hydraulic conductivity of a soil can be readily reduced by two orders of magnitude (e.g., 4 inches/hour for unfrozen conditions to 0.01 inches/hour for frozen soil conditions). This has a tremendous impact on the process of generation of runoff from snowmelt as well as rainfall on frozen ground following snow disappearance, and will partially explain why much of the runoff in the Lower Poplar is generated during the snowmelt period.

Setting soil hydrologic and erosion parameters

In setting the parameters for the soils within the Lower Poplar watershed the soil horizon properties provided by the WEPP soil database were used without modification since the study of Hansen et el. (2010) did not measure soil horizon properties in the field. Parameters that were assigned, other than the default values provided, were the effective saturated hydraulic conductivity K_e, the critical shear stress τ_c, and the soil erodibility coefficient k_r. Measured values of K_e were reported by Hansen et al. for forested areas, golf course areas and for ski slopes (graded and non-graded). As mentioned above, the lower values of K_e were about 4 inch/hour (100 mm/hour), so that value was used for all soils within the watershed except for pavement in developed/commercial areas, and for roads/trails. Values of τ_c were assigned based on the measurements reported by Hansen et al., and these values were all in the range of 2-3 N/m^2. Data for determining values of k_r was derived in the study by Hansen et al.; however values were not determined from the data. Additional work will need to be done to make this determination. Instead, the values of k_r were determined from regression equations given in the WEPP model documentation. Depending on soil classification, resident root density, and soil bulk density the value of k_r ranged from 0.0002 to 0.0008 s/m.

The WEPP model default condition for deep drainage from the soil profile is to assume free drainage out of the bottom of the profile at a potential rate equal to the saturated hydraulic conductivity of the soil. If deep drainage is truly free to occur the loss of water from the soil profile can constitute a significant effect on the water balance of the soil profile. In general it is fast enough in every case to bring the soil profile back to field capacity following any significant infiltration event and thereby provide plenty of storage capacity in the soil to prevent surface runoff in subsequent rainfall or snowmelt events. However, the situation in the Lower Poplar watershed is that the soils are generally underlain by shallow bedrock, generally less than 0-2 feet below the soil surface. A map showing the distribution of depth to bedrock is shown in Figure 4. One does see some places in the landscape where the depth to bedrock is quite large, 60-70 feet; however, in most instances the depth is quite small. The locations where bedrock depth is large might be locations of large fractures in the bedrock. Maps showing the bedrock geology and the locations of available well logs in the area are included in Appendix A.

The WEPP model facilitates the accounting of the effect of a restricting layer at the base of the soil profile on the soil profile water balance by allowing one to specify whether such a layer exists, and then also allows one to specify the depth of the layer and the saturated hydraulic conductivity of the layer. The resulting water balance is very sensitive to the assignment of the restricting layer saturated hydraulic conductivity value. If that value is sufficiently small, the resulting lack of downward percolation will allow for water buildup in the soil profile, leading then to saturated soil conditions and consequently to surface runoff generation by the Dunne mechanism. Since the soils in the area were determined to have very high saturated hydraulic conductivities for the soil surface, it is unlikely that surface runoff will be generated by the Horton mechanism for any but the most intense storm events in summer periods.

Figure 4. Map showing the depth to bedrock as indicated from the well logs for the locations shown.

The effect of this restricting layer on the soil profile water balance is illustrated in Figure 5. The illustration shows the temporal variation in stored soil moisture for a soil, with one plot representing the variation when the profile drainage is not restricting, and the other plot when the profile is restricted by a layer having a saturated hydraulic conductivity of zero. We can see that with free drainage the moisture profile remains well below the 118.6 mm, but with the restrictive layer the profile reaches the 118.6 mm limit frequently for the case of the short prairie grass. With the perennial forest this is not the case; the moisture profile is drawn down significantly due to evapotranspiration from the forest. This plot was using results generated by the WEPP model, and shows that the soil water storage responds to precipitation, evapotranspiration, and deep drainage. For the case with deep drainage equal to zero the graph shows that at times the profile becomes saturated. At those times, if rainfall or snowmelt occurs the incident rainfall/snowmelt will not infiltrate but will contribute to runoff, streamflow, and possibly to soil erosion.

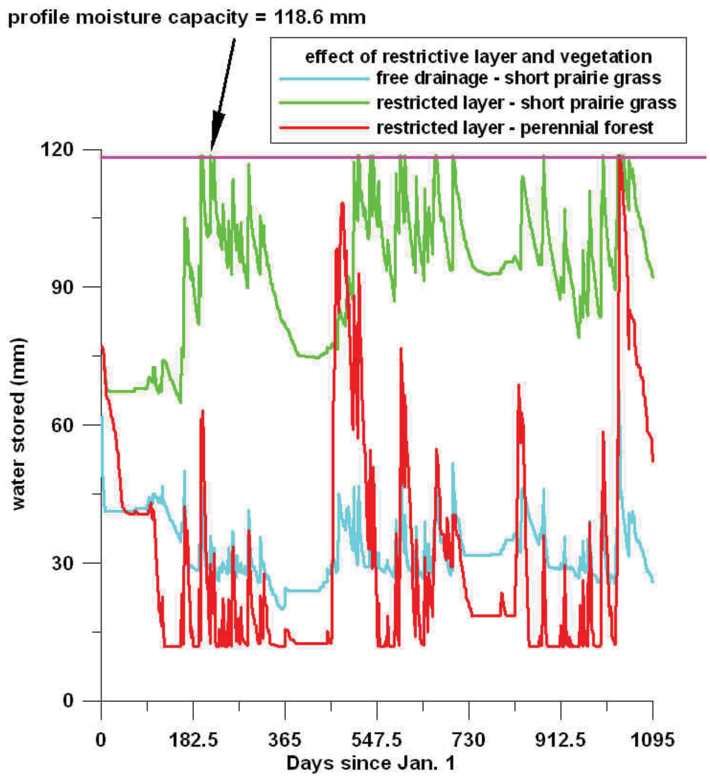

Figure 5. Illustration of the effect of the restrictive layer on the water balance of the hillslope. When the soil water stored reaches 118.6 mm, any rainfall will run off. This is for the Quetico - Barto soil (13 inches thick) over unweathered bedrock.

Influence of soil freezing on runoff generation

As mentioned above, the freezing of the soil fills some or all soil pores with ice, and these pores are then not available to transmit water. The effect of freezing drastically reduces the saturated hydraulic conductivity of a soil. So, even if a soil has a very large saturated hydraulic conductivity, when freezing occurs the actual hydraulic conductivity can decrease by orders of magnitude and even be reduced to zero in the case where all soil pores become filled with ice. Besides the calculation of the balance of liquid water in the soil profile, the WEPP model also conducts calculations on the thermal energy balance of the soil profile and determines the fraction of soil pores filled with ice during freezing periods (late fall, winter, and early spring).

An illustration of the effect of soil freezing on soil hydraulic conductivity is illustrated in Figure 6. The time scale begins with January 1 of the year at which time the soil is frozen and the effective hydraulic conductivity is zero. The soil then thaws around the end of April and the effective hydraulic conductivity increases to near the saturated hydraulic conductivity value. The soil freezes once around the first week of December, sufficiently so that the effective hydraulic conductivity of the soil drops to zero once again and this cycle moves into the next winter season and snowmelt season.

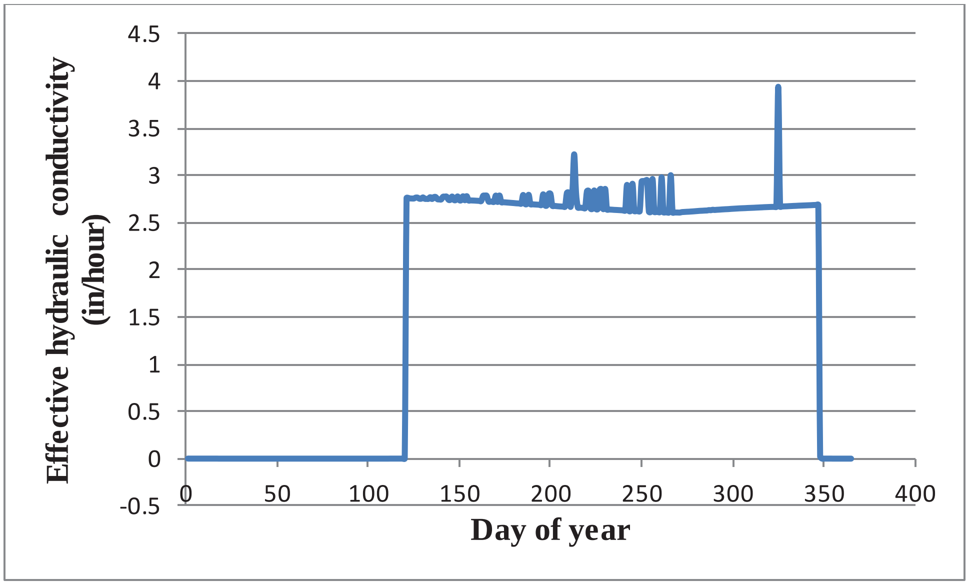

Figure 6. Illustration of the effect of soil freezing on the hydraulic conductivity of the soil. Shown is a plot of the hydraulic conductivity versus time for the period during the winter season, the time of soil freezing.

Naturally, if the soil hydraulic conductivity is decreased as a result of freezing, then rainfall or snowmelt incident on the soil will result in the generation of surface runoff if the rainfall rate or snowmelt rate exceeds the hydraulic conductivity of the frozen soil. The greater the degree of freezing, the lower will be the hydraulic conductivity and therefore the greater the rate of surface runoff generation, and also the greater the potential for generation of soil erosion. Hydrologic records for the Poplar River show that runoff generation is greatest during spring snowmelt periods, indicating partially the effect of the large amount of water made available due to the stored snowpack, but also the effect of reduced soil infiltration capacity due to soil freezing.

The effect of soil insulation by snow and by vegetative cover/organic residue on the soil freezing process is dramatic. Denser vegetation and higher surface residue delays the date of first freezing and also decreases the intensity of freezing. The snow pack that develops during winter also helps to reduce soil freezing, with greater amounts of insulation being provided by deeper snowpacks. The 'fluffier' the snow in the pack the greater the insulation benefit. Packing by snow aging (metamorphosis), or by machine grooming/skiing/snowboarding decreases this insulating effect.

Modeling variation of vegetative cover

The WEPP model simulates the temporal variation in vegetative cover and root biomass for a given plant species. The details for the plant growth model are given in Arnold et al. (1995), chapter 8 of the WEPP model documentation. That documentation explains that the plant growth model in WEPP is based on empirical equations that use air temperature and incident solar radiation to simulate daily plant biomass growth. The model does not directly account for nutrient cycling, nor deficit or excess soil moisture conditions. The model also simulates the accumulation of biomass residue on the soil surface, the temporal degradation of the residue, and the temporal degradation of below-ground biomass. The below-ground biomass is limited to root mass only since for the hillslopes in the Lower Poplar River watershed there is no tillage and therefore no burial of surface biomass.

Biomass cover, both live and dead standing biomass and flattened dead biomass provide protection of the soil from erosion caused by raindrop impact and overland flow. The plant growth component of the WEPP model simulates the growth and decay of vegetative biomass. The amount of surface coverage provided by plant materials (live or dead) has been correlated to biomass accumulation based on field observations in a number of studies (e.g., Weltz et al., 1992 and these relations are used by WEPP to predict soil surface protection by vegetation.

As an example of the dynamics of soil surface protection for two vegetative cover conditions the fraction of cover provided by standing vegetative biomass is illustrated in Figure 7, while the variation of residue cover is provided in Figure 8. The two cases shown in these figures are both for plants in the category of short prairie grass, with a maximum stand height of 15 inches. In one case the leaf area index of the plant was assigned a maximum seasonal value of 0.5, while in the other case the maximum value was set to 4.0. The leaf area index (LAI) is defined as the ratio of total area of leaves (one side of each leaf) to the area of the soil directly beneath the vegetative canopy. For an LAI of 0.5 it means that if all the leaves on the canopy were picked off the plant and laid on the soil underlying the canopy the leaves would cover only one-half of the soil area. In contrast, with an LAI of 4.0, the leaves would be able to cover a soil area that is four times the area of the soil underlying the canopy.

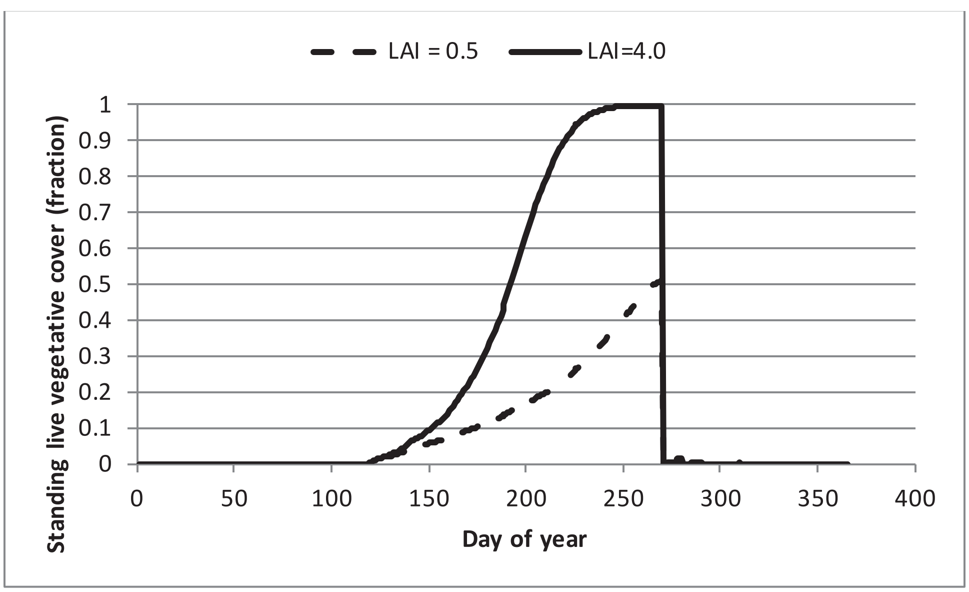

Figure 7. Variation of surface cover provided by standing vegetation for two cases of maximum leaf area index, 0.5 and 4.0.

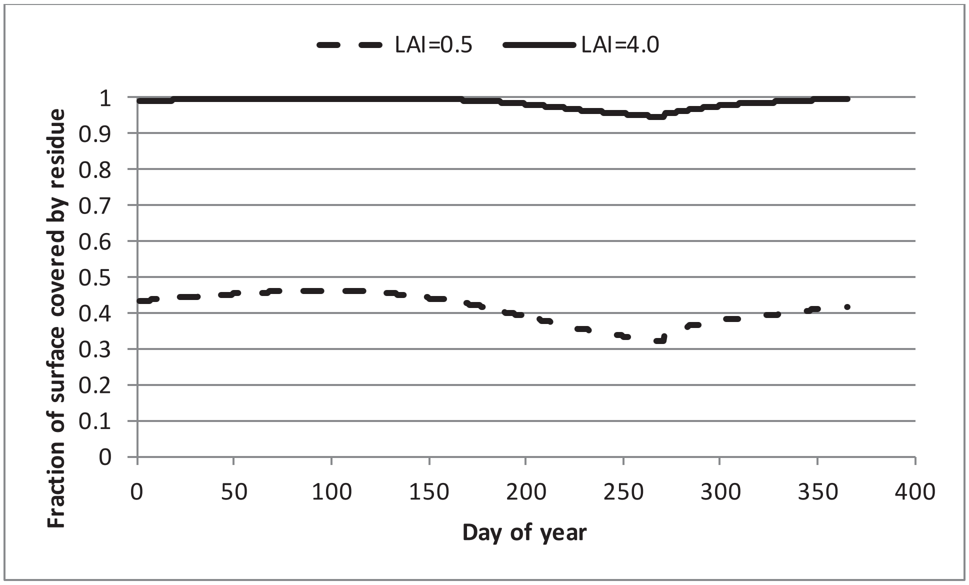

Figure 8. Variation of surface cover provided by plant residue for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

WEPP application to Lower Poplar River watershed

The GIS data layers available for the Lower Poplar River watershed were the 30-m DEM, the 2006 NLCD layer for land use (MnDNR Data Deli), and the soils data layer using either STATSGO format (NRCS U.S. General Soils Map) or for the more refined soil data (Coastal Zone Management Area soils data). The land use data layer provided a description of the type of land cover and therefore characterized the vegetation present on the landscape.

Delineation of watershed boundary and designation of hillslopes/stream channel

The ArcHydro tool was used in ArcView to construct the boundary of the Lower Poplar River Watershed. The resulting delineation for the UofM effort is shown in Figure 9 along with the delineation produced by the RTI study (RTI, 2008). The differences in the boundaries extents are clear, especially at the northern part of the watershed. Since both studies applied the same input data (30 m resolution DEM, Minnesota Department of Natural Resources data deli) to delineate the watershed for the study area, the differences in watershed area and shape are unexpected. It is conceivable that, the two studies having been conducted at different times (2007 and 2010), some of the input data, especially the DEM data, could have been modified or even upgraded. In their delineation of watershed and sub-catchments, the RTI study located the outlet point more southerly compared to the UofM study; this is evident in the more downstream extension (towards Lake Superior) of the watershed in the RTI study, adding more area to the watershed compared to that by the UofM study. These factors might explain the difference (200 acres) in the areas of the delineated watershed as evaluated in the two studies.

The GeoWEPP preprocessor was applied to the DEM data to delineate the individual hillslopes in the watershed. Naturally, the preprocessor model examines the topographic features contained in the DEM data and determines the length and width of each hillslope. This process produced the map shown in Figure 10. The land use and land cover features were assigned to these individual hillslope segments.

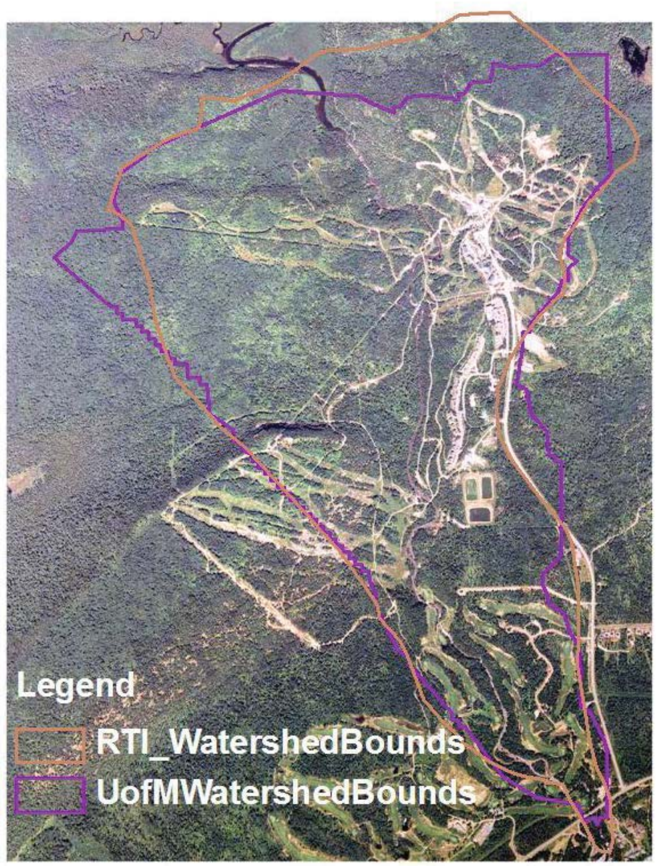

Figure 9. Watershed delineations for the Lower Poplar River watershed. One delineation is for the current effort (UofM) while the other one is for the RTI study (RTI, 2008).

Assignment of soil type

The soil type GIS layer downloaded in the more detailed Coastal Zone Management Area (CZMA) format was opened into GeoWEPP to assign the soil type properties to the hillslope elements generated in GeoWEPP. The CZMA data base showed eight distinct soil types within the Lower Poplar River watershed, while the STATSGO database (map not shown) had only three soil types within the watershed boundary. The soil parameters contained in the CZMA database include the soil thickness, field capacity, wilting point, hydraulic conductivity, soil erodibility, and soil critical shear strength. A map of the soil map with the overlay of the delineated hillslope elements is presented in Figure 11. A detailed description of these soils is presented in Appendix C.

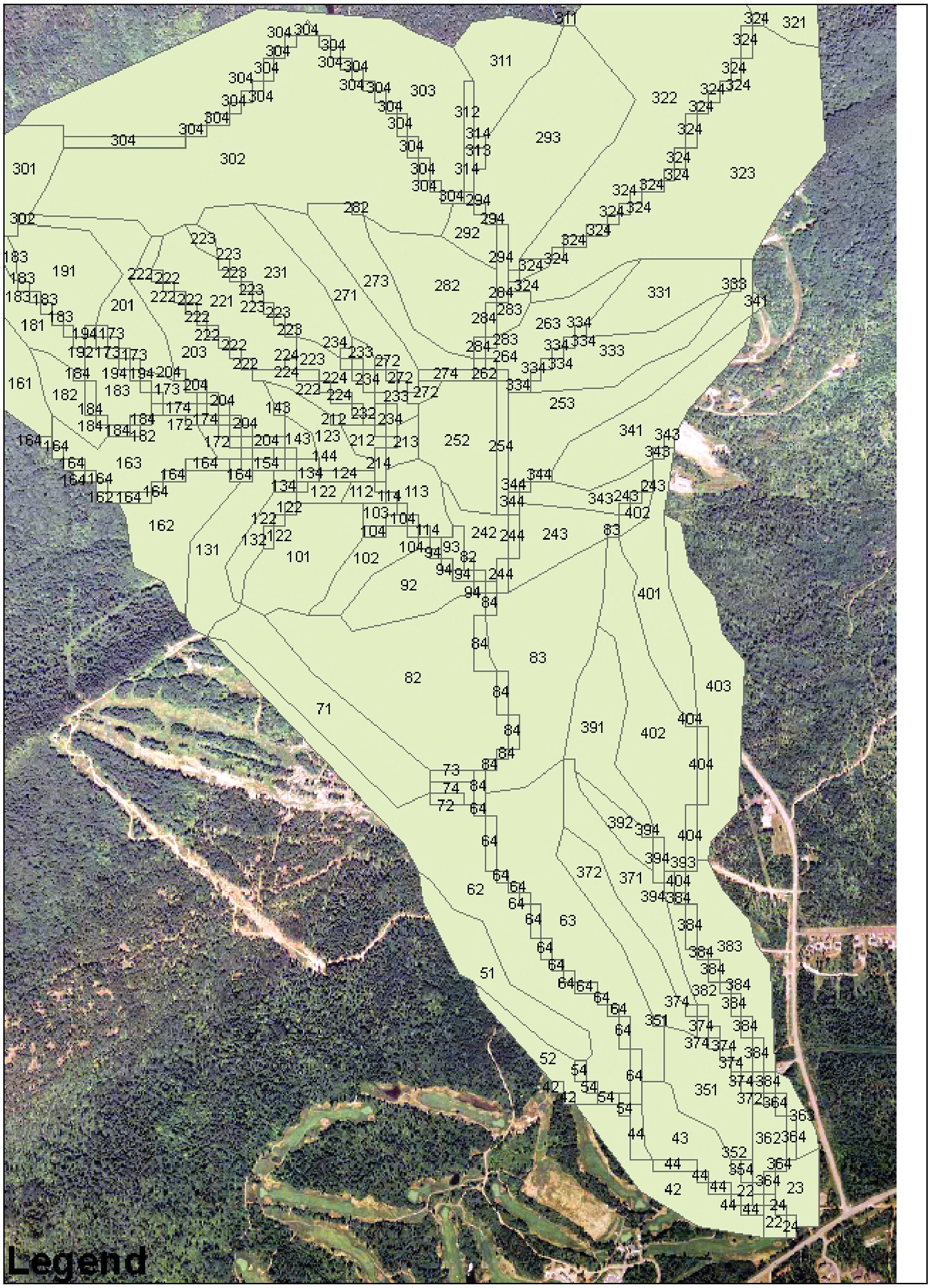

Figure 10. Delineated hillslopes and stream elements of the Lower Poplar River watershed. Individual hillslopes are assigned a unique number. The stream elements are identified by a linear sequence of elements that have the same number. Different stream segments are distinguished by the assigned numbers.

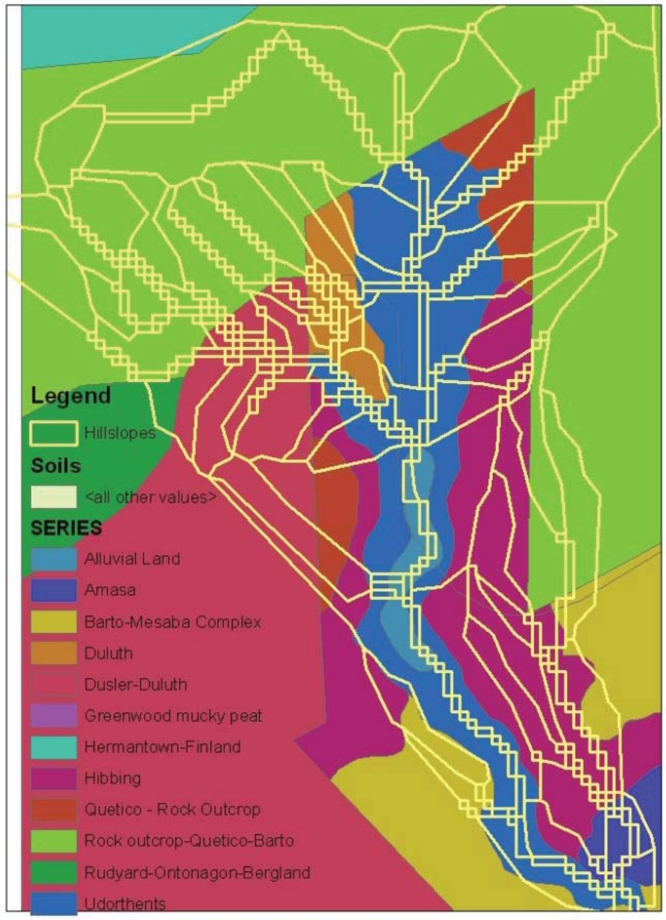

Figure 11. Distribution of soil types with the Lower Poplar River watershed using the Coast Zone Management Area soil database.

Assignment of land use and cover type

Land cover type affects the parameterization in WEPP related to the protection of the soil surface from direct shear by water flowing over the surface. In effect, the presence of plants on the surface serves two purposes with respect to soil protection. First, the plants reduce the direct impact of raindrops on the soil surface, and second, the shear stress exerted by water flowing over a surface is partitioned between the soil particles, and any plant stems/surface residue present. The presence of vegetation is also important with respect to the soil water balance because plants enhance the removal of water from the soil profile by transpiration processes, and this then reduces the potential for surface runoff during subsequent rainfall events.

The land use and land cover data downloaded from the Minnesota Department of Natural Resources (DNR) website Data Deli accepted in GeoWEPP was used to assign land use/cover classes to the hillslope elements delineated within the watershed. The data is a vegetative cover map with a one acre resolution generated from two season pairs of satellite imagery. Model parameters related to vegetative cover, runoff, surface erosion, and infiltration, were estimated using this land use data. These parameters were applied in combination with the land use data to generate suitable format land, which was then incorporated in the erosion simulation by the WEPP models. The areas identified by the GeoWEPP delineation of land uses and cover types in the watershed are presented in Table 1. The areas reported in the RTI (2008) report are also presented. Some differences in areas exist between the two studies; however, the differences are not too large considering the difference (200 acres) in overall areas of the watersheds for the two studies. One potential source of error generated during assignment of land use/cover types in the WEPP model is due to aggregations of land use/land cover types for each hillslope. While the WEPP model does allow for changes in land use/land cover along the slope axis of a hillslope, small deviations can occur in the direction parallel to the slope and this can lead to some misrepresentation of the conditions. A description of each land use and cover type is presented in the following paragraphs.

Forest cover type in the Lower Poplar River watershed comprises lowland conifer forest, lowland deciduous forest, upland conifer forest, and upland deciduous forest (RTI, 2008). According to the same report by RTI, these forested areas are historically known to have been logged between 1890 and 1930. For the purposes of this modeling effort (UofM), the land use type is assumed to be mature forest with an average age of "20-years or greater".

Golf Course cover type areas have been represented as "short grass or lawn-grass with 100% cover".

Ski Runs were identified from land cover data as those areas designated in the land cover data as shrub and grasslands. The areas contained roads and trails, but these roads and trails were not separated out from the land cover type since erosion from those features were modeled using a different method (Rosgen, 2007) to be described later. This cover type was represented in WEPP/GeoWEPP simulation as either "tall grass prairie" or "short grass prairie" with initial residue cover of 40%. The description of these two grass types is described in the manual for the Disturbed WEPP Model (http://forest.moscowfsl.wsu.edu/fswepp/docs/distweppdoc.html). Descriptions are copied below directly from Table 3 of that online source.

"**Tall Grass Prairie –** Areas covered by tall bunch grasses, with gaps between bunches. Plants are about 0.6 m tall and 0.3 m average spacing. The percent cover entered is an indication of the percent of the canopy or ground covered by the vegetation. This vegetation treatment would best describe blue-stem or similar range communities in the west, or ryegrass, brome, or orchard grass pastures in the east. It may also describe post-fire conditions where wheat or oats have germinated to provide post-fire erosion mitigation. This treatment may also be a reasonable estimate of a harvested forest 2 years after a prescribed burn, or 3 years after a wild fire.
Short grass prairie - Areas covered by short sod-forming grasses. Plants are about 0.4 m tall and with an average spacing of 0.2 m. The percent cover entered is an indication of the percent canopy or ground covered by the vegetation. This vegetation treatment would best describe

buffalo grass or similar sodding grasses in the west, or Kentucky bluegrass in the east. It may also best describe sparsely-covered reclaimed mine lands. This treatment may best describe forest conditions 1 year after a prescribed fire or two years after a wild fire."

With the disturbance caused by snow being compacted on top of the grass each ski season it would seem that the grass would not come back each growing season to the tall grass type. The loss of vegetative diversity is described in Rixen et al. (2003). They show that the snow and snowmaking/grooming process and the skiing itself can lead to stands of less species diversity for grasses. Generally higher diversity provides for more resilience to disturbance. There is also a decrease in species diversity on ski slopes that have been graded with machinery as reported by Pohl et al. (2012).

One aspect of snowmaking that Rixen et al. (2003) pointed out that may be beneficial to ski slope plant populations is that the added water may help with reducing the severity in events of drought and this can then lead to more vigorous vegetative growth. A second aspect is that constituents (nutrients in particular) added to the snowmaking water will also help to fertilize the soil and thereby improve plant growth conditions.

Vegetative residue from the prairie grass does decay over time with decay being slower during the snow season. To initiate simulations it was assumed that the initial residue cover was 40%. Thereafter the model accounts for accumulation and decay of the residue cover. The amount of cover that develops during a given growing season depends on plant growth conditions (temperature, solar radiation, moisture, soil conditions, and nutrients). In general it was found that the maximum residue cover developed to a maximum of about 55% toward the end of each growing season.

Developed areas were identified from the DNR Land coverage data, verified with FSA (2003) digital orthophoto quad data for the area. These areas were represented in the model as well maintained resort areas with low infiltration capacity and very low erodibility. This land use type was represented in GeoWEPP as Pavement, and also assigned soil type as pavement ("pavement.rot").

S**lumps, roads, and ravines** were all mapped through the field investigations reported by Hansen et al. (2010) and not using the GIS database. Overland flow erosion from slumps was modeled using the WEPP model, while the estimated erosion from roads and ravines was derived by other methods to be discussed in separate sections. For the slumps the field measurements were used to determine the slope and the surface area by a procedure described by Hansen et al. Erosion simulation for the slump areas assumed bare soil surface condition with some minimal (10%) vegetation cover. The slump units were not included directly in the WEPP watershed model, but instead the simulation of slump surface erosion was conducted using the WEPP hillslope model. Slumps were presented in this simulation as "fallow" cover type, with minimal cover. The location of the slumps examined in this study is presented in Figure 12.

Table 1. Areas (acres) of the Lower Poplar River watershed occupied by various land use and cover types. Areas reported by the RTI (2008) study are also listed for comparison.

Sediment source	RTI (acres)	UofM (acres)
Developed	32	30
Forest	878	734
Golf	61	85
Ski	164	146
Total of surface features	1,135	1,005
Slumps	2.6	4.6
Roads	8.8	18
Ravines	No area given	2.05

The land use and land cover classifications assigned to the hillslope units are illustrated in Figure 13. The polygons representing the individual hillslope units are outlined in this figure. This land surface discretization contains 195 land surface elements representing specific land cover types and soil types. Even with the level of discretization shown in the figure there are polygons that contain more than one land cover type. The small square units that appear to be variously arranged in somewhat linear patterns represent the locations of the first-order and higher-order streams.

The network representation of the hillslope polygons and channel units shown in Figure 13 is illustrated by the screen shot in Figure 14. The polygons are represented as rectangles in the WEPP model calculations and that is how they are shown in Figure 14. The connection of each polygon to a stream channel (ephemeral, intermittent, or perennial stream channel) is shown in the figure. The channel network is more clearly shown in Figure 15 by hiding the hillslope rectangles.

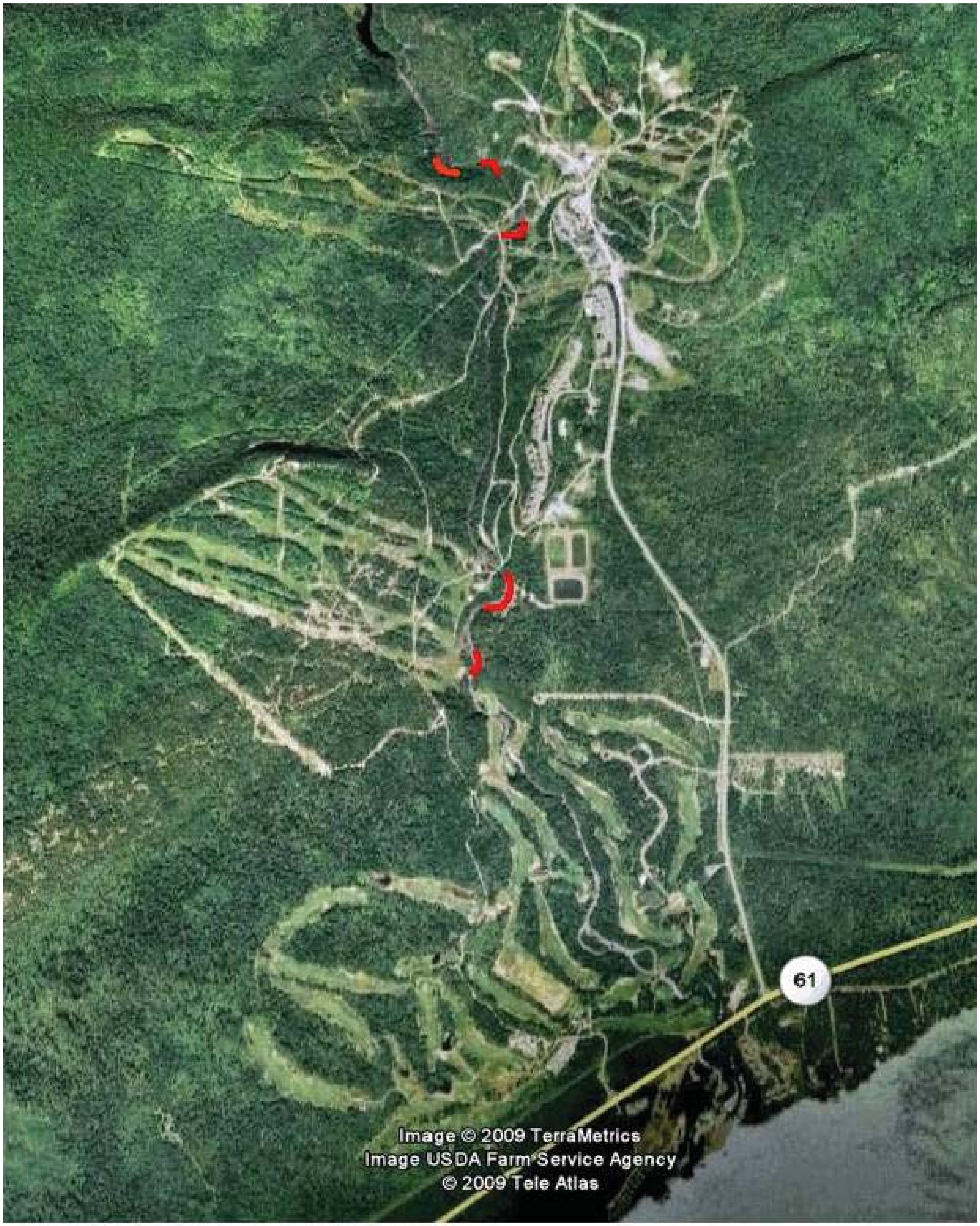

Figure 12. Location of slumps identified in the Lower Poplar River watershed are shown in red.

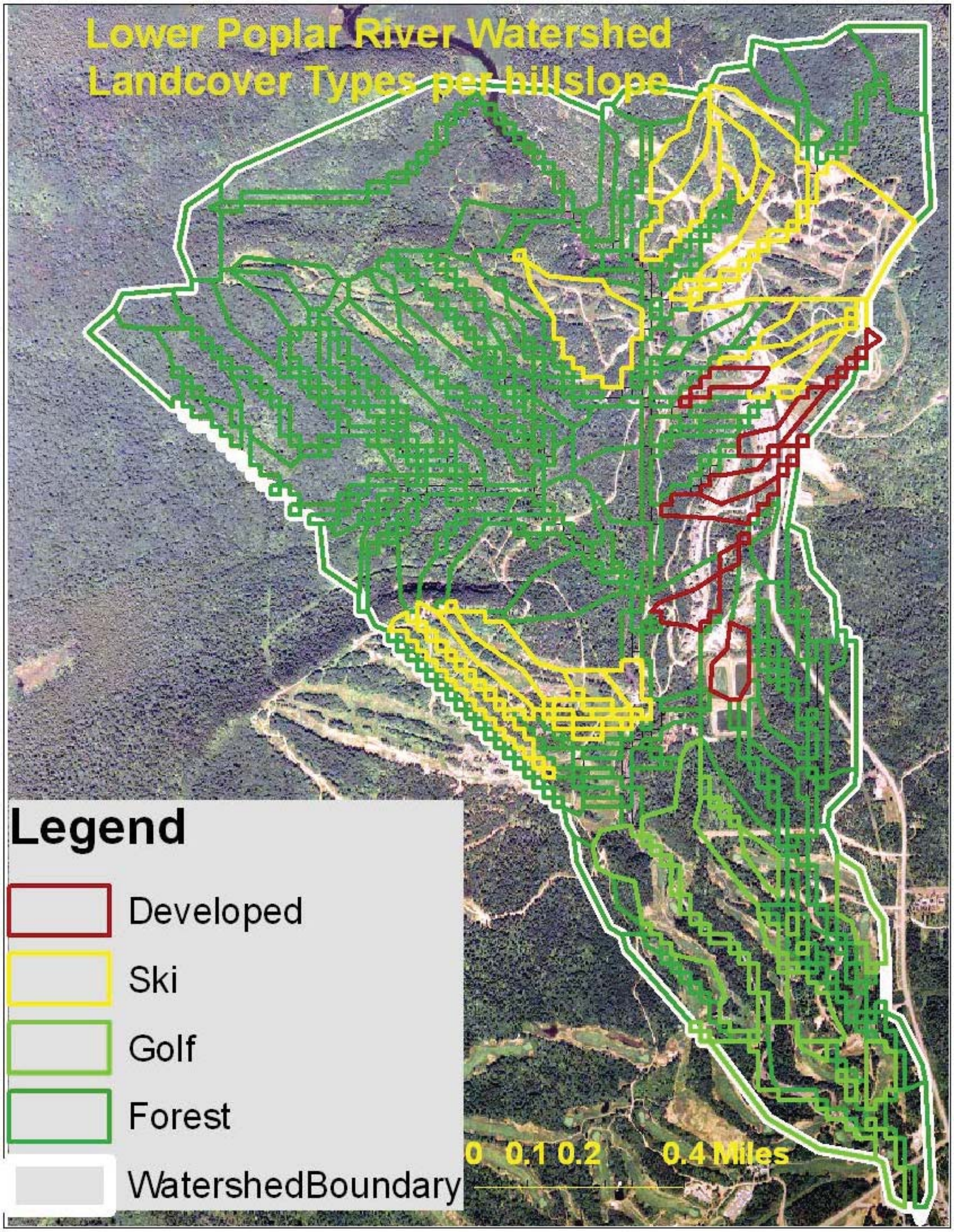

Figure 13. The land use and land cover classifications assigned to the hillslope elements for the WEPP model.

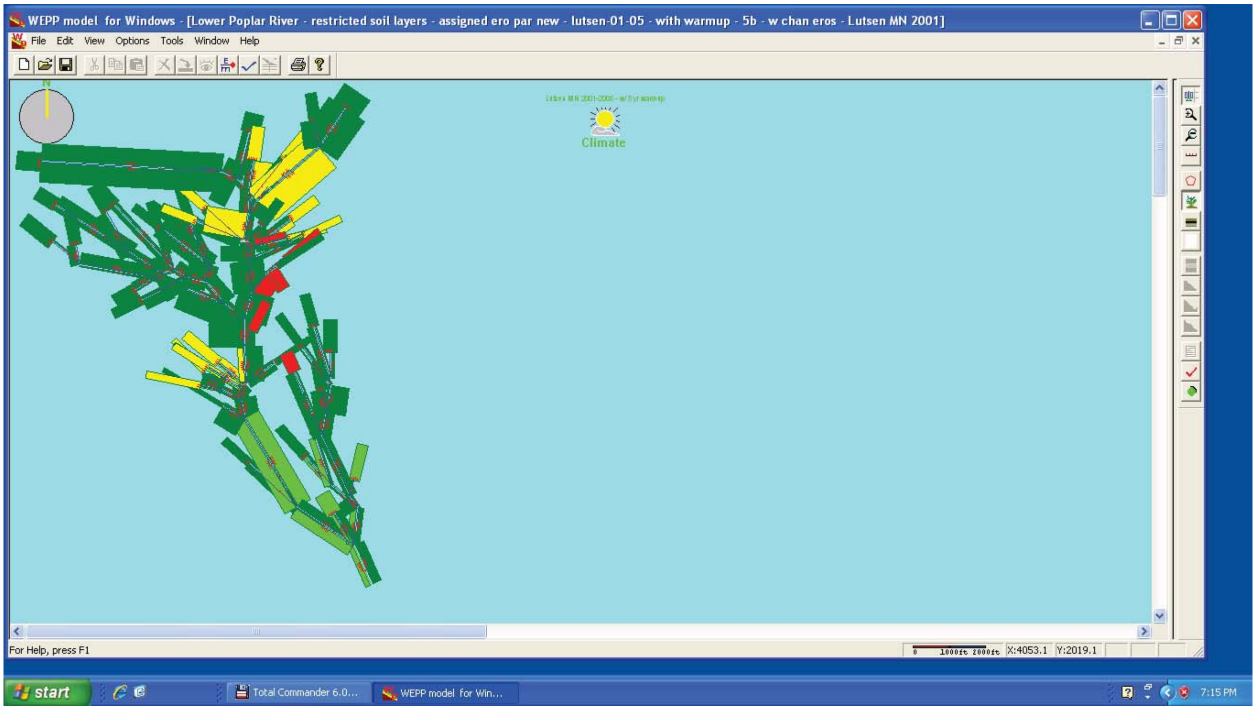

Figure 14. Representation of the hillslope units and the channels for the Lower Poplar River watershed in the WEPP model. Color codes for land uses: Dark green – forested; yellow – ski slopes; red – developed/impervious; light green – golf.

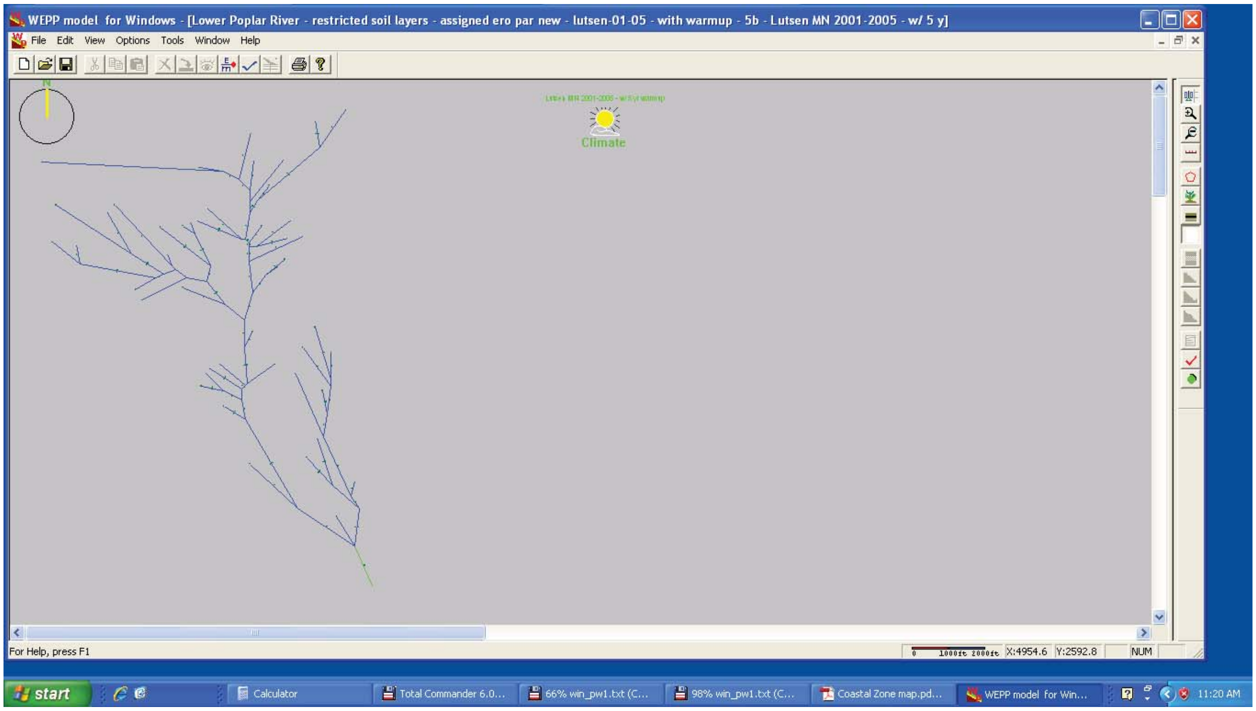

Figure 15. Similar to Figure 14 but with the hillslope units suppressed and without the satellite image.

Climate input data

To assess how well the developed WEPP model fits to the field situation in the Lower Poplar River watershed it was necessary to acquire a climate input data set that corresponds to the period of flow and sediment monitoring at the gaging station near the mouth of the Poplar River. Such an assessment was previously conducted by RTI for the period 2001 to 2005. The RTI analysis produced a climate file for that period of time and the data was made available for the present modeling work. While all of the weather variables were not measured on site, the variables that were measured were the daily precipitation, the storm duration, and the maximum and minimum temperatures. Other variables of interest were the solar radiation, relative humidity and wind speed. The variables were derived by simulation using the CLIGEN model, a model that synthesizes weather data that are serially correlated based on statistics measured at local weather stations in the region. The annual rainfall amounts observed at the Lutsen station for the Minnesota High Density Climate Station network were found to be: 2001 - 42.96 inches; 2002 – 28.79 inches; 2003 – 21.90 inches; 2004 – 34.79 inches; and 2005 – 29.87 inches. These are also illustrated in Figure 16. These values show the high degree of inter-annual variability of the precipitation. The intra-annual variability of precipitation at the Lutsen location is illustrated in Figure 17 which displays the mean precipitation for each month of the year for the period from 2001-2005. The precipitation that falls within each season of the year is also of interest here and this is displayed in Figure 18 for each year 2001 to 2005.

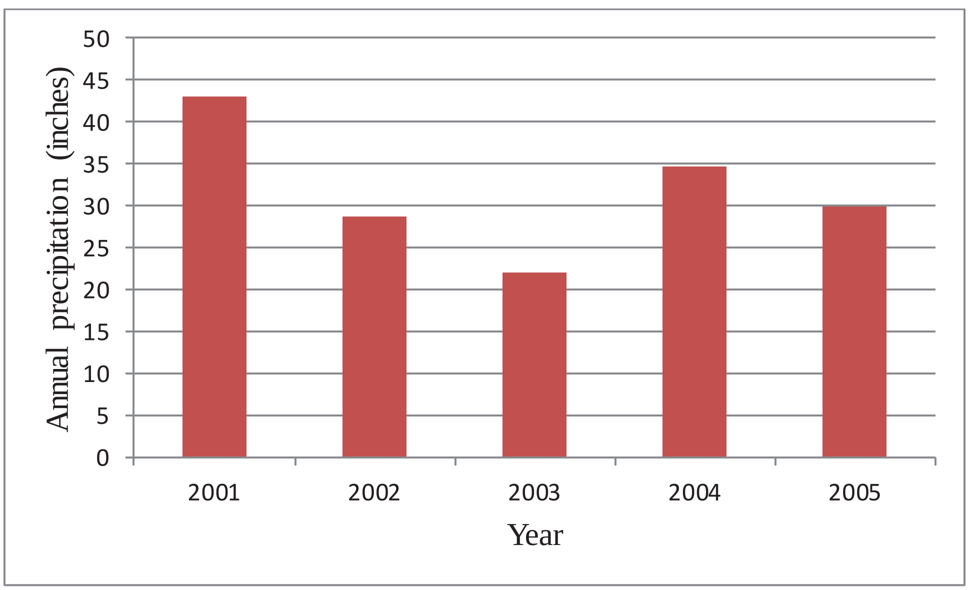

Figure 16. The distribution of inter-annual precipitation at Lutsen as generated through the RTI (2008) study using local and regional precipitation analysis.

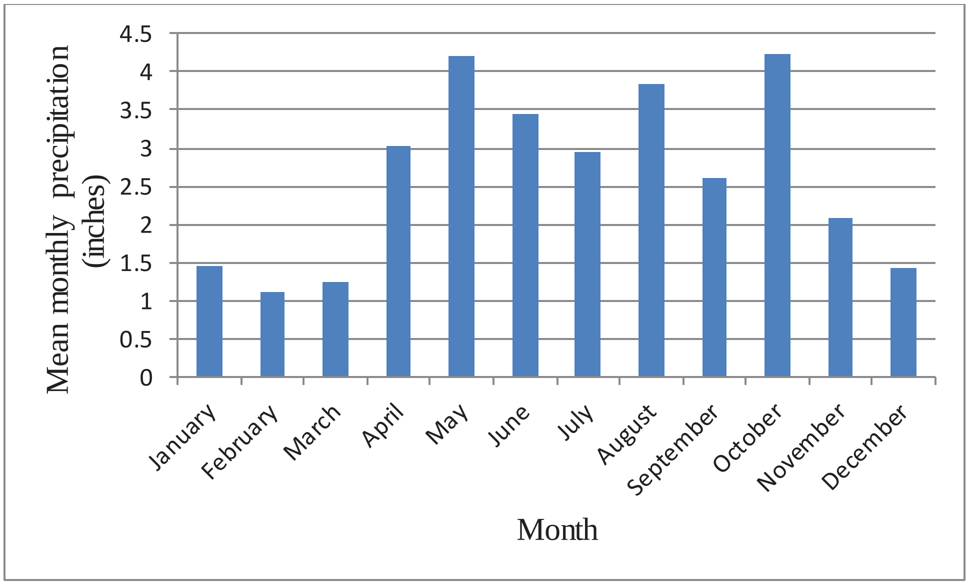

Figure 17. The distribution of inter-annual precipitation at Lutsen as represented by the mean monthly precipitation for the period from 2001 to 2005. The data for this originated from the RTI (2008) study which used local and regional precipitation analysis to derive daily precipitation amounts.

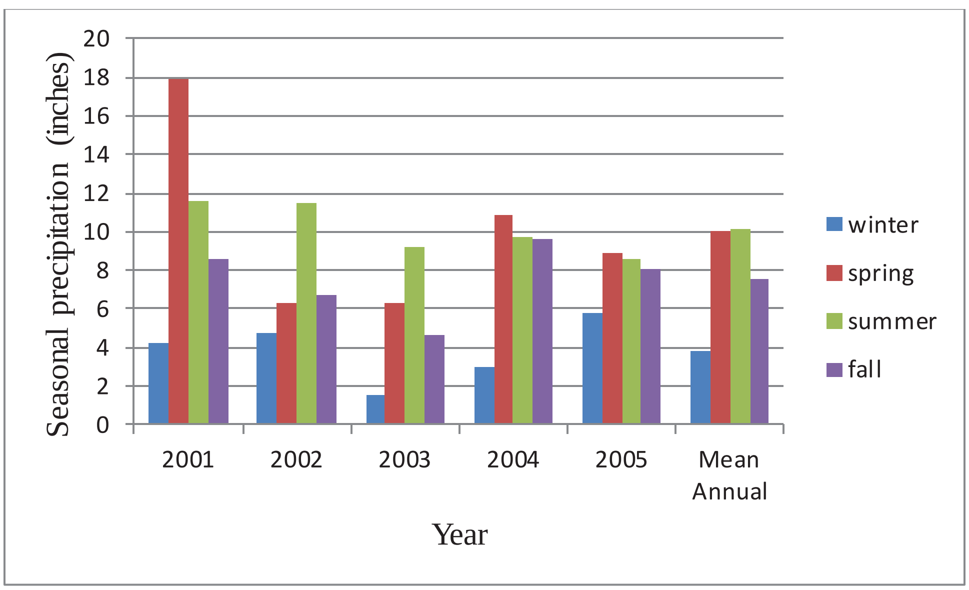

Figure 18. The distribution of precipitation by season at Lutsen for each year 2001 to 2005. The data for this originated from the RTI (2008) study which used local and regional precipitation analysis to derive daily precipitation amounts.

Predicted runoff

After the setup of the watershed WEPP model for the Lower Poplar River watershed using GeoWEPP the weather data prepared for the 2001 – 2005 time period was input to allow for a 5-year simulation of daily runoff, daily erosion, and daily sediment yield. For this simulation a 'warmup period' in the simulation was added to the front end of the 5-year simulation to eliminate the effect of imposed initial conditions. The 'warmup' period was composed of 5 years of weather input identical to the 5-year simulation period.

The daily values of output variables are available in detailed output files, but they are also compiled internally within the model and erosion and sediment yield can then be summarized by land use and land cover type for various time periods of interest.

The runoff generated in the watershed for each of the years of observation was predicted by the WEPP model and the results for this are illustrated in Figure 19. Although the gauging station is located at the outlet of the Lower Poplar River watershed, it is not possible to know how much of the flow at the outlet is generated from within the Lower Poplar River watershed since the flow at the upper end of the watershed was not measured. This is unfortunate because it would have been valuable to determine the actual runoff generated from the Lower Poplar River watershed as information for the development of the hydrologic and the soil erosion parameters for the WEPP model.

For the flows shown in Figure 20, the period 2002 – 2005 has measured flow for the Poplar River and the simulated result is compared to the measured flows. The simulated flows are the peak flows for different events as output by the WEPP model. Also shown is the WEPP-predicted flow for the year 2001, and the 'measured' flow is that which was synthesized by correlation of the Poplar River flow with the record from the Pigeon River. Since the flows in the Poplar River and the Pigeon River are highly correlated the 'measured' flow shown should be a good representation of the actual flow. Note the logarithmic scale for the vertical (discharge) axis.

When compared to the flows measured at the gauging station it is seen that the WEPP model predicts higher rates of runoff than that measured at the gauging station for many of the warm season storms as well as for many of the snowmelt month flows.

To arrive at the fairly good comparison between the measured and the WEPP-predicted flows shown in Figure 19 the WEPP parameters associated with runoff generation were adjusted until the somewhat reasonable agreement shown in Figures 19 and Figure 20 was achieved. The parameters adjusted centered around the permeability of the bedrock underlying the soils in the region, and the setting of the parameter for anisotropy of hydraulic conductivity on sloping soils. For the context used here anisotropy is the ratio of the hydraulic conductivity along the slope to the hydraulic conductivity perpendicular to the slope (i.e., down into the soil). The bedrock permeability was set to 0.1 mm/hour, while the anisotropy was set to 25. An increase in either of these parameters decreased the amount of surface runoff generated by either snowmelt or rainstorm events. An increase of the bedrock permeability also decreases the amount of total runoff, which includes both surface runoff and interflow. Water percolating through and below the bedrock recharges groundwater which in the Lower Poplar River watershed does not contribute significantly to streamflow. The value of 0.1 mm/hour is larger than the WEPP associated default value for basalt. That default value is 0.0036 mm/hour. The value of 25 for anisotropy is a reasonable value for undisturbed soils (Brooks et al., 2004).

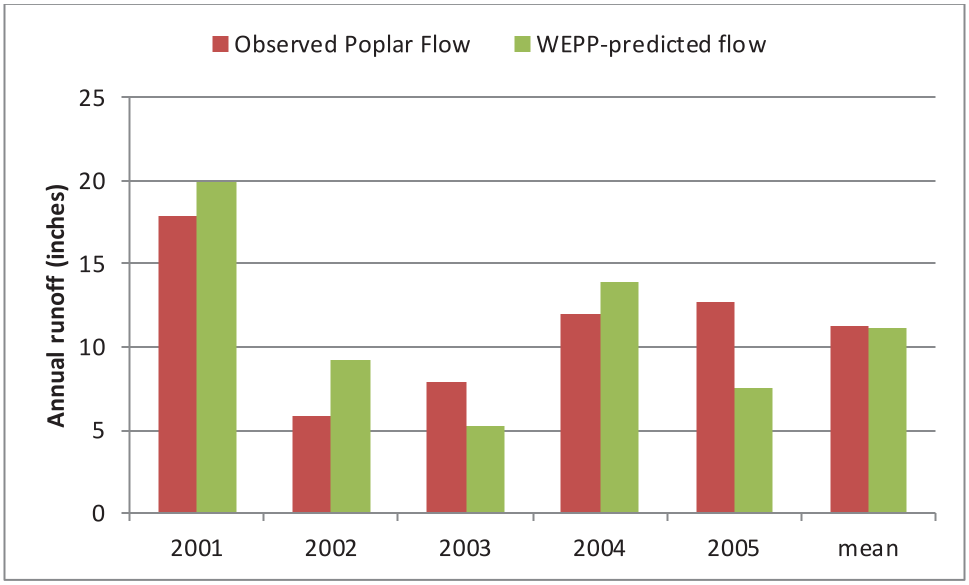

Figure 19. The Poplar River runoff depth derived from the gauging station flows, and the runoff depth predicted by the WEPP model for the Lower Poplar River, for the period 2001 – 2005. The average annual values are given as well. The value for the Poplar River for 2001 is from the synthesized flow data.

Predicted erosion and sediment yield

The total simulated erosion delivered from the upland areas to the watershed outlet is presented in Figure 21. The WEPP model predictions are quite different from the measured values for most of the years, with the differences ranging between -72% (over-prediction) and 133% (under-predicted).

These results are for the case with the vegetative cover on ski slopes being composed of short prairie grasses having a maximum LAI of 0.5 and initial residue cover of 40%. Results for other cases with higher LAI and higher initial residue cover will also be presented in the following.

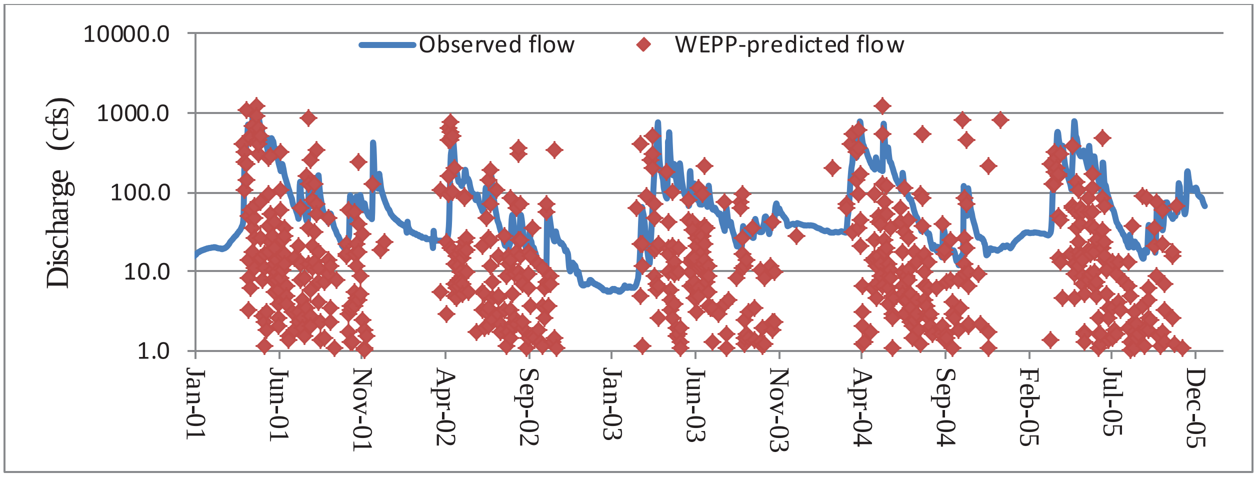

Figure 20. The flows simulated by the WEPP model for the period from 2001 – 2005 compared with the measured flow at the Poplar River gauging station. The first year of observed data and all of the winter periods (December – March) was actually synthesized by correlation with the Pigeon River.

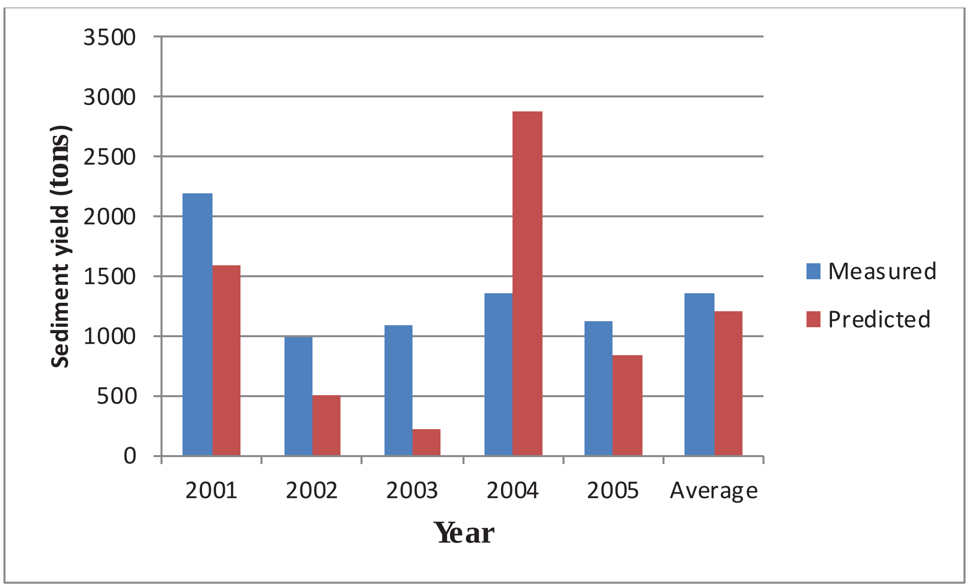

Figure 21. The annual sediment yield estimated from measurements at the outlet of the Lower Poplar River gauging station and the predicted sediment yield from the WEPP model simulations for the years 2001 – 2005. The annual average values are given for both as well. The WEPP model simulation results include contributions from the upland areas with the various land covers, forested, golf, developed and ski, and also the sediment contribution from upland ephemeral channels. These results are for the case with the ski slope vegetation cover being composed of short prairie grasses with a maximum LAI of 0.5.

Sediment yield at the outlet of the Poplar River watershed as simulated by the WEPP model for the period 2001 – 2005 is illustrated in Figure 22. This is compared to the observed turbidity levels for the period 2002 to 2005. While the erosion events in the spring snowmelt period line up quite well with the observed sediment yield, it is seen that there are some simulated sediment yield events that occur during the warmer season that are not found in the observed turbidity record. Those simulated warm season erosion events correspond to simulated runoff events in the warm season that do not have a counterpart in the flow record either. That is, examining Figure 20 one can see that there are discharges predicted by the WEPP model that exceed the discharge observed for the whole Poplar River watershed. It is not reasonable that the Lower Poplar River area would produce a higher discharge than the discharge from the watershed as a whole.

For the simulations of the sediment delivery to the watershed outlet from the 195 modeled hillslopes in the watershed it was initially assumed that the flow channels shown in Figure 15 are all non-eroding channels. This was imposed in the WEPP model by representing the channels as being made up of non-erodible rock material. This was accomplished by assigning a very high critical shear stress for the channel material. This facilitated the separation of channel erosion effects from overland flow erosion on the hillslope elements shown in Figure 14. The sediment delivery at the outlet for the watershed was then partitioned up to identify the delivered sediment sources among the various landuse conditions. For this partitioning of sediment the mean annual sediment delivery at the watershed outlet for the 5-year simulation is summarized in Table 2. The sediment delivery for this is about 45%, that is, of the amount of sediment eroded from watershed hillslopes, about 45% of that sediment reaches the outlet of the Lower Poplar River watershed.

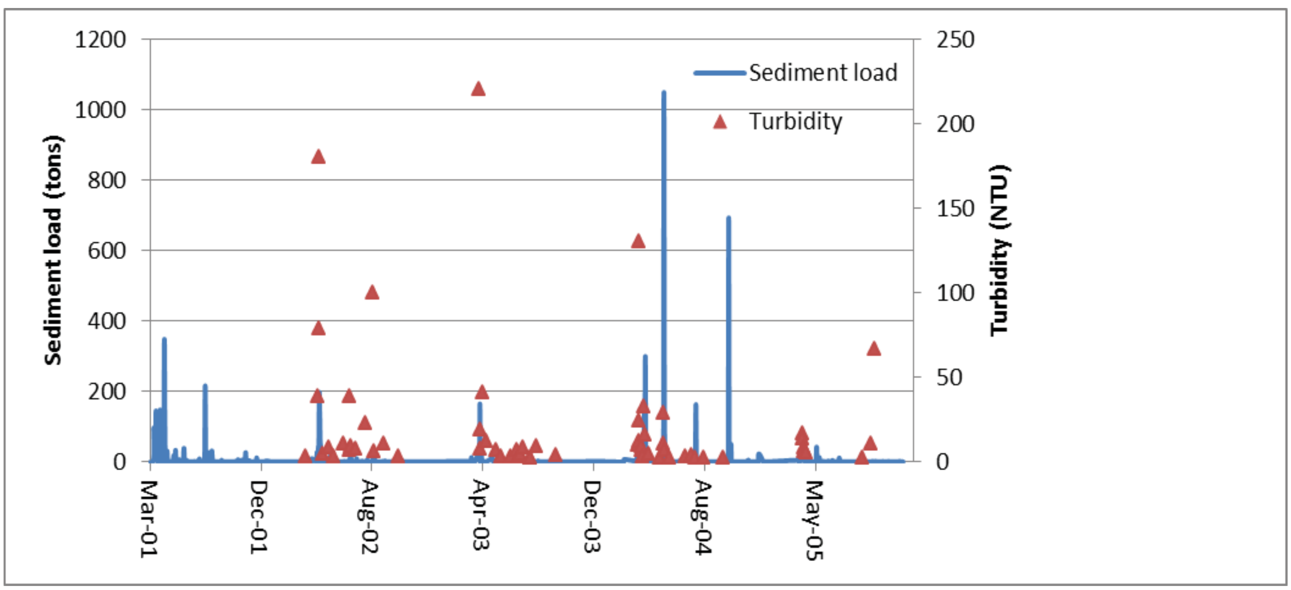

Figure 22. Temporal distribution of sediment yield (tons) at the outlet of the Poplar River watershed as simulated by the WEPP model (for 2001 – 2005) and as observed (2002 – 2005) in terms of turbidity level.

The sediment loss from the developed area shows up as zero. This is the result because the developed area is assumed to be covered with impervious and non-erodible material. This does not mean that the developed area has no effect on watershed erosion. The effect of the developed area on watershed erosion is found in the upland channels that the runoff from the developed areas passes through.

The sediment loss from forested hillslopes as estimated by the WEPP model is significantly different from that predicted in the RTI (2008) report. In that report the sediment yield from the forested hillslopes was estimated with the WEPP 2006.5 model to be 0.32 tons/acre/year, while the present analysis with the WEPP 2010 model shows a value of 0.009 tons/acre/year. The publication by Patric et al. (1984) provides support for the estimate given in the present analysis. In their study Patric et al. examined sediment yield data from 812 forested plots and watersheds from areas around the United States. The majority of the reported sediment yields lie within the range of 0.01 to 1.0 tons/acre/year, with a few exceeding 1.0 tons/acres/year. About one-third of the locations had yields of less than 0.02 tons/acre/year, and three-fourths of all observations had yields less than 0.25 tons/acre/year. All the locations with higher sediment yields are located on the Pacific Coast. In another reference, Brooks et al. (1997), states that erosion from undisturbed forested areas rarely exceed 0.04 tons/ha/year (0.016 tons/acre/year). They state that as long as the soil is not exposed by disturbing/removing natural surface residue the erosion rates will remain low.

The erosion of upland channels can be a significant source of sediment. Runoff from the hillslope areas is concentrated into ephemeral channels and the resulting flows can produce significant erosion. To simulate this, the erosion properties of the upland channels were changed from those for rock to those for the native soil materials present in the area (soil map in Figure 11). The properties were the same properties assigned to those same soils for the hillslopes. Performing simulations with erodible upland channels resulted in a sediment load at the watershed outlet equal to 1,092 tons/year on a mean annual basis for the 5-year period. This result was obtained for the case with the grass cover on the ski slopes being short grass prairie with and LAI equal to 0.5. Comparing this to the value for the case of non-erodible upland channels (780 tons/year) the amount of sediment generated by the upland channels is predicted to be 312 tons/year.

Erodible soil surfaces are sensitive to the density of vegetative cover and to the amount of surface residue accumulated on the soil surface. Of course the higher the residue cover and the higher the LAI the better the vegetative cover will protect the soil from raindrop impact and overland flow shear stress. The model itself calculates the change of vegetative cover during the growing season using these input vegetative parameters. To examine the effect of higher vegetative density and higher accumulated surface residue the input parameters for the short prairie grass land cover condition on the ski slopes was modified. For these the LAI value was varied including values of 0.5, 2.0 and 4.0, and the initial accumulated surface residue was assumed to be 80%.

Table 2. Soil erosion values from WEPP simulation (5-year) for the Lower Poplar River Watershed.

Watershed Method (WEPP) – 5-year results				
Land use	Area Under Cover Type (acres)	Proportion of area under cover	Soil Loss (ton/ac/yr)	Soil Loss Rate (ton/yr)
Developed	30.0	0.030	0.0	0.0
Forest	743.4	0.739	0.006	6
Golf	85.8	0.085	0.07	6
Ski	146.5	0.146	3.92[&&]	575[&&]
Upland channels	--	--	--	312
Total	1005.7	1.000	1.08[&]	1,092

[&]Average rate

[&&]This value is for the case of short grass prairie cover with an LAI equal to 0.5. For tall grass prairie and LAI = 4.0 the erosion rate is 0.9 tons/ac/yr or 143 tons/year

The results of the simulation for these conditions are summarized in Figure 23. It is observed from this figure that the density of vegetative cover and the type of grass has a dramatic effect on erosion from the ski slopes. The resulting sediment contributions range from 575 tons/year for the case of short grass prairie (SGP) with a LAI of 0.5, to 143 tons/year for the case of tall grass prairie (TGP) with a LAI of 4.0. The LAI value directly affects the rate of biomass production and this directly affects the amount of accumulated residue on the soil surface. These results demonstrate the importance of vegetative cover density and accumulated residue on soil surface erosion resistance.

The length of a slope also has a strong impact on the generated sediment. To evaluate this effect the WEPP hillslope model was used to simulate the effect of shortening the effective length of one hillslope in the watershed. The hillslope selected has a slope angle of 35% and a slope length of 680 feet. The soil on the slope is mapped as Quetico, a shallow soil with bedrock close to the surface. The average solum (upper layers of soil profile) thickness is about 5 inches. The saturated hydraulic conductivity of the soil was assumed to be 4 inch/hour consistent with measurements reported by Hansen et al. (2010) for ski slopes. The vegetative cover was assumed to be short prairie grass with 80% initial accumulated residue and LAI of 0.5.

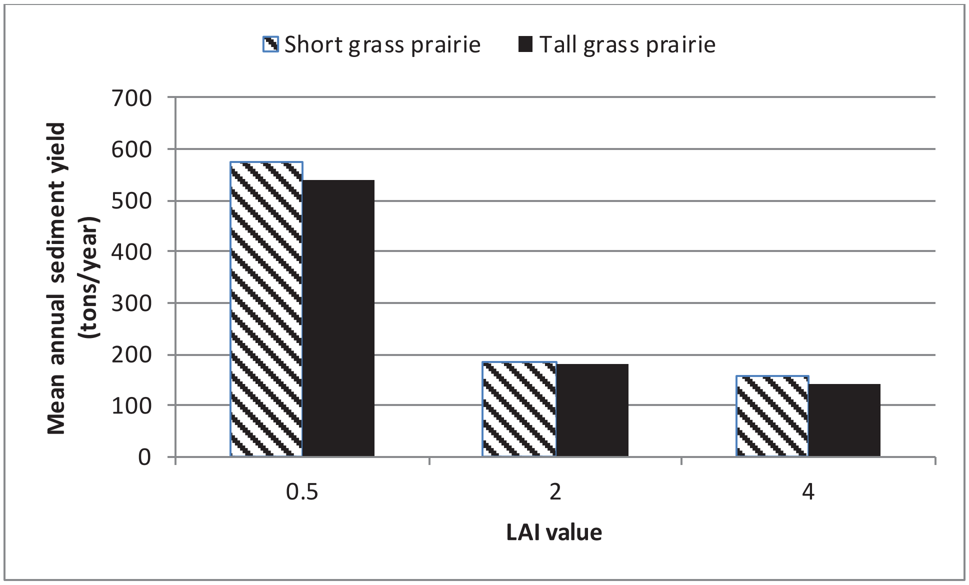

Figure 23. The cumulative mean annual sediment yield from ski slopes within the Lower Poplar River watershed as affected by the biomass growth potential of the plant as reflected by the leaf area index (LAI). Two vegetation classifications are considered, short grass prairie and tall grass prairie. The LAI values include 0.5, 2.0 and 4.0.

The mean annual sediment yielded to the base of the hillslope for the original slope length was 4.7 tons/year. Decreasing the slope length to 340 feet reduces this sediment yield to 0.3 tons/year, demonstrating the dramatic effect of slope length on erosion and sediment yield. The ski slopes at Lutsen Mountains ski area use water bars as a best management practice. 'Water bars' act like agricultural field terraces in shortening the effective overland flow length on hillslopes. Detailed information on the number, placement, and specific slope locations of these water bars was not available as input for the WEPP model developed here. However, this result shows the significance of the erosion reducing effect of water bars, assuming that they are functioning properly.

Effect of increased snow

During the period of monitoring there is a record that shows that artificial snow was added to nearly all ski slopes on the Lutsen mountain ski area including those lying outside the boundaries of the Lower Poplar River watershed. The average annual water use to provide this snow was reported by RTI (2008) as being about 70 million gallons. According to reports, this snow was added to about 214 acres of ski slopes, which would include those inside the Lower Poplar River watershed, and those lying outside the Lower Poplar. The equivalent depth of water associated with this volume of applied water is about 12 inches. It is expected that this additional snow will have some effect on the hydrology of the hillslopes; perhaps beneficial, perhaps detrimental. It is of interest to evaluate the effect of added snow on the winter hydrology and the runoff and sediment generated during the spring snowmelt period. The runoff produced from the Lower Poplar River watershed is assumed to be higher during the spring snowmelt period since the runoff from the whole watershed, as reflected at the gauging station, is highest during that period. The effect of snow added to the ski slopes was evaluated using a single hillslope since the current version of the WEPP model does not allow a different amount of precipitation to be added to different hillslope areas.

The hillslope selected has the same parameters as the one used in the previous section to demonstrate the effect of the hillslope effective length. Vegetative cover was varied in the same manner as that in that last section where the LAI value was used to represent the vegetative cover, and accumulated surface residue was varied. Both short grass prairie and tall grass prairie vegetation types were considered in the analysis.

The climate data input to the model was the same as that described in the **Climate input data** section. To account for artificial snow applications the precipitation in the weather input file was augmented with added precipitation on days when the air temperature was below zero degrees thereby producing snow in the model. The amount of water applied to the modeled hillslope in the form of artificial snow on given dates was based on actual monthly water withdrawal records (provided by Randall Doneen, MNDNR) for the five-year period. The amount of water added to the modeled slope was varied, including values of 0 inches, 10.8 inches, 20.9 inches and 31.5 inches, to examine the effect of different amounts of added snow in the model. The amount of 10.8 inches is close to the figure for the amount of water added each year during the past decade (70 million gallons on average), while the other figures are associated with increased proposed allocations (up to 225 million gallons, personal communication Randall Doneen, MNDNR).

One limitation of the WEPP 2010 model is that it assumes that snow formed (natural or artificial) has a 10% water equivalent. Actually artificial snow is closer to a 50% water equivalent value (and natural snow is not always at 10% either). Due to this lower snow density assigned by the model, the artificial snow represented in the model will simulate deeper snowpacks than would actually occur on a managed ski slope, an effect that will insulate the soil more and thereby reduce soil freezing in the model predictions. This will have the effect to predict potentially reduced surface runoff. Thus the sediment yields presented might be underestimated compared to what would actually occur. However, the trend in the effect of vegetative cover and slope length on sediment yield will not be affected by this snow density assumption.

The results of the simulations are summarized in Table 3. In general, the amount of sediment yielded by the hillslope increases as the amount of artificial snow applied increases. It is also observed that in general as the vegetative cover increases the sediment yield decreases.

The reduction of slope length dramatically decreases the sediment yield for all cases of added artificial snow. It is interesting however that the trend for sediment yield for the shorter slope counters that for the longer slope. Examination of the detailed runoff simulated for this case of a shorter hillslope showed that the amount of runoff in non-winter season decreases as the depth of added snow increases. This might be explained by the following two phenomena. First, the deeper snow will reduce soil freezing and thereby offer increased opportunity for deep percolation loss through the slowly permeable bedrock base. Second, the lateral flow that occurs will be greater for the longer hillslope, leading to higher saturation and greater runoff potential at the footslope position. Reducing the slope length reduces the lateral flow and the footslope saturation, thereby reducing runoff potential.

It is clear from these simulated results that it is greatly beneficial to increase the vegetative cover (short grass prairie or tall grass prairie) for a slope, and it is also very beneficial to reduce the slope length.

Table 3. Mean annual sediment (tons/acre/year) delivered to the toe of the hillslope for various conditions of added artificial snow (given as depth of snow water equivalent), vegetative cover, and slope length. The vegetative cover is expressed by type, either short grass prairie (SGP) or tall grass prairie (TGP) and by leaf area index (LAI). The slope length used for nearly all of the calculations was 680 feet.

Vegetative cover; Type, LAI	Snow water equivalent of artificial snow (inches)			
	0	10.8	20.9	31.5
SGP, 0.5	3.0	5.0	12.6	53.8
SGP, 2.0	0.32	0.97	1.3	3.5
SGP, 4.0	0.22	1.3	0.96	2.3
TGP, 0.5	2.7	4.6	11.2	47.3
TGP, 2.0	0.27	0.93	1.0	2.8
TGP, 4.0	0.23	0.86	0.77	1.93
SGP, 0.5 with half slope length (340 feet)	0.96	0.5	0.3	0.08

Surface erosion generated from slumps

To simulate the sediment originating from the slumps the hillslope option for the WEPP model was used. The watershed option was not necessary because the slumps exist next to the main channel and a tributary channel is not needed to deliver eroded sediment to the river.

The total area of the slumps identified in the Lower Poplar River watershed was estimated from field surveys (Hansen et al., 2010). The area was estimated to be 4.6 acres. The average slope of the slumps is approximately 70%. The slumps were treated as having saturated hydraulic conductivities of about 12 mm/hour, and were considered to be bare most of the year. Application of the WEPP model to the slumps yielded a sediment load of 61.7 tons/acre/year or 284 tons per year entering the main stem of the Poplar River.

Sediment contribution from other sources

Besides the obvious sediment sources from the forested areas, the ski slopes, the golf course, and the developed areas there is also the possible sources related to roads, ATV and pedestrian trails, ravines, gullies and mass wasting from slumps. The WEPP model is not able to predict the erosion from these sources, except maybe for roads and ATV trails and pedestrian trails. Instead of using the WEPP model for the roads and trails a method developed by Rosgen (2007) was applied. Estimates of erosion from all of these remaining sources will now be presented.

Sediment contribution by roads

The placement of roads across a landscape can significantly modify the natural flow pathways by concentrating overland flow into rills and ephemeral channels, thereby increasing the erosion potential of runoff events. Roads have this effect by focusing overland flow or subsurface flow from upslope areas into ditches and the ditches then convey this concentrated flow to culverts. This concentration of flow has a way of increasing the drainage density of a watershed, leading to more flashiness of flows and increasing erosion during runoff events. Unpaved roads are also a source of sediment, and the ditches and sideslopes associated with a road (paved or unpaved) are also a source of sediment when the soil is not sufficiently vegetated. In addition, when a road is placed across an existing stream channel, the change in local hydraulics can lead to instability of the channel upstream and/or downstream of the crossing, meaning that the transported sediment will increase. The processes of sediment production from roads are quite complicated due to the unlimited number of different geometric conditions that could be considered. A method that makes the estimation of sediment production from roads is presented by Rosgen (2007). The method is referred to as the Road Impact Index (RII) method. The contribution of roads to sediment yield in the Lower Poplar River was estimated using the RII equations presented by Rosgen. These equations are,

$$SY=1.7+40*RII \quad ; \quad \text{for road with lower slope position} \qquad (1)$$

$$SY=-0.1595+3.0913*RII \quad ; \quad \text{for roads with mid or upper 1/3 slope position} \qquad (2)$$

where SY is the sediment yield in tons from the road per year per acre of road, and RII is the road impact index. The road impact index is determined based on the following factors:

- Acres of subwatershed containing the road segment of interest;
- Within the subwatershed the acres of surface disturbance of roads including road surface, cut, fill and ditch line;
- Within the watershed the number of stream crossings by the road;
- Position of the road (lower, medium, upper) on the slope relative to stream location;

- Slope of the road;
- Age of the road;
- Mitigation such as road surfacing, ditch lining (e.g., vegetation, paving, armoring, etc.);
- Vegetative cover of cut banks and road fills;
- Presence of unstable terrain associated with mass erosion processes.

Data with parameters from the above list for a particular road are entered into a worksheet (Rosgen, 2007) and the RII value is calculated. Field measurements of roads were conducted in the summer/fall 2009 as reported in Hansen et al. (2010). The total area of road surface, including the ditches and cut banks was estimated to be just less than 18 acres. Most of this area was found to be in middle or upper level positions in the landscape. Data corresponding to the list outlined above was entered and the RII values calculated along with the estimated annual sediment load. The summarized results are presented in Table 4. The total estimated annual sediment load from roads in the Lower Poplar River watershed is 35.3 tons.

Table 4. Road impact index (RII)

Position in watershed	Sub-watershed acres	Acres of roads	Number of crossings	Road Impact Index	Tons/acre	Annual load Tons
Lower	25	2.27	3	0.27	12.6	28.59
Mid to Upper 1/3	249	15.7	3	0.19	0.42	6.66

River channel/banks

Geomorphic assessment of the condition of the river channel showed that the channel bottom and the channel banks are armored with large rock and cobble materials. While high flows can move large rocks downstream it seems from observations that the river will not downcut at a significant rate. The armoring protects the erodible material composing the channel bottom from direct impact from flowing water and this reduces the potential for detachment of soil particles from the bottom material. While the critical shear stress and the erodibility coefficient for the channel bottom material might be equal to that for the upland soils, the boundary shear stress imposed on the material is drastically reduced due to the armoring of the surface provided by the deposited cobbles and boulders in the channel. The suspended sediment load originating from the river channel and channel banks was therefore considered to be negligible in comparison to other sources.

Mass wasting at slumps

The estimates for erosion and sediment yield due to overland flow on slumps as derived from WEPP modeling were given in the first section along with a map showing the locations of the identified slumps (Figure 12). The issue arises whether sediment production from the slumps might be occurring at the sites along the Lower Poplar River as a result of mass wasting processes. Mass wasting processes along a river will be operative if the river abuts up against the toe of the slumps, thereby removing wasted materials and effectively steepening the slope of the slump. Such a process occurs at slumping bluffs along the Minnesota River and many of its tributaries, e.g., the Blue Earth River (Sekely et al., 2004). For the Lower Poplar River the toes of two of the slumps did abut up against the river bank during the time prior to the repair of the megaslump. These were the megaslump and one other slump upstream of the megaslump near the location of the Brule ravine.

The regression equation developed by Sekely et al. (2002) for estimating mass wasting from slumps is given by

$$SY = 0.23\ A_b \qquad (3)$$

where SY is the sediment yield to the river (tons/year) and A_b is the exposed surface area of the bluff in m^2. The megaslump was estimated to have an exposed surface area of 2.02 acres, or 8178 m^2. Applying this area to equation (3) would give a sediment yield for the megaslump of 1,881 tons/year. This estimate of sediment yield does not seem to be credible since the mean annual sediment load is 1,354 tons/year. In the study reported by Hansen et al. (2010) a hydrologic analysis was conducted to determine estimates of the frequency of occurrence of flood flows in the Lower Poplar River. Then a HEC-RAS model was developed for the entire Lower Poplar River channel starting at the downstream station and ending at the upstream station. Using the hydraulic model to compute water surface profiles in the river for various frequency flows it was possible to relate water surface elevation at selected cross-sections to the discharge and frequency of occurrence of those flows. It was also possible to then determine the elevation required to overtop the rock-protected river banks and potentially access sediment deposited at the toes of slumps.

The flow elevation-flow frequency curves, and present-day channel cross-sections are all presented in the report by Hansen et al. (2010). According to the flow elevation-flow frequency analysis it is clear that the river remains inside the armored channel for all flow less than about the 5-year return period event for most of the channel locations. We would therefore not expect that the toes of slumps near those locations to be affected by out-of-bank flows. However, according to the RTI report (RTI, 2008) prior to the channel repair work completed in 2008 the megaslump and the other slump near the Brule ravine had toes within the near bankfull flow stage, thereby making those slumps susceptible to erosion at the toe. However, the condition is not the same as the slumps associated with the development of the empirical relation given by equation (3). According to the flow records during the monitoring period the daily mean flows never exceeded about 750 cfs in any given year, and those flows occurred only briefly during what appears to be the spring snowmelt period. Unlike the conditions in the Blue Earth River where within the last two decades high flows have been sustained over long periods of time, the high flows in the Poplar River are very short duration. To account for the short duration of the flow it would make sense to reduce the load of 1,881 tons/year to only a fraction of that number. Here we use an amount equal to 10% of the value or 188 tons/year.

The restoration work on the megaslump in 2008 puts the toe of the megaslump well above the elevation of the mean annual flow in the channel. According to the analysis presented in Hansen et al. (2010) the elevation of the toe for the restored system requires a flow of greater than the 100-year event to reach the toe. Based on field surveyed cross-sections reported by Hansen et al. (2010) and RTI (2008), and the record of high flows in the Poplar River it is estimated that to reach the toes of those other slumps requires a flow close to the 5-year flow event. This flow is estimated to be 1,189 cfs (Hansen et al., 2010). Therefore for the present conditions, mass wasting processes should not be a source of sediment from the megaslump area and other slump areas on a mean annual basis.

Ravines

Ravines are defined by Wikipedia (http://en.wikipedia.org/wiki/Ravine) as *"A **ravine** is a landform narrower than a canyon and is often the product of streamcutting erosion. Ravines are typically classified as larger in scale than gullies, although smaller than valleys. A ravine is generally a fluvial slope landform of relatively steep (cross-sectional) sides, on the order of twenty to seventy percent in gradient. Ravines may or may not have active streams flowing along the downslope channel which originally formed them; moreover, often they are characterized by intermittent streams, since their geographic scale may not be sufficiently large to support a perennial watercourse"*. Several ravines exist within the Lower Poplar River watershed. The locations and paths of the major ravines identified by Hansen et al. (2010) and by NAWE (2003) and RTI (2008) are shown in Figure 24. Measurements of these ravines by Hansen et al. provided the ravine morphological characteristics summarized in Table 5.

Table 5. Morphological characteristics of major ravines within the Lower Poplar River watershed.

Ravine	Contributing area (acres)	Length (ft)	Mean longitudinal slope (%)	Mean cross-section (ft^2)	Sediment Produced (tons)
Ullr	4.6[&]	380	44	280	5,586
Brule	155[#]	200	47	188	1,974
Moose Mountain	232	3,500	10	44	8,085

[&]Some runoff from Brule had been diverted to this ravine making the effective contributing area about 22 acres.
[#]The installation of a tightline to bypass the ravine has reduced the contributing area to the ravine.

The ravine designated as the Brule ravine previously received runoff from the ski slopes on Eagle Mountain and also from the building/parking complex around the ski lodge and ticketing office. A diversion was constructed in 2006 to divert this runoff and bypass this ravine. The diversion is in the form of a runoff collection structure and a buried pipeline (tightline). Since the construction of this diversion, and the seeding of the ravine itself, the Brule ravine has been revegetating and erosion from the ravine drastically reduced. The contributing area for the Ullr ravine is measured to be about 4.6 acres, but accounting for the effect of the development in the ski complex to the northeast of the ravine the effective contributing area of the ravine is estimated to be about 22 acres. The Ullr ravine is an actively developing ravine and is a source of sediment. It is not clear over what time the Ullr ravine and the Brule ravine developed. These ravines might have existed prior to the development of the Ullr Mountain and the Eagle Mountain ski facilities. It is very clear that the two ravines have been actively growing in the last decade or two, maybe longer. In contrast, the Moose Mountain ravine appears to be a natural feature as it shows up clearly on the survey map for the 1860 survey. The fact that the entire contributing area of the Moose Mountain ravine is forested points to the fact that natural conditions are promoting further ravine development. There might however be some human impacts due to the access road that crosses the ravine contributing area. The estimated amount of sediment produced in the development of each of these ravines is presented in the last column of Table 5. The estimate was determined by first estimating the volume of each of the ravines using the length and mean cross-sectional area, and then applying an assumed dry bulk density of 105 lb/ft^3 for the eroded material. The total amount of sediment for the three ravines is 15,645 tons. For the two ravines assumed to be formed more recently, Ullr and Brule the total amount of sediment is 7,560 tons. If it is assumed that these two ravines formed during the last forty years following the heavier development of the ski slopes on Ullr and Eagle mountains the mean annual load from the ravines is 189/year. It is not clear what rate the sediment might be produced by the Moose Mountain ravine because the fact that is has existed prior to the 1860's. If one considers only the period from 1860 to present, a period of 150 years, the mean sediment production rate for the Moose Mountain ravine would be about 54 tons/year. Combining the estimated sediment production rates for the three ravines the total is 243 tons/year.

Other concentrated flow pathways

The development of ski runs, walking trails, and access roads within the Lower Poplar River watershed has led to the formation of concentrated flow pathways along which erosion potential is significantly increased. During the field reconnaissance surveys reported by Hansen et al. (2010) the location of these pathways was clearly manifested by the presence of gully formation. Unchecked, these concentrated flow pathways could develop into larger sized erosion features like the Ullr and Brule ravines. The major concentrated flow pathways discovered during the field reconnaissance work are identified by location on the map presented in Figure 25. Estimates of erosion from the concentrated flow pathways were not derived in this study. Since those pathways are much like gullies, their sediment production rates might be on the order of those for other Upper Midwest areas, about 12 tons/acre/year. The surface area of the gullies along these flow pathways was not measured so at this time this erosion rate cannot be converted to a total load from that source.

Figure 24. Illustration of the location of major ravines in the Lower Poplar River watershed. (a). Ullr ravine; (b). Brule ravine; (c). Moose Mountain ravine. Image is by courtesy of Google Maps.

Figure 25. Illustration of the location of major pathways of concentrated flow in the landscape of the Lower Poplar River watershed. These flow pathways show evidence of excessive soil erosion in the form of gullies. (a). White Birch pathway; (b). Caribou Highlands pathway; (c). Lower Meadow pathway. Image is by courtesy of Google Maps.

Summary and comparison of estimated sediment loads

The total sediment delivery from the various landscape features in the Lower Poplar River watershed for the NAWE study (NAWE, 2003), the RTI study (RTI, 2008) and the present study are listed in Table 6. The NAWE study considered only the area near the river and this would be one reason for the differences with the other two studies (RTI and UofM). These figures can be compared to the estimate of sediment load derived from the monitoring data. The mean sediment load at the outlet of the Lower Poplar River watershed was estimated from flow records and total suspended solids concentrations to be 1,354 tons/year (+/- 270 tons/year, or a range of 1,084 tons/year to 1,624 tons/year) for the period 2001 to 2005 by RTI (2008). The median estimate of mean annual sediment load given by the RTI study is 1,985 tons/year, with a range of 986 tons/year to 2,983 tons/year. The figure given by the UofM study provides a mean annual sediment yield ranging from 938 tons to 1,370 tons.

Table 6. Summary of sediment deliver estimates for various sediment sources in the Lower Poplar River watershed for three studies.

<table>
<tr><th>Sediment Source</th><th>NAWE (tons/yr)</th><th>RTI (tons/ac/yr)</th><th>RTI (tons/yr)</th><th>UofM (tons/ac/yr)</th><th>UofM (tons/yr)</th></tr>
<tr><td>Developed</td><td rowspan="5">179</td><td>0.8</td><td>25</td><td>0[&]</td><td>0[&]</td></tr>
<tr><td>Forest</td><td>0.32</td><td>280</td><td>0.006[&]</td><td>5[&]</td></tr>
<tr><td>Golf</td><td>0.25</td><td>15</td><td>0.07[&]</td><td>6[&]</td></tr>
<tr><td>Ski</td><td>4.03</td><td>661</td><td>0.98 – 3.93[&]</td><td>143 - 575</td></tr>
<tr><td>Roads</td><td>--</td><td>--</td><td>0.72[**]</td><td>35</td></tr>
<tr><td>Ravines</td><td rowspan="5">--</td><td>--</td><td>225[##]</td><td>**</td><td>243[##]</td></tr>
<tr><td>Slumps, overland flow erosion</td><td>--</td><td>48[&&&]</td><td>61.7[&&&]</td><td>284[&&&]</td></tr>
<tr><td>Slumps, mass wasting</td><td></td><td>726[&&]</td><td>27.7</td><td>188[###]</td></tr>
<tr><td>Channel incision</td><td>--</td><td>53</td><td>0</td><td>0</td></tr>
<tr><td>Concentrated flow pathways</td><td>N/A</td><td>N/A</td><td>12[@]</td><td>N/A</td></tr>
<tr><td>Upland channels</td><td>--</td><td>--</td><td>--</td><td>--</td><td>312[&]</td></tr>
<tr><td>Total</td><td></td><td>N/A</td><td>1,985[%]</td><td>N/A</td><td>938 – 1,370</td></tr>
</table>

[&]Estimated with WEPP watershed model (version 2010)

[&&] Estimated using photos and field observations

[&&&]Estimated using WEPP hillslope model (version 2006.5)

[&&&&]Estimated with WEPP hillslope model (version 2010)

[#]Average rate for Upper Midwest conditions

[**]Estimated with Rosgen (2007) roads model

[##] Prior to ravine erosion control work.

[###]Estimated from the empirical model of Sekely et al. (2002)

[@]A figure from a global review of erosion rates from gullies and this applies to upper Midwest region.

[%]Median estimated total; the range was 986 – 2,983 tons/yr

The differences between the RTI and UofM numbers are likely the result of various factors. The UofM modeling incorporated the climate data and time period used by RTI to minimize the potential for differences. The RTI modeling was completed without some of the detailed field measurements made by the UofM. The field measurements enabled the UofM to provide a more complete inventory of the ravines and other flow paths for the model, a separate estimate of sediment from roads and upland channels, an improved estimate of the sheet erosion from slumps, and refined model inputs to address runoff processes. The field work helped to validate and/or improve the modeling assumptions made in the previous studies, especially in terms of infiltration and soil critical shear resistance to erosion. The WEPP model produced by the UofM study is more detailed than the model produced in the RTI study. The new modeling also provided the opportunity to examine the influence of the effective length of ski slopes and the effect of vegetation density on estimated sediment yield from ski slopes.

The modeling showed that the use of water bars on a ski slope to divert accumulating runoff from the slope, shortens the effective length of the ski slope with respect to erosion processes, and thereby significantly reduces the amount of erosion. Additional work is needed to map the water bars on the ski slopes to determine the effect of this existing conservation practice on the cumulative load of sediment from the ski slopes within the watershed.

The modeling also showed that by enhancing vegetation stands on the ski slopes, the covering of the soil with live biomass and residue will increase, thereby significantly reducing erosion from the ski slopes. Additional work is needed to better characterize the temporal and spatial distributions of vegetation stands on the ski slope areas. It is important to know how much biomass (live, dormant and dead) is present on the ski slopes at times of the year when snow cover is not present. The modeling showed that when vegetation density and surface residue is consistently high, the erosion rate will be very low.

Neither the RTI or UofM estimates of sediment yield to the Poplar River exactly matched the monitored estimated suspended solids load, but both estimates are reasonably close. For nearly every load source category (forest, ski slopes, golf course, etc.) the UofM estimates of load are less than those given by the RTI study, and the sum total of loads from the UofM estimates is closer to the monitored estimated load than that for the RTI study. This improvement in matching of observations is attributed to the refined model inputs in the UofM modeling allowing a better characterization of the runoff generation, soil erosion, and sediment transport processes occurring in the watershed.

Conclusion

The Poplar River is one of four priority areas designated by the Great Lakes Commission as eligible for their erosion and sediment reduction grants under the Great Lakes Restoration Initiative. The detailed field reconnaissance and data analysis reported by Hansen et al. (2010) and the more detailed WEPP modeling presented in this report provide an in-depth evaluation of the sources and processes of sediment erosion in the lower Poplar River watershed. The work by the University of Minnesota allowed a unique exploration of the hydrology and erosion processes affecting the Poplar River in the development of a turbidity TMDL and ensuing implementation plan for the river. The work was warranted given anticipated future development in the watershed, the significance of the area to the local community and regionally, and the broader impact to Lake Superior.

The WEPP model estimates of sheet and rill erosion, and open channel flow erosion in the upland areas, along with estimates of sediment generated from established ravines, roads, and slumps add up to a value similar to estimates based on monitored stream flow and turbidity during the period 2002 to 2005. The study indicates that the primary sources of sediment in the lower Poplar River watershed include sheet and rill erosion from the ski runs, ephemeral upland channel and ravine erosion, and mass wasting from slumps.

Ski slopes are a potentially significant source of sediment in watersheds due to their high slope angle and large length. One method to reduce erosion from the ski slopes is to reduce the effective length of the slopes. As demonstrated by the simulations with the WEPP 2010 model presented in this report, reducing the effective length of a slope dramatically reduces the soil erosion from the slope. Water bars have been constructed into the ski slopes at Lutsen to cause this effect. Locations of these water bars were not mapped during the field study reported by RTI (2008) or by Hansen et al. (2010). To fully account for the cumulative beneficial effect of these water bars on erosion reduction from the ski slopes it will be necessary to map the locations of the water bars. It is recommended that such a map be produced.

A second method for reducing erosion from ski slopes is to manage the vegetation on the slope to promote high biomass production. Increased live standing vegetation, and high cumulative surface residue, has a dramatic effect on the reduction of sediment production from steep and long slopes, as demonstrated by the simulations with the WEPP 2010 model presented in this report. Detailed measurements of vegetation density were not conducted by RTI (2008) or Hansen et al. (2010) although many photographs of the vegetation were acquired. Those photographs illustrated that there is a wide variation in soil cover provided by the standing vegetation and the cumulated residue. To better characterize the spatial distribution of live standing vegetation and residue cover on the ski slopes surveys should be conducted during at least one complete season. Such a survey would provide quantitative information on how the standing vegetation and residue cover vary from the time of snowmelt until first snowfall.

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Appendix A. Bedrock geology of the Lower Poplar River watershed.

A bedrock map for the Lutsen area is available as a bedrock quadrangle map produced by Boerboom et al. (2007), and is attached here in the next page.

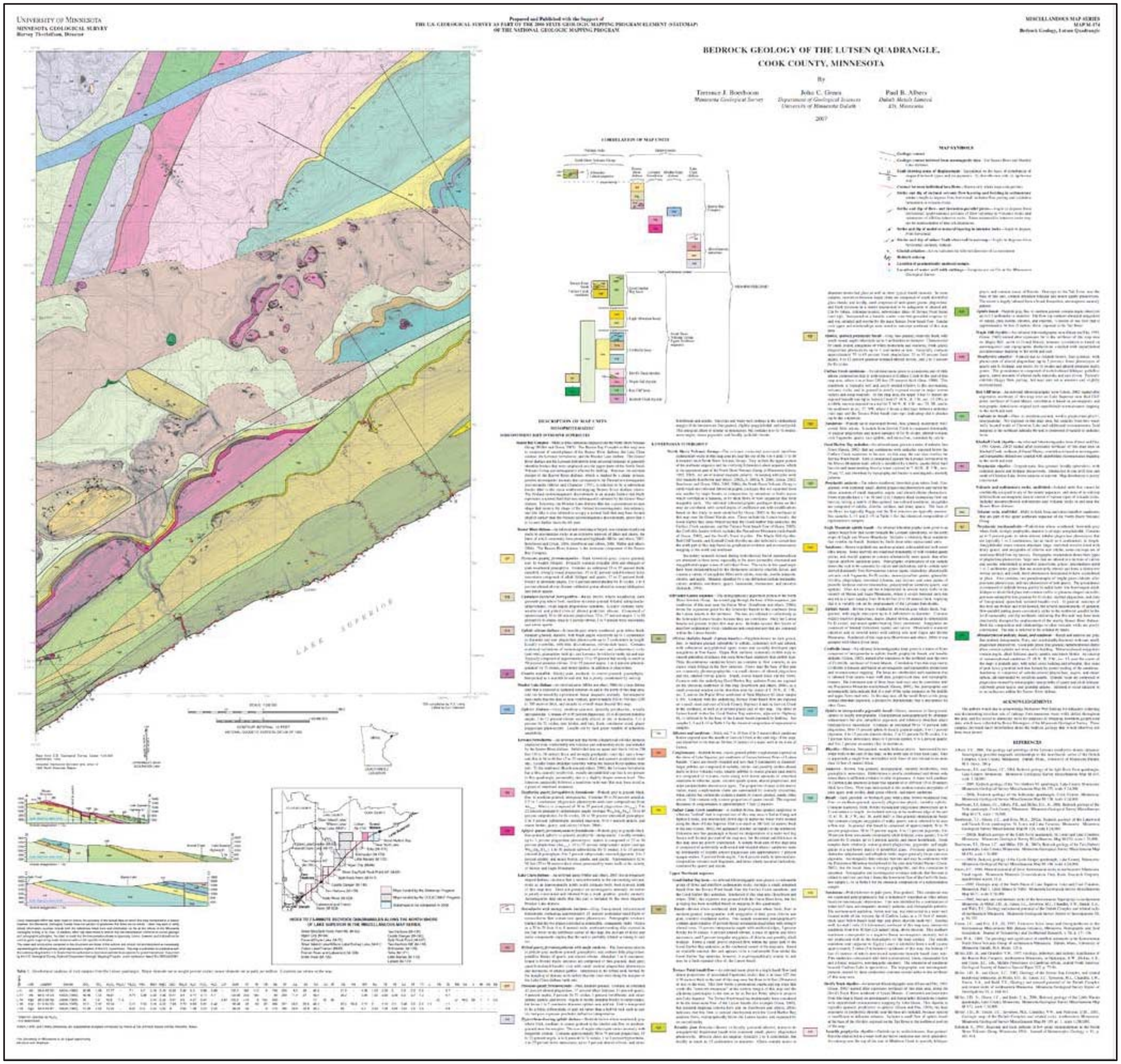


Figure A.1. Bedrock geology map of the Lower Poplar River.

Figure A.2. Map showing location of drilling logs in the Lower Poplar River watershed. These logs are available from the Minnesota Geological Survey.

Appendix B. Vegetative cover inputs

The inputs for the WEPP model for vegetative cover parameters are presented in the form of screen shots for short grass prairie and for tall grass prairie. The input parameters are mainly related to the process of biomass production and to the correlated vegetative cover in the form of live vegetative cover and flat residue. The definitions of these terms are given in Arnold et al. (1995).

For both the short grass prairie and the tall grass prairie, the cases shown are where the initial residue cover is 80% and the maximum leaf area index is 4.0. It should be noted that within the first year of simulation the residue cover condition reaches a quasi-equilibrium condition. For the short grass prairie the quasi-equilibrium value is about 95% cover for the residue cover for the case with LAI equal to 4.0, while it is about 41% for the case with LAI equal to 0.5. The quasi-equilibrium values are slightly higher for both cases for the tall grass prairie. Figure B.1 illustrates the temporal variation in LAI and Figure B.2 provides an illustration of the temporal variation in residue cover.

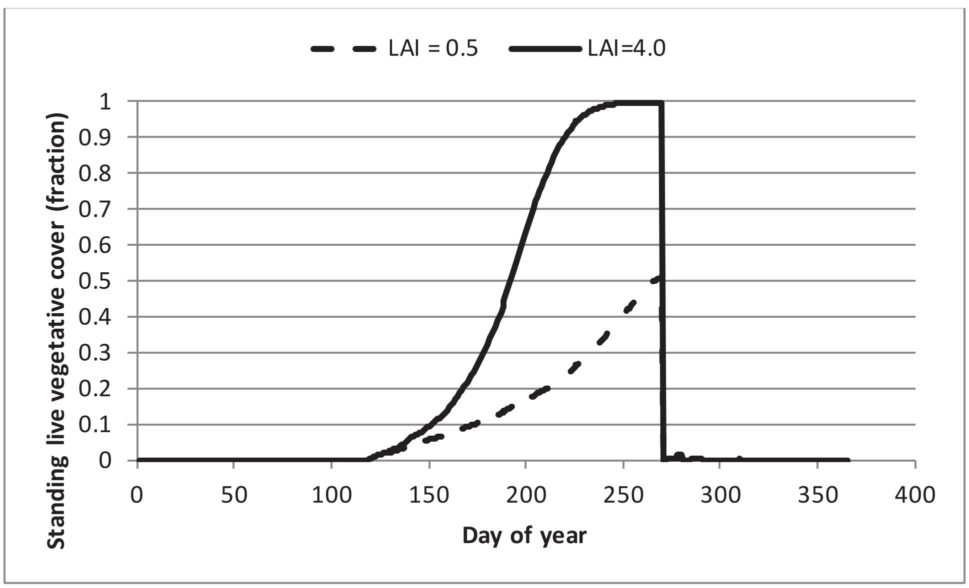


Figure B.1. Variation of surface cover provided by standing vegetation for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

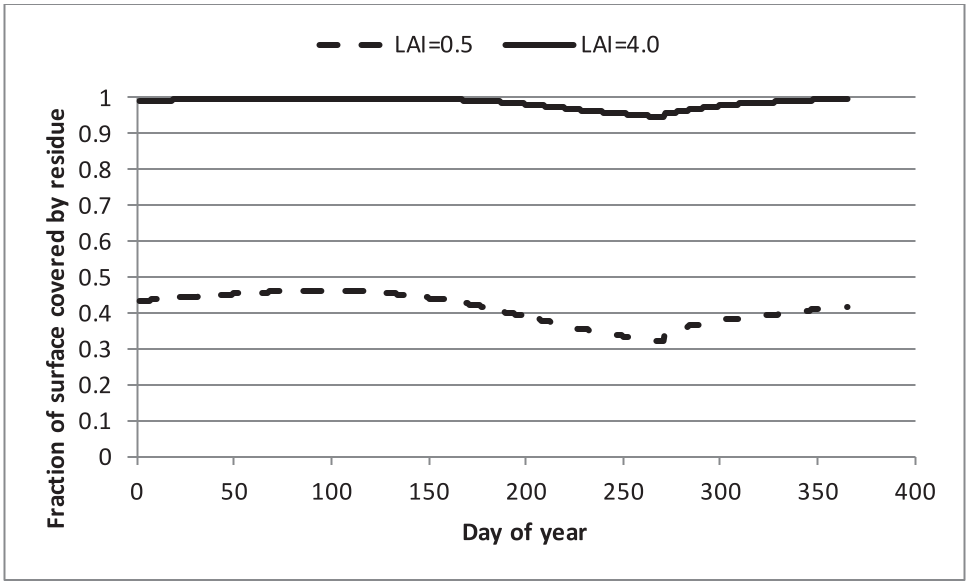
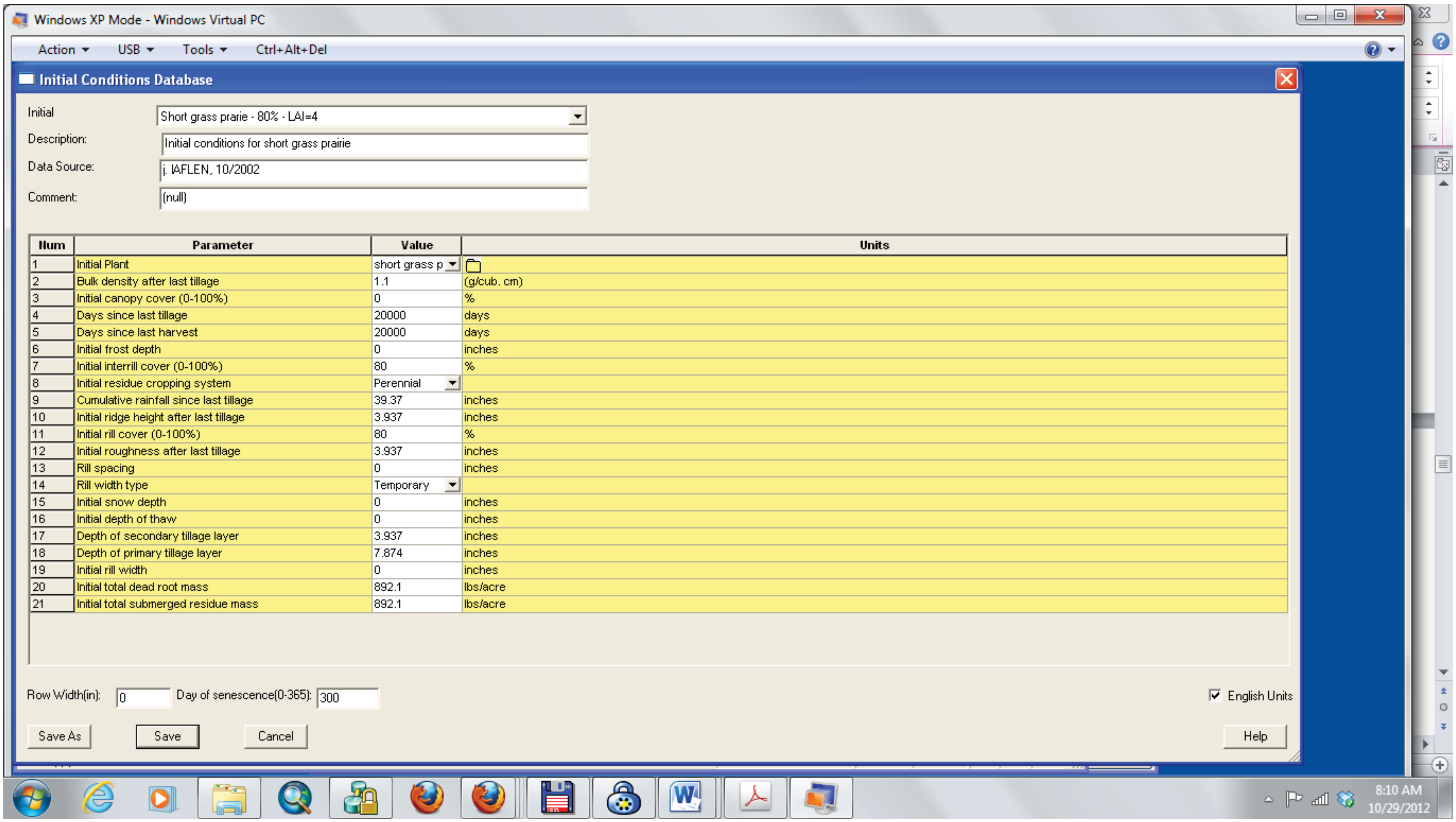
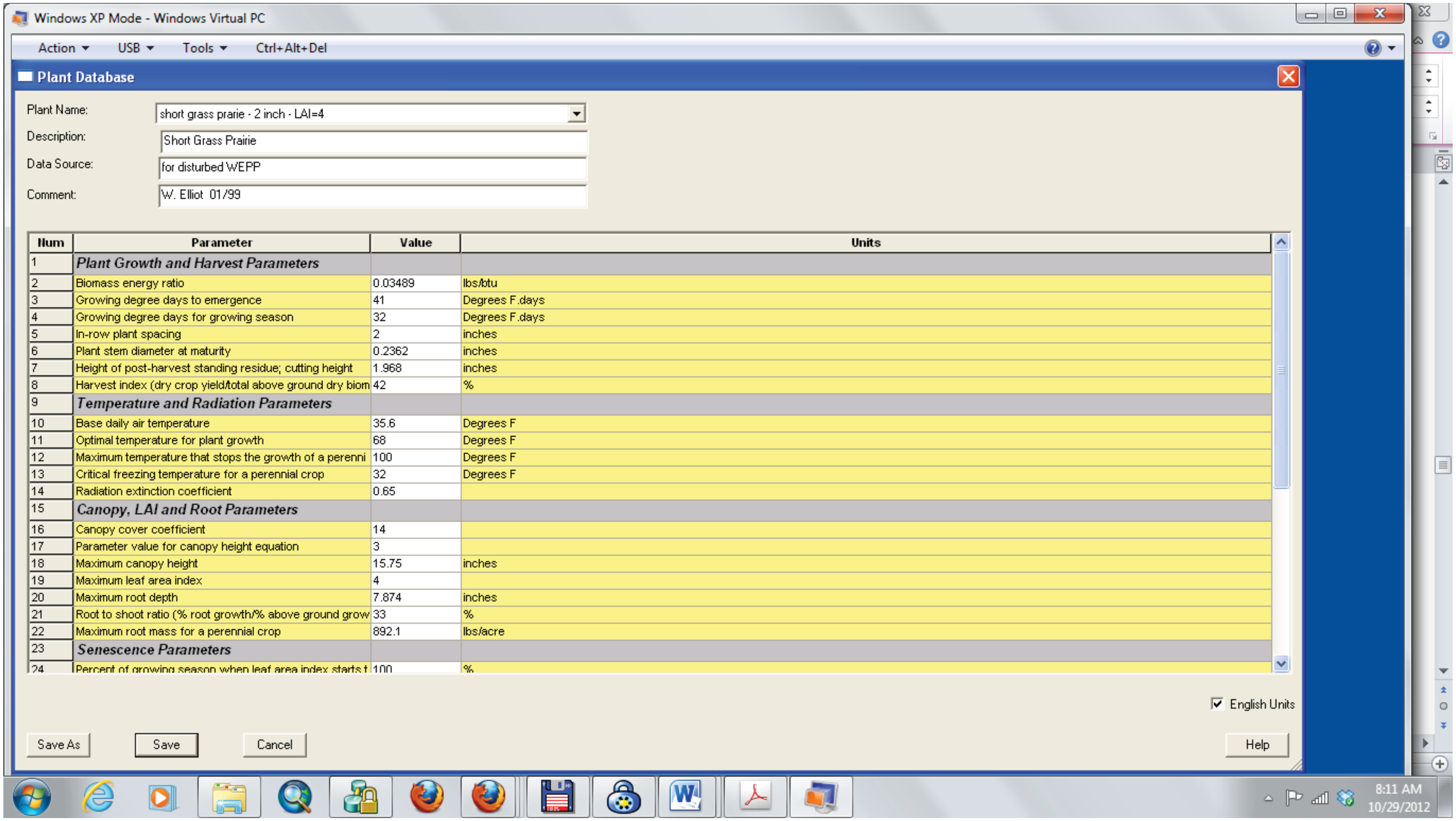


Figure B.2. Variation of surface cover provided by plant residue for two cases of maximum leaf area index, 0.5 and 4.0. Both of these cases are for short grass prairie.

Screen shots for short grass prairie




Windows XP Mode - Windows Virtual PC
Action
USB
Tools
Ctrl+Alt+Del
Plant Database
Plant Name: short grass prarie - 2 inch - LAI=4
Description: Short Grass Prairie
Data Source: for disturbed WEPP
Comment: W. Elliot 01/99
Num | Parameter | Value | Units
1 Plant Growth and Harvest Parameters
2 Biomass energy ratio 0.03489 lbs/btu
3 Growing degree days to emergence 41 Degrees F.days
4 Growing degree days for growing season 32 Degrees F.days
5 In-row plant spacing 2 inches
6 Plant stem diameter at maturity 0.2362 inches
7 Height of post-harvest standing residue; cutting height 1.968 inches
8 Harvest index (dry crop yield/total above ground dry biom 42 %
9 Temperature and Radiation Parameters
10 Base daily air temperature 35.6 Degrees F
11 Optimal temperature for plant growth 68 Degrees F
12 Maximum temperature that stops the growth of a perenni 100 Degrees F
13 Critical freezing temperature for a perennial crop 32 Degrees F
14 Radiation extinction coefficient 0.65
15 Canopy, LAI and Root Parameters
16 Canopy cover coefficient 14
17 Parameter value for canopy height equation 3
18 Maximum canopy height 15.75 inches
19 Maximum leaf area index 4
20 Maximum root depth 7.874 inches
21 Root to shoot ratio (% root growth/% above ground grow 33 %
22 Maximum root mass for a perennial crop 892.1 lbs/acre
23 Senescence Parameters
24 Percent of growing season when leaf area index starts t 100 %
English Units
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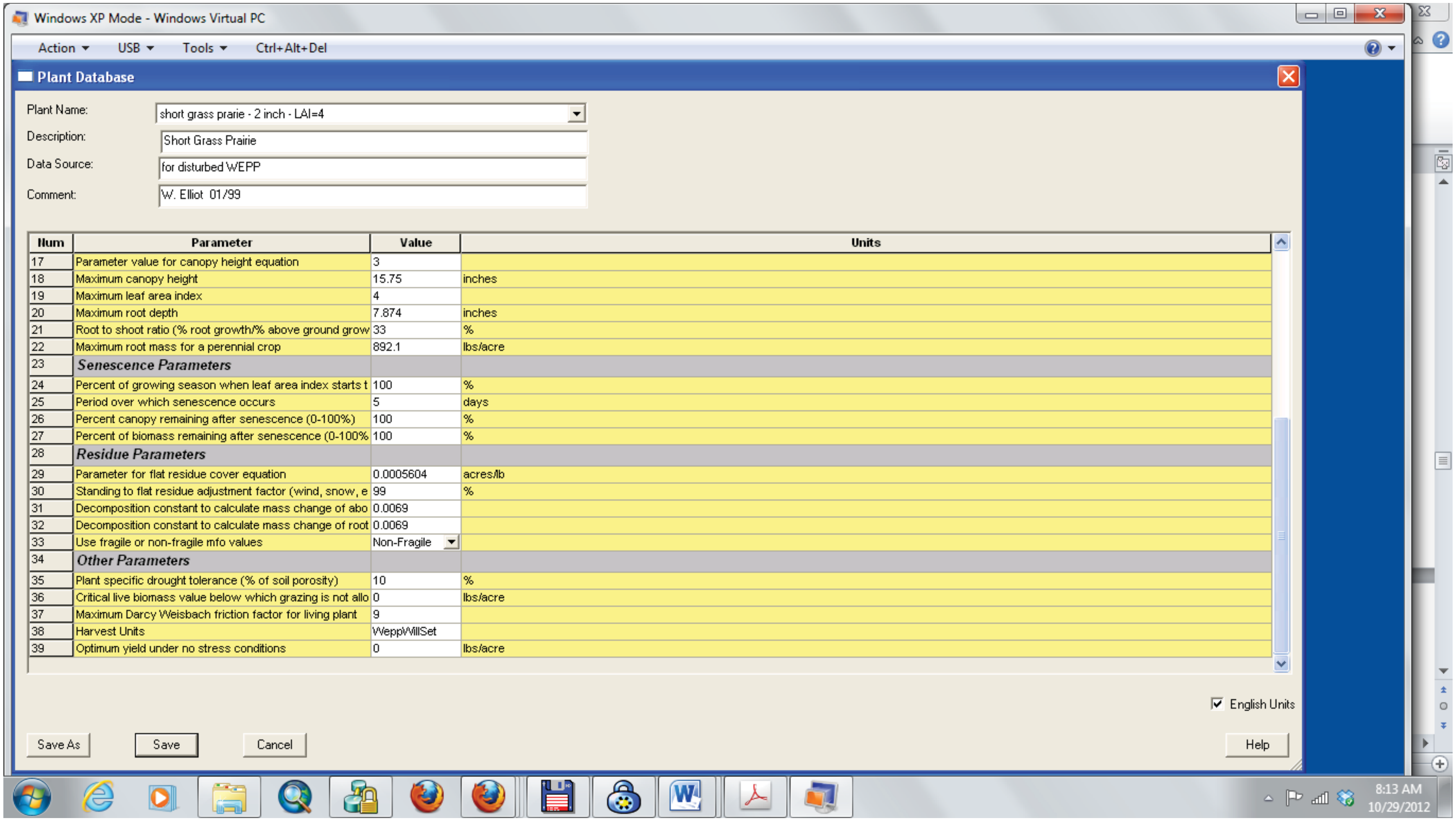
Windows XP Mode - Windows Virtual PC
Action USB Tools Ctrl+Alt+Del
Plant Database
Plant Name: short grass prarie - 2 inch - LAI=4
Description: Short Grass Prairie
Data Source: for disturbed WEPP
Comment: W. Elliot 01/99
Num | Parameter | Value | Units
17 | Parameter value for canopy height equation | 3 |
18 | Maximum canopy height | 15.75 | inches
19 | Maximum leaf area index | 4 |
20 | Maximum root depth | 7.874 | inches
21 | Root to shoot ratio (% root growth/% above ground grow | 33 | %
22 | Maximum root mass for a perennial crop | 892.1 | lbs/acre
23 | Senescence Parameters
24 | Percent of growing season when leaf area index starts t | 100 | %
25 | Period over which senescence occurs | 5 | days
26 | Percent canopy remaining after senescence (0-100%) | 100 | %
27 | Percent of biomass remaining after senescence (0-100% | 100 | %
28 | Residue Parameters
29 | Parameter for flat residue cover equation | 0.0005604 | acres/lb
30 | Standing to flat residue adjustment factor (wind, snow, e | 99 | %
31 | Decomposition constant to calculate mass change of abo | 0.0069 |
32 | Decomposition constant to calculate mass change of root | 0.0069 |
33 | Use fragile or non-fragile mfo values | Non-Fragile |
34 | Other Parameters
35 | Plant specific drought tolerance (% of soil porosity) | 10 | %
36 | Critical live biomass value below which grazing is not allo | 0 | lbs/acre
37 | Maximum Darcy Weisbach friction factor for living plant | 9 |
38 | Harvest Units | WeppWillSet |
39 | Optimum yield under no stress conditions | 0 | lbs/acre
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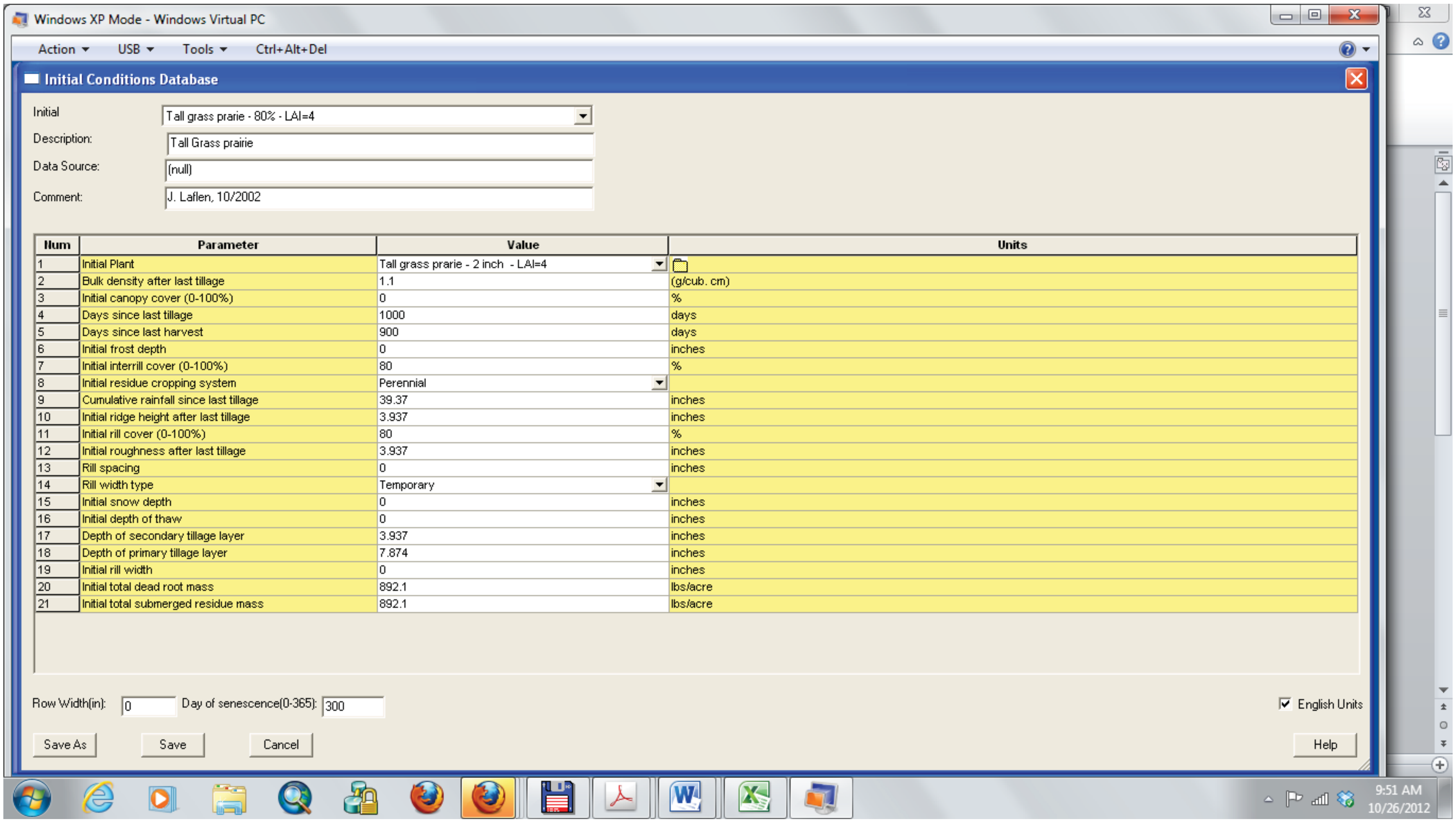
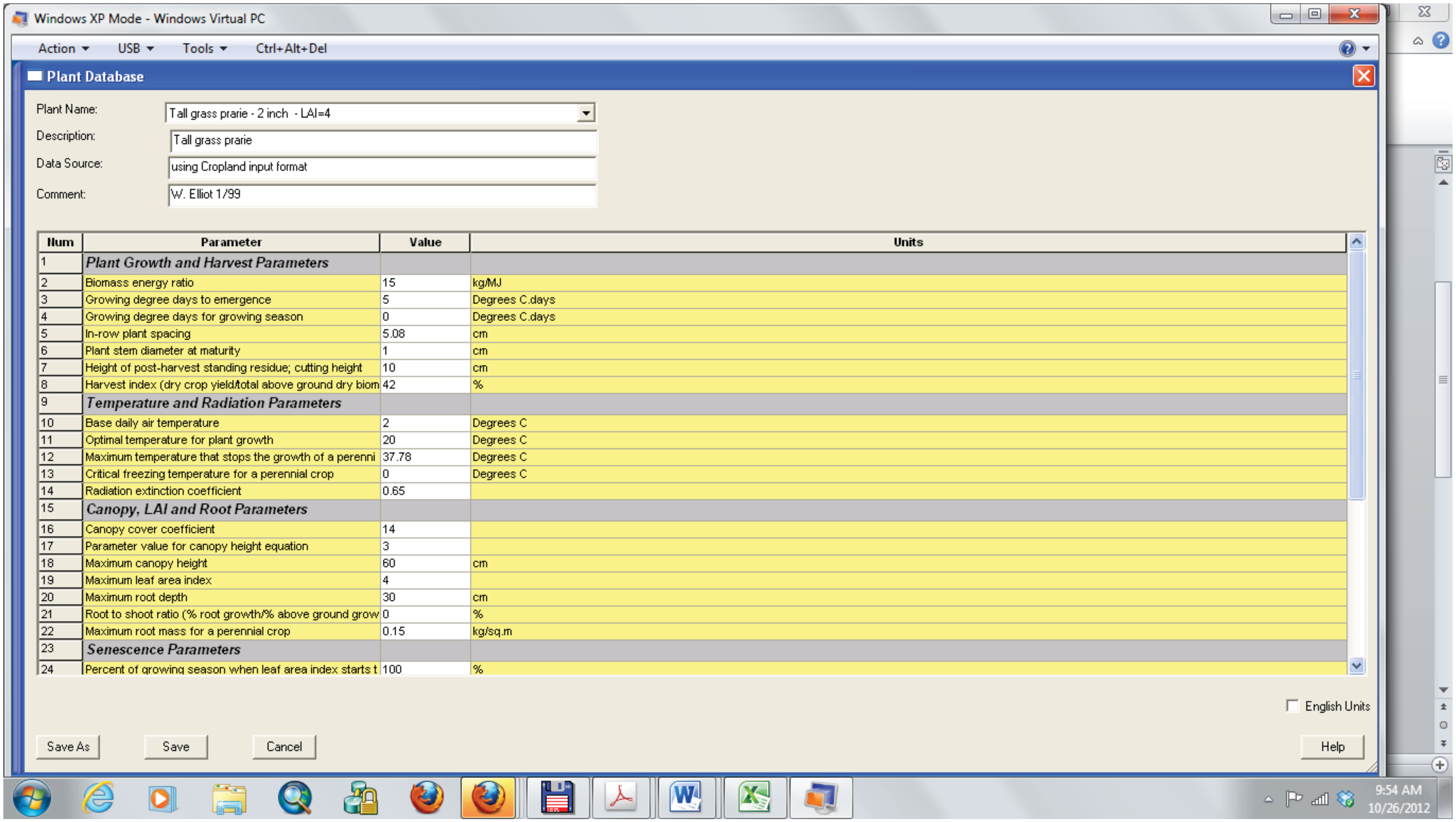
Screen shots for tall grass prairie




Windows XP Mode - Windows Virtual PC
Action
USB
Tools
Ctrl+Alt+Del
Plant Database
Plant Name: Tall grass prarie - 2 inch - LAI=4
Description: Tall grass prarie
Data Source: using Cropland input format
Comment: W. Elliot 1/99
Num | Parameter | Value | Units
1 | Plant Growth and Harvest Parameters
2 | Biomass energy ratio | 15 | kg/MJ
3 | Growing degree days to emergence | 5 | Degrees C.days
4 | Growing degree days for growing season | 0 | Degrees C.days
5 | In-row plant spacing | 5.08 | cm
6 | Plant stem diameter at maturity | 1 | cm
7 | Height of post-harvest standing residue; cutting height | 10 | cm
8 | Harvest index (dry crop yield/total above ground dry biom | 42 | %
9 | Temperature and Radiation Parameters
10 | Base daily air temperature | 2 | Degrees C
11 | Optimal temperature for plant growth | 20 | Degrees C
12 | Maximum temperature that stops the growth of a perenni | 37.78 | Degrees C
13 | Critical freezing temperature for a perennial crop | 0 | Degrees C
14 | Radiation extinction coefficient | 0.65
15 | Canopy, LAI and Root Parameters
16 | Canopy cover coefficient | 14
17 | Parameter value for canopy height equation | 3
18 | Maximum canopy height | 60 | cm
19 | Maximum leaf area index | 4
20 | Maximum root depth | 30 | cm
21 | Root to shoot ratio (% root growth/% above ground grow | 0 | %
22 | Maximum root mass for a perennial crop | 0.15 | kg/sq.m
23 | Senescence Parameters
24 | Percent of growing season when leaf area index starts t | 100 | %
English Units
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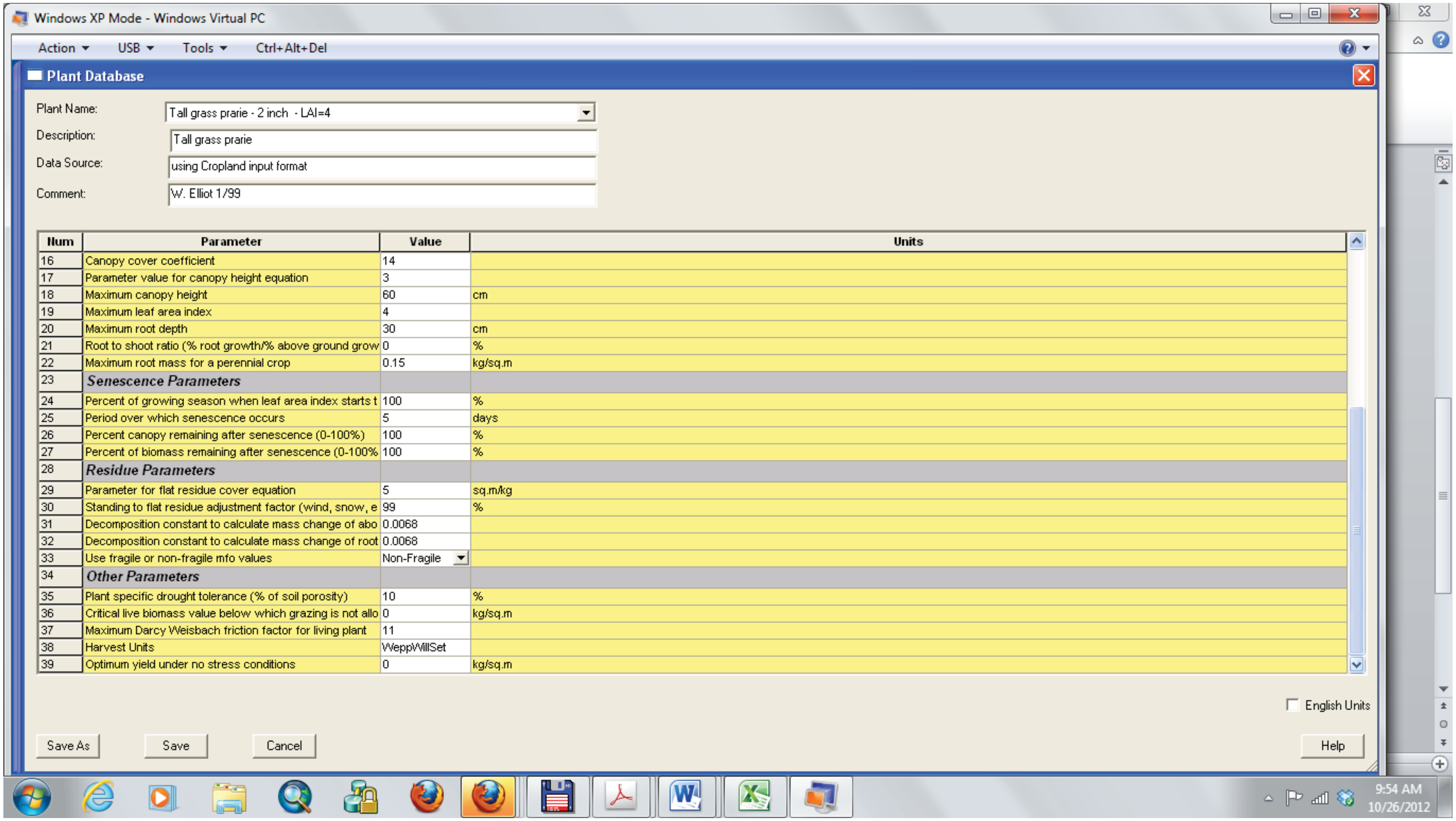

Num	Parameter	Value	Units
16	Canopy cover coefficient	14	
17	Parameter value for canopy height equation	3	
18	Maximum canopy height	60	cm
19	Maximum leaf area index	4	
20	Maximum root depth	30	cm
21	Root to shoot ratio (% root growth/% above ground grow	0	%
22	Maximum root mass for a perennial crop	0.15	kg/sq.m
23	***Senescence Parameters***		
24	Percent of growing season when leaf area index starts t	100	%
25	Period over which senescence occurs	5	days
26	Percent canopy remaining after senescence (0-100%)	100	%
27	Percent of biomass remaining after senescence (0-100%	100	%
28	***Residue Parameters***		
29	Parameter for flat residue cover equation	5	sq.m/kg
30	Standing to flat residue adjustment factor (wind, snow, e	99	%
31	Decomposition constant to calculate mass change of abo	0.0068	
32	Decomposition constant to calculate mass change of root	0.0068	
33	Use fragile or non-fragile mfo values	Non-Fragile	
34	***Other Parameters***		
35	Plant specific drought tolerance (% of soil porosity)	10	%
36	Critical live biomass value below which grazing is not allo	0	kg/sq.m
37	Maximum Darcy Weisbach friction factor for living plant	11	
38	Harvest Units	WeppWillSet	
39	Optimum yield under no stress conditions	0	kg/sq.m

Appendix C. Poplar River watershed soils

The information for these soil series was obtained from the NRCS web site on soils descriptors, http://soils.usda.gov/technical/classification/osd/index.html. Very detailed information is available at that site. A brief descriptor for each soil series is presented below.

QUETICO SERIES

The Quetico series consists of very shallow, well drained soils that formed in loamy noncalcareous glacial drift on uplands with relief controlled by the underlying bedrock. These soils have bedrock beginning at depths ranging from 4 to 10 inches. The saturated hydraulic conductivity is moderate in the loamy mantle. Slopes range from 2 to 90 percent. Mean annual precipitation is about 28 inches and mean annual air temperature is about 37 degrees F.

BARTO SERIES

The Barto series consists of shallow, well drained soils that formed in a 20 to 51 cm thick mantle of loamy till overlying unweathered bedrock. They have slopes of 2 to 45 percent. Mean annual precipitation is about 750 mm and mean annual air temperature is about 4.5 degrees C.

MESABA SERIES

The Mesaba series consists of moderately deep, well drained soils that formed in a mantle of loamy friable till over gabbro, basalt, or granite bedrock at depths of 51 to 102 cm. Slopes range from 2 to 45 percent. Mean annual precipitation is 750 mm and the mean annual temperature is 4.5 degrees C.

HIBBING SERIES

The Hibbing series consists of very deep, moderately well drained soils that formed in a thin mantle of loess and underlying fine, dense till on till plains and moraines. Slopes range from 3 to 45 percent. Saturated hydraulic conductivity is very slow. Mean annual air temperature is about 39 degrees F. Mean annual precipitation is about 27 inches.

FINLAND SERIES

The Finland series consists of moderately deep, well drained soils that formed in a friable loamy mantle and underlying firm loamy glacial till on moraines. Permeability is moderate in the upper layers and moderately slow to slow in the dense till. Slopes range from 1 to 35 percent. Mean annual temperature is 39 degrees F, and mean annual precipitation is 29 inches.

DUSLER SERIES

The Dusler series consists of very deep, somewhat poorly drained soils that formed in loamy glacial till on till floored lake plains, and moraines. Permeability is moderate in the mantle and slow in the underlying material. Slopes range from 0 to 3 percent. Mean annual air temperature is about 38 degrees F. Mean annual precipitation is about 28 inches.

DULUTH SERIES

The Duluth series consists of very deep, well drained soils that formed in a friable mantle of loamy eolian or glaciofluvial deposits and in the underlying firm loamy till on moraines and till plains. Slopes range from 6 to 45 percent. Mean annual air temperature is about 4.0 degrees C. and mean annual precipitation is about 711 millimeters.

AMASA SERIES

The Amasa series consists of very deep, well drained and moderately well drained soils formed in loamy materials underlain by sandy materials on outwash plains, stream terraces, kames, eskers, and moraines. Permeability is moderate in the loamy materials and rapid or very rapid in the underlying sandy material. Slopes range from 0 to 70 percent. Mean annual precipitation is about 30 inches, and mean annual temperature is about 43 degrees F.

HERMANTOWN SERIES

The Hermantown series consists of very deep, somewhat poorly drained soils that formed in a friable loamy mantle and the underlying dense loamy till on moraines, till plains and drumlins. Slopes range from 0 to 3 percent. Mean annual air temperature is about 4.0 degrees C. and mean annual precipitation is about 750 mm.

RUDYARD SERIES

The Rudyard series consists of very deep, somewhat poorly drained soils formed in clayey deposits on lake plains. These soils have very slow permeability. Slopes range from 0 to 4 percent. Mean annual precipitation is about 30 inches, and mean annual temperature is about 43 degrees F.

ONTONAGON SERIES

The Ontonagon series consists of very deep, well drained soils formed in clayey glaciolacustrine deposits on lake plains. Permeability is very slow. Slopes range from 6 to 50 percent. Mean annual precipitation is about 30 inches, and mean annual air temperature is about 41 degrees F.

BERGLAND SERIES

The Bergland series consists of very deep, poorly drained soils formed in clayey deposits on glacial lake plains and till plains. Permeability is very slow. Slopes range from 0 to 2 percent. Mean annual precipitation is about 30 inches. Mean annual temperature is about 44 degrees F.

AHMEEK SERIES

The Ahmeek series consists of very deep, well drained soils that formed in a friable loamy mantle and the underlying dense loamy till. These soils are on till plains, moraines, and drumlins. Slope ranges from 0 to 45 percent. Mean annual air temperature is about 4 degrees C. Mean annual precipitation is about 750 millimeters.