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

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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, 10 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 7.64 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. In many cases roads and impervious surface development negatively impact landscape hydrologic interactions; often this may lead to destabilization of slopes, increasing sediment losses and subsequently decreasing 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. 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).

Understanding the extent and origin of water quality impairments is a pressing issue for land managers. Currently 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 unknown.

Chapter 1 investigates the extent of road connectivity at the watershed and local level (at road-stream crossings); by 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. In its entirety this investigation 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 geomorphic stability at stream segments above and below road-stream crossings using Rosgen level I and Pfankuch stability assessments. by examining channel network extension, sediment availability and in-stream geomorphic stability at road-stream crossings.

Study site background

North Shore watershed – North Shore streams

<u>Land uses</u>

This study evaluated portions of the Lake Superior watershed in Minnesota; a watershed draining an area of 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 (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.

<u>Soil type</u>

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).

<u>Geomorphic Association</u>

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), both the USGS 1:100,000 and 1:24,000 scale topographic maps; accessed through the DNR GIS spatial database (Minnesota DNR Data Deli, 2011). This data layer describes the glacial terrain of the North Shore watershed, giving clues towards the age and underlying stratigraphy of the watershed. 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 % (Table 3). Topographically, much of the watershed is composed of gentle to undulating rolling terrain (63%) along with steep gradients with abrupt peaks and ridges (24%).

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 aged approximately 2.5 billion to 543 million years old. There is 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. 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 within 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 large 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 (1^{st}-2^{nd} 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.

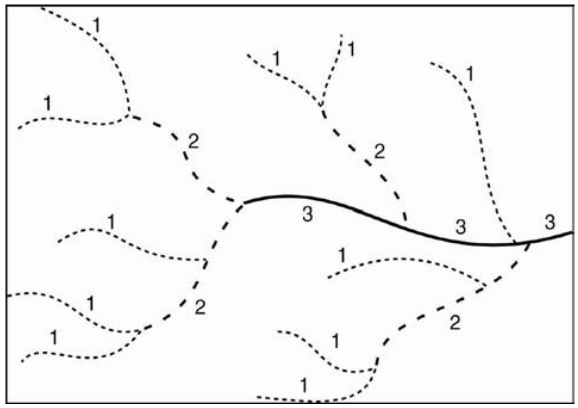


Figure 1. Stahler stream ordering (Ward et al., 2008)

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 (Figure 2). 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 4). 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).

Figures and tables

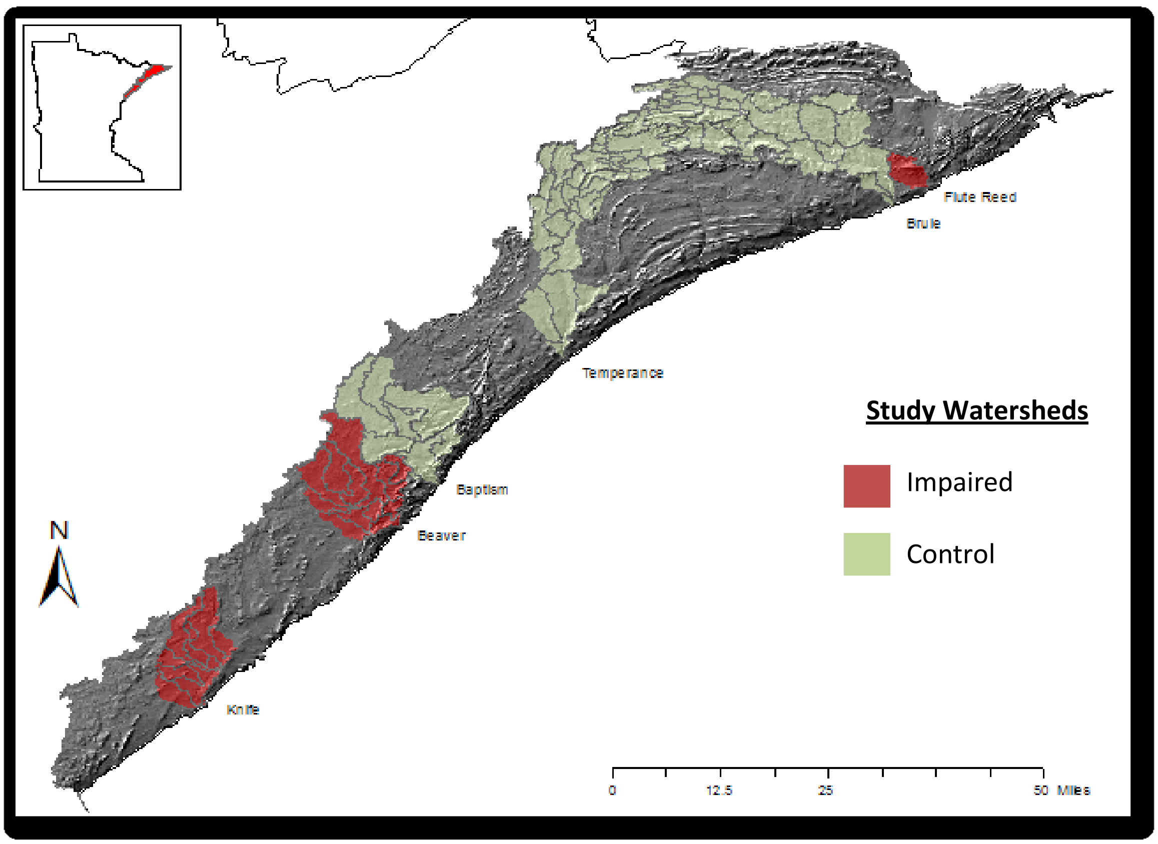


Figure 2. Study watersheds (impaired vs. control)

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 area ($mile^2$)**	**Brimson**	**Grand Marais**	**Grand Portage**	**Isabella**	**Lutsen 3NNE**	**Two Harbors**	**Two Harbors - 7NW**	**Wolf Ridge**	**Avg 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

Hydrologic effects of roads

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.

Road crossings

Roads impart legacy hydrologic effects on the landscape. Erosion and sedimentation from forest road stream crossings may affect the sediment budgets of streams for decades after construction. Wayne Swank from the Coweeta hydrologic lab, NC., conducted a paired watershed experiment beginning in 1976 to study the sediment budget after construction of a forest road-stream crossing and logging treatment. An initial pulse of sediment was noted after construction along with increases after the logging treatment ((Swank, Vose, & Elliott, 2001)). Over a 15 year study period an apparent cumulative increase over time was noted, indicating a long term rerouting of sediment existed for the study watershed, ultimately resulting in a 300 metric ton difference (Figure 3) ((Reidel, Swift, Vose, & Clinton, 2007)).

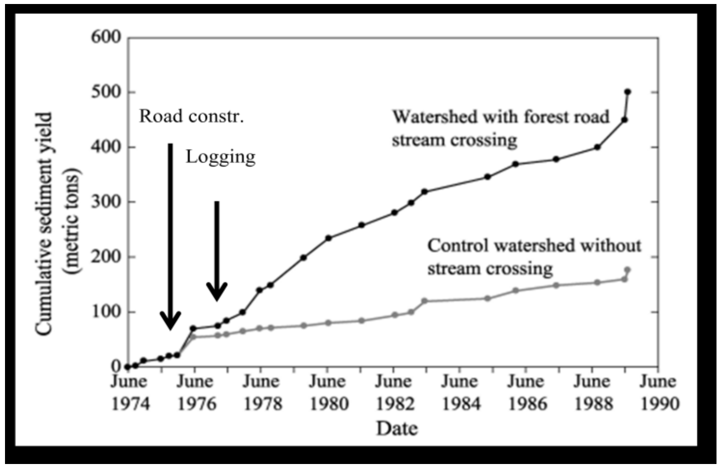


Figure 3. Cumulative sediment yield comparison for a paired watershed experiment studying road crossing construction at Coweeta Hydrologic Lab ((Swank, Vose, & Elliott, 2001), (Reidel, Swift, Vose, & Clinton, 2007))

Connectivity

Road connectivity in a broader context is considered to be the relationship between multiple 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 (considered aspects of road construction), and the ability of the *riparian buffer* area (adjacent to the road) to reduce sediment dispersal downslope (Figure 4)(Bracken & Croke, 2007). At a local scale, the connectivity of roads to stream networks and conveyance of sediment from road networks to streams is driven by landform hydrologic processes.

A better understanding of road-stream connectivity can be gained by examining the extent of flow delivery pathways off of road prisms to nearby streams. The major hydrologic processes that interplay with sediment conveyance to streams are Hortonian overland flow (infiltration excess), saturation excess overland flow (SOF) and the variable source area concept (VSA). Hortonian overland flow (HOF) is a form of runoff that is directly dependent on rainfall rate, such that when the rainfall rate exceeds the rate of infiltration into the soil, runoff is generated. HOF often occurs on sealed or impervious surfaces resulting in sheet flow. Saturation excess overland flow occurs when soils become saturated, forcing additional inputs of water to runoff. The Variable Source Area concept (VSA) is a hydrologic process that connects subsurface saturated hillslopes to stream channels, illustrating inter-relationships between soil water carrying capacity, hillslope gradient, vegetation, and rainfall rate.

Local connectivity: Flowpaths and channel initiation

Flowpaths

Roadways can significantly alter local hydrologic processes, often delivering runoff to stream networks. Runoff can be conveyed off of the road prism in two categorical ways, as a *dispersive flow* or a *directed flow* (Figure 5, 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) (Figure 6). 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 (Figure 7). This type of runoff typically creates a direct roadway connection to streams, often resulting in ephemeral flowpaths that may detach soil over time.

Connectivity of flowpaths to stream networks results in channel network extension if direct flowpaths are observed. Quantifying and evaluating connectivity in the field can be done following various techniques. LaMarche and Lettenmaier (2001) quantify the extent of flowpath processes at culvert locations by describing four potential ends runoff may have, ultimately two of which describe road-stream connectivity. Their definition for observable connectivity is incorporated into the road-stream site survey used within this analysis.

<u>LaMarche and Lettenmaier (2001) Flowpath process and connectivity:</u>

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 <u>connected</u> to the stream network, directly or indirectly (respectively)

Wemple (1996) also evaluated road-stream connectivity quantifying the observable extent 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. Expanding upon this idea Croke and Mockler (2001) employed a modified Wemple (1996) in which a categorical system was developed to determine connectivity by as the length of the erosion feature and its distance to the stream by at distances greater than 10 meters and less than 10 meters from the stream. Their methods were utilized within this report for comparison of road survey site connectivity to an analysis at a watershed scale. The a watershed scale evaluation of road-stream connectivity for this study expanded on the Croke and Mockler (2001) method and incorporated methods by Miller (2010), in which connectivity was examined using a GIS at road to stream buffers of 3.04 m – 30.4m (10ft, 50ft, and 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 land sliding (Figure 5). This study focused on rill and gully erosion.

To date there are many interpretations of gully processes, this study follows size classifications by posed by Poesen *et al.* (2003). Where gullies 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 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, for gullies thresholds can lie between 14.5 mm - 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 in their 1983 study of roads in Minnesota, found water related erosion was most frequently observed along roadsides, accounting for 15,309 occurrences or 81.5% of the dataset. Citing precipitation intensity and duration were primary factors for sediment detachment, often dictating where sediment was deposited along a road side vegetated buffer (Sullivan and Foote, 1983).

Vegetative buffers

Vegetative buffers are key to reducing runoff flows and to the retention of sediment conveyed off of the road prism. Often hillslope surfaces are prone to become sediment sources if left un-vegetated particularly evident after construction, in which unvegetated buffers act as a major source of sediment, continuing for 1 – 2 years (MacDonald & Coe, 2008). Sullivan and Foote (1983) conducted an intensive roadside erosion investigation in 1983 within the state of Minnesota (17,902 sites, 185,991 km (115,570 miles) of roadway), finding a lack of vegetative cover was the "single most important cause of erosion" for their dataset.

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).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). Unsealed 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 armored 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 erodible 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 8).

Figures

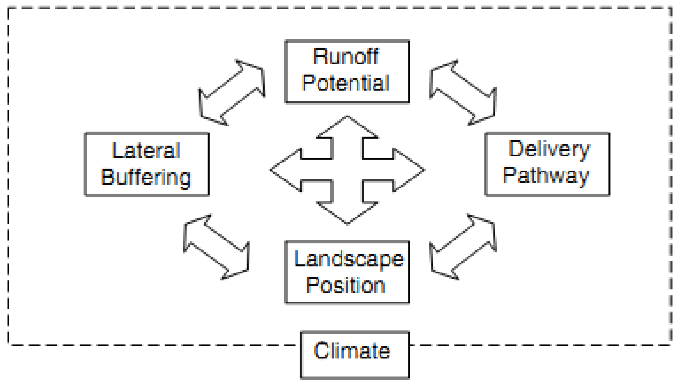


Figure 4. Components of catchment connectivity from Bracken & Croke (2007)

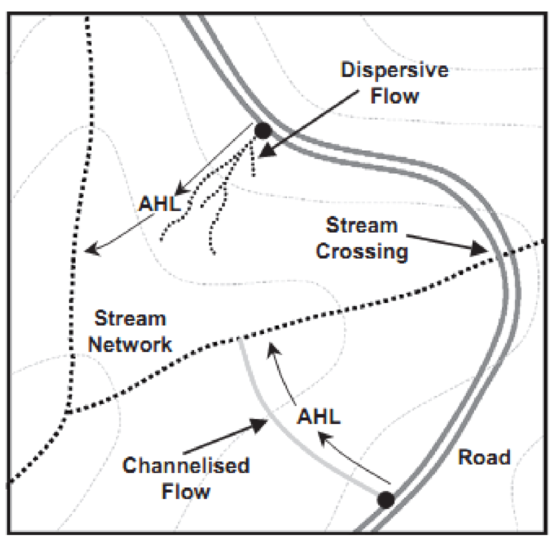


Figure 5. Examples of runoff pathways (from Croke *et al.*, 2005)

Figure 6. Dispersive flowpath

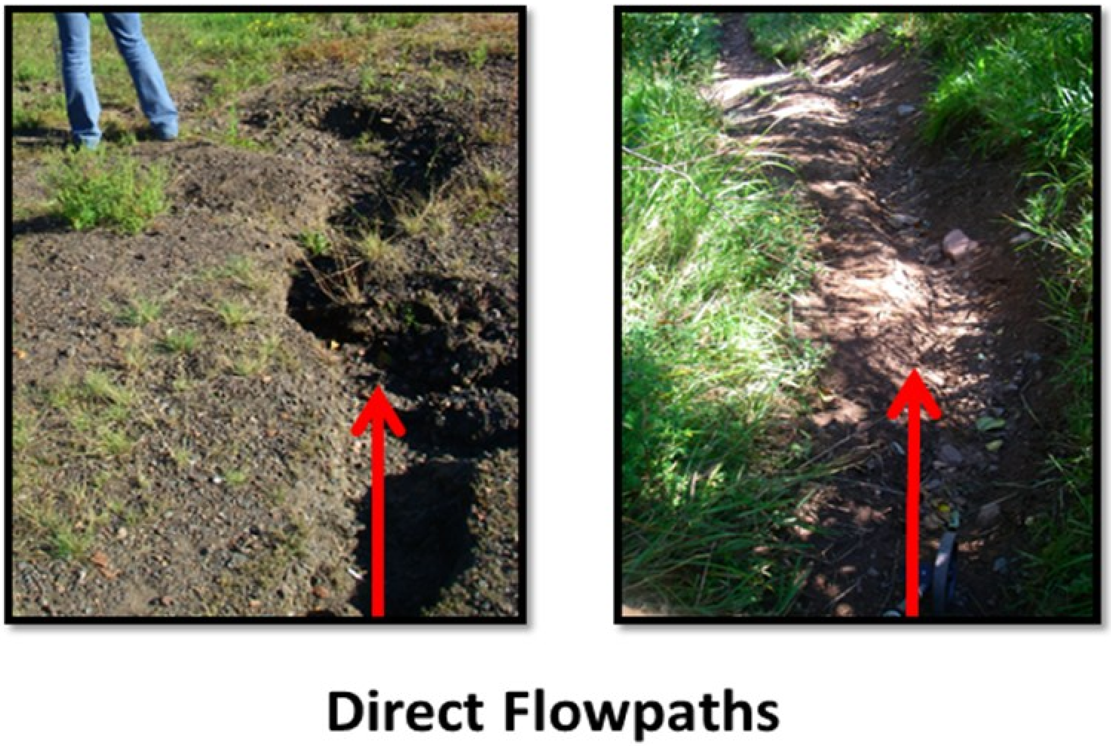


Figure 7. Direct flowpath

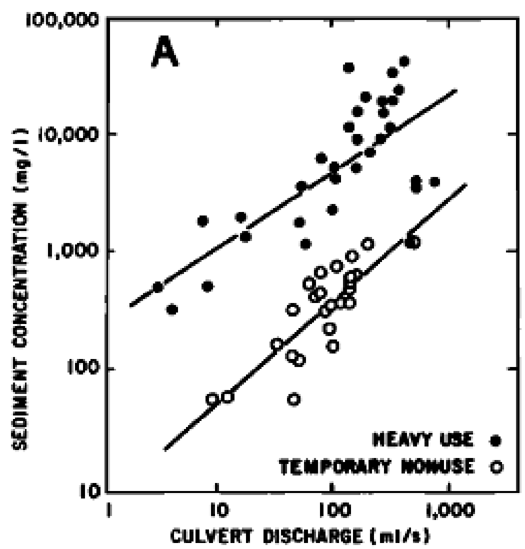


Figure 8. Sediment concentrations as a result of traffic usage (from Reid and Dunne 1984)

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.

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 9).

This dataset was randomly 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 10). 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 multiple GIS data layers including: 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 buffer interval. In-field observations of direct road-stream connectivity were also incorporated into this analysis. The modified drainage area at each buffer interval is calculated using the equation below. All lengths are expressed in miles.

$$D_d' = \frac{\sum(L_S + L_{RC} + L_G)}{A}$$

Where D'_d = modified drainage area, L_S = stream length, L_{RC} = length of road segments discharging runoff directly to stream channels, L_G = length of gullies connecting roads to streams on previously unchanneled hillslopes (L_G, pertains to infield observations only) (based on Wemple *et al.*, 1996).

<u>Road survey site direct connectivity</u>

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.

<u>Field survey</u>

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 11).

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 11). 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 13). 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 analyzed statistically using non-parametric tests and logistic regression using a presence/absence approach. The Student’s t test was used in the connectivity analysis as the dataset satisfied rules of normality. 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).

Logistic regression

Statistical tests were performed to examine the presence or absence of erosion on a per site basis using logistic regression which results in a probability. Logistic regression is a type of regression that is used when the dependent variable is binary value (ie: 0, 1). Logistic regression is a robust type of analysis that may utilize independent variables that are not normally distributed, and has no assumptions of linearity between the independent and dependent variables. Logistic regression models employ a measure of "goodness of fit" based on a chi-squared distribution.

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 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/).

Figures

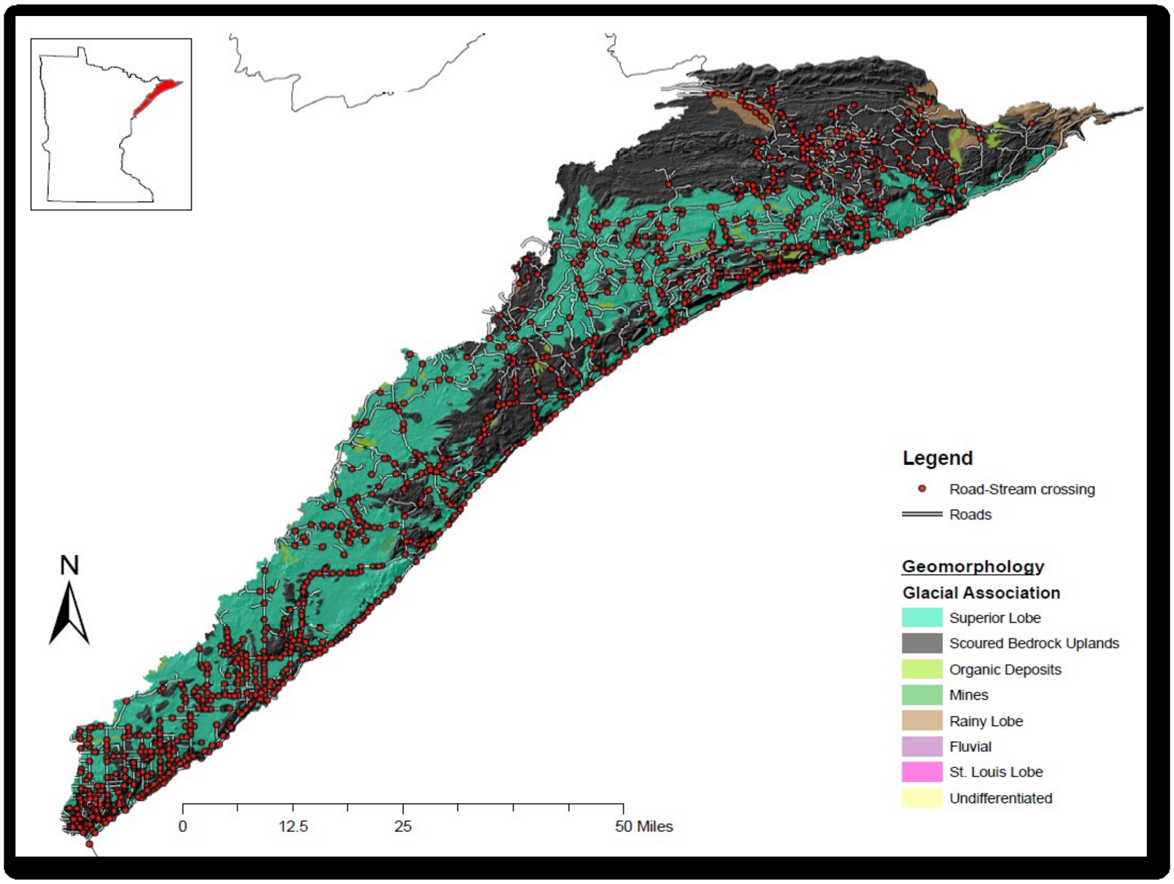


Figure 9. All crossings estimated using road and hydrography layers within GIS

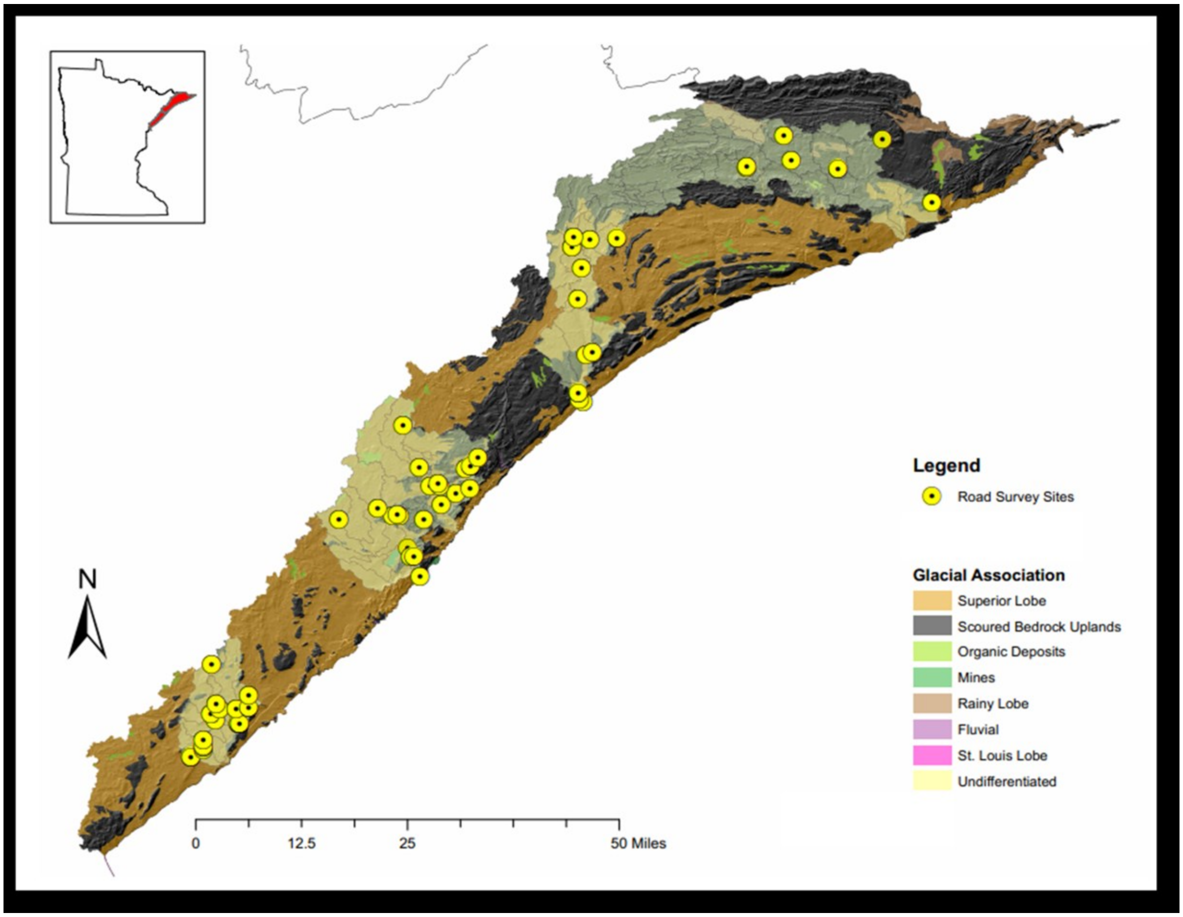


Figure 10. Road survey locations

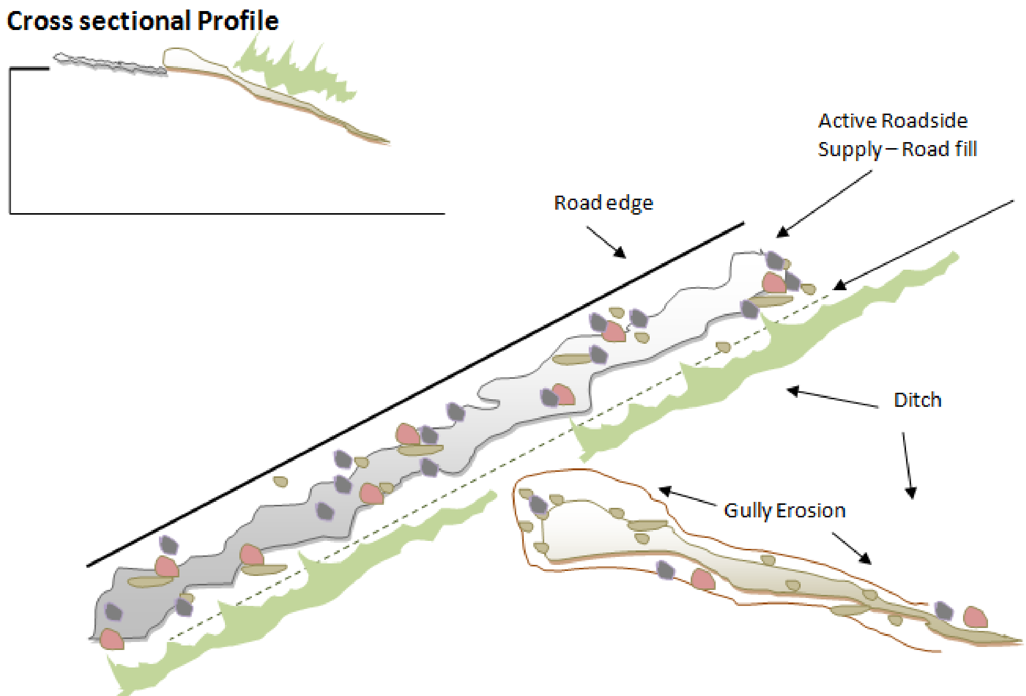


Figure 11. Field Survey Diagram and Cross Sectional Profile

Table 8. Sampling distribution

	Total Crossings	Total # of crossings when sampled at 15%	Scoured Bedrock Uplands	Superior Lobe				Organic Deposits		Rainy Lobe	
			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 – 6.92%. 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 (6.92%) was found within the control watersheds for roads located 50-100 ft (15.24-30.48 m) from streams. This was true for the overall North Shore stream watershed (9.47%), and for impaired watersheds (5.11%) (Table 9). 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%). Overall the greatest increase in drainage density was found within the control watersheds, compared to impaired watersheds, although this was not a significant relationship when tested with Student's t test ($p = 0.6661$, $df = 5.51$, $\alpha = 0.05$).

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 (Table 10). 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 10). The total sum of all observed erosion was 93.26 m^3 (3,293.44 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). If excluding outliers the total sum of erosion observed was 14.78 m^3 (521.95 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 (Table 11).

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 54.05 m^3 (1908.76 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 – 333 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 (395 m – 468 m) at 2.21×10^{-4} m^3 (0.01 ft^3) (Table 12). The total sum of erosion was greatest within control watershed survey sites (55.81 m^3, or 2.82 m^3 excluding outliers) than for impaired watersheds sites (37.45 m^3, or 11.96 m^3 excluding outliers). Excluding outliers, impaired watershed sites had the greatest mean average per site erosion (0.22 m^3 (7.77

ft^3)), compared to control watersheds (0.05 m^3 (1.77 ft^3)). *Note "average per site erosion" is the mean of the average erosion measured at each site for all data points.*

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 native sites in impaired watersheds had the greatest per site average erosion at 1.17 m^3 (gravel) and 0.52 m^3 (native) (Table 13). Statistically analyzed using the Kruskal-Wallis ranked sums non-parametric test, there was no significant difference between groups when cumulative erosion was tested against geomorphic, watershed or road surface types.

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 (12.05 m^3 (425.542 ft^3)). Excluding outliers, the greatest erosion was found on Superior Lobe paved sites (8.29 m^3 (292.76 ft^3)) and gravel (2.97 m^3 (104.89 ft^3)) road survey sites and on gravel scoured bedrock sites (1.19 m^3 (42.02 ft^3)).

If observed sediment losses were scaled from the 16% survey sampling distribution(65% of road survey sites, 93.27 m^3) 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 14). If scaled to the entire North Shore watershed representing the estimated 1346 crossings that may exist, an estimated eroded volume of 348.41 - 2,324.59 m^3 may have occurred. This calculation assumes material may have been transported to nearby water bodies (stream, lakes, wetlands) or nearby riparian areas. Note, the limited dataset for this project along with unequal sampling distribution in regards to geomorphic factors and characteristics may not adequately represent total erosion occurrences within the North Shore watershed as a whole as this project represents only 4% of the total watershed and with observations occurring at only one site visit.

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.

Road Segment Factors

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), road surface type, hillslope angle, planar distance (roadside to stream), traffic and width of shoulder material. On a road segment wide basis, **traffic use** measured as (0 indicating low use or minimum maintenance roads, 1 indicating medium or high traffic roads) was found to be the best predictor of erosion although this was not a significant relationship (p= 0.1326 alpha=0.05, weighted AIC = 0.54) (Table 15).

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 found to be the **width of shoulder materia**l, a significant relationship, (p value equal to 0.0097, alpha=0.05, weighted AIC=0.60) (Table 15).

Environmental Factors

Presence / Absence logistic regression – Environmental Factors

A stepwise logistic multiple regression test determined the best environmental drivers for the occurrence of erosion. Explanatory variables included surficial geology, watershed water quality association (impaired, control), Stahler stream order, 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) were watershed water quality association (control, impaired) and soil k factor although this was not a significant relationship, (p value = 0.1899, weighted AIC= 0.62) (Table 15).

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 environmental 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 (p= 0.0171, alpha=0.05, weighted AIC = 0.58) (Table 15).

All characteristics

Presence / Absence logistic regression – All characteristics

When all road segment and environmental characteristics were grouped and tested to determine the presence of erosion using a stepwise logistic multiple regression test ; hillslope position was found to be the best predictor although this was not a significant relationship (p=0.1195, alpha=0.05, weighted AIC = 0.39) (Table 15).

Total volume of erosion multiple linear regression

Using stepwise linear regression tests, hillslope position and road supply factors were found to best predict the total eroded volume within the dataset; this relationship was significant (p=0.0056, alpha=0.05, weighted AIC = 0.43) (Table 15).

Tables

Table 10. 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%	57.1%	67.9%
% 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 11. 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	9	28	13	41	27	27
# of sites with erosion	11	7	17	10	25	16	19
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 [a]	464.78 [a]	354.39	465.00*	382.39	436.74*	367.81
Road to stream distance (ft)	3.29	1.98	5.94 [a]	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 (alpha = 0.05).*

Table 12. Erosion by elevation

Water Quality	Geomorphic attribute	Road Surface	Elevation (m)	Sum of total (minus outliers)
Control				
	Scoured Bedrock Uplands	*Gravel*	472-520	0.00
			522-574	1.53
		Native	472-520	0.23
		Paved	472-520	0.00
	Superior Lobe	*Gravel*	189-301	0.03
			350-393	0.17
			395-468	0.43
			522-574	0.00
		Native	350-393	0.00
			395-468	0.00
			522-574	0.07
		Paved	189-301	0.00
			350-393	0.03
			395-468	0.32
			472-520	0.00
			522-574	0.01
Impaired				
	Scoured Bedrock Uplands	*Gravel*	472-520	0.41
			522-574	0.00
		Native	395-468	0.00
		Paved	298-319	0.55
			304-333	0.00
			350-393	0.00
	Superior Lobe	*Gravel*	350-393	0.00
			472-520	2.34
		Native	350-393	2.21E-04
			472-520	0.72
		Paved	189-301	2.55
			298-319	1.08E-03
			304-333	5.39
			350-393	0.00
			522-574	0.00

Table 13. 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)	Mean average site erosion (minus outliers)
Gravel	*Control*	*Scoured Bedrock Uplands*	3	1.53	1.53	0.25
		Superior Lobe	8	0.63	0.63	0.02
	Impaired	*Scoured Bedrock Uplands*	4	0.41	0.41	0.09
		Superior Lobe	2	2.34	2.34	1.17
Native	*Control*	*Scoured Bedrock Uplands*	1	0.23	0.23	0.23
		Superior Lobe	5	0.07	0.07	0.01
	Impaired	*Scoured Bedrock Uplands*	1	13.77	0.00	0.52
		Superior Lobe	2	0.72	0.72	0.35
Paved	*Control*	*Scoured Bedrock Uplands*	1	0.00	0.00	0.00
		Superior Lobe	9	53.35	0.36	0.02
	Impaired	*Scoured Bedrock Uplands*	3	12.27	0.55	0.29
		Superior Lobe	15	7.94	7.94	0.08

** Note "mean average site erosion" is the mean average of measured erosion per site, average erosion was calculated as the average volume of all erosion observations (gully, rill, mass erosion) measured per site.*

Table 14. Scaled erosion volume for North Shore Watershed

Type of observation	**Definition**	**Total erosion (m^3)**
Field Observations	All erosion (m^3)	93.26
	Excluding outliers (m^3)	14.78
Study watersheds	**Estimated crossings**	342
	Scaling factor (16%)	6.25
Estimated total erosion	All erosion (m^3)	582.88
for study watersheds	Excluding outliers (m^3)	92.38
North Shore watershed	**Estimated crossings**	1346
	Scaling factor (4%)	24.93
Estimated total erosion	All erosion (m^3)	2324.59
for North Shore watershed	Excluding outliers (m^3)	348.41

Table 15. Erosion prediction model outputs

Road segment characteristics	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Presence/Absence of erosion (Logistic regression)					
Erosion ~ Traffic	77.05	0.00	1.00	0.54	0.1326
Erosion ~ Traffic + avg. Road Segment length (length)	78.46	1.41	0.49	0.27	
Erosion ~ Traffic + Road length+ Vegetation type (hillslope)	79.79	2.74	0.25	0.14	
Erosion ~ Traffic + Road length+ Vegetation type (hillslope)+Rd. Area	81.40	4.35	0.11	0.06	
Volume prediction (Stepwise multiple linear regression)					
log(Erosion Volume)~ Width shoulder material (road supply)	79.25	0.00	1.00	0.60	0.0097
log(Erosion Volume)~ Road supply + avg. Road Segment length (length)	80.93	1.68	0.43	0.26	
log(Erosion Volume)~ Road supply + Road length + Stream order	82.87	3.62	0.16	0.10	
log(Erosion Volume)~ Road supply + Road length + Stream order + avg. Road width	84.71	5.46	0.07	0.04	
Environmental characteristics					
Presence/Absence of erosion (Logistic regression)					
Erosion ~ K factor + Water Quality group (impaired, control)	77.91	0.00	1.00	0.62	0.1899
Erosion ~ K factor + Water Quality group	79.69	1.78	0.41	0.25	
Erosion ~ K factor + Water Quality group + Geomorphic Assoc.	81.68	3.77	0.15	0.09	
Erosion ~ K factor + Water Quality group + Geomorphic Assoc. + Stream order	83.68	5.77	0.06	0.03	
Volume prediction (Stepwise multiple linear regression)					
log(Erosion Volume)~ Hillslope position (0-10%, 10%, 10-25%)	79.54	0.00	1.00	0.58	0.0171
log(Erosion Volume) ~ Hillslope position + Geomorphic Assoc.	81.08	1.54	0.46	0.27	
log(Erosion Volume)~ Hillslope position + Geomorphic Assoc. + k factor	82.99	3.45	0.18	0.10	
log(Erosion Volume)~ Hillslope position + Geomorphic Assoc.+ K factor + Stream order	84.86	5.32	0.07	0.04	
All characteristics	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
Presence/Absence of erosion (Logistic regression)					
Erosion ~ Hillslope position (0-10%, 10%, 10-25%)	76.93	0	1.00	0.39	0.1195
Erosion ~ Hillslope position + receiving hillslope vegetation type	77.48	0.55	0.76	0.30	
Erosion ~ Hillslope position + vegetation type + Water Quality group	78.23	1.3	0.52	0.20	
Erosion ~ Hillslope position + vegetation type + Water Quality group + critical angle of receiving hillslope	79.39	2.46	0.29	0.11	
Volume prediction (Stepwise multiple linear regression)	**AICc**	**Δi**	**likelihood of model**	**wi**	**p value**
log(Erosion Volume) ~ Hillslope position + Road supply	76.51	0.00	1.00	0.43	0.00576
log(Erosion Volume) ~ Hillslope position + Road supply + Geomorphic Assoc.	77.06	0.55	0.76	0.33	
log(Erosion Volume) ~ Hillslope position + Road supply + Geomorphic Assoc.+ avg. Road length	78.56	2.05	0.36	0.16	
log(Erosion Volume) ~ Hillslope position + Road supply + Geomorphic Assoc.+ avg. Road length + Traffic (0,1)	79.85	3.34	0.19	0.08	

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 rate and ultimate scale 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 93.26 m^3 (3,293.5 ft^3) or 7.64 m^3/km (434.5 ft^3/mile). 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 93.26 m^3 (scaled to estimate total losses within study watersheds: 92.38 m^3 or 528.88 m^3 (including outliers)). Without a comparison study of road erosion rates for the North Shore of Minnesota this study compares total sediment losses observed in this study to literature findings. In a 2007 synthesis study by Cafferata, Coe and Harris road erosion rates from various research investigations were investigated across California. Road related erosion rates were estimated to range from 90 m^3/km to 5200 m^3/km for the Coastal ranges of California. Within this context the North Shore study compares much lower with an estimated erosion rate of 7.64 m^3/km. A comparison of coastal California road erosion rates to Northern Minnesota is not ideal considering the regional variations in climate, geology, topography and road construction practices that may drive distinct differences in geomorphic processes between the two study areas.

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 water bodies. 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 decreases to 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 and rill 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, of that 6% of sites were 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).

A total of 6% of study sites were directly connected to the stream network via gullying, the remaining 25% were observed to convey sediment and runoff diffusely onto vegetative surfaces. If this study were completed over time and monitored during and after precipitation events, observed “connected channels” would surely increase. Within the literature many long term investigations have observed the legacy effects of road-stream connectivity. For instance, a 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. 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. The literature gives clues to the potential extent of road-stream connectivity within the North Shore. Considering this project compiled a short term observational dataset, it is unclear if the observations in field are a short term or long term effect of road-stream connectivity. The legacy effects of road-stream connectivity may be currently unknown for study watersheds without an increased dataset or long term monitoring effort.

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 width, 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.

<u>Cut and Fill slopes</u>

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 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 (*Fill* only: 20 gullies (16 survey sites)). Much of the observed erosion is estimated to result from increases in surface road runoff with flowpath induced erosion occuring on 41% of the sample set at sites with fillslopes, 30% at sites with cutslopes, 17% at sites with both cut and fillslopes. 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%. Although slope construction was observed to characteristically define different modes of runoff ultimately inducing erosion at survey sites, it is not known with certainty if slope construction was the dominating road variable or if other conditions also were at play.

Modeling erosion presence and volume

Considering the findings of Wemple et al., (2001) whom described road type, placement, condition, hillslope vegetation, watershed geology and storm characteristics as major contributors to observed sediment losses; study variables were modeled to find predictors of erosion. Using logistic regression at the road survey site and watershed level field observations and key environmental variables were tested separately. This was to allow for possible separation of road specific and watershed specific factors.

Model predictions: Road survey site

Presence of Erosion: Traffic

Survey sites were visited once in the summer of 2010, due to this singular observation this study assumes observed traffic patterns may fluctuate by the hour, weekday and seasonally. Therefore traffic density (low, medium, high) was not characterized nor tested. 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 = 0.54). 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=0.60). 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.

Environmental 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) suggests 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 (1^{st} order- 21 sites, 2^{nd} order - 14 sites, 3^{rd} order- 11 sites) (Figure 14). Past studies indicate roads on 1^{st} 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: Environmental 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= 0.62). 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

Investigating the role of environmental drivers, observed erosion was best predicted by contributing hillslope gradient (p = 0.0171, weighted AIC = 0.58). 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 - 14.4 m^3 (13% - 15% of observed erosion) on shallow soiled scoured bedrock parent material; and 0.11 – 55.82 m^3 (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 lower 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

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, at various elevations, road surface types, and soil type.

Conclusions and Future Work

This project investigated the extent of road-stream linkages, 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. Results of this exploratory research suggest 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). Therefore future work could employ the methodologies of this project to further investigate the relation of sediment transport to geomorphic attributes.

Lastly, a confined sub-watershed 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

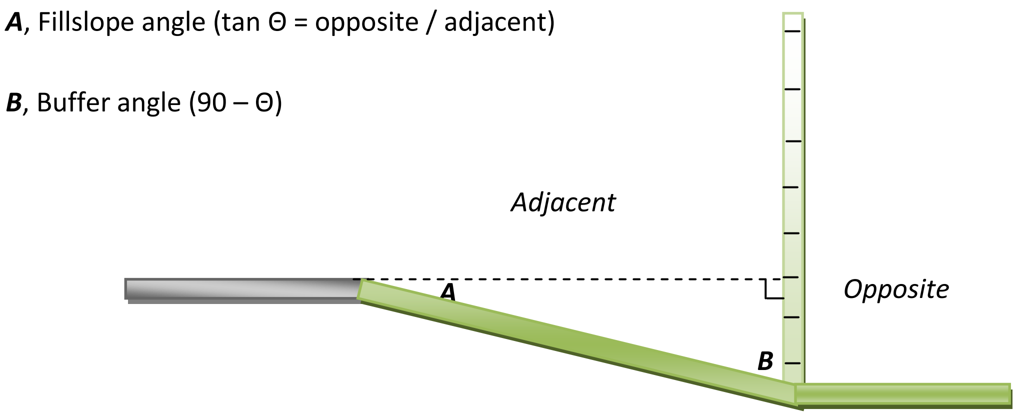


Figure 12. Depiction of ditch measurements and calculation of fillslope, and buffer slope angles

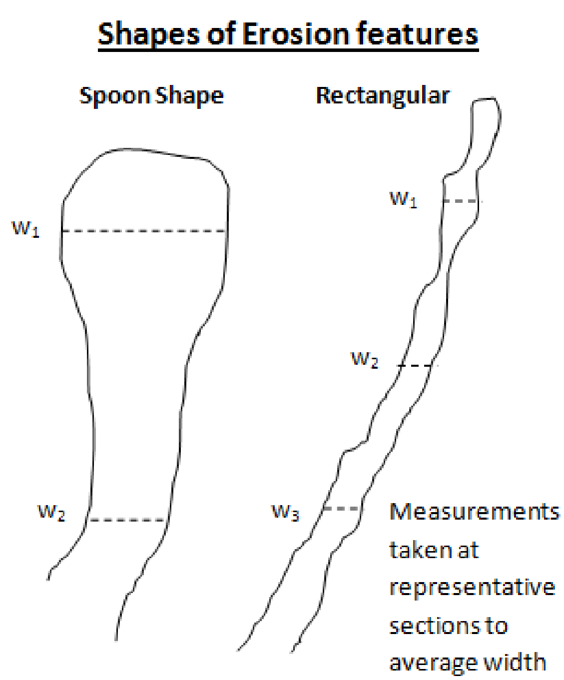
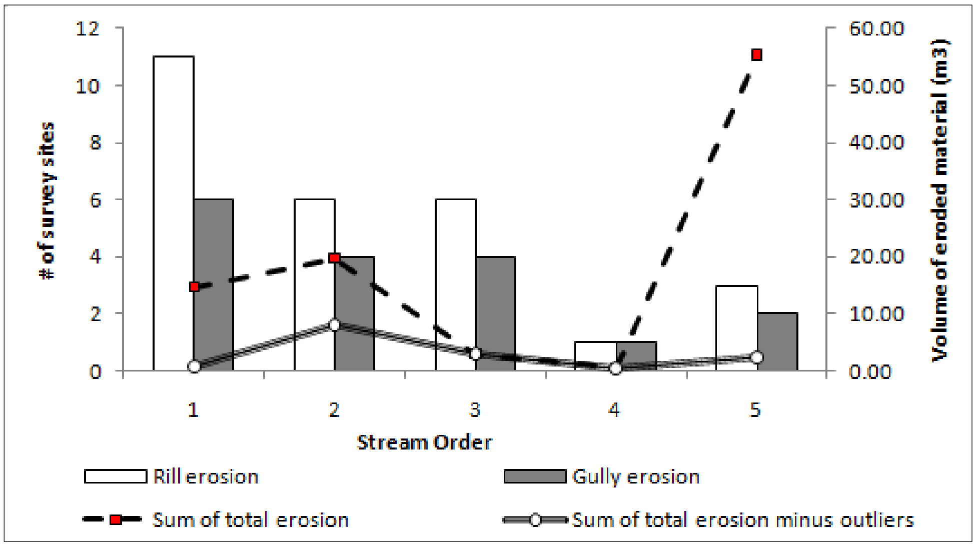


Figure 13. Depiction of measurement locations for erosion features



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

Figure 14. Per site erosion occurrences as a function of stream order

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

The goal of this project was 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. Roads were investigated as possible sediment sources to neighboring waterways (streams, lakes, wetlands). This study 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 to North Shore study 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.

Literature Review

Empirical predictions of stream stability based on imperviousness

Local factors of increased imperviousness 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 watershed areas ranging in size from 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 15). Conclusively this scale predicts sub-watersheds with > 60% IC to be "non functioning" simply acting as conduits for flood waters (Schueler *et al.*, 2009); sub-watersheds with 25% – 60% IC are "non supporting" in that they no longer support hydrologic, channel stability, habitat, water quality or biological diversity uses; sub-watersheds with 10-25% are capable of supporting basic stream functions but are noted to be declining in health, and sub-watershed with IC of < 10% (average ~7%) are sensitive to cover changes but are predicted to retain 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 sub-watershed response can be highly variable based on local conditions (Bledsoe & Watson, 2001).

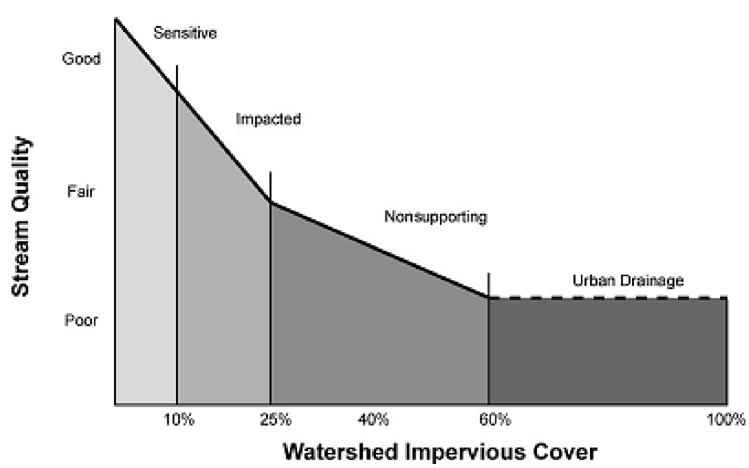


Figure 15. Impervious Cover Model (ICM) (Schueler et al 2009)

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 sub-watershed, with health decreasing as a function of increasing stream crossings (Figure 17) (Alberti *et al.*, 2007).

Studies have reasoned that although stream reach response to watershed development is highly variable, watersheds with less than **<u>~10% imperviousness</u>** 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).

Sub-watershed sensitivity to impervious cover as indicated by stream channel instability is most likely related to storage capacity (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 sub-watersheds 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 sub-watershed (Hammer, 1972). This is a result of the idea that a channel will counteract the changed hydrology of the sub-watershed, recovering to a quasi-stable state. The caveat being, if the sub-watershed 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 storm water 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

An immediate consequence 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).

Focus of this project

This project characterized in-channel stability above and below road-stream crossing structures within sub-watersheds 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.

Figures

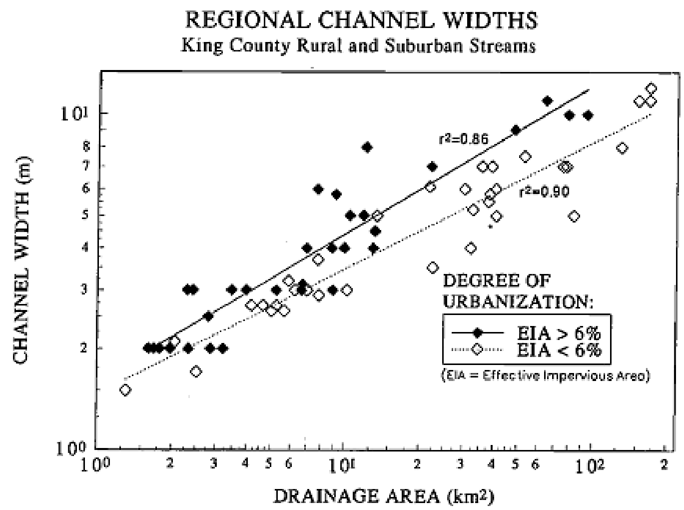


Figure 16. Channel widths as a function of contributing drainage area (Booth and Jackson 1997)

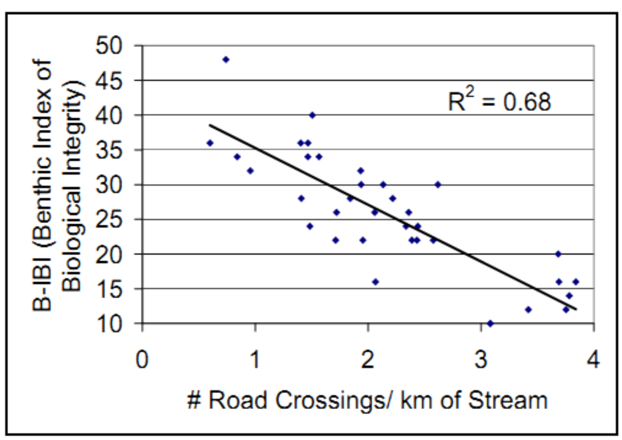
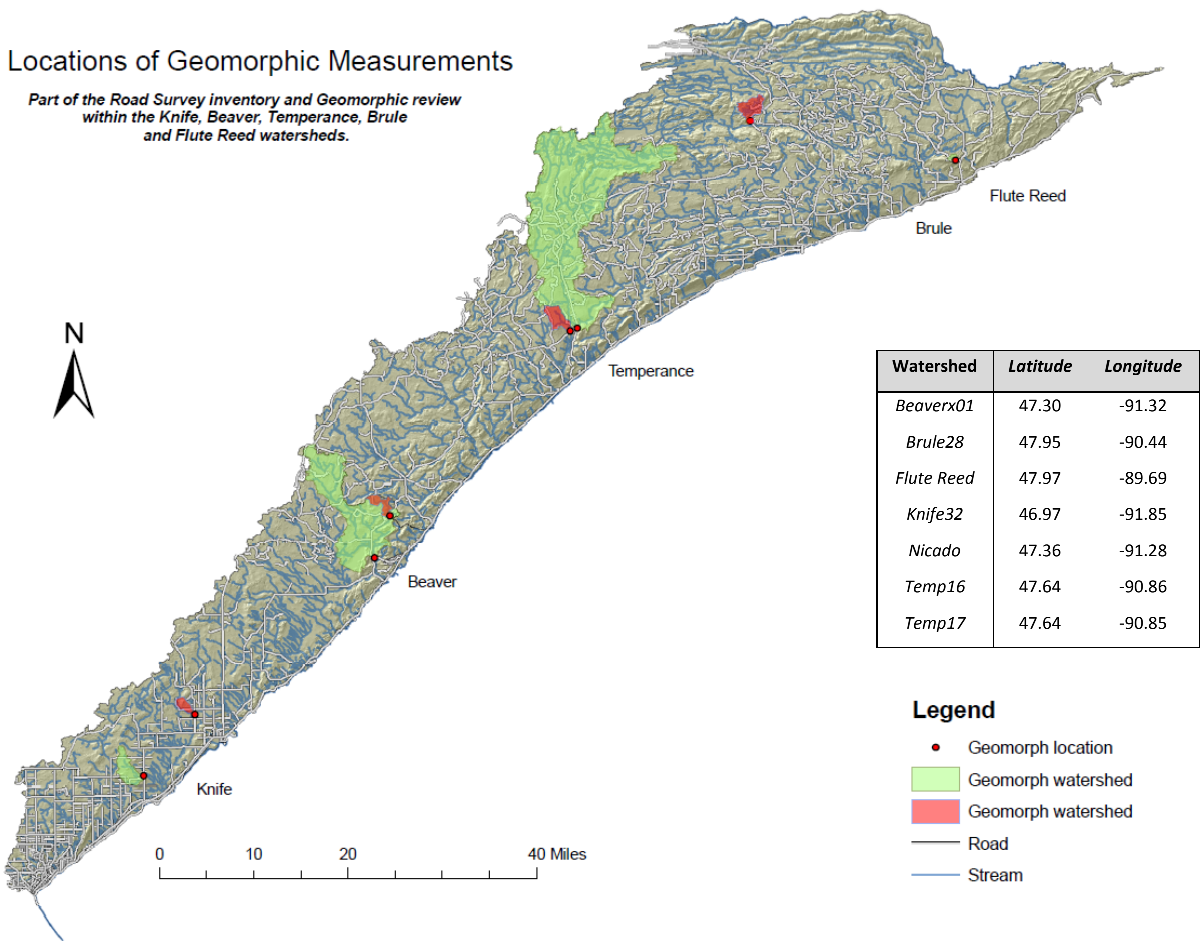


Figure 17. Relationship between stream ecological health and total number of road crossings per km upstream of sampling location (work of Alberti *et al.*, 2007, figure from Avolio, 2003).

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 18. 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 18. 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 19).

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.

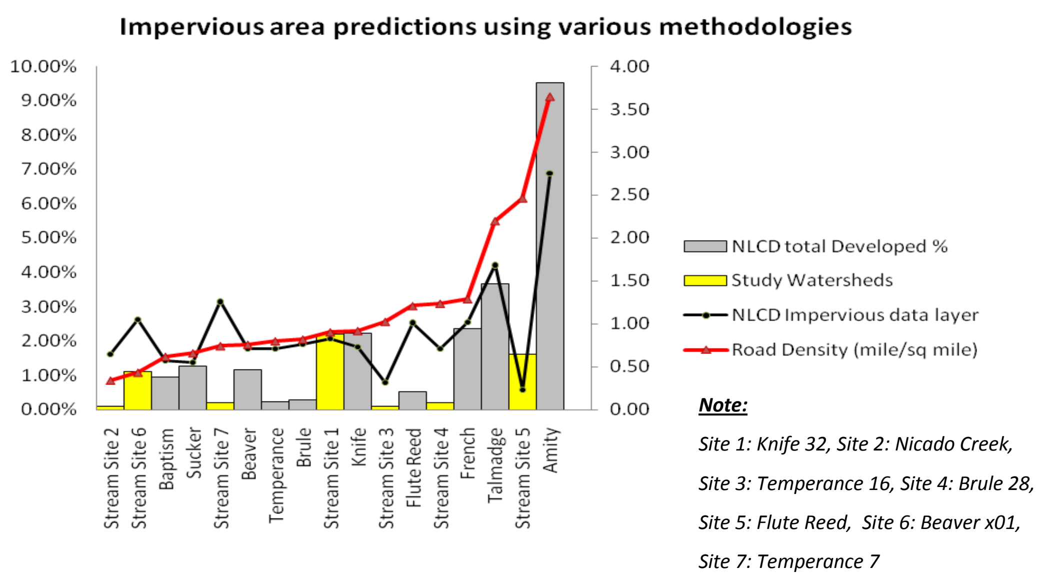


Figure 19. Selected Lake Superior watershed characteristics: Development and open water.

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, a qualitative assessment of channel stability was conducted using the modified Pfankuch channel stability assessment (Pfankuch, 1975, Rosgen, 2006). 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. 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. *Examples of field forms used can be found in the Appendix, Appendices B: Field forms*

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)

For some streams a test of embeddedness was initially carried out following a Wisconsin DNR Fisheries methodology (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 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

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 1st order to 4th 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 21). 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 C. 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* Appendix C. Stream Survey (Table 17, Figure 21).

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%

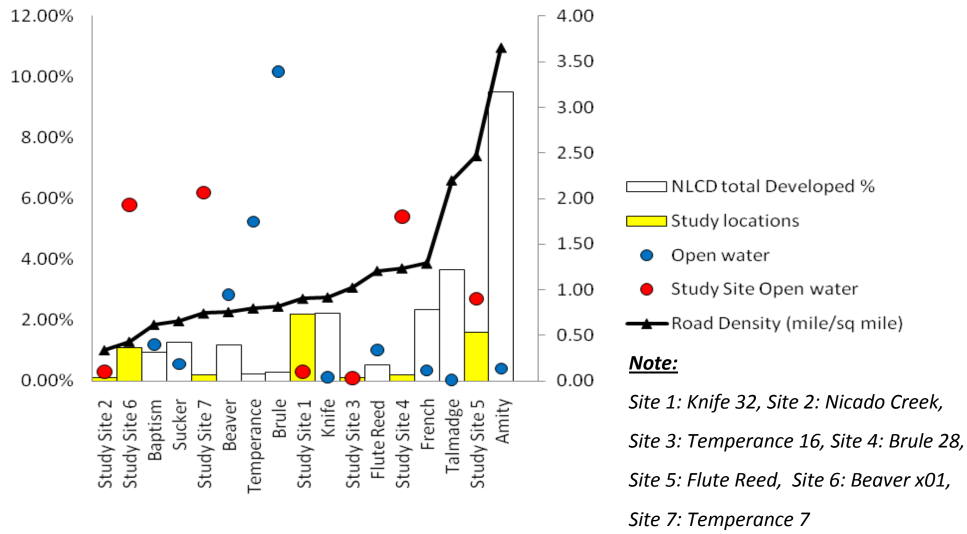


Figure 20. Watershed characteristics for geomorphic and road survey watersheds

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***

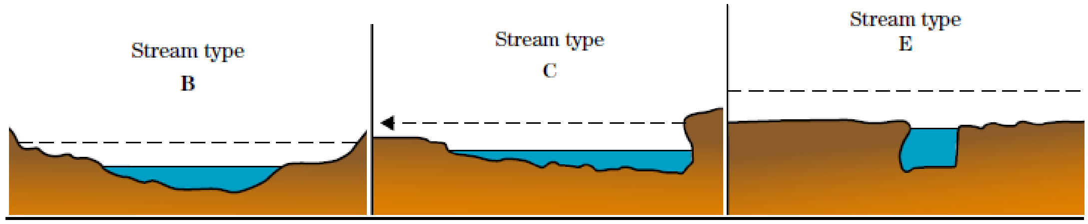


Figure 21. Stream types predominant in stream survey study (NRCS, 2007)

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 22).

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					✓

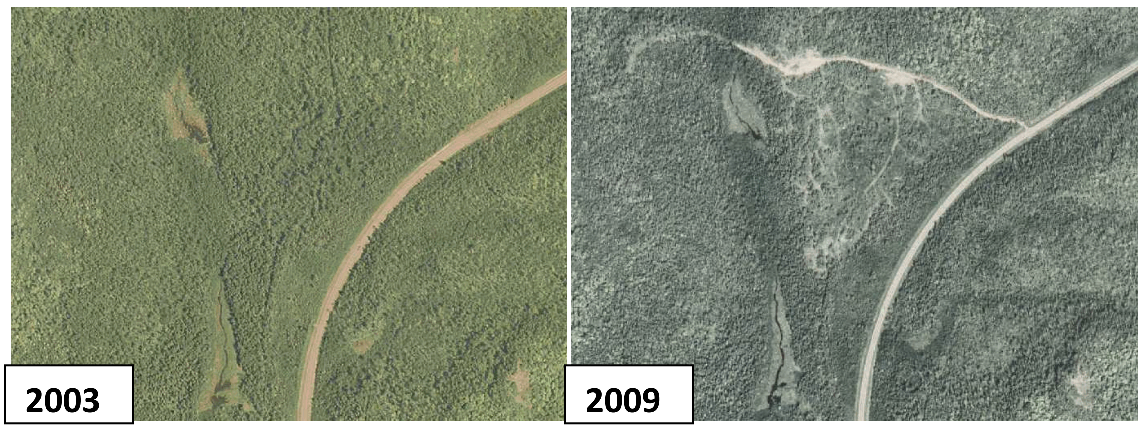


Figure 22. Comparison of land use change detected in Beaver watershed, road survey sites B01-B03 are found on the new road featured in the 2009 photo

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.

Within North Shore watersheds a stable stream condition is occurring in many sub-watersheds. 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 over time. Although many watersheds within the North Shore (outside of the Duluth area) have less than 10% impervious cover, the localized stresses 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 investigate 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% of the dataset) 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. Following the Pfankuch stability assessment methodology, 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). Individual declines were observed in the lower banks and stream bottoms. Categories with observed stream stability were in the upper and lower banks, with notable 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 at all sites with the greatest declines in the upper, lower banks, notably for bank cutting and 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 sub-watersheds 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. An 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. Sub-watershed 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 sub-watershed (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 sub-watershed development due to localized sensitivity to change.

There are also 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 sub-watershed 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 5.11-6.92% within study watersheds . The greatest increase in drainage density was found within the control watersheds, which were more likely to increase drainage density of the stream network at riparian buffer widths 100 ft (6.92%), 50 ft (3.73%), < 10 ft (1.39%); although this was not a significant relationship ($p = 0.6661$, $df = 5.51$, $\alpha = 0.05$).

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 sub-watersheds 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 in-stream 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:

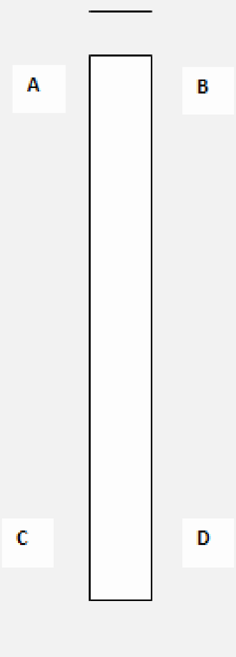
DRAW GULLIES, RILLS, etc

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. 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 23. Soil triangle (USDA)

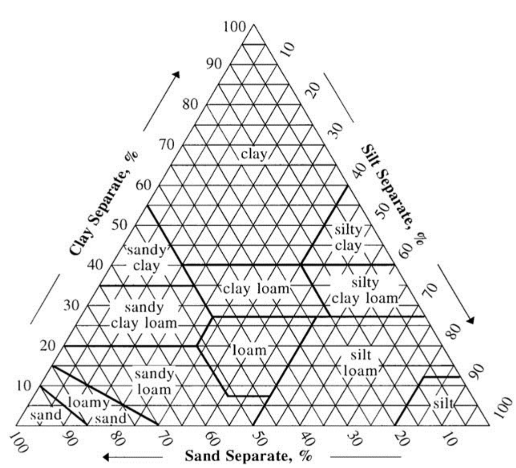


Table 19. Comparisons of soil characterizations using particle size analysis, field texturing, and STATSGO data

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 C. 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

Detailed Steam survey site analysis (upstream -> downstream)

<u>Beaver x01: B3c -> C4</u>

<u>Pfankuch stability</u>: 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.

<u>Brule 28: C4 -> B4c</u>

Pfankuch stability: Good -> Fair

**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.

<u>Flute Reed: B4a -> B4a</u>

Pfankuch stability: 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.

<u>Knife 32: B4c -> B4c</u>

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.

<u>Nicado: E5 -> C3</u>

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.

<u>Temperance 16: E4b -> C4</u>

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.

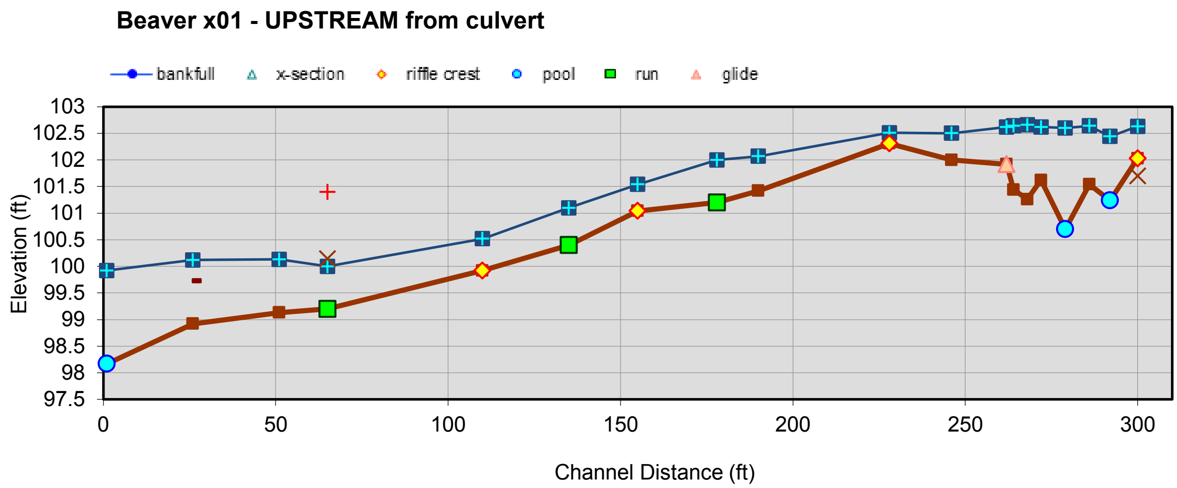
Nicado and the Knife River sites (Knife 32) were found to have a change in meander pattern when analyzed by aerial photography between 1991-2009. This adjustment could be due to a variety of reasons, with most probable cause of channel avulsions due to the presence of the crossing structure. Whereas 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.

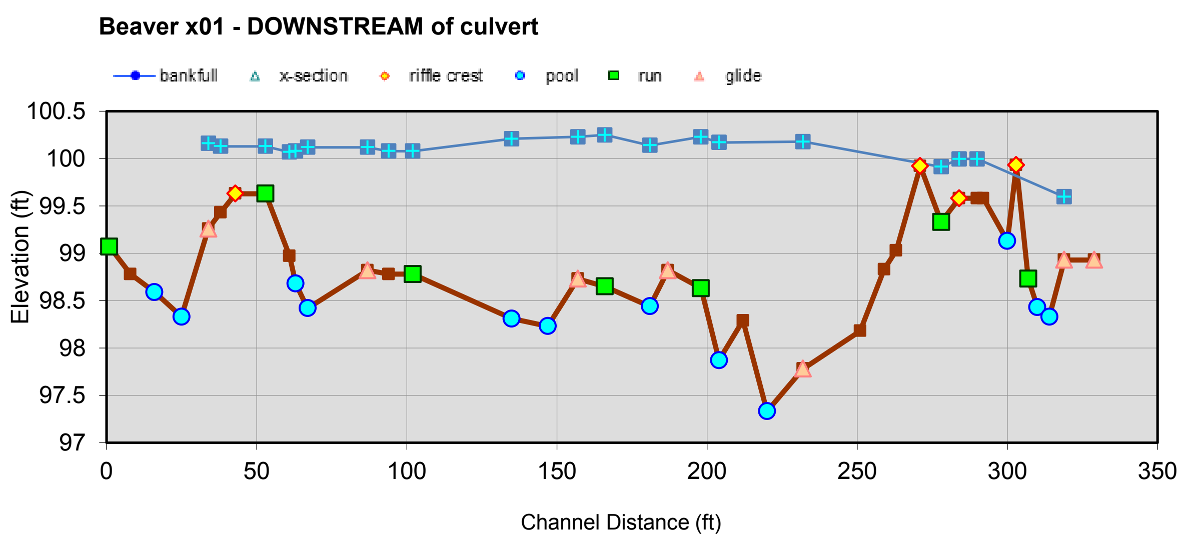
Raw data from field survey

Beaver x01 - Longitudinal profile

Upstream

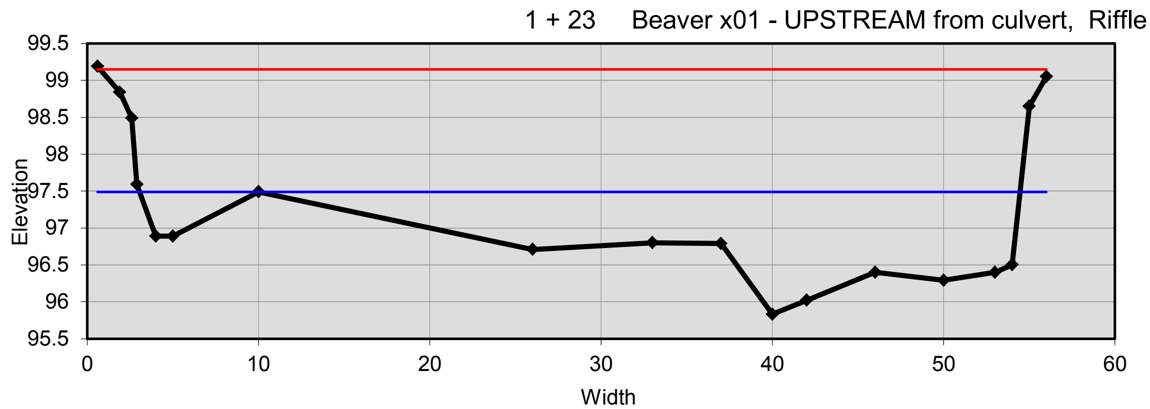


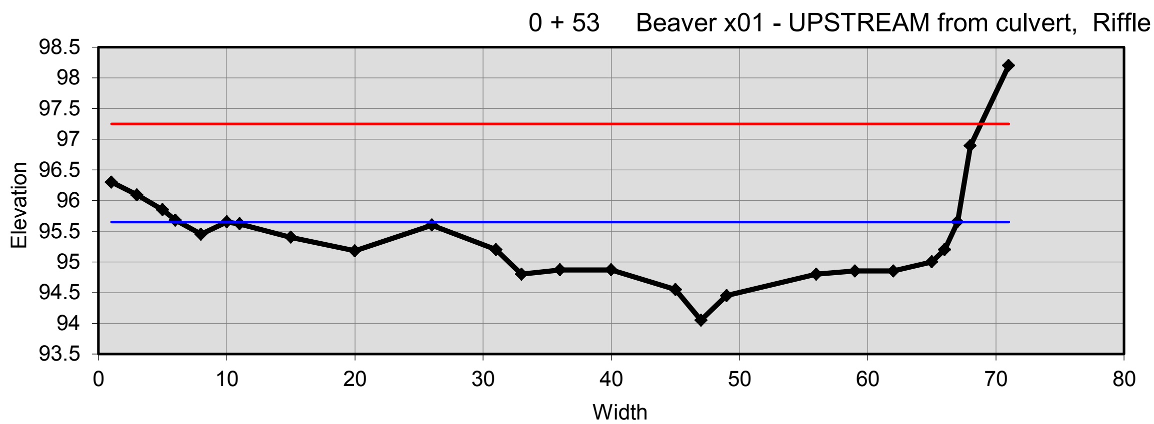
Downstream



Beaver x01 - Cross Sections

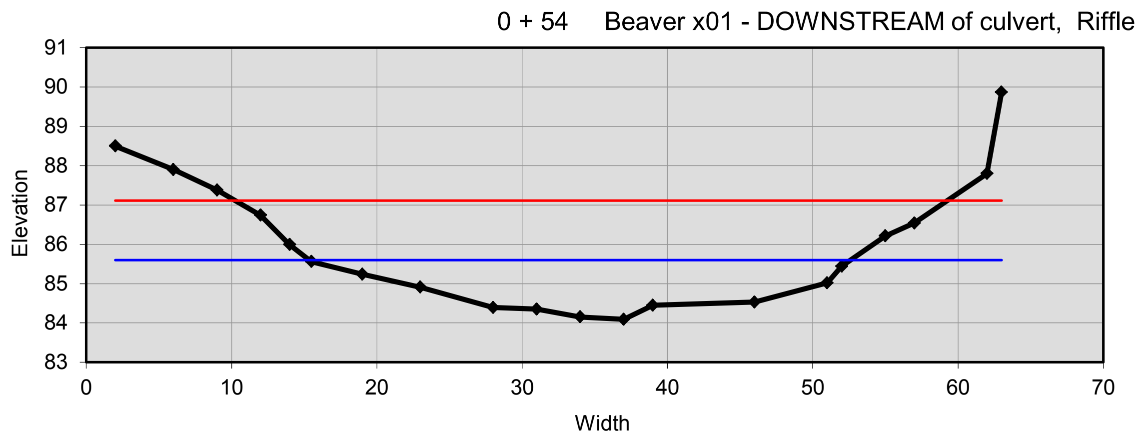
Upstream

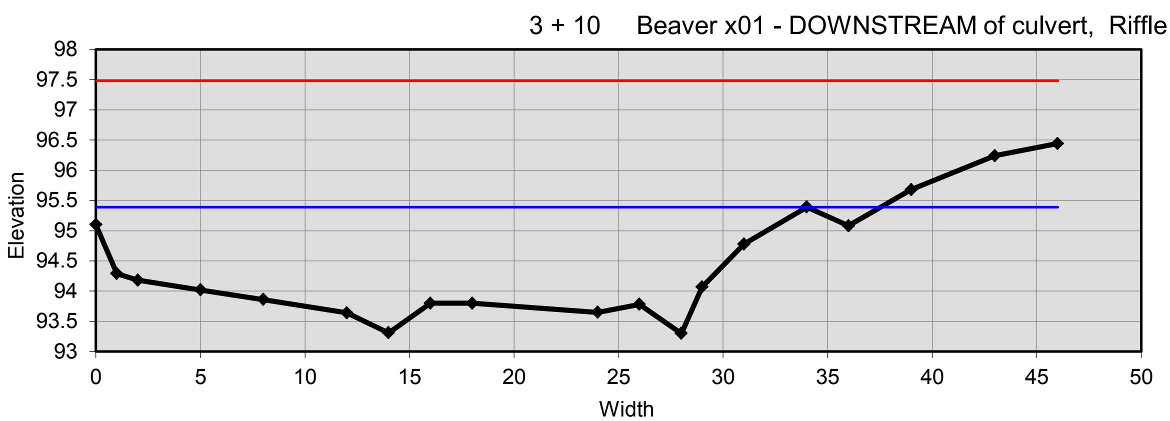




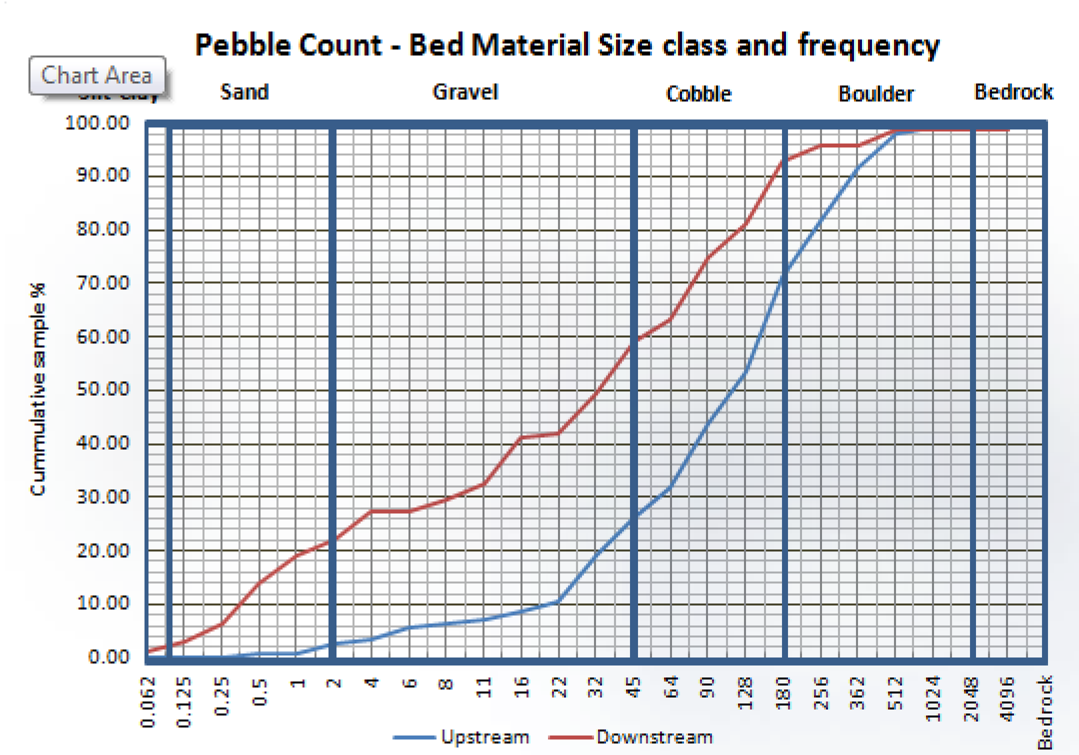
Beaver x01 - Cross Sections

Downstream



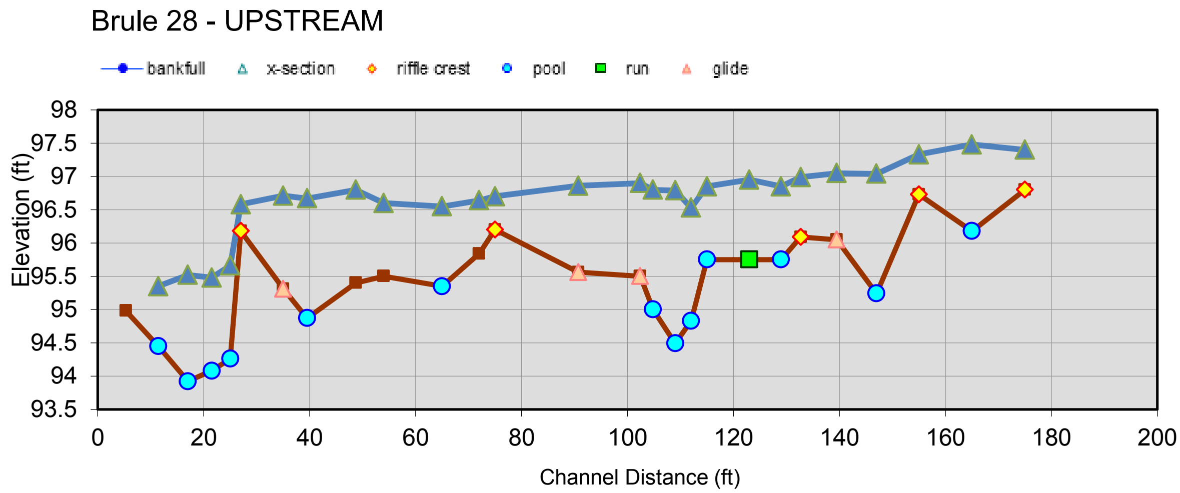


Beaver x01 - Material Composition



Brule 28 - Longitudinal profile

Upstream



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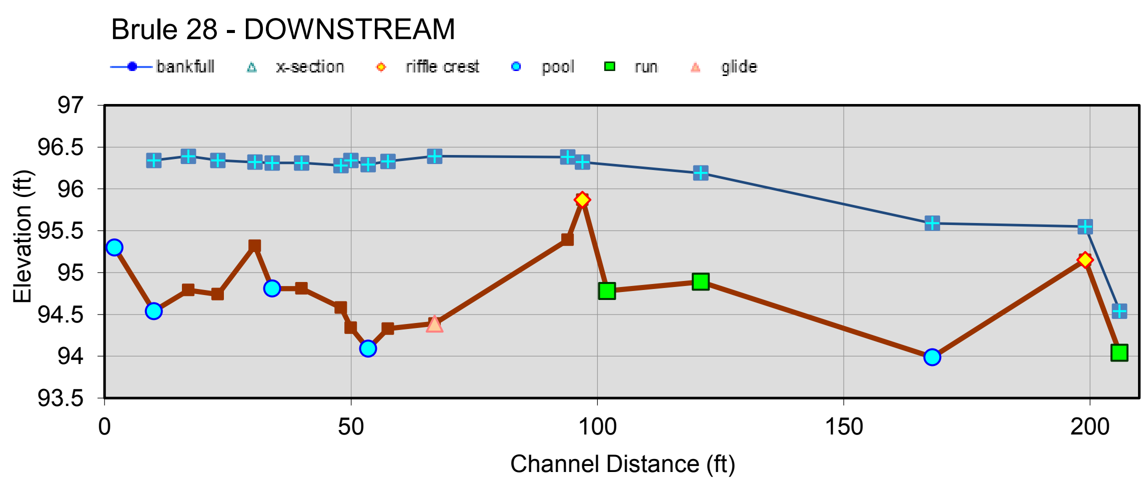
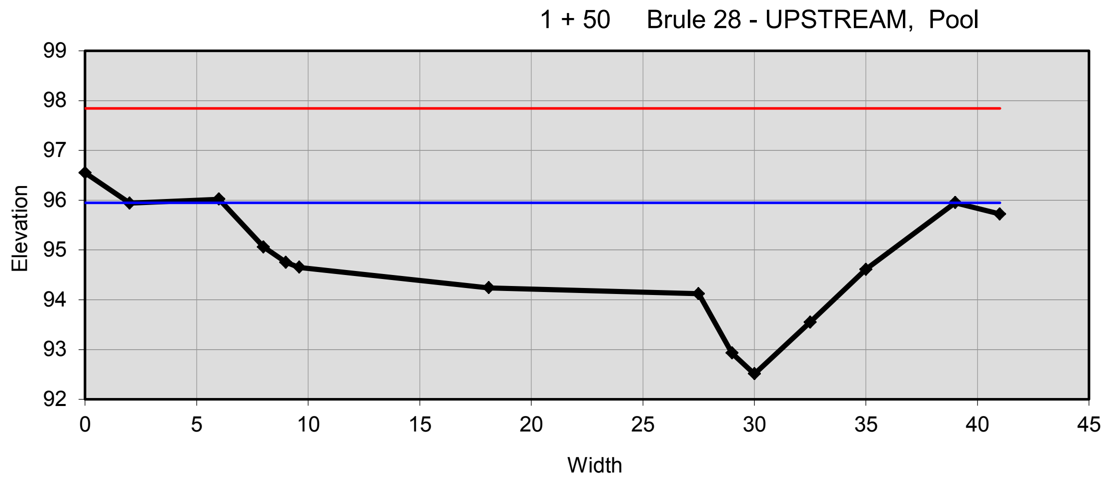
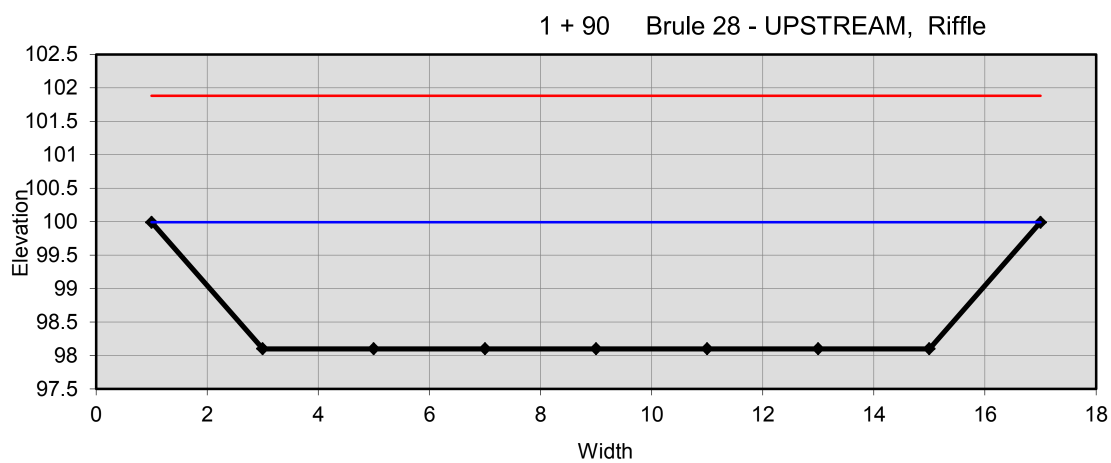


Brule 28 - Cross Sections

Upstream





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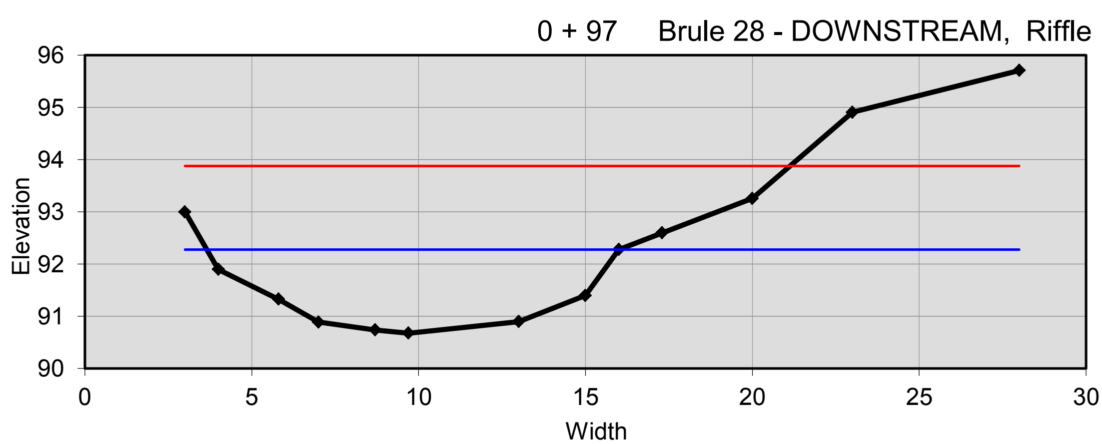
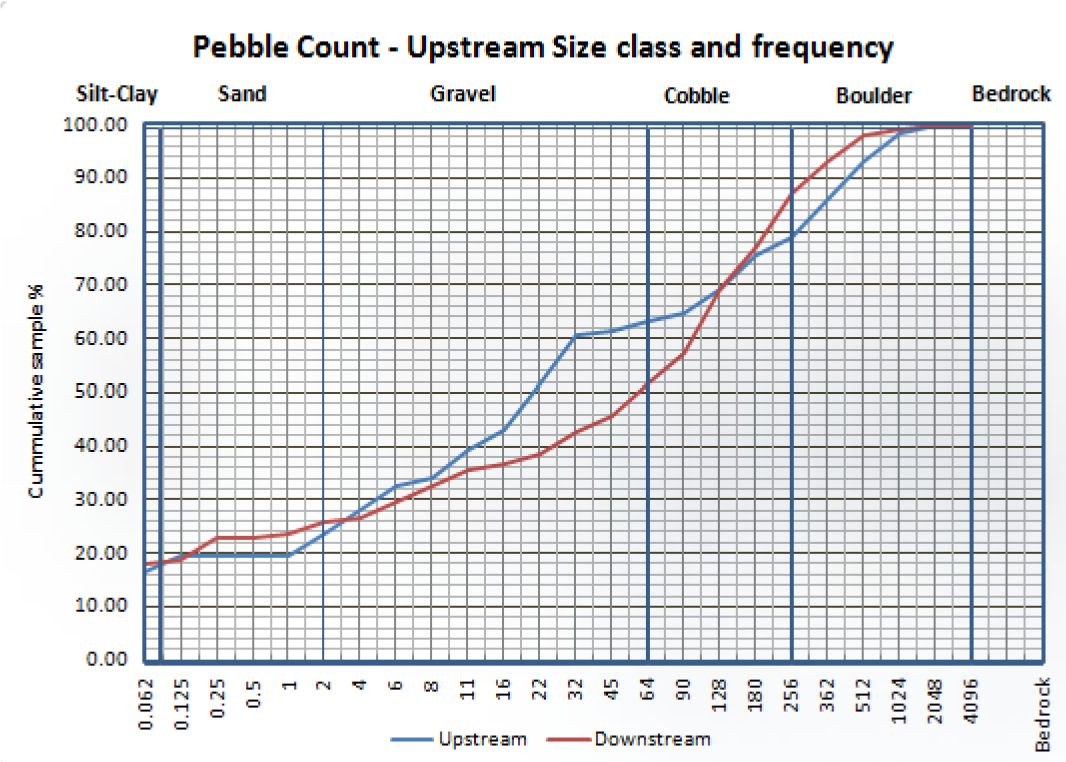
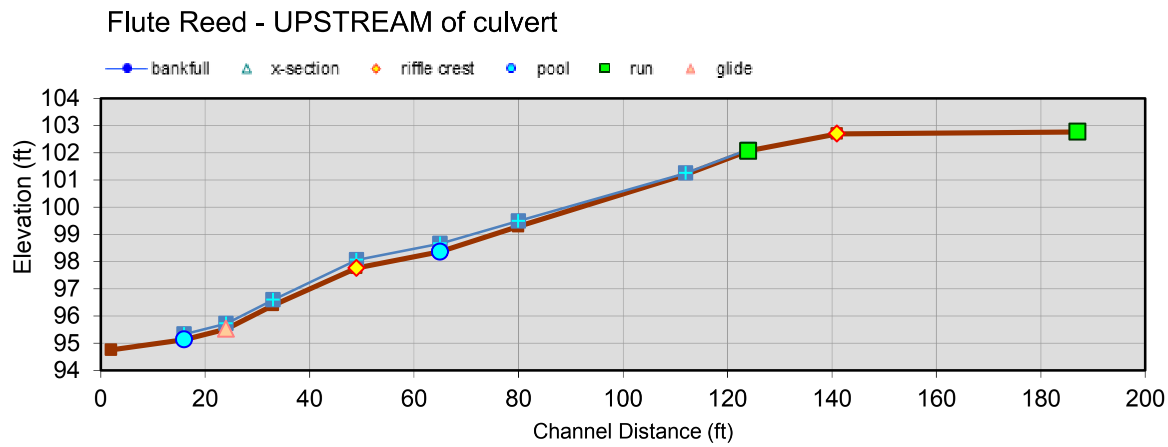


Brule 28 - Material Composition



Flute Reed - Longitudinal profile

Upstream



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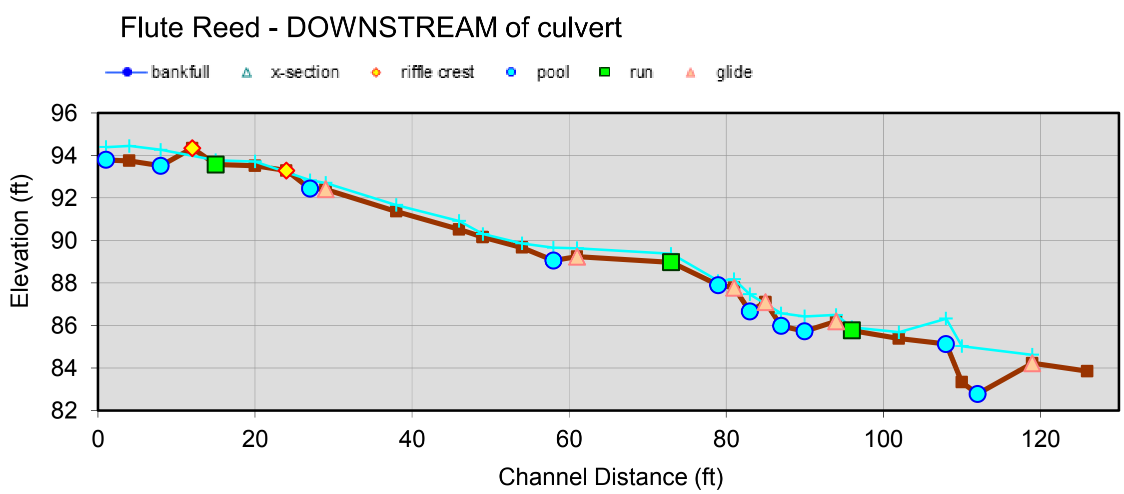
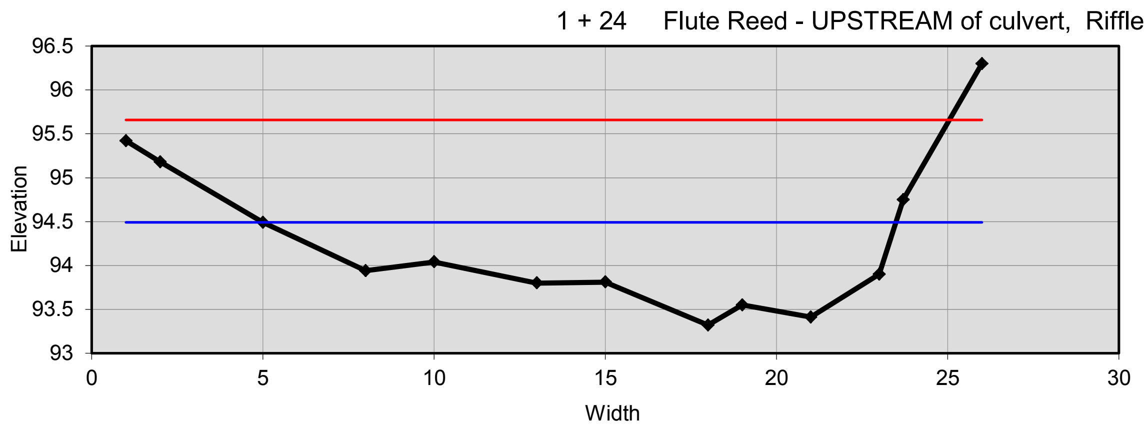
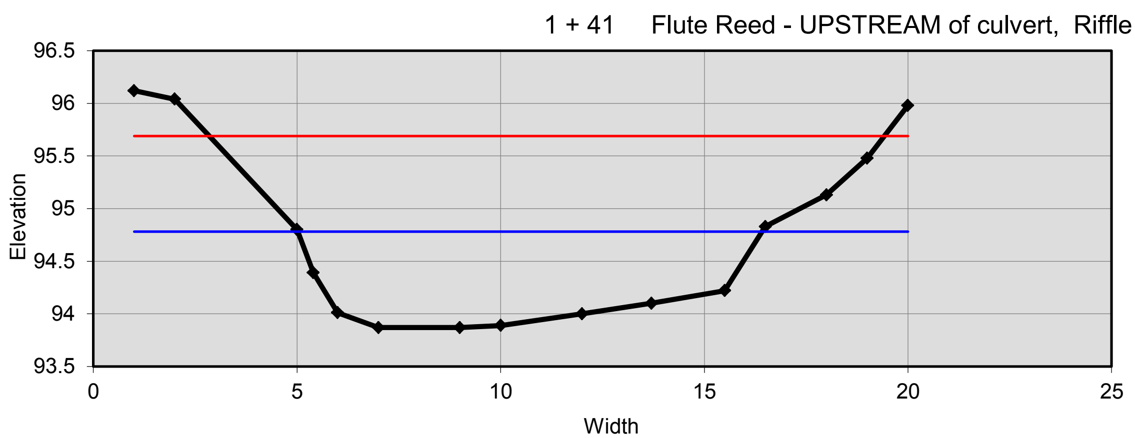


Flute Reed - Cross Sections

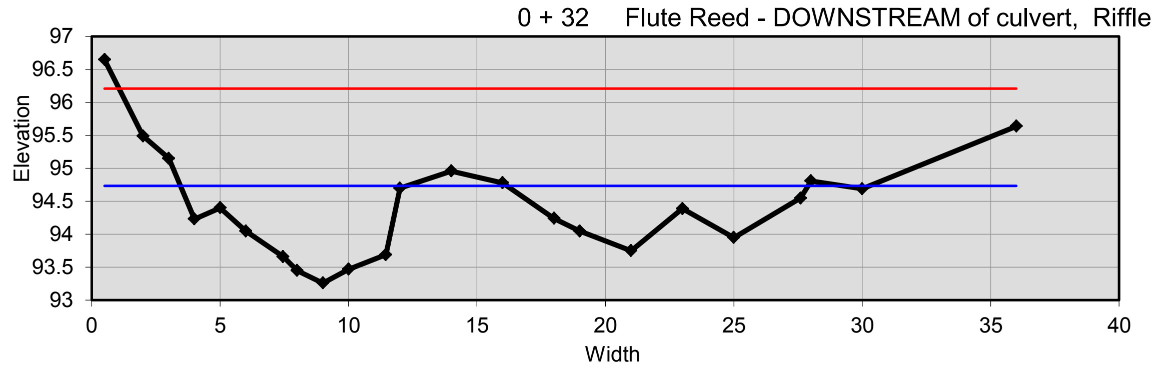
Upstream

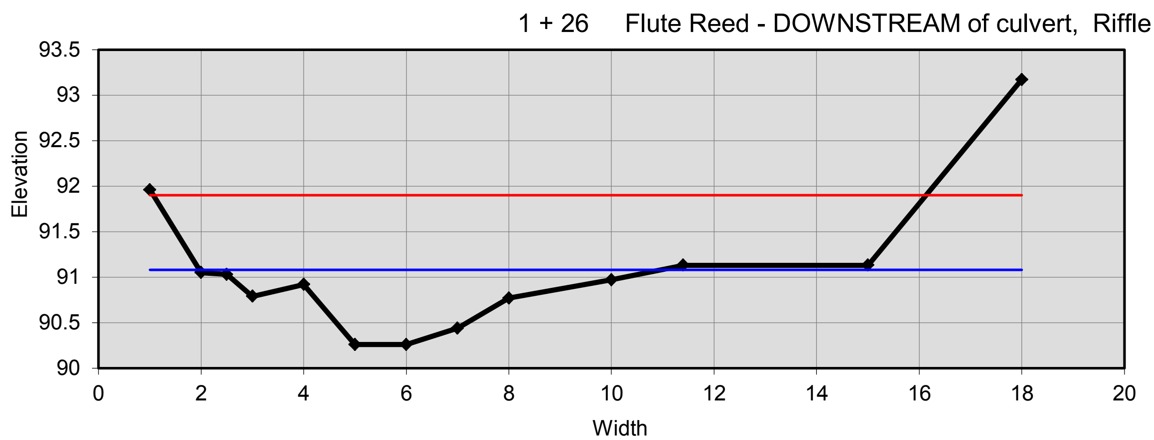




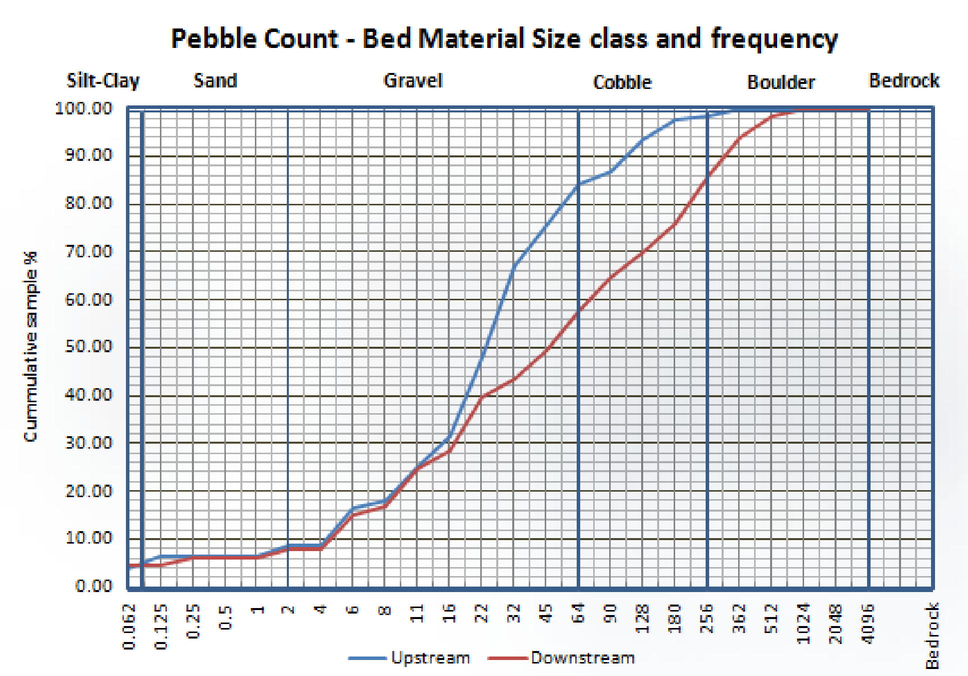
Flute Reed - Cross Sections

Downstream



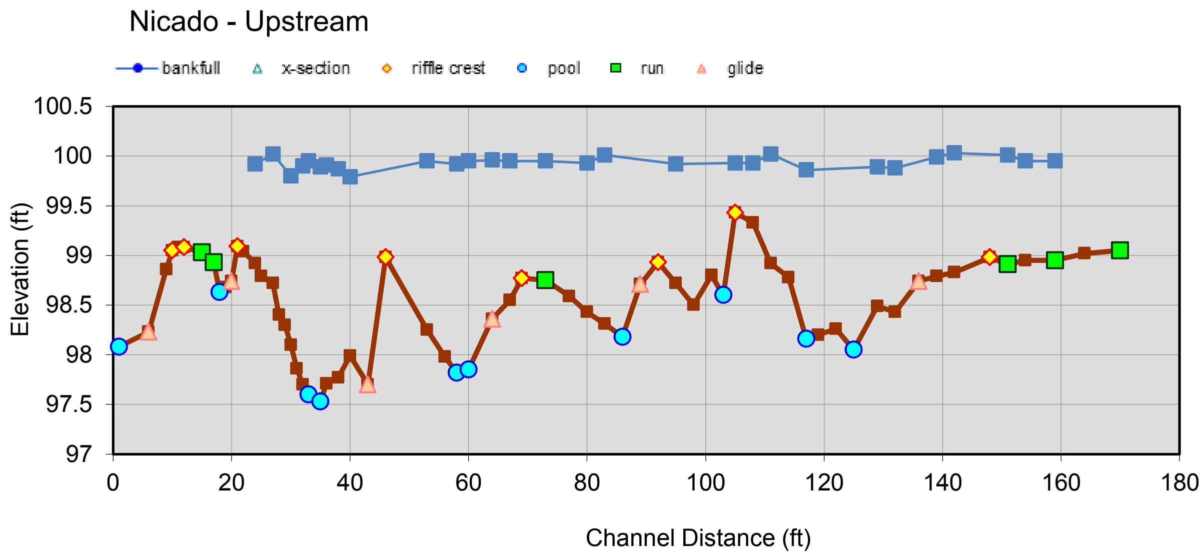


Flute Reed site - Material Composition

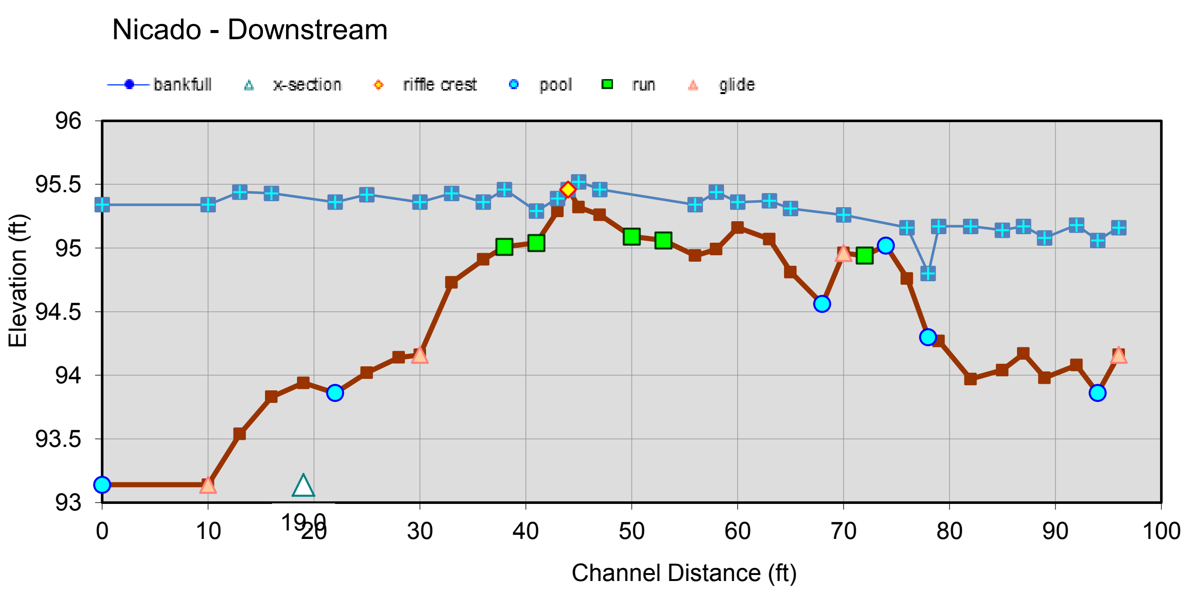


Nicado - Longitudinal profile

Upstream

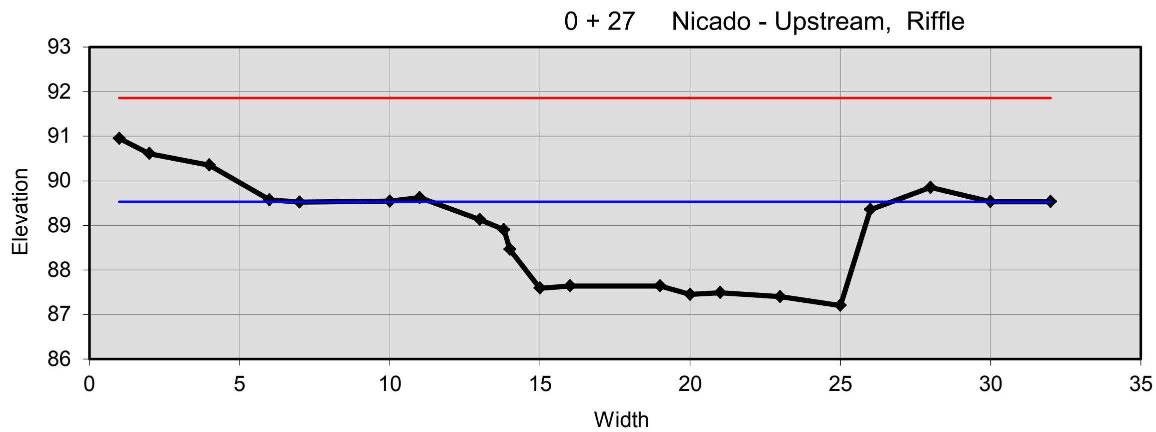


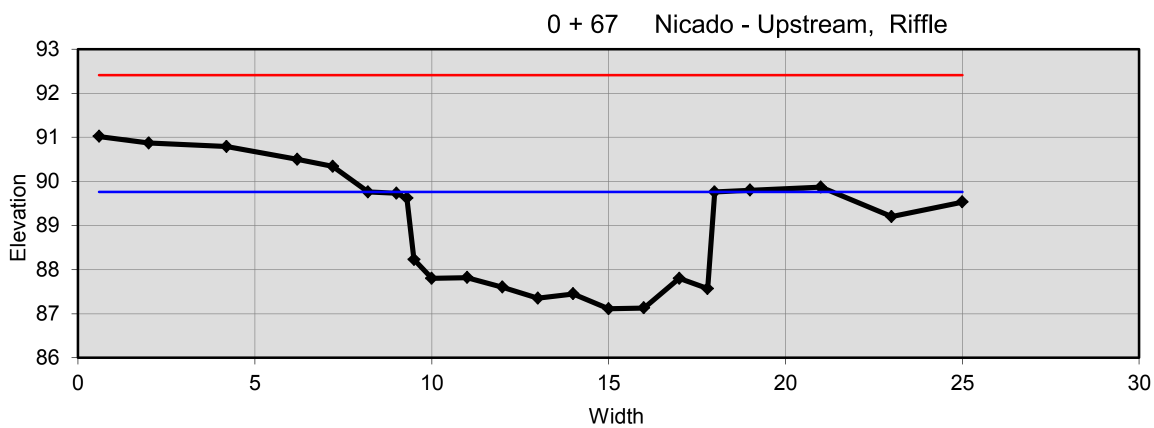
Downstream



Nicado - Cross Sections

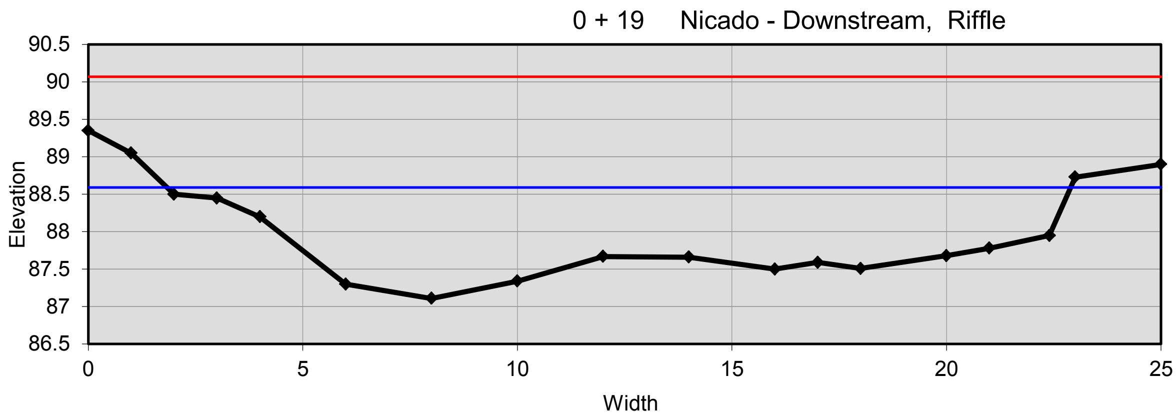
Upstream

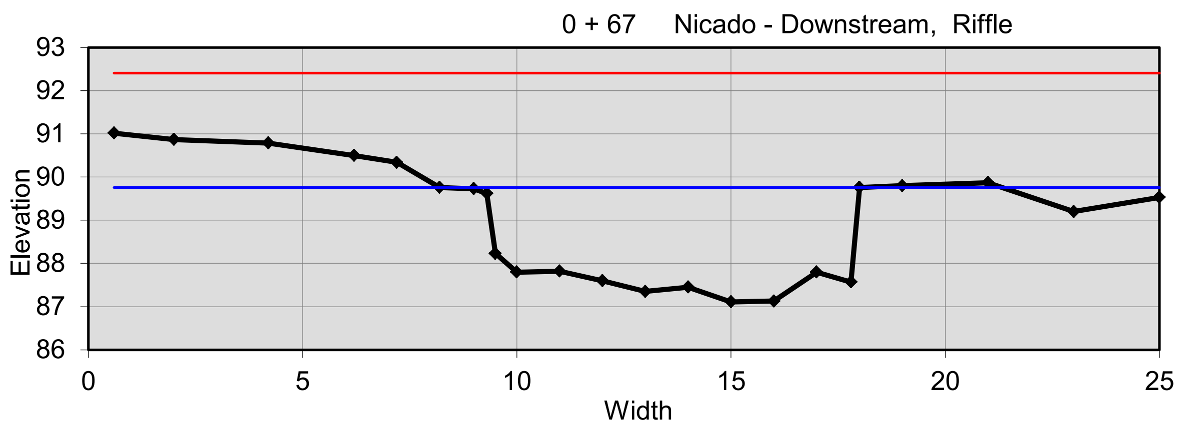




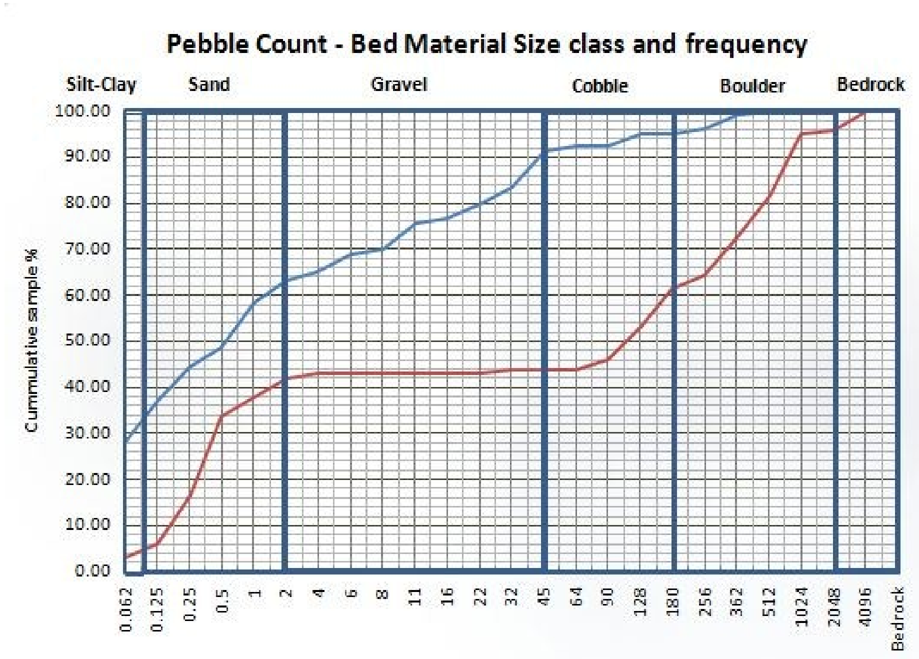
Nicado - Cross Sections

Downstream

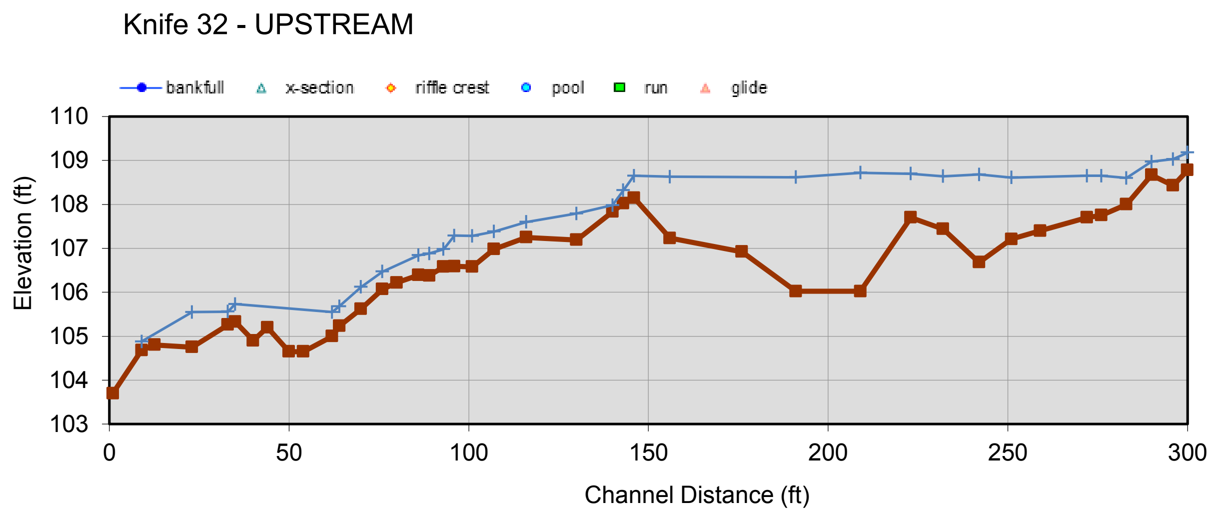




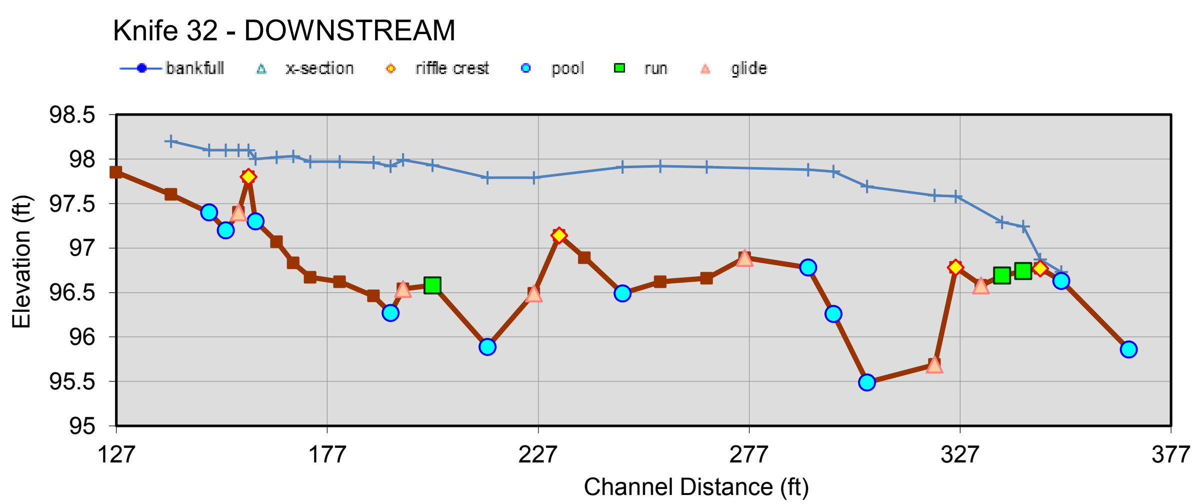
Nicado - Material Composition



Knife 32 - Longitudinal profile
Upstream

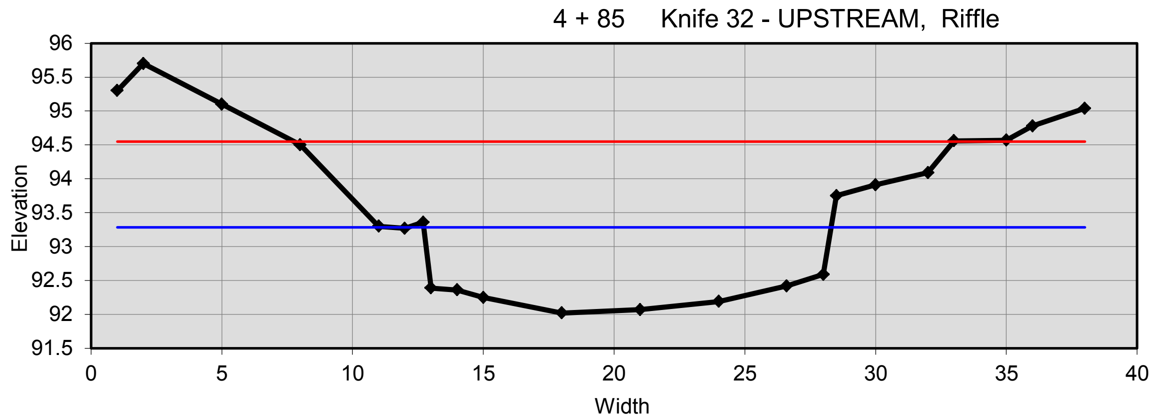


Downstream



Knife 32 - Cross Sections

Upstream



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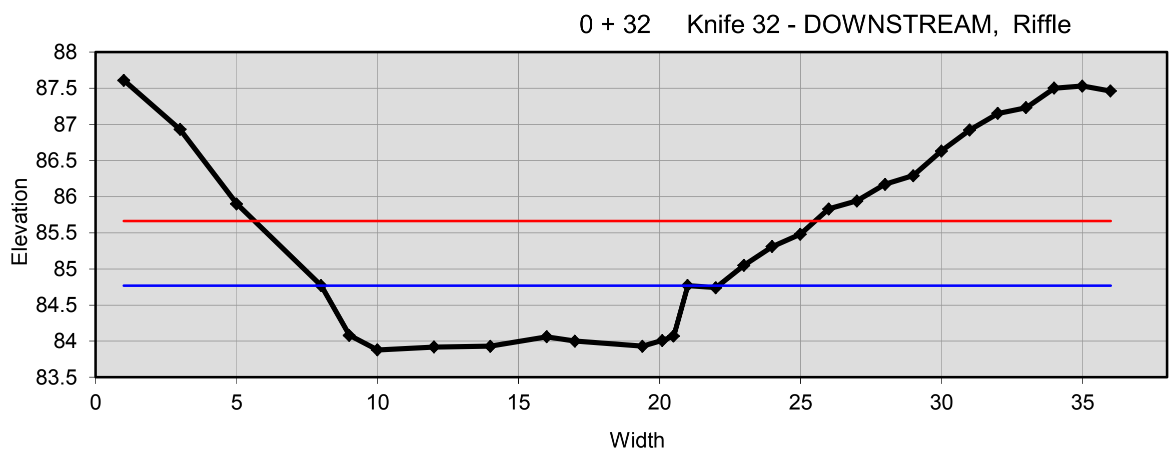
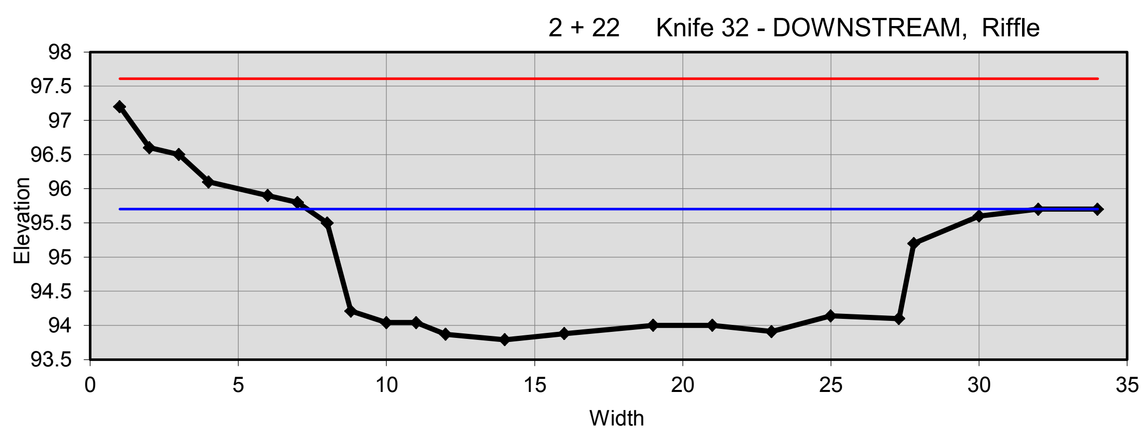
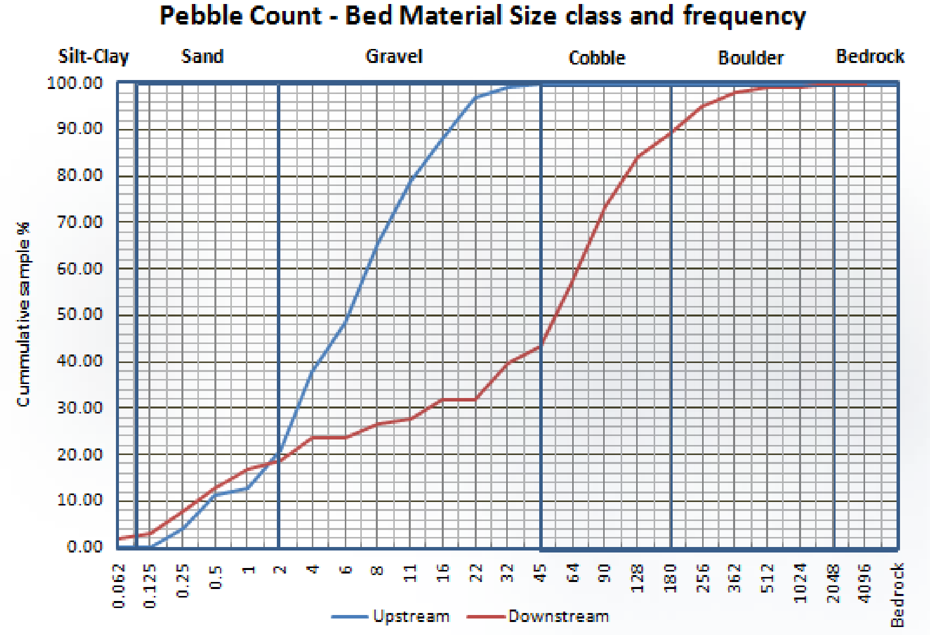


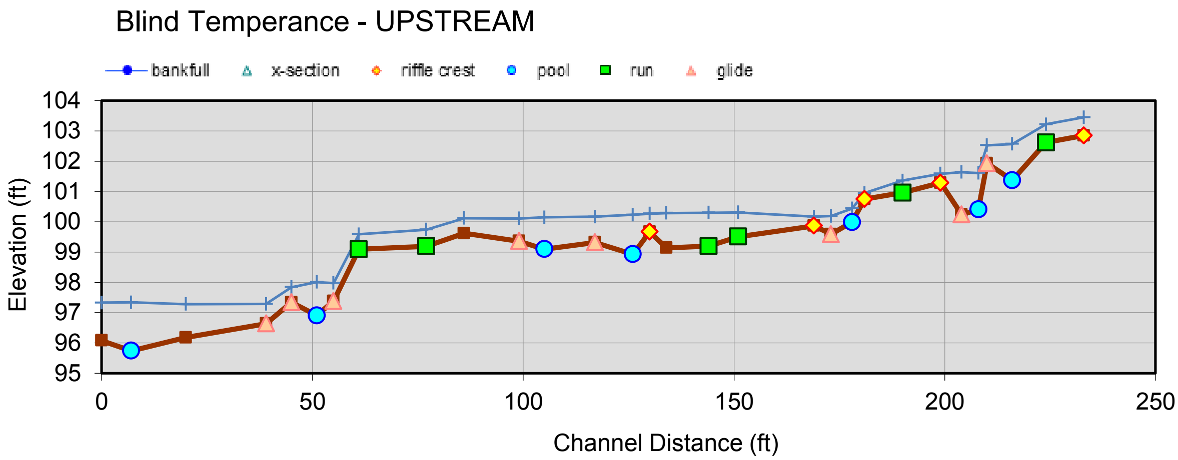


Knife 32 - Material Composition

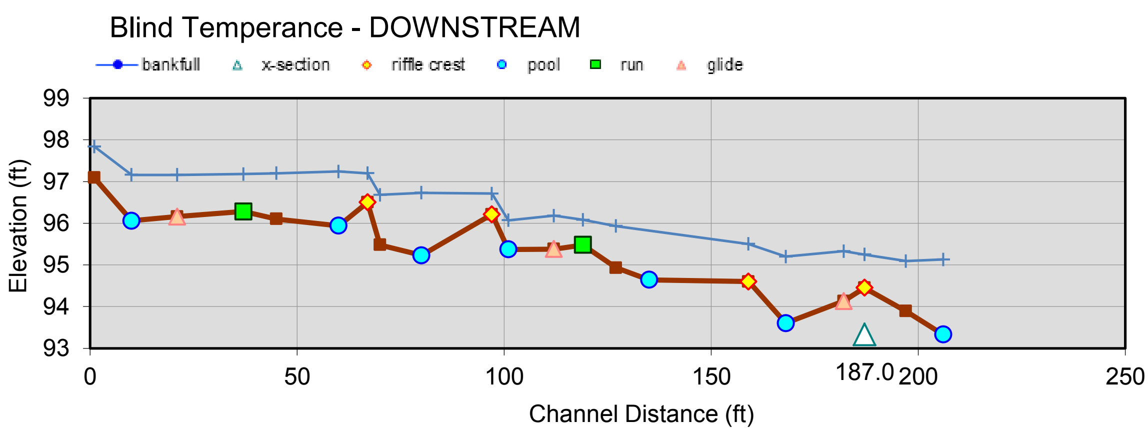


Temperance 16 - Longitudinal profile

Upstream

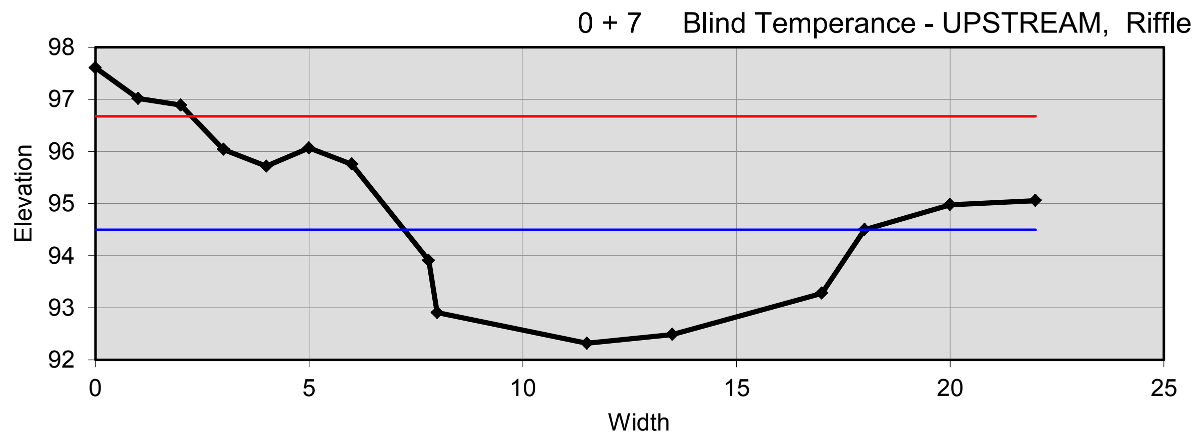


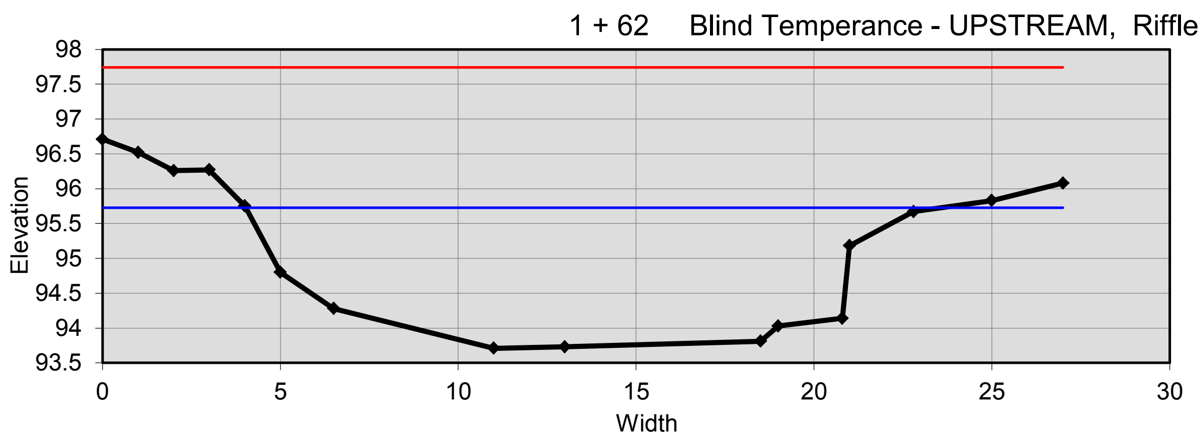
Downstream



Temperance 16 - Cross Sections

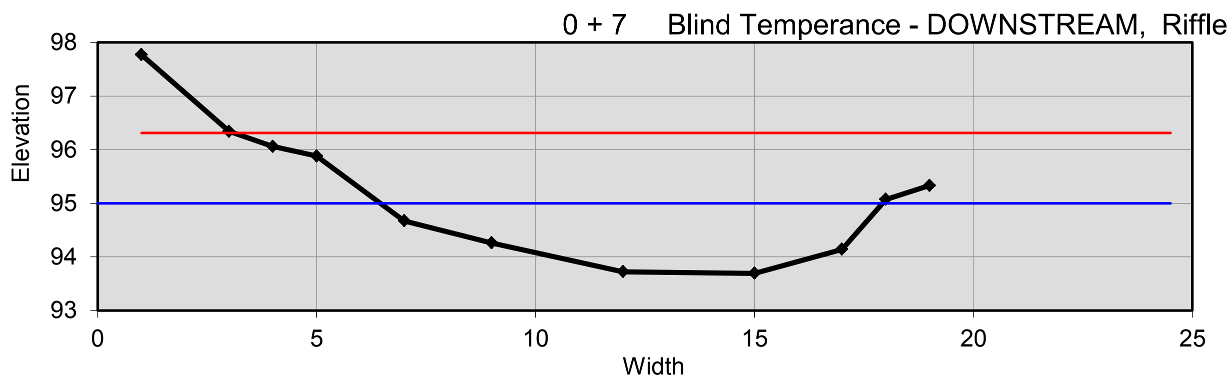
Upstream

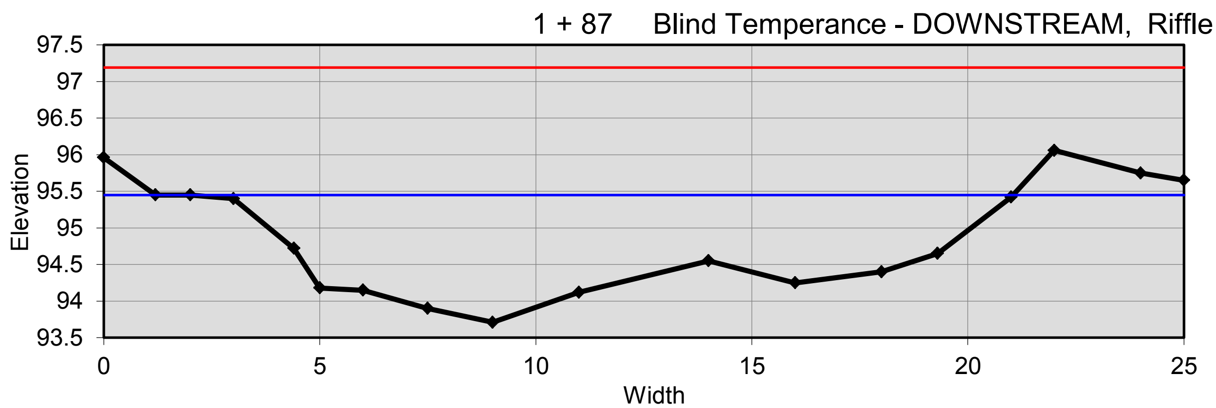




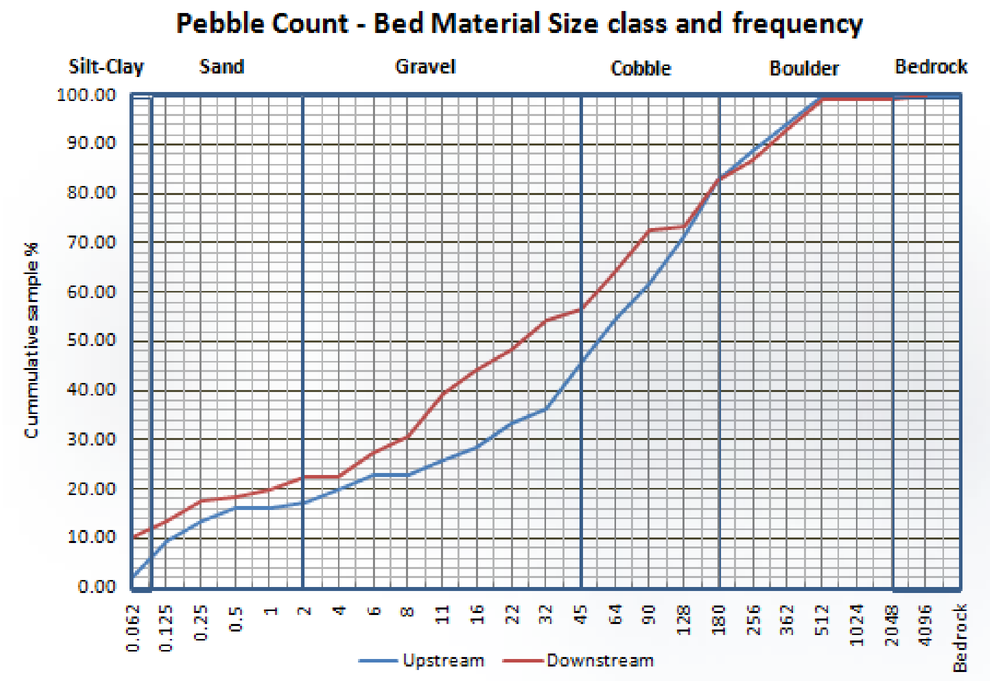
__Temperance 16 - Cross Sections__

__Downstream__



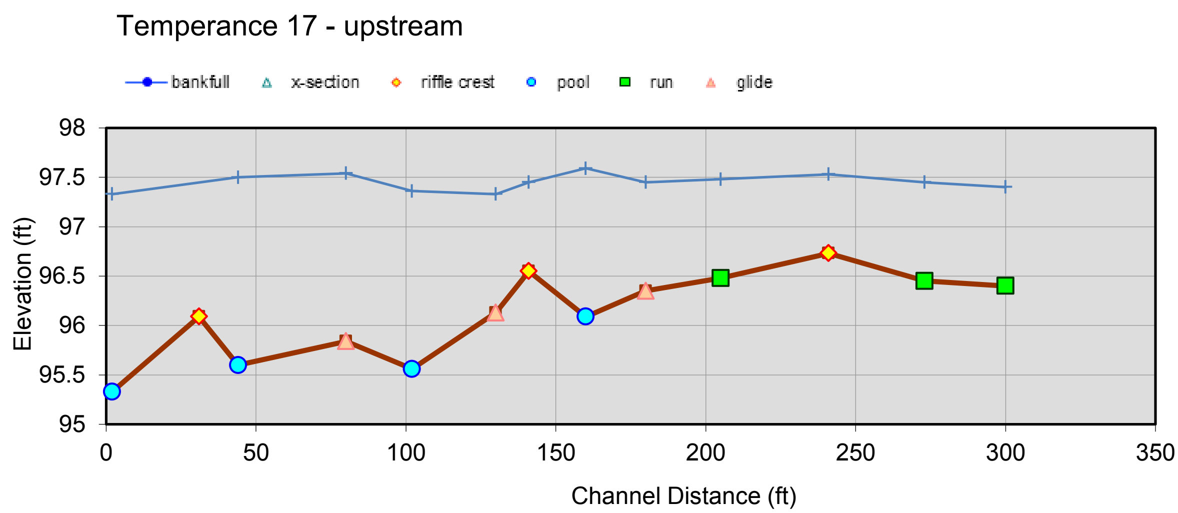


Temperance 16 - Material Composition

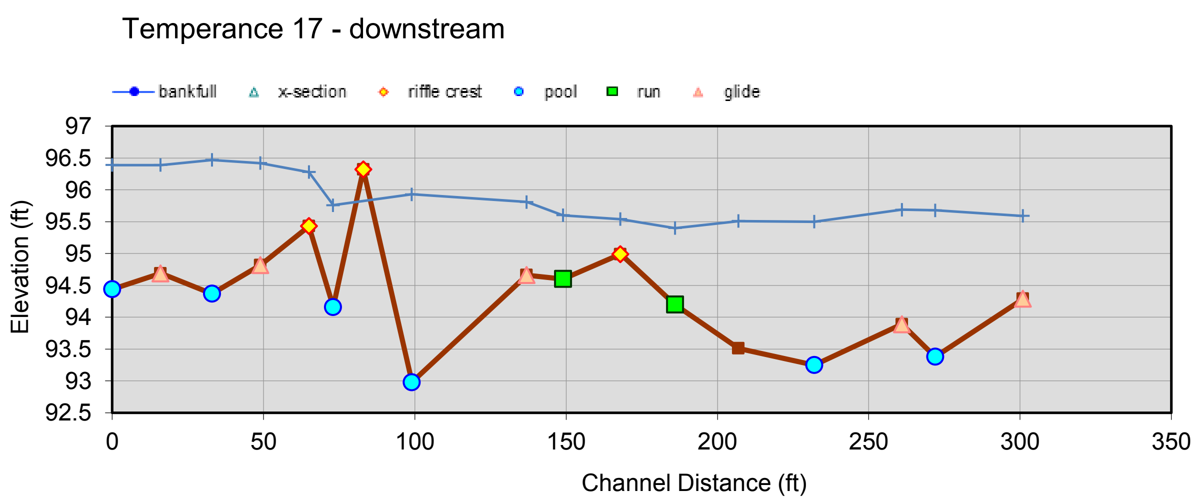


Temperance 17 - Longitudinal profile

Upstream

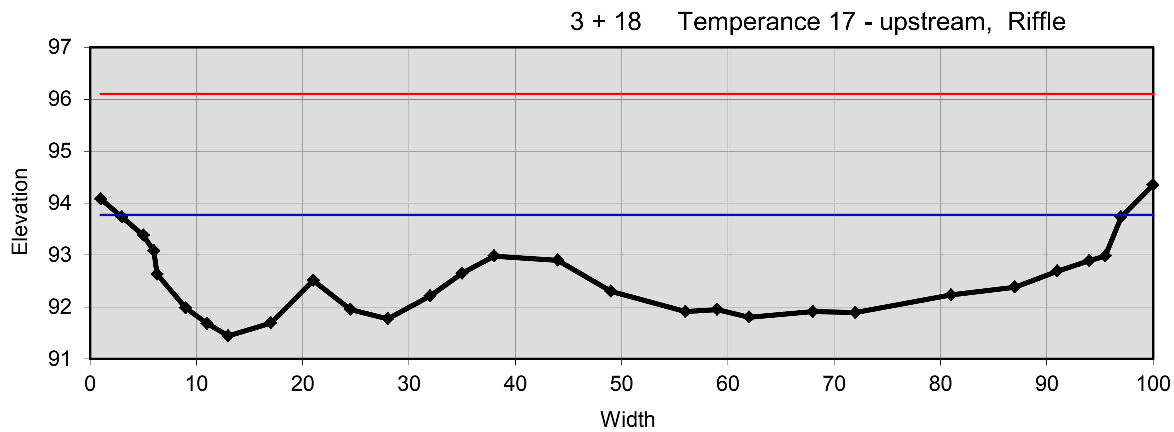


Downstream

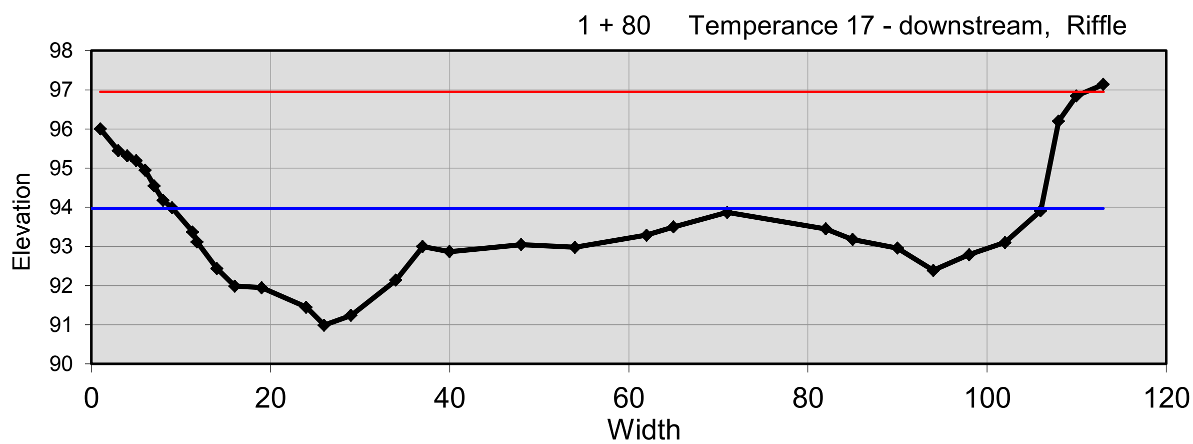


Temperance 17 - Cross Sections

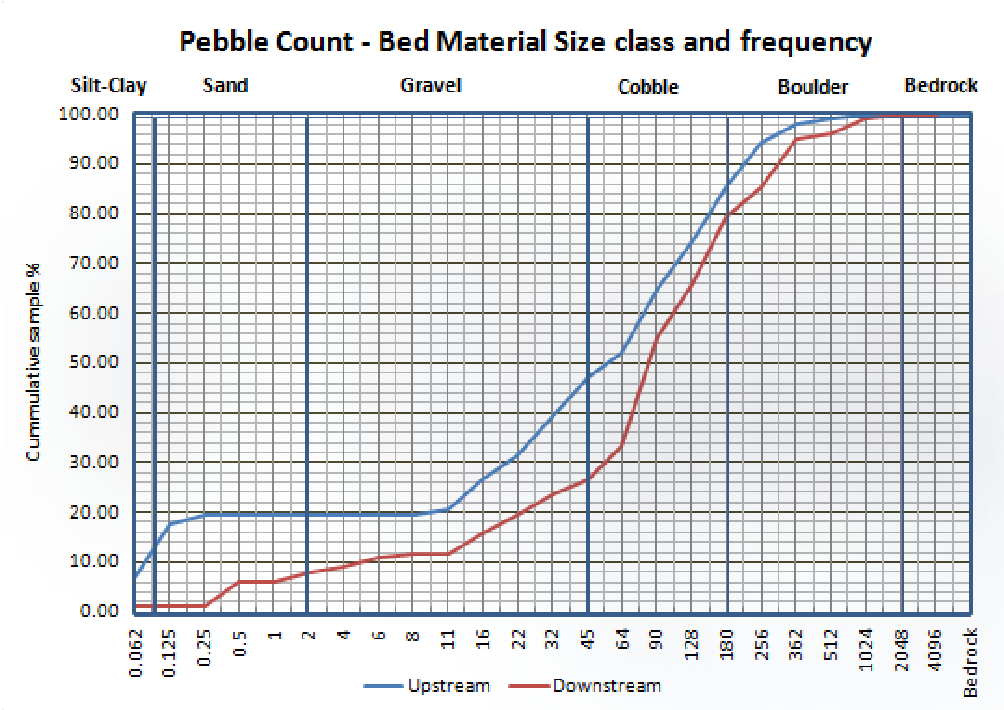
Upstream



Downstream



Temperance 17 - Material Composition



Appendix D. 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.

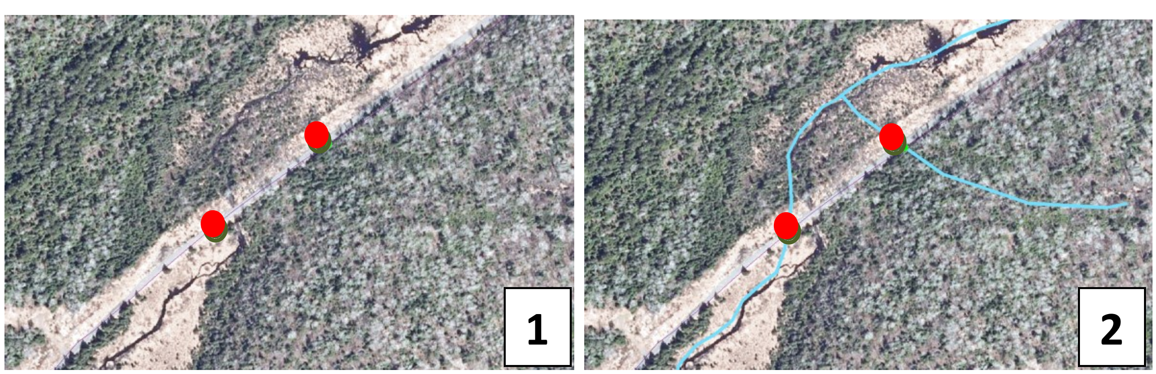


Figure 24. Example of sampling error

Appendix E. Road survey raw data file

Site #	Long (x)	Lat (y)	Elev (m)	WQ ID	Watershed	Geomorphic ID	Erosion (0,1)	Erosion volume (m3)	Stream order	Rd Surface	Traffic (0,1)	Rd Width (m)	Rd Length (m)	Rd avg Length (m)	Rd Slope	shoulder supply (m)
0	-91.24	47.38	387	Control	Baptism	Superior Lobe	0	0.00	4	Paved	1	10.61	475.31	237.65	0.05	0.00
3	-91.20	47.40	384	Control	Baptism	Superior Lobe	1	0.03	1	Paved	1	10.17	338.05	169.03	0.03	2.04
4	-91.17	47.41	352	Control	Baptism	Superior Lobe	0	0.00	2	Paved	1	10.04	319.28	159.64	0.05	3.05
5	-91.27	47.41	427	Control	Baptism	Superior Lobe	1	0.10	3	Paved	0	6.13	225.73	112.87	0.08	0.00
7	-91.25	47.42	399	Control	Baptism	Superior Lobe	1	0.17	1	Paved	1	8.02	187.79	93.89	0.03	0.00
8	-91.18	47.44	411	Control	Baptism	Superior Lobe	0	0.00	1	Gravel	1	8.08	161.48	80.74	0.01	0.00
9	-91.16	47.45	414	Control	Baptism	Superior Lobe	1	0.01	1	Gravel	1	7.67	139.90	69.95	0.01	0.00
10	-91.29	47.45	455	Control	Baptism	Superior Lobe	0	0.00	2	Gravel	1	9.11	84.31	42.15	0.02	2.57
11	-91.14	47.46	414	Control	Baptism	Superior Lobe	1	0.43	3	Gravel	1	10.47	227.29	113.64	0.01	0.00
12	-91.33	47.52	570	Control	Baptism	Superior Lobe	1	0.01	2	Paved	1	3.41	785.41	392.70	0.04	0.00
14	-90.88	47.56	246	Control	Temperance	Superior Lobe	0	0.00	1	Gravel	1	6.64	52.12	90.43	0.03	0.67
15	-90.89	47.57	298	Control	Temperance	Superior Lobe	1	0.03	1	Gravel	1	7.07	180.87	90.43	0.03	1.45
16	-90.86	47.64	369	Control	Temperance	Superior Lobe	1	0.17	2	Gravel	1	6.02	151.24	75.62	0.05	0.77
17	-90.85	47.64	373	Control	Temperance	Superior Lobe	0	0.00	5	Native	1	9.04	185.93	92.96	0.03	0.70
19	-90.88	47.73	468	Control	Temperance	Superior Lobe	1	0.00	5	Native	1	9.12	361.77	180.88	0.03	0.70
20	-90.87	47.78	499	Control	Temperance	Superior Lobe	0	0.00	1	Paved	0	7.47	267.49	133.75	0.05	0.00
21	-90.89	47.82	545	Control	Temperance	Superior Lobe	0	0.00	1	Native	1	6.54	317.91	158.95	0.05	0.74
22	-90.85	47.83	522	Control	Temperance	Superior Lobe	1	0.06	1	Native	0	3.35	75.99	37.99	0.01	0.00
23	-90.78	47.84	537	Control	Temperance	Superior Lobe	0	0.00	2	Gravel	1	7.54	134.26	67.13	0.01	0.62
24	-90.89	47.84	540	Control	Brule	Superior Lobe	1	0.01	1	Native	1	6.18	131.80	65.90	0.07	1.38
26	-90.33	47.96	502	Control	Brule	Scoured Bedrock	0	0.00	1	Paved	1	9.11	207.26	103.63	0.03	0.73
28	-90.44	47.95	524	Control	Brule	Scoured Bedrock	1	0.03	3	Gravel	1	4.65	154.72	77.39	0.01	0.15
30	-90.34	48.00	546	Control	Brule	Scoured Bedrock	1	1.50	2	Gravel	1	2.41	231.90	115.95	0.05	2.25
31	-91.88	46.96	314	Impaired	Knife	Superior Lobe	1	0.00	1	Paved	1	6.63	207.26	103.63	0.02	1.97

32	-91.85	46.97	293	Impaired	Knife	Superior Lobe	1	0.01	3	Paved	1	7.31	485.55	214.88	0.03	0.90
34	-91.85	46.99	326	Impaired	Knife	Superior Lobe	0	0.00	1	Paved	1	7.08	236.30	118.15	0.02	1.06
36	-91.76	47.01	286	Impaired	Knife	Superior Lobe	0	0.00	4	Paved	1	7.87	391.97	195.99	0.03	1.81
37	-91.76	47.01	292	Impaired	Knife	Superior Lobe	1	0.00	1	Paved	1	6.34	200.56	100.28	0.03	0.93
38	-91.82	47.02	333	Impaired	Knife	Superior Lobe	1	0.00	1	Paved	1	6.93	320.52	160.26	0.04	0.00
39	-91.83	47.03	356	Impaired	Knife	Superior Lobe	1	0.00	3	Native	0	4.16	81.61	40.81	0.08	0.00
40	-91.81	47.04	350	Impaired	Knife	Superior Lobe	0	0.00	3	Paved	1	6.68	297.54	148.77	0.03	1.21
41	-91.76	47.04	323	Impaired	Knife	Superior Lobe	1	5.39	2	Paved	1	7.97	139.98	69.99	0.03	1.26
42	-91.73	47.04	304	Impaired	Knife	Superior Lobe	0	0.00	2	Paved	0	7.68	215.44	107.72	0.01	1.74
44	-91.81	47.05	366	Impaired	Knife	Superior Lobe	1	0.00	3	Gravel	0	5.05	165.00	82.50	0.04	0.00
45	-91.73	47.06	320	Impaired	Knife	Superior Lobe	0	0.00	1	Paved	1	7.95	126.67	63.33	0.01	1.88
46	-91.82	47.12	472	Impaired	Knife	Superior Lobe	1	0.72	2	Native	1	5.46	185.65	92.82	0.02	1.26
47	-91.30	47.26	189	Impaired	Beaver	Superior Lobe	1	2.37	5	Paved	1	18.29	95.99	47.99	0.04	1.04
50	-91.31	47.30	322	Impaired	Beaver	Scoured Bedrock	1	11.72	2	Paved	1	6.49	467.56	233.78	0.06	1.94
54	-91.50	47.36	524	Impaired	Beaver	Superior Lobe	0	0.00	2	Paved	1	9.42	90.32	45.16	0.02	1.41
57	-91.40	47.38	505	Impaired	Beaver	Superior Lobe	1	2.34	3	Gravel	1	4.33	204.39	102.20	0.03	0.48
500	-90.87	47.55	197	Control	Temperance	Superior Lobe	1	52.99	5	Paved	1	29.64	375.67	187.83	0.04	8.08
503	-89.97	47.88	409	Impaired	Flute Reed	Scoured Bedrock	1	13.77	1	Native	0	3.58	134.42	67.21	0.07	0.23
504	-90.09	47.99	574	Impaired	Flute Reed	Scoured Bedrock	0	0.00	0	Gravel	1	3.50	75.04	37.52	0.02	0.41
505	-91.24	47.42	395	Control	Baptism	Superior Lobe	1	0.05	3	Paved	1	8.52	312.45	156.23	0.07	2.03
506	-91.28	47.36	393	Impaired	Beaver	Scoured Bedrock	1	0.00	2	Paved	0	9.16	88.27	44.14	0.01	0.00
508	-91.33	47.31	321	Impaired	Beaver	Superior Lobe	0	0.00	3	Paved	1	10.07	160.93	80.47	0.03	0.99
25map	-90.21	47.94	498	Control	Brule	Scoured Bedrock	1	0.23	2	Native	0	2.90	166.94	83.47	0.07	0.00
28g	-90.44	47.95	520	Control	Brule	Scoured Bedrock	0	0.00	3	Gravel	1	5.33	219.52	109.76	0.03	0.93
33a	-91.85	46.97	301	Impaired	Knife	Superior Lobe	1	0.08	1	Paved	1	6.75	177.70	88.85	0.02	0.91
33b	-91.85	46.97	301	Impaired	Knife	Superior Lobe	1	0.08	1	Paved	1	6.75	63.70	31.85	0.02	0.85
B01	-91.36	47.37	476	Impaired	Beaver	Scoured Bedrock	1	0.07	1	Gravel	0	2.21	206.55	103.28	0.05	0.00
B02	-91.35	47.37	486	Impaired	Beaver	Scoured Bedrock	1	0.35	1	Gravel	0	3.27	142.52	71.26	0.05	0.13

B03	-91.34	47.37	476	Impaired	Beaver	Scoured Bedrock	1	0.00	2	Gravel	0	3.91	101.80	50.90	0.08	0.13
x01	-91.32	47.30	319	Impaired	Beaver	Scoured Bedrock	1	0.55	4	Paved	1	9.69	599.54	299.77	0.05	1.73