Total Maximum Daily Load Study of Turbidity on the Knife River Watershed

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Region 5
Chicago, Illinois

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TMDL Summary Table

EPA/MPCA Required Elements	Summary	TMDL Page #
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303(d) Listing Information	Knife River (Headwaters to Lake Superior) Assessment Unit ID: 04010102-504 Impaired Beneficial Use(s) – Aquatic Life Impairment/TMDL Pollutant(s) of Concern: Turbidity Priority ranking of the waterbody – Target start and completion dates were 2002 and 2007 Listed for Turbidity (1998) and pH (2002) – pH is not addressed in this TMDL	13
Applicable Water Quality Standards/ Numeric Targets	Class 2A waters; aquatic life and recreation. The quality of Class 2A surface waters shall be such as to permit the propagation and maintenance of a healthy community of cold water sport or commercial fish and associated aquatic life, and their habitats. These waters shall be suitable for aquatic recreation of all kinds, including bathing, for which the waters may be usable. This class of surface waters is also protected as a source of drinking water. Turbidity: 10 NTU	13
Loading Capacity (expressed as daily load)	Using five flow categories (High Flows, Moist Conditions, Mid-Range Flows, Dry Conditions, and Low Flows) in a Load Duration Curve approach, the Loading Capacity was calculated to be 5.3, 0.86, 0.27, 0.12, and 0.04 tons per day, respectively. *See Section 6.0*	51

Wasteload Allocation	Using five flow categories (High Flows, Moist Conditions, Mid-Range Flows, Dry Conditions, and Low Flows) in a Load Duration Curve approach, the Loading Capacity was calculated to be 0.3, 0.004, 0.002, 0.001, and 0.001 tons per day, respectively. *See Section 6.1*	51
Load Allocation	Using five flow categories (High Flows, Moist Conditions, Mid-Range Flows, Dry Conditions, and Low Flows) in a Load Duration Curve approach, the Loading Capacity was calculated to be 2.67, 0.406, 0.196, 0.069, and 0.025 tons per day, respectively. *See Section 6.2*	51
Margin of Safety	Using five flow categories (High Flows, Moist Conditions, Mid-Range Flows, Dry Conditions, and Low Flows) in a Load Duration Curve approach, the Loading Capacity was calculated to be 2.6, 0.45, 0.072, 0.50, and 0.017 tons per day, respectively. *See Section 6.3*	53
Seasonal Variation	The load duration curve method takes into account seasonal variation; *see Section 6.4*	54
Reasonable Assurance	Reasonable assurance for construction storm water activities is present through the requirements for and provisions of the Construction General Permit under the NPDES program as described in Section 6.1. Statements in Section 7.0 address implementation efforts that will work to achieve sediment load reductions for nonpoint sources. *See Section 7.0*	56
Monitoring	Continued monitoring will be described in a separate Implementation Plan; *see Section 8.0*	57
Implementation	Implementation plans, BMPs, and costs will be outlined in a separate implementation plan; *see Section 9.0*	57

Public Participation	• Public Comment period: October 12 – November 11, 2009; seven written comments received during the Public Comment period • Public stakeholder meeting held November 4, 2009 • Public Comment Period for revised TMDL: April 12 – May 12, 2010; no public written comments received during the Public Comment period • Various public participation and outreach efforts were conducted; *see Section 6.10.* *Note: EPA regulations require public review [40 CFR §130.7(c)(1)(ii), 40 CFR §25] consistent with State or Tribe's own continuing planning process and public participation requirements.*	58

Executive Summary

The Clean Water Act, Section 303(d), requires that states publish, every two years, a list of waters that do not meet water quality standards and do not support their designated uses. These waters are then considered to be “impaired”. Once a water body is placed on the impaired waters list, a Total Maximum Daily Load (TMDL) must be developed. The TMDL provides a calculation of the maximum amount of a pollutant that a water body can receive and still meet water quality standards (MPCA, 2005). It is the sum of the individual wasteload allocations (WLAs) for point sources, load allocations (LAs) for nonpoint sources and natural background, plus a margin of safety (MOS). TMDLs can be expressed in terms of mass per time, toxicity, or other appropriate measures that relate to a state’s water quality standard (USEPA, 1999).

The Knife River was placed on the 1998 Minnesota 303(d) list as being impaired for aquatic life due to excessive turbidity in the river. The designation was based on the fact that greater than 10% of the available turbidity data between 1986 and 1996 exceeded the Class 2A water quality standard for turbidity (10 NTU). In 2002, the Knife River was listed for exceedances in pH, but that is not addressed in this document.

The Knife River watershed is a heavily forested watershed along the North Shore of Lake Superior, 15 miles north of Duluth, MN. The purpose of this TMDL study is to identify the amount of turbidity-causing pollutants that can be in the water and still meet the water quality standard for turbidity. The TMDL is also intended to identify the sources and amounts of pollutants causing turbidity in the river, the relative impacts of human-related activities (primarily development, agriculture, and forestry) within the Knife River watershed and to identify appropriate sediment reduction strategies that will achieve the load goals. The ultimate goal of the TMDL is to return the water quality of the stream to the levels identified by the State of Minnesota as water quality standards that protect the beneficial uses of the Knife River Watershed.

The TMDL study began with the recognition that additional data was needed to complete the TMDL. The study utilized the existing USGS gage site for flow data combined with water quality sampling near the gage site. Water quality and flow monitoring sites were also established at three other locations in the watershed. Macroinvertebrate sampling and stream channel measurements and modeling were also included in the study.

The Knife River TMDL is based on turbidity and TSS data gathered at the Fish Trap site near the mouth of the stream between 2004 to 2006. Using TSS as a surrogate for turbidity, a load duration curve was created based on 3 years of grab samples and over 30 years of USGS flow data. The 3 other sites on the Knife River that collected continuous and grab sample turbidity data over the 3 year period (2 years at the Culvert site) were used to help identify sources. The Load Duration method (Cleland, 2002) was used to assign all allocations, adjust for seasonal variation, and account for Margin of Safety.

1.0 Introduction

The Knife River watershed is a heavily forested watershed along the North Shore of Lake Superior, 15 miles north of Duluth, MN. The purpose of this Total Maximum Daily Load (TMDL) study is to identify the amount of turbidity-causing pollutants that can be in the water and still meet the water quality standard for turbidity. The TMDL is also intended to identify the sources and amounts of pollutants causing turbidity in the river, the relative impacts of human-related activities (primarily development, agriculture, and forestry) within the Knife River watershed and to identify appropriate sediment reduction strategies that will achieve the load goals. The ultimate goal of the TMDL is to return the water quality of the stream to the levels identified by the State of Minnesota as water quality standards that protect the beneficial uses of the Knife River Watershed. This goal will be achieved by allocating sediment loadings based on the anticipated impact on the water quality of the stream. Currently, water quality within the stream does not meet the water quality standards set by the State. Because the Knife River does not meet these standards, the stream was placed on Minnesota’s 1998 Clean Water Act (CWA) Section 303(d) list as water quality limited due to turbidity. The level of turbidity was judged too high to support the cold water fishery of the Knife River. The river was also identified as impaired for pH on the 2002 303(d) list.

Section 303(d) of the federal Clean Water Act requires that states identify waters that do not meet State designated water quality standards. The State must then develop a TMDL for these listed waters. The term “TMDL” represents the reporting format required by EPA as defined by, "A written plan and analysis of an impaired waterbody established to ensure that the water quality standards will be attained and maintained throughout the waterbody in the event of reasonably foreseeable increases in pollutant loads" (EPA definition of TMDL from Clean Water Act). In these terms, a TMDL is an assessment of “carrying capacity” of the stream (how much of a pollutant can be in a stream and still meet the water quality standard) and an allocation of this load among all of the sources. It is also a report documenting this assessment, allocations of the load to the sources of pollutants, a margin of safety, and information that provides “reasonable assurance” that the load allocations will be met. This can be done with an outline of an implementation plan.

The TMDL related activities are just the latest in a long history of conservation efforts in the Knife River Watershed. Since 1991, the Knife River Forest Stewardship Committee (KRFSC) and the Knife River Watershed Education Project have been implementing projects “to minimize and/or prevent soil erosion and sedimentation in the Knife River Watershed, which directly impacts Lake Superior, and thus protect and improve water quality as well as wildlife and fish habitat.” (Knife River Watershed Education Project Goals, 1996) These efforts have dwindled in the last few years, but the practices implemented by this group are continuing to have impacts on the Knife River Watershed. Through past efforts approximately 1,700 trees were planted on public and private land, riparian areas were planted and stabilized, GIS layers were created for use in planning and management activities, a newsletter was disseminated to over 600 residents, and almost 10,000 acres of private land in the watershed are under a forest stewardship plan.

There are several groups actively working on the Knife River, including the Knife River Stewardship Committee. The KRFSC is made up of area resource managers and associations who work in the Knife River watershed or are interested in protecting it. Many groups like Lakes Superior Steelhead Association (LSSA), the Minnesota Department of Natural Resources (DNR), the South St. Louis Soil & Water Conservation District (SWCD), the Minnesota Pollution Control Agency (MPCA), and others are always on the lookout for conservation projects in the watershed. These efforts will continue and be strengthened when the TMDL is completed.

TMDL Description

A TMDL as a load is an established value (or set of values) determining the amount of a given pollutant that a waterbody can withstand without exceeding its water quality standard. Allocations of the allowable pollutant load are also determined for the various pollutant sources. A TMDL is defined as "the sum of the individual wasteload allocations for point sources and load allocations for nonpoint sources and natural background" (40 CFR 130.2) such that the waterbody's ability to receive pollutant loadings (Loading Capacity) is not exceeded. The requirements of a TMDL are described in 40 CFR 130.2 and 130.7 and Section 303(d) of the CWA.

The TMDL is developed according to the following equation:

$$\text{TMDL} = \text{LC} = \Sigma\text{WLA} + \Sigma\text{LA} + \text{MOS}$$

Where:

Σ = the sum of;

LC = loading capacity, the greatest pollutant load a waterbody can assimilate without exceeding water quality standards;

WLA = wasteload allocation, existing and future point source pollutant sources that would require a NPDES permit;

LA = load allocation, includes existing and future nonpoint sources of pollution, "natural background" contributions, and any other pollutant sources affecting turbidity in the river;

MOS = margin of safety, the uncertainty in the relationship between pollutant loads and the quality of the receiving water.

Given that the Knife River is impaired for turbidity and turbidity is not a measure of concentration, a surrogate parameter is needed to calculate the TMDL. As explained later, the surrogate parameter will be total suspended solids (TSS) and the TMDL will be expressed in tons of TSS/day. This approach is consistent with Federal regulations (40CFR 130.2(1)) which state that TMDLs can be expressed in terms of mass per time, toxicity or other appropriate measures.

2.0 Applicable Water Quality Standards

Reach Name: Knife River (from Headwaters to Lake Superior)

Major Watershed: Lake Superior (South)
County: Lake County and St. Louis County

8-digit Hydrologic Unit Code: 04010102
AUID: 04010102-504

Drainage Area: 83.6 sq. miles

Stream Length: 23.8 miles

Designated Use to be addressed: Cold water fishery (Class 2A)

> **Class 2A waters; aquatic life and recreation.** The quality of Class 2A surface waters shall be such as to permit the propagation and maintenance of a healthy community of cold water sport or commercial fish and associated aquatic life, and their habitats. These waters shall be suitable for aquatic recreation of all kinds, including bathing, for which the waters may be usable. This class of surface waters is also protected as a source of drinking water. (MN Rule 7050.0222 subp. 2.)

Listed on the 1998 303(d) List; target start and end dates on the 303(d) list were 2002 and 2007, respectively.

Impairment: Turbidity	Impaired Use: Aquatic Life

Water Quality Standard: 10 NTU

Impairment Assessment: At least 10% of a minimum 10 observations within a ten year period exceeded the turbidity standard of 10 NTU.

Section 303(d) of the Clean Water Act requires states to publish a list of streams and lakes that do not meet their designated uses, because of excess pollutants, every two years. The MPCA developed an assessment process to evaluate available data for impairments that is documented in guidance published for each list (http://www.pca.state.mn.us/water/tmdl/tmdl-waterquality.html). Minnesota's 1998 303(d) List identified stream reaches as being impaired based on a comparison of available water quality data with the state's water quality standards for turbidity, fecal coliform, pH, un-ionized ammonia, dissolved oxygen, and mercury. Once specific stream reaches are identified as impaired, the Clean Water Act, Section 303(d), requires that a total maximum daily load (TMDL) be developed for those reaches.

One monitoring site on the Knife River had sufficient water quality data available for use in determining whether or not to include it on the 1998 303(d) List. Based on this data, the entire river was placed on the list as being impaired for turbidity as a single reach. The 2002 303(d) list added the Knife River as being impaired for pH. The 2008 303(d) list added the Little East Branch of the Knife River as being impaired due to turbidity and low dissolved oxygen.

The Knife River, as with most North Shore streams, is "flashy" meaning that it has a quick response to a rain event which causes water levels in the river to rise very fast and return to base flow almost as quickly. Turbidity is tied closely to this rise and fall of stream levels, and high turbidity levels are associated with the short lived high flows. The Knife River quickly returns to low flows and low turbidity levels soon after a storm event or spring snowmelt. This is illustrated in the Load Duration Curve in **Section 6** of this document.

The activities used in this TMDL study to address the Knife River turbidity listing are being used in part as a template for the development and completion of additional TMDL work for the other turbidity listings in the Lake Superior Basin.

3.0 Background Information

The Knife River watershed has been the focus of considerable watershed management efforts over the past several years through the Knife River Stewardship Project, MN DNR Fisheries, and the Lake Superior Steelhead Association. The primary focus of the effort is the protection and improvement of the cold water fishery (trout and salmon). Monitoring data from related efforts put the stream on Minnesota's 1998 and 2002 303(d) lists as impaired for turbidity and pH, respectively. These listings prompted the commencement of monitoring for the TMDL study in 2004.

The Knife River's turbidity levels are tightly associated with discharge. The Knife River's flashy nature causes frequent short-lived exceedances during spring melt and during rain events.

Much of the Knife River flows along the St. Louis and Lake County border (**Figure 3.1**). It flows into Lake Superior approximately 15 miles northeast of Duluth along Scenic Highway 61. A slightly more detailed map of the watershed is provided in **Figure 3.2**. The headwaters begin in a sparsely populated and heavily forested area over 25 river miles from the confluence. Two of the three main tributaries (Stanley Creek and the West Branch) also begin in this sparsely populated, forested region. The third main tributary, the Little Knife River begins in a slightly more "developed" area and enters the mainstem near the confluence with Lake Superior. The only large developed area is a municipal airport approximately 1/3 of the way down the mainstem. There are also 80 miles of county and township roads and many pastures within the watershed. The confluence with Lake Superior lies within the Village of Knife River, a small residential area with several small businesses and a post office. This village is the only concentrated residential area in the 86.3 square mile watershed.

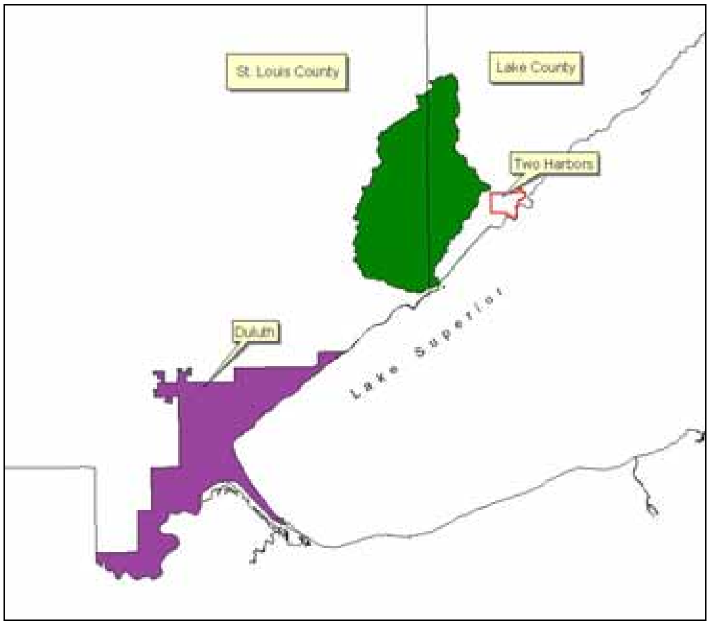

Figure 3.1. Geographic location of the Knife River Watershed.

Figure 3.2. Knife River and Watershed.

3.1 Land Use

Approximately 50% of the land in the Knife River watershed is owned by state and county government and the other half is owned privately. The dominant land uses in the watershed include forest (70%), grassland (15%), and wetlands (9%). There have been concentrated efforts within the watershed to promote reforestation. In response to these efforts 11% of the watershed was enrolled in the MN DNR's forest stewardship program in 1999. A rough estimate of current stewardships is about 17% of the watershed area. A significant portion of the grassland is abandoned pasture, but a portion is still actively grazed. **Table 3.1** and **Figure 3.3** show a detailed breakdown of land use, based on Gap Analysis Program (GAP) levels 2 and 3, in the Knife River watershed. GAP is a scientific means for assessing to what extent native animal and plant species are being protected. It can be done at a state, local, regional, or national level (http://gapanalysis.usgs.gov). The GAP land cover map was created using satellite imagery by the DNR Division of Forestry. The GAP level 2 enlists broad landuse/cover categories, using the MN DNR's Ecological Classification System (ECS), ultimately assigning a GAP category down to one acre. The level 3 GAP categories are simply expanded level 2 categories which provide a more detailed look at landuse/cover.

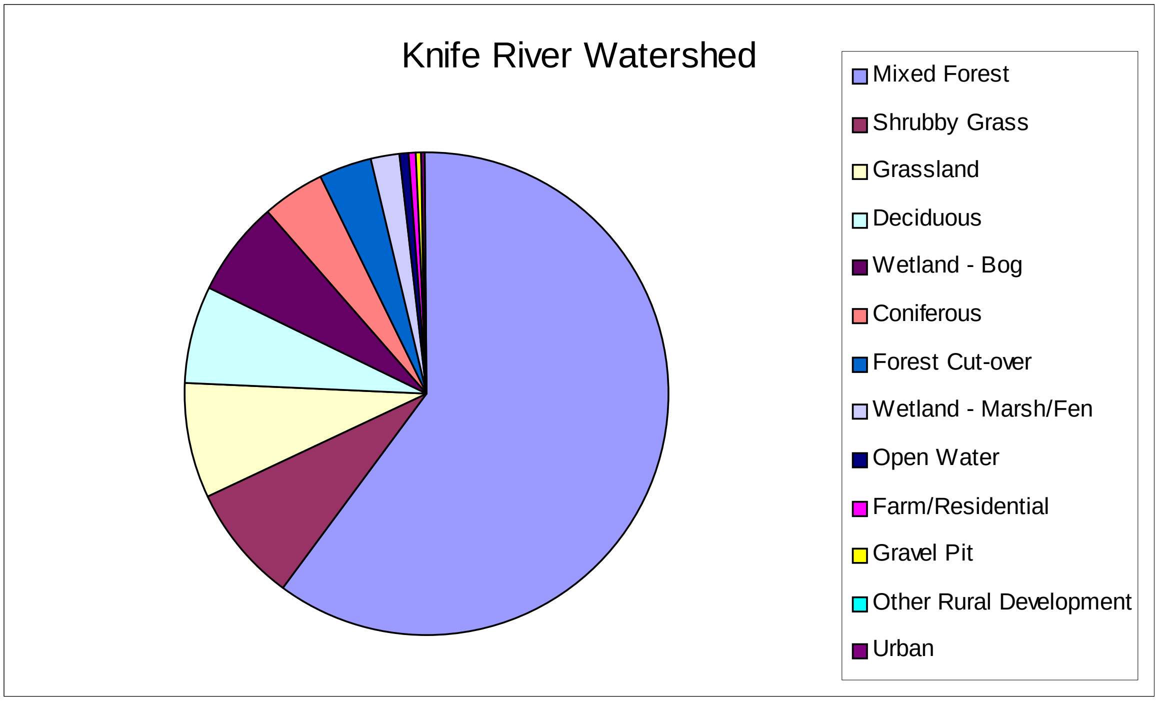

Figure 3.3. GAP land use in the Knife River Watershed (MN DNR Data Deli).

GAP Level 2	Acres	Percentage	GAP Level 3	Acres	Percentage
Aquatic Environments	89.37	0.16%	Aquatic	69.12	0.12%
Crop/Grass	3143.58	5.68%	Aspen/White Birch	37944.36	68.54%
Lowland Conifer Forest	1872.49	3.38%	Barren	95.19	0.17%
Lowland Deciduous Forest	652.16	1.18%	Black Ash	652.16	1.18%
Non-Vegetated	699.49	1.26%	Cropland	807.19	1.46%
Shrubland	6183.87	11.17%	Developed	604.30	1.09%
Upland Conifer Forest	3435.54	6.21%	Grassland	2336.40	4.22%
Upland Deciduous Forest	39282.55	70.96%	Lowland Black Spruce	115.43	0.21%
			Lowland Northern White-Cedar	1370.52	2.48%
			Lowland Shrub	5352.57	9.67%
			Maple/Basswood	1338.19	2.42%
			Marsh	20.25	0.04%
			Pine	619.04	1.12%
			Spruce/Fir	2541.37	4.59%
			Tamarack	386.54	0.70%
			Upland Cedar	260.93	0.47%
			Upland Conifer	14.20	0.03%
			Upland Shrub	831.30	1.50%
Total	55359	100.00%	Total	55359	100.00%

Table 3.1. GAP land use summary for the Knife River Watershed (MN DNR Data Deli).

According to "The History of Lumbering on the Minnesota North Shore," (Fritzen, no year given) most of the Knife River watershed was not logged until 1899 when Alger, Smith, & Co. received their first shipments from the Knife River operations. Soon after, the Knife River Village became a boom town. Logging was intense in the area until approximately 1909 when most of the pine forest near Duluth was gone, although logs were rafted to Duluth from Knife River until 1919 (www.mnhs.org viewed 12/31/07). Since that time, the largely publicly owned watershed has been harvested at a more sustainable level. Logging has been more sustainable due to the drastic reduction in demand since the area was being settled (early 1900's), foresters are managing for future harvests, and sensitive areas are protected during the harvest (riparian buffers, wetlands, etc.). Much of the watershed has been converted to aspen since the original pine forests that were harvested at the end of the 1800's and early 1900's. This type of conversion has been found to have water quality and fishery impacts in other streams. The larger the woody debris in the channel and riparian corridor, the more likely it is to stay in place and have a positive physical impact on the immediate area (scouring, sediment retention, energy reduction, etc.) It has been shown that "when wood debris was removed from a stream, the surface area, number, and size of pools decreased, water velocity increased . . ." (Elliott, 1986) For this reason it is important to have mature trees in the riparian management zone (RMZ) that will stay in place when deposited. This favors conifers in the RMZ rather than the smaller, more frequently harvested, and more frequently targeted by beaver, aspen species. Beaver impacts are two-fold; they drop smaller trees and they remove the natural anchor that will hold large woody debris in place longer (Verry, 1992).

3.2 Sub-watersheds

The Knife River watershed is small when compared to watersheds outside of the Lake Superior basin (Cloquet River, St. Louis River, Mississippi River, etc.). On the other hand, the Knife is slightly above average in size when compared to the other North Shore streams (**Figure 3.4**). There are a number of small tributaries that discharge into the Knife River (**Figure 3.5**). Since the mainstem is relatively straight and narrow, the tributaries make up much of the watershed. The most significant tributaries are the West Branch (25%), Stanley Creek (9%), and the Little Knife (12%). **Table 3.2** shows the contributing sub-watersheds, all of which are named after the tributary, except for the mainstem sub-watersheds. This study has the watershed broken into 19 sub-watersheds with none being more than 16% of the total watershed.

Sub-Watershed	Acres	Percentage of watershed	Sub-Watershed	Acres	Percentage of watershed
West Branch	9051.036	16.35%	Tributary #9	2194.241	3.96%
Little Knife	6711.062	12.12%	Upper Main Stem	2153.477	3.89%
Stanley Creek	4826.387	8.72%	Mid-Main Stem #4	2102.41	3.80%
Little West Branch	4280.412	7.73%	Mid-Main Stem #3	1810.983	3.27%
Little East	4088.051	7.38%	Mid-Main Stem #1	1208.359	2.18%
Capt. Jacobsen	3276.087	5.92%	Lower West	1174.729	2.12%
McCarthy Creek	3140.531	5.67%	Lower Main Stem	884.301	1.60%
Mid-Main Stem #2	3092.597	5.59%	Mid-West Branch	271.854	0.49%
Tributary #2	2633.272	4.76%	Tributary #1	257.047	0.46%
Tributary #6	2201.004	3.98%	**Total**	**55357.84**	**100.00%**

Table 3.2. Knife River sub-watersheds and areas (delineated by MN DNR).

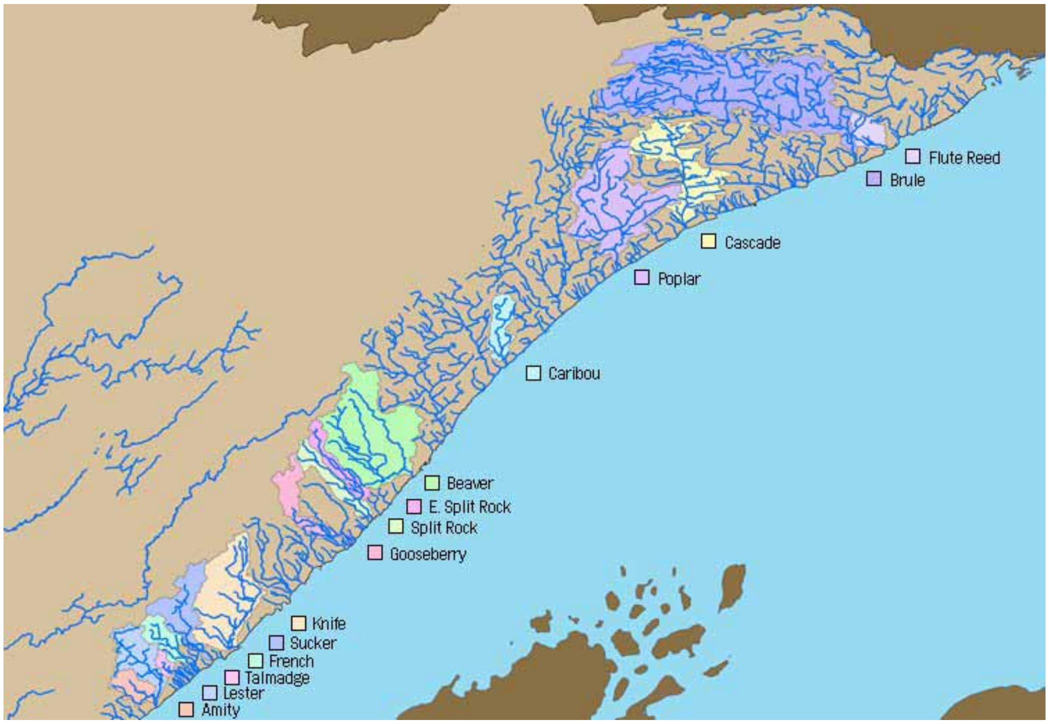

Figure 3.4. North Shore watersheds (from www.lakesuperiorstreams.org).

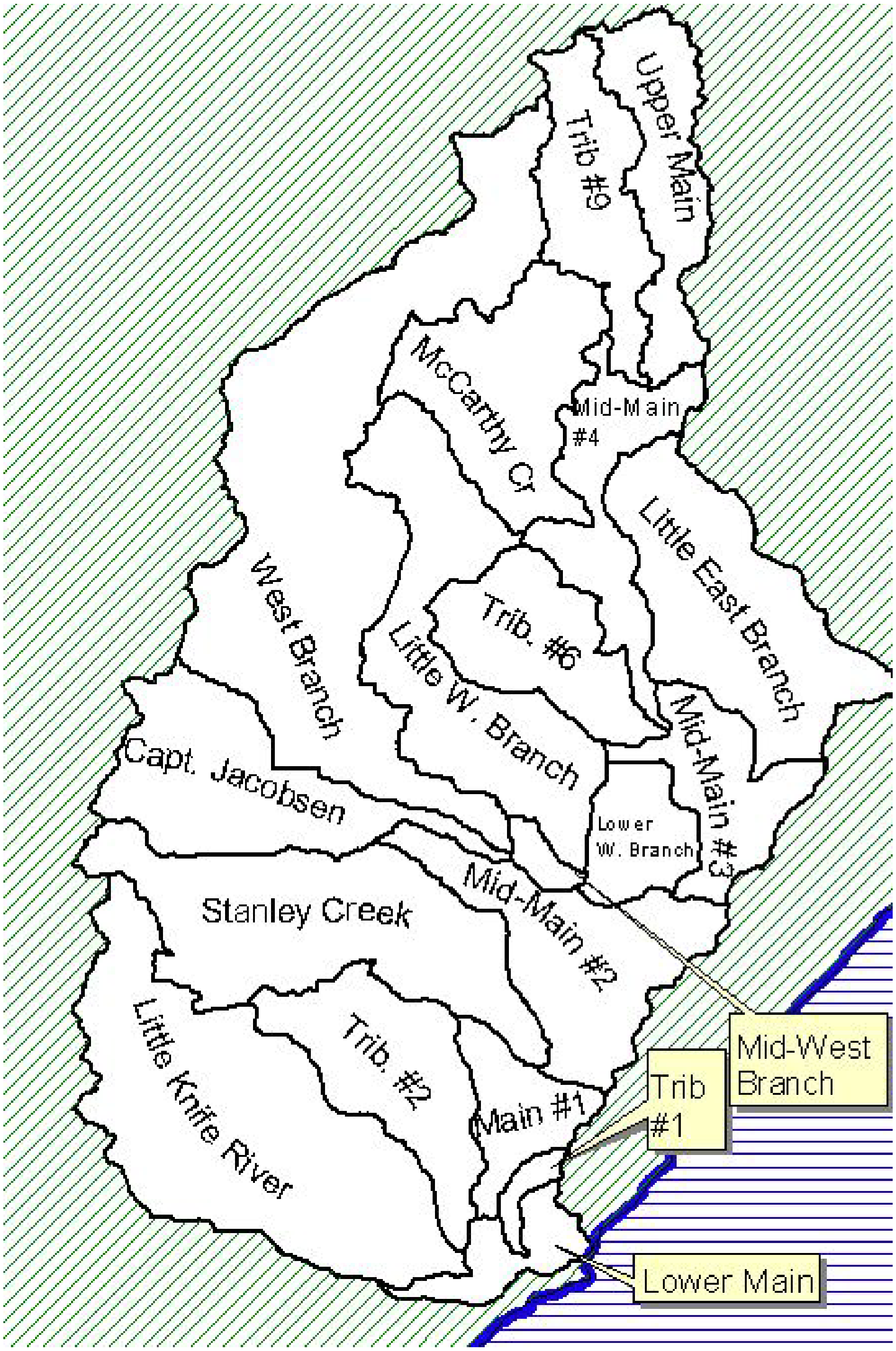

Figure 3.5. Sub-watersheds of the Knife River.

3.3 Hydrology

Flows in the Knife River are notoriously flashy and do not match the North Shore regional hydrologic curve. **Figure 3.6** illustrates how the Knife River lies above the curve based on available flow and the drainage area for North Shore streams. **Table 3.3** shows that the spring melt causes high average monthly discharge, and flows continue to decline through the summer. High flows happen often during summer months but the stream's flashiness and low base flow keep the average monthly flows down. Note that April is the wettest month and August is the driest month during open water season.

As shown in **Figure 3.7,** the Knife River flows respond quickly to precipitation events. Clay soils and bedrock in the lower half of the watershed, lack of wetlands or open water storage, and a steep gradient likely contribute to the quick runoff rate. Other possible factors contributing to the flashy nature of the Knife River include the drainage pattern, disconnection of the stream from the floodplain in some areas, and shallow depth to bedrock.

Another way to look at the river's quick response time to precipitation is through the use of the Richards-Baker Flashiness Index (R-B Index) (Baker et al., 2004). A river with a quick flow response to precipitation is considered flashy while a stream that responds slower is considered not flashy as shown in **Figure 3.8** (Fongers et al., 2007).
The term flashiness reflects the frequency and rapidity of short term changes in stream flow (Baker et al, 2004). A stream described as flashy responds to rainfall by rising and falling quickly. Conversely, a stream that is not flashy would rise and fall less for an equivalent rainfall and would typically derive more of its overall flow from groundwater.

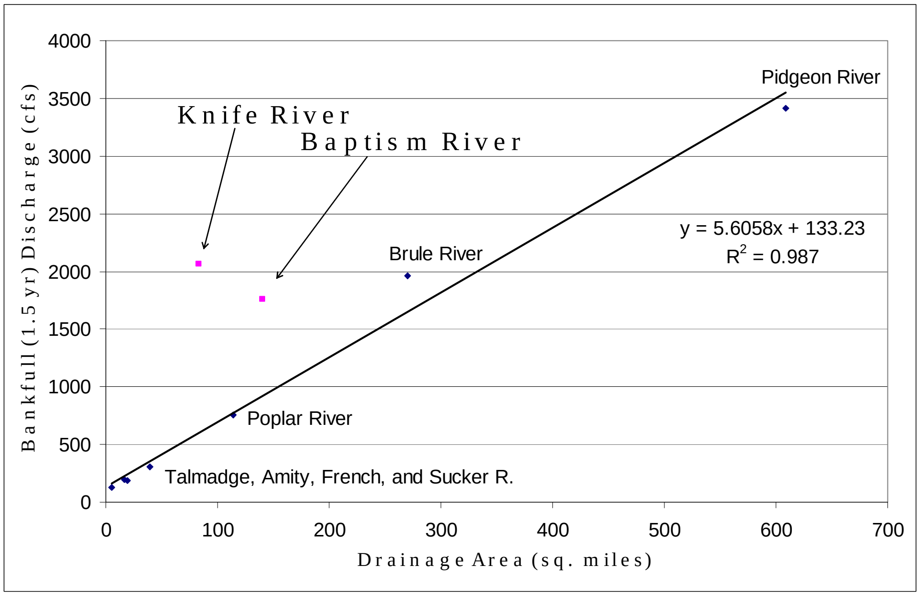

Figure 3.6. North Shore Regional Curve based on the best available data from the USGS and MPCA.

Month	Avg. (cfs)	Month	Avg. (cfs)
January	10.92	July	83.00
February	12.78	**August**	**34.00**
March	60.32	September	72.40
April	**373.00**	October	86.00
May	158.00	November	78.16
June	90.00	December	23.20

Table 3.3. Average monthly discharge (cfs) for the Knife River.

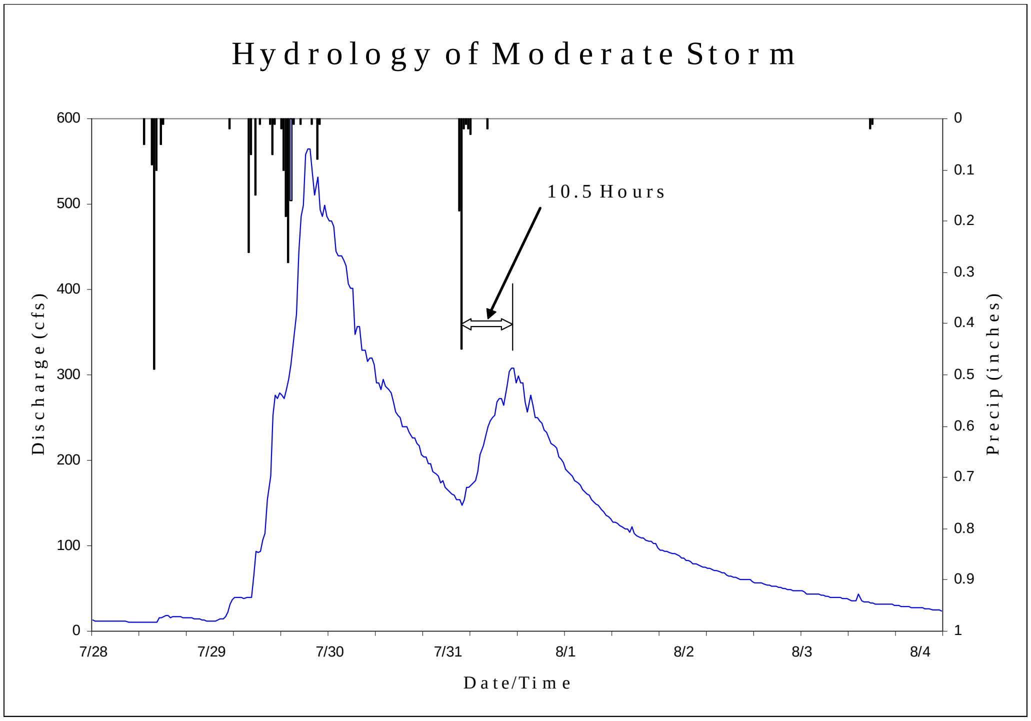

Figure 3.7. Response of the Knife River watershed to a moderate storm (0.5 inches in 1 hour) with a high antecedent moisture condition. The precipitation was measured in upper 1/3 of watershed and discharge was measured near the mouth.

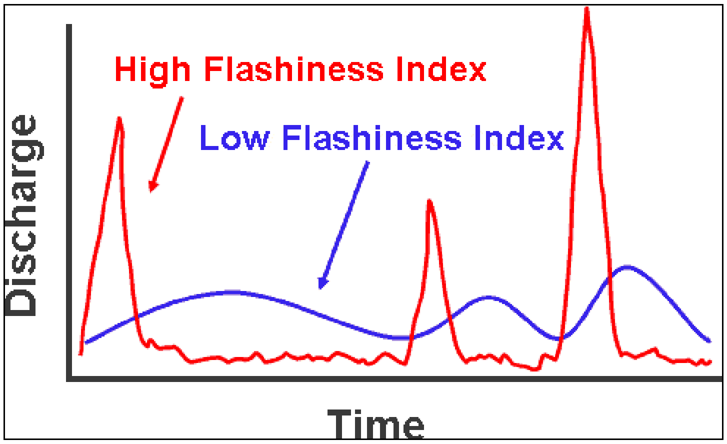

Figure 3.8. Example hydrographs (Fongers et al., 2007).

Figure 3.9 uses the Richards-Baker Flashiness Index (R-B Index) to illustrate how the Knife River responds more dramatically to rain events and recedes faster than other area streams. The R-B Index is a dimensionless ratio of the sum of day to day difference in daily mean flow to the sum of all daily mean flows over the same time period. The Baptism River is a North Shore stream that has a much lower R-B Index than the Knife River. The Nemadji River is a South Shore stream that is impaired for turbidity which is partially attributed to "flashiness" (Erosion and Sedimentation in the Nemadji River Basin, 1998). The Knife River has an R-B Index about two times that of the Nemadji River even with the high turbidities present in the Nemadji River.

Box plots of the historical flow record and the study flow record are shown in **Figure 3.10**. They indicate that the sampling period (2004-2006) was relatively representative of the 30+ years of hydrology data collected by the USGS near the Fish Trap site in that the median and 25th percentile values were similar.

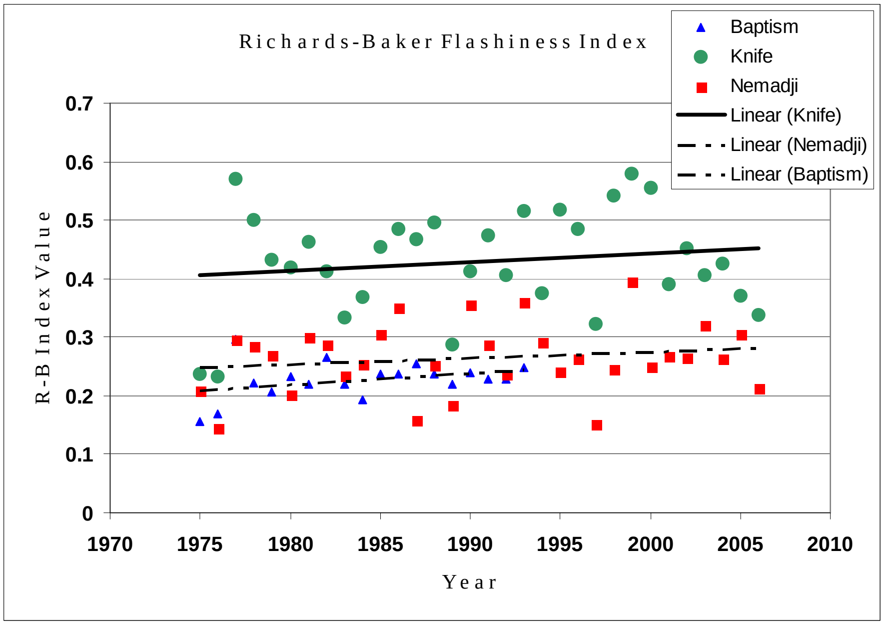

Figure 3.9. Flashiness index in comparison to other nearby streams.

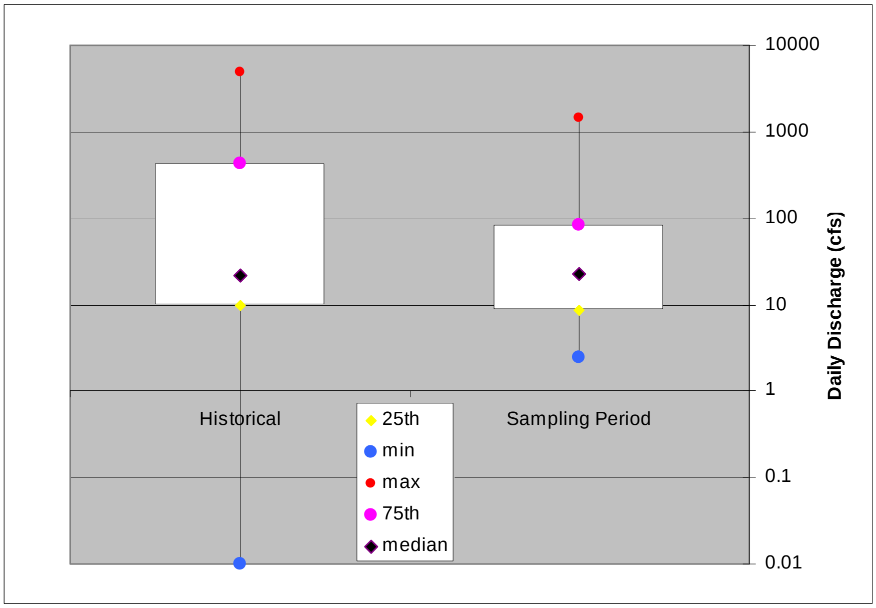

Figure 3.10. Boxplot showing flow statistics for the USGS gage site.

3.4 Climate

The entire Knife River watershed is within 11 miles of Lake Superior, and this proximity to a large body of water creates a climate quite different at times from the rest of Northern Minnesota. The entire watershed falls within the ecological subsection "North Shore Highlands" and the following is a description of the climate of that subsection. "Total annual precipitation ranges from 28 to 30 inches, about 40% of which occurs during the growing season. The growing season ranges from approximately 121 to 135 days, with the longest growing season occurring along the shore of Lake Superior. The growing season on Lake Superior is about 10 days longer than at the equivalent latitude 6 miles inland. Lake effect increases the amount of snowfall by about 10 inches within 5 miles of the Lake Superior shoreline, but a similar trend is not apparent in the annual precipitation data." (www.dnr.state.mn.us viewed 12/3/07).

The amount of precipitation in any given year greatly affects stream flow and sediment loading. **Table 3.4** ranks the seasonal precipitation for the 32 years that the USGS has had a gage site on the Knife River. Precipitation in the three years of monitoring was average to below average when compared to the period of record.

3.5 Soils

There are four major geomorphic areas that span the Knife River Watershed. **Figure 3.11** shows the extent of the three main geomorphic areas (Highland Moraine, transitional area, and Superior Lobe Clay Plain) in the watershed. The fourth geomorphic area, Outwash Soils, is interspersed in small areas of the Highland Moraine. These areas have unique soil properties based on different parent material, physical makeup and chemical composition. However, one thing they all have in common is the presence of high amounts of iron which give the soil a reddish hue.

The headwaters of the watershed occur within the Highland Moraine. This geomorphic area has hummocky topography with scattered areas of small lakes and depressions of organic deposits. A majority of the soils have properties of a loamy (silt loam, loam, fine sandy loam) mantle over dense glacial till. Depth of the dense till ranges from 25 to 60 inches and varies depending on soil series and landscape position. Permeability is moderate in the mantle and very slow in the dense till. The dense till has a high bulk density which acts like an impermeable layer. This dense till impedes water movement downward into the soil column thus a perched water table condition occurs. Some of the major soils in this area are: Ahmeek, Normanna, Hermantown and Canosia. These soils are relatively stable and are likely not a major source of sediment in a watershed.

Outwash soils are another component of the Highland Moraine. Geomorphically these areas are scattered on the moraine and occur as small outwash plains or along old glacial river channels. These soils often have a loamy (sandy loam or loam) mantle over sand and/or gravel and can act like a ground water recharge area. Some of the major soils in this area are: Aldenlake, Pequaywan, Rollins, Grayling, Grytal, Cromwell and Hulligan.

Year	Precip (inches)	Rank
1999	33.68	1
1986	32.94	2
1995	29.56	3
1982	29.03	4
1985	27.9	5
1996	27.76	6
1991	27.66	7
1977	26.72	8
1984	26.65	9
1981	26.29	10
2001	26.23	11
1988	25.34	12
1978	25.12	13
2004	24.76	14
1990	24.73	15
1998	24.59	16
1993	24.54	17
2002	23.53	18
1979	22.71	19
1992	22.55	20
1987	22.41	21
2005	22.33	22
1994	21.61	23
1980	20.58	24
2003	19.9	25
1983	19.51	26
1997	18.33	27
1975	18.31	28
2000	17.65	29
1989	17.18	30
2006	16.47	31
1976	12.84	32
Mean Precip		23.73156
Median		24.565

Table 3.4. Precipitation from April 1st to October 31st taken near Two Harbors, MN.

There is a transition area between the Highland Moraine and the Superior Lobe Clay Plain. This geomorphic area has a discontinuous mantle of eolian (wind deposited sediment often finer silts) or water laid sediments over friable till underlain by dense till. The dense till in this area occurs between 60 and 80 inches below the surface. Bedrock also appears in this geomorphic area. Soils of concern would be eolian deposits on steeper slopes that if disturbed could easily erode. Some of the major soils in this area are: Forbay, Augustana, Hegberg, Eldes, Wahbegon, Mesaba and Barto.

The Superior Lobe Clay Plain encompasses the lower quarter of the watershed and is the area of most concern. This area has deep incised drainage patterns that run perpendicular to Lake Superior. The clay plain has a Southeast aspect with an average slope of 6 to 8 percent. Soils in this area have textures that range from 60 to 80 percent clay throughout the soil profile. Permeability in these soils is very slow, therefore they are rated as having a very high runoff potential. Clay soils are also highly susceptible to shrink and swell action due to properties of the clay. A major concern is that the clay soils can slump creating a mass movement of soil down slope. Stream bank sloughing is also another concern of sediment into the waterways.

A positive feature in parts of the Clay Plain is that there are bedrock controlled channels and bedrock walls adjacent to the Knife River which greatly reduce any sediment loading. Lower parts of the Knife River also have a broader floodplain. Soils in these floodplain areas tend to be more sand and gravel and not clay deposits.

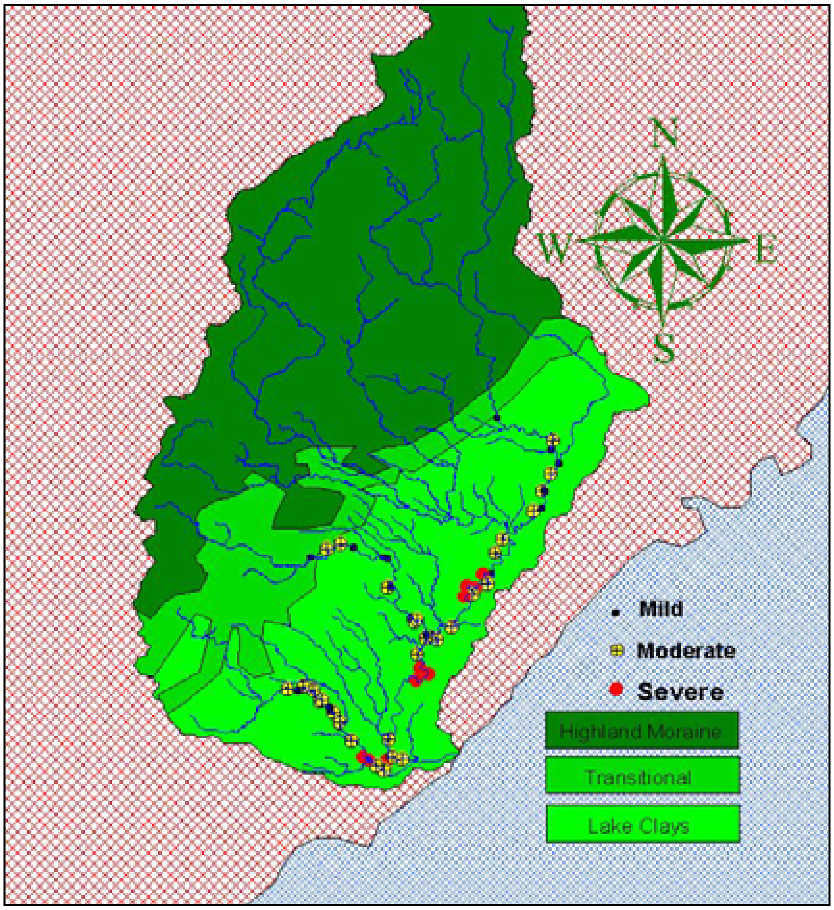

Figure 3.11. Three major geomorphic areas and areas of bank erosion in the Knife River Watershed.

The erosion areas shown in **Figures 3.12 – 3.14** were photographed during a helicopter reconnaissance flight in 1999. The severity of the bank erosion was estimated from these photographs. Severe bank erosion was determined by the complete lack of vegetation, exposed bank around a complete "bend in the river," an associated depositional bar, and the height of the bank (difficult to estimate from photographs). Moderate bank erosion was determined by the lack of vegetation in places and exposed bank that did not reach completely around a bend. Everything else was listed as "Mild," and all of these banks had some vegetation on the bank and were usually only 10-50' long.

(Written by: Mike Walczynski, USDA-NRCS Area Resource Soil Scientist)

Figure 3.12. Example of mild bank erosion.

Figure 3.13. Example of moderate bank erosion.

Figure 3.14. Example of severe bank erosion.

3.6 Fish

The fish population supported by the Knife River and its tributaries is diverse. Fourteen non-game fish have been sampled, which include blacknose dace, brook stickleback, central mudminnow, common shiner, creek chub, emerald shiner, fathead minnow, finescale dace, Johnny darter, longnose dace, longnose sucker, northern redbelly dace, spottail shiner, and white sucker (MNDNR unpublished data; Smith and Moyle 1944). Of the game fish species present, the brook trout is most abundant in the upper reaches, while migratory rainbow trout (steelhead) are most abundant in the middle to lower reaches of the watershed. Other game fish that utilize the watershed include brown trout, Kamloops strain of rainbow trout, Chinook salmon, Coho salmon, and Pink salmon. The MDNR actively manages the game fishery in the river via population surveys, stocking, and fishing regulations.

The amount of suspended solids present within the water column and deposited on the substrates can influence the fish and invertebrate communities present. Fish and invertebrates are dependent on flowing water to deliver much-needed suspended solids, which include organic materials on which they feed and live. Organic materials decay and become the primary food resource for the invertebrates inhabiting the streambed. However, too many suspended solids result in deposition and substrates becoming embedded. The interstitial spaces between gravel and cobble serve numerous important functions, which include habitat for the macroinvertebrates on which fish feed and places for fish to deposit eggs prior to the eggs hatching. As substrate embeddedness increases, the amount of suitable spawning habitat decreases. Egg hatching rates decrease due to suffocation and the amount of food (macroinvertebrates) available to fish decrease due to habitat loss. The diversity of both the fish and macroinvertebrate communities becomes reduced, and as riffles become embedded and pools become filled, rivers transform into elongated runs and habitat diversity is greatly reduced.

(Written by Matt Ward, MN DNR Fisheries)

3.7 Macroinvertebrates

Macroinvertebrates are often used as a broad stream health indicator, and it is a useful tool when dealing with an impairment as difficult to assess as turbidity. The Natural Resources Research Institute (NRRI) conducted a macroinvertebrate stream survey in August of 2006, and published the results in "Knife River Macroinvertebrate and Sediment Survey" (Technical Report #NRRI/TR-2007/14). This report is included in Appendix C.

The study found that there is a range of "stream health" based on macroinvertebrates over the entire Knife River watershed. Several of the smaller tributaries have healthy macroinvertebrate communities, and low embeddedness, while others have an abundance of more tolerant species and high embeddedness. Overall, the Knife River sites show high enough levels of embeddedness to have an impact on macroinvertebrate communities, and when compared to other North Shore streams the metrics used seem to indicate a more "poor condition" than expected for North Shore streams. While analysis of the available data was unable to make a strong link between sediment (turbidity) and macroinvertebrate community health, it is assumed that sediment along with other unknown stressors are causing the Knife River to rate poor when compared to other North Shore streams. A bigger data set will be required to identify other possible stressors and the real impact of sediment on macroinvertebrate community health.

4.0 Description of the Study and Methods

Monitoring for the Knife River Turbidity TMDL study was set up to sample turbidity, total suspended solids (TSS), volatile suspended solids (VSS), and flow over a three year period to evaluate the turbidity levels and TSS concentrations present in the river in comparison to its water quality standard for turbidity. In order to complete the TMDL, a relationship between turbidity and TSS also had to be established.

The monitoring effort included four continuous monitoring and discrete sampling sites (**Figure 4.1)**. The continuous monitoring at the sites included stage and in-situ sonde parameters, including turbidity. Discrete grab samples were collected over a range of flows and were analyzed in a laboratory for turbidity, TSS, and VSS. Samples and data were collected over a three year period (2004 – 2006). All samples were collected following the EPA Region V Minimum Requirements for Field Sampling Activities (September 1996). Field measurements were taken for temperature, pH, dissolved oxygen, turbidity, and conductivity.

The Fish Trap site was established given its proximity to the USGS gage station near the mouth of the Knife River and the protection the DNR fish trap provided to the in-situ sonde deployed for the project. Flow data for this site was obtained from the USGS National Water Information System (NWIS). The three other sites (Nappa, Culvert, and Airport) were selected to be representative of the watershed areas contributing flow and sediment to the Knife River. Flow data was calculated using rating curves developed for each site and continuous stage data from the sites.

Biological (macroinvertebrate) sampling was completed by the Natural Resources Research Institute (NRRI). The macroinvertebrate sampling was done on 5 sites along the mainstem and tributaries of the river. Benthic samples were collected using a multi-habitat sampling approach (Lenat 1988) during baseflow conditions. Samples were then identified to the lowest practical taxonomic level using appropriate keys (Hilsenhoff 1981, Widerholm 1983, Brinkhurst 1986, Thorp and Covich 1991, Merritt and Cummins 1996). This work along with MN DNR routine fish surveys were used to estimate the impairment's impact on the biological integrity of the stream when compared to other North Shore streams.

Extensive GIS work used available data and created layers for various types of analyses (landuse, erosive potential, contributing drainage, etc.).

A physical channel, streambank, and bluff assessment was also completed for the project. Initial field work was completed by SWCD and MPCA staff. Additional assessment work was completed by the University of Minnesota. Field measurements and analyses were completed using methods described by Rosgen (1996) and best professional judgment.

The following sub-sections provide additional information on the monitoring completed for the project.

4.1 Site Locations

The four water quality monitoring sites were established specifically for the project, although the lower mainstem site was only a short distance from the USGS gaging station on the river. **Figure 4.1** and **Table 4.1** show the locations of the sites in the watershed and provide a narrative description of the sites, respectively.

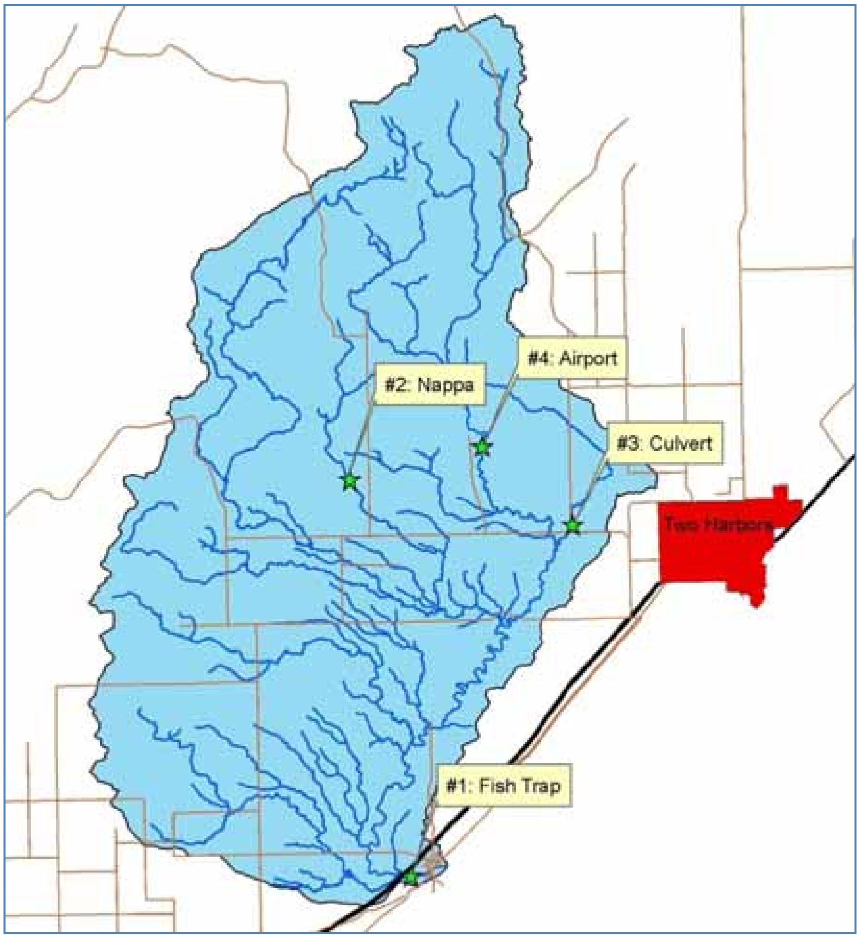

Figure 4.1. Water quality monitoring sites for the Knife River TMDL study.

Site (STORET ID)	Latitude/Longitude	Location
#1: Fish Trap (S003-642)	Lat. 46.9465 N Long. -91.7939 W	Just downstream of Hwy 61 bridge at the DNR Fish Trap
#2: Nappa (S003-642)	Lat. 47.0472 N Long. -91.8129 W	Approximately 200' downstream of where the Little West Branch goes under Nappa Rd
#3: Culvert (S003-642)	Lat. 47.0337 N Long -91.7310 W	Approximately 200' North of Hwy 11 and Hwy 12 intersection where Hwy 12 goes over the Little East Knife
#4: Airport (S003-642)	Lat. 47.0545 N Long. -91.7633 W	At Airport Rd (Maki Rd) bridge over Knife River

Table 4.1. Location and description of water quality monitoring sites in the Knife River Watershed.

4.2 Water Quality and Flow Monitoring

Water quality and flow monitoring was completed at four sites in the watershed. The sites included two mainstem and two tributary locations. Data was collected during the open water period of three years (approx. May – October) – 2004 - 2006.

4.2.1 Grab Sampling and Field Measurements

Water quality samples were collected using grab sampling techniques. All samples were collected in clean 1-liter polyethylene bottles. The bottles were rinsed three times with the source water before samples were taken. All samples were preserved as necessary, tagged, and logged on an approved chain-of-custody form. Field measurements, including pH, DO, temperature, conductivity, and turbidity were taken at each sampling location with a YSI 6820 series multi-parameter probe. Transparency tube measurements were also taken.

4.2.2 In-situ Water Quality Measurements

Continuous monitoring was done at all four sites during the open water season, with the exception of 2004 at site #3 due to road construction. The monitoring was done using Campbell Scientific data loggers connected to YSI multi-parameter probes. The data loggers were set to record temperature, percent saturation of dissolved oxygen, dissolved oxygen concentration, conductivity, pH, and turbidity at 15 minute intervals at the Fish Trap site and 30 minute intervals at the remaining 3 sites. The sondes were calibrated monthly or when necessary according to paired field measurements.

4.2.3 Stage and Flow Monitoring

Daily flow data was obtained from the USGS gage site on the Knife River (USGS 04015330, Knife River near Two Harbors) for use with the Fish Trap site water quality data. Discharge for the three other sites required the development of rating curves. Flow measurements were completed, when possible, at a range of flows by SWCD staff using a USGS Type AA current meter, or pygmy meter. Measurements for high discharges were conducted by USGS staff. The stage-discharge rating curves were developed by MPCA Brainerd staff using Hydstra. All three sites were outfitted with equipment to acquire continuous stage (Appendix A: Table A.1). Daily flows were computed using the stage data and rating curves for each site.

4.3 Biological Monitoring

The project did not conduct fish sampling given that the MN DNR conducts annual fish surveys at 7 sites along with intensive sampling at the Fish Trap site. Five of the sites are Steelhead Index Stations and 2 sites are Brook Trout Index Stations (personal communication, Matt Ward, MN DNR, 12/18/07). The DNR fish sampling is completed following the Fisheries Stream Survey Manual Version 2.1 (2007). The Knife River

“Fish Trap” site was named because it is near the location of the MN DNR’s actual fish trap. The DNR uses this trap to measure migration of fish (primarily steelhead) up and down the Knife River. This trap operates, on average, from April 8th until November 1st annually.

Macroinvertebrate sampling was completed by the Natural Resources Research Institute (NRRI) in August of 2006. The following is an excerpt from the Knife River Macroinvertebrate and Sediment Survey report by NRRI (Brady and Breneman 2007) describing the sampling methods:

> “Benthic samples were collected using a multi-habitat sampling approach (Lenat 1988) during baseflow conditions. Quantitative samples were collected in triplicate from run, riffle, and pool habitats using a modified Hess (0.086 m2) in riffles or sediment core tube (0.0045 m2) in shallow depositional areas. All quantitative samples were washed on-site through a 254-µm mesh net or sieve. Where habitat was available, qualitative samples were collected from beneath bank or over-hanging vegetation , woody debris dams, boulder piles or rip-rap, or sediments and aquatic vegetation in run and pool habitats using a D-frame kick net (mesh size: 500 µm). The D-net effort was timed and measured (approx. 30 seconds per sample and a 10 m distance). Extensive herbaceous bank vegetation and instream aquatic vegetation were swept, while wood dams and boulder piles were jabbed (sensu Barbour et al. 1999) to dislodge invertebrates. All invertebrates from each sample type were preserved in the field using a Kahle’s preservative, 10% Formalin, or 70% ethyl alcohol.”

4.4 Geomorphic Survey

Geomorphic surveys were done to help identify near channel sources of sediment to the river. The initial measurements were made along two reaches that had apparent severe erosion problems. One reach was in the process of cutting off a meander, while another contained a large slumping clay bank. A third reach was used to classify the lower reaches of the Knife River according to Rosgen’s Classification of Natural Rivers. The initial surveys used Level 2 classification methods outlined by Rosgen (1996).

Following the initial surveys, it was determined that additional geomorphic assessment was needed to further evaluate streambank and stream bluff erosion to better identify and quantify the potential sources of sediment to the river. The University of Minnesota was contracted to do this additional work. The work included use of sediment and flow data for storm event load calculations; performance of surveys of the main stem of the river to collect geomorphic data including cross-section geometry and longitudinal slope, bed sediment characteristics, and physical properties of streambanks; and application of three models for prediction of sediment production and transport. The three models used included CONCEPTS (Conservational Channel Evolution and Pollutant Transport Model), BEHI (Bank Erosion and Hazard Index), and SEDIMOT II (a small watershed hydrology and sedimentology model). Detailed methods are described in the report, Assessment of Streambank and Bluff Erosion in the Knife River Watershed (Nieber et al. 2008), in Appendix E.

4.5 Water Quality Parameters and Data Management

Table 4.2 lists the water quality parameters measured with field meters, in-situ sondes with data loggers, and in the laboratory. Field data and measurements, along with sampling information, were recorded in a field book in a standard format. The in-situ sensors were checked against field measurements and the sensor values were recorded in the field book as well. All grab sample data collected during an annual sampling period were held in-house, and at the conclusion of each sampling year the data was submitted to MPCA for entry into STORET.

All lab results were reported to SWCD staff within 2 weeks of water sample collection. Lab results were recorded in specified spreadsheet for storage and eventual submission to STORET. All continuous data from in-situ sensors was stored with the SWCD and submitted to MPCA Brainerd office for entry into Hydstra. Mean Daily Flows (MDFs) were calculated by MPCA for all sites except the Fish Trap (where USGS gage data was available).

Precipitation was measured with a tipping bucket rain gauge at the Nappa monitoring site.

Field Parameters	In-situ Parameters	Lab Analytes
Temperature (^{o}C)	Temperature (^{o}C)	Total Suspended Solids, TSS (mg/L)
Conductivity (uS/cm)	Conductivity (uS/cm)	Volatile Suspended Solids, VSS (mg/L)
Dissolved Oxygen (mg/L and % Saturation)	Dissolved Oxygen (mg/L and % Saturation)	Turbidity (NTU)
pH	pH	
Turbidity (FNU)	Turbidity (FNU)	

Table 4.2. Field, data logger, and lab parameters.

5.0 Evaluation of Study Data

The monitoring during the TMDL study provided the additional data needed to better characterize turbidity levels in the Knife River, develop a surrogate for load determinations for the TMDL, evaluate the macroinvertebrate community, and provide an estimate of the sources and contributions of sediment to the river. The need for a surrogate variable in calculating loads for turbidity TMDLs was especially important in completing the additional monitoring. The concentration of suspended sediment in a stream is a product of several factors, including land use practice, soil type, vegetative cover, topography, precipitation and time of year (Wood and Armitage, 1997). These site specific factors made it necessary to calculate a relationship specific to the Knife River watershed rather than use existing "regional" data. The following paragraphs lay out the process used.

5.1 Data Available Prior to TMDL Study

Prior to the TMDL study, the primary source of the water quality data in STORET was from the MPCA ambient monitoring program (now called Minnesota Milestone monitoring). A small amount of additional data was collected by the Western Lake Superior Sanitary District. Most of the data was collected near the mouth of the river. The sites were labeled KN-0.2 and Knife 00 for the two programs, respectively. **Figure 5.1** provides a plot of the data from STORET prior to the TMDL study. The figure does not show turbidity data collected in the mid-1970's.

The Knife River was identified as being impaired for aquatic life due to turbidity using data from the ten-year period, 1986 to 1996. The data assessment for the Knife River is summarized in Table 5.1. A need for additional data was recognized quickly given the small amount of data present.

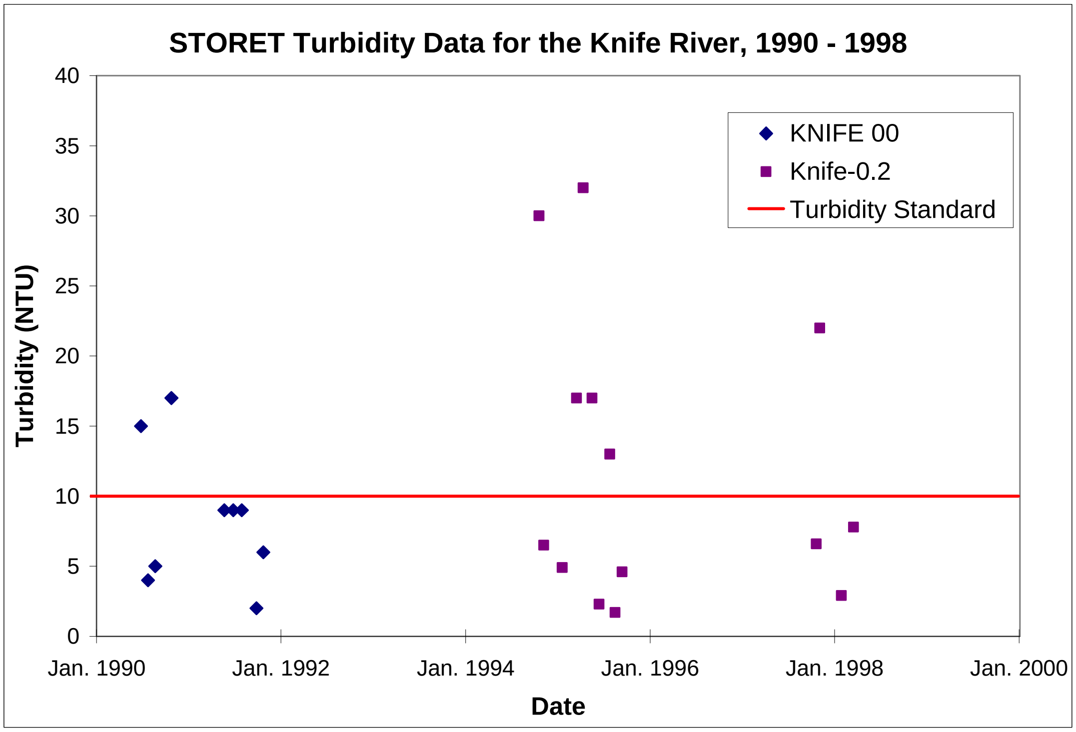

Figure 5.1. Knife River turbidity data available between 1990 and 1998.

303(d) List Reach Name	Knife River, Headwaters to Lake Superior
Monitoring Stations	KN-0.2, Knife 00
Reach Number (AUID)	04010102-012
# of Observations	19
# Exceeding the Standard of 10 NTU	7
Percent Exceeding the Standard	37

Table 5.1. Data summary for the 1998 303(d) List assessment of the Knife River for turbidity.

5.2 Grab Sampling

The TMDL study completed three years of grab sampling to provide a broader range of turbidity measurements combined with TSS and accompanying flow data. Sampling was based on a regular bi-weekly schedule combined with storm event sampling starting in April and ending in October. The three years of sampling occurred in relatively dry years, and thus resulted in few data on the high end of the river's flow range; however, some event samples were obtained in the upper 10 percent of the stream's mean daily flows. The sampled flows included 7 storm events and 15 routine samples in 2004, 6 storm events and 12 routine samples in 2005, and 2 storm events and 14 routine samples in 2006 (**Figures 5.2, 5.3,** and **5.4**, respectively).

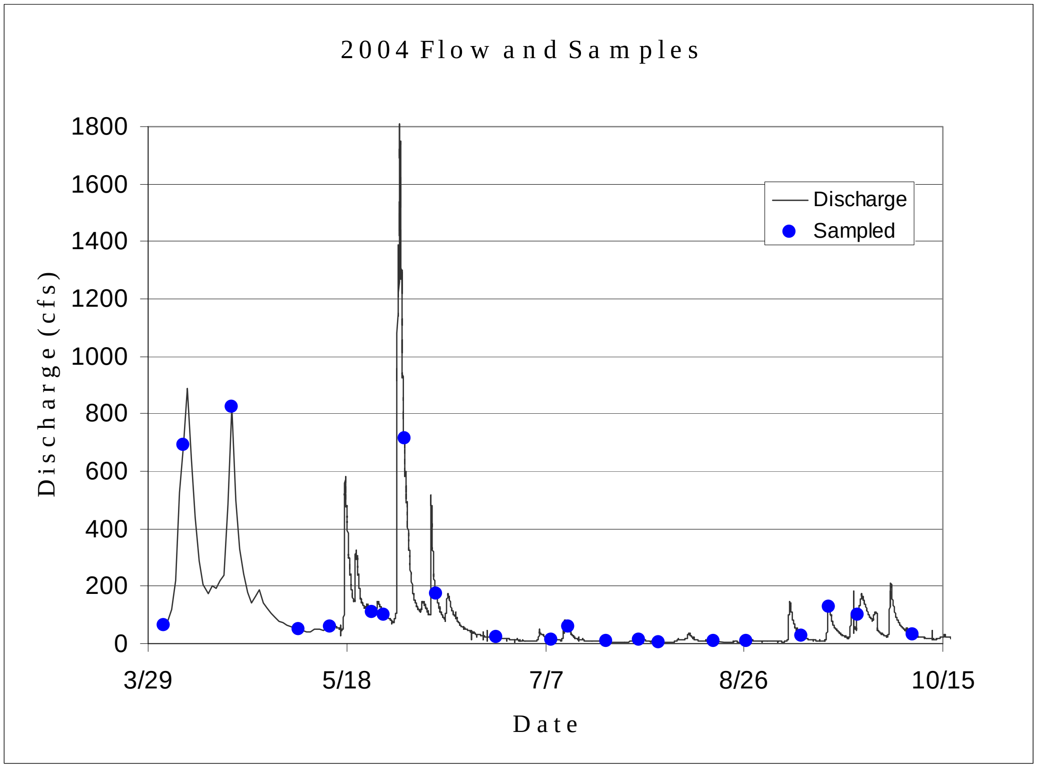

Figure 5.2. Location of grab samples on the Knife River hydrograph (USGS gage site) in 2004.

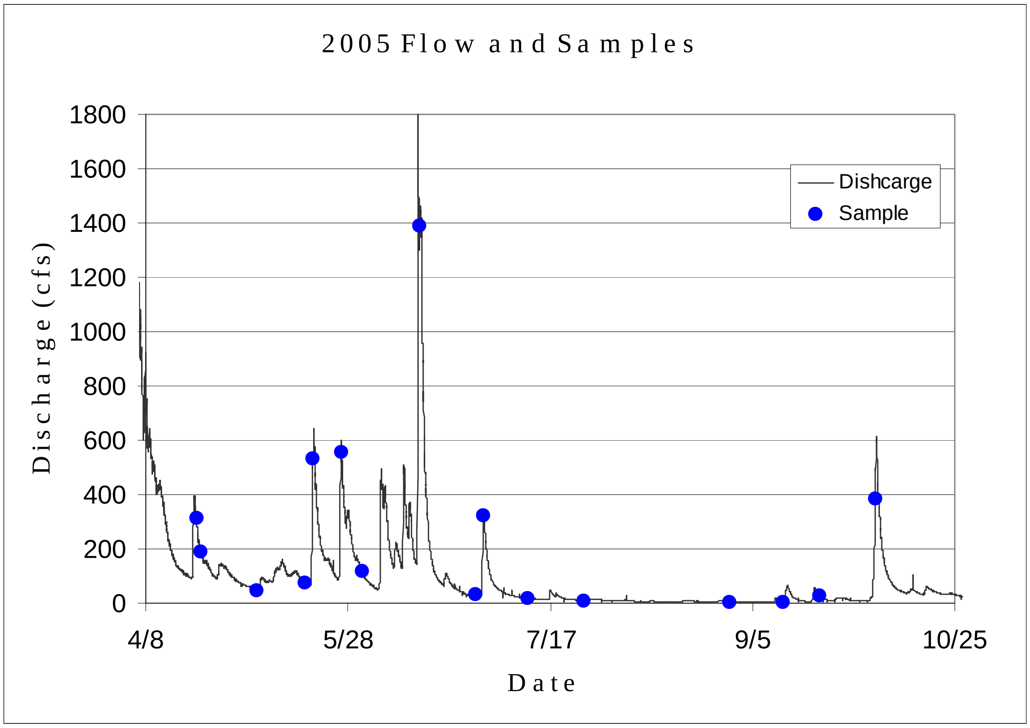

Figure 5.3. Location of grab samples on the Knife River hydrograph (USGS gage site) in 2005.

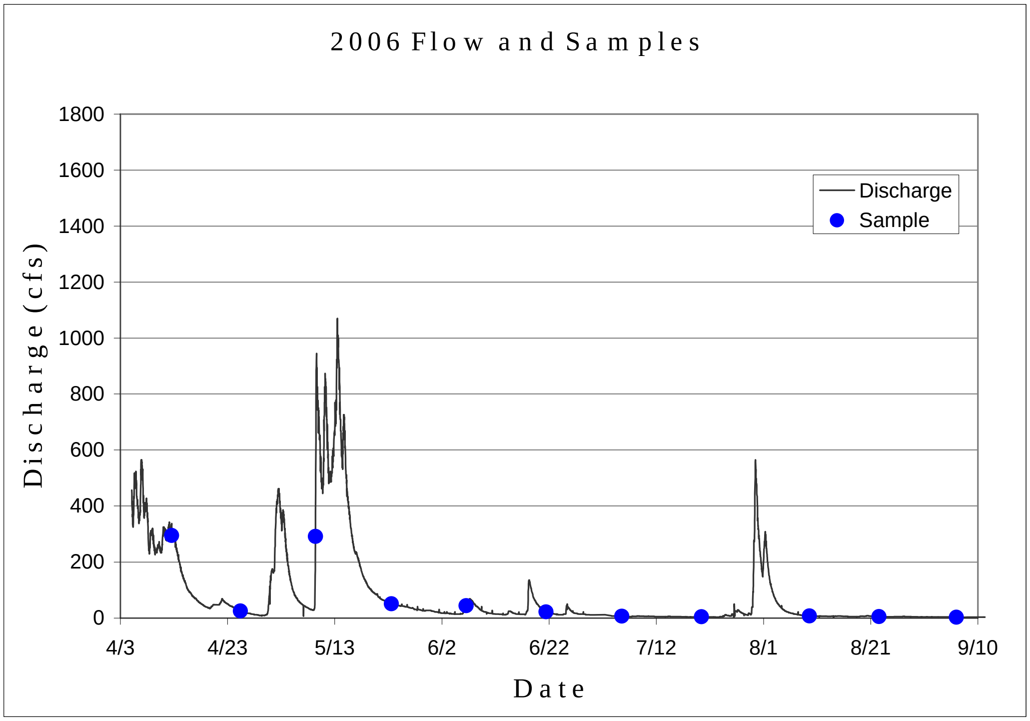

Figure 5.4. Location of grab samples on the Knife River hydrograph (USGS gage site) in 2006.

The figures show that samples were collected near the peak flows for several of the storm event flows. An emphasis on runoff event sampling is important in the accurate calculation of loads in a stream given that elevated sediment concentrations are closely associated with the higher flows. The figures show that staff was efficient at getting water samples for the majority of the storm flows through all 3 years.

The grab samples collected at each monitoring site were analyzed for turbidity, TSS, and VSS in the laboratory. Field measurements of turbidity and transparency tube depths were also made. **Figures 5.5** through **5.7** plot the turbidity values measured in the grab samples at the Fish Trap site (S003-642) along with the hydrograph and water quality standard for each year of the TMDL study sampling. Similar plots of the data could be produced for the other monitoring sites and water quality parameters. A summary of the data for each site is included in Tables 5.2 – 5.5.

The turbidity water quality standard was exceeded in 26 of the 56 grab samples collected between 2004 and 2006.

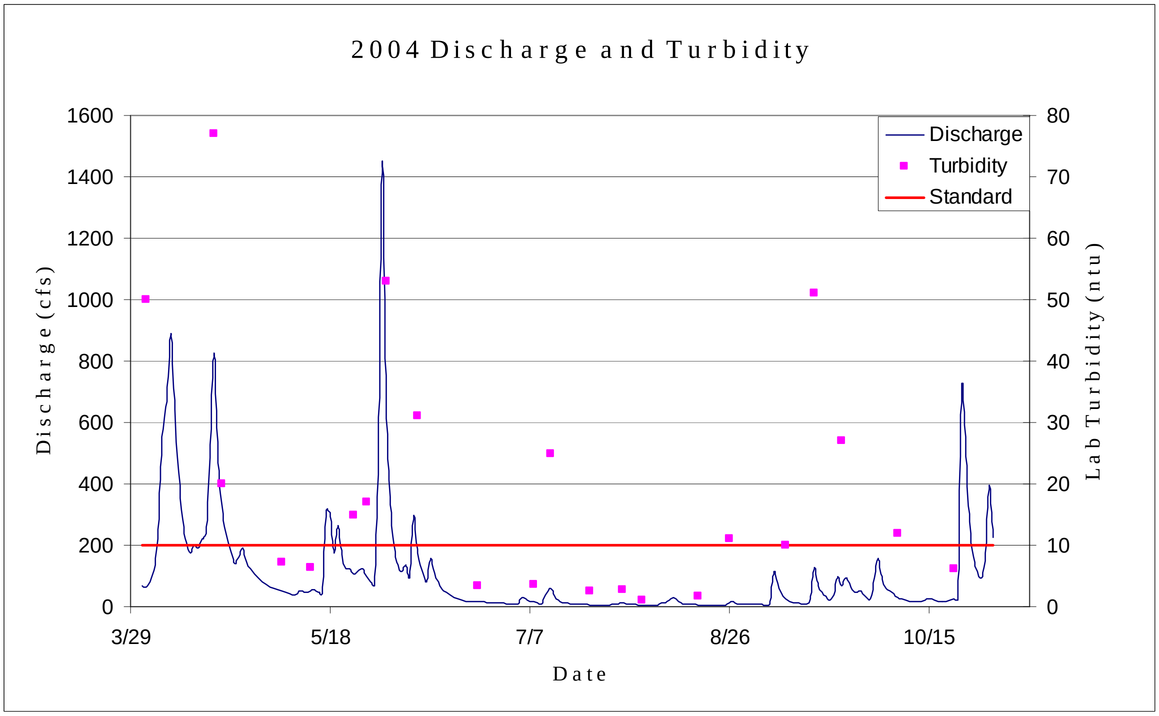

Figure 5.5. 2004 mean daily flows and lab turbidity data for the Fish Trap monitoring site.

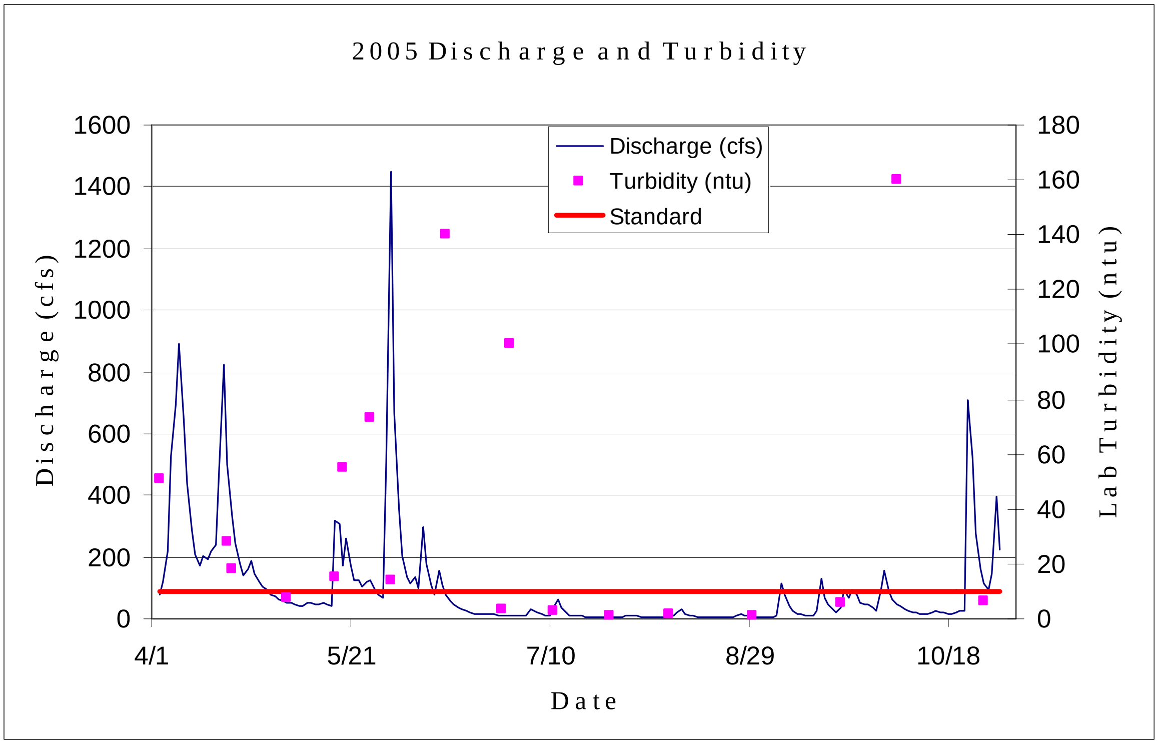

Figure 5.6. 2005 mean daily flows and lab turbidity data for the Fish Trap monitoring site.

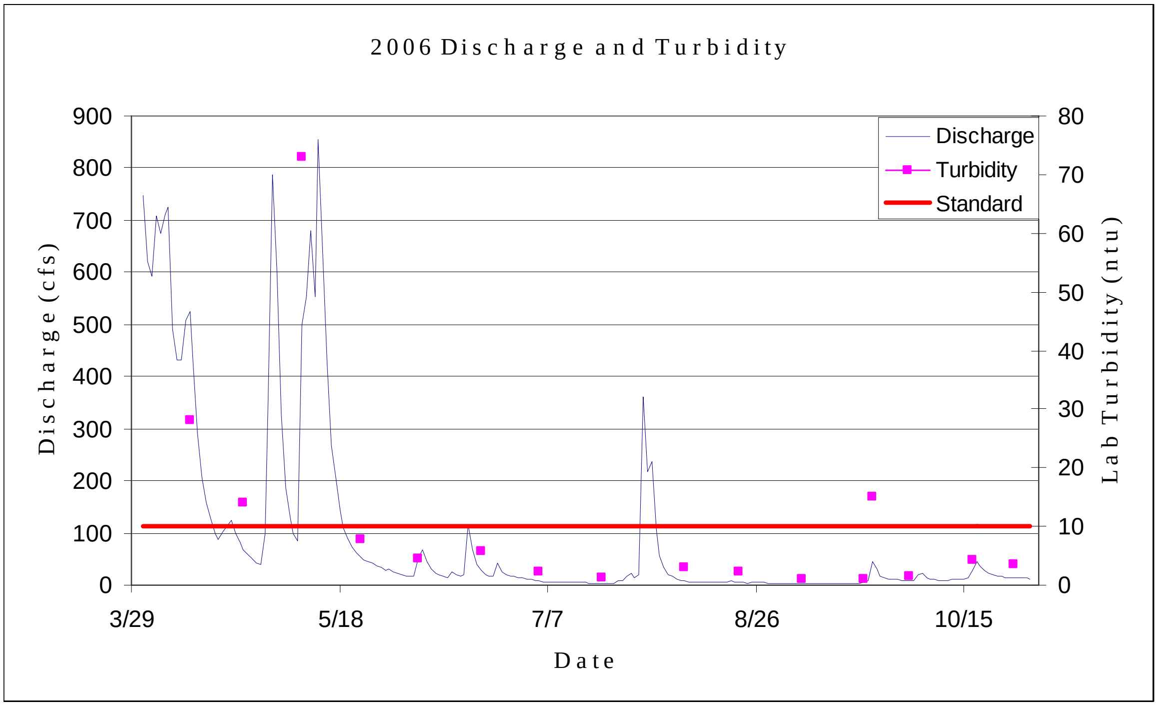

Figure 5.7. 2004 mean daily flows and lab turbidity data for the Fish Trap monitoring site.

Fish Trap Site (S003-642), Knife River – Grab Sample Data, 2004 - 2006				
	Turbidity	**TSS**	**VSS**	**T-tube**
# of samples	64	64	60	37
Mean	20.8	16	2.3	82.8
Median	7.4	2	1	100
Std. deviation	32	32	3.3	31.5
Minimum	0.9	Detection Limit	Detection Limit	6
Maximum	160	155	15	>100
# > 10 NTU	29			
% > 10 NTU	45			

Table 5.2. Summary statistics for the Fish Trap site on the Knife River.

Airport Site (S003-670), Knife River – Grab Sample Data, 2004 - 2006				
	Turbidity	**TSS**	**VSS**	**T-tube**
# of samples	60	60	60	34
Mean	2.82	5.1	1.8	96
Median	1.4	2	1	>100
Std. deviation	3.64	8.8	2.85	13.8
Minimum	Detection Limits	Detection Limit	Detection Limit	37
Maximum	22	52	17	>100
# > 10 NTU	3			
% > 10 NTU	5			

Table 5.3. Summary statistics for the Airport site on the Knife River.

Nappa Site (S003-668), Knife River – Grab Sample Data, 2004 - 2006				
	Turbidity	**TSS**	**VSS**	**T-tube**
# of samples	57	57	57	37
Mean	2.43	3.6	1.3	97
Median	1.7	2	1	>100
Std. deviation	2.01	5.07	1.3	11.2
Minimum	0.08	Detection Limit	Detection Limit	50.5
Maximum	10	23	6	>100
# > 10 NTU	1			
% > 10 NTU	1.8			

Table 5.4. Summary statistics for the Nappa site on the Knife River.

Culvert Site (S003-669), Knife River – Grab Sample Data, 2004 - 2006				
	Turbidity	**TSS**	**VSS**	**T-tube**
# of samples	53	53	53	33
Mean	25.9	8.6	2	43
Median	23	6	2	37
Std. deviation	16.4	7	1.2	20.9
Minimum	0.9	1	0.68	9
Maximum	79	35	7	96
# > 10 NTU	49			
% > 10 NTU	92			

Table 5.5. Summary statistics for the Culvert site on the Knife River.

Low volatile suspended solids (VSS) concentrations indicate very little organic matter present in the water column of the streams. The predominance of inorganic solids in the samples indicates that the turbidity impairment is mainly due to inorganic sediment.

5.3 Turbidity Data

In addition to the laboratory data obtained from the grab samples, field measurements and continuous in-situ measurements for turbidity along with dissolved oxygen, pH, and temperature were made. Variability in turbidity meter and sensor configurations and sensor response to the turbidity-causing materials in water required an evaluation of the degree to which the different data sets can be considered equivalent.

Turbidity was measured in the lab using a Hach 2100AN turbidimeter with the ratio compensation mode 'Off' (Era Lab procedures). The laboratory turbidity data is reported in units of NTU following the USGS reporting categories for different types and configurations of turbidity meters. The field and in-situ sondes (YSI 6800 and 6900 series sondes) provide turbidity values reported as FNU. The USGS reporting categories were developed as a means of specifying the type and configuration of different turbidity meters and sensors (Anderson, 2005). A visual review of the data from each source showed some differences in the values collected or measured at the same time; however, the differences generally were relatively small. The following figures present various comparisons of the three measurements. **Figure 5.8** plots the three paired measurements (data values with the same date and time collected) against the rank order of the lab data from lowest to highest lab value. The data show that the field data measurements are fairly similar to the lab values, but the in-place sondes show greater differences although many values are fairly similar.

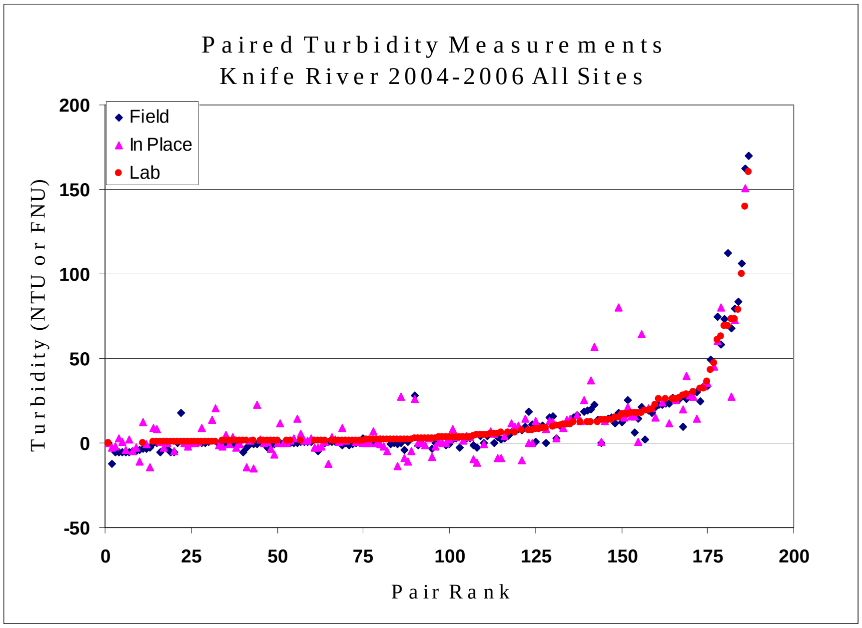

Figure 5.8. Paired turbidity values for lab, field, and in-place turbidity measurements for all Knife River TMDL study sites – 2004 – 2006.

A more direct comparison of the lab and field turbidity data is seen by plotting the data against each other (**Figure 5.9**). The correlation between the two is strong, but the plot and line of best fit (regression) equation indicate that the paired values are not exactly the same.

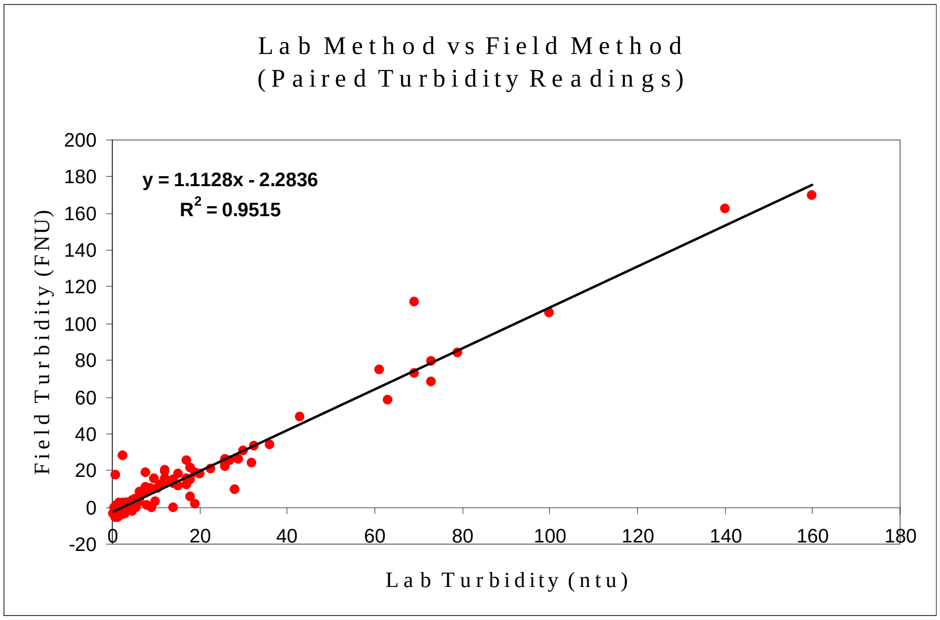

Figure 5.9. Lab vs. field turbidity (All sites/All years).
Plot shows a tight fit and good slope. Negative Y-intercept is explained by negative readings on the field sonde at very low turbidity levels.

Plotting the paired in-place sonde and lab data for the monitoring sites shows a greater variability in the turbidity values reported from the in-place sondes when compared to the lab data (**Figure 5.10**). The increased variability between the values was expected given the environmental factors such as sedimentation, algae growth that can cause turbidity sensor fouling and drift, extraneous light, and varying response to the light source given the free movement of particles in the water when sondes are continuously deployed in the streams.

Given the slight to relatively large variation between the types of turbidity measurements, it was decided to limit the turbidity data measured in the lab as the data being evaluated against the standard and used to determine the TSS surrogate. Additional data analysis could have been completed to more quantitatively describe how the data types match up, but it was not completed given the decision to use the laboratory turbidity measurements for the actual TMDL analyses.

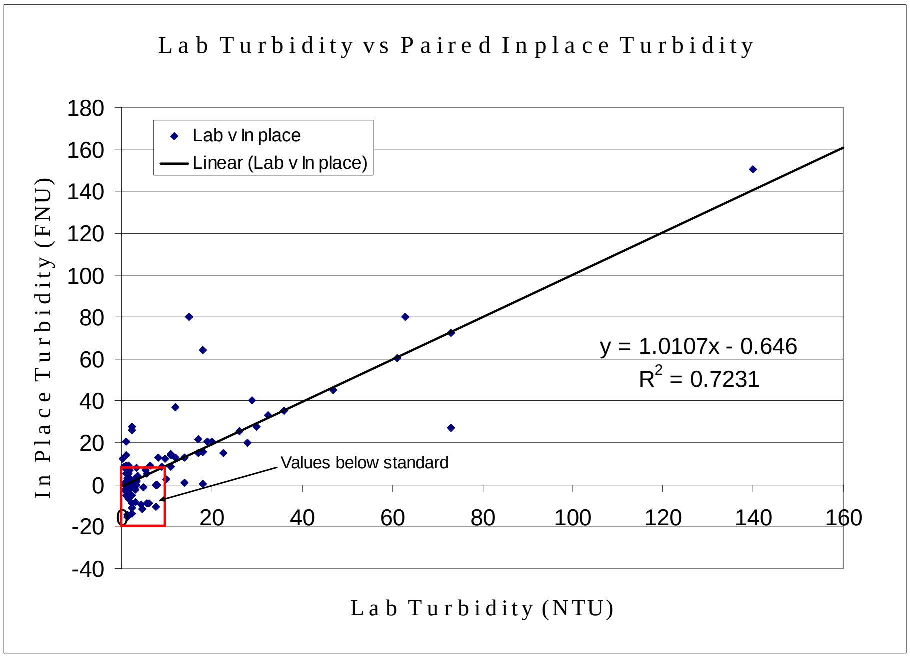

Figure 5.10. Lab turbidity (NTU) vs Inplace Turbidity (FNU).

The in-place sonde data provided a near continuous (15-minute intervals) record of turbidity at each of the four monitoring sites during the project. **Figure 5.11** shows the data recorded for the Fish Trap site in 2006. Plots of the other sites for each year are provided in Appendix G. **Figure 5.12** provides an excerpt of the 2006 Fish Trap site data that shows the turbidity in the stream changing over a storm event hydrograph.

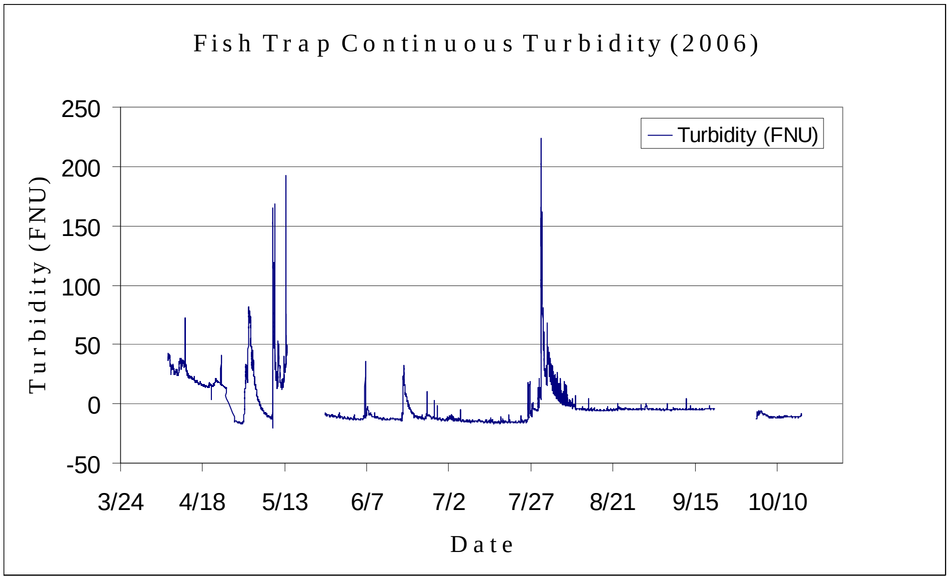

Figure 5.11. 15-minute interval turbidity at the Fish Trap site over the entire 2006 monitoring season.

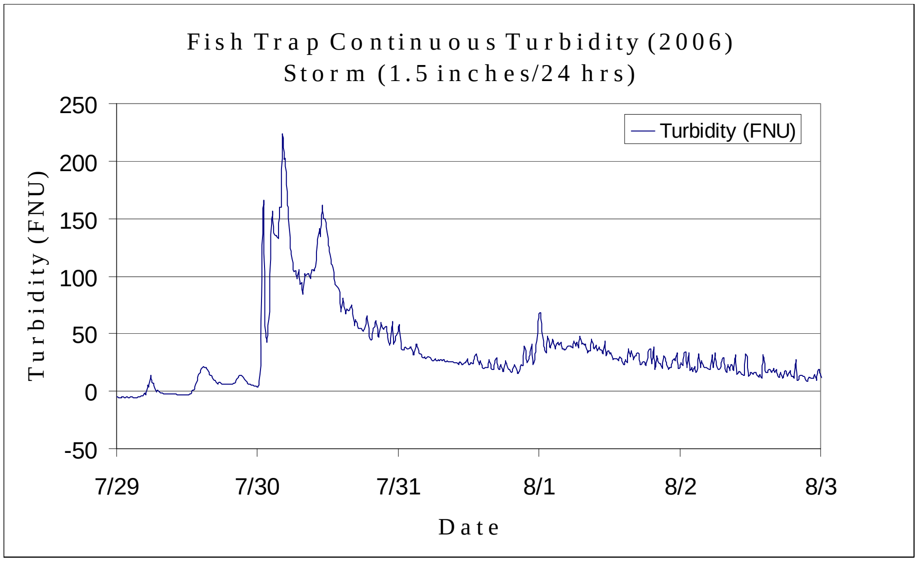

Figure 5.12. 15-minute interval turbidity at the Fish Trap site over one precipitation event.

5.4 *Turbidity to TSS Target*

As noted previously, a surrogate for turbidity is needed to enable the calculation of loads for a TMDL. Sediment, particularly the red clay particles, is the dominant material affecting turbidity in the Knife River based on the reddish brown coloration of the river under turbid conditions and the low percentage of volatile suspended solids present compared to TSS (less than 25% for TSS concentrations greater than 10 mg/L). A plot of turbidity against TSS data for the Fish Trap site is shown in **Figure 5.13**. To calculate a TSS surrogate, regression analysis was completed on the data. To meet statistical methods assumptions for regression analyses, the data were log-transformed to approximate a normal distribution of the data. The strength of the correlation between log-transformed turbidity and TSS data allowed a TSS surrogate value to be estimated for the turbidity standard of 10 NTU at the Fish Trap site using the regression equation **Figure 5.14** and **Table 5.6**. The surrogate is calculated by solving the regression equation for TSS given a NTU of 10. Hence, the predicted TSS concentration given a turbidity of 10 for the Fish Trap site is 10^(0.920 * Log(10) – 0.23).

Site	Regession Equation	R^2	TSS Target (Rounded)
Fish Trap	Log(TSS) = 0.920(Log(Turb.)) – 0.230	0.74	4.89 (5)
Nappa	Log(TSS) = 1.327(Log(Turb.)) – 0.074	0.71	17.91 (18)
Culvert	Log(TSS) = 0.759(Log(Turb.)) – 0.195	0.50	3.67 (4)
Airport	Log(TSS) = 1.085(Log(Turb.)) – 0.098	0.70	15.23 (15)

Table 5.6. Results of Turbidity to TSS regression analysis.

Table 5.6 also provides the regression equations, R^2 values, and estimated surrogate values for 10 NTU at the other monitoring sites. The results indicate a difference in the

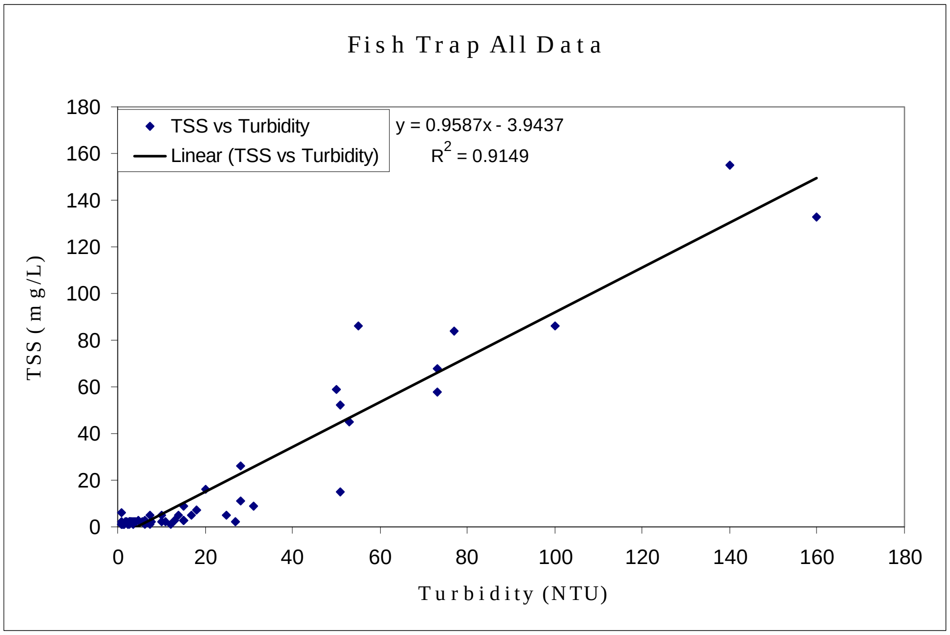

Figure 5.13. Turbidity versus TSS at the Fish Trap monitoring site on the Knife River – 2004 – 2006.

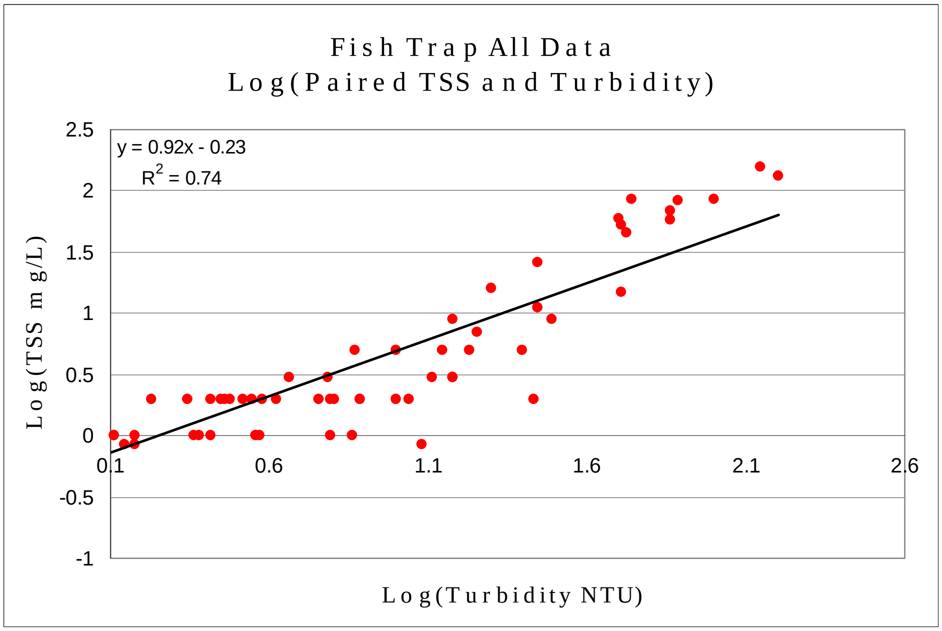

Figure 5.14. Plot of log-transformed turbidity and TSS data at the Fish Trap monitoring site on the Knife River – 2004 – 2006.

TSS values predicted to be equivalent to 10 NTU between the four sites. Such differences have also been shown in other projects (Lower Ottertail River TMDL, Minnesota; Lower Cannon River Turbidity TMDL, Minnesota; and Jemez Watershed TMDLs, New Mexico). In many cases, different sites on the same stream or in the same watershed will show a different relationship between TSS and turbidity due to different soils or other factors.

The TSS surrogate for the 10 NTU water quality standard for the Knife River is 5 mg/l TSS based on the regression analysis described above for the Fish Trap monitoring site. A similar TSS concentration (4 mg/l) was estimated to be equivalent to 10 NTU at the Culvert site. The similarity of the TSS concentrations at the two sites makes sense given the proximity of the sites to the red clay lacustrine soils in the lower portion of the watershed. The relationships between turbidity and TSS at the upper watershed monitoring sites (Nappa and Airport) provide TSS concentrations estimates of 18 and 15 mg/l, respectively, as equivalents to 10 NTU.

The differences in TSS to turbidity relationships are likely due to suspended sediment size. Fish Trap and Culvert sites have a larger portion of fine sediments from the red clay lacustrine soils, which would contribute to turbidity without much mass; while the Nappa and Airport sites have more till soils likely to have larger sediment particles contributing to turbidity. Aside from the sediment size, there is the possibility of bias in the target on the Nappa and Airport sites, because of the lack of values above 10 NTU. These two sites each average about 1 exceedance of the 10 NTU standard per 20 samples and the exceedances are low when compared to the exceedances at the Fish Trap site and Culvert site. This lack of range is probably the source of some bias in the Nappa and Airport targets. Fortunately, this bias only further illustrates that these two sites are not exceeding water quality standards for turbidity.

5.5 TSS Loads

TSS loads were calculated using FLUX Version 5.1(COE, 1999). Pollutant loads are calculated using concentration data, associated flow data, and a continuous flow record. Stream loading is estimated by multiplying flow rate and a concentration over a given amount of time. This estimate is easy and accurate if there is continuous flow and concentration data, but streams are complex with flow and pollutant concentrations varying at different rates continuously. So in order to determine an accurate load estimate on a real stream it is necessary to have a complete time-series of (with few or no interruptions) flow data, at least daily mean flow, and concentration data over a variety of flows. TSS loads were calculated, because TSS is used as a surrogate for turbidity in order to calculate a "load."

FLUX is a commonly used tool for estimating loading using grab samples and continuous daily flow data. The FLUX program allows estimation of mass discharges (loadings) from sample concentration data and continuous (e.g., daily) flow records. Five estimation methods are available and potential errors in estimates are quantified. The flow and concentration information is loaded into the model and then there are options on how to analyze the data. Stratifying the data with flow boundaries is often used to get more accurate results. Using the Knife River data, we found that at least 2 strata were needed to get statistically significant results.

Table 5.7 provides the results of the FLUX estimates for each year of sampling in the TMDL study. FLUX load estimates were computed for each year. The numbers presented in the table represent the best combinations of method and data stratification based on the statistical tools present in FLUX, especially the coefficient of variation (CV). Using the average of the three estimates in each year, the TSS load for the monitoring season in 2004, 2005, and 2006 was about 1,500, 2,800, and 1,300 tons (1.4, 2.6, and 1.2 million kilograms), respectively. The CVs indicate that the selected FLUX methods estimated the TSS load in the Knife River in 2004 and 2005 fairly well given the data present. The elevated CVs for the 2006 data indicate a higher degree of uncertainty in the estimated loads due to a greater variance between observed and predicted values. The higher uncertainty translates to wider range of estimated loads in which the actual load would lie (i.e., the 95th percentile confidence interval is larger about the estimated value).

	FLUX Method	Strata	Estimated Annual Load (kg)	Load During Monitoring Period[1] (kg)	CV[2]	Average Daily Load (kg/day)
2004						
	6	2	2,559,716	1,402,584	0.23	7,013
	5	3	2,635,441	1,443,089	0.15	7,215
	6	3	2,549,774	1,396,180	0.21	6,981
		Average	**2,581,644**	**1,413,951**		**7,070**
2005	4	2	4,198,177	2,425,230	0.18	11,494
	4	3	5,643,416	3,260,125	0.20	15,451
	4	2[3]	3,579,412	2,067,778	0.19	9,800
		Average	**4,473,668**	**2,584,378**		**12,248**
2006	3	2	2,300,078	1,234,265	0.50	6,297
	2	3	2,166,867	1,162,782	0.47	5,933
	3	3	2,254,094	1,209,589	0.50	6,171
		Average	**2,240,346**	**1,202,212**		**6,134**

[1] Length of monitoring period was 200, 211, and 196 days for 2004, 2005, and 2006, respectively.

[2] CV is the coefficient of variation (explained in Appendix A)

[3] Three different stata were used

Table 5.7. Summary of TSS load estimates using FLUX.

5.6 Load Duration Analysis

Using the duration curve in **Figure 5.16**, it is easy to determine when the turbidity exceedances start, in the middle of the moist conditions, approximately 46 cfs or a 32% exceedance flow. A duration curve that shows exceedances starting at higher flows is typical of a stream without point sources contributing to the impairment. If there were a waste water plant on the Knife River causing the impairment you might expect to see exceedances at low flows due to the lack of dilution, but in this case the impairment is occurring at high flows likely due to erosion from overland flow and in-stream sediment sources (flushing, bank erosion, incision).

Load duration analysis as described by Cleland (2002) was used to integrate flow and TSS data, and to provide graphical displays, loading capacity and margin of safety values for the actual TMDL, and estimates of load reductions necessary for attainment of the turbidity water quality standard. **Figure 5.15** is a flow duration curve developed from the streamflow data from the USGS site on the river near Two Harbors. The curved line that goes from upper left to lower right on the graph relates mean daily flow values to the percent of time those values have been met or exceeded. For example, a flow of 220 cfs is met or exceeded only 10% of the time based on the 1974-2006 record; such flows are classified as "high." At the other end of the curve, a flow of 5 cfs is exceeded 90% of the time. Flows less than 5 cfs are classified as "low." The other flow zones are "moist conditions" (10 - 40%), "mid-range flows" (40 - 60%), and "dry conditions" (60 - 90%). The ranges and break points for the zones are somewhat arbitrary, although the mid-point percentiles of each zone are commonly used in statistics (i.e. 50th percentile = median; 75th percentile = upper quartile, etc.).

The combination of flow and pollutant concentration defines pollutant loading. Loading capacity is defined by the combination of flow and a concentration-based water quality standard or target. It is the pollutant load that a river can carry and still be in attainment of the pollutant's water quality standard or target. The TSS target value "equivalent" to the 10 NTU water quality standard is 5 mg/l, as defined earlier in this section. **Figure 5.16** is the product of the Knife River flow duration curve (**Figure 5.15**) and the 5 mg TSS/l target value. The result is a load duration curve that describes the loading capacity of the Knife River near Two Harbors in tons of TSS/day. Based on the 1974-2006 flow record, the capacity ranges from just over 5 tons/day for the high flow zone, to just over 0.04 ton/day for the low flow zone.

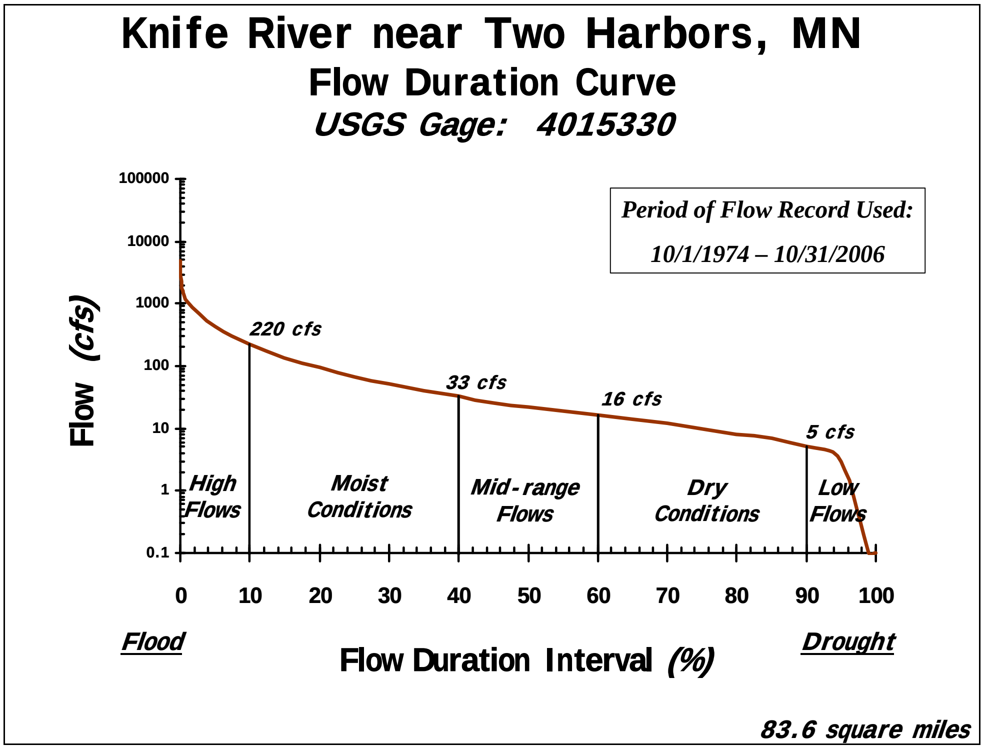

Figure 5.15. Flow duration curve for the Knife River near Two Harbors.

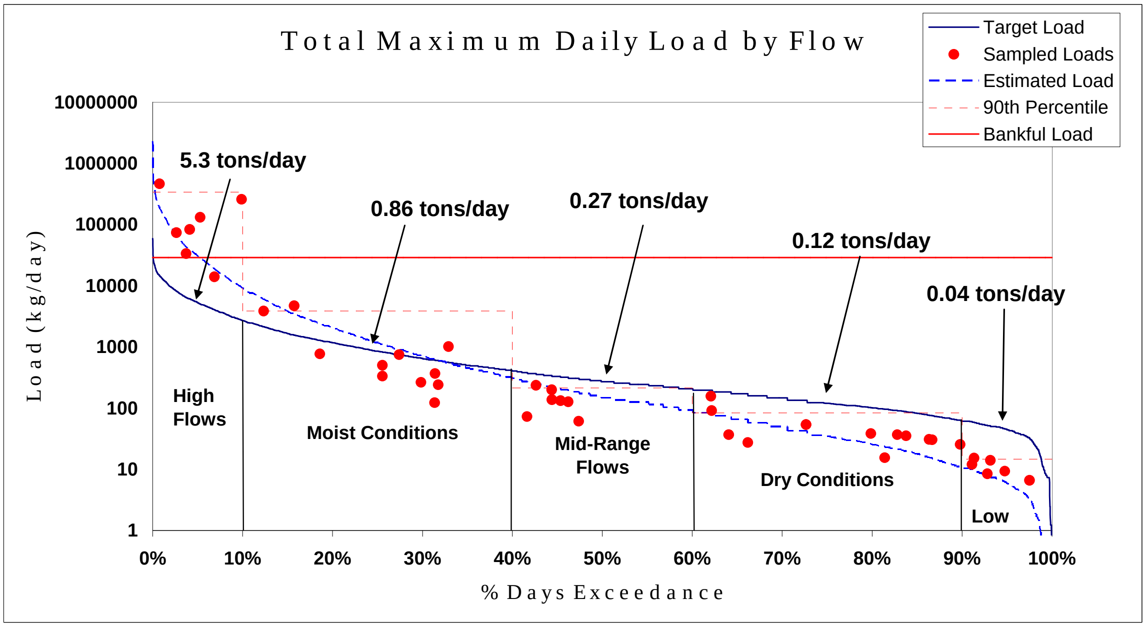

Figure 5.16. TMDL as determined by load duration curve.
The estimated load is explained in Figure E.2.

5.7 Biological Monitoring

“Overall, embeddedness levels are high enough at most Knife TMDL sites that we would predict effects on macroinvertebrates. Plots of percent riffle embeddedness versus various insect community measures that would be expected to show such effects, in fact show very little correlation. However, these same metrics indicate that sites within the Knife River watershed, and in particular those sampled for this study, have insect communities indicative of sites that are of a poorer condition than those at other North Shore stream sites. Although it is likely that the true differences among sites are not as extreme as they appear because of the spread in time of the sampling events and the differences in methodology, these data do suggest that the invertebrates at the Knife TMDL sites are experiencing enough stress to alter their community structure. Thus, the invertebrates at these sites are likely responding to a variety of stresses, only one of which is embeddedness. The Fish Trap site in particular is likely experiencing the cumulative effects of a variety of upstream stressors.” (Brady and Breneman, 2007).

5.8 Physical Monitoring and Modeling

The results of the initial surveys were limited; but data obtained from the initial measurements are included in Appendix D. As noted in Section 4.3, additional geomorphic assessment was completed to further evaluate streambank and stream bluff erosion to better identify and quantify the potential sources of sediment to the river.

The results of this University of Minnesota study indicated that the main sources of sediment to the Knife River are the stream banks and bluffs along the mainstem of the Knife River. The sediment reaching the river from these sources was determined to be from two distinct but interrelated mechanisms (fluvial bank erosion and raindrop/overland flow erosion). These source areas are primarily located on the mainstem of the river downstream of the confluences of the West Branch Knife River and Stanley Creek. The greatest net benefit of restoration efforts would occur in these areas (Nieber et al., 2008).

The final report for this study is included as Appendix E.

6.0 TMDL

The Knife River turbidity TMDL consists of three main components: WLA, LA, and MOS as defined in Section 1.0. The TMDL is based on using a TSS concentration as a surrogate for the turbidity standard of 10 NTU, and calculating target loads to meet the standard. The surrogate TSS concentration was calculated to be 5 mg/l TSS as discussed in Section 5.3). The TMDL is developed using the Load Duration Curve approach as described by EPA (Cleland, 2002) and applied in several of Minnesota’s approved TMDLs.

The “loading capacity” loads (the TMDL) developed for the Knife River turbidity TMDL is shown as a load duration curve in **Figure 5.16**. The TMDL is calculated as the flow in the river multiplied by the TSS surrogate (5 mg/l) multiplied by a conversion factor to provide loads as kg TSS/day. The TMDL is then presented as five equations representing five flow zones identified in the load duration curve approach. The numbers for each equation are provided in Table 6.1. A discussion of each component is given in the following sections.

As shown in **Figure 5.16** and **Table 6.2**, the loading capacity for the river was only exceeded in the Moist Conditions and High Flow zones of the load duration curve based on the 2004 – 2006 sampling data. A duration curve based on a regression of observed data and corresponding flow values provides an estimated curve of “observed” loads in the river. A comparison of these values against the load duration curve for the TMDL indicates that a load reduction of about 70 to 90 percent for the Moist Conditions and High Flow zones, respectively.

Knife River Assimilative Capacity by Flow Zone All values in tons/day					
	High Flows	Moist Conditions	Mid-Range Flows	Dry Conditions	Low Flows
TMDL	5.300	0.860	0.270	0.120	0.043
WLA - Construction	0.030	0.0004	0.002	0.001	0.001
WLA – Duluth Township MS4 (Permit # MS400134)	0.427	0.066	0.031	0.011	0.004
LA	2.243	0.344	0.165	0.058	0.021
MOS	2.600	0.450	0.072	0.050	0.017

Table 6.1. TMDL (loading capacity), waste load allocation, load allocation, and margin of safety for each flow interval of the load duration curve for the Knife River turbidity TMDL.

6.1 Waste Load Allocation

There are no NPDES permitted municipal or industrial wastewater treatment facilities in the Knife River watershed. Current development projections suggest that a NPDES permitted wastewater treatment facility will not be built within the watershed. Therefore, a WLA is not needed for these categories of point source pollution. There is one permitted MS4 stormwater area in the watershed. Duluth Township is designated as a mandatory small MS4 (MS4 NPDES Permit # MS400134). As such, the township has been given a WLA as shown in Table 6.1.

Duluth Township is primarily a low density, rural residential community located along Lake Superior that covers approximately 29,000 acres. About 6,385 of these acres are classified as tax-forfeited land and are managed by St. Louis County as part of their forest management program (Duluth Township Comprehensive Plan 2002). Duluth Township encompasses 33 percent of the Knife River watershed. Approximately seven miles of township owned and maintained roads are located in the watershed (**Figure 6.1**). The town hall and a fire station are also located in the watershed. The roads and the town hall/fire station property comprise the conveyances the township is responsible for via the MS4 stormwater regulations. The township roads and property represent less than 50 percent of township area in the watershed. Given that most of the undeveloped areas in the township are zoned for 35-acre minimum lot sizes (Duluth Township Zoning Ordinance 2005), there are no plans for new township roads. Therefore, the WLA for the Duluth Township MS4 is calculated as 16 percent (50% of 33%) of the TMDL minus the MOS and WLA for construction stormwater.

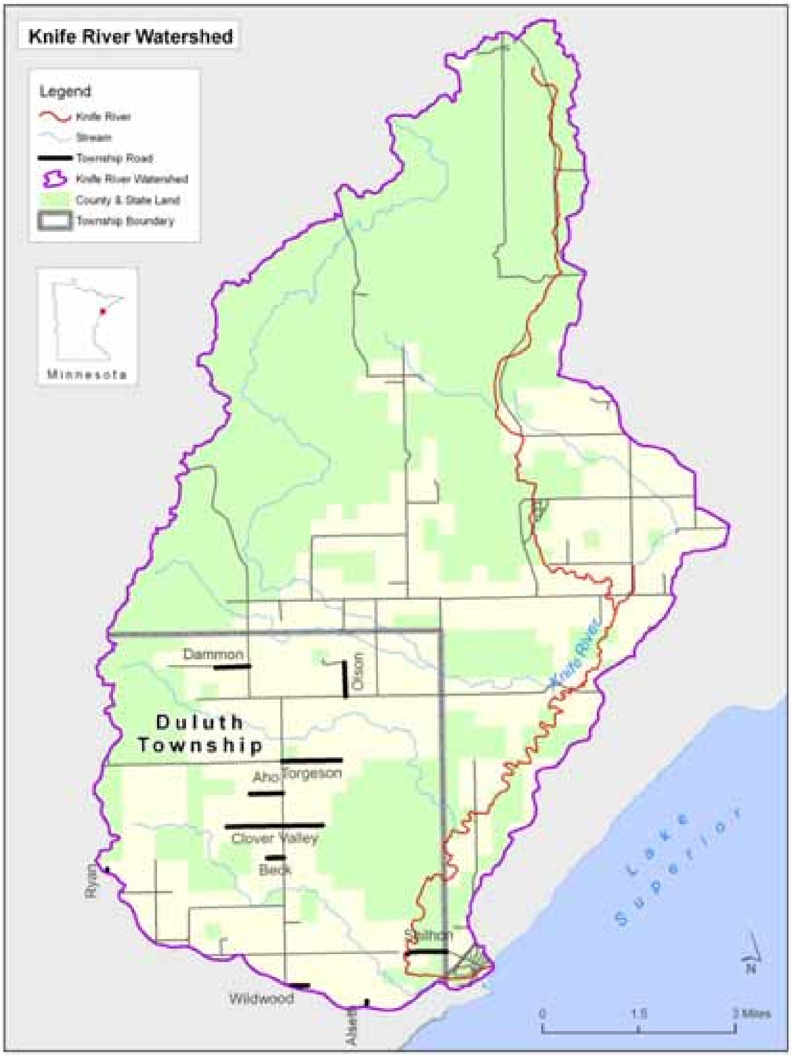

Figure 6.1. Duluth Township and Duluth Township roads in the Knife River watershed.

There were five permitted construction projects in the watershed in 2008. This level of construction is likely to continue and increase slightly, especially near Lake Superior. The five current projects will have disturbed approximately 115 acres which is approximately 0.2 % of the whole watershed. Looking at demographic projections, the watershed is expected to experience an approximately 18% increase in population over the next 28 years. This would suggest that NPDES construction stormwater permits may be needed on up to 136 acres or 0.25% of the watershed. Due to the extremely small percentage and to account for any increased future growth, the percentage of the watershed subject to construction was increased to 1%. Using this number (1%), the WLA associated with construction activity was computed as 1% of the loading capacity minus the MOS for each flow zone except the low flow zone. The WLA for the low flow zone was assumed to be the same as for the dry flow zone given the very small value that would have resulted using 1% of the loading capacity. Construction storm water activities are considered in compliance with provisions of the TMDL if they obtain a Construction General Permit under the NPDES program and properly select, install and maintain all BMPs required under the permit, or meet local construction stormwater requirements if they are more restrictive than requirements of the State General Permit.

6.2 Load Allocation

The load allocation (LA) for each flow zone is calculated as the Total Maximum Daily Load (TMDL) minus the waste load allocation (WLA) and margin of safety (MOS). The load allocation includes nonpoint pollution sources that are not subject to NPDES permit requirements, as well as “background” sources, such as natural soil erosion from stream channel and upland areas. The load allocation also includes runoff from agricultural and forest lands and non-NPDES stormwater runoff.

The LA and MOS were set using a Duration Curve Method. The Duration Curve Method uses flow duration (from long term USGS gage) to determine percentage of time that a certain discharge occurs. Applying the TSS concentration target to ranked discharges allows the creation of a load duration curve. The LA or assimilative capacity was determined by the median load of each category, and the MOS was determined to be the difference between the median and low value for each range. These results are summarized in **Table 6.1**.

6.3 Margin of Safety

Under section 303(d) of the Clean Water Act, a “margin of safety” (MOS) is required as part of a TMDL. The purpose of the MOS is to account for uncertainty that the allocations will result in attainment of water quality standards. The margin of safety for each flow category is calculated as the difference between the median flow duration interval and minimum flow duration interval in each zone except the low flow zone. For the low flow zone, this approach would result in an extremely high MOS due to the fact that flow in the river and the resulting TSS load approaches zero at the 99th percentile flow duration interval. To account for this extreme, the MOS for the low flow zone is assumed to be the same percentage of the loading capacity as in the adjacent dry flow zone. This is reasonable given that stream flows at these low levels carry very little TSS. The purpose of the MOS is to account for the uncertainty that the allocations are a direct function of flow; accounting for potential flow variability is an appropriate way to address the MOS. The MOS is shown for each of the five flow zones in Table 6.1.

6.4 Critical Conditions and Seasonal Variation

EPA states that the critical condition *"…can be thought of as the "worst case" scenario of environmental conditions in the waterbody in which the loading expressed in the TMDL for the pollutant of concern will continue to meet water quality standards. Critical conditions are the combination of environmental factors (e.g., flow, temperature, etc.) that results in attaining and maintaining the water quality criterion and has an acceptably low frequency of occurrence"* (USEPA, 1999). Turbidity levels are generally at their worst following significant storm events during the spring and summer months, as described in Section 5. Sections 2, 3, and 5 address seasonal variations. The variations are fully captured in the duration curve methodology used in this TMDL.

6.5 Source Analysis

A modeling study was completed by the University of Minnesota (Nieber, 2008) in an effort to provide some quantification of the major sediment sources to the river. While a TMDL is not required to perform an evaluation of the sources and loads comprising the Load Allocation portion of the TMDL, this work is important in identifying appropriate restoration measures to reduce the sediment load in the river. The final report for the study is included in this report as Appendix E.

The study involved the acquisition of sediment and flow data from the South St. Louis SWCD; performance of surveys of the main stem of the river to collect geomorphic data including cross-section geometry and longitudinal slope, bed sediment characteristics, and physical properties of streambanks; and application of three models for prediction of sediment production and transport.

The objective of the study was to apply the selected models of streambank and stream bluff erosion to help identify and possibly quantify the potential sources of sediment. The models used in the study for quantifying streambank sources of sediment included the Rosgen's BEHI-NBS model and the USDA-ARS CONCEPTS model. The model used to quantify erosion from stream bluffs was the SEDIMOT II model.

The observed total sediment load in the channel was measured for the three storms at the Fish Trap gaging station located near the mouth of the Knife River. The proportions of the sediment originating from streambanks, from bluff areas, and the tributaries were estimated using the CONCEPTS and the SEDIMOT II models. The total predicted sediment loads from the three sources were 563, 161 and 53 tons for storms 1, 2 and 3, respectively, while the observed loads for the corresponding storms were 881, 131 and 30 tons. These values are reasonably close in that they are well within one order of magnitude of each other. The model results indicated that the sources of the sediments were mostly from the streambanks, followed by the contributions from bluffs, and finally followed by the tributary areas. For the total from all three storms, the models estimated that 59%, 29%, and 12% of the sediment to be from streambanks, bluffs, and tributary areas, respectively (Nieber, 2008).

6.6 Reserve Capacity

The townships within the Knife River watershed are expected to grow in population by approximately 18% by the year 2035 according to the Minnesota State Demographic Center's "Extrapolated population for Minnesota cities and townships outside the Twin Cities region, 2006 to 2035" database. Most of this growth is expected to be in Duluth Township, which is partially connected to an existing sanitary sewer system. According to these projections, it is unlikely that any point source discharge will be needed in the Knife River watershed in the next 30 years. Therefore, no reserve capacity is provided in this TMDL.

Figure 6.2. Townships used in Knife River population growth prediction.

6.7 Reasonable Assurance

Reasonable assurance of meeting the TMDL targets for construction storm water activities is present through the requirements for and provisions of the Construction General Permit under the NPDES program as described in Section 6.1. While a discussion of reasonable assurance of attaining load reductions for the Load Allocation portion of the TMDL is not required, the following statements indicate that implementation will occur and result in sediment load reductions in the Knife River to meet its designated use.

- The South St. Louis and Lake County SWCDs will continue to be involved in assisting land owners in implementing erosion control activities.

- The local water plans for St. Louis and Lake Counties address erosion control as a key priority for current and future projects.
- Monitoring and research will be conducted to track progress and guide adjustments in the implementation approach, if needed.
- Continued funding for TMDL implementation and water quality monitoring will be pursued.

7.0 Monitoring and Research Plan

An important step in the implementation process will be on-going monitoring of flow, turbidity, TSS, and transparency in the river to determine if the conditions are changing and determine the effectiveness of reduction strategies. Partners in this process will include: citizen stream monitors, the MPCA, the South St. Louis SWCD, the MN DNR, and the USGS. Funding for monitoring is a critical issue that needs to be addressed. Key monitoring requirements and objectives include:

- Maintaining the USGS flow monitoring station on the Knife River.
- Reestablishing water quality monitoring at the Fish Trap site or the USGS gage site.
- Ensure that all implementation activities, whether they occur through local, state, or federal programs, or other means, are tracked using a reporting database such as the BWSR E-link system. This will be crucial for gauging general implementation progress.
- Continue to promote and expand citizen stream monitoring in the Knife River watershed.
- Coordinate with the University of Minnesota and MPCA in conducting research on soil erosion and sediment delivery processes and the effectiveness of particular BMPs. Apply results of sediment “fingerprinting” and other research that will be completed as part of the Lake Superior Streams Sediment Project.
- Maintain all monitoring activities for a period of no less than 10 years, and preferably on a permanent basis.

8.0 Implementation

An implementation plan has been drafted and will be completed for the TMDL. Implementation activities will focus on the Moist Conditions and High Flow zones of the TMDL Load Duration Curve given that all of the observed exceedances of the loading capacity occurred in these two zones. Table 6.2 provides the estimated “observed” and the “load capacity” loads for the two zones along with estimated reduction estimates based on those numbers. Flows in these zones are primarily due to spring snowmelt and storm event runoff. Activities that will be in the plan include streambank and channel restoration, gully stabilization, ditch maintenance practices, proper implementation of construction stormwater BMPs, tree planting and other open land management, riparian buffer management, residential BMPs, water storage practices, and forest management BMPs.

Knife River TSS Load Reductions by Flow Zone					
	High Flows	Moist Conditions	Mid-Range Flows	Dry Conditions	Low Flows
TMDL	5.3	0.86	0.27	0.12	0.04
Estimated Current Load	31	1.2	0.15	0.04	0.01
Approximate Percent Reduction	90%	65%	n/a	n/a	n/a
All load values in units of tons/day					

Table 6.2. TMDL, estimated current loads, and percent reductions needed to meet TMDL.

9.0 Public Participation

The Knife River TMDL study incorporated various actions to provide public involvement in the project. Public participation during the study was somewhat limited, but there has been significant public involvement in the watershed in previous years. This section provides a summary of past, current study, and expected future public participation in the watershed. As the TMDL study process comes to a close and emphasis is placed on the implementation portion of the project, public outreach and involvement will ramp up.

9.1 History of Participation

The Knife River has had a "public" that was active in watershed related activities for about two decades. There have been many forest stewardship plans completed, thousands of trees planted, and, through the help of fishing clubs, several habitat related projects were completed. These groups were all tied together when the Knife River Forest Stewardship Committee was formed in 1991. This group had a quarterly newsletter, meetings, and led projects in the watershed. This group disbanded, but was unofficially brought back together when the TMDL project began.

9.2 Activities During TMDL Study

The TMDL project looked to area resource managers regularly for help, and did organize and hold two meetings to update these important players in local and state water quality issues on the progress and direction of the Knife River TMDL. These meetings were instrumental in the completion of a comprehensive TMDL. The public has been approached on two separate occasions to participate and comment on the TMDL, but local resident interest was limited. The first meeting was cancelled due to lack of interest. The second meeting was held to discuss the draft TMDL in June 2009 with only 5 watershed residents attending. The watershed residents have been tough to reach, but SWCD and MPCA staff have presented at many meetings of local units of government and organizations. A list of meetings and presentations on the TMDL study is given below:

Date	Meeting
1/23/06	Laurentian Resource Conservation & Development board meeting (Virginia, MN)
2/22/06	Knife River Forest Stewardship Committee meeting (Duluth, MN)
8/30/06	Brief TMDL update at Regional Stormwater Protection Team meeting (Duluth, MN)
12/19/06	Update for Lake County Water Planners (Two Harbors, MN)
1/8/07	Update for Lake Superior Steelhead Association (Duluth, MN)
2/21/07	Update for SWCD board (Duluth, MN)
6/10/09	Public Information Meeting (Knife River, MN)
6/17/09	Update for SWCD board (Duluth, MN)
6/24/09	Natural Resource Managers Meeting (Duluth, MN)

In addition to the meetings, an interest mailer (2006), newsletter (January 2009), and invitations for the June 2009 public meeting were sent to all watershed residents. A preliminary draft TMDL was also posted on the South St. Louis County SWCD website.

9.3 Formal Public Notice

An opportunity for further public comment of the TMDL draft was done through a public notice in the State Register of a 30-day comment period that occurred from October 12 through November 11, 2009. A public stakeholder meeting was held on November 4, 2009. Seven written comments were received. Response letters were sent to the individuals and organizations that provided comments. One major and some minor revisions were made based on the comments.

The major revision to the TMDL resulted from an oversight regarding the presence of a MS4 stormwater entity in the watershed. Duluth Township is a MS4 and the township board chair noted that in a comment letter. With the addition of a WLA, the revised TMDL was public noticed again.

The public notice period for the revised TMDL was April 12 through May 12, 2010. No public written comments were received during this period.

9.4 On-going Public Participation/Outreach

As the Implementation Plan is drafted and revised there will be opportunities for both the general public and area resource managers to provide input. Before the Implementation

Plan is complete there will be two more resource manager meetings and a public outreach campaign consisting of rejuvenation of the Knife River Forest Stewardship Committee and its newsletter, and TV/radio/newsprint informational pieces. The South St. Louis SWCD will be assisted in these efforts by staff from the Laurentian RC&D and the Minnesota Environmental Partnership.

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Appendix A: Data

Appendix A presents three tables showing examples of the water quality data collected during the study. Table A.1 provides an example of the field and in-place sonde data collected during routine monitoring visits. The field data is used in conjunction with laboratory data from the associated water samples collected and/or to check the function and status of the in-place sondes. The complete data set was submitted to the MPCA to be stored in Hydstra.

Table A.2 provides an example of recorded grab sample laboratory data paired with field sonde readings. Grab samples were collected approximately 20 times per year at each of the monitoring sites. The data presented in this table has been entered into STORET and is available via the MPCA Environmental Data Access system linked to the MPCA web site.

Table A.3 presents a short excerpt of the “continuous” data collected by the in-place sondes located at each monitoring site. The continuous data was recorded as the average values in 30-minute intervals by the data loggers linked to the in-place sondes. All of the continuous data is stored in the MPCA/DNR Hydstra system.

								Field Sonde Readings						CR-10 Readings						
Site	**Date**	**Time**	**USGS GH**	**GH CR10**	**GH Field**	**Q (cfs)**	**Ttube**	**Temp ºC**	**SC (µs)**	**DO%**	**DO (mg/L)**	**pH**	**Turbidity FNU**	**Temp ºC**	**SC (µs)**	**DO%**	**DO (mg/L)**	**pH**	**Turbidity FNU**	**Battery**
4-Airport	4/12/06	15:00	4.05	8.5214	8.51									6.94	0.07	98.4	11.96	7.01	6.8	
4-Airport	4/25/06	10:30	2.71	7.36	7.39			5.17	0.1	91.50	11.63	7.39	-0.4	5	0.114	108.5	13.85	7.34	1.8	13.46
4-Airport	5/9/06	10:00	3.96	8.156	8.1			9.33	0.066	82.30	9.44	7.46	8.5	9.28	0.112	104.3	11.97	7.08	9.3	13.39
4-Airport	5/23/06	14:45	3.07	7.3761	7.39			14.93	0.089	91.80	9.27	7.62	0.4	14.73	0.137	112.4	11.39	7.27	2.2	13.436
4-Airport	5/25/06	10:50	2.97	7.7	7.7	1.42														
4-Airport	6/6/06	13:15	2.99	7.4662	7.47			16.1	0.128	97.00	9.55	7.83	-4.4	16.02	0.136	92.2	9.1	7.86	-9	13.541
4-Airport	6/21/06	11:30	2.74	7.11	7.13		>100	16.36	0.15	95.80	9.38	7.64	-1	16.3	0.162	91.3	8.95	7.67	-6.9	13.49
4-Airport	6/28/06	10:30	2.57	7.0518			>100	14.72	0.167	97.60	9.9	7.99	-1.2							13.626
4-Airport	7/5/06	11:30	2.33	6.949				17.57	0.179	100.30	9.58	8.08	-1.2							13.534
4-Airport	7/20/06	12:10	2.26	6.8806	6.9		>100	21.14	0.196	104.20	9.25	8.13	-1.1	20.64	0.194	95.3	8.55	7.99	-2.1	13.409
4-Airport	8/9/06	15:00	2.43	6.8619	6.88		>100	20.08	0.189	100.70	9.13	8.31	-2.3	20.28	0.177	102.9	9.3	8.42	-2	13.396
4-Airport	8/14/06																			
4-Airport	8/22/06	~14:45	2.31	6.8213			>100							18.94	0.195	96.9	9	8.25	0.2	13.416
4-Airport	8/29/06	12:00	2.26	6.8354	6.84		>100	16.01	0.191	96.10	9.49	8.28	-5.3	15.91	0.198	92.4	9.13	8.16	1	13.646
4-Airport	9/6/06	14:45	2.22	6.8003	6.8		>100	18.18	0.191	101.50	9.56	8.38	-5.5	18.02	0.197	89.4	8.46	8.25	1	13.501
4-Airport	9/12/06	10:30	2.22	6.7755	6.82		>100	11.62	0.189	104.90	11.41	8.29	-5.2	11.4	0.196	82.6	9.02	8.04	2.2	13.7
4-Airport	9/21/06	15:00	2.31	6.781	6.82		>100							11.1	0.186	109.1	12	8.24	-2.8	13.652
4-Airport	10/2/06	15:05	2.44	6.885	6.905		>100							12.01	0.186	109	11.74	8.18	20.4	13.429
4-Airport	10/3/06			6.893			>100	10.8		93.80	9.23		-0.8	10.84	0.187	108.2	11.97	8.16	22.9	13.731
4-Airport	10/10/06	14:24	2.45	6.887	6.88		>100	7.15	0.18	97.20	11.75	8.29	-5.8	6.823	0.182	102.8	12.53	8.08	-2.09	
4-Airport	10/17/06	13:00	2.77	7.21	7.2									6.68	0.162	100	12.23	7.99	-4.85	
4-Airport	10/27/06	14:43	2.60					3.64	0.168	104.80	13.86	7.91	-5.7							

Table A.1: Example of field and in-place sonde data recorded during routine monitoring visits

Site	Year	Date	time	Lab Data				Field Sonde Readings					
				VSS (mg/L)	TSS (mg/L)	Turbidity NTU	T Tube (cm)	Temp (^{o}C)	SC (uS)	DO%	DO (mg/L)	pH	Turbidity FNU
1-Fish Trap	2006	4/12	14:00	3	26	28							
2-Nappa	2006	4/12	15:30	2	7	3.2		7.78	0.051	105.1	12.51	7.53	0
3-Culvert	2006	4/12	14:30	<2	4	26		6.91	0.06	98.2	11.94	7.38	25.4
4-Airport	2006	4/12	15:00	3	11	5.2		6.94	0.07	98.4	11.96	7.01	6.8
1-Fish Trap	2006	4/25	9:20	<2	3	13		5.53	0.101	91.8	11.57	7.04	13.2
1-Fish Trap	2006	4/25	9:20	<2	3	15		5.53	0.101	91.8	11.57	7.04	13.2
2-Nappa	2006	4/25	11:00	<1	2	1.8		5.99	0.082	115.2	14.34	7.63	1.9
3-Culvert	2006	4/25	10:00	<2	3	30		5.85	0.104	85.7	10.64	7.38	30.4
4-Airport	2006	4/25	10:30	1	2	3.3		5.17	0.1	91.50	11.63	7.39	-0.4
1-Fish Trap	2006	5/9	9:15	8	68	73		10.14	0.083	86.1	9.69	7.42	68
2-Nappa	2006	5/9	10:30	5	20	7.8		10.52	0.055	80.2	8.94	7.51	10.8
3-Culvert	2006	5/9	9:30	2	16	61		9.88	0.08	74.4	8.42	7.47	75
4-Airport	2006	5/9	10:00	5	17	6.3		9.33	0.066	82.30	9.44	7.46	8.5

Table A.2: The above table is a summary of each bi-weekly/storm sampling round. This is a portion of the 2006 data.

Knife River Continuous Monitoring

Airport 2006

NW of Two Harbors airport on Airport Rd.

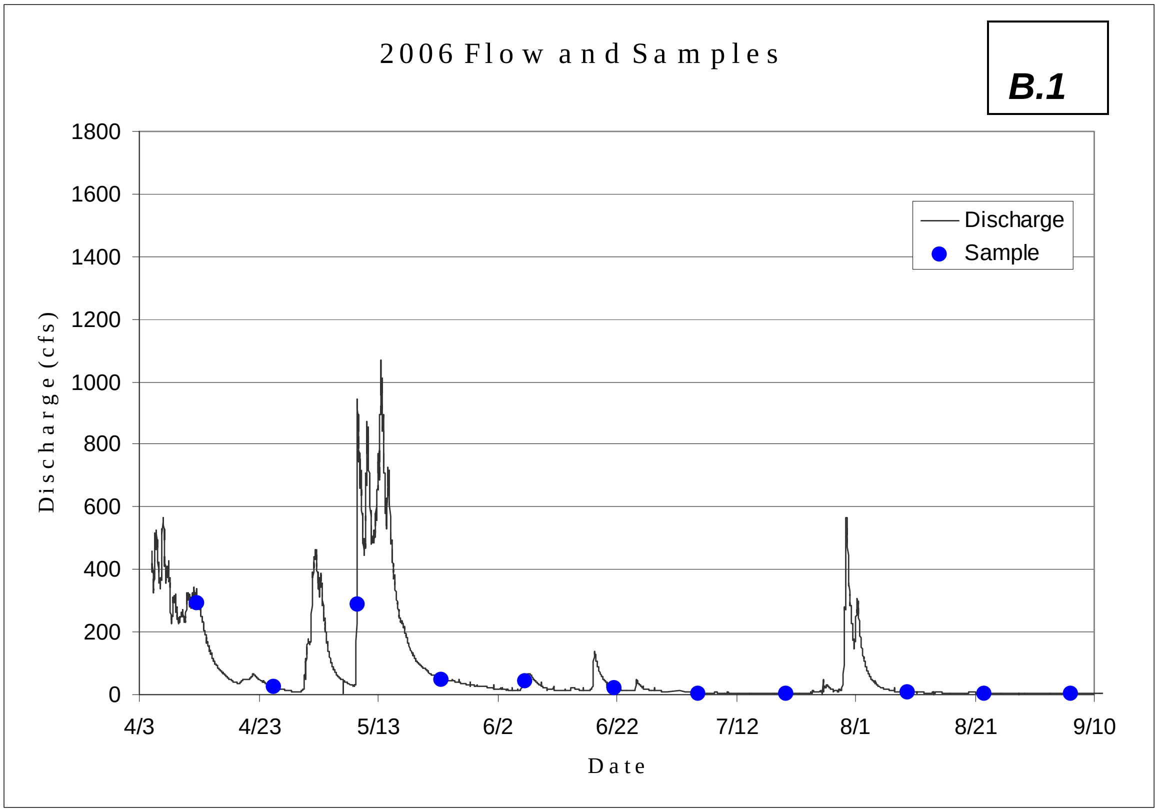
Site	Year	Real Date	Julian	time	stage (ft)	blank	Temp (^{o}C)	SC (uS)	DO%	DO mg/L	DO charge	pH	pH, millivolts	Turbidity FNU
4	2006	4/7	97	1230	8.45	0	1.119	0.061	98.3	13.93	48.3	6.852	-35.22	9.09
4	2006	4/7	97	1300	8.45	0	1.438	0.061	96.6	13.57	49.9	6.874	-36.48	7.49
4	2006	4/7	97	1330	8.46	0	1.761	0.061	95.4	13.28	51.86	7	-43.24	7.04
4	2006	4/7	97	1400	8.43	0	2.056	0.061	96	13.26	52.4	6.993	-42.92	7.01
4	2006	4/7	97	1430	8.45	0	2.296	0.061	95.7	13.13	53.8	7.01	-43.65	6.64
4	2006	4/7	97	1500	8.42	0	2.491	0.061	95.8	13.06	54	7.03	-44.64	6.52
4	2006	4/7	97	1530	8.41	0	2.624	0.062	96	13.05	55.3	7.05	-45.74	6.22
4	2006	4/7	97	1600	8.44	0	2.691	0.061	96.2	13.05	55.2	7.05	-45.99	6.47
4	2006	4/7	97	1630	8.46	0	2.681	0.061	95.4	12.95	54.8	7.01	-44.02	6.8
4	2006	4/7	97	1700	8.46	0	2.614	0.061	95.2	12.95	54.4	7.01	-43.76	6.8
4	2006	4/7	97	1730	8.49	0	2.484	0.061	95.1	12.97	54.7	7	-43.1	7.31
4	2006	4/7	97	1800	8.47	0	2.31	0.061	95	13.02	54.3	6.999	-43.1	8.19
4	2006	4/7	97	1830	8.47	0	2.11	0.061	95.2	13.12	54.3	6.985	-42.45	8.05
4	2006	4/7	97	1900	8.48	0	1.916	0.061	95.2	13.2	53.8	6.977	-42.06	8.4
4	2006	4/7	97	1930	8.49	0	1.721	0.061	95.5	13.31	53.8	6.967	-41.57	8.62
4	2006	4/7	97	2000	8.53	0	1.524	0.061	95.5	13.38	53.8	6.974	-41.84	8.55
4	2006	4/7	97	2030	8.53	0	1.321	0.062	95.7	13.48	53.8	6.969	-41.62	8.39
4	2006	4/7	97	2100	8.51	0	1.137	0.062	95.7	13.56	53.7	6.965	-41.21	8.44
4	2006	4/7	97	2130	8.52	0	0.964	0.062	95.5	13.59	53.3	6.96	-41.06	7.99
4	2006	4/7	97	2200	8.51	0	0.811	0.062	95.9	13.7	53.3	6.971	-41.57	9.1
4	2006	4/7	97	2230	8.5	0	0.678	0.062	95.6	13.72	53.3	6.963	-41.18	7.14
4	2006	4/7	97	2300	8.5	0	0.559	0.063	95.5	13.75	53.3	6.962	-41.09	7.07
4	2006	4/7	97	2330	8.48	0	0.449	0.063	95.7	13.81	53.3	6.97	-41.66	6.45
4	2006	4/7	97	2400	8.47	0	0.351	0.063	95.6	13.84	53.3	6.97	-41.61	6.42

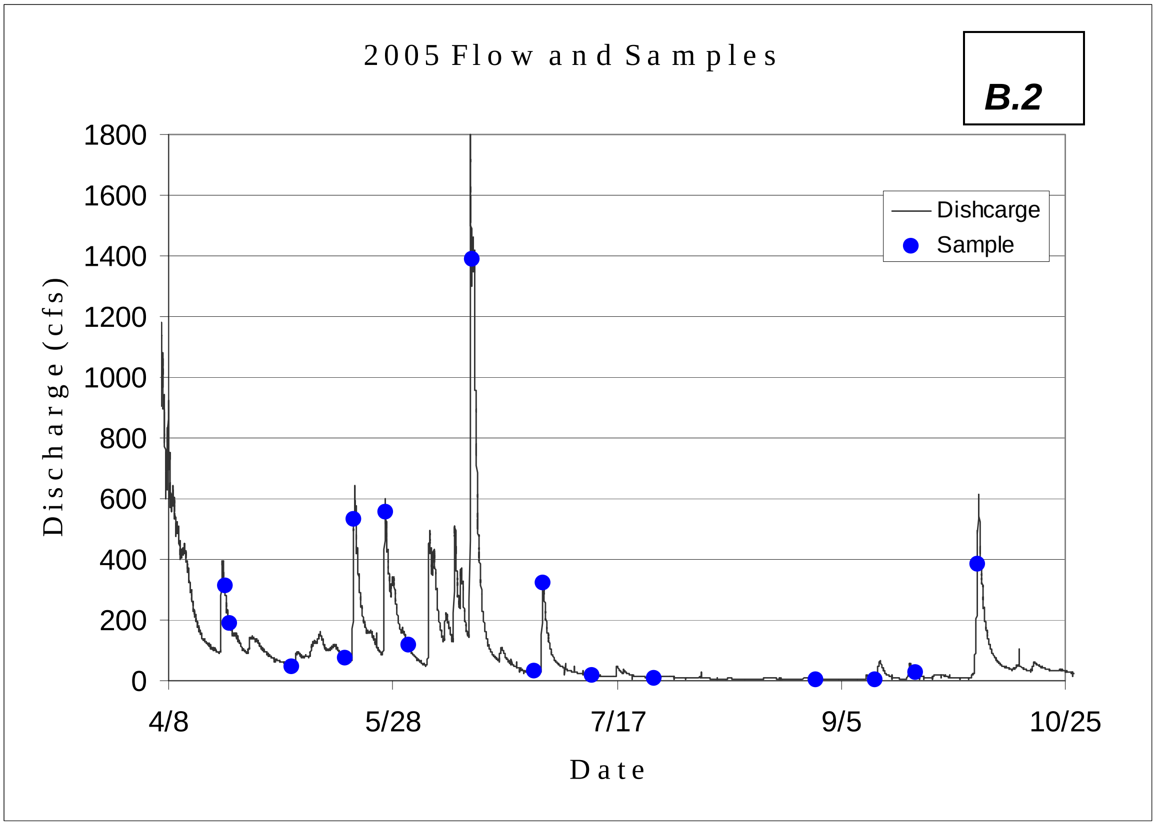
Table A.3: Small section of continuous data. The above table is only a 12 hour section of continuous data that logged from early April to mid-October during 2004 (partial record), 2005, and 2006 for each monitoring season.

Appendix B: Hydrology

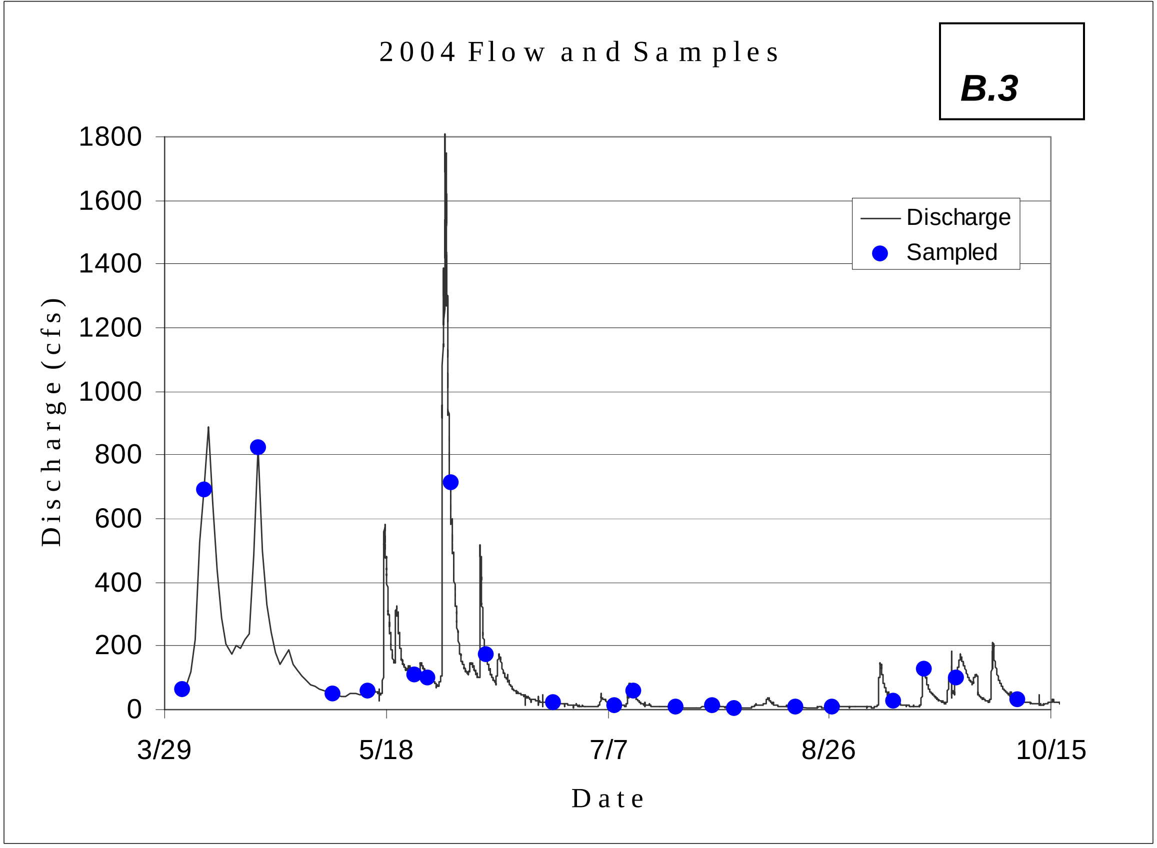
Appendix B provides three figures (**Figures B.1, B.2,** and **B.3**) that plot the mean daily flows and the timing of the grab samples collected during the monitoring period for 2004 through 2006 at the Fish Trap site.

The appendix also contains figures that describe some of the stream discharge information, including the annual peak discharge, monthly average discharges, and the average annual discharges for the period of record at the USGS gage site near the Fish Trap monitoring location; a comparison of the study period flows versus the period of record discharges, and a figure used to estimate the bankfull discharge for the site based on a 1.5 year recurrence interval.





B.2



B.3

Figures B.1-3: Annual hydrographs plotted with sampled flows (blue dots).

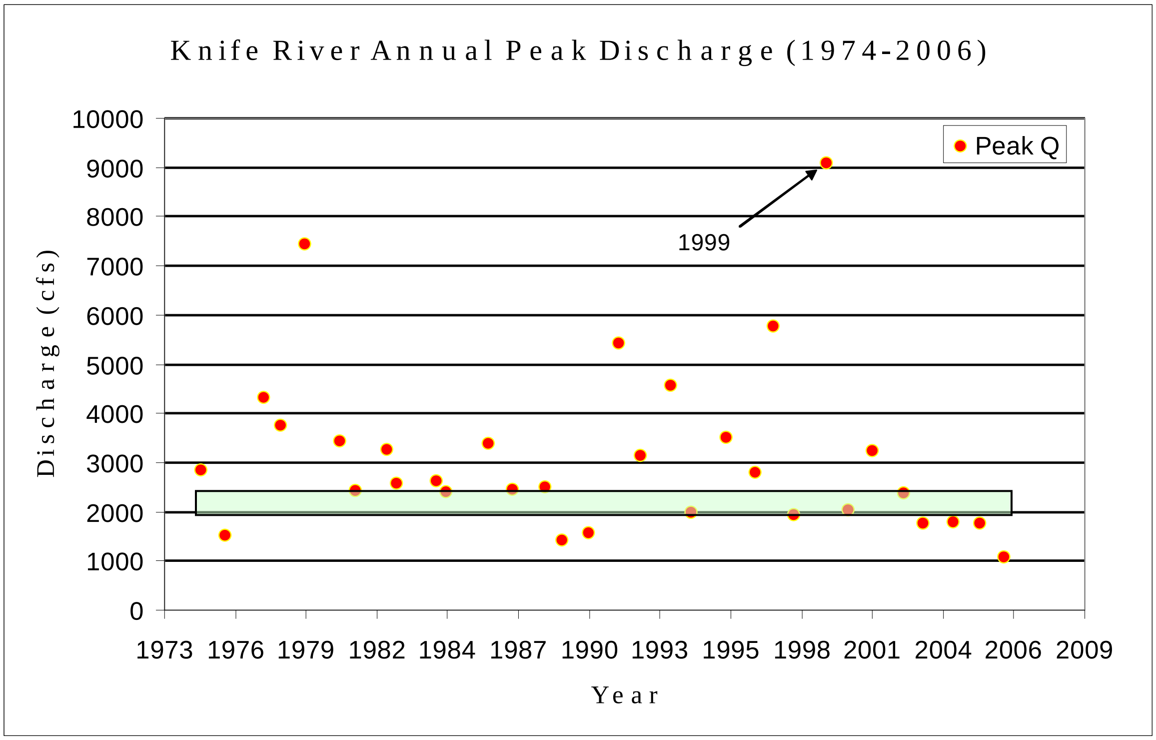


Figure B.4: Annual peak discharge at USGS Gage over period of record. Shaded green area is approximately bankfull. (1.43-1.57 Recurrence Interval)

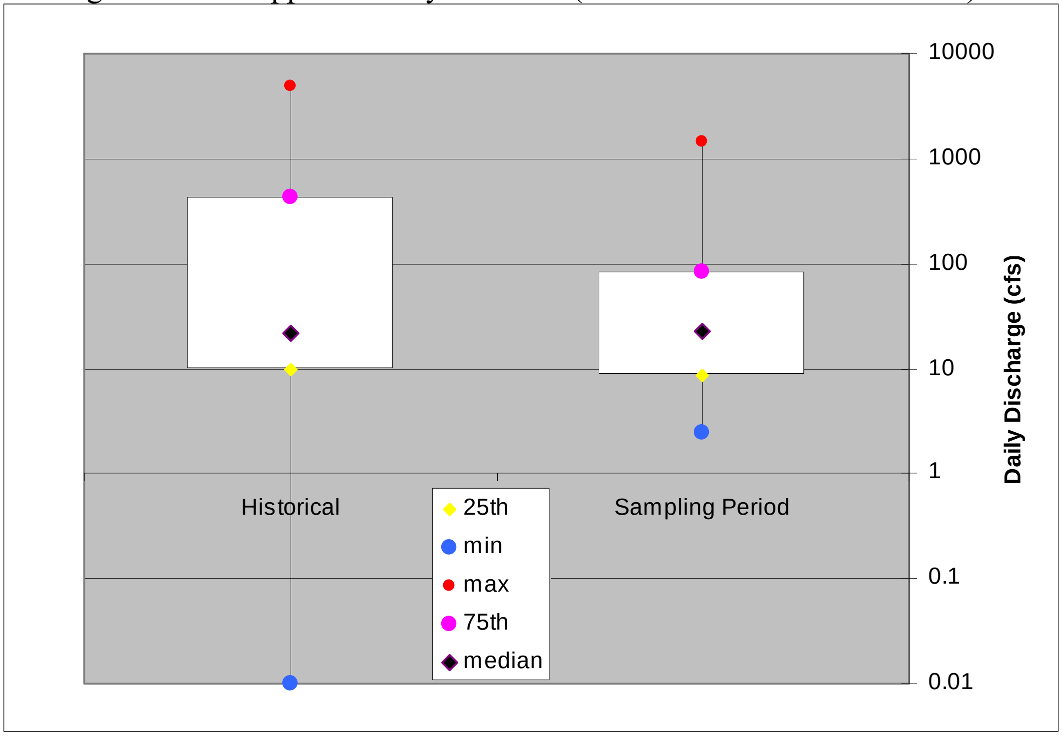


Figure B.5: Box and Whisker plot showing sampling period vs period of record. Plot shows that the sampling period was representative

Year	Jan Mean Q	Feb Mean Q	Mar Mean Q	Apr Mean Q	May Mean Q	Jun Mean Q	Jul Mean Q	Aug Mean Q	Sep Mean Q	Oct Mean Q	Nov Mean Q	Dec Mean Q
							10.8	23.3	6.03	10.8	24.5	10.3
1975	31.4	13.9	20.1	603.9	253.3	48.7	22.8	3.27	11.5	11.1	120.7	27.3
1976	9.72	9.86	135.8	452.7	16	25.2	7.21	2.95	1.43	3.06	1.58	0
1977	0	0	65.5	73.6	34.7	20.2	9.04	11.8	314.1	212.3	131.4	48.8
1978	15	8.86	24.8	346.7	229.8	149.7	267.4	81.2	98	25.7	30.6	13.3
1979	9.87	8.98	87.4	545.8	427.2	113.5	28.6	13.7	22.8	30.6	45.7	9.54
1980	4.41	5.26	8.65	222.5	21.9	21.9	5.83	42.2	202.2	37.7	19.2	5.39
1981	3.58	9.36	50.9	382.5	112.7	198.5	37.6	34.4	7.06	136.5	22	14.4
1982	4.38	5	17.3	631.3	236.1	34.2	249.1	16.6	38.6	226.2	189.4	60.6
1983	20.8	15.3	62.9	317.7	186.9	48.5	93.7	22.4	65.4	157.5	147.7	49.7
1984	21.9	22.2	34.6	396.6	134	240.5	19.7	31.2	50.8	214.7	66.4	15.1
1985	4.21	4.1	79	405.2	238.3	140.6	76.5	43.7	139.2	162.4	54.9	22.1
1986	14	12.3	53.1	518	211.8	165.4	180.5	85.5	280.6	111.2	86.4	21.6
1987	13.7	10.1	75.9	78.7	254.9	21.6	57.5	11.4	94.7	13.5	26.5	7.61
1988	3.22	3.17	21.6	259.7	108.9	15.5	4.87	162.8	98.5	23.4	96.3	25.2
1989	12.9	8.59	24	456.2	123.3	68	19.2	5.81	28.3	8.98	14.5	1.16
1990	0.603	0.734	46.7	220.6	84.5	47.2	19.2	48.9	58.7	145.1	16.7	8.29
1991	6.2	6.49	61.8	321.3	198.2	138.9	117	5.58	130.5	75.3	197.7	50.4
1992	27.4	17.8	60.9	534.5	156.9	35.2	151.8	14.7	60	38.8	82.5	12.9
1993	9.86	8.49	75	256.7	193.8	202.1	344.7	25.8	22.2	20.3	23.1	16
1994	8.11	5.66	11.1	425.8	87.4	105.9	20	21.8	69.4	66.5	36.9	29.5
1995	6.86	5	118.4	221	201.2	13	143.7	137.2	57.1	267	115.2	29.9
1996	20.4	16	27.3	435.1	147	89.4	162.8	31.7	151.9	177.1	172.9	33.5
1997	23.6	20.5	32.8	610	90	164.5	28	10.2	14.6	36.6	26.9	9.16
1998	7.77	79.2	204.4	209.1	23.5	124.9	10.6	5.49	25.6	196	238.5	75.1
1999	16.7	16.2	143.1	422.5	101.5	46.7	401.9	112.4	195.4	90.8	53.1	27
2000	9.7	51.6	124.1	97.1	139.1	54.3	54.1	7.09	30	14.8	210.6	12.4
2001	5.89	4.22	6.75	888.9	203.3	41.6	10.7	18.7	9.05	26.9	69.2	47.4
2002	7.56	4.25	6.3	302.4	123.2	123.5	73.1	31.8	29.5	64.3	27.9	13
2003	1.25	0	67.6	310.2	165.8	36.1	36.2	12.9	13.5	12.3	25.8	5.76
2004	3.2	5.08	19.6	292.6	157.3	102.9	14	8.75	41.9	112.1	48.2	16.8
2005	14.4	17.9	102.4	381.5	139.9	200.8	24	5.2	14.1	ice	ice	ice
2006	ice	ice	ice	314.7	260.8	30.2	25.7	20.45	7.4	16.2	ice	ice
Average	**10.92**	**12.78**	**60.32**	**372.97**	**158.23**	**89.66**	**82.66**	**33.66**	**72.43**	**85.80**	**78.16**	**23.20**

Figure B.6: Monthly Average discharges for the period of record (http://waterdata.usgs.gov/mn/nwis/rt viewed 5/10/07)

Average Discharge (March-October)

Year	Avg Q	Rank	Recurrence	% Exceedance
1999	164.4	1	33.00	3.13%
1986	146.6	2	16.50	6.25%
1978	135	3	11.00	9.38%
1996	124.3	4	8.25	12.50%
1985	119.1	5	6.60	15.63%
2001	118	6	5.50	18.75%
1982	117.3	7	4.71	21.88%
1992	114.8	8	4.13	25.00%
1997	114.2	9	3.67	28.13%
1979	110.7	10	3.30	31.25%
1983	109.4	11	3.00	34.38%
1984	108.2	12	2.75	37.50%
1993	106.5	13	2.54	40.63%
1991	96.5	14	2.36	43.75%
2005	89.6	15	2.20	46.88%
1975	87.6	16	2.06	50.00%
1995	87.1	17	1.94	53.13%
2006	79.8	18	1.83	56.25%
1981	74.6	19	1.74	59.38%
1989	73.8	20	1.65	62.50%
1987	70.3	21	1.57	65.63%
2002	70.3	22	1.50	68.75%
1976	67.8	23	1.43	71.88%
1994	67.4	24	1.38	75.00%
1998	63.1	25	1.32	78.13%
2003	62.5	26	1.27	81.25%
2000	61.6	27	1.22	84.38%
1988	60.4	28	1.18	87.50%
2004	57.1	29	1.14	90.63%
1980	51.2	30	1.10	93.75%
1990	45.9	31	1.06	96.88%
1977	44.2	32	1.03	100.00%

Figure B.7: Average annual discharge over period of record highlighting years monitored

Knife River Bankfull Calculation

Date	Peak Q	Rank	Recurrence
7/5/1999	9100	1	33.00
5/10/1979	7440	2	16.50
6/24/1997	5780	3	11.00
6/29/1991	5440	4	8.25
7/4/1993	4580	5	6.60
9/24/1977	4320	6	5.50
5/29/1978	3750	7	4.71
8/25/1995	3510	8	4.13
9/4/1980	3450	9	3.67
6/10/1986	3380	10	3.30
7/3/1982	3270	11	3.00
4/23/2001	3240	12	2.75
4/21/1992	3140	13	2.54
4/23/1975	2860	14	2.36
9/27/1996	2810	15	2.20
6/10/1984	2630	16	2.06
11/21/1982	2580	17	1.94
8/13/1988	2510	18	1.83
5/18/1987	2450	19	1.74
4/23/1981	2430	20	1.65
10/19/1984	**2400**	**21**	**1.57**
7/8/2002	**2390**	**22**	**1.50**
5/8/2000	**2050**	**23**	**1.43**
4/15/1994	2000	24	1.38
3/29/1998	1950	25	1.32
5/31/2004	1790	26	1.27
4/10/2003	1780	27	1.22
6/14/2005	1760	28	1.18
4/30/1990	1580	29	1.14
4/6/1976	1520	30	1.10
4/16/1989	1430	31	1.06
5/13/2006	1070	32	1.03

Figure B.8: Using recurrence intervals, the bankfull discharge at Fish Trap (USGS site) was determined to be between 2050 and 2400 using the 1.5 year recurrence interval (Leopold, 1994)

Appendix C: Knife River Macroinvertebrate and Sediment Survey

See separate document included with TMDL report.

Knife River Macroinvertebrate and Sediment Survey

In support of the Knife River TMDL Study

Prepared for

South Saint Louis Soil and Water Conservation District

By

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INTRODUCTION

This effort was conducted as part of the Knife River TMDL (total maximum daily load) study for turbidity, and includes data to compare invertebrate community composition, habitat structure, and sediment deposition among Knife River sites. Macroinvertebrate, stream substrate, water quality, and fish and invertebrate habitat data were collected from five sites along the Knife River and its tributaries in August 2006. The study's objectives were two-fold: first, to collect baseline data from several locations within the Knife River watershed, which is currently listed as impaired for turbidity; and second, to compare these data to historical data from the Knife River watershed and other North Shore streams.

Turbidity and embeddedness affect stream invertebrates and fish by raising water temperature, reducing search distances for visual predators, clogging or abrading delicate gill tissue, filling in interstitial spaces among stream cobbles, and other detrimental effects. To put current data into perspective, Knife River TMDL sample locations were compared to historical samples within the Knife River watershed and other North Shore streams using macroinvertebrate assemblage metrics and, for one set of samples, substrate and water physical parameters. Due to differences in sampling methodology, macroinvertebrate metrics had to be calculated differently for comparison with historical data.

METHODS

Study Sites

Knife River TMDL study sites were selected as a collaborative effort between South Saint Louis Soil and Water Conservation District (hereafter SWCD). Sites were sampled in August 2006 and included stream sections near five different stream-road crossings (Fig. 1). Sample locations included established SWCD and Minnesota Pollution Control Agency (MPCA) gauging stations, or were chosen to dissect the watershed into sub-basin units.

Historic datasets used for comparison include macroinvertebrate abundances, substrate composition, and habitat data collected by Valerie Brady and colleagues for a U.S. EPA study during August 1997 and 1998 (Detenbeck et al. 2000). Comparisons were also made with macroinvertebrates collected by Andy Wold and Anne Hershey during August 1998 (Wold and Hershey 1999). Urban streams were excluded from comparisons, leaving the Brady-EPA dataset with 19 North Shore stream sites (including two in the Knife River watershed), and the Hershey (AH) dataset with six North Shore sites (four in the Knife River watershed; Fig. 1).

Habitat characteristics

Habitat data for the Knife River TMDL sites were collected from transects established across the channel perpendicular to flow and from whole-reach observations. A minimum of ten transects were placed at 10 m intervals (100 m minimum reach length) to evaluate substrate characteristics, stream features, bank conditions, and available habitats. A schematic stream reach diagram noting habitat characteristics, and a cross-section diagram at each transect, were completed.

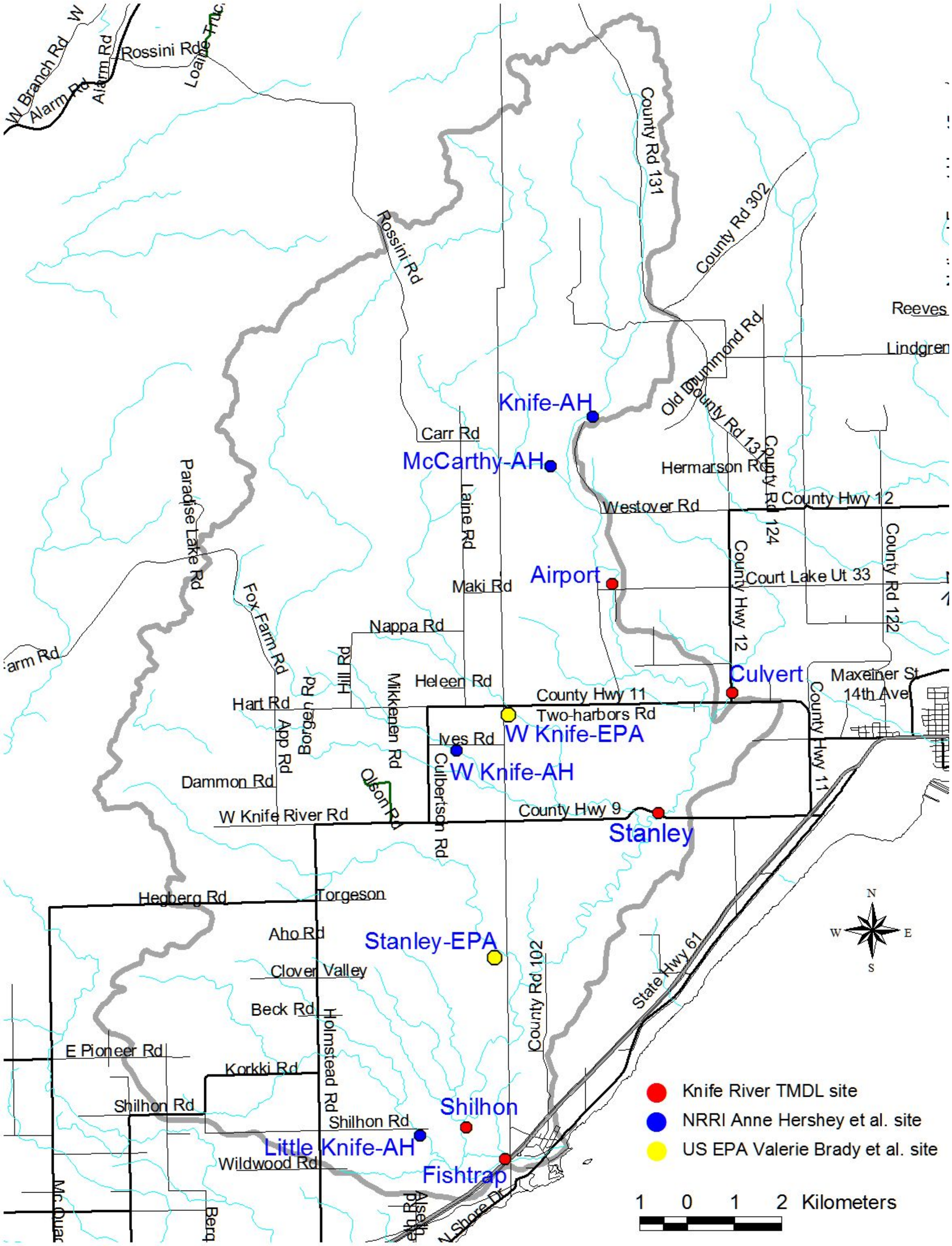

Figure 1. Location of macroinvertebrate sampling locations within the Knife River watershed, color-coded by study. Samples were collected in August 2006 for the TMDL study, 1996 for the Hershey study, and 1997 for the Brady-EPA study.

Transect points

Point estimates were used to evaluate stream features, discharge rates, substrate type and proportional coverage (dominant and sub-dominant particles), substrate embeddedness by fine particles, in-stream habitat cover, bank and riparian condition, and riparian corridor extent. Five points evenly spaced along each transect were used to quantify substrate size categories and composition (percent coverage).

Substrate

Within each grid (25 cm^2), the extent (in percent surface area covered) and types of substrate particles were estimated for dominant and subdominant particles. Classification schemes adhered to standardized particle size categories (e.g., Brusven and Prather 1974, Friedman and Sanders 1978, Gee and Bauder 1986). The extent large substrate particles were embedded by fine particles (sand, silt, and clay) was also estimated (as percent embedded) at 1 point within each grid. An additional sediment depth measurement along each transect was recorded to determine the maximum depth of fine particle deposition using a sediment rod. This point was not random; rather, a subjective choice was made based on the amount of fine particle accumulation. This measurement was repeated to obtain a maximum reading per transect. Finally, fine sediments were collected using a 7.62 cm diameter core from three locations along the stream reach and returned to the laboratory for particle size analysis.

Flow

Stream discharge was estimated from flow recordings at 5 points on each transect. Water depth was recorded at each transect point and flow rates were recorded from a point equivalent to 60% of total water depth. Instructions for flow-weighted averaging (FWA) are provided in the Marsch-McBirney Flow-mate operator’s manual.

In-stream cover

When transect lines intersected in-stream habitat cover, the type, size, and stability were described. Schematic diagrams of size, shape, and dimensions of habitat cover, such as large boulders, islands, etc., were also recorded. Large woody debris (greater than 1 m in length and 10 cm dia.), debris dams, roots wads, etc., that intersected each transect were recorded in detail, noting length or surface area, stability, and position along each transect. Total amount of woody debris per reach was also estimated by counting the number of intact units (≥ 100 cm in length by 10 cm dia.). A reach survey qualitative habitat evaluation index (Ohio EPA 1987) to rank overall stream condition was completed for each site following the sampling event. QHEI categories include substrate, cover, channel type, riparian zone, width/depth ratio, and riffle/run quality; the gradient metric was not calculated or included in the final score.

Bank structure

Bank or shoreline structure and condition (stable or unstable) were evaluated on all transects by noting bank substrate type and presence or absence of undercut banks. Bank-full width was recorded, as well as high water marks or indicators of flood extent.

Riparian corridor

Densiometer readings at a mid-stream point on each transect were used to estimate stream shading potential. Riparian width was estimated and vegetation type (ranked categories) noted. Adjacent riparian and landuse characteristics from 10-30 m and beyond were categorized.

Water quality parameters

Water chemistry parameters at each location were recorded with a YSI 556 multi-probe meter to establish baseline information on water temperature, dissolved oxygen, conductivity, pH, and oxidation-reduction potential (ORP) during the sampling effort. Water clarity observations were completed in triplicate using a transparency tube.

Macroinvertebrate sampling

Benthic samples were collected using a multi-habitat sampling approach (Lenat 1988) during baseflow conditions. Quantitative samples were collected in triplicate from run, riffle, and pool habitats using a modified Hess (0.086 m^2) in riffles or sediment core tube (0.0045 m^2) in shallow depositional areas (App. 1). All quantitative samples were washed on-site through a 254-µm mesh net or sieve. Where habitat was available, qualitative samples were collected from beneath bank or over-hanging vegetation, woody debris dams, boulder piles or rip-rap, or sediments and aquatic vegetation in run and pool habitats using a D-frame kick net (mesh size: 500 µm; App. 2). The D-net effort was timed and measured (approx. 30 seconds per sample and a 10 m distance). Extensive herbaceous bank vegetation and instream aquatic vegetation were swept, while wood dams and boulder piles were jabbed (*sensu* Barbour et al. 1999) to dislodge invertebrates. All invertebrates from each sample type were preserved in the field using a Kahle's preservative, 10% Formalin, or 70% ethyl alcohol.

Sample processing

Benthic macroinvertebrates

Samples were processed by washing materials through two sieve sizes (4 and 0.25 mm) to separate contents into large and small size fractions. The large size fraction (>4 mm) was completely picked ('whole picked') for invertebrates. The amount of 4-0.25 mm fraction processed was determined individually by the time and volume of material. All samples were ¼, ½, or whole picked. Invertebrates were removed from organic and inorganic sample materials under a dissecting microscope or a 2x magnification lens. Each completed sample was subject to quality assurance/quality control (QA/QC) inspection (100% inspection). Rejected samples were re-processed until QA/QC guidelines were passed. A subsample of the Chironomidae (Diptera) consisting of 30-100 individuals per sample was permanently mounted on slides for identification to genus. Other macroinvertebrates were identified to the lowest practical taxonomic level using appropriate keys (Hilsenhoff 1981, Wiederholm 1983, Brinkhurst 1986, Thorp and Covich 1991, Merritt and Cummins 1996). A reference collection was also established from invertebrates at all sites, and specimens were subject to a rigorous QA/QC inspection (further details available from NRRI/TR-99/37).

Sediment

Approximately 300 cm^3 of sediment from each depositional area was composited for each site (typically collected from four to six transects per site). Composite samples (approximately 1200-2000 cm^3 per site) were labeled and stored on ice and/or frozen prior to analysis. In the lab, thawed sediment samples were transferred to a basin and homogenized for 1 minute. A small amount of water was added to each sample to facilitate thorough mixing. Homogenized sediment in the mixing container was tamped to settle material uniformly. Sediment was sub-sampled in triplicate by extracting 250 cm^3 using a 5 cm (dia.) sediment core. Sub-samples were placed in labeled pans and dried (105^o C) to a constant weight determined with a standard balance. Dried samples were ignited for 1 h at 500^o C. After samples cooled, reagent-grade water was added to re-wet ash and compensate for water weight not driven off from clay particles during the drying period (APHA 1992). Samples were dried to a constant weight at 105^o C and re-weighed to determine the ash-free dry weight of each sub-sample.

Dried sub-samples were run through a set of six sieves (4, 2, 0.5, 0.25, and 0.0625 mm) for 1 minute using a row-tapper to obtain six particle size fractions: 1) > 4 mm, 2) 4-2 mm, 3) 2-0.5 mm, 4) 0.5-0.25 mm, 5) 0.25-0.0625 mm, and 6) < 0.0625 mm (Gordon et al. 1992). Sediment retained in each size fraction was weighed using a standard balance.

Data analyses

Comparison among Knife TMDL sites

Trait characteristics for each invertebrate taxon were derived from a NRRI-maintained database compiled from a variety of sources (Merritt and Cummins 1996, Thorp and Covich 1991, Weiderholm 1983). These traits consist of functional feeding group classifications, trophic levels, methods of locomotion, preferred habitats, and other characteristics which help define aquatic invertebrate interactions within their environment. Invertebrate community metrics were generated based on known taxonomic sensitivities to environmental degradation (e.g., Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa) and on traits that may make select groups more or less sensitive (e.g., scraper-grazer feeders, burrowers, etc). Invertebrate metrics were compared among Knife TMDL sites using a one-way ANOVA. Substrate, habitat, and water chemical/physical parameters were compared among sites in a similar fashion. Each invertebrate taxon was assigned a tolerance value (0 to 10), indicating the taxon's overall level of tolerance of stressors. A value of 0 represents the least tolerant. Tolerance values came primarily from Hilsenhoff (1987), and were supplemented by values from EPA (Barbour et al. 1999). Sensitive taxa were defined as taxa with a tolerance value of 3 or less, and tolerant taxa were those with a tolerance value of 7 or higher. Tolerance scores for entire sites were calculated by multiplying the tolerance value of each taxon by abundance of that taxon per sample, summing the resulting products, and dividing by the total number of invertebrates per sample. This was done for riffle samples only because the most sensitive insects typically reside in riffles. Riffle sample scores were then averaged to generate site tolerance scores.

Comparison with historic data

Invertebrates in the historic comparison datasets were collected in a manner similar to the current data (quantitative samples in riffles using similar mesh sizes). However, there were some differences in sample processing. The Hershey-data include few non-insect taxa, and those included have coarse taxonomic resolution. Thus, invertebrate assemblage metrics had to be re-calculated and based solely on insect taxa. Metrics relying solely or primarily on non-insect taxa were not included in historic comparisons. In addition, fewer insect taxa than expected are included in the Hershey dataset, so comparisons using taxa richness were made with caution. Both the Hershey- and Brady-EPA studies sampled the same location on Skunk Creek, but in different years (1996 and 1997, respectively). Comparison of these two sampling events is encouraged to help illuminate differences due to methods and/or data processing.

Finally, substrate composition data were collected differently between the Knife TMDL and

Hershey- and Brady-EPA study. In the former studies, only dominant and subdominant substrate types were noted in each grid, whereas in the EPA study, all substrate types within each grid were assigned a percent cover to sum to 100%. The resulting data bias makes the Knife TMDL and Hershey sites appear to have higher amounts of dominant substrates and lower amounts of less dominant substrates (typically gravels, sands, silts, and clays) than actually occurred. This methodological difference precludes direct substrate composition comparisons between studies. However, percent embeddedness and depth of fine sediments were collected using similar methods during the Knife TMDL and Brady-EPA studies (the Hershey dataset does not include these two variables). In summary, data comparisons across studies are fraught with difficulties, most stemming from sample collection and processing differences for which there are no easy corrections, or for which no corrections exist. Thus, assessments and decisions using such comparisons should be made with caution. In undertaking these analyses, we attempted to correct for biases whenever possible, and to make clear when we felt that bias may still exist.

RESULTS AND DISCUSSION

Habitat Conditions

Knife River sampling sites for the current study included (upstream to downstream) Airport, Culvert, Stanley, Shilhon, and Fishtrap locations (Fig. 1). Study sites included a minimum of 100 m of stream reach, and began at least 50 m from a road crossing or other man-made structures (Table 1). Although the Airport and Stanley sites were in close proximity and similar in size to the Culvert site, habitat conditions were quite different. The Culvert site included an extremely altered riparian habitat (Table 2). Although the stream had incorporated a slight meander and one bank was regenerated with scrub and alder, the opposite bank was a road abutment and maintained ditch. Airport, Stanley, and Shilhon sites exhibited typical meanders. Historic flows, based on total bank width and flood sign (e.g., scours, large wood deposits, debris lodged in standing trees) were also consistent from an upstream to downstream perspective. Total stream widths at the Airport and Culvert sites were only slightly greater than the wetted width measured at baseflow (Table 3). Wetted width to total width comparisons doubled going downstream at Stanley, then tripled at Shilhon and Fishtrap sampling locations. These greater total widths indicate greater flow rates, and the flows impact habitat structure as stream power dramatically increases. This progression was also noted in velocity and discharge measurements, with the Culvert site having the lowest readings which increased at each downstream sampling location (Table 3).

Table 1. Knife River TMDL sampling site locations and macroinvertebrate sampling effort.

			UTM coordinates			Gear Type (n)		
Site	Date	Reach (m)	X	Y	Habitat	Core	D-net	Hess
Airport	8/7/06	100	593901	5212082	Bank		1	
					Riffle			3
					Debris		1	
Culvert	8/7/06	100	596436	5209787	Bank		1	
					Riffle			3
					Debris		1	
Stanley	8/4/06	102.5	594881	5207268	Bank		1	
					Pool	3		
					Run		1	
					Riffle			3
Shilhon	8/4/06	136	590840	5200657	Riffle		1	3
					Run		1	
Fishtrap	8/3/06	100	591646	5199993	Bank		1	
					Riffle			3
					Wood		1	
Grand Total						3	10	15

Table 2. Knife River habitat and riparian zone characteristics for the TMDL sampling locations. Entries divided by a "/" indicate conditions separately for each bank; otherwise the banks are similar. Bank substrate and substrate percent are the percent of the dominant substrate as total bank surface area along transects. Adjacent landuse is that adjacent to the riparian zone. QHEI score was calculated without including the gradient component, worth 10 pts. Undercut bank is the percent occurrence of undercut banks on transects. Amount of organic matter in sediments is expressed as grams dry weight after ashing (Organic). Large woody debris (LWD) are expressed as counts per reach.

Site	Bank Substr	Subs %	Adj landuse	Ripn zone	Ripn width (m)	QHEI score	Under bank (%)	Organic (g)	LWD
Airport	Gravel	54	Forest	Con/Asp	>50	70	35	5.13	100
Culvert	Silt-clay	94	Rd/fldpln	Grass/Ald	0/30	36	10	2.53	0
Stanley	Silt-clay	49	Forest	Con/Asp	>50	64	10	2.60	0
Shilhon	Cobble	73	Forest	Con/Asp	>50	53	0	2.97	0
Fishtrap	Boulder	54	Forest	Con/Asp	>50	61	40	2.73	0

Rd = road; fldpln = floodplain; Ripn = riparian; Con = conifer; Asp = aspen; Ald = alder.

An important consideration when comparing data from various streams and sites are physical differences, such as stream size, velocity, substrate type, and amount of shading. Stream sites in the present study tended to be wider, have shallower depths for their width, and have faster baseflow in riffles than sites from historic datasets (Table 3, Fig. 2). The notable exception was the Culvert site, which had one of the smallest widths and shallowest depths, in part due to its channel alteration into essentially a road drainage ditch (Table 2). We noted a marked difference in average riffle velocities between the Hershey and Knife TMDL sites versus the Brady-EPA sites. While this may indicate real differences among sites, it is also possible there was some inherent difference in the way velocity was measured, may be due to instrumentation differences (the Hershey and Knife TMDL studies used the same velocity meter and setup, which was different from the meter used in the Brady-EPA study), or there may have been a difference in the way the data were summarized.

Stream substrate has a pivotal influence on macroinvertebrate community taxonomic composition and structure. The type of substrate and amount of interstitial space beneath and around large substrate chiefly determines which macroinvertebrate taxa inhabit stream riffles. Flow, temperature, and dissolved oxygen are also important, but are more highly variable and, thus, snapshot measurements of these variables often do not correlate well with macroinvertebrate assemblages. Therefore, we have chosen to concentrate on some substrate comparisons among sites.

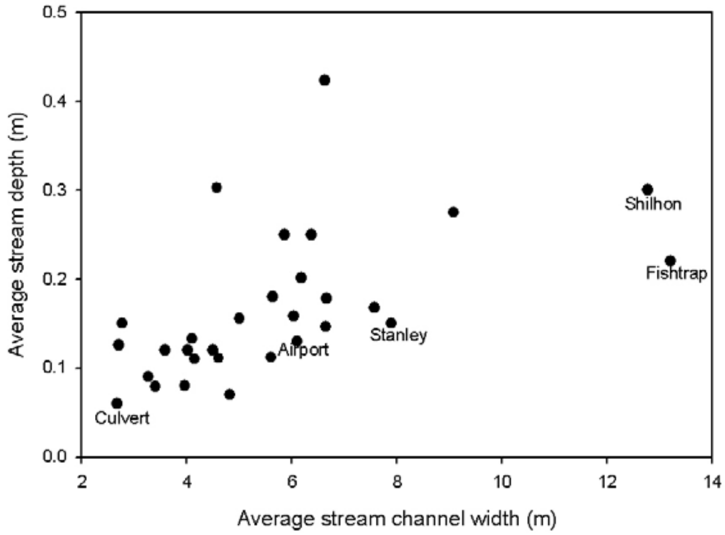

Figure 2. Relationship of stream channel width to depth for 30 North Shore stream sites. Current sites on the Knife River are

Embeddedness, an inverse estimate of the amount of interstitial space available to aquatic invertebrates, fish fry, and fish eggs, is measured as the percent that larger substrates (e.g., boulders, cobbles, and pebbles) are surrounded by fine substrates of sand, silt, and clay. This measurement is notoriously prone to personnel bias, so values are typically estimated only to the nearest 25%. Higher stream velocities keep larger sediment particles in suspension and move them downstream, typically resulting in lower embeddedness. There is a trend toward lower

Table 3. Physical characteristics of North Shore streams presented as means. Stream site code includes stream name, site name (if any), project abbreviation (see Methods), and year sampled (all sampling was done in August). Sites from the current study (Knife TMDL) in blue. Depth and velocity (flow) were measured in riffles. "Shade" represents mean percentage that the center of the stream channel was shaded.

Stream-site	Wet Width (m)	Bankfull width (m)	Depth (m)	Flow (m/s)	Temp [C]	Shade (%)
Knife-Culvert-TMDL2006	2.67	3.62	0.06	0.14	18.95	66.56
McCarthy-AH1996	2.7		0.126	0.395	-	43.3
Stanley-EPA1997	2.77		0.15	0.004	19.94	16.15
West Knife-EPA1997	3.26		0.09	0.062	18.29	48.85
Skunk-AH1996	3.4		0.079	0.127	-	81.7
Blind Temperance-EPA1997	3.58		0.12	0.037	16.29	36.25
Talmadge-EPA1997	3.96		0.08	0.001	19.07	16.92
Onion-EPA1997	4.02		0.12	0.016	18.36	7.69
Knife-AH1996	4.1		0.133	0.167	-	56.7
Palisade-EPA1997	4.15		0.11	0.028	18.28	15.00
Skunk-EPA1997	4.5		0.12	0.068	18.24	49.23
Two Island-EPA1998	4.57		0.30	0.02	17.93	28
West Br Knife-AH1996	4.6		0.111	0.242	-	33.3
Encampment-EPA1997	4.82		0.07	0.0161	18.82	13.85
East Split Rock-AH1996	5		0.155	0.143	-	20
Little Knife-AH1996	5.6		0.112	0.085	-	36.7
Lester2-EPA1997	5.63		0.18	0.062	20.00	23.08
East Beaver-EPA1997	5.86		0.25	0.014	20.15	26.15
French-EPA1997	6.03		0.16	0.06	19.72	5
Knife-Airport-TMDL2006	6.09	7.58	0.13	0.29	20.47	75.71
Lester3-EPA1998	6.18		0.20	0.03	20.11	22
Caribou-EPA1997	6.37		0.25	0.099	21.81	45.00
Beaver-EPA1998	6.62		0.42	0.03	21.94	3
Temperence-EPA1998	6.64		0.15	0.09	21.57	11
Sucker-EPA1998	6.66		0.18	0.13	21.15	6
Baptism-EPA1998	7.57		0.17	0.10	20.21	3
Knife-Stanley-TMDL2006	7.89	8.33	0.15	0.2	20.99	42.43
Cascade-EPA1998	9.07		0.27	0.03	21.20	4
Knife-Shilhon-TMDL2006	12.77	22.86	0.3	0.26	20.53	10.82
Knife-Fishtrap-TMDL2006	13.2	19.02	0.22	0.55	20.95	7.07

embeddedness at sites with higher velocity (Fig. 3), but the relationship is not clear-cut because of differences in erodible material among sites The Culvert and Stanley sites have more erodible banks than other sites (Table 2). Mean embeddedness in riffles at the Knife TMDL sites is within the range of the two other sites within the watershed where such data were collected, and are in the middle to high range overall for the historic data (Table 4, Fig. 3).

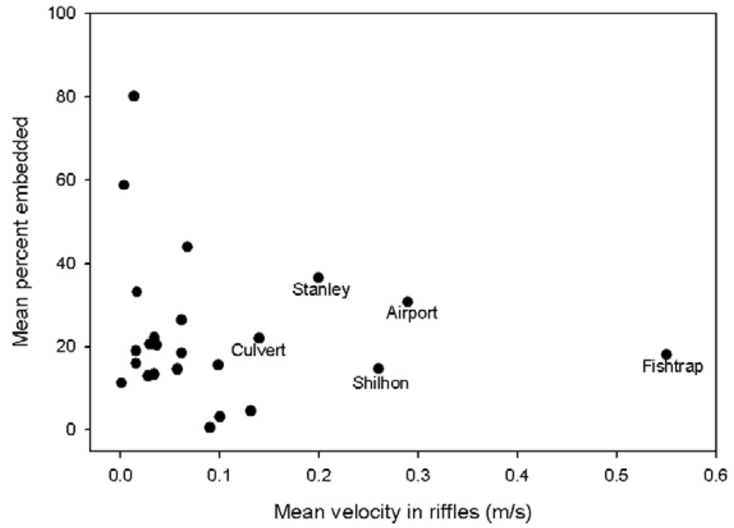

Figure 3. Average riffle velocity versus average amount of riffle embeddedness for North Shore streams. Sites from the current study are labeled.

Another measurement of the amount of excessive sedimentation in streams is the depth of fine sediments deposited in areas of slower current velocity (such as behind boulders, along bank edges, behind sand bars, etc.). Fine sediment depth measured in depositional areas (e.g., eddies behind in-stream habitats such as boulders) increased from Airport to Culvert to Stanley, then decreased at Shilhon and Fishtrap sites (Table 4). This may be explained by normal processes as the stream picks up and deposits sediment load. Sand and silt deposits were highest at the middle site; such buildup would be expected to continue downstream to the point at which flow becomes adequate to entrain the particles and move them further downstream. Shilhon and Fishtrap sites most likely experience flow regimes strong enough to flush fine sediments, even gravels, farther downstream or out into Lake Superior during high flow events. Fine sediment depth at the Knife TMDL sites was in the middle to high range compared to other sites, and the Airport site is the highest of any site in the dataset.

Size class fractionation of fine sediment deposits at Knife TMDL sites again indicated that Stanley has the highest percentages of all fine sediments (Fig. 4). This indicates that the stream at this point has the least power among sampled TMDL sites to move sediments through the system and has a supply of erodible material (i.e., banks of silt and clay, Table 2). The Shilhon site, consistently had one of the lowest percentages of fine sediments and therefore the highest power to entrain and move these particles resulting in fewer erodible banks Table 2). It is important to note that absence of silt and clay at the Airport site may indicate a lack of clay and other fine-grained materials to be eroded. Instead, embeddedness at this site is primarily from fine sand. Together, these measurements indicate the Knife TMDL sites are experiencing relatively high levels of sedimentation, likely on a par with other streams currently experiencing high turbidity and sedimentation (e.g., Amity Creek, Poplar River).

Table 4. Substrate characteristics of North Shore streams. Sites from the current study shown in blue. Substrates were characterized as bedrock (bed), boulder (bldr), cobble (cbl), pebble (pbl), sand, and silt and clay (st/cl) and are expressed as percents. Total fines (Tfines) are the sum of percents of sand, silt, and clay. Depth of fines is the depth of fine sediments in slow current areas. Embeddedness is the amount that large substrates (boulders to pebbles) are surrounded by fine substrates.

Stream-site	Bed (%)	Bldr (%)	Cbl (%)	Pbl (%)	Sand (%)	St/cl (%)	Tfines (%)	Depth Fines (m)	Embed (%)
McCarthy-AH1996	0.0	20	80.0	0.0	0.0	0.0	0.0	-	-
Skunk-AH1996	0.00	33.3	66.70	0.00	0.00	0.00	0.00	-	-
Knife-AH1996	0.0	60	40.0	0.0	0.0	0.0	0.0	-	-
West Br Knife-AH1996	0.0	21.7	65.0	10	0.0	0.0	0.0	-	-
East Split Rock-AH1996	0.00	20	80.00	0.00	0.00	0.00	0.00	-	-
Little Knife-AH1996	0.00	26.7	60.00	13.1	0.00	0.00	0.00	-	-
Caribou-EPA1997	0.0	52.9	38.2	8.8	0.0	0.0	0.0	0.02	15.55
Knife-Fishtrap-TMDL2006	0.00	31.16	66.57	2.27	0.00	0.00	0.00	0.03	18.13
Sucker-EPA1998	0.0	23.0	50.2	26.4	0.4	0.0	0.5	0.00	4.61
Lester2-EPA1997	0.0	3.8	49.5	45.7	0.9	0.0	0.9	0.02	26.4
Baptism-EPA1998	0.0	24.8	50.2	24.1	1.0	0.0	1.0	0.00	3.17
Temperence-EPA1998	26.5	17.3	42.5	12.8	0.8	0.2	1.0	0.00	0.61
Skunk-EPA1997	0.0	13.6	47.7	36.4	2.3	0.0	2.3	0.1	43.93
Knife-Shilhon-TMDL2006	0.00	28.93	58.24	10.53	2.29	0.00	2.29	0.07	14.70
Lester3-EPA1998	0.0	0.0	72.5	25.0	2.2	0.3	2.5	0.02	22.14
Onion-EPA1997	0.0	26.0	48.7	22.7	2.4	0.1	2.5	0.03	18.92
Encampment-EPA1997	0.0	29.5	45.7	21.5	3.2	0.1	3.4	0.03	16.03
Palisade-EPA1997	43.9	7.3	21.9	21.9	4.9	0.1	5.0	0.01	12.96
Talmadge-EPA1997	12.8	15.4	41.1	25.7	4.8	0.2	5.0	0.26	11.28
French-EPA1997	0.0	0.0	58.8	35.4	5.5	0.3	5.8	0.01	14.64
Knife-Airport-TMDL2006	0.00	3.28	52.46	37.27	0.00	6.98	6.98	0.04	30.71
West Knife-EPA1997	0.0	4.7	46.5	41.9	6.8	0.2	7.0	0.02	18.51
Cascade-EPA1998	0.0	12.7	32.7	46.9	6.9	0.8	7.7	0.00	13.41
Stanley-EPA1997	0.0	0.0	45.4	45.4	9.0	0.3	9.3	0.1	58.75
Blind Temperance-EPA1997	0.0	38.3	30.6	17.9	13.1	0.2	13.3	0.04	20.37
Beaver-EPA1998	0.0	0.0	3.3	83.3	12.0	1.3	13.3	0.03	20.54
Knife-Stanley-TMDL2006	0.00	1.58	24.02	60.46	6.02	7.92	13.94	0.09	36.50
Two Island-EPA1998	0.0	0.0	37.8	42.8	15.8	1.4	17.2	0.02	33.13
Knife-Culvert-TMDL2006	0.00	0.00	16.48	64.79	4.87	13.86	18.73	0.06	22.00
East Beaver-EPA1997	0.0	0.0	0.0	50.0	48.1	1.9	50.0	0.17	80

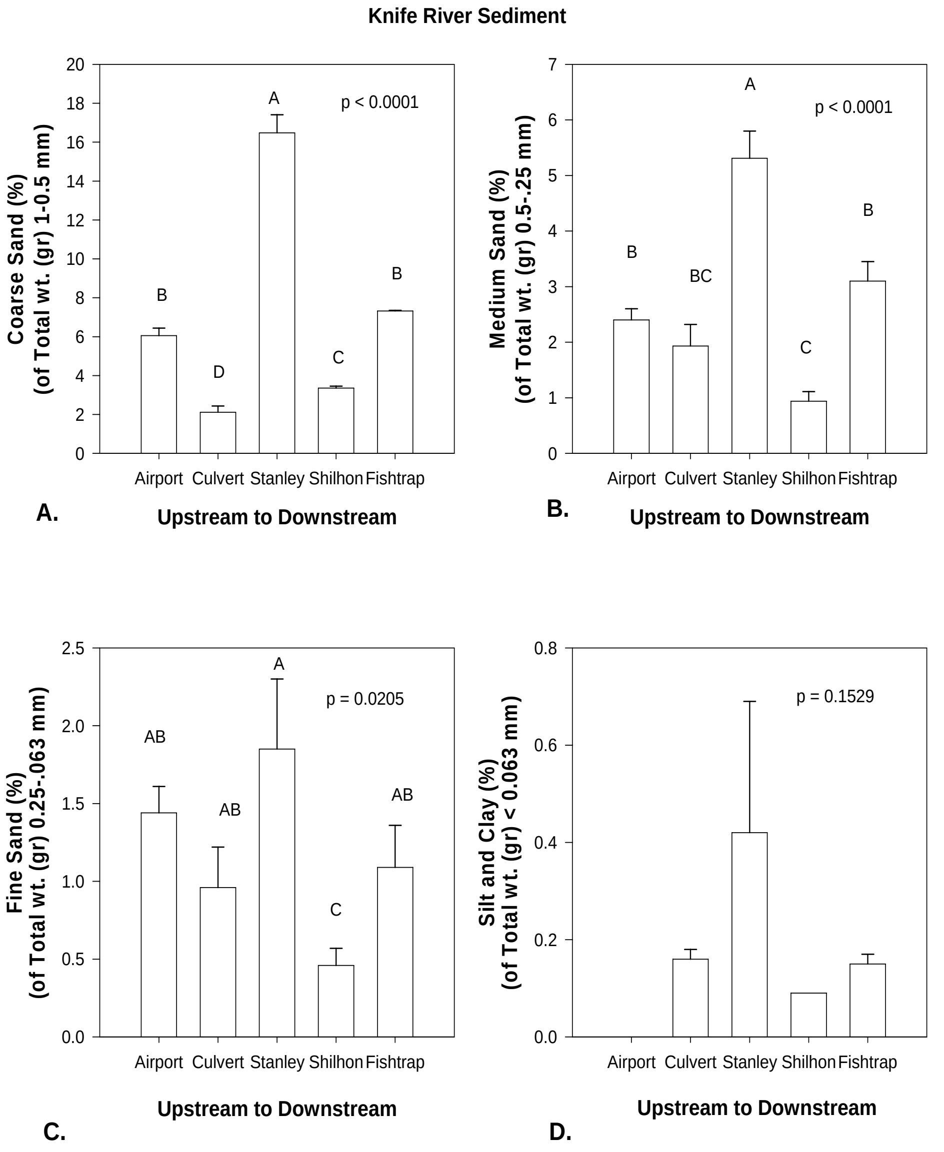

Figure 4. Mean proportion of sediment size particles from the total volume (weight in grams) of fine sediments sampled at locations along the Knife River, MN. Data represent mean proportions + 1 standard error of A) coarse, B) medium, and C) fine sand, plus D) silt and clay particles. The value of *p* is from the overall ANOVA. Bars with the same letter are not significantly different based on Tukey's procedure.

Differences in substrate characterization among the studies make matching sites with similar substrate almost impossible across studies (see Methods). Thus, the percentage of fine sediments in Knife TMDL riffle sites is quite likely higher than shown in the present data. Even given these caveats, the Stanley and Culvert TMDL sites have among the highest percentages of fine sediments in their riffles of any measured site (Fig. 5). On the other end of the spectrum, the Fishtrap and Shilhon sites have high amounts of boulders (Fig. 5), in some cases with bedrock beneath them (data not shown). Bedrock stream beds provide less habitat for macroinvertebrates, fish fry, and fish eggs due to the lower amount of interstitial space. Consequently, streams with high amounts of bedrock can share similarities in invertebrate assemblages with streams in which the substrate is embedded. Because bedrock was a subdominant rather than dominant feature of the downstream Knife sites, it is unclear how much of an effect its presence had on the macroinvertebrates.

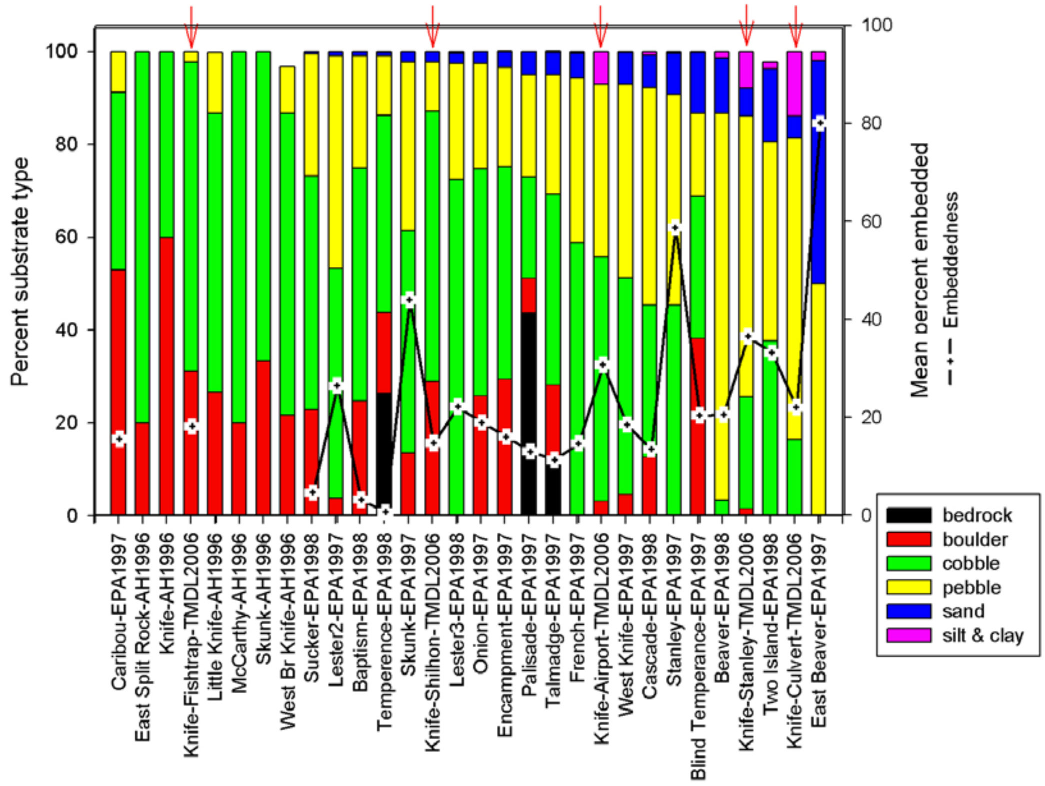

Figure 5. Average percent substrate types in riffles for North Shore streams, with average percent riffle embeddedness shown as dashed lines with + symbols. Sites from the current study marked with red arrows. See Methods for description of substrate sampling differences among studies.

Notable habitat differences among the Knife TMDL study sites included substantial amounts of large woody debris (LWD) at the upstream Airport site, with an apparent lack of debris at the remaining locations. The riparian vegetation at the Airport site was primarily a contiguous, mature conifer/aspen stand. A difference in woody debris deposits can be attributed to two potential factors: 1) stream flow (indicated above), and 2) riparian vegetation. Large riparian woody vegetation was lacking at the Culvert site, which consisted of a maintained ditch on one bank, and a heavily vegetated bank on the other (Table 2). Riparian vegetation was primarily composed of alder clumps (less than 10 cm dia.). Allochthanous inputs at the Culvert site could easily be transported downstream by high flows due to the channelized design. Although the stream channels at the remaining sites appeared natural, and abundant forest existed on both banks at each site, LWD was only noted as deposits on the bank or gravel bar (e.g., Shilhon and Fishtrap), and not intersecting stream flow. Therefore, these materials were present, with ample supply available, but were not incorporated into stream processes during base flow conditions. Thus, this LWD was not included in the total count. It is likely the stream power at these sites was great enough to keep LWD from accumulating in the active channel, resulting in a loss of this habitat type for macroinvertebrates and as fish cover. It is probable that such power represents an increase over pre-logging conditions, as has been shown for other area streams (Fitzpatrick and

Knox 2000). Canopy cover, measured as proportion of the stream channel that was shaded, steadily declined from upstream to downstream, with the Airport site being 75% shaded and the Fishtrap site only 7% shaded (Table 3). The Airport site sediments also contained significantly more organic matter than other sites (ANOVA $p < 0.01$; Table 2), in keeping with greater canopy cover and more LWD in the channel. Finally, fish habitat assessment (QHEI) scores were highest (best) at the Airport site and lowest (worst) at the Culvert site, indicating poor habitat quality at this site (Table 2). Differences among the sites included amount of cover, LWD, and sinuosity, channel shape, and condition of riffles/runs (extremely low for the Culvert site). Organic particles embedding larger substrates should have less effect on macroinvertebrates because they can be more easily moved about or burrowed through. However, these particles do still decrease habitat space.

Table 5. Knife River TMDL site water chemistry measurements. Water clarity values were all significantly different from each other (ANOVA $P < 0.05$).

Site	Temp (^{o}C)	Scond (us/s)	DO (%)	DO (mg/L)	pH	ORP	Clarity (cm)
Airport	20.47	136	105.4	9.49	7.63	202.3	>120^{a}
Culvert	18.95	138	81.8	7.56	6.46	259.9	52.1^{e}
Stanley	20.99	124	106.3	9.45	7.26	235.6	91.0^{b}
Shilhon	20.53	110	78.3	6.62	6.12	273	74.3^{c}
Fishtrap	20.95	104	104.0	9.33	7.19	n/a	68.1^{d}

Water chemistry parameters were similar among sites, although water clarity among sites was significantly different (Table 5). Transparency tube readings were highest at the Airport site, substantially lower at the Culvert site, came back up for the Stanley site, but declined again at the two downstream sites. A large storm system came through the area on July 29 and 30, 2006, dropping over 2 inches of rain on areas of the North Shore (www.lakesuperiorstreams.org). The low clarity values may be due to this high water event, but it is important to note that even eight days postrainfall, the Culvert site still had quite low water clarity. This indicates substantial erosion problems at the Culvert site and presumably at some upstream reaches or tributaries above the Shilhon and Fishtrap sites.

Macroinvertebrates

Use of macroinvertebrate community information to assess stream ecosystem condition relies on the varying sensitivities of the different taxa to the variety of different stressors to which they may be subjected. Because of the differences in methods and identification among studies, we calculated some of the metrics separately for the Knife TMDL sites so as to take advantage of greater taxonomic resolution and inclusion of non-insect taxa (Table 6). Metrics for comparison with the historic data were calculated using only insect taxa (Table 7).

Some of the most sensitive taxa are found in the Ephemeroptera (mayfly), Plecoptera (stonefly), and Trichoptera (caddisfly) orders of insects. We calculated the proportion of EPT individuals from all macroinvertebrates (Table 6) or insects (Table 7) collected from riffles in the various stream studies. Proportions at the Knife TMDL sites were all at the lower end of the range for

Table 6. Knife River TMDL site macroinvertebrate metrics generated from quantitative riffle samples. Numbers represent mean values ($\pm$ 1 standard error). Metric values with letters indicate a significant test result ($p \leq 0.05$). Means with the same letter were not different based on Tukey's comparison.

Invertebrate metrics	Airport	Culvert	Stanley	Shilhon	Fishtrap
Proportion EPT indiv.	36.5 (8.47)	15.3 (6.10)	22.6 (7.34)	27.2 (5.93)	25.2 (3.63)
Count of sensitive taxa	10.6 (2.18)^{ab}	7 (0.57)^{ab}	8 (1.00)^{ab}	11.3 (1.20)^{a}	5.6 (1.20)^{b}
Percent tolerant indiv.	28.7 (6.98)^{ab}	23.5 (3.07)^{ab}	13.5 (3.64)^{b}	20.3 (1.47)^{b}	42.2 (3.4)^{a}
Percent Tanytarsini (of Chironomidae)	37.5 (5.87)	43.9 (7.66)	51.9 (5.61)	66.6 (7.27)	48.6 (11.3)
Percent burrowers	9.2 (2.21)	11.3 (1.71)	24.2 (6.46)	9.6 (2.21)	13.6 (4.70)
Percent climbers	12.6 (1.29)^{b}	17.7 (2.68)^{b}	15.5 (3.11)^{b}	42.5 (2.10)^{a}	39.4 (3.74)^{a}
Percent clingers	56.6 (2.84)	47.7 (3.52)	28.9 (12.0)	28.2 (2.70)	31.0 (2.45)
Percent collector-filterers	35.2 (7.29)	21.8 (2.67)	27.2 (10.8)	19.3 (1.85)	14.4 (0.50)
Percent collector-gatherers	33.2 (1.42)	43.0 (7.50)	36.6 (7.71)	44.2 (2.59)	47.5 (2.27)
Percent predators	12.5 (1.88)	14.5 (2.03)	26.9 (5.46)	15.3 (1.30)	24.7 (1.07)
Percent scraper-grazers	8.8 (1.45)^{a}	10.8 (3.14)^{a}	2.0 (0.83)^{b}	7.4 (0.68)^{a}	5.9 (0.47)^{a}
Percent shredders	9.5 (5.91)	2.4 (0.21)	3.8 (2.03)	8.0 (0.64)	3.4 (1.34)
Site Tolerance Score	5.2 (0.21)^{ab}	5.5 (0.03)^{a}	5.2 (0.01)^{ab}	4.5 (0.31)^{b}	5.4 (0.23)^{a}

North Shore streams, with the Culvert site having the lowest at only 19% (Fig. 6). In contrast, Hershey reported 80% or more EPT individuals for sites on the Little Knife and McCarthy Creek. The number of EPT taxa is another commonly used indicator of invertebrate community condition. However, due to the differences in taxonomy among studies, this indicator is not a good one for comparison. For example, the Brady-EPA study found 24 EPT taxa at exactly the same site where, in the same month the previous year, the Hershey study reported only 13 EPT taxa (Table 7). It is unlikely that environmental conditions improved greatly in just a year, especially since percent EPT was not appreciably different between the two sampling events. For similar reasons, we were unable to use the number of sensitive taxa in historic comparisons. Among the Knife TMDL sites, EPT taxa richness and sensitive taxa richness were highest at the Shilhon site and lowest at the Airport site (Table 6).

One genus of stream stonefly, Pteronarcys, is occasionally used to indicate stream condition and habitat and food resource stability. Pteronarcids are large, shredder stoneflies that take several years to reach maturity in northern streams, and do best in cool, well-oxygenated water (Merritt and Cummins 1996). They feed by shredding deciduous tree leaves that fall into streams, and thus are not found in stream areas that lack deciduous trees nearby or upstream. Approximately ⅓ of North Shore streams contained Pteronarcys stoneflies, including the Airport site, the Brady-EPA Stanley Creek site, and the Hershey West Branch of the Knife site (Table 7).

Table 7. Metrics calculated using riffle insect taxa collected from North Shore streams. Current study sites in blue. See Methods for description of other studies. “Taxa” indicate richness counts. “Tol score” is site tolerance score. “Sensit” is number of sensitive taxa; “% Tol” is percentage of tolerant insects in samples (tolerance values ≥7); “Pteronarcys” is presence or absence of the stonefly Pteronarcys at sites. “Hydropsych” is proportion of Trichoptera from the family Hydropsychidae.

Stream-site	Taxa	Insect taxa	EPT taxa	% EPT	Tol score	Sensit	% Tol	Ptero-narcys	Hydro-psych
Knife-Culvert-TMDL2006	27.3	22	9.7	19.1	4.70	6.30	4.30	A	0.81
Cascade-EPA1998	49	39	24	25.9	5.30	19.00	1.00	P	0.19
Stanley-EPA1997	40	33	23	26.3	5.30	12.70	16.00	P	0.40
Knife-Shilhon-TMDL2006	28.7	24	16.3	30.5	5.20	9.00	3.60	A	0.71
Encampment-EPA1997	43	33	23	31.2	4.40	12.70	0.40	P	0.45
Knife-Fishtrap-TMDL2006	24	20	13.7	32.9	5.20	4.70	12.00	A	0.36
West Knife-EPA1997	32	26	19	32.9	3.30	11.00	0.00	A	0.34
Knife-Stanley-TMDL2006	27.7	21	13.7	38.3	5.00	7.00	0.30	A	0.92
Knife-AH1996	22	21	15	40.0	3.10	7.70	0.00	A	0.31
French-EPA1997	36	27	18	41.0	4.70	16.00	3.00	A	0.89
Knife-Airport-TMDL2006	28	24	14.3	42.4	4.70	10.00	5.20	P	0.58
Baptism-EPA1998	45	38	26	42.9	4.30	22.00	0.90	A	0.67
Temperence-EPA1998	32	26	16	47.8	4.70	13.00	0.80	A	0.62
Caribou-EPA1997	41	33	23	51.6	4.10	14.70	0.70	A	0.35
Sucker-EPA1998	38	33	24	53.1	4.30	20.00	2.20	P	0.60
Lester2-EPA1997	41	33	20	53.4	3.10	14.00	0.50	A	0.20
Beaver-EPA1998	42	36	27	54.3	4.20	19.00	7.00	A	0.41
Two Island-EPA1998	38	30	21	56.2	3.60	19.00	6.20	P	0.46
West Br Knife-AH1996	17	17	11	56.7	3.30	5.70	0.00	P	0.17
East Beaver-EPA1997	34	29	17	57.0	3.50	13.70	1.10	A	0.90
Skunk-EPA1997	46	40	24	58.0	3.60	14.70	1.40	P	0.42
Lester3-EPA1998	43	37	23	59.3	4.40	20.00	3.00	A	0.86
Skunk-AH1996	20	19	13	59.9	3.70	5.70	1.70	A	0.42
Blind Temperance-EPA1997	36	29	21	63.8	3.30	9.70	0.90	A	0.46
Talmadge-EPA1997	29	20	15	66.9	3.50	7.30	0.70	P	0.46
Onion-EPA1997	29	23	16	71.0	2.70	9.70	0.50	A	0.31
Palisade-EPA1997	33	25	15	72.3	2.80	8.00	1.20	A	0.13
McCarthy-AH1996	21	20	12	79.9	1.70	8.00	0.00	A	0.12
Little Knife-AH1996	12	12	8	82.2	3.50	3.70	0.00	A	0.79
East Split Rock-AH1996	18	17	13	82.5	1.90	6.00	2.10	A	0.22

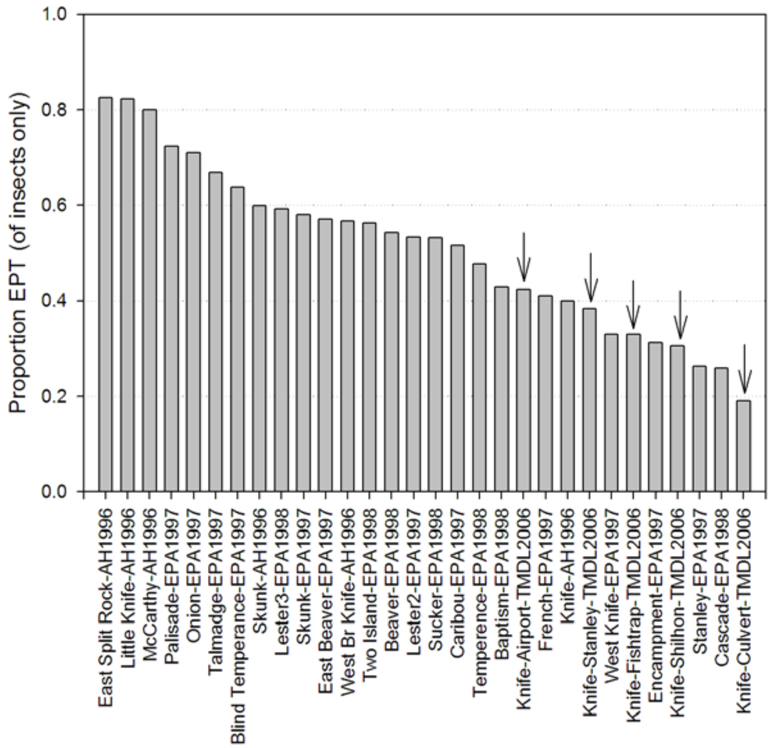

Figure 6. Proportion of insects in the orders Ephemeroptera, Plecoptera, and Trichoptera in North Shore stream riffles. Sites from current study marked with arrows.

Of course, not all species within the EPT orders are highly sensitive to environmental stress. A family of net-spinning caddisflies (the Hydropsychidae) is among the more tolerant of the Trichopera. Calculating the percentage of Trichoptera that are Hydropsychidae is a metric recommended by the U.S. EPA for stream assessment (Barbour et al. 1999). At three of the Knife TMDL sites, most of the caddisflies were in the family Hydropsychidae (Table 7; Fig. 7). However, the Fishtrap and Airport sites were exceptions with lower proportions of hydropsychids. Several sites had high proportions of Hydropsychidae, including; Lester River 3 (a third-order Lester River site), East Beaver River, French River, and Little Knife. Hydropsychidae construct spun-silk retreats that include nets; these retreats are attached to rocks in the current in riffles, and the insects use the nets to capture particles carried by the current, which they eat. High numbers of hydropsychid caddisflies are considered indicative of nutrient enrichment. Large amounts of sedimentation would potentially clog or bury their nets, but we did not find a correlation between proportion Hydropsychidae and percent embeddedness.

Other insects, such as the Diptera family Chironomidae (non-biting midges), are considered even more tolerant of stressors. In particular, some members of this group have hemoglobin to help them remove oxygen from the water under low oxygen conditions. Proportions of Chironomidae at Knife TMDL sites were among the highest of the three studies for non-urban North Shore streams (Fig. 8), indicating stressful conditions. Other Chironomidae, in particular the family Tanytarsini, spin nets to filter food from the current and have the potential to be adversely affected by both turbidity and sedimentation. The proportion of Tanytarsini comprising the Chironomidae was highest at the Shilhon site and lowest at the Airport site (Table 6). This likely reflects increasing amounts of nutrients and food particles in the water at downstream sites, rather than any impact of sediments or turbidity. The low percent of Tanytarsini at the Fishtrap site may indicate poor habitat.

Comparing major taxonomic groups of insects among sites causes one of the Knife TMDL sites to stand out from the others. The Culvert site contained a much higher proportion of Coleoptera than was reported for any other site (Fig. 8). The channel alteration of this site, lack of a true pool-riffle and meander structure, and its slow flow probably account for this marked difference.

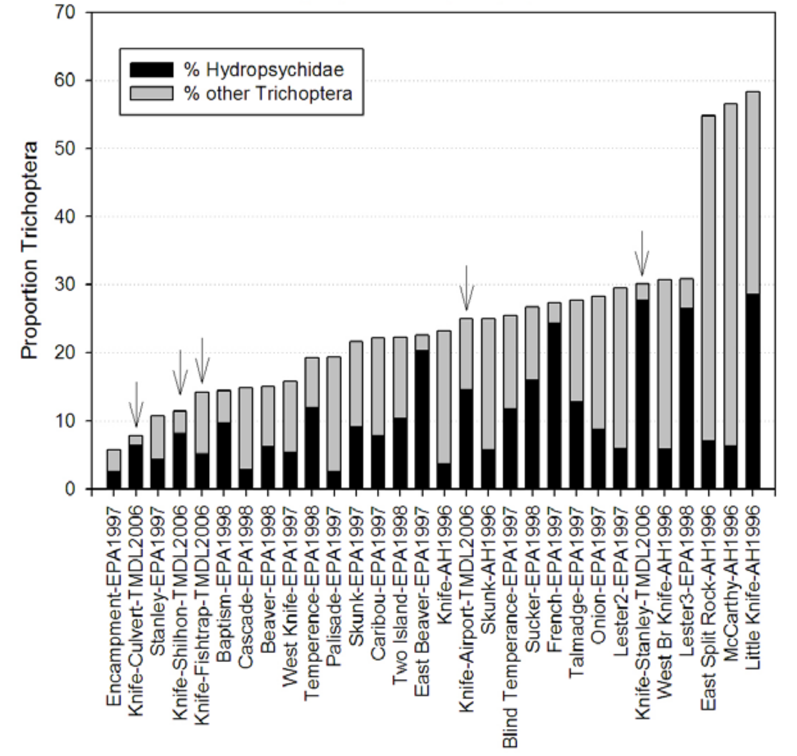

Figure 7. Percent of riffle insect community comprised of Trichopera, and percent of Trichoptera in the family Hydropsychidae, in North Shore streams. Current study sites marked by arrows.

Potential tolerance scores range from 0 to 10, with higher scores indicating that the insects are more tolerant of various types of stress, including nutrient enrichment, low dissolved oxygen, some chemical pollutants, and sedimentation and turbidity. Comparing the percent of tolerant insects in riffles (those with tolerance values of 7 and higher) among sites shows a now-familiar pattern, with most of the Knife TMDL sites having a higher percentage of tolerant individuals than was found in other North Shore streams (Fig. 9, Tables 6 and 7). Although some of the variation may be due to differences in taxonomy among studies, the two Skunk Creek sampling events cluster close together in this analysis, suggesting that taxonomic variability had little influence.

When tolerance scores were calculated for entire sites using insects collected from riffles, the Knife TMDL sites clustered tightly together within the overall comparison among stream samples (Fig. 9). Again, the close proximity of the two Skunk Creek samples suggests taxonomic differences among studies did not have a large effect, and that the differences among sites are due to true differences in the insect communities. Tolerance scores for Knife TMDL sites ranged from 4.7 to 5.2 (4.5 – 5.5 based on all macroinvertebrates, Table 6), while non-urban North Shore streams had a range of 1.7 to 5.3 (Table 7, Fig. 9). Sites within the Knife River watershed covered that entire range, with the Hershey-McCarthy site having the lowest (best) score at 1.7 and the Brady-EPA Stanley site having the highest (worst) at 5.3.

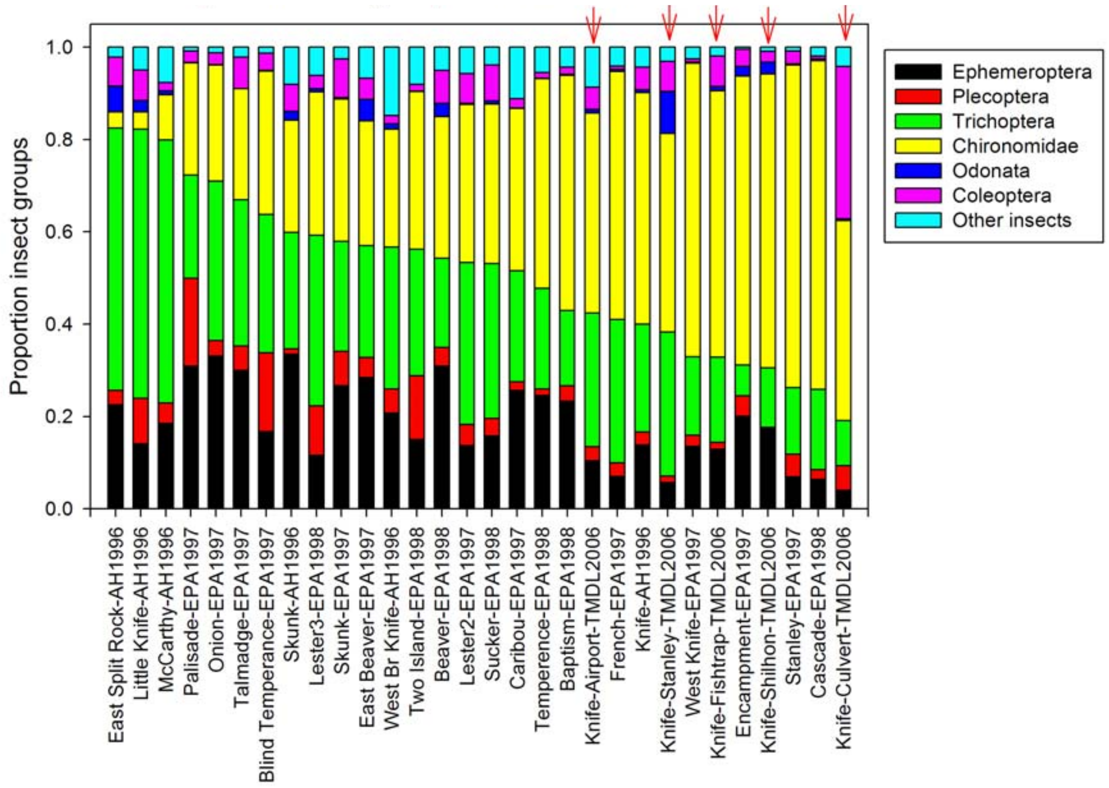

Figure 8. Proportion of taxonomic groups making up riffle insect communities in North Shore streams. Current study sites marked with arrows.

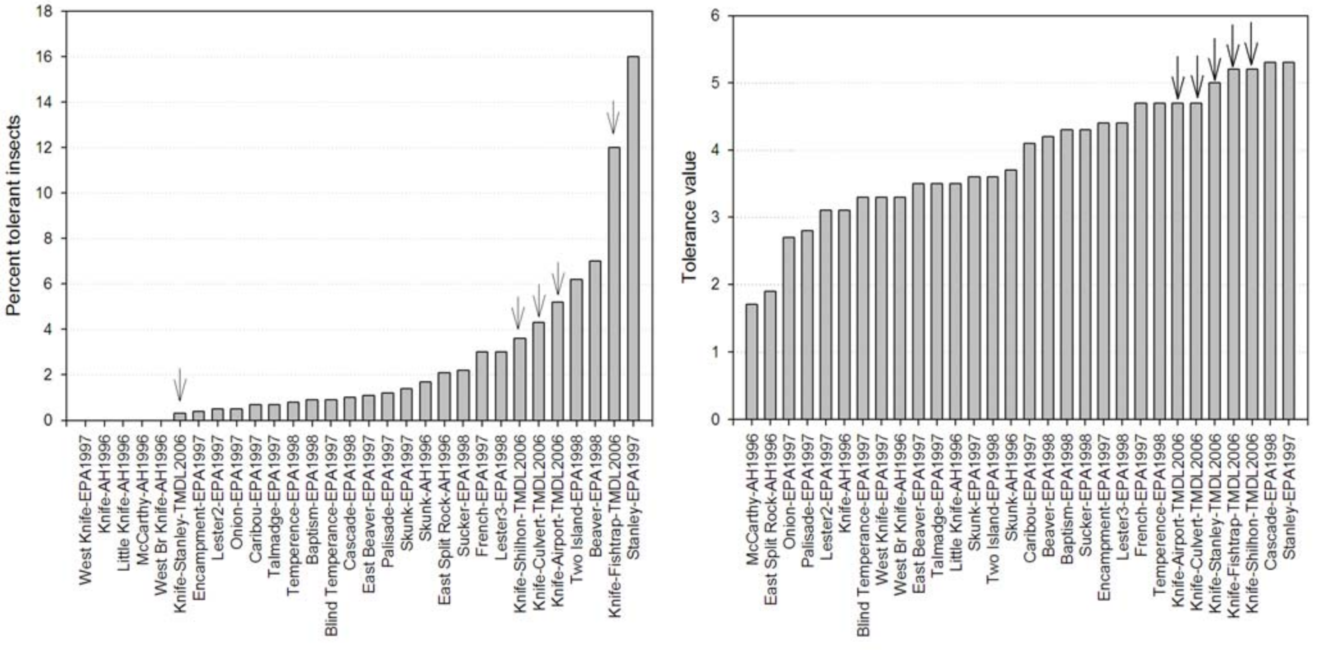

Figure 9. (left) Percent of "tolerant" insects in North Shore stream riffles. (Right) Tolerance score for North Shore stream sites based on riffle insects. Current study sites marked with arrows.

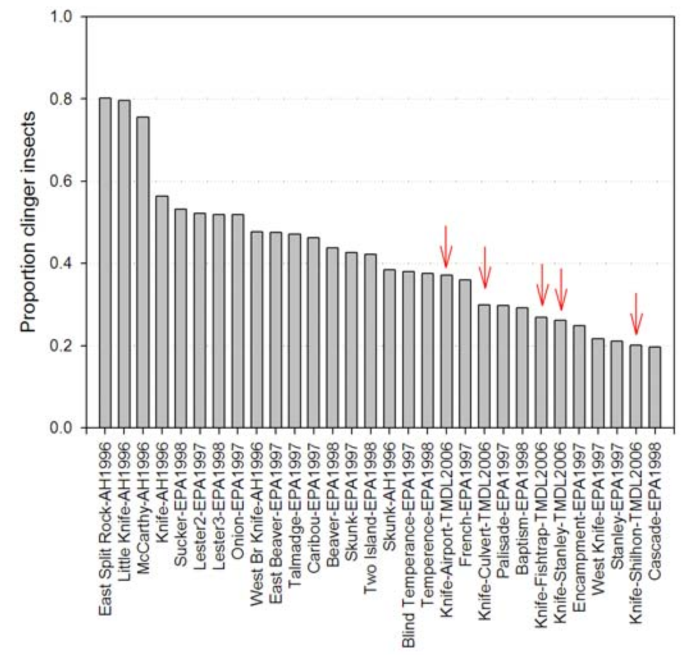

Figure 10. Proportion of insect community considered "clingers" in North Shore stream riffles.

Another set of metrics used with macroinvertebrates assesses various traits that the invertebrates exhibit. These include; how and on what the taxa feed, how they move about, and how long they live, etc. Insects considered "clingers" cling to rocks in riffles in the current; many of these insects need interstitial space among the riffle rocks to find food particles, escape from predators, and find refuge from the current. As space around rocks becomes filled with sediment, clingers lose habitat and become less abundant. Most mayflies, stoneflies, and caddisflies are considered clingers, so this metric is also sensitive to nutrient pollution and low dissolved oxygen conditions. The proportion of clinger insects at Knife TMDL sites is in the lower half of the range reported from North Shore stream sites (Fig. 10). The Airport and Culvert sites have the highest proportion of clingers among the Knife TMDL sites. The beetles (Coleoptera) at the culvert site are considered clingers, which explains why this site looks less degraded than would be expected based on other metric values.

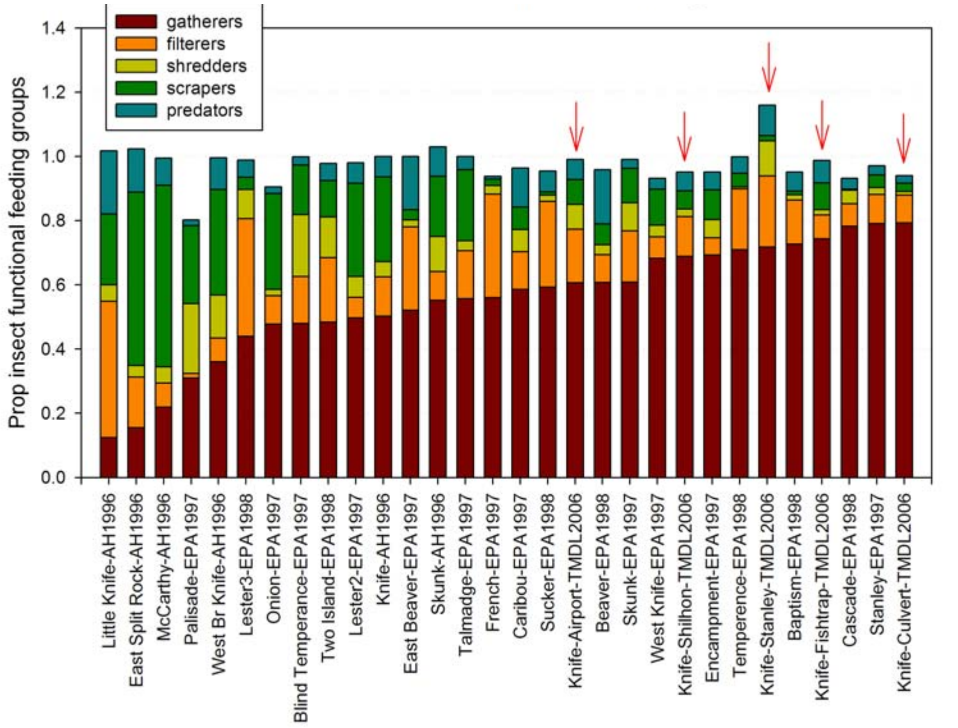

Figure 11. Functional feeding groups if insects in North Shore stream riffles. Proportions do not always add up to 1 because of lack of information on some groups, or due to lumping of taxa.

Comparing sites based on insect trophic groups shows that Knife TMDL sites tend to have more gatherers than average for North Shore streams (Fig. 11). Insects that eat many types of food would be expected to be more tolerant of stressful conditions than their more resource-specific counterparts such as carnivores. Herbivorous insects, particularly those that scrape algae off of rocks, would not be expected to thrive in high-sedimentation conditions, and the proportion of grazers reported for Knife TMDL sites was lower than for many other North Shore streams (Fig. 11). Grazers proportions were highest at the more open Culvert site, and they may be getting nutrients from the sediment eroding into the stream. The low proportion of grazers at the Stanley site may reflect its high embeddedness, forested banks, and land cover. There was a trend toward lower proportion grazers with increased riffle embeddedness (Fig. 12), but there were too few highly embedded sites to show this strongly. Grazer amounts can also be affected by amount of stream shading (which would limit algal growth), but we found no correlation or trend when plotting proportion grazers vs. stream canopy cover measurements (data not shown).

SUMMARY AND CONCLUSIONS

The Airport and Shilhon sites are in the best condition of the Knife TMDL sites, with Airport representing the smaller tributaries and Shilhon representing the better of the large stream sites. Overall, embeddedness levels are high enough at most Knife TMDL sites that we would predict effects on macroinvertebrates. Plots of percent riffle embeddedness versus various insect community measures that would be expected to show such effects, in fact show very little correlation. However, these same metrics indicate that sites within the Knife River watershed, and in particular those sampled for this study, have insect communities indicative of sites that are of a poorer condition than those at other North Shore stream sites. Although it is likely that the true differences among sites are not as extreme as they appear because of the spread in time of the sampling events and the differences in methodology, these data do suggest that the invertebrates at the Knife TMDL sites are experiencing enough stress to alter their community structure. Thus, the invertebrates at these sites are likely responding to a variety of stresses, only one of which is embeddedness. The Fishtrap site in particular is likely experiencing the cumulative effects of a variety of upstream stressors. On the other hand, turbidity and embeddedness may be having more of an effect on macroinvertebrate communities than we can currently demonstrate. We recommend that the Hershey sites on the Little Knife, McCarthy, and West Knife be re-sampled and evaluated as potential reference sites for the Knife system, in comparison with the Airport site from this study. Continued efforts should be made to add historic invertebrate, substrate, and turbidity data from the Knife River watershed and similar streams to better calibrate current Knife River biotic conditions evaluated in this study.

LITERATURE CITED

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Appendix 1. Mean number of taxa per square meter occurring in habitats at each sampling location. SE = standard error; CV = coefficient of variation.

Gear	Site	Habitat	Taxa	Abundance (#/m^2)	SE	CV
Hess	Airport	Riffle	Acari	2739.13	630.560	0.399
Hess	Airport	Riffle	Acroneuria	565.22	319.499	0.979
Hess	Airport	Riffle	Antocha	507.25	251.440	0.859
Hess	Airport	Riffle	Atherix	43.48	na	na
Hess	Airport	Riffle	Baetidae	456.52	53.250	0.202
Hess	Airport	Riffle	Bezzia	652.17	na	na
Hess	Airport	Riffle	Brachycentrus	434.78	212.999	0.849
Hess	Airport	Riffle	Cardiocladius	1720.11	na	na
Hess	Airport	Riffle	Ceratopogonidae	173.91	na	na
Hess	Airport	Riffle	Cheumatopsyche	594.20	233.239	0.680
Hess	Airport	Riffle	Collembola	217.39	35.500	0.283
Hess	Airport	Riffle	Cricotopus	1751.23	1042.352	1.031
Hess	Airport	Riffle	Dolophilodes	173.91	na	na
Hess	Airport	Riffle	Empididae	173.91	na	na
Hess	Airport	Riffle	Epeorus	43.48	na	na
Hess	Airport	Riffle	Eukiefferiella	2585.74	720.695	0.483
Hess	Airport	Riffle	Eurylophella	304.35	35.500	0.202
Hess	Airport	Riffle	Ferrissia	333.33	181.594	0.944
Hess	Airport	Riffle	Glossosoma	3028.99	2246.938	1.285
Hess	Airport	Riffle	Glossosomatidae	43.48	na	na
Hess	Airport	Riffle	Gomphidae	449.28	268.410	1.035
Hess	Airport	Riffle	Hemerodromia	173.91	na	na
Hess	Airport	Riffle	Hydropsyche	7173.91	3824.440	0.923
Hess	Airport	Riffle	Hydropsychidae	6347.83	71.000	0.019
Hess	Airport	Riffle	Leptophlebiidae	2782.61	1239.194	0.771
Hess	Airport	Riffle	Leuctra	1913.04	na	na
Hess	Airport	Riffle	Limnephilidae	217.39	na	na
Hess	Airport	Riffle	Lopescladius	1320.01	537.793	0.706
Hess	Airport	Riffle	Microtendipes	1146.74	na	na
Hess	Airport	Riffle	Nematoda	898.55	358.824	0.692
Hess	Airport	Riffle	Nigronia	260.87	175.715	1.167
Hess	Airport	Riffle	Oligochaeta	3536.23	1423.171	0.697
Hess	Airport	Riffle	Ophiogomphus	43.48	na	na
Hess	Airport	Riffle	Optioservus	2304.35	821.881	0.618
Hess	Airport	Riffle	Paragnetina	130.43	71.000	0.943
Hess	Airport	Riffle	Paraleptophlebia	347.83	na	na
Hess	Airport	Riffle	Parametriocnemus	428.44	118.333	0.478
Hess	Airport	Riffle	Paratanytarsus	573.37	na	na
Hess	Airport	Riffle	Physella	173.91	na	na
Hess	Airport	Riffle	Plecoptera	413.04	230.749	0.968
Hess	Airport	Riffle	Polypedilum	1416.63	605.313	0.740
Hess	Airport	Riffle	Protoptila	869.57	na	na
Hess	Airport	Riffle	Pseudocloeon	347.83	na	na

Appendix 1 (cont).

Gear	**Site**	**Habitat**	**Taxa**	**Abundance (#/m^2)**	**SE**	**CV**
Hess	Airport	Riffle	Psychomyia	86.96	na	na
Hess	Airport	Riffle	Pteronarcys	130.43	71.000	0.943
Hess	Airport	Riffle	Pycnopsyche	43.48	na	na
Hess	Airport	Riffle	Rheotanytarsus	3550.11	499.665	0.244
Hess	Airport	Riffle	Sialis	130.43	71.000	0.943
Hess	Airport	Riffle	Simulium	2463.77	2021.362	1.421
Hess	Airport	Riffle	Stempellinella	283.51	na	na
Hess	Airport	Riffle	Stenonema	1333.33	463.768	0.602
Hess	Airport	Riffle	Synorthocladius	397.08	92.723	0.404
Hess	Airport	Riffle	Tanytarsus	4567.93	951.840	0.361
Hess	Airport	Riffle	Thienemanniella	1676.17	891.716	0.921
Hess	Airport	Riffle	Thienemannimyia	1720.11	na	na
Hess	Airport	Riffle	Trichoptera	869.57	177.499	0.354
Hess	Culvert	Riffle	Acari	2000.00	1134.885	0.983
Hess	Culvert	Riffle	Acroneuria	43.48	0.000	0.000
Hess	Culvert	Riffle	Antocha	86.96	na	na
Hess	Culvert	Riffle	Bezzia	782.61	354.999	0.786
Hess	Culvert	Riffle	Boyeria	86.96	35.500	0.707
Hess	Culvert	Riffle	Caenis	869.57	695.652	1.386
Hess	Culvert	Riffle	Cheumatopsyche	2811.59	787.558	0.485
Hess	Culvert	Riffle	Chrysops	86.96	0.000	0.000
Hess	Culvert	Riffle	Cricotopus	1523.85	652.438	0.742
Hess	Culvert	Riffle	Dicranota	391.30	248.499	1.100
Hess	Culvert	Riffle	Dicrotendipes	1373.19	na	na
Hess	Culvert	Riffle	Dubiraphia	347.83	71.000	0.354
Hess	Culvert	Riffle	Elmidae	7304.35	1561.993	0.370
Hess	Culvert	Riffle	Endochironomus	225.54	na	na
Hess	Culvert	Riffle	Ephemera	43.48	na	na
Hess	Culvert	Riffle	Erpobdellidae	43.48	na	na
Hess	Culvert	Riffle	Eukiefferiella	1022.64	98.364	0.167
Hess	Culvert	Riffle	Ferrissia	5884.06	2750.418	0.810
Hess	Culvert	Riffle	Gomphidae	86.96	0.000	0.000
Hess	Culvert	Riffle	Helicopsyche	239.13	124.249	0.900
Hess	Culvert	Riffle	Hemerodromia	130.43	35.500	0.471
Hess	Culvert	Riffle	Hexatoma	86.96	na	na
Hess	Culvert	Riffle	Hydrophilidae	86.96	na	na
Hess	Culvert	Riffle	Hydropsyche	637.68	466.478	1.267
Hess	Culvert	Riffle	Hydropsychidae	260.87	na	na
Hess	Culvert	Riffle	Larsia	798.61	289.386	0.628
Hess	Culvert	Riffle	Limnephilidae	217.39	na	na
Hess	Culvert	Riffle	Lopescladius	225.54	na	na
Hess	Culvert	Riffle	Micropsectra	1143.12	na	na
Hess	Culvert	Riffle	Microtendipes	1373.19	na	na
Hess	Culvert	Riffle	Nematoda	391.30	175.715	0.778
Hess	Culvert	Riffle	Oligochaeta	6188.41	3059.619	0.856

Appendix 1 (cont).

Gear	**Site**	**Habitat**	**Taxa**	**Abundance (#/m^2)**	**SE**	**CV**
Hess	Culvert	Riffle	Ophiogomphus	43.48	na	na
Hess	Culvert	Riffle	Optioservus	15188.41	9002.567	1.027
Hess	Culvert	Riffle	Paragnetina	130.43	na	na
Hess	Culvert	Riffle	Paraleptophlebia	1695.65	1100.495	1.124
Hess	Culvert	Riffle	Parametriocnemus	1413.50	687.440	0.842
Hess	Culvert	Riffle	Paratanytarsus	686.59	na	na
Hess	Culvert	Riffle	Paratendipes	686.59	na	na
Hess	Culvert	Riffle	Perlidae	173.91	na	na
Hess	Culvert	Riffle	Physella	173.91	0.000	0.000
Hess	Culvert	Riffle	Plecoptera	1797.10	853.966	0.823
Hess	Culvert	Riffle	Polypedilum	1064.31	204.903	0.333
Hess	Culvert	Riffle	Procladius	225.54	na	na
Hess	Culvert	Riffle	Pseudolimnophila	173.91	na	na
Hess	Culvert	Riffle	Psychomyia	434.78	283.999	1.131
Hess	Culvert	Riffle	Rheotanytarsus	686.59	na	na
Hess	Culvert	Riffle	Sialis	152.17	88.750	1.010
Hess	Culvert	Riffle	Simulium	695.65	437.672	1.090
Hess	Culvert	Riffle	Sphaeriidae	260.87	na	na
Hess	Culvert	Riffle	Stempellina	571.56	na	na
Hess	Culvert	Riffle	Stempellinella	2476.15	1076.053	0.753
Hess	Culvert	Riffle	Stenelmis	884.06	142.737	0.280
Hess	Culvert	Riffle	Stenonema	478.26	106.500	0.386
Hess	Culvert	Riffle	Tanypus	624.09	42.896	0.119
Hess	Culvert	Riffle	Tanytarsus	9709.54	3656.982	0.652
Hess	Culvert	Riffle	Thienemannimyia	2054.95	1034.647	0.872
Hess	Culvert	Riffle	Trichoptera	86.96	0.000	0.000
Hess	Culvert	Riffle	Zavrelimyia	1672.40	537.005	0.556
Hess	Fishtrap	Riffle	Ablabesmyia	345.11	na	na
Hess	Fishtrap	Riffle	Acari	3782.61	739.557	0.339
Hess	Fishtrap	Riffle	Acroneuria	152.17	17.750	0.202
Hess	Fishtrap	Riffle	Antocha	202.90	101.449	0.866
Hess	Fishtrap	Riffle	Baetis	152.17	17.750	0.202
Hess	Fishtrap	Riffle	Bezzia	86.96	na	na
Hess	Fishtrap	Riffle	Caenis	1260.87	230.065	0.316
Hess	Fishtrap	Riffle	Cardiocladius	157.61	na	na
Hess	Fishtrap	Riffle	Cheumatopsyche	565.22	239.460	0.734
Hess	Fishtrap	Riffle	Chimarra	43.48	0.000	0.000
Hess	Fishtrap	Riffle	Cladotanytarsus	423.91	217.437	0.888
Hess	Fishtrap	Riffle	Corynoneura	345.11	na	na
Hess	Fishtrap	Riffle	Cricotopus	461.05	216.565	0.814
Hess	Fishtrap	Riffle	Cryptochironomus	345.11	na	na
Hess	Fishtrap	Riffle	Dicrotendipes	1217.39	656.155	0.934
Hess	Fishtrap	Riffle	Elmidae	782.61	na	na
Hess	Fishtrap	Riffle	Ephemeroptera	673.91	53.250	0.137
Hess	Fishtrap	Riffle	Eukiefferiella	146.74	na	na

Appendix 1 (cont).

Gear	Site	Habitat	Taxa	Abundance (#/m^2)	SE	CV
Hess	Fishtrap	Riffle	Eurylophella	43.48	na	na
Hess	Fishtrap	Riffle	Ferrissia	86.96	na	na
Hess	Fishtrap	Riffle	Glossosoma	43.48	na	na
Hess	Fishtrap	Riffle	Gomphidae	144.93	14.493	0.173
Hess	Fishtrap	Riffle	Helicopsyche	666.67	188.406	0.489
Hess	Fishtrap	Riffle	Hemerodromia	130.43	na	na
Hess	Fishtrap	Riffle	Hexatoma	43.48	na	na
Hess	Fishtrap	Riffle	Hydropsyche	637.68	233.239	0.634
Hess	Fishtrap	Riffle	Hydroptila	65.22	17.750	0.471
Hess	Fishtrap	Riffle	Isonychia	43.48	0.000	0.000
Hess	Fishtrap	Riffle	Leptoceridae	43.48	na	na
Hess	Fishtrap	Riffle	Limnephilidae	43.48	na	na
Hess	Fishtrap	Riffle	Lopescladius	345.11	na	na
Hess	Fishtrap	Riffle	Microtendipes	534.42	78.465	0.254
Hess	Fishtrap	Riffle	Nematoda	173.91	0.000	0.000
Hess	Fishtrap	Riffle	Oecetis	898.55	247.652	0.477
Hess	Fishtrap	Riffle	Oligochaeta	710.14	623.694	1.521
Hess	Fishtrap	Riffle	Optioservus	652.17	156.763	0.416
Hess	Fishtrap	Riffle	Parametriocnemus	423.91	217.437	0.888
Hess	Fishtrap	Riffle	Physella	65.22	17.750	0.471
Hess	Fishtrap	Riffle	Plecoptera	282.61	124.249	0.761
Hess	Fishtrap	Riffle	Polycentropus	43.48	na	na
Hess	Fishtrap	Riffle	Polypedilum	146.74	na	na
Hess	Fishtrap	Riffle	Pseudocloeon	43.48	0.000	0.000
Hess	Fishtrap	Riffle	Rheotanytarsus	692.03	145.909	0.365
Hess	Fishtrap	Riffle	Stempellina	4122.28	1609.460	0.676
Hess	Fishtrap	Riffle	Stempellinella	694.75	208.788	0.521
Hess	Fishtrap	Riffle	Stenelmis	231.88	88.156	0.658
Hess	Fishtrap	Riffle	Stenonema	318.84	167.139	0.908
Hess	Fishtrap	Riffle	Tanypus	345.11	na	na
Hess	Fishtrap	Riffle	Tanytarsus	1214.67	608.880	0.868
Hess	Fishtrap	Riffle	Thienemannimyia	245.92	80.984	0.570
Hess	Fishtrap	Riffle	Trichoptera	478.26	106.500	0.386
Hess	Shilhon	Riffle	Acari	3362.32	751.949	0.387
Hess	Shilhon	Riffle	Acroneuria	173.91	106.500	1.061
Hess	Shilhon	Riffle	Antocha	65.22	17.750	0.471
Hess	Shilhon	Riffle	Baetidae	666.67	76.688	0.199
Hess	Shilhon	Riffle	Baetis	115.94	28.986	0.433
Hess	Shilhon	Riffle	Bezzia	347.83	na	na
Hess	Shilhon	Riffle	Boyeria	43.48	na	na
Hess	Shilhon	Riffle	Caenis	826.09	109.418	0.229
Hess	Shilhon	Riffle	Cheumatopsyche	2782.61	1094.179	0.681
Hess	Shilhon	Riffle	Chimarra	43.48	na	na
Hess	Shilhon	Riffle	Cladotanytarsus	412.14	na	na
Hess	Shilhon	Riffle	Cricotopus	2817.33	214.523	0.132

Appendix 1 (cont).

Gear	Site	Habitat	Taxa	Abundance (#/m^2)	SE	CV
Hess	Shilhon	Riffle	Cryptochironomus	412.14	na	na
Hess	Shilhon	Riffle	Curculionidae	43.48	na	na
Hess	Shilhon	Riffle	Dicranota	86.96	na	na
Hess	Shilhon	Riffle	Dicrotendipes	1648.55	na	na
Hess	Shilhon	Riffle	Ephemerellidae	86.96	na	na
Hess	Shilhon	Riffle	Ephemeroptera	782.61	na	na
Hess	Shilhon	Riffle	Erpobdellidae	86.96	na	na
Hess	Shilhon	Riffle	Ferrissia	202.90	115.942	0.990
Hess	Shilhon	Riffle	Gomphidae	1101.45	331.438	0.521
Hess	Shilhon	Riffle	Helicopsyche	130.43	na	na
Hess	Shilhon	Riffle	Hemerodromia	43.48	na	na
Hess	Shilhon	Riffle	Heptageniidae	2971.01	1278.570	0.745
Hess	Shilhon	Riffle	Hexatoma	86.96	0.000	0.000
Hess	Shilhon	Riffle	Hydropsyche	782.61	301.226	0.667
Hess	Shilhon	Riffle	Hydropsychidae	753.62	370.062	0.851
Hess	Shilhon	Riffle	Hydroptila	43.48	na	na
Hess	Shilhon	Riffle	Isonychia	3239.13	1721.743	0.921
Hess	Shilhon	Riffle	Laevapex	43.48	na	na
Hess	Shilhon	Riffle	Larsia	642.21	na	na
Hess	Shilhon	Riffle	Lepidostoma	1695.65	na	na
Hess	Shilhon	Riffle	Leucrocuta	1289.86	471.182	0.633
Hess	Shilhon	Riffle	Lopescladius	692.03	na	na
Hess	Shilhon	Riffle	Microtendipes	667.12	20.338	0.053
Hess	Shilhon	Riffle	Nanocladius	642.21	na	na
Hess	Shilhon	Riffle	Nematoda	681.16	355.294	0.903
Hess	Shilhon	Riffle	Nyctiophylax	86.96	na	na
Hess	Shilhon	Riffle	Oecetis	884.06	365.781	0.717
Hess	Shilhon	Riffle	Oligochaeta	1420.29	642.112	0.783
Hess	Shilhon	Riffle	Ophiogomphus	152.17	17.750	0.202
Hess	Shilhon	Riffle	Optioservus	717.39	337.249	0.814
Hess	Shilhon	Riffle	Parametriocnemus	812.80	293.248	0.625
Hess	Shilhon	Riffle	Paratendipes	642.21	na	na
Hess	Shilhon	Riffle	Phaenopsectra	692.03	na	na
Hess	Shilhon	Riffle	Polycentropus	86.96	na	na
Hess	Shilhon	Riffle	Polypedilum	1705.16	867.897	0.882
Hess	Shilhon	Riffle	Procladius	692.03	na	na
Hess	Shilhon	Riffle	Pseudocloeon	202.90	63.172	0.539
Hess	Shilhon	Riffle	Psychomyia	101.45	38.344	0.655
Hess	Shilhon	Riffle	Rheotanytarsus	1455.01	623.596	0.742
Hess	Shilhon	Riffle	Stempellina	14057.97	2946.283	0.363
Hess	Shilhon	Riffle	Stempellinella	1548.91	633.275	0.708
Hess	Shilhon	Riffle	Stenelmis	434.78	260.870	1.039
Hess	Shilhon	Riffle	Synorthocladius	692.03	na	na
Hess	Shilhon	Riffle	Tanytarsus	3518.57	517.336	0.255
Hess	Shilhon	Riffle	Thienemanniella	1284.42	na	na

Appendix 1 (cont).

Gear	**Site**	**Habitat**	**Taxa**	**Abundance (#/m^2)**	**SE**	**CV**
Hess	Shilhon	Riffle	Thienemannimyia	758.15	53.989	0.123
Hess	Shilhon	Riffle	Tipulidae	695.65	na	na
Hess	Shilhon	Riffle	Trichoptera	420.29	185.031	0.763
Hess	Shilhon	Riffle	Tricorythodes	173.91	na	na
Core	Stanley	Pool	Acari	518.52	74.074	0.247
Core	Stanley	Pool	Baetidae	222.22	na	na
Core	Stanley	Pool	Caenis	2370.37	296.296	0.217
Core	Stanley	Pool	Calopterygidae	222.22	na	na
Core	Stanley	Pool	Cladotanytarsus	7828.46	955.055	0.211
Core	Stanley	Pool	Corixidae	222.22	na	na
Core	Stanley	Pool	Cricotopus	611.11	na	na
Core	Stanley	Pool	Cryptochironomus	1135.96	428.541	0.653
Core	Stanley	Pool	Cryptotendipes	859.16	202.533	0.408
Core	Stanley	Pool	Dubiraphia	666.67	181.444	0.471
Core	Stanley	Pool	Ephemeroptera	888.89	na	na
Core	Stanley	Pool	Eurylophella	222.22	na	na
Core	Stanley	Pool	Ferrissia	444.44	na	na
Core	Stanley	Pool	Larsia	553.61	na	na
Core	Stanley	Pool	Leptoceridae	888.89	na	na
Core	Stanley	Pool	Lopescladius	796.30	na	na
Core	Stanley	Pool	Microcricotopus	1222.22	na	na
Core	Stanley	Pool	Mystacides	444.44	na	na
Core	Stanley	Pool	Nematoda	740.74	74.074	0.173
Core	Stanley	Pool	Oligochaeta	555.56	272.166	0.849
Core	Stanley	Pool	Optioservus	444.44	na	na
Core	Stanley	Pool	Pagastiella	11493.50	3249.657	0.490
Core	Stanley	Pool	Paracladopelma	674.95	99.078	0.254
Core	Stanley	Pool	Paratendipes	553.61	na	na
Core	Stanley	Pool	Probezzia	777.78	272.166	0.606
Core	Stanley	Pool	Procladius	611.11	na	na
Core	Stanley	Pool	Pseudochironomus	4982.46	na	na
Core	Stanley	Pool	Saetheria	1307.34	146.438	0.194
Core	Stanley	Pool	Stempellina	1388.24	536.264	0.669
Core	Stanley	Pool	Stempellinella	1022.74	323.486	0.548
Core	Stanley	Pool	Stenonema	444.44	na	na
Core	Stanley	Pool	Stictochironomus	3518.52	378.008	0.186
Core	Stanley	Pool	Tanytarsus	1838.21	674.307	0.635
Core	Stanley	Pool	Zavrelimyia	2768.03	na	na
Hess	Stanley	Riffle	Acari	5246.38	1807.415	0.597
Hess	Stanley	Riffle	Acroneuria	652.17	106.500	0.283
Hess	Stanley	Riffle	Antocha	4043.48	1281.933	0.549
Hess	Stanley	Riffle	Baetidae	1608.70	816.497	0.879
Hess	Stanley	Riffle	Baetis	43.48	na	na
Hess	Stanley	Riffle	Boyeria	43.48	na	na

Appendix 1 (cont).

Gear	Site	Habitat	Taxa	Abundance (#/m^2)	SE	CV
Hess	Stanley	Riffle	Caecidotea	173.91	na	na
Hess	Stanley	Riffle	Caenis	347.83	na	na
Hess	Stanley	Riffle	Calopterygidae	173.91	na	na
Hess	Stanley	Riffle	Cheumatopsyche	35797.10	14774.344	0.715
Hess	Stanley	Riffle	Cladotanytarsus	2285.33	na	na
Hess	Stanley	Riffle	Cricotopus	7284.76	1724.022	0.410
Hess	Stanley	Riffle	Empididae	173.91	na	na
Hess	Stanley	Riffle	Ephemeroptera	2608.70	851.996	0.566
Hess	Stanley	Riffle	Eukiefferiella	5687.50	911.902	0.278
Hess	Stanley	Riffle	Ferrissia	3594.20	1480.249	0.713
Hess	Stanley	Riffle	Glossosoma	43.48	na	na
Hess	Stanley	Riffle	Gomphidae	13768.12	5725.518	0.720
Hess	Stanley	Riffle	Helicopsyche	173.91	na	na
Hess	Stanley	Riffle	Helisoma	43.48	na	na
Hess	Stanley	Riffle	Hemerodromia	717.39	550.248	1.329
Hess	Stanley	Riffle	Heptageniidae	521.74	na	na
Hess	Stanley	Riffle	Hydropsyche	9989.13	7381.818	1.280
Hess	Stanley	Riffle	Hydropsychidae	6608.70	2981.988	0.782
Hess	Stanley	Riffle	Hydroptilidae	173.91	0.000	0.000
Hess	Stanley	Riffle	Isonychia	478.26	212.999	0.771
Hess	Stanley	Riffle	Larsia	969.42	134.430	0.240
Hess	Stanley	Riffle	Lepidostoma	1217.39	na	na
Hess	Stanley	Riffle	Leptophlebiidae	3884.06	1030.515	0.460
Hess	Stanley	Riffle	Lopescladius	3889.14	813.925	0.362
Hess	Stanley	Riffle	Nematoda	695.65	265.657	0.661
Hess	Stanley	Riffle	Nigronia	369.57	17.750	0.083
Hess	Stanley	Riffle	Oecetis	173.91	na	na
Hess	Stanley	Riffle	Oligochaeta	2753.62	942.029	0.593
Hess	Stanley	Riffle	Ophiogomphus	985.51	276.504	0.486
Hess	Stanley	Riffle	Optioservus	8681.16	1581.703	0.316
Hess	Stanley	Riffle	Parametriocnemus	1134.06	na	na
Hess	Stanley	Riffle	Physella	173.91	na	na
Hess	Stanley	Riffle	Plecoptera	1565.22	100.409	0.111
Hess	Stanley	Riffle	Polycentropodidae	347.83	na	na
Hess	Stanley	Riffle	Polycentropus	173.91	na	na
Hess	Stanley	Riffle	Polypedilum	3194.12	861.103	0.467
Hess	Stanley	Riffle	Psychomyia	695.65	425.998	1.061
Hess	Stanley	Riffle	Rheotanytarsus	15769.13	6209.969	0.682
Hess	Stanley	Riffle	Simulium	695.65	na	na
Hess	Stanley	Riffle	Sphaeriidae	43.48	na	na
Hess	Stanley	Riffle	Stempellina	1944.57	406.963	0.362
Hess	Stanley	Riffle	Stempellinella	3620.88	694.555	0.332
Hess	Stanley	Riffle	Stenonema	4695.65	1987.992	0.733
Hess	Stanley	Riffle	Stratiomyidae	43.48	na	na
Hess	Stanley	Riffle	Tanypus	1609.55	na	na

Appendix 1 (cont).

Gear	**Site**	**Habitat**	**Taxa**	**Abundance (#/m^2)**	**SE**	**CV**
Hess	Stanley	Riffle	Tanytarsus	26196.43	14329.938	0.947
Hess	Stanley	Riffle	Thienemannimyia	1134.06	na	na
Hess	Stanley	Riffle	Trichoptera	2333.33	1368.549	1.016
Hess	Stanley	Riffle	Turbellaria	521.74	141.999	0.471

Appendix 2. Mean number of taxa occurring in stream habitats sampled qualitatively at each sampling location.

Type	Site	Habitat	Taxa	Mean Count
Dnet	Airport	Bank	Brachycentrus	1.00
Dnet	Airport	Bank	Calopteryx	2.00
Dnet	Airport	Bank	Cladotanytarsus	2.33
Dnet	Airport	Bank	Corynoneura	2.33
Dnet	Airport	Bank	Cricotopus	2.33
Dnet	Airport	Bank	Curculionidae	2.00
Dnet	Airport	Bank	Ferrissia	2.00
Dnet	Airport	Bank	Leptophlebiidae	2.00
Dnet	Airport	Bank	Nematoda	2.00
Dnet	Airport	Bank	Oecetis	2.00
Dnet	Airport	Bank	Oligochaeta	10.00
Dnet	Airport	Bank	Ophiogomphus	1.00
Dnet	Airport	Bank	Optioservus	2.00
Dnet	Airport	Bank	Paratendipes	2.33
Dnet	Airport	Bank	Polypedilum	14.00
Dnet	Airport	Bank	Pycnopsyche	2.00
Dnet	Airport	Bank	Rheotanytarsus	7.00
Dnet	Airport	Bank	Sphaeriidae	12.00
Dnet	Airport	Bank	Stempellinella	11.67
Dnet	Airport	Bank	Tanytarsus	4.67
Dnet	Airport	Bank	Thienemanniella	2.33
Dnet	Airport	Bank	Trichoptera	6.00
Dnet	Airport	Wood	Acari	4.00
Dnet	Airport	Wood	Antocha	4.00
Dnet	Airport	Wood	Baetidae	4.00
Dnet	Airport	Wood	Bezzia	12.00
Dnet	Airport	Wood	Eukiefferiella	11.79
Dnet	Airport	Wood	Ferrissia	4.00
Dnet	Airport	Wood	Gomphidae	4.00
Dnet	Airport	Wood	Hydropsyche	12.00
Dnet	Airport	Wood	Leptophlebiidae	4.00
Dnet	Airport	Wood	Leuctra	8.00
Dnet	Airport	Wood	Microtendipes	3.93
Dnet	Airport	Wood	Nanocladius	3.93
Dnet	Airport	Wood	Nigronia	12.00
Dnet	Airport	Wood	Oligochaeta	42.00
Dnet	Airport	Wood	Ophiogomphus	1.00
Dnet	Airport	Wood	Optioservus	4.00
Dnet	Airport	Wood	Orthocladius	7.86
Dnet	Airport	Wood	Parametriocnemus	11.79
Dnet	Airport	Wood	Polypedilum	39.29
Dnet	Airport	Wood	Rheotanytarsus	11.79
Dnet	Airport	Wood	Stempellinella	3.93
Dnet	Airport	Wood	Stenochironomus	7.86

Appendix 2 (cont).

Type	Site	Habitat	Taxa	Mean Count
Dnet	Airport	Wood	Stenonema	4.00
Dnet	Airport	Wood	Tanytarsus	3.93
Dnet	Airport	Wood	Thienemannimyia	3.93
Dnet	Airport	Wood	Trichoptera	20.00
Dnet	Culvert	Bank	Acroneuria	1.00
Dnet	Culvert	Bank	Aeshnidae	1.00
Dnet	Culvert	Bank	Calopterygidae	2.00
Dnet	Culvert	Bank	Collembola	12.00
Dnet	Culvert	Bank	Cricotopus	6.58
Dnet	Culvert	Bank	Dicrotendipes	9.88
Dnet	Culvert	Bank	Dixella	2.00
Dnet	Culvert	Bank	Dubiraphia	15.00
Dnet	Culvert	Bank	Ephemerellidae	2.00
Dnet	Culvert	Bank	Hydropsyche	2.00
Dnet	Culvert	Bank	Hygrotus	2.00
Dnet	Culvert	Bank	Larsia	9.88
Dnet	Culvert	Bank	Leptophlebia	8.00
Dnet	Culvert	Bank	Limnephilidae	2.00
Dnet	Culvert	Bank	Microtendipes	3.29
Dnet	Culvert	Bank	Oligochaeta	2.00
Dnet	Culvert	Bank	Paracymus	6.00
Dnet	Culvert	Bank	Paraleptophlebia	1.00
Dnet	Culvert	Bank	Parametriocnemus	3.29
Dnet	Culvert	Bank	Paratanytarsus	13.17
Dnet	Culvert	Bank	Phaenopsectra	6.58
Dnet	Culvert	Bank	Physella	2.00
Dnet	Culvert	Bank	Polypedilum	55.96
Dnet	Culvert	Bank	Pycnopsyche	1.00
Dnet	Culvert	Bank	Rheotanytarsus	6.58
Dnet	Culvert	Bank	Simulium	2.00
Dnet	Culvert	Bank	Stenochironomus	3.29
Dnet	Culvert	Bank	Tanypus	3.29
Dnet	Culvert	Bank	Tanytarsus	36.21
Dnet	Culvert	Bank	Triaenodes	2.00
Dnet	Culvert	Wood/Pool	Ablabesmyia	1.12
Dnet	Culvert	Wood/Pool	Caenis	5.00
Dnet	Culvert	Wood/Pool	Chironomus	1.12
Dnet	Culvert	Wood/Pool	Cladotanytarsus	1.12
Dnet	Culvert	Wood/Pool	Collembola	1.00
Dnet	Culvert	Wood/Pool	Cryptotendipes	1.12
Dnet	Culvert	Wood/Pool	Dicrotendipes	4.49
Dnet	Culvert	Wood/Pool	Dubiraphia	1.00
Dnet	Culvert	Wood/Pool	Eukiefferiella	1.12
Dnet	Culvert	Wood/Pool	Ferrissia	9.00
Dnet	Culvert	Wood/Pool	Glyptotendipes	1.12
Dnet	Culvert	Wood/Pool	Larsia	4.49

Appendix 2 (cont).

Type	Site	Habitat	Taxa	Mean Count
Dnet	Culvert	Wood/Pool	Leptophlebiidae	1.00
Dnet	Culvert	Wood/Pool	Mystacides	3.00
Dnet	Culvert	Wood/Pool	Oligochaeta	1.00
Dnet	Culvert	Wood/Pool	Ophiogomphus	1.00
Dnet	Culvert	Wood/Pool	Paratanytarsus	2.24
Dnet	Culvert	Wood/Pool	Polypedilum	4.49
Dnet	Culvert	Wood/Pool	Sphaeriidae	1.00
Dnet	Culvert	Wood/Pool	Stempellinella	4.49
Dnet	Culvert	Wood/Pool	Stenelmis	1.00
Dnet	Culvert	Wood/Pool	Stenochironomus	3.37
Dnet	Culvert	Wood/Pool	Tanypus	1.12
Dnet	Culvert	Wood/Pool	Tanytarsus	7.85
Dnet	Culvert	Wood/Pool	Thienemannimyia	6.73
Dnet	Fishtrap	Bank	Baetis	4.00
Dnet	Fishtrap	Bank	Caenis	1.00
Dnet	Fishtrap	Bank	Dubiraphia	1.00
Dnet	Fishtrap	Bank	Oligochaeta	1.00
Dnet	Fishtrap	Bank	Parachironomus	1.12
Dnet	Fishtrap	Bank	Polypedilum	13.41
Dnet	Fishtrap	Bank	Pseudocloeon	4.00
Dnet	Fishtrap	Bank	Rheotanytarsus	1.12
Dnet	Fishtrap	Bank	Simulium	2.00
Dnet	Fishtrap	Bank	Stenelmis	2.00
Dnet	Fishtrap	Bank	Tanytarsus	1.12
Dnet	Fishtrap	Bank	Thienemanniella	2.24
Dnet	Fishtrap	Wood	Cricotopus	3.00
Dnet	Fishtrap	Wood	Dicrotendipes	1.00
Dnet	Fishtrap	Wood	Dubiraphia	4.00
Dnet	Fishtrap	Wood	Eukiefferiella	1.00
Dnet	Fishtrap	Wood	Helicopsyche	1.00
Dnet	Fishtrap	Wood	Heptageniidae	1.00
Dnet	Fishtrap	Wood	Physella	2.00
Dnet	Fishtrap	Wood	Polypedilum	2.00
Dnet	Fishtrap	Wood	Pseudocloeon	1.00
Dnet	Fishtrap	Wood	Rheotanytarsus	4.00
Dnet	Fishtrap	Wood	Stenelmis	1.00
Dnet	Fishtrap	Wood	Stenochironomus	1.00
Dnet	Fishtrap	Wood	Tanytarsus	1.00
Dnet	Fishtrap	Wood	Thienemanniella	1.00
Dnet	Shilhon	Riffle	Acari	2.00
Dnet	Shilhon	Riffle	Acroneuria	1.00
Dnet	Shilhon	Riffle	Baetidae	10.00
Dnet	Shilhon	Riffle	Baetis	2.00
Dnet	Shilhon	Riffle	Caenis	4.00
Dnet	Shilhon	Riffle	Cheumatopsyche	43.00
Dnet	Shilhon	Riffle	Chimarra	4.00

Appendix 2 (cont).

Type	Site	Habitat	Taxa	Mean Count
Dnet	Shilhon	Riffle	Cricotopus	3.27
Dnet	Shilhon	Riffle	Empididae	2.00
Dnet	Shilhon	Riffle	Erpobdellidae	2.00
Dnet	Shilhon	Riffle	Eukiefferiella	6.54
Dnet	Shilhon	Riffle	Gomphidae	3.00
Dnet	Shilhon	Riffle	Helicopsyche	6.00
Dnet	Shilhon	Riffle	Heptageniidae	2.00
Dnet	Shilhon	Riffle	Hexatoma	2.00
Dnet	Shilhon	Riffle	Hydropsyche	32.00
Dnet	Shilhon	Riffle	Isonychia	15.00
Dnet	Shilhon	Riffle	Nematoda	2.00
Dnet	Shilhon	Riffle	Oecetis	2.00
Dnet	Shilhon	Riffle	Oligochaeta	15.00
Dnet	Shilhon	Riffle	Optioservus	12.00
Dnet	Shilhon	Riffle	Physella	2.00
Dnet	Shilhon	Riffle	Polypedilum	81.77
Dnet	Shilhon	Riffle	Pseudocloeon	10.00
Dnet	Shilhon	Riffle	Rheotanytarsus	26.17
Dnet	Shilhon	Riffle	Simulium	2.00
Dnet	Shilhon	Riffle	Stempellina	16.35
Dnet	Shilhon	Riffle	Stenelmis	13.00
Dnet	Shilhon	Riffle	Tanytarsus	19.63
Dnet	Shilhon	Riffle	Thienemannimyia	3.27
Dnet	Shilhon	Riffle	Trichoptera	2.00
Dnet	Shilhon	Run	Acari	4.00
Dnet	Shilhon	Run	Caenis	14.00
Dnet	Shilhon	Run	Cheumatopsyche	3.00
Dnet	Shilhon	Run	Cladotanytarsus	6.13
Dnet	Shilhon	Run	Cryptochironomus	3.06
Dnet	Shilhon	Run	Didymops	2.00
Dnet	Shilhon	Run	Eukiefferiella	3.06
Dnet	Shilhon	Run	Ferrissia	2.00
Dnet	Shilhon	Run	Gomphidae	5.00
Dnet	Shilhon	Run	Hexatoma	2.00
Dnet	Shilhon	Run	Hydrophilidae	4.00
Dnet	Shilhon	Run	Hydropsyche	1.00
Dnet	Shilhon	Run	Isonychia	2.00
Dnet	Shilhon	Run	Larsia	3.06
Dnet	Shilhon	Run	Leucrocuta	14.00
Dnet	Shilhon	Run	Macronychus	2.00
Dnet	Shilhon	Run	Microtendipes	3.06
Dnet	Shilhon	Run	Mystacides	1.00
Dnet	Shilhon	Run	Oecetis	8.00
Dnet	Shilhon	Run	Ophiogomphus	2.00
Dnet	Shilhon	Run	Optioservus	8.00
Dnet	Shilhon	Run	Physella	2.00

Appendix 2 (cont).

Type	**Site**	**Habitat**	**Taxa**	**Mean Count**
Dnet	Shilhon	Run	Polypedilum	9.19
Dnet	Shilhon	Run	Rheotanytarsus	36.77
Dnet	Shilhon	Run	Stempellina	6.13
Dnet	Shilhon	Run	Stempellinella	6.13
Dnet	Shilhon	Run	Stenelmis	2.00
Dnet	Shilhon	Run	Tanytarsus	64.34
Dnet	Shilhon	Run	Thienemannimyia	3.06
Dnet	Shilhon	Run	Tricorythodes	3.00
Dnet	Stanley	Bank	Acari	4.00
Dnet	Stanley	Bank	Acroneuria	2.00
Dnet	Stanley	Bank	Baetidae	8.00
Dnet	Stanley	Bank	Brillia	2.03
Dnet	Stanley	Bank	Caenis	12.00
Dnet	Stanley	Bank	Calopteryx	11.00
Dnet	Stanley	Bank	Cheumatopsyche	12.00
Dnet	Stanley	Bank	Cladotanytarsus	2.03
Dnet	Stanley	Bank	Collembola	4.00
Dnet	Stanley	Bank	Corynoneura	2.03
Dnet	Stanley	Bank	Cricotopus	8.11
Dnet	Stanley	Bank	Decapoda	2.00
Dnet	Stanley	Bank	Dubiraphia	4.00
Dnet	Stanley	Bank	Eukiefferiella	2.03
Dnet	Stanley	Bank	Glossiphoniidae	59.00
Dnet	Stanley	Bank	Gomphidae	4.00
Dnet	Stanley	Bank	Helisoma	2.00
Dnet	Stanley	Bank	Hydropsyche	4.00
Dnet	Stanley	Bank	Lepidoptera	2.00
Dnet	Stanley	Bank	Leptophlebiidae	2.00
Dnet	Stanley	Bank	Oecetis	2.00
Dnet	Stanley	Bank	Oligochaeta	8.00
Dnet	Stanley	Bank	Ophiogomphus	2.00
Dnet	Stanley	Bank	Optioservus	8.00
Dnet	Stanley	Bank	Oxyethira	2.00
Dnet	Stanley	Bank	Pagastiella	2.03
Dnet	Stanley	Bank	Physella	7.00
Dnet	Stanley	Bank	Plecoptera	2.00
Dnet	Stanley	Bank	Polypedilum	16.22
Dnet	Stanley	Bank	Pycnopsyche	12.00
Dnet	Stanley	Bank	Rhagovelia	4.00
Dnet	Stanley	Bank	Rheotanytarsus	12.17
Dnet	Stanley	Bank	Simulium	6.00
Dnet	Stanley	Bank	Sphaeriidae	5.00
Dnet	Stanley	Bank	Stempellina	6.08
Dnet	Stanley	Bank	Stenonema	4.00
Dnet	Stanley	Bank	Tanytarsus	20.28
Dnet	Stanley	Bank	Tricorythodes	2.00

Appendix 2 (cont).

Type	Site	Habitat	Taxa	Mean Count
Dnet	Stanley	Riff/Run	Acari	30.00
Dnet	Stanley	Riff/Run	Acroneuria	2.00
Dnet	Stanley	Riff/Run	Antocha	4.00
Dnet	Stanley	Riff/Run	Atherix	2.00
Dnet	Stanley	Riff/Run	Baetis	24.00
Dnet	Stanley	Riff/Run	Boyeria	2.00
Dnet	Stanley	Riff/Run	Caenis	4.00
Dnet	Stanley	Riff/Run	Ceraclea	2.00
Dnet	Stanley	Riff/Run	Cheumatopsyche	32.00
Dnet	Stanley	Riff/Run	Cladotanytarsus	9.15
Dnet	Stanley	Riff/Run	Corynoneura	9.15
Dnet	Stanley	Riff/Run	Cricotopus	18.29
Dnet	Stanley	Riff/Run	Cryptochironomus	9.15
Dnet	Stanley	Riff/Run	Ferrissia	16.00
Dnet	Stanley	Riff/Run	Gomphidae	108.00
Dnet	Stanley	Riff/Run	Helichus	2.00
Dnet	Stanley	Riff/Run	Hexatoma	6.00
Dnet	Stanley	Riff/Run	Hydropsyche	20.00
Dnet	Stanley	Riff/Run	Hydroptilidae	4.00
Dnet	Stanley	Riff/Run	Leptophlebia	14.00
Dnet	Stanley	Riff/Run	Lopescladius	18.29
Dnet	Stanley	Riff/Run	Microtendipes	9.15
Dnet	Stanley	Riff/Run	Monodiamesa	9.15
Dnet	Stanley	Riff/Run	Oecetis	10.00
Dnet	Stanley	Riff/Run	Oligochaeta	52.00
Dnet	Stanley	Riff/Run	Ophiogomphus	27.00
Dnet	Stanley	Riff/Run	Optioservus	104.00
Dnet	Stanley	Riff/Run	Pagastiella	9.15
Dnet	Stanley	Riff/Run	Parametriocnemus	27.44
Dnet	Stanley	Riff/Run	Physella	12.00
Dnet	Stanley	Riff/Run	Plecoptera	22.00
Dnet	Stanley	Riff/Run	Polypedilum	73.17
Dnet	Stanley	Riff/Run	Pseudocloeon	20.00
Dnet	Stanley	Riff/Run	Rhagovelia	2.00
Dnet	Stanley	Riff/Run	Rheotanytarsus	18.29
Dnet	Stanley	Riff/Run	Simulium	2.00
Dnet	Stanley	Riff/Run	Stempellinella	36.58
Dnet	Stanley	Riff/Run	Stenonema	12.00
Dnet	Stanley	Riff/Run	Tanytarsus	173.77
Dnet	Stanley	Riff/Run	Thienemannimyia	18.29
Dnet	Stanley	Riff/Run	Trichoptera	32.00
Dnet	Stanley	Riff/Run	Turbellaria	12.00

Appendix D: Physical Data

As described in Section 4.4 of the TMDL, limited physical channel measurements were made as part of the original project. Physical stream data was measured at three locations on the Knife River and its tributaries. Data collected included cross-section elevations, channel slope, and pebble counts. The following figures are examples of the physical data collected or interpreted in the original scope of the project from 2004-2006.

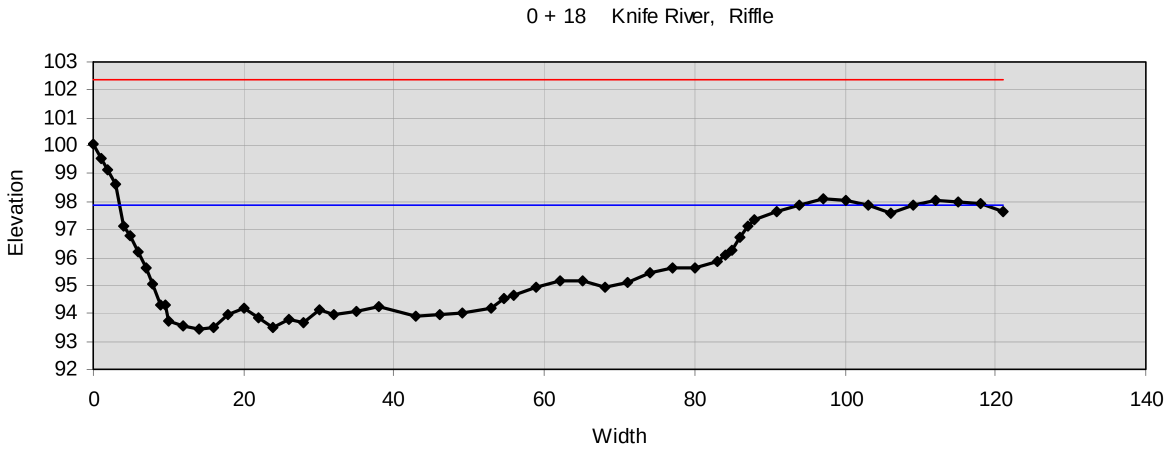


Figure D.1: Typical Knife River cross-section. This particular section is on a failing bank which is a common feature on the Knife River. The left side of the plot is the outside bend and the right side is a gravel/cobble depositional bar.

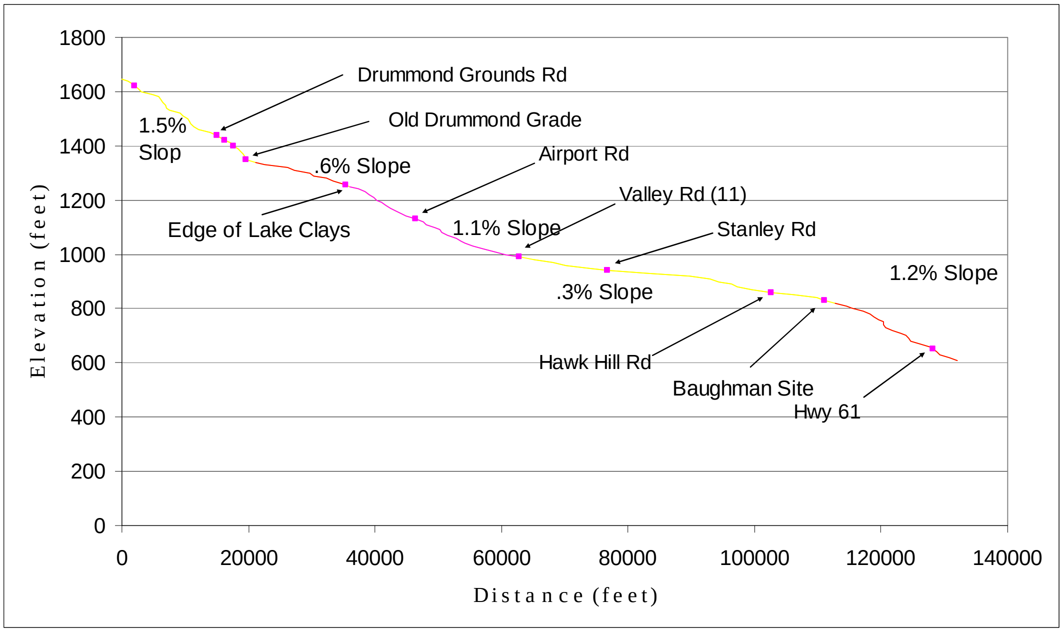
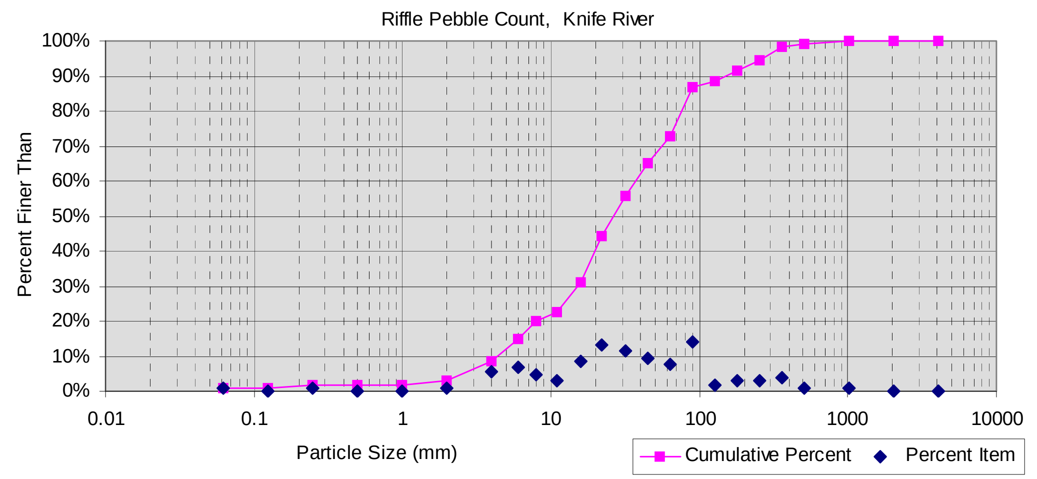


Figure D.2: Profile of mainstem with landmarks and slopes associated as determined by USGS topographical maps.

	Knife River
	Lake Superior Basin
	Downstream of USGS gage near Hwy 61 bridge
Note:	



Size percent less than (mm)					Percent by substrate type					
D16	D35	D50	D84	D95	silt/clay	sand	gravel	cobble	boulder	bedrock
6.341	17.56	26.5	84	272	1%	2%	69%	21%	6%	2%

Figure D.3: Example pebble count sample from Fish Trap site (1 of 6 completed)

Appendix E: Assessment of Streambank and Bluff Erosion in the Knife River Watershed

Assessment of Streambank and Bluff Erosion in the Knife River Watershed

Final Report
Submitted to Minnesota Pollution Control Agency

by

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1. Executive Summary

This report describes a study to assess the potential sources of sediment in the Knife River basin located along the north shore of Lake Superior. The Knife River discharges into Lake Superior just south of the city of Two Harbors. The river was placed on the state impaired waters list in 1998, with the impairment being turbidity caused by suspended sediment. The impaired waters listing led to a TMDL study to assess the sources of sediment transported along the main stem of the Knife River. This study has been ongoing with the South St. Louis County Soil and Water Conservation District (SLC-SWCD) since 2004.

The MPCA contracted with the University of Minnesota to perform an analysis related to the source of sediment and transport of sediment in the Knife River. The objective of the study was to apply selected models of streambank and stream bluff erosion to help to identify and possibly quantify the potential sources of sediment. The models used in the study for quantifying streambank sources of sediment included the Rosgen's BEHI-NBS model, and the USDA-ARS CONCEPTS model. The model used to quantify erosion from stream bluffs was the SEDIMOT II model.

While some flow, sediment, and river cross-section data for the Knife River were available from the SLC-SWCD, the application of the BEHI and CONCEPTS models required more detailed information about the river channel than was available from the TMDL study. Thus, a number of stream cross-sections, and bluff geometry measurements were made in the field. Bluff geometry and river meandering information was also acquired from digital orthoquads. During field surveys samples of bank material, bluff material, and channel bed material were collected to facilitate the characterization of sediment source materials.

Flow and sediment data were available at the downstream gaging station for a number of runoff producing events for the river. Three events were selected for analysis with the models and model predictions of sediment loads derived for those three events were than compared to the measured sediment loads. The events represented fairly frequent runoff producing events, all having estimated return periods less than one year.

The modeling required the development of data about the numerous catchments contributing runoff to the main stem of the Knife River. The data developed included catchment area, soil conditions, channel slope, and channel length. These data were then used to quantify the sediment entering the main channel by scaling (based on watershed area) the measured data available from one of the tributaries. The modeling also required the development of a methodology to interpolate channel cross-sections between measured cross-sections. A total of 20 cross-sections were measured along the main stem by the U of M, and an additional five cross-sections were available from data collected by the SLC-SWCD. An automated procedure was developed because of the large number of channel cross-sections needed by the CONCEPTS model; doing the interpolation manually would have required far too much labor. The automated procedure accounted for watershed contributing area effect on bankfull cross-sectional area, and also thalweg depth at bends in the channel.

Scores to be used with the BEHI-NBS model were generated using information generated for the CONCEPTS model. The BEHI scores generated in this way were compared to those quantified for each of the measured cross-sections. The comparisons were very favorably agreeable. The calibration relation for conversion from BEHI scores to actual bank erosion is not available for the upper Midwest region. Instead, a relation derived for Colorado streams was used. Additional work will be needed to develop such a calibration for streams in Minnesota.

The modeling of erosion from identified bluffs required the estimation of bluff surface area, bluff height, bluff slope angle, the length of exposed bluff surfaces, and the erodibility of bluff materials. The SEDIMOT II model calculates erosion using the modified universal soil loss equation (MUSLE). Possible mass wasting of bluff surfaces was not accounted for in this study. The amount of vegetation on the bluff was taken into account in the analysis of erosion calculation.

The observed total sediment load in the channel for the three storms was measured at the Fish Trap gaging station located near the mouth of the Knife River. The proportions of the sediment originating from streambanks, from bluff areas, and the tributaries were estimated using the CONCEPTS and the SEDIMOT II models. The totals for these estimated sources showed values that might be considered to be in reasonable agreement with the observed loads for each storm. The predicted sediment loads were 563, 161 and 53 tons for storms 1, 2 and 3 respectively, while the observed loads for the corresponding storms were 881, 131 and 30 tons. The model results indicated that the sources of the sediments were mostly from the streambanks, followed by the contributions from bluffs, and finally followed by the tributary areas. For the total from all three storms the models estimated that 59% to be from streambanks, 29% to be from bluffs, and 12 % to be from the tributary areas.

2. Introduction

The Knife River (USGS designations: Latitude 46°56'49", Longitude 91°47'32", Hydrologic Unit 04010102) drains an area of 83.6 sq. miles along the north shore of Lake Superior. It is contained in Lake and St. Louis Counties with about half the drainage coming from each of these counties. The river discharges into Lake Superior along the north shore of the lake to the southwest of Two Harbors. An illustrative map of the site was collected from the USGS website and is presented in Figure 1.

The USGS record for the Knife River extends from July 1974 until the present. For that period of time the following flow statistics were determined:

Largest annual peak flow = 9,100 cfs
Smallest annual peak flow = 1,410 cfs
Mean annual peak flow = 3,147 cfs
Mean annual daily discharge = 90.6 cfs = 0.04 in/day = 14.71 inches/year

Viewing Figure 1 it is clear that the main stem of the Knife River flows nearly parallel with the north shore of Lake Superior until it directs itself into the lake southwest of Two Harbors. There are four or five major tributaries contributing to the main stem, and some of these tributaries are branched. These tributaries are oriented in a direction perpendicular to the orientation of the north shore of Lake Superior. The tributaries begin on fairly mild slopes but quickly gain slope as they approach the main stem. This condition provides for opportunities for potential sediment production in erodible bed and streambank materials.

Water quality data were collected at this site by the USGS for only one date, September 25, 1974. That sampling included many water quality parameters, but not sediment. However, in recent years, flow data and sediment data have been collected by the MPCA and the SLC-SWCD, and based on the turbidity data it has been determined that the lower part of the Knife River is impaired for turbidity.

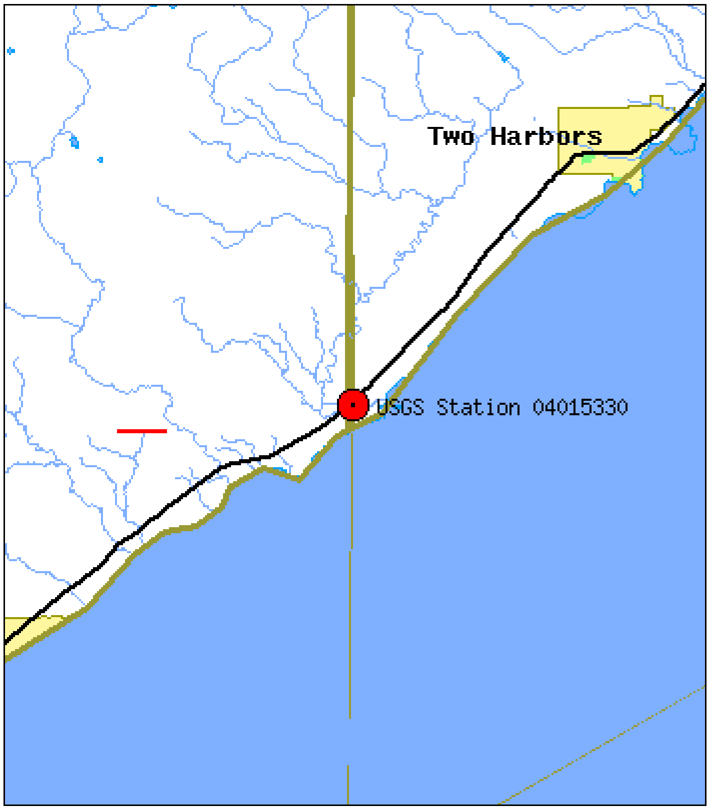


Figure 1. Map of the location for the USGS gage for the Knife River near Two Harbors.

Questions then arise as to the sources of the sediment transported to down the Knife River to Lake Superior. Identification of sediment sources and quantification of the magnitude of sediment generated from those sources is necessary to assess possible measures to reduce the sediment transported by the river. In May of 2007, the U of M TMDL team was contracted by the MPCA to perform a sediment modeling study for the main stem of the Knife River. The study involved the acquisition of sediment and flow data from the SLC-SWCD, performance of surveys of the main stem of the river to collect geomorphic data including cross-section geometry and longitudinal slope, bed sediment characteristics, and physical properties of streambanks, and application of three models for prediction of sediment production and transport. Due to the short time frame for the project, May 15 to September 30, the objective set for the project was to acquire the data required for the selected sediment production models, test the selected sediment production models and to provide an assessment of the potential sources of sediment. Presumably the work and results described in this report will provide the background data and model testing needed for a later follow-up project.

The models used in this study were: (1) The CONCEPTS model; (2) The Rosgen BEHI model; and (3) The SEDIMOT II model. The CONCEPTS and BEHI models are both used for modeling erosion of streambanks. The SEDIMOT II model was not on the original list of models to be tested, but was added during the project because of the need to estimate erosion from the exposed surfaces of bluffs present along the main stem. Originally it was intended that the BSTEM model would be applied as well. The BSTEM model is a very simplified version of the CONCEPTS model. After consideration during the project, it was decided to not include the BSTEM model application because of the effort expended on applying the CONCEPTS and SEDIMOT II models.

In the original proposal, the study was to be limited to a 900 m section of the main stem of the river. As the project progressed, however, it was decided it would be necessary to extend that length to 21 km to be able to include the information available from the monitoring station at the upstream end of the Knife mainstem.

3. Methods

3.1. Overall Summary of Approach

To assess sediment sources of the Knife River mainstem, it was initially proposed that the U of M use three different modeling approaches: (1) CONCEPTS, (2) BSTEM, and (3) BEHI.

CONCEPTS (Conservational Channel Evolution and Pollutant Transport Model; Langendoen, 2000) is a computer model that simulates unsteady, one-dimensional flow, graded-sediment transport, and bank-erosion processes in the stream corridors (Langendoen, 2000). CONCEPTS is a continuous, time-series model that requires an upstream boundary condition providing flow and sediment data entering the modeled channel schema.

BSTEM (Bank-Stability and Toe-Erosion Model; Simon et al., 2006) is a simplified MS Excel version of CONCEPTS that only takes into account bank erosion processes for a single storm event with steady flow and at a small scale (e.g., single cross-section; the outside bank of a single channel bend). CONCEPTS and BSTEM are products of the USDA’s National Sediment Laboratory in Oxford, MI.

BEHI (Bank Erosion and Hazard Index; Rosgen, 2006) is an empirical bank erosion model. It takes into account bank geometry and material stability as well as near-bank stresses resulting from flow conditions. BEHI determines annual bank erosion from a single bank using regression relationships from published experimental datasets.

As the project progressed it was evident that CONCEPTS would both produce results more in line with the project goals as well as require a considerable amount of time and effort to implement. As a result, the scope of the modeling approach was reduced to exclude implementation of BSTEM.

The work plan specified that a 900 meter section of the mainstem would be investigated and modeled with the assumption that results could be extended throughout the length of the channel. However, after several site visits and consultations with SLC-SWCD and MPCA staff, it was determined that (1) considerable channel variability exists that warrants further investigation of channel/bank conditions along upper and lower reaches of the channel, and (2) erosion from rainfall impacts and overland flow on the 20+ bluffs on the mainstem may be contributing significant sediment, irrespective of the fluvial bank erosion occurring at each bluff site (i.e., additional erosion was observed that is not simulated by CONCEPTS).

As a result, it was decided to more thoroughly investigate and characterize bank and bluff conditions along the entire length of the Knife mainstem starting from the Airport Rd. gaging station and ending at the Knife River outlet (Fish Trap gaging station). This approach was later altered to reduce the total length of the modeled channel by moving the model end-point to just above a steep bedrock riffle approximately 1.6 stream km (str-km) upstream of Shilhon Rd. (approximately 4.6 str-km upstream of the Knife River outlet). Thus, total stream length from model start-point (S1-Airport) to model end-point was 21.7 str-km.

The impact of this reduction was three-fold. First, the steep bedrock riffle, because of its relatively large slope would cause a flow discontinuity that would require special consideration in CONCEPTS. Second, the riffle signifies the approximate start of the Knife's descent through relatively impervious bedrock and thus was assumed that the sediment generated from the model end-point to the Lake Superior outlet overall was insignificant compared to that occurring in the areas above the model end-point. Last, decreasing the model channel length excludes the Little Knife tributary from being directly accounted for in CONCEPTS simulations. This is noteworthy because the Little Knife is thought to supply a disproportionate amount of sediment in relation to its drainage area.

To simulate bluff erosion directly, a small watershed hydrology and sedimentology model, SEDIMOT II (Wilson et al., 1982) was employed. SEDIMOT II is an event-based model that uses the NRCS Curve Number method for runoff prediction and MUSLE (modified universal soil loss equation) for erosion prediction.

Given the changes discussed above, the refined methodology contained the following components:

1. Visit field sites on the mainstem to gain insight as to channel condition and variability; collect data for models.
2. Identify observed storm events producing significant sediment; select storms for model simulations.
3. For selected storms, quantify flow and sediment data for incoming tributary and overland inputs to Knife River mainstem using observed data and/or small watershed models.
4. Develop hydraulic geometry vs. drainage area relationships for Knife River mainstem to assist in prediction of channel properties for setup of models.
5. Model bank erosion on Knife River mainstem using CONCEPTS for selected storms.

6. Model bluff erosion on Knife River mainstem using SEDIMOT II for selected storms.
7. Model annual bank erosion using BEHI; compare to CONCEPTS results.
8. Compile total inputs from all observed and modeled inputs to estimate per storm sediment source masses and percentages; compare to observed sediment output data at Knife River watershed outlet

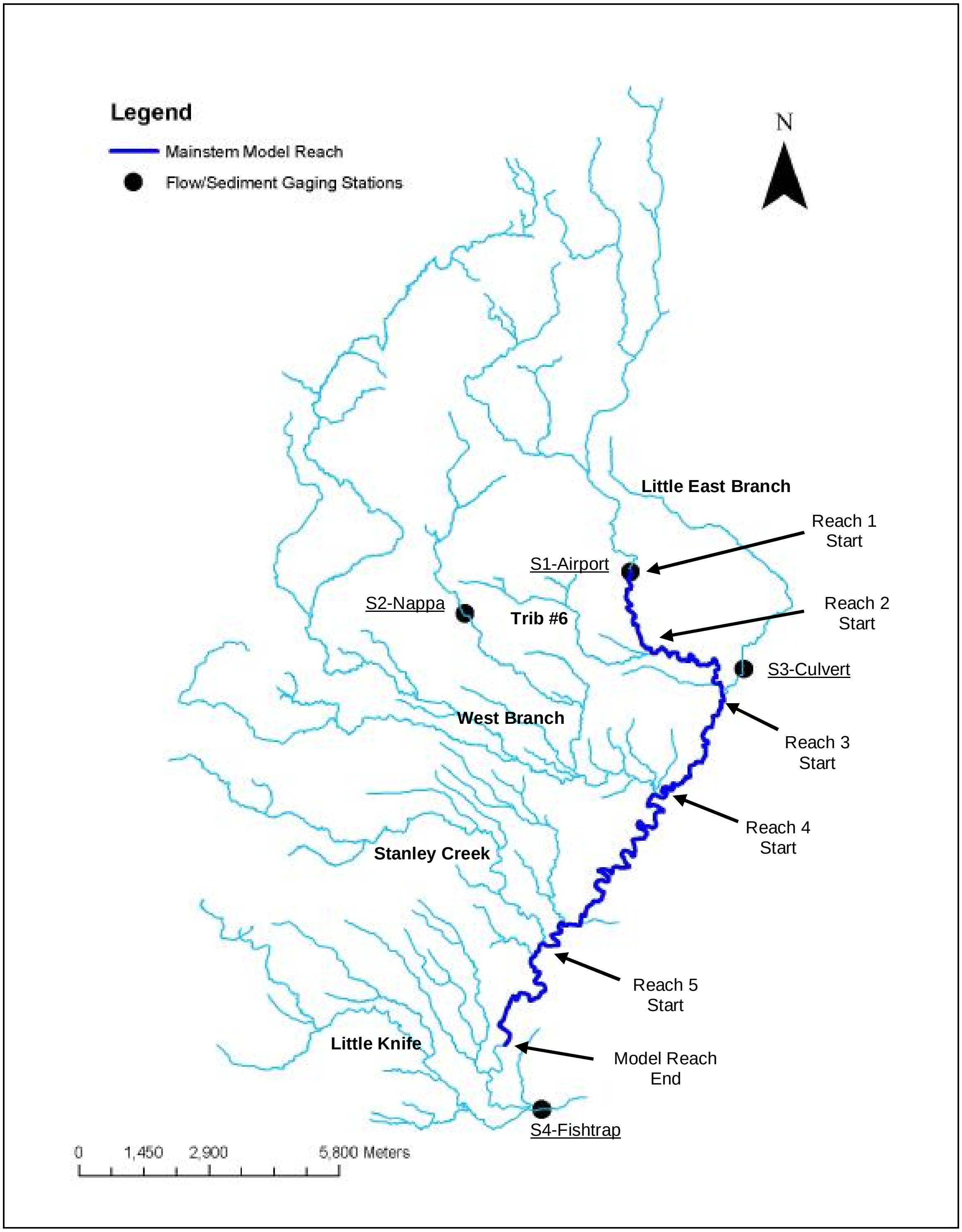


Figure 2. Map of Study Area

3.2. Field Data Collection

Three field trips were undertaken during 2007 (5/31-6/1, 6/13, 8/21-8/22) to gather surveyed cross-sectional data and general channel data for CONCEPTS and BEHI. In total, five sites were sampled. A summary of the field visits is presented in Table 1.

CONCEPTS requires surveyed cross-sections along each representative section of the simulated channel, approximately one cross-section per every 50-300 meters. Because of this, surveying as many cross-sections as possible was the focus of the field visits. However, CONCEPTS cannot account for large, local-scale geometric changes such as those associated with riffle-run-pool sequences. Instead, cross-sections should reflect the average channel conditions over a given section. As a result, field visits focused on surveying run features mainly although some pools and riffles were also surveyed for assessment of overall variability.

Cross-sections were sampled in the five areas of the Knife mainstem. Access to many areas was very limited due to the lack of roads and as a result field surveys were largely confined to road crossings except where landowner permission was attainable and access to the channel was reasonably easy. Cross-sectional surveys were conducted using a laser level and/or total station depending on the extent of elevation change; bluff and taller bank cross-sections required use of the total station. Bankfull elevation was estimated from channel conditions. Flow velocity was estimated at several points by timing a floating marker between to two measured points. Longitudinal profiles were not conducted because of time constraints. All stream surveys followed the methodology from Harrelson et al. (1994).

Data was recorded in field notebooks and later entered into the Reference Reach Spreadsheet (RRS) from Rivers4m Ltd. (Version 2.2L; 1999). Cross-sectional data was checked for quality assurance and accuracy. Of most consequence and potential subjective field judgment was determination of bankfull elevation. Bankfull cross-sectional areas were compared to those predicted by the regional hydraulic geometry curve for Northeast Minnesota (Magner, 2007); small adjustments were made if surveyed bankfull cross-sectional area was significantly different (and if field observations did not contradict the adjustment). On the whole, surveyed cross-sections compared reasonably well with the regional curve predictions.

The BEHI survey was also conducted at several locations. Start- and end-points of each field reach as well as heights of eroded bluff and bank sections were noted and photographs taken at regular intervals.

Bed soil types were sampled in the field using a 100-sample pebble count, recorded on paper and later entered in the RRS to calculate particle size distributions. Bank soil samples were placed in plastic bags and brought back for lab analysis. Bank samples were analyzed using the sieve/hydrometer method as described in Lambe (1951) and particle size distributions calculated and plotted.

Table 1. Summary of 2007 Field Visits

Field Site	Date(s) visited	Location	Distance from Model Start-pt. (km)	Total Stream Distance Sampled (m)	No. Cross-sections Surveyed
Cty Rd. 11	6/13	300 stream meters below Cty Rd 11	5.5	200	3
Swanson	5/31	400 stream meters above Cty Rd 9	8.5	200	4
Bergman	8/22	4000 stream meters below Cty Rd 9 (between Cty Rd 9 and Hawk Hill Rd)	13.0	2500	4
Hawk Hill Rd	6/13, 8/21	200 stream meters below Hawk Hill Rd	16.8	2100	7
Baughman	6/1	2500 stream meters below Hawk Hill Rd	19.5	200	2

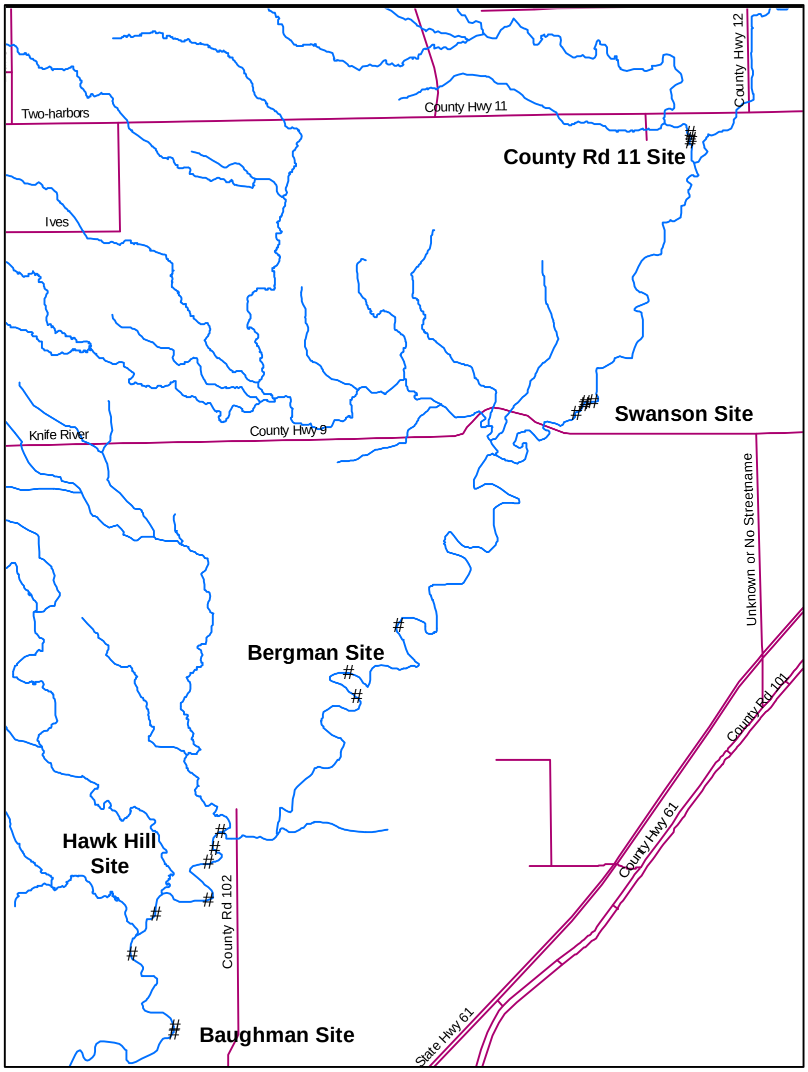


Figure 3. Locations of Field Surveyed Cross-Sections

3.3. *Identify Storm Flow Events for Modeling*

Three storm events were selected as representative events for the modeling simulations. The three observed storms were chosen from 2005 data and were intended to represent a range of flow conditions coinciding with the "High Flows" (0-10% days exceedance) and "Moist Conditions" (10-40% days exceedance) flow intervals on the S4-Fishtrap load duration curve. It is in these two flow intervals that the majority of yearly sediment is transported. Storm 1 reflects a significant -- but lower than bankfull -- flow event that occurred 6/14–6/18. However, Storm 1 flow produced bankfull conditions in many section of the channel when simulated by CONCEPTS (See Results and Discussion) and simulated erosive effects from Storm 1 were considered those produced by flows close to bankfull. Storms 2 and 3 were of lesser magnitude and occurred 5/19-5/23 and 6/29-7/2, respectively. See Table 2 for characteristics of storms selected for this study.

Peak flow for each storm was determined from 30-minute flow data at S4-Fishtrap. Mass of sediment per storm was estimated using a regression curve (SLC-SWCD) of mean daily discharge versus daily sediment mass. Storm 30-minute rainfall depths were available from the S2-Nappa 30-minute rainfall gauge for computing the 30-minute intensities.

Table 2. Observed Characteristics of Storms Used in Study

Name	**Total Precip Depth (in)**	**Duration (hr)**	**Peak 30 minute intensity (in)**	**Estimated Return Period (yr)**	**Observed Peak Flow (cfs)**	**Observed Sediment Mass (tons)[1]**
Storm 1	1.73	24.0	0.59	0.7	1800	881
Storm 2	1.30	12.0	0.68	0.5	645	138
Storm 3	0.94	4.5	0.36	0.5	334	30

[1] Estimated from regression relationship of average daily discharge vs. daily total sediment mass

3.4. *Watershed Hydraulic Geometry Relationships*

Analyses of contributing drainage area at significant points in the watershed were necessary to (1) establish hydraulic geometry relationships at channel cross-sections not surveyed/sampled, and (2) re-scale observed flow and sediment data from gaged stations to quantify ungaged inputs that are significant to the overall Knife River flow regime. Both objectives were crucial for generating data for CONCEPTS and BEHI simulations.

Drainage areas were determined using the Arc Hydro Toolset for ArcGIS 9.2 (ESRI, 2007; Maidment, 2002). GIS inputs were (1) the 5-meter cell-size, digital elevation model (DEM) for the Knife River watershed, digitized from 10 foot contour USGS 7.5 minute quadrangle maps, and (2) Minnesota Dept. of Natural Resources (MN-DNR) 24K Streams shapefiles. (All GIS data was provided by the SLC-SWCD.) Arc Hydro uses Flow Direction and Flow Accumulation DEM terrain analyses that take into account the known locations of streams. The resulting "reconditioned" DEM will output drainage area polygon features at any point desired. Contributing drainage areas were calculated for every 20 meter channel section of the mainstem between S1-Airport and S4-Fishtrap (includes all surveyed cross-sections and tributaries).

Because field surveys only sampled a small fraction of the total channel length selected for modeling, channel geometry needed to be characterized in the majority of proposed modeling areas using hydraulic geometry vs. drainage area relationships. Analyses of how channel cross-sectional area, width and thalweg depth changes with drainage area were conducted using linear and non-linear regression techniques (as available in MS Excel). Observed data was plotted vs. drainage area and regression curves generated (See Figure 4-Figure 7).

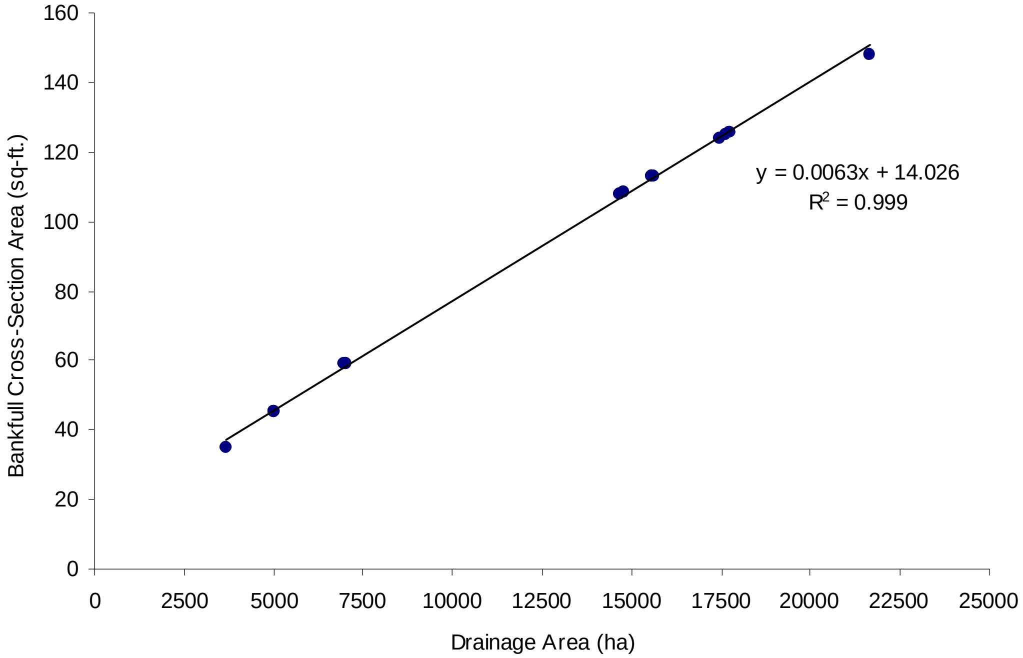


Figure 4. Hydraulic Geometry Drainage Area Relationships: Bankfull Cross-Sectional Area

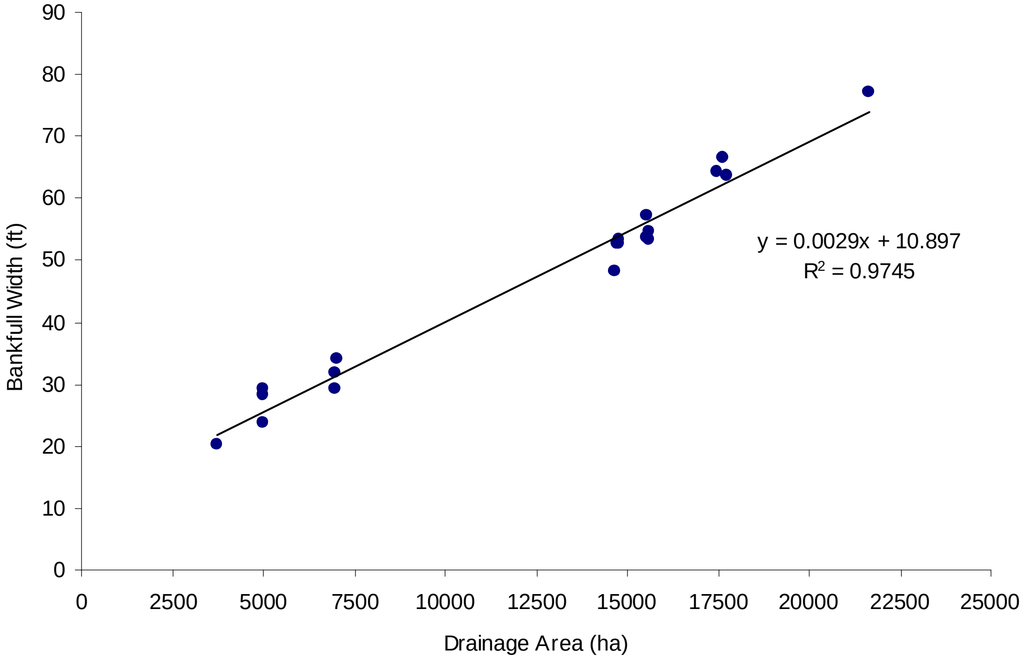


Figure 5. Hydraulic Geometry Drainage Area Relationships: Bankfull Width

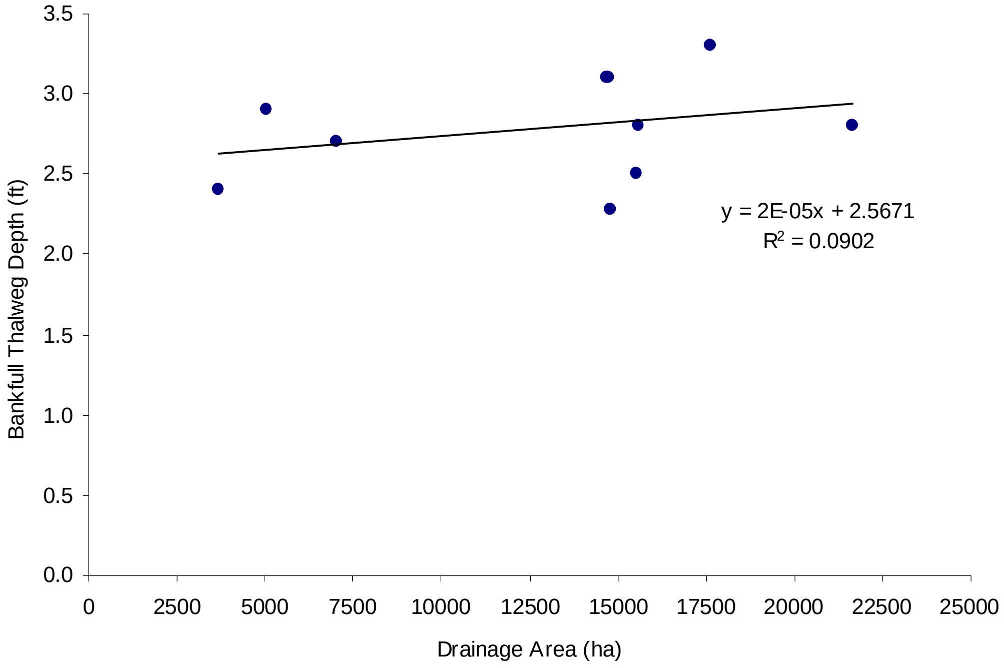


Figure 6. Hydraulic Geometry Drainage Area Relationships: Bankfull Thalweg Depth (Straight Planforms)

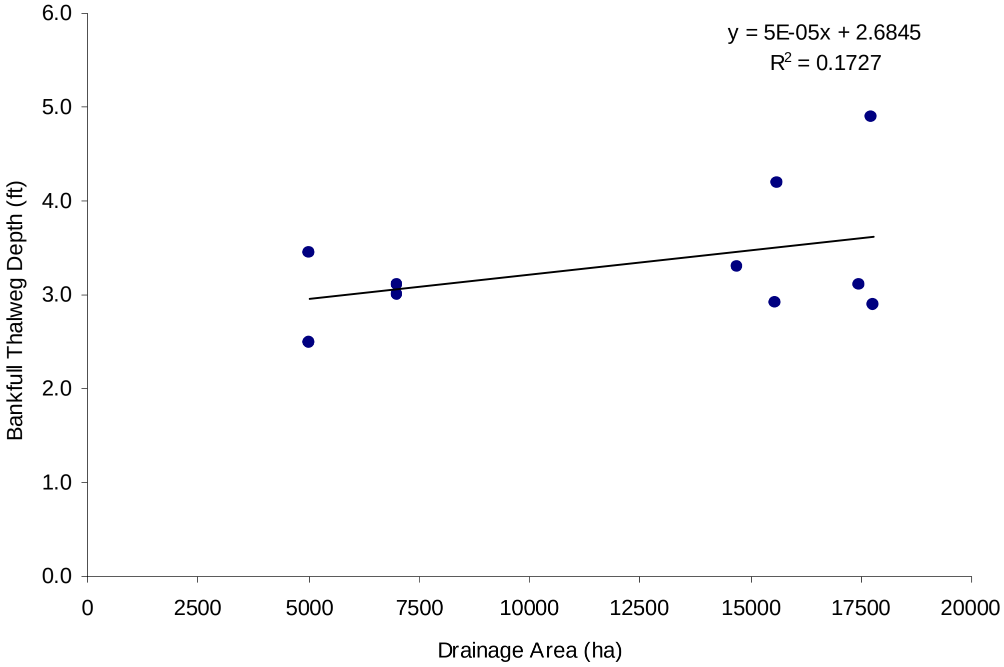


Figure 7. Hydraulic Geometry Drainage Area Relationships: Bankfull Thalweg Depth (Curve Planforms)

Analyses of the hydraulic geometry and drainage area relationships revealed bankfull cross-sectional area and width were readily predictable using drainage area; linear regression was adequate and demonstrated an excellent goodness-of-fit (r^2=0.99 and 0.97, respectively). However, bankfull thalweg depths for straight and curve planforms both showed significant variability and only weak trends with drainage area were found (r^2=0.09 and 0.17, respectively). Nevertheless, it was assumed linear relationships between drainage area and thalweg depths would suffice and could be used to predict channel conditions along the entire length of the channel.

3.5. Quantify Flow and Sediment Data for Tributary and Overland Inputs

Four gaging stations are located in the watershed: S1-Airport (Airport Rd), S2-Nappa (Nappa Rd; located on a small tributary of the West Branch), S3-Culvert (Little East Branch) and S4-Fishtrap (Knife River watershed outlet at Lake Superior). These stations possess drainage areas of 3764, 1687, 958, 22116 hectares, respectively. Each station records flow height and turbidity data at 30 minute intervals (Note: height and turbidity data were converted to flow (cfs) and TSS [mg/l], respectively, using per station regression curves generated by SLC-SWCD). S2-Nappa also possesses a 30-minute rainfall gage. Hydro- and sediment graphs for these four stations for storms 1-3 are presented in the Appendix.

Three significant tributaries enter the mainstem between the model start- and end-points: the Little East Branch, West Branch and Stanley Creek. In addition, overland flow from the Knife mainstem watershed also needed to be accounted for (Note: for simplicity, several smaller tributaries' drainage areas were incorporated into the mainstem watershed rather than be considered as separate tributaries). Of these four inputs, only the Little East Branch possessed observed flow and sediment data (S3-Culvert). Therefore, the flow and sediment data needed to be quantified for the West Branch, Stanley and the mainstem watersheds. Attempts at applying a simple watershed model (SEDIMOT II; Wilson et al., 1982; see Bluff Erosion sections) failed to produce realistic results due to the lack of finer resolution soils, topographic and channel data necessary to properly set model parameters. Instead, it was assumed that reasonable estimates of flow and sediment for an ungaged input could be obtained by scaling the existing observed data from one of the four gaging stations in the watershed. The value of the scaling factor would be the ratio between contributing drainage areas for ungaged and gaged sites, respectively.

Representative gaging stations were selected for use in estimating flow and sediment data for each ungaged input (West Branch, Stanley and mainstem watershed) for each storm. However, for a given ungaged input and storm, two methodologies were used to calculate estimates: one for flow and one for sediment.

To estimate flow, it was assumed that a roughly equal proportion of the rainfall volume from each ungaged input watershed would discharge over the course of a multi day flow event, and that the runoff volume would be proportional to watershed drainage area. Consequently, it was also assumed a single gaging station could be used to estimate flow in all ungaged input watersheds. Conversely, it was assumed that sediment delivery from ungaged sites was more variable, and that sediment estimations would have to be based on a gaged tributary whose watershed was most representative of the ungaged watershed in terms of soils, landuse and landscape.

Flow hydrographs for each ungaged input were generated by first calculating the total runoff volumes for each storm. This was done by multiplying the observed flow volume at S4-Fishtrap by a factor equal to ratio between the S4 and ungaged drainage areas. Then, each 30-minute discharge from the S1-Airport hydrograph was multiplied by the same ratio to create the ungaged hydrograph with the calculated runoff volume. In other words, total runoff volume for each ungaged input was calculated using S4-Fishtrap data while the shape and duration of the storm hydrograph conformed to the S1-Airport hydrograph. Therefore, it was assumed that total runoff volume should be in agreement from a water budget perspective to that observed at the S4 watershed outlet but that S1 represented a more reasonable flow distribution and duration.

Time-series sediment data for gaged and ungaged inputs was not required as it was decided to not account for it directly in CONCEPTS. However, total sediment masses per input, per storm were necessary for comparison with modeled bank and bluff erosion inputs and determination of sourcing percentages. However, using observed sediment data from S4 (i.e., the same approach used to estimate flows) would have generated sediment masses that were assumed to be over estimated on account of relatively high sediment masses observed/estimated at S4 (and because of the assumption that the Little Knife tributary was generating a disproportionally high amount of the sediment observed/estimated at S4). Instead, a specific gaging station was selected for each storm and ungaged input to provide what was judged to be a reasonable estimate of total sediment mass. See Table 3 for summary of representative storms and gaging stations. The S2-Nappa station is located on a tributary of the West Branch and possesses an upstream watershed that roughly conforms in soils and landscape to the West Branch. Consequently, S2 was scaled to determine West Branch sediment masses for all three storms. The Knife mainstem watershed and Stanley tributary were both dealt with in the same way: for Storms 1 and 2, S1-Airport was used; for storm 3, S3-Culvert was used. This selection for storm 3 was due to the unexpectedly high sediment mass at S1 for storm 3 (mass for storm 3 [4.5 tons] was larger than that associated with the more intense storm 2 [4.2 tons]) and consequently, it was assumed that S3 provided a more realistic mass estimate.

Table 3. Summary of Per Storm Sediment Masses for Ungaged Inputs

		Storm 1		***Storm 2***		***Storm 3***	
Input Name	**Data Source**	**Sed. Mass (tons)**	**Gaging Station Used[2]**	**Sed. Mass (tons)**	**Gaging Station Used[2]**	**Sed. Mass (tons)**	**Gaging Station Used[2]**
Airport Upstream Boundary	Observed	22	--	4.2	--	4.5	--
Little East Branch	Observed	16	--	3.5	--	1.3	--
MainStem Watershed	DAA[1]	17	Airport	3.2	Airport	2.3	Little East
West Branch	DAA[1]	15	Nappa	2.1	Nappa	1.5	Nappa
Stanley	DAA[1]	11	Airport	2.2	Airport	1.5	Little East

1 Per storm sediment mass generated using drainage area analysis (DAA)
2 Representative gaging station used for DAA of ungaged input

3.6. Model Bank Erosion using CONCEPTS

3.6.1. Longitudinal and Cross-Sectional Schema

The most fundamental and important input data in CONCEPTS are channel cross-sections, which are required for approximately every 50-300 meters of stream length depending on channel variability; the more the variability over a given channel reach, the more cross-sections that are required to ensure changes occur as gradually as possible. Model cross-sections on the Knife River mainstem were designated by referring to GIS stream and digital orthoquad photograph layers. As a general rule, one cross-section was placed at each curve and straight section, yielding 146 cross-sections between model start- and end-points (i.e., approximately one cross-section for every 150 meters of channel).

Selected cross-sections were separated into three general planform types: straight, gradual curve and sharp curve. Distinction between gradual and sharp curves was somewhat subjective. While GIS analyses of the Knife River mainstem were undertaken to determine both radius of curvature and sinuosity at cross-sections, results were not considered consistently reliable because of local scale variation in the accuracy of the GIS stream line layer from one cross-section to another. As a result, visual inspection in ArcGIS was the primary determinant. Curves with an arc angle of approximately 45 to 90 degrees over a stream length of approximately 120 meters (60 meters upstream, 60 meters downstream) were designated as gradual; similarly, those curves with angles of approximately 90 degrees and above were designated as sharp. Curves with angles near the 90 degree boundary were assessed by evaluating an additional 20 to 40 meters up- and downstream and reapplying the 90 degree angle criterion. Of the 146 cross-sections selected for the model schema, planform types were distributed as 21% straight, 16% gradual curve and 63% sharp curve. (See
Table **4** for distribution of cross-section planform types.)

Generally, in areas where field data does not exist, “simulated” cross-sections must be created for CONCEPTS. These simulated cross-sections will often take the form of surveyed cross-sections that are adjusted geometrically for differences in location such as contributing drainage area, channel slope, soils, etc. In this study a slightly different approach was taken: all 20 surveyed cross-sections from the five field sites were analyzed to yield three generic cross-sectional forms to be used as simulated cross-sections, one for each straight, gradual curve and sharp curve planform type. This was deemed a reasonable approach given surveyed cross-sectional geometry was estimated to be as variable between cross-sections *at* a given field site as it was *between* cross-sections at field sites in different reaches. It also allowed for a much simpler model schema to manage in CONCEPTS. Consequently, all cross-sections were of a generic, simulated type and none of the surveyed cross-sections were used in their original forms for CONCEPTS; however, other field data such as bank soils, vegetation and floodplain data were applied where simulated cross-section locations coincided with surveyed locations.

To further simplify the model schema, the full model channel length was split into five model reaches to coincide with areas of relatively constant drainage area. At points where major tributaries intersect the mainstem, a new reach was designated. Refer to the map in Figure 2 and
Table 4 for a description of the model reaches.

All cross-sections in the model schema must conform to a single elevation reference to enable CONCEPTS to calculate flow from one cross-section to the next taking into account the correct channel slope. However, local elevation benchmarks were not available or too impractical for use. As a result, GIS analyses of the Knife River DEM were used to estimate actual elevation for each cross-section in the simulation. This ensured that CONCEPTS simulated a reasonably accurate elevation difference between cross-sections. The DEM values for the valley bottom adjacent to the channel were used for this purpose. However, because the DEM is created from 10 foot contour topographic maps, its resolution is not suitable for determining localized elevations as several hundred meters of channel length may have the same elevation value listed in the DEM depending on the slope of the valley. In order to determine unique elevations at each cross-section, linear interpolation was used to sub-divide the 10 foot contours into 1 foot contours along the river channel. While this method ignores local scale slope variation caused by changes in riffle-run-pool features, it was assumed to provide reasonably accurate elevations when applied at the reach scale. The calculated elevation at each cross-section was set to correspond to the bankfull elevation at each cross-section. See Table 16 (Appendix) for general channel and bank information for all 146 cross-sections.

Cross-sectional channel roughness parameters for bed, banks and floodplain are represented separately in CONCEPTS using Manning's *n* coefficients. Channel conditions that were considered when quantifying roughness values included:

1. Channel meander: straight, gradual or sharp curve planform; degree of curve increases roughness
2. Channel obstruction: in-stream boulders are main example in this study; effect assumed to increase from minor to appreciable (upstream to downstream) based on field observations
3. Vegetation: variable presence on banks; assumed to have a moderate effect on bank roughness based on field observations; no vegetation present on bed
4. Channel irregularity and changes in shape/size: cross-section variability due riffle-run-pool sequences; assumed to have moderate effect based on field observations

Resultant roughness coefficients incorporating the above conditions were determined using the method of Arcement and Schneider (1984).

Groundwater can be an important factor in stream bank erosion and is an integral part of CONCEPTS' bank erosion algorithm. However, after consultations with SLC-SWCD and MPCA staff it was decided that groundwater played a relatively small role in the overall hydrology of the Knife River channel and watershed, and consequently was not included in model simulations.

Table 4. Characteristics of Model Reaches

Reach No.	**Dominant Inflow Source**	**Drainage Area (ha)**	**Reach Length (m)**	**No. Sharp Curves**[2]	**No. Grad Curves**[2]	**No. Straight**[2]	**Mean Channel Slope (%)**	**SD Channel Slope (%)**
1	Mainstem upstream boundary (S1-Airport)	3905	2360	11 (9/2)	4 (2/2)	4 (2/2)	1.08	0.24

2	Trib #6[1]	1123	3440	21 (6/15)	3 (1/2)	3 (0/3)	0.53	0.10
3	Little East Branch Trib (S3-Culvert)	2029	4000	19 (8/11)	4 (2/2)	6 (3/3)	0.33	0.23
4	West Branch Trib	8560	8100	28 (22/6)	7 (4/3)	12 (2/10)	0.33	0.17
5	Stanley Creek Trib	2347	5140	13 (9/4)	5 (1/4)	6 (1/5)	0.55	0.20

1 Trib #6 drainage area was incorporated into the mainstem watershed rather than considered as a separate input.

2 Parentheses indicate number of each planform type with banks comprised of: (valley wall-parent material / floodplain alluvium).

3.6.2. Hydrologic Inputs

Observed flow data from S1-Airport representing the mainstem upstream boundary and the S3-Culvert (Little East Branch) were imported into CONCEPTS as inputs. Also imported were the three ungaged inputs (West Branch and Stanley Creek tributaries; overland flow from the Knife mainstem watershed) that were estimated using the drainage area analyses discussed previously. All data were at a 30-minute time resolution. The Knife mainstem overland flow was managed in CONCEPTS by use of a Lateral Inflow object. This model option allows each 30-minute overland flow volume to be distributed evenly as lateral input over the entire length of the simulated channel. Note: for simplicity, smaller tributaries such as Trib#6 (located between S1 and S3) and Trib#3 (downstream of Stanley Creek) were incorporated into the Knife mainstem watershed input rather than quantified separately.

3.6.3. Cross-Sectional Geometry

As discussed previously, cross-sectional geometries were fixed for all cross-sections (per planform type) within a given reach. This allowed for a more manageable model schema as each reach would only contain 3 distinct cross-sections. Generic cross-sections were generated for the reach furthest upstream (Reach 1) and then re-scaled for each subsequent downstream reach (Reaches 2-5) based on watershed hydraulic geometry analyses. Certain geometric properties were held fixed while others were adjusted according to changes in contributing drainage area. It was assumed that the sole sources of cross-sectional variation were planform type (straight or curve) and differences in drainage area. Thus, areas of locally varying channel slope, vegetation and bed/bank soils were not considered when creating generic cross-sectional geometry; however, these characteristics were taken into account when determining non-geometric parameters such as roughness and bank shear strength. Important geometric properties and general descriptions of their designated variabilities are listed below (See Figure 8 for a cross-sectional diagram of geometric properties):

- Cross-sectional area (calculated using RRS; using bankfull elevation as a top reference) per planform type was held roughly equal (gradual and sharp curves varied +/- 5% compared with straight sections); however, it was increased in each successive reach. Cross-sectional variation between reaches was determined using regression curves analyzed from field measured cross-sectional area vs. drainage area (See Figure 4).

- Channel width (as measured from bank-to-bank bankfull elevations) per planform type was increased in each successive reach. In a given reach, straight sections had the greatest channel widths; sharp curves were assumed to have widths 10% less than straight sections and gradual curves 5% less. These assumptions are generally supported by cross-sectional surveys and digital orthoquad photographs. Channel width variation between reaches was determined using regression curves analyzed from field-measured channel width vs. drainage area (See Figure 5).

- Thalweg depth (as measured from bankfull elevation) per planform type was increased in each successive reach. Sharp curves had the deepest thalwegs followed gradual curves and straight sections. Sharp curves were assumed to have thalweg depths 20% greater than straight sections and gradual curves, 10% greater. These assumptions are supported by the cross-sectional surveys. Thalweg depth variation between reaches was determined using regression curves analyzed from field measured thalweg depth vs. drainage area (See Figure 6 and Figure 7).

- Upper bank angles per planform type were held constant over all five reaches.

- The upper bank height (as measured from bankfull elevation to bank top) for sharp and gradual curves was increased in each successive reach; those for straight sections were held constant across all reaches. This bank property is a measure of channel bed incision which was observed on the majority of curves and increased in depth from upstream to downstream. For a given reach, sharp curves had the highest upper bank heights followed by gradual curves and straight sections. Variation between reaches was estimated from field visits and photographs, and a simple linear relationship with drainage area was developed.

- Elevations of floodplain points were estimated by GIS analyses of the DEM and generalizations made from field photographs; it was assumed this method would produce reasonably accurate measurements of floodplain geometries.

The properties listed above were calculated for each cross-section (given contributing drainage area calculated for each cross-section) using the hydraulic geometry regression curves discussed previously (bankfull cross-sectional area, width and thalweg depth) or by following trends observed from field surveys and photographs (upper and lower bank angles and heights, overall cross-section shape, and floodplain characteristics). Calculated cross-section properties were then generalized and scaled for the five designated model reaches.

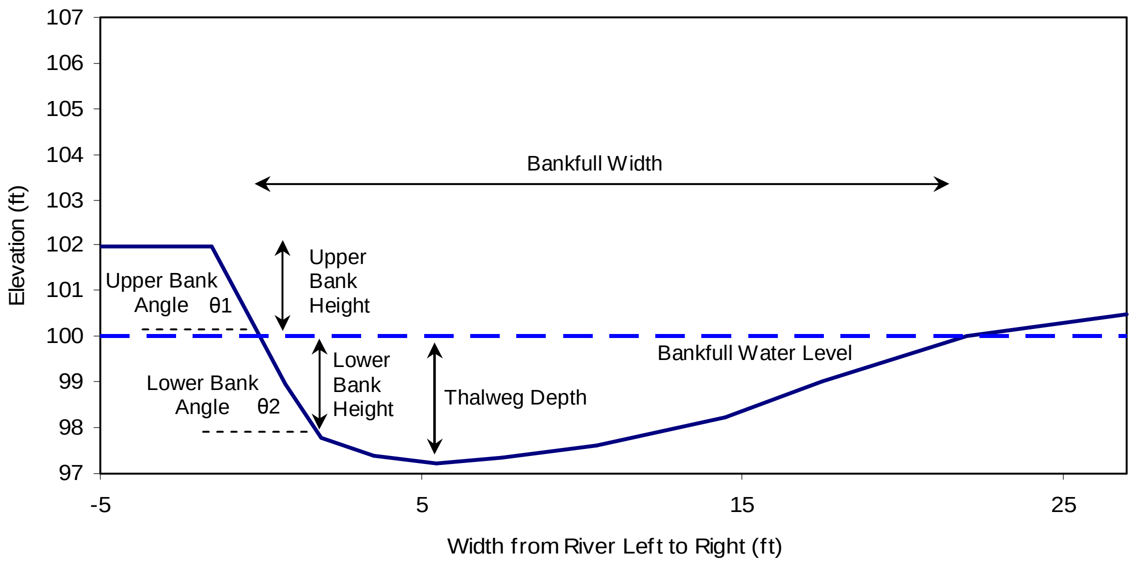


Figure 8. Diagram of Important Cross-Sectional Geometric Properties

CONCEPTS is a one-dimensional flow and sediment transport model and thereby assumes a straight or very low sinuosity channel for its flow and erosion algorithms. It does not take into account width- or depth-wise spatial variability of parameters or simulated flows in a given channel cross-section. As a result, the model will not differentiate between flow conditions on straight vs. curve cross-sections. This is important as the preponderance of bank erosion occurs where curves create a local increase in fluvial shear stress on the outer bank. To differentiate the erosional potential of curves, outer bank soil parameters associated with shear strength were adjusted, thereby decreasing erosional resistance. This was assumed to account for the increased fluvial shear stress; this procedure is discussed in more detail in the next section. See Figure 9-Figure 14 for cross-section examples of straight, sharp and gradual curve planform types.

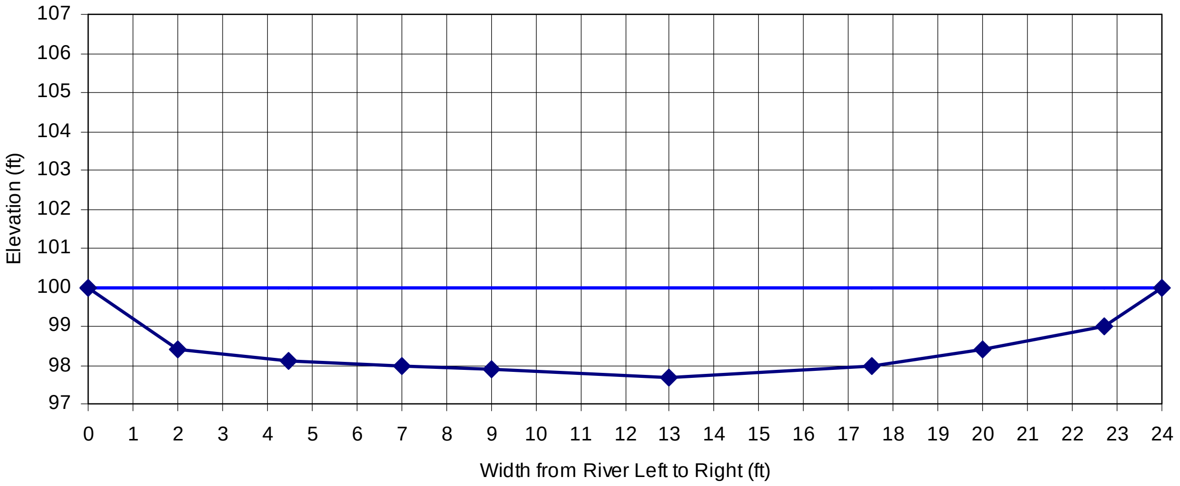


Figure 9. Generic Cross-section for Straight Planform Type, Reach 1

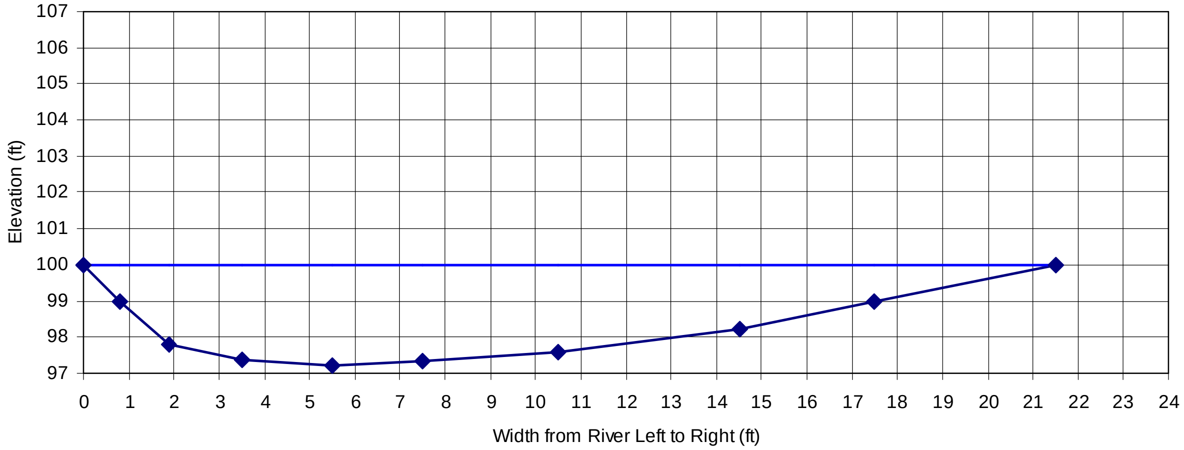


Figure 10. Generic Cross-section for Sharp Curve Planform Type, Reach 1

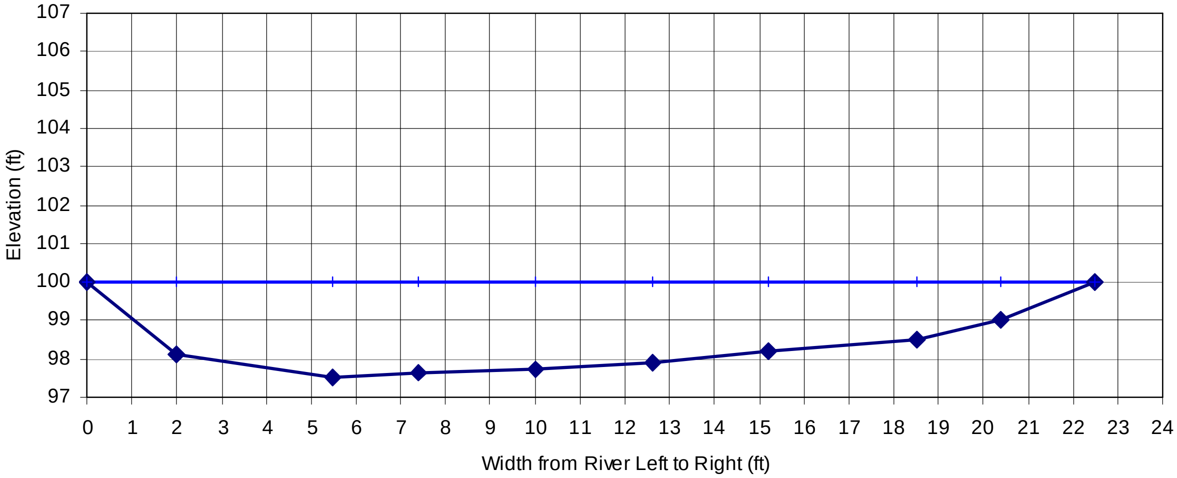


Figure 11. Generic Cross-section for Gradual Curve Planform Type, Reach 1

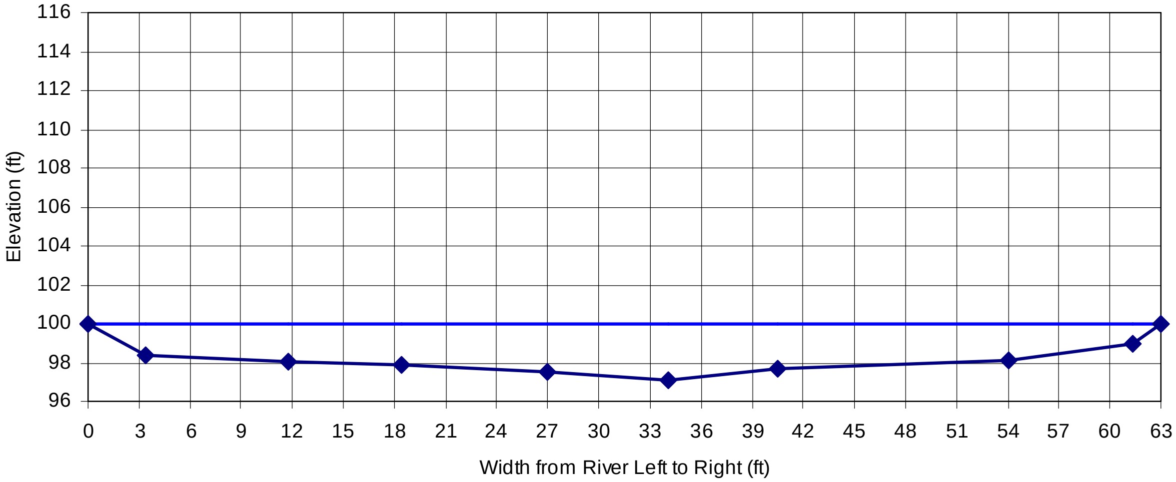


Figure 12. Scaled Cross-section for Straight Planform Type, Reach 5

Figure 13. Scaled Cross-section for Sharp Curve Planform Type, Reach 5

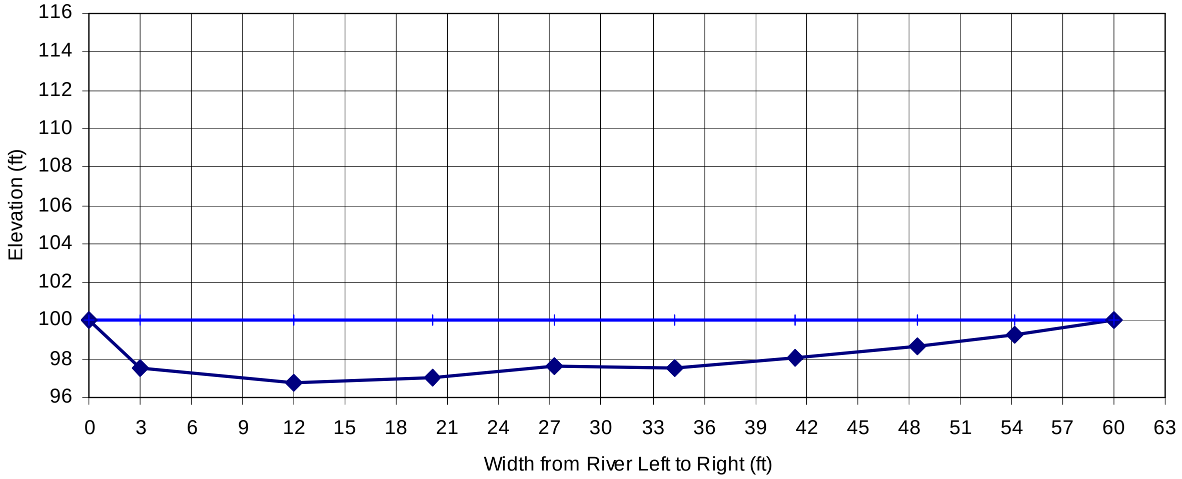


Figure 14. Scaled Cross-section for Gradual Curve Planform Type, Reach 5

Table 5. Per Reach Cross-Sectional Geometry (Straight Planform)

	Straight							
Reach No.	**Cross-section Area (ft^2)**	**Top Width (ft)**	**Thal. Depth (ft)**	**Mean Depth (ft)**	**Hyd. Radius (ft)**	**Lower Bank Angle (deg)**	**Upper Bank Height (ft)**	**Upper Bank Angle (deg)**
1	42.0	24.0	2.3	1.8	1.7	40.0	1.5	30.0
2	49.0	27.0	2.4	1.8	1.8	37.0	1.5	30.0
3	60.0	33.0	2.4	1.8	1.8	30.0	1.5	30.0
4	113.0	56.0	2.8	2.0	2.0	30.0	1.5	30.0
5	127.0	63.0	2.9	2.0	2.0	30.0	1.5	30.0

Table 6. Per Reach Cross-Sectional Geometry (Gradual Curve Planform)

	Gradual Curve							
Reach No.	**Cross-section Area (ft^2)**	**Top Width (ft)**	**Thal. Depth (ft)**	**Mean Depth (ft)**	**Hyd. Radius (ft)**	**Lower Bank Angle (deg)**	**Upper Bank Height (ft)**	**Upper Bank Angle (deg)**
1	40.0	22.5	2.5	1.8	1.7	45.0	1.75	50.0
2	49.0	25.5	2.7	1.9	1.8	42.0	1.75	50.0
3	60.0	31.0	2.8	1.9	1.9	40.0	1.90	50.0
4	107.0	52.0	3.0	2.0	2.0	40.0	2.25	50.0
5	125.0	60.0	3.2	2.1	2.0	40.0	2.50	50.0

Table 7. Per Reach Cross-Sectional Geometry (Sharp Curve Planform)

	Sharp Curve							
Reach No.	**Cross-section Area (ft^2)**	**Top Width (ft)**	**Thal. Depth (ft)**	**Mean Depth (ft)**	**Hyd. Radius (ft)**	**Lower Bank Angle (deg)**	**Upper Bank Height (ft)**	**Upper Bank Angle (deg)**
1	39.0	21.5	2.8	1.8	1.7	50.0	2.0	70.0
2	46.0	24.5	2.9	1.9	1.8	50.0	2.0	70.0
3	58.0	30.0	3.0	1.9	1.9	45.0	2.3	70.0
4	105.0	50.0	3.4	2.0	2.0	45.0	3.0	70.0
5	123.0	57.0	3.6	2.2	2.1	45.0	3.5	70.0

3.6.4. Soil Types and Cross-Sectional Designation

Proper characterization of cross-sectional soils is crucial for CONCEPTS bank erosion algorithms and is required for the left bank, right bank and bed sections of each channel cross-section. The STATSGO soils database only provides a general spatial distribution of parent material soils in the watershed and, therefore, did not suffice for a local scale implementation of CONCEPTS. The more specific SSURGO database might have provided finer resolution soils data but a spatially referenced version was not available for Lake County, Minnesota (which comprised roughly 90% of the mainstem channel area). Consequently, bank soil samples were collected at numerous sites along the mainstem and brought back to the U of M for lab analysis (See Table 8 for a summary of sampled soils that were applied to CONCEPTS cross-sections). The distribution of soil types followed general trends that were consistent along the entire modeled channel length and can be summarized as follows:

1. Silt/clay loam and clay soil types occur where stream banks and/or bluffs are composed of the mainstem valley wall materials (i.e., parent material; where the channel makes contact with the valley wall).

2. Sandy loam soil types occur where stream banks are comprised of floodplain materials (i.e., alluvium; where the channel flows within confines of the valley floodplain).

3. Coarser sandy loams and sands occur on the inside stream banks of gradual and sharp curves, respectively, regardless of whether valley wall or floodplain soils exist on the outside bank.

4. While the prominence of in-stream boulders increased from upstream to downstream (and factored into estimates of channel bed roughness), bed sediments did not vary significantly over the mainstem channel length.

As a result of these observed trends, considerable effort was spent estimating soil types at the 126 (of 146) cross-section locations where field data was not collected. In conjunction with observed data from field visits and low altitude aerial photographs, inspection of an ArcGIS relief map (.TIF), generated from the Knife River DEM, provided a reasonable estimate as to where the mainstem channel was near or in contact with the valley wall and where it was not. When necessary, further GIS investigation was conducted using a 5 meter cell-size slope raster and applying buffers to the mainstem stream polyline feature. The buffer widths were set to roughly coincide with the estimated stream widths at bankfull stage. Cross-sections where the buffer intersected cells of the slope raster with a value greater than roughly 20% were assumed to be in contact with valley wall soils.

Cross-sectional soil types were designated by determining (1) planform type (straight or curve), (2) whether left and/or right banks were comprised of valley wall vs. floodplain material, (3) the nearest field sampled soil that conformed to the criteria in (1) and (2). (See Table 8; Note: “5600 Sand” was used for the bed material in *all* cross-sections.)

Table 8. Soils Collected and Analyzed for Use in CONCEPTS

Soil Name[1]	**Sand/Silt/Clay Percent**	**D50 (mm)**	**Usage**
5320 Clay	23.5 / 41 / 35.5	0.007	Valley wall outer banks of 2 sharp curves near where samples originated (Reach 1: CS 41,43)
5320 Sand	89.5 / 10 / 0.5	17.640	Inner banks of sharp curves for all reaches
5600 Sand	92 / 7 / 1	3.000	Channel bed for all reaches
8500 Sandy Loam	58 / 37 / 5	0.080	Floodplain outer banks of sharp and gradual curves, banks of straight sections (Reaches 1-4)
8600 Sandy Loam	66.5 / 30 / 3.5	0.172	Inner banks of gradual curves for all reaches
9000 Silty Clay Loam	20.5 / 49 / 30.5	0.008	Valley wall outer banks of sharp and gradual curves, both banks and bluffs (Reaches 3-4)
13100 Clay	28 / 31 / 41	0.013	Valley wall outer banks of 7 sharp curves, both banks and bluffs (Reach 4)
13640 Clay Loam	27 / 46 / 27	0.016	Valley wall outer banks of 12 sharp and gradual curves, banks of straight sections, both banks and bluffs (Reach 4)
17460 Loam	37 / 43 / 20	0.031	Floodplain outer banks of sharp and gradual curves, banks of straight sections (Reaches 4-5)
18500 Heavy Clay	20 / 15 / 65	0.003	Valley wall outer banks of 2 sharp curves near where samples originated (Reach 4)
19480 Silty Clay Loam	16 / 50 / 34	0.007	Valley wall outer banks of 7 sharp curves, both banks and bluffs (Reach 5)
19620 Sandy/Silty Loam	45 / 49 / 6	0.029	Floodplain outer banks of sharp and gradual curves, banks of straight sections (Reach 5)

1 Soil name comprised of the distance from the model start-point (m) to where soil was sampled, followed by the soil texture

3.6.5. Soil Geotechnical Properties

CONCEPTS requires specific soil geotechnical parameters for prediction of bank erosion and mass failure. See Table 9 for parameters and values used in this study.

Table 9. CONCEPTS Bank Geotechnical Parameters and Assigned Study Values

	Resistance to Erosion					**Resistance to Mass Failure**		
Soil Name	**Bulk Density (kg/m^3)**	**Particle Density (kg/m^3)**	**Porosity (m^3/m^3)**	**Critical Shear Stress (Pa)**	**Erodibility (m/[s*Pa])**	**Cohesion (Pa)**	**Friction Angle (deg)**	**Suction Angle (deg)**
5320 Clay	1350	2700	0.50	20.8	2.19E-08	6000	26	15
5320 Sand	1492	2650	0.44	2.7	6.10E-08	500	35	15
5600 Sand	--	2650	0.35	2.3	6.65E-08	0	36	15
8500 Sandy Loam	1450	2650	0.45	10.9	3.03E-08	2000	31	15
8600 Sandy Loam	1450	2650	0.45	8.5	3.44E-08	2000	32	15
9000 Silty Clay Loam	1325	2650	0.50	21.3	2.17E-08	6000	26	15
13100 Clay	1350	2700	0.50	18.2	2.34E-08	7000	26	15
13640 Clay Loam	1420	2650	0.46	18.9	2.31E-08	6000	27	15
17460 Loam	1423	2650	0.46	18.3	2.34E-08	5000	28	15
18500 Heavy Clay	1350	2700	0.50	21.8	2.15E-08	9000	24	15
19480 Silty Clay Loam	1404	2650	0.47	21.9	2.14E-08	7000	25	15
19620 Sandy / Silty Loam	1391	2650	0.48	13.6	2.71E-08	3000	30	15

Particle density was assumed to be 2700 kg/m^3 for clays and 2650 kg/m^3 for all other textures as per Langendoen (2000). Porosity was estimated from Rawls (1989). Bulk density was then calculated using the function

$$BD = (1 - l) \times r \quad (1)$$

where BD is bulk density (kg/m^3), l is porosity (m^3/m^3) and r is particle density (kg/m^3).

Critical shear stress is the pressure exerted by flowing water at which the detachment of a given soil occurs, and is a very important bank and bed soil parameter in CONCEPTS. Ideally, critical shear stress is measured in situ with a device such as the submersible jet tester developed by Hanson (1990); however, given the project time and cost constraints, another method for estimating this value was needed. Julian and Torres (2006), in a study that produced a conceptual model for hydraulic bank erosion, developed a regression curve to predict critical shear stress using percent silt-clay content as an independent variable. The regression equation was modified slightly for this study and is as follows:

$$\tau_c = 0.0003SC^2 + 0.2177SC \tag{2}$$

where τ_c is the critical shear stress (Pa) to entrain a soil and SC is the percent silt-clay content of the soil. This method was employed to estimate critical shear stress of soils sampled in this study. Erodibility is generally quantified using observed rates of erosion for a given bank soil. Since these data were not available for the study area, the empirical relationship developed by Hanson and Simon (2001) was used to estimate erodibility (K_1):

$$K_1 = 0.1 \times 10^{-6} t_c^{-0.5} \tag{3}$$

where K_1 is the erosion rate constant (i.e., erodibility) of the soil (m/s Pa) and τ_c is the critical shear stress to entrain a soil (Pa) as calculated previously in (2). Given τ_c and K_1, CONCEPTS uses an excess shear stress approach to calculate the lateral erosion rate of a given soil using the equation

$$E = K_1(t - t_c) \tag{4}$$

where E is the soil lateral erosion rate (m/s), τ is the applied shear stress from flow to the soil (Pa) and, τ_c and K_1 are as previously defined in (2) and (3), respectively.

Cohesion, friction angle and suction angle parameters determine the mass failure potential of stream banks in CONCEPTS. Cohesion describes the strength of a soil due to the presence of clay particles and other cementing minerals. Clays have the highest cohesion while sands have no cohesion whatsoever. Friction angle describes the extent to which the shape of individual soil particles affects overall soil strength. A bank soil with a higher friction angle is more resistant to mass failure in absence of other factors (i.e., cohesion and matric suction). Suction angle is the slope of the linear relationship between a soil's matric suction and shear strength; in other words, the rate that the strength of a soil increases with increases in matric suction (i.e., decreases in pore-pressure). These three parameters are generally measured in situ using a device such as the Iowa Borehole Shear Tester (Luggenegger and Hallberg, 1981). However, in this study, estimates were made using reported experimental data (Selby, 1982; Langendoen, 2000).

As mentioned previously, the increased effects of flowing water on a channel curve are not taken into account explicitly within CONCEPTS. Instead, the bank soil parameters on a curve need to be adjusted to properly simulate the increased erosive effects of flow. In this study, critical shear stress was reduced by 50% for gradual curves and 90% for sharp curves. In turn, erodibility values were recalculated using the reduced critical shear stress values. These adjustments are consistent with work done by Langendoen (2007). Bank mass failure parameters were not altered for curves.

3.6.6. Model Runs

CONCEPTS was run once for each storm initially. Output was investigated to ensure that simulated channel depths were reasonably consistent with the estimated depths associated with each storm. This had particular importance in the case of Storm 1 which was intended to simulate conditions at near bankfull. As a result, in subsequent model runs, tributary hydrologic input volumes were adjusted where applicable to ensure simulated flow in all five reaches represented the estimated cross-sectional flow conditions for each observed storm.

CONCEPTS has a number of process submodels that can be selectively turned on and off. All four submodels (hydraulics, sediment transport, bank toe erosion, bank mass failure) were run in this study. However, initial results from the sediment transport submodel greatly over predicted bed erosion. Time was not available to adjust and calibrate the bed erosion parameters; however, net *bank* erosion at the model end-point (erosion – deposition) needed to be determined using the sediment transport submodel. As a result, the bed parameters were adjusted so as to create a non-erodible bed; bed material was set as 99% clay with a critical shear stress of 100 Pa. This allowed CONCEPTS to route the bank sediment and calculate deposition but not entrain bed sediment. Necessarily, net bed erosion was assumed to be zero in this study.

Incoming sediment from the upstream boundary and tributaries was also not accounted for by CONCEPTS in this study. This was deemed necessary given that while time-series total suspended solids (TSS) data was available for the gaged inputs and reasonable estimates attained for the ungaged inputs, particle size information for the incoming sediment loads was not known. As a result, initial model runs predicted an unrealistic amount of deposition from incoming sources immediately after confluence with the mainstem. It was assumed this was due in large part to over-estimation of larger sediment size masses within the incoming flows. Therefore, it was decided to not input these sediment loads into the CONCEPTS schema. Nevertheless, since these loads still factor into the overall analysis of sources their transport out of the system had to be accounted for. In absence of other means to estimate delivery of these incoming sediment loads, it was assumed that it could be estimated from bank sediment delivery ratios calculated by CONCEPTS. This was accomplished by increasing the CONCEPTS predicted delivery ratios to account for the finer particle distribution of the tributary and overland flows (See Results and Discussion).

Output data consisted of (1) sediment erosion data per cross-section: bank erosion, bed deposition, floodplain deposition (also, per size class) and, (2) time-series flow and sediment parameters for the last downstream cross-section in each of the five reaches. The output data were imported in MS Excel and aggregated with macros for analysis.

3.7. Model Bluff Erosion using SEDIMOT II

Numerous steep valley bluffs exist on the Knife River mainstem; where identified, they occur on the outside banks of sharp curves where the channel makes contact with the valley walls in the lower reaches. Thus, the bluffs are often very steep (often greater than 100% slope), possess very little vegetation and consist of valley wall-parent material type soils (i.e., clays and silty clay loams). The rills observed on many of these bluffs indicate that significant erosion from rain drop impacts and overland flow is likely occurring. This is confirmed by observations by SLC-SWCD and MPCA staff that indicated significant erosion was occurring during even relatively small "steady shower" rainfall events. In addition, areas of soil slumping on the upper bluff slopes were observed during field visits.

Twenty-one bluffs were identified by a combination of low altitude aerial photographs provided by SLC-SWCD and field visits (See Figure 15 for locations of bluffs). Bluff lengths, heights and slopes were estimated using ArcGIS and where available, field observations. Based on compiled measurements, the observed bluffs were generalized into two types for modeling purposes. Thirteen bluffs were designated type-1 and represent more significant bluffs possessing steep slopes and bare soil surfaces. Eight bluffs were designated type-2 and represent less significant bluffs possessing more gentle slopes and some cover vegetation. Type-1 and -2 parameters represent average characteristics of each type. See

Table 10 for a summary of bluff characteristics. The average Type-1 bluff possessed a slope length of 120 feet, 40% slope, 0.75 acres surface area and no vegetation. The average Type-2 bluff possessed a slope length of 100 feet, 25% slope, 0.50 acres surface area and 50% cover.

Bluffs were modeled using SEDIMOT II (Wilson et al., 1982), an event-based small watershed model that uses the NRCS Curve Number method for runoff prediction and MUSLE (modified universal soil loss equation) for erosion prediction. The model was run once for each bluff type for each of the three storms in the study. The rain hyetographs for each storm were available from the S2-Nappa rain gauge data and SEDIMOT II utilized this time-series rainfall data directly for runoff and erosion prediction. To simplify the modeling process, bluff soil types were all assumed to be a Silty Clay Loam similar to the 9000 and 19480 soil types (See Table 8). In addition, only the bluff slope area itself was considered for generating runoff thereby ignoring possible overland flow volumes from the individual bluff (upslope) watersheds.

Selection of the MUSLE erodibility factor (denoted as K_2 in this study) was crucial given the individual sensitivities of all the MUSLE parameters. STATSGO listed a K_2 of 0.43 for the Silty Clay Loam soil that is common in the southern half of the watershed. However, this value was deemed too high based on other published experimental data and as a result 0.28 was selected from work reported in Haan et al. (1994). It is possible the value designated in STATSGO represents an annualized mean erodibility factor taking into account various periods during the year, most notably late winter/early spring, when soil erodibility is relatively high. In any case, 0.28 was considered a more reasonable value for the middle of May through the end of June.

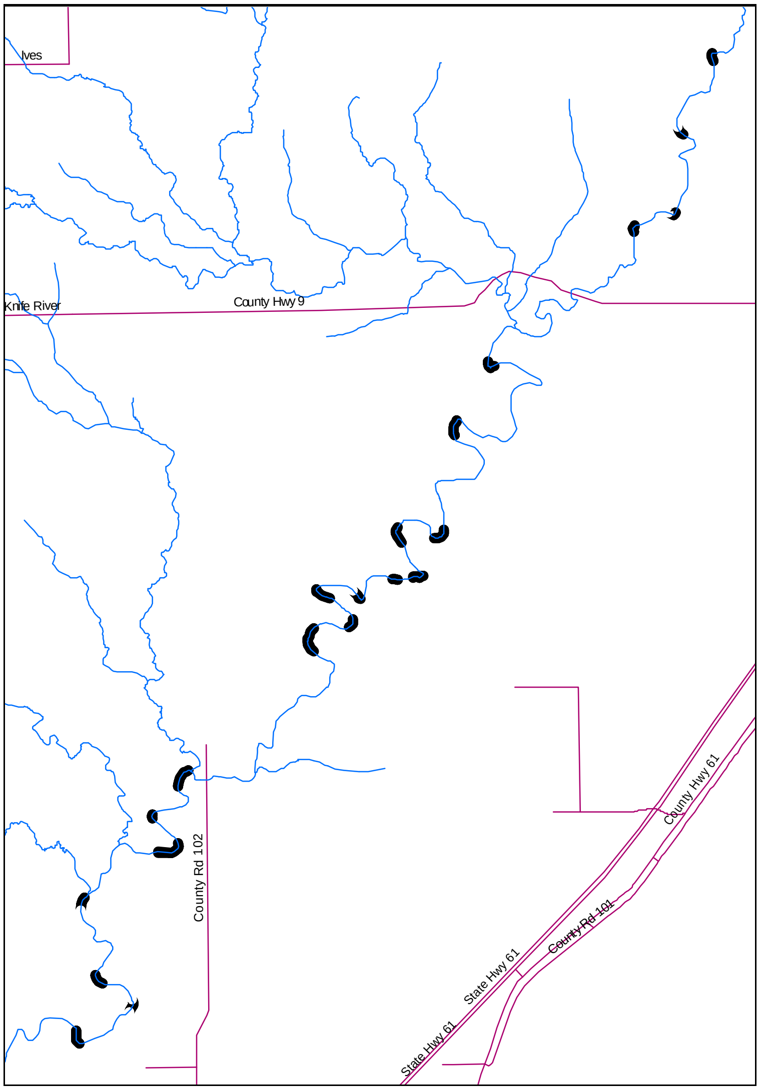


Figure 15. Location of Bluff Features on Knife River mainstem
(Note: The two Baughman bluffs are located furthest downstream [bottom left])

Table 10. Bluff Characteristics and Parameters used in SEDIMOT II Model

Bluff Type	**No. Observed**	**Mean Slope Area (ac)**	**Mean Height (ft)**	**Mean Slope (%)**	**Mean Slope Length (ft)**	**NRCS Curve Number**	**MUSLE *CP* factor**[1]	**MUSLE K_2 factor**[2]
1	13	0.75	45	40	120	80	1.00	0.28
2	8	0.50	25	25	100	80	0.1	0.28

[1] CP factor of 1.0 for unvegetated bare-soil surface, 0.1 for 50% canopy cover

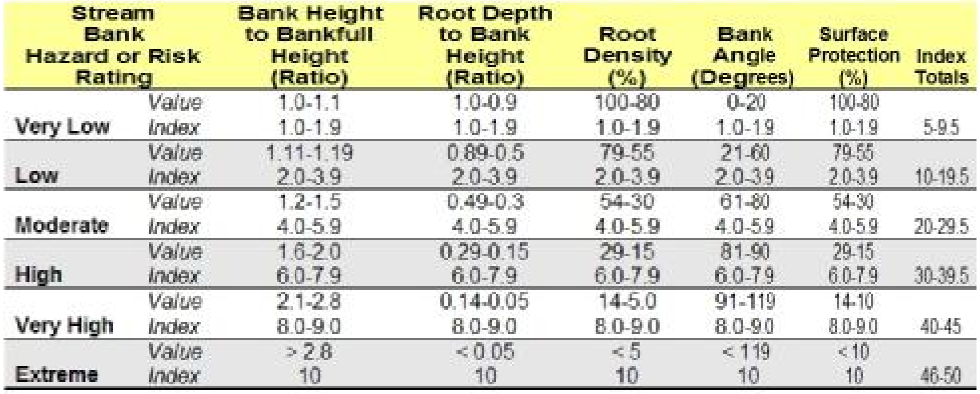
[2] Soil erodibility factor; estimated from Haan et al., 1994

3.8. Model Yearly Bank Erosion using BEHI

BEHI (Bank Erosion Hazard Index) and NBS (Near-Bank Stress) assessments were conducted to provide bank erosion estimates for comparison with CONCEPTS estimates. Both tools are associated with the BANCS (Bank Assessment for Non-point source Consequences of Sediment) methodology (Rosgen, 2006). BEHI evaluates properties of stream banks related to stability; NBS evaluates channel flow conditions and how they affect bank stability. See Figure 16. Together, BEHI and NBS are utilized as independent variables in a series of regression equations that predict annual lateral bank retreat. This one-dimensional erosion estimate is then multiplied by bank height and length to determine annual bank erosion volume.

BEHI scores were calculated using the cross-sections generated for CONCEPTS; thus, the same geometric assumptions and generalizations were applied. Scores for bank height to height ratio, root depth to bank height ratio, and bank angle reflect the 146 per cross-section bank dimensions. Root depth and density for all reaches and cross-sections were assumed to be 2 feet and 50%, respectively. Surface protection for straight, gradual curve and sharp curve planforms were estimated to be 80%, 20% and 10%, respectively. In addition, per cross-section BEHI adjustments were made to differentiate floodplain and parent material soils (+5 and 0, respectively). BEHI scores for each cross-section were tabulated to yield a BEHI rating for each of the 146 cross-sections in the study. Scores and ratings were compared to those gathered in the field and showed good agreement.

NBS scores were determined using the NBS method 5 which uses the ratio of near-bank maximum depth to bankfull mean depth. These depth measurements were readily available for each cross-section. Resulting BEHI and NBS ratings were used to estimate annual lateral bank erosion using the BANCS regression relationships. For each cross-section, bank erosion volume was calculated by multiplying predicted annual lateral bank erosion by total bank height (sum of upper and lower bank heights) and cross-sectional channel length (a measure of one half the channel length between the previous upstream cross-section and the next downstream cross-section). The resulting bank erosion volumes for all cross-sections were added together and multiplied by the estimated bulk density (assumed to be 1400 kg/m^3) to calculate total annual erosion mass.



Stream Bank Hazard or Risk Rating		Bank Height to Bankfull Height (Ratio)	Root Depth to Bank Height (Ratio)	Root Density (%)	Bank Angle (Degrees)	Surface Protection (%)	Index Totals
Very Low	*Value*	1.0-1.1	1.0-0.9	100-80	0-20	100-80	
	Index	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	1.0-1.9	5-9.5
Low	*Value*	1.11-1.19	0.89-0.5	79-55	21-60	79-55	
	Index	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	2.0-3.9	10-19.5
Moderate	*Value*	1.2-1.5	0.49-0.3	54-30	61-80	54-30	
	Index	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	4.0-5.9	20-29.5
High	*Value*	1.6-2.0	0.29-0.15	29-15	81-90	29-15	
	Index	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	6.0-7.9	30-39.5
Very High	*Value*	2.1-2.8	0.14-0.05	14-5.0	91-119	14-10	
	Index	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	8.0-9.0	40-45
Extreme	*Value*	> 2.8	< 0.05	< 5	< 119	< 10	
	Index	10	10	10	10	10	46-50

Figure 16. BEHI Parameters (image from Rosgen, 2006). Note: Bank angle interval for the Extreme rating should read "> 119" degrees.

4. Results and Discussion

4.1. *Overall Results and Sediment Source Percentages*

Each storm was modeled using CONCEPTS to simulate bank erosion and bed deposition, and SEDIMOT II to simulate bluff erosion. These results were compiled with those from gaged and ungaged tributary and overland flow inputs determined from observed data or drainage area relationships to calculate overall proportions of sediment sources. Results of each model are described below. See Table 11 and Figure 17 for compiled results for all models.

Table 11. Erosion and Source Proportion Results from All Models

Storm	**1**	**2**	**3**
Bank Sources			
Bank Erosion (tons)	512.0	133.0	34.0
Bed Deposition (tons)	168.0	36.0	13.0
Calculated Yield Ratio[1]	0.67	0.73	0.62
Net Bank Erosion (tons)	344.0	97.0	21.0
Bank Source Percent	**61.1**	**60.3**	**39.7**
Bluff Sources			
No. of Type-1 Bluff	13	13	13
Type-1 Bluff Erosion Per (tons)	15.9	7.0	5.4
Bluff Erosion Type-1 total (tons)[2]	206.7	90.4	69.6
Applied Yield Ratio[3]	0.73	0.56	0.33
Net Bluff Erosion (tons)	150.9	50.6	23.0
Bluff Source Percent	**26.8**	**31.5**	**43.4**
Trib and Overland Sources			
Airport Upstream Boundary (tons)	22.0	4.2	4.5
Little East Branch TRIB (tons)	16.0	3.5	1.3
Main Stem Watershed (tons)	17.0	3.2	2.3
West Branch TRIB (tons)	15.5	2.1	1.5
Stanley TRIB (tons)	11.0	2.2	1.5
Sub-total (tons)	81.5	15.2	11.1
Applied Yield Ratio[4]	0.84	0.86	0.81
Net Tributary Erosion (tons)	68.1	13.1	8.9
Trib Source Percent	**12.1**	**8.2**	**16.9**
TOTAL SIMULATED (tons)[5]	**563.0**	**160.7**	**52.9**
TOTAL OBSERVED (tons)	**881.0**	**138.0**	**30.0**

1 Overall average bank sediment delivery ratios across all reaches calculated by CONCEPTS (See Tables 12-14)

2 Type-2 bluffs were omitted from the results as they were predicted to produce relatively insignificant amounts of erosion.

3 Average of delivery ratios for reaches 4 and 5 calculated by CONCEPTS; reaches correspond to locations of Type-1 bluffs (See Tables 12-14)

4 Estimated to be halfway between 100% delivery and the overall average delivery ratios calculated by CONCEPTS (see footnote 1)

5 Sum of net erosion estimates for bank, bluff, and tributary and overland sources to the modeled end point of the river.

CONCEPTS predicted 512, 133 and 34 tons of bank erosion (gross) for storms 1, 2 and 3, respectively, with 344, 97 and 21 tons predicted to be transported out of the modeled watershed. SEDIMOT II predicted bluff erosion (gross) of 207, 90 and 70 tons for storms 1, 2 and 3, respectively. To compute net bluff erosion out of the watershed, it was assumed that bluff sediment had similar transport properties to that of banks (a valid assumption given the majority of banks were comprised of the same material) and thus, the CONCEPTS-calculated bank sediment delivery ratios (per storm and per reach) were applied yielding 151, 51 and 23 tons of net bluff erosion for storms 1, 2 and 3, respectively.

Estimates of sediment from observed gaged and estimated ungaged tributary inputs also utilized CONCEPTS delivery ratios. However, sediment associated with the tributary inputs was assumed to be comprised of relatively finer particles when compared to those entrained from bank/bluff erosion. This was based on the assertion that tributary sediment suspended at the point of confluence with the mainstem was the net result of channel deposition that had previously occurred upstream in each tributary. Thus, these sediment loads would be assumed to have greater transport capacity than those generated within the Knife mainstem yet less than 100%. A delivery ratio of less than 100% was selected to allow for a margin of uncertainty accounting for differences in tributary vs. mainstem transport capacity during different periods of each storm. For example, depending on a tributary's time of concentration and location of confluence with the mainstem, it may reach its peak transport capacity early in a storm while mainstem transport capacity is relatively small. Similarly, actual channel geometries of tributaries at their points of confluence with the mainstem are also not known. As a result of these uncertainties, the net bank delivery ratios were adjusted to split the difference between per storm delivery ratio and 100% transport capacity (e.g., storm 1 tributary sediment delivery ratio = 1.0 – [1.0 – 0.67]/2), thereby estimating the greater transport potential of the tributary input sediment. This methodology yielded 68, 13 and 9 tons of tributary sediment exiting the model end-point for storms 1, 2 and 3, respectively.

Sediment source percentages were determined by dividing each of the three sources of net erosion by the total net erosion. Resulting sediment source percentages for banks, bluffs and tributary inputs are, respectively: Storm 1=61%, 27%, 12%; Storm 2=60%, 32%, 8%; Storm 3=40%, 43%, 17%. The source percentages would seem to indicate a number of consistent trends. Bank erosion is a significant source of delivered sediment and its percent contribution increases with magnitude of the flow event. Bluff erosion is also a significant source but its percent contribution decreases with magnitude of flow event. Percent contribution of tributary-borne sediment remains relatively constant with magnitude of flow event. (Note: magnitude is defined here in a general sense to mean the overall effect of the resulting flow from a given storm, whether driven by peak flow, mean flow and/or duration).

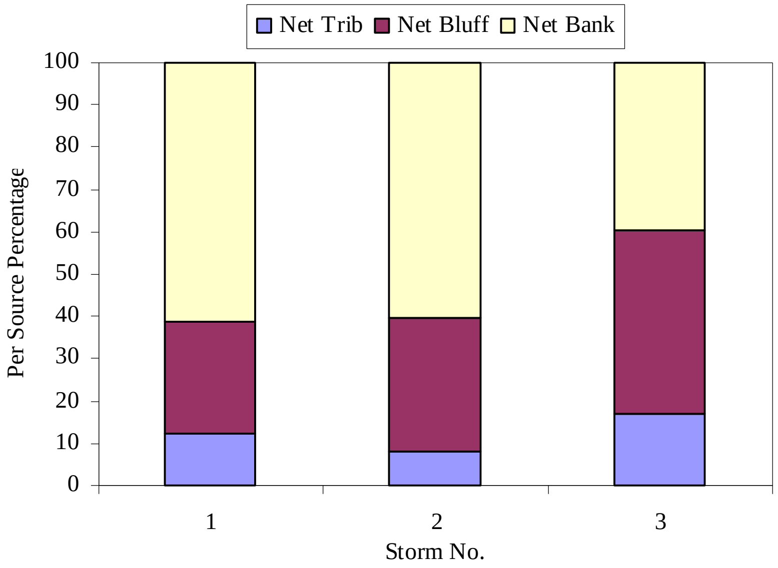


Figure 17. Per Source Percentages for Storms 1, 2 and 3

A per reach breakdown of the source percentages outlined above gives a more precise view of which areas of the mainstem are the primary sediment contributors. See

Table 12 -Table 14.

Reaches 1 and 2 contributed a relatively small amount of net bank erosion, together yielding 26%, 21% and 20% in storms 1, 2 and 3, respectively. Reach 3 was predicted to be the section of the channel where the most deposition was occurring in storm 1 but contributed 9% and 16% of the net bank erosion in storms 2 and 3, respectively.

Reach 5 was predicted to produce 52%, 52% and 59% of the net bank erosion in storms 1, 2 and 3, respectively, as well as 38%, 47% and 80% of the net bluff erosion (type-1). When these proportions are multiplied into the overall source percentages outlined above, Reach 5 produced roughly 44%, 47% and 60% of the total predicted net sediment load from all sources in storms 1, 2 and 3, respectively. In kind, Reach 4 was predicted to contribute 33%, 19% and 5% of the net bank erosion for storms 1, 2 and 3, respectively and 62%, 53% and 20% of the bluff erosion (type-1) yielding 40%, 30% and 13% of the total predicted net sediment load from all sources.

Overall, Reaches 4 and 5, representing the channel length from the West Branch tributary confluence to the model end-point, contributed 84%, 78% and 73% of the total predicted net sediment load (all sources) at the model end-point for storms 1, 2 and 3, respectively. The distribution of bluffs also contributed to the dominance of Reaches 4 and 5: Reach 4 possesses nine type-1 bluffs and Reach 5, four. Reach 3 possesses eight type-2 bluffs but overall these bluffs produced relatively negligible amounts of erosion and are not reported or discussed in this report. Reaches 1 and 2 possessed no bluffs at all. More detailed discussions of modeled bank and bluff erosion are undertaken in subsequent sections.

Table 12. Per-Reach Breakdown of Erosion Sources for Storm 1

	All Reaches	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Per-Reach Bank Erosion Source Percentage[2]	**61.1**	**7.1**	**8.7**	**-6.7**	**20.1**	**31.9**
Gross Bank Erosion (tons)		40.4	49.7	47.1	173.4	202.0
Floodplain and Bed Deposition (tons)		0.1	0.6	84.9	60.2	22.2
Net Bank Erosion (tons)		40.3	49.0	-37.9	113.2	179.8
Bank Erosion Delivery Ratio		1.00	0.99	-0.80	0.65	0.89
Percent of Total Bank Erosion[3]		11.7	14.2	-11.0	32.9	52.2
Per-Reach Bluff Erosion Source Percentage[2]	**26.8**	**0.0**	**0.0**	**0.0**	**16.7**	**10.1**
No. of Type-1 Bluff		0	0	0	9	4
Type-1 Bluff Erosion Per Bluff (tons)		15.9	15.9	15.9	15.9	15.9
Bluff Erosion Type-1 total (tons)		0	0	0	143.1	63.6
Delivery Ratio		1.00	0.99	-0.80	0.65	0.89
Net Type-1 Bluff Erosion (tons)[1]		0.0	0.0	0.0	93.4	56.6
Percent of Total Type-1 Bluff Erosion[3]		0.00	0.00	0.00	62.3	37.7
Per-Reach Overland/Trib Source Percentage[2]	**12.1**	**3.5**	**0.4**	**2.8**	**3.2**	**2.2**
Airport (mainstem) Upstream Boundary (tons)		22.0	--	--	--	--
Little East Branch TRIB (tons)		--	--	16.0	--	--
Main Stem Watershed (tons)		1.7	2.5	3.0	6.0	3.8
West Branch TRIB (tons)		--	--	--	15.5	--
Stanley TRIB (tons)		--	--	--	--	11.0
Delivery Ratio		0.84	0.84	0.84	0.84	0.84
Net Overland and Trib Erosion (tons)		19.9	2.1	15.9	18.0	12.4
Percent of Total Overland and Trib Erosion[3]		29.1	3.1	23.3	26.3	18.2
Per-Reach All Sources Percentage[4]	**100.0**	**10.7**	**9.1**	**-3.9**	**40.0**	**44.2**

[1] Type-2 bluffs were omitted from the results as they were predicted to produce relatively insignificant amounts of erosion.

[2] Percentage of a single erosion source (bank, bluff or overland/trib) with respect to the total erosion from all sources; reported for all reaches and per-reach

[3] Percentage of per-reach erosion with respect to a single erosion source (bank, bluff or overland/trib)

[4] Percentage of per-reach erosion with respect to the total erosion from all sources

Table 13. Per-Reach Breakdown of Erosion Sources for Storm 2

	All Reaches	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Per Reach Bank Erosion Source Percentage[2]	**60.3**	**5.9**	**6.4**	**5.3**	**11.7**	**31.1**
Gross Bank Erosion (tons)		9.8	10.7	8.9	44.5	60.0
Floodplain and Bed Deposition (tons)		0.2	0.3	0.3	25.5	9.4
Net Bank Erosion (tons)		9.6	10.3	8.6	19.0	50.5
Bank Erosion Delivery Ratio		0.98	0.97	0.97	0.43	0.84
Percent of Total Bank Erosion[3]		9.8	10.5	8.8	19.4	51.5
Per Reach Bluff Erosion Source Percentage[2]	**31.5**	**0.0**	**0.0**	**0.0**	**16.8**	**14.7**
No. of Type-1 Bluff		0	0	0	9	4
Type-1 Bluff Erosion Per Bluff (tons)		7.0	7.0	7.0	7.0	7.0
Bluff Erosion Type-1 total (tons)		0	0	0	63	28

Delivery Ratio		0.98	0.97	0.97	0.43	0.84
Net Type-1 Bluff Erosion (tons)[1]		0.0	0.0	0.0	27.0	23.6
Percent of Total Type-1 Bluff Erosion[3]		0.00	0.00	0.00	53.3	46.7
Per Reach Overland/Trib Source Percentage[2]	**8.2**	**2.4**	**0.3**	**2.2**	**1.7**	**1.6**
Airport (mainstem) Upstream Boundary (tons)		4.2	--	--	--	--
Little East Branch TRIB (tons)		--	--	3.5	--	--
Main Stem Watershed (tons)		0.3	0.5	0.6	1.1	0.7
West Branch TRIB (tons)		--	--	--	2.1	--
Stanley TRIB (tons)		--	--	--	--	2.2
Delivery Ratio		0.86	0.86	0.86	0.86	0.86
Net Overland and Trib Erosion (tons)		3.9	0.4	3.5	2.8	2.5
Percent of Total Overland and Trib Erosion[3]		29.8	3.2	26.9	21.0	19.0
Per Reach All Sources Percentage[4]	**100.0**	**8.3**	**6.6**	**7.5**	**30.2**	**47.3**

1 Type-2 bluffs were omitted from the results as they were predicted to produce relatively insignificant amounts of erosion.
2 Percentage of a single erosion source (bank, bluff or overland/trib) with respect to the total erosion from all sources; reported for all reaches and per-reach
3 Percentage of per-reach erosion with respect to a single erosion source (bank, bluff or overland/trib)
4 Percentage of per-reach erosion with respect to the total erosion from all sources

Table 14. Per-Reach Breakdown of Erosion Sources for Storm 3

	All Reaches	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Per Reach Bank Erosion Source Percentage[2]	**39.7**	**3.6**	**4.5**	**6.4**	**1.9**	**23.3**
Gross Bank Erosion (tons)		2.2	2.7	4.0	10.7	14.8
Floodplain and Bed Deposition (tons)		0.2	0.3	0.6	9.7	2.2
Net Bank Erosion (tons)		2.0	2.4	3.5	1.0	12.6
Bank Erosion Delivery Ratio		0.89	0.88	0.86	0.09	0.85
Percent of Total Bank Erosion[3]		9.1	11.3	16.1	4.7	58.7
Per Reach Bluff Erosion Source Percentage[2]	**43.4**	**0.0**	**0.0**	**0.0**	**8.7**	**34.7**
No. of Type-1 Bluff		0	0	0	9	4
Type-1 Bluff Erosion Per Bluff (tons)		5.4	5.4	5.4	5.4	5.4
Bluff Erosion Type-1 total (tons)		0	0	0	48.6	21.6
Delivery Ratio		0.89	0.88	0.86	0.09	0.85
Net Type-1 Bluff Erosion (tons)[1]		0.0	0.0	0.0	4.6	18.4
Percent of Total Type-1 Bluff Erosion[3]		0.00	0.00	0.00	20.0	80.0
Per Reach Overland/Trib Source Percentage[2]	**16.9**	**3.6**	**0.4**	**3.3**	**2.5**	**2.3**
Airport (mainstem) Upstream Boundary (tons)		4.2	--	--	--	--
Little East Branch TRIB (tons)		--	--	3.5	--	--
Main Stem Watershed (tons)		0.3	0.5	0.6	1.1	0.7
West Branch TRIB (tons)		--	--	--	2.1	--
Stanley TRIB (tons)		--	--	--	--	2.2
Delivery Ratio		0.81	0.81	0.81	0.81	0.81
Net Overland and Trib Erosion (tons)		3.7	0.4	3.3	2.6	2.3
Percent of Total Overland and Trib Erosion[3]		29.8	3.2	26.9	21.0	19.0
Per Reach All Sources Percentage[4]	**100.0**	**7.2**	**4.9**	**9.7**	**13.1**	**60.3**

1 Type-2 bluffs were omitted from the results as they were predicted to produce relatively insignificant amounts of erosion.
2 Percentage of a single erosion source (bank, bluff or overland/trib) with respect to the total erosion from all sources; reported for all reaches and per-reach
3 Percentage of per-reach erosion with respect to a single erosion source (bank, bluff or overland/trib)

4 Percentage of per-reach erosion with respect to the total erosion from all sources

4.2. CONCEPTS Bank Erosion Results

4.2.1. Model Output data

CONCEPTS output data consisted of per cross-section bank erosion and bed deposition broken down by each of 14 sediment size classes. These data were aggregated by model reach and net sediment yield was determined for each reach by subtracting total bed deposition from total bank erosion. CONCEPTS per cross-section output represents the total amount of predicted bank erosion from a point equidistant between the specified cross-section and the previous upstream cross-section to a point equidistant between the specified cross-section and next downstream cross-section. Except in cases where a mass bank failure occurs, CONCEPTS erosion prediction represents fluvial erosion at the wetted surface of the bank only.

4.2.2. Storm 1 and Bankfull Simulation

Storm 1 was estimated to have a 0.7 year return period thereby resulting in a flow depth below bankfull. However, initial model runs showed that in certain reaches and modeled time periods CONCEPTS was routing flows for this storm at a depth close to bankfull. This variation could have been caused by a number of factors including inaccurate estimations of roughness coefficients, cross-sectional geometries, and/or ungaged input hydrograph shape, duration and total volume. Calibration of the model could have resolved some of these flow issues but was not scoped in the project timeframe. An attempt at creating a larger (synthetic) storm representing bankfull conditions would have resulted in widespread floodplain flows that would have significantly changed erosion and deposition predictions. Therefore, Storm 1 was assumed to predict erosion results for a storm with a return period between 0.7 and 1.5 years.

4.2.3. Spatial Variation of Predicted Results

Bank erosion predicted by CONCEPTS was affected by the generalized approach used for designation of cross-sectional geometry (i.e., geometries of sharp/gradual curves and straight forms were held constant in each model reach). As a result, soil geotechnical properties and flow rate/depth were the primary factors in the variation of CONCEPTS bank erosion prediction. Banks composed of floodplain soils have a lower critical shear stress (i.e., the threshold to detach sediment) -- because of their predominately loamy texture -- than finer, more cohesive soils. Consequently, CONCEPTS will predict higher bank erosion of these soils when holding all other factors equal. Conversely, the transport potential of these loam soils is less than that of finer soils because of the higher proportion of sands and thus would be more readily deposited in the stream channel. Sharp curves also greatly increase the shear stress on outer bank soils. Taking both these factors into account, it is not surprising that sharp curves with floodplain soils were predicted to contribute the most erosion while straight sections with valley wall soils were predicted to contribute the least. Other important factors that affected shear stress in this study were channel slope (positively correlated) and channel roughness (negatively correlated).

As discussed previously, Reaches 4 and 5 were predicted to produce the majority of bank erosion. Per reach changes in simulated flow conditions at each cross-section (See Table 7) were a major factor in the increased incidence of bank erosion from Reach 3 to Reach 4. The West Branch tributary lies at the start of Reach 4 and was predicted to be the most significant tributary input in terms of flow volume and as a result cross-section geometry changed dramatically from Reach 3 to Reach 4. Overall, from model start- and end-points, bankfull width of the per reach cross-sections increased significantly from Reach 1 to 5 (21 to 57 feet), thalweg and average depth also increased significantly (2.8 to 3.6 feet and 1.8 to 2.2 feet, respectively). These ranges were the result of the generic cross-section analyses of observed cross-sections (See Section 3.6.3 and Figures 4, 6, and 7). These geometric trends had the overall effect of increasing hydraulic radius from 1.7 to 2.1 from Reach 1 to 5, which in turn would cause an increase in flow velocity. Further, the overall increase in thalweg depth would be correlated to increased upper- and lower bank height in Reaches 4 and 5, thereby increasing the wetted area for fluvial erosion. The increased upper bank height (see Figure 8) was also a factor in predicted bank mass failures (i.e., mass wasting, sloughing, slumping). Upper bank heights in Reach 1 and 5 were 2.0 and 3.5 feet, respectively.

Further investigation into the bank sediment contributions from Reaches 4 and 5 reveal that while overall bank erosion masses were similar, per curved cross-section masses were not. For storm 1, Reach 5 was predicted to contribute 15 tons per sharp curve while Reach 4 was predicted to contribute 6 tons. Similar trends were observed for storms 2 and 3 where per sharp curve contributions for Reaches 4 and 5 were 4.5 vs. 1.6 tons and 1.1 vs. 0.4 tons, respectively. The main factor in these discrepancies is the difference in mean channel slope: Reach 4 had a mean channel slope of 0.32% (SD=0.23%) and Reach 5, 0.55% (SD=0.19%). The relative increase in mean channel slope, in conjunction with the incremental increases in bankfull flow depth and upper bank height discussed previously, are the reasons for the disproportionate increase in per curve bank erosion in Reach 5 relative to Reach 4.

4.2.4. Bed Erosion

CONCEPTS was run with the sediment transport submodel enabled but with the bed sediment parameters fixed so that bed erosion would be negligible. This allowed prediction of deposition from bank eroded sediment but eliminated what were assumed to be unrealistic bed erosion and overall bed sediment delivery ratio predictions. A number of factors may have caused this over-prediction including assigned values for bed roughness (manning's n) and bed erodibility. An alternative explanation is that CONCEPTS was realistically predicting a migrating, moving bed but was under predicting deposition resulting in an over-estimation of transport out of the channel. In any case, it was assumed that bed incision in the Knife was not significant in a given storm when compared to the three primary sediment processes quantified in this study.

4.2.5. Assumptions and Uncertainties

Characterization of the channel conditions for CONCEPTS relied on many assumptions regarding cross-sectional geometries and distribution, soil types and geotechnical properties, and estimation of hydrologic inputs. These assumptions significantly impact uncertainty in the model results. Of potentially the greatest impact is the assignment of critical shear stress values for bank soils, per planform and soil type. This geotechnical property (along with the dependent soil erodibility constant) is the foremost determinant of bank erosion in CONCEPTS. However, because in situ measurements of this parameter were not available, use of relatively simple statistical relationships (Julian and Torres, 2006) were necessary to obtain estimations of critical shear stress.

In addition, subaerial erosion processes can have a substantial impact on critical shear stress and were not evaluated in this study. Subaerial erosion, in contrast to fluvial (hydraulic) erosion, refers to weakening of soils in response to freezing/thawing and wetting/drying processes that can affect cohesive soils in particular (Thorne, 1982). Hanson and Cook (2004) found critical shear stress to vary from four to six orders of magnitude depending on the seasonal variation of subaerial effects. In general, one would expect soil erodibility to be greatest during freeze/thaw cycles of the late winter/early spring and late fall/early winter periods as well as summer periods of high temperature and relatively low precipitation. It is difficult to estimate the extent of subaerial potential during the storm events simulated in this study. However, it is extremely probable, given seasonal climate variability and relatively high soil cohesiveness in the Knife watershed, that annualized critical shear stress values could be lower than those estimated in this study. Therefore, significantly higher bank erosion could be produced if storms with similar magnitudes as those simulated in this study occur during periods with high subaerial potential.

Additional consequential assumptions with respect to critical shear stress and overall erodibility potential were (1) designation of one cross-section per curve planform feature and (2) assignment of critical shear stress values of -50% and -90% for gradual and sharp planforms, respectively.

Ideally, two gradual curve cross-sections would have been added to the model schema for every sharp curve. This would simulate the effect of bank conditions in the transitional areas between the apex of the curve and straight sections before and after the curve. However, these additional cross-sections would have more than doubled the total number of cross-sections in the model schema making the model simulations unmanageable in the project timeframe. Nonetheless, since gradual curves were simulated to generate significantly less erosion, the overall effect of these additional cross-sections would have been a reduction in total predicted bank erosion.

Furthermore, adjustments made to critical shear stress values for gradual and sharp curves (as well as unadjusted values for straight sections) may not be optimal given analyses of the output. Overall, total predicted bank erosion seems reasonable given channel observations and total measured per storm sediment loads at S4-Fishtrap. On the other hand, CONCEPTS predicted scant amounts of bank erosion from gradual curve and straight planforms (less than one percent combined of total per storm) when compared to observed conditions. Given bank erosion is observed to occur on these planform types in the Knife (albeit at a reduced level) and total predicted bank erosion seems reasonable, it could indicate that the critical shear stress values for straight and gradual curve planforms were set too high while values on sharp curves may have been set too low. It is unclear to what extent these positive and negative effects offset each other overall.

4.3. SEDIMOT II Bluff Erosion Results

As discussed in the overall model results, bluff erosion was predicted to contribute significant sediment in this study. This prediction is in general agreement with the predominance of bluffs with steep, rilled slopes and bare soil conditions as well as observations of erosion during rain events. Predicted soil mass eroded per bluff expressed as mean depth of soil loss per bluff slope for Storms 1, 2 and 3 was 0.13, 0.06 and 0.05 inches, respectively (assuming a mean bulk density of 1400 kg/m^3).

However, the relatively high extents of erosion predicted in Storms 2 and 3 (7 and 5.4 tons per type-1 bluff; , respectively) when compared to the estimated storm totals at S4-Fishtrap (138 and 30 tons, respectively) may call into question the accuracy of the model and/or its set parameters. Some model uncertainty exists in the proper calculation of the MUSLE *LS* factor on steep sloped sites and it is generally accepted that without proper revisions the standard methodology for calculating *LS* will result in over-estimations of erosion when applied to steeper slopes. Revision of the *LS* was not undertaken in this study. A detailed discussion of MUSLE and USLE is contained in Haan et al. (1994).

Yet, SEDIMOT II parameter values were generally set such that they were assumed to also under predict erosion. For instance, GIS analyses were used to estimate a mean bluff slope for 15 of 21 type-1 bluffs not measured in the field. Nevertheless, based on low altitude photographs of all 21 type-1 bluffs (and field observations of six), the assigned 40% mean slope value is significantly less than what was generally observed.

As well, upslope contributing watershed area was not represented in the simulations; only the bluff slope area was modeled for runoff. The average upslope contributing drainage area for type-1 bluffs was approximately six acres. And given the clay-based soils in these small forested watersheds bounding the mainstem, one could expect significant runoff to the bluff slopes, thereby increasing erosive potential.

Another potential under-predictor of erosion for bluffs (and banks) is the effects of subaerial erosion described previously. The cracking and deformation that can occur as a result of these processes would significantly increase the MUSLE K_2 factor during certain periods of the year. And in fact, while the K_2 factor in this study was set at 0.28, STATSGO specifies a $K_2 = 0.43$ (resulting in a 50% increase in bluff erosion). Evidence of mass wasting on the upper- and mid slopes of bluffs was also observed. This effect ranged from sloughing of saturated soil masses to planar failures along the bluff rim. These discrete, non-linear processes are not simulated by SEDIMOT II.

Given these positive and negative erosion factors, it was assumed overall that the over-estimation of *LS* would be roughly offset by the under-estimations of slope %, drainage area and soil erodibility related parameters. That stated, it is still likely in the case of Storms 2 and 3 that an over-estimation of bluff erosion is occurring. More discussion on the predictive capability of the bluff erosion modeling approach follows in subsequent sections.

4.4. BEHI Bank Erosion Results

BEHI modeling was conducted to provide comparative estimations of stream bank erosion in relation to those predicted by CONCEPTS. Determination of BEHI scores followed the geometries of the 146 generic cross-sections generated for the CONCEPTS modeling, supplemented by field observations of root density and depth. See Table 15 for BEHI results. Mean BEHI scores were rated as having a high degree of bank instability. However, mean NBS (near-bank stress) scores were rated as low. Low NBS ratings were surprising given the extent of bank erosion observed in the field.

BEHI scores were also field calculated for 14 observed channel sections. Scores by reach were: Reach 1: field surveys not conducted; Reach 2: 17, 24, and 39; Reach 3: 22, 23, 26, and 31; Reach 4: 27, 31, 35, and 37; Reach 5: 32, 35, and 36. These scores are in general agreement with the 146 scores calculated using the CONCEPTS generic cross-sections. Near-bank stress scores were not determined for the field calculated BEHI sites.

BEHI and NBS scores from the 146 generic cross-sections were used to predict annual lateral bank erosion using regression curves generated from Colorado USDA Forest Service data for sedimentary and/metamorphic geology (Rosgen, 2006). Ideally, regionally derived BEHI versus NBS regression relationships are used. Minnesota currently does not have BEHI/NBS data available. Other studies have yielded BEHI/NBS curves for regions within North Carolina (Jessup and Harman, 2004) and Arkansas (Van Eps et al., 2004); however, the potential applicability of curves from these studies was not evaluated for this study.

BEHI predictions of lateral erosion per cross-section were converted to volume per cross-section and then to tons per year (as outlined in the Methods) resulting in a total predicted annual (gross) bank erosion of 2,219 tons. Assuming a sediment delivery ratio equal to the average of that predicted by CONCEPTS for Storms 1-3 (0.68), the predicted total annual net bank erosion from model start- to end-point was 1,509 tons.

To convert BEHI annual totals to per storm totals for direct comparison with CONCEPTS predictions, estimated S4-Fishtrap sediment masses for Storms 1-3 were divided by the three-year average of total annual sediment masses for S4 (1850 tons; 2004-2006; from SLC-SWCD) resulting in per storm ratios of 0.32, 0.05 and 0.01, respectively. These ratios were multiplied by the predicted annual BEHI total to yield estimates of per storm net bank erosion of 481, 82 and 16 tons, respectively. These amounts show reasonable agreement with the CONCEPTS predictions of 344, 97 and 21 tons.

Table 15. BEHI Overall and per Reach Results

	Mean BEHI Score	**Mean BEHI Rating**	**Mean NBS Score**	**Mean NBS Rating**	**Annual Net Bank Erosion (tons)**	**Storm 1 Total Net Bank Erosion (tons)**	**Storm 2 Total Net Bank Erosion (tons)**	**Storm 3 Total Net Bank Erosion (tons)**
BEHI predicted total	**32.59**	**High**	**1.44**	**Low**	**1509**	**481**	**82**	**16**
Reach 1	29.96	Mod/High	1.38	Low	133	42	7	1

Reach 2	34.28	High	1.44	Low	206	66	11	2
Reach 3	32.90	High	1.41	Low	236	75	13	2
Reach 4	32.23	High	1.44	Low	545	174	30	6
Reach 5	33.11	High	1.51	Low	390	124	21	4
CONCEPTS predicted total	--	--	--	--	--	***344***	***97***	***21***

Similar to CONCEPTS, BEHI predicted the most bank erosion on curves with the most bank area, i.e., those that occur in Reaches 4 and 5. Resulting BEHI lateral erosion rates were very similar planform-to-planform and reach-to-reach given the uniform average BEHI and NBS ratings study-wide; similarly, distance between cross-sections did not vary appreciably. Accordingly, the greatest differentiator for overall sediment mass was the upper- and lower bank heights which increased considerably in Reaches 4 and 5. Overall, sharp curves were predicted to contribute the majority of BEHI bank erosion. However, unlike CONCEPTS, BEHI predicted gradual and straight planforms to contribute significant amounts of bank erosion as well; this behavior is consistent with observed bank conditions.

4.5. Estimates of Little Knife Tributary Erosion

It has been observed that the Little Knife tributary generates a disproportionally large amount of sediment per unit drainage area during storm events. This is likely due in part to the (1) considerable bank erosion occurring in lower reaches observed by MPCA/SLC-SWCD field visits and in low altitude aerial photographs and (2) sub-watershed wide predominance of clay and clay loam soils.

Estimation of sediment delivery from this tributary however is difficult as it is not gaged. Scaling gaged tributary sediment data, as done with other ungaged inputs in this study, can provide a rough estimate of per storm sediment contributions. The Little East Branch lies in similar soils and is also observed to generate a disproportional amount of sediment per unit drainage area like the Little Knife. Scaling observed sediment data from the S3-Culvert station by drainage area yields Little Knife sediment masses of 25, 6, and 2 tons for storms 1, 2, and 3, respectively. On the other hand, using estimated sediment from S4-Fishtrap as the scaling station yields estimated sediment masses of 108, 17, and 4 tons for storms 1, 2, and 3, respectively.

Alternatively, CONCEPTS bank erosion results for the Knife mainstem can be extended to roughly estimate net bank erosion from the Little Knife (thereby ignoring overland and bed sediment contributions). Low altitude aerial photos reveal stream bank erosion occurring on curves from a point roughly corresponding to Holmstead Rd to the confluence with the Knife mainstem; this start point also corresponds to the start of more prominent curves (sharper and longer) on the Little Knife. Drainage areas at these start- to end-points are roughly 3600 and 6700 acres, respectively. Reach 1 of the Knife mainstem contains channel conditions most similar to the lower reaches of the Little Knife in terms of geometry vs. contributing drainage area (i.e., Reach 1 has the smallest channel geometry in the CONCEPTS model schema). As a result, CONCEPTS results from Reach 1, adjusted for differences in contributing drainage area, were used to estimate Little Knife bank erosion.

Splitting the Little Knife into smaller reaches corresponding to channel segments of relatively constant contributing drainage area (between confluences of tributaries) yielded three reaches (denoted as A, B, and C) with average drainage areas of roughly 3800, 5500 and 6500 acres, respectively. The number of sharp curves for reaches A, B, and C (as identified using GIS) was estimated to be 15, 8 and 8, respectively. The number of gradual curves for reaches A, B, and C was estimated to be 4, 6, and 5, respectively. (Note: cross-sections surveyed by MPCA/SLC-SWCD in 2004 are located near the end of Little Knife reach B).

For mainstem Reach 1, CONCEPTS predicted net bank erosion masses for sharp and gradual curves of 3.5 and 0.5 tons, 0.8 and 0.2 tons, and 0.05 and 0.15 tons, for storms 1, 2, and 3, respectively. Average contributing drainage area of mainstem Reach 1 was roughly 9500 acres; dividing the Little Knife average reach drainage areas by 9500 resulted in drainage area ratios of 0.4, 0.6 and 0.7 for reaches A, B and C, respectively. Estimated net bank erosion for the Little Knife was calculated by multiplying the aforementioned masses (for each reach and curve type) by the drainage ratios. See Table 16 for summary of these calculations. Resulting total Little Knife net bank erosion was estimated as 62, 15 and 2 tons for storms 1, 2, and 3, respectively. These predicted masses are in general agreement with the masses estimated previously by scaling S4-Fishtrap sediment data.

Table 16. Estimation of Little Knife Bank Erosion using CONCEPTS Results from Knife Mainstem

	Little Knife Reach	**No. Little Knife Sharp Curves**	**No. Little Knife Grad. Curves**	**Mainstem Reach 1 CONCEPTS Net Erosion: per sharp curve (tons)**	**Mainstem Reach 1 CONCEPTS Net Erosion: per grad. curve (tons)**	**Drainage Area ratio**	**Est. Little Knife Net Bank Erosion (tons)**
Storm 1	A	15	4	3.5	0.5	0.4	21.8
	B	8	6	3.5	0.5	0.6	18.6
	C	8	5	3.5	0.5	0.7	21.4
						Total	**61.8**
Storm 2	A	15	4	0.8	0.2	0.4	5.1
	B	8	6	0.8	0.2	0.6	4.6
	C	8	5	0.8	0.2	0.7	5.2
						Total	**14.9**
Storm 3	A	15	4	0.05	0.15	0.4	0.5
	B	8	6	0.05	0.15	0.6	0.8
	C	8	5	0.05	0.15	0.7	0.8
						Total	**2.1**

4.6. Overall Performance and Uncertainty of Modeling Approach

Observed sediment masses were not available at the designated model end-point for comparison with total predicted sediment masses; however, observed estimates at the S4-Fishtrap watershed outlet can serve as a rough reference for judging overall model performance (See Table 11 and Figure 18). For storm 1, the overall model approach under predicted total sediment load by 318 tons, or -36%. For storms 2 and 3, total sediment load was over predicted in both cases by 23 tons, or +17% and +77%, respectively.

With respect to storm 1, given the model end-point is upstream of the Little Knife tributary – an input assumed to contribute a disproportionally large amount of sediment as result of the predominance of both (1) clay and clay loam soils and, (2) observed bank and “mini” bluff erosion -- it is reasonable to conclude that inclusion of the Little Knife, as well as several other smaller tributaries between the model end-point and S4, could increase sediment load prediction to roughly equate with the observed load for storm 1. Reasons for over-prediction of Storm 2 and 3 are more uncertain. In addition, given the assumption that the Little Knife and smaller tributaries would be significant contributors in both storms, the over-predictions would be incrementally higher than 17% and 77%, respectively.

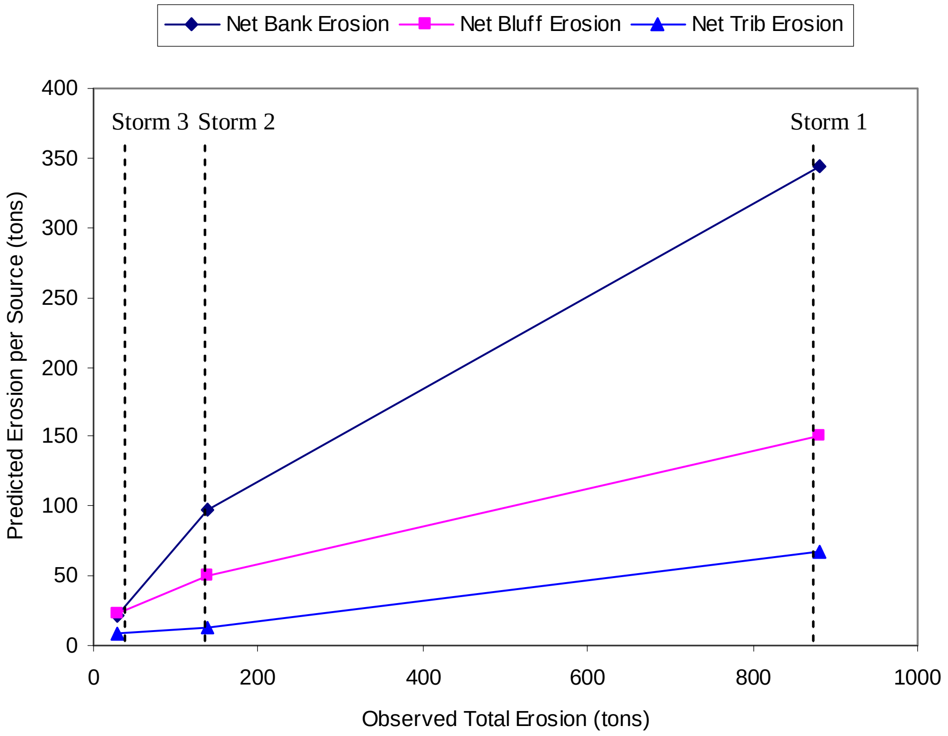


Figure 18. Predicted Erosion per Source vs. Observed Total Erosion for Storms 1, 2 and 3

Overall, uncertainty of the combined model approach is difficult to ascertain as each model component (drainage area analysis for determination of ungaged data using gaged data, CONCEPTS, SEDIMOT II, and BEHI) has its own inherent uncertainties. This is largely because of the relative lack of field data to properly estimate channel and watershed parameters along the entire modeled channel length.

Drainage area analyses relied on assumptions that runoff and sediment from ungaged tributary and overland flow watersheds could be predicted using a gaged watershed. However, many watersheds in the Knife show considerable variability of soils, slopes and land-uses. For example, overall runoff volume over a 4-day flow event could be affected by potential watershed storage such as lakes and wetlands. In particular, the West Branch watershed, based on drainage area (18,050 acres), was predicted to be the most significant mainstem tributary in terms of runoff volume. Yet, 17% of the watershed is open water or wetland, a markedly greater percentage than other mainstem tributaries. Combined with the relatively gentle slopes and sandier soils in much of the West Branch watershed, the per storm predicted runoff (and to some extent, sediment delivery) may have been over-estimated. This would have affected flow conditions in Reaches 4 and 5 where the majority of bank erosion was predicted to occur.

The observed data collected at the four gaging stations possessed uncertainties as well. For example, time-series TSS data used to calculate per storm loads were based on measured turbidity vs. TSS regression curves generated from periodic grab samples. Although 2005 regressions for S1-S4 showed a high goodness-of-fit (r^2=0.97, 0.95, 0.80 and 0.94, respectively), they were not adjusted for periodic calibrations or drift changes. Similarly, S4-Fishtrap per storm observed sediment masses (used for comparison with predicted results) were calculated using a non-linear regression of observed average daily discharge vs. observed daily sediment mass. Although the regression model had an r^2=0.91, considerable error existed for average daily discharges over 400 cfs (storms 1, 2 and 3 had observed average daily discharges of 1200, 446, and 224 cfs, respectively.).

CONCEPTS and SEDIMOT II, as discussed previously, heavily relied upon estimations of essential soil erodibility parameters. Ideally, data collection would have included in situ measurements of soil critical shear stress, detailed soil mapping data (e.g., SSURGO) and observed annual and per storm rates of lateral bank erosion. In addition, collecting these data seasonally would have had the added benefit of capturing the effects of subaerial erosion. In the case of BEHI, it is unclear to what extent near-bank stress was under estimated (mean of “Low” in all reaches) in the model implementation, as discussed previously; or how the differences in regional erosion potential between NE Minnesota and the Colorado dataset used to derive the BEHI regression curves affect predicted erosion in the Knife. Van Eps et al. (2004) showed that curves derived for subsequent BEHI studies in Arkansas and North Carolina varied up to 84% when compared to those from the Colorado dataset.

5. Conclusions and Future Work

The results of this study illustrate with reasonable confidence the proportional contributions of different sources of sediment in the Knife River watershed. In particular, eroding banks and bluffs present on the mainstem downstream of the West Branch and Stanley Creek tributaries, by means of two distinct but interrelated mechanisms (fluvial bank erosion and raindrop/overland flow erosion), contribute the majority of sediment as a result of significant flow events. It is in these reaches that bank and/or bluff stability efforts would provide the greatest net benefit.

Nevertheless, more comprehensive data collection should be undertaken if this modeling approach is extended for use in the implementation phases of a restoration plan. Specifically, in situ measurements of soil geotechnical properties as well as observed rates of bank and bluff retreat would be crucial to confirm and more accurately quantify the results and assertions presented in this study.

This study also shows that watershed- to regional scale implementations of both physically and empirically based, local scale, bank erosion models (CONCEPTS and BEHI, respectively) can still provide useful results despite using parameters estimated using coarser scale GIS, aerial photo and regional hydraulic geometry analyses, supplemented by field data collected in a relatively small number of representative reaches.

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7. Appendix

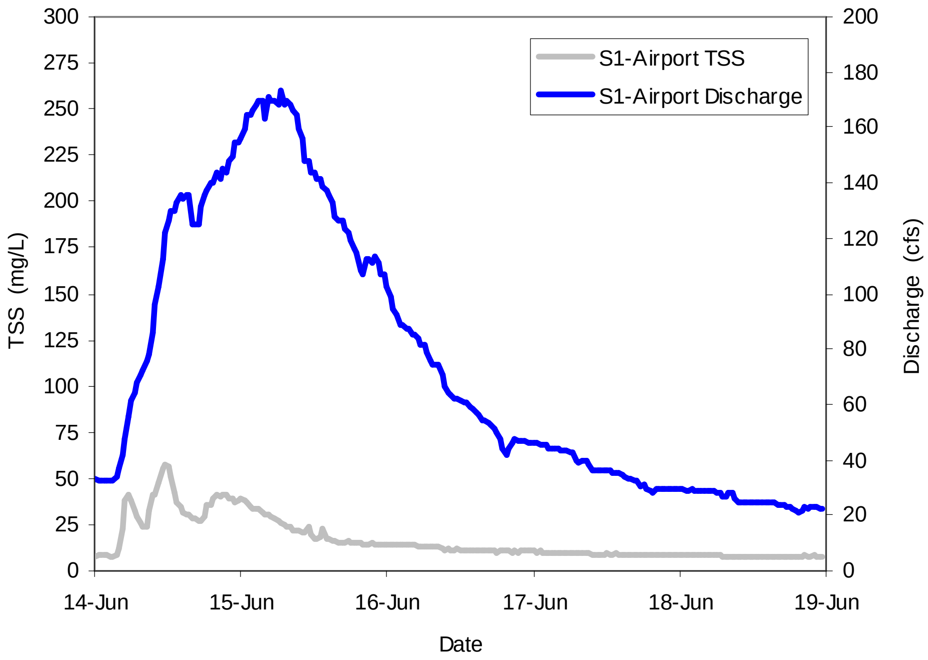


Figure 19. Flow and Sediment Graph for S1-Airport: Storm 1

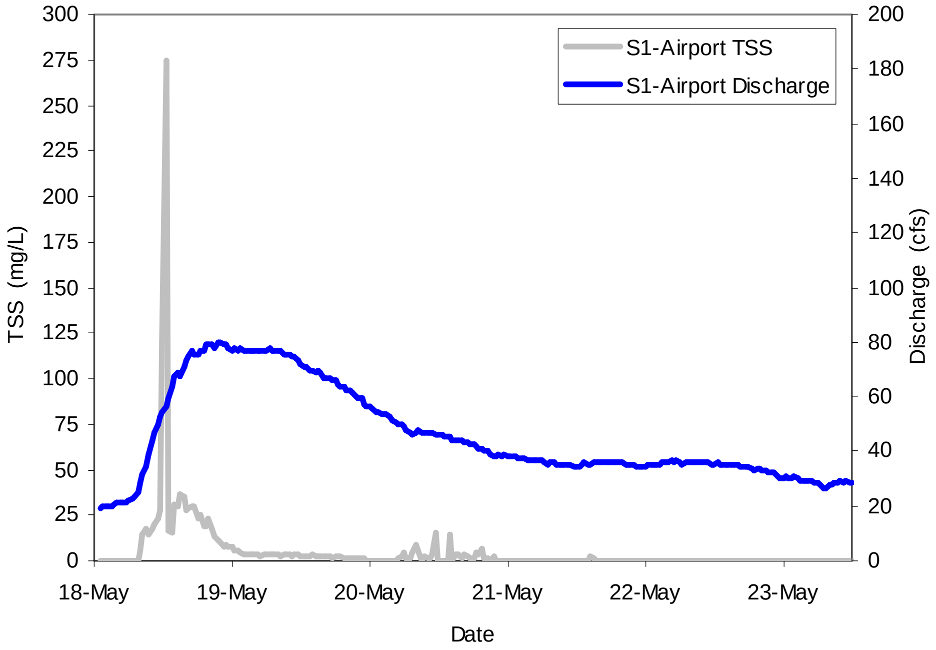


Figure 20. Flow and Sediment Graph for S1-Airport: Storm 2

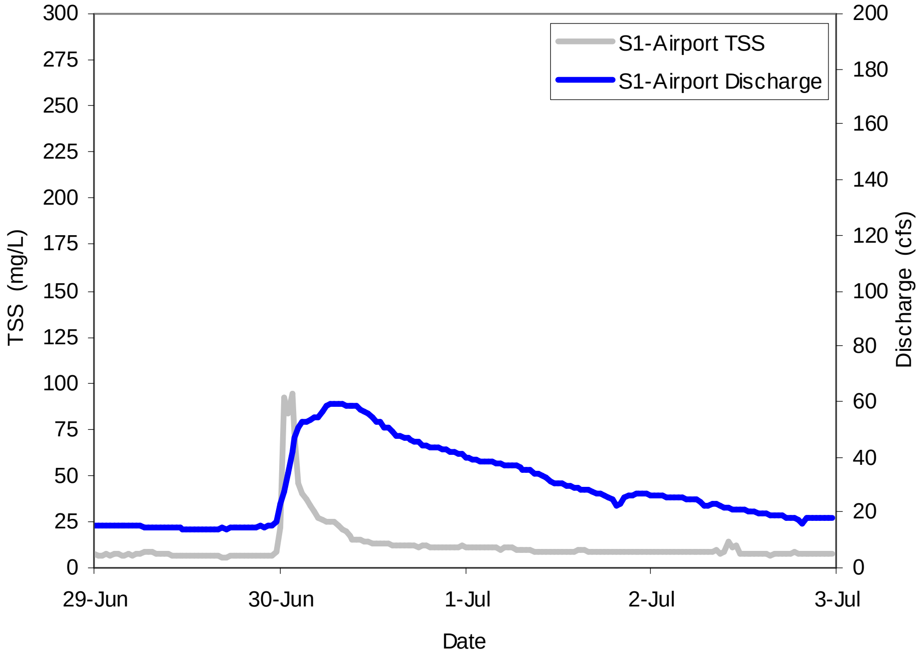


Figure 21. Flow and Sediment Graph for S1-Airport: Storm 3

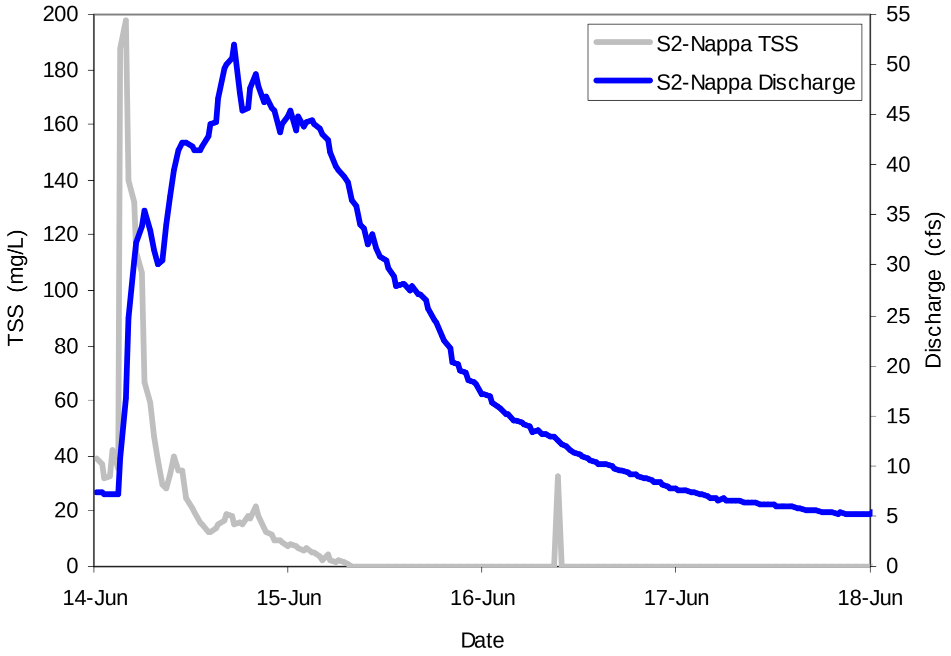


Figure 22. Flow and Sediment Graph for S2-Nappa: Storm 1

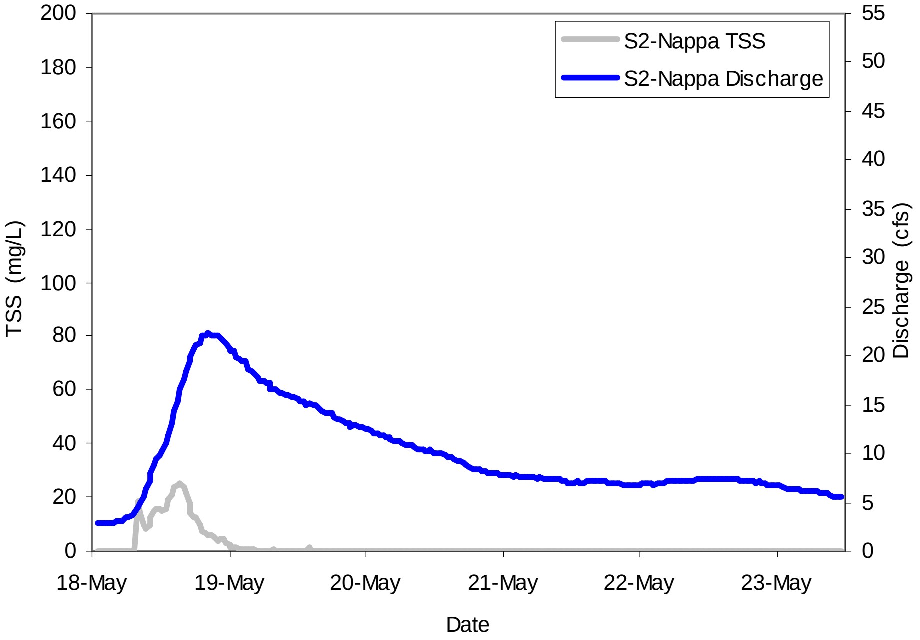


Figure 23. Flow and Sediment Graph for S2-Nappa: Storm 2

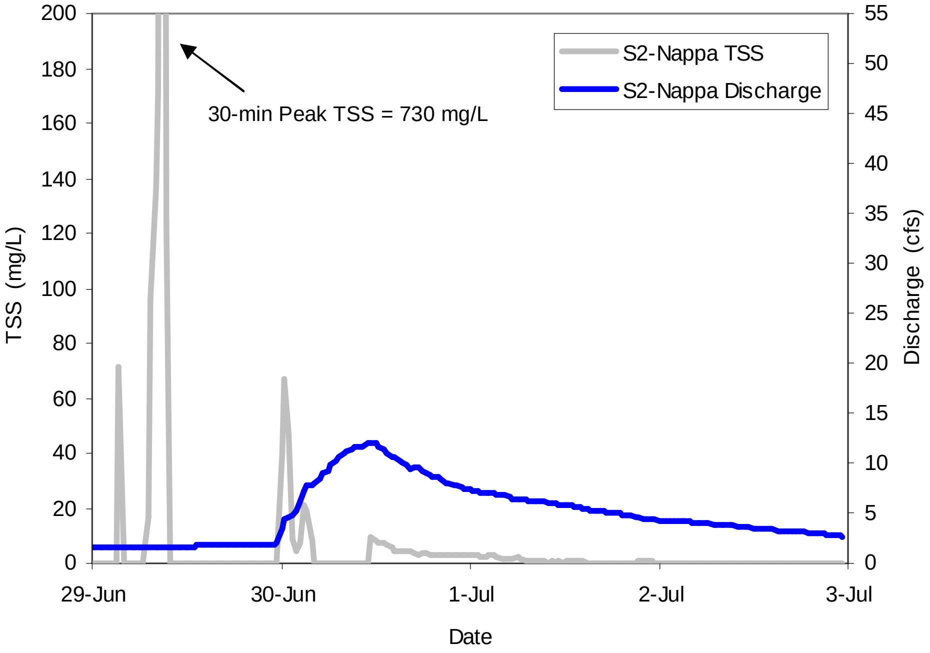


Figure 24. Flow and Sediment Graph for S2-Nappa: Storm 3

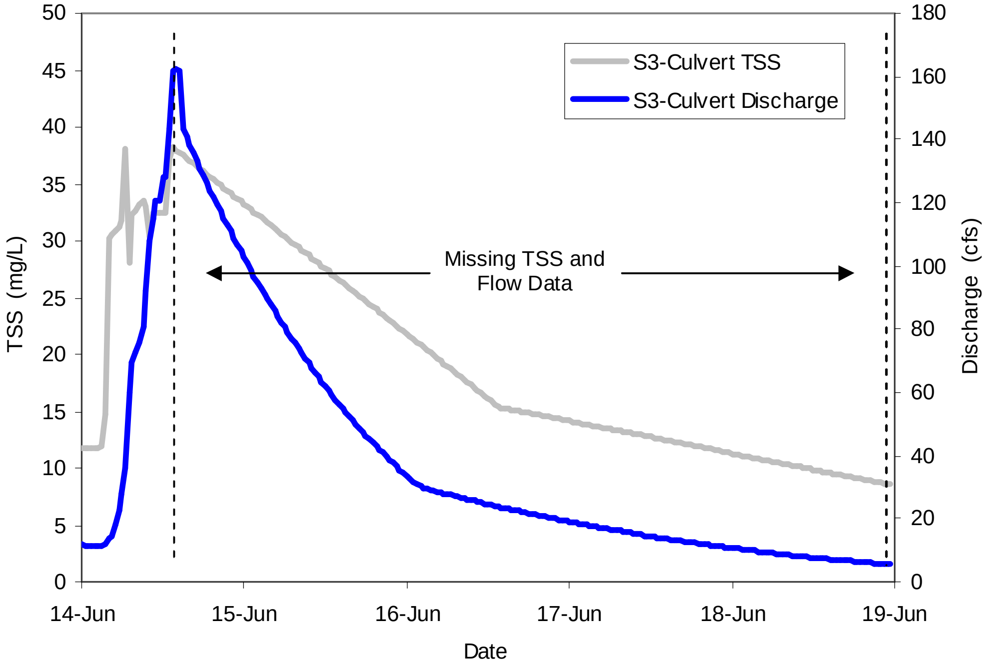


Figure 25. Flow and Sediment Graph for S3-Culvert: Storm 1

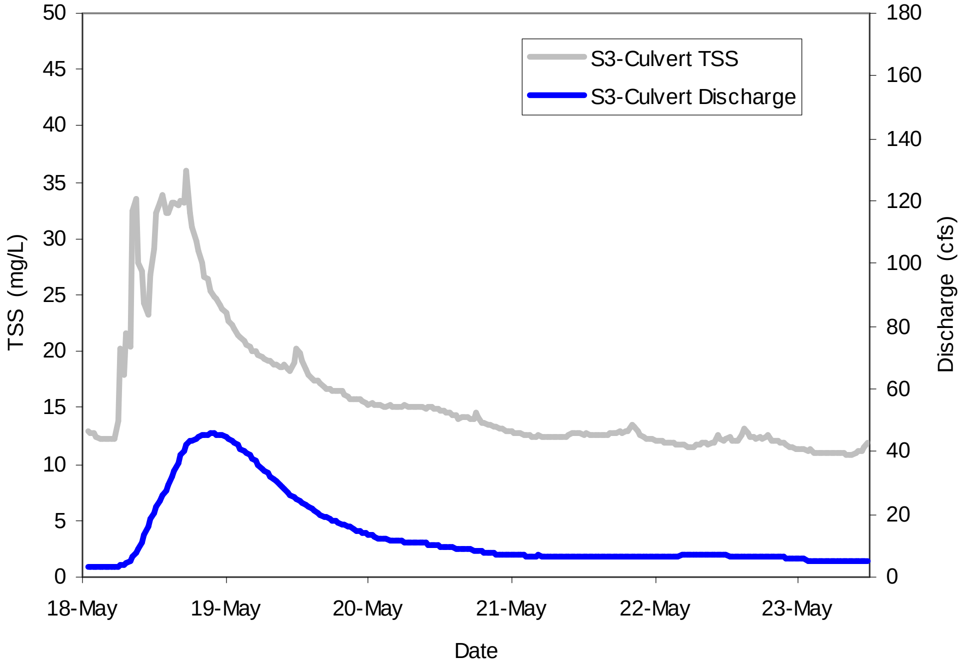


Figure 26. Flow and Sediment Graph for S3-Culvert: Storm 2

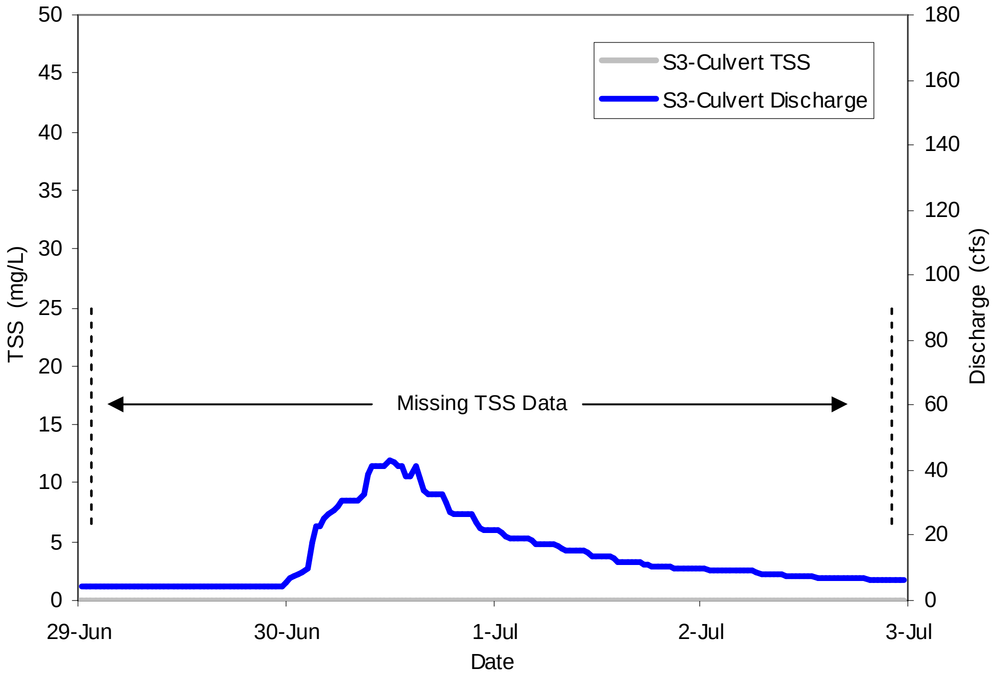


Figure 27. Flow and Sediment Graph for S3-Culvert: Storm 3

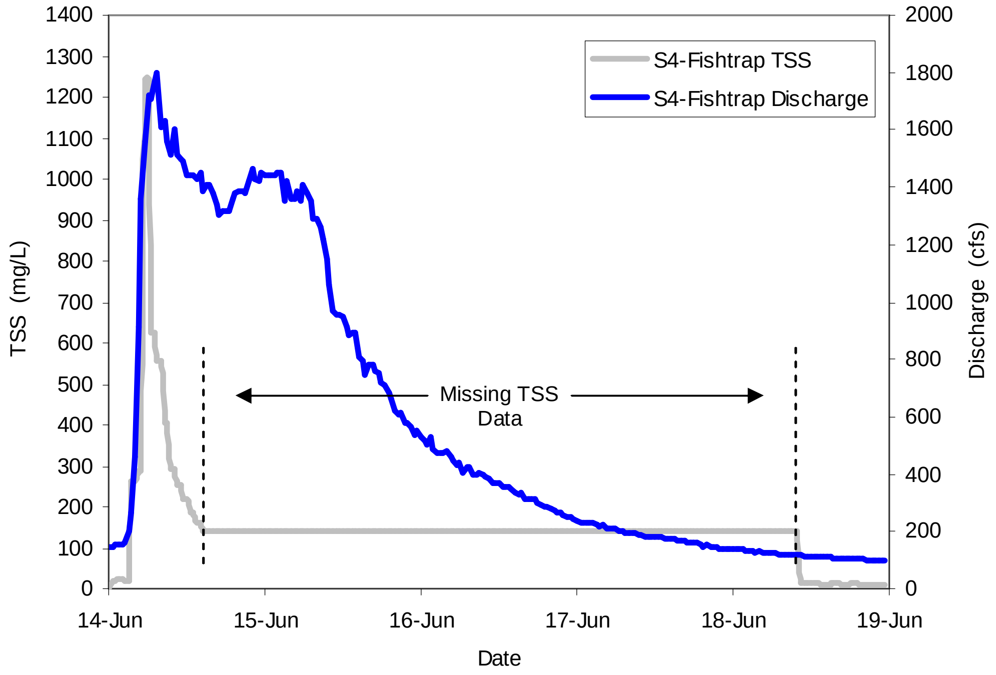


Figure 28. Flow and Sediment Graph for S4-Fishtrap: Storm 1

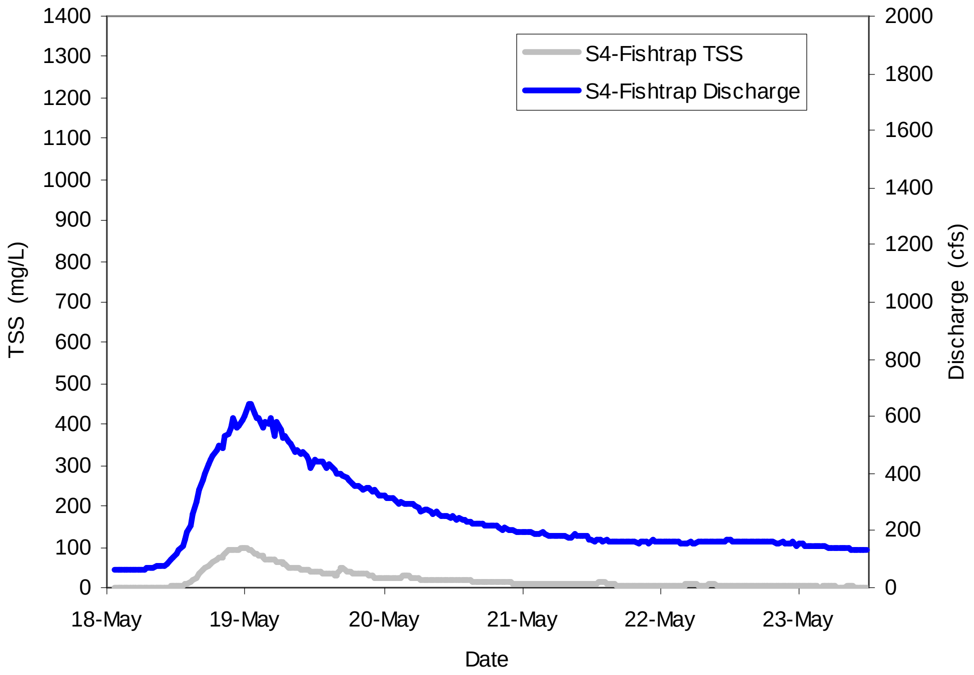


Figure 29. Flow and Sediment Graph for S4-Fishtrap: Storm 2

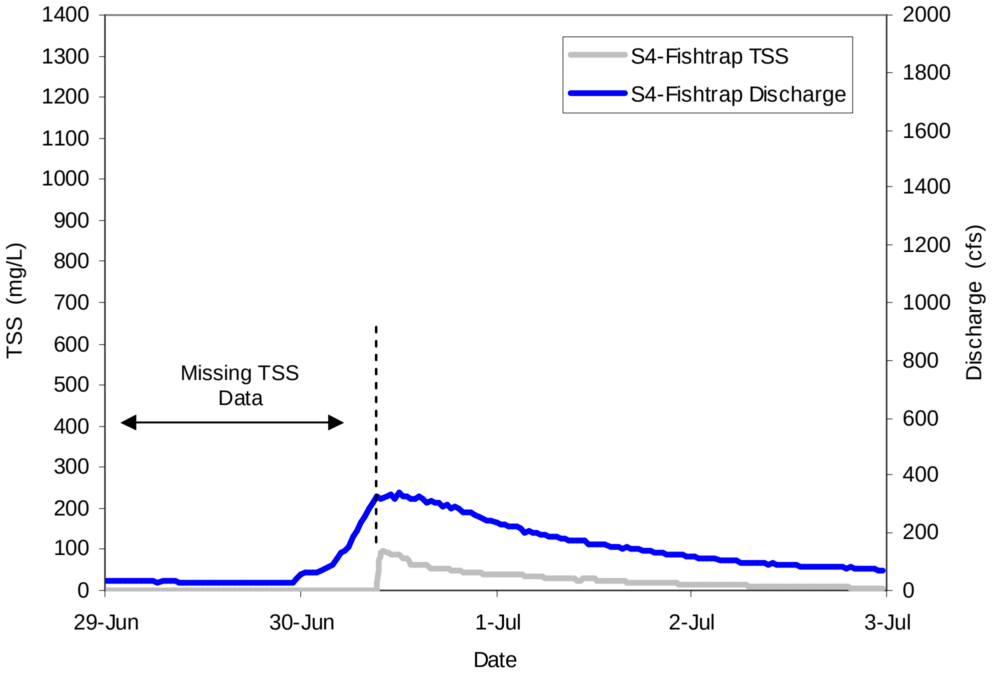


Figure 30. Flow and Sediment Graph for S4-Fishtrap: Storm 3

Table 17. General Cross-Sectional Properties Used for CONCEPTS and BEHI

Cross-Section No.	Dist. from Start (m)	Reach No.	Drain. Area (ac)	Right Bank Soil	Left Bank Soil	Bankfull Elevation (ft)	Avg Slope (%)	Planform
1	0	1	9269	8500 FP Sandy Loam	9000 VW Silt Cl Loam	1121.0	0.90	Grad. Lt. Curve
2	20	1	9276	8500 FP Sandy Loam	9000 VW Silt Cl Loam	1119.4	0.90	Grad. Lt. Curve
3	120	1	9284	8500 FP Sandy Loam	8600 PB Sandy Loam	1116.5	0.90	Grad. Lt. Curve
4	220	1	9293	9000 VW Silt Cl Loam	5320 PB Sand	1113.5	0.90	Sharp Lt. Curve
5	320	1	9299	9000 VW Silt Cl Loam	8500 FP Sandy Loam	1110.6	0.94	Straight
6	400	1	9308	5320 PB Sand	9000 VW Silt Cl Loam	1108.0	1.00	Sharp Rt Curve
7	540	1	9321	9000 VW Silt Cl Loam	5320 PB Sand	1103.3	1.04	Sharp Lt. Curve
8	680	1	9336	9000 VW Silt Cl Loam	9000 VW Silt Cl Loam	1098.5	1.12	Sharp Rt Curve
9	800	1	9340	9000 VW Silt Cl Loam	8600 PB Sandy Loam	1093.8	1.19	Grad. Lt. Curve
10	940	1	9347	5320 PB Sand	9000 VW Silt Cl Loam	1088.3	1.24	Sharp Rt Curve
11	1040	1	9353	9000 VW Silt Cl Loam	5320 PB Sand	1084.2	1.60	Sharp Lt. Curve
12	1200	1	9374	8500 FP Sandy Loam	8500 FP Sandy Loam	1074.0	1.67	Straight
13	1360	1	9392	5320 PB Sand	9000 VW Silt Cl Loam	1066.7	1.12	Sharp Rt Curve
14	1420	1	9394	8500 FP Sandy Loam	5320 PB Sand	1065.0	0.85	Sharp Lt. Curve
15	1560	1	9411	9000 VW Silt Cl Loam	5320 PB Sand	1061.1	0.89	Sharp Lt. Curve
16	1840	1	9432	8500 FP Sandy Loam	8500 FP Sandy Loam	1052.5	1.01	Straight
17	2040	1	9633	9000 VW Silt Cl Loam	8500 FP Sandy Loam	1045.4	1.06	Straight
18	2280	1	9646	9001 VW Silt Cl Loam	5320 PB Sand	1037.2	0.94	Sharp Lt. Curve
19	2360	1	9650	5320 PB Sand	8500 FP Sandy Loam	1035.0	0.85	Sharp Rt Curve
20	2500	2	11730	9001 VW Silt Cl Loam	8600 PB Sandy Loam	1031.1	0.78	Sharp Lt. Curve
21	2780	2	11757	5320 PB Sand	9000 VW Silt Cl Loam	1024.5	0.70	Sharp Rt Curve
22	2900	2	11839	8500 FP Sandy Loam	8500 FP Sandy Loam	1021.8	0.67	Straight
23	3020	2	11846	8500 FP Sandy Loam	5320 PB Sand	1019.3	0.59	Sharp Lt. Curve
24	3180	2	11859	8600 PB Sandy Loam	9000 VW Silt Cl Loam	1016.4	0.54	Grad. Rt Curve
25	3320	2	11924	5320 PB Sand	8500 FP Sandy Loam	1013.9	0.54	Sharp Rt Curve
26	3500	2	11936	8500 FP Sandy Loam	8600 PB Sandy Loam	1010.7	0.56	Sharp Lt. Curve
27	3600	2	11942	8500 FP Sandy Loam	8500 FP Sandy Loam	1008.8	0.58	Straight
28	3680	2	11953	8500 FP Sandy Loam	5320 PB Sand	1007.3	0.59	Sharp Lt. Curve
29	3820	2	11958	5320 PB Sand	9000 VW Silt Cl Loam	1004.6	0.59	Sharp Rt Curve
30	3920	2	11964	8600 PB Sandy Loam	8500 FP Sandy Loam	1002.7	0.59	Sharp Rt Curve
31	4000	2	11965	9000 VW Silt Cl Loam	5320 PB Sand	1001.2	0.58	Sharp Lt. Curve
32	4080	2	11970	8600 PB Sandy Loam	8500 FP Sandy Loam	999.7	0.54	Sharp Rt Curve
33	4180	2	11979	8500 FP Sandy Loam	5320 PB Sand	998.0	0.51	Sharp Lt. Curve
34	4280	2	11986	8600 PB Sandy Loam	8500 FP Sandy Loam	996.3	0.51	Grad. Rt Curve
35	4360	2	11990	8500 FP Sandy Loam	5320 PB Sand	995.0	0.51	Sharp Lt. Curve
36	4480	2	11997	8500 FP Sandy Loam	8500 FP Sandy Loam	993.0	0.51	Straight
37	4580	2	12000	5320 PB Sand	8500 FP Sandy Loam	991.3	0.51	Sharp Rt Curve
38	4680	2	12114	5320 PB Sand	8500 FP Sandy Loam	989.7	0.50	Sharp Rt Curve
39	4780	2	12129	8500 FP Sandy Loam	8600 PB Sandy Loam	988.1	0.49	Grad. Lt. Curve
40	4880	2	12137	5320 PB Sand	8500 FP Sandy Loam	986.5	0.49	Sharp Rt Curve
41	4980	2	12145	5320 VW Clay	5320 PB Sand	984.8	0.49	Sharp Lt. Curve
42	5120	2	12151	5320 PB Sand	8500 FP Sandy Loam	982.6	0.49	Sharp Rt Curve
43	5260	2	12169	5320 VW Clay	5320 PB Sand	980.3	0.42	Sharp Lt. Curve
44	5460	2	12401	5320 PB Sand	8500 FP Sandy Loam	978.0	0.34	Sharp Rt Curve
45	5640	2	12413	8500 FP Sandy Loam	5320 PB Sand	976.1	0.33	Sharp Lt. Curve
46	5800	2	12425	5320 PB Sand	8500 FP Sandy Loam	974.3	0.33	Sharp Rt Curve
47	5920	3	16601	5320 PB Sand	8500 FP Sandy Loam	973.0	0.33	Sharp Rt Curve
48	6060	3	16609	8500 FP Sandy Loam	5320 PB Sand	971.5	0.33	Sharp Lt. Curve
49	6200	3	16719	8500 FP Sandy Loam	8600 PB Sandy Loam	970.0	0.33	Grad. Lt. Curve
50	6360	3	16729	5320 PB Sand	8500 FP Sandy Loam	968.3	0.32	Sharp Rt Curve

51	6500	3	16777	5320 VW Clay	8600 PB Sandy Loam	966.8	0.32	Sharp Lt. Curve
52	6620	3	16782	8500 FP Sandy Loam	8500 FP Sandy Loam	965.5	0.32	Straight
53	6740	3	16817	5320 PB Sand	8500 FP Sandy Loam	964.3	0.32	Sharp Rt Curve
54	6920	3	16835	9000 VW Silt Cl Loam	8600 PB Sandy Loam	962.3	0.32	Grad. Lt. Curve
55	7040	3	17011	9000 VW Silt Cl Loam	9000 VW Silt Cl Loam	961.1	0.32	Grad. Lt. Curve
56	7140	3	17025	9000 VW Silt Cl Loam	5320 PB Sand	960.0	0.92	Sharp Lt. Curve
57	7260	3	17049	5320 PB Sand	8500 FP Sandy Loam	954.0	1.25	Sharp Rt Curve
58	7400	3	17061	9000 VW Silt Cl Loam	5320 PB Sand	949.5	0.61	Sharp Lt. Curve
59	7580	3	17109	8500 FP Sandy Loam	8500 FP Sandy Loam	948.0	0.25	Straight
60	7700	3	17162	8500 FP Sandy Loam	8500 FP Sandy Loam	947.0	0.25	Straight
61	7820	3	17199	5320 PB Sand	9000 VW Silt Cl Loam	946.1	0.25	Sharp Rt Curve
62	8000	3	17251	8600 PB Sandy Loam	8500 FP Sandy Loam	944.6	0.25	Grad. Rt Curve
63	8120	3	17278	9000 VW Silt Cl Loam	5320 PB Sand	943.6	0.25	Sharp Lt. Curve
64	8280	3	17289	8500 FP Sandy Loam	8500 FP Sandy Loam	942.3	0.25	Straight
65	8380	3	17297	5320 PB Sand	8500 FP Sandy Loam	941.5	0.25	Sharp Rt Curve
66	8500	3	17305	9000 VW Silt Cl Loam	8600 PB Sandy Loam	940.5	0.24	Sharp Lt. Curve
67	8600	3	17362	9000 VW Silt Cl Loam	5320 PB Sand	939.7	0.22	Sharp Lt. Curve
68	8740	3	17372	5320 PB Sand	8500 FP Sandy Loam	938.8	0.21	Sharp Rt Curve
69	8900	3	17384	8500 FP Sandy Loam	5320 PB Sand	937.7	0.21	Sharp Lt. Curve
70	9040	3	17407	9000 VW Silt Cl Loam	9000 VW Silt Cl Loam	936.7	0.21	Sharp Rt Curve
71	9180	3	17416	8500 FP Sandy Loam	8500 FP Sandy Loam	935.8	0.21	Straight
72	9320	3	17423	8500 FP Sandy Loam	8600 PB Sandy Loam	934.8	0.21	Sharp Lt. Curve
73	9460	3	17427	8500 FP Sandy Loam	5320 PB Sand	933.8	0.21	Sharp Lt. Curve
74	9620	3	17433	5320 PB Sand	8500 FP Sandy Loam	932.7	0.21	Sharp Rt Curve
75	9800	3	17440	8500 FP Sandy Loam	9000 VW Silt Cl Loam	931.5	0.21	Straight
76	9900	4	35635	9000 VW Silt Cl Loam	5320 PB Sand	930.8	0.20	Sharp Lt. Curve
77	10080	4	35645	9000 VW Silt Cl Loam	8500 FP Sandy Loam	929.7	0.18	Straight
78	10240	4	35667	9000 VW Silt Cl Loam	5320 PB Sand	928.8	0.16	Sharp Lt. Curve
79	10420	4	35675	8500 FP Sandy Loam	8500 FP Sandy Loam	927.8	0.16	Straight
80	10620	4	35801	5320 PB Sand	13100 VW Clay	926.8	0.16	Sharp Rt Curve
81	10840	4	35808	9000 VW Silt Cl Loam	5320 PB Sand	925.6	0.16	Sharp Lt. Curve
82	10980	4	35873	9000 VW Silt Cl Loam	8500 FP Sandy Loam	924.8	0.16	Straight
83	11100	4	35882	5320 PB Sand	13100 VW Clay	924.2	0.16	Sharp Rt Curve
84	11280	4	35896	8500 FP Sandy Loam	8600 PB Sandy Loam	923.2	0.16	Grad. Lt. Curve
85	11400	4	35904	8500 FP Sandy Loam	8500 FP Sandy Loam	922.6	0.16	Straight
86	11640	4	35987	9000 VW Silt Cl Loam	8600 PB Sandy Loam	921.3	0.16	Grad. Lt. Curve
87	11840	4	35998	8500 FP Sandy Loam	8500 FP Sandy Loam	920.2	0.17	Straight
88	12000	4	36049	5320 PB Sand	8500 FP Sandy Loam	919.3	0.17	Sharp Rt Curve
89	12200	4	36086	8500 FP Sandy Loam	8500 FP Sandy Loam	918.2	0.18	Straight
90	12340	4	36107	13100 VW Clay	5320 PB Sand	917.4	0.18	Sharp Lt. Curve
91	12500	4	36148	8500 FP Sandy Loam	8500 FP Sandy Loam	916.4	0.18	Straight
92	12700	4	36207	13100 VW Clay	13100 VW Clay	915.3	0.18	Sharp Rt Curve
93	12840	4	36211	8500 FP Sandy Loam	5320 PB Sand	914.5	0.18	Sharp Lt. Curve
94	13100	4	36266	13100 VW Clay	5320 PB Sand	913.0	0.18	Sharp Lt. Curve
95	13300	4	36275	13100 VW Clay	8600 PB Sandy Loam	911.8	0.18	Grad. Lt. Curve
96	13460	4	36318	5320 PB Sand	13100 VW Clay	910.9	0.19	Sharp Rt Curve
97	13640	4	36329	8600 PB Sandy Loam	13640 VW Clay Loam	909.7	0.35	Grad. Rt Curve
98	13760	4	36345	13640 VW Clay Loam	5320 PB Sand	907.7	0.49	Sharp Lt. Curve
99	14000	4	36360	5320 PB Sand	13640 VW Clay Loam	903.9	0.49	Sharp Rt Curve
100	14140	4	36483	8500 FP Sandy Loam	8600 PB Sandy Loam	901.6	0.52	Grad. Lt. Curve
101	14340	4	36567	13640 VW Clay Loam	5320 PB Sand	898.1	0.56	Sharp Lt. Curve
102	14500	4	36574	8500 FP Sandy Loam	8500 FP Sandy Loam	895.0	0.59	Straight
103	14640	4	36580	5320 PB Sand	13640 VW Clay Loam	892.3	0.60	Sharp Rt Curve
104	14820	4	36600	13640 VW Clay Loam	8600 PB Sandy Loam	888.6	0.66	Grad. Lt. Curve
105	14980	4	36609	13640 VW Clay Loam	5320 PB Sand	885.0	0.69	Sharp Lt. Curve
106	15100	4	36614	8500 FP Sandy Loam	8500 FP Sandy Loam	882.3	0.65	Straight
107	15280	4	36675	8600 PB Sandy Loam	13640 VW Clay Loam	878.7	0.55	Sharp Rt Curve
108	15440	4	36693	5320 PB Sand	13100 VW Clay	876.1	0.49	Sharp Rt Curve

109	15620	4	36712	17460 FP Loam	5320 PB Sand	873.2	0.49	Sharp Lt. Curve
110	15820	4	36783	17460 FP Loam	8600 PB Sandy Loam	870.0	0.49	Grad. Lt. Curve
111	16020	4	36824	8600 PB Sandy Loam	17460 FP Loam	866.8	0.49	Sharp Rt Curve
112	16100	4	36850	13640 VW Clay Loam	5320 PB Sand	865.5	0.49	Sharp Lt. Curve
113	16380	4	37049	8600 PB Sandy Loam	17460 FP Loam	861.0	0.42	Sharp Rt Curve
114	16550	4	37746	17460 FP Loam	17460 FP Loam	859.0	0.31	Straight
115	16880	4	38443	13640 VW Clay Loam	8600 PB Sandy Loam	856.0	0.28	Sharp Lt. Curve
116	16940	4	38446	13640 VW Clay Loam	5320 PB Sand	855.5	0.28	Sharp Lt. Curve
117	17060	4	38453	5320 PB Sand	13640 VW Clay Loam	854.4	0.28	Sharp Rt Curve
118	17180	4	38537	17460 FP Loam	17460 FP Loam	853.3	0.28	Straight
119	17320	4	38546	18500 Heavy Clay	5320 PB Sand	852.0	0.28	Sharp Lt. Curve
120	17460	4	38551	17460 FP Loam	17460 FP Loam	850.7	0.30	Straight
121	17660	4	38567	18500 Heavy Clay	8600 PB Sandy Loam	848.6	0.33	Sharp Lt. Curve
122	17900	4	38592	5320 PB Sand	17460 FP Loam	845.9	0.35	Sharp Rt Curve
123	18060	5	43189	17460 FP Loam	5320 PB Sand	844.1	0.35	Sharp Lt. Curve
124	18200	5	43195	8600 PB Sandy Loam	17460 FP Loam	842.5	0.35	Grad. Rt Curve
125	18340	5	43251	8600 PB Sandy Loam	17460 FP Loam	840.9	0.36	Grad. Rt Curve
126	18500	5	43522	18500 Heavy Clay	5320 PB Sand	839.0	0.37	Sharp Lt. Curve
127	18620	5	43645	19620 FP Sand/Silt Loam	8600 PB Sandy Loam	837.5	0.38	Grad. Lt. Curve
128	18780	5	43713	19620 FP Sand/Silt Loam	5320 PB Sand	835.5	0.38	Sharp Lt. Curve
129	18900	5	43720	5320 PB Sand	19480 VW Si Cl Loam	834.0	0.38	Sharp Rt Curve
130	19010	5	43730	19620 FP Sand/Silt Loam	19620 FP Sand/Silt Loam	832.6	0.38	Straight
131	19160	5	43739	19480 VW Si Cl Loam	5320 PB Sand	830.8	0.31	Sharp Lt. Curve
132	19320	5	43811	8600 PB Sandy Loam	19480 VW Si Cl Loam	829.5	0.45	Grad. Rt Curve
133	19480	5	43883	5320 PB Sand	19480 VW Si Cl Loam	826.1	0.56	Sharp Rt Curve
134	19620	5	43895	19620 FP Sand/Silt Loam	8600 PB Sandy Loam	823.9	0.46	Grad. Lt. Curve
135	19760	5	43923	19620 FP Sand/Silt Loam	19620 FP Sand/Silt Loam	821.8	0.53	Straight
136	19940	5	43966	5320 PB Sand	19480 VW Si Cl Loam	818.3	0.72	Sharp Rt Curve
137	20080	5	43972	19620 FP Sand/Silt Loam	8600 PB Sandy Loam	814.4	0.81	Sharp Lt. Curve
138	20300	5	44012	19480 VW Si Cl Loam	8600 PB Sandy Loam	808.8	0.70	Sharp Lt. Curve
139	20440	5	44023	5320 PB Sand	19480 VW Si Cl Loam	806.0	0.61	Sharp Rt Curve
140	20560	5	44049	19480 VW Si Cl Loam	5320 PB Sand	803.6	0.61	Sharp Lt. Curve
141	20780	5	44110	19620 FP Sand/Silt Loam	19620 FP Sand/Silt Loam	799.2	0.60	Straight
142	21020	5	44153	19620 FP Sand/Silt Loam	19620 FP Sand/Silt Loam	794.6	0.59	Straight
143	21280	5	44229	19480 VW Si Cl Loam	8600 PB Sandy Loam	789.5	0.70	Sharp Lt. Curve
144	21460	5	44237	19480 VW Si Cl Loam	19480 VW Si Cl Loam	784.7	0.80	Straight
145	21620	5	44267	5320 PB Sand	19480 VW Si Cl Loam	780.5	0.89	Sharp Rt Curve
146	21740	5	44278	19620 FP Sand/Silt Loam	19620 FP Sand/Silt Loam	776.7	1.00	Straight

Abbreviations:
Cl = Clay; Si = Silt; PB = Point bar: Inside corner bank material; VW = Valley wall: Parent bank material; FP = Floodplain: Alluvial bank material; Rt. = Right; Lt. =Left

Appendix F: Load Estimates

To calculate a TSS surrogate, regression analysis was completed on the data. To meet statistical methods assumptions for regression analyses, the data were log-transformed to approximate a normal distribution of the data. The strength of the correlation between log-transformed turbidity and TSS data allowed a TSS surrogate value to be estimated for the turbidity standard of 10 NTU at the Fish Trap site using the regression equation **Figure E.1** and **Table 5.6** in Section 5. The surrogate is calculated by solving the regression equation for TSS given a NTU of 10. Hence, the predicted TSS concentration given a turbidity of 10 for the Fish Trap site is 10^(0.920 * Log(10) – 0.23).

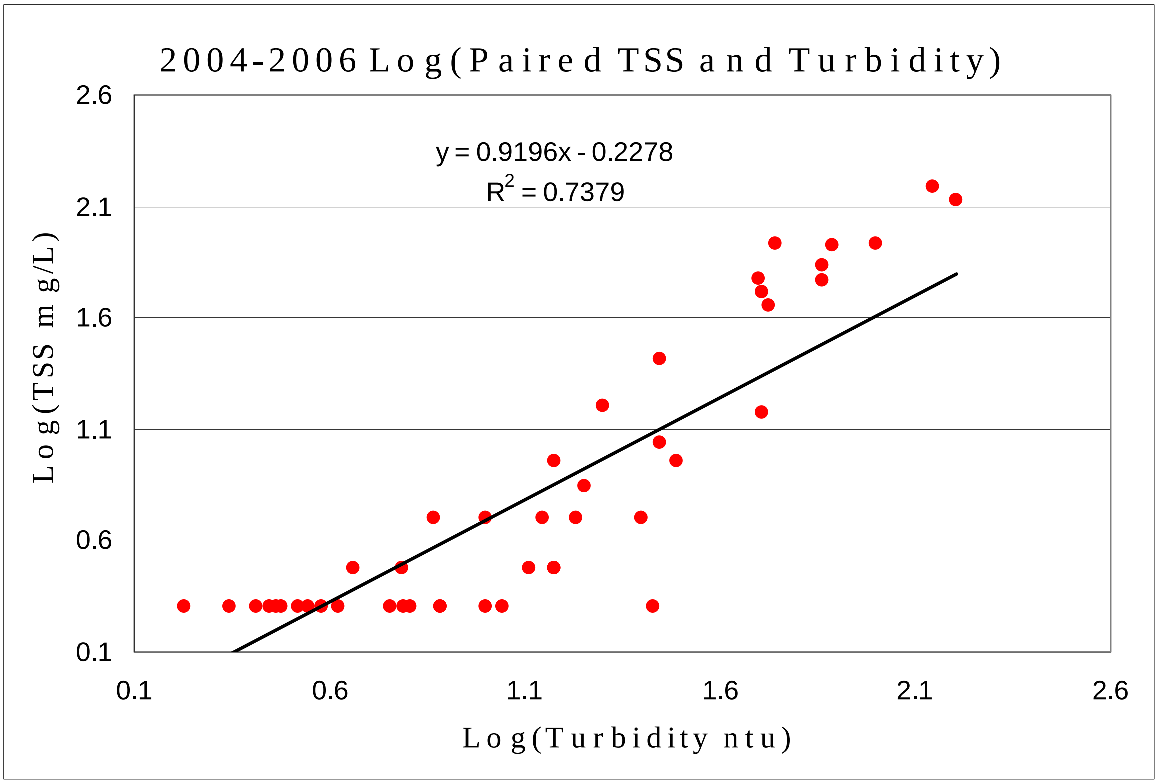


Figure E.1: Regression used to establish target concentration (TSS) from turbidity standard (10 NTU) at the Fish Trap site (S003-642).

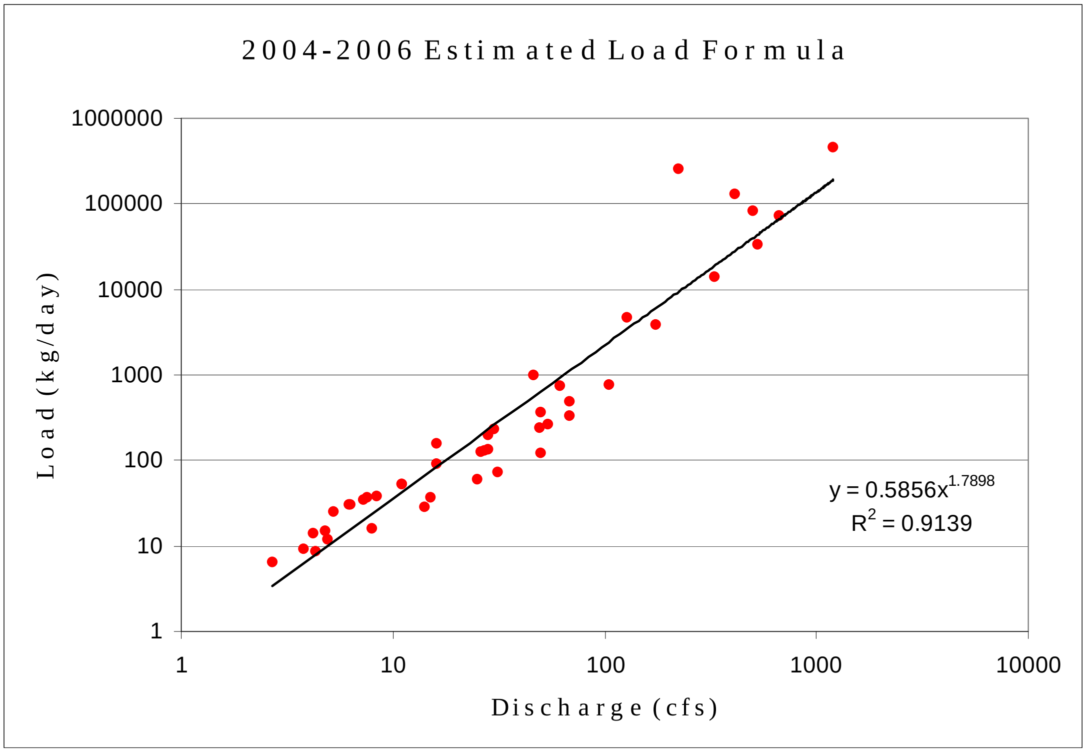


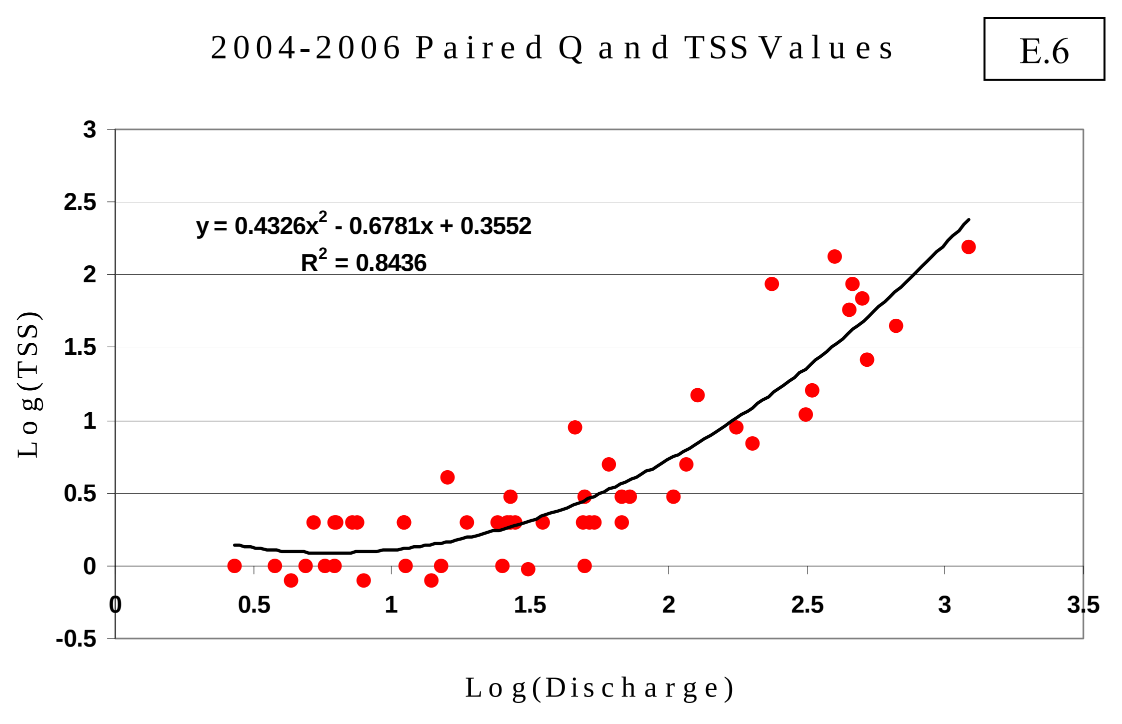
Figure E.2: Regression used to derive formula for estimated load used in duration curve and load duration method (Red dots are grab samples with associated discharge)

Figure E.2 was used to create the "Estimated Load" line on the load duration curve presented in section 5 (**Figure 5.16**). This line is only a tool to help visualize actual versus maximum allowable. The line derived from **Figure E.2** has some introduced bias due to discharge being part of the X variable and the Y variable. This bias is noted and this line serves only an illustrative purpose. No part of the TMDL calculation came from this regression.

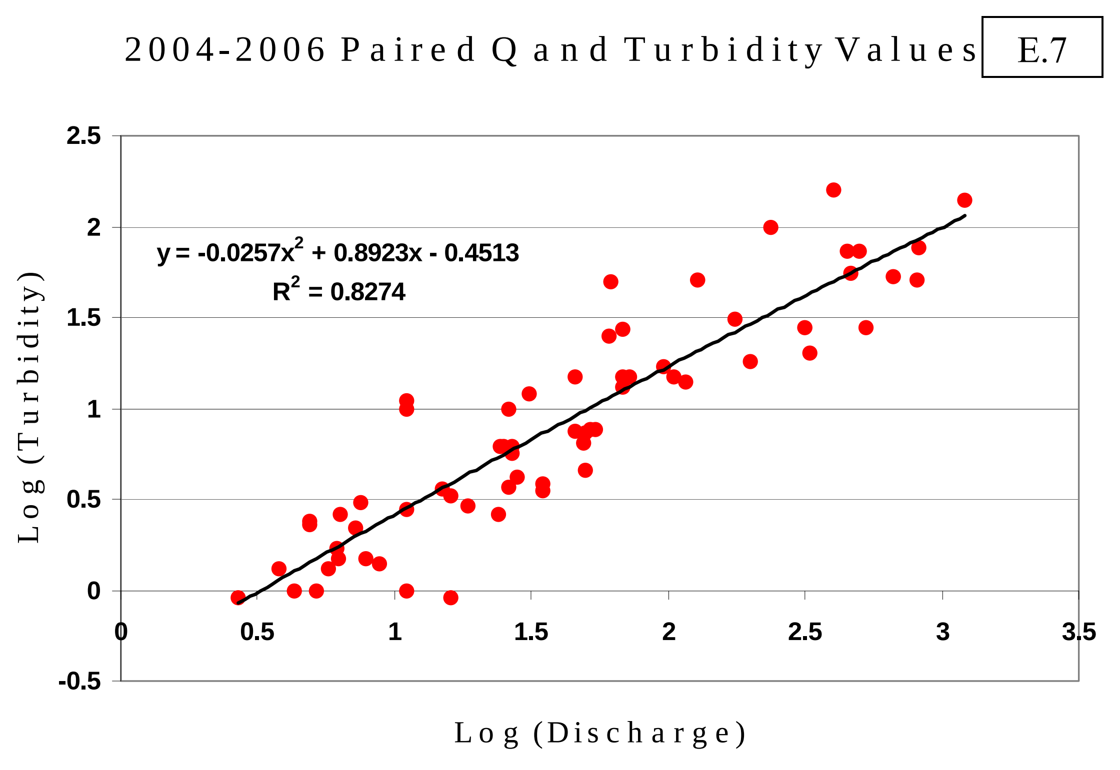
Method	Year	Annual Load (kg)	Mass Sampled (kg)	CV*	FLUX Method	Strata	kg/day	% Sampled
FLUX	2004	2,559,716	1,402,584	0.234	6	2	7013	54.79%
FLUX	2004	2,635,441	1,443,089	0.145	5	3	7215	54.76%
FLUX	2004	2,549,774	1,396,180	0.212	6	3	6981	54.76%
Average		**3,030,875**	**1,611,661**				**7950**	53.17%
FLUX	2005	4,198,177	2,425,230	0.184	4	2	11494	57.77%
FLUX	2005	5,643,416	3,260,125	0.199	4	3	15451	57.77%
FLUX	2005	3,579,412	2,067,778	0.191	4*	2	9800	57.77%
Average		**3,016,276**	**1,598,754**				**7849**	53.00%
FLUX	2006	2,300,078	1,234,265	0.501	3	2	6297	53.66%
FLUX	2006	2,166,867	1,162,782	0.472	2	3	5933	53.66%
FLUX	2006	2,254,094	1,209,589	0.502	3	3	6171	53.66%
Average		**2,366,752**	**1,228,064**				**6202**	51.89%

Table E.1: Summary of all the calculated loads using all of the different methods

E.6



E.7



Figures E.6-7: Alternative methods to predict turbidity and TSS

Figure E.6 and **E.7** present alternative methods to predict turbidity and TSS using discharge. These parameters are often related to each other, but were not used in any calculations for this TMDL