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.

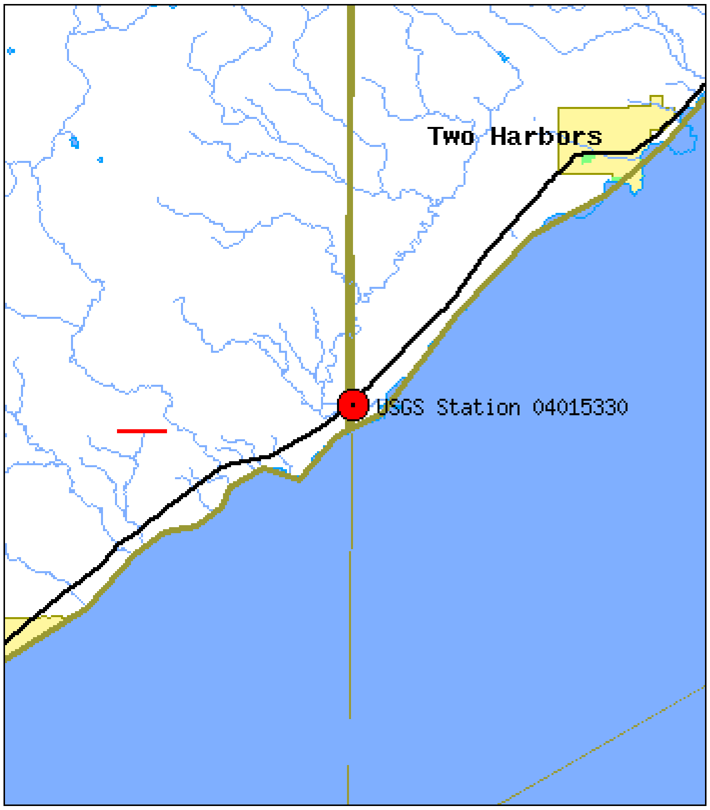


Figure 1. Map of the location for the USGS gage for the Knife River near Two Harbors.

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

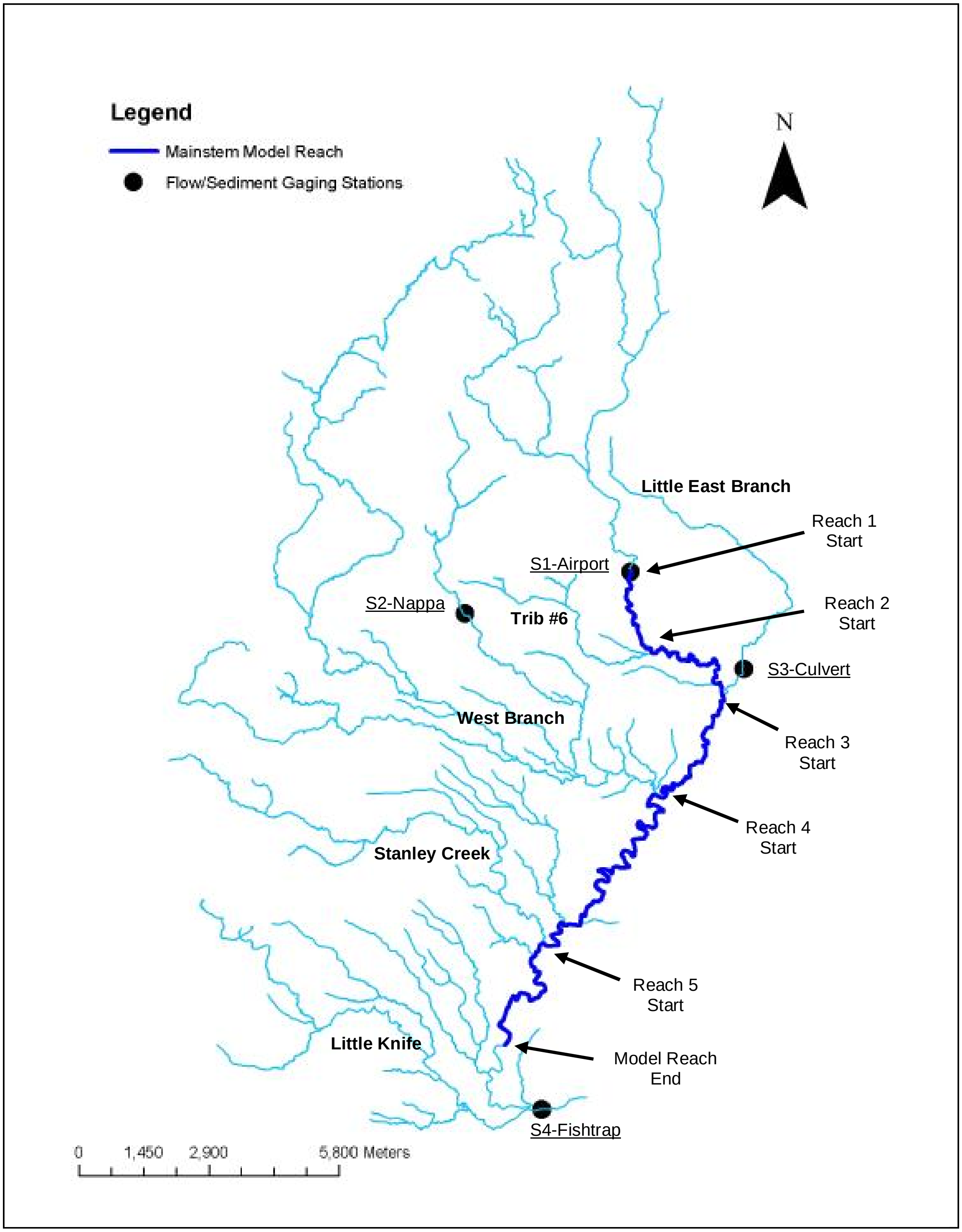


Figure 2. Map of Study Area

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

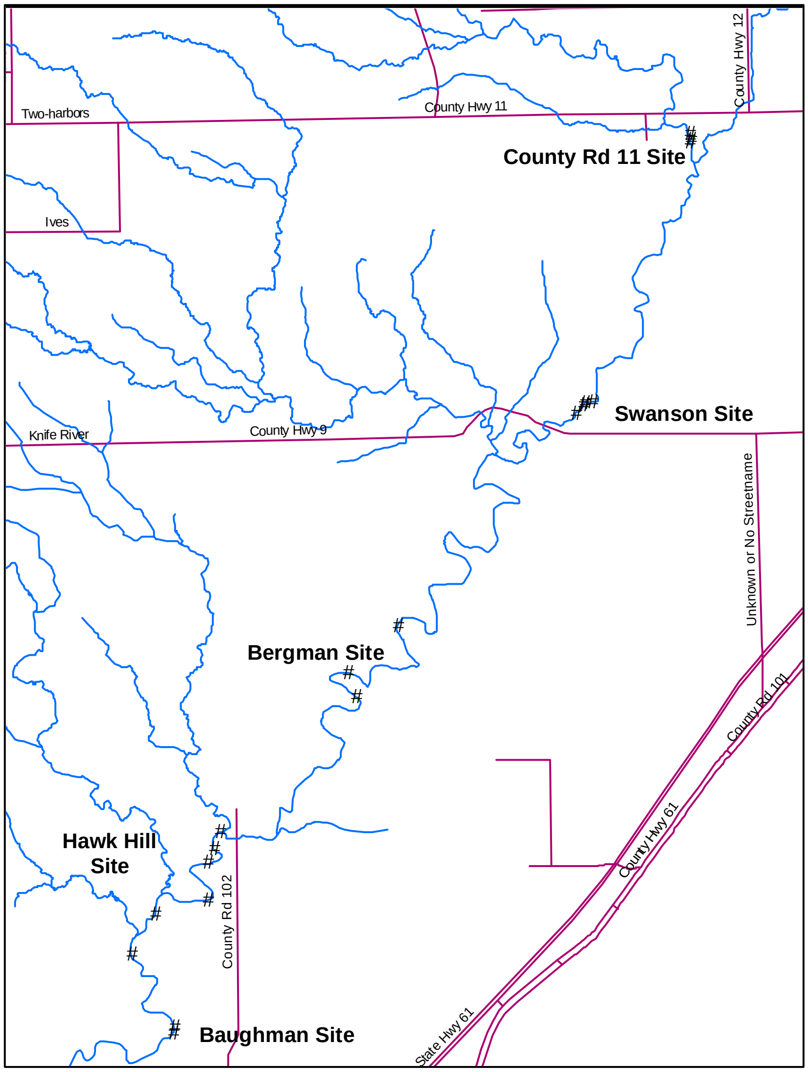


Figure 3. Locations of Field Surveyed Cross-Sections

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).

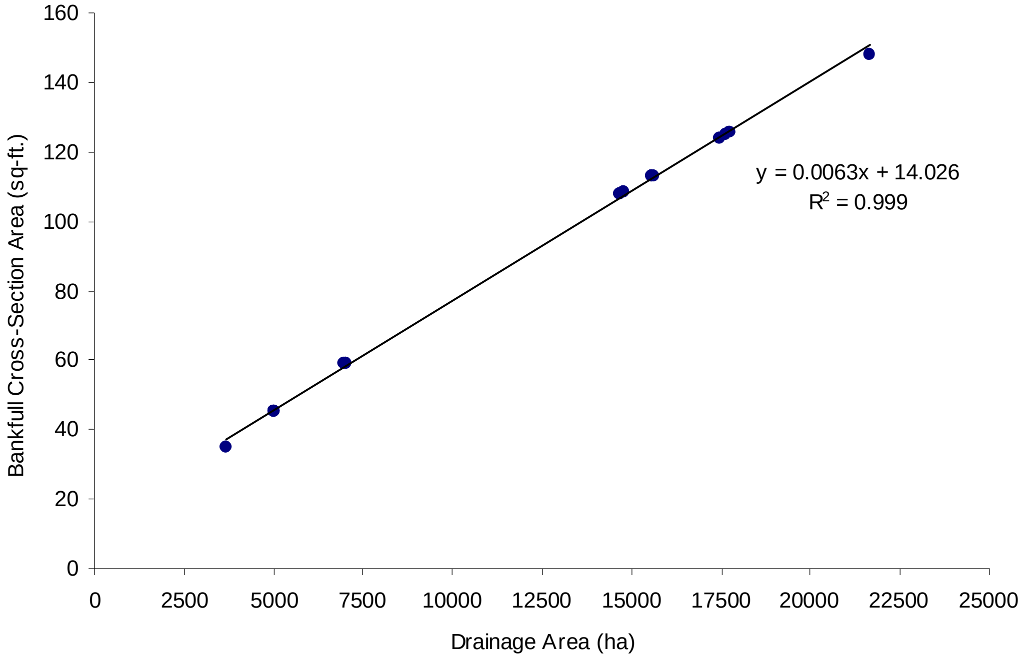


Figure 4. Hydraulic Geometry Drainage Area Relationships: Bankfull Cross-Sectional Area

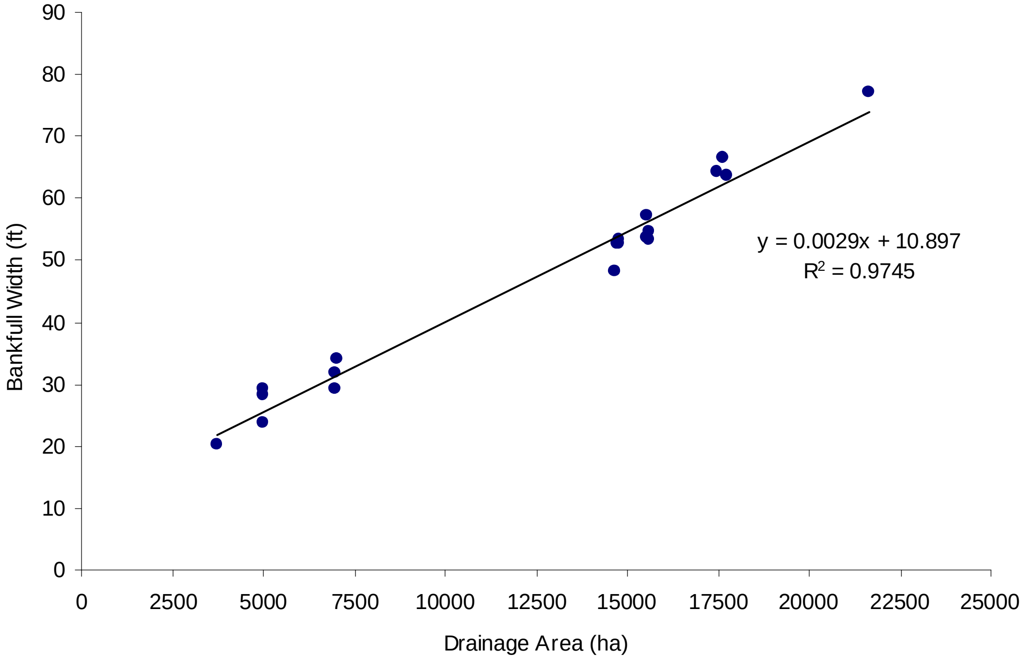


Figure 5. Hydraulic Geometry Drainage Area Relationships: Bankfull Width

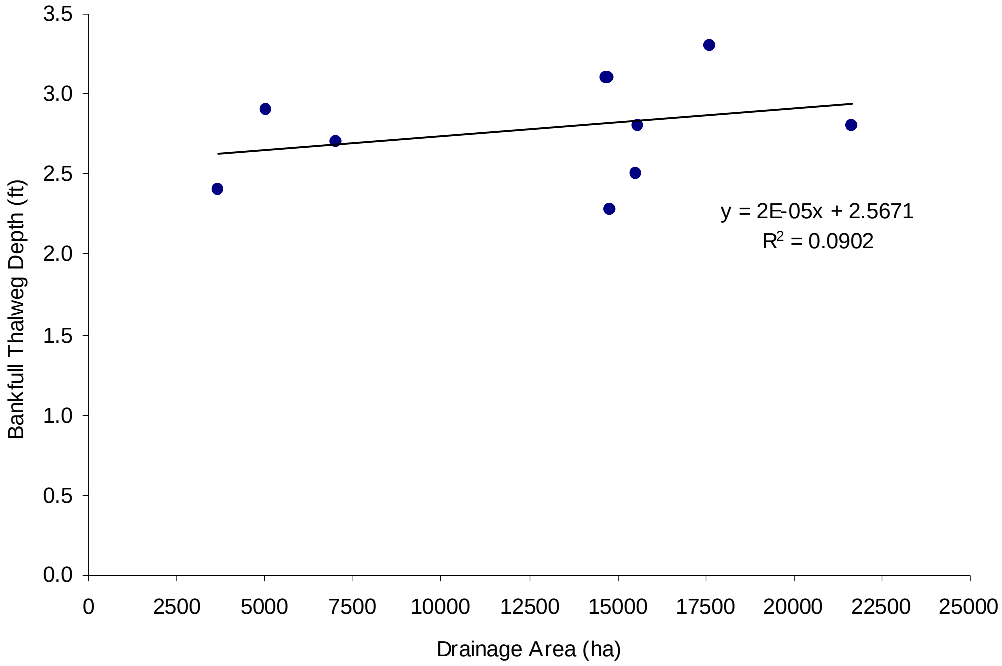


Figure 6. Hydraulic Geometry Drainage Area Relationships: Bankfull Thalweg Depth (Straight Planforms)

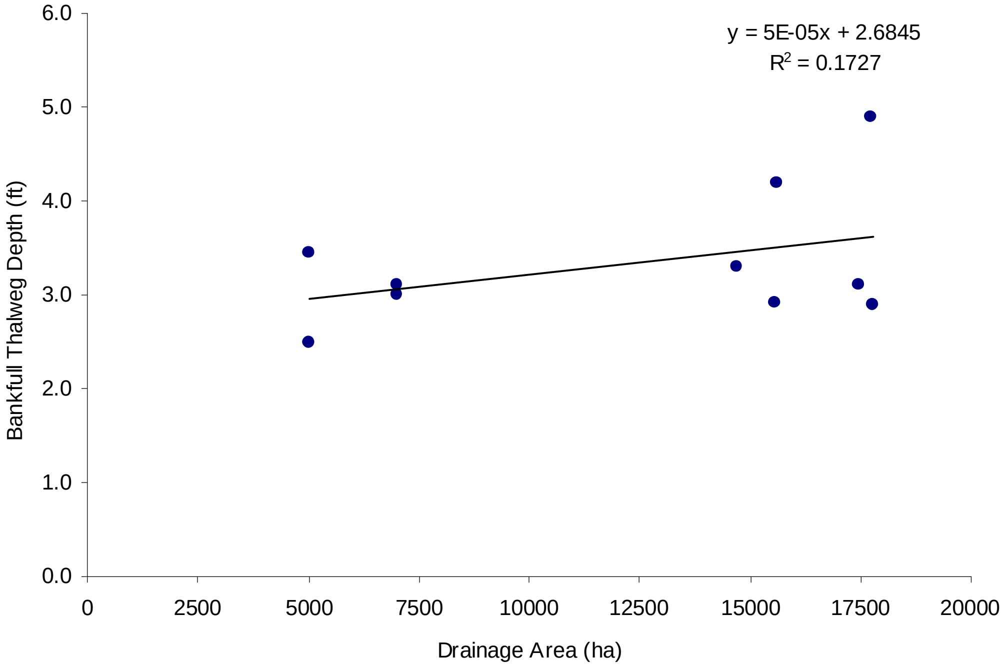


Figure 7. Hydraulic Geometry Drainage Area Relationships: Bankfull Thalweg Depth (Curve Planforms)

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.

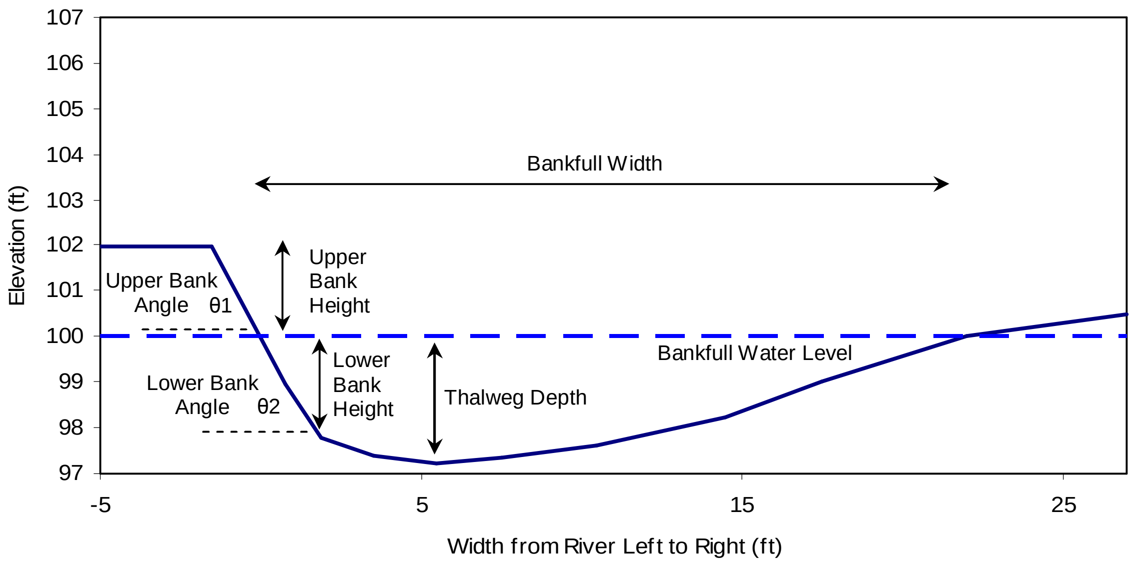


Figure 8. Diagram of Important Cross-Sectional Geometric Properties

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.

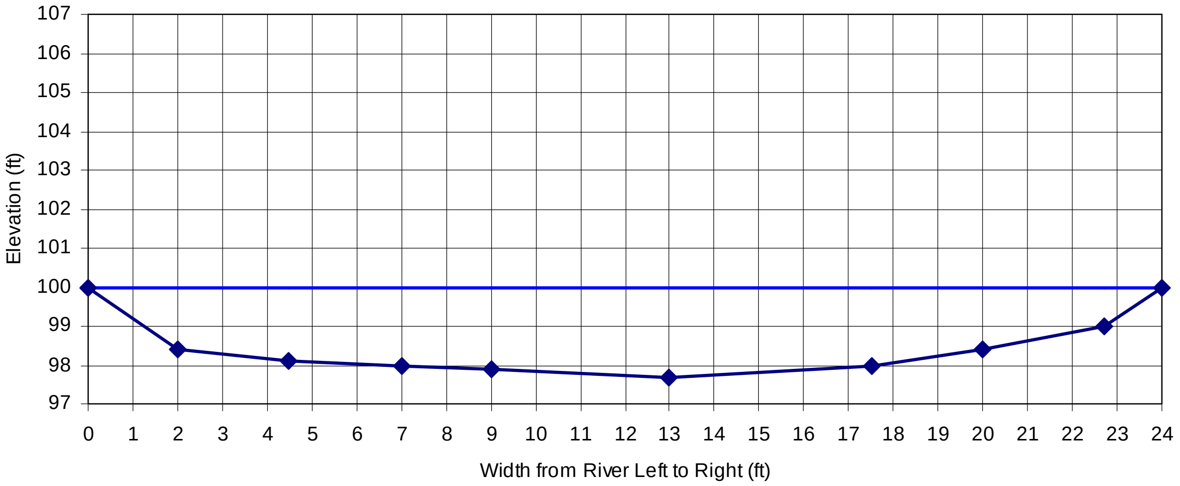


Figure 9. Generic Cross-section for Straight Planform Type, Reach 1

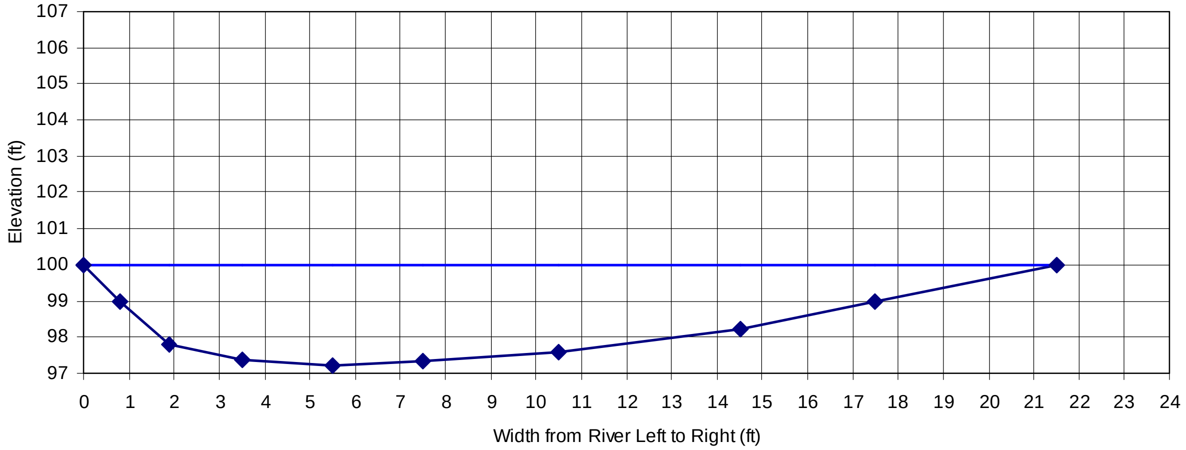


Figure 10. Generic Cross-section for Sharp Curve Planform Type, Reach 1

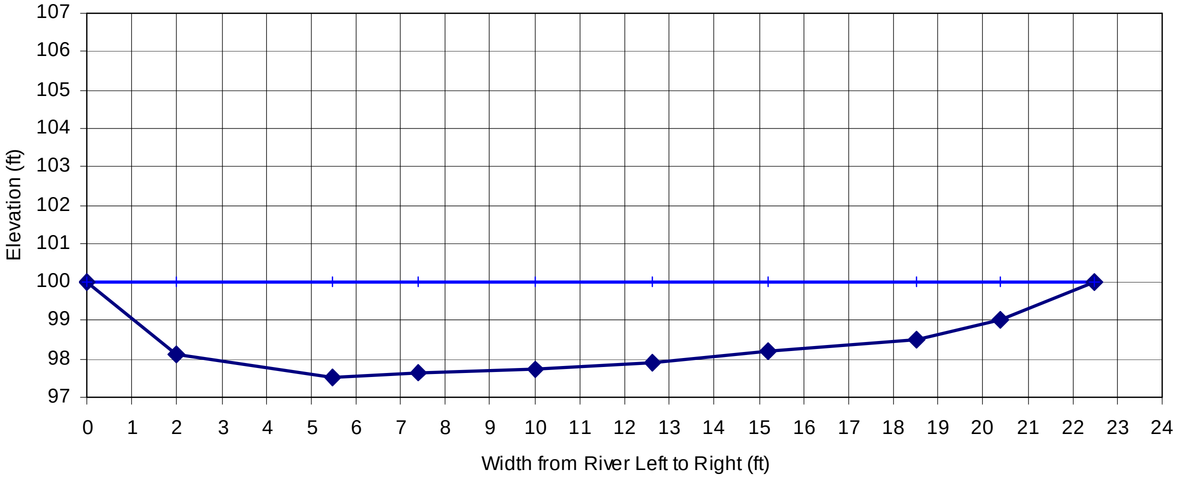


Figure 11. Generic Cross-section for Gradual Curve Planform Type, Reach 1

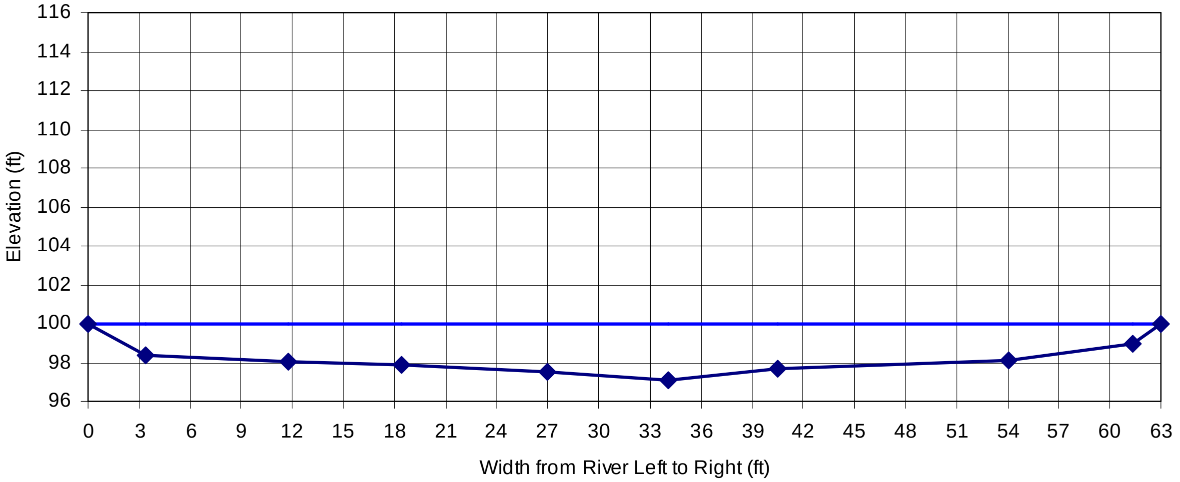


Figure 12. Scaled Cross-section for Straight Planform Type, Reach 5

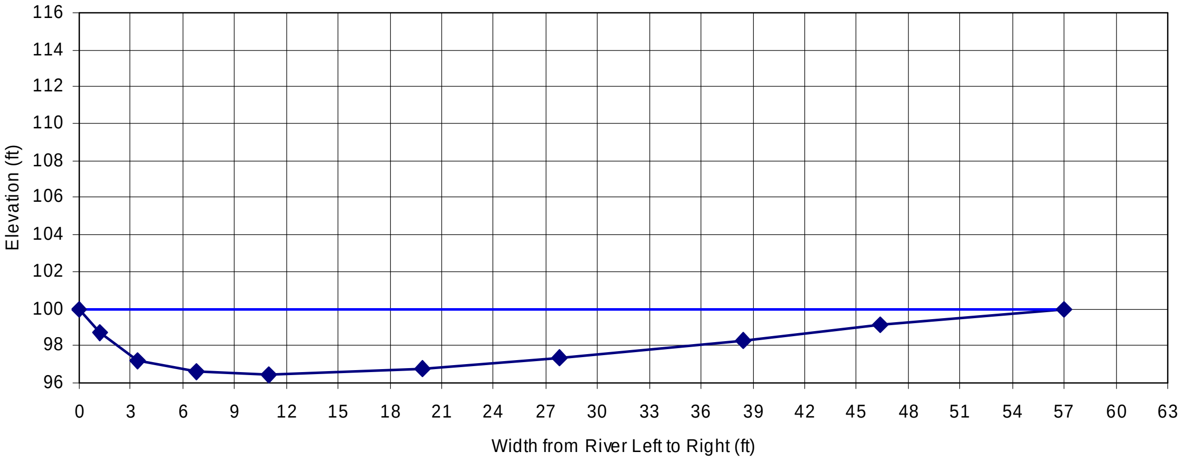


Figure 13. Scaled Cross-section for Sharp Curve Planform Type, Reach 5

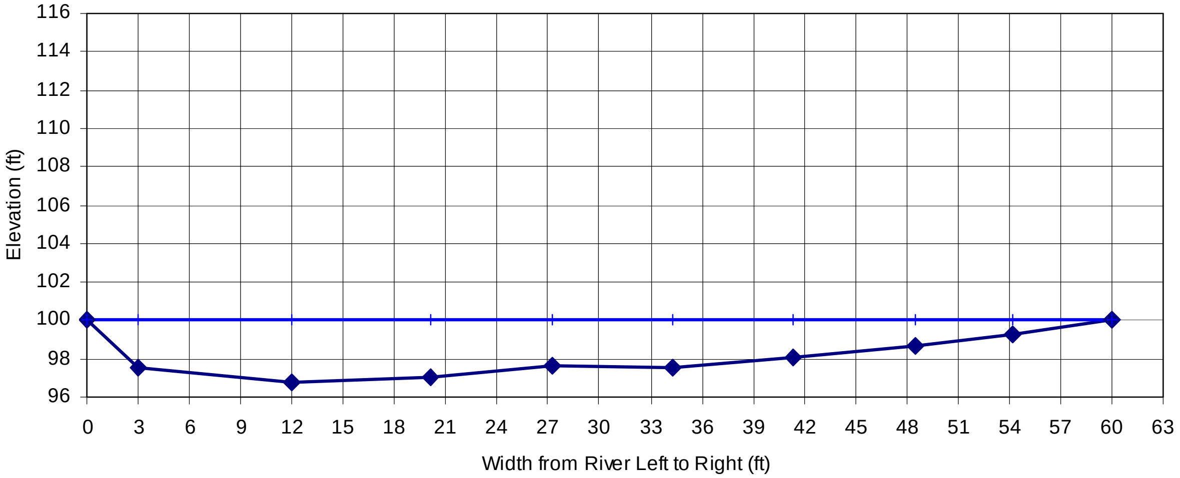


Figure 14. Scaled Cross-section for Gradual Curve Planform Type, Reach 5

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

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

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):

$$K_1 = 0.1\times10^{-6} t_c^{-0.5} \tag{3}$$

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.

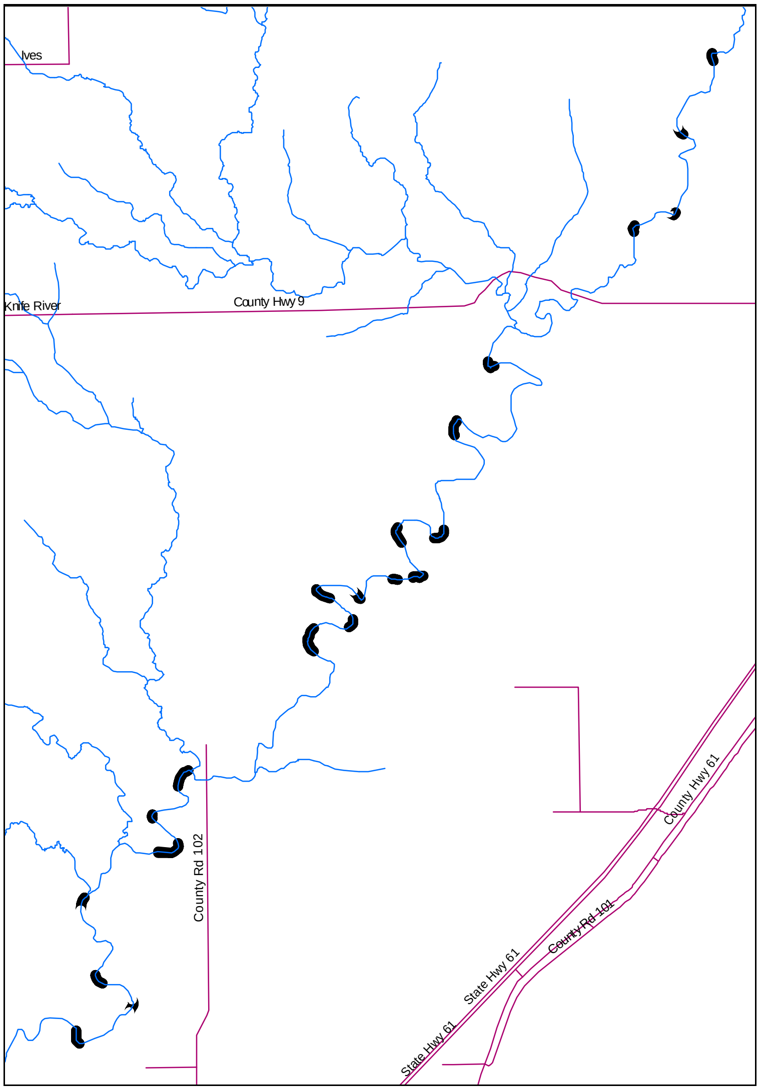


Figure 15. Location of Bluff Features on Knife River mainstem
(Note: The two Baughman bluffs are located furthest downstream [bottom left])

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

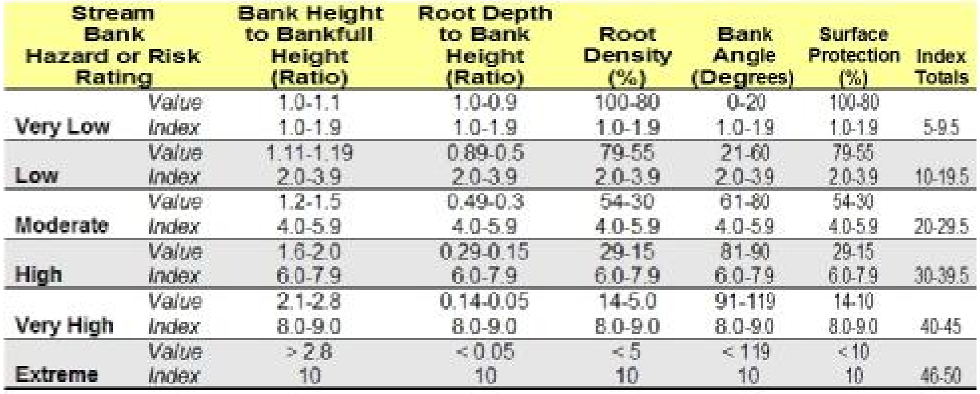
[2] Soil erodibility factor; estimated from Haan et al., 1994

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).

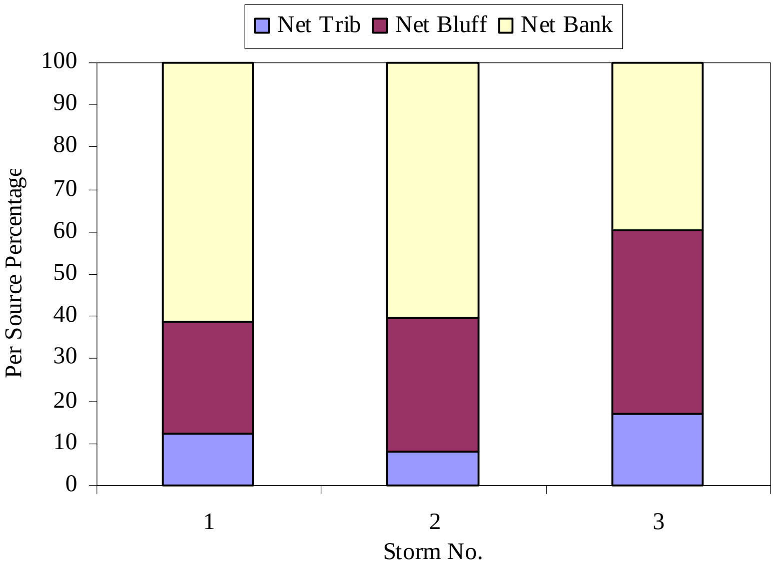


Figure 17. Per Source Percentages for Storms 1, 2 and 3

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.

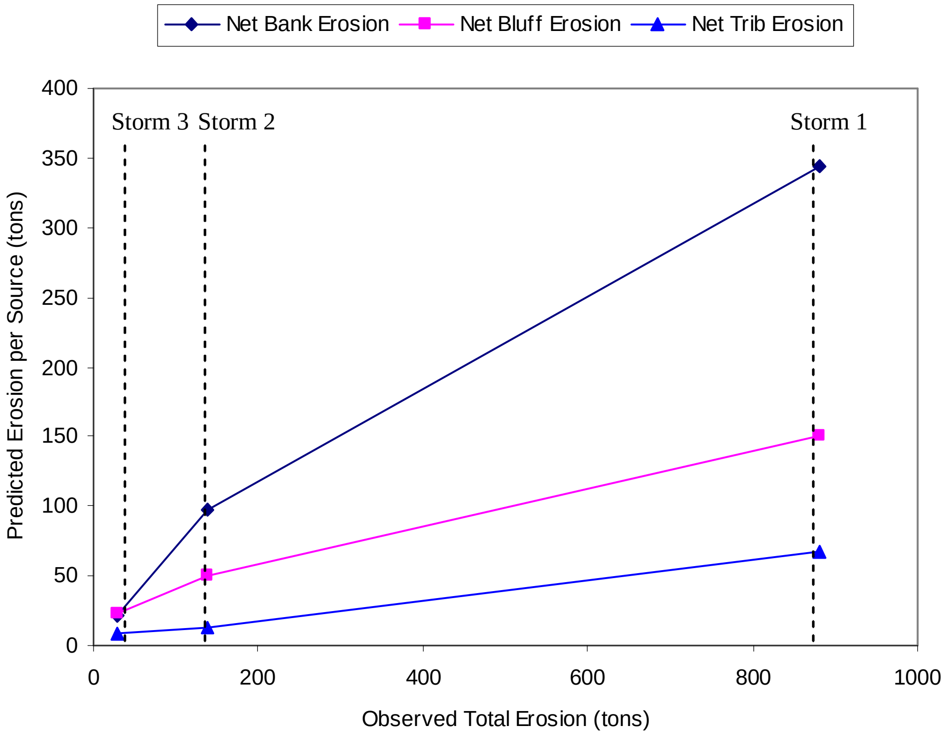


Figure 18. Predicted Erosion per Source vs. Observed Total Erosion for Storms 1, 2 and 3

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.

6. References

Arcement, G.J. and V.R. Schneider. 1984. Guide for Selecting Manning's Roughness Coefficients for Natural Channels and Flood Plains. United States Geological Survey Water-supply Paper 2339.

ESRI, Inc. 2007. Arc Hydro Data Model Version 1.2 for ArcGIS 9.2. ESRI, Inc., Redlands, California.http://support.esri.com/index.cfm?fa=downloads.dataModels.filteredGateway&dmid=15

Haan, C.T., B.J. Barfield and J.C. Hayes. 1994. Design Hydrology and Sedimentology for Small Catchments. San Diego, California: Academic Press.

Hanson, G. J., and K. R. Cook. 2004. Apparatus, test procedures, and analytical methods to measure soil erodibility in situ. Applied Engineering in Agriculture 20 (4):455-462.

Hanson, G.J. 1990. Surface erodibility of earthen channels at high stresses. Part II - Developing an in situ testing device. Transactions of the American Society of Agricultural Engineers 33(1):132-137.

Hanson, G.J. and A. Simon. 2001. Erodibility of cohesive streambeds in the loess area of the midwestern USA. Hydrol. Process. 15, 23–38.

Harrelson, C.C., C.L. Rawlins and J.P. Potyondy. 1994. Stream Channel Reference sites: an illustrated guide to field technique. Gen. Tech. Rep. RM-245. U.S. Department of Agriculture, Forest Service, Rocky Mountain and Range Experiment Station.

Jessup, A. and W. Harman. 2004. Unpublished BEHI results cited in Van Eps et al. USDA-NRCS, Salisbury, NC.

Julian, J.P. and R. Torres. 2006. Hydraulic erosion of cohesive riverbanks. Geomorphology 76 (2006) 193–206.

Lambe, T. W. 1951. Soil Testing for Engineers. John Wiley and Sons, New York.

Langendoen, E. J. 2000. CONCEPTS – Conservational Channel Evolution and Pollutant Transport System. Research Report 16, United States Department of Agriculture – Agricultural Research Service National Sedimentation Laboratory. Oxford, MS. http://www.ars.usda.gov/SP2UserFiles/Place/64080510/AGNPS/Concepts/Doc/manual.pdf

Langendoen, E. J. 2007. Personal Communication. United States Department of Agriculture – Agricultural Research Service National Sedimentation Laboratory. Oxford, MS.

Luttenegger, J.A. and B.R. Hallberg. 1981. Borehole shear test in geotechnical investigations. ASTM Spec. Publ. 740, 566–578.

Magner, J. 2007. Personal communication regarding as yet unpublished work of Northeast Minnesota hydraulic regional curves. Minnesota Pollution Control Agency, St. Paul, MN.

Maidment, D.R,. [ed.]. 2002. Arc Hydro: GIS for Water Resources. ESRI Press. Redlands, California.

Rawls, W.J., L.R. Ahuja, and D.L. Brakensiek. 1989. Estimating soil hydraulic properties from soils data. In proceedings of the International Workshop on Indirect Methods for Estimating the Hydraulic Properties of Unsaturated Soils, Ed. Van Genuchten, Leij, and Lund: 329-340.

River 4m, Ltd. and D. Mecklenburg. 1999. The Reference Reach Spreadsheet, Version 2.2L. Ohio Department of Natural Resources.

Rosgen, D.L. 2006. A Watershed Assessment for River Stability and Sediment Supply (WARSSS). Wildland Hydrology Books, Fort Collins, CO. (In press). Also in http://www.epa.gov/warsss/

Selby, M.J. 1982. Hillslope Materials and Processes. Oxford University Press.

Simon, A. and R. E. Thomas. 2002. Processes and forms of an unstable alluvial system with resistant, cohesive streambeds. Earth Surface Processes and Landforms 27(7): 699-718.

Simon, A., A. Curini, E. J. Langendoen and R. Thomas. 2006. Bank-Stability and Toe-Erosion Model. http://ars.usda.gov/Research/docs.htm?docid=5044. USDA-ARS National Sedimentation Laboratory, Oxford, MS.

Thorne, C. R. 1982. Processes and mechanisms for river bank erosion. In Gravel-bed rivers: fluvial processes, engineering, and management, edited by R. D. Hey, J. C. Bathurst and C. R. Thorne. New York: John Wiley & Sons Ltd.

Van Eps, M.A., S.J. Formica, T.L. Morris, J.M. Beck, and A.S. Cotter. 2004. Using a bank erosion hazard index (BEHI) to estimate annual sediment loads from streambank erosion in the west fork white river watershed. Arkansas Department of Environmental Quality, Environmental Preservation Division, Little Rock, AR.

Wilson, B.N., B.J. Barfield, and I.D. Moore. 1982. A Hydrology and Sedimentology Watershed Model and Modeling Technique. Department of Agricultural Engineering, University of Kentucky, Lexington, Kentucky.

7. Appendix

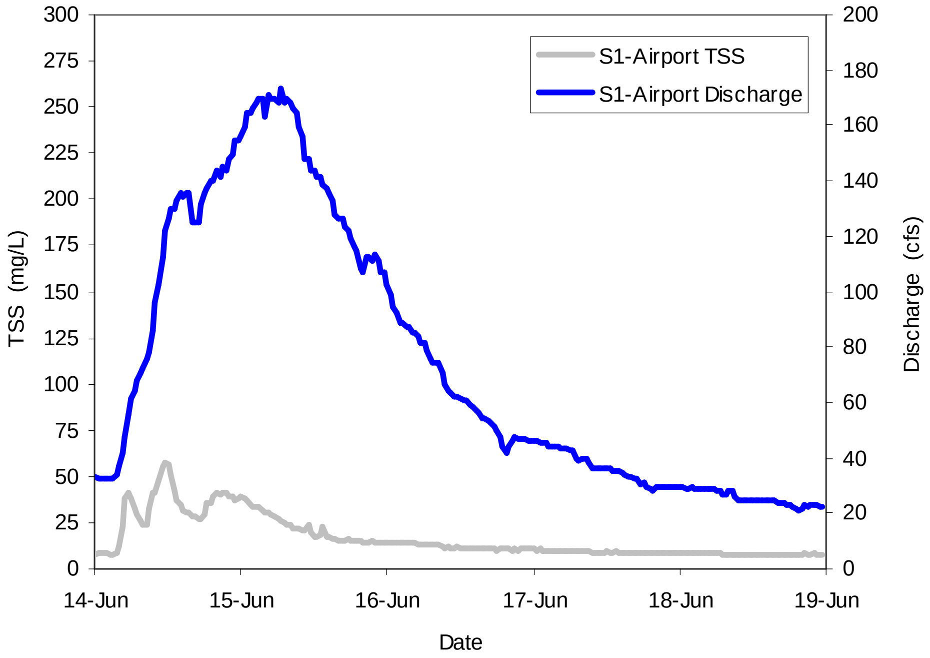


Figure 19. Flow and Sediment Graph for S1-Airport: Storm 1

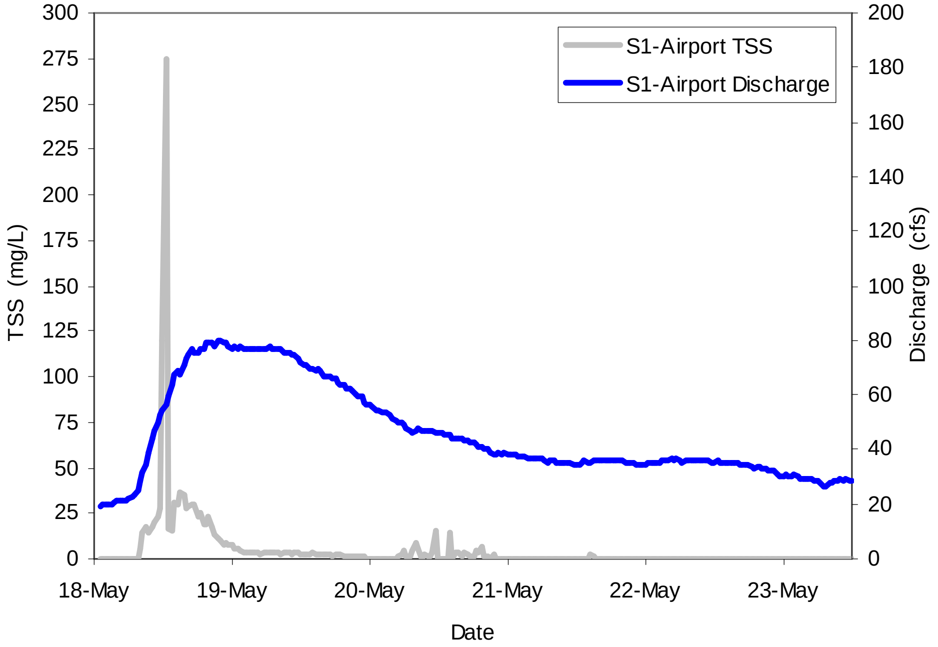


Figure 20. Flow and Sediment Graph for S1-Airport: Storm 2

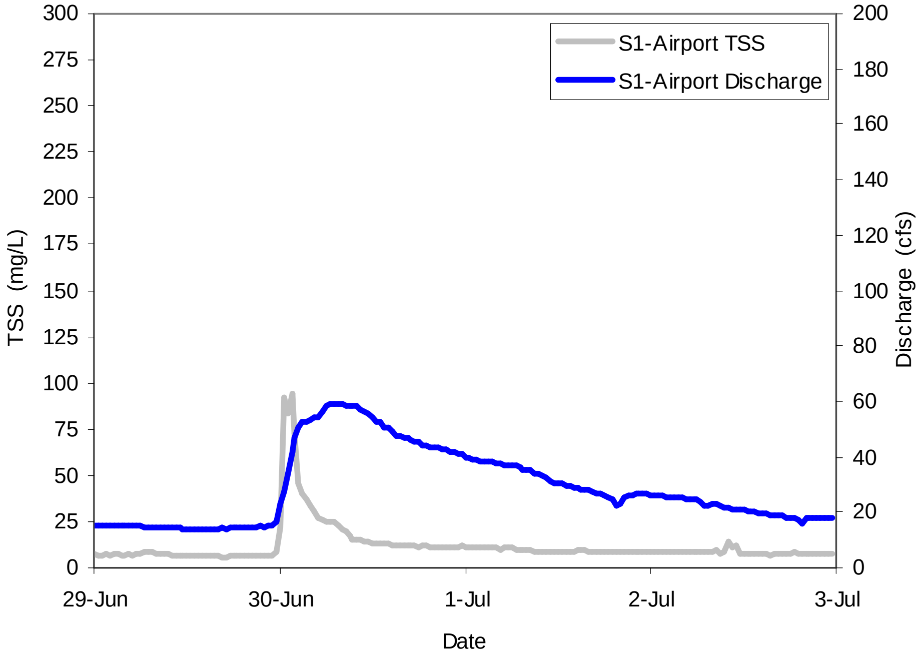


Figure 21. Flow and Sediment Graph for S1-Airport: Storm 3

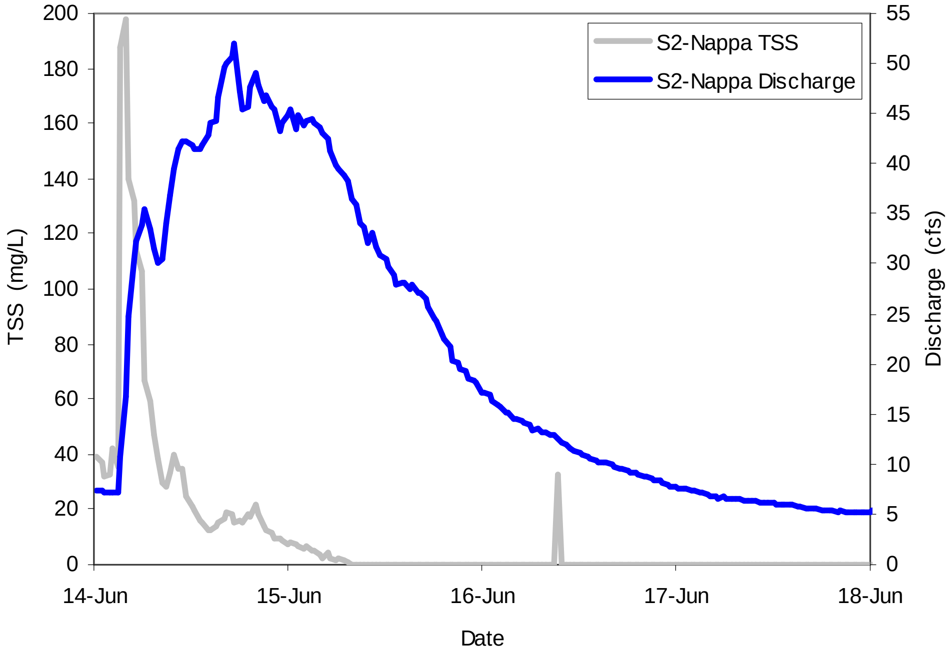


Figure 22. Flow and Sediment Graph for S2-Nappa: Storm 1

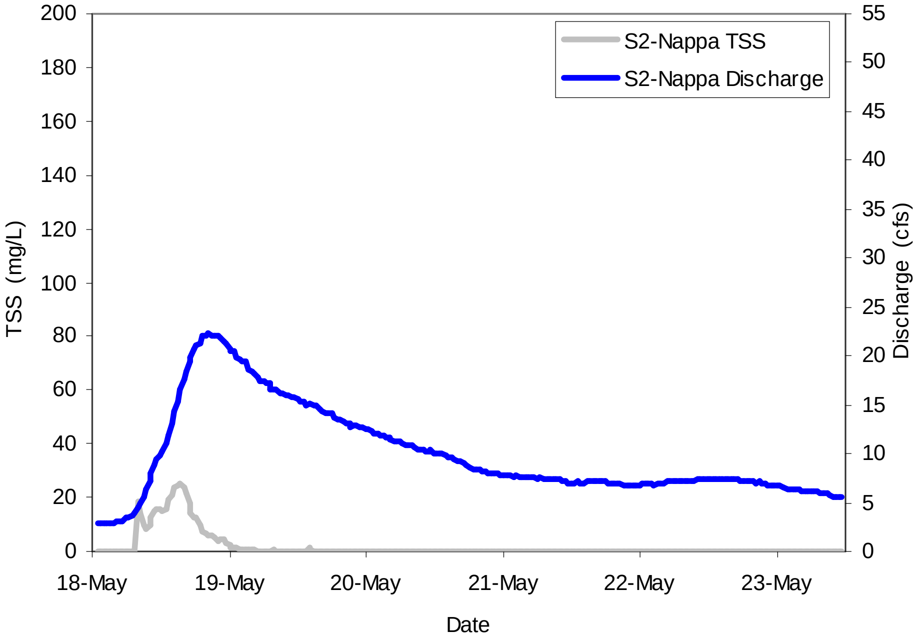


Figure 23. Flow and Sediment Graph for S2-Nappa: Storm 2

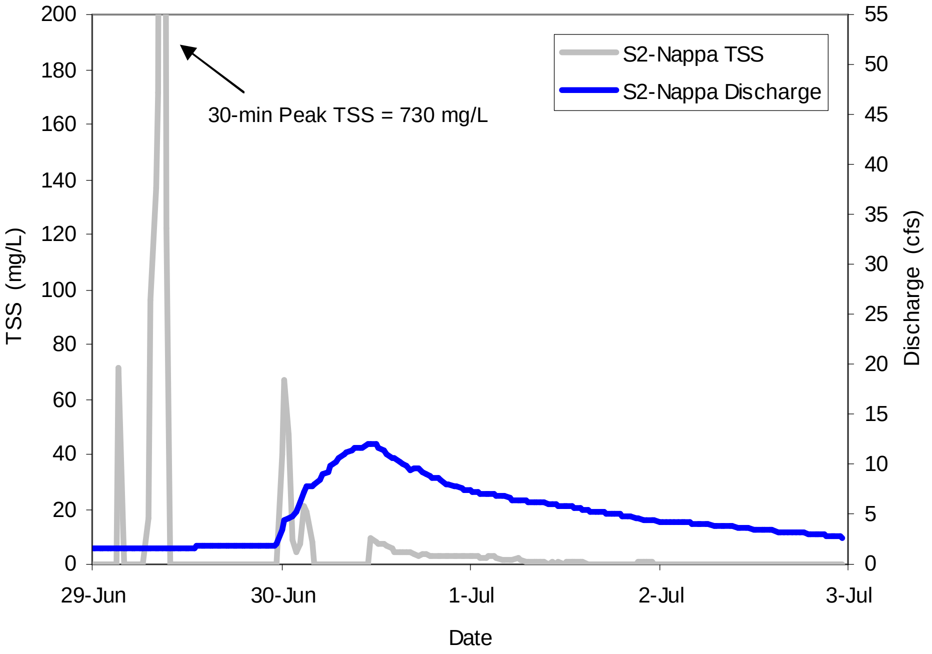


Figure 24. Flow and Sediment Graph for S2-Nappa: Storm 3

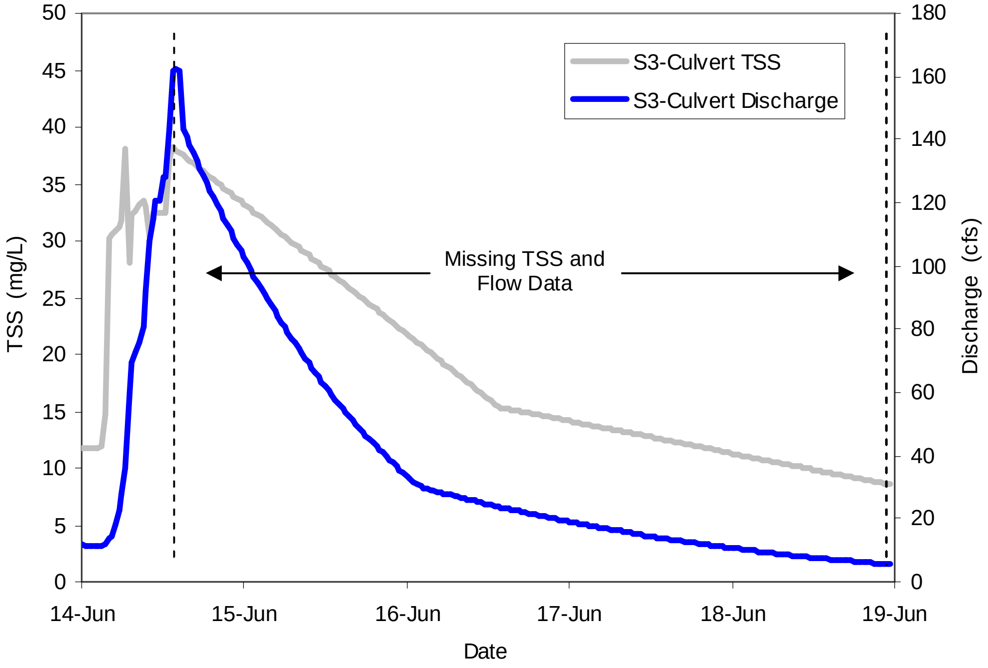


Figure 25. Flow and Sediment Graph for S3-Culvert: Storm 1

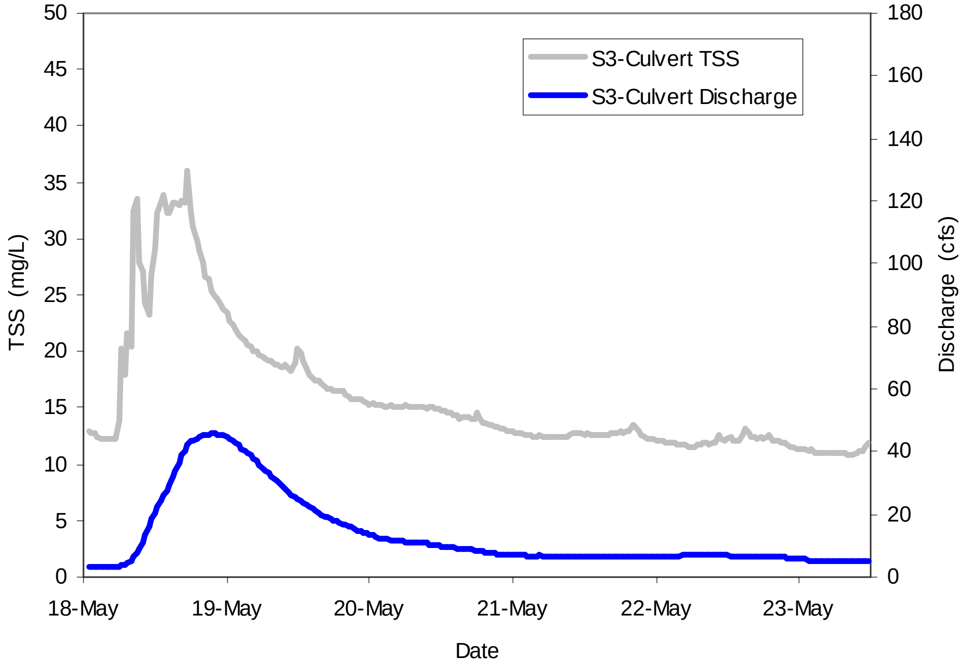


Figure 26. Flow and Sediment Graph for S3-Culvert: Storm 2

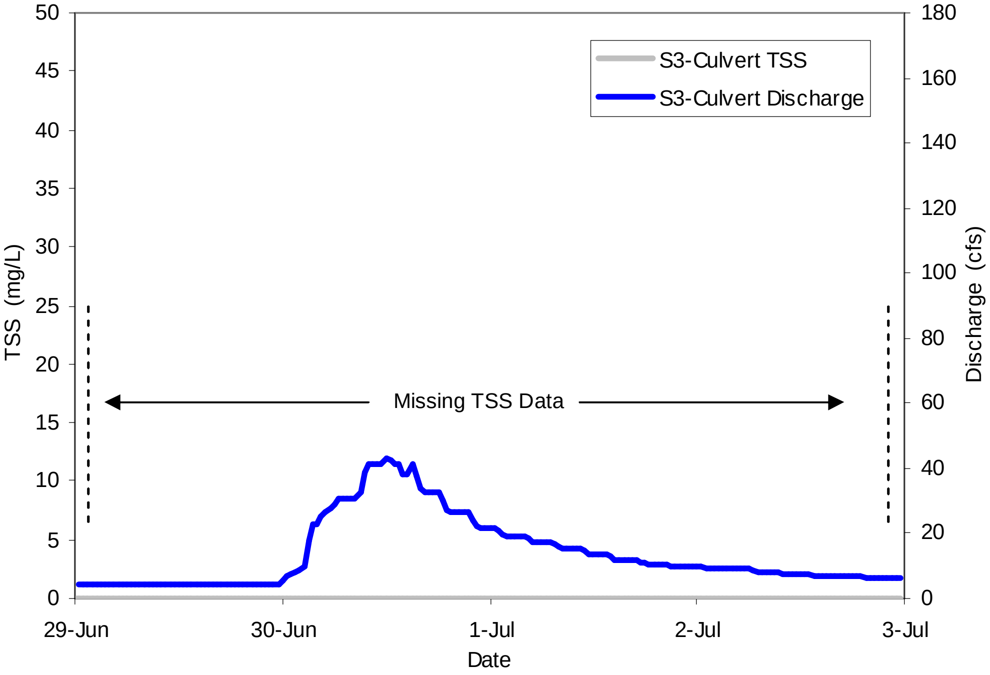


Figure 27. Flow and Sediment Graph for S3-Culvert: Storm 3

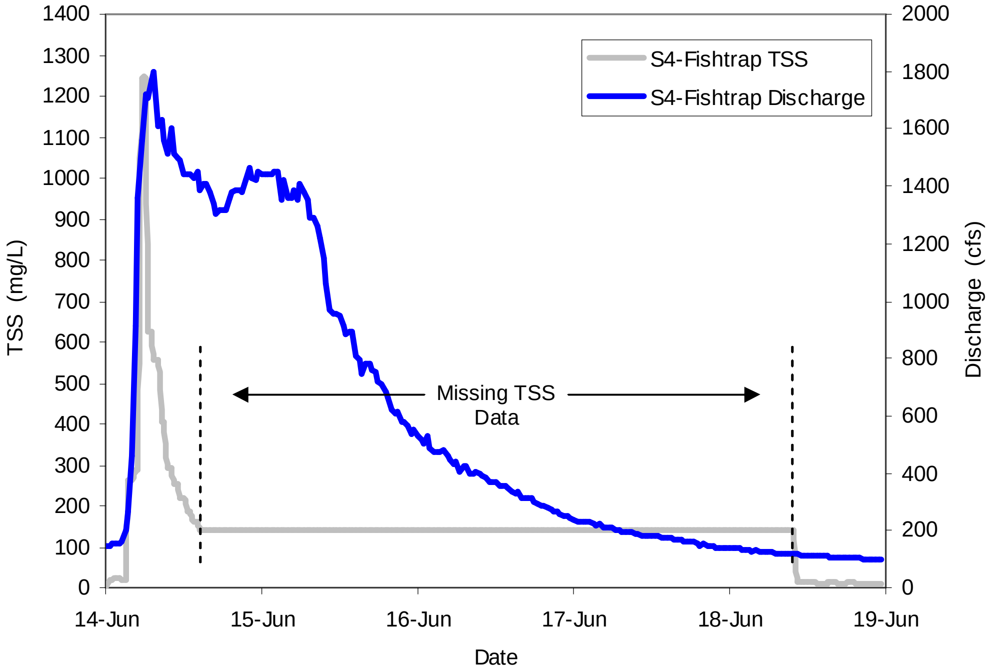


Figure 28. Flow and Sediment Graph for S4-Fishtrap: Storm 1

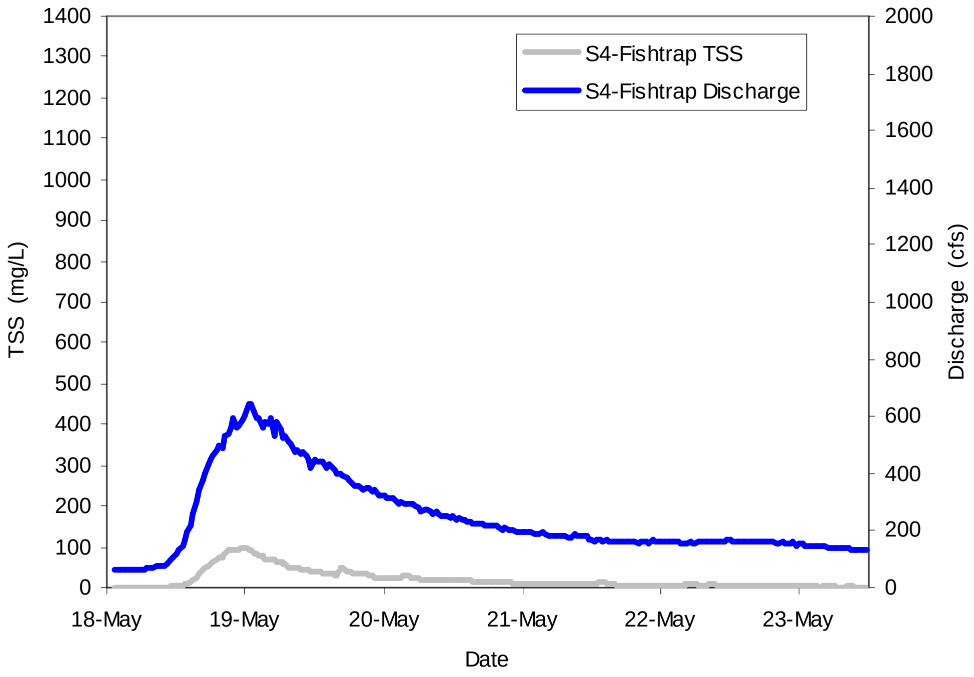


Figure 29. Flow and Sediment Graph for S4-Fishtrap: Storm 2

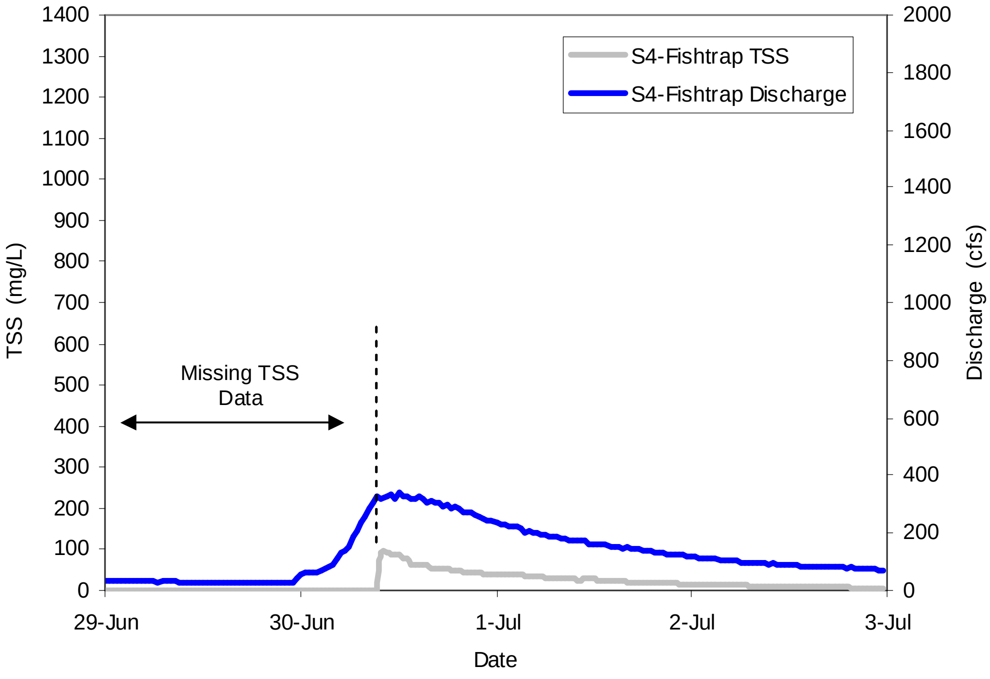


Figure 30. Flow and Sediment Graph for S4-Fishtrap: Storm 3

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