EVALUATION AND DEVELOPMENT OF PREDICTIVE STREAMBANK EROSION CURVES FOR NORTHEAST KANSAS USING ROSGEN'S "BANCS" METHODOLOGY

by

CHRISTOPHER K. SASS

B.S., Missouri Western State College, 2004
M.L.A., Kansas State University, 2008

AN ABSTRACT OF A DISSERTATION

submitted in partial fulfillment of the requirements for the degree

DOCTOR OF PHILOSOPHY

Department of Environmental Design & Planning
College of Architecture, Planning & Design

KANSAS STATE UNIVERSITY
Manhattan, Kansas

2011

Abstract

The original purpose of this investigation was to develop streambank erosion prediction curves for Northeast Kansas streams. Rosgen's (2001, 2006) methods were employed and eighteen study banks were measured and monitored over a four-year period, summer 2007 through summer 2010. At each study bank, a toe pin and two to three bank pins were set at a recorded longitudinal profile station of the stream. Vertical and horizontal measures from the toe pin to the bank face were taken each summer, 2007 as the baseline measure and 2008 - 2010 as bank change years. Bank profiles were overlaid to gain insight into bank area lost or gained due to erosional or depositional processes. A Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) combination rating was assessed and calculated for each study bank during the initial survey of 2007. The streambanks experienced varied erosion rates for similar BEHI/NBS combinations producing R^2 values from 0.43 as the High/Very High BEHI rating and 0.80 as the Moderate BEHI rating. In addition, Moderate BEHI ratings provided higher erosion rates than the High/Very High BEHI rating and curves intersected at lower NBS ratings, suggesting a discrepancy in the fit of the model used in the Northeast Kansas region and conditions. In this light, modification of the BEHI model was evaluated and variables were assessed in the model for additional influence exerted in the Northeast Kansas region. Vegetation seemed to provide the most influence to bank resistance and was more closely evaluated. Banks with and without woody riparian vegetation were then plotted against BEHI and NBS values, as banks lacking woody vegetation eroded at higher rates. This study's findings can allow us to calibrate the BEHI model according to woody vegetation occurrence levels along streambanks in the Black Vermillion watershed. Modifications regarding vegetation occurrence of the BEHI model was completed and the results of these modifications generated R^2 values of 0.78 for High/Very High BEHI and 0.82 for Moderate BEHI ratings. High/Very High ratings provided higher predicted erosion rates than Moderate ratings, while the curve slopes did not intersect at lower NBS ratings.

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The Black Vermillion project was funded by USDA-CSREES. Thank you very much for allowing me to continue my education and continuing to support students and research. It does make a difference.

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Finally, to my wife and sons, Jessica, Andrew and Logan, a heartfelt thank you for putting up with the late nights and early mornings throughout this crazy endeavor. Your support and encouragement will never be forgotten and was always appreciated. I can only hope to make you proud. Thank you. Who would have thunk it?

Preface

Completion of my Master's thesis was integral to this dissertation and was basic to understanding the Black Vermillion watershed system, changes in the system, and how the hydrologic system was converted to its present state. The thesis, "Inventory and analysis of the Black Vermillion river system riparian corridors," completed in 2008 is maintained online at K-State Research Exchange (KREx). Literature in the thesis concentrated on riparian corridors and importance of riparian vegetation. In this dissertation, as an expansion of the thesis, connections between riparian vegetation and bank erosion were established while concentrating on bank erosion processes.

CHAPTER 1 - Introduction and Study Background

"No man ever steps into the same river twice, for it is not the same river and he is not the same man." Heraclitus of Ephesus

Sediment and Streambank Erosion

Worldwide, sediment is one of the most pervasive non-point source pollutants in freshwater, and Kansas is no exception (Boggess et al. 1980; US-EPA, 2009). It is anticipated by 2020 that 36 states in the United States will be experiencing freshwater shortages, some will be extreme (Rogers, 2008; USDA, 2010). Excess streambank erosion contributes a large amount of non-point pollution of sediment to streams in humid temperate regions with loess dominated soils (Simon et al. 2004) and causes loss of fertile agricultural land, loss of valuable urban space, and decreases aesthetic, recreational and habitat value (Van Eps et al. 2004; Piegay et al. 2005; Riley, 2008). In this light, it is imperative we study stream-channel sediment sources, understand streambank erosional processes, and mitigate sediment pollution of our freshwater supplies. As we work in rivers and begin to assimilate all their intricacies, we step out of these rivers with different perspectives and understanding of the many processes they undergo throughout the season.

Thirty to 80% of total sediment loading in streams is directly related to streambank erosion (Bull, 1997; Simon and Darby, 1999; Sekely et al. 2002; Evans et al. 2006; Fox et al. 2007). Preliminary results for this Black Vermillion watershed study show amounts of sediment coming from streambanks can be 100 to 1000 times more per acre than estimated from fields and overland sources (Keane & Sass unpublished data, 2010). Stream erosion and subsequent deposition of sediment impacts include:

- Sedimentation of reservoirs and waterways (Beach, 1994; Hargrove et al. 2010).
- Loss of water storage capacity in reservoirs (Beach, 1994; Williams & Smith, 2008; Hargrove et al, 2010).
- Higher water treatment costs (Boggess et al. 1980; Williams & Smith, 2008).
- Increase in ambient water temperature (Naiman & Decamps, 1997).
- Decreased dissolved oxygen in streams (Ringler & Hall, 1975).

- Loss of stream habitat and biotic diversity (Odum, 1971; Naiman & Decamps, 1997).
- Decreased aesthetic and recreational value or potential value (Riley, 2008; Williams & Smith, 2008).
- Increased bank erosion and channel instability (Rosgen, 1996; Knighton, 1998).
- Increased flooding potential (Thorne, 1999).

These impacts are costly and long lasting and unfortunately, these impacts are more costly to remediate than prevent.

Research questions, goals and significance

Questions

Naturally, a given amount of sediment is transported in streams; however, humans have accelerated overall erosion rates, increasing the amount of sediment delivered to streams and other water bodies (Dunne & Leopold, 1998; Rosgen, 2001; Knox, 2006). Erosion can be accelerated through channel modification, removal of riparian vegetation, gravel mining, increased overland runoff, increased impervious surface runoff, climate change and a myriad of other environmental modifications (Knighton, 1998; Rosgen, 2001; Fox et al. 2007). Often, increases in erosion are inadvertent and a result of good intensions or ignorance of process; nonetheless, resulting erosional impacts may not be visible for decades and may last much longer (Helms, 1991; Simon & Rinaldi, 2000; Magner & Brooks, 2008).

Questions guiding this research project included:

- Can we quickly and accurately predict erosion rates of streambank material?
- Do erosional processes and rates differ between urban, suburban and agricultural land uses?
- Are environmental conditions that influence erosion rates the same across all environments, ecosystems, and ecoregions?

Research goal and significance

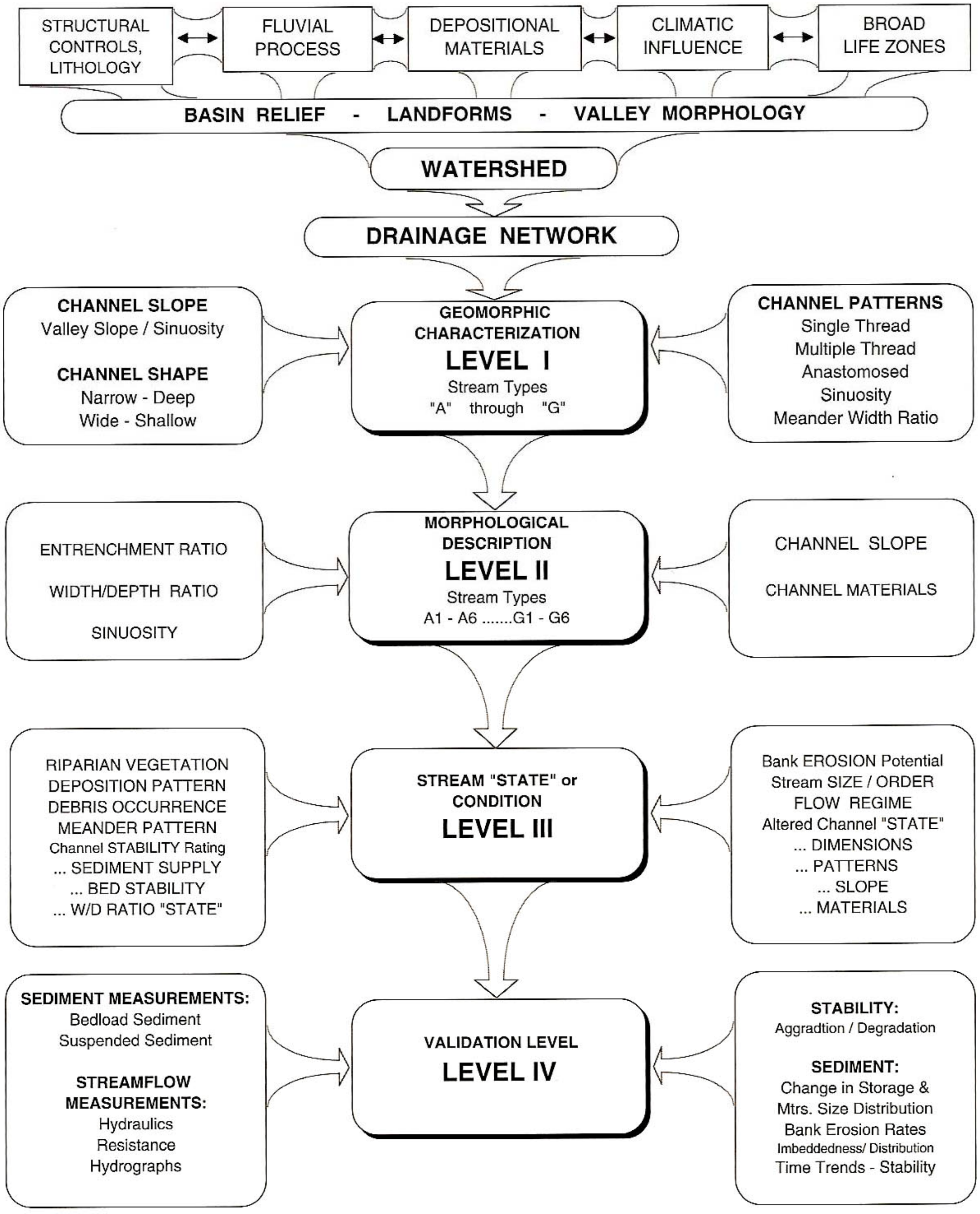
The ultimate goal of this research is to provide a tool that can accurately predict annual streambank erosion rates and sediment contributions from streambanks in Northeast Kansas and evaluate Rosgen methodology in developing prediction curves in this region. Once developed, it is expected that these erosion prediction curves can be extrapolated to similar hydrophysiographic regions throughout the world. Quickly and accurately estimating sediment contributions from streambanks will help in accurate development of watershed sediment budgets. Regarding remediation, these curves allow us to assess and predict streambank problem areas, bank retreat rates and become an integral part of the site inventory and analysis for stream restoration and stabilization design. These predictive curves may also help in setting United States Environmental Protection Agency (US-EPA) water quality standards for sediment, commonly known as Total Maximum Daily Loads (TMDLs). Then we may discern what acceptable and natural baseline loads to a stream should be on a stream by stream basis according to hydrophysiographic regions. Lastly, building a library of erosion rates from different ecoregions across the country will only strengthen scientific endeavors during climate change.

General methodology

Rosgen (1996, 2006) methodology of stream classification and monitoring was chosen due to its combined quantitative and qualitative nature and US-EPA adaptation of Rosgen's (2006) Watershed Assessment of River Stability and Sediment Supply (WARSSS) protocol. Some of the Rosgen methodology includes longitudinal profiling of the stream reach, cross sections at stream facets, streambank profile measurements, scour chains, sediment characterization and general velocity calculations. A general flowchart of Rosgen's methods is shown in Figure 1.1.

Specifically for this study, bank profiling and bank assessments regarding stresses encountered by the bank and proneness to erosion of the bank are important. Rosgen (2001, 2006) developed two sets of predictive erosion rating curves for Southern Colorado and Yellowstone regions using Near Bank Stress assessment and Bank Erosion Hazard Index assessment. Predictive erosion curves have been developed in other hydrophysiographic regions of the United States using the same or similar approach; Northern Arkansas (Van Eps et al. 2004) and the Piedmont region of North Carolina (Jennings and Harman, 2001).

Figure 1.1 Flowchart for Rosgen Classification system showing all parameters (Rosgen, 1996)



Bank Profiling

Rosgen (2006) notes the most accurate way to attain streambank erosion rates is through field measured bank profiles. A bank profile entails setting a control point (toe pin) and measuring both vertical and horizontal distances from that point to the bank surface. This process is repeated throughout the year or can be done annually over many years. In this study, we measured annually over a four-year period. Once measures are taken and graphed, graphs can be overlaid for an accurate measure of bank area change. The area change equates to an amount of gross erosion or deposition during that period. During study bank installation, each bank is rated for Near Bank Stress (NBS) and Bank Erosion Hazard Index (BEHI). NBS is a measure of the stress a bank encounters from the water column of the stream. BEHI is a predictor of bank stability using visual indicators. Specifics for this study are included in Chapter 3 - Methodology.

Bank Assessment for Non-point source Consequences of Sediment (BANCS)

Near Bank Stress and Bank Erosion Hazard Index

Erosion prediction curves are developed using two stream channel boundary characteristics, both of which affect streambank erosion potential. The first characteristic is Near Bank Stress (NBS), which is a measure of erosive strength, or power, of the stream at the outer 1/3rd of the channel cross section, or the eroding bank (Rosgen, 1996, 2001, 2006). There are seven ways to estimate NBS with the result being an adjective description of potential erosive force. Six adjective ratings are possible ranging from very low NBS to extreme NBS (numerically 1-6). NBS ratings are typically plotted along the X-axis. Corresponding measured annual erosion rates are plotted along the Y-axis.

Bank Erosion Hazard Index (BEHI) values are the second characteristic used to create annual erosion prediction curves. The BEHI bank stability assessment model does not isolate individual erosion processes, but integrates many related erosional processes influencing overall erosion rates (Rosgen, 2001). Bank characteristics affecting erosional processes are study bank height / bankfull height ratio, root depth / bank height ratio, weighted root density percentage, bank angle, bank surface protection, bank material, and stratification of bank surface material (Rosgen, 2006). BEHI is then plotted with five different ratings ranging from extreme, high and very high (combined), moderate, low, and very low. Each BEHI rating is a best fit line with its corresponding erosion rates plotted against NBS.

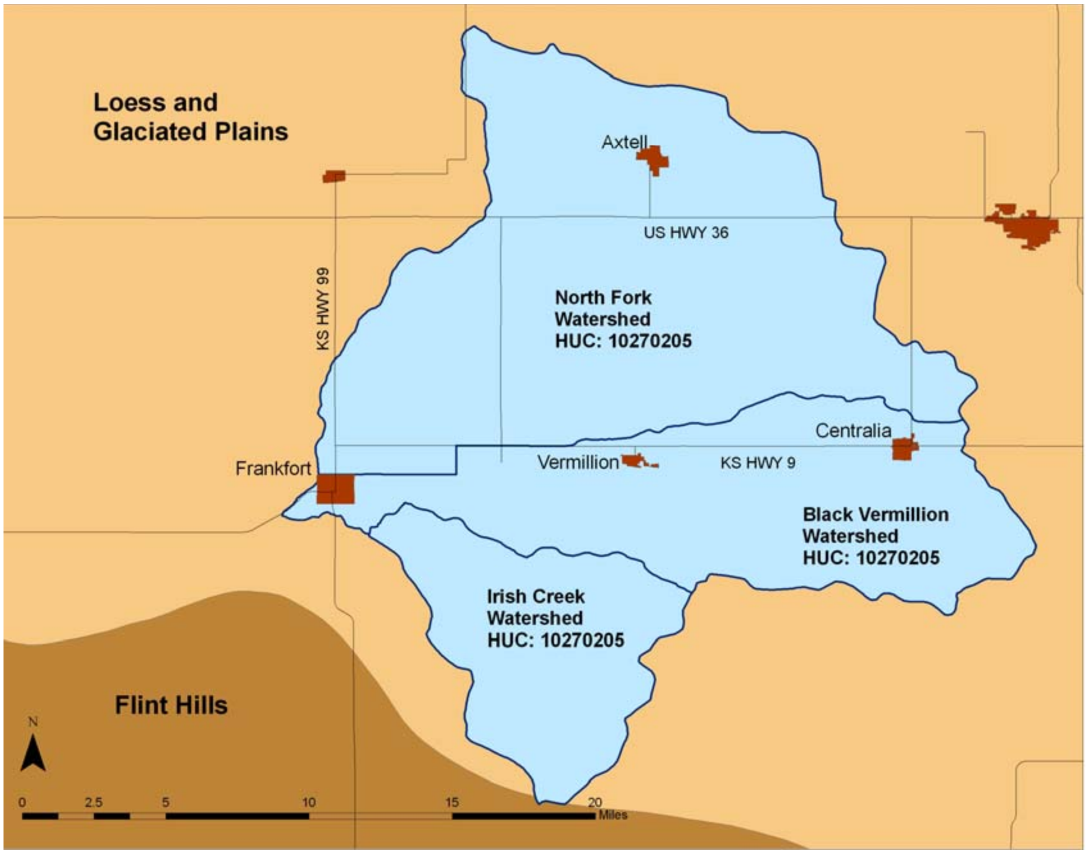
BEHI / NBS curves are used to predict erosion rates in a given hydrophysiographic region. Once erosion prediction curves are developed and verified for a given hydrophysiographic region, they can be used to quickly and accurately predict streambank erosion rates. Streams may be assessed using BEHI and NBS models, now collectively known as Bank Assessment for Non-point source Consequences of Sediment (BANCS) model (Rosgen, 2006). Hence in theory, sediment contributions from streambanks can be calculated along miles of stream quickly and accurately.

Study Area

The Black Vermillion watershed is located in eastern Marshall County, Kansas, and western Nemaha County, Kansas. A small portion of the watershed is located in Northern Pottawattamie County, Kansas. The river system lies in the glaciated region of Kansas and northeast of the Flint Hills Ecoregion (Figure 1.2). The watershed drains approximately 1062Km^2 (410 miles^2) at the USGS gauge near Frankfort, Kansas, before emptying into the Big Blue River west of Frankfort, Kansas. The Big Blue River then flows into Tuttle Creek Federal Reservoir, a multi-use reservoir controlled by the United States Army Corps of Engineers (US-COE), northeast of Manhattan, Kansas. Three sub-drainage basins located within the Black Vermillion Watershed were selected for study: Irish Creek (South Fork of the Black Vermillion), Main Stem of the Black Vermillion, and North Fork of the Black Vermillion (Figure 1.3).

Figure 1.2 Black Vermillion watershed location in Kansas.

Figure 1.3 The three sub-watersheds in the Black Vermillion system.



Irish Creek Sub-watershed

Irish Creek (Black Vermillion South Fork, or IC) is a tributary located in southern Marshall County and extreme northern Pottawattamie County with a total drainage area of approximately 120.5Km^2 (46.5 miles^2), Figure 1.4. Irish Creek enters the Black Vermillion to the east of Frankfort, Kansas, and flows north primarily through glaciated plains; however, it is influenced heavily by Flint Hills Uplands. The southwestern portion of the watershed typically resembles Flint Hills Uplands physiography while the eastern portion resembles the glaciated region with Kansan till soils (USDA-SCS, 1966a). Watershed topography is rolling with a total fall of 88m (290 feet) in 27.4Km (17 miles) of stream (USDA-SCS, 1966a). This sub-watershed lies in the tallgrass prairie region of Kansas that consisted of native grasses such as big bluestem (*Andropogon gerardii*), little bluestem (*Schizachyrium scoparum*), Indian grass (*Sorghastrum nutans*), sideoats grama (*Bouteloua curtipendula*), and switchgrass (*Panicum virgatum*) (Haddock, 2005; Reichman, 1987). Irish Creek sub-watershed contains many flow-through water impoundments altering drainage area and stream flow characteristics from historic conditions (USDA-SCS, 1966a). These flow-through impoundments also create anomalies when calculating flow rates and runoff in the sub-watershed (US-COE, 1998). Representative photos of the Irish Creek sub-watershed are included as Figures 1.5, 1.6, 1.7, 1.8 and 1.9.

Figure 1.4 Irish Creek sub-watershed with study reach locations in red.

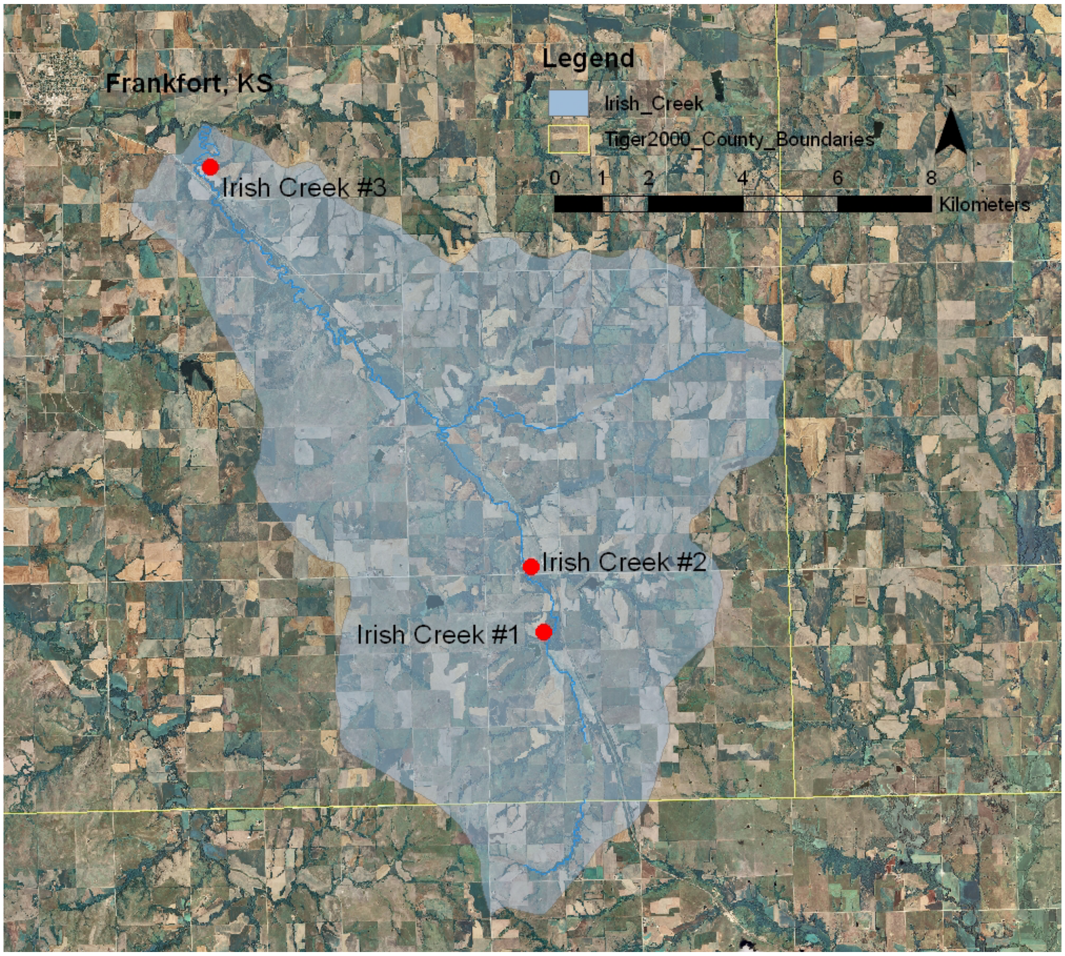


Figure 1.5 Irish Creek study reach 1, upstream view from pool cross-section (Keane, 2010).

Figure 1.6 Irish Creek study reach 2, downstream view from pool cross section (Keane, 2010). Willows beginning to re-establish near stream.

Figure 1.7 Irish Creek study reach 2, study bank (Keane, 2010).

Figure 1.8 Irish Creek study reach 2, same study bank upstream of Figure 1.7 (Keane, 2010).

Figure 1.9 Irish Creek study reach 3, downstream of riffle cross section (Keane, 2010).

Black Vermillion Main Stem

The Black Vermillion Main Stem (Black Vermillion, or MS) flows westward and drains an area of approximately 217Km^2 (83.8 miles^2), Figure 1.10. The Black Vermillion flows through alluvial and glacial deposits on its way into the Big Blue River and Tuttle Creek Reservoir. Predominant land use in the watershed is tillage agriculture with scattered pasture. The Black Vermillion system also contains many small flow-through water impoundments with one large, controlled impoundment. Centralia Lake, completed in 1991, is an approximate 161.9ha (400-acre) impoundment and is the largest water impoundment in the entire Black Vermillion watershed (Jones, 2008). Centralia Lake controls approximately 32.4Km^2 (12.5miles^2) of the watershed. Watershed topography is rolling with deeply dissected drainages in the system. There is approximately 79.25m (260 feet) of fall in 43.5Km (27 miles) making this the flattest sub-watershed in the system (UDSA-SCS, 1966b). Ridges are generally capped with thin layers of loessial soils (USDA-SCS, 1966b). The Black Vermillion lies in the tallgrass prairie region of Kansas, historically composed of the same plant assemblages as Irish Creek. Representative photos of the Main Stem sub-watershed are included as Figures 1.11, 1.12, and 1.13.

Figure 1.10 Black Vermillion sub-watershed with study reach locations in red.

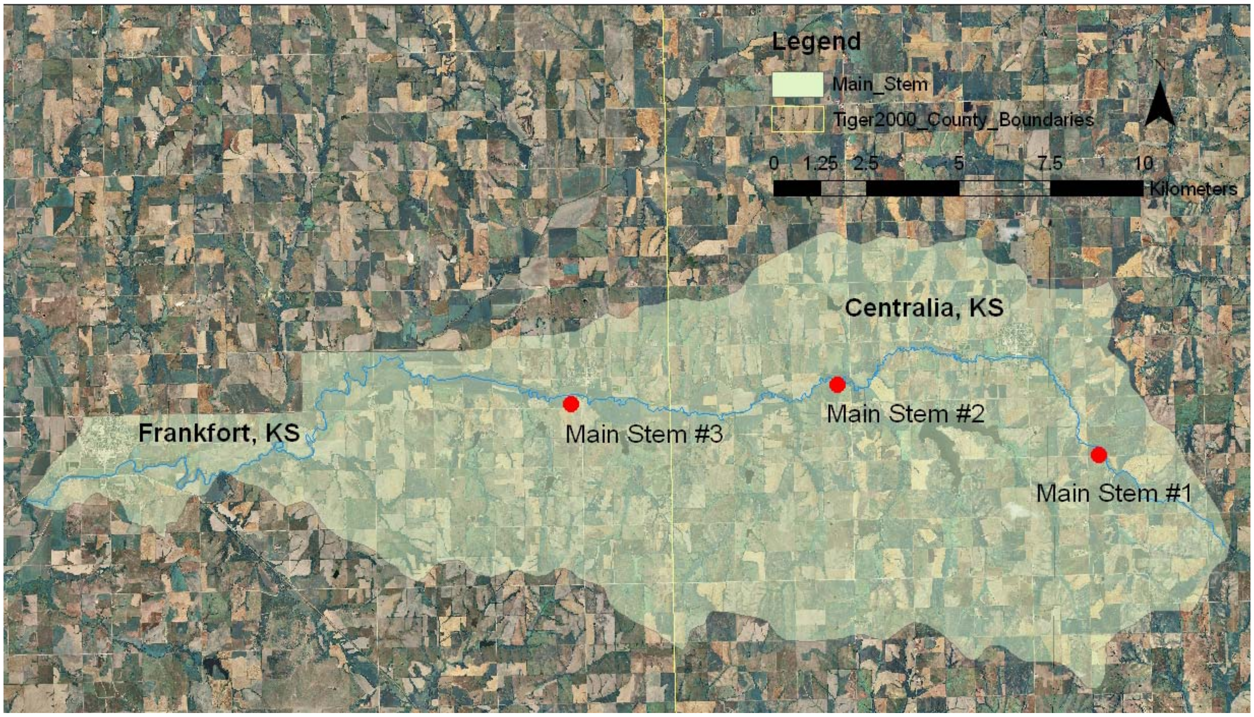


Figure 1.11 Black Vermillion study reach 1, general character of the reach (Keane, 2010).

Figure 1.12 Black Vermillion study reach 2, downstream of riffle cross section (Keane, 2010).

Figure 1.13 Black Vermillion study reach 3, upstream of riffle cross section (Keane, 2010).

North Fork of the Black Vermillion

The North Fork of the Black Vermillion (North Fork, or NF) flows to the south and is the largest sub-watershed of the three, covering approximately 313.4Km^2 (121 miles^2), Figure 1.14. The North Fork flows through alluvial and glacial deposits as it makes its way to the Black

Vermillion River east of Frankfort, KS. Watershed topography is rolling with deeply dissected and entrenched streams. Total fall in the sub-watershed is 100.25m (329 feet) in 37Km (23 miles) (USDA-SCS, 1966c). Ridges and flatter tops typically are covered in thin layers of loess soils. This sub-watershed is also located within the tallgrass prairie region of Kansas. Typically, woodlands are located in the lowlands near streams as gallery forests. Predominant land use in the watershed is tillage agriculture with minimal pasture. Representative photos of the North Fork sub-watershed are included as Figures 1.15, 1.16, 1.17, and 1.18.

Figure 1.14 North Fork sub-watershed with study reach locations in red.

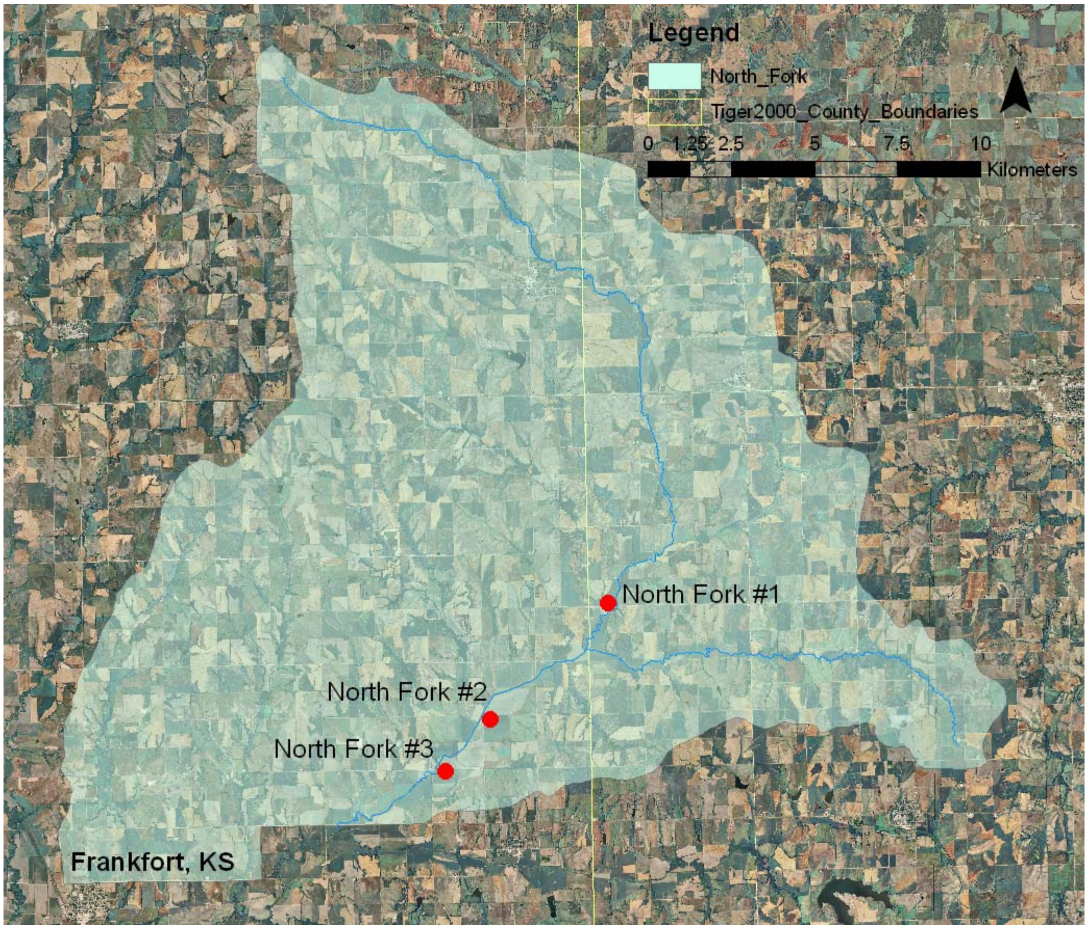


Figure 1.15 North Fork study reach 1, general character upstream of pool cross section (Keane, 2010).

Figure 1.16 North Fork study reach 1, downstream of pool cross section (Keane, 2010).

Figure 1.17 North Fork study reach 2, photo showing bar buildup (Keane, 2010).

Figure 1.18 North Fork study reach 3 showing deposition pattern including sidebars and beginning meanders (Keane, 2010).

Land use and cover

Land use and land cover vary throughout the watershed. Cultivated lands, pastured lands, small urban areas, and natural areas are included within the watershed. However, the majority of land located within the watershed is currently tillage agriculture (Figure A.1 in Appendix-A for detailed land use map). Other disturbances to land use and land cover include work performed by United States Army Corps of Engineers (US-COE), Soil Conservation Service (SCS), now the Natural Resources Conservation Service (NRCS), and individual landowners (Sass, 2008). In conjunction, they have modified most streams in the watershed in some fashion, through straightening the channel, water impoundment flood control, by placing levee systems between fields and streams, or some combination of the above (USDA-SCS, 1966a, 1966b, 1966c; US-COE, 1998; Sass, 2008). Stream length in the watershed has been shortened 25.4 Km (15.8 miles), from 114.8Km (71.3mi) to 89.3Km (55.5mi) with a down valley length of 73.2Km (45.5mi) (US-COE, 1998). These modifications decimated riparian vegetation and led to an increased stream discharge and velocity, which in turn increased erosion rates along streambed and banks while destroying remaining riparian habitat. Discharges are estimated to have increased by 40% over historic levels (US-COE, 1998).

The Black Vermillion watershed contains numerous small water impoundments, reservoirs, or farm ponds. Many of these impoundments are "flow-through" flood control structures, which attempt to mimic a flow regime of past conditions. Dense prairie vegetation once intercepted precipitation before it fell to the ground, temporarily storing water and lessening runoff. In addition, rooting density and depth provided a network of pore space for water storage and movement deep into the soil (Reichman, 1987). Historically, a majority of precipitation delivered to the watershed would evaporate into the air from vegetation or infiltrate into the soil providing very little surface runoff quickly to the stream (Reichman, 1987; US-COE, 1998). Today, precipitation generally is not intercepted by dense prairie vegetation, but by open soils allowing runoff to move quickly toward the stream and lessening the time for infiltration. Soils with dense vegetation once provided more storage capacity of groundwater, lessened surface runoff and provided a less-flashy hydrograph (decreased stream discharge). Historic flow regimes with groundwater flow to the streams provided a sustained base flow year round (US-COE, 1998).

Common terminology

Ecoregion – Regions that exhibit patterns of homogeneity using both biotic and abiotic indicators including geology, physiography, vegetation, climate, soils, land use, wildlife and hydrology. The system was developed for resource management. These regions become smaller and finer in homogeneity as the Roman Numerals increase (I-IV) (Omernik, 1995). Watersheds, depending on scale, may be influenced and show characteristics of the ecoregions they flow through, as they may flow through more than one ecoregion.

Hydrophysiographic Region - a region characterized by homogeneous climate, geology, soils and vegetative communities that effects the hydrology, or movement of water, of that region. Hydrophysiographic regions may be influenced by numerous ecoregions depending on the ecoregion scale (I-IV) being studied (Omernik & Bailey, 1997).

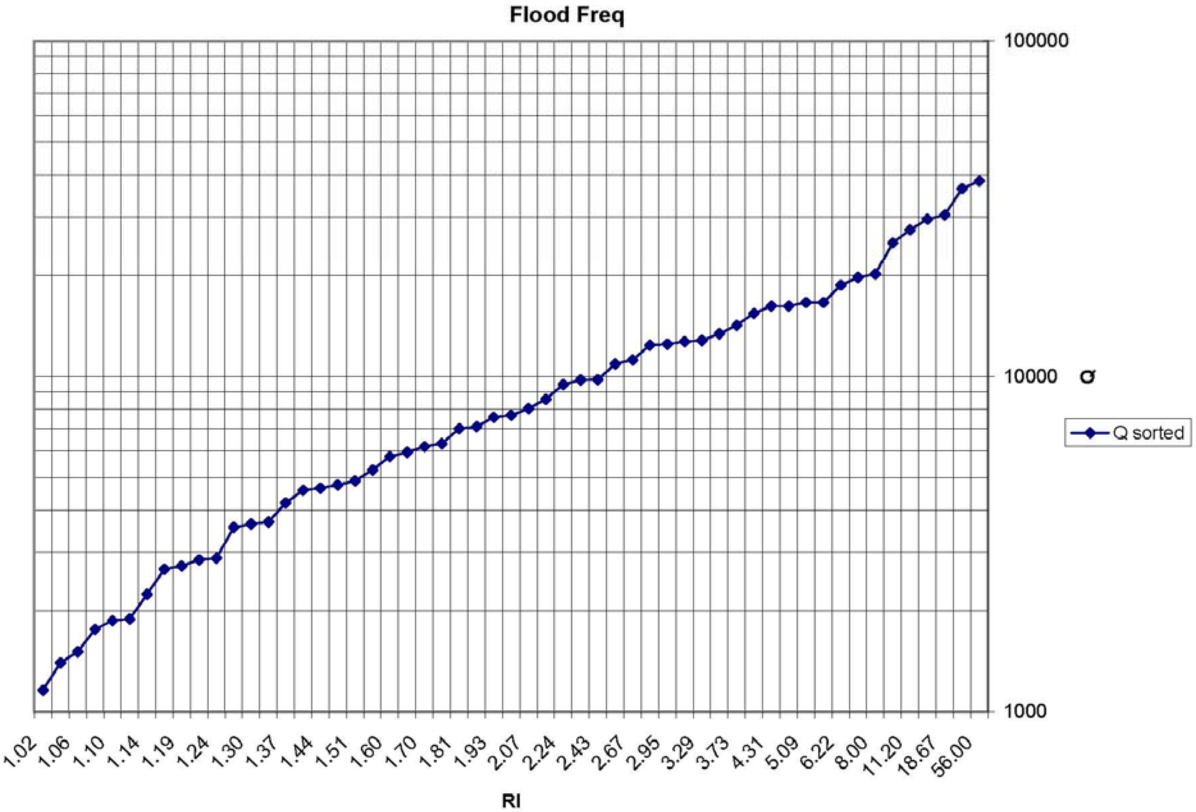
Erosion - a natural process by which soil particles are washed, blown, or otherwise moved by natural agents from one place on the landscape to another (Harpstead et al. 2001). This dissertation will refer to erosion as soil particles moved by fluvial entrainment, or through stream power.

Mass movement (failure) – process by which soil is moved downslope in large amounts, or masses (Dunne & Leopold, 1998; Harpstead et al. 2001). Mass movement is much different than erosion, as erosion is typified by movement of single particles. Slump, fall, soil creep and mudslides are examples of mass movement. Mass movement is the primary erosion process that occurs in the Black Vermillion watershed stream channels.

Bankfull stage / discharge - bankfull stage is the elevation at the incipient point of flooding (flow onto the stream's associated floodplain). Bankfull stage and its corresponding discharge is responsible for channel maintenance and formation as it exists under the current climatic regime due to its common occurrence, versus extreme flood events that do not occur as frequently. Bankfull discharge is the amount of water that corresponds to the bankfull stage and occurs approximately every two out of three years, or an average of 1.5 years (Rosgen, 1996; Dunne & Leopold, 1998). Simon, Dickerson and Heins (2004) describe the 1.5-year return interval flow as the channel forming discharge, while others refer to the 1.5-year recurrence interval discharge as effective discharge. The difference between the definitions is how the discharge is found. Bankfull stage is a geomorphic feature found in the field, while the 1.5-year return interval is calculated from a flood frequency analysis.

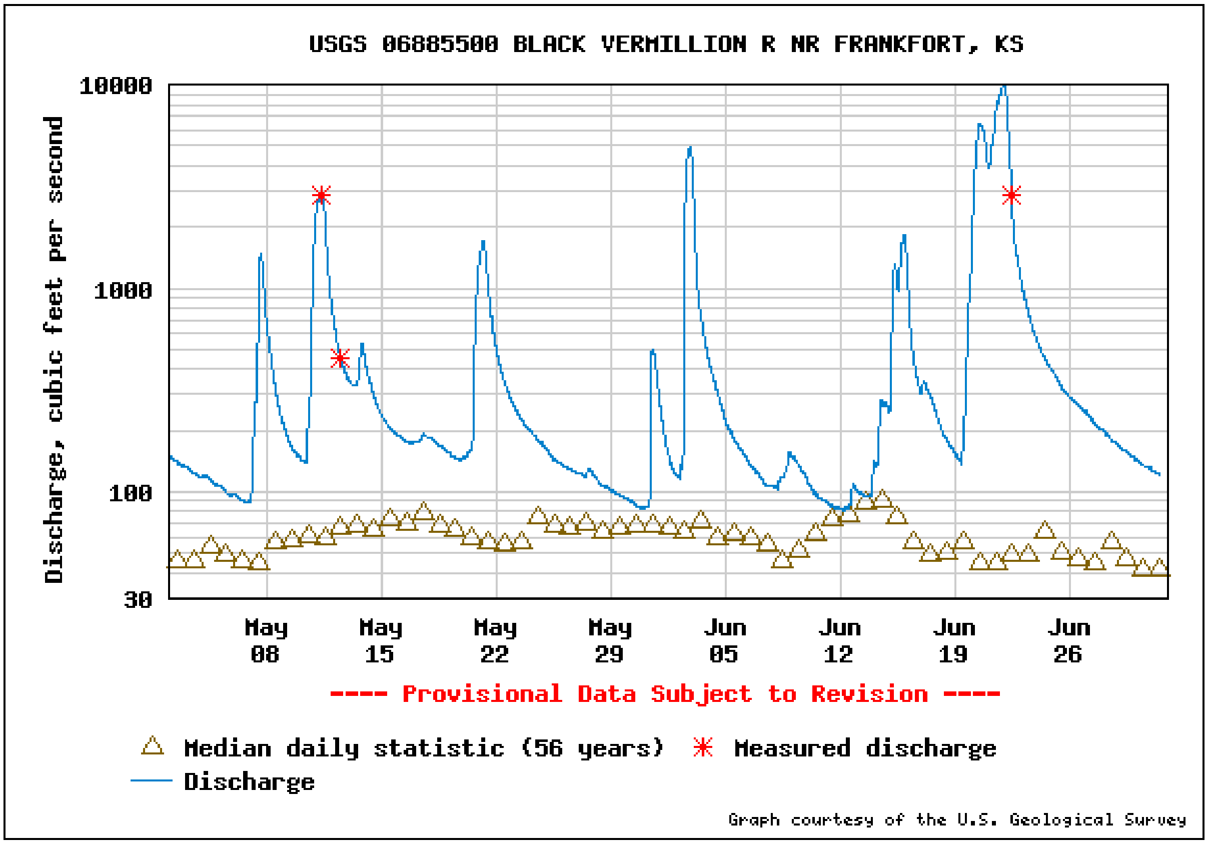
Bankfull discharge is determined by flood frequency analysis using the peak annual discharge. Flows are ranked from largest flow to lowest flow. Then probability is calculated by dividing the rank (numerical value ranging from first to last flow) by the total number of data points plus one. The quotient is then multiplied by 100. Next, recurrence interval is figured by dividing one by the probability and then multiplying by 100. Recurrence interval is then plotted against its corresponding discharge to develop the flood frequency analysis. The Black Vermillion flood frequency analysis follows in Figure 1.19, which was then calibrated through field observation with geomorphic features at the gage site.

Figure 1.19 Flood frequency analysis for Black Vermillion river at Frankfort, KS. 1.5-year return interval discharge is approximately 4900cfs calculated from the annual peak maximum (USGS, 2010).



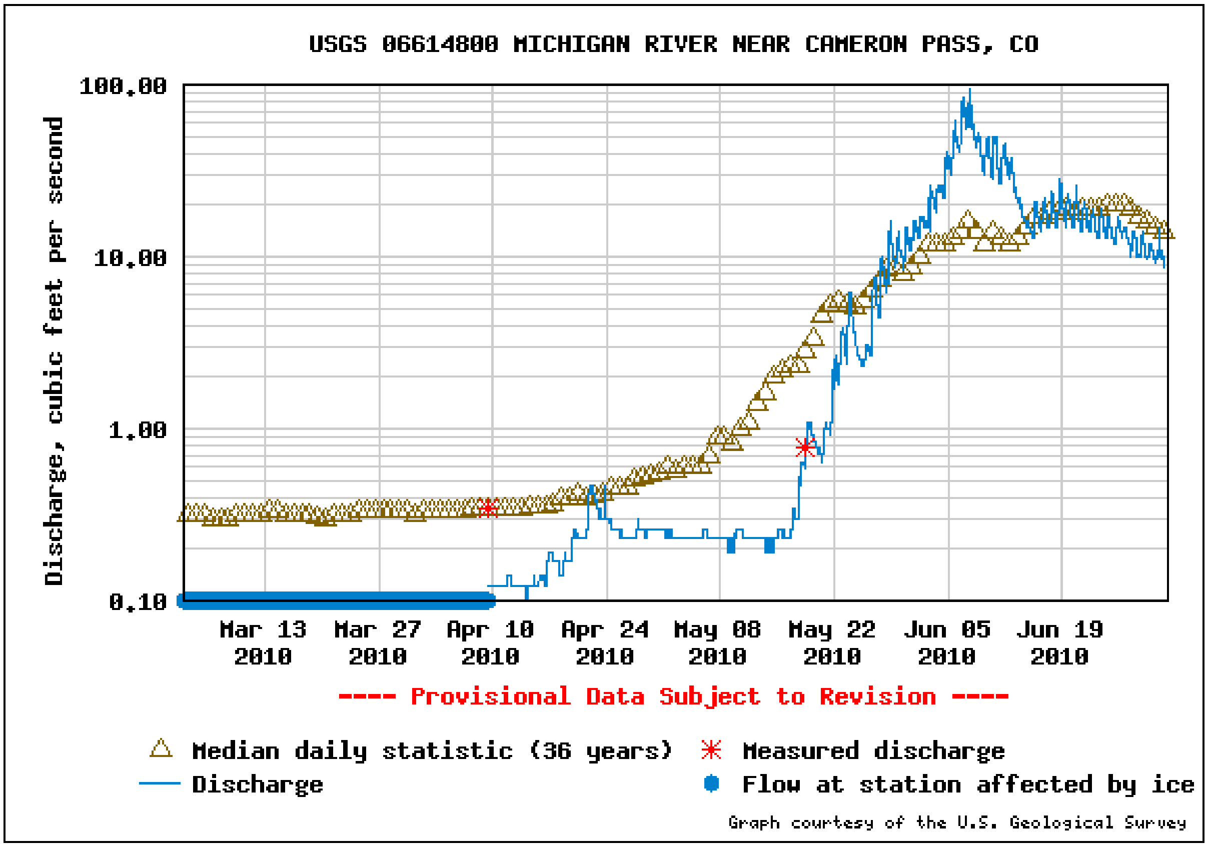
Hydrograph - graph of stream discharge past a given point plotted against time, Figure 1.20. A hydrograph displays how quickly water discharge rises and recedes. Historic hydrographs in Northeast Kansas watersheds had lower peak flows and the recession limb fell much slower than they do today (US-COE, 1998). Current hydrographs in our hydrophysiographic region are considered flashy, as they rise higher, faster, and recede quicker than in the past. This flashiness is attributed to increased impervious and semi-impervious surface not allowing precipitation infiltration, thus producing more runoff. The triangles in the hydrograph (Figure 1.20) illustrate a 56-year mean discharge, while the plotted blue line illustrates 2010 discharges.

Figure 1.20 Example hydrograph from Black Vermillion downstream of Frankfort, KS, May 8 through June 26, 2010 (USGS, 2010).



Snowmelt-generated vs. storm-generated hydrograph – runoff that increases a stream's discharge is created one of two ways; either melting snow from mountainous areas or precipitation directly from a storm. Snowmelt-generated hydrographs are usually more predictable than storm generated hydrographs, as seen in Figure 1.21. The triangles in the hydrograph illustrate a 36-year mean, while the plotted blue line illustrates this year's discharges. The erosion curves developed in Southern Colorado and Yellowstone were developed using snowmelt-generated hydrographs, thus bankfull conditions are often reliable as noted by the average discharge and yearly discharge in Figure 1.21 versus Figure 1.20. In our hydrophysiographic region, storms generate the majority of runoff to streams.

Figure 1.21 Snowmelt generated hydrograph from North-central Colorado (USGS, 2010). Notice mean daily statistic, quite different than Figure 1.19 a storm generated hydrograph.



Sediment Budget - is an accounting of sources and movement of sediment as it travels from its point of origin to its eventual exit from a watershed. A sediment budget accounts for rates and processes of erosion, transport and deposition, weathering and break down of sediment in transit, and temporary storage of sediment (Reid & Dunne, 1996).

Sediment load - amount of total sediment including bedload, suspended load and dissolved load, that is being transported by the stream (Knighton, 1998).

Pre-disturbance sediment levels - total sediment naturally associated within a stream prior to Euro-American induced hydrologic regime changes, or development of land.

Floodplain – is a flat, geomorphic feature adjacent to the channel that is currently being formed by the stream in its present condition and present climate (Figure 1.22, 1.23 and 1.24). Floodplain formation is maintained by the bankfull discharge, or 1.5-year recurrence interval discharge (Dunne & Leopold, 1998). The floodplain allows for the dissipation of excess energy during a flood event (Knighton, 1998).

Cutbank - outer bank of meander bend being eroded, and is an erosion produced, geomorphic feature of a stream (Figure 1.22 and 1.24) (Rosgen, 1996).

Point bar - a depositional feature typically located toward the inner bank of a meander bend and opposite of the cut bank (Figure 1.22 and 1.24) (Rosgen, 1996). If a stream is stable, the point bar builds as much in area as the cutbank erodes, thus there is no change in channel area and the channel remains stable by definition.

Flood prone area – defined as the area inundated at a depth of two-times maximum bankfull depth at a riffle cross-section (Figure 1.23) (Rosgen, 1996).

Terrace – geomorphic feature produced by the stream during a previous climatic regime, in essence an abandoned floodplain, Figure 1.22, 1.23, and 1.24 (Dunne & Leopold, 1998).

Figure 1.22 Plan view illustrating general geomorphic features.

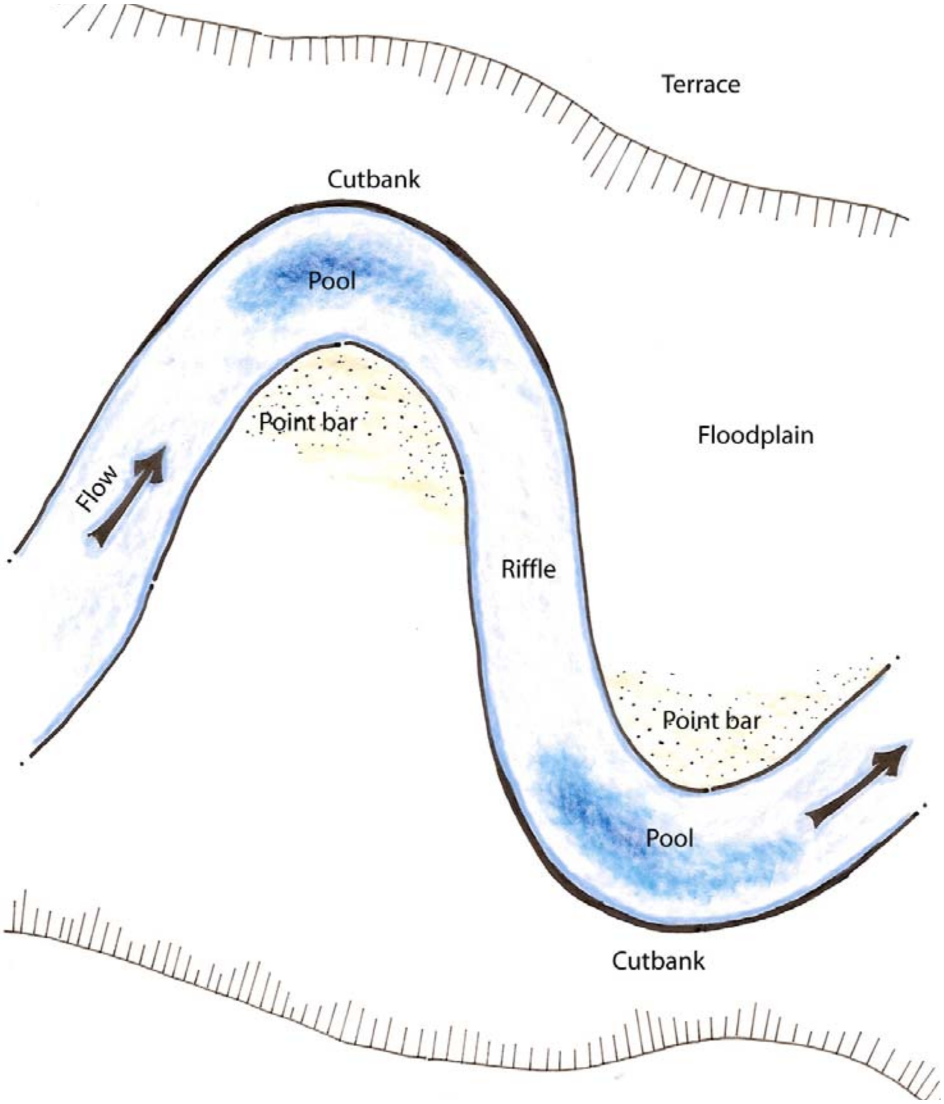


Figure 1.23 Typical riffle cross section of a stream.

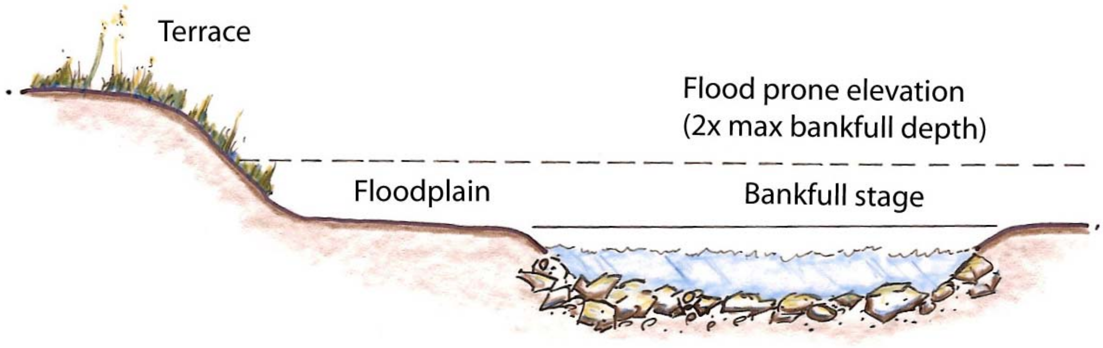
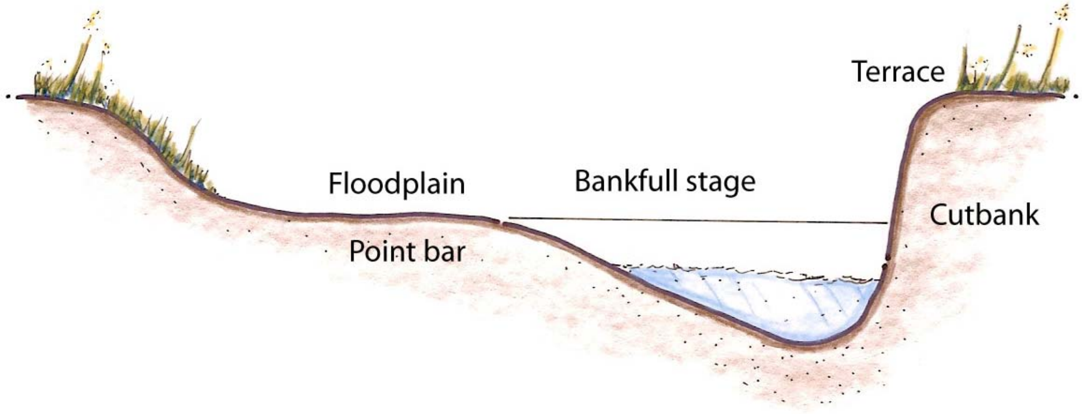


Figure 1.24 Typical pool cross section of a stream.



Rosgen classification system (1994, 1996)– classification of streams according to geomorphic characterization and morphologic descriptions. Geomorphic characterizations include channel slope (valley slope / sinuosity), shape and patterns. Morphological descriptions include entrenchment ratio, width to depth ratio, sinuosity, channel slope (measured via a longitudinal profile), and channel materials. Streams are assigned a letter ranging from A – G according to above parameters, then a number 1 – 6 representing the average bed material size ($D_{50\ sed}$). Rosgen (1996) developed his classification and assessment model to accomplish four goals; 1) Predict a river's behavior from appearance, 2) Develop hydraulic and sediment relations for a given stream type and state, 3) Provide a mechanism to extrapolate site-specific data to stream reaches with similar characteristics, 4) Provide a consistent frame of reference for communication between disciplines. Figures 1.25 and 1.26 illustrate Rosgen Classification.

Figure 1.25 General characteristics of streams in Rosgen Classification system showing cross sectional shapes and plan views (Rosgen, 1996).

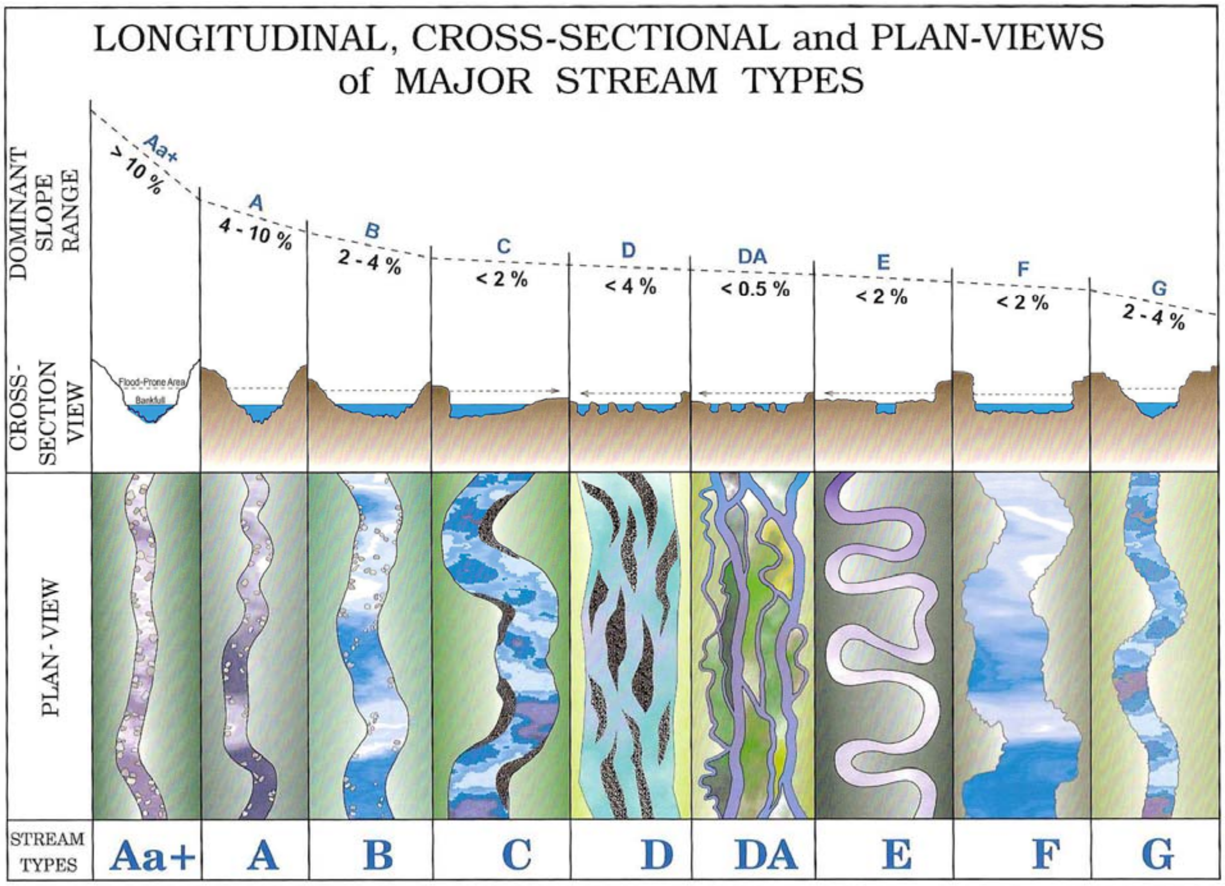
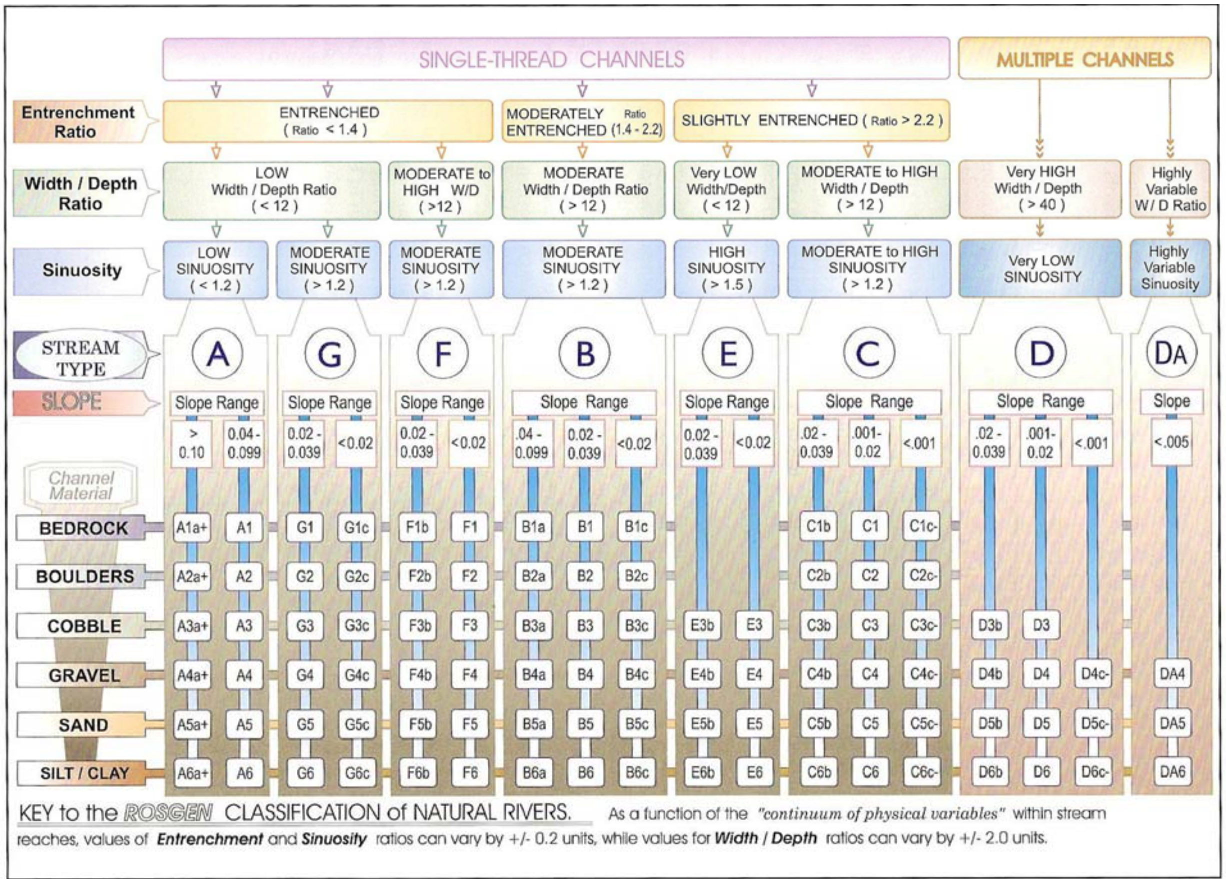


Figure 1.26 Flowchart with parameter cutoffs for Rosgen Classification system (Rosgen, 1996).

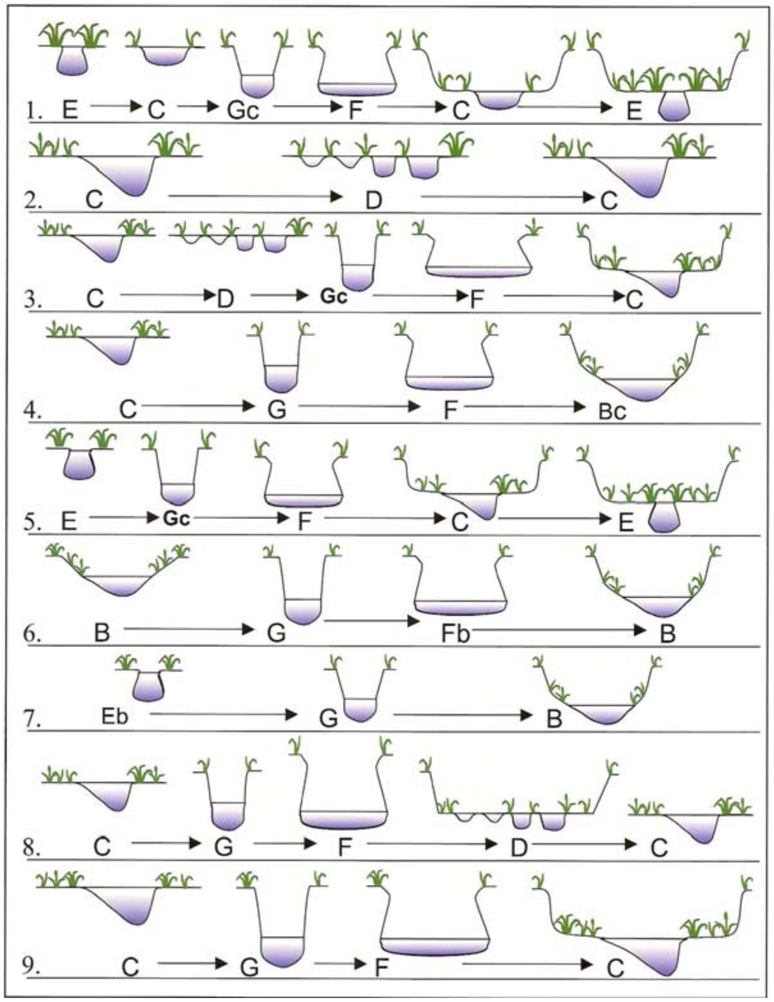


Stream Evolution models – a series of channel form adjustments over time accommodating changes of driving variables, such as increased or decreased runoff, increased slope, increased sediment supply or any combination of the aforementioned. Three popular models of stream evolution are the Rosgen Model (2006), Simon–Hupp Model (1986), and Schumm-Harvey-Watson Model (1984).

Stream stability - ability of a stream to maintain consistent dimension, pattern, profile, and channel features while neither aggrading nor degrading. Stability is achieved by the stream's ability to transport sediment (size and quantity) and water delivered to the stream by the attendant watershed (Rosgen, 1996).

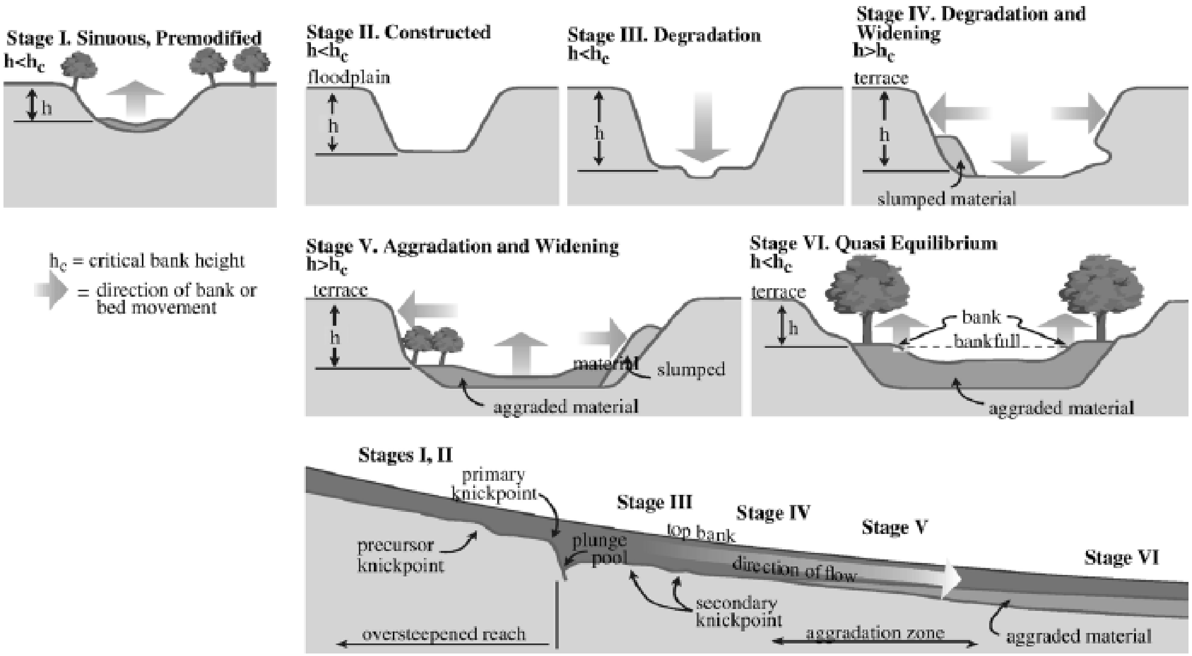
***Rosgen* (2006)** - The Rosgen model of stream evolution is based upon his classification of stream types. Streams in general will undergo a series of adjustments starting by down-cutting, then widening and move back to a stable stream form regarding the current climatic conditions. Depending on why the stream changed initially, a stream may not regain its original form due to changes in sediment loads or changes in runoff creating different effective or bankfull stream discharge than before. Figure 1.27 illustrates some of Rosgen's (2006) stream evolution sequences.

Figure 1.27 Sample of Rosgen evolutionary sequences (Rosgen, 2006).



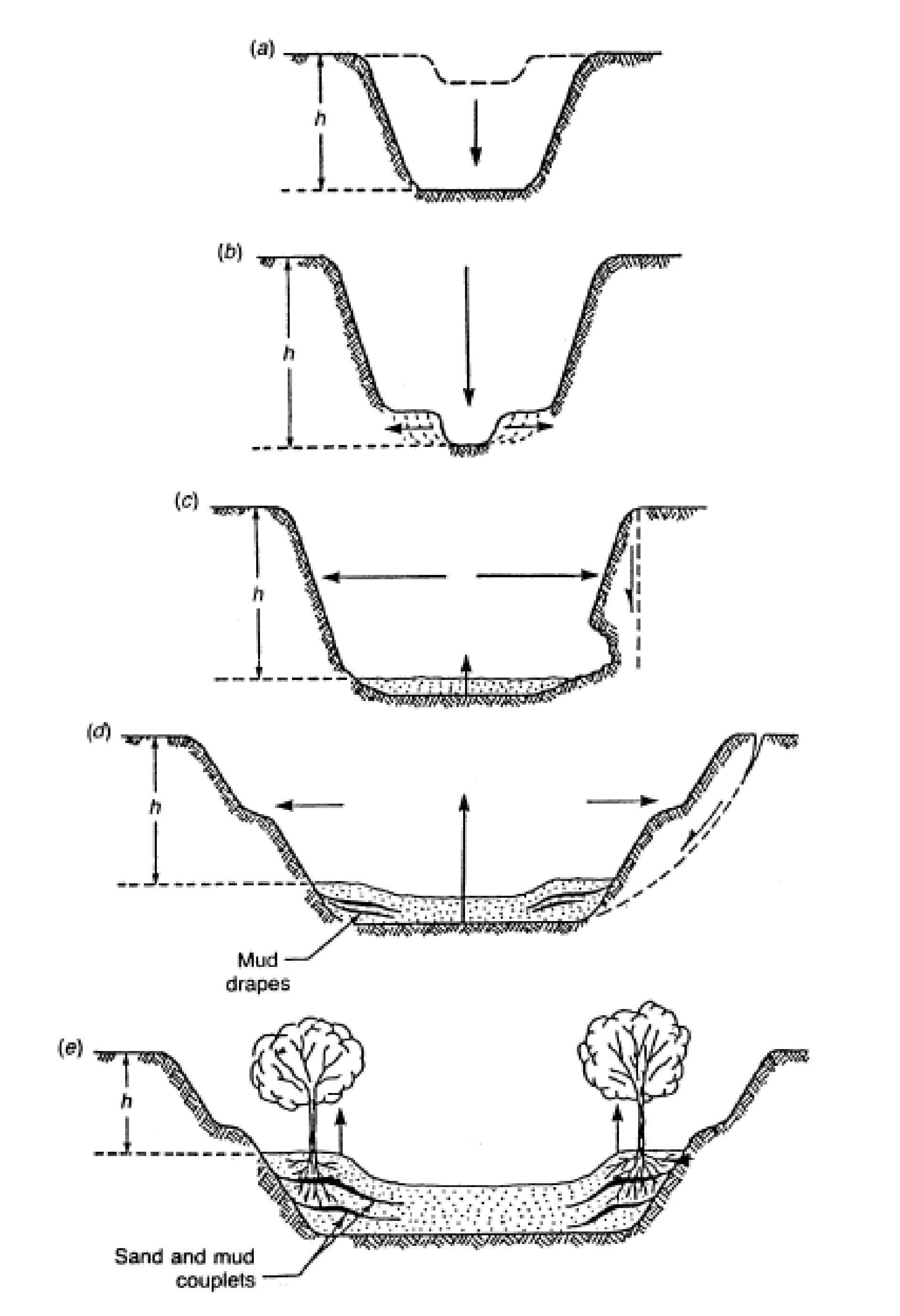
Simon-Hupp (1986, revised) - The Simon–Hupp model (Figure 1.28) is more general in terms of stream morphology than the Rosgen model. There are six stages associated with this model. Stage I is a pre-modified, sinuous stream. Stage II is a constructed stream, typically overwide and trapezoidal. Stage III begins degradation of the stream bed. Stage IV degradation and bank erosion (widening). Stage V, the channel aggrades and widens. Stage VI, the stream has reached a new quasi-equilibrium at the new elevation, climate, and hydrologic regime. Streams may go through all six stages or stages may be seen at six different points along the stream with the upstream site in Stage I and subsequent stages downstream. A seventh stage has been suggested by Thorne (1999), a stage of stream channel migration that is moving across the valley floor while maintaining stable cross-section channel dimensions.

F**igure 1.28 Simon–Hupp (1986) model of channel evolution (Simon and Rinaldi, 2006).**



Schumm-Harvey-Watson (1984) - The Schumm–Harvey–Watson model (Figure 1.29) is very similar to the Simon–Hupp model in that it is based on stages, however, there are only five stages in this model. Stage II (constructed channel) of Simon–Hupp (1986) is omitted. In addition, Schumm-Harvey-Watson model stage III (c) shows the bed aggrading while the Simon–Hupp model shows the bed continuing to degrade during the equivalent stage (IV). Again, an argument could be made for an additional stage regarding channel migration of stable cross-section channel dimensions (Thorne, 1999).

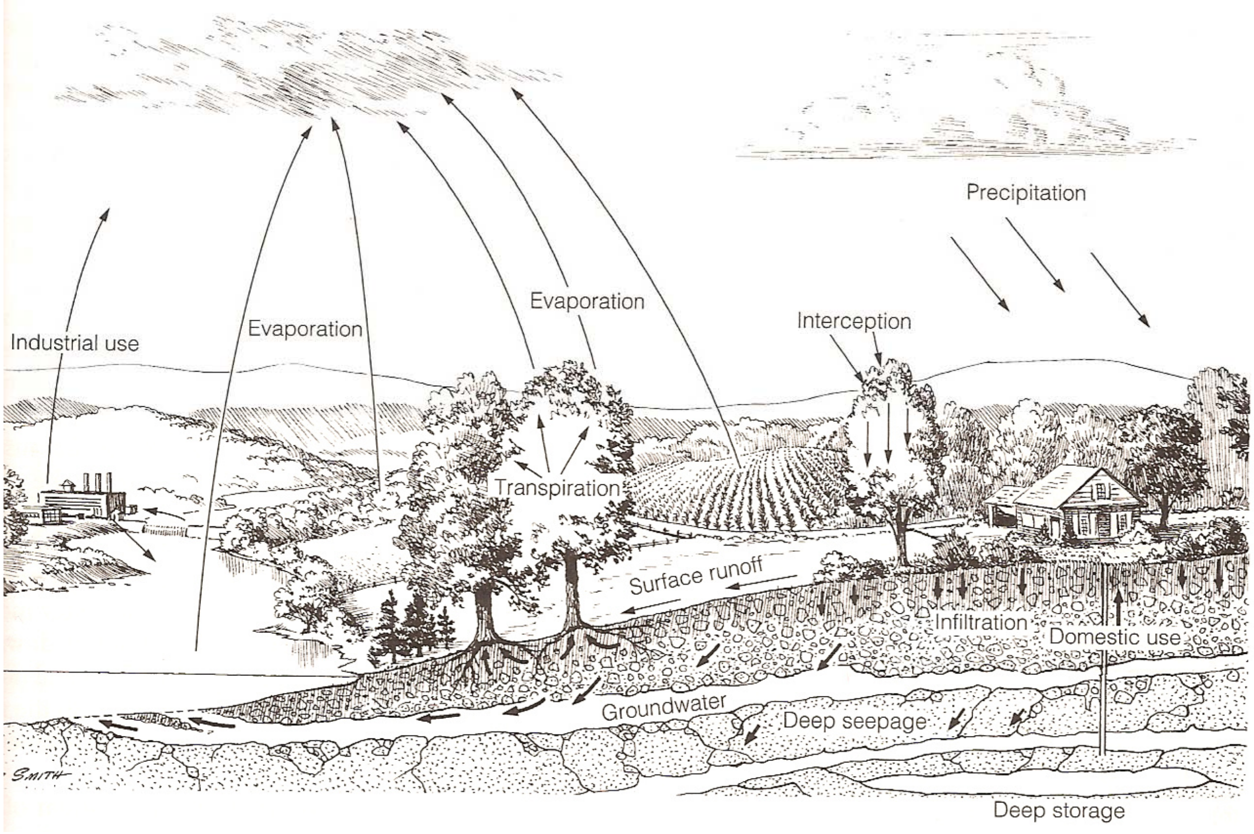
Figure 1.29 Schumm – Harvey – Watson (1984) Channel evolution model (Schumm, 1993).



Note: (a) is Stage I, (b) is Stage II, (c) is Stage III, (d) is Stage IV, and (e) is Stage V.

Hydrologic cycle - Movement of water through the terrestrial system from ocean, atmosphere, landscape and back again, Figure 1.30 (Odum, 1971; Smith and Smith, 2000).

Figure 1.30 Hydrologic cycle illustrated (Smith & Smith, 2000).



CHAPTER 2 - Literature Review

"Research is to see what everybody else has seen, and to think what nobody else has thought."
Albert Szent-Gyorgi

Introduction

Chapter 2 introduces, explains and discusses aspects important to the questions raised in this research and study. I begin by describing regional traits using the Ecoregion concept provided and established by the United States Environmental Protection Agency (US-EPA) (2010). Along with Ecoregion descriptions, I include climatic, vegetative and geologic factors affecting the study area's hydrology and ecology. Land use and land cover changes since the original Kansas Territory surveys (1857) (KSLS, 2005) are briefly described. Specifics of land use and land cover changes in this watershed may be found in my thesis (Sass, 2008). Literature important to understanding historical significance of erosion and denudation of the landscape in the U.S. is then discussed. These concepts and factors help in understanding place, both ecologically and culturally. Individual erosional processes are discussed next.

Many processes contribute to streambank erosion. Some specifically contributing to streambank erosion have been studied for less than 100 years, even less in natural settings. Flume studies representing stream behavior and processes have been common since the late 1800's (Davis, 1899; Gilbert, 1914; Leopold & Wolman, 1957). Late in this chapter, singular erosional processes are discussed along with different methods of bank erosion measures and models. A general look at Rosgen's classification and stream assessment system, specifically the BANCS model, ends this chapter to allow a better understanding of how Rosgen's system functions and is applied in this study.

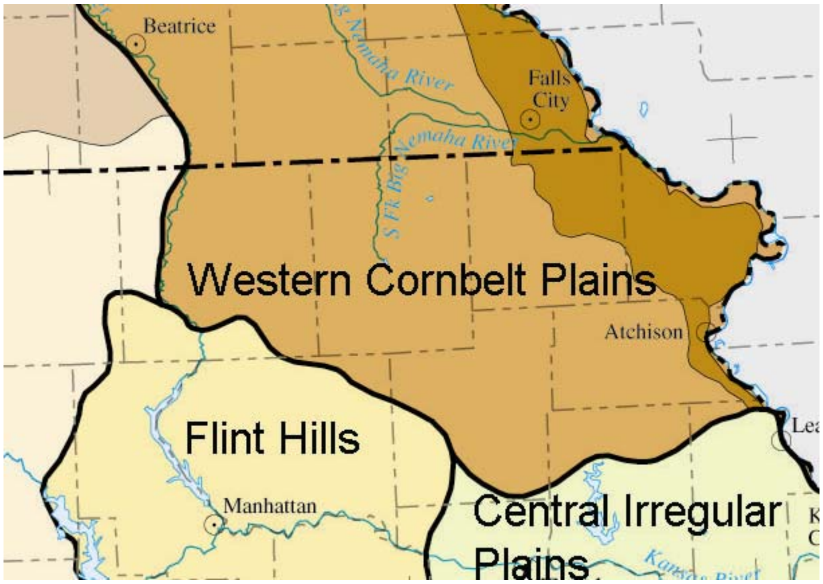
Regional Background

Ecoregions

Ecoregions were developed to aid in organizing ecosystem resources culminating in five outcomes: 1) compare the similarities and differences of land – water relationships; 2) establish water quality standards that are in tune with regional patterns; 3) locate monitoring, demonstration, or reference sites; 4) extrapolate from existing site-specific studies; 5) predict the effects of changes in land use and pollution controls. Four different sources of information were synthesized in developing Ecoregions and include Major Land Uses (Anderson, 1970), Classes of land-surface form (Hammond, 1970), Potential Natural Vegetation (Kuchler, 1970) and soils maps from various sources. Development of the Ecoregion concept and model was not intended for precise, large-scale inventory (Omernik, 1987). There are four levels (I-IV) of Ecoregions; each higher level becomes finer in homogeneity, thus should produce similar reactions to climatic or cultural landscape changes.

Ecoregions can be used to describe large areas of landscape that are similar in many ecological respects. The Level III Ecoregion affecting the Black Vermillion watershed in Northeast Kansas is the Western Corn Belt Plains. However, Flint Hills and Central Irregular Plains influence the watershed as they are adjacent ecoregions to the watershed. These Level III ecoregions are described below and are illustrated in Figure 2.1 (Chapman et al. 2001).

Figure 2.1 Level III and IV Ecoregions of Northeast Kansas and Southeast Nebraska (Chapman et al. 2001, modified).



Western Corn Belt Plains (Ecoregion 47)

"Once covered with tallgrass prairie, over 75 percent of the Western Corn Belt Plains is now used for cropland agriculture and much of the remainder is in forage for livestock. A combination of nearly level to gently rolling glaciated till plains and hilly loess plains, an average annual precipitation of 63-89 cm, which occurs mainly in the growing season, and fertile, warm, moist soils make this one of the most productive areas of corn and soybeans in the world. Major environmental concerns in the region include surface and groundwater contamination from fertilizer and pesticide applications as well as impacts from concentrated livestock production." (Chapman et al. 2001)

The Flint Hills (Ecoregion 28)

"The Flint Hills is a region of rolling hills with relatively narrow steep valleys, and is composed of shale and cherty limestone with rocky soils. In contrast to surrounding ecological regions that are mostly in cropland, most of the Flint Hills region is grazed by beef cattle. The Flint Hills mark the western edge of the tallgrass prairie, and contain the largest remaining intact tallgrass prairie in the Great Plains." (Chapman et al. 2001)

Central Irregular Plains (Ecoregion 40)

"The Central Irregular Plains have a mix of land use and are topographically more irregular than the Western Corn Belt Plains (47) to the north, where most of the land is in crops. The region, however, is less irregular and less forest covered than the ecoregions to the south and east. The potential natural vegetation of this ecological region is a grassland/forest mosaic with wider forested strips along the streams compared to Ecoregion 47 to the north. The mix of land use activities in the Central Irregular Plains also includes mining operations of high-sulfur bituminous coal. The disturbance of these coal strata in southern Iowa and northern Missouri has degraded water quality and affected aquatic biota." (Chapman et al. 2001)

Northeast Kansas Climate and Geology

Climate and geology are two factors that influence plant communities of a region (Leopold, Wolman and Miller, 1964; Odum, 1971; Smith & Smith, 2000). Northeast Kansas has a unique combination of climate and geology that contributes to its prairie setting. Two general land formations are located in the study area, the Glaciated Region of Kansas and Flint Hills Uplands (Figure 2.1). These physiographic regions present differing geology but similar climates, generating similar plant communities. Geologic formation of underlying bedrock is similar between the two regions since the area was once an inland sea, the last inland sea being extant approximately 270 million years ago. Shale and limestone layers that dip slightly to the northwest are prevalent under the glacial till in the glaciated region of the state (Walters, 1954; Aber, 2007a). The Flint Hills have no glacial till covering the tilted shale and limestone layers, creating a different hydrophysiographic region. Between the two Ecoregions, the Flint Hills and Western Corn Belt Plains, there lies a transition zone where both ecoregions influence local hydrology and ecology, similar to an ecotone.

Northeast Kansas Climate

Climate is defined as the average weather pattern over time in a given region (Smith & Smith, 2000). The climate in northeast Kansas is considered continental with an average precipitation of approximately 81-89cm (32”-35”) per year. In terms of precipitation, the area enjoys a water surplus, allowing water to move into stream channels via overland and subsurface flows after evapo-transpiration and flora uptake of water (Aber, 2007c). Most precipitation falls during the growing season, April through September (Oznet, 2008). Relative humidity in the region averages 45-50%. Average annual temperatures of 12.8˚ Celsius (55˚ Fahrenheit) characterize the climate (Oznet, 2008). Daily range in temperature is around 11.1˚ -12.2˚ C (20˚ -22˚ F). The coldest month on average is January while February usually harbors the coldest days. Average highs in January are 5.5˚ C (42˚ F). Eight to ten days a year temperatures can dip to -17.8˚ C (0˚ F). July is usually the hottest month on average with temperatures reaching near 34.4˚ C (94˚ F). About ten days each summer temperatures reach or exceed the 37.8˚ C (100˚ F) mark. There are approximately 145 days of clear sky, while winds may reach peak gust velocities of 75.6km/hr (47mph) or higher (Oznet, 2008).

Geology and Soils

Glaciated Region

The Pre-Illinoian Glacier terminated at the foot of the Flint Hills in Northeast Kansas approximately 600,000 years ago; see Figure 2.2 for location of the glaciated region and Flint Hills region (KGS, 2007). Many glacial erratics are found throughout the glaciated area, most erratics being of Sioux quartzite, which is a reddish, granitic material from South Dakota, Iowa and Minnesota (KGS, 2007). The underlying bedrock in the glaciated area of Northeast Kansas is Pennsylvanian and Permian limestone and shale that dip gently to the west and northwest, much like the Flint Hills. However, a layer of glacial till including clay, silt, sand, gravel, cobbles, and boulders covers this bedrock. Figure 2.3 is a cross section of Marshall County, Kansas, the location of the Black Vermillion watershed, showing approximate depths of glacial and alluvial deposits across the county (KGS, 2007). Glacial deposits may be quite deep with areas exceeding 40’.

Figure 2.2 Generalized physiographic map of Kansas (KGS, 2007).

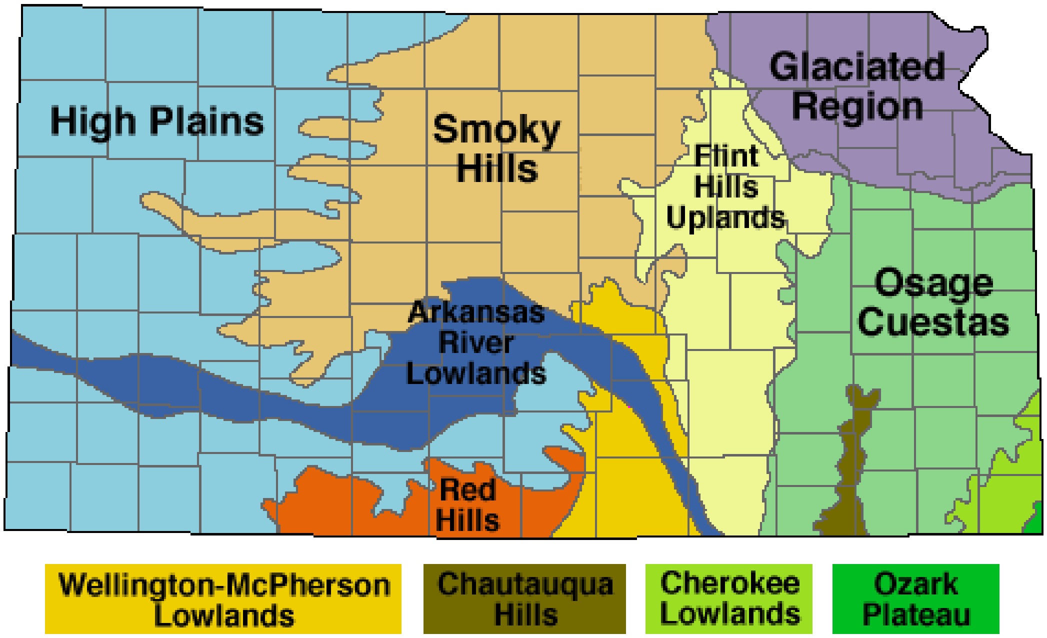
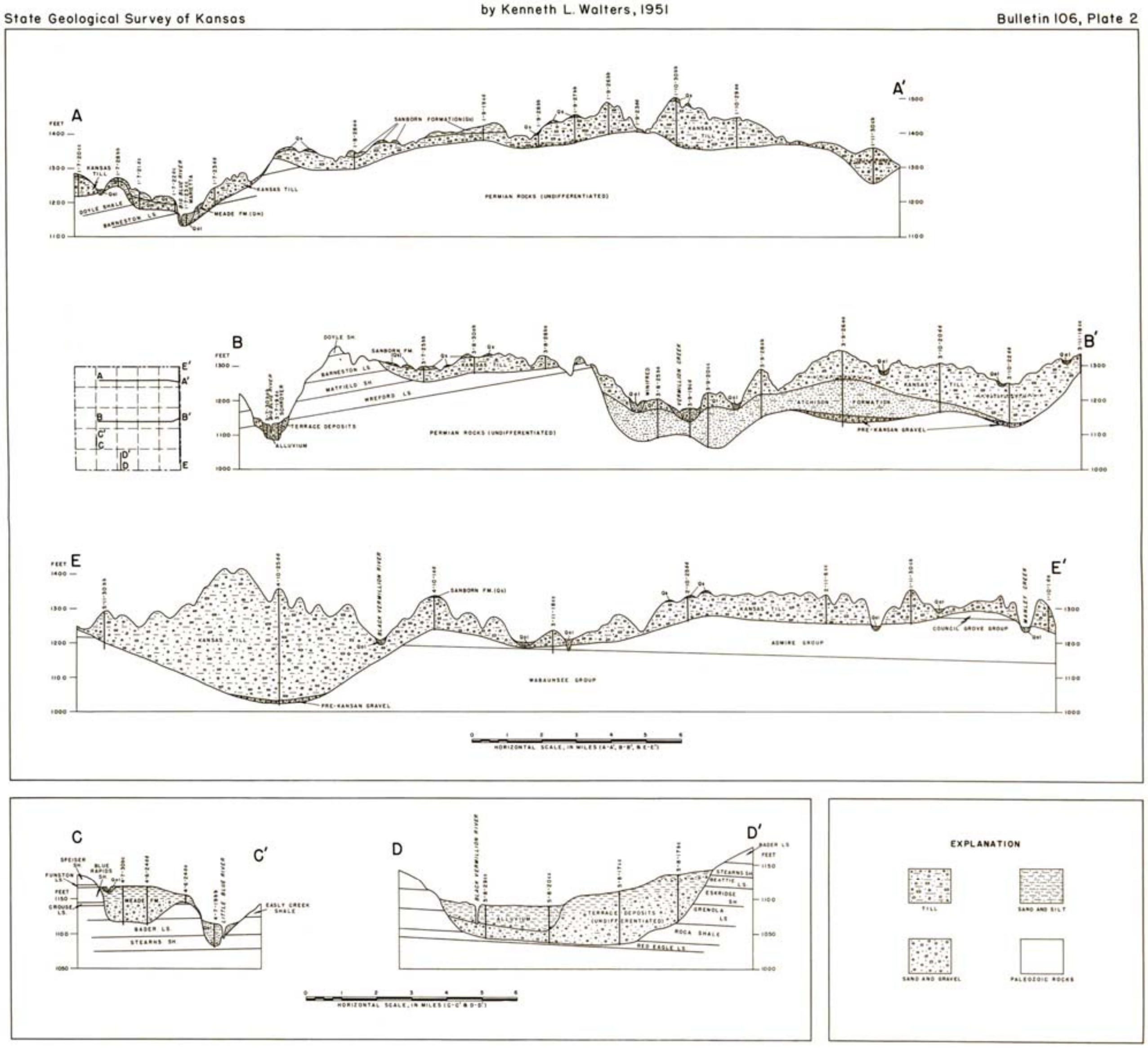


Figure 2.3 Cross sections of glaciated region Marshall County, Kansas (Walters, 1954) (Larger version Appendix Figure A.2).



Soils

Vegetation community formation depends on climate, soil characteristics, and formation of soils. Soil characteristics and formation are determined by the interaction of five factors; these factors are parent material, biota, climate, relief, and time. Each of these five factors affect the formation of soil and influences the other four formation factors (Smith & Smith, 2000; Harpstead et al. 2001; NRCS, 2008). Soils in this portion of northeast Kansas are of the order Mollisol. Mollisols, or soils formed primarily by the organic contributions of grasses, have distinct horizons or layers, are rich in organic matter, and take hundreds to thousands of years to form (Reichman, 1987; Smith & Smith, 2000). Today's cultivated fields of row crops were once humus rich soils covered by native grasses, as these soils are the most agriculturally productive soils (Harpstead et al. 2001). However, these fertile soils have been moved from the fields to streams, then carried downstream and deposited. Three modes of transportation, water, gravity and wind move soils. Soils deposited by wind are termed loess and cap many of the watershed ridges (SCS, 1966a, b, c). Soil particles moved by fluvial processes are addressed as alluvium, while dry, gravitational movement is considered colluvium.

Alluvium, or soils that are moved and deposited by fluvial processes on floodplains, should be common in riparian corridors due to repeated flooding and deposition of sediment on the floodplain. Soils adjacent to channels in the Black Vermillion watershed have formed from alluvium parent material. These soils range in clay content from 23% to 47%, or high clay contents. Table 1 displays major soil properties and stream reach locations of soil types adjacent to streams in the Black Vermillion watershed.

Table 1 Soil names and properties adjacent to streams (NRCS, 2010).

Location	Soil Name	Parent Material	Percent Clay	Liquid Limit	Bulk Density	Minor Association
MS1	Kennebec Silt Loam	Fine-silty alluvium	25.4%	40.5%	1.37 g/cm^3	Wabash
MS2	Kennebec Silt Loam	Fine-silty alluvium	25.4%	40.5%	1.37 g/cm^3	Wabash
MS3	Nodaway Silt Loam	Calcareous fine-silty alluvium	23%	35.3%	1.30 g/cm^3	Wabash, Aquolls
NF1	Kennebec Silt Loam	Fine-silty alluvium	25.4%	40.5%	1.37 g/cm^3	Wabash
NF2	Wabash silty clay loam	Clayey alluvium	47.1%	62.6%	1.35 g/cm^3	none
NF3	Nodaway silt loam	Calcareous fine-silty alluvium	23%	35.3%	1.30 g/cm^3	Wabash, Aquolls
IC1	Kennebec Silt Loam	Fine-silty alluvium	25.4%	40.5%	1.37 g/cm^3	Wabash
IC2	Kennebec Silt Loam	Fine-silty alluvium	25.4%	40.5%	1.37 g/cm^3	Wabash
IC3	Wabash silty clay loam	Clayey alluvium	47.1%	62.6%	1.35 g/cm^3	none

Flint Hills Uplands

The Flint Hills Uplands is a unique physiographic region found in east-central Kansas (Figure 2.2). This area was formed by an inland sea that rose and fell repeatedly approximately 270-300 million years ago and was always less than 30.5m (100') deep, as indicated by ripple marks, algal laminations and oolites found in the limestone units (Aber, 2007a, b, c). The bedrock stratigraphy is consistent laterally and layers alternate between shale and limestone maintaining thickness consistency. A limestone cap is responsible for maintaining the topographic relief due to resistance to weathering and erosional forces. Dip is typically westward to northwestward at an angle of 4-10 degrees (Aber, 2007a). Limestone layers contain flint nodules, from which the region received its name.

Chert, or flint, is found in nodules embedded into the limestone formations. Chert is highly resistant to weathering and when it is left behind as residual lag, helps maintain limestone caps and topographic relief (Aber, 2007a, b). Due to chert's hardness, landform and depth to bedrock on terraces, most of the region has never been plowed. The result is the largest, contiguous region of native tallgrass prairie remaining in North America. Most of the Flint Hills region is home to cattle ranching and grazing land.

Deep valleys have been created in the Flint Hills due to stream erosion (Aber, 2007c). Topographic relief in the area can be up to 30.5m (100') and deeply entrenched streams are common, drainages tend to follow in troughs and synclines of the formations (Aber, 2007c). Flash flooding is common in this region due to the semi-permeable layers of limestone and shale as well as the shallow, clay-rich soils of the areas. Valleys usually have deeper soils than ridge tops due to the steep slopes typically found on the formations. Surface runoff occurs mostly during storm events that happen in the spring and early summer and then again in fall (Aber, 2007c). In Figure 2.3, we can see a typical Flint Hill formation in eastern Marshall County in Section B-B^1.

Northeast Kansas Vegetation

Historic Plant Composition

Approximately 42% of the earth's terrestrial surface was once covered by grasslands (Reichman, 1987; Smith & Smith, 2000; Briggs et al. 2005). Grasslands, or prairies, typically receive precipitation between 25.4-81.28cm (10"-32") and require periodic fires and grazing for maintenance, renewal, and elimination of woody growth (Briggs et al. 2005; Smith & Smith, 2000). Northeast Kansas historically supported a tallgrass prairie ecosystem (Briggs et al. 2005; Haddock, 2005) and typically included the grasses big bluestem (*Andropogon gerardii*), Indian grass (*Sorghastrum nutans*) and switchgrass (*Panicum virgatum*) (Reichman, 1987; Haddock, 2005). Northeast Kansas received sufficient precipitation to support deciduous forests, but with fire and grazing as disturbance regimes, woody species were confined to riparian corridors. Northeast Kansas did support a wide-open expanse of tallgrass prairie along with scattered trees, such as bur oak (*Quercus macrocarpa*) and narrow riparian corridors with large woody species such as black walnut (*Juglans nigra*), sycamore (*Platanus occidentalis*) and cottonwood (*Populus deltoides*) (KSLS, 2005).

Riparian vegetation once covered approximately 2% of North America with more than 89% of the 2% being lost over the last 200 years (Popotnik & Giuliano, 2000). North America is approximately 24.4 million Km^2 (9.45 million $miles^2$), which means of the approximately 488,000 Km^2 (189,000 $miles^2$) of historical riparian vegetation, there are 1073.6 Km^2 (414 $miles^2$) of riparian corridors left in North America. These corridors have been victim to logging, agricultural practices and urban development (Popotnik & Giuliano, 2000). The Black Vermillion watershed alone has lost an average of 80-85% of woody riparian corridor (Sass, 2008). If 2% of riparian cover in the Black Vermillion watershed is assumed historically, then of the original $21.2Km^2$ (8.2 $miles^2$), only $3.2Km^2$ (1.2 $miles^2$) remains. An assumption of 2% woody riparian vegetation is likely a safe assumption for the Black Vermillion since the smallest average amount of woody vegetation was $3.5Km^2$ (1.35 $miles^2$) remained (Sass, 2008).

Historically, riparian forests located within the prairie were found only on floodplains of streams and did not establish far from the centerline of the creek (Reichman, 1987; KSLS, 2005). Headwater streams generally flowed through native prairie grasses, sedges, rushes and forbs as opposed to woody riparian vegetation corridors (KSLS, 2005). This set of circumstances is due to the unfavorable conditions for the growth of woody species; the typical burning and grazing of the prairie (Knight et al. 1994; Richardson et al. 2007). Historically, wooded riparian corridors located within prairie settings were narrow and linear in form (gallery forest) with few areas that increased in width, usually a tributary confluence. Riparian forests contained understory shrubs and forbs along with scattered canopy trees (Knight et al. 1994; KSLS, 2005). The Territory of Kansas survey of 1857 documented native vegetation of the area, soil ratings and stream channel dimensions when crossed at a section or quarter section (KSLS, 2005). These historic observations provide a glimpse of how channels have changed in this area.

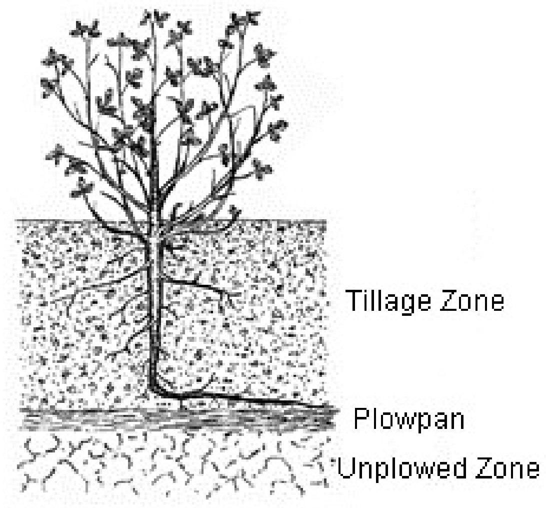
Land Cover & Use

Land cover and use in Northeast Kansas has changed dramatically since the original Kansas Territory Surveys of 1857. What was once a lush, tallgrass prairie with narrow gallery forests has become a sea of row crops of corn, soy beans and winter wheat with even more narrow to non-existent gallery forests. Historic grazers such as mule deer (*Odocoileus hemionus*) and bison (*Bison bison*) have been replaced with horse and cattle that typically are overstocked, which impacts the landscape through soil compaction while decreasing native vegetation (Clary, 1999). White-tailed deer (*Odocoileus virginianus*) populations have exploded due to land cover changes and have become a concern due to their browsing and grazing habits. Precipitation runoff has increased in agricultural fields and grazed pastures due to bare and compacted soils acting as a semi-impervious surface. Consequently, land use change not only affects the stream systems but impacts many aspects of the landscape. Impacts from overgrazing and uncontrolled populations of native wildlife also include loss of flora and fauna, loss of diverse and important habitat, and reduced water quality with increased sediment in streams from overland, streambed and streambank erosion (Odum, 1971; Popotnik & Giuliano, 2000). Woody riparian vegetation is known to filter overland flow and help stabilize banks from erosion (Gurnell, 1997; Naiman & Decamps, 1997; Pollen, 2007). The most important result of land cover and use change is how these changes increased runoff to the stream, thus increasing discharge and flashiness of the stream.

Agricultural Land Development

Development of agricultural land in Kansas since 1857 changed the hydrology of the watershed dramatically. The Black Vermillion watershed historically was covered by lush prairie that protected the soil and allowed slow infiltration of precipitation; it is now a vast area of less permeable soils and tilled landscape. Agricultural land that is tilled at a constant depth develops a plowpan (Figure 2.4), or an impermeable layer of soil at the plowed depth. This layer no longer allows water to percolate to the depths it once did, lessening the soil's storage capacity for water and saturation time, and creating runoff faster than historic conditions. Precipitation that is stored moves along the pan to the stream instead of slowly percolating downward and toward the stream as baseflow. Both the plowpan and bare soils during the rainy season allow for more runoff to reach the stream faster and provide less base flow during drought, creating flashy stream conditions. When streams become flashy they can provide more erosive force against the bed and banks due to higher stages and quicker flows. After quick, high flows, streams can loose hydrostatic pressure against the bank material after a rapid retreat in stage causing mass failure of the bank. Channel modification increases channel slope, which increases velocity and increases erosive force. Combine extra discharge and erosive force with human channel modifications, such as channelization, and the stream degrades quickly. The result is what we typically see in Northeast Kansas and similar Midwestern agricultural areas; steepened high banks, little woody vegetation, straight stream reaches, and excess sediment ready to be mobilized and transported downstream.

Figure 2.4 Plowpan illustrated below restricting root growth. Top layer of soil is constantly tilled to the plowpan depth creating impermeable layer (Hearpstead et al. 2001)



Brief Historical Perspective of Soil Erosion

Concerns regarding erosion and soil loss in the United States began as early as the late 1700s when Patrick Henry was quoted as saying, "…since the achievement of our independence, he is the greatest patriot who stops the most gullies." Thomas Jefferson's son-in-law, Thomas Mann Randolph, circulated the idea of horizontal plowing, or what is know today as contour farming. Erosion concerns elevated during the dustbowl of the 1930s and continue today (Helms, 1991, 1989). Hugh Hammond Bennett led the charge to conserve soil and was appointed as head of the Soil Erosion Service in 1933. His efforts helped shape the Soil

Conservation Act of 1935, creating the Soil Conservation Service as a permanent entity. Since then, many experiments have been conducted both in labs and on fields to increase knowledge of conservation practices regarding soils throughout the nation (Helms, 1989, 1991). Unfortunately, the original concentration of study was on the uplands, not both uplands and streams.

There are two types of erosion generally noted; overland and in-channel. Sediment eroded from upland sources (overland) makes its way to the stream or riparian corridor and can exit the watershed, be temporarily stored in stream or deposited on the floodplain, or reside permanently in stream or on the floodplain. Deposition of excess sediment can cause problems in and near streams. First, deposition next to the stream on the floodplain can actually raise the floodplain elevation, disconnecting the stream from its floodplain (Knox, 2006). A disconnected floodplain may increase shear stress in the channel by increasing velocity, thus increase bed and bank erosion, and loss of floodplain biodiversity. Second, excess sediment delivered to a stream can raise the bed level of the stream, causing excess and increased flooding potential (Knighton, 1998). As of 1995, the U.S. spent $520 million annually dredging sediment from waterways (Pimentel et al. 1995). However, overland erosion rates have decreased significantly (65%) since the mid-20th century (Hargrove et al, 2010). The question arises, where does the excess sediment now come from if overland erosion rates have decreased significantly and sedimentation of our reservoirs continues at alarming rates? An overview of overland and in-channel erosional processes will be helpful in understanding this study and erosion processes.

Overland Erosional Processes

Overland erosion may be experienced in four ways; rainsplash, interrill (sheetwash), rill, and gully (Dunne & Leopold, 1998; Knighton, 1998). Channel banks may not experience overland processes specifically, however these overland processes do influence channel bank erosion. An explanation of each process is described below.

Rainsplash & Interrill

Rainsplash and interrill erosional processes are small in scale and are hardly noticed over time; however, they may lead to rill and gully erosion. Rainsplash erosion occurs when a single droplet of rain hits bare soil, throwing soil into the air (on a small scale). It also destroys soil structure and moves single soil particles, typically downslope (Dunne & Leopold, 1998).

Interrill erosion, also known as sheetwash, occurs on hill slopes in a manner similar to a sheet of water on the soil surface and contains small streams in the water column that are slightly deeper and faster than surrounding water. Sheetwash begins to accumulate as runoff increases due to increases in rainfall intensity versus infiltration rates. Interrill erosion increases with steepened slopes and longer slope lengths, as sheetwash increases its depth and power while runoff moves downslope (Knighton, 1998). Sheetwash and rainsplash erosion are responsible for a majority of overland erosion rates (Dunne & Leopold, 1998; Knighton, 1998).

Interrill and rainsplash erosion can be deterred through conservation practices, especially no-till practice (Bradford & Huang, 1994). Bradford and Huang (1994) found that erosion on conventional tillage plots depends on amount of residue cover, roughness, moisture conditions and drying following rainfall. In addition, no-till infiltration rates were high compared to conventional till. No-till created less sediment yield because of lowered soil detachment rates due to rainsplash, thus sediment was not available for transport (Bradford & Huang, 1994). Additional conservation practices mitigating interrill erosion include field terracing and contour farming.

Rill

Rill erosion begins when sheetwash concentrates and cuts separate, small-scale channels in the landscape. Concentration of runoff increases erosive energy, which in turn causes efficient and intense soil removal (Dunne & Leopold, 1998). Rills are ephemeral features that can move from one place to another and are generally less than one foot in depth. Thus, these features are typically removed from agricultural fields by the next storm and runoff event, or by farming implements and tillage practices (Knighton, 1998; Marston, 2007).

Gully

Rills that become permanent in location and carve into the landscape are referred to as gullies. Dunne and Leopold (1998) state that gully erosion accounts for a small percentage of soil erosion (<5%) compared to sheetwash and rill erosion (>90%). However, these measures were taken in arid rangelands. Poesen, Vandaele and Van Wesemael (1996) found ephemeral gullies in European agricultural environments to produce 44% of the sediment yield. Closer to the Black Vermillion system, Cheney Lake watershed in south-central Kansas has shown 76% of the sediment load in streams is produced by gully erosion and comes from approximately 10% of the watershed acreage. NRCS states treating ephemeral gullies in the watershed could reduce the total sediment load by 35% in the Cheney Lake watershed (NRCS, 2006).

In-Channel Erosional Processes

Bank erosion occurs through a combination of three main processes; subaerial processes and erosion, fluvial entrainment, and mass failure (Lawler, 1995). These processes are influenced by many variables. Table 2 lists variables associated with bank erosion and relevant characteristics. It is important to note these variables are not processes, but factors influencing processes.

Table 2 Factors influencing bank erosion (Knighton, 1998).

Factor (variable)	**Relevant Characteristics**
Flow properties	Magnitude – frequency and variability of stream discharge Magnitude and distribution of velocity and shear stress Degree of turbulence
Bank material composition	Size, gradation, cohesivity and stratification of bank sediments
Climate	Amount, intensity and duration of rainfall Frequency and duration of freezing
Subsurface conditions	Seepage forces, piping Soil moisture levels, porewater pressures
Channel geometry	Width, depth and slope of channel Height and angle of bank Bend curvature
Biology	Type, density and root system of vegetation Animal burrows, trampling
Man-induced factors	Urbanization, land drainage, reservoir development, bank protection structures

Fluvial Entrainment

Fluvial entrainment is erosion of individual particles from the bank, typically at the bank toe. We can further define entrainment as the function of shear stresses at the bank-water interface (MacIntyre, Lick & Tsai, 1990). Thus, entrainment is a function of stream power, or the amount and size of particles a stream column is able to move or detach from the streambed or bank. This process of erosion leads to undercutting of banks often resulting in mass failure of steepened streambanks, which after failure remain steepened.

Larger sediment particles require more critical shear stress (or in effect, velocity) to be moved or entrained. Sediment size being entrained can be estimated using the Hjulstrom (velocity) or Shields' relation curve (critical shear stress) (Knighton, 1998; Rosgen, 2008a and b). Hjulstrom's curve illustrates that velocity decreases with particle size until cohesive forces become significant, and then velocity must be increased to move smaller grains (clays) (Schumm, 1973). However, Shields' curve assumes channels with homogeneous bed material and typically under predicts size of entrained materials (Rosgen, 1996), while Hjulstrom's curve only indicates motion of single particles at a given velocity. Leopold, Wolman and Miller (Rosgen, 2008a and b) added data to the Shields curve in 1964, while Rosgen (2006; Rosgen and Silvey, 2007) added data from Colorado to the Shields curve.

Rosgen protocol samples sediment size transported in a stream through a modified pavement / sub-pavement sample called a bar sample. A measure of sediment size entrained by the stream at bankfull stage can be gauged through bar samples and assessing these samples for the D_{84}, or the sediment size that falls at the 84th percentile (Rosgen, 1996, 2008a and b). Understanding the sizes of sediment transported by the stream can provide insight into shear forces being applied to bank materials and stream boundaries.

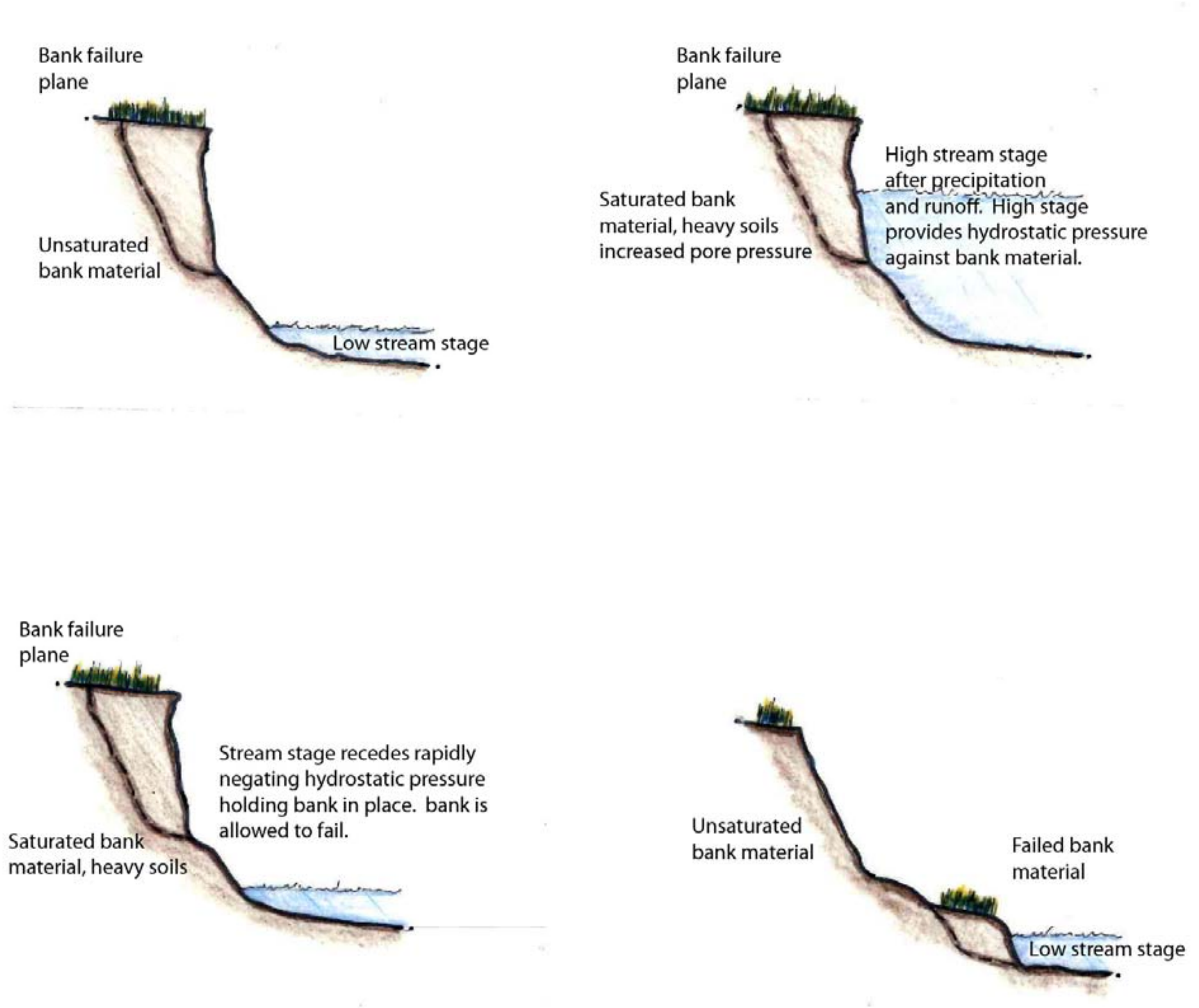
Fluvial entrainment of smaller clay and silt particles of the lower bank toe may contribute small amounts of sediment yield overall. However, if the bank is undercut by erosion of the toe, overhanging banks are susceptible to mass wasting. Once mass failure has occurred and the debris moves to the stream channel, the debris can be entrained and moved downstream. Evidence of this type of erosional sequence may be found on isolated banks in the Black Vermillion system.

Pore Pressure

Pore pressure refers to the amount of saturation pressure a soil experiences. Two types of soil pore pressure exist, positive and negative. A negative pressure is an abundance of free water not held tightly through hydrogen bonding by the soil, where a positive number reflects dryer conditions. Thus, the higher the pore pressure, the less free water is available. Generally, loosely structured soils tend to contract with higher pore pressure, while tighter soils such as clays expand. Contraction of loosely structured soils leads to increases in pore water pressure and decreases frictional strength (shear strength) (Iverson et al. 2000).

As pore pressure approaches negative numbers, the water content of the soil increases. This increase happens during infiltration of precipitation, rising waters in the groundwater table or rising streams. As stream stage rises, the stream surface elevation increases, or moves up the bank providing pressure against the bank, which negates pore pressure that pushes bank material out toward the stream channel. Upward movement in stage increases the pressure toward the bank helping maintain the bank's profile. However, once stream stage recedes, hydrostatic force is lost and the bank can then fail in a planar or rotational fashion (Simon & Collison, 2001; Rinaldi et al, 2004). Figure 2.5 illustrates this phenomenon. Simon and Collison (2001) note "negative pore water pressures increase the shear strength of unsaturated, cohesive materials by providing tension between particles (p1422)." These hypotheses might explain why in northeast Kansas we see an increase in bank erosion after high flows under saturated conditions.

Figure 2.5 Illustration of bank failure and pore water pressure.



Dry Ravel

Dry ravel is movement of soil clumps downslope by rolling, bouncing or sliding (Gabet, 2003). Steeper slopes tend to exacerbate dry ravel due to exceeding shear strength of the dry soil particles connected to the rest of the bank material. Common initiators of dry ravel include animal movement on unstable slopes, wind, and movement of vegetation stems (Rice, 2010). According to Gabet (2003), dry ravel may be the "...primary creep-like transport process on other planets (p22.2)." Wildfires tend to increase dry ravel erosion. Once fire sweeps through an area, it can leave behind a water repellent layer accelerating dry ravel production and surface runoff. Ravel is then moved to streams typically by mudflows and may be stored there until the next extreme flooding event (Rice, 2010). Arid environments prone to intense wildfires tend to produce larger amounts of dry ravel than humid or semi-humid environments, such as northeast Kansas. Thus, dry ravel is likely a minor contributor to bank erosion in northeast Kansas.

Soil Piping / Seepage

Precipitation that has infiltrated the soil moves through the soil in two different ways, piping and seepage. Piping is the movement of water in well defined, underground channels, while seepage is the movement of water through interstitial spaces in the soil matrix. As water moves through pipes, velocity is increased and erosion of the pipes occurs. Water is moved through the pipe system to the stream and empties into the stream as groundwater discharge. Generally, water moving through pipes has a lag time 30-40% shorter than throughflow, or seepage (Jones, 1997). Two types of pipes exist and convey water to the stream. The first is ephemeral, only flows after a storm event, and the second is perennial, or always flowing. Shallow, depth about 150mm, ephemeral pipes tend to be efficient collectors and transmitters of water and have the highest discharge rate in proportion to drainage area (Jones, 1997). Pipes may lead to stream channel initiation due to the top of the pipe collapsing, thus forming a channel (Knighton, 1998).

Seepage and soil piping are two erosional processes that may lead to mass bank failure (Wilson et al. 2007). Pipe erosion occurs where pipes empty into the stream and may result in fluvial entrainment of the lower banks, causing undercut bank formations. Seepage erosion creates similar consequences by allowing water to flow onto the surface of the bank, eroding particles from the bank. Seepage may cause erosion of clay particles, leading to less cohesion of bank material and mass failure (Knighton, 1998). Once a bank becomes undercut, gravitational forces and shear stresses exceed shear strength causing the bank to fail (Wilson et al. 2007). Failure of banks generally occurs during the recession limb of the hydrograph when bank material is still saturated and hydrostatic pressure from the stream itself is lost (Simon & Collison, 2001; Wilson et al. 2007). *In situ* studies by Wilson et al. (2007) have found sediment concentrations increase during high flow discharges to as much as 660g/L, and in laboratory settings, sediment concentrations reach as high as 4500g/L illustrating high erosion rates due to piping and seepage.

Freeze – Thaw

Freeze – thaw is simply the influence of frost, or ice crystals, on bank soils, and is a process bank soils in humid-temperate and sub-arctic regions undergo (Lawler, 1995). Water droplets enter small cracks and crevices that then freeze, as water freezes it expands, further detaching small soil masses from the bank. When the water in the crevice thaws, it moves further into the crevice, which may then freeze again and further the process. This expansion and contraction of water in the crevices detaches soil particles from the bank. Larger particles are then prepared for erosion by fluvial entrainment or dry ravel; dry ravel can then be entrained and carried downstream through fluvial entrainment while at the bank toe. Freeze – thaw action becomes less significant in downstream reaches compared to other erosional processes (Lawler, 1995).

Freeze – thaw has been attributed as a major force in erosion. Many researchers have concluded freeze –thaw is responsible for a majority of bank erosion during the winter months (Wolman, 1959; Lawler, 1986; Stott, 1997; Wynn & Mostaghimi, 2006a). Desiccation, like freeze – thaw, results in cracking of the bank soil, preparing the newly loosened soil to be eroded by fluvial entrainment or dry ravel. Regardless, processes such as freeze – thaw and desiccation result in dry ravel, which falls to the bank toe and is subsequently removed during the next high flow event (Lawler, 1986; Lawler, 1995; Wynn & Mostaghimi, 2006a).

Ice Scour / Ice Jams

Ice contributes to bank erosion through mechanical action applied to the bank surface while the ice is flowing on top of the stream and through ice jams re-routing the stream across meander bends (Collinson, 1971; Smith & Pearce, 2002). Mechanical action of floating ice banging and beating the bank may erode the bank at whatever stage the stream is currently experiencing, albeit irregularly and unpredictably. Ice also scours the bed of the stream creating holes and undulating topography of the bed. In addition, unfrozen water flows around ice jammed against the side unable to move, causing localized scour against the bed and bank (Smith & Pearce, 2002) similar to debris jams or logs jammed against banks. When ice jams occur on a meander bend, flow may begin to work across the meander and create a meander cutoff and oxbow lake (Collinson, 1971; Smith and Pearce, 2002). Flows across the meander floodplain erode the floodplain and associated banks to match the base level of the stream. The Black Vermillion watershed has few meanders and is generally steeply incised, not allowing many winter flows out of its banks. Thus, ice jams do not contribute to meander cutoffs as they might in other regions. However, this region does get cold enough to freeze running water and mechanical scour of streambed and streambanks does occur.

Soil Liquefaction

Soil liquefaction refers to the point soil becomes so saturated it begins to liquefy, or become plastic and fails. Soil liquefaction is often considered a concealed hazard, because the hazard resides underground and few know about soil liquefaction process and erosion (Peterson, 1985). Soils tend to be more prone to liquefaction when the clay content is less than 15%, the soil has a liquid limit less than 35 and the water content is greater than 0.9 x liquid limit. Soils high in silt or sand content tend to be the most susceptible to liquefaction (Andrews & Martin, 2000). The reason for silts and sands being associated with liquefaction is due their physically rounded shape and non-cohesiveness, versus clay materials that are flat and cohesive. Most often soil liquefaction is a side effect of earthquakes (Peterson, 1985). None of the soil types in the Black Vermillion system meet these criteria, and thus may not be as susceptible to liquefaction. However, most if not all of the processes aforementioned lead to mass wasting of the eroding bank.

Mass Wasting

The process of mass wasting, or mass failure, is defined as movement of large masses of soil down slope due to gravitational forces (Dunne & Leopold, 1998; Harpstead et al. 2001). Erosion is distinguished from mass wasting by the amount of soil moved; erosion is the movement of single particles of soil. Mass failure can be caused by various sources, such as soil piping, excess shear stress and general loss of cohesive soil strength (Dunne & Leopold, 1998; Fox et al. 2007).

The initial incision of channels due to channelization or land-use change induces steep banks with acute angles. Due to the scour of bed and streambank toe material, these banks are weaker and tend to fail much easier than prior to incision (Thorne, 1999). Steeper slopes favor mass failure due to physical characteristics controlling bank failure (Dunne & Leopold, 1998). The steeper bank failure plane provides more gravitational force on the soil overcoming the threshold of frictional forces exerted by individual soil particles. Steep banks tend to fail through planar slab failures, while shallow banks tend to fail rotationally (Thorne, 1999; Simon & Collison, 2001).

Certain Rosgen stream types are more vulnerable to mass failure than other stream types due to general bank steepness of certain stream types. Removal of woody streamside vegetation on steep slopes removes cohesive strength added by roots, which in addition to soil saturation can expedite mass failure (Dunne & Leopold, 1998; Rosgen, 2006; Pollen, 2007). In addition, decomposing root systems from removed streamside vegetation can create areas of seepage and piping, lessening the strength of the bank as well (Knighton, 1998; Cannon, Kirkham & Parise, 2001). Stream types F and G maintain steep bank slopes that tend to fail due to undercutting of upper banks. However, riparian vegetation can influence both stream types by maintaining soil cohesion (Rosgen, 1996). Northeast Kansas banks associated with F and G stream types tend to fail due to lack of riparian vegetation, bank steepness (steep failure plane) and height of banks. Banks in the Black Vermillion system average 17’ in height with upper bank angles reaching 90-degree angles or higher.

Streams in northeast Kansas typically experience two types of mass failure; fall and rotational slump. However, a mix of fall and rotational slump seem to be common in the Black Vermillion system especially where woody vegetation is absent. Failures may be initiated by soil piping, fluvial entrainment of the bank toe, pore pressure changes, soil liquefaction, and freeze – thaw processes. Once these mass failures occur, resultant colluvium from the bank may be entrained by the stream increasing channel width. Figures 2.6 and 2.7 illustrate common bank failures in the Black Vermillion system. To paraphrase John Muir, pull one tiny string in nature and find out it is connected to everything else. This is especially true when studying streambank erosion.

Figure 2.6 Irish Creek 2 study bank after June 2010 rains. Four-foot erosion pins were lost and the bank profile toe pin was buried (Keane, 2010).

Figure 2.7 North Fork study reach 1 illustrating episodic and sporadic failures along field with no woody vegetation holding bank material (Keane, 2010).

Bank Failure Prediction

Many models have been developed to illustrate and predict bank failure by mass wasting. Darby and Thorne (1996) describe a model of bank stability concerning mass failure. This model attempts to reproduce failure results in a realistic manner, including lateral erosion, bank failure plane not passing through a bank toe, failure plane angle, bank angle, and pore pressure. This model tends to over-predict stability by admission of the authors, but has made marked improvements over previous models concerning mass failure.

Rosgen's (2006) Bank Erosion Hazard Index (BEHI) model takes into account mass failure as one of the many integrated processes for the prediction of bank erosion. Along with the Near Bank Stress (NBS) model, both make up the Bank Assessment for Non-point source Consequences of Sediment (BANCS) model, one can predict erosion rates of banks in question. The BANCS model may also over- or under-predict in some hydrophysiographic regions (Harmel et al, 1999; Van Eps et al. 2004; Magner & Brooks, 2008).

Stream Energy

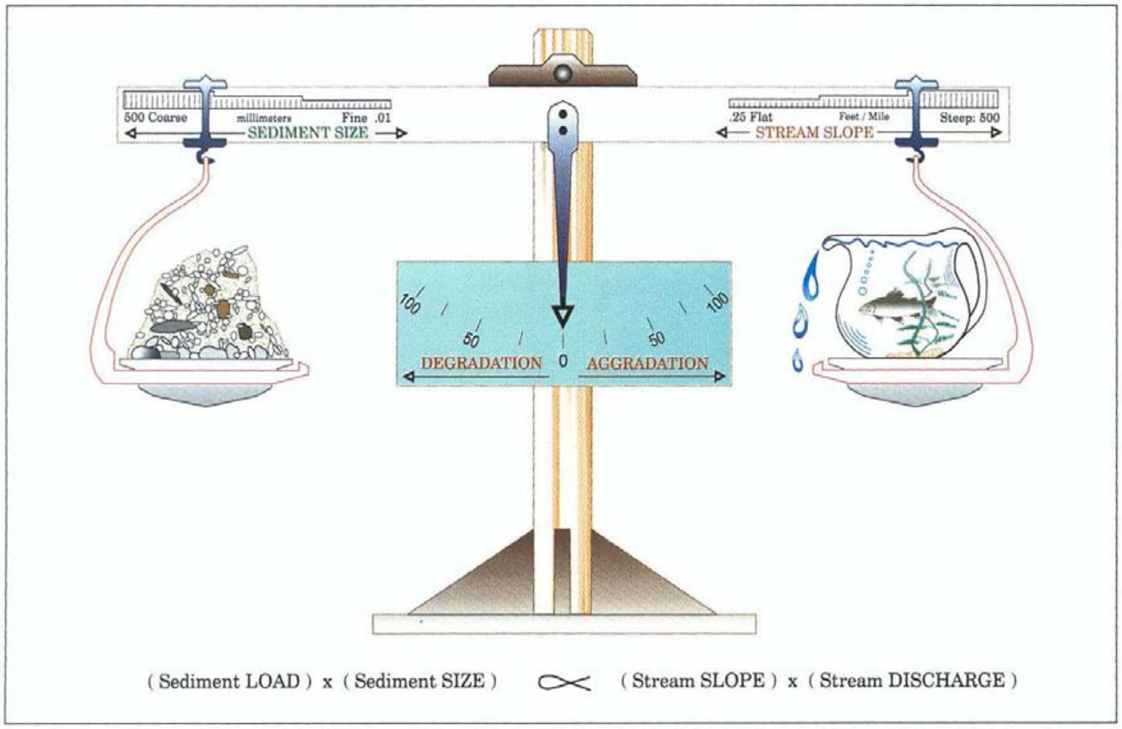
Stream energy and stream power are important entities when discussing streambed and bank erosion. Three general types of energy exist in a stream system; potential, kinetic, and thermal. Potential energy is energy that is stored in an object and is driven by gravity, thus upstream reaches have high potential energy while downstream reaches have lower potential energy. Kinetic energy is the energy of motion, or doing work. Potential energy is converted to kinetic energy as water (the mass with energy that does work) moves downstream (Knighton, 1998). In a general sense, there are four types of work stream flow performs; 1. work done against viscous shear and turbulence (or internal friction), 2. work done against friction at the channel boundary, 3. work done eroding the channel boundary, 4. work done transporting sediment load (Knighton, 1998). These four types of work happen in order, thus it takes so much energy, or work, to overcome viscous shear and boundary friction before the stream can do work on eroding the boundary or bed and then transport sediment. Some potential energy is converted and lost to thermal energy, and not kinetic, due to friction and thermal loss. Narrow, deep channels tend to have more energy than wide, shallow channels. Kinetic energy may be dissipated through different forms; spill resistance (drops or steps), form roughness (sinuosity), bed undulations, cross sectional shape, and stream particles (Rosgen, 1996; Knighton, 1998; Marston, 2007).

Energy can be increased a number of ways, such as increasing slope or increasing water discharge. Channelization leads to increased slope and reduction in stream length, resulting in increased stream energy. In addition, the Black Vermillion watershed has experienced land cover changes that have decreased infiltration and increased runoff, which increased discharge. This increase in discharge ultimately leads to a flashy hydrograph with higher peak flows than historic highs. Stream energy can be expressed as stream power, or

$$\Omega = \gamma QS. \qquad \text{(Equation 1)}$$

Where Ω is stream power, γ is the specific weight of water (constant), Q is discharge of water and S is slope (Knighton, 1998). If discharge or slope is changed, stream power is changed and energy dissipation must be changed. Energy dissipation can be increased through sediment quantity, increased sediment size, undulation of bed features, increased roughness, meander pattern or any combination of these variables. We can refer to Lane's (1950) proportionality that states a change in water discharge will need a change in sediment load to balance the system so the stream neither aggrades nor degrades as described in Rosgen (1996) (Figure 2.8).

Figure 2.8 Illustration of Lane's proportionality, 1950 (Rosgen, 1996).



Stream Energy as Shear Stress

Stream energy can be expressed as shear stress, which is the force experienced by the outer eroding bank by the outer third of the water column in the stream channel. This force is typically measured at bankfull stage, or the 1.5-year recurrence interval flow. Shear stress can be expressed as

$$\tau = \gamma RS, \qquad \text{(Equation 2)}$$

where τ is shear stress, γ is specific weight of fluid (water), R is hydraulic radius (cross-sectional area / wetted perimeter) and S is slope (water surface), notice similarities to Equation 1. We can tie unit stream power and shear stress together using the equation

$$\omega_a = \tau u, \qquad \text{(Equation 3)}$$

where ω_a is unit stream power, τ is defined by equation 2 and u equates to mean velocity. Again, we see when one variable, such as slope is increased, there is an increase in stream power and shear stress. An increase in slope also increases velocity, creating more stream power that all leads to increased erosion rates of bed and streambank material.

Rosgen Stream Assessment

Rosgen (1996) based stream classification and assessment utilizes measured variables to classify stream types, understand current stream condition, and predict stream trends. The system is stratified into four levels (I-IV). Rosgen classification and assessment is measured at the reach scale, generally a minimum of 20-times the bankfull width, and at least one representative riffle cross section.

Stream Level Classification & Assessments

Level I assessment and inventory requires a basic understanding of the region and regional geomorphology. Variables such as geologic control (lithology), fluvial process, available channel materials, climate, valley slope, channel shape, and channel pattern are included in Level I inventory. Delineating streams at this scale is very course and can be determined from topographic maps and aerial photography. Level I is designated by a letter “A” through “G”, which is a signature of the Rosgen (1996) classification system, Figure 1.25.

Level II is more detailed in scope than Level I and requires field measured data from the study reach. Here we glean insight into entrenchment ratio (flood-prone area width / bankfull width, Figure 1.23), width to depth ratio, sinuosity, channel slope and channel materials. This level provides a number (1 through 6 depending on the D_{50} of the channel material) and lower case letter if channel slope does not fit within the delineated Level I letter. A number of 1 represents bedrock as the dominant bed material and a 6 represents clay/silt as the dominant bed material. Required for this level is at least one cross section at a riffle, a modified Wolman reach pebble count, and a longitudinal profile measuring at least 20-bankfull widths in (Rosgen, 1996, 2006). Figure 1.26 illustrates the combinations possible using the Rosgen (1996, 2006) classification system.

Level III assessment characterizes the existing state, or condition, of the stream reach relating to stability, response potential and function (Rosgen, 1996). Additional field verification and inventory is required. Parameters included in the inventory are riparian vegetation, sediment deposition patterns, debris occurrence, meander patterns, sediment supply, stream size and order, bank erosion potential, and flow regime. Level III includes both reach and feature specific data and was intended to be useful for companion studies such as fish habitat inventories and riparian communities surveys (Rosgen, 1996). In addition, this level provides a basis for predicting future trends of the stream reach, such as erosion and depositional patterns.

Level IV is the most detailed and provides further basis for prediction and extrapolation of stream characteristics to similar stream reaches. This level seeks to verify process relationships inferred from Levels I-III. Level IV inventory and analysis includes sediment measurements of both bedload and suspended load; streamflow measures of hydraulics, resistance and hydrographs; stability regarding aggradation or degradation; and sediment storage, erosion rates, time trends and overall stability (Rosgen, 1996). The empirical relationships developed in Level IV are specifically for individual stream types in their current state and should only be extrapolated to similar stream types in similar conditions.

Rosgen Stream Types

Nine Level I stream type classifications exist in the Rosgen (1996) system. They include; Aa+, A, B, C, D, DA, E, F, and G. Each Level I stream type can be combined with a number (1-6) and a lower case letter depending on slope for a total of 94 stream type combinations (Figure 1.26). Table 3 illustrates the general characteristics of Level I stream type classification descriptions.

Table 3 General stream type descriptions for Level I delineative criteria (adapted from Rosgen, 1996).

Stream Type	General Description	Entrenchment Ratio	Width / Depth Ratio	K	S
Aa+	Very steep, deeply entrenched, torrent streams	<1.4	< 12	1.0-1.1	>.10
A	Steep, high energy, entrenched, cascading step/pool streams	<1.4	< 12	1.0-1.2	.04-.10
B	Moderate entrenchment, moderate gradient, riffle dominated with infrequent pools	1.4-2.2	>12	>1.2	.02-.039
C	Low gradient, meandering point-bar, riffle/pool alluvial channels with broad, well defined floodplains	>2.2	>12	>1.2	<.02
D	Braided channel with longitudinal and transverse bars, very wide and shallow with eroding banks common	n/a	>40	n/a	<.04
DA	Anastomosing, narrow and deep with extensive and well vegetated floodplains and associated wetlands. Very stable streambanks	>2.2	Highly variable	Highly variable	<.005
E	Low gradient, sinuous channel, very efficient and stable	>2.2	<12	>1.5	<.02
F	Entrenched meandering riffle/pool channel on low gradients, elongated "U" shape cross-section	<1.4	<12	>1.2	<.02
G	Entrenched gully step/pool and narrow "V" shaped cross-section	<1.4	<12	>1.2	.02-.039

Notes: K denotes sinuosity, S denotes slope. Most all reaches in Black Vermillion system classified as F and G, with one exception Irish Creek 3, classification of B.

BANCS Model

The Bank Assessment for Non-point source Consequences of Sediment (BANCS) model includes measured erosion rates, Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) as input variables (Rosgen, 2006). The BANCS model was first published in *Watershed Assessment of River Stability and Sediment Supply (WARSSS) (*Rosgen, 2006); however, the model concept had been published and developed in both *Applied River Morphology* (Rosgen, 1996) and "A practical method to compute streambank erosion" (Rosgen, 2001). The model was used to develop predictive streambank erosion curves for the Southern Colorado and Yellowstone regions.

Using BEHI and NBS on banks here in Northeast Kansas, we can extrapolate those predictions from Southern Colorado and Yellowstone and compare measured erosion rates from our region. If measured erosion rates differ, then a new set of erosion curves using the BEHI and NBS ratings can be developed. Once BEHI and NBS has been evaluated and assigned to bank stretches, a prediction can be made as to how much sediment can be expected from bank material. Chapter 3 – Research Methods, describes how BEHI and NBS were used in this study.

Criticisms of Rosgen Methods

Rosgen methods have been questioned multiple times for various reasons. Magner and Brooks (2008) found that stream reaches may have multiple stream types causing confusion when describing a reach. However, they also note that Schumm-Harvey-Watson model causes the same problems. Roper et al. (2008) note that different stream classifications can come from different observers assessing the same reach. Most often differences in entrenchment ratio was to blame. However in their study, Rosgen methods varied with groups and were not standardized. Both Magner and Brooks (2008) along with Harmel et al. (1999) found that Rosgen predictive erosion curves tend to over-predict erosion rates for Minnesota and Oklahoma, respectively. In addition, many (Kondolf 1998, 2000; Simon et al. 2007) have criticized the Rosgen system as being a form-based "scheme", not taking into account natural processes or the fact alluvial streams are dynamic, open systems that must change due to altered inputs from the watershed. Rosgen methods account for change in the system and fluvial processes as evidenced by stream evolutionary sequences, processes integrated into many models developed to assess streams, and the acknowledgment of a continuum of stream types.

Regardless, there are difficulties in following some of Rosgen's methodology (1996, 2001, 2006). Some protocols may not be clear and can be difficult to discern and employ consistently based upon Rosgen's books and papers. In this light, it is imperative to remember no method is perfect and modification can be made to any model or method to attain the best possible outcomes for understanding, especially regarding differing regions and processes.

CHAPTER 3 - Research Methods

"You can observe a lot by watching." Yogi Berra

Introduction to Methods

Acquisition of field-measured data is critical in the development of predictive streambank erosion curves that can accurately predict annual streambank erosion rates in this specific region. This research study employed the Rosgen (1996, 2001, 2006) methodology of collection and assessment of field data. Rosgen (1996, 2001, 2006) Level I through IV assessment was applied to three sub-watersheds in the Black Vermillion system (Figure 1.3). Bank profiling of selected banks was performed over a four-year period to attain measured erosion rate data. A bank's ability to resist erosion and the erosive force exerted by stream flow were rated using Rosgen's (1996, 2001, 2006) Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) models, respectively. Measured erosion rates, BEHI and NBS data, were synthesized to develop predictive streambank erosion curves for this hydrophysiographic region of Northeast Kansas.

Study Area

Three sub-watersheds of the Black Vermillion watershed were selected for a number of reasons (Figure 1.3). First, a USDA-CSREES (NIFA) grant (Project # KS600399) was sought and awarded to study and model sedimentation and erosion throughout the watershed that ultimately empties into Tuttle Creek Reservoir. Second, there are varied land uses and land cover throughout the watershed that may inhibit or enhance erosion and sedimentation of overland surfaces or streambed and banks (Figure A.1). Third, the sub-watersheds have experienced varied temporal and structural levels of channel modification that have exacerbated erosion of both overland surfaces and streambed and banks (SCS, 1966a, 1966b, 1966c). Fourth, varied riparian corridor maintenance practices exist throughout the watershed, from well-established and maintained riparian corridors to completely extirpated riparian vegetation along streams.

Study Reach Selection

Nine study reaches, three per sub-watershed, were selected as representative reaches in the Black Vermillion system upstream of Frankfort, Kansas. An upper, middle and lower reach were selected for detailed study on each stream system in the respective sub-watershed (Figures 1.4, 1.10, 1.14). These nine reaches have experienced varied levels or have incurred impacts of direct channel modification such as in-stream floodwater impoundments, channelization, riparian vegetation removal, streambed stabilization structures and levees.

Rosgen Stream Classification System

Classification systems attempt to assign items within groups containing similar structure, origin, morphology and the like. The Rosgen stream classification system is an attempt to group together streams with shared morphological characteristics. Be mindful that this classification system is based on a continuum, as are many classification systems, and is not discrete so that stream reaches may be designated by more than one stream type (Rosgen, 2008c). Other attempts at stream classification exist, as noted in the literature section; however, Rosgen's classification system employs measured quantifiable variables. Rosgen developed this classification system with specific goals:

1. Provide the ability to predict a stream’s behavior from its appearance;
2. To develop relationships for hydraulic and sediment relationships for a given stream type and state;
3. Provide a mechanism to extrapolate data having similar stream characteristics; and
4. Provide a common language between disciplines regarding stream morphology and condition (Rosgen, 1996).

Rosgen (1996) employs four levels in his classification and monitoring system, Levels I-IV. Each level contains more information, thus more detailed data collection. Level I is the simplest and characterizes general geomorphic stream and valley conditions. Level I results are assigned a letter (A-G) based on channel slope, channel shape, and channel pattern. Level II classification takes into account entrenchment ratio, width/depth ratio, sinuosity, and channel materials. A stream in this classification level receives its characteristic number designation from the D_{50} of the modified reach pebble count (1-6) depending on whether the D_{50} is bedrock (1), boulders (2), cobble (3), gravel (4), sand (5), and silt/clay (6). Level II classification terminates the classification process, generating a stream type of 'B3', for example. Level III begins the monitoring phase and assesses stream state or condition while Level IV assesses long-term monitoring and validation of Level III prediction of state and trends.

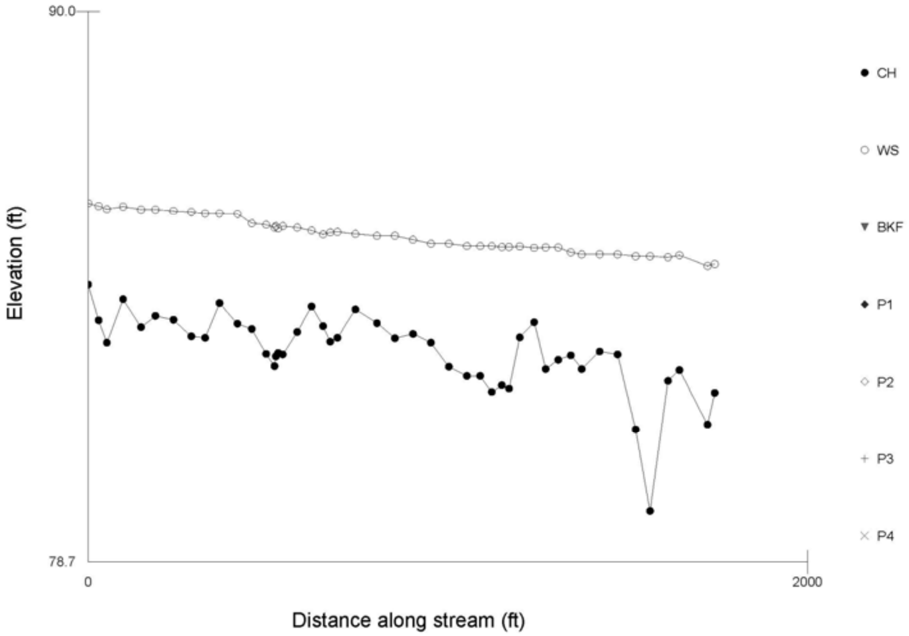
Figure 1.1 is a flow chart that describes the Rosgen protocol in general terms. Detailed protocol for Rosgen stream classification and monitoring can be found in *Applied River Morphology* (Rosgen, 1996), *Watershed Assessment of River Stability, Sediment and Supply (WARSSS)*, (Rosgen, 2006), and "Stream Channel Reference Sites: An Illustrated Guide to Field Technique" (Harrelson et al. 1994). Following is an explanation of some procedures used in Rosgen classification that were applied to all three sub-watersheds of the Black Vermillion.

Longitudinal profile

The longitudinal profile characterizes the stream's average, minimum and maximum water surface slopes and bed feature depths that can be used to classify streams using the Rosgen (1994, 1996, 2006) methodology. The longitudinal profile, when plotted, can show bed features and undulations that might not be visible from above the stream (Figure 3.1). Longitudinal profiles are measured in the downstream direction and require basic surveying skills as described in Harrelson et al. (1994). Longitudinal profiles start at the head of a riffle, continue in a downstream direction, end at a riffle at least 20-times bankfull width distance from the beginning riffle of the survey, and are stationed using a tape measure. At least two measures, or survey shots, are taken at each station, one at the thalweg (deepest part of the channel) and the second at the edge of water / bank interface (right or left). Two more measurements may be taken if features are present and/or are accessible; the first at bankfull stage elevation and second, the lowest bank elevation. Often in this study, neither of these measures were discernable regarding bankfull elevation nor accessible regarding lowest bank height (Figure 3.2).

Profile reach lengths are typically 20-times bankfull width; however, our reach profile lengths ranged from 317m to 697m (1040' to 2286'), which exceeds 20-times bankfull width of any stream. Three years (2007-2009) of longitudinal profile data was collected. At each study reach, a benchmark was established at the time of the initial survey (2007), was assumed at an elevation (100') and was marked by a ½" yellow-capped, steel re-bar with a wooden stake and flagging. Profile survey data was entered into RiverMorph. These profiles were overlaid after subsequent year's surveys to analyze streambed change at that reach.

Figure 3.1 Resultant example longitudinal profile for Irish Creek 2.

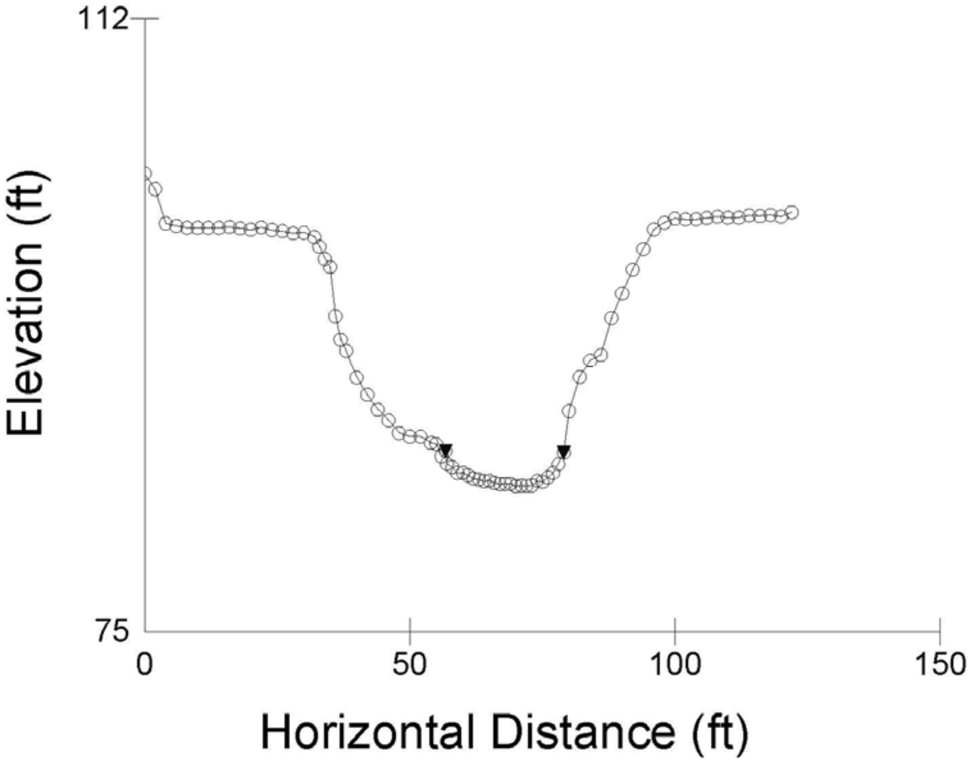


Note: Water surface is notated by hollow circles, bed formation is notated by solid circles, no bankfull features or low bank height were shot on this long profile.

Cross-sections

Cross-sectional measures of stream facets provide a majority of morphological inputs for the Rosgen (1994, 1996, 2006) classification system. Cross-sectional area, mean bankfull depth, maximum bankfull depth, width to depth ratio and entrenchment ratio can all be calculated using riffle cross-section data. For this study, two cross-sections per longitudinal profile reach were selected and measured. The first cross-section was located on a representative riffle and was used for classification purposes. The second cross-section was located on a representative pool. Both cross-sections were tied into the longitudinal profile by station. Cross-sections were monumented using steel re-bar pins and wooden stakes to designate each end of the cross-section. Cross-sections extended beyond the immediate top of bank that measured and documented upland conditions directly associated and adjacent to the stream. An example cross-section is illustrated in Figure 3.2. Again, cross-sectional survey data was entered into RiverMorph. These cross-sections were overlaid after subsequent year's surveys to analyze streambed and bank change at that cross-section.

Figure 3.2 Resultant example cross-section at Irish Creek 3 riffle.

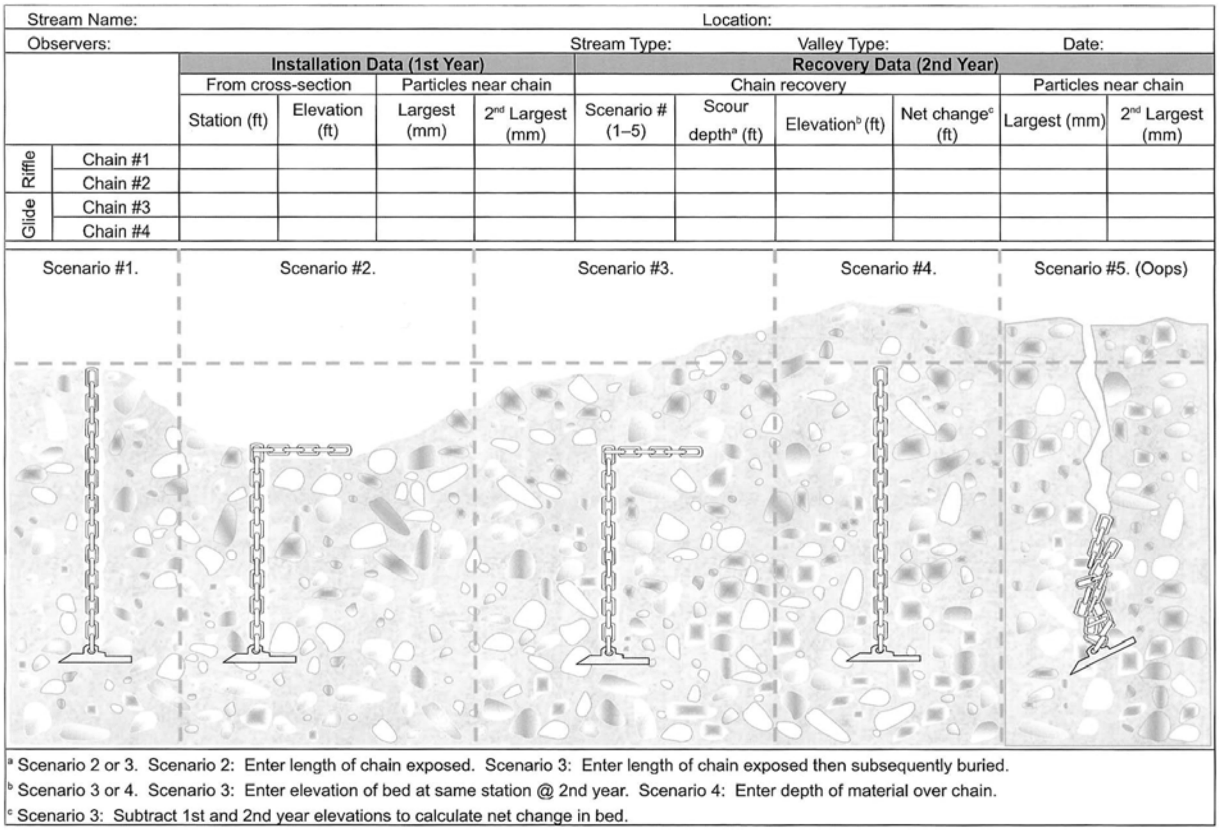


Note: Bed and banks are notated by hollow circles, water surface at time of survey are notated by triangles. Notice no clearly discernable bankfull features are present and low bank heights are 16' above the bed indicating the channel is deeply incised.

Scour chains

Scour chains were installed at each riffle cross-section to measure streambed scour depth, size and volume of bed material entrained, deposition or degradation, and size of particle deposited (Rosgen, 2006). Scour chains measure the amount of scour and/or deposition that happens at a riffle. Four scenarios are possible; 1) no change, 2) scour only, 3) scour then fill, or 4) fill only (Figure 3.3). Often, the process of scour and then deposition happens many times throughout the year with no net change in streambed elevation of the riffle cross-section. Thus, it would be impossible to gauge movement of sediment through the system without scour chain measures. Scour chain data can be used to understand sediment transport in the system, both in quantity and size.

Figure 3.3 Scour chain form with possible scenarios and data required (Rosgen, 2006).



Stream Name: Location:

Observers: Stream Type: Valley Type: Date:

		Installation Data (1st Year)				Recovery Data (2nd Year)					
		From cross-section		Particles near chain		Chain recovery				Particles near chain	
		Station (ft)	Elevation (ft)	Largest (mm)	2nd Largest (mm)	Scenario # (1–5)	Scour depth^a (ft)	Elevation^b (ft)	Net change^c (ft)	Largest (mm)	2nd Largest (mm)
Riffle	Chain #1										
	Chain #2										
Glide	Chain #3										
	Chain #4										

[a] Scenario 2 or 3. Scenario 2: Enter length of chain exposed. Scenario 3: Enter length of chain exposed then subsequently buried.

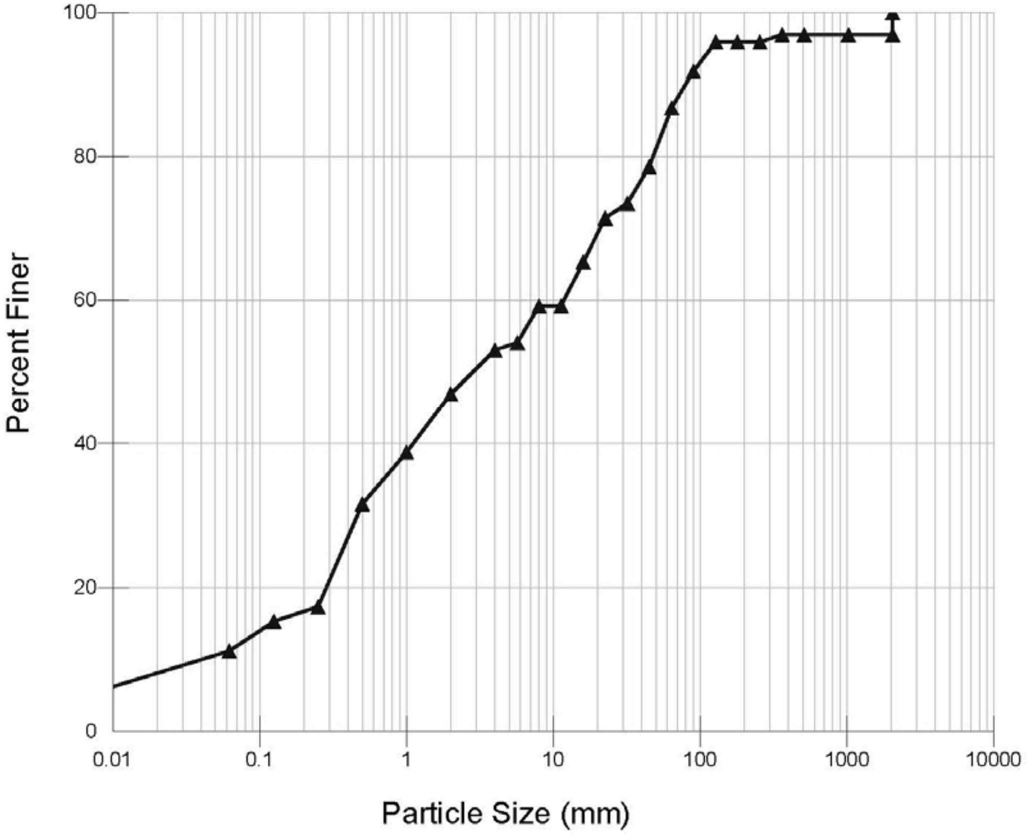
[b] Scenario 3 or 4. Scenario 3: Enter elevation of bed at same station @ 2nd year. Scenario 4: Enter depth of material over chain.

[c] Scenario 3: Subtract 1st and 2nd year elevations to calculate net change in bed.

Sediment characterization

Sediment characterization provides Level II classification of the Rosgen stream type and allows for calculations of velocity and sediment competence. Three different inventories of sediment are taken at each reach; reach stratified pebble count, active cross-sectional pebble counts (pool and riffle), and a bar sample. The reach stratified pebble count proportionally samples, according to ratio of pools to riffles, bed material over the entire reach and is used to classify the stream reach (Figure 3.4). The active riffle cross-sectional pebble count is used to calculate velocity estimations and sediment competence. The active pool cross-sectional pebble count is used to discern change of bed material in the pool. The bar sample is taken from a depositional feature, such as a point bar, and data is used to calculate bankfull dimensionless shear stress while providing an estimation of sediment size competence of the stream at bankfull discharge (Rosgen, 2006).

Figure 3.4 Graphed results of a modified pebble reach count for Irish Creek study reach 2.



Note: The 50% mark is approximately 2.5mm in this example, which would indicate very fine gravel.

Other considerations

Riparian vegetation inventory and analysis has been done for the entire watershed (Sass, 2008). Riparian vegetation is important in that it helps banks maintain cohesion and adhesion through a soil-root matrix (Rosgen, 1996; Genet et al. 2005; Pollen, 2007). Over 80% of the original woody riparian vegetation in the Black Vermillion system has been removed along with removal of upland prairie, thus increasing direct runoff equating to increased discharge in streams. Increases in water discharge along with channel modification have wreaked havoc with streams causing degradation and instability.

In addition to vegetation inventory and analysis, Level III and IV require additional stream assessments. Depositional patterns, width to depth ratio state, meander patterns, dominant BEHI/NBS, and degree of confinement lead to an understanding of channel stability ratings and lateral stability. Sediment competence and capacity, width to depth ratio state, succession stage shifts, depositional patterns and channel blockages account for vertical aggradational stability of the stream. Sediment competence and capacity, degree of incision, successional stage shifts, and degree of confinement account for vertical degradational stability. The Pfankuch stability rating, riparian vegetation, flow regime, and stream order/size worksheets were also completed for Level III assessment. Level IV monitoring and validation was completed through three years, initial 2007 survey through 2009, with additional monitoring of banks through 2010.

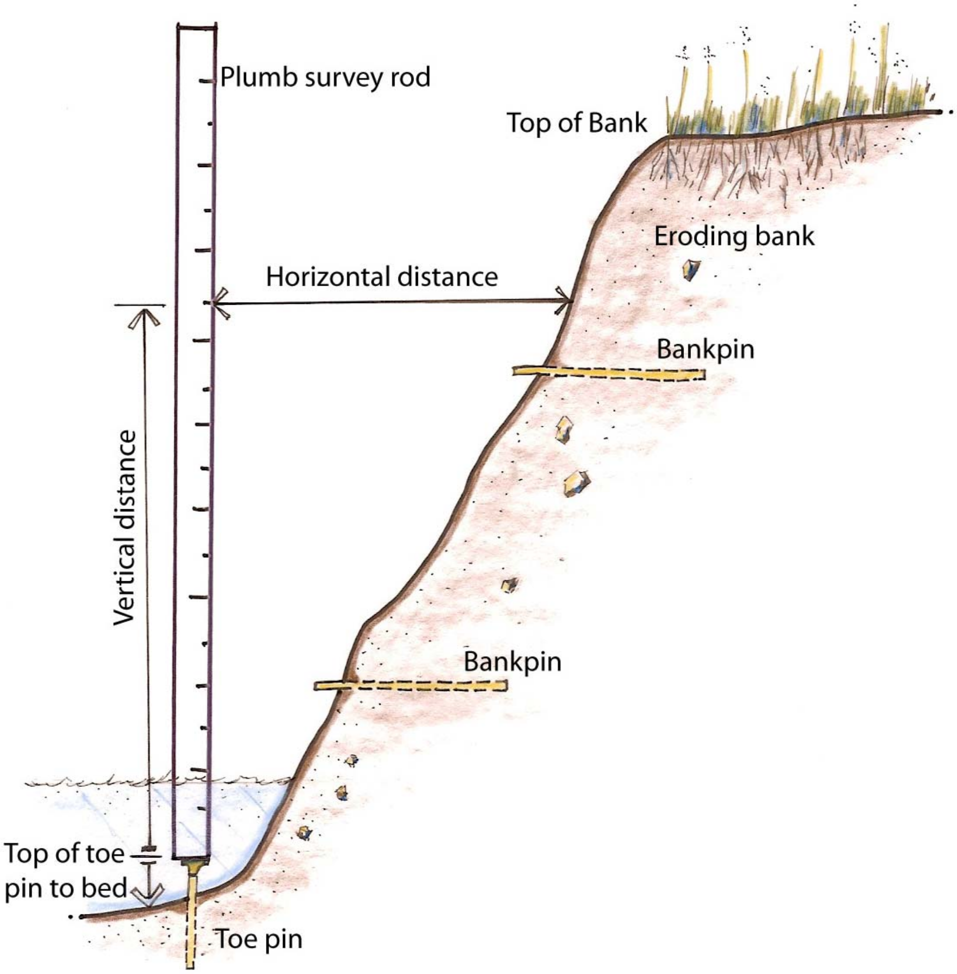
RiverMorph is a computer program designed to store and organize data collected through Rosgen methodology. As such, data collected during this study utilized the RiverMorph program and its tools. RiverMorph currently does not have a repository for scour chain data, so scour chain data was kept as a Microsoft Excel spreadsheet.

Bank Erosion monitoring, ratings and measures

Bank profiles

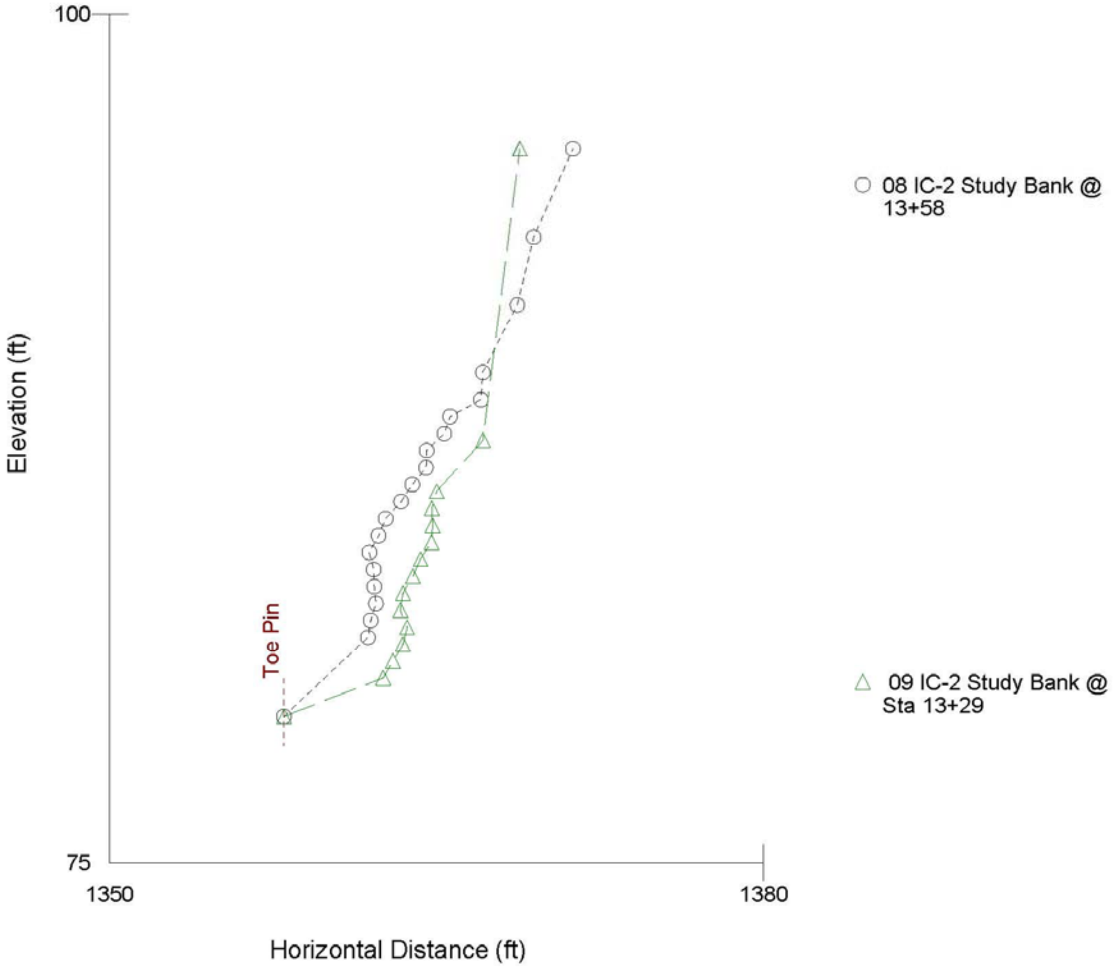
Rosgen (2008a) notes the most detailed measure of bank erosion can be made through bank profiling, or the actual measurement of the bank face from a fixed point. Bank profiles were completed on two banks per study reach. The first bank was located on the cutbank, or eroding bank, of the pool cross-section. The second bank was located on a representative stretch of the reach and was tied into the longitudinal profile by station number. Bank profiles were monumented with a toe pin, which was set into the streambed with the top of the toe pin set close to the streambed to avoid debris. Each toe pin became the control point for measures to the bank face. A plumb surveyor's rod was set flush with the bank side of the toe pin and a level tape strung from the face of the rod to the face of the bank. Horizontal measures were taken every one-half vertical foot. The vertical zero-point was located at the top of the pin. Measures were taken to the bottom of the toe pin (negative vertical measure and zero horizontal measure) to establish a closing point for bank area. Figure 3.5 illustrates a bank profile. Overlays of bank profiles provided insight into the area lost or gained at the bank once bank profiles are complete (Figure 3.6). While this study concentrated upon data collected from bank profiles, cross-sections describing upland characteristics adjacent to the stream were measured and catalogued as described previously.

Figure 3.5 Illustration of a bank profile.



Bank, or erosion, pins were inserted at various vertical points in the face of the bank and provided a quick visual check of bank erosion. Bank pins could be measured throughout the year quickly without having to perform a complete bank profile, and still provide a comparison of erosion rates. These pins were four-foot, steel re-bar pins, driven flush into the bank at a variety of vertical heights on the bank face (Figure 3.5). Once failure, or erosion occurs, the pins become exposed exhibiting how much erosion had occurred since the last bank pin measurement. The pins could be set flush again for measurements later. Bank profiles and bank pins are the most important portion of monitoring for this study, as the curves were developed using actual erosion rates collected through bank profiling. In addition, two assessments, Bank Erosion Hazard Index and Near Bank Stress, were conducted for each bank profile at installation in 2007.

Figure 3.6 Overlay of consecutive years of bank profiles at Irish Creek study reach 2 study bank. These overlays are used to discern change in bank area (erosion or deposition).



Bank Erosion Hazard Index (BEHI)

The Bank Erosion Hazard Index (BEHI) (Rosgen, 1996, 2001, 2006, 2008a and b) is a process-integrated evaluation regarding the susceptibility of a bank to erosion. BEHI is a combination of several variables, both visual assessments and measured ratios that are typical indicators of proneness of a bank to erosion. Seven variables are assessed and scored. The seven individual category scores are added together to get an overall BEHI score that correlates to an overall adjective rating for that bank (very low, low, moderate, high, very high, extreme). The seven variables scored in this evaluation are:

1. Study bank height / bankfull height ratio

Total bank height divided by bankfull height to compensate and adjust for stream size. The closer the ratio is to 1.0, the lower the risk of erosion of the bank.

2. Root depth / study bank height ratio

Predominant rooting mass depth divided by total bank height calculates approximate cohesion of bank material by vegetation. If the root mass does not reach the bottom of the bank, undercutting of the bank material may occur causing the top of the bank to fail.

3. Weighted root density (percentage)

Visual assessment of root density multiplied by root depth / study bank height ratio. The greater the weighted root density, the lower the risk of erosion.

4. Bank angle degrees

The steeper the bank angle, the greater the risk of mass failure of the bank due to gravitational force and shear stresses.

5. Bank surface protection

Measure of bank area as a percentage that is protected by sod mats, large woody debris, and revetments. The more protection, the lower the risk of erosion.

6. Bank material adjustment

Adjustment categories (Bank Material and Stratification) aid in the correction of erosive variables that might not show up in the previous categories. Different types of soils have different erosion rates, thus an adjustment may be appropriate. For example, cohesive clay banks erode more slowly than sand banks. In this category, one can adjust for bank material erosion differential by adding or subtracting 5 or 10 points to the BEHI score.

7. Stratification of bank material

Layers in the soil matrix can cause weak points on the bank face. If stratification exists specifically at the bankfull stage height, 5 or 10 points may be added to the total BEHI score to account for such stratification.

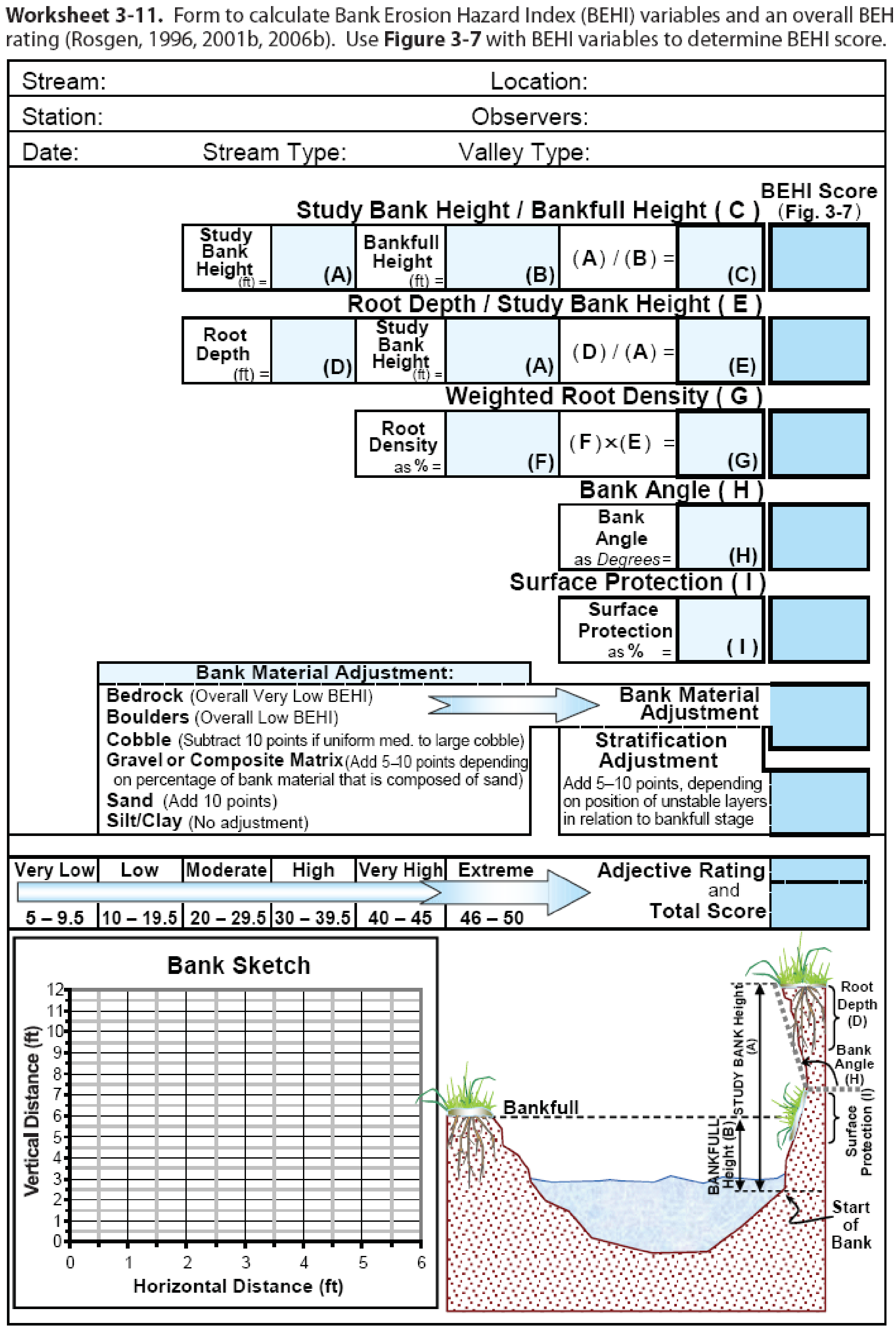
See Figure 3.7 and Figure 3.8 for BEHI worksheet and score conversion sheet.

Near Bank Stress (NBS)

The third and final variable to streambank erosion prediction curves is Near Bank Stress (NBS) assessments (Rosgen, 1996, 2001, 2006, 2008a and b). Near Bank Stress approximates erosional force of the outer 1/3 of the water column acting on the eroding bank (cutbank) at bankfull stage flow. There are seven ways to assess near bank stress and they vary depending on the level of stream monitoring completed. These methods are not averaged; the highest resultant adjective rating (very low, low, moderate, high, very high, extreme) of all calculated methods is used (Rosgen, 2006). See Figure 3.9 for the worksheet associated with NBS. Seven assessments to assign a rating to NBS are listed:

1. Channel pattern, transverse bar or split channel / central bar creating NBS (Level I),
2. Ratio of radius of curvature to bankfull width (Level II),
3. Ratio of pool slope to average water surface slope (Level II),
4. Ratio of pool slope to riffle slope (Level II),
5. Ratio of near-bank maximum depth to bankfull mean depth (Level III),
6. Ratio of near-bank shear stress to bankfull shear stress (Level III),
7. Velocity profiles / Isovels / Velocity gradients (Level IV).

Figure 3.7 BEHI rating form, Worksheet 3-11 (Rosgen, 2008b).



Worksheet 3-11. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001b, 2006b). Use **Figure 3-7** with BEHI variables to determine BEHI score.

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

BEHI Score (Fig. 3-7)

Study Bank Height / Bankfull Height (C)

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

Root Depth / Study Bank Height (E)

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

Weighted Root Density (G)

Root Density as % = (F) (F)×(E) = (G)

Bank Angle (H)

Bank Angle as *Degrees* = (H)

Surface Protection (I)

Surface Protection as % = (I)

Bank Material Adjustment:

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

Bank Material Adjustment

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**

Bank Sketch

Figure 3.8 BEHI assessment value to score conversion sheet (Rosgen, 2008b).

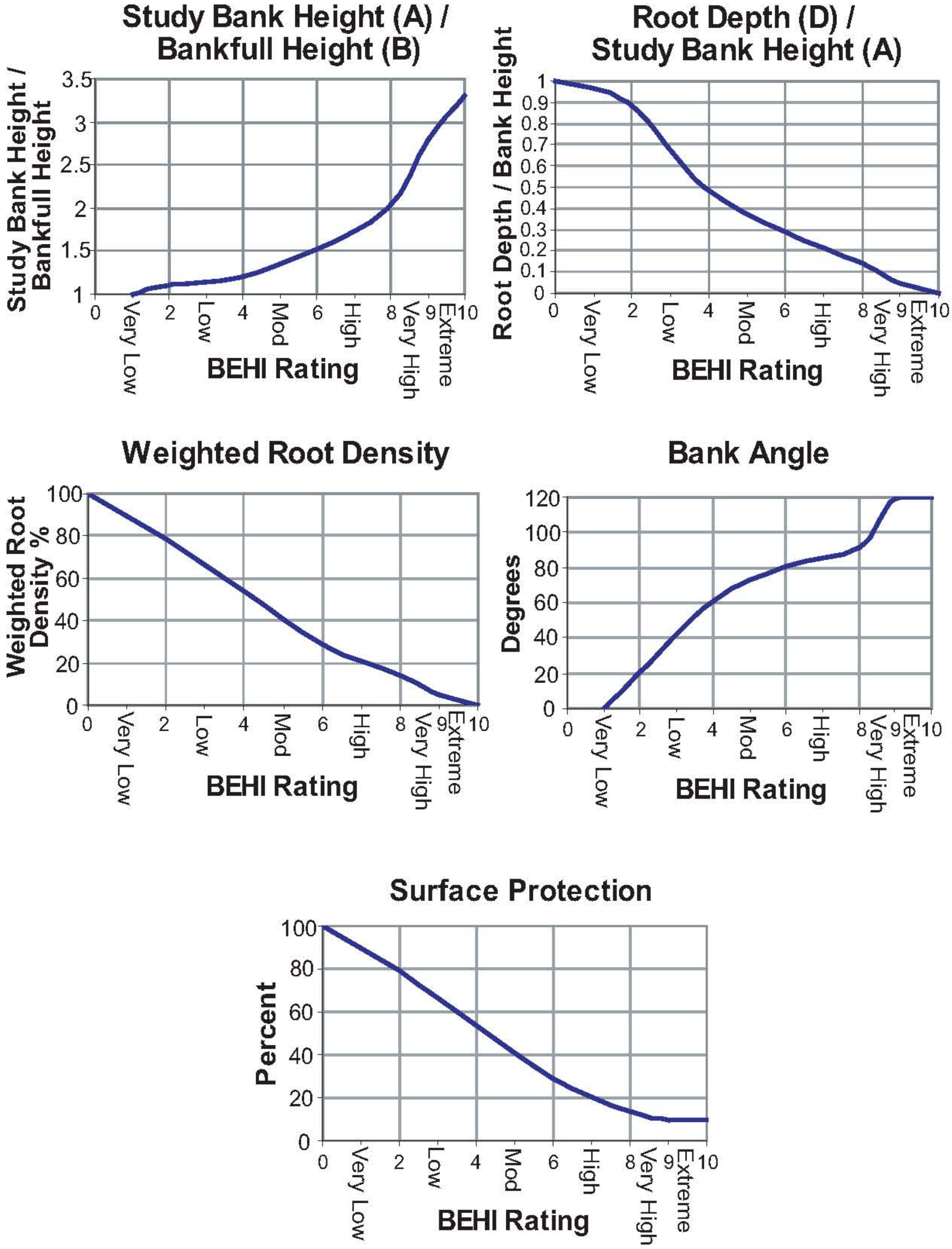
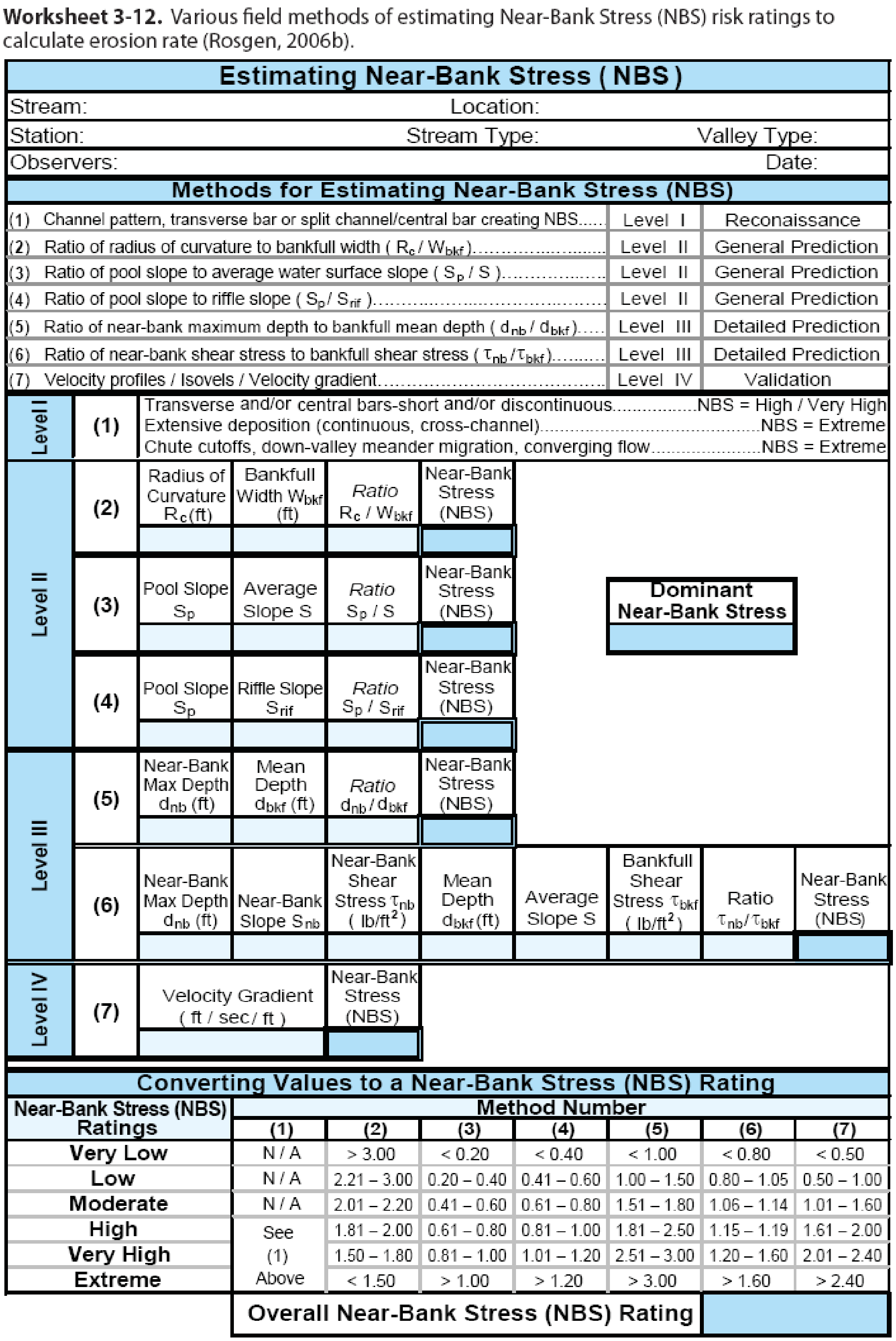


Figure 3.9 Near Bank Stress (NBS) rating worksheet, Worksheet 3-12 (Rosgen, 2008b).



Worksheet 3-12. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate (Rosgen, 2006b).

Estimating Near-Bank Stress (NBS)

Stream: Location:

Station: Stream Type: Valley Type:

Observers: Date:

Methods for Estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS.....	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})......................	Level II	General Prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)......................	Level II	General Prediction
(4) Ratio of pool slope to riffle slope (S_p/ S_{rif})..	Level II	General Prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf}).....	Level III	Detailed Prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf}).........	Level III	Detailed Prediction
(7) Velocity profiles / Isovels / Velocity gradient..	Level IV	Validation

Level I

(1)

Transverse and/or central bars-short and/or discontinuous................NBS = High / Very High

Extensive deposition (continuous, cross-channel)...NBS = Extreme

Chute cutoffs, down-valley meander migration, converging flow.....................NBS = Extreme

Level II

(2)

Radius of Curvature R_c(ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb}/ τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

Velocity Gradient (ft / sec/ ft)	Near-Bank Stress (NBS)

Converting Values to a Near-Bank Stress (NBS) Rating

Near-Bank Stress (NBS) Ratings	Method Number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) Rating

BEHI / NBS combinations

Eighteen study banks were assessed in the Black Vermillion watershed over a four-year period. Banks were assigned both BEHI and NBS adjective ratings the initial year (2007). Table 4 illustrates the results of BEHI and NBS combinations for these 18 study banks. Most bank combinations fell between moderate BEHI and very high BEHI ratings with no ratings resulting as very low, low, nor extreme. BEHI bank ratings that were not acquired need to be addressed, studied, and added to the developing predictive erosion curves for Northeast Kansas to establish a full set of predictive erosion curves.

Table 4 BEHI / NBS rating combinations for each bank location in the Black Vermillion system.

	Near Bank Stress Rating						
BEHI Rating		*Very Low*	*Low*	*Moderate*	*High*	*Very High*	*Extreme*
	Very Low						
	Low						
	Moderate	IC1s	MS1p, IC2p	NF3p	NF2s, NF3s		
	High	MS2p, MS1s	MS3p, IC3s	MS3s, IC3p	NF1s	NF2p	MS2s, IC2s
	Very High		IC1p	NF1p			
	Extreme						

Note: IC = Irish Creek, MS = Main Stem, NF = North Fork: p = pool, s = study bank

Flow Normalization

Predictive erosion curves were developed by Rosgen (2001) using bankfull stage flows in snowmelt dominated systems, namely Southern Colorado and Yellowstone regions. As noted, snowmelt dominated systems have a predictable pattern. However, in our storm-dominated hydrograph, we must normalize flows according to bankfull flow using Rosgen protocol. We experienced flows exceeding the bankfull stage three times in magnitude between 2007 and 2008, and up to six times in magnitude between 2008 and 2009. A normalization of these flows was performed to account for excessive erosion that might take place during events greater than bankfull stage.

To normalize flows exceeding bankfull stage discharge of a given event, we needed flow data from each creek. Dr. Phil Barnes provided mean daily flow data for Irish Creek, Black

Vermillion Main Stem and North Fork (2007-2009). Irish Creek's gage station was located at Irish Creek Reach 2 (Figure 1.4), while Main Stem and North Fork were located on the third, or lowest reach (Figures 1.10 and 1.14 respectively).

Mean daily flows for each stream were converted to dimensionless flow duration curves to establish a ratio of flow discharge exceeding bankfull discharge. Rosgen (2006) WARSSS illustrates how to accomplish this conversion on pages 5-89 through 5-90. The first step was to determine if the bankfull discharge was greater than the mean daily discharge the day bankfull occurred. Then, establish a new mean daily bankfull discharge by choosing the mean daily discharge on the day bankfull occurred from the mean daily discharge record. Divide the mean daily discharge flows from the flow duration curve by mean daily bankfull discharge to develop a dimensionless flow curve. Establish a ratio by dividing the mean daily bankfull discharge by the bankfull discharge. This allows the conversion of the dimensionless curve to a dimensioned curve. Results may be found in Appendix B (Figures B.1 through B.9). Converting dimensioned flow curves (cfs) to dimensionless flow curves affords assessment of flow magnitudes versus bankfull flow. In essence, how much more flow was experienced beyond bankfull flow.

Bank Assessment for Non-point source Consequences of Sediment (BANCS)

Bank Assessment for Non-point source Consequences of Sediment model (Rosgen, 2001, 2006, 2008a) (BANCS) was utilized to develop predictive erosion curves for Northeast Kansas (Figure 3.10). Two sets of curves for western regions were developed by Rosgen (2001) using this model, Southern Colorado and Yellowstone. These two regions differ greatly from Northeast Kansas in climate, soils, and precipitation runoff delivery and timing. Three variables are used in the BANCS model, Bank Erosion Hazard Index (BEHI), Near-Bank Stress (NBS), and measured erosion rates. Both BEHI and NBS are assessments made on actively eroding study banks, while corresponding erosion rates are measured using established field techniques (bank profiles).

The first step in the BANCS model was to find representative study banks for the reach being studied. One study bank was located at the representative pool cross-section; the second study bank was located at a representative bank of the reach. We tried to diversify banks regarding expected BEHI/NBS ratings while maintaining the approach to chose a representative bank on the reach. After the study banks were located, BEHI and NBS assessments were completed and banks rated. Then the initial bank profile was completed and graphed. After one year, bank profiles were completed again at the same locations with no new BEHI/NBS ratings scored. Bank measurements were taken annually for a total of four years (initial and three years after).

Once field data was completed and synthesized, we compared our measured data to both Southern Colorado and Yellowstone prediction curves (Figure 3.11). New erosion prediction curves are being developed for Northeast Kansas because both the Southern Colorado and Yellowstone curves were developed in differing regions and climatic conditions than Northeast Kansas. These Kansas curves were developed by plotting NBS rating versus erosion rates, while each BEHI adjective rating is plotted as a trend line. In addition to comparing predicted erosion rates between regions having developed erosion prediction curves, an evaluation of variables influencing Northeast Kansas erosion rates was completed. This evaluation was to determine if there were any variables that might prove to be more or less influential in the Northeast Kansas region than in the Southern Colorado, Yellowstone, Northeast Arkansas, and Piedmont regions.

Figure 3.10 Bank Assessment for Non-point source Consequences of Sediment model flowchart (Rosgen, 2006).

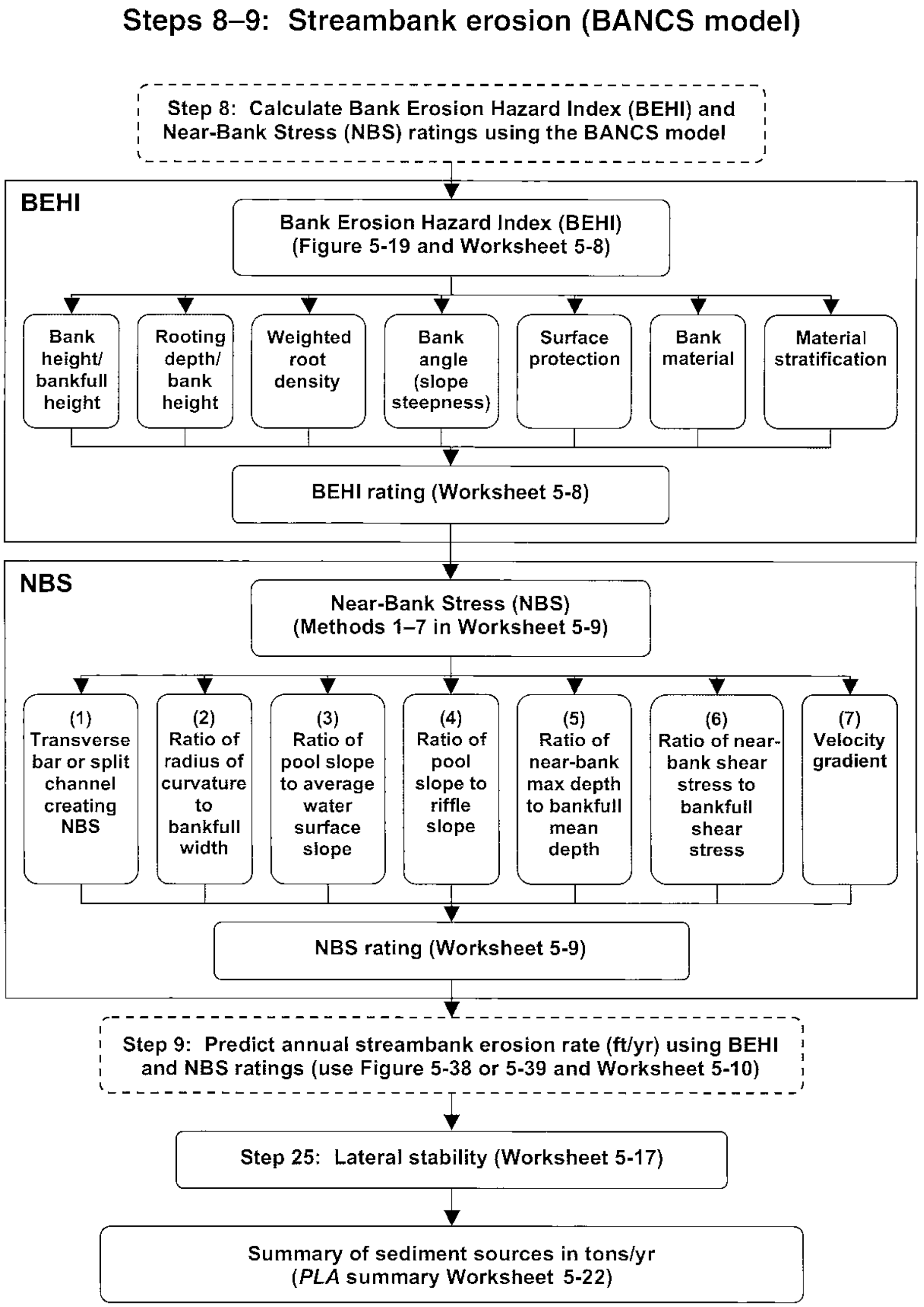
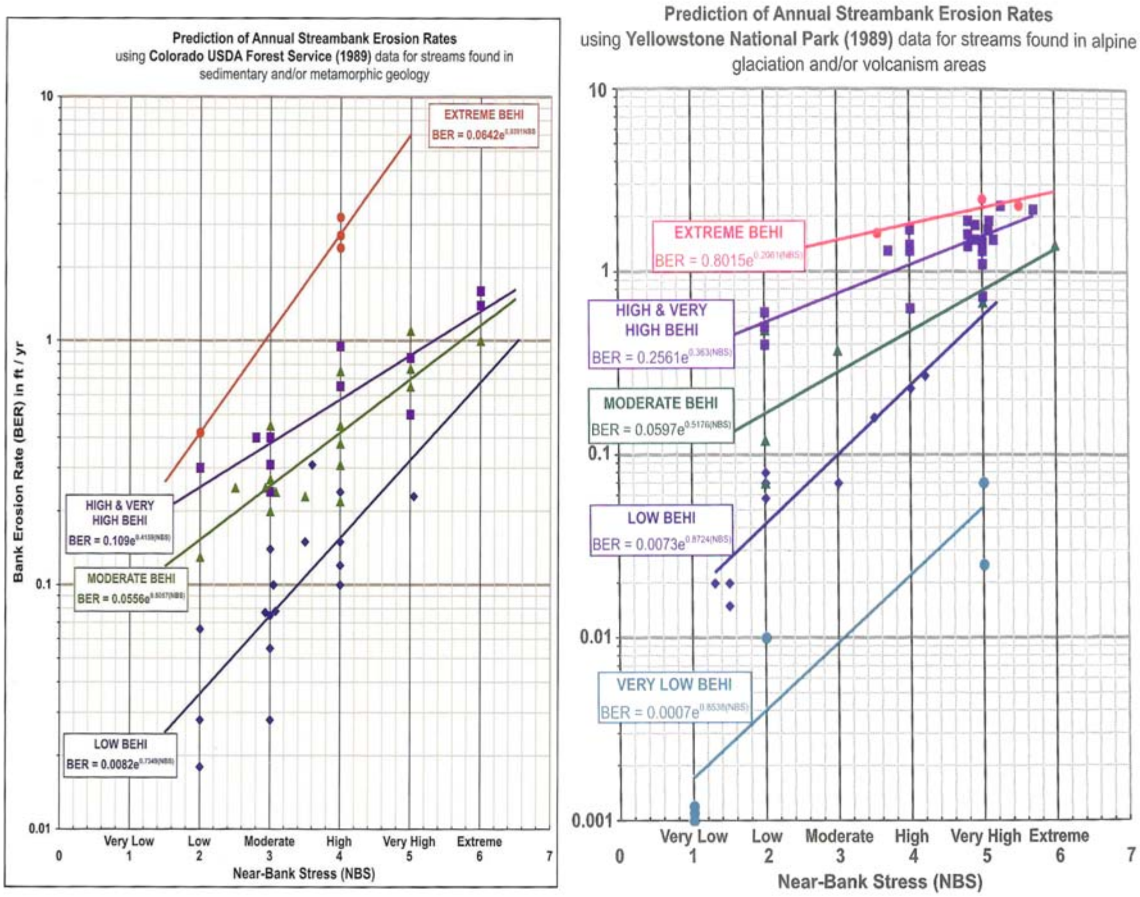


Figure 3.11 Erosion prediction curves developed using Colorado and Yellowstone data (Rosgen, 2001).



Saturation (Precipitation Rates) and Higher Bank Erosion Rates

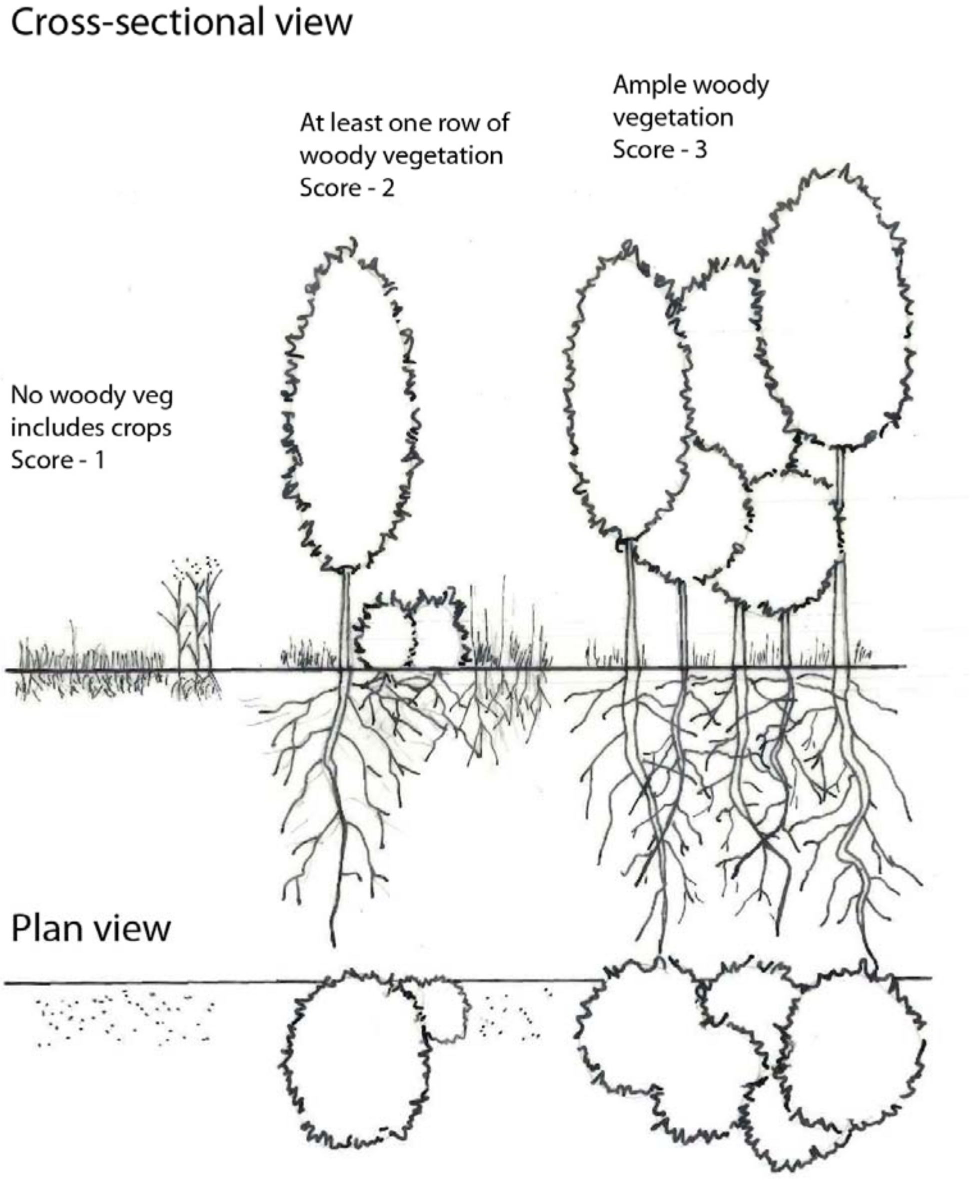
A comparison was completed between erosion rates and precipitation data to determine if bank saturation (pore pressure) was a significant contributor to streambank erosion process in the Black Vermillion system. Simon and Collison (2001) state mass failure often occurs during the recession limb of the hydrograph after banks have been saturated. Seepage and piping erosion of the bank may play a part in mass failure of Northeast Kansas banks as well (Jones, 1997; Fox et al. 2007; Wilson et al. 2007). Observation of bank failures along with erosion data might suggest high saturation along with seepage or piping are influential variables in the Black Vermillion watershed.

Daily precipitation data for the Black Vermillion system over a forty-year period (1970-2010) was secured through the Kansas State Weather Data Library, Kansas State University, Mary Knapp, State Climatologist. In addition, monthly statistics were secured for the past 10 years, 2000-2010. From these sets of data, an average and standard deviation was calculated. In addition, the number of times an average year's amount of precipitation within 1.3cm (0.5") was counted. The four-year study period was analyzed further by separating years by months from June 2006 through May 2007, June 2007 through May 2008, June 2008 through May 2009 and June 2009 through May 2010. This allowed for a direct comparison of study bank retreat for a study year of precipitation, as we resurveyed banks from the end of May through July.

Woody Riparian Vegetation and Bank Erosion Rates

Both pool cross-sections and study bank locations were grouped according to influential amounts of riparian vegetation on and above the assessed bank. Three groups regarding vegetation amounts were formed from the 18 study bank locations: no vegetation (1), little vegetation (2), and ample vegetation (3) (Figure 3.12). No vegetation included those banks influenced by tillage agriculture, brome pasture and shallow-rooted herbaceous plants only. Little vegetation included some woody vegetation, corridor widths usually less than two rows of trees with little age or species diversity. Willow thicket influence was also included in this category. Ample vegetation included those areas with strong influences from surrounding riparian vegetation. This grouping exceeded two rows of woody vegetation and included diverse age and species composition in the riparian corridor. These woody vegetation groupings were plotted against BEHI and NBS scores.

Figure 3.12 Woody vegetation amount types and scores for BEHI modification.



CHAPTER 4 - Results

"Come forth into the light of things, let nature be your teacher." William Wordsworth

Study Background

This study measured bank erosion rates for four years (2007-2010) using bank profiling techniques to develop a predictive erosion tool. Bank profiles were measured in the field once per year, then catalogued and analyzed in both RiverMorph and Excel software. Rosgen (1996, 2001, 2006) methodology was employed using the BANCS model including BEHI and NBS as variables to predict streambank stability and hydraulic shear stresses. This study was guided by the question, "can we develop a tool that can predict erosion rates in the hydrophysiographic region of Northeast Kansas similar to erosion prediction curves developed for Southern Colorado and Yellowstone (Rosgen, 2001) regions?"

Reach Characteristics

Nine stream reaches in the Black Vermillion watershed were monitored for three years using Rosgen (1996, 2001, 2006) protocol to classify and monitor these stream reaches according to measured morphological characteristics. Longitudinal profiles, cross-sections at both the pool and riffle stream facets, sinuosity measurements, bank profiling, and scour chain installation and recovery were completed on all nine reaches. Sediment characterization for both the study reaches and riffle cross sections were included. Total reach assessment was completed for three years (2007-2009), while study banks were measured for four years to collect erosion rates data (2007-2010). Reach characteristics regarding stream type and morphological descriptions are noted in Table 5.

Table 5 Black Vermillion Study Reach characteristics and Rosgen classification using bankfull (1.5-yr) recurrence interval.

	Rosgen Stream Type	D_{50} (mm)	W_{bkf} (ft)	W:D	Entren-chment ratio	Slope (ft/ft)	K	Reach Length (ft)	Average Bank Height (ft)
Main Stem 1	G5c	0.82	33.7	8.8	1.5	0.0015	1.2	1040	14.0
Main Stem2	G5c	10.25	37.8	8.8	1.5	0.0014	1.2	1551	15.1
Main Stem 3	F5	9.13	46.3	13.5	1.3	0.0007	1.2	1360	18.8
North Fork 1	G5c	2.92	45.6	7.1	1.6	0.0013	1.2	1676	20.7
North Fork 2	G5c	2.78	64.1	10.9	1.5	0.0008	1	2286	16.2
North Fork 3	G5c	1.86	67.2	10.6	1.5	0.0013	1.2	2041	16.1
Irish Creek 1	G4c	6.98	33.7	9.9	1.4	0.0014	1.3	1235	16.9
Irish Creek 2	G4c	18.86	44.6	8.7	1.2	0.0017	1.3	1674	22.1
Irish Creek 3	B5c*	0.35	42.8	7.7	2.1	0.0006	1.3	1722	17.2

* Irish Creek 3 classified as a B5c at chosen riffle; however, the reach alternates stream classification between B5c and G5c.

Bank Profiles

Bank profiles were completed on an annual basis over a four-year period. Initial profiles were completed in 2007, then bank resurveys were conducted annually through the summer 2010. Sampling of banks went from the end of May through the end of July. A bank profile was completed at each the pool cross-section and a representative streambank noted as the study bank. Assessments of BEHI and NBS were done during the initial bank profile, summer 2007. Tables 6 and 7 illustrate the results of bank assessments and erosion rates calculated from bank profiles from pool cross-section banks and study banks.

Table 6 Pool bank profile changes 2007-2010. Negative (-) numbers indicate deposition.

	Rosgen Stream Type	BEHI/ NBS Combination	07-08 (ft)	08-09 (ft)	09-10 (ft)	Average retreat / yr (ft)	Average bank height (ft)
Main Stem 1	G5c	Moderate/Low	1.28	0.65	-0.38	0.51	14.0
Main Stem 2	G5c	High/Moderate	0.34	-2.00	Slump	0.34	15.1
Main Stem 3	F5	High/Low	0.46	-0.25	Slump	0.46	18.8
North Fork 1	G5c	V. High/ Moderate	3.63	1.19	n/m	2.41	20.7
North Fork 2	G5c	High/V. High	4.19	0.88	-0.62	1.48	16.2
North Fork 3	G5c	Moderate/ Moderate	1.61	0.91	1.32	1.28	16.1
Irish Creek 1	G4c	V. High/Low	0.47	0.53	0.98	0.66	16.9
Irish Creek 2	G4c	Moderate/ Moderate	-0.88	-0.33	n/m	-0.61	22.1
Irish Creek 3	B5c	High/Moderate	0.54	0.44	1.3	0.76	17.2

Note: "n/m" = not measured that year due to no change according to bank pins; "Slump" indicates toe pin was lost due to aggradation or upper bank failure and bank was not profiled.

Lost Bank Data

Banks throughout the Black Vermillion watershed experienced mass failures and bank data lost due to those mass failures (Tables 6 and 7). Banks marked as "n/m" were not measured in 2010 due to no change in the bank according to bank pin exposure and visual inspection of the bank and pins. Banks marked "Slump" in Tables 6 and 7 indicate a lost toe pin either due to aggradation of the bed, upper bank failure, or a combination. Table 6 indicates that Main Stem 2 and 3 pool bank data was lost due to slump. Main Stem 2 Pool profile experienced a debris jam after a 2007 ice storm, which promoted local scour on the upper bank while depositing a large mass of soil over the toe pin. Overall, the bank experienced little change as evidenced by the average retreat per year (reconstructed from the pool cross-section data). Main Stem 3 also indicates slump, however for a different reason. The bank at Main Stem 3 Pool profile experienced aggradation near the bank consisting mostly of woody debris, sand, and silt. Table 7 indicates Main Stem 3 Study bank profile was also lost to slump. In this case, aggradation near the bank occurred, in addition to mass failure of sections of the bank resulting in a covered toe pin and bank pins missing.

Bank retreat rates indicating "Gone" refer to banks that had lost the toe pin and all bank pins were removed due to obvious mass failure of the bank (Figure 2.6). Table 7 indicates three banks being lost completely to mass failure; North Fork 1 (2007), North Fork 3 (2010) and Irish Creek 2 (2010). North Fork 1 Study bank was lost shortly after initial installation during a large storm event in 2007. A new bank was installed the following year upstream of the lost bank. North Fork 3 Study bank was lost to excessive erosion as well. Two major factors affected this bank, a log created local scour at lower flows and convergence of two channels at higher flows were directed toward this bank. Following June 2010 (heavy rains during month), the North Fork experienced high flows that exacerbated erosion rates in some places, North Fork 3 Study bank being one of them. Irish Creek 2 Study bank experienced mass failure during June 2010 as well. Figure 2.6 is the resultant failure at Irish Creek 2 Study bank. One bank toe pin, North Fork 2 Study bank, was reset after the toe pin was pulled due to ice.

Table 7 Study bank profile changes 2007-2010. Negative (-) numbers indicate deposition.

	Rosgen Stream Type	**BEHI/ NBS Combination**	**07-08 (ft)**	**08-09 (ft)**	**09-10 (ft)**	**Average retreat / yr (ft)**	**Average bank height (ft)**
Main Stem 1	G5c	High/V. Low	1.28	0.35	0.18	0.52	14.0
Main Stem 2	G5c	High/Moderate	1.34	-0.24	2.54	1.21	15.1
Main Stem 3	F5	High/Moderate	-0.33	-0.33	Slump	-0.33	18.8
North Fork 1	G5c	High/High	Gone	0.78	0.66	0.72	20.7
North Fork 2	G5c	Moderate/High	0.78	Reset	1.3	1.04	16.2
North Fork 3	G5c	Moderate/High	2.34	2.41	Gone	2.38	16.1
Irish Creek 1	G4c	Moderate/ V. Low	0.2	0.37	n/m	0.29	16.9
Irish Creek 2	G4c	High/Extreme	0.93	1.29	Gone	1.11	22.1
Irish Creek 3	B5c	High/Low	0.23	0.36	0.62	0.4	17.2

Note: "n/m" = not measured that year due to no change according to bank pins; "Slump" indicates toe pin was lost due to aggradation or bank failure; "Gone" indicates bank eroded more than four feet and toe pin was removed or missing; "Reset" indicates the bank toe pin was lost and then reset at the appropriate longitudinal profile station.

Flow Normalization

Flow normalization was completed to calibrate flows exceeding bankfull stage (1.5-year recurrence interval), Tables 8-10, for each sub-watershed, Irish Creek, North Fork, and Main Stem. Dimensionless flow duration curves were completed for each stream and year (Appendix Figures B.1-B.9) according to WARSSS protocol (Rosgen, 2006; p 5-89 through 5-90). Flow data for each reach (2007-2009) was measured by an automated water sampler provided by Dr. Philip Barnes. Dr. Barnes sampled for flow, total suspended solids (TSS), nitrogen (N), and phosphorus (P). The automated sampler takes a stage reading every 5 minutes, which is then averaged over the hour. The hours are then averaged over the day for an average daily flow. Point samples for TSS, N and P are taken through a sampling tube located midstream approximately 5cm (2") above the bed of the stream. Samples were taken starting in April of 2007 through December 31st 2009 at Black Vermillion study reach 3, North Fork study reach 3 and Irish Creek study reach 2. The sampler at Irish Creek study reach 2 is the only sampler sampling to date (late 2010).

The calendar year 2007 flow data was regressed from the USGS gauge (gauge number USGS 06885500) located downstream of Frankfort, Kansas. For each sub-watershed, a percentage of total flow at the Frankfort gauge was partitioned to the appropriate watershed. This regression assumes uniform precipitation and runoff between the three sub-watersheds according to the sub-watershed area. The following results confirm 2007 providing the most discharge using these assumptions. The $Q_{1.5}$, or bankfull discharge was exceeded by a multiple of 3 to 5-times (dimensionless ratio) during 2007. From these results we see that flow events above bankfull typically last about a day (2008 and 2009), providing insight into the flashiness of this stream system.

Table 8 Black Vermillion Main Stem normalized flow bankfull (Bkf) events.

Main Stem	**Bkf Q**	**Days Bkf exceeded**	**Events**	**Highest Flow**	**Dimensionless ratio**
2007	601cfs	36	3	3202cfs	5.32
2008		6	6	1630cfs	2.71
2009		6	5	997cfs	1.65

Note: Dimensionless ratio is calculated as Highest flow / Bkf Q. This ratio illustrates magnitude of flows above bankfull flow. For example, Black Vermillion Main Stem in 2007 experienced flows 5.32-times greater than bankfull flow discharge.

Table 9 North Fork normalized flow Bkf events.

North Fork	Bkf Q	Days Bkf exceeded	Events	Highest Flow	Dimensionless ratio
2007	1032cfs	37	3	5091cfs	4.93
2008		0	0	1025cfs	0.99
2009		2	2	1862cfs	1.80

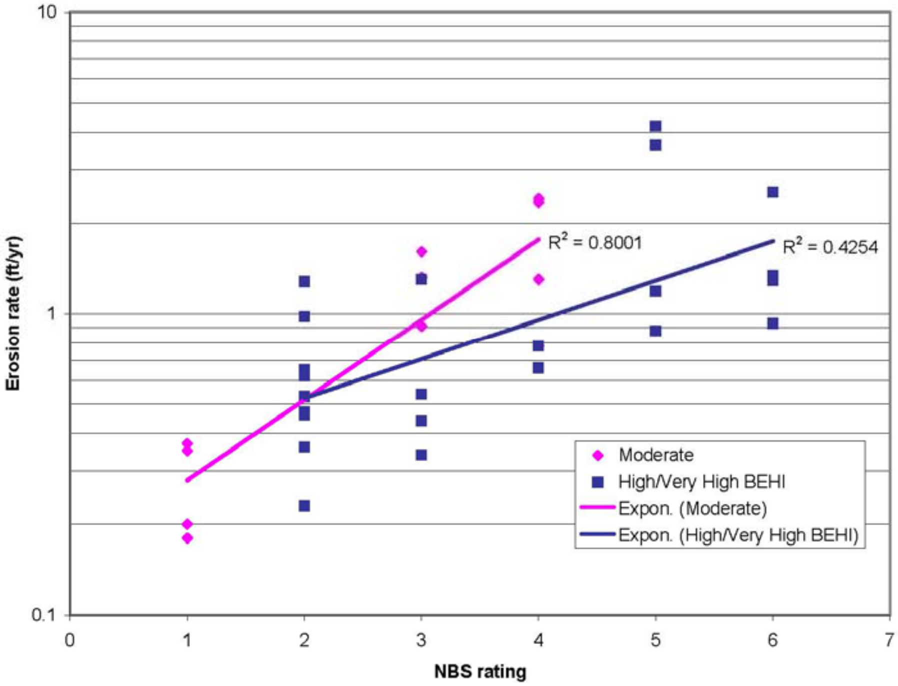
Table 10 Irish Creek normalized flow Bkf events

Irish Creek	Bkf Q	Days Bkf exceeded	Events	Highest Flow	Dimensionless ratio
2007	230cfs	7	4	729cfs	3.16
2008		1	1	256cfs	1.11
2009		1	1	372cfs	1.62

BANCS Model

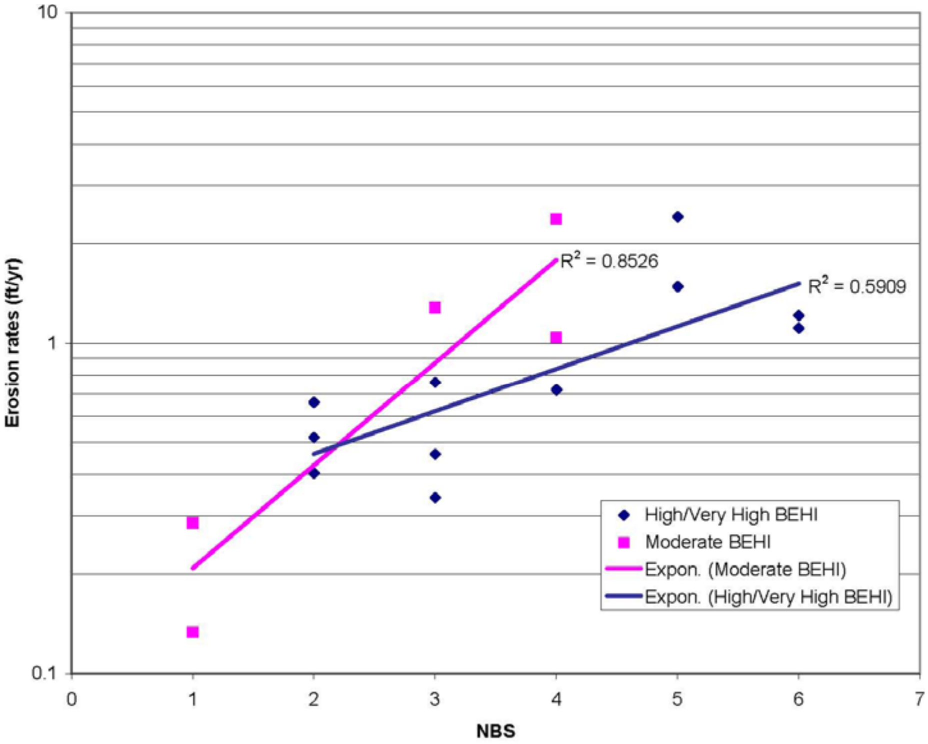
The Bank Assessment for Non-point source Consequences of Sediment (BANCS) model developed by Rosgen (1996, 2001, 2006) was used to synthesize BEHI, NBS and measured erosion rate data. Figure 4.1 illustrates the results of this synthesis where NBS is plotted along the X-axis, erosion rate (in feet) is plotted along the Y-axis and each trend line is a BEHI rating. Each BEHI adjective rating is plotted separately with their corresponding erosion rate data points. Figure 4.1 used all erosion rate data points gathered during this study. A correlation test and R^2 analysis were completed for these results; Moderate BEHI provided a positive correlation 0.81 (R^2 0.80), and High/Very High BEHI provided a positive correlation 0.55 (R^2 0.59). This study did not include very low, low or extreme BEHI ratings as those hazard ratings were not available in our study reaches, nor did this study include negative erosion rates (deposition). Figure 4.2 illustrates the results using average erosion rates from the eighteen study banks in the Black Vermillion watershed.

Figure 4.1 BEHI / NBS curve developed with Black Vermillion data in Northeast Kansas.



Notes: Each data point represents one year's erosion rate at a site. Some bank sites were lost, reset or were not re-measured.

Figure 4.2 BEHI / NBS curve developed using average erosion rates over four-year study period with Black Vermillion data in Northeast Kansas.



Average erosion rates calculated in Tables 6 and 7 do not factor excess bank retreat rates that would be provided by those banks that failed and were listed as "Gone." If assumptions were made regarding bank retreat rates for those banks listed as gone, the bank retreat average would increase. North Fork 3 Study bank could warrant a 4' bank retreat assumption because all bank pins were gone as well as the toe pin. If a 4' retreat rate was assumed and averaged, then the average retreat rate would jump from 2.38' to 2.92' (+0.54'). Looking at Irish Creek 2 Study bank, a safe assumption of 3' of bank retreat could be made. Figure 2.6 illustrates that the bank failed and left a bench approximately 1/4 the total bank height. Assuming the 4'-bank pins were lost and 4' of mass failure occurred, a deduction in bank retreat area difference of 1/4 of the 4' would also need to be assumed. With this assumption, approximately 3' of bank retreat could be assumed as the total. When averaged, this 3' of bank retreat would equate to an average of 1.74' instead of 1.11' (+0.63'). These assumptions were not included in the initial calculations. However, if included the values change; Moderate BEHI R^2 decreases slightly from 0.8526 to 0.8429 while the High BEHI R^2 increases from 0.5909 to 0.6752 if these higher average figures were included in Figure 4.2.

Table 11 compares predicted erosion rates in feet of bank retreat per year from the different curves developed around the country. Four different rating combinations were used as comparison. Note the North Carolina Piedmont curves were developed differently in that Jennings and Harmon (2001) used a best fit line for all sites with BEHI scores along the X-axis. In addition, Northeast Kansas field sites were monitored for four years while the other four studies were monitored one year. If higher averages were used to develop the erosion prediction curves, High/High for Northeast Kansas would change from 0.75'/yr to 1.25'/yr, while the other predictions would stay the same.

Table 11 Comparison table illustrating erosion differences between different curves developed across the country (shown in feet of predicted bank retreat per year).

BEHI/NBS Rating	**Colorado**	**Yellowstone**	**North Carolina**	**Arkansas**	**NE Kansas**
Moderate/Low	0.15	0.17	0.10	0.06	0.44
Moderate/High	0.42	0.48	0.10	0.18	1.80
High/Low	0.26	0.53	0.25	0.16	0.39
High/High	0.57	1.10	0.25	0.39	0.75 (1.25)

Note: These are all predictions from each respective curve developed from measured data. Erosion rates predicted using High/Low in NE Kansas curves predict lesser erosion than that predicted by Moderate/High NE Kansas curves. The prediction for Northeast Kansas using the higher averages at High/High would change from 0.75'/yr to 1.25'/yr, the rest remain the same, still less than the Moderate/High predicted value.

Both Figures 4.1 and 4.2 suggest some part, or parts, of the BANCS model as described by Rosgen (2001, 2006) does not fit our set of conditions in Northeast Kansas. Inconsistencies include the High/Very High BEHI rating curve trend line predicting lower erosion rates than the Moderate BEHI, while the opposite should be true. In addition, trend line slopes should not intersect, as both sets do at low NBS ratings. The R^2 values of the prediction curve trend lines are relatively low, even for natural systems and variances. Predicted erosion rates in Northeast Kansas illustrate under moderate BEHI ratings demonstrate higher erosion rates than High BEHI, suggesting a modification may be necessary. Discrepancies such as these indicate an erosion variable or process may not be accounted for, or may be over or under represented, using the BANCS model. Since NBS is an approximation of shear stresses applied to a bank using variables such as slope and radius of curvature, it should approximate similar stress conditions in all systems equally. Since NBS should predict similar stresses encountered by banks equally across regions, it was not considered for modification in this study. BEHI, which is used as an assessment of erosion resistance, may need modification for differing erosional processes and controls.

Curve "Discrepancies"

The Northeast Kansas erosion prediction curves have produced questions regarding the curves themselves and controlling agents on erosion rates in this region. Regarding controlling variables, some literature (Simon & Collison, 2001) points to precipitation and saturation of bank material having an effect on erosion rates in this region, which might confound the results of the curves developed in Northeast Kansas. Saturation of bank material can lead to mass failure through collapse of the bank due to increased weight of the bank, loss of frictional force between soil particles, and soil liquefaction (Knighton, 1998; Andrews & Martin, 2000; Iverson et al. 2000). Simon and Collison (2001) suggests soil saturation increases the likelihood of mass failure in banks after a rapid drawdown in stream stage following a high stage event (Figure 2.5).

Additional literature suggests vegetation having a profound effect on erosion rates due to energy dissipation of the water column by increasing roughness and by increasing tensile strength and cohesion root structure provides the soil matrix (Schumm, 1973; Thorne, 1990; Gurnell, 1997; Genet et al. 2005; Pollen, 2007). Vegetation roots in soil provide a soil-root matrix increasing the soil strength and lessening erosion. Different species of vegetation provide varied amounts of tensile strength to soils (Genet et al. 2005; Pollen, 2007). Vegetation also influences each of the three bank erosion processes as described by Lawler (1995); subaerial processes and erosion, fluvial entrainment, and mass failure. These influences are modification of the local microclimate, alteration of soil moisture, and reinforcement of the bank material against hydraulic and mechanical shear stresses (Wynn & Mostaghimi, 2006b). Wynn and Mostaghimi (2006b) found root density to have a significant impact on bank erosion in Southwestern Virginia. In this light, additional analysis was conducted to test both saturation and vegetative influences on erosion in this region.

A third variable not further considered in this study is soil material and properties. Wynn and Mostaghimi (2006b) found that bulk density of soils was the most significant factor effecting bank erosion, where the higher bulk density soils resulted in decreases in soil erodibility. Soils rich in clays typically have high bulk density, which is the case in Northeast Kansas and more specifically the Black Vermillion watershed. In addition, clays tend to hold together much better than other soil particle sizes and the threshold of failure is much higher (Schumm, 1973). As noted by Wynn and Mostaghimi (2006b), Grissinger (1982) states that "Soils with low interparticle distances (high bulk density) are less susceptible to swelling and erosion upon wetting (p78)." The soils in the Wynn and Mostaghimi (2006b) study were much lower in clay content (2 - 11%) than expected clay content in this study (23 - 47%). It is expected with additional analysis of the bank material soils that clay content will be very high and exerts a profound effect upon bank erosion processes and rates in the Black Vermillion watershed.

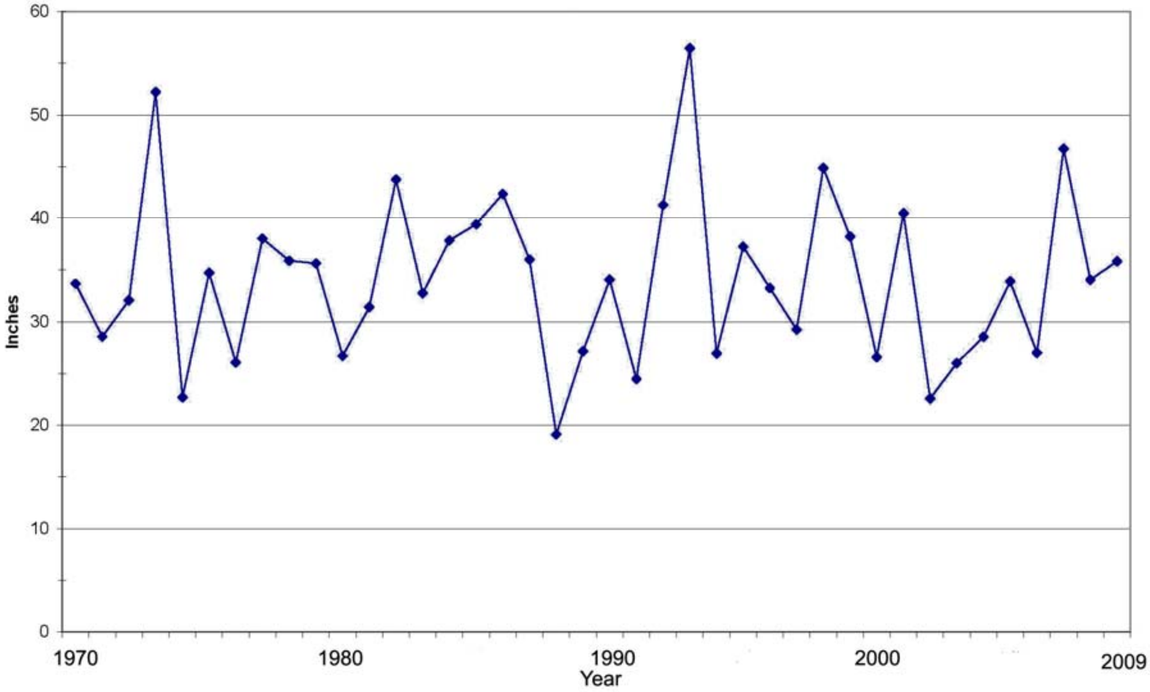
Soil Saturation (Precipitation) and Erosion Rates

To account for soil saturation, precipitation over a 40-year period of record (1970-2010) was assessed for annual mean precipitation 87.91cm (34.61”), recurrence of annual mean, and standard deviation 20.68cm (8.14”). Mean precipitation occurs once every twenty years [within +/-1.27cm (0.5”)]. Results of the 40-year precipitation totals are illustrated in Figure 4.3, while Table 12 illustrates the precipitation rates in the Black Vermillion watershed from select rain gauges in, or near, the watershed operated by Kansas State University over the study period. It was assumed that higher annual precipitation rates would produce higher saturated conditions in the watershed, thus promoting higher erosion rates.

Annual precipitation amounts varied over the study period (May 2007 through July 2010) ranging from near average [87.6cm (34.6")] to 30.4cm (12") above average. Notice that 2007 exceeds the annual precipitation average by more than one standard deviation [30.9cm (12.2")]. However, in June of 2010, the Frankfort gage received 27.4cm (10.8”), which exceeded the average for the month by more than 15.2cm (6") alone. All except 0.2cm (0.06”) of the precipitation fell between June 2nd and June 22nd, 2010. There were no more than three days in a row without rainfall of 0.8cm (0.3”) or less for the month of June 2010. Rainfall conditions such as this would saturate soils and bank material (bank weight increases) while increasing discharge of the stream. These rainfall conditions would provide for quick increases in stage and an equally quick recession limb of the hydrograph, thus present a flashy hydrograph and quickly change hydrostatic pressures against the streambanks for the Black Vermillion watershed. This flashiness of the Black Vermillion watershed hydrograph is illustrated in Figure 1.20, which is the hydrograph during June 2010.

By definition, flashy stream systems rise and recede rapidly allowing for a temporary resistance to bank failure by providing pressure against the saturated bank material while at a high stage. Once the stream recedes, pressure provided by the water column against the heavy, saturated bank material is lost and the bank may experience mass failure. If banks in the Black Vermillion watershed failed due to saturation, we would expect to see higher erosion rates during June 2010 due to measurable and constant precipitation from June 2nd through June 22nd. Figure 4.4 illustrates annual erosion rates versus mean annual precipitation rates from June through May (a study year). As illustrated in Tables 6 and 7, five banks (of the original 18) had been lost due to excessive erosion in 2010 (after June precipitation). Figure 4.4 does not show all data points for each bank regarding 2010 due to the loss of those five banks. If those banks could be measured, the assumption could be made that those bank's rates would exceed rates in 2007 (possibly in excess of 4' of bank retreat per study site).

Figure 4.3 Annual precipitation over the last 40-years [87.6cm (34.6")average], period of record 1970-2009.



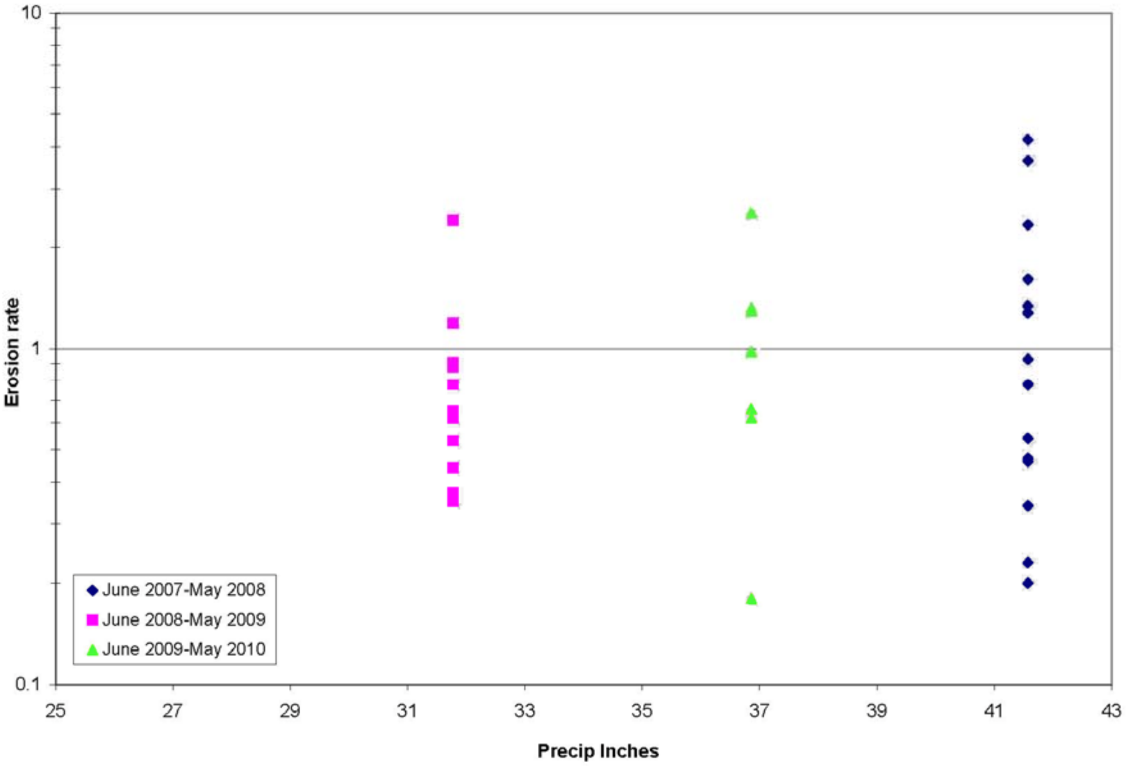
Mean precipitation for the Black Vermillion area is 87.9cm (34.6") and a standard deviation of 20.4cm (8.04") period of record for average was 1970 through 2010.

Table 12 Precipitation rates in Black Vermillion watershed.

Year	**Centralia (Goff)**	**Frankfort**	**Lillis**	**Watershed Mean**
2007	108.5cm (42.7")	125.7cm (49.5")	122cm (48.0")	118.7cm (46.8")
2008	94.5cm (37.2")	84.9cm (33.4")	80.1cm (31.6")	86.5cm (34.1")
2009	89.9cm (35.4")	83.7cm (33.0")	91.6cm (36.1")	91.6cm (36.1")
2010*	80.2cm (31.7")	72.2cm (28.5")	76.1cm (30.1")	76.2cm (30.1")

Notes: 2010 data through October. Includes early June rains at Frankfort station, which exceeded average by 16.2cm (6.4"). Centralia station did not have data from 2007-2010, thus Goff station was used (10miles east, 4miles south). Mean precipitation for the Black Vermillion area is 87.9cm (34.6") and a standard deviation of 20.4cm (8.04") period of record for average was 1970 through 2010.

Figure 4.4 Annual precipitation versus bank erosion rates.



Notes: Each data point represents a bank's erosion rate for that year. June through May was used to illustrate erosion rates between sampling years. If precipitation influenced erosion rates, we would expect to see higher erosion rates with increased precipitation, which is not what we see in this figure.

BEHI/NBS Score and Woody Vegetation Erosion Rates

Bank Erosion Hazard Index (BEHI) and Near Bank Stress (NBS) scores and ratings were plotted versus erosion rates and separated by whether a study bank site exhibited woody vegetation or not. The eighteen study banks were assessed for woody vegetation in 2007 and again in 2010. Three distinct categories of no vegetation (1), little vegetation (2), and ample vegetation (3) were delineated (Figure 3.12). The no woody vegetation sites were usually lined with exotic herbaceous species such as smooth brome, corn, or soy beans. Little vegetation category included sites with scattered trees to single trees along the bank. Ample vegetation category included sites with more than two rows of trees and continuous coverage along the bank. The woody vegetation results by location can be found in Table 13, while the plotted results of BEHI score versus erosion rates (by amount of vegetation) and NBS score versus erosion rates (by amount of vegetation) can be found in Figures 4.5 and 4.6 respectively.

Table 13 Location and amount of Woody Vegetation at bank sites; categories for vegetation influence (1) no vegetation, (2) little vegetation, and (3) ample vegetation (Figure 3.12).

Location	Woody Vegetation		Location	Woody Vegetation
MS1p	Yes (2)		**MS1s**	No (1)
MS2p	Yes (3)		**MS2s**	Yes (3)
MS3p	Yes (3)		**MS3s**	Yes (3)
NF1p	No (1)		**NF1s**	Yes (2)
NF2p	No (1)		**NF2s**	No (1)
NF3p	No (1)		**NF3s**	No (1)
IC1p	Yes (3)		**IC1s**	Yes (3)
IC2p	Yes (2)		**IC2s**	No (1)
IC3p	Yes (2)		**IC3s**	Yes (2)

Figures 4.5 and 4.6 illustrate higher erosion rates occur where no vegetation exists. On the contrary, where at least some vegetation exists erosion rates are much less. The BEHI model developed by Rosgen (2001, 2006) incorporates two vegetation components, however, looking at the BANCS model results, the BEHI model may not evaluate vegetation in a way that fits our conditions in the Northeast Kansas region. The NBS model developed by Rosgen (2001, 2006) does seem to work in this region. Figure 4.6 illustrates that banks having lower NBS ratings, regardless of the woody vegetation influence, produce lower erosion rates than banks with higher NBS ratings. In addition, banks with vegetation with the same NBS ratings erode approximately half the rate than banks without woody vegetation. The NBS model is an assessment of shear stress as a function of slope, radius of curvature, and water depth at bankfull. These variables included in NBS should result in the same adjective ratings anywhere in the world if all things considered are the same.

Figure 4.5 Plot of BEHI versus Erosion rates, comparing woody vegetation amounts.

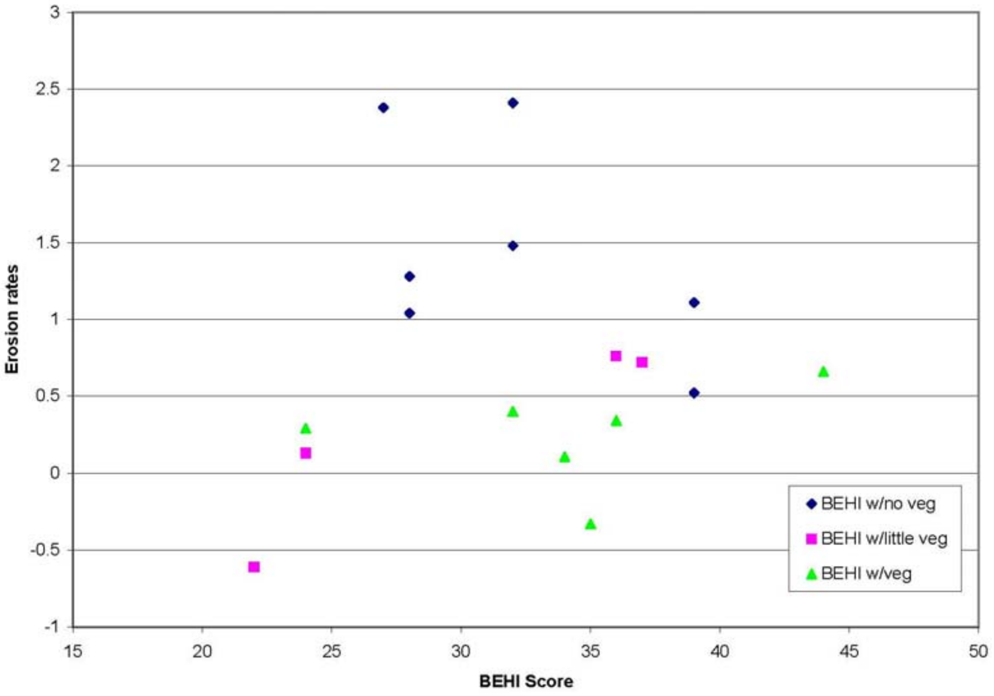
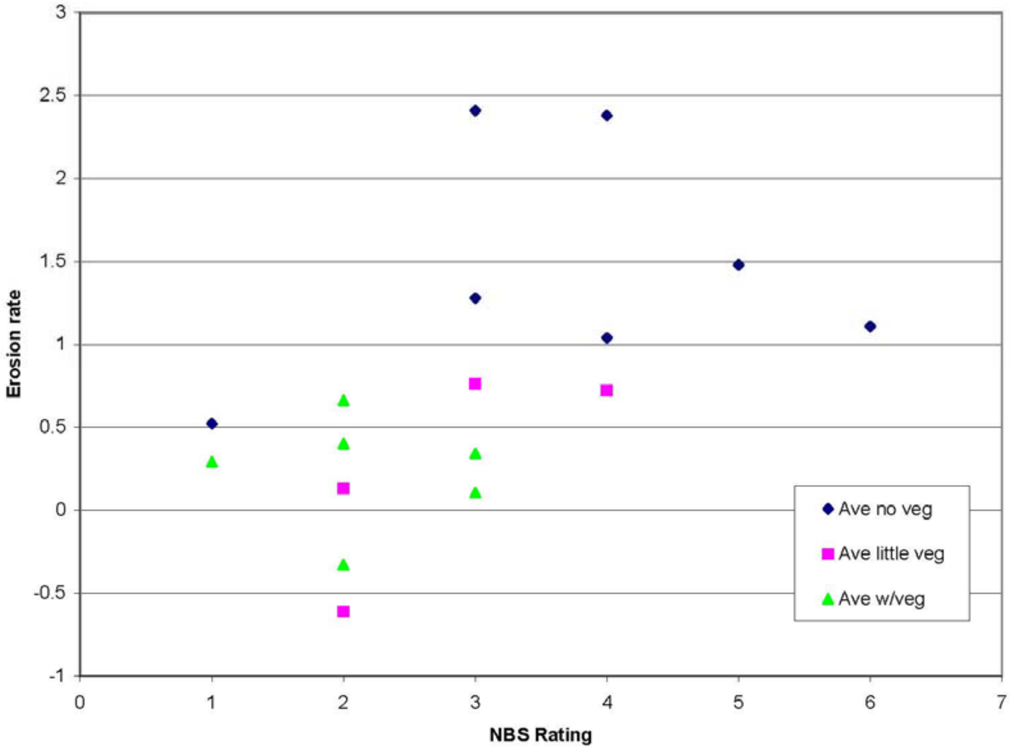


Figure 4.6 NBS versus Erosion rates, comparing woody vegetation amounts.



Statistical Analysis of Vegetation

Statistical analysis using a difference of means was calculated using the erosion rate means between banks with woody vegetation and those banks without woody vegetation. Banks exhibiting negative rates, or deposition, were not used in the statistical calculation since this study was evaluating erosion rates, not channel change. A normal population of bank erosion rate was assumed and sample variance was calculated under this assumption. The mean rate of erosion on banks with woody vegetation was 0.16m (0.51’), while a mean rate of erosion on a bank without woody vegetation was 0.41m (1.35’). The test statistic used was a standardized *z*-test with an alpha of 0.05. The resultant *z*-score of -185 indicated a significant statistical difference between the woody vegetation influenced banks versus non-vegetated banks' means analyzed. This significance between the means indicates some portion of vegetation may play a larger role in bank stabilization, or lack of stabilization, than the BEHI model accounts for in our region (Northeast Kansas).

Summary

The Black Vermillion watershed in Northeast Kansas exhibited unexpected results using the Rosgen (2001, 2006) methodology to develop erosion prediction curves. Reaches in the system typically classified as G5c and F5 stream types. Both the G5c and F5 are transitional stream types likely working toward a C-type stream (Figure 1.27 successional sequence). The lone B5c stream alternated between B5c and G5c, as the riffle used for classification was located in a B5c stretch of the reach. Rosgen stream types G and F tend to exhibit accelerated bank erosion and banks in the Black Vermillion system mirrored that fact. However, the bank retreat rates were varied and seemed to correspond to woody vegetation influences.

The synthesis of BEHI, NBS and measured erosion rates did not correspond as well as expected. There are many possible reasons explaining the BANCS model discrepancies. One such explanation is that this region is dominated by a storm-generated hydrograph, which may present different scenarios regarding soil saturation and erosion potential than snowmelt-generated hydrograph conditions. Measured erosion rates for the development of the BANCS model were measured under bankfull conditions and a snowmelt-generated hydrograph. Those conditions, which are predicable and regular unlike storm-generated hydrograph conditions, are assumed when applying the BANCS model in a different climate and region. Northeast Kansas flows vary yearly and seasonally, as evidenced by the discharge hydrograph (Figure 1.20) and by flow normalization showing streams exceeding bankfull discharge some years, while other years bankfull discharge was never achieved (Tables 8, 9 and 10).

Bank profiles measured during this study provided accurate erosion rates and deposition rates and the resulting streambank channel changes. Bank erosion in this region is typified by mass wasting of bank material as evidenced by six studied banks being lost over the four year study period due to complete failure. More than likely, saturation of bank material creates a scenario of high weight coupled with steep bank angles exceeding the shear strength of the bank. This erosional process is exacerbated by flashy flows providing an initial pressure from the water column itself that is exerted against the bank, which is then quickly released during the recession limb of the hydrograph allowing momentary shear stress to exceed shear strength. Mass failure of the saturated bank material then follows. However, streambanks exhibiting woody vegetation influences tended to hold together due to the added shear strength provided by the root systems. Streams experienced high flows exceeding the bankfull stage by 3-5-times in magnitude during the study period. Flashiness of streams in the watershed is illustrated by the number of flood events (events exceeding bankfull discharge) equaled by the number of days of events in most instances, flood events lasting roughly a day.

In addition, seepage and pipe erosion may influence mass failure in this region, as the streams in the Black Vermillion have been channelized and modified extensively. Seepage and underground water movement in old channels that were filled with soil return to the channelized portion of the stream and may induce bank erosion, decreasing bank stability. Old meanders interweave throughout the stream valley and cross the new channelized stream at many various points. Where these old and new channels cross, weak points in the bank may form. Erosion induced by seepage creates weak points in the bank and on the bank face. Weak points such as an old channel containing different soils and bulk densities will fail before well compacted, high bulk density, clay rich soils that make-up the majority of the bank material.

High clay content exhibited in alluvial and glacial soils deposited in the watershed (approximately 23-47% clay) may have an effect on soil erosion and mass failure. Soils high in clay content tend to erode at lower rates than silts and sands due to physical properties of each particle classification (Schumm, 1973). Clays also tend to fail in large masses due to cohesiveness of clay particles.

Lastly, woody vegetation in Northeast Kansas may have greater influence on bank material cohesion and stability than those settings and conditions in which the model was developed. Riparian vegetation in mountainous regions such as Southern Colorado and Yellowstone are very different than riparian vegetation found here in Northeast Kansas. Vegetation in Southern Colorado and Yellowstone typically exhibit a dense, fibrous root system, whereas vegetation in Northeast Kansas exhibits a much less dense, woody root system with fibrous roots near the top of the bank. Vegetation influence tends to explain the most variation between erosion rates and suggests some modification to the BEHI model may be necessary. All Black Vermillion sites, except two, historically were vegetated with woody riparian vegetation (KSLS, 2005) and now the largest erosion rates and frequency of failures occur at sites without woody vegetation influence.

CHAPTER 5 - Conclusions and Discussion

“It’s like déjà vu, all over again.” Yogi Berra

Black Vermillion Conclusions & Discussion

As with any natural system or process, bank erosion is a very complex set of processes that are all interconnected with driving variables being active or inactive at any time. Bank erosion is influenced by overland and in-channel processes, soil texture, riparian vegetation, channel modification, adjacent land uses, discharge of sediment and water, bank material and sediment size, stream morphology changes, among many other factors. These variables and processes are interconnected with biotic and abiotic entities and processes in the ecosystem and are virtually limitless in their combinations. To paraphrase John Muir, pull one string in nature and find it connected to everything else. This chapter is structured to discuss Rosgen classification results and implications; results of the BANCS model for this study; possible modifications of the BANCS model to more accurately predict erosion in the Northeast Kansas region; ideas regarding current controls in the watershed for keeping erosion in check; conclusions and future studies to help further understand bank erosion in this region.

Reach Characteristics and Erosion Rates

As previously mentioned, stream reaches in the watershed were classified under the Rosgen (1996) classification system. Streams classified as stream types G5c or F5 with one noted exception (Stream Classification Figure 1.25 and 1.26). Irish Creek study reach 3 classified as a B5c stream due to entrenchment ratio; the stream reach is aggradational allowing stream flow to reach the flood-prone area and thus classifying as a B-type stream at the chosen riffle cross section instead of a G-type stream (for flood-prone depth see Figure 1.23). However, the stream alternates between B5c and G5c classification depending on bank height, which affects entrenchment ratio. Stream reaches alternating between stream classification types are not uncommon, especially when two stream types are only separated by one variable, such as entrenchment ratio. Both G and F stream types tend to be unstable, which often results in high rates of bank erosion (Rosgen, 2006). All reaches in this study are semi-straight with very low gradients.

Using the Simon-Hupp (1986) classification model, Black Vermillion watershed stream reaches classify as Stages IV-V (Figure 1.28), which would result in aggradation and high streambank erosion rates. Similarly, the Schumm-Harvey-Watson (1984) stream classification model would result in Stages III-IV (Figure 1.29), which are also prone to accelerated bank erosion. Unfortunately for Tuttle Creek Reservoir, these streams are in the early stages of transition and stream evolution, thus higher rates of bank erosion can be expected, sending more sediment downstream toward Tuttle Creek Reservoir.

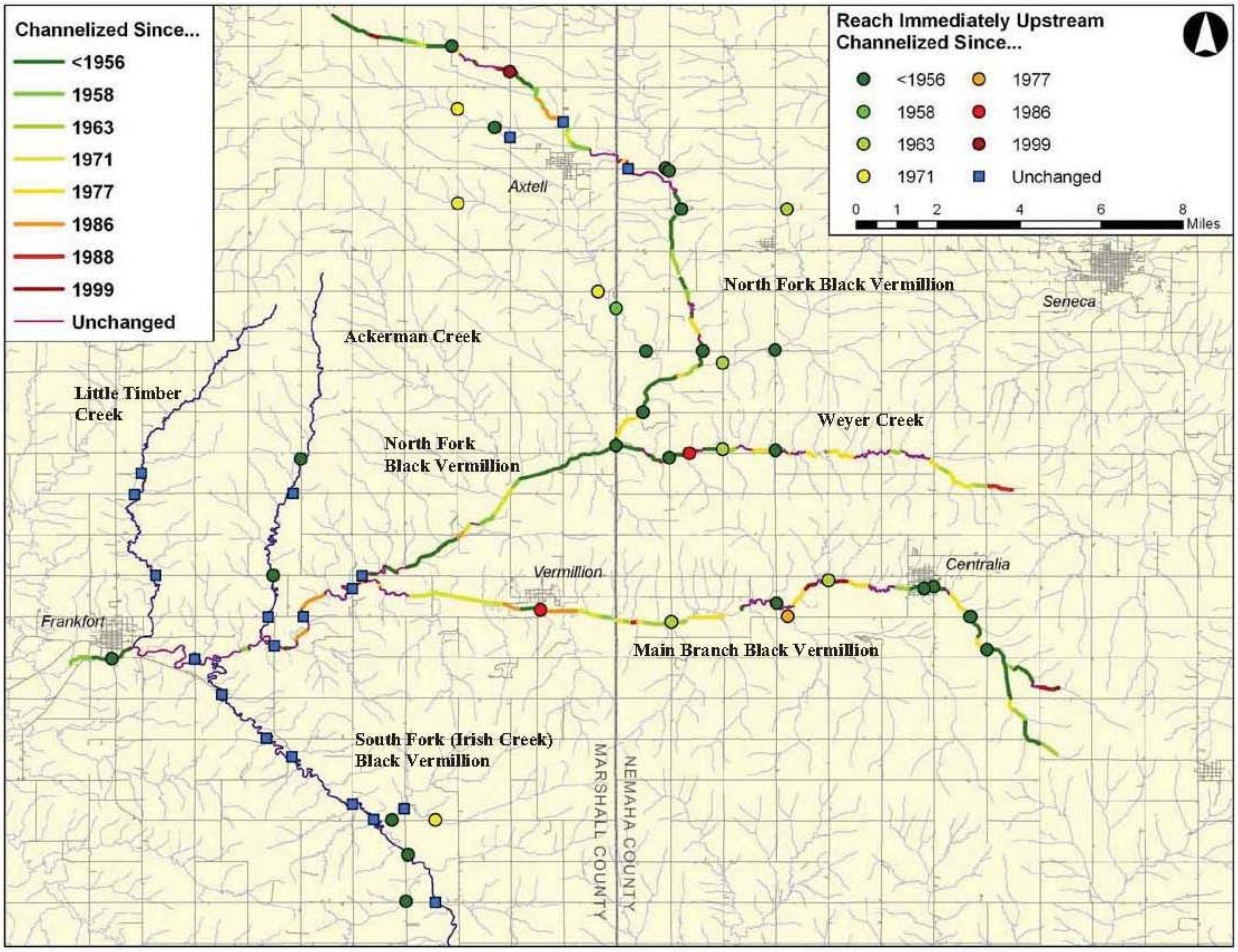
Historically, the streams in the Black Vermillion watershed may have classified as C or E-type channels (Figure 1.25 and 1.26) using Rosgen classification, or Stage I streams using Simon-Hupp or Schumm-Harvey-Watson (Figures 1.28 and 1.29). C-type streams are sensitive to changes in riparian vegetation, especially woody vegetation (Rosgen, 1996). E-type streambanks are typically held together by fibrous grass, sedge, and rush roots along with willow shrubs (Rosgen, 1996). Once prairies were converted to agricultural fields, E-type streams likely degraded due to increased runoff and decreased vegetation along the banks, or were mechanically straightened. C-type streams would have experienced a similar fate.

With channelization and channel modification, the vegetation along C-type streams changed, the channel slope increased, and land use changes increased runoff. These changes ultimately increased discharge and velocity. Changes in discharge and velocity accelerated degradation of the stream channel. Once the main trunk of the stream degraded, the first portion of the stream to be straightened mechanically, the rest of the system began to rejuvenate, or send nickpoints upstream to adjust to the new base level established by the trunk stream (Dunne & Leopold, 1998; Knighton, 1998). Once a new base level and gradient is established within the current climate, meanders may begin to form and stream length can be regained. To regain stream length in a channelized system, streambanks must erode while in-channel deposition occurs. Once the channel has widened, it can begin to build a new floodplain at a lower elevation. The channel then begins to create a meandering pattern by building new floodplain area on both sides of the widened channel. See Figure 1.27 (Rosgen), Figure 1.28 (Simon-Hupp) and Figure 1.29 (Schumm-Harvey-Watson) for examples of channel evolution and adjustment.

Sub-watershed characteristics

Differences exist between the three sub-watersheds of the Black Vermillion in Northeast Kansas. Irish Creek sub-watershed is influenced by Flint Hills physiography and contains more grassland than tillage agriculture, while the other two watersheds contain more tillage agriculture. North Fork sub-watershed hydrology is more controlled by terracing in the fields with some small watershed flood control structures. The Main Stem sub-watershed hydrology is controlled primarily through watershed flood control structures, especially Centralia Lake, which is the largest control structure in the entire Black Vermillion watershed. All sub-watersheds have experienced channelization or channel modification since 1950, which ultimately decimated most riparian corridor vegetation, Figure 5.1 (Sass, 2008; Meade, 2009).

Figure 5.1 Channelization sequence and timing in the Black Vermillion (Meade, 2009).



Woody Riparian Vegetation and Mass Failure

During this study we noticed that reaches without woody vegetation influencing banks seemed to fail at higher rates than areas with at least some woody vegetation (Figures 4.5 and 4.6). As noted by Masterman and Thorne (1992), Gurnell (1997), and Wynn and Mostaghimi (2006a and b), cohesive soil strength is increased with vegetation roots, especially woody root systems. The woody riparian vegetation that remains along the streams of the Black Vermillion system provide an extra tensile strength not found on those banks lacking woody riparian vegetation. Banks in Northeast Kansas tend to fail in large masses due to the cohesive clay content, but bank failure is retarded due to woody vegetation root systems. A difference occurs between bank failures of those banks with and without woody vegetation control. An extreme example of differences is illustrated by Irish Creek study reach 2.

An example of bank failure differences exists and can be illustrated using Irish Creek study reach 2, between the study bank profile and pool bank profile. These two banks are approximately 300’ apart, reacted very differently regarding failure during the same flows, and are influenced by different amounts of woody vegetation. The pool bank profile actually experienced overall deposition and was heavily influenced by vegetation. The study bank profile, 300’ upstream, failed catastrophically, losing enough bank material to lose all three 4’-bank pins, and which buried the toe pin between the 2009 and 2010 measurements (Figure 5.2). The study bank profile, Figure 5.2, was not influenced at all by woody vegetation, but by agricultural tillage as seen in Figure 1.7 and 1.8.

Figure 5.2 Irish Creek 2 study bank after June 2010 rains (Keane, 2010). Four-foot erosion pins were lost and the bank profile toe pin was buried.

Episodic mass failure was not exclusive to Irish Creek, but happened throughout the Black Vermillion watershed. Areas such as North Fork study reach 1 exhibited similar episodic erosion along the banks. North Fork study reach 1 study bank, located approximately 170’ down stream of the pool cross section, experienced little erosion compared to just 10’ upstream. Had our study bank been placed 10' upstream of where it was, the bank and pins would have been lost to erosion; in essence, bank failures are sporadic regarding intensity and extent along the reaches. Figures 5.3 and 5.4 illustrate sporadic mass failure along North Fork study reach 1. North Fork study reach 3 seemed to be farther along regarding stream evolution, as many banks experienced continuous mass failure along the stream, which came to rest at the bank toe in the over widened channel. These longitudinally continuous failures helped to narrow the stream while establishing a new bankfull bench (Figure 5.5 and 5.6). However, areas with woody vegetation tended to adhere bank material not allowing mass failure. Banks with woody riparian roots tended to be vertical in profile with tree roots extending vertically almost to the bank toe, or about 16’ from the top of the bank as illustrated at Black Vermillion Main Stem 3 and Irish Creek 2 (Figure 5.7

and 5.8). Knowing that Northeast Kansas' ecoregion, climate, soils and vegetation differ greatly than Southern Colorado, Yellowstone, Northwestern Arkansas, and the Piedmont region of North Carolina, we may benefit from modifications to the BANCS model, especially portions of the BEHI model. Suggestions regarding modifications to the BANCS model pieces must be addressed so that the model may be adapted to many regions and climates.

Figure 5.3 North Fork study reach 1 illustrating episodic and sporadic failures along field with no woody vegetation holding bank material (Keane, 2010).

Figure 5.4 North Fork study reach 1 upper bank of Figure 5.3 illustrating typical riparian vegetation, tillage agriculture, in system (Keane, 2010).

Figure 5.5 North Fork study reach 3 illustrating deposition along stream sides and formation of meanders in the straightened channel (Keane, 2010).

Figure 5.6 North Fork study reach 3 typical bank failure along reach establishing a new bankfull bench along both sides and re-vegetating streambanks (Keane, 2010).

Figure 5.7 Main Stem study reach 3 illustrating vertical banks held together with woody vegetation root structure (Keane, 2010).

Figure 5.8 Irish Creek study reach 2 upstream of study bank (Figure 5.2) illustrating vertical banks held together by woody vegetation (Keane, 2010).

BANCS Model

Variation (scatter) in natural systems is an important consideration for field studies and is often cause for consternation in field collected data. The R^2 values for BEHI/NBS curves for the Black Vermillion system are relatively low and the BEHI rating and predicted erosion rate combinations were not expected (Figure 4.1 and 4.2); however, some variability can be explained. Annual and seasonal changes such as magnitude and frequency of stream discharge, amount and intensity of rainfall, frequency and duration of freeze – thaw period, soil moisture levels, vegetation type and density of root systems, animal burrows, land drainage, reservoir development, and channelization projects all effect the processes of bank erosion and dictate erosion rates of any particular year in any watershed. These variables are not only difficult to isolate and predict, but often vary from season to season and year to year.

The BANCS model is process integrated, for in that the BEHI model considers many processes by assessing certain controlling variables. Processes integrated into the model include; overland erosion, fluvial entrainment, pore pressure (both negative and positive), dry ravel, soil piping, groundwater seepage, freeze-thaw, ice scour, soil liquefaction, and mass wasting (Rosgen, 2001). BEHI assessment is designed to account for these processes quickly using indicators for stability that are typical in mountainous areas. As mentioned previously, the BANCS model, specifically the BEHI model, was developed in the intermountain west of Southern Colorado and Yellowstone. These processes, or their relative importance, may differ significantly in regions dominated by glacial till or loess soils, which are typically high in clay content, for instance. Thus, a process integrated model developed for a specific region may not work as well in a region dominated by one or two bank erosion processes. If this is the case, then the components reflecting the importance of dominant process(es) should be weighted differently given differing regional circumstances.

Comparing the erosion prediction curves developed in Arkansas (Van Eps et al. 2004), Colorado and Yellowstone (Rosgen, 2001), and the Piedmont region of North Carolina (Jennings and Harmon, 2001), we see that curves developed here in Northeast Kansas exhibit lower R^2 values and thus more variability. In addition, Table 11 may indicate a lack of fit of the BEHI model for Northeast Kansas conditions and vegetation influence due to the predicted moderate BEHI outcomes being higher than High/Very High BEHI. The Piedmont region, Colorado and Yellowstone predictive erosion rating curves were developed in similar climates, controls and soils to each other that are far different from Northeast Kansas conditions. I expected the curves developed in Arkansas to be similar to those developed in this study. However, some of the variables controlling erosion were different, such as soil material and higher clay content in Northeast Kansas versus Northwest Arkansas. Arkansas bank materials are composed of more sand and gravel content, which is more erodible. Vegetation was not discussed in the Arkansas curves, so the assumption was made that BEHI predicted accurately for their conditions.

One major difference between this study and the other three is the duration of the study. This study was conducted over four years, while the other three studies were observed for only one season. Completing a study in a natural setting with few controls for one season does not allow natural annual and seasonal variability to be expressed. A field based study should be monitored for as long as possible to allow natural variability effecting the measurements to average in the current set of conditions. More time studying the Black Vermillion system's erosion rates will only enhance this study's data and our understanding and accuracy of predictive erosion curves for Northeast Kansas.

Possible Influential Variables of Bank Erosion in Northeast Kansas

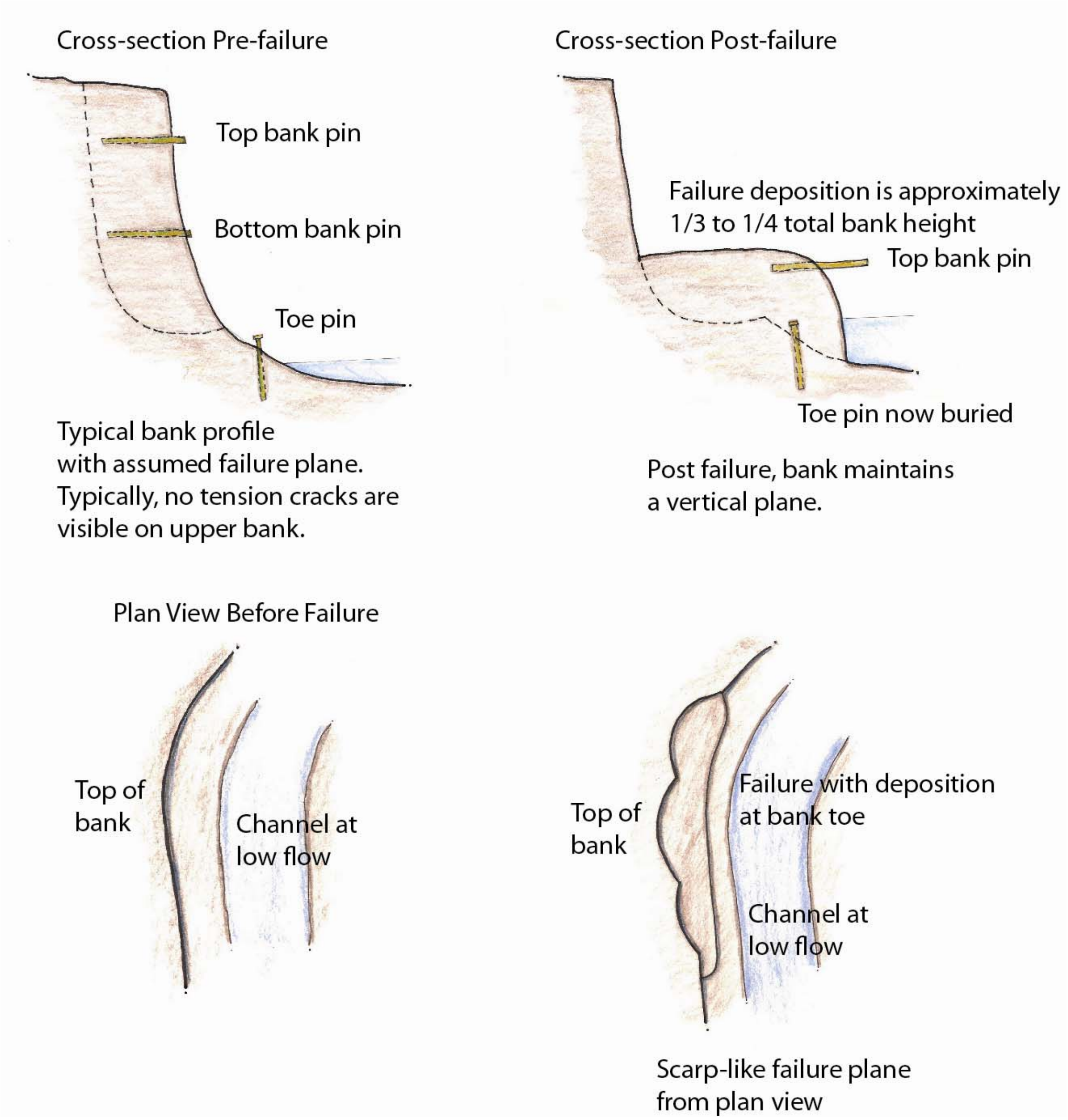
Antecedent Soil Moisture Conditions

Simon et al. (2000), state streambank erosion is directly related to saturated conditions and fluvial entrainment of the bank toe. The Black Vermillion system experienced varied saturated conditions throughout the study period, from desiccation to a month of probable fully saturated conditions. Precipitation rates and distributions over the study years varied creating differential levels of saturation in the system (Table 12 and Figures 4.3 and 4.4). The project started in May of 2007, when initial bank profiles were conducted. The year between June 2007 and May 2008 was a relatively wet year, above one standard deviation from average precipitation. The following year, June 2008 through May 2009, was a relatively average year with precipitation distributed more evenly throughout the year. Then, June 2009 through May 2010 was just above average. June 2010 was an anomaly, providing 27.3cm (10.8”) of rain over 28-days. June 2010's concentrated distribution created an environment of saturated soil and bank material that ultimately facilitated sporadic and coincident mass failure of banks throughout the system.

Saturation of bank material often becomes critical when there is no hydrostatic pressure from high flows holding the bank in place or when the shear strength of the bank material is reduced below a critical threshold. If banks are saturated and there is no hydrostatic pressure (elevated stream levels that hold bank material static), banks may fail catastrophically. When bank material experiences high saturation and low inter-particle frictional forces, the banks will exceed a critical threshold and also fail. In addition, extra weight provided by interstitial water when the bank is saturated may cause bank failure at a weak failure plane in the bank. Fortunately, thresholds can be increased by a soil-root matrix through increased tensile strength.

A wetted clay bank face at the bank toe tends to protect the lower bank from erosion by fluvial entrainment, almost like bedrock. If the bank toe were to be eroded, a result in undercutting of the upper bank would promote mass failure of the upper bank. However, banks tend to fail vertically and maintain a vertical profile creating a shelf and lower bank angle at the toe, sometimes at bankfull stage elevation. These shelves are created by bank failures in large masses, or chunks, which settle at the bank toe adjacent the stream. Bank material, mostly clays, after failure can be easily entrained and then carried downstream or left as a bankfull bench next to the stream if vegetated quickly enough before the next high flow event. Clay particles, while difficult to erode, once in suspension in the water column can stay in suspension for vast amounts of time (Knighton, 1998). Most upper banks in the Black Vermillion continue to maintain their vertical nature after mass failure (Figure 5.9). The top third of the bank tends to come to rest at the bank toe, suggesting the middle portion of the bank material is carried downstream.

Figure 5.9 Typical bank failure result in Black Vermillion watershed.



Climate, Precipitation, and Runoff

Curves developed in Yellowstone and Southern Colorado were developed using bankfull stage flows under typical snowmelt-generated hydrograph conditions. Rosgen (2001, 2006) methods dictate curves developed in storm generated runoff regions need to “normalize” flow rates to account for flows that exceed bankfull discharge. This normalization is done so a direct non-dimensioned comparison of flows can be made. The results of flow normalization in the Black Vermillion watershed show bankfull was exceeded most in 2007, thus we should have experienced the highest erosion rates in the year 2007-2008. During the 2007-2008 year, bankfull was exceeded in magnitude by 5-times the normal bankfull discharge. We did not see the highest erosion rates in 2007-2008; only five of the eighteen study banks showed highest erosion rates occurring in a year other than 2009-2010. In other words, approximately 72% of the banks eroded at their highest rates during 2009-2010, even though annual precipitation was not the highest during that year. Perhaps this study should not look at highest rain totals for the year, but look at precipitation month to month and day to day, which might better indicate antecedent moisture conditions of bank materials.

In 2008, the region experienced close to average annual precipitation and was the driest year of this study. Average precipitation occurs about every 20 years in this watershed (within 0.5"). There were few to no bankfull flows throughout the watershed (Tables 8, 9 and 10), which might be expected for average conditions in the watershed. For 2008, the few bankfull occurrences lasted one day or less in duration. In 2008-2009 we experienced the least amount of erosion per site possibly because of lower precipitation, less ground saturation, and less stream flow.

Although 2007-2008 was a wet year overall, 2010 produced more sporadic, coincident and catastrophic bank failure throughout the system. The reason for catastrophic bank failure in 2010 was 71% of the annual precipitation fell before July 1, with 30% falling between June 2nd and June 22nd producing wide-spread saturated soil conditions. With saturated soil conditions we would expect to see increased runoff and overland erosion because the precipitation would not be able to infiltrate the soil as it would during non-saturated soil conditions. Conversely, precipitation during 2007-2008 was distributed evenly throughout the year with few prolonged periods of precipitation. In this light, saturated conditions occurred more during the month of June 2010 and were not much of a factor during the study year 2007-2008. Figure 5.2 showing

Irish Creek 2 study bank illustrates this point. From 2007-2008, the bank lost 14.4sqft (or an average of 0.78' retreat), while during 2009-2010 we lost all three bank pins that measure 4’ in length (assumed 3' of erosion in calculations). The study year 2009-2010 at Irish Creek study bank 2 experienced over 2.5-times the erosion than the wettest year of 2007-2008. Changes in storm duration, storm intensity, and land cover changes may change the hydrograph of Northeast Kansas along with erosion patterns.

Predictive erosion curves developed in storm-generated runoff conditions present unique challenges and may provide more questions than answers. What will the storm cycle be like this year? How and when will precipitation be delivered? Storm variables such as rain intensity, individual storm duration, drop size, duration since last rain, time of year delivered, among others all contribute to runoff delivery methods to streams. Saturation of soil material is dependent upon these variables and as noted affects bank erosion. In June 2010, we experienced copious amounts of precipitation delivered over a short duration possibly coinciding with sporadic bank failure on most reaches in the watershed.

Woody Bank Vegetation (Tensile Strength)

Banks in our study with no woody vegetation tended to fail through mass failure more frequently and more catastrophically than banks with woody vegetation. Woody riparian vegetation in the Black Vermillion watershed plays a vital role regarding erosion rates, as evidenced by the difference of mean erosion rates of those banks with, versus those without woody vegetation. Woody vegetation is commonly thought to provide bank material with tensile strength (horizontal strength) that combines with the compressive strength (vertical strength) of soils (Rosgen, 1996; Gurnell, 1997; Genet et al. 2005; Pollen, 2007). Roots provide a matrix in the soil to help hold soil material together, much like reinforcing bar (re-bar) helps provide tensile strength in concrete. For example, when a sidewalk is undercut, consequently due to fluvial soil erosion, the sidewalk would fail if there were no re-bar in place because concrete is high in compressive strength but low in tensile strength. However, since re-bar is in place, the overhanging concrete can remain in that position without any support from below until the sidewalk fails due to gravity overcoming the tensile strength provided by the re-bar.

As noted, streams typically have vegetation on their banks and banks rely heavily on this vegetation to provide stability. There are certain Rosgen (1996) stream types that are more reliant on woody vegetation than other stream types to maintain bank stability. Once vegetation is removed from dependant stream types, banks may fail catastrophically and stability may not be regained for decades or even centuries (Rosgen, 1996; Manger & Brooks, 2007). The C, G and F-type streams are considered most impacted through removal of vegetation. If vegetation is removed from a C-type stream, then channel change may occur and a succession of channel types begins (Figure 1.27).

Banks in the Black Vermillion system that exhibit woody riparian vegetation in any amount tend not to erode nearly as much as those without woody vegetation (Figure 4.5 and 4.6). Unfortunately, the system has lost over 80% of its original woody riparian area (Sass, 2008) and thus a vital soil root matrix that slows erosion rates. Some riparian areas remain and are providing bank strength with an established woody root system. If these remaining riparian areas are lost, bank erosion rates in those areas will increase. As noted in stream characteristics (Table 5), most stream types in the Black Vermillion watershed are G and F. Historically, these streams may have been C-type or E-type streams. Regardless of the classification and succession system we use, Rosgen or Simon – Hupp models, bank erosion in this system is expected to accelerate as we move from G-type streams to F-type, Figure 1.27. The Simon – Hupp model would illustrate the same lateral bank movement evolving from Stage IV to Stage V, Figure 1.28. Bank erosion will likely be catastrophic in areas lacking woody bank vegetation.

Knowing vegetation plays a critical role in maintaining bank stability and strength, modifications to variables in the BEHI model that are measured by vegetation may be necessary for Northeast Kansas. These modifications may apply to other regions with soils that rely significantly on vegetation to maintain bank stability and strength as well. As such, regression models testing each individual variable rating in BEHI versus erosion rates were performed and compared. Individual variable ratings were also compared with each other in an attempt to eliminate overlapping ratings. Using these assessments and Figure 4.5 as guides, the following modifications to the BEHI model were completed.

BEHI Model Modifications

BEHI is a prediction of bank stability, as it incorporates many erosional processes by assessing indicators that commonly influence resistance to erosional processes. Since these erosional processes are weighted equally in the BEHI model, there may be a need to modify this model to reflect the dominate processes in a given region. A closer look at BEHI scores and ratings for this study revealed that there may be only one or two variables that influence erosional processes in this region. Table 14 illustrates each ratio or assessment's BEHI scores from the original study as recorded in the field. Each ratio and assessment results are scored according to a ratio to score conversion curve developed by Rosgen (Figure 3.8). Each assessment and ratio included in BEHI is described and analyzed following Table 14 for possibilities of modifications.

Table 14 Original BEHI scores of individual ratings using Rosgen's BEHI form (Figure 3.7).

Bank Location	SBH: BkfH	Rt D: SBH	WRD	BA	SP	BMA	SA	Total Score	Rating
Main Stem 1p	8.8	1	8.5	3.9	1.9	0	0	24.1	Moderate
Main Stem 1s	8.8	8.5	10	5	7	0	0	39.3	High
Main Stem 2p	8	1.9	8.5	2.5	10	0	5	35.9	High
Main Stem 2s	7.8	1.8	7.6	7.9	10	0	5	40.1	Very High
Main Stem 3p	10	1.3	8.7	4.5	5.0	0	5	34.5	High
Main Stem 3s	8	1	7.5	3	10	5	0	34.5	High
North Fork 1p	10	2	7.8	3.0	9.0	0	0	31.8	High
North Fork 1s	8.5	6	9	3.5	10	0	0	37	High
North Fork 2p	8.8	2.5	8.0	3.0	10	0	0	32.3	High
North Fork 2s	8.5	1	6.5	2.5	9	0	0	27.5	Moderate
North Fork 3p	8.25	1	6.5	3	9	0	0	27.75	Moderate
North Fork 3s	7.9	2.3	5.5	3	7.9	0	0	26.6	Moderate
Irish Creek 1p	10	1	9	9	10	0	5	44	Very High
Irish Creek 1s	10	1.8	8	3	1.5	0	0	24.3	Moderate
Irish Creek 2p	10	1	4	2.5	2	0	0	19.5	Moderate
Irish Creek 2s	10	6	10	3.5	10	0	0	39.5	Very High
Irish Creek 3p	10	2	8.5	4.5	10	0	0	35	High
Irish Creek 3s	9	1	5.9	5.9	10	0	0	31.8	High

Note: Symbols used are as follows; SBH:BkfH is Study Bank Height ratio, Rt D:SBH is Root depth ratio, WRD is weighted root density, BA is bank angle, SP is surface protection, BMA is bank material adjustment, SA is stratification adjustment.

Ratios and Assessments

Study bank height : Bankfull height ratio (SBH:BkfH)

Study bank height : Bankfull height ratio is an assessment of the degree of incision a stream is currently experiencing. The total bank height is divided by the bankfull height to get a ratio (Figure 3.7). This ratio is then converted to a score between 1 and 10 using the established scoring curve developed by Rosgen (2006). Erosional processes considered in this ratio are;

surface erosion, dry ravel, freeze - thaw, cantilever and mass failure (Rosgen, 2006). All Black Vermillion watershed stream reaches are deeply incised as indicated by stream types. Banks scored 7.8 to 10 out of 10 possible in this category, with an average score of 9.0. In general, there is nothing to modify with this predictor.

Root depth : Study bank height ratio (Rt D:SBH)

Root depth : Study bank height ratio accounts for rooting depth over the entire height of the bank, essentially accounting for bank strength using vegetation roots. Root depth is a visual assessment of depth of roots in the soil matrix, and is divided by the total study bank height. "...roots can have a major stabilizing influence on many erosional processes." (Rosgen, 2006, p 5-59). Black Vermillion streambanks scored a rating indicating a high bank stability in this category, scoring close to 1-ratio, indicating roots went from top to bottom of the study bank. If roots did not extend from the top of the bank to the toe, a low ratio would result along with a higher BEHI score. Scores ranged from 1 to 8.5, with an average of 2.4, illustrating most often roots extended from top of the bank to the toe. This ratio is carried into the next category of weighted root density.

Weighted root density (WRD)

Weighted root density is not a ratio, but a visual assessment of the amount of root material in the banks. Root density is estimated and multiplied by the Root depth : Study bank height ratio to get a weighted root density. This is another measure of strength of bank material provided by vegetation roots. Root density in Northeast Kansas rarely exceeds 30% and automatically produces a high score in this category; whereas root density where this model was developed may approach 80-90% due to sedge, rush and willow vegetative mix. A percentage of root mass such as 80-90% correlates to a low score on the BEHI in this category unlike 30%. Most natural riparian vegetation in Northeast Kansas includes large, woody trees and shrubs with wide reaching, deep, and sparse root networks. Black Vermillion watershed bank scores ranged from 4 to 10, with an average of 8. When Root depth : Study bank height ratio combined with Weighted root density we attain a median score, canceling out both the high score and low score, in essence one score negates the other.

Examples of such cancellation are Irish Creek 1 study bank (IC1s) and North Fork 3 study bank (NF3s). Both banks' overall scores were assessed a moderate overall score for the

BEHI assessment, Table 14. However, both banks eroded quite differently. Irish Creek study reach 1 was strongly influenced by woody riparian vegetation, unlike North Fork study reach 3. Irish Creek 1 study bank's Rooting Depth : Study Bank Height ratio score was 1.8 because there were roots that went from the top of the bank to near the bottom. The Weighted Root Density score for Irish Creek 1 study bank was 8 because there was little density of woody riparian vegetation, which is common with woody species. When averaged together, we get a score of 4.9, or moderate. At the North Fork study reach 3 site, the Rooting Depth : Study Bank Height ratio score was 2.3 and the Weighted Root Density was 5.5. When these scores are averaged, they create a score of 3.9, or moderate. The North Fork 3 site eroded at a much higher rate due to lack of woody vegetation root structure holding the bank together. Most of the rooting density for North Fork 3 study bank was from shallow-rooted herbaceous species that eroded away the following year. Regardless, both sites scored similarly, but eroded differently due to the woody vegetation influences.

Bank angle (BA)

Bank angle is an assessment, not a ratio, that is affected by bankfull flow and is estimated by visual assessment or by instrument. This BEHI variable estimates the risk of mass failure, such as planar and cantilever failures, assuming higher bank angles are more susceptible to mass failures (Rosgen, 2006). Bank angles ranged from 30˚ to 110˚ resulting in scores between 2.5 and 9 with an average score of 4.1. In this study, higher bank angles (higher BEHI score) often equated to lower erosion rates. This negative correlation and discrepancy from the established model signifies a modification to this category may account for Northeast Kansas soils and may be appropriate for similar ecoregions.

Surface protection (SP)

Surface protection is a visual assessment of the amount (by percent) of bank protected from erosive forces by sod mats, woody debris, other vegetation, or vegetated slump. Surface protection scores for the Black Vermillion system ranged between 1.5 and 10 with an average of 7.9. These higher scores are evidence that the system has raw banks that are not well protected.

Bank material adjustment (BMA)

An adjustment to the overall BEHI score may be made if the bank is amassed primarily of certain constituents. This category takes into account the differential erosion susceptibility of different bank materials. Bedrock and boulder banks attain a Very Low or Low BEHI score regardless of other individual factor BEHI scores. Bedrock and boulder banks override all other factors scored thus far because bedrock and boulder sized banks erode at very slow rates, if at all (Rosgen, 2006). Banks composed of cobble size material direct for a subtraction of 10-points from the overall BEHI score if cobble is uniform and medium to large in size at the median axis (96mm-256mm). Cobble sized bank material provide surface protection against erosion and are difficult to erode themselves at shear stresses attained at bankfull stage. Gravel and gravel-sand mixed banks add 5-10-points to the overall BEHI score depending on amount of sand mixed with the gravel. Sand banks automatically add 10-points to the overall BEHI score. Sand and gravel are easily eroded from banks, are highly friable, and are less cohesive than bedrock, boulders, cobble and clays. Clay banks add nothing to the overall BEHI score (Rosgen, 2006). Scores for the Black Vermillion streambanks assessed in this category were 0 to 5-points with an average of 0.3. One bank, Black Vermillion Main Stem 3 study bank, was given 5-points for sandy material. Most banks in the watershed were scored as zero, due to clay / silt material being the dominant bank material. High clay content may provide strength similar to that of bedrock; however, all banks in the Black Vermillion watershed contained high clay contents ranging from 23-47%.

Stratification adjustment (SA)

Stratification adjustment is an assessment of bank layering of materials and weak strata associated with the layering of different bank materials. Along with actual layering of materials, position of layers is taken into consideration. If a layer of sand is 16-feet above the bankfull discharge, that layer does not carry the same weight as a layer of sand at the bankfull discharge stage. Using the above example, the layer at bankfull stage would erode more quickly over time than the layer 16-feet above the bankfull stage. Five to 10 points may be added to a bank having layers of gravel or sand (Rosgen, 2006). Black Vermillion Main Stem and Irish Creek sub-watersheds were the only streams given points due to gravel and sand lenses and minor layering below and at bankfull elevation. Scores in this category were 0 to 5-points with an average of 1.1. Few banks contained layering of any consequence as evidenced by the average score.

Modification of BEHI Assessments

Two plausible outcomes exist regarding the BEHI portion of the BANCS model; if it does not work as it should in a given region, can we (1) modify the existing model or (2) do we create a new model. Both options are legitimate; however, modification of an existing model that is used extensively and can be utilized easily makes the most sense. Assessment of the current BEHI model produced some intriguing options regarding modification.

First I assessed if there were any ratios or assessments that could be removed from modification consideration. Starting at the beginning of the BEHI model assessment, Study bank height : Bankfull height ratio was removed from modification consideration first. All channels in this study were incised, and all corresponding BEHI scores reflected this fact. The second variable removed from modification consideration from the BEHI model was the Surface protection assessment. Surface protection of the banks is rare and is also reflected in the individual BEHI scores. The third and fourth variables removed from modification consideration of the BEHI model were Bank material adjustment and Stratification adjustment. We saw little stratification nor variation in bank materials and the adjustment scores reflected this fact. The elimination of these four variables left Bank angle assessment, Root depth : Study bank height ratio, and Weighted root density as factors to be considered for adjustment in scoring and/or weighting.

Bank angle modifications

As mentioned previously, Bank angle in this study tended to correspond negatively to erosion rates. The steeper bank angles eroded less than shallow bank angles. The negative correspondence between bank angle and erosion rates is opposite of the BEHI predictor and would contribute to confounding results. Three explanations exist; first, angles may have been misidentified in the field. Second, the cohesion of bank material is higher in Northeast Kansas than Colorado or Yellowstone (where BEHI model was developed) and this variable may need to be modified for this area. Third, both angles may have been misidentified and bank material is more cohesive in Northeast Kansas. Banks in the Black Vermillion watershed typically exhibited compound angles, confounding field assessment, which may have contributed to misidentification of angles in the field.

In an effort to standardize this portion of the BEHI model, bank profiles were plotted and overlaid using RiverMorph software. Then, I measured all angles of all bank profiles and recorded those angles on the banks. The next step was to use the bank angle most closely associated with the bankfull stage as the angle scored from the compound angle banks. RiverMorph software was utilized to measure all bank angles for scoring as BEHI, as angles could be discerned and calculated separately. While upper banks maintained angles in excess of 70-degrees, lower banks tended to have lower slope angles. Lower banks averaged a 45-degree angle, providing a lower score for this BEHI variable. This step changed some individual bank angle scores and thus changed the overall BEHI adjective rating for some banks. Tables 14 and 15 illustrate previous Bank angle scores versus new Bank angle scores. It became obvious angles may have been overestimated in the field or the wrong angle used for this category.

Vegetation modifications

Modification to the vegetation assessment sections of BEHI is suggested in light of vegetation scores consistently creating a median score in this study. Both rooting depth ratio and weighted root density variables relate to similar processes and when combined produce a median score as illustrated earlier so I combined the two categories into one creating a new category, Woody Vegetation Present. If woody vegetation was present at the study bank, the bank scored a low adjective rating and a numerical score of 2.5. If there was no woody vegetation present, the bank scored a high adjective rating and a numerical score of 8.5. This protocol is similar to Rosgen's BEHI scoring for Bank Material Adjustment when large boulders or bedrock is the bank material. Banks having large boulders or bedrock receive a Low or Very Low BEHI automatically. However, this modification does not override all other BEHI scores like the adjustment for large boulders and bedrock. Figure 4.5 illustrates that banks without vegetation erode at least 3-times more than banks with vegetation (1.35' erosion/yr without; 0.51' erosion/yr with woody vegetation), thus 8.5 is approximately 3-times higher than the low average score of 2.5.

Combining Root depth : Study bank height ratio, and Weighted root density ratings into one category allows us to assess combined vegetation effects on erosional processes. Vegetation creates a soil-root matrix that inhibits and protects bank material against erosion and mass failure (Rosgen, 1996; Gurnell, 1997; Dunne and Leopold, 1998; Genet et al. 2005). While weight on the bank material is increased by the extra weight of vegetation itself, the increased bank shear strength and bank protection must prevail over that extra weight, as exemplified by the standardized z-test between the mean erosion rates of banks with and without woody vegetation. When the erosion rate means were compared using the standardized z-test, a resultant score of -185 was attained. This is a significant score at any alpha-level, thus illustrating a large difference between those means. If this is the case, then vegetation affects erosion rates in this region at sites without a copious percentage of root density holding the bank together. Root density in Northeast Kansas rarely exceeds 30%, however, the soil-root matrix that is created by woody roots provides extra tensile strength that is needed in clay-rich soils. Combining root density and root depth into one category allows us to score vegetation as high or low, and in doing so, we account for our lower root densities compared to those root densities where the model was developed. Once woody vegetation influences were scored, new overall BEHI ratings were attained and new predictive erosion curves developed.

New BEHI Scores and Explanation

Combining the root depth : Study bank height ratio with Weighted root density did not change the scale by which overall adjective ratings are assigned by BEHI additive scores. Using the modifications developed in this study, there are now 12.5 less total points possible in the total BEHI score (original developed by Rosgen total score possible 70, modified by Sass total score possible 58.5). Table 15 illustrates overall score comparison between the original BEHI model and the modified model. The adjective ratings associated with overall BEHI scores continue to be: 5.5-9.5 total points equates to Very Low, 9.5-19.5 total points equates to Low, 19.5-29.5 total points equates to Moderate, 29.5-45.5 total points equates to High/Very High (combined), 45.5-58.5 total points equates to Extreme. High and Very High adjective ratings were combined as they were in the original curves developed in Colorado and Yellowstone (Rosgen, 2001, 2006). Extreme ratings can only occur with this modification of BEHI if stratification or bank material adjustments are required. Table 15 illustrates a comparison between Rosgen scoring for the BEHI model versus the new modifications for Northeast Kansas. Table 16 illustrates the new BEHI scores and associated ratings with each bank in the Black Vermillion watershed as converted from Figure 3.8.

Table 15 Comparison between Rosgen BEHI and Northeast Kansas modifications scores per category. Different scoring systems are bolded.

Category	**Rosgen**	**NE Kansas**
Study Bank Height : Bkf Height	1 to 10	1 to 10
Root Depth : Study Bank Height	**1 to 10**	**N/A**
Weighted Root Density	**1 to 10**	**N/A**
Woody Vegetation Present	**N/A**	**2.5 or 8.5**
Bank Angle	1 to 10	1 to 10
Surface Protection	1 to 10	1 to 10
Bank Material Adjustment	-10 to 10	-10 to 10
Stratification Adjustment	1 to 10	1 to 10
Total Score Possible	**70**	**58.5**

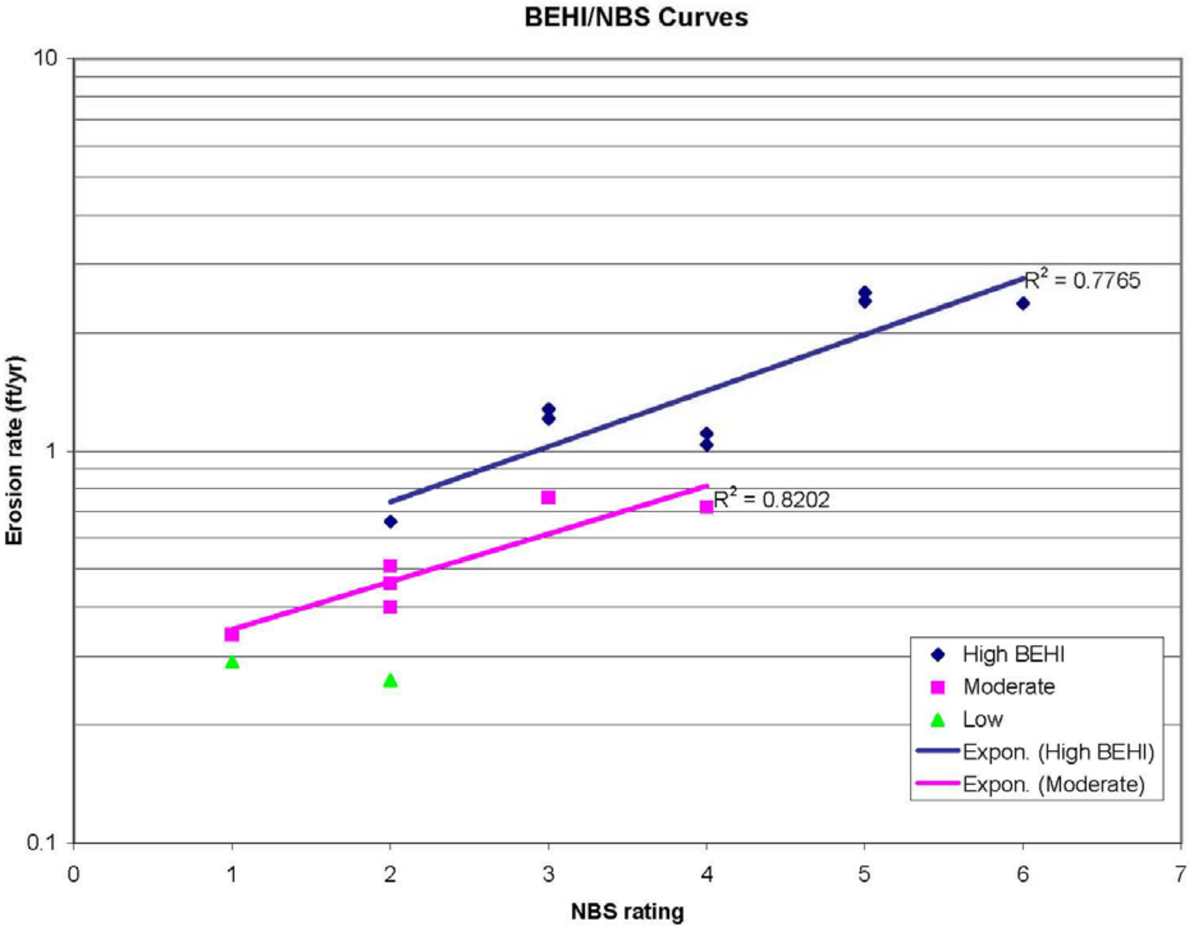
Table 16 New adjusted BEHI scores with modifications to BEHI model.

Bank Location	SBH: BkfH	WV	BA	SP	BMA	SA	Overall Score	New Rating	Old Rating
Main Stem 1p	8.5	2.5	3	2	0	0	16	Low	Moderate
Main Stem 1s	8.5	8.5	4	6.5	0	0	27.5	Moderate	High
Main Stem 2p	8	2.5	2.5	10	0	0	23	Moderate	High
Main Stem 2s	8	8.5	3	10	0	5	34.5	High	V. High
Main Stem 3p	10	2.5	3	5	0	5	25.5	Moderate	High
Main Stem 3s	10	2.5	3	5	0	5	25.5	Moderate	High
North Fork 1p	10	8.5	3	10	0	0	31.5	High	High
North Fork 1s	8.5	2.5	4	10	0	0	25	Moderate	High
North Fork 2p	9	8.5	4	10	0	0	31.5	High	High
North Fork 2s	8.5	8.5	3.5	10	0	0	30.5	High	Moderate
North Fork 3p	8.5	8.5	3.5	10	0	0	30.5	High	Moderate
North Fork 3s	8	8.5	3.5	10	0	0	30	High	Moderate
Irish Creek 1p	10	2.5	3.5	10	0	5	31	High	Very High
Irish Creek 1s	10	2.5	1	1	0	0	14.5	Low	Moderate
Irish Creek 2p	10	2.5	2.5	2	0	0	17	Low	Moderate
Irish Creek 2s	10	8.5	4.5	10	0	0	33	High	V. High
Irish Creek 3p	10	2.5	3.5	10	0	0	26	Moderate	High
Irish Creek 3s	9	2.5	3.5	10	0	0	25	Moderate	High

Note: Symbols used are as follows; SBH:BkfH is Study Bank Height ratio, WV is woody vegetation present, BA is bank angle, SP is surface protection, BMA is bank material adjustment, SA is stratification adjustment. A "p" denotes pool cross-section study bank while "s" denotes representative study bank.

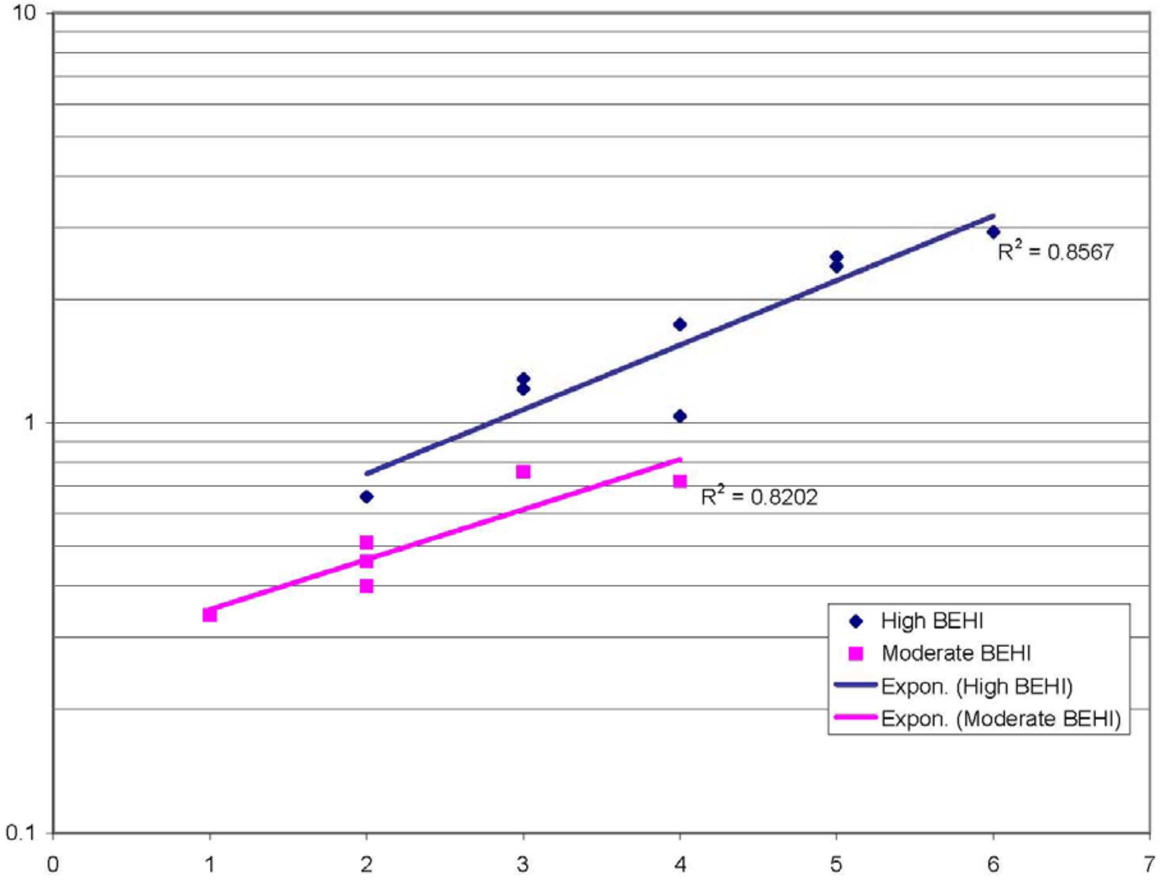
The new BEHI ratings were combined with NBS ratings and mean erosion rates to develop a new, modified BEHI/NBS curve for Northeast Kansas conditions. Figure 5.10 illustrates these new curves. High, Moderate, and Low BEHI scores were graphed separately and a best fit line was drawn. Only two banks attained a Low BEHI rating, thus no best fit line was used nor R^2 value calculated. Figure 5.11 includes higher average erosion rates with bank erosion assumptions mentioned in Chapter 4, Lost Bank Data. Including the higher average erosion rates increased the R^2 value suggesting that these higher average bank erosion assumptions may be correct.

Figure 5.10 New adjusted BEHI/NBS curves for Northeast Kansas. Vegetation modification of 2.5 or 8.5 is included in this edition of curve.



Note: High BEHI slope : $y=0.3838e^{0.3283x}$; Moderate BEHI slope : $y=0.2646e^{0.2806x}$

Figure 5.11 New adjusted BEHI/NBS curves with higher averages included for Northeast Kansas. Vegetation modification of 2.5 or 8.5 is included in this edition of curve.



Note: High BEHI slope : $y=0.3634e^{0.3624x}$; Moderate BEHI slope : $y=0.2646e^{0.2806x}$. Including higher erosion rates increased R^2 value of High BEHI, indicating the assumptions of higher erosion rates may be truer to real erosion rates.

Confounding Controlling Factors

As suggested previously, there may be more than one factor controlling streambank erosion rates in a given region. This study demonstrated that vegetation plays a vital role in influencing erosion rates in Northeast Kansas. However, soil materials may also play a vital role, as these soils are high in clay content that may act as bedrock when wetted. In addition, groundwater flow through buried channels and old landforms may move water and increase seepage erosion, accounting for sporadic erosion patterns. The sporadic failure of banks, as evidenced by complete loss of 1/3rd of study banks over a four-year period, may suggest such a role of old, buried channels. Knowing most reaches in the watershed were channelized both privately and through government installation affords insight into old buried channels that might move water underground to the streams at a faster rate than interstitial movement alone. These old buried streams once conveyed water, and probably still do.

Remnant channels were cut-off and bypassed sometime between 1950 through 2000, as channelization continued through those years (US-COE, 1998; Meade, 2009). Once bypassed, the remnant channel was often filled and farmed. Typically when a stream is channelized, the new channel is cut through the middle of the meanders in a straight line. The remnant channel bed that has been bypassed now enters the new channelized channel at various points along the new channel. The remnant channel typically enters from a higher elevation as the new streambed has degraded and is now established at a lower elevation. However, the old channels are buried with spoil from the channelization work and entrance points to the new channel are sometimes evident (Figure 5.12). Much more work is needed to determine dominant controlling factors in Northeast Kansas and other similar regions throughout the nation.

Figure 5.12 Example of old channel that was filled in and returns to channelized stream, Irish Creek study reach 2 (Keane, 2010).

Additional Questions & Studies

This study, as with most studies, produced more questions than it solved or answered. Additional studies regarding the Black Vermillion watershed and erosion should be conducted. Northeast Kansas streams rely heavily upon woody riparian vegetation roots to naturally combat bank erosion, studies need to address this issue in this area and climate. Some large idea study questions include, "Are unstable streams that are being 'restored' through laying back of bank material and vegetating banks really stable or do they experience the same, or similar, episodic and catastrophic erosion we see in the Black Vermillion until natural stability is regained at a new base level?" "Should we try and 'fix' streams knowing they are unstable and knowing the input variables (Lanes' Proportionality) may change quickly and drastically?"

In addition to the above questions, when vegetation is present, we know it plays a role in bank stability. "How much of a role does precipitation and saturation play when vegetation is present? ...not present?"

"How can the BANCS model be modified to account for vegetation influence in agricultural streams in the Midwest? Are there points that can be given or subtracted using the BEHI portion of BANCS to account for the difference woody vegetation makes?" There may be more than one BEHI variable needing modification in this region, such as bank materials or subsurface topography, both of which need further study.

Future Studies

Studies regarding the Black Vermillion and other watersheds in the Midwest are crucial in understanding sediment, bank erosion, and how they affect both aquatic and terrestrial biota. Studies such as this would help create predictive streambank erosion curves for this area, however, many data points would be needed to get an accurate average of bank erosion. Studies might include:

- Bank erosion studies in the same physiographic region to provide more data points to this study.
- Bank erosion studies in other Midwest physiographic regions to develop predictive erosion curves for comparison and usage.
- Continue to experiment with BEHI attributes and scoring to account for vegetation’s influence on bank stability.

- Collect velocity profiles to calibrate shear stresses acting against outer banks, or banks that are being eroded.
- Long term studies to monitor Black Vermillion stream reaches to ascertain how they fit current channel succession or evolutionary models.
- Using the long term study above, stratify streams and reaches of streams regarding vegetation influence. Compare with the three commonly used models of stream channel evolution and develop meander studies to account for the stream pattern.
- Test WARSSS (Rosgen, 2006) model in the Black Vermillion watershed to find and validate erosion problem areas.
- Develop a scheme to test both soil properties and vegetation versus erosion rates.

Summary

As noted, the original curves developed in this study displayed more variation than Yellowstone, Colorado, Piedmont, or Arkansas curves. Nevertheless, development of these cures are vital as erosion and subsequent sedimentation are ruining our freshwater supplies. Runoff delivery and timing differences between Northeast Kansas and the mountainous regions of Yellowstone, Colorado, and the Piedmont region of North Carolina lead to discharge differences creating episodic and sporadic erosion in our system. In addition, soil material differences and woody vegetation controls may play a larger role in Northeast Kansas than these other regions.

Vegetation seems to play a vital role in maintaining bank stability in this region of Northeast Kansas. Assessing the original BEHI/NBS curves for Northeast Kansas illustrated something was not being accounted for in the model. Low R^2 values along with inverted expected erosion rates confirmed this notion. Erosion rates then plotted against both BEHI score and NBS rating with each site's woody vegetation cover showed a clustering of sites with woody vegetation versus sites without. Thus, the vegetation portion of the BEHI was modified and simplified, which resulted in better fitting curves with higher R^2 values and correct order of the BEHI curve. Masterman and Thorne (1992) stated streams with a W:D ratio less than 16 were subject to vegetation controls more so than streams with a higher ratio. All study stream reaches in the Black Vermillion have a W:D ratio less than 13.5. These streams are currently in a transitional state in their stream evolutionary sequence, moving from degradation of the stream bed to aggradation and widening through bank erosion processes.

Sporadic rains and episodes of saturation that are naturally driven during climate change present a problem unto itself, such as changing bankfull stage discharge, or the 1.5-year recurrence interval. If the climate begins to increase storm duration and storm precipitation over time, then more runoff will be delivered to the stream, making the stream adjust its dimensions to carry the new 1.5-year recurrence interval. If we experienced bankfull flows on a regular basis, such as in a snowmelt dominated stream system, we may be able to predict for this system using the BEHI/NBS BANCS model. However, it is necessary to accumulate more data in storm-generated, flashy systems that have been highly modified, such as the Black Vermillion watershed. Data from stable systems must also be collected in storm-generated hydrographs to compare with unstable systems in similar regions. It is possible that in this region (system), in the current climate and with exhibited variability of failure, we may never develop accurate predictive erosion curves using the BEHI/NBS, BANCS model as described by Rosgen (2001, 2006).

It is evident more studies need to be completed to determine dominant processes of streambank erosion and associated controlling variables dictating bank shear strength in given hydrophysiographic regions. Once these studies begin to untangle the different processes and controlling variables for given regions, we can modify or abandon the current BANCS model for better predictability of bank erosion in those regions. If abandonment of the BANCS model is needed, then a new model can be developed utilizing these new studies illustrating the dominant processes and controlling variables. Nevertheless, our predictive capacity regarding erosion of streambank material is furthered from this study and has set precedent for modifying the BEHI portion of the BANCS model, which is utilized by many state and federal agencies.

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Appendix A - Maps

Figure A.1 Land Use map of Black Vermillion Watershed (Jeff Neel, 2007).

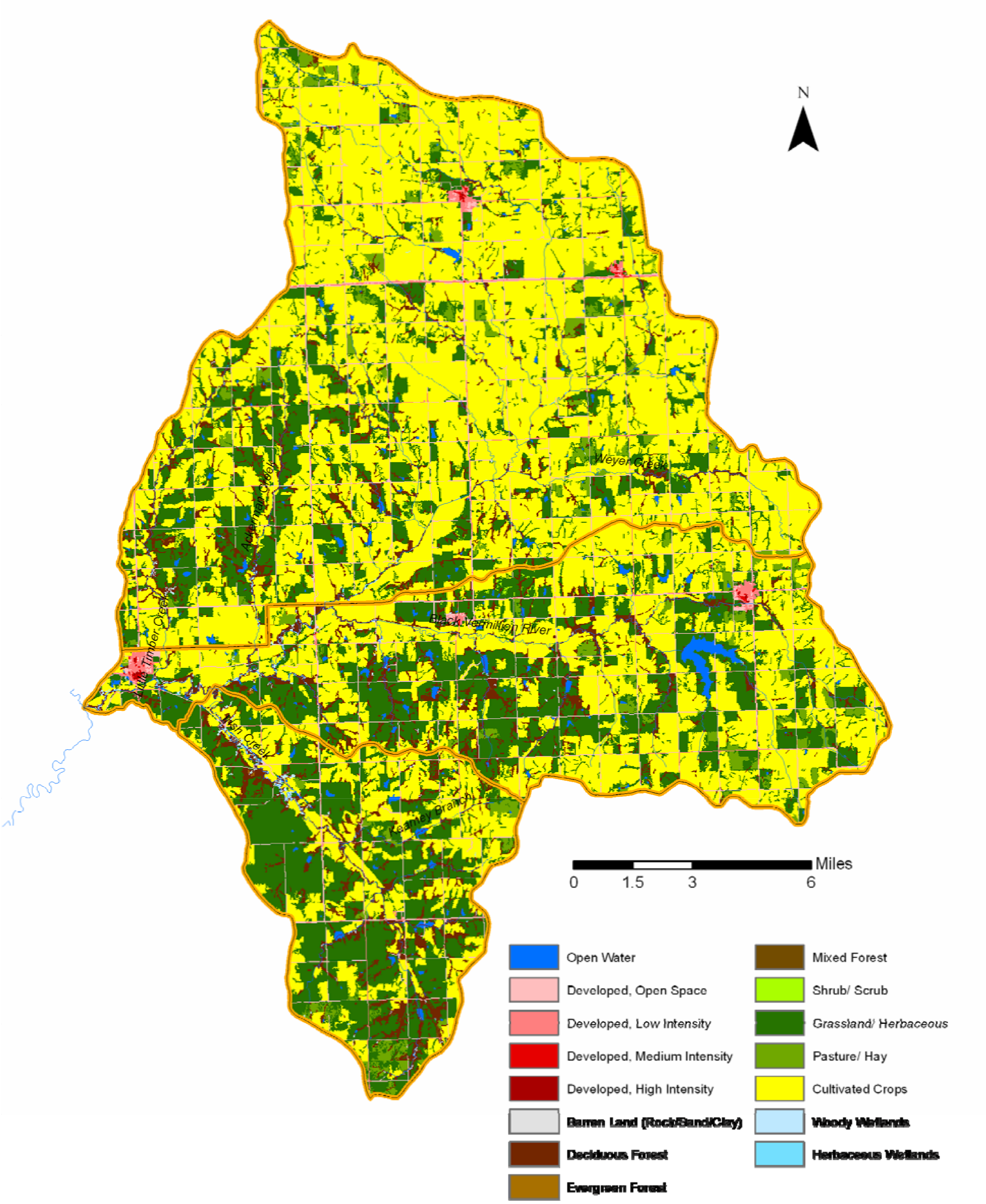
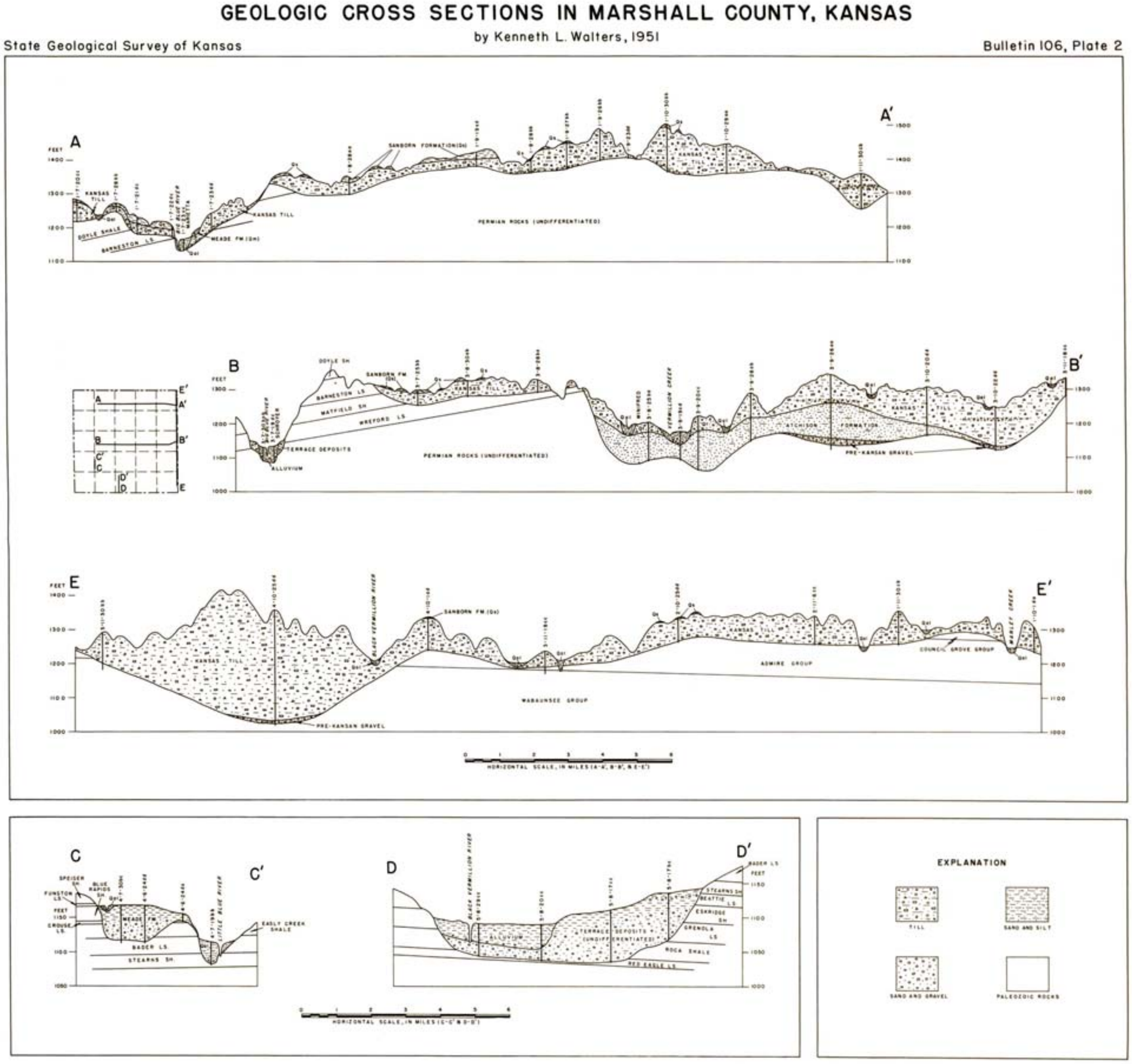


Figure A.2 Enlarged Cross section of Marshall County, KS (Walters, 1951).



Appendix B - Dimensionless Flow Duration Curves

Figure B.1 Dimensionless flow duration curve, Irish Creek 2007.

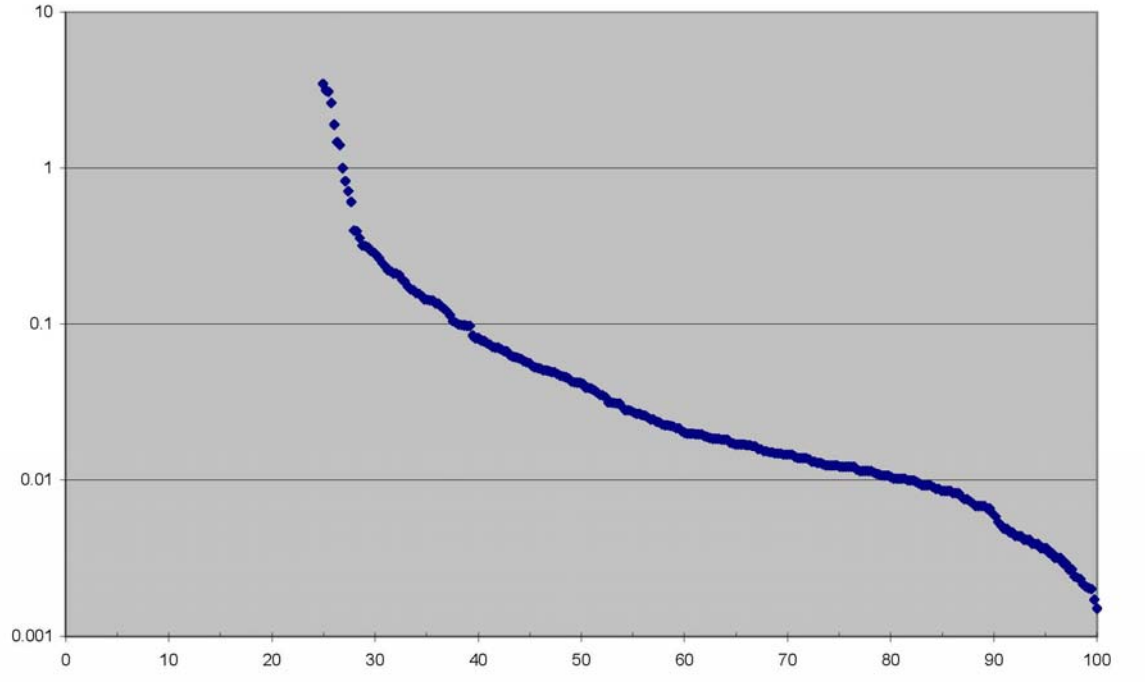


Figure B.2 Dimensionless flow duration curve, Irish Creek 2008.

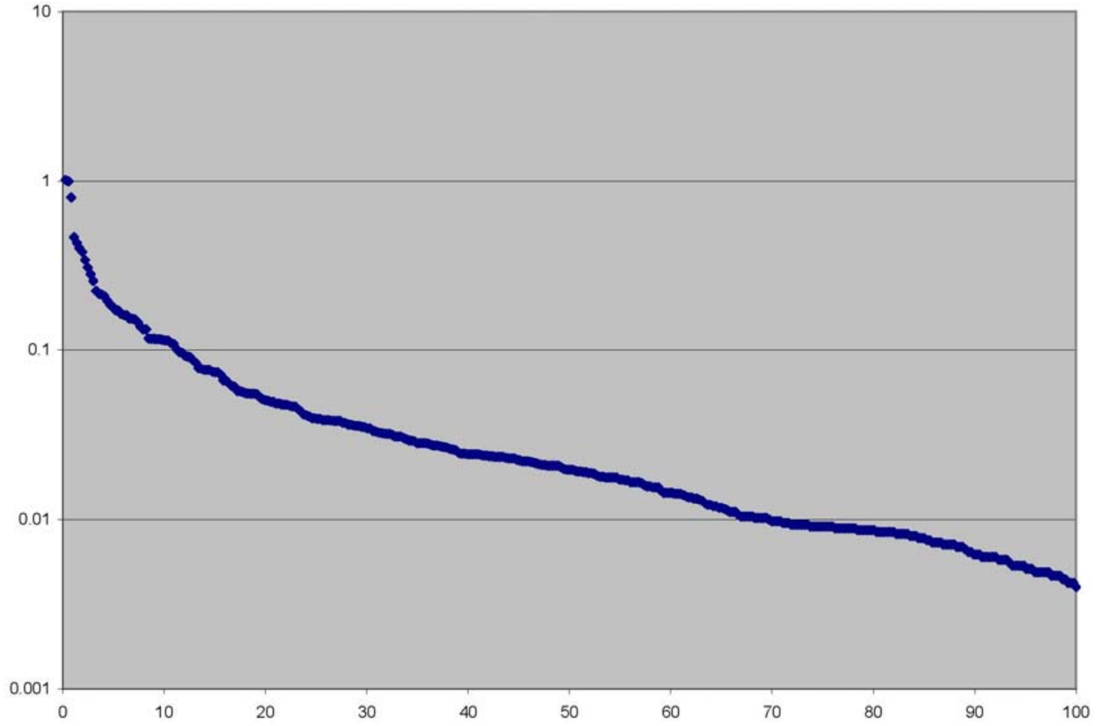


Figure B.3 Dimensionless flow duration curve, Irish Creek 2009.

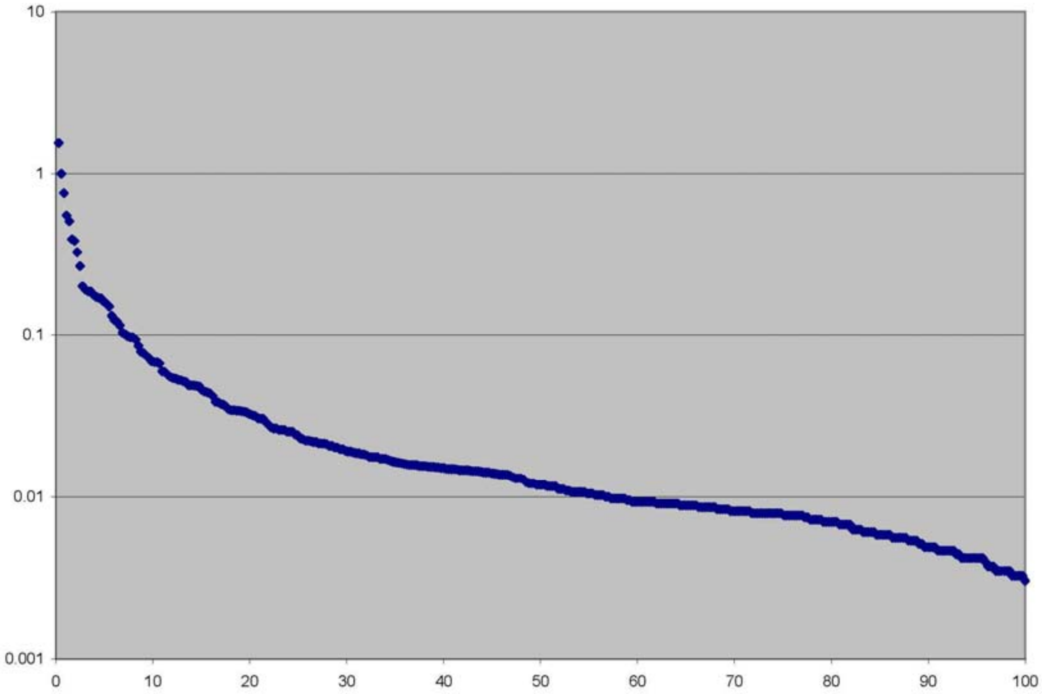


Figure B.4 Dimensionless flow duration curve, Main Stem 2007.

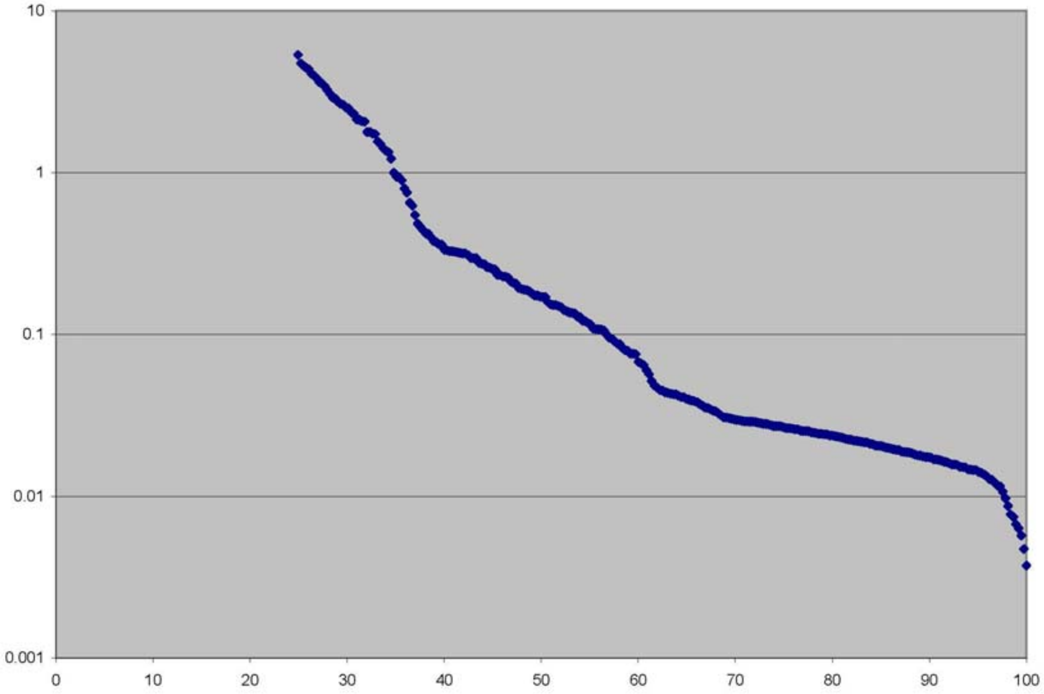


Figure B.5 Dimensionless flow duration curve, Main Stem 2008.

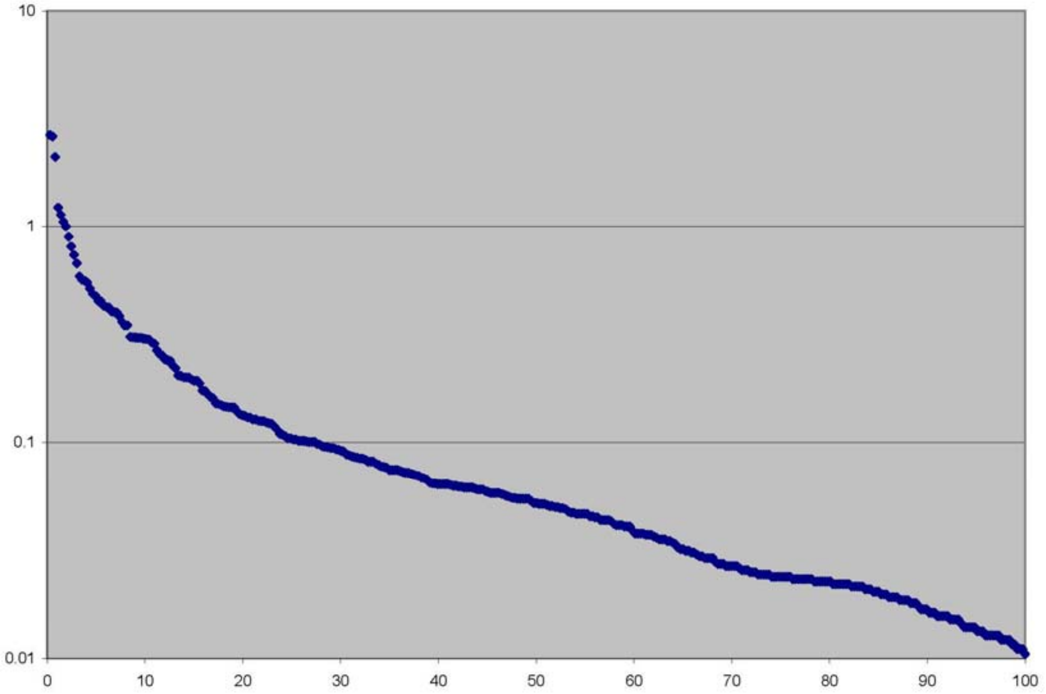


Figure B.6 Dimensionless flow duration curve, Main Stem 2009.

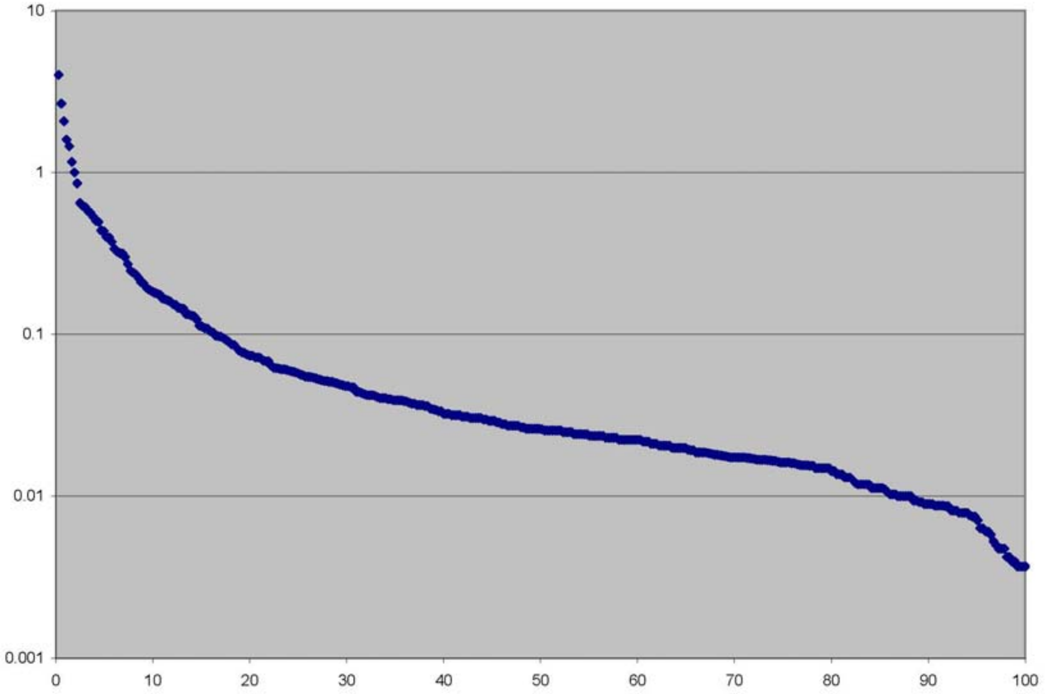


Figure B.7 Dimensionless flow duration curve, North Fork 2007.

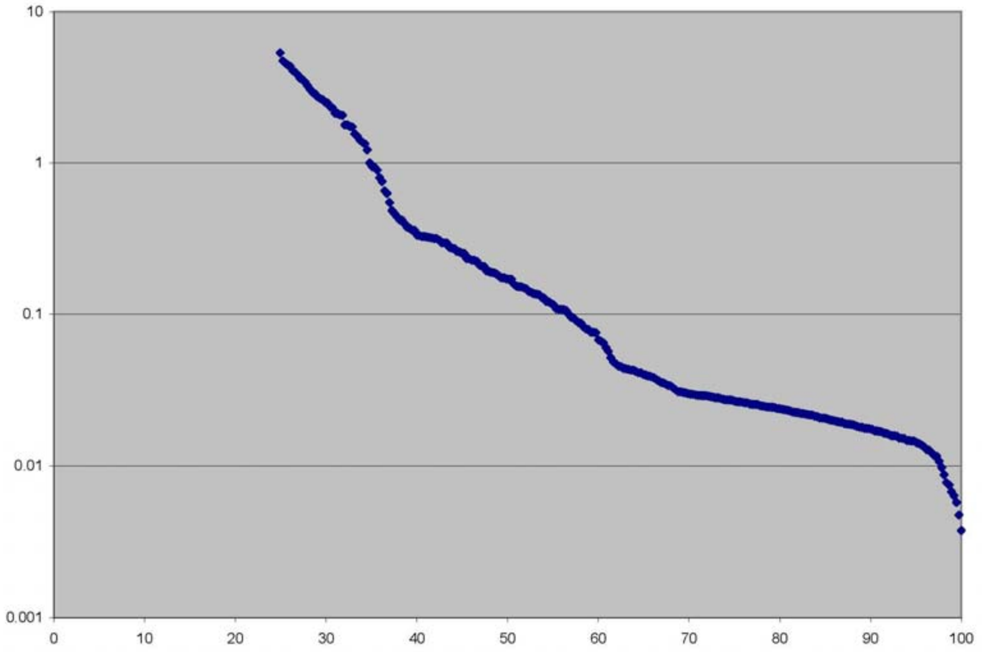


Figure B.8 Dimensionless flow duration curve, North Fork 2008.

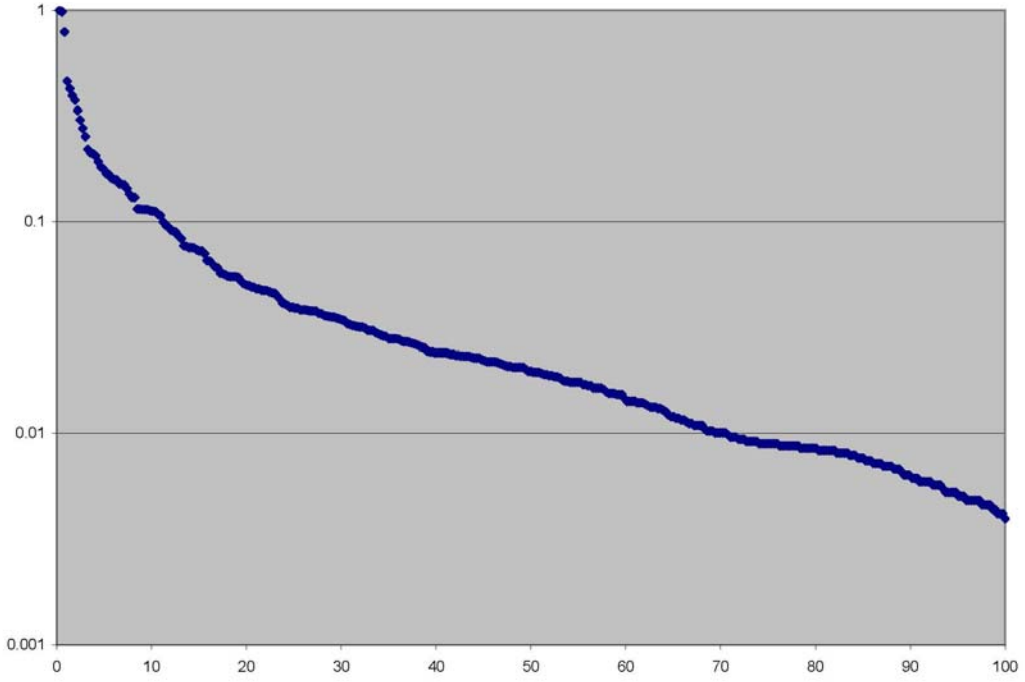
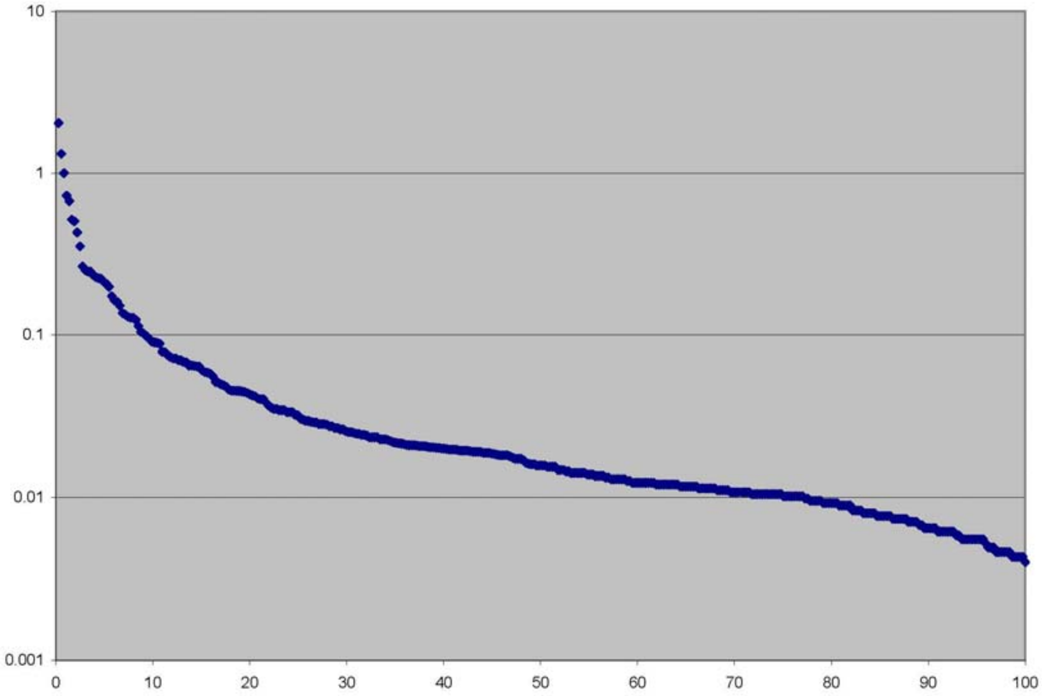


Figure B.9 Dimensionless flow duration curve, North Fork 2009.



Appendix C - BEHI / NBS Sheets

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Black Vermillion Main Stem Location: Reach 1

Station: 9+38 Pool X-sect Observers:

Date: Stream Type: Valley Type:

					BEHI Score (Fig. 5-19)
Study Bank Height / Bankfull Height (C)					
Study Bank Height (ft) =	13 (A)	**Bankfull Height** (ft) =	5 (B)	(A) / (B) = 2.6 (C)	8.8
Root Depth / Study Bank Height (E)					
Root Depth (ft) =	13 (D)	**Study Bank Height** (ft) =	13 (A)	(D) / (A) = 1 (E)	1
Weighted Root Density (G)					
		Root Density as % =	10 (F)	(F) x (E) = 10 (G)	8.5
Bank Angle (H)					
			Bank Angle as *Degrees* =	60 (H)	3.9
Surface Protection (I)					
			Surface Protection as % =	80 (I)	1.9

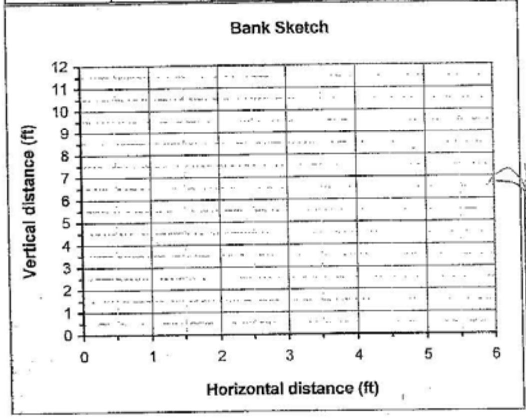
Bank Material Adjustment:
- **Bedrock** (Overall Very Low BEHI)
- **Boulders** (Overall Low BEHI)
- **Cobble** (Subtract 10 points if uniform medium to large cobble)
- **Gravel or Composite Matrix** (Add 5–10 points depending on percentage of bank material that is composed of sand)
- **Sand** (Add 10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

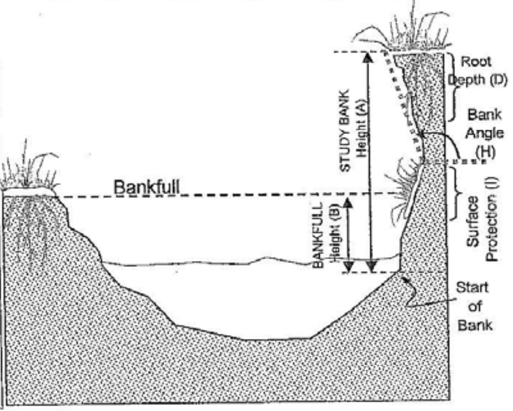
Bank Material Adjustment —

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

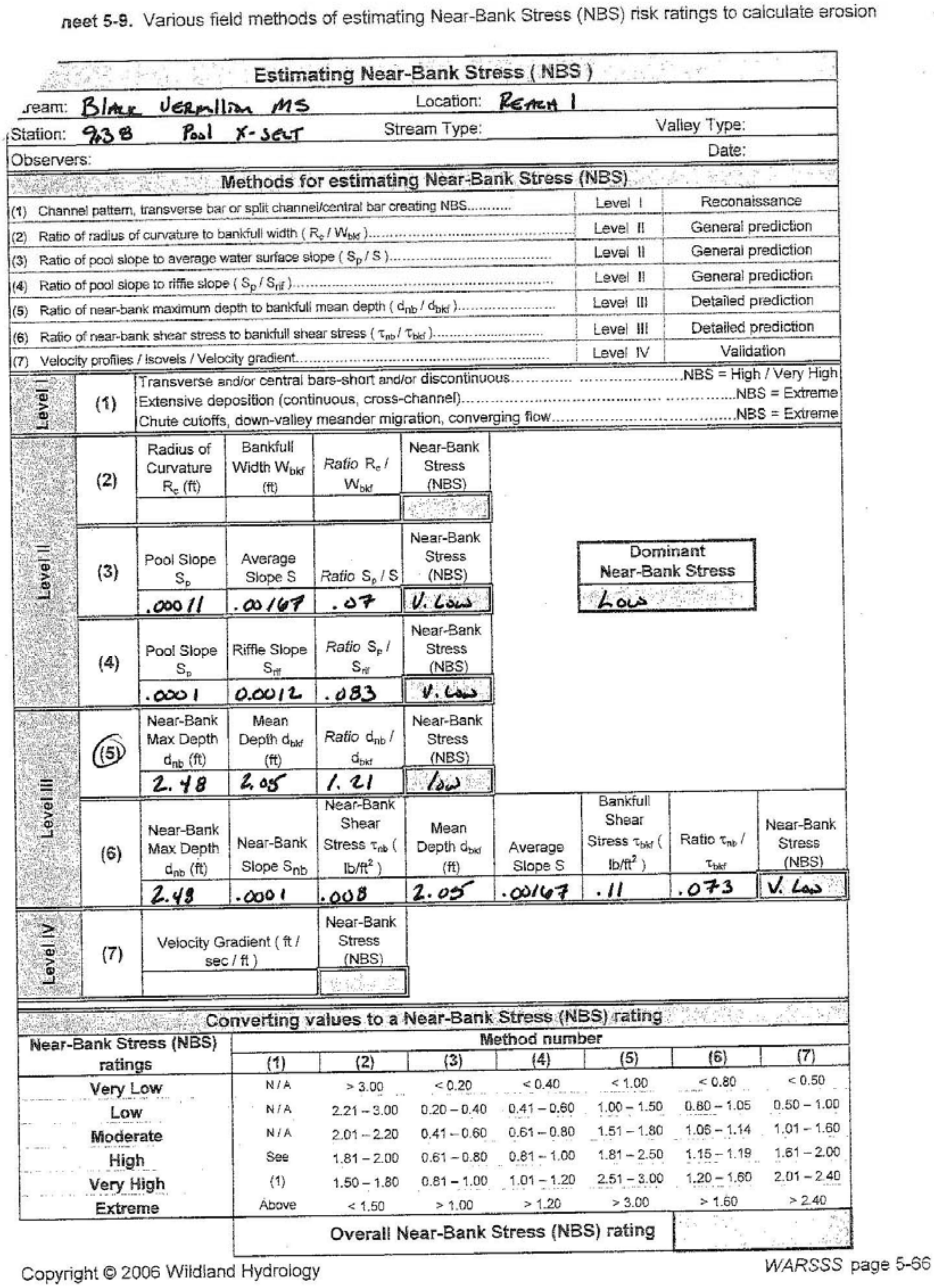
Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score Mod 24.1





WARSSS page 5-56



neet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion

Estimating Near-Bank Stress (NBS)

ream: Black Vermilion MS Location: Reach 1
Station: 9+38 Pool X-Sect Stream Type: Valley Type:
Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I (1)
Transverse and/or central bars-short and/or discontinuous........NBS = High / Very High
Extensive deposition (continuous, cross-channel)........NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow........NBS = Extreme

Level II

(2)	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
	.00011	.00167	.07	V. Low

(4)	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
	.0001	0.0012	.083	V. Low

Dominant Near-Bank Stress
Low

Level III

(5)	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
	2.48	2.05	1.21	low

(6)	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
	2.48	.0001	.008	2.05	.00167	.11	.073	V. Low

Level IV

(7)	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

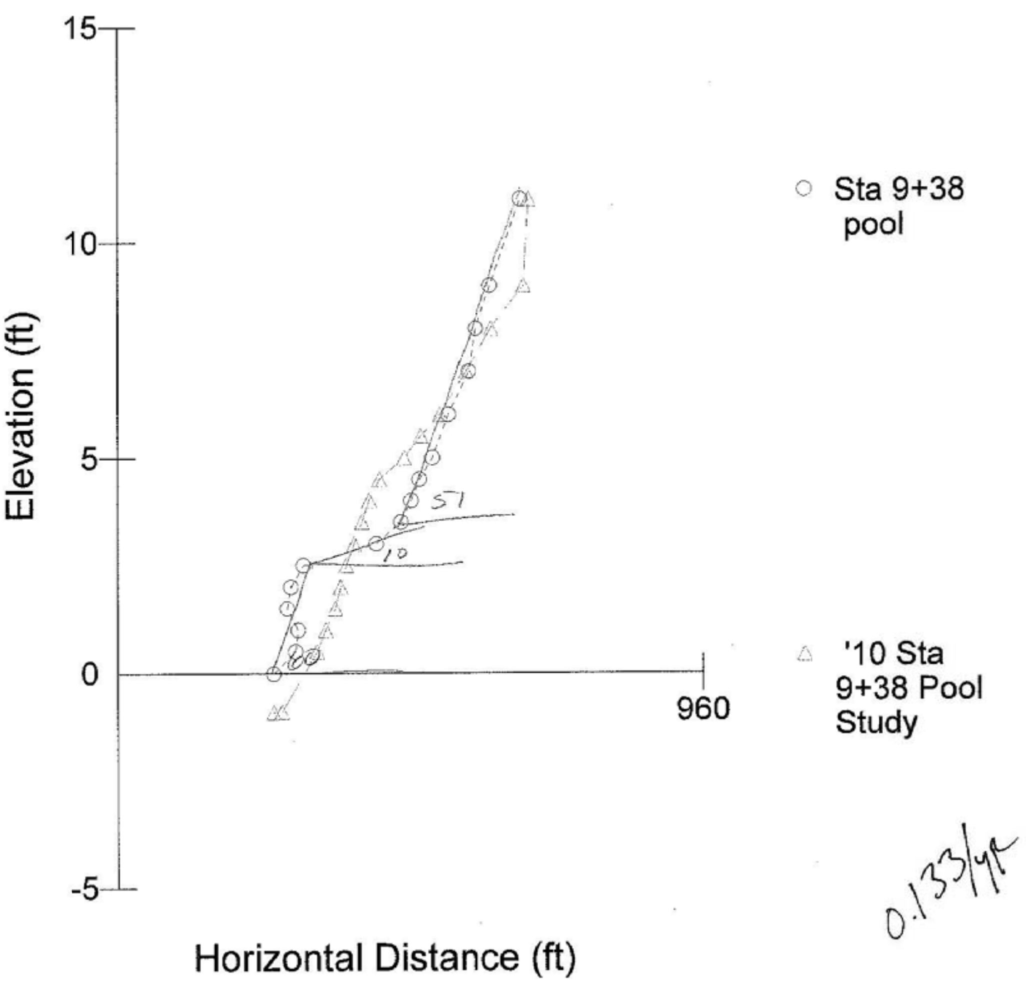
Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

WARSSS page 5-66

BU1 pool


15
10
5
0
-5
Elevation (ft)
960
Horizontal Distance (ft)
57
10
○ Sta 9+38 pool
△ '10 Sta 9+38 Pool Study
0.133/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Black Vermillion MS Location: REACH 1

Station: 5+82 Study bank Observers:

Date: Stream Type: Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	13 **(A)**	**Bankfull Height** (ft) =	5 **(B)**	(A) / (B) =	2.6 **(C)**	8.8

Root Depth / Study Bank Height (E)

Root Depth (ft) =	1.5 **(D)**	**Study Bank Height** (ft) =	13 **(A)**	(D) / (A) =	.11 **(E)**	8.5

Weighted Root Density (G)

Root Density as **%** =	10 **(F)**	(F) x (E) =	1.1 **(G)**	10

Bank Angle (H)

Bank Angle as *Degrees* =	70 **(H)**	5

Surface Protection (I)

Surface Protection as **%** =	25 **(I)**	7

Bank Material Adjustment:

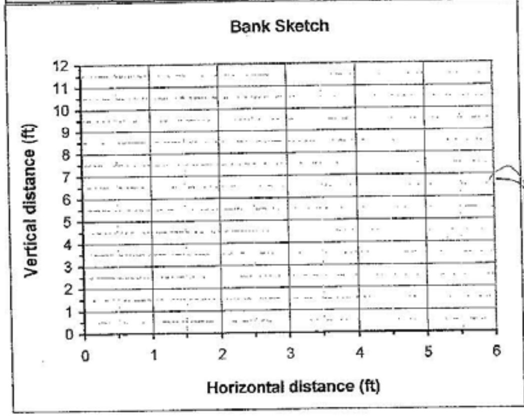
- **Bedrock** (Overall Very Low BEHI)
- **Boulders** (Overall Low BEHI)
- **Cobble** (Subtract 10 points if uniform medium to large cobble)
- **Gravel or Composite Matrix** (Add 5–10 points depending on percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt/Clay** (no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

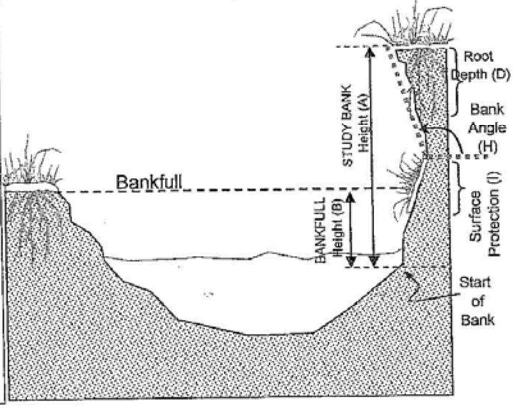
Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score High 39.3





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WARSSS page 5-56

Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Blak Vermllion MS Location: Reach 1

Station: 5+82 Study bank Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........................	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........................	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........................	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........................	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........................	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........................	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous........................NBS = High / Very High
Extensive deposition (continuous, cross-channel)........................NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow........................NBS = Extreme

Level II

(2)	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
	.0001	.00167	.06	V. Low

(4)	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
	.0001	.0074	.014	V. Low

Dominant Near-Bank Stress
V. Low

Level III

(5)	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

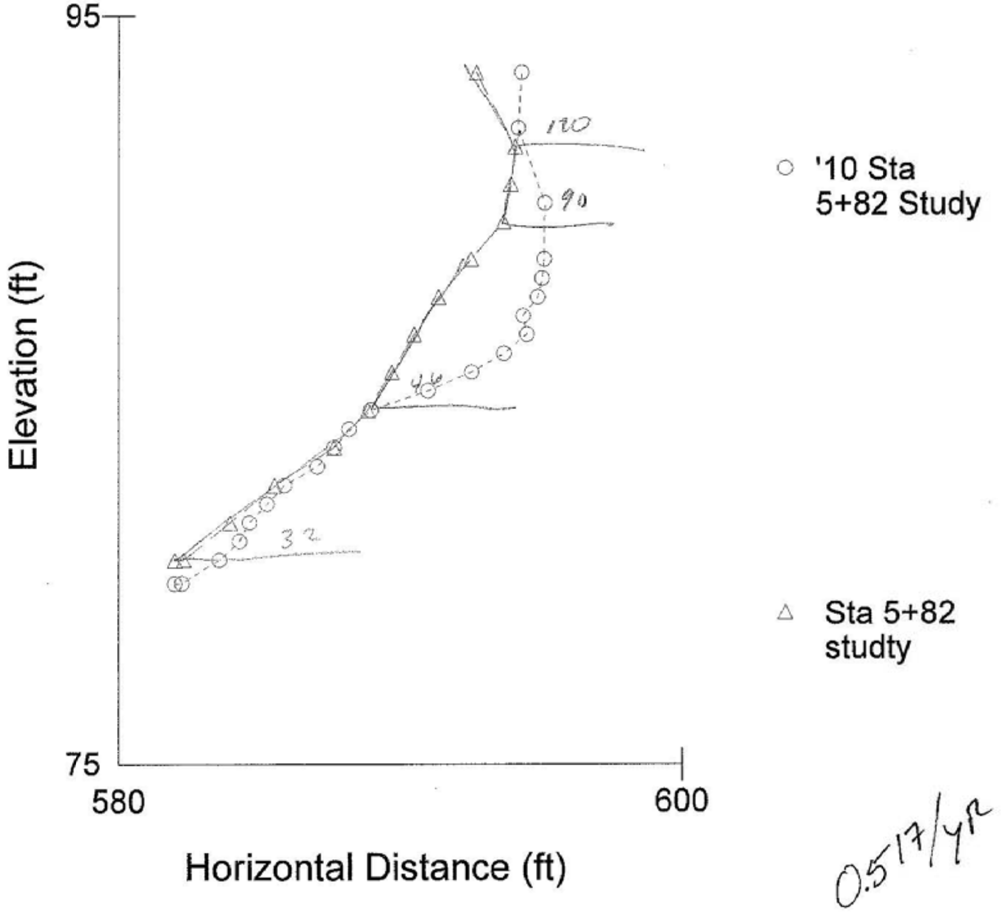
Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

BU1 Study bank

'10 Sta 5+82 Study



0.517/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Black Vermillion MS
Location: REACH 2
Station: 1+90 Pool X-SECT
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	11.5 (A)	Bankfull Height (ft) =	5 (B)	(A)/(B) =	2.3 (C)	8

Root Depth / Study Bank Height (E)

Root Depth (ft) =	11 (D)	Study Bank Height (ft) =	11.5 (A)	(D)/(A) =	.96 (E)	1.9

Weighted Root Density (G)

Root Density as % =	10 (F)	(F)x(E) =	9.6 (G)	8.5

Bank Angle (H)

Bank Angle as *Degrees* =	30 (H)	2.5

Surface Protection (I)

Surface Protection as % =	0 (I)	10

Bank Material Adjustment:

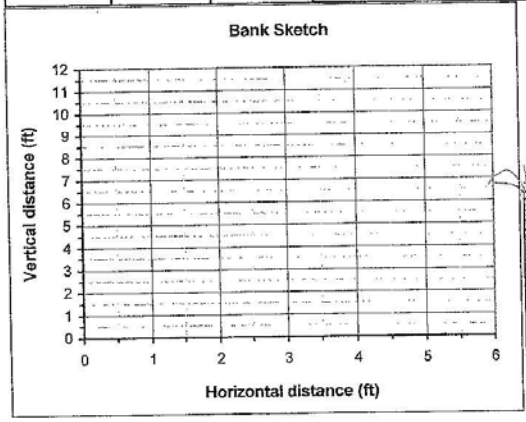
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

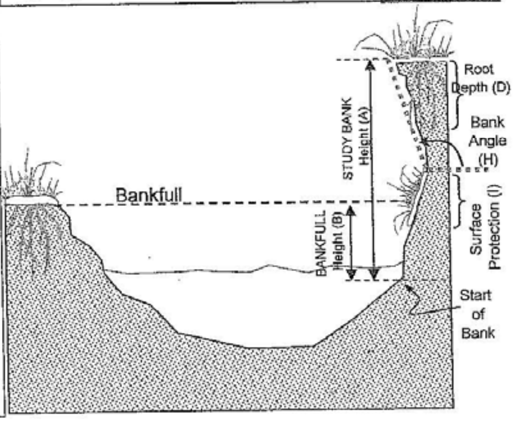
Bank Material Adjustment —

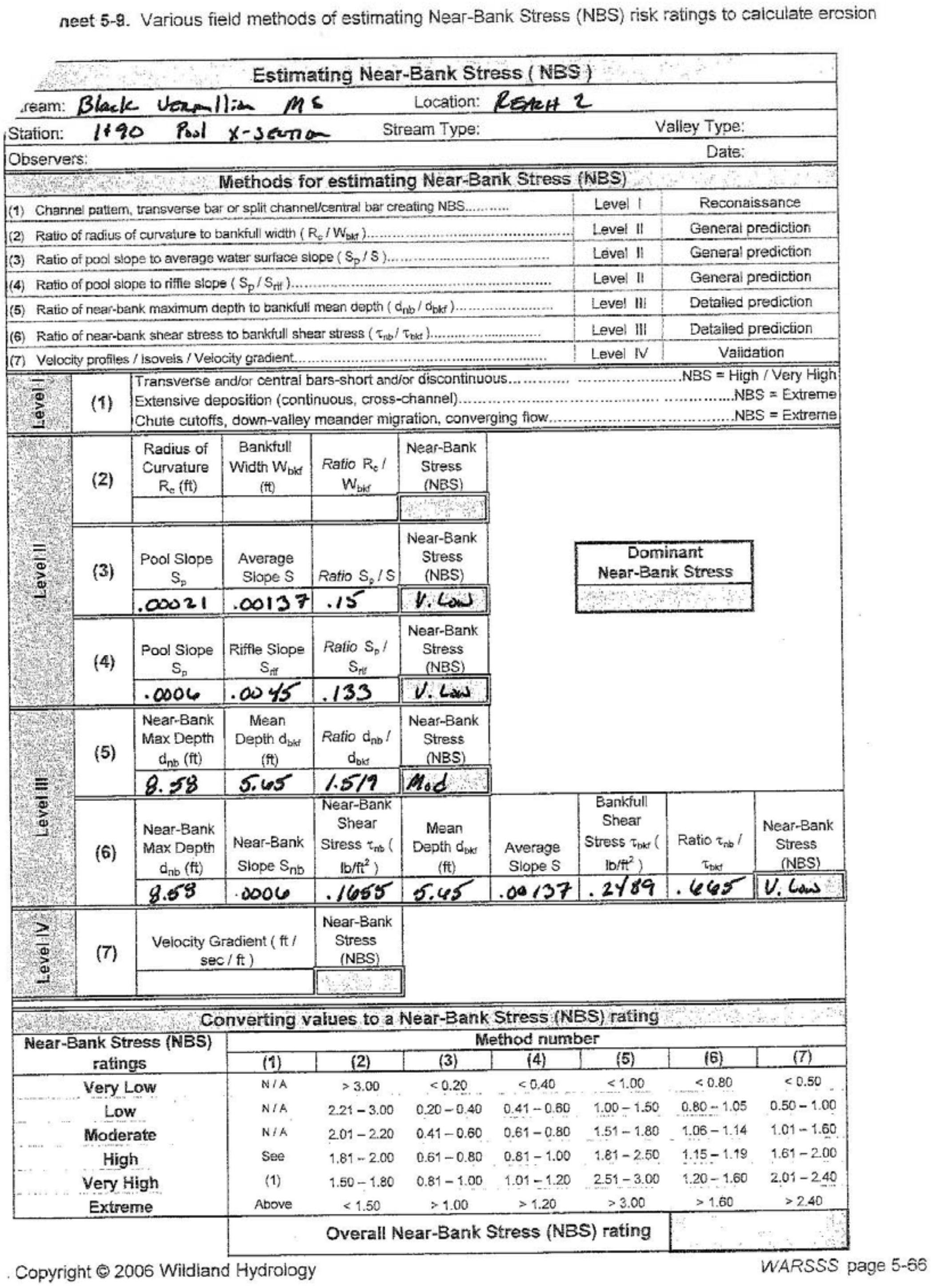
Stratification Adjustment
Add 5–10 points, depending on position of unstable layers in relation to bankfull stage — 5

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score: High 35.9







neet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion

Estimating Near-Bank Stress (NBS)

ream: Black Vermillion MS Location: REACH 2

Station: 1+90 Pool X-Section Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous.......................NBS = High / Very High
Extensive deposition (continuous, cross-channel)..........................NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow..........................NBS = Extreme

Level II

	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	Ratio R_c / W_{bkf}	Near-Bank Stress (NBS)
(2)				

	Pool Slope S_p	Average Slope S	Ratio S_p / S	Near-Bank Stress (NBS)
(3)	.00021	.00137	.15	V. Low

	Pool Slope S_p	Riffle Slope S_{rif}	Ratio S_p / S_{rif}	Near-Bank Stress (NBS)
(4)	.0006	.0045	.133	V. Low

Dominant Near-Bank Stress

Level III

	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	Ratio d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
(5)	8.58	5.65	1.519	Mod

	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
(6)	8.58	.0006	.1655	5.45	.00137	.2489	.665	V. Low

Level IV

	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)
(7)		

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

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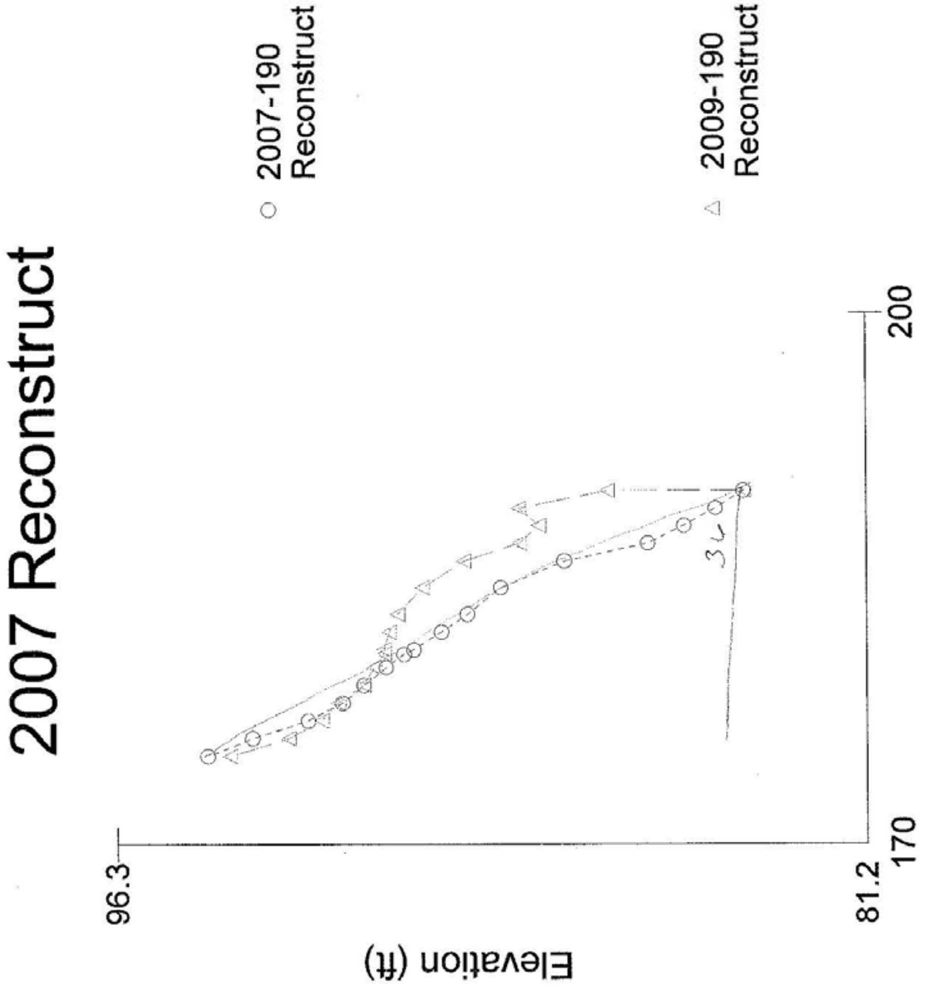
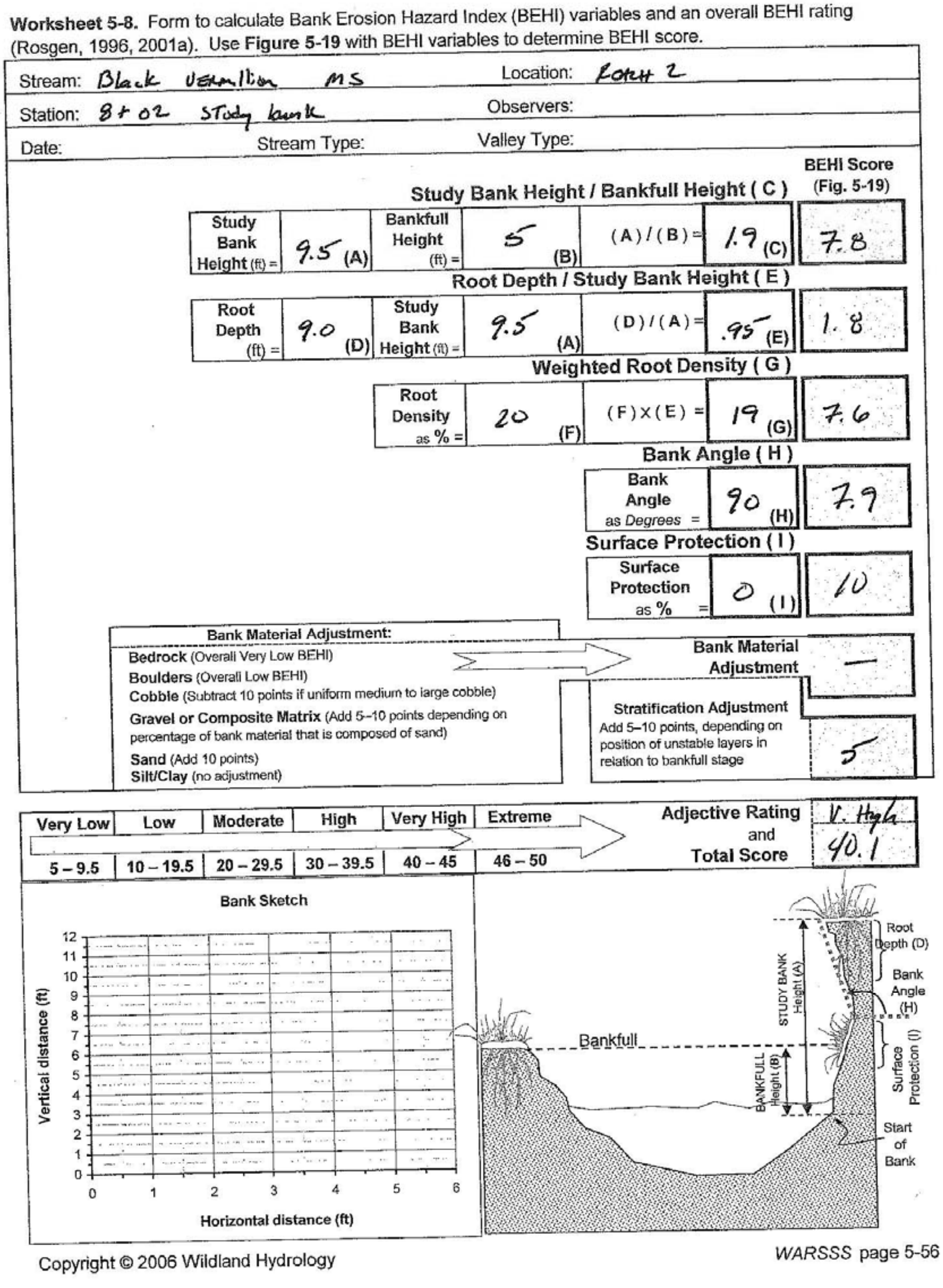
BV2 pool



0.34/yr



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Black Vermilion MS
Location: Reach 2
Station: 8+02 Study bank
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	9.5 **(A)**	**Bankfull Height** (ft) =	5 **(B)**	(A)/(B) =	1.9 **(C)**	7.8

Root Depth / Study Bank Height (E)

Root Depth (ft) =	9.0 **(D)**	**Study Bank Height** (ft) =	9.5 **(A)**	(D)/(A) =	.95 **(E)**	1.8

Weighted Root Density (G)

Root Density as **%** =	20 **(F)**	(F)x(E) =	19 **(G)**	7.6

Bank Angle (H)

Bank Angle as *Degrees* =	90 **(H)**	7.9

Surface Protection (I)

Surface Protection as **%** =	0 **(I)**	10

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score V. High 40.1

Bank Sketch

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Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Black Vermillion MS   Location: Reach 2
Station: 9+02 Study bank   Stream Type: Valley Type:
Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous........ ....NBS = High / Very High
Extensive deposition (continuous, cross-channel)........ ....NBS = Extreme
Chute cutoffs, down-valley meander migration, [✓ converging flow]........NBS = [✓ Extreme]

Gully US ~20'

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
00064	.00137	.47	Mod

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00108	.00199	.543	low

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

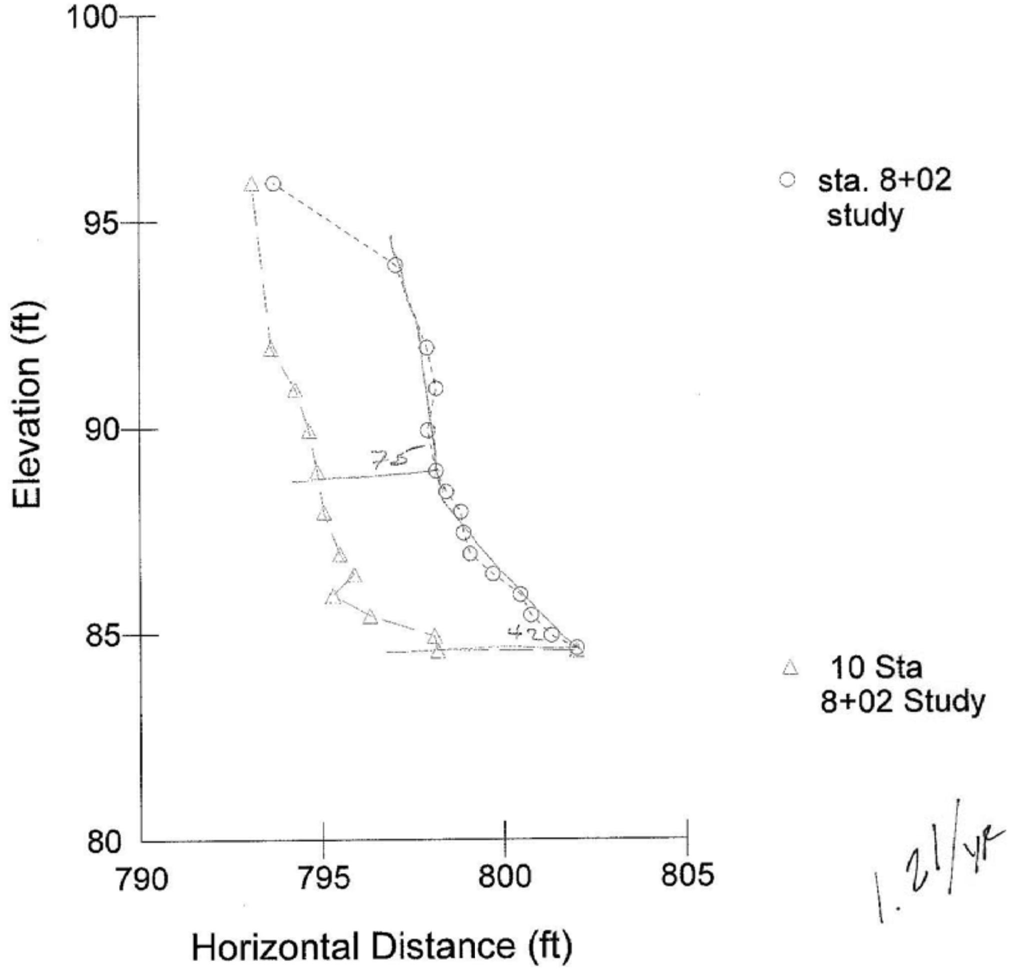
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

BU2 study bank



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Black Vermillion M S	Location: REACH 3

Station: 5+38 Pool X-SECT	Observers:

Date:	Stream Type:	Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	20 (A)	Bankfull Height (ft) =	5.5 (B)	(A) / (B) =	3.6 (C)	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	19 (D)	Study Bank Height (ft) =	20 (A)	(D) / (A) =	.95 (E)	1.3

Weighted Root Density (G)

Root Density as % =	10 (F)	(F) x (E) =	9.5 (G)	8.7

Bank Angle (H)

Bank Angle as *Degrees* =	70 (H)	4.5

Surface Protection (I)

Surface Protection as % =	40 (I)	5.0

Bank Material Adjustment:

Bedrock (Overall Very Low BEHI)

Boulders (Overall Low BEHI)

Cobble (Subtract 10 points if uniform medium to large cobble)

Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)

Sand (Add 10 points)

Silt/Clay (no adjustment)

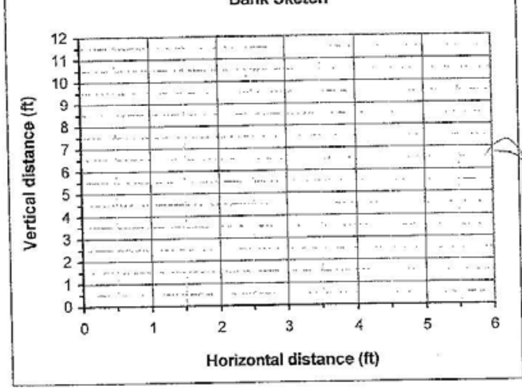
Bank Material Adjustment —

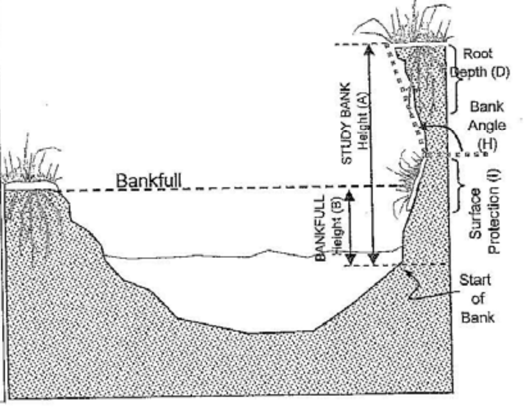
Stratification Adjustment
Add 5–10 points, depending on position of unstable layers in relation to bankfull stage 5

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

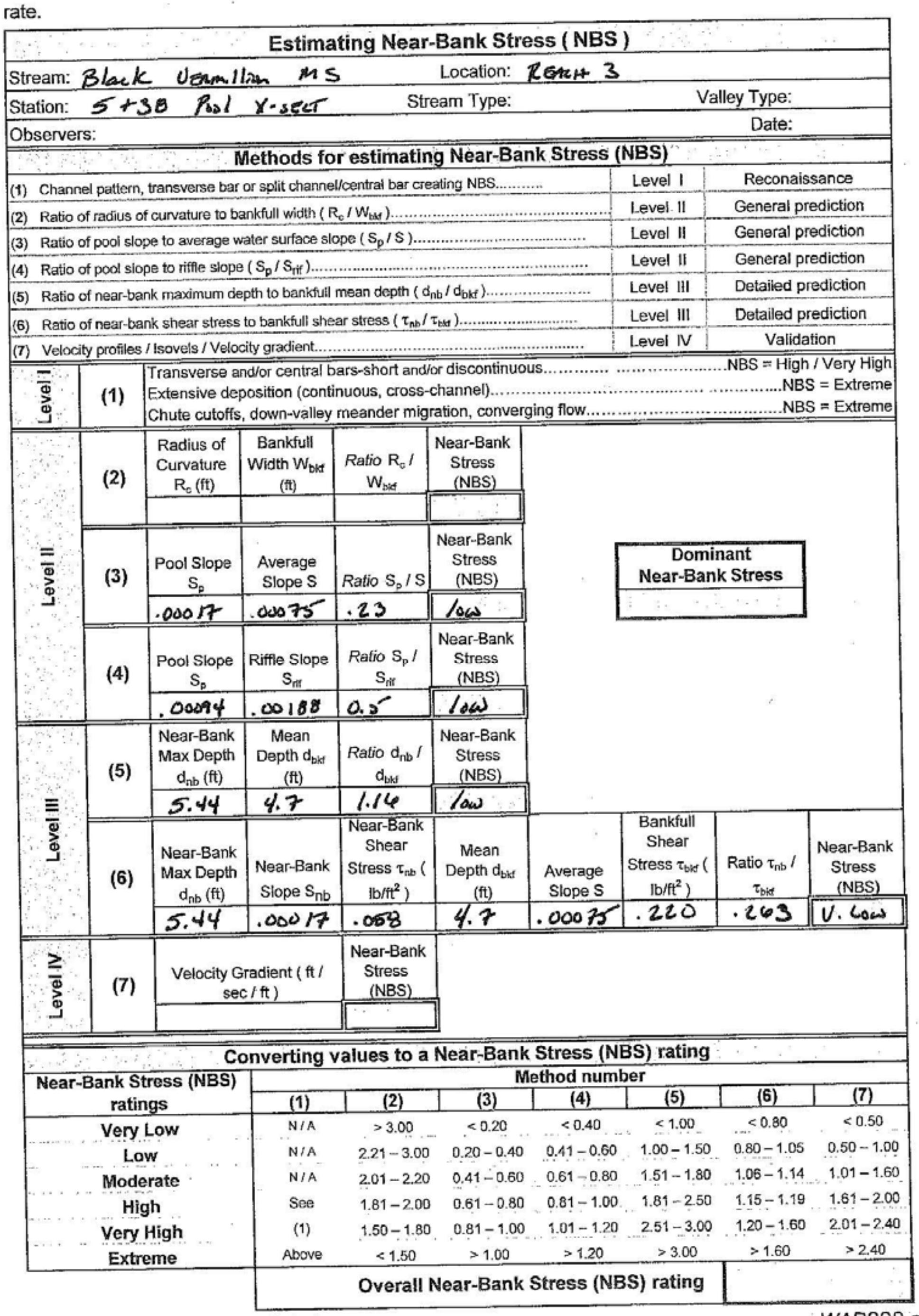
Adjective Rating and Total Score High 34.5

Bank Sketch





Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.



Estimating Near-Bank Stress (NBS)

Stream: Black Vermillion MS Location: Reach 3
Station: 5+38 Pool X-sect Stream Type: Valley Type:
Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I (1)
Transverse and/or central bars-short and/or discontinuous........NBS = High / Very High
Extensive deposition (continuous, cross-channel)........NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow........NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	Ratio R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	Ratio S_p / S	Near-Bank Stress (NBS)
.00017	.00075	.23	low

(4)

Pool Slope S_p	Riffle Slope S_{rif}	Ratio S_p / S_{rif}	Near-Bank Stress (NBS)
.00094	.00188	0.5	low

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	Ratio d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
5.44	4.7	1.16	low

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
5.44	.00017	.058	4.7	.00075	.220	.263	V. Low

Level IV

(7)

Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

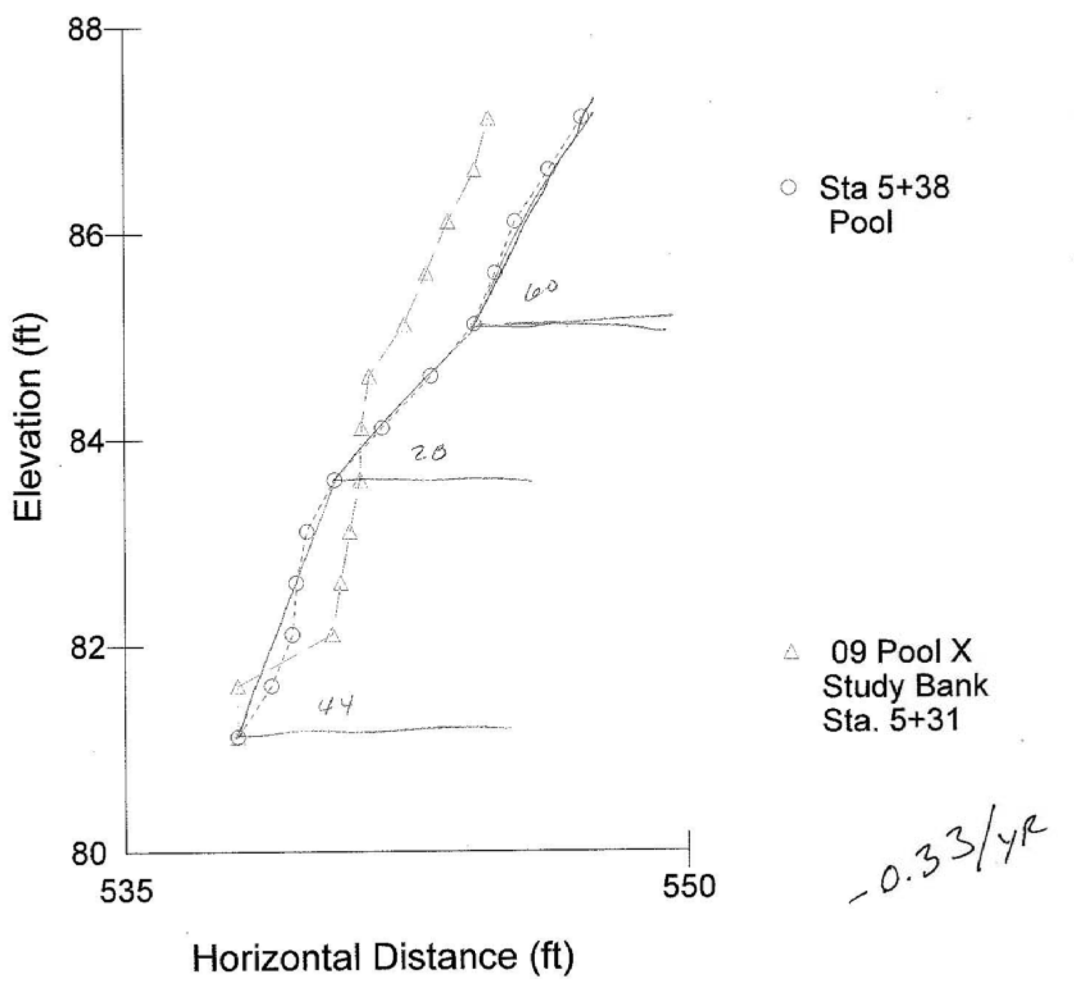
Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

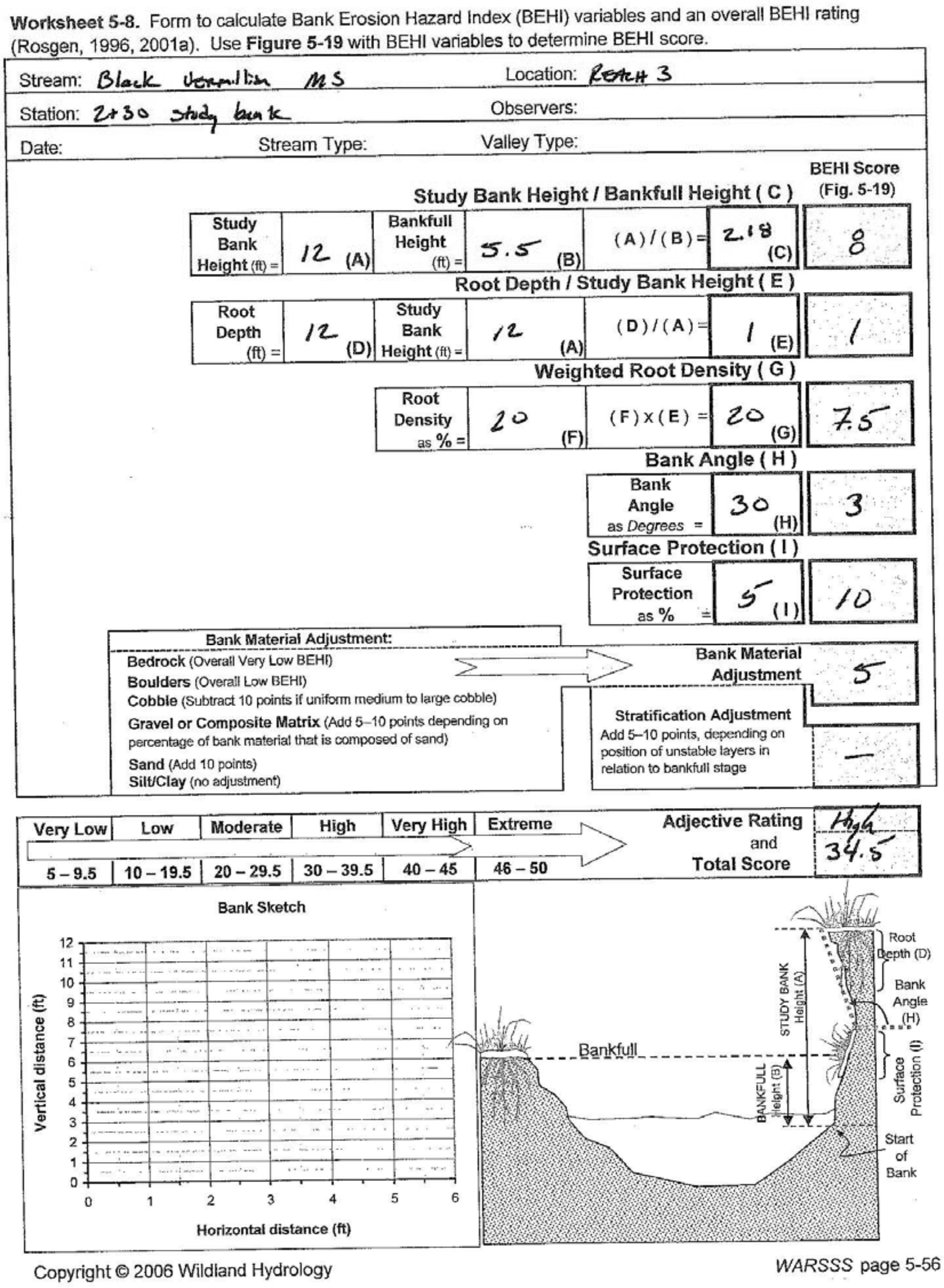
Overall Near-Bank Stress (NBS) rating

WARSSS page 5-66

BU3 pool


88
86
84
82
80
Elevation (ft)
535
550
Horizontal Distance (ft)
○ Sta 5+38 Pool
△ 09 Pool X Study Bank Sta. 5+31
60
28
44
-0.33/YR

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.



Stream: Black Vermilion MS
Location: REACH 3
Station: 2+30 study bank
Observers:
Date:
Stream Type:
Valley Type:

						BEHI Score (Fig. 5-19)
Study Bank Height / Bankfull Height (C)						
Study Bank Height (ft) =	12 (A)	Bankfull Height (ft) =	5.5 (B)	(A) / (B) =	2.18 (C)	8
Root Depth / Study Bank Height (E)						
Root Depth (ft) =	12 (D)	Study Bank Height (ft) =	12 (A)	(D) / (A) =	1 (E)	1
Weighted Root Density (G)						
		Root Density as % =	20 (F)	(F) x (E) =	20 (G)	7.5
Bank Angle (H)						
				Bank Angle as *Degrees* =	30 (H)	3
Surface Protection (I)						
				Surface Protection as % =	5 (I)	10

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

Bank Material Adjustment: 5

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**: High 34.5

Bank Sketch

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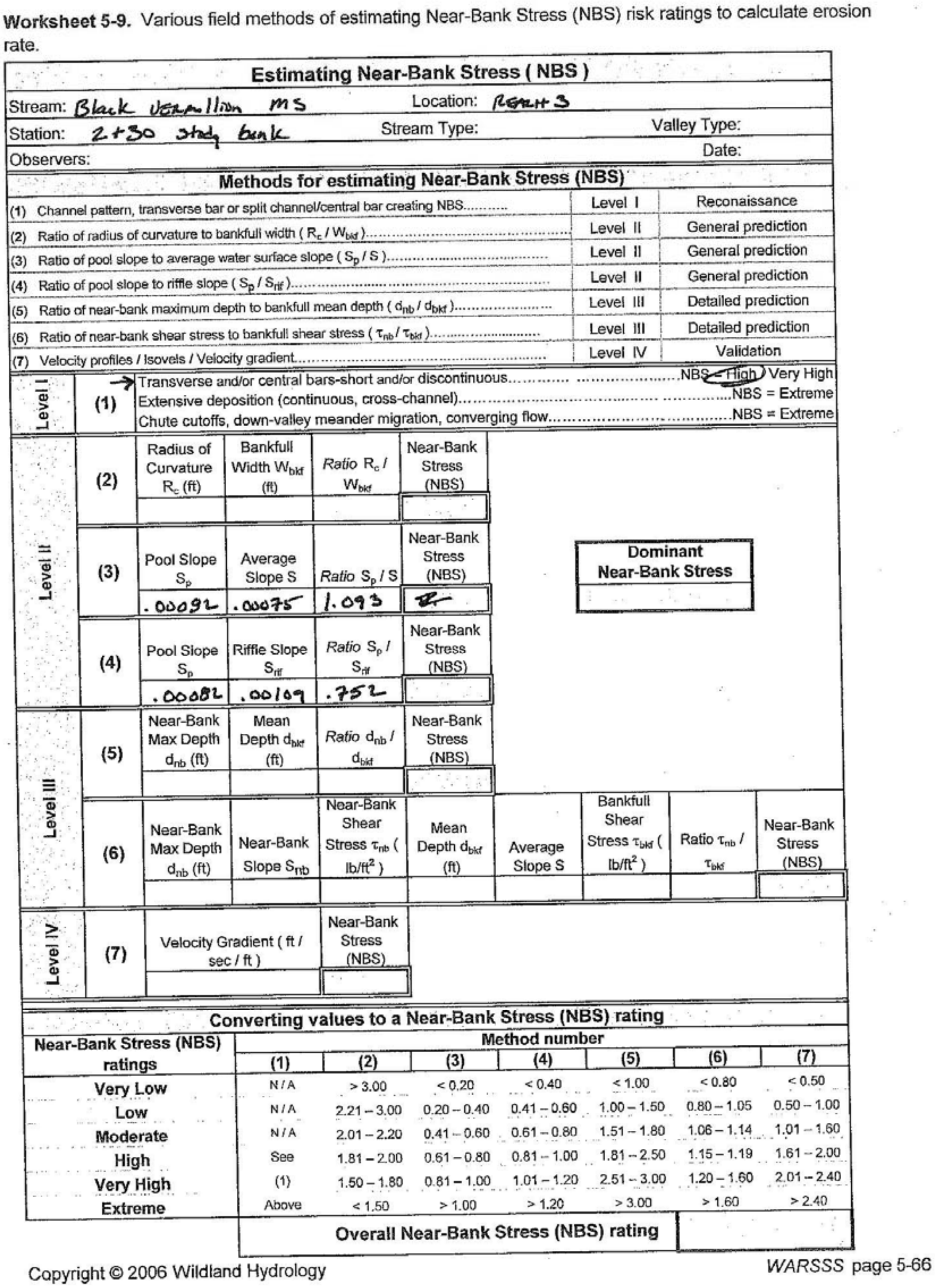

Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Black VERmillion MS Location: REACH 3

Station: 2+30 study bank Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I (1)

→ Transverse and/or central bars-short and/or discontinuous........NBS [✓ = High] / Very High

Extensive deposition (continuous, cross-channel)........NBS = Extreme

Chute cutoffs, down-valley meander migration, converging flow........NBS = Extreme

Level II

(2)	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	Ratio R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)	Pool Slope S_p	Average Slope S	Ratio S_p / S	Near-Bank Stress (NBS)
	.00092	.00075	1.093	[illegible]

(4)	Pool Slope S_p	Riffle Slope S_{rif}	Ratio S_p / S_{rif}	Near-Bank Stress (NBS)
	.00082	.00109	.752	

Dominant Near-Bank Stress

Level III

(5)	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	Ratio d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

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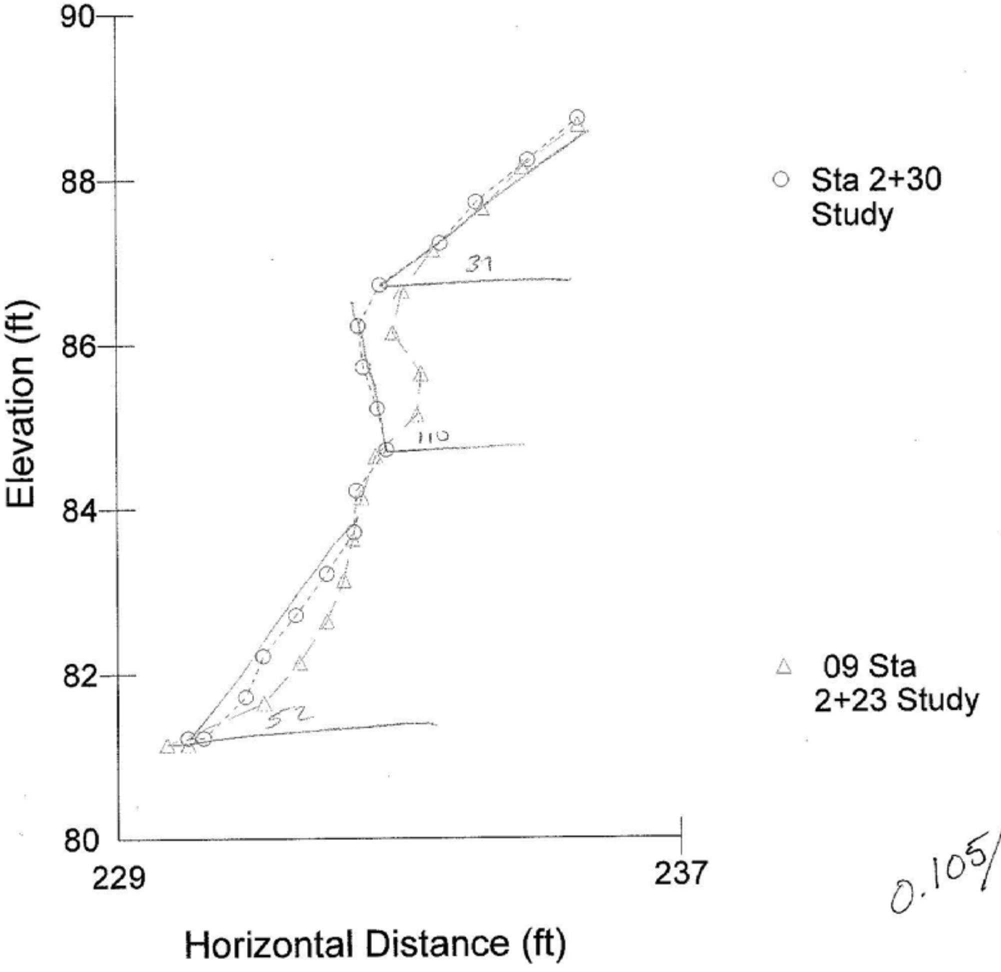
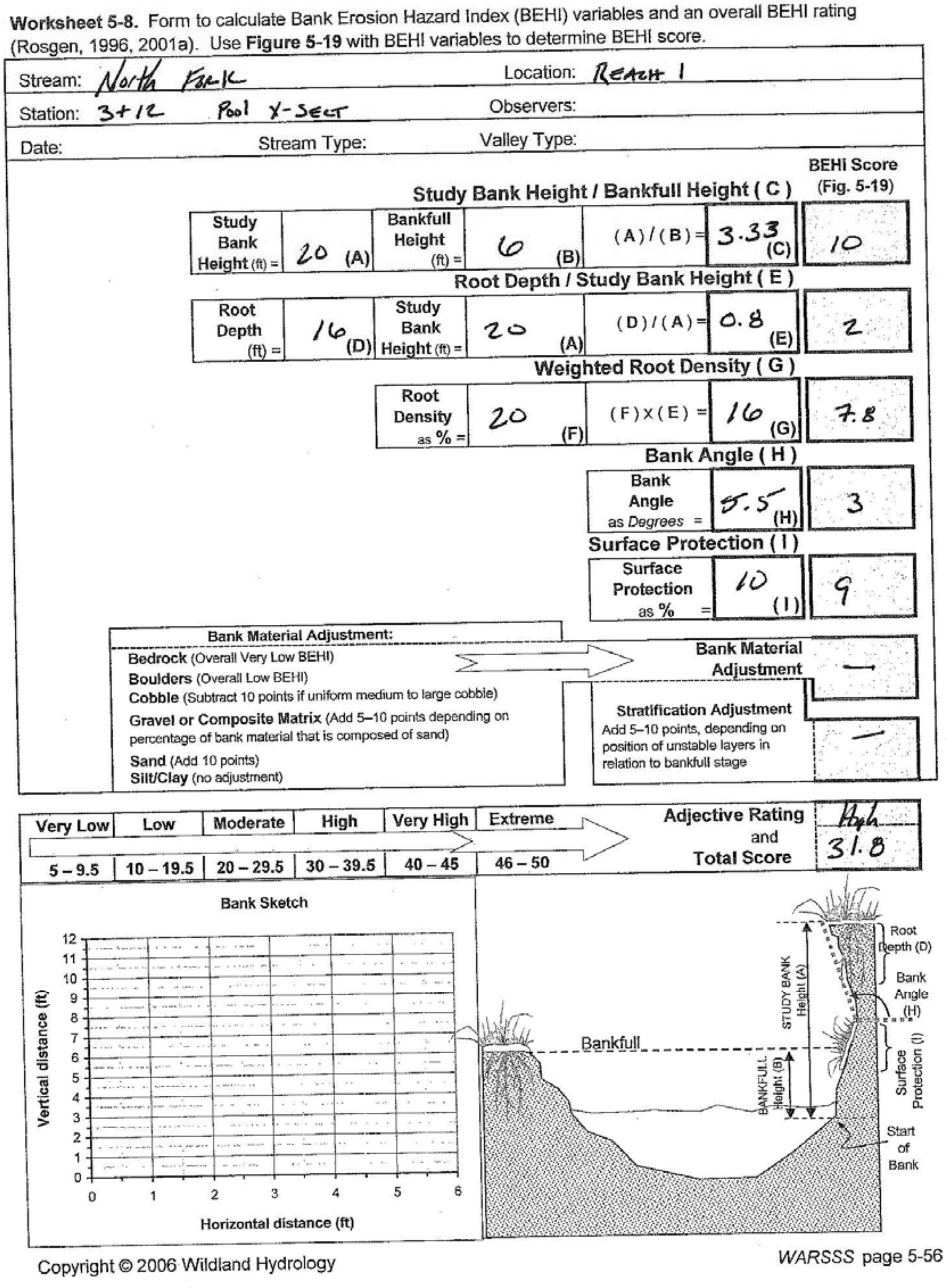
BU3 study



0.105/YR



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: North Fork
Location: Reach 1
Station: 3+12 Pool X-Sect
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	20 (A)	Bankfull Height (ft) =	6 (B)	(A)/(B) = 3.33 (C)	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	16 (D)	Study Bank Height (ft) =	20 (A)	(D)/(A) = 0.8 (E)	2

Weighted Root Density (G)

Root Density as % =	20 (F)	(F)x(E) = 16 (G)	7.8

Bank Angle (H)

Bank Angle as *Degrees* =	55 (H)	3

Surface Protection (I)

Surface Protection as % =	10 (I)	9

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**: High 31.8

Bank Sketch

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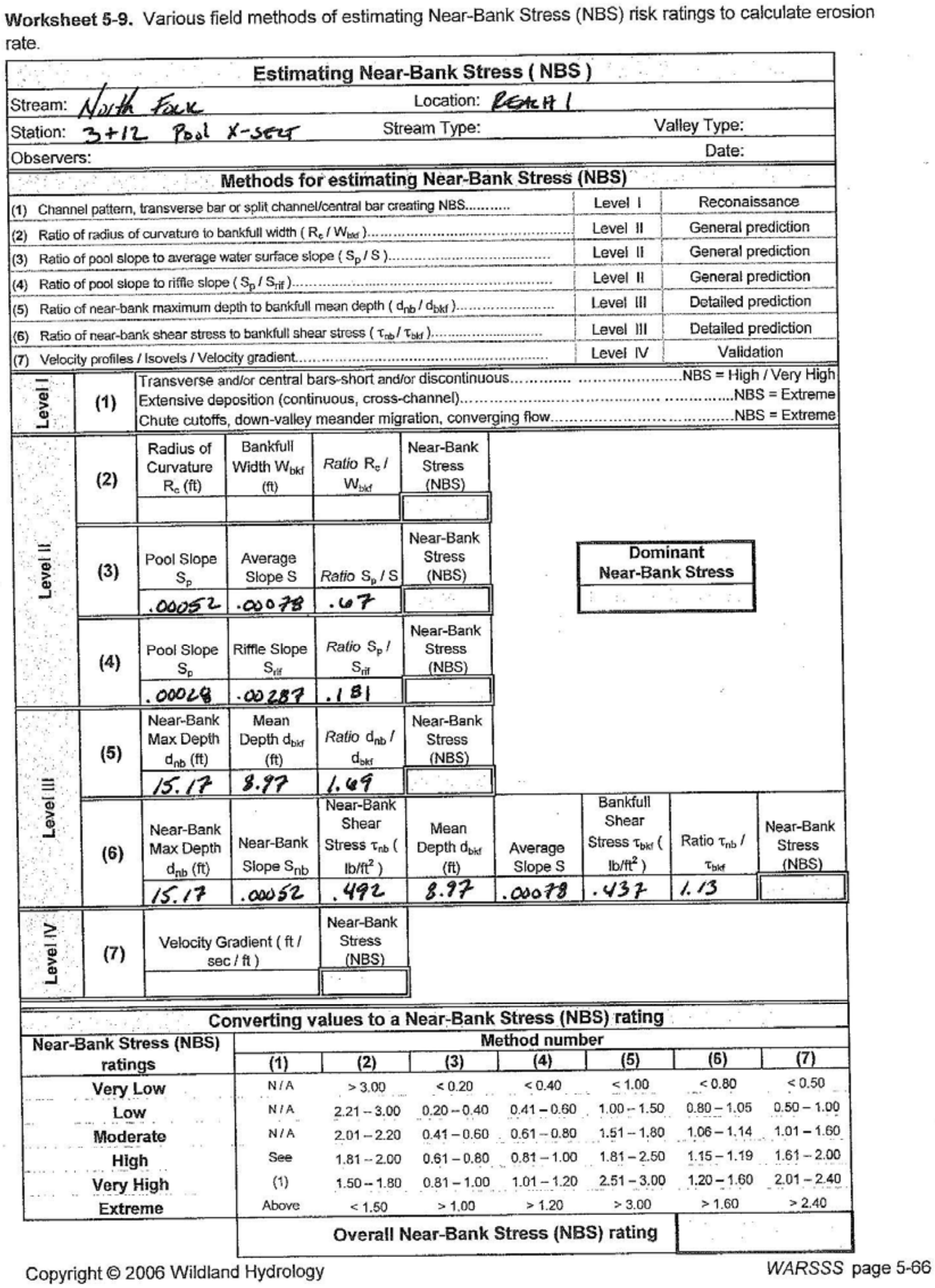


Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: North Fork
Location: REACH 1
Station: 3+12 Pool X-sect
Stream Type:
Valley Type:
Observers:
Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I (1)
Transverse and/or central bars-short and/or discontinuous..........NBS = High / Very High
Extensive deposition (continuous, cross-channel)..........NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow..........NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.00052	.00078	.67	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00028	.00287	.181	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
15.17	8.97	1.69	

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
15.17	.00052	.492	8.97	.00078	.437	1.13	

Level IV

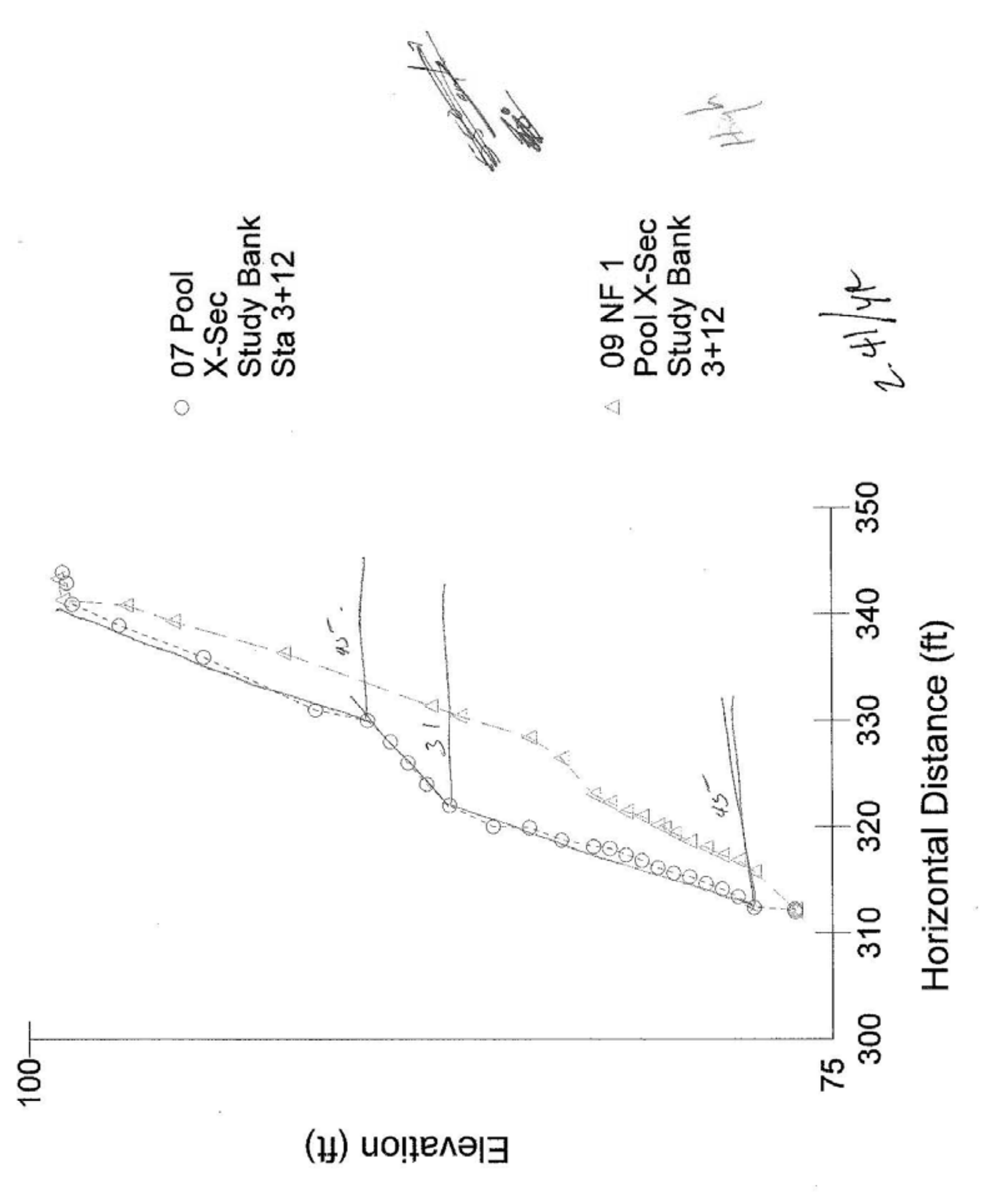
(7)

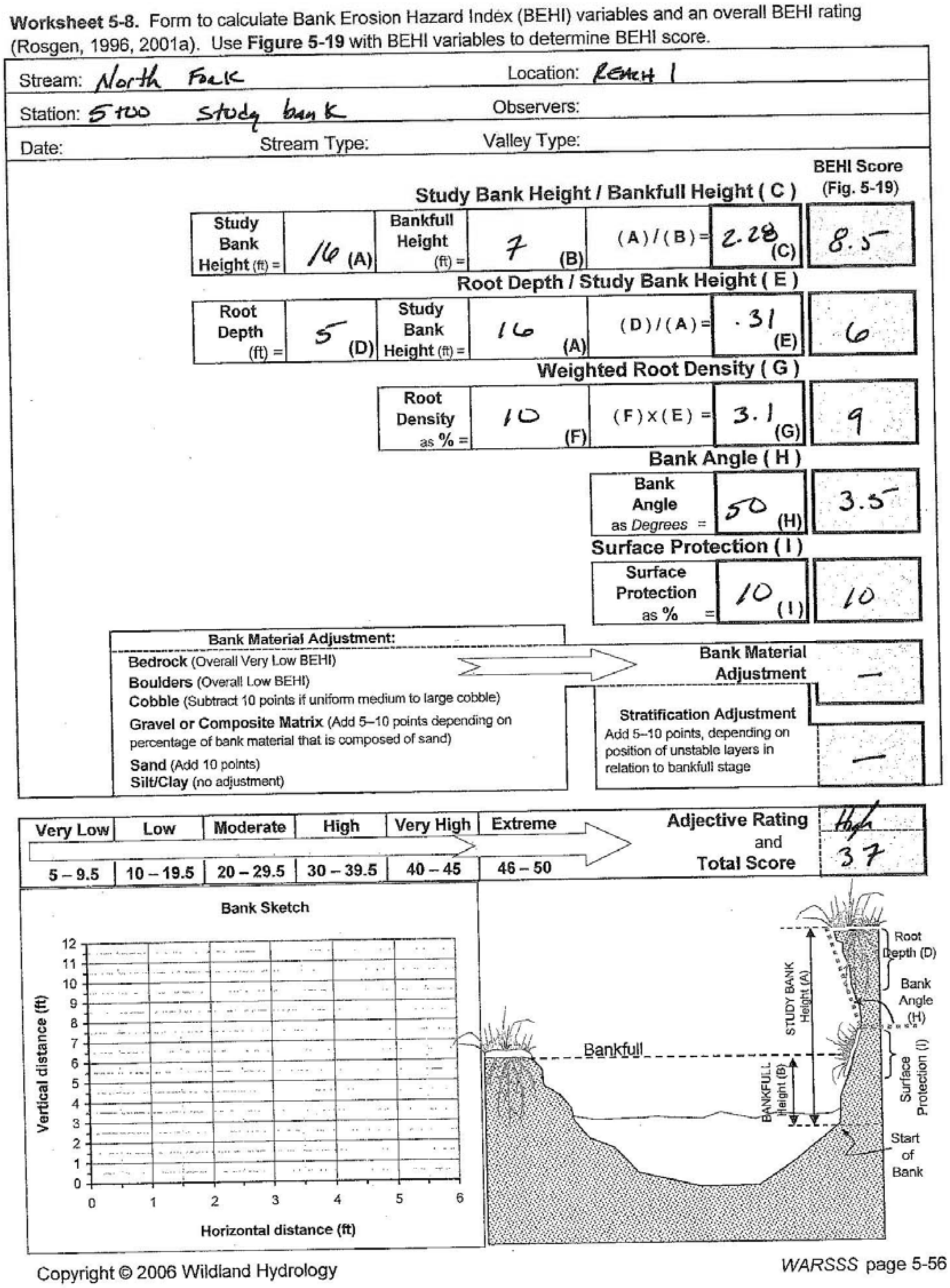
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating


NF 1 pool
Elevation (ft)
100
75
Horizontal Distance (ft)
300
310
320
330
340
350
45°
31
45°
○ 07 Pool X-Sec Study Bank Sta 3+12
△ 09 NF 1 Pool X-Sec Study Bank 3+12
2.4ft/yr



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: North Fork Location: Reach 1

Station: 5+00 study bank Observers:

Date: Stream Type: Valley Type:

						BEHI Score (Fig. 5-19)
Study Bank Height / Bankfull Height (C)						
Study Bank Height (ft) =	16 **(A)**	**Bankfull Height** (ft) =	7 **(B)**	(A) / (B) =	2.28 **(C)**	8.5
Root Depth / Study Bank Height (E)						
Root Depth (ft) =	5 **(D)**	**Study Bank Height** (ft) =	16 **(A)**	(D) / (A) =	.31 **(E)**	6
Weighted Root Density (G)						
		Root Density as **%** =	10 **(F)**	(F) x (E) =	3.1 **(G)**	9
Bank Angle (H)						
				Bank Angle as *Degrees* =	50 **(H)**	3.5
Surface Protection (I)						
				Surface Protection as **%** =	10 **(I)**	10

Bank Material Adjustment:

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

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score: High 37

Bank Sketch

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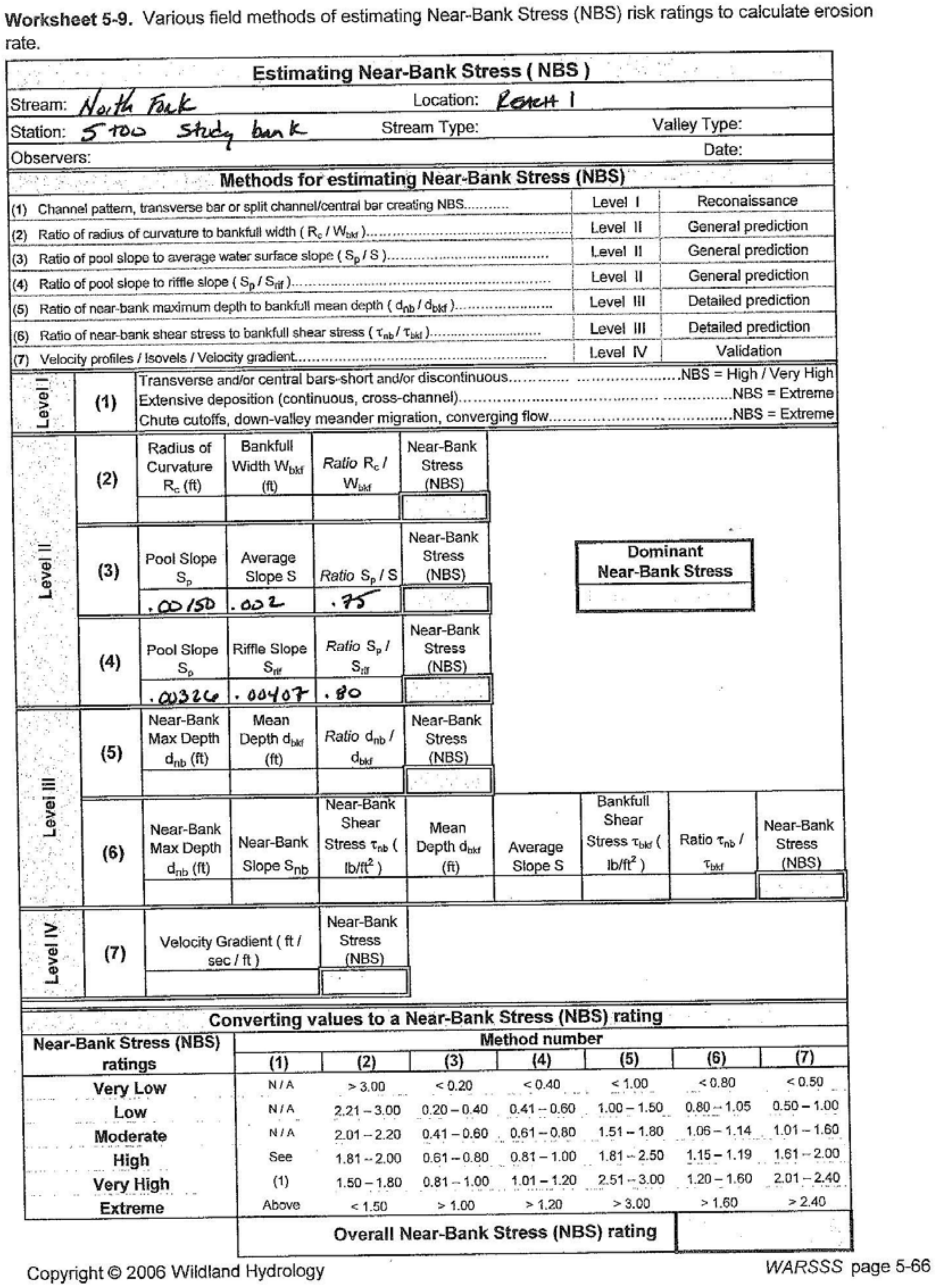
Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.



Estimating Near-Bank Stress (NBS)

Stream: North Fork Location: REACH 1

Station: 5+00 study bank Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........................	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........................	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........................	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........................	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........................	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........................	Level IV	Validation

Level I

(1)

Transverse and/or central bars-short and/or discontinuous........................NBS = High / Very High

Extensive deposition (continuous, cross-channel)........................NBS = Extreme

Chute cutoffs, down-valley meander migration, converging flow........................NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.00150	.002	.75	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00326	.00407	.80	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

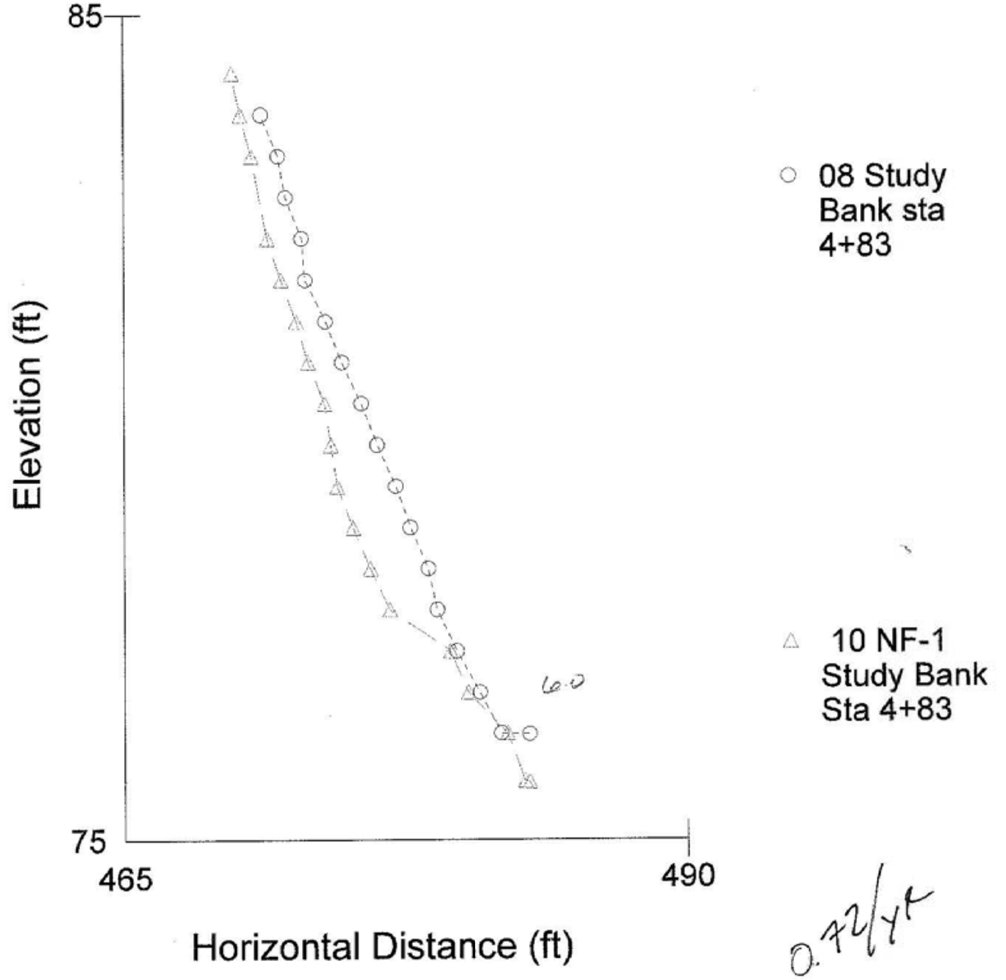
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

NFI Study



Mid

0.72/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: North FORK
Location: REACH 2
Station: 5+86 Pool X-SECT
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	18 **(A)**	**Bankfull Height** (ft) =	7 **(B)**	(A) / (B) = 2.57 **(C)**	8.5

Root Depth / Study Bank Height (E)

Root Depth (ft) =	15 **(D)**	**Study Bank Height** (ft) =	18 **(A)**	(D) / (A) = .83 **(E)**	2.5

Weighted Root Density (G)

Root Density as **%** =	15 **(F)**	(F) x (E) = 12.45 **(G)**	8

Bank Angle (H)

Bank Angle as *Degrees* =	45 **(H)**	3

Surface Protection (I)

Surface Protection as **%** =	5 **(I)**	10

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

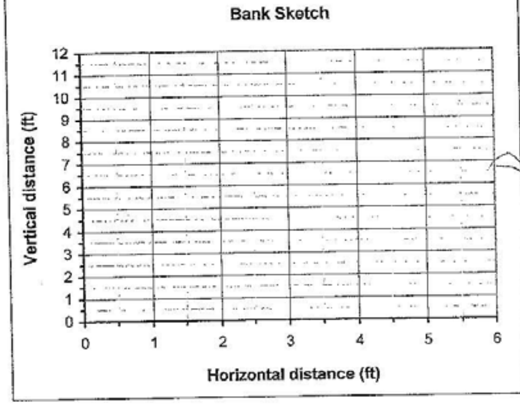
Bank Material Adjustment —

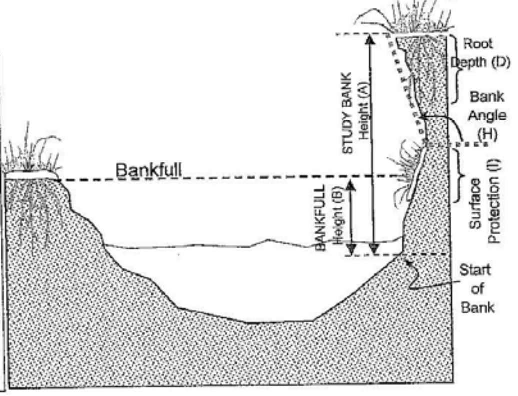
Stratification Adjustment
Add 5–10 points, depending on position of unstable layers in relation to bankfull stage —

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score: High 32.5

Bank Sketch





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Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: North Fork
Location: REACH 2
Station: 5+86 Pool X-SECT
Stream Type:
Valley Type:
Observers:
Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})............	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)............	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})............	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})............	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})............	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient............	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous.............................NBS = High / Very High
Extensive deposition (continuous, cross-channel)..........................NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow..........................NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.00089	.000818	.11	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00082	.00115	.713	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
11.76	7.8	1.51	

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
11.76	.00082	.310	7.8	.000818	.205	1.512	

Level IV

(7)

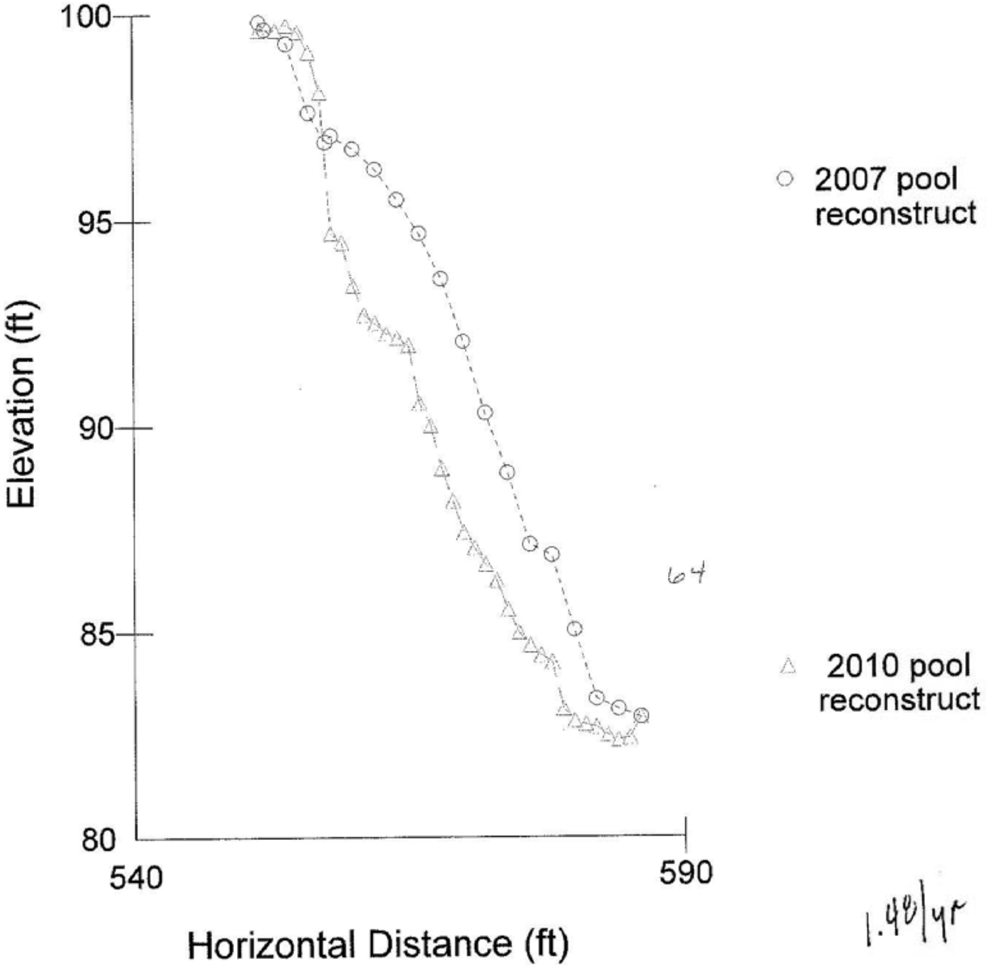
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number (1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

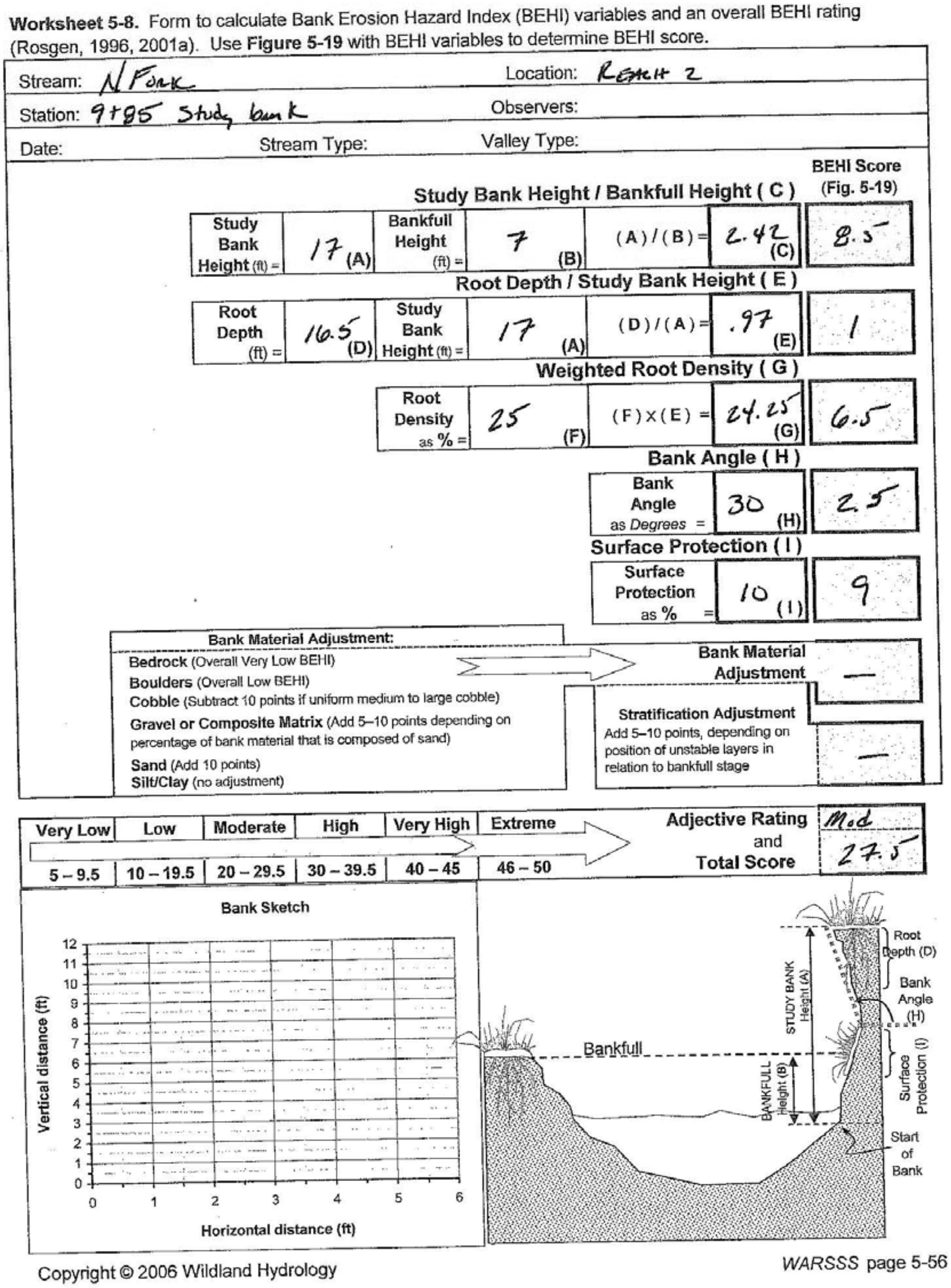
Overall Near-Bank Stress (NBS) rating

NF2pool



64

1.48/yr



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: N Fork
Location: Reach 2
Station: 9+95 Study bank
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	17 (A)	**Bankfull Height** (ft) =	7 (B)	(A)/(B) = 2.42 (C)	8.5

Root Depth / Study Bank Height (E)

Root Depth (ft) =	16.5 (D)	**Study Bank Height** (ft) =	17 (A)	(D)/(A) = .97 (E)	1

Weighted Root Density (G)

Root Density as **%** =	25 (F)	(F)×(E) = 24.25 (G)	6.5

Bank Angle (H)

Bank Angle as *Degrees* =	30 (H)	2.5

Surface Protection (I)

Surface Protection as **%** =	10 (I)	9

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score: Mod 27.5

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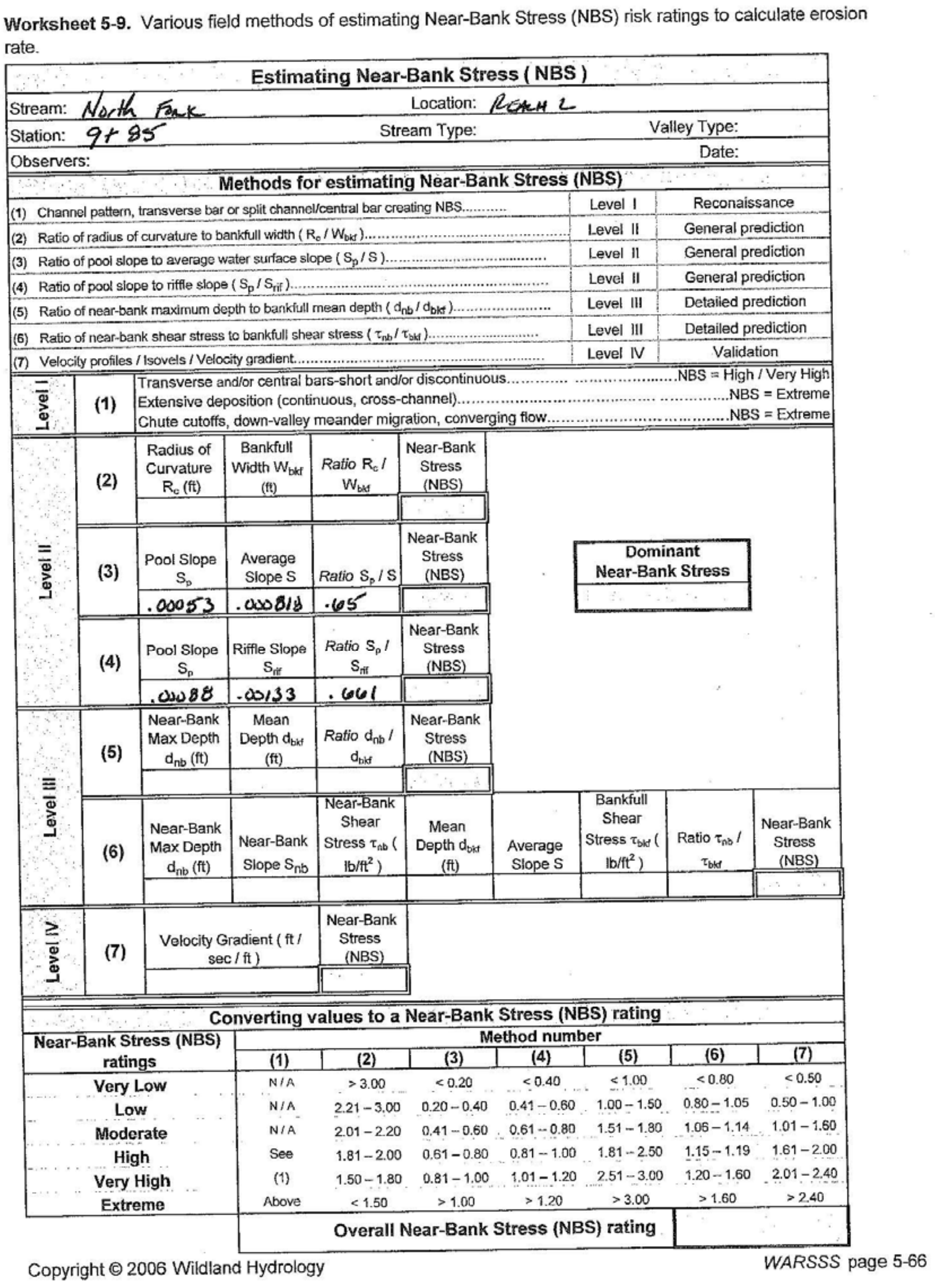


Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: North Fork   Location: REACH 2

Station: 9+85   Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf}).......	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S).......	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif}).......	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf}).......	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf}).......	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient.......	Level IV	Validation

Level I

(1)

Transverse and/or central bars-short and/or discontinuous....................NBS = High / Very High

Extensive deposition (continuous, cross-channel)....................NBS = Extreme

Chute cutoffs, down-valley meander migration, converging flow....................NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.00053	.000818	.65	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00088	.00133	.661	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

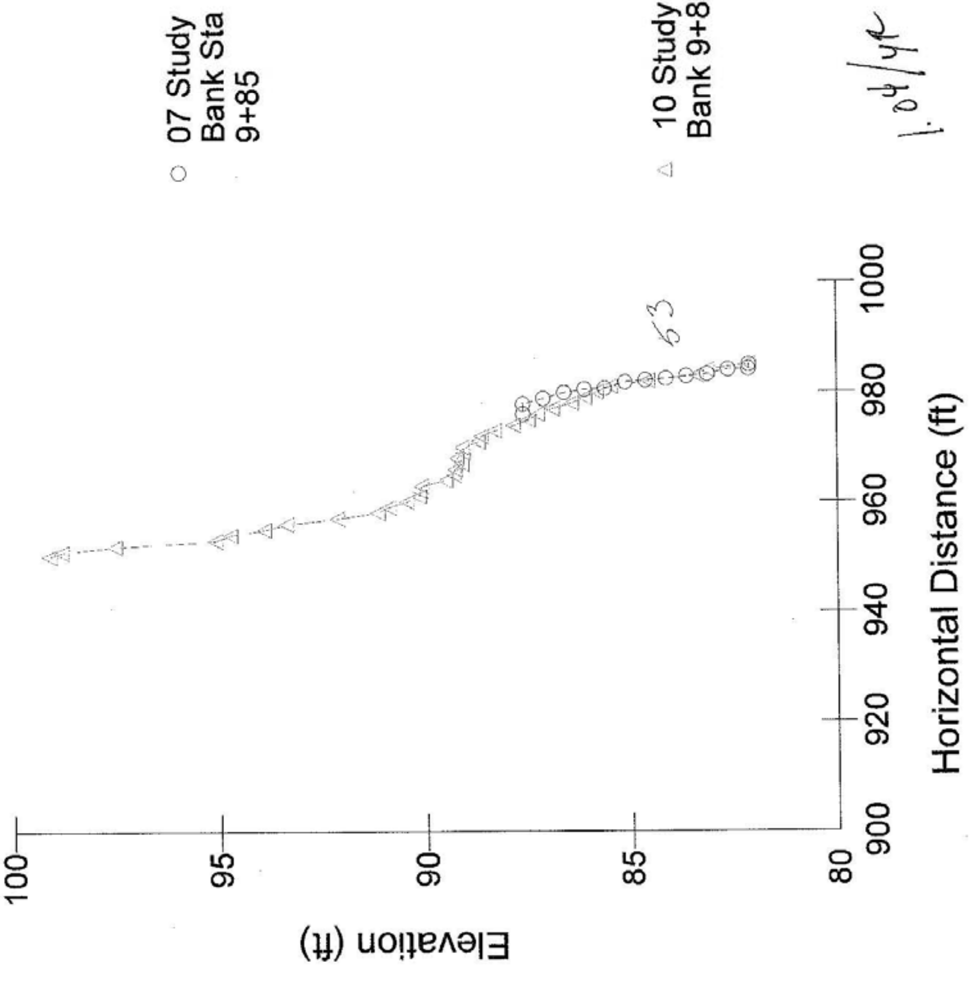
Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

NF2 study

n.h



63

1.04/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: North Fork
Location: Reach 3
Station: 10+52 Pool X-Sect
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) = 18 (A) | Bankfull Height (ft) = 8 (B) | (A)/(B) = 2.25 (C) | 8.25

Root Depth / Study Bank Height (E)

Root Depth (ft) = 18 (D) | Study Bank Height (ft) = 18 (A) | (D)/(A) = 1 (E) | 1

Weighted Root Density (G)

Root Density as % = 25 (F) | (F)x(E) = 25 (G) | 6.5

Bank Angle (H)

Bank Angle as *Degrees* = 45 (H) | 3

Surface Protection (I)

Surface Protection as % = 10 (I) | 9

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

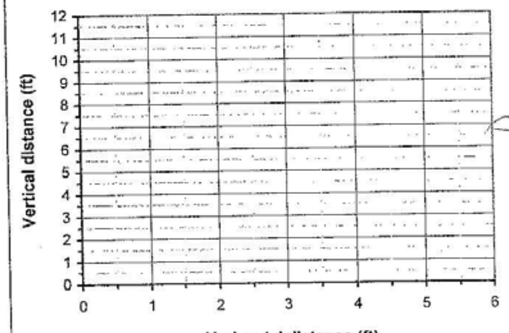
Bank Material Adjustment —

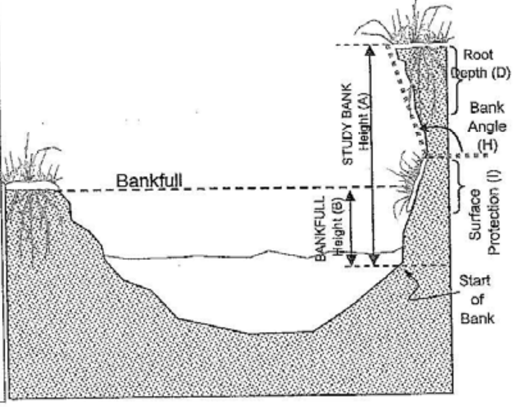
Stratification Adjustment
Add 5–10 points, depending on position of unstable layers in relation to bankfull stage —

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score Mod. 27.75

Bank Sketch





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Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: North Fork　Location: Reach 3

Station: 10+52 Pool X-Sect　Stream Type:　Valley Type:

Observers:　Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})..	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)......................................	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})..	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})......................	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........................	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient...	Level IV	Validation

Level I

(1)	Transverse and/or central bars-short and/or discontinuous.............. ....NBS = High / Very High Extensive deposition (continuous, cross-channel).. ....NBS = Extreme Chute cutoffs, down-valley meander migration, converging flow.......................................NBS = Extreme

Level II

(2)	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
	.00045	.00128	.35	

(4)	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
	.00073	.00131	.557	

Dominant Near-Bank Stress

Level III

(5)	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
	11.45	8.49	1.35	

(6)	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
	11.45	.00073	.269	8.49	.0009	.2454	1.093	

Level IV

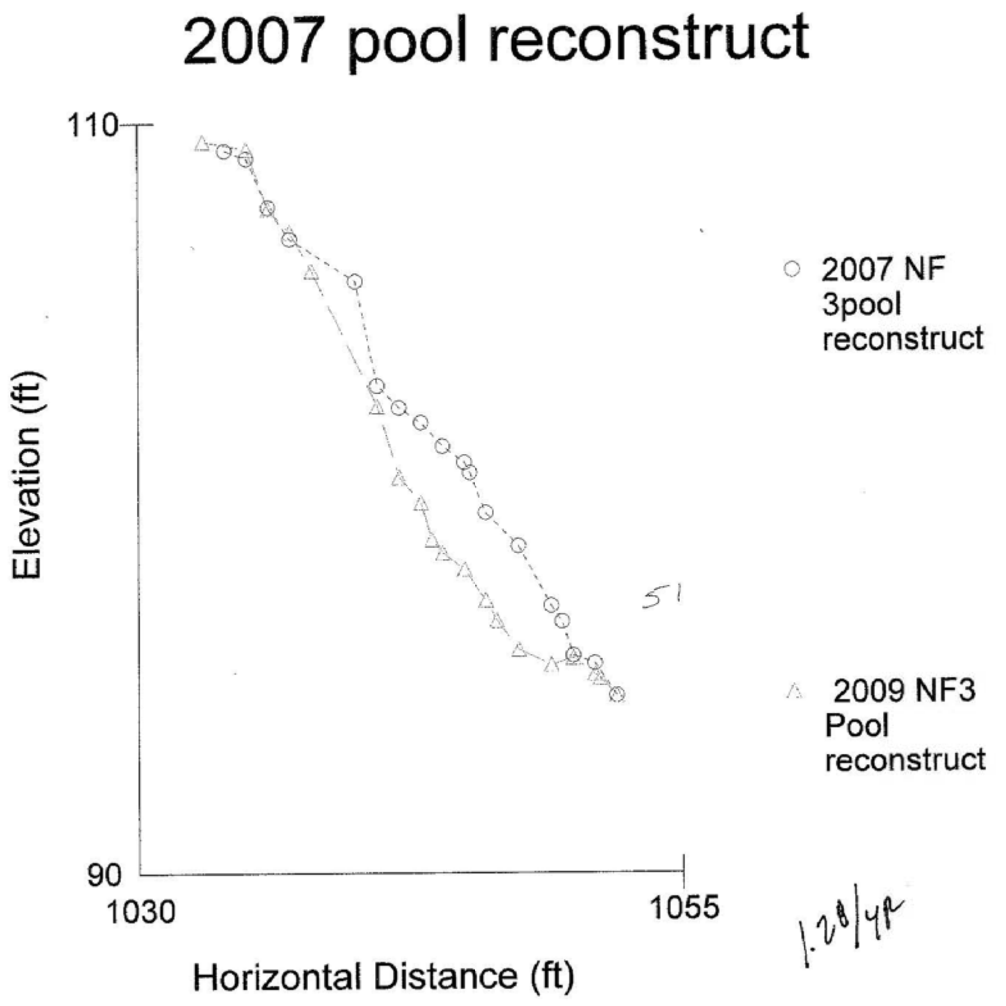
(7)	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

NF3 pool



51

1.28|4ft

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: North Fork
Location: REACH 3
Station: 19+32 study bank
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	16 (A)	Bankfull Height (ft) =	8 (B)	(A)/(B) =	2 (C)	7.9

Root Depth / Study Bank Height (E)

Root Depth (ft) =	14 (D)	Study Bank Height (ft) =	16 (A)	(D)/(A) =	.875 (E)	2.3

Weighted Root Density (G)

Root Density as % =	35 (F)	(F) x (E) =	30.6 (G)	5.5

Bank Angle (H)

Bank Angle as *Degrees* =	45 (H)	3

Surface Protection (I)

Surface Protection as % =	15 (I)	7.9

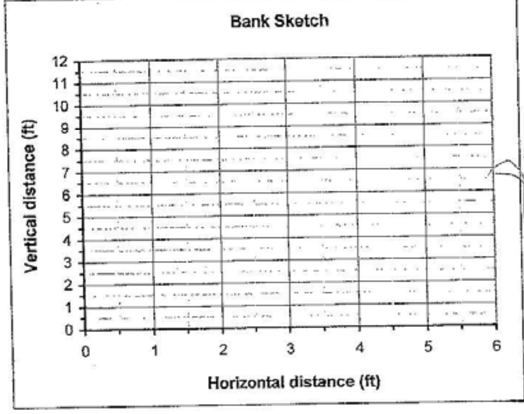
Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

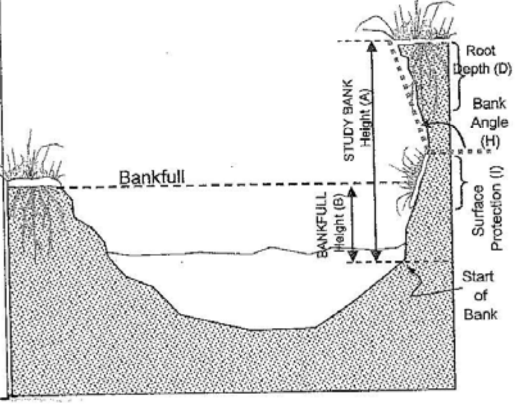
Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**: Mod. 26.6





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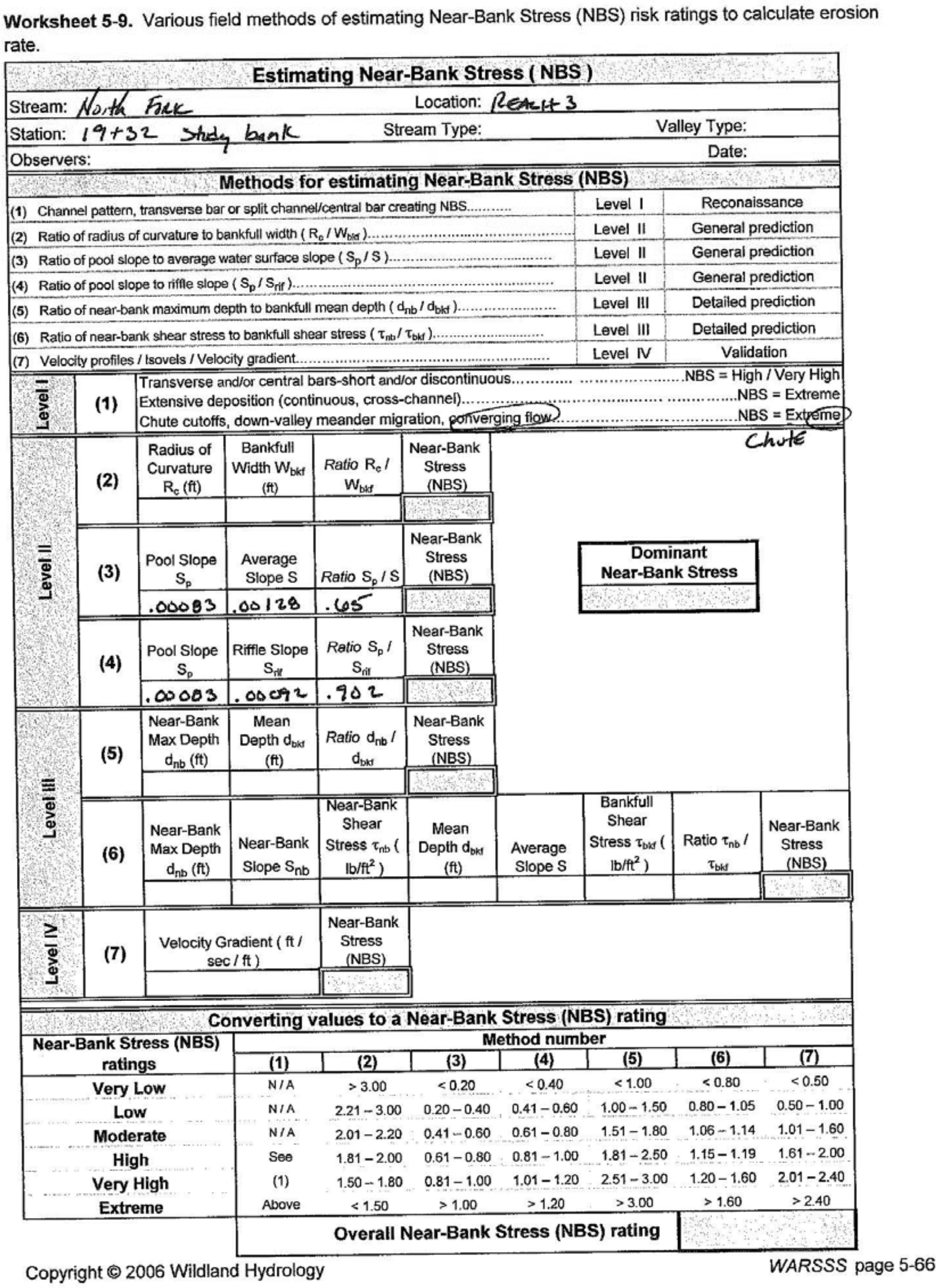

Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: North Fork | Location: Reach 3
Station: 19+32 Study bank | Stream Type: | Valley Type:
Observers: | Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous..........NBS = High / Very High
Extensive deposition (continuous, cross-channel)..........NBS = Extreme
Chute cutoffs, down-valley meander migration, [✓ converging flow]..........NBS = [✓ Extreme]
Chute

Level II

	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)
(2)				

	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
(3)	.00083	.00128	.65	

	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
(4)	.00083	.00092	.902	

Dominant Near-Bank Stress

Level III

	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
(5)				

	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
(6)								

Level IV

	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)
(7)		

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number (1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

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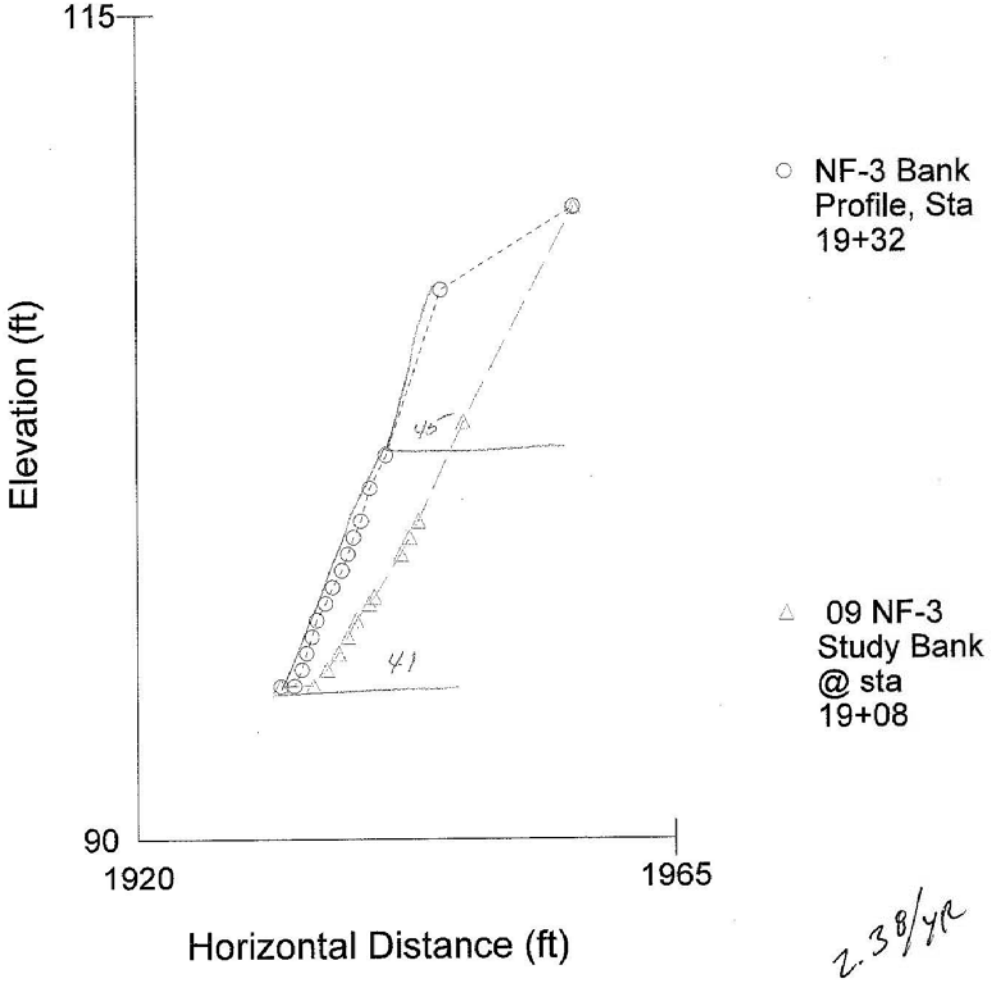
NF3 Study



2.38/YR

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: IRISH CREEK
Location: REACH 1
Station: 5+72 POOL X-SECT
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	17 (A)	Bankfull Height (ft) =	5.4 (B)	(A) / (B) =	3.1 (C)	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	17 (D)	Study Bank Height (ft) =	17 (A)	(D) / (A) =	1 (E)	1

Weighted Root Density (G)

Root Density as % =	5 (F)	(F) x (E) =	5 (G)	9

Bank Angle (H)

Bank Angle as *Degrees* =	110 (H)	9

Surface Protection (I)

Surface Protection as % =	0 (I)	10

Bank Material Adjustment:

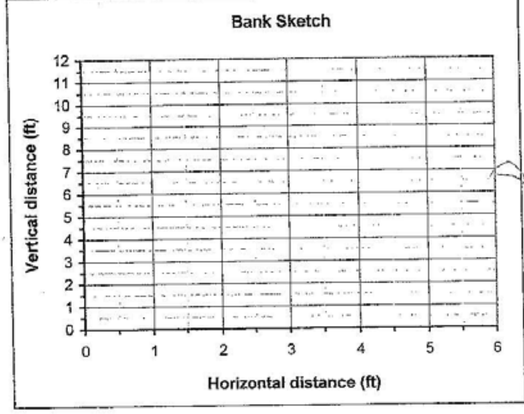
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

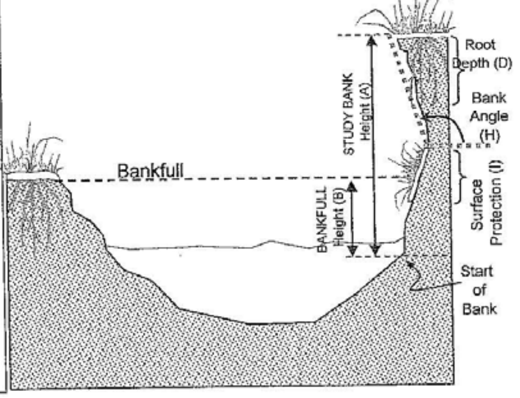
Bank Material Adjustment –

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating V. High
and
Total Score 44





Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: IRish CREEK Location: REACH 1

Station: 5+72 Pool X-SECT Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........................	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........................	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........................	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........................	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........................	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........................	Level IV	Validation

Level I

(1)

Transverse and/or central bars-short and/or discontinuous.............................NBS = High / Very High
Extensive deposition (continuous, cross-channel).............................NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow.............................NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.0001	.00302	.03	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.0001	.00064	.16	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
6.01	5.27	1.14	

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
10.01	.0001	.019	5.27	.00302	.512	.037	

Level IV

(7)

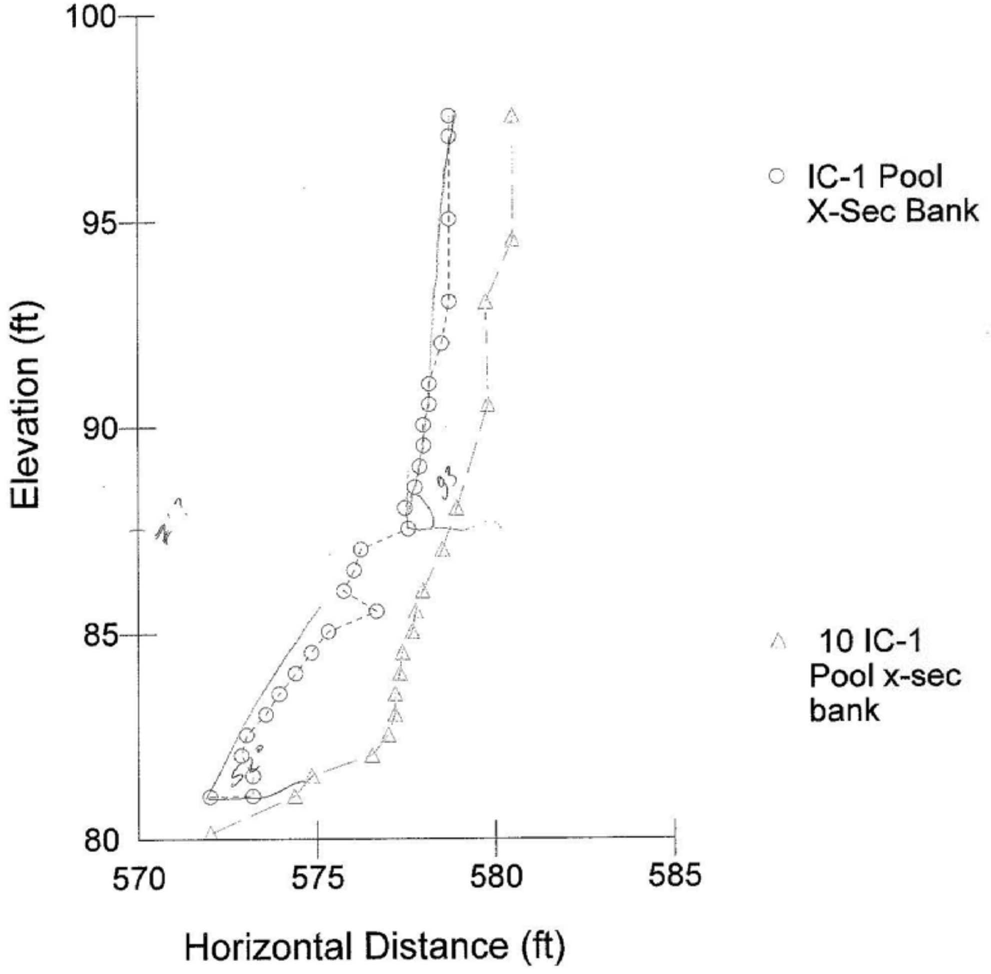
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

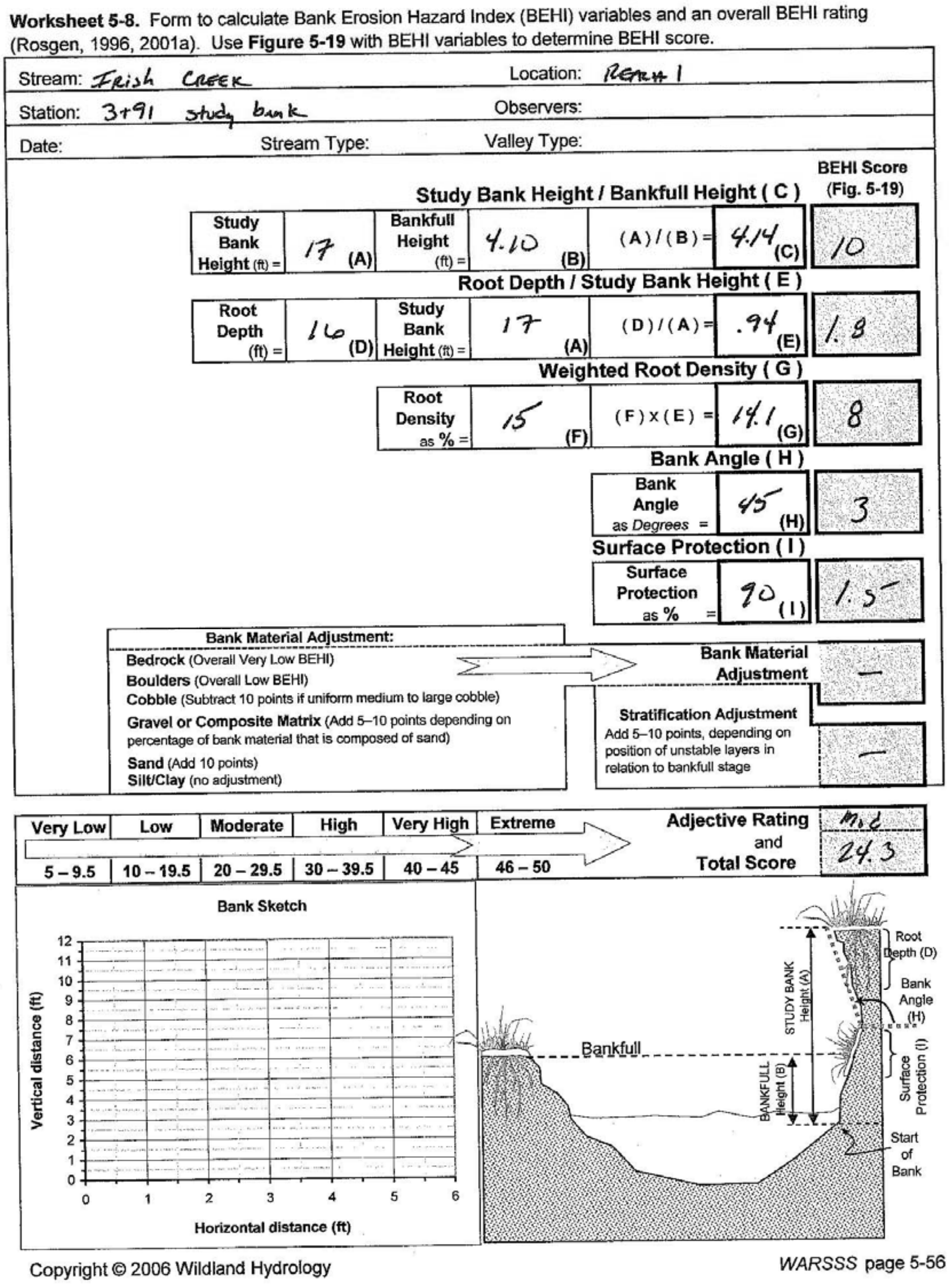
Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

IC 1 pool



0.66/yr



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Irish Creek Location: Reach 1

Station: 3+91 study bank Observers:

Date: Stream Type: Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	17 **(A)**	**Bankfull Height** (ft) =	4.10 **(B)**	(A) / (B) = 4.14 **(C)**	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	16 **(D)**	**Study Bank Height** (ft) =	17 **(A)**	(D) / (A) = .94 **(E)**	1.8

Weighted Root Density (G)

Root Density as **%** =	15 **(F)**	(F) x (E) = 14.1 **(G)**	8

Bank Angle (H)

Bank Angle as *Degrees* =	45 **(H)**	3

Surface Protection (I)

Surface Protection as **%** =	90 **(I)**	1.5

Bank Material Adjustment:

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

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating Mod
and
Total Score 24.3

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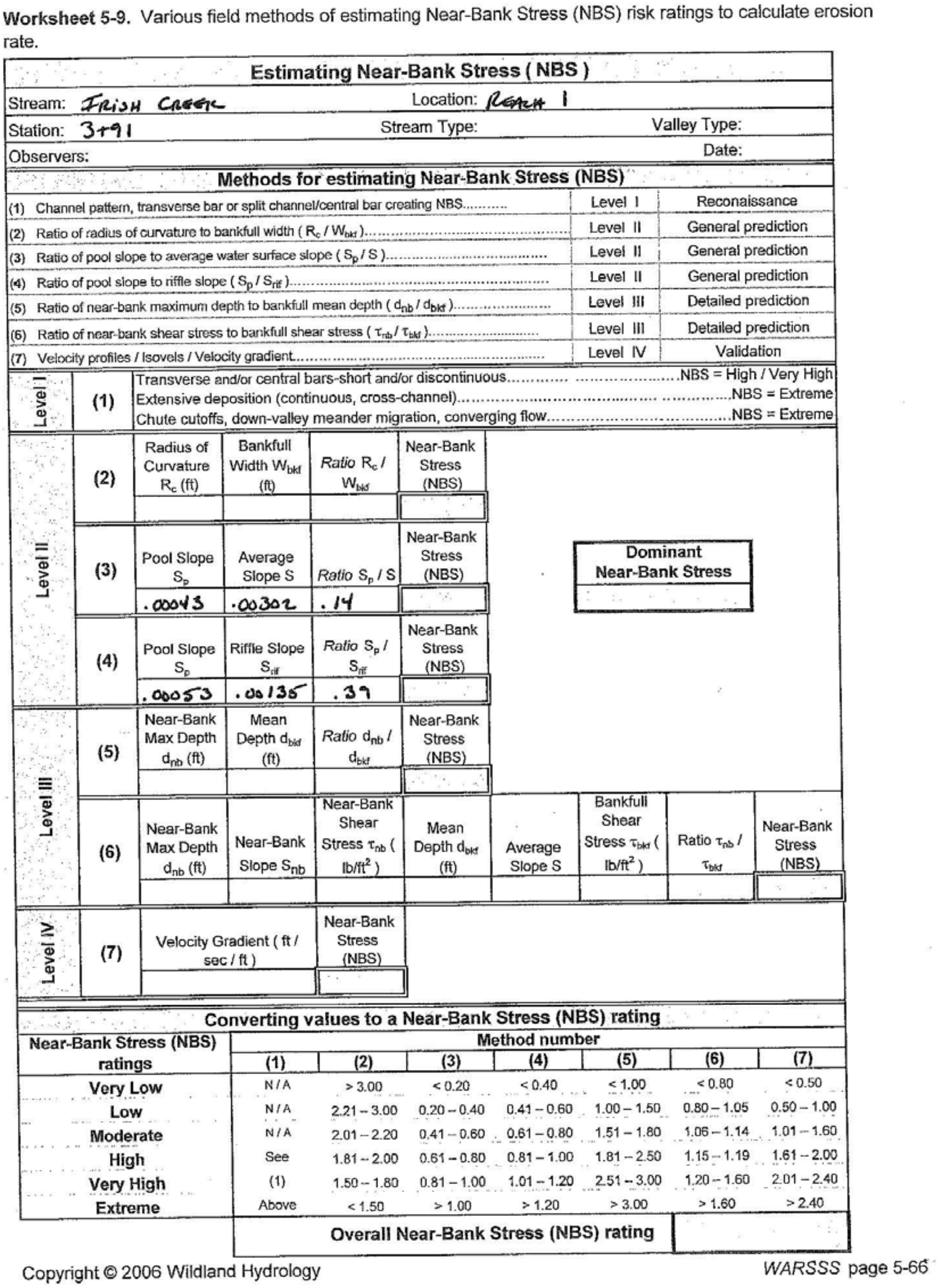

Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: IRISH CREEK Location: REACH 1
Station: 3+91 Stream Type: Valley Type:
Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})..........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)..........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})..........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})..........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})..........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient..........	Level IV	Validation

Level I **(1)**
Transverse and/or central bars-short and/or discontinuous..........NBS = High / Very High
Extensive deposition (continuous, cross-channel)..........NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow..........NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.00043	.00302	.14	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00053	.00135	.39	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

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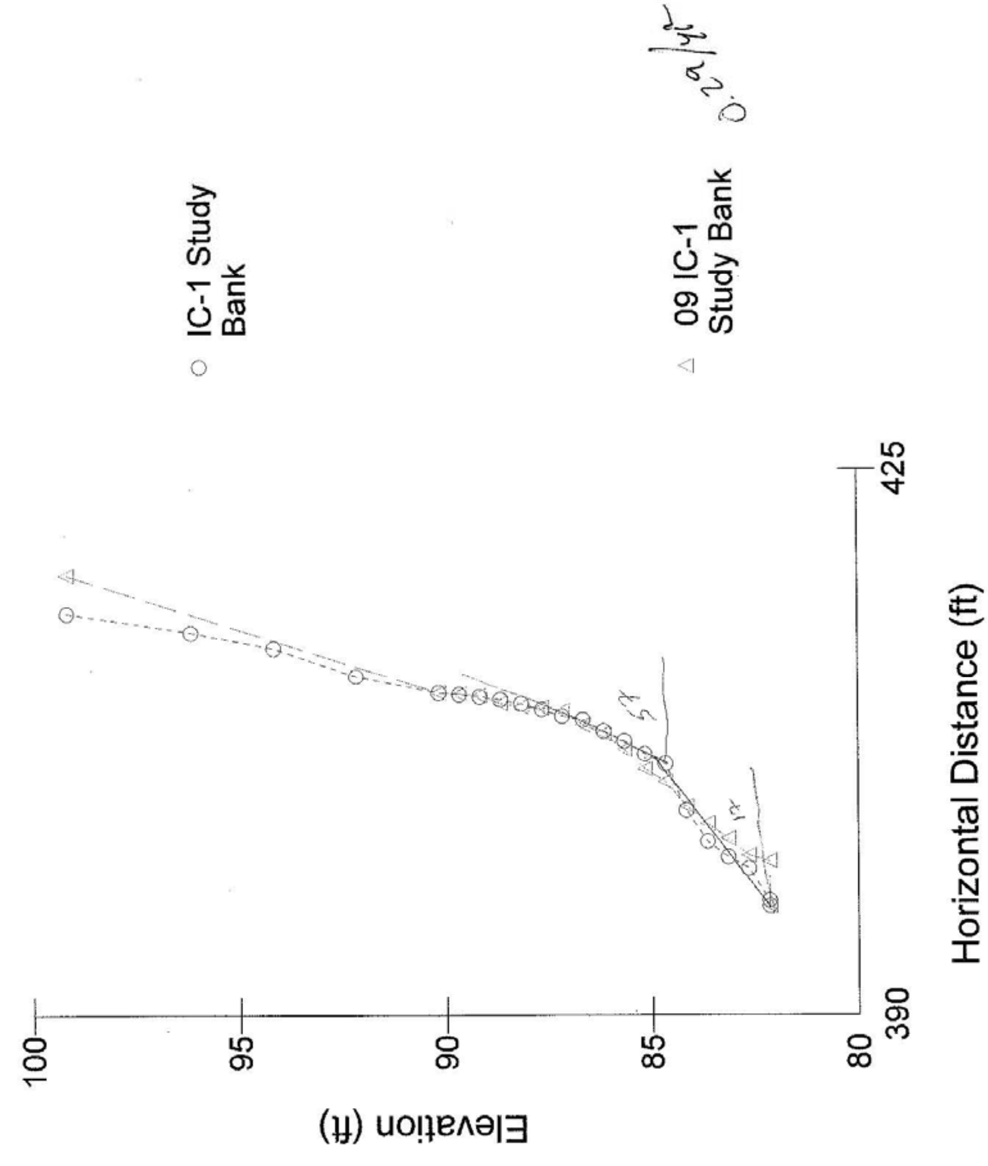
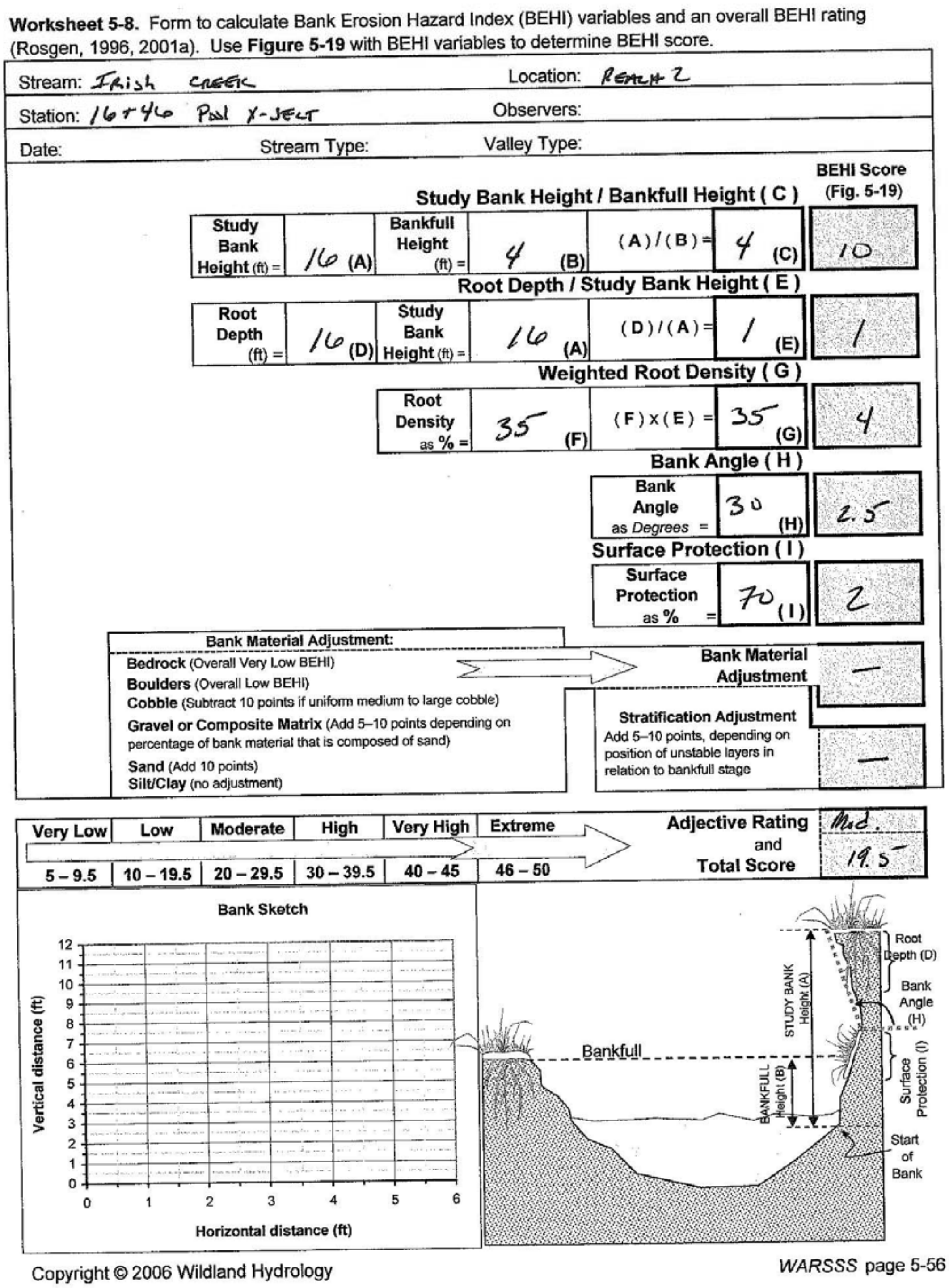
IC 1 study


Elevation (ft)
100
95
90
85
80
390
425
Horizontal Distance (ft)
IC-1 Study Bank
09 IC-1 Study Bank
0.2a/yr
5x
1x



Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Irish Creek
Location: Reach 2
Station: 16+46 Pool X-Sect
Observers:
Date:
Stream Type:
Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	16 **(A)**	**Bankfull Height** (ft) =	4 **(B)**	(A)/(B) = 4 **(C)**	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	16 **(D)**	**Study Bank Height** (ft) =	16 **(A)**	(D)/(A) = 1 **(E)**	1

Weighted Root Density (G)

Root Density as % =	35 **(F)**	(F)x(E) = 35 **(G)**	4

Bank Angle (H)

Bank Angle as *Degrees* =	30 **(H)**	2.5

Surface Protection (I)

Surface Protection as % =	70 **(I)**	2

Bank Material Adjustment:
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**: Mod. 19.5

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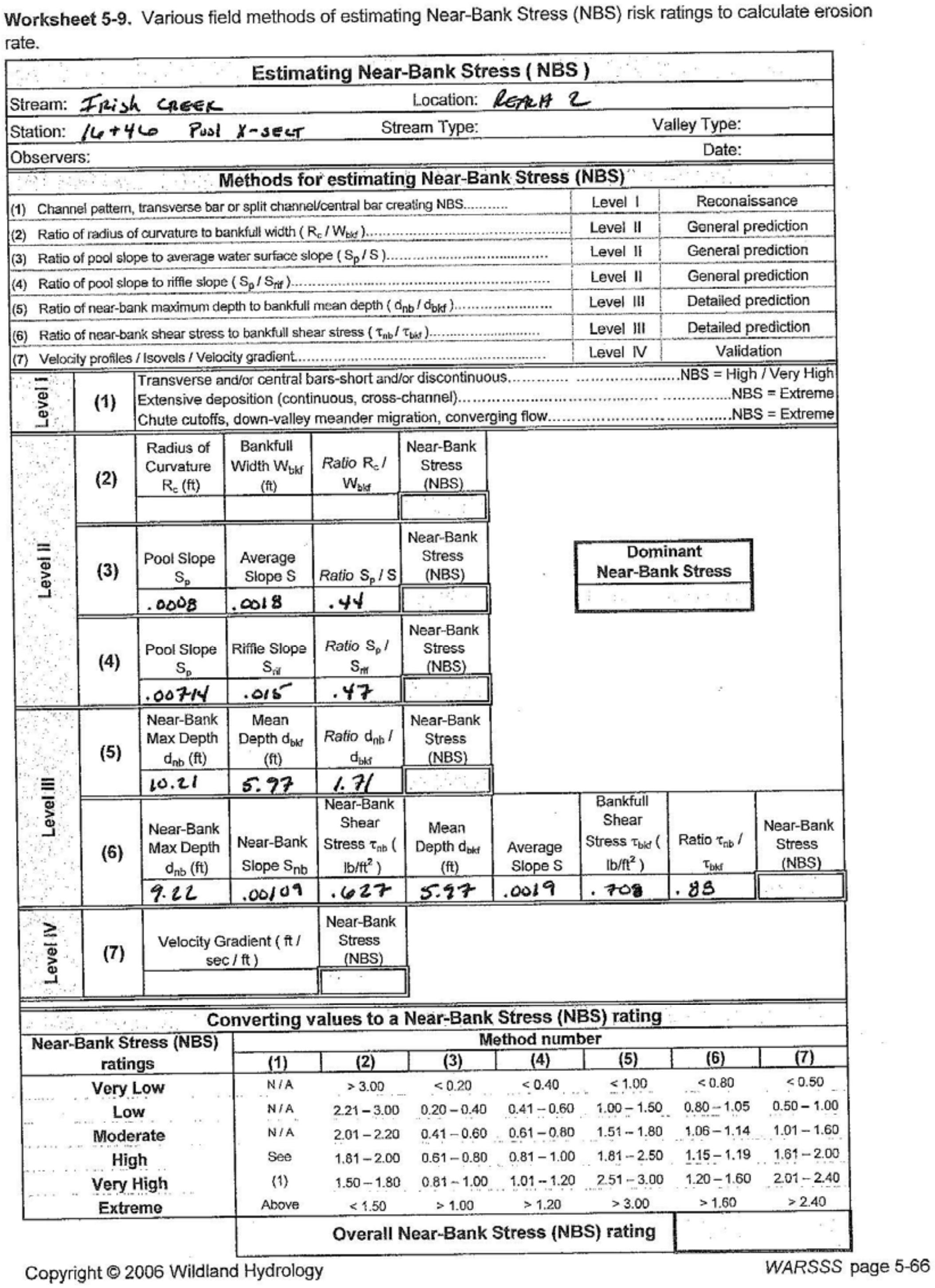

Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Irish Creek　Location: Reach 2

Station: 16+460 Pool X-sect　Stream Type:　Valley Type:

Observers:　Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous............NBS = High / Very High
Extensive deposition (continuous, cross-channel)............NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow............NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.0008	.0018	.44	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.00714	.015	.47	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
10.21	5.97	1.71	

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
9.22	.00109	.627	5.97	.0019	.708	.88	

Level IV

(7)

Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

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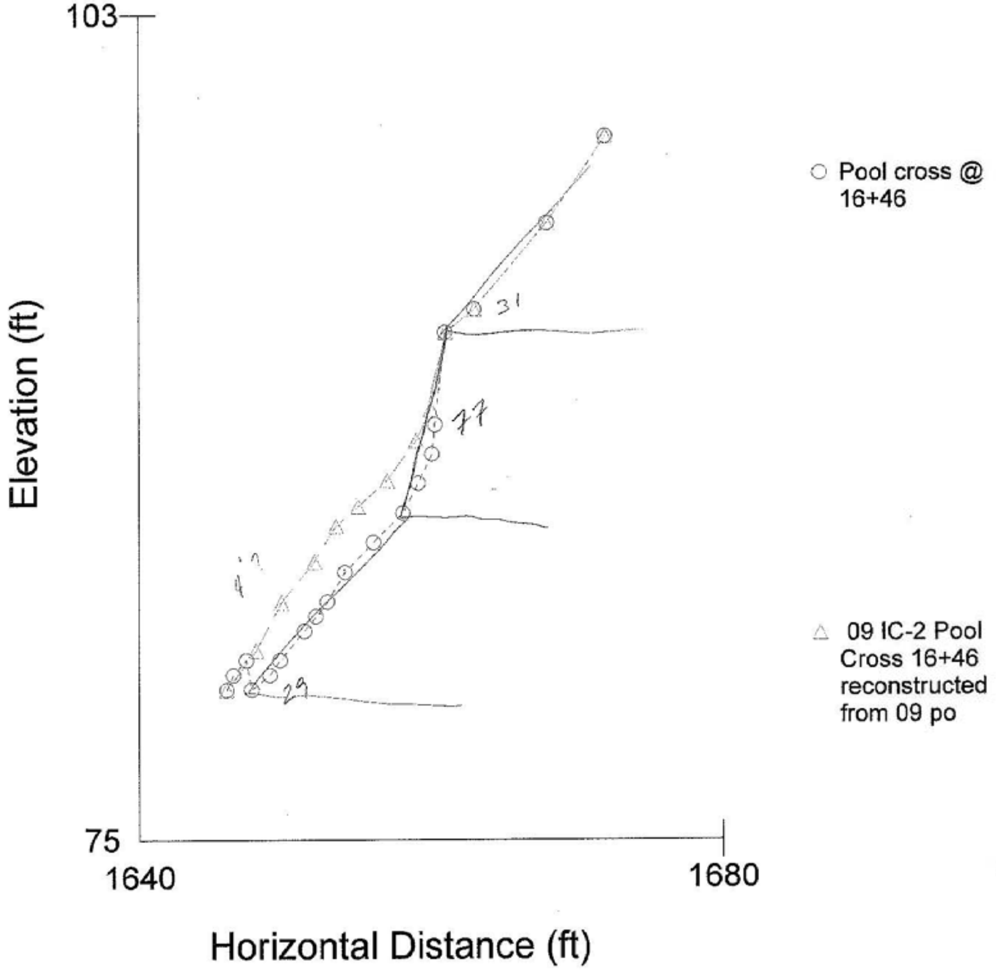
IC 2 pool



-0.61/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Irish Creek Location: Reach 2
Station: 13+58 Observers:
Date: Stream Type: Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	15.6 **(A)**	**Bankfull Height** (ft) =	4 **(B)**	(A) / (B) =	3.9 **(C)**	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	4.5 **(D)**	**Study Bank Height** (ft) =	15.6 **(A)**	(D) / (A) =	.29 **(E)**	6

Weighted Root Density (G)

Root Density as % =	7.5 **(F)**	(F) x (E) =	2.18 **(G)**	10

Bank Angle (H)

Bank Angle as *Degrees* =	50 **(H)**	3.5

Surface Protection (I)

Surface Protection as % =	5 **(I)**	10

Bank Material Adjustment:

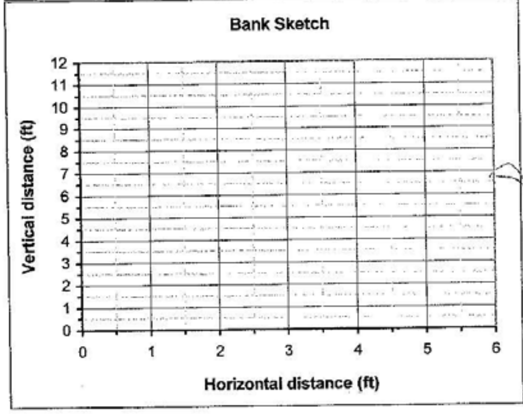
- **Bedrock** (Overall Very Low BEHI)
- **Boulders** (Overall Low BEHI)
- **Cobble** (Subtract 10 points if uniform medium to large cobble)
- **Gravel or Composite Matrix** (Add 5–10 points depending on percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt/Clay** (no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

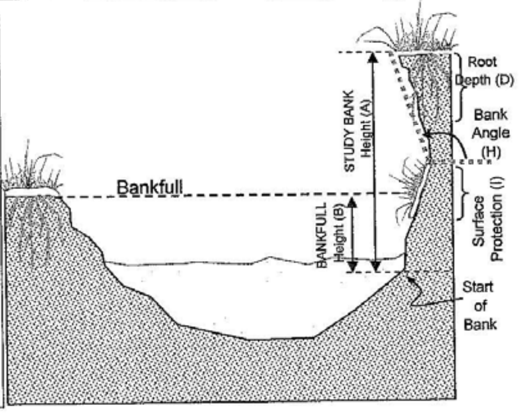
Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and Total Score V. High 39.5





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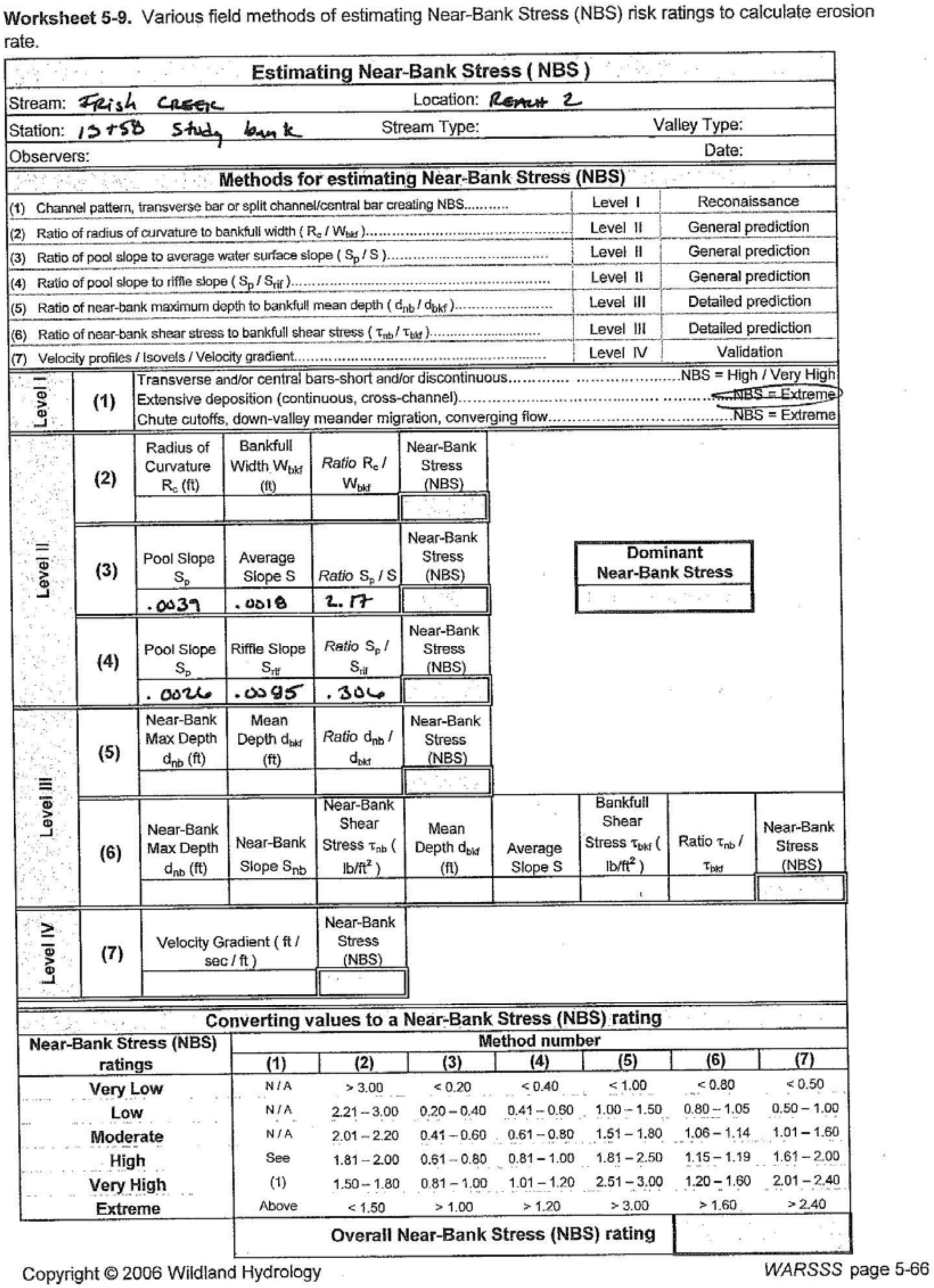


Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Frish Creek Location: Reach 2

Station: 13+58 Study bank Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous........ ....NBS = High / Very High
Extensive deposition (continuous, cross-channel)........ ....[✓ NBS = Extreme]
Chute cutoffs, down-valley meander migration, converging flow........NBS = Extreme

Level II

(2)

Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)

Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
.0039	.0018	2.17	

(4)

Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
.0026	.0085	.306	

Dominant Near-Bank Stress

Level III

(5)

Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)

Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

Level IV

(7)

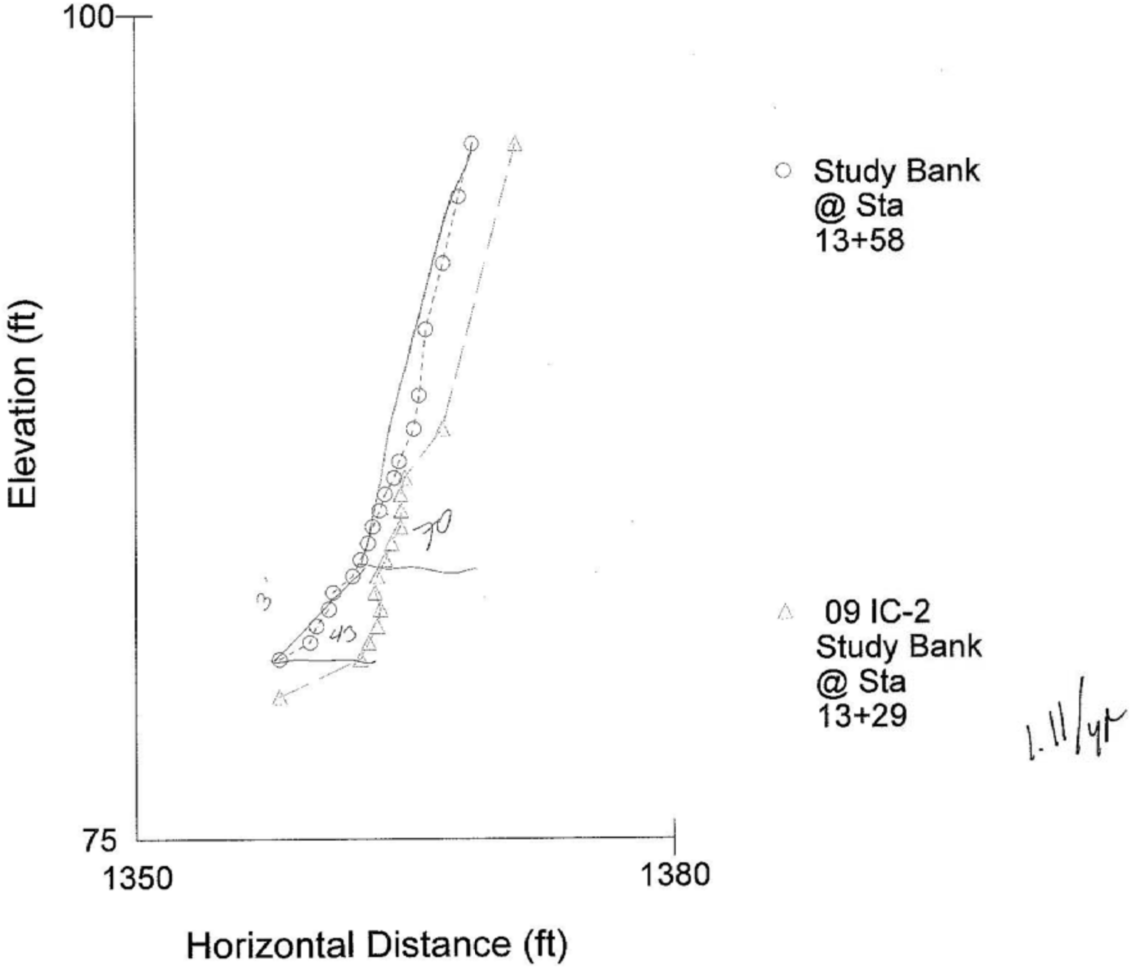
Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

IC 2 Study


100
75
Elevation (ft)
1350
1380
Horizontal Distance (ft)
○ Study Bank @ Sta 13+58
△ 09 IC-2 Study Bank @ Sta 13+29
3'
43
70
1.11/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Irish Creek Location: Reach 3

Station: 5+51 Pool X-sect Observers:

Date: Stream Type: Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	16 (A)	Bankfull Height (ft) =	5 (B)	(A) / (B) = 3.2 (C)	10

Root Depth / Study Bank Height (E)

Root Depth (ft) =	14 (D)	Study Bank Height (ft) =	16 (A)	(D) / (A) = .875 (E)	2

Weighted Root Density (G)

Root Density as % =	10 (F)	(F) x (E) = 8.75 (G)	8.5

Bank Angle (H)

Bank Angle as *Degrees* =	70 (H)	4.5

Surface Protection (I)

Surface Protection as % =	0 (I)	10

Bank Material Adjustment:

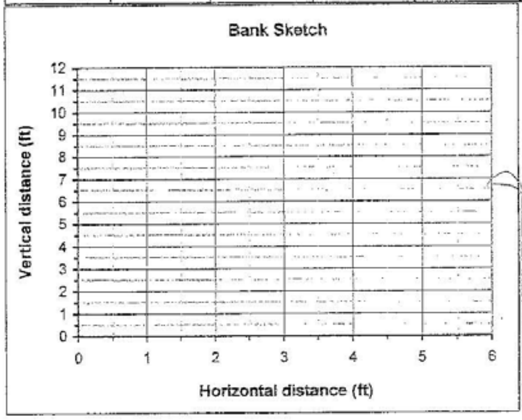
- **Bedrock** (Overall Very Low BEHI)
- **Boulders** (Overall Low BEHI)
- **Cobble** (Subtract 10 points if uniform medium to large cobble)
- **Gravel or Composite Matrix** (Add 5–10 points depending on percentage of bank material that is composed of sand)
- **Sand** (Add 10 points)
- **Silt/Clay** (no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

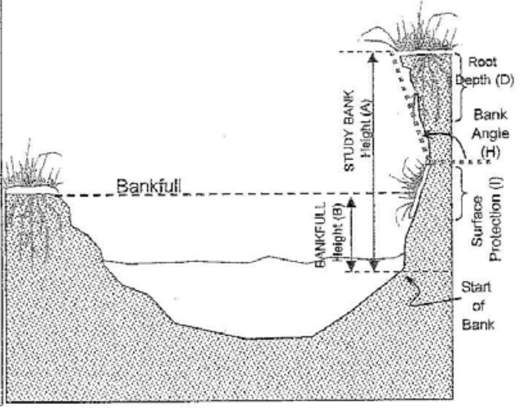
Bank Material Adjustment —

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

Very Low	Low	Moderate	High	Very High	Extreme	Adjective Rating and Total Score
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50	High 35

Bank Sketch





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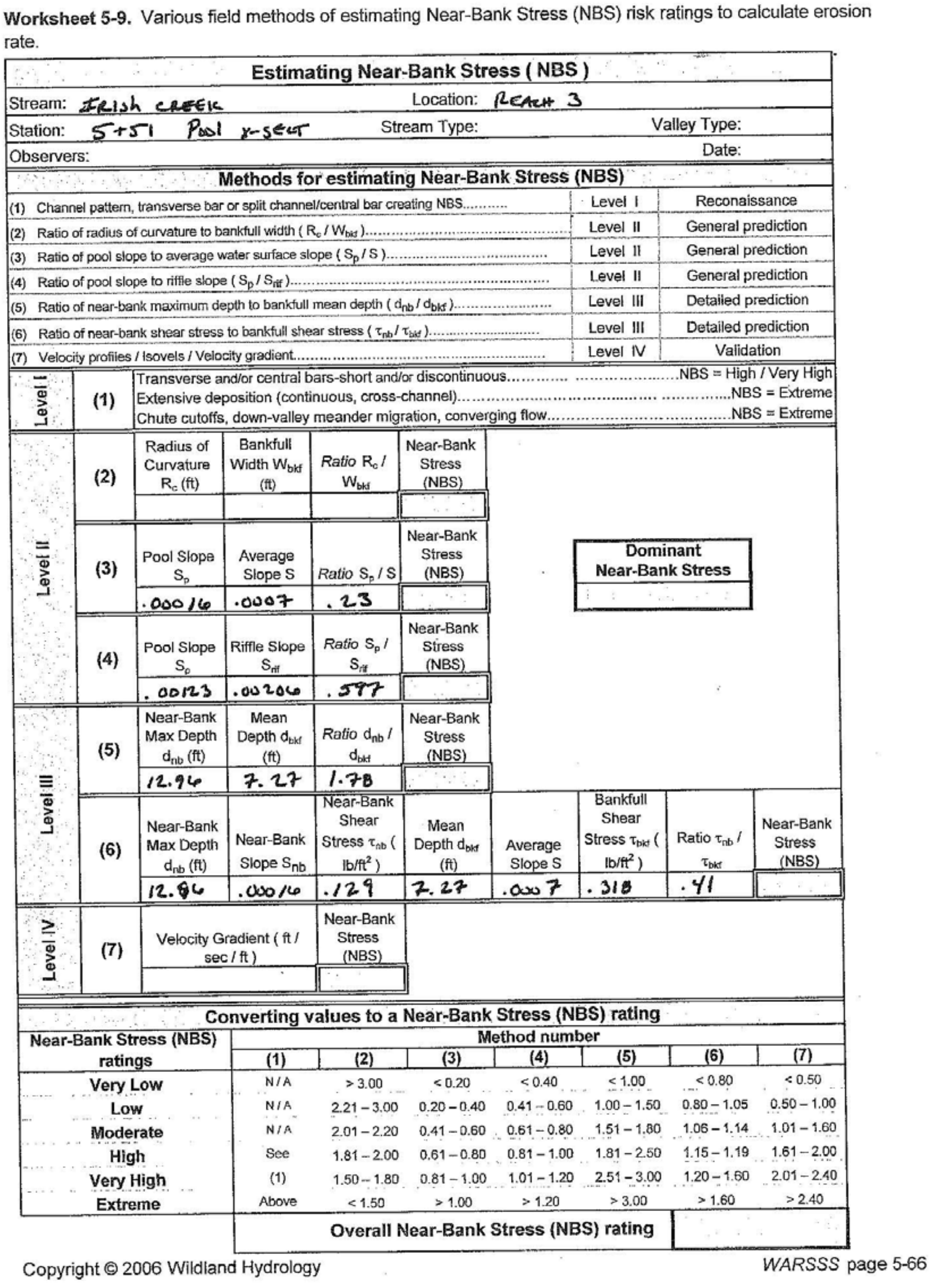


Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: IRISH CREEK Location: REACH 3

Station: 5+51 Pool x-sect Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})........	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)........	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})........	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})........	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})........	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient........	Level IV	Validation

Level I (1)

Transverse and/or central bars-short and/or discontinuous........NBS = High / Very High

Extensive deposition (continuous, cross-channel)........NBS = Extreme

Chute cutoffs, down-valley meander migration, converging flow........NBS = Extreme

Level II

	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)
(2)				

	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
(3)	.00016	.0007	.23	

	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
(4)	.00123	.00206	.597	

Dominant Near-Bank Stress

Level III

	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)
(5)	12.96	7.27	1.78	

	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)
(6)	12.86	.00016	.129	7.27	.0007	.318	.41	

Level IV

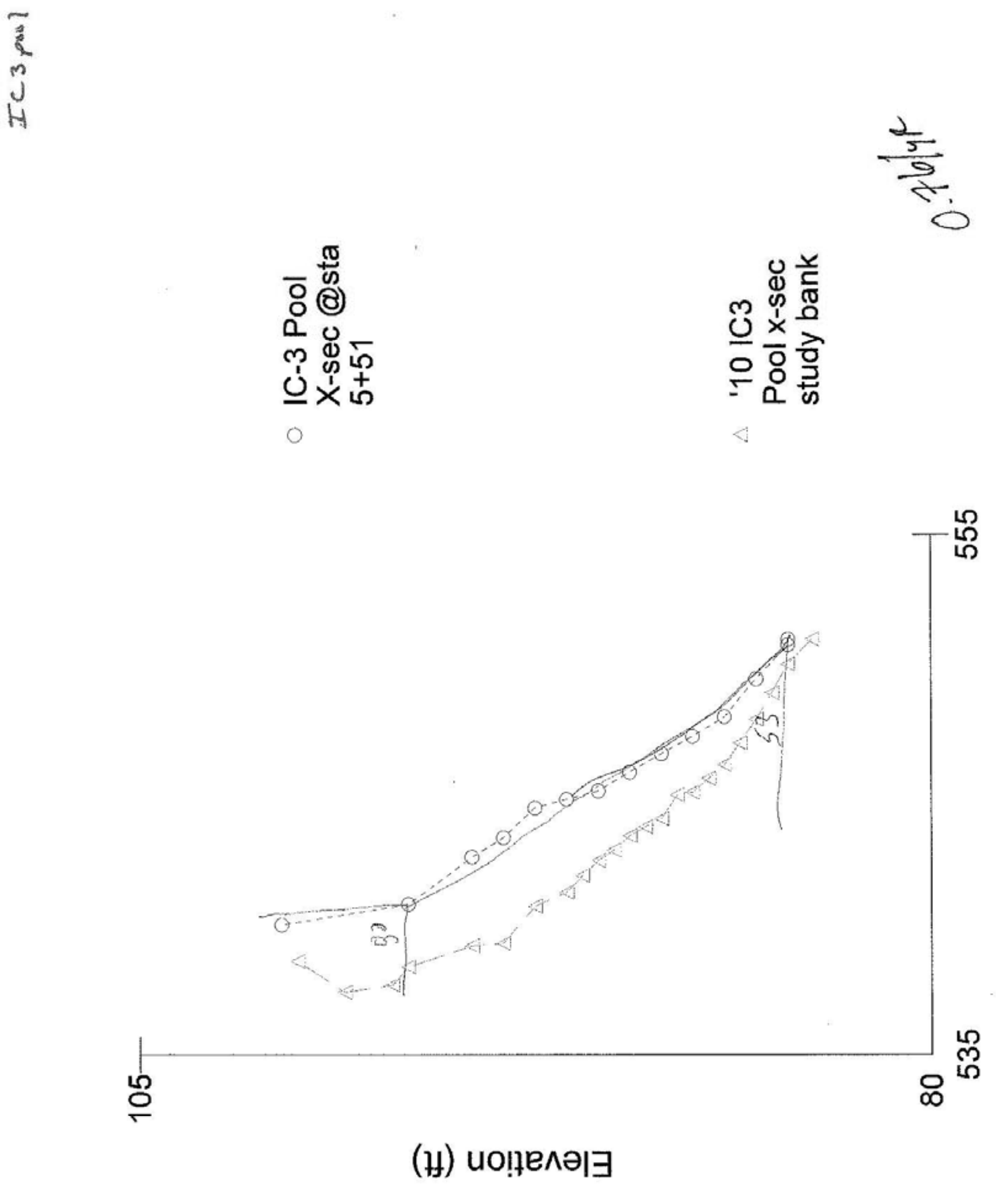
	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)
(7)		

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number (1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N/A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N/A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N/A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating

WARSSS page 5-66


IC3 pool
105
80
Elevation (ft)
535
555
Horizontal Distance (ft)
53
53
○ IC-3 Pool X-sec @sta 5+51
△ '10 IC3 Pool x-sec study bank
0.7ft/yr

Worksheet 5-8. Form to calculate Bank Erosion Hazard Index (BEHI) variables and an overall BEHI rating (Rosgen, 1996, 2001a). Use **Figure 5-19** with BEHI variables to determine BEHI score.

Stream: Irish Creek Location: Reach 3

Station: 16+47 study bank Observers:

Date: Stream Type: Valley Type:

BEHI Score (Fig. 5-19)

Study Bank Height / Bankfull Height (C)

Study Bank Height (ft) =	13 (A)	Bankfull Height (ft) =	5 (B)	(A) / (B) = 2.6 (C)	9

Root Depth / Study Bank Height (E)

Root Depth (ft) =	13 (D)	Study Bank Height (ft) =	13 (A)	(D) / (A) = 1 (E)	1

Weighted Root Density (G)

Root Density as % =	30 (F)	(F) x (E) = 30 (G)	5.9

Bank Angle (H)

Bank Angle as Degrees =	80 (H)	5.9

Surface Protection (I)

Surface Protection as % =	0 (I)	10

Bank Material Adjustment:

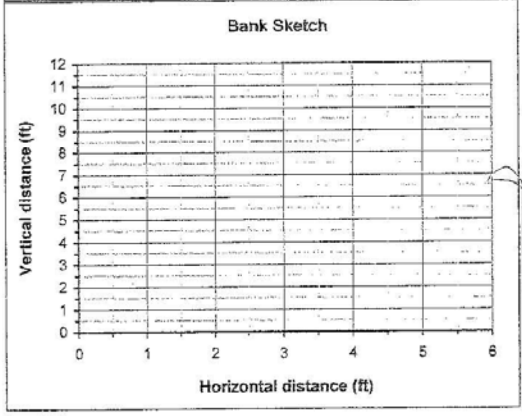
Bedrock (Overall Very Low BEHI)
Boulders (Overall Low BEHI)
Cobble (Subtract 10 points if uniform medium to large cobble)
Gravel or Composite Matrix (Add 5–10 points depending on percentage of bank material that is composed of sand)
Sand (Add 10 points)
Silt/Clay (no adjustment)

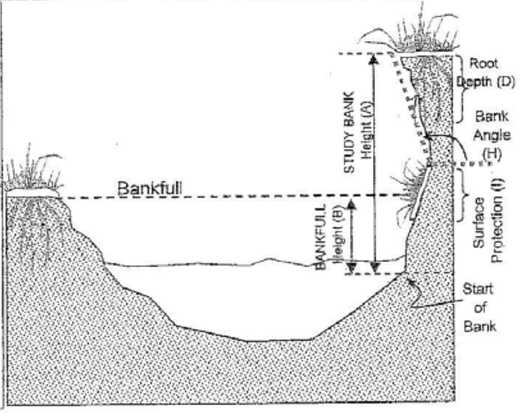
Bank Material Adjustment —

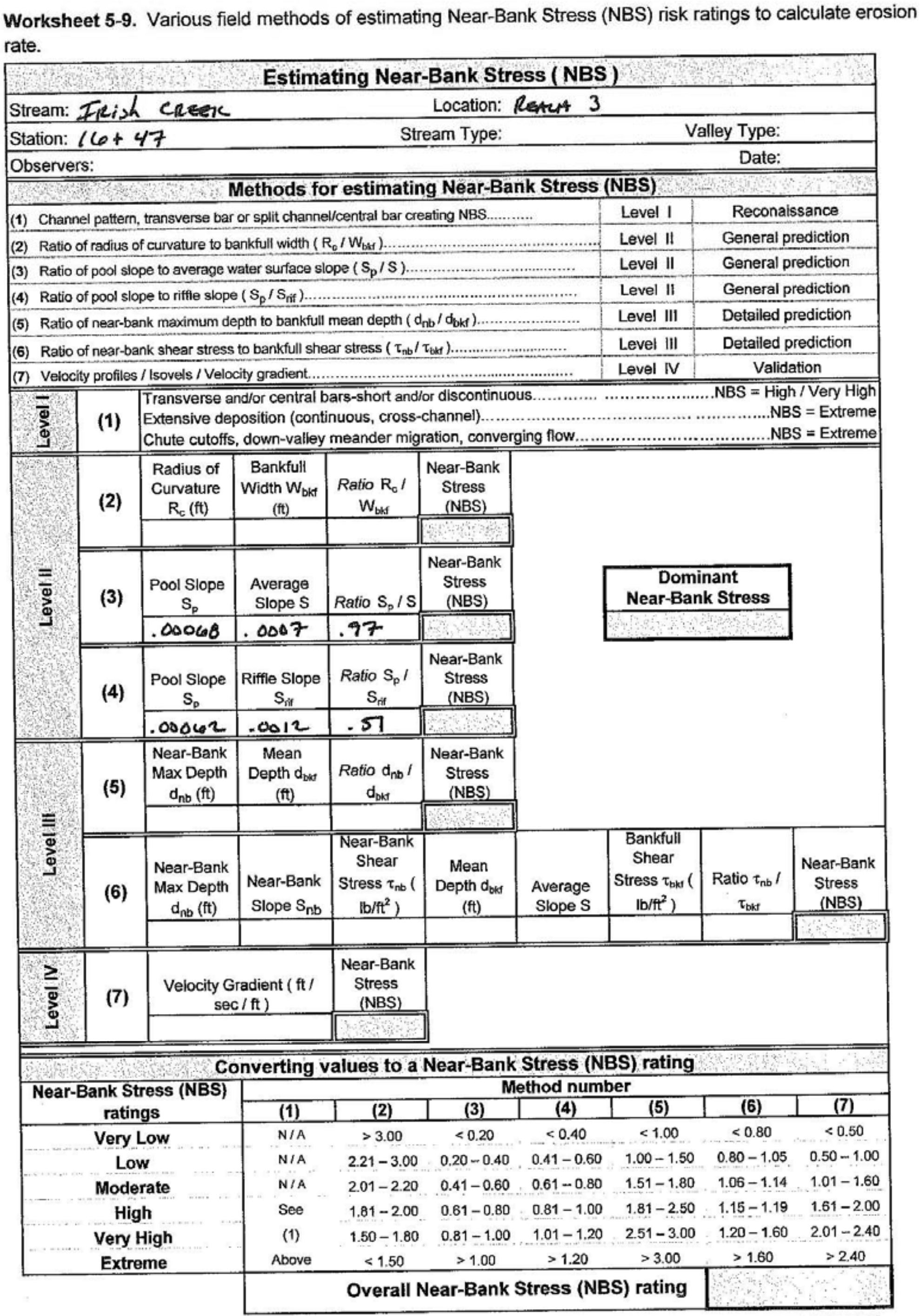
Stratification Adjustment
Add 5–10 points, depending on position of unstable layers in relation to bankfull stage —

Very Low	Low	Moderate	High	Very High	Extreme
5 – 9.5	10 – 19.5	20 – 29.5	30 – 39.5	40 – 45	46 – 50

Adjective Rating and **Total Score**: High 31.9







Worksheet 5-9. Various field methods of estimating Near-Bank Stress (NBS) risk ratings to calculate erosion rate.

Estimating Near-Bank Stress (NBS)

Stream: Irish Creek Location: Reach 3

Station: 16+47 Stream Type: Valley Type:

Observers: Date:

Methods for estimating Near-Bank Stress (NBS)

(1) Channel pattern, transverse bar or split channel/central bar creating NBS..........	Level I	Reconaissance
(2) Ratio of radius of curvature to bankfull width (R_c / W_{bkf})..................	Level II	General prediction
(3) Ratio of pool slope to average water surface slope (S_p / S)..................	Level II	General prediction
(4) Ratio of pool slope to riffle slope (S_p / S_{rif})..................	Level II	General prediction
(5) Ratio of near-bank maximum depth to bankfull mean depth (d_{nb} / d_{bkf})..................	Level III	Detailed prediction
(6) Ratio of near-bank shear stress to bankfull shear stress (τ_{nb} / τ_{bkf})..................	Level III	Detailed prediction
(7) Velocity profiles / Isovels / Velocity gradient..................	Level IV	Validation

Level I

(1)
Transverse and/or central bars-short and/or discontinuous.............NBS = High / Very High
Extensive deposition (continuous, cross-channel).............NBS = Extreme
Chute cutoffs, down-valley meander migration, converging flow.............NBS = Extreme

Level II

(2)	Radius of Curvature R_c (ft)	Bankfull Width W_{bkf} (ft)	*Ratio* R_c / W_{bkf}	Near-Bank Stress (NBS)

(3)	Pool Slope S_p	Average Slope S	*Ratio* S_p / S	Near-Bank Stress (NBS)
	.00068	.0007	.97	

(4)	Pool Slope S_p	Riffle Slope S_{rif}	*Ratio* S_p / S_{rif}	Near-Bank Stress (NBS)
	.00062	.0012	.51	

Dominant Near-Bank Stress

Level III

(5)	Near-Bank Max Depth d_{nb} (ft)	Mean Depth d_{bkf} (ft)	*Ratio* d_{nb} / d_{bkf}	Near-Bank Stress (NBS)

(6)	Near-Bank Max Depth d_{nb} (ft)	Near-Bank Slope S_{nb}	Near-Bank Shear Stress τ_{nb} (lb/ft^2)	Mean Depth d_{bkf} (ft)	Average Slope S	Bankfull Shear Stress τ_{bkf} (lb/ft^2)	Ratio τ_{nb} / τ_{bkf}	Near-Bank Stress (NBS)

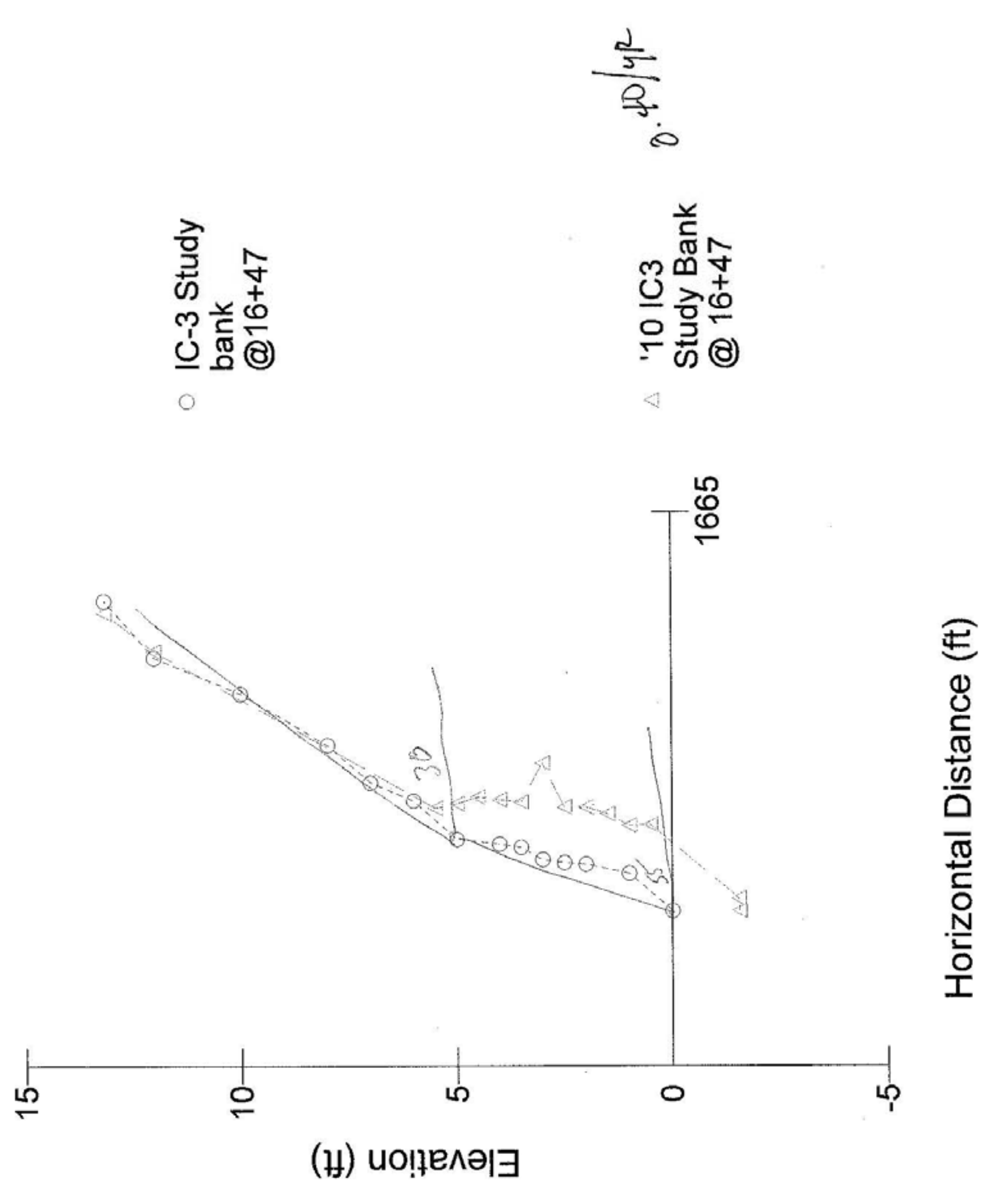
Level IV

(7)	Velocity Gradient (ft / sec / ft)	Near-Bank Stress (NBS)

Converting values to a Near-Bank Stress (NBS) rating

Near-Bank Stress (NBS) ratings	Method number						
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Very Low	N / A	> 3.00	< 0.20	< 0.40	< 1.00	< 0.80	< 0.50
Low	N / A	2.21 – 3.00	0.20 – 0.40	0.41 – 0.60	1.00 – 1.50	0.80 – 1.05	0.50 – 1.00
Moderate	N / A	2.01 – 2.20	0.41 – 0.60	0.61 – 0.80	1.51 – 1.80	1.06 – 1.14	1.01 – 1.60
High	See	1.81 – 2.00	0.61 – 0.80	0.81 – 1.00	1.81 – 2.50	1.15 – 1.19	1.61 – 2.00
Very High	(1)	1.50 – 1.80	0.81 – 1.00	1.01 – 1.20	2.51 – 3.00	1.20 – 1.60	2.01 – 2.40
Extreme	Above	< 1.50	> 1.00	> 1.20	> 3.00	> 1.60	> 2.40

Overall Near-Bank Stress (NBS) rating


IC 3 study
0.40/yr
IC-3 Study bank @16+47
'10 IC3 Study Bank @ 16+47
15
10
5
0
-5
Elevation (ft)
Horizontal Distance (ft)
1665
30
55