

**Estimating streambank erosion using GPS-based watershed-scale video  
mapping and USEPA BANCS for the development of sediment TMDLs**

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## Abstract

According to the United States Environmental Protection Agency (USEPA), sediment is one of the most common water pollutants in the nation's rivers. Consequently, the identification of streambank locations with high erosion potential is important in reducing sediment input via management and monitoring practices. Furthermore, the estimation of erosion rates and sediment loads can assist in the development of Total Maximum Daily Loads (TMDLs). The objective of this study was to integrate two USEPA-recommended approaches with the Streambank Video Mapping System (SVMS) in order to predict site-specific Total Daily Sediment Loads (TDSLs) and calculate sediment TMDLs for streambank erosion over several river kilometers. The SVMS, a GPS-based watershed-scale data collection method, was incorporated with the USEPA-approved Bank Assessment for Non-point source Consequences of Sediment (BANCS) model to evaluate streambank erodibility using the Bank Erosion Hazard Index (BEHI) and stream erosivity using Near Bank Stress (NBS). The SVMS was implemented to collect georeferenced video footage of streambank condition using three above water cameras mounted on a kayak. In addition, GPS and stream width were concurrently recorded. The video was ocularly evaluated using four parameters of a modified BEHI (mBEHI): bank angle, bank height to bankfull ratio, surface protection, and riparian diversity. The site-specific mBEHI scores and NBS scores were used along with the North Carolina Piedmont region erosion prediction curves to estimate annual Bank Erosion Rates (BERs). Additionally, USGS stream gage discharge data was utilized to estimate TDSLs. Sediment TMDLs for streambank erosion were calculated using TDSL estimates and the Maximum Daily Limit (MDL) equation, a statistically-based long-term average approach devised by the USEPA. This integrated methodology was implemented on a 22.5 kilometer section of the Driftwood River in Indiana and a 20.4 kilometer section of Upatoi Creek in Georgia. The Total Sediment Load (TSL) of Driftwood River was  $222 \text{ t yr}^{-1} \text{ km}^{-1}$  [tonnes per year per kilometer] and the TMDL was  $66 \text{ t d}^{-1}$  [tonnes per day]. The TSL for Upatoi Creek was  $109 \text{ t yr}^{-1} \text{ km}^{-1}$  and the TMDL was  $24 \text{ t d}^{-1}$ .

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## **Chapter 1: Introduction**

The United States Clean Water Act (CWA) was passed in 1972 as an amendment to the Federal Water Pollution Control Act (USEPA, 1999). The goal of this act is to protect, preserve, and restore the quality of our nation's rivers, lakes, and streams by eliminating point source pollution and reducing non-point source pollution. If a body of water does not meet the water quality standards of the CWA it is considered impaired and placed on the 303(d) list. Once added to this list, state agencies are required to monitor the waterbody and develop a plan that will restore it to acceptable water quality standards. An increasingly important component of stream restoration plans is a Total Maximum Daily Load (TMDL). This maximum allowable load per unit time is a numerical limit or goal established for pollutants of concern, such as pathogens, mercury, and sediment (USEPA, 1999).

According to the United States Environmental Protection Agency (2002), sediment is one of the most common water pollutants in the nation's rivers. Lane (1955) proposed that a fluvial system is in equilibrium when the sediment load and sediment size are proportional to the river slope and discharge. If one component becomes disproportionate, the system will no longer be in equilibrium, initiating the process of aggradation or degradation. An excess supply of sediment impacts various physical, chemical, and biological functions (Waters, 1995). For example, high concentrations of suspended sediment in water bodies can block sunlight required for photosynthetic processes. Excess sediment eventually settles out of the water column and onto the channel bed. As this occurs, interstitial spaces become clogged, reducing the amount of suitable habitat for benthic macroinvertebrates and fish spawning. Furthermore, sediment-laden water is more difficult to treat and filter causing an increase in the cost of municipal water (Waters, 1995).

Sediment can originate from a variety of sources; however, the most common are erosion due to overland flow and in-stream processes (Knighton, 1998). Overland flow erosion is caused by surface

runoff originating from the landscape adjacent to a stream, while in-stream erosion is caused by fluvial forces and bank or channel instability. Models, such as the Universal Soil Loss Equation (USLE), use topography, climate, soil erodibility, cover, and management practices to estimate sediment loads resulting from overland flow (Morgan, 2005). The resultant sediment load predictions from these models can then be used to develop TMDLs for a particular site (USEPA, 1999). An increasing number of models have been developed to predict erosion rates from in-stream processes since recent studies have attributed between 30 and 80% of the total sediment supply to such sources (Rinaldi and Darby, 2008). Consequently, the identification of stream reaches with high erosion rates may assist in reducing the sediment load to fluvial systems. Therefore, it is important to predict in-stream erosional processes, such as streambank erosion, in order to quantify its contribution to sediment loading and possible water quality issues.

## **Chapter 2: Literature Review**

### **2.1 Factors that Influence Streambank Erosion**

The movement of soil by water occurs in three phases: detachment, transport, and deposition (Troeh et al., 1991). The detachment of a material by wind or water is known as erosion. Water erosion can be sorted into two categories: overland and stream. Furthermore, in-stream erosional processes can be classified as either streambed or streambank. Fluvial entrainment, the removal of soil particles from the bank by the force of water, and mass wasting, episodic events of material collapse from bank instability, are the main types of streambank erosion (ASCE, 1998).

Studies have highlighted the importance of geotechnical and fluvial conditions on bank erosion rates (Hickin and Nanson, 1975; Simon et al., 2000; Thorne and Tovey, 1981). These mechanisms are dependent on various flow regimes and physiographic attributes such as topography, climate, and soil properties (ASCE, 1998). As a result, the rate of erosion is a function of the erodibility of a material and the erosivity of a force (Knighton, 1998; Rosgen, 2001; Simons and Li, 1982). Streambank erodibility, the susceptibility of bank material to erosional forces, is a function of the geotechnical structure of streambank material such as height, angle, surface protection, type of riparian vegetation, pore water pressure, and material properties (Knighton, 1998). These bank characteristics have a combined effect on bank stability (Osman and Thorne, 1988). Stream erosivity is the propensity of water to cause erosion, which is influenced by stream hydraulics (Knighton, 1998). Flow rate, channel pattern, and channel slope are hydraulic properties that influence the magnitude and distribution of near bank stress (Hickin and Nanson, 1975). Thus, in order to model lateral streambank erosion rates, it is essential to acknowledge the interrelationship between hydraulic and geotechnical processes as well as predict the influence of both erodibility and erosivity factors (Midgley et al., 2012; Rosgen, 2001).

### 2.1.1 Geotechnical Processes

Riparian vegetation increases bank stabilization (Pollen, 2007; Smith, 1976; Thorne, 1990). A study in British Columbia, Canada used aerial photography from pre- and post-flood events in 1990 to determine the impact of vegetation on streambank erosion rates for 748 meander bends along four representative streams (Beeson and Doyle, 1995). Bends without riparian vegetation were five times more likely to have visual erosion than bends with established vegetation. The presence or absence of riparian vegetation, as a result of land management, has also been shown to impact streambank erosion rates. In central Iowa, Zaines et al. (2006) used erosion pins on sections of Bear Creek to record streambank recession rates over a four-year period. The erosion rates for three adjacent land use types were compared and significantly less erosion was observed on reaches with a forested riparian buffer. Sediment loading per unit stream length was also estimated for each land use with the following results: forested riparian buffer (75 tonnes km<sup>-1</sup>), row-crop fields (484 tonnes km<sup>-1</sup>), and grazed pastures (557 tonnes km<sup>-1</sup>). Furthermore, it was estimated that bank erosion rates could be reduced by 77 to 97% if riparian buffers were established along the stream corridors lacking vegetation (Zaines et al., 2006).

Pollen (2007) signified the importance of soil, strong in compression but weak in tension, and roots, weak in compression but strong in tension, in forming a soil-root matrix. Through experimental studies, Smith (1976) found erosion rates decreased as the percentage of roots in the soil increased. Consequently, roots provide a reinforcing effect by adding tensile and shear strength to bank material. The type of riparian vegetation is also important in predicting bank stabilization, because the reinforcing effect of the soil-root matrix is only present to the extent of rooting depth (Thorne, 1990). Grasses and other herbaceous vegetation have dense root systems in the upper bank profile whereas trees and other woody vegetation have less dense root systems but greater rooting depths (Smith, 1976; Wynn et al., 2004). Using the CONCEPTS model to predict streambank erosion, Langendoen (2000) found the low rooting depth to bankfull height ratio of grassy vegetation resulted in negligible bank stabilization.

Similarly, Davies-Colley (1997) observed undercutting of the lower bank, known as the bank toe, at sites with grassy riparian vegetation. Thorne and Tovey (1981) identified cantilever failure as a type of mass wasting that occurs when undercutting of the bank toe by hydraulic forces results in an overhang with low bank stability. Therefore, both root depth and root density impact streambank stabilization.

Bank stability is also a function of soil (mechanical) strength and is directly related to bank geometry (Osman and Thorne, 1988). Hydraulic erosion increases both the bank height, by scouring the channel bed, and bank angle, by undercutting the bank toe. An increase in either of these geotechnical properties decreases bank stability and will result in mass wasting when gravitational driving forces exceed the resistive forces of cohesion and friction (ASCE, 1998). Simon et al. (2009) used the Bank Stability and Toe Erosion Model (BSTEM) to predict sediment loads along three stream reaches within the Lake Tahoe drainage basin. Bank toe erosion contributed approximately 14% of the total sediment load from streambank erosion and resulted in five mass failure events. Adding toe stabilization practices to the model reduced the total bank erosion load by almost 90% and decreased the occurrence of mass failure to a single event (Simon et al., 2009). This result demonstrates the strong relationship between hydraulic forces, toe erosion, and the frequency of mass wasting events.

Streambank stabilization practices, such as rip rap, are installed to decrease bank erodibility and increase shear resistance by decreasing the percentage of exposed bank material and increasing surface roughness (Biedenharn et al., 1997; Simon et al., 2011). An increase in bank surface roughness diverts stream flow and associated hydraulic forces to the channel center (Wynn, 2006). Consequently vegetative material, such as stems, leaves, woody debris, and protruding roots, as well as rocks provide bank surface protection by deflecting flow and decreasing the magnitude of hydraulic forces on the bank surface (Wynn, 2006).

### 2.1.2 Hydraulic Processes

Lateral migration rates of channel bends are directly related to channel curvature, discharge, and water surface slope (Hickin and Nanson, 1975). As water flows around a meander bend, water velocity increases near the outside bank. Velocities can exert twice as much hydraulic force on bends compared to straight sections of stream. The channel curvature component is known as the radius of curvature to channel width ratio ( $R_c/W$ ). A circle is drawn to fit the shape of a meander bend, the radius of which is the radius of curvature. This value is useful in predicting meander bend migration as well as bank erosion rates (Biedenharn et al., 1997). In a dendrochronological study on the Beatton River in British Columbia, Hickin and Nanson (1975) established a relationship between meander migration and  $R_c/W$  by fitting field measurements with regression equations. Based on results, the authors suggested an  $R_c/W$  component be included in any model predicting lateral migration rates for a meandering channel. Hudson and Kesel (2000) also found a relationship between meander bend migration and  $R_c/W$  for the lower Mississippi. Most meander migration occurred at  $R_c/W$  values of approximately one and migration rates decreased as the value of  $R_c/W$  increased. Consequently, holding width constant, streams with sharper bends (i.e. shorter radius of curvature) were experiencing greater rates of lateral migration (Hudson and Kesel, 2000).

The influence of stream discharge on bank erosion rates is difficult to establish due to the complexity of fluvial systems (ASCE, 1998). Magnitude, frequency, and rate of sediment loading were found to be regionally influenced by climate, topography, soil properties, and vegetation (Benda and Dunne, 1997). Furthermore, sediment loading is driven by spatial and temporal variability in stream flow and rainfall. On an annual basis, Wolman and Miller (1960) observed the largest amount of sediment transport occurring at small to moderate discharge events. The flow at which 90% of the total annual sediment was transported had a 1.4 to 5-year recurrence interval based on daily discharge duration curves for Brandywine Creek at Wilmington, Delaware and Rio Puerco near Bernardo, New Mexico

respectively. As a result, high frequency, moderate flow events were more effective in transporting sediment on an annual basis than low frequency, high flow events (Wolman and Miller, 1960).

Julian and Torres (2006) looked at event peak, variability, duration, and magnitude as explanatory variables for streambank erosion along three monitored transects on the upper reach of Sand River in Aiken, South Carolina. Event peak had the strongest correlation to hydraulic erosion of cohesive streambanks at the two transects with moderate critical shear stress while event variability had the strongest correlation at one transect with low critical shear stress. Hooke (1979) completed a multiple regression analysis using bank erosion pin measurements in order to determine the main parameters controlling the magnitude and distribution of erosion over a 2.5 year period in Devon, England. Fluvial erosion and mass wasting were the two bank erosion processes responsible for a majority of lateral incision events. Fluvial erosion was attributed to flow condition and mass wasting was attributed to streambank soil moisture (Hooke, 1979).

A study by Bledsoe and Watson (2001) focused on stream power and its relationship to channel characteristics and flow rates in urban watersheds. The impacts of urbanization on the stream system were not solely reflected by flow magnitudes. Streambank stability was also related to the characteristics of the receiving channel such as bank condition, riparian vegetation, entrenchment and channelization. Consequently, a stream instability risk index should incorporate flow energy as well as channel boundary erodibility. Lawler et al. (1997) also emphasized the difficulty of establishing a relationship between flow energy and erosion rates in channel systems due to the presence of both fluvial entrainment and mass wasting. The issue becomes more complicated when considering the potential for lags in the system between process (i.e. storm events) and channel response (i.e. erosion). To further our understanding of erosional processes, a recommendation was made to measure erosion rates at an event time scale.

The contribution of streambank erosion to the total sediment supply varies between spatial scales (i.e. site, reach, and watershed) and between different time scales. Bull (1997) used turbidity meters to estimate suspended sediment transport and a photo-electronic erosion pin system (PEEP) to obtain streambank erosion rates for various discharge events. Compared to upstream locations, streambank erosion contributed more to the suspended sediment load at downstream locations and during smaller time intervals due to a shift in the dominant mechanisms of in-channel erosion from fluvial entrainment to mass wasting events. Streambank erosion also varied temporally with higher rates occurring in the winter and summer months. Walling et al. (1999) used sediment fingerprinting and mixing models to identify the main sources of suspended sediment in relation to the entire load for River Ouse in Yorkshire, U.K. Streambank erosion had a load weighed mean contribution of 37%. Furthermore, it was noted that streambank erosion had a greater contribution during high flow rather than low flow events. Based on these results, higher discharges result in higher detachment rates. Rutherford (2000) compiled average meander migration rates for various streams by completing a global review of the literature. These rates were plotted against flow in order to establish a relationship between bankfull discharge ( $Q$ ,  $\text{m}^3 \text{s}^{-1}$ ) and lateral migration rates ( $M$ ,  $\text{m yr}^{-1}$ ). Using regression analysis, the highest R-squared value was produced when the data were fit to the following power function:  $M = 0.0435Q^{0.6}$ . Thus, discharge can be used to predict streambank erosion (Rutherford, 2000). Despite the variability in results throughout the literature, flow has been found to have a direct impact on erosion rates for all studies.

## **2.2 Measuring Streambank Erosion**

Erosion pins, bank surveys, and aerial photography are the most traditional methods for determining the lateral erosion rates of streambanks (Lawler, 1993). In general, erosion pins are placed at the bank toe and equally spaced until the top of bank to account for spatial variability in the vertical direction. Pins are horizontally installed when the objective is to determine erosion rates along a length

of bank. As bank recession occurs, the length of pin exposed at the bank face will increase. Erosion pins are initially surveyed and then periodically resurveyed depending on the time frame of interest or the amount of erosion expected (Lawler, 1993). Advances in technology have made it possible to measure the timing and magnitude of erosion rates at an event-scale. The photo-electronic erosion pin system (PEEP) is an automated technique using photo-voltaic cells in an acrylic tube connected to a data logger (Bull, 2007). Tubes are inserted into the bank using the same method as traditional erosion pins. Erosion rates are determined by recording voltage readings since voltage output increases in proportion to the length of pin exposed to light. Traditional erosion pins are generally cheap, easy to install, and able to detect small amounts of recession,  $\pm 3\text{mm}$  (Lawler, 1993). Due to the in-situ nature of this technique, erosion pins may be lost as a result of bank failure and high flow events. Installation of pins can weaken the bank face and subsequently increase erosion susceptibility. Additionally, pins cannot be used on banks dominated by non-cohesive material, such as sand and gravel, due to geotechnical instability.

Bank surveys are completed at fixed locations along the bank with permanent benchmarks established to ensure measurement accuracy (Lawler, 1993). Erosion rates are determined by taking the difference of bank profile areas between surveys. Unlike erosion pins, this technique requires the use of survey equipment and a two person team to collect the data. Measurement accuracy and precision are dependent upon the survey equipment and data collectors (Lawler, 1993). Both measurement methods require a time investment during installation and subsequent site visits.

Long-term erosion rates can also be determined by overlaying photographs from different time periods (Lawler, 1993). Aerial photography is particularly useful for studies focused on stream channel adjustment. The determination of bank erosion is limited to years with photographic record and is sensitive to spatial scale. A study by Harmel et al. (1999) was unable to detect lateral erosion rates less than two meters because of the small scale of the images. Aerial photos can also be used to qualitatively

assess erosion rates by noting the presence or absence of erosion (Beeson and Doyle, 1995). Despite the ease of obtaining and assessing photographs, positional errors and image distortions may occur when rectifying a photo (Lawler, 1993).

Often, erosion pins and bank surveys are conducted to establish a relationship between empirically derived data and parameters influencing the erosion process (Knighton, 1998; Rosgen, 2001). Furthermore, measured bank erosion rates can be used to validate or modify a model, especially if the model will be used in a new physiographic region. Subsequently, direct field measurements or ocular estimates of bank and channel parameters can be used as inputs to streambank erosion prediction models (Rosgen, 2001; Simon et al., 2009).

### **2.3 Predicting Streambank Erosion**

Streambank erosion is a complex process involving numerous variables that impact rates both spatially and temporally (ASCE, 1998). Streambank erosion and habitat indices have been established by academic and governmental agencies. An extensive review of these indices, including parameters assessed, was completed by Connell (2012). Unfortunately, most of these indices do not integrate the erosional influences of bank conditions and fluvial processes (Rinaldi and Darby, 2008). Furthermore, the goal of most erosion indices is not to predict erosion rates, but to identify the locations of current and/or future erosion potential (USEPA, 1999).

Erosion prediction models are focused on the rates of erosion over various time scales. These models are often used when direct field measurements are too costly, intrusive, or energy/time intensive (Morgan, 2005). Some models are software based while others require the collection of field data. Models that predict streambank erosion can prove beneficial in determining the location and appropriate design for stream restoration projects as well as developing water quality TMDLs for streambank sources (Smith et al., 2011). TMDL development must assess the type, location, and

magnitude of a pollutant. Models are increasingly being used to develop TMDLs by predicting source loading, estimating the quality of receiving water bodies, and allocating load reductions. These models range from simplistic generalized functions using one or two physical parameters to complex algorithms with intensive data analysis capabilities (Borah et al., 2006). Selection of the most feasible model is based on various time, labor, and cost constraints. The model user must also understand the required inputs, resultant outputs, assumptions, and limitations in order to make the most appropriate selection (Borah et al., 2006).

An effective model should predict the loading rates of all potential sources for a target pollutant. Neglecting sources may result in the selection of inefficient management practices (Gellis and Walling, 2011; Mukundan et al., 2011). Consequently, if a model is being used to develop sediment TMDLs, it should include both upland and in-channel sediment sources. Unfortunately most erosion models do not include a function to predict in-channel sediment sources, such as streambank erosion (Borah et al., 2006; USEPA, 1999). A report by Shoemaker et al. (2005) evaluated the research needs of various TMDL models. In this report, out of the 35 watershed and receiving water models capable of predicting sediment loads for river systems, only 10 had a sediment component that included streambank erosion. This report as well as a report by Borah et al. (2006) suggested that streambank erosion be incorporated into sediment transport models, especially if the models are being used to develop sediment TMDLs. Neglecting this direct supply of sediment to the stream system may result in loading estimates that are missing a large component of the total sediment supply for small-scale stream sections or large-scale watershed assessments (Gellis and Walling, 2011). Recent studies have attributed between 30 and 80% of the total sediment supply to in-stream processes (Rinaldi and Darby, 2008). Models such as SWAT, BSTEM, AVGWLF, and BANCS have incorporated algorithms to predict streambank erosion rates in order to quantify sediment loading from this in-stream process (Rosgen, 2001; Evans et al., 2003, Simon et al.,

2009). Thus, using streambank erosion prediction models is a key component in developing a robust TMDL for sediment (Borah et al., 2006; Gellis and Walling, 2011).

### 2.3.1 Excess Shear Stress

Models that employ the sediment transport equation to predict hydraulic erosion of streambanks compute erosion rates using the following excess shear stress principal (Partheniades, 1965; Wolman and Miller, 1960):

$$E = k (\tau_o - \tau_c) \quad (1)$$

$E$ = erosion rate (cm)

$k$ = erodibility constant ( $\text{cm}^3 \text{N}^{-1} \text{s}^{-1}$ )

$\tau_o$ = average boundary shear stress (Pa)

$\tau_c$ = critical shear stress (Pa)

Critical shear stress, a function of soil strength, depends on material cohesion resulting from inter-particle and biological interactions, whereas boundary shear stress depends on the average value of stress imposed by fluvial forces (Papanicolaou et al., 2007). Erosion does not occur until the average boundary shear stress exceeds the critical shear stress for a specific material. The erodibility constant and critical shear stress value can either be measured by employing in-situ submerged jet tests or estimated by empirically derived relationships (Hanson and Simon, 2001).

In its simplest form, the excess shear stress equation can be written as the following power function:  $q = X^n$ , where  $q$  is the rate of detachment,  $X$  is a stress, and  $n$  is a calibration coefficient (Wolman and Miller, 1960). This excess shear stress equation has been used in field experiments as well as multiple soil erosion models (Clark and Wynn, 2007; Hanson, 1990; Simon et al., 2009).

### 2.3.2 BSTEM

The Bank Stability and Toe Erosion (BSTEM) model was developed by the United States Department of Agriculture – Agricultural Research Service (USDA-ARS) through the National Sediment Laboratory (Midgley et al., 2012). The bank stability submodel allows the user to input bank geometry, soil material, vegetation, and pore-water pressure. In order to account for the vertical heterogeneity of bank material, up to five soil layers can be generated in the model. The output of the bank stability submodel is a numerical value referred to as the factor of safety (Simon et al., 2009). This value is generated based on the difference between driving and resistive forces acting on the bank. Driving forces include steep bank angle, tall bank height, and non-cohesive material while resistive forces include surface protection, shallow bank angle, low bank height, and cohesive material. The factor of safety (FS) is classified into the following three categories:  $FS < 1$  is unstable,  $FS > 1.3$  is stable, and FS from  $1 - 1.3$  is conditionally stable. The toe erosion submodel predicts hydraulic erosion of the bank and bank toe based on the excess shear stress equation (eq. 1). The critical shear stress is estimated for cohesive material using a relationship developed by Hanson and Simon (2001) or for non-cohesive material using Shields dimensionless critical shear stress equation. The average boundary shear stress is estimated using a direct relationship between the unit weight of water ( $9.81 \text{ kN m}^{-3}$ ), hydraulic radius (m), and channel slope ( $\text{m m}^{-1}$ ) (Simon et al., 2009).

Once the bank stability inputs have been entered, the model predicts the amount of hydraulic erosion at current bank conditions (Simon et al., 2009). If toe erosion has occurred, the new geometry is input into the bank stability submodel to determine if the bank is stable. The bank can become unstable as a result of cantilever failure and planar surface failure, which may result from horizontal layers or vertical slices with tension cracks. BSTEM can be run once or iteratively for various scenarios, flow rates, and time periods. The model predicts lateral bank erosion vertically along the bank surface; as a result,

the horizontal length of stream must be known to predict a volumetric rate of erosion. Additionally, this information can be used to predict the effectiveness of various restoration practices.

In a study by Simon et al. (2009), BSTEM was used to predict sediment loading and the effectiveness of bank stabilization methods in reducing sediment loads. An annual hydrograph was employed to estimate flow depths and durations in order to establish the driving hydraulic forces, and then the model was iteratively run for all flow events to predict annual sediment loading. Additionally, the model was run using toe protection and vegetation enhancements. Rock toe protection reduced sediment loading from 69 to 100 percent, and bank top vegetation reduced loading from 42 to 54 percent. The addition of both stabilization methods reduced the amount of hydraulic erosion as well as mass failure events, thus demonstrating the importance of protecting the bank toe from hydraulic forces. Subsequently, the results were used to calculate the cost of protecting the most unstable banks compared to the entire length of stream (Simon et al, 2009). BSTEM proved to be effective in predicting bank erosion from both fluvial entrainment and mass wasting as well as highlighting the need to identify locations of excess erosion.

### 2.3.3 SWAT

The Soil and Water Assessment Tool (SWAT) developed by the USDA-ARS and Texas A&M AgriLife Research is a watershed-scale model that predicts the loading and routing of water, sediment, nutrients, and pesticides for various land management practices (Neitsch et al., 2009). The in-channel erosion algorithm uses the excess shear stress approach (eq. 1). The erodibility constant and critical shear stress can be measured by employing in-situ submerged jet tests (Neitsch et al., 2009). If field data is not available, these parameters can also be estimated using empirically derived relationships: boundary shear stress (Eaton and Millar, 2004), critical shear stress (Julian and Torres, 2006) and erodibility constant (Hanson and Simon, 2001). Resultant critical shear stress values are multiplied by an appropriate bank vegetation coefficient to account for the reinforcing effects of roots. A coefficient of

one is designated for banks lacking riparian vegetation while coefficient values of 1.97 and 19.20 are used for grasses and dense trees, respectively. Erosion rates are predicted for one channel bank, because SWAT assumes active erosion only occurs on the outside bend of a meandering river (Neitsch et al., 2009).

#### 2.3.4 AVGWLF

The Generalized Watershed Loading Function (GWLF) developed by Haith and Shoemaker (1987), simulates watershed characteristics in order to identify and quantify non-point source pollution. The GWLF simulates runoff and sediment loading based on physiographic inputs such as soil type, topography, and climate. The surface runoff component is calculated using the Soil Conservation Service Curve Number method and the monthly sediment loading component is predicted using the Universal Soil Loss Equation (USLE). The ArcView GWLF (AVGWLF) is a revised version of the model that interfaces with Geographic Information Systems (GIS) software (Evans et al., 2003). This model incorporates overland as well as streambank erosion. The routine for streambank erosion predicts the “watershed-specific lateral erosion rate (LER)” as a function of flow (Evans et al., 2003). The LER is predicted using the following formula:

$$LER = \alpha Q^{0.6} \quad (2)$$

LER= lateral erosion rate ( $\text{m mo}^{-1}$ )

Q= average monthly stream discharge ( $\text{m}^3 \text{s}^{-1}$ )

$\alpha$ = empirically derived watershed constant, where

$$\alpha = (0.00147 \cdot \text{PD}) + (0.000143 \cdot \text{AD}) + (0.000001 \cdot \text{CN}) + (0.000425 \cdot \text{KF}) + (0.000001 \cdot \text{MS}) - 0.000016$$

PD= percent developed land in watershed

AD= animal density, animal equivalent units per acre

CN= area-weighted curve number of watershed

KF= area-weighted soil erodibility factor of watershed

MS= mean topographic slope (%) of watershed

Additionally, the sediment load resulting from streambank erosion can be calculated by multiplying together the LER, total stream length, average streambank height, and average soil bulk density. All values are in metric units and generalized for the entire watershed (Evans et al., 2003).

#### 2.3.5 BANCS

The USEPA-approved Bank Assessment for Non-point source Consequences of Sediment (BANCS) model utilizes two indices to integrate the components of erosion mentioned previously: erodibility and erosivity (Rosgen, 2009). The Bank Erosion Hazard Index (BEHI) estimates streambank erodibility by characterizing the erosion susceptibility of a bank using five bank condition parameters: ratio of bank height to bankfull height, root density, ratio of root depth to bank height, bank angle, and surface protection. Each parameter is given a BEHI score from 1 to 10 associated with erosion susceptibility ratings ranging from very low to extreme (Table 2.1). The total BEHI score for a streambank location is the summation of all five BEHI parameters. For a watershed-scale BANCS assessment or for site-specific predictions, an observer can employ an ocular method to determine BEHI indexes by calibrating field measurements with visual estimates. Near Bank Stress (NBS) estimates stream erosivity by characterizing the distribution of hydraulic forces against a streambank using one of seven methods including velocity gradients, water surface slopes, depth ratios, and channel patterns –  $R_c/W$  (Rosgen, 2009).

Table 2.1. Bank Erosion Hazard Index (Rosgen, 2009).

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

While the BANCS model can be used to identify highly eroded areas, it can also be combined with established bank erosion prediction curves in order to graphically predict lateral Bank Erosion Rates (BERs) on an annual basis. Bank erosion prediction curves have been developed for various physiographic regions in order to correlate BEHI and NBS scores for the estimation of annual erosion rates in feet per year. Rosgen (2001) developed BER curves for the Yellowstone region in Montana and the Fort Range in Colorado. Recently curves were established for Sequoia National Forest, a colluvium dominated region in California, to evaluate post-wildfire impacts on streambank recession (Kwan and Swanson, 2014). BER curves are generated by collecting field measurements of erosion rates from streambank locations with different BEHI and NBS score combinations. The BEHI and NBS scores of each site are plotted on a graph with the measured annual erosion rate as the dependent variable (Figure 2.1). The y-axis represents the annual BER on a logarithmic scale while the x-axis represents the NBS index scores. Linear regression lines represent the moderate, high, very high, and extreme BEHI ratings.

Therefore, BERs can be predicted once the BEHI and NBS scores are determined for each streambank location. Information regarding the methodology and application of the BANCS model for the prediction of total streambank erosion rates can be found on the USEPA website (<http://www.epa.gov/warsss/>).

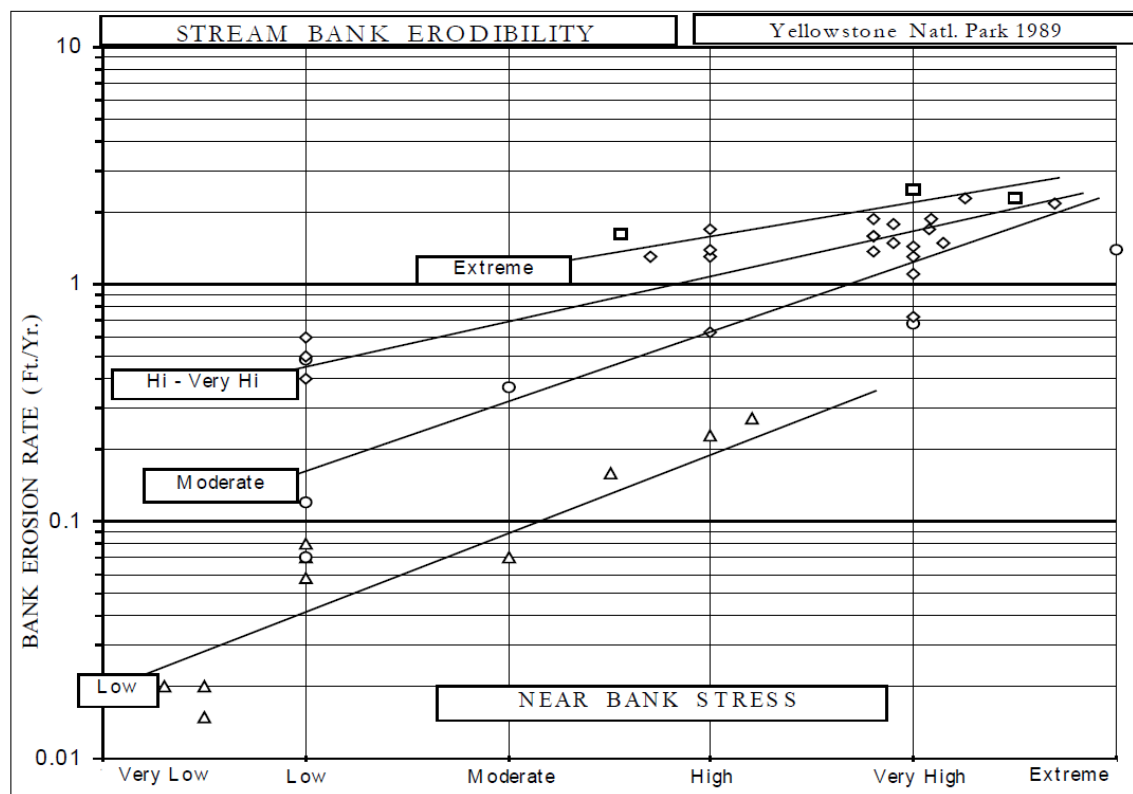


Figure 2.1. Yellowstone Region Bank Erosion Prediction Curves (Rosgen, 2001)

Rather than generating new regional relationships, several streambank erosion studies have been conducted using previously established BER curves to compare predicted and measured results. Rosgen (2001) used the Yellowstone region curve to predict BERs for the East Fork of the San Juan River in Southern Colorado, because both river systems were classified as braided channels. By incorporating various BEHI and NBS combinations, the predicted rates differed from measured rates by  $0 - 0.12 \text{ m yr}^{-1}$  (Rosgen, 2001). Other BANCS assessments have employed multiple BER curves in order to compare predicted bank erosion rates between different regional relationships. Using various BEHI and NBS combinations in the moderate to extreme categories, predicted values from the West Fork White River (WFWR) watershed curves were compared to predicted values when utilizing the North Carolina and Colorado BER curves. The WFWR curve predicted BERs that ranged from 1.3 to 2.8 times greater than the other two curves (Van Eps et al., 2004). Differences in physiographic characteristics such as soil and precipitation along with dissimilarities in watershed areas can result in erroneous BER predictions. Therefore, BER curves should be carefully selected based on physiographic similarities between a study site and regional area.

Multiple studies have implemented the BANCS model as a means of estimating bank erosion rates and sediment loading. Van Eps et al. (2004) used BEHI and NBS scores along with lateral erosion rates derived from bank surveys to generate bank erosion prediction curves for the West Fork White River watershed in Northwest Arkansas. According to the results, streambanks were annually supplying 21,455 metric tons of sediment into the river system over a length of 64 river kilometers. A study on the Housatonic River assessed 24,928 linear meters of streambank using an ocular assessment of the BANCS model and the North Carolina Piedmont region erosion prediction curves (Stantec, 2009). It was estimated that 5,625 tonnes of sediment entered the river system annually.

Studies have also collected erosion measurements in the field as a way to validate the BANCS model. Harmel et al. (1999) conducted an evaluation in Northeastern Oklahoma by installing erosion

pins on streambanks with various BEHI and NBS ratings. The study found BEHI to be a good predictor of erosion. Another study was completed along the Haora River of Tripura in the country of India, where thirty cross-sections were established and annually surveyed over a three year period (Bandyopadhyay et al., 2013). Approximately 75% of the surveyed streambanks had erosion rates similar to the designated BEHI and NBS ratings.

#### 2.3.6 Model Limitations

BSTEM and SWAT use the excess shear stress approach to predict fluvial erosion, which requires the following inputs: critical shear stress ( $\tau_c$ ), average boundary shear stress ( $\tau_o$ ), and the erodibility constant ( $k$ ) (Simon et al., 2009; Neitsch et al., 2009). Estimated values of these parameters can therefore induce bias into the models (ASCE, 1998). In a comparison study by Clark and Wynn (2007), in-situ jet test measurements found  $k$  values up to two orders of magnitude greater than estimated  $k$  values from the empirical equation developed by Hanson and Simon (2001). Multiple reasons were proposed for this result, but it was noted that the Hanson and Simon (2001) empirical relationship between  $k$  and  $\tau_c$  was originally generated using data from 83 in-situ jet tests on streambeds of the Midwestern United States. As a result, streambank material may have a higher erodibility value because, unlike bed material, bank material is exposed to the influences of weathering and soil moisture conditions (Clark and Wynn, 2007). On a 100 m section of Barren Fork Creek in northeastern Oklahoma, bank erosion rates were under predicted when using BSTEM default values for fluvial erosion variables. Measured values of  $\tau_c$  and  $k$  were an order of magnitude less than and two orders of magnitude greater than default values, respectively (Midgley et al., 2012). SWAT calculates the erosion rate for one bank based on an assumption that erosion occurs on the outside bend and deposition on the inside bend of meandering streams (Neitsch et al., 2009). This assumption does not account for the relatively straight sections of a stream between meander bends. Therefore, SWAT may be underestimating streambank

erosion rates since straight channel sections could be experiencing erosion on both banks, especially in sections of low bank stability (Biedenharn et al., 1997).

The AVGWLF, BANCS, and SWAT models do not predict the number and timing of mass wasting events, which may be important for stream restoration planning. BSTEM is able to predict mass wasting events, because it assesses the impact of both bank stability and hydraulic forces on changes in bank dimensions over time (Simon et al., 2011). Completing a geotechnical analysis like BSTEM requires a detailed site assessment to collect in-situ data on geometry, material properties, stratigraphy, and pore water pressure. Obtaining these measurements can be time and energy intensive with a crew of four needing one day of data collection per site. BSTEM can be used on a small site-specific scale but the results cannot be generalized and used for an entire reach due to bank heterogeneity (ASCE, 1998). The AVGWLF is a simplified model, but its channel erosion algorithm focuses on stream flow and watershed characteristics such as percent developed land, animal density, and area-weighted curve number to calculate the empirically derived erosion potential (Evans et al., 2003). The model neglects streambank condition, which includes important in-stream parameters such as bank angle, bank height, and surface protection. The literature has shown the importance of streambank condition on bank stability (Osman and Thorne, 1988; Simon et al., 2009; Wynn, 2006). Consequently, models focused on predicting lateral streambank erosion rates should include stream parameters including but not limited to stream flow. The BANCS model is an index based method that allows the user to visually assess several aspects of bank condition without collecting field measurements (Rosgen, 2009). This model also predicts hydraulic forces acting on the bank by using various combinations of channel characteristics. The USEPA promotes the BANCS model for estimating lateral bank erosion rates and total annual sediment loads for a stream reach. Because the model does not require in-situ field measurements, it can be used on a site- as well as watershed-scale (Rosgen, 2009).

## 2.4 Video Mapping Research

Advances in technology have been used to monitor fluvial systems in novel ways. The Video Mapping System (VMS) is a kayak-based approach to collecting field data (Connell, 2012). The VMS consists of GPS receivers, multiple under/above water sensors, and video cameras recording georeferenced footage for both under and above water attributes. Variations of the VMS have been used to collect large-scale georeferenced river data for dimensional measurements as well as habitat assessments. Longitudinal depth measurements were collected over a short period of time on an 18 km section of the Driftwood River near Edinburg, Indiana (Swinson, 2012). Additionally, the VMS was utilized as a tool for mapping cross-sectional profiles (Swinson, 2012). On Citico Creek in Southeastern Tennessee, traditional water depth measurements were collected with a handheld survey rod and compared to average sonar measurements for 10 passes using the VMS. At depths greater than 0.5 m, the average root mean square error (RMSE) was 0.01 m. Consequently, the VMS proved advantageous in collecting continuous depth measurements, approximately one channel location every meter (Swinson, 2012). Furthermore, the VMS has been used to conduct river habitat assessments. In a study by McConkey (2010), above water cameras were utilized to collect video footage of river surface characteristics in order to distinguish between pools, riffles, and runs while underwater cameras were utilized to classify substrate into particle sizes ranging from sands to large boulders. Similarly, the VMS was employed on the Obed Wild and Scenic River to identify suitable habitat for federally threatened or endangered fish and freshwater mussel species (Candlish, 2010).

The Streambank Video Mapping System (SVMS) consists of GPS receivers, multiple under/above water sensors, and video cameras recording georeferenced footage of streambank condition. SVMS data can be incorporated with various stream habitat indices, geospatial interfaces (GIS) and erosion prediction models, such as BANCS. The SVMS was first used by Connell (2012) to collect georeferenced streambank video footage on a 7.6 km section of Beaver Creek and a 7.7 km section of New River, both

located in Tennessee. The video was visually interpreted using the Bank Erosion Susceptibility Index (BESI), an ocular adaptation of the BEHI, in order to identify areas of high erosion susceptibility. One modification was to combine the root depth and root density parameters to create a surrogate parameter known as riparian diversity. Rather than collecting in the field root samples, the riparian diversity parameter allows for a visual estimation of rooting depths and densities by assessing the abundance and composition of bank vegetation (i.e. grasses, shrubs, and trees). Sass and Keane (2012) created a similar surrogate for the BEHI root parameters, termed woody vegetation, during an assessment of streambank erosion in Northeast Kansas. The BESI results were validated by comparing field measurements from random sites along Beaver Creek and New River with BESI index scores of four parameters: bank height, surface protection, bank angle, and riparian diversity (Connell, 2012). Viewer validation was also conducted to statistically determine the scoring variation between participants. A - 1.46 average percent error between field measurements and video interpretation scores was considered to be acceptable.

Streambank condition can vary over several miles of stream due to the heterogeneity of vegetation, near bank stress, geotechnical features, and other parameters that influence bank erosion rates. Consequently, collecting continuous streambank condition and channel dimension data is important for predicting erosion rates on a watershed-scale (Russo et al., 2009). The SVMS has proven effective in conducting watershed-scale river surveys especially when direct field measurements are too expensive, difficult, time consuming or access limited. Furthermore, the SVMS data can be incorporated into ArcGIS to produce thematic maps. These maps can assist in the identification of streambanks with high erosion susceptibility along with the determination of total streambank erosion rates or sediment loads for an entire stream section.

## 2.5 Developing Sediment TMDLs

A TMDL must be site- and pollutant-specific because of the physiographic and hydrologic differences that exist between stream systems (USEPA, 1999). TMDLs have been developed for sections of stream or entire watersheds. TMDL development must assess the sources of a pollutant based on type, location, and magnitude. The magnitude of sediment loading can be estimated using direct measurements or loading models (Shirmohammadi et al., 2006; USEPA, 1999). After the source and magnitude of sediment loading are predicted, a quantifiable target can be established. This numerical target may be based on water quality standards (i.e. turbidity and TSS limits), loading rates, or a percent reduction approach (USEPA, 1999). For example, a sediment TMDL was developed for a section of Deep Creek, MT with the goal of reducing streambank erosion by 50% (Endicott and McMahon, 1996).

The AVGWLF model has been used by the Pennsylvania Department of Environmental Protection (2011) to calculate a sediment TMDL for the Plum Run watershed using a reference watershed approach. This comparative method requires the selection of an unimpaired reference watershed based on physiographic similarities to the impaired watershed. The goal was to reduce the total sediment load of the impaired watershed to the level of the reference watershed. The TMDL was calculated by taking the normalized sediment load of the reference watershed and multiplying the value by the total area of the impaired watershed. Based on the results, 17% of the total sediment load in the impaired watershed resulted from streambank erosion. Reducing streambank erosion by 26% and overland flow by 74% would produce an acceptable sediment loading rate.

The USEPA (2006) has devised an approach for developing waterbody TMDLs based on load duration curves. Due to the complexity and variability of sediment loading, this approach uses the long-term average of a chosen recurrence interval. Therefore, a Maximum Daily Limit (MDL) can be developed from data acquired on a monthly, seasonal, or annual time period. The limit can then be

transformed into a daily load using the proper unit conversions. Assuming a log-normal distribution, the statistical approach for calculating the MDL is as follows:

$$\text{MDL} = \text{LTA} \times e^{(Z\sigma - 0.5\sigma^2)} \quad (3)$$

MDL= maximum daily limit

LTA= long-term average

z= z-score for recurrence interval

$$\sigma^2 = \ln(\text{CV}^2 - 1)$$

CV= coefficient of variation

This equation is not pollutant- or site-specific; however, the resultant limit or load is. Based on this statistical approach, the MDL of a 365-day averaging period will have a recurrence interval of 99.7%. Therefore, the MDL will be exceeded when a concentration or load occurs less often than the chosen recurrence interval.

The final stage of a TMDL plan is to monitor the stream and identify practices that will be most effective in reducing pollutant loads (USEPA, 1999). For streambank erosion, there is a direct two-way link between stream restoration and sediment loading (Smith et al., 2011). Stream restoration projects are initiated as stabilization and/or reduction measures. Stabilizing an eroding streambank will reduce the quantity of sediment entering a waterbody. In order to reduce sediment loading, it's important to target the main sources of sediment as well as the location of these sources. It's also essential to determine whether the sediment influx is a result of upland or in-stream erosional problems (Gellis and Walling, 2011). Restoration strategies will vary depending on the targeted site, dominant erosional process, and erosion rates. The State of Virginia established a step-by-step protocol for assisting government, non-profit, and private organizations in the selection of optimal locations for stream restoration projects and management practices. First, the assessment identifies degraded stream reaches (Virginia DCR, 2004). Depending on the focus of the study, a stream reach could be identified as

degraded based on biological indexes, water quality monitoring, or geomorphic assessments. Second, the degraded sections are ranked by erosion potential. Third, sections are prioritized based on various constraints such as land accessibility, ownership, and cost in order to determine the sites most feasible for restoration projects.

The TMDL for Deer Creek, MT utilized a qualitative measure in assessing streambank stability based on the presence or absence of vegetation and rock cover. In this identification approach, a bank was placed on the priority list if it was classified as having low streambank stability with a bank length greater than 100ft and/or a bank height greater than 5ft (Endicott and McMahon, 1996). An estimated figure of over 1 billion dollars is spent annually on stream restoration projects in the United States (Palmer et al., 2007). Therefore, taking steps to identify the source, location, and magnitude of a pollutant before implementing restoration practices is a key component behind successful as well as cost effective projects.

## **2.6 Summary of Literature Review**

The USEPA (1999) and sediment TMDLs include in-stream erosional processes as a potential source of sediment (Endicott and McMahon, 1996; PADEP, 2011). Many current sediment TMDLs do not quantify the loading rates resulting from in-stream sources despite the direct supply of sediment these sources contribute to the fluvial system (Borah et al., 2006). The BSTEM, SWAT, AVGWLF, and BANCS models have been developed and implemented to quantify streambank erosion. Although each model has limitations arising from inherent assumptions, predicting sediment loads from streambank erosion will assist in the development of more robust TMDLs that predict when and where a TMDL will be exceeded. Combining the SVMS watershed-scale data collection method with the BANCS model for watershed-scale assessments of streambank and fluvial conditions will create a time- and cost-efficient method for predicting streambank erosion rates. Furthermore, incorporating a statistically-based

approach to develop sediment TMDLs will create a more holistic assessment of streambank sediment loads.

## **Chapter 3: Justification and Objectives**

### **3.1 Project Justification**

Because sediment is one of the major pollutants in United States waterways (USEPA, 2002), it is not only important to determine the total amount of sediment entering a waterbody but also to identify the locations contributing the largest amounts of sediment. Since in-stream erosional processes provide a direct supply of sediment to river systems, the identification of streambanks with high erosion rates will prove beneficial for selecting effective management practices and establishing reference data for monitoring programs.

The Streambank Video Mapping System (SVMS) has demonstrated its usefulness as a watershed-scale data collection method (Connell, 2012; McConkey, 2010). Georeferenced video footage has been used to conduct ocular assessments of current streambank conditions and therefore predict bank erodibility. Incorporating additional channel data, such as river width and radius of curvature, will allow for the prediction of stream erosivity. The USEPA-approved Bank Assessment for Non-point source Consequences of Sediment (BANCS) model has been utilized on a reach-scale to predict total annual sediment loads for riverine systems based on erodibility and erosivity assessments (Rosgen, 2009). As a result, the BANCS model could be used to analyze SVMS data in order to estimate site-specific streambank erosion rates as well as the total sediment load for a stream reach.

The USEPA (2006) has developed an equation (eq. 3) to predict the Maximum Daily Limit (MDL) for a water pollutant using a statistically based long-term average approach derived from load duration curves. Resultant sediment load estimates from the BANCS model could be converted into daily load estimates and used as input values into the MDL equation. Integrating the SVMS, BANCS model, and MDL equation provides a new methodology for collecting and analyzing data as well as applying the results to develop robust sediment Total Maximum Daily Loads (TMDLs) for streambank erosion. This

methodology will also reduce the time, energy, and cost associated with developing TMDLs and can be employed on both reach- and watershed-scales.

### **3.2 Project Objectives**

The overall objective of this study was to develop and demonstrate a protocol that integrated a rapid watershed-scale data collection method with the BANCS model and the MDL equation, two USEPA-approved approaches, in order to calculate numerical sediment TMDLs based on streambank erosion estimates. In order to accomplish this goal, specific objectives were identified and completed. First, the SVMS was used to collect georeferenced streambank and channel data for two study sites. A 22.5 km section of the Driftwood River located adjacent to Camp Atterbury near Edinburg, Indiana and a 20.4 km section of Upatoi Creek located within Fort Benning near Columbus, Georgia. Second, the acquired data were analyzed using the BANCS model for the prediction of streambank erodibility using the Bank Erosion Hazard Index (BEHI) and stream erosivity using Near Bank Stress (NBS). The BEHI was modified to create a completely ocular assessment of streambank condition. A site-similar bank erosion prediction curve was selected to convert index values to lateral erosion rates. Sediment loads were also estimated for an entire stream reach using bank height, bank length, and soil bulk density. Third, flow induced lateral erosion potentials were calculated from United States Geological Survey (USGS) time-averaged daily discharge data as a means of converting annual loading rates into daily loads. Fourth, a TMDL for streambank erosion was calculated using daily sediment loads estimates and the MDL equation, a statistically based long-term average approach. As a result of this methodology, streambank locations with high erosion rates were identified as potential targets for restoration efforts and further monitoring.

## Chapter 4: Equipment

### 4.1 Streambank Video Mapping System

The SVMS (Figure 4.1) was used to collect raw river data. The system consists of a Tarpon 100 sit-on-top kayak, two laser distance sensors, a National Marine Electronics Association (NMEA) multiplexer, a GPS unit, and 3 Contour GPS video cameras. Two SVMS equipped kayaks were utilized at each study site. The Trimble AgGPS 132 (1 Hz) with OmniSTAR differential correction was used for sub-meter GPS accuracy with data recorded onto a flash drive along with distance sensor output so that each point had an associated UTC (Coordinated Universal Time) and location. The GPS data strings, \$GPGGA and \$GPRMC, were imported using the NMEA multiplexer (Figure 4.2).

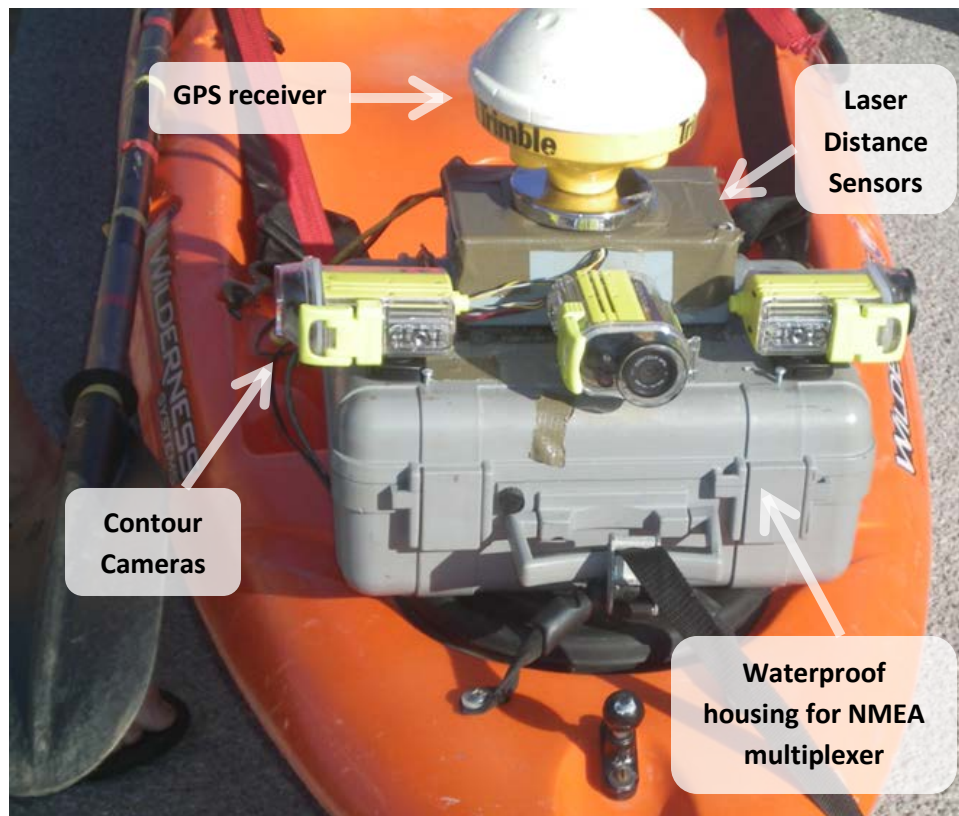


Figure 4.1. Kayak-mounted Streambank Video Mapping System.

The Contour GPS model 1400 cameras (Figure 4.3) were housed in waterproof cases while capturing georeferenced video footage using a 135° wide angle lens and built-in GPS receiver (<http://contour.com/collections/cameras>). GPS data from the cameras were used to synchronize the video and distance sensor output. The 720 pixel setting was used (1280x720 at 30 fps) to reduce the amount of storage needed for each run. A 4 GB micro SD card was needed to collect one hour of video footage and batteries were replaced every two hours. The Opti-Logic RS-100 laser distance sensors (Figure 4.4) were used running at 1 Hz to collect second by second measurements at a range of 92 m (100 yd) (<http://www.opti-logic.com/RS-800-800-Yard-Laser-Rangefinder-p/00619.htm>). Two distance sensors mounted in opposite directions (180°), one on river left and one on river right, were used to measure river width. Distance readings were exported in the following \$DDIST structure: \$DDIST 1, 6.89, M. The "1" represents the sensor number in order to differentiate between distance sensors.



Figure 4.2. The NMEA 0183 multiplexer used to combine distance sensor output and GPS data into a single data string (<http://nolandeng.com/nm42.php>, accessed May 2014).



Figure 4.3. Contour GPS video camera (<http://contour.com/collections/cameras>, accessed May 2014).

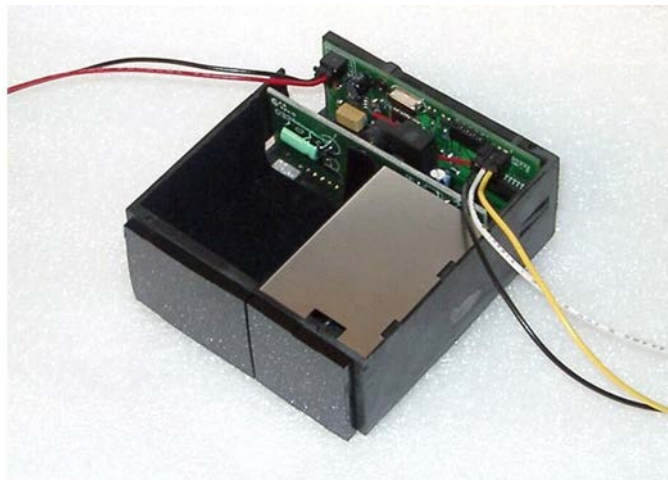


Figure 4.4. Opti-logic RS-100 laser distance sensors (<http://www.opti-logic.com/RS-800-800-Yard-Laser-Rangefinder-p/00619.htm>, accessed May 2014).

## Chapter 5: Study Areas

Two geographically different study sites were selected in order to compare sediment loads and TMDLs between stream systems. The Driftwood River is part of the Driftwood watershed, located within the Indiana and Ohio Till Plain of central Indiana (USDA, 2008). Upatoi Creek is part of the Middle Chattahoochee watershed, located within the Piedmont region of southwestern Georgia (Kunkle and Vana-Miller, 2000).

### 5.1 Driftwood River

A 22.5 kilometer section of Driftwood River (Figure 5.1) was surveyed on 7 June 2012 at a flow of approximately 360 cubic feet per second ( $10.2 \text{ m}^3 \text{ s}^{-1}$ ). The mapped section is located adjacent to Camp Atterbury near Edinburg, Indiana and drains a watershed area of  $2,745 \text{ km}^2$  ( $1,060 \text{ mi}^2$ ). The SVMS equipped kayaks were put in near USGS gage station 03363000 off Hendricks Ford Rd ( $39.33897^\circ \text{ N}$ ,  $85.98674^\circ \text{ W}$ ) and streambank video footage along with distance measurements were collected until the taken out at ( $39.20392^\circ \text{ N}$  and  $85.92920^\circ \text{ W}$ ). Average daily discharge data was compiled from 1942 – 1991 using flow measurements obtained from USGS gage station 03363000 (Figure 5.3).

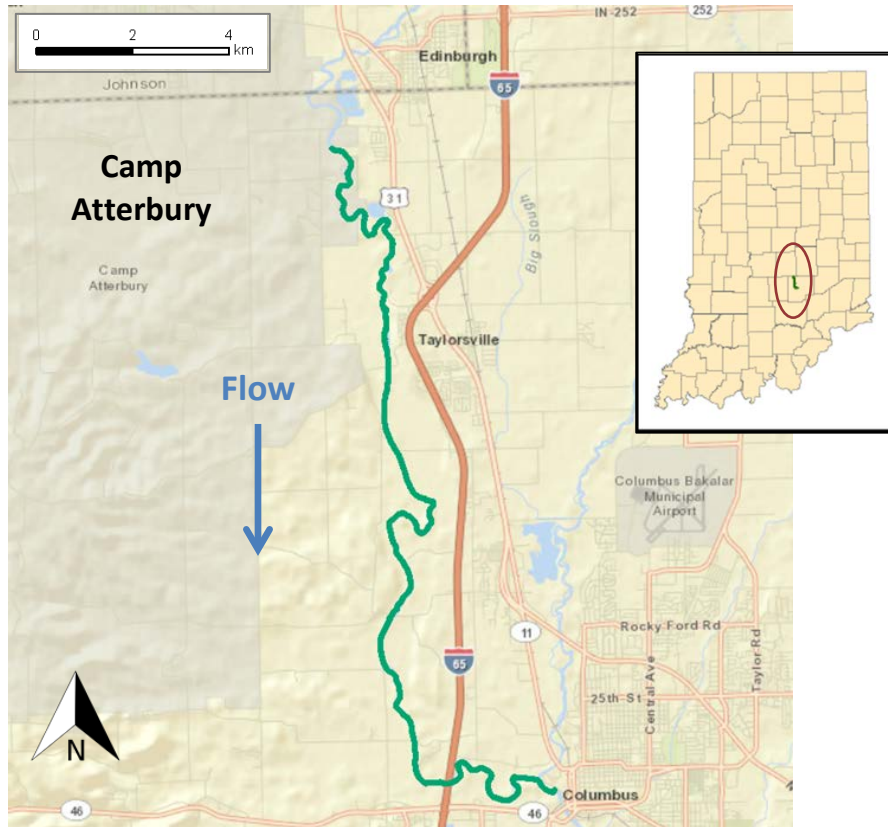


Figure 5.1. The 22.5 km reach of Driftwood River in Indiana. Left bank (east) and right bank (west).

## 5.2 Upatoi Creek

A 20.4 kilometer section of Upatoi Creek (Figure 5.2) was surveyed on 5 January 2013 at a flow of approximately 190 cfs ( $5.4 \text{ m}^3 \text{ s}^{-1}$ ). The mapped section is located inside Fort Benning near Columbus, Georgia and drains a watershed area of  $886 \text{ km}^2$  ( $342 \text{ mi}^2$ ). The kayakers were put in at McBride's Bridge near USGS gage station 02341800 ( $32.41333^\circ \text{ N}$ ,  $84.84000^\circ \text{ W}$ ) and data were collected until the confluence with the Chattahoochee River ( $32.37792^\circ \text{ N}$ ,  $84.97048^\circ \text{ W}$ ). Average daily discharge data was compiled from 1969 – 2012 using flow measurements obtained from USGS gage station 02341800 (Figure 5.3).

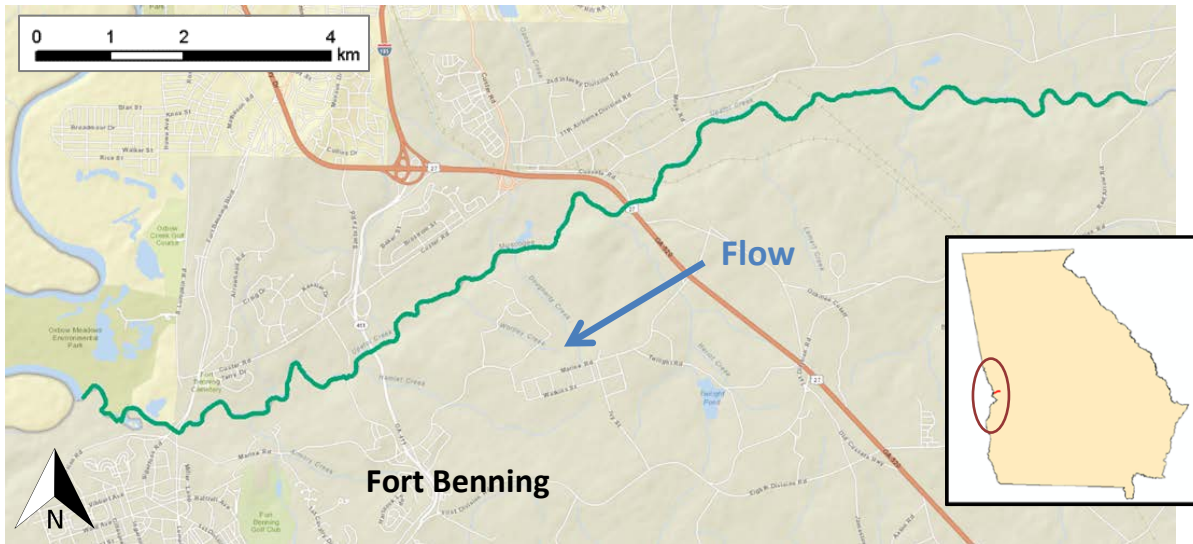


Figure 5.2. The 20.4 km reach of Upatoi Creek in Georgia. Left bank (south) and right bank (north).

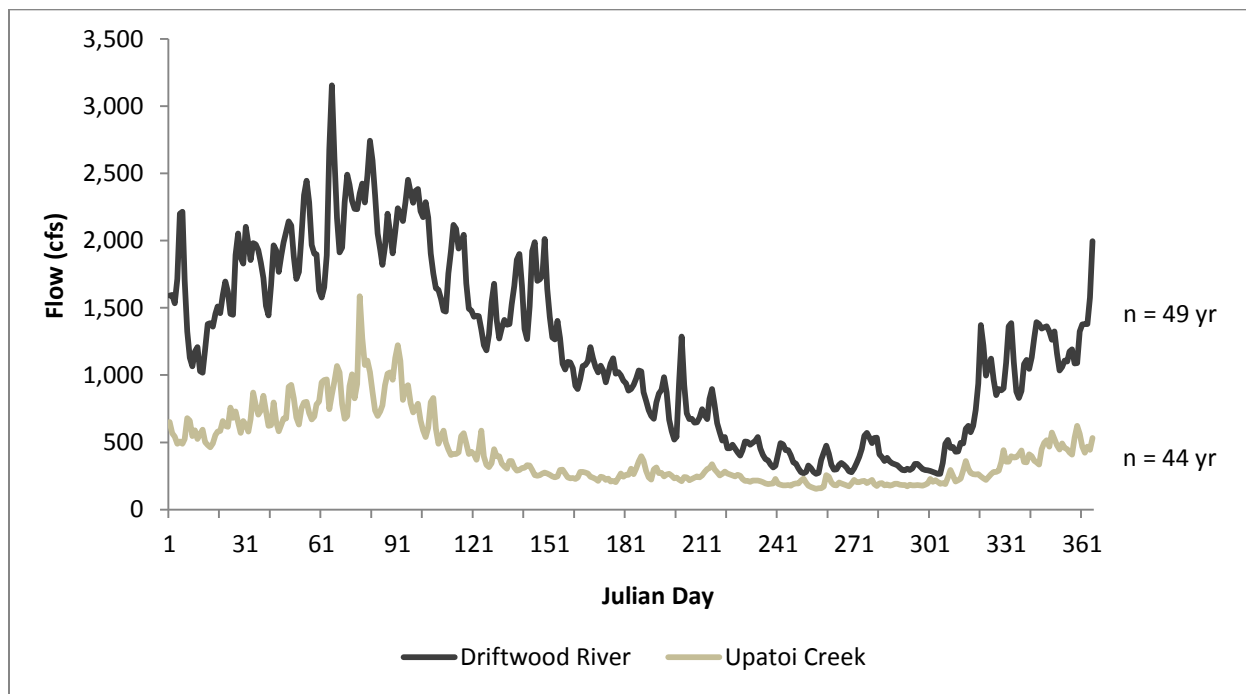


Figure 5.3. Time-averaged daily flow for Driftwood River (1942 – 1991) and Upatoi Creek (1969 – 2012).

## Chapter 6: SVMS Data Processing

### 6.1 Data Filtering

Laser distance sensor output was filtered to remove exceedingly large and small values (i.e. river widths) from the data set. A filter was created in Microsoft Excel to replace distance values 1.5 times greater or smaller than the preceding value. All outliers were replaced with the previous distance value. Outliers may have resulted from the distance sensors being obstructed by large woody debris and rocks or the sensors not remaining perpendicular to the streambanks. GPS output was filtered to remove positional data at the beginning and ending of video files when kayaks were stationary. Likewise, GPS output was removed if the kayak was stationary in a location for longer than 10 seconds. Filtering the GPS data removed extraneous information and reduced the potential for positional error. Subsequently, river width measurements were linked to corresponding GPS positions.

### 6.2 Distances between GPS Points

On small spatial scales the Euclidean distance between two points can be calculated using the Pythagorean formula, but on larger scales, distances should be calculated using an equation that accounts for the curvature of Earth (O’Sullivan and Unwin, 2010). Consequently, bank length was determined by calculating the distance between GPS data points using the following equation (Wilkerson, 2012):

$$\text{Distance} = \sqrt{(((\text{Lat1} - \text{Lat2}) * 110946)^2) + (((\text{Lon1} - \text{Lon2}) * 111319 * \cos((\text{Lat1})^2))} \quad (4)$$

Distance= Distance between GPS coordinate points in meters

Lat= Latitude in decimal degrees

Lon= Longitude in decimal degrees

Based on the great circle, a 1 degree change in latitude equals 110,946 meters and a 1 degree change in longitude equals 111,319 meters. The cosine of the latitude angle in degrees is used to account for diminishing meridian widths from the equator to poles. On average, the distance traveled by kayak was  $1.5 \text{ m s}^{-1}$ .

### **6.3 Spatial Joins**

In order to capture good quality video footage of streambank condition, two SVMS equipped kayaks were used, one focusing on the left bank and the other on the right bank. Streambank video footage was analyzed using the kayak nearest to the bank of interest. Collecting data from multiple kayaks provides redundant data, which can be used as backup information if a camera or sensor fails to work properly. Video footage was linked with positional data from the GPS enabled Contour cameras while distance measurements were linked with GPS output from the Trimble AgGPS 132 using a NMEA multiplexer. After the SVMS data was filtered, GPS output from the cameras were used to synchronize the video footage and distance sensor measurements by spatially joining the data sets in ArcGIS. The spatial join function merges two data layers by matching each feature of a layer to the closest feature in another layer based on spatial location (ArcGIS, 2014). Once the data sets were joined, the footage and distance measurements were analyzed using methods outlined in the following section.

## **Chapter 7: Total Sediment Load Calculations**

### **7.1 Introduction**

The Bank Assessment for Non-point source Consequences of Sediment (BANCS) model, a USEPA-approved approach, was integrated with the Streambank Video Mapping System in order to estimate site- and reach-specific streambank erosion rates and sediment loads. In regards to the BANCS model, a modified version of the Bank Erosion Hazard Index (mBEHI) was used to predict streambank erodibility and a Near Bank Stress (NBS) approach was used to predict stream erosivity. Annual Bank Erosion Rates (BERs) were graphically estimated by combining mBEHI and NBS index values with an empirically derived bank erosion prediction curve. Erosion rates were converted to volumetric estimates by incorporating a bulk density value as well as bank height and bank length components to account for the vertical and horizontal dimensions of the streambank. Figure 7.1 outlines the protocol for estimating Total Sediment Loads (TSLs) using SVMS data and the BANCS model.

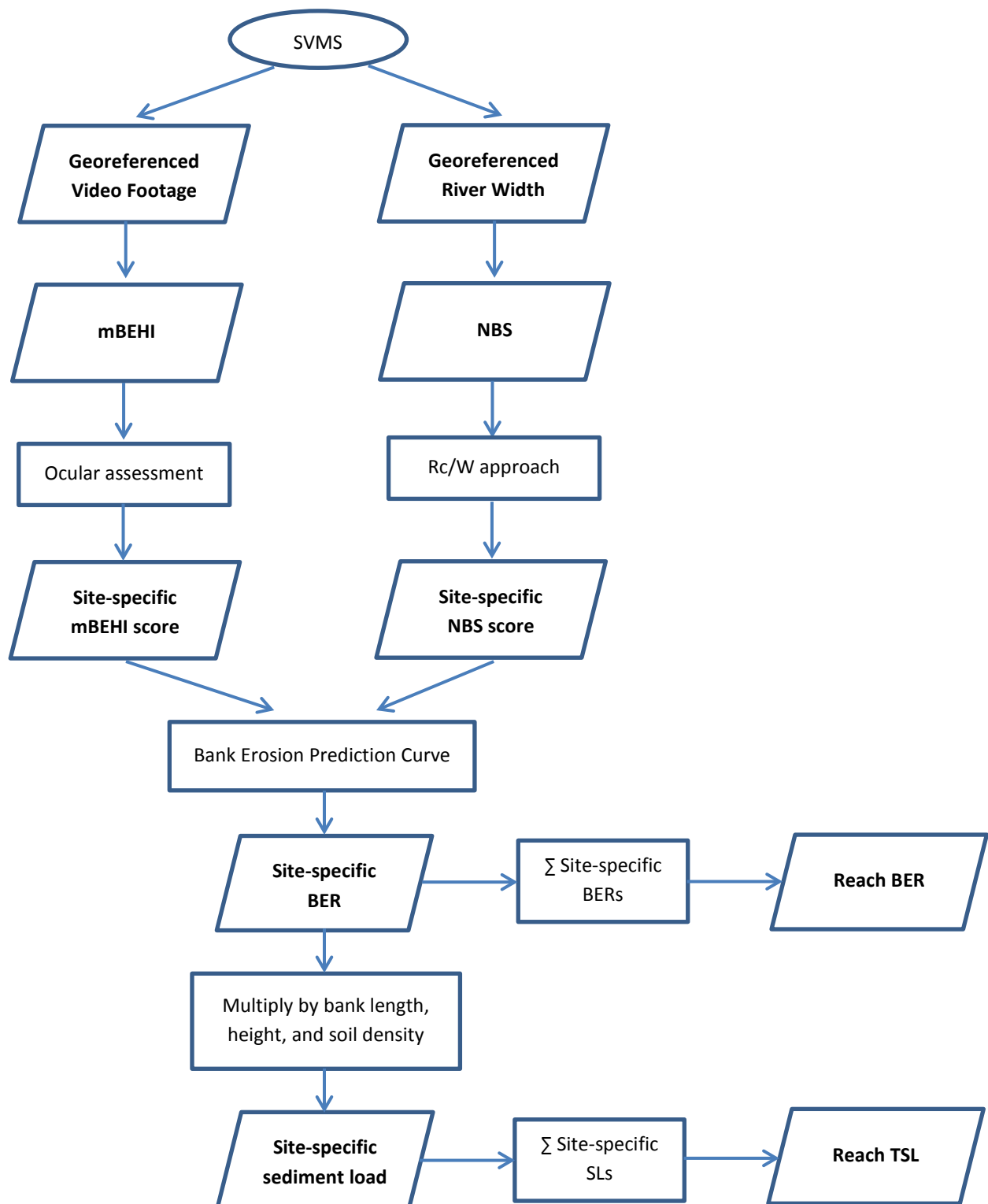


Figure 7.1. Protocol for estimating Total Sediment Loads using the BANCS model.

## **7.2 BANCS Model**

### **7.2.1 mBEHI Development**

The BEHI, the erodibility component of the BANCS model, characterizes the erosion susceptibility of a streambank using five parameters: ratio of bank height to bankfull height, root density, ratio of root depth to bank height, bank angle, and surface protection (Rosgen, 2001). The original BEHI scores of 1.5, 3, 5, 7, 8.5, and 10 relate to very low, low, moderate, high very high and extreme erosion susceptibility (Table 2.1). For a watershed-scale BANCS assessment or for site-specific predictions, an observer can employ a visual determination of BEHI scores by calibrating field measurements with ocular estimates (Rosgen, 2009). A completely ocular assessment of streambank erodibility was developed by Connell (2012) in order to make the SVMS feasible for the BANCS model. The Bank Erosion Susceptibility Index (BESI) assesses streambank erodibility using four parameters: bank angle, bank height, surface protection, and riparian diversity. The riparian diversity index was created using a visual estimation of root density and root depth that accounts for differences in root composition between bank vegetation classes, such as grasses, shrubs and trees. Sass and Keane (2012) created a similar surrogate for the BEHI root parameters, termed woody vegetation, during an assessment of streambank erosion in Northeast Kansas. The study found differences in mean bank retreat rates to be statistically significant between sites with and without bank vegetation.

Each BESI parameter has 4 erosion susceptibility categories: low, moderate, high, and extreme. The numerical range corresponding to each category was averaged based on the original BEHI (Connell, 2012). For this study, the BESI was adjusted to better reflect the original BEHI. Similar to BESI, the mBEHI is an ocular-based index composed of four streambank parameters: bank angle, bank height, surface protection, and riparian diversity. However, the riparian diversity parameter is doubly weighted to represent both the original root depth and root density parameters of the BEHI. Consequently, a site-

specific location on the streambank may have an mBEHI score ranging from 12.25 – 45. Table 7.1 shows the mBEHI scores in relation to the four streambank condition parameters and erosion susceptibility ratings.

Table 7.1. Modified Bank Erosion Hazard Index (mBEHI).

| <b>Bank Erosion Susceptibility Rating</b> |       | <b>Bank Height to Bankfull Height (Ratio)</b> | <b>Riparian Diversity (%)</b> | <b>Bank Angle (Degrees)</b> | <b>Surface Protection (%)</b> | <b>Index Totals</b> |
|-------------------------------------------|-------|-----------------------------------------------|-------------------------------|-----------------------------|-------------------------------|---------------------|
| <b>Low</b>                                | Value | 1.0 – 1.19                                    | Optimal                       | 0 – 60                      | 55 – 100                      |                     |
|                                           | Index | 2.45                                          | 4.90                          | 2.45                        | 2.45                          | 12.25 – 23.2        |
| <b>Moderate</b>                           | Value | 1.2 – 1.5                                     | Sub Optimal                   | 61 – 80                     | 30 – 54                       |                     |
|                                           | Index | 4.95                                          | 9.9                           | 4.95                        | 4.95                          | 23.2 – 30.5         |
| <b>High</b>                               | Value | 1.6 – 2.0                                     | Marginal                      | 81 – 90                     | 15 – 29                       |                     |
|                                           | Index | 6.95                                          | 13.9                          | 6.95                        | 6.95                          | 30.5 – 38.0         |
| <b>Very High</b>                          | Value | > 2.1                                         | Poor                          | > 91                        | < 14                          |                     |
|                                           | Index | 9                                             | 18                            | 9                           | 9                             | 38.0 – 45.0         |

Once the index was developed, video footage was reviewed using the spreadsheet shown in Figure 7.2. Video files were watched focusing on one parameter per view, meaning one hour of video footage required four hours of ocular assessment. A 22.5 km section of the Driftwood River had 4.5 h of video footage per bank and a 20.4 km section of Upatoi Creek had 4 h per bank. During the Driftwood River survey, the Contour cameras stopped recording for a 2.5 km stretch, equivalent to 10% of the total distance kayaked. Thus, this section was not included in the analysis. Average distance traveled was 1.5 m s<sup>-1</sup> for both surveys. The Video Time Recorded (VTR) was marked when a visual change in streambank condition was noted for the parameter of interest (Figure 7.3). However, if the streambank condition changed for less than five seconds, the parameter index value was not changed. All video footage was reviewed by the author to maintain scoring consistency in the review process for each parameter. A constant bankfull height of 1.37 m (4.5 ft) was used for the mBEHI analysis of both study sites. This value was selected based on an average ocular bankfull height for the entire length of reach. For a different stream system, it may be necessary to have a variable bankfull height over several kilometers. However, in this study, a drastic increase or decrease in bankfull height was not noted for either reach.

| Bank Angle (deg) |       |       |     | Bank Height (ft) |         |           |         |          |           |       |  | Surface Protect (Avg. %) |       |       |    | Riparian Diversity |         |          |      |
|------------------|-------|-------|-----|------------------|---------|-----------|---------|----------|-----------|-------|--|--------------------------|-------|-------|----|--------------------|---------|----------|------|
| 0-60             | 61-80 | 81-90 | >91 |                  |         |           |         |          |           |       |  |                          |       |       |    | 100-56             | 55-30   | 29-15    | <14  |
| =2.45            | =4.95 | =6.95 | =9  | 0-1ft            | 1ft-3ft | 3ft - 6ft | 6ft-9ft | 9ft-12ft | 12ft-18ft | >18ft |  | =2.45                    | =4.95 | =6.95 | =9 | Optimal            | Sub Opt | Marginal | Poor |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |
|                  |       |       |     |                  |         |           |         |          |           |       |  |                          |       |       |    |                    |         |          |      |

Figure 7.2. Spreadsheet for recording VTR times when changes in streambank condition parameters were observed (Connell, 2012).

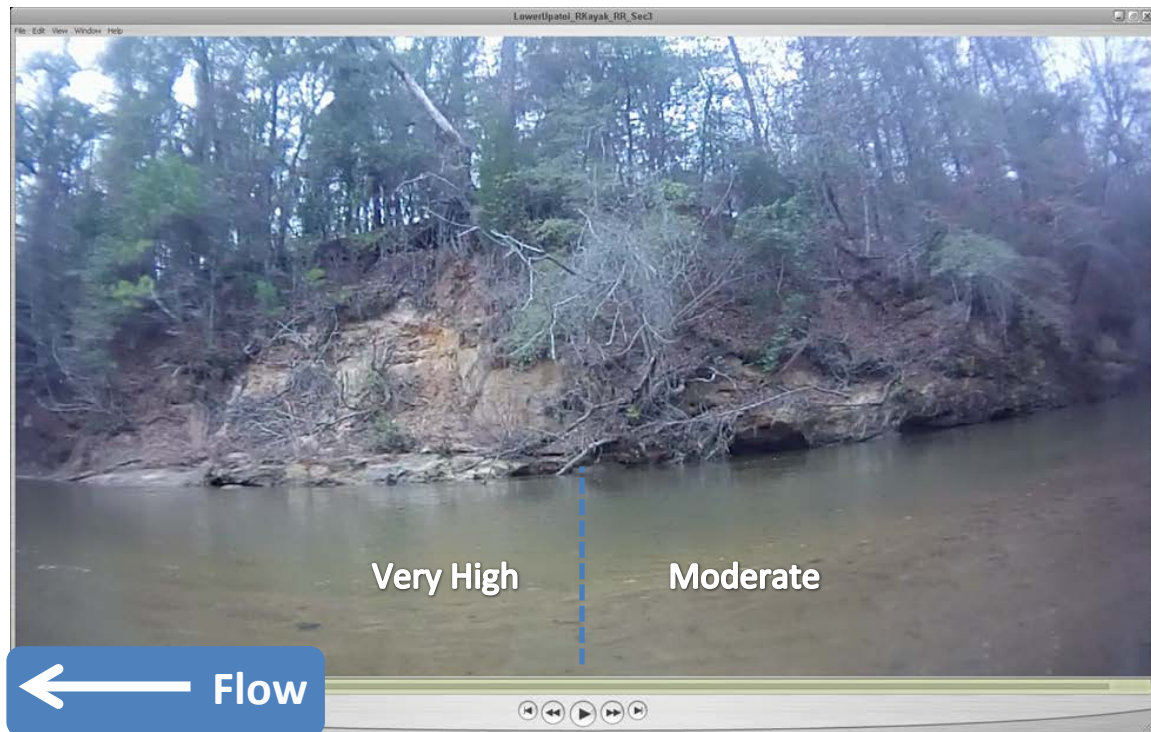


Figure 7.3. Upatoi Creek site showing a transition between moderate and very high mBEHI ratings.

A comparison of individual index scores for each parameter can be found in Appendix C for both Driftwood River and Upatoi Creek. After the ocular assessment was completed, the individual index scores for each streambank location were summed together to calculate the site-specific total mBEHI score. All streambank locations were categorized according to the bank erosion susceptibility ratings in Table 7.1. Thematic maps were produced in ArcGIS to visually identify streambanks with high and very high erosion susceptibility. For each stream system, individual parameter scores and total mBEHI scores were analyzed based on total and percent bank length. Within stream comparisons were made between the left and right bank as well as between stream comparisons for Driftwood River and Upatoi Creek.

Out of the total 45 km streambank length (left and right), 42% of Driftwood River received an mBEHI rating of low while 13% was rated very high, totaling 5,618 meters (Figure 7.4). Further analysis

of the results showed 25% of the streambank length in the high and very high categories for the left bank (river left) in comparison to 40% for the right bank (Figure 7.5). The average mBEHI score for the entire reach was 25.9, giving it an overall moderate mBEHI rating. Figures 7.6 and 7.7 are thematically mapped with mBEHI ratings for both left and right streambanks. For Driftwood River, thematic maps of all mBEHI parameter scores by erosion susceptibility categories can be found in Appendix A.

With 28% low, 46% moderate, (Figure 7.8), and an average mBEHI score of 25.4, Upatoi Creek received an overall moderate mBEHI rating. Out of the total 40.8 km streambank length (left and right), a total length of 2,072 m was rated very high. This 5% portion would include streambank locations in most need of attention. Further analysis of the results showed 34% of the streambank length was categorized as high and very high for the left bank in comparison to 18% for the right bank (Figure 7.9). Figures 7.10 and 7.11 are thematically mapped with mBEHI ratings for both left and right streambanks. For Upatoi Creek, thematic maps of all mBEHI parameter scores by erosion susceptibility categories can be found in Appendix B.

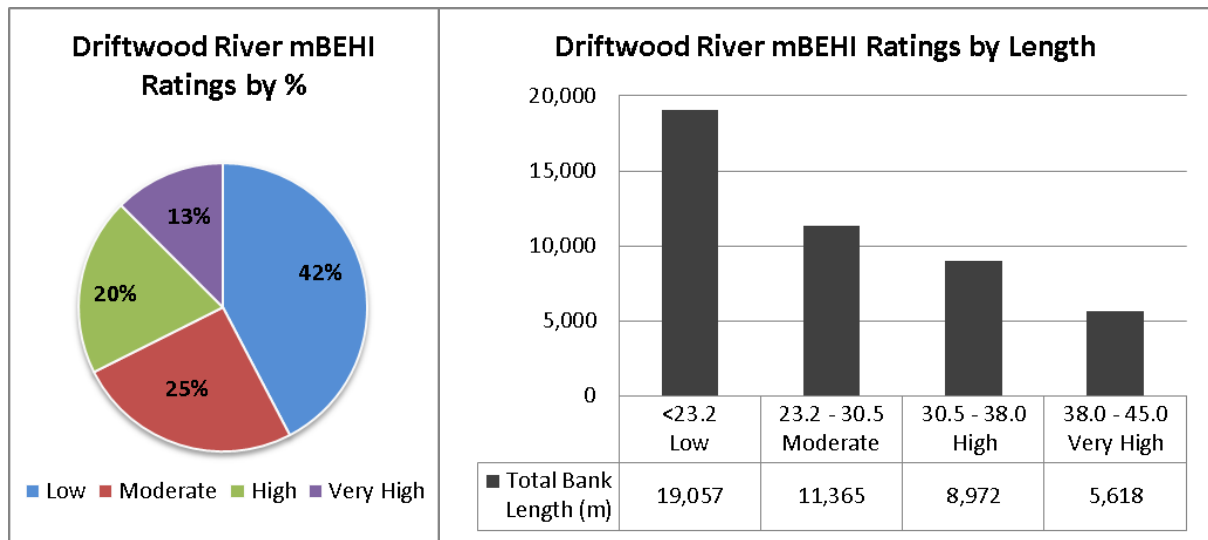


Figure 7.4. Driftwood River combined mBEHI percentages and bank lengths.

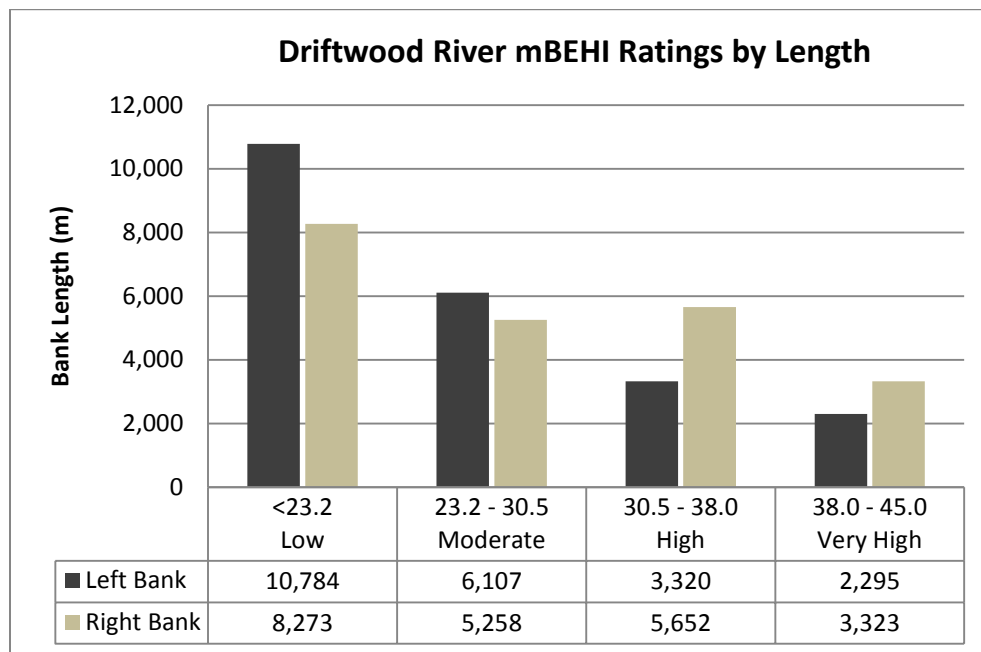


Figure 7.5. Driftwood River mBEHI categories by length for left and right banks.



Figure 7.6. Driftwood River mBEHI ratings for the left bank (east).

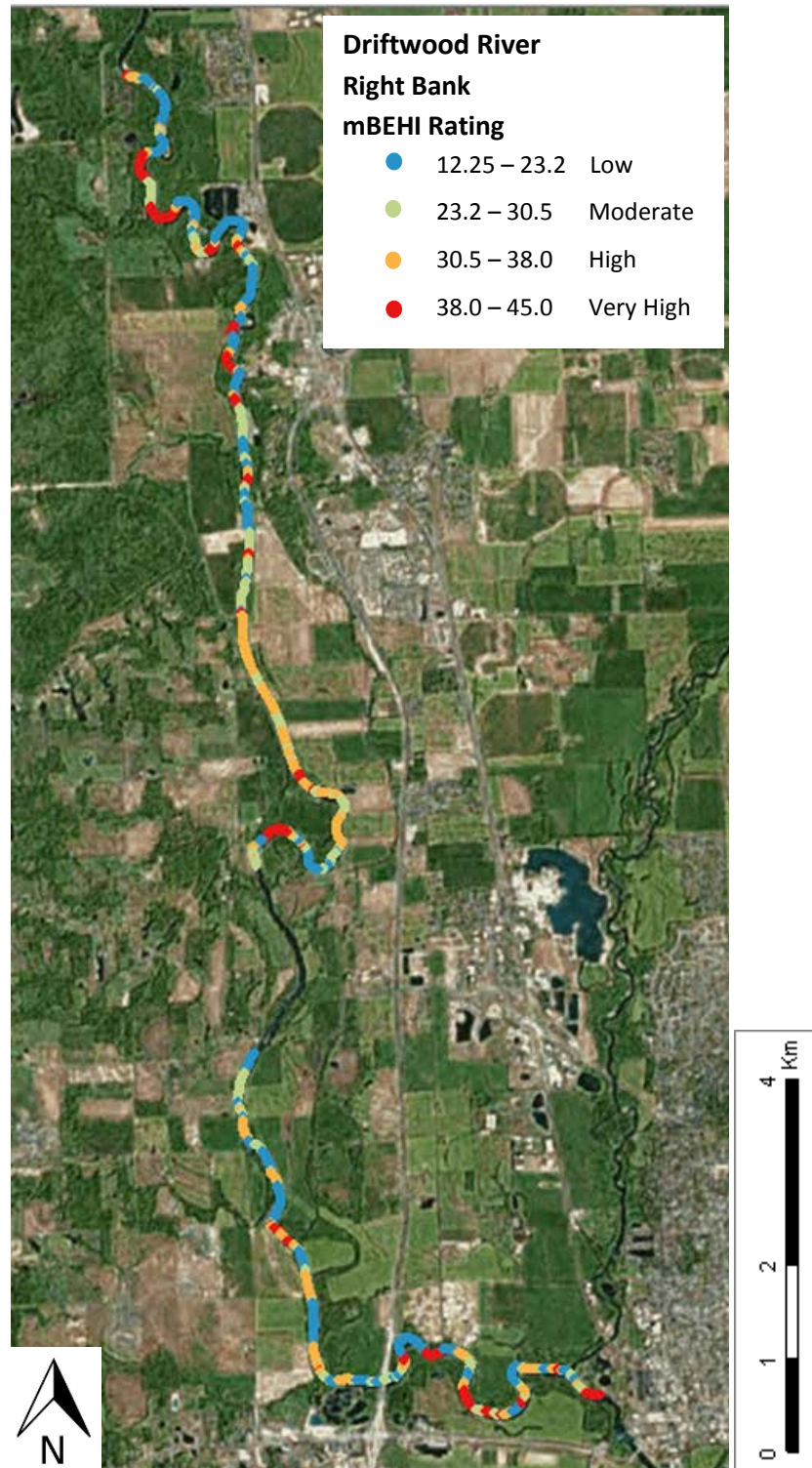


Figure 7.7. Driftwood River mBEHI ratings for the right bank (west).

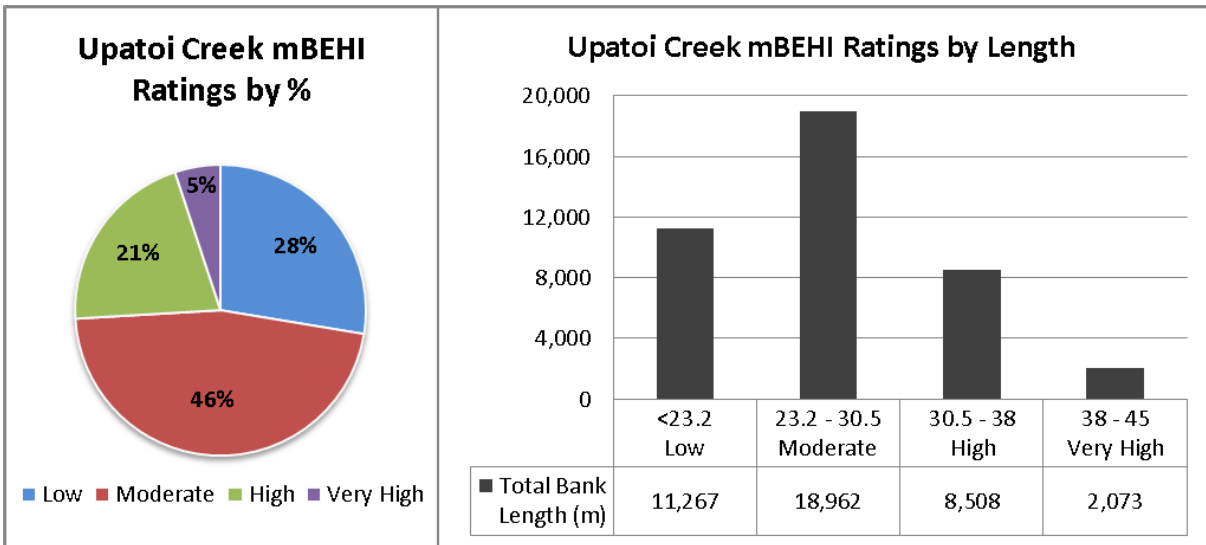


Figure 7.8. Upatoi Creek combined mBEHI percentages and bank lengths.

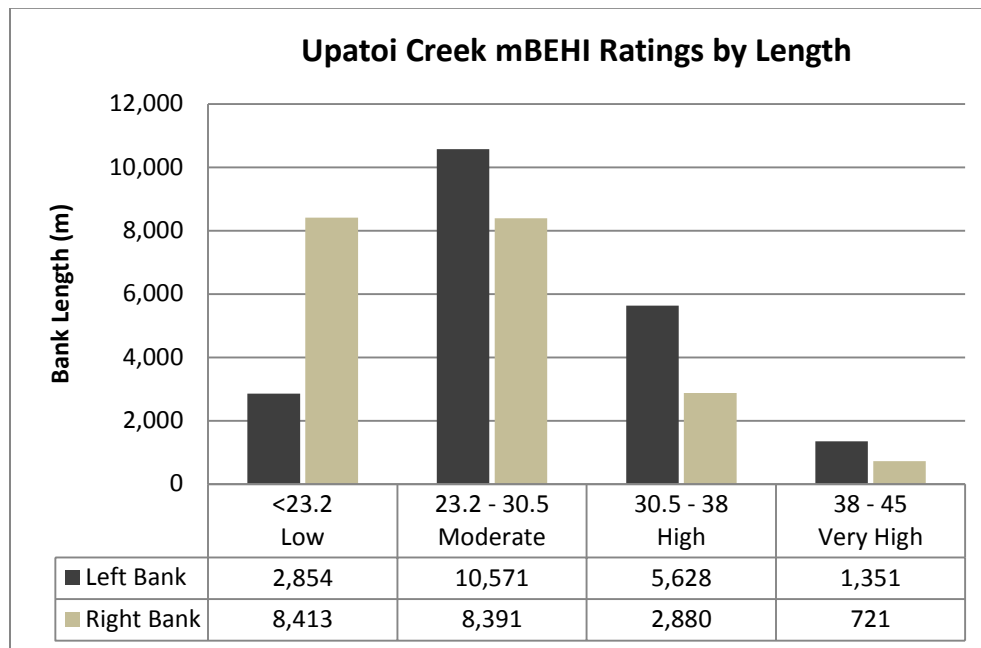
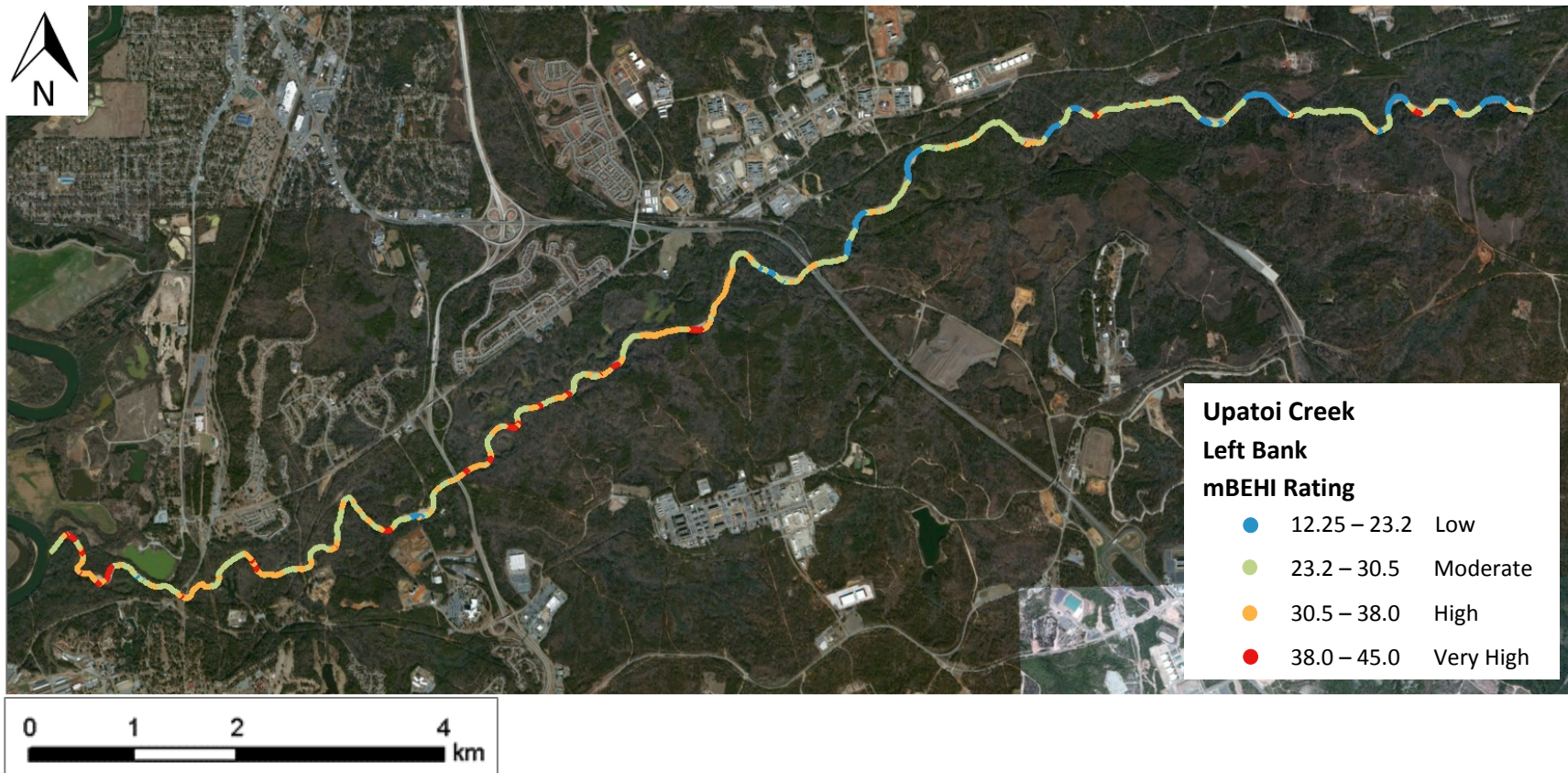


Figure 7.9. Upatoi Creek mBEHI categories by length for left and right banks.



Figures 7.10. Upatoi Creek mBEHI ratings for the left bank (south).



Figures 7.11. Upatoi Creek mBEHI ratings for the right bank (north).

A streambank condition line can be illustrated by plotting the percent bank length associated with combined mBEHI scores for both left and right streambanks. Similar to the bar charts that displayed mBEHI ratings by bank length, this illustration shows the distribution of erosion susceptibility for a stream reach. Driftwood River had a greater percentage of stream length in both the low and very high mBEHI categories while Upatoi Creek had a greater percentage in the moderate category (Figure 7.12). This graphical representation highlights the differences between stream systems or within the same stream reach when separately assessing the left and right banks.

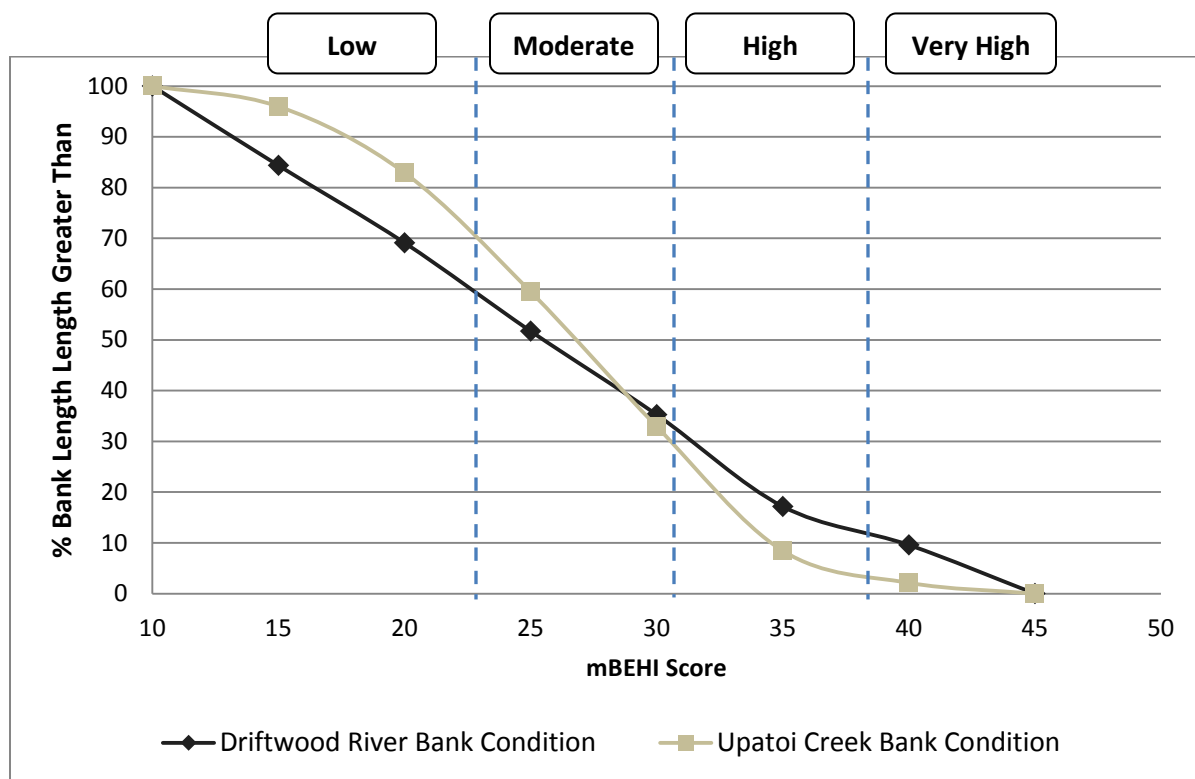


Figure 7.12. Comparison of Driftwood River and Upatoi Creek streambank condition distributions.

### 7.2.2 Near Bank Stress (NBS)

NBS focuses on stream erosivity and can be predicted with the BANCS model using one of seven different approaches (Rosgen, 2009). For this study, NBS was estimated using the stream radius of curvature to width ratio ( $R_c/W$ ), a channel pattern approach, and was selected based on the data collected with the SVMS. Channel width values were calculated by adding the individual distance readings from the left and right sensors on a kayak. GPS data was used to estimate the radius of curvature based on the resultant circle defined by the current GPS point and an upstream and downstream point selected via a river width factor (Figure 7.13). This factor is a numerical value by which the river width is to be multiplied. Increasing the river width factor will increase the distance used to select the GPS endpoints both upstream and downstream of a current streambank location. For the NBS analysis, a river width factor of two was selected, meaning a site-specific radius of curvature was calculated using a distance of two river widths. Numerical  $R_c/W$  values were converted to NBS index scores using Table 7.2. An NBS index score of 1 was categorized as very low stream erosivity ( $R_c/W > 3.0$ ) while an NBS index score of 6 was designated as extreme ( $R_c/W < 1.5$ ).

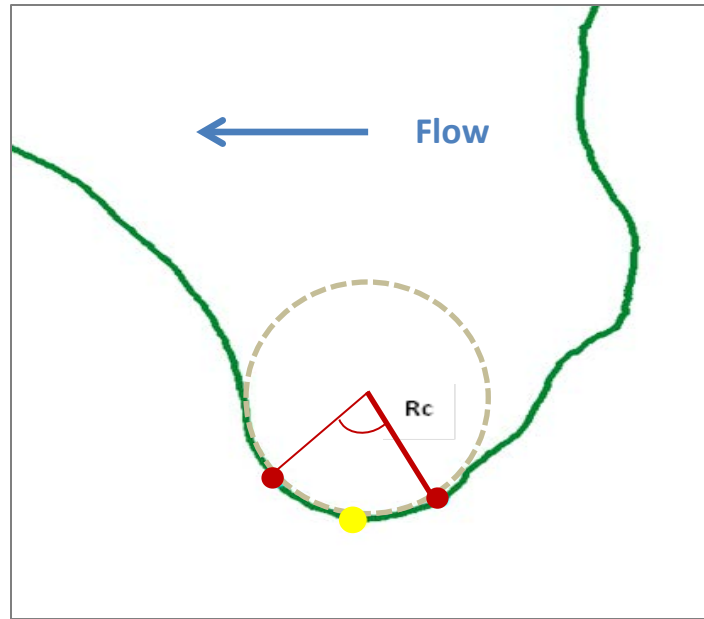


Figure 7.13. Illustration of the radius of curvature ( $R_c$ ) calculation for a meander bend on the Driftwood River. A circle connects the current GPS point (yellow) with upstream and downstream points (red).

Table 7.2. Near Bank Stress Index based on the channel pattern approach (Rosgen, 2009).

| NBS Description | NBS Score | $R_c/W$    |
|-----------------|-----------|------------|
| Very Low        | 1         | > 3.0      |
| Low             | 2         | 2.21 - 3.0 |
| Moderate        | 3         | 2.01 – 2.2 |
| High            | 4         | 1.81 – 2.0 |
| Very High       | 5         | 1.5 – 1.8  |
| Extreme         | 6         | < 1.5      |

As meander migration occurs, lateral erosion along the outside streambank results in deposition on the inside bank (Knighton, 1998). Thus, depositional features such as point bars were excluded from this analysis, because bank erosion rates were assumed to be zero on the inside of sharp meander bends (Figure 7.14). In addition to the NBS score, a filter was created based on the turn direction of the kayak from one location to the next. The same data points that were used to calculate the radius of curvature were used to determine turn direction. For example, a kayak turning left around a meander bend would have a BER equal to zero on the left bank when the NBS score was greater than one,  $R_c/W < 3.0$ . In comparison, the BER on the right bank would remain greater than zero. Straighter sections of stream were excluded from this filter as a result of the conditional statement:  $\text{if}(\text{NBS} > 1, \text{BER} = 0)$ . Additionally, for  $R_c/W$  values greater than 3, an NBS score of 1 was assigned to both left and right banks.

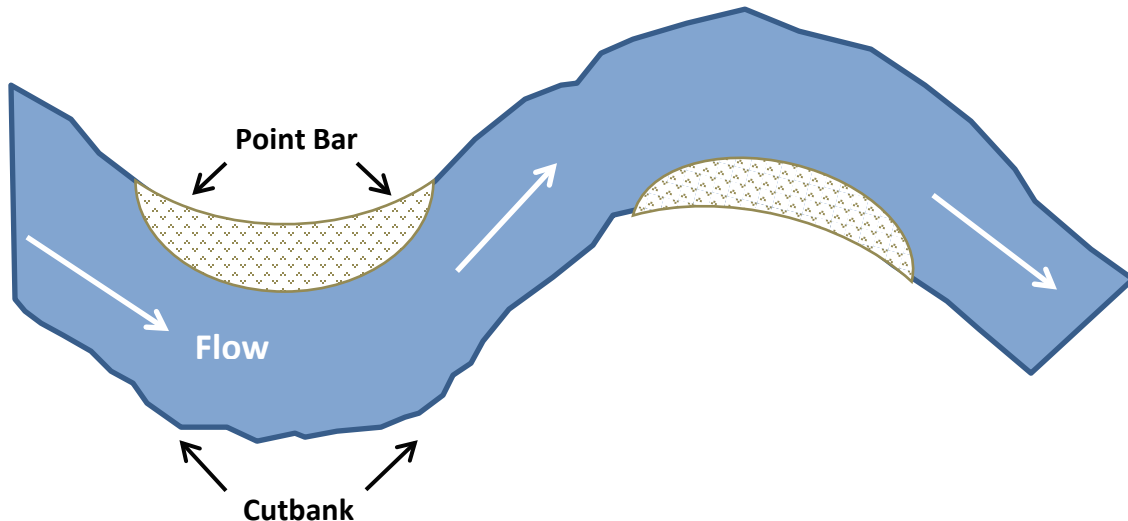


Figure 7.14. Illustration of a meandering channel with depictions of point bar and cutbank areas.

Inspired by the Riffle/Pool System diagram (Rosgen, 2009).

Similar to the mBEHI analysis, NBS scores were evaluated by total and percent bank length both within and between streams. Based on bank length, Driftwood River received a very low NBS rating for 89.7% of the reach and a zero NBS rating for 5.1% (Figure 7.15). A bank erosion rate of 0 m yr<sup>-1</sup> was estimated at all streambank locations with a zero NBS score, because depositional features, such as point bars, were present. A comparison of both banks showed higher NBS scores on the left bank with 7.6% of the total length receiving NBS scores ranging from 2 – 6 while the right bank received 2.6% (Figure 7.16). Upatoi Creek received a very low NBS rating for 83.0% of the total bank length and 8.5% received an NBS score of zero (Figure 7.15). A comparison of both banks showed 10.9% of the total bank length received an NBS score ranging from 2 – 6 on the left bank while the right received 6.0% (Figure 7.17). Figure 7.18 shows two thematic maps of NBS scores varying along several meander bends of the Driftwood River.

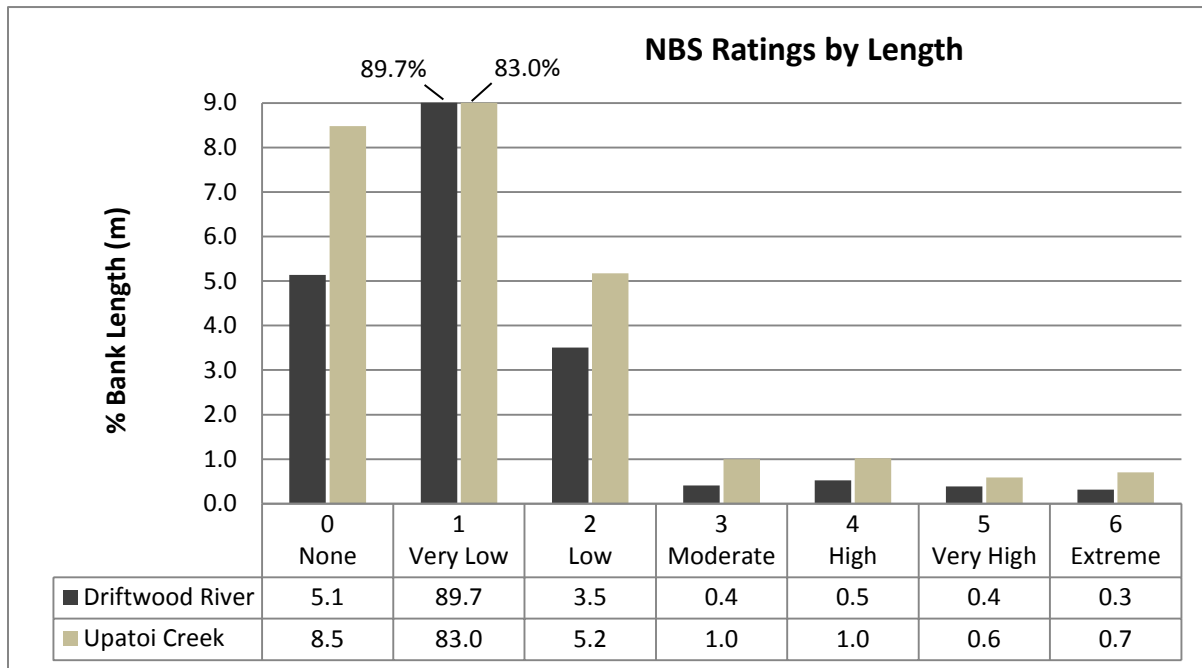


Figure 7.15. Comparison of Driftwood River and Upatoi Creek by combined bank length and NBS score.

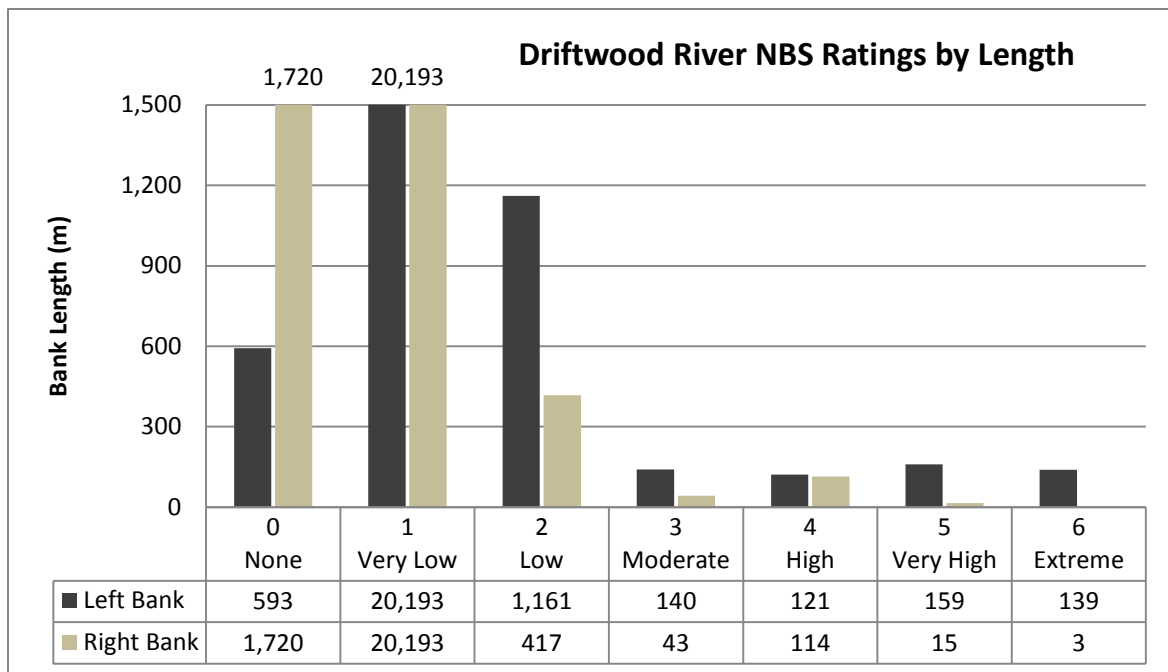


Figure 7.16. Comparison of Driftwood River left and right banks by length and NBS score. Length values exceed the scale range for NBS scores of zero (right bank) and one (both banks).

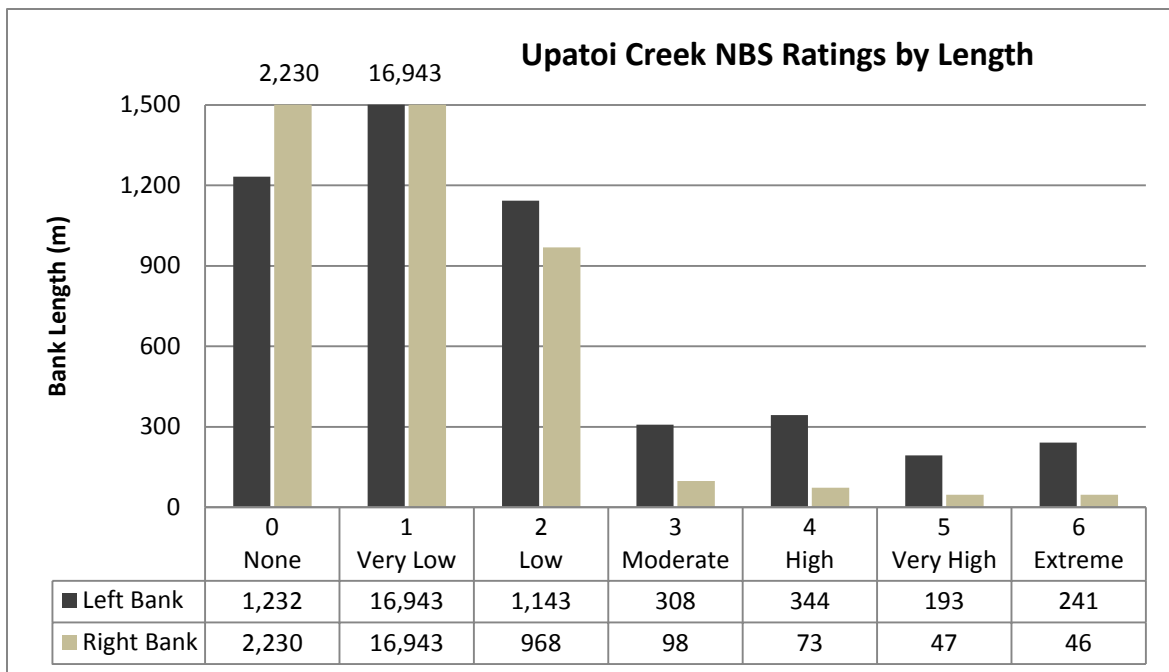


Figure 7.17. Comparison of Upatoi Creek left and right banks by length and NBS score. Length values exceed the scale range for NBS scores of zero (right bank) and one (both banks).

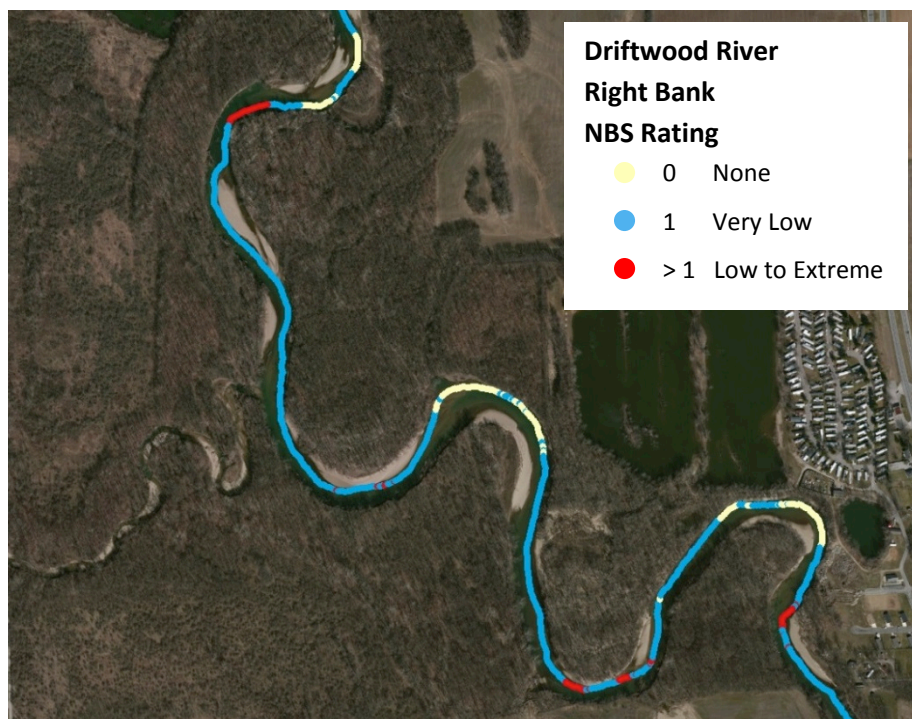
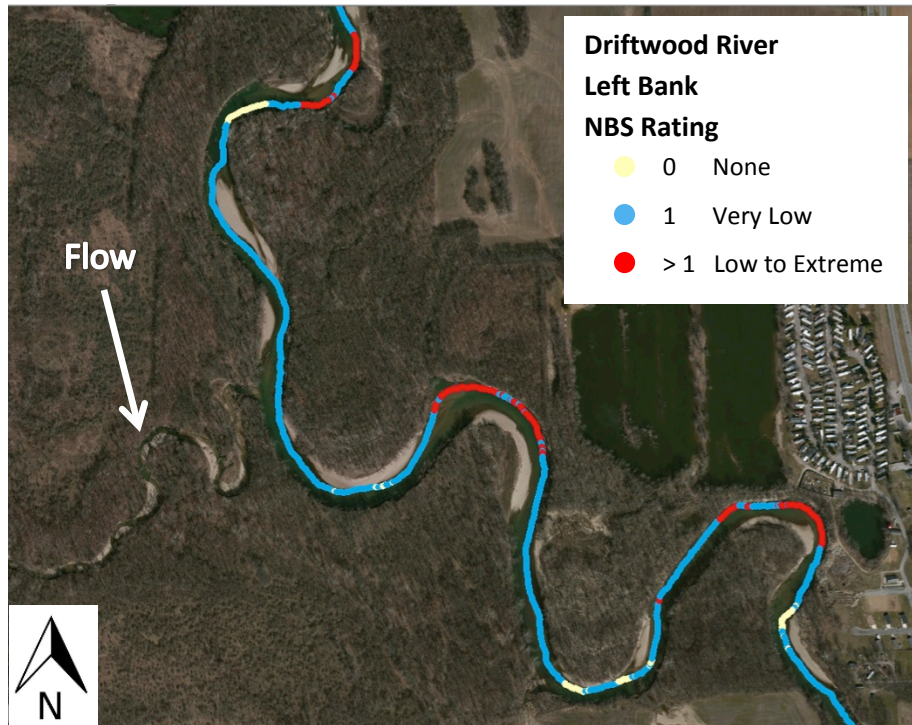


Figure 7.18. Thematic maps of NBS around several meanders for the a) left bank (east) and b) right bank (west) of Driftwood River.

### 7.2.3 Bank Erosion Rates (BERs) and Total Sediment Loads (TSLs)

The BER is the amount of lateral erosion that occurs over a period of time. Bank erosion prediction curves have been developed for various physiographic regions in order to correlate BEHI and NBS scores for the prediction of annual erosion rates in feet per year. For these prediction curves, the y-axis represents the BER on a logarithmic scale while the x-axis represents the NBS index scores. Linear regression lines represent the moderate, high, very high, and extreme BEHI ratings. Therefore, BERs can be predicted once the BEHI and NBS scores are determined for each streambank location.

For this study, the BER was graphically estimated using the already established North Carolina Piedmont region bank erosion prediction curves (Figure 7.19), which were generated by the United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS) and North Carolina State University Stream Restoration Program (1989). Compared to other regions with established bank erosion prediction relationships such as Northwest Arkansas (Van Eps et al., 2004), Southern Colorado (Rosgen, 2001), Northeast Kansas (Sass and Keane, 2012) and Southwestern Montana (Rosgen, 2001), the North Carolina curves (NCSU, 1989) were specifically developed for the Piedmont region, which is the most physiographically similar to the Driftwood River and Upatoi Creek study sites. BERs were estimated by inputting NBS index scores into the linear equations for each BEHI category. Since the North Carolina curves were plotted on a semi-logarithmic graph, the base 10 logarithm of the categorical BEHI linear regression equations was taken. Next, an interpolation process was utilized for mBEHI values within the moderate, high, and very high BEHI categorical ratings. For mBEHI values within these ranges, the BER was interpolated between the lower and upper BEHI category lines. In contrast, BER values were not interpolated for BEHI values less than the moderate range and greater than the very high range. Last, the antilog of each logarithmic BER estimate was taken to achieve a final annual BER. For Driftwood River, the greatest distribution of BER estimates were within the moderate BEHI rating and very low to low NBS scores (Figure 7.20).

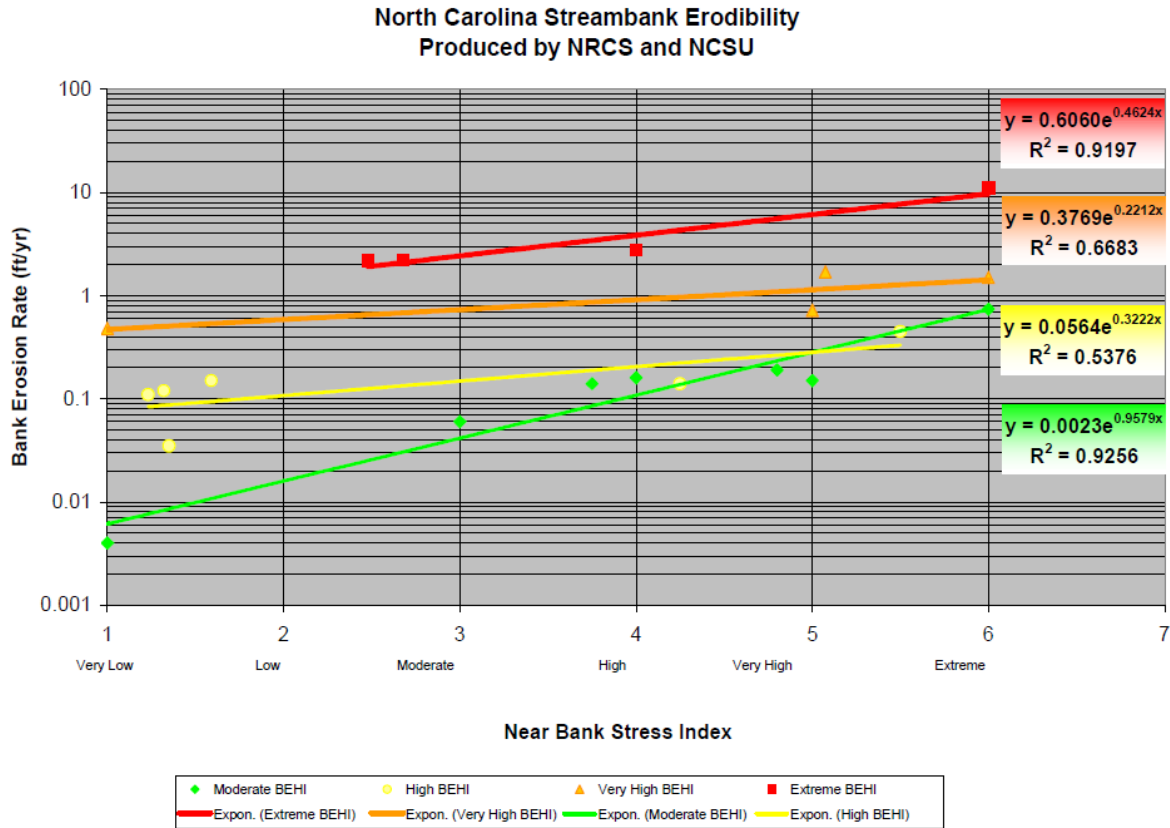


Figure 7.19. Streambank erosion prediction curves for the North Carolina Piedmont region produced by NRCS and NCSU (1989).

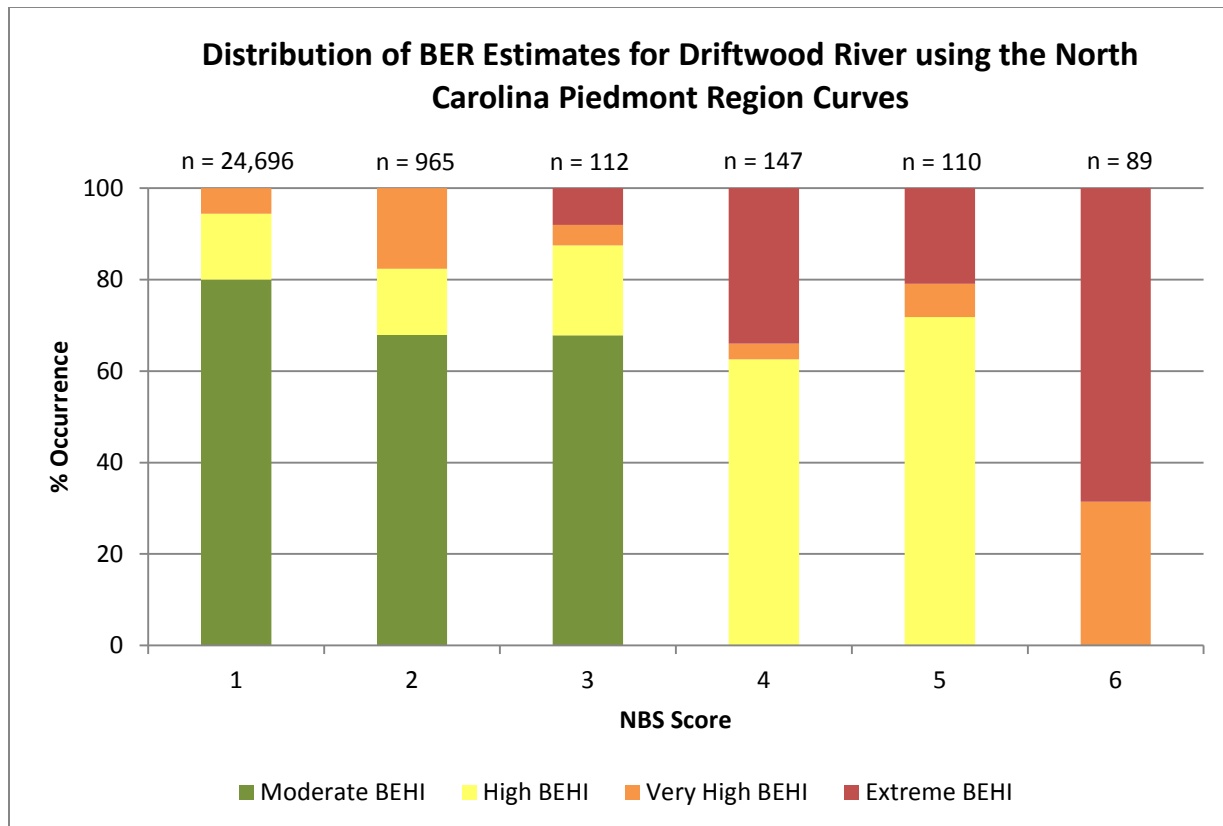


Figure 7.20. Distribution of BER estimates by NBS scores and BEHI ratings for Driftwood River using the North Carolina Piedmont region curves. n is the number of BER estimates for each NBS score.

After this method was used to estimate the BER for each streambank location, the site-specific annual sediment load was estimated by multiplying together the BER ( $\text{ft yr}^{-1}$ ), bank height (ft), bank length (ft) and soil density (Rosgen, 2009). The bank length was determined by calculating the distance between GPS points (eq. 4) and the bank height was approximated as the median value of the corresponding mBEHI category range. The volume of erosion in cubic feet was divided by  $27 \text{ ft}^3 \text{ yd}^{-3}$  to convert the value into cubic yards, which was then multiplied by a bulk density factor of 1.3 to convert from a volume of sediment to a weight in tons. The annual sediment load values were converted into the metric units of tonnes per year. The Total Sediment Load (TSL) of the entire reach was calculated by

summing together the site-specific sediment load values (Rosgen, 2009). The TSL value can then be divided by the total stream length to normalize the estimate in tonnes per year per kilometer.

For both streams, the BER ranged from  $1.83 \text{ mm yr}^{-1}$  –  $1 \text{ m yr}^{-1}$  with an average erosion rate of  $11.3 \text{ mm yr}^{-1}$  for Upatoi Creek and  $25.2 \text{ mm yr}^{-1}$  for Driftwood River. The maximum annual BERs for Driftwood River and Upatoi Creek occurred over a continuous bank length of 18 m and 2 m, respectively. The TSL for Driftwood River was 4,984 tonnes per year with 57.7% derived from the right bank. Approximately 23% of the TSL for the left bank occurred along a continuous 167 m section of streambank ( $39.20577^\circ \text{ N}$ ,  $85.94029^\circ \text{ W}$  to  $39.20678^\circ \text{ N}$ ,  $85.93959^\circ \text{ W}$ ), resulting in 483 tonnes of sediment annually. The TSL for Upatoi Creek was  $2,225 \text{ t yr}^{-1}$  with 58.0% derived from the left bank. In order to compare TSLs between river systems, the values were normalized by bank length to calculate a site-specific loading rate in tonnes per year per meter. Thematic maps of normalized site-specific Sediment Load (SL) values for Driftwood River (Figures 7.21 and 7.22) and Upatoi Creek (Figures 7.23 and 7.24) were generated to identify streambank locations with high recession rates. These maps can then be used to prioritize areas for restoration (Rosgen, 2009). TSL per unit stream channel length was  $222 \text{ t yr}^{-1} \text{ km}^{-1}$  and  $109 \text{ t yr}^{-1} \text{ km}^{-1}$  for Driftwood River and Upatoi Creek, respectively.

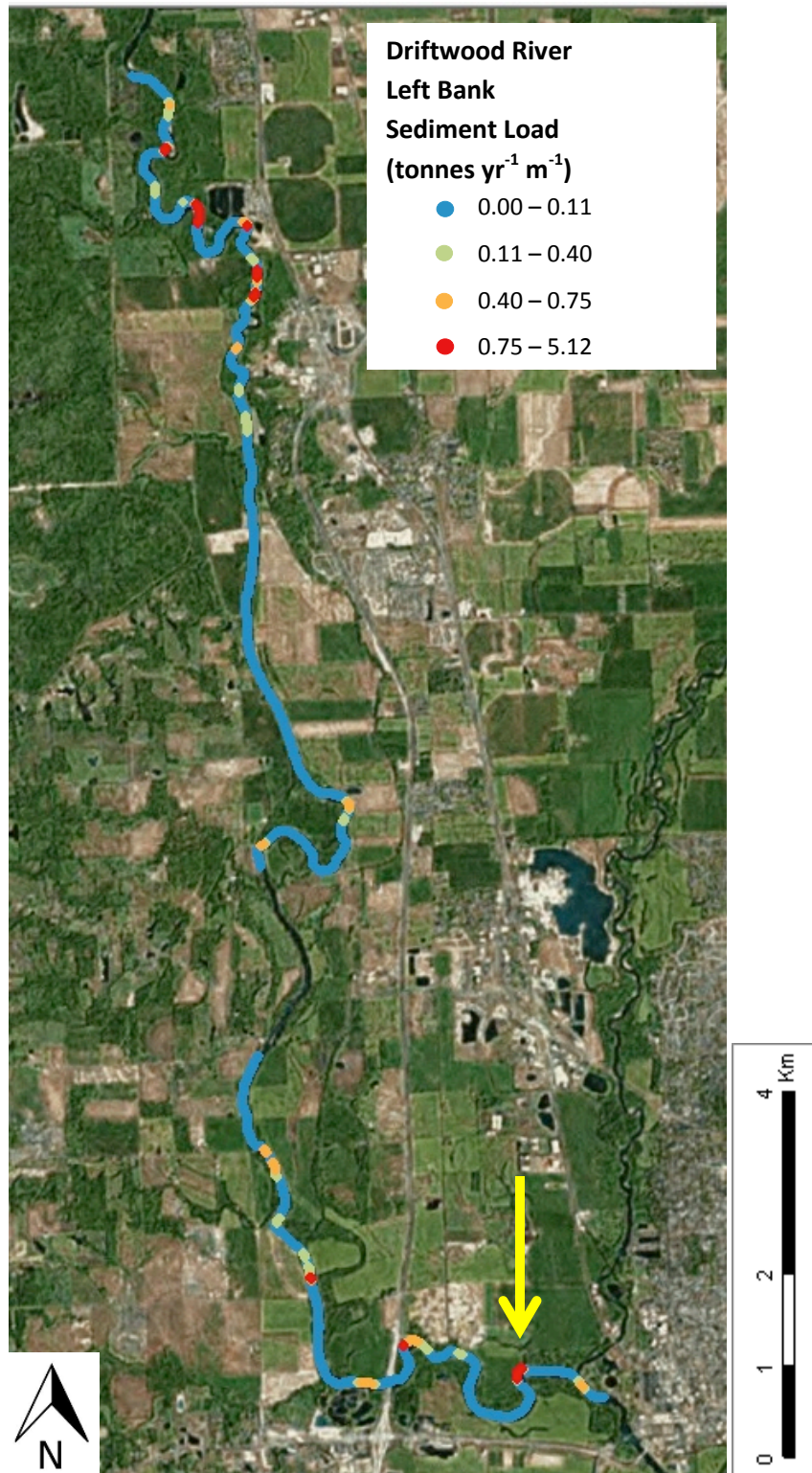


Figure 7.21. Driftwood River site-specific sediment loads for the left bank (east). The yellow arrow highlights a 167 m stretch of bank with the highest sediment load values.

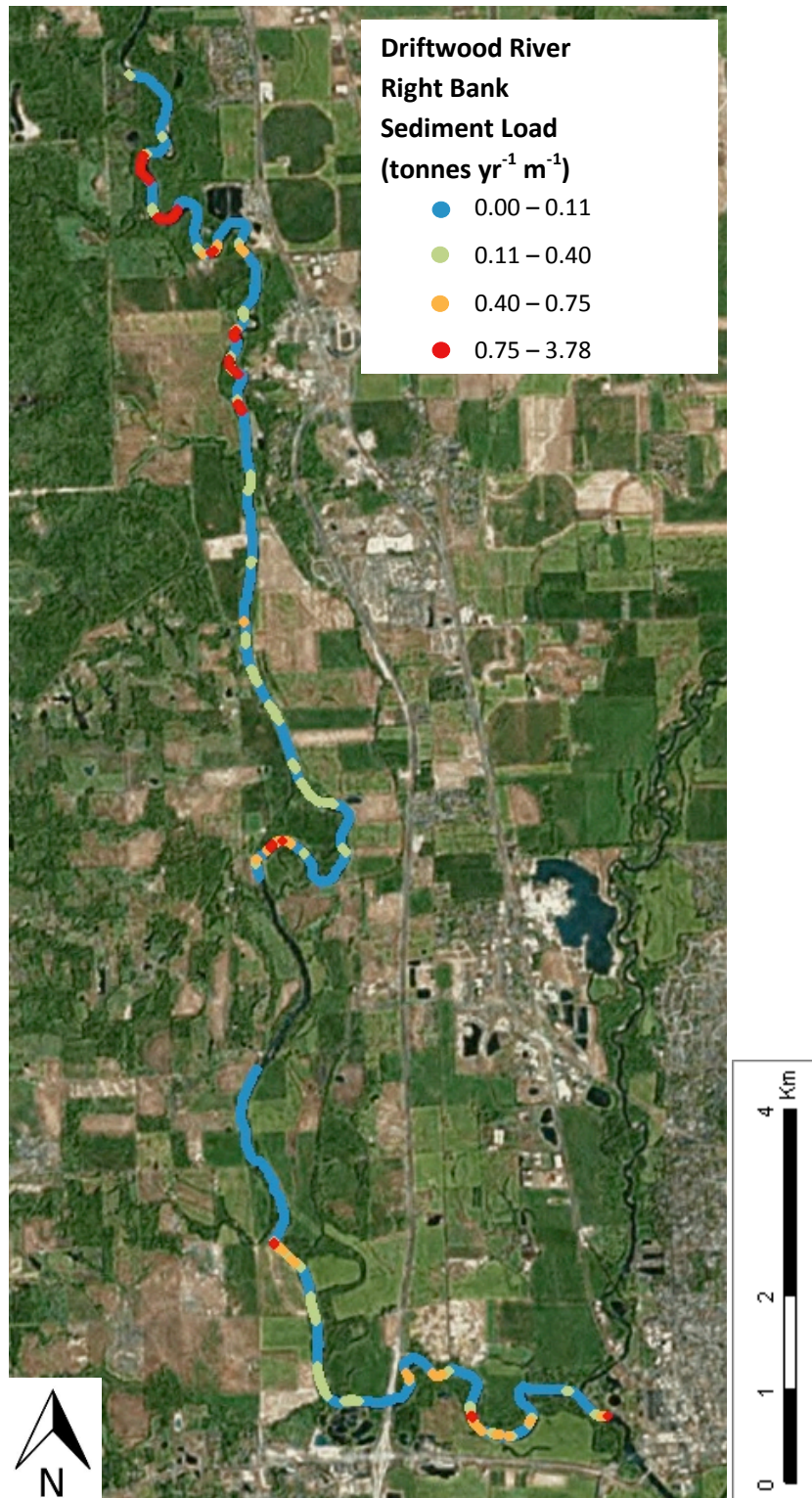


Figure 7.22. Driftwood River site-specific sediment loads for the right bank (west).



Figure 7.23. Upatoi Creek site-specific sediment loads for the left bank (south).



Figure 7.24. Upatoi Creek site-specific sediment loads for the right bank (north).

The TSL for Driftwood River was 2.2 times greater than Upatoi Creek primarily due to streambank condition, assessed using the mBEHI (Appendix C). Driftwood River had 13% of mBEHI scores within the very high erosion susceptibility rating compared to 5% for Upatoi Creek. Further analyses showed the percentage of very high ratings were 2.8 and 2.0 times greater for Driftwood River in the riparian diversity and surface protection parameters. Consequently, the larger TSL value for Driftwood River was the result of poor riparian diversity and a low percentage of bank surface protection (Figure 7.25). Ocular assessments of video footage provided further information about the study site such as the major land use type adjacent to each river system. The surveyed section of Driftwood River was predominately surrounded by agricultural areas with periodic residential houses. A transition into these land use types was noted by a decrease in both surface protection and riparian diversity due to the presence of pastures and mowed grasses. In contrast, the surveyed section of Upatoi Creek was entirely within Fort Benning, a military base, and surrounded by predominately forested lands. Similar analyses of mBEHI distributions can be completed to provide detailed information about the location and possible causes of high erosion rates, which can then be utilized by watershed managers for the development of site-suitable restoration designs.



Figure 7.25. Driftwood River site with a low percentage of bank surface protection. This streambank location received a high bank erosion susceptibility rating, mBEHI score = 36.80.

The utility of the BANCS model is two-fold, because the method allows for the comparison of TSL estimates between and within stream systems. If restoration efforts are planned on a reach-scale, TSL estimates can be used to identify the streambank locations contributing the greatest amount to the annual sediment load. For example, in certain stream systems, like Upatoi Creek, one bank may have a greater annual contribution to the sediment load. On the other hand, if restoration efforts are planned on a watershed-scale, TSL estimates can be used to prioritize restoration sites between streams.

Additionally, the estimated TSLs of this study were compared with predicted values reported in the literature from other BANCS assessments. The North Carolina and Colorado BER curves were employed along with field determined BEHI and NBS scores for sections of the Housatonic River

(Stantec, 2009). Along 24.9 linear kilometers of streambank (12.45 km of stream channel), the Colorado curves predicted an annual sediment load of 7,711 tonnes compared to an annual load of 5,625 tonnes using the North Carolina curves. The TSL per unit stream channel length was  $617 \text{ t yr}^{-1} \text{ km}^{-1}$  and  $450 \text{ t yr}^{-1} \text{ km}^{-1}$  using the CO and NC curves, respectively (Stantec, 2009). Utilizing the Northern Arkansas curves, the sediment load from streambank erosion was predicted to be  $335 \text{ t yr}^{-1} \text{ km}^{-1}$  over 64 km of stream channel in the West Fork White River watershed (Van Eps et al., 2004).

#### 7.2.4 Evaluation of Zero NBS

Previously reported TSL values for this study were calculated under the assumption that an NBS score of zero would result in a BER value of  $0 \text{ m yr}^{-1}$ . An analysis of this NBS filter was completed to identify its impact on resultant TSL values. The BANCs model employs NBS index scores ranging from 1 to 6 and does not mention a protocol for predicting BERs at streambank locations with depositional features. Therefore, if all site-specific locations with an NBS score of zero received the lowest possible BER value of  $1.83 \text{ mm yr}^{-1}$ , the annual TSL of Driftwood River would be  $4,992 \text{ t yr}^{-1}$  and  $2,242 \text{ t yr}^{-1}$  for Upatoi Creek. Consequently, using the lowest BER value would increase the TSL of Driftwood River and Upatoi Creek by approximately  $8 \text{ t yr}^{-1}$  and  $17 \text{ t yr}^{-1}$ , respectively. This increase is less than 1% of the total sediment load for both river systems.

#### 7.2.5 Evaluation of One Eroding Bank

The SWAT model assumes erosion only occurs along one channel bank (Neitsch et al., 2009). Based on this assumption, an analysis was conducted to identify the impact of one eroding bank on the TSL prediction for Upatoi Creek. An NBS score of one, very low stream erosivity, occurs on the straighter sections of stream between meander bends. In order to predict streambank erosion for one bank, all NBS scores of one were assigned a BER value of  $0 \text{ m yr}^{-1}$  for either the right or left bank. For Upatoi Creek, if zero erosion was predicted on the left bank, the annual TSL value would be  $1,189 \text{ t yr}^{-1}$

compared to the original value of 2,225 t yr<sup>-1</sup> for erosion on both banks. Additionally, if zero erosion was predicted on the right bank, the annual TSL value would be 1,474 t yr<sup>-1</sup>. Consequently, the assumption that erosion occurred on only one bank would reduce the predicted TSL of Upatoi Creek by 34% for the right bank and 47% for the left bank, depending on which bank was designated as eroding. A higher percent reduction for the left bank was due to a higher overall TSL for the bank.

#### 7.2.6 Stream Restoration Impacts

There is a direct two-way link between stream restoration and sediment loading. Stream restoration projects are initiated as a reduction measure, because the stabilization of eroding streambanks will reduce the quantity of sediment entering a waterbody (Smith et al., 2011). To estimate the potential sediment load reduction resulting from improved streambank and channel conditions, TSL predictions were normalized by bank length and sorted in descending order with the top 1% of streambank locations, representing approximately 1% of the total bank length (left and right combined), selected for Driftwood River and Upatoi Creek. The BERs of these locations were changed to 1.83 mm yr<sup>-1</sup>, the lowest possible BER value. Results of this application are presented in Table 7.3 for both stream reaches. Reducing one percent of the total stream length from high to low erosion potential would reduce sediment loading by 18.0% for Driftwood River and 26.8% for Upatoi Creek. A one percent change for Upatoi Creek produced a greater impact on the right bank, with a 33.0% reduction, due to higher normalized TSL values. In contrast, the left bank had a reduction of 21.9%. Using this potential sediment load reduction approach demonstrates the value of selecting appropriate locations for stream restoration projects.

Table 7.3. Potential sediment load reductions for Driftwood River and Upatoi Creek by changing one percent of the highest normalized TSL values.

| Variable           | Driftwood River<br>TSL (t yr <sup>-1</sup> ) | Upatoi Creek<br>TSL (t yr <sup>-1</sup> ) |
|--------------------|----------------------------------------------|-------------------------------------------|
| <b>Original</b>    | 4,984                                        | 2,225                                     |
| <b>1% Change</b>   | 4,085                                        | 1,629                                     |
| <b>Reduction</b>   | 899                                          | 596                                       |
| <b>% Reduction</b> | 18.0                                         | 26.8                                      |

A similar reduction assessment was completed for streambank erosion in the West Fork Gallatin River watershed of Montana (PBS&J, 2009). All BEHI values with a high erosion susceptibility rating were reduced to a moderate rating if the source of streambank erosion was identified as anthropogenic. Streambank location estimates were extrapolated to predict a percent reduction for the entire stream reach. Using this approach, streambank sediment loads resulting from anthropogenic disturbances showed a 31% reduction in the West Fork Gallatin River watershed (PBS&J, 2009).

Restoration strategies will vary depending on the problem, targeted sites, and erosion rates (Gellis and Walling, 2011). The State of Virginia established a step-by-step protocol for aiding government, non-profit, and private organizations in the selection of optimal locations for stream restoration projects and management practices. Steps include ranking the degraded sections by erosion potential and prioritizing sites based on a combination of various constraints such as land accessibility, ownership, and cost (Virginia DCR, 2004). It has been estimated that over 1 billion dollars is spent annually on stream restoration projects in the United States (Palmer et al., 2007). Therefore, taking similar steps before implementing restoration practices is a key component behind successful as well as cost effective projects.

Variations of this TSL reduction method could be completed for other goals such as identifying optimal sites for riparian vegetation plantings. In regards to prioritizing riparian zone restoration efforts, the data would be sorted first by normalized TSL values, second by riparian diversity scores, and third by bank height to bank full ratio scores. The bank height to bankfull ratio (BH:BF) parameter should be included in the assessment, because an increase in riparian diversity (i.e. species composition and abundance) will have the greatest impact at streambank locations with low BH:BF ratios due to the potential for rooting depths and densities to provide a higher percentage of reinforcement to the bank (Thorne, 1990).

### **7.3 TSL Limitations**

For this study, the North Carolina bank erosion prediction curves were used to estimate annual sediment loads for two stream reaches, one on Driftwood River and one on Upatoi Creek. These prediction curves have established a relationship between BEHI ratings and NBS scores from empirically derived erosion rate measurements for the Piedmont region. This curve was selected for the Upatoi Creek study site, because the stream reach was located within the Piedmont region. The Driftwood River study site is not within the Piedmont region; however, the North Carolina curves were still used to estimate BERs because erosion prediction curves have not been established for the site's physiographic setting. Consequently, TSL estimates for Driftwood River will not represent the physiographic conditions of southern Indiana. Still, a comparative analysis of two study sites provides valuable information about the potential differences impacting streambank erosion between riverine systems.

The BANCS model does not specify whether or not interpolating should be a part of the estimation process. This TSL protocol interpolated between the BEHI rating regression lines in order to obtain a wider range of annual BERs. Without interpolating there would only be 24 possible BER values. This study did not interpolate between NBS ratings because each  $R_c/W$  value was converted to a whole

number NBS score ranging from 1 – 6. The sensitivity of BER estimates varies with the erosion prediction curves as well as the BEHI and NBS scores. Using various NBS scores, the sensitivity of BER estimates is greatest along prediction curves (i.e. regression lines) with the steepest slopes. Using various BEHI scores, the sensitivity of BER estimates is greatest between prediction curves with a large intercept difference. For the North Carolina curves, the moderate BEHI regression line is most sensitive to changes in NBS due to a steep slope of 0.9579 while the very high BEHI regression line is least sensitive due to a shallow slope of 0.2212 (NCSU, 1989).

Future work may need to be focused on the bank height to bankfull ratio (BH:BF), a parameter of the mBEHI. For this study, the average bankfull height was visually estimated and held constant for both stream reaches. However, the bankfull height may vary considerably within a reach. Underestimating the bankfull height will result in higher BH:BF scores and subsequently higher erosion susceptibility ratings. The BH:BF is one of four mBEHI parameters and has a weight of 20%, because the riparian diversity parameter is doubly weighted, 40%. So, even though underestimation of the bankfull height will increase the overall erosion susceptibility, the resulting percent change in the BH:BF score would be reduced by 80% in the total mBEHI score.

## Chapter 8: TMDL Development

### 8.1 Daily Flow Erosion Potentials and Total Daily Sediment Loads

A protocol for establishing sediment Total Maximum Daily Loads (TMDLs) was developed for the Georgia Conservancy and University of Georgia by The Sediment TMDL Advisory Group (Keyes and Radcliffe, 2002). This report highlighted the importance of using flow rates to predict daily sediment loads. Likewise, the USEPA (1999) created a guidance document for establishing sediment TMDLs and emphasized the importance of temporal variability in developing this numerical limit. As a result, sediment TMDLs need to consider the flow rate at which sediment loading is of concern. Thus, annual erosion rates were converted to daily rates using discharge data.

Time-averaged daily discharge measurements were obtained from USGS gage stations (<http://waterdata.usgs.gov/usa/nwis/>). Driftwood River had 49 years of flow data (1942 – 1991) while Upatoi Creek had 44 years (1969 – 2012). The seasonal variation in flow rates followed a similar trend for both river systems. Highest annual discharges occurred in the winter and spring whereas the lowest annual discharges occurred in summer and fall (Figure 5.3).

The lateral erosion rate (LER) for a given flow was predicted using the all-flow (all-Q) approach by raising the time-averaged daily discharge to a 0.6 power factor. This power factor was obtained from a global review of meander migration rates plotted against discharge (Rutherford, 2000). In the streambank erosion routine of the AVGWLF model, the same 0.6 factor is used to predict lateral erosion rates based on discharges (Evans et al., 2003). Therefore, an LER was calculated for all 365 days using equation 2.

The daily flow erosion potential (DFEP) was predicted by dividing the LER for a specific day by the sum of LERs for all 365 days:  $LER_i / \sum_{i=1}^{365} LER_i$ . For instance, if daily flow rates were constant over a one year period, the average DFEP would be 0.27%. For Driftwood River, the a highest average DFEP,

0.41%, occurred during the month of March at an average flow rate of 2206 cfs while the lowest average DFEP, 0.13%, occurred during September at 337 cfs (Figure 8.1). For Upatoi Creek, the highest average DFEP, 0.46%, occurred during March at an average flow rate of 938 cfs while the lowest average DFEP, 0.18%, occurred during September at 192 cfs (Figure 8.1).

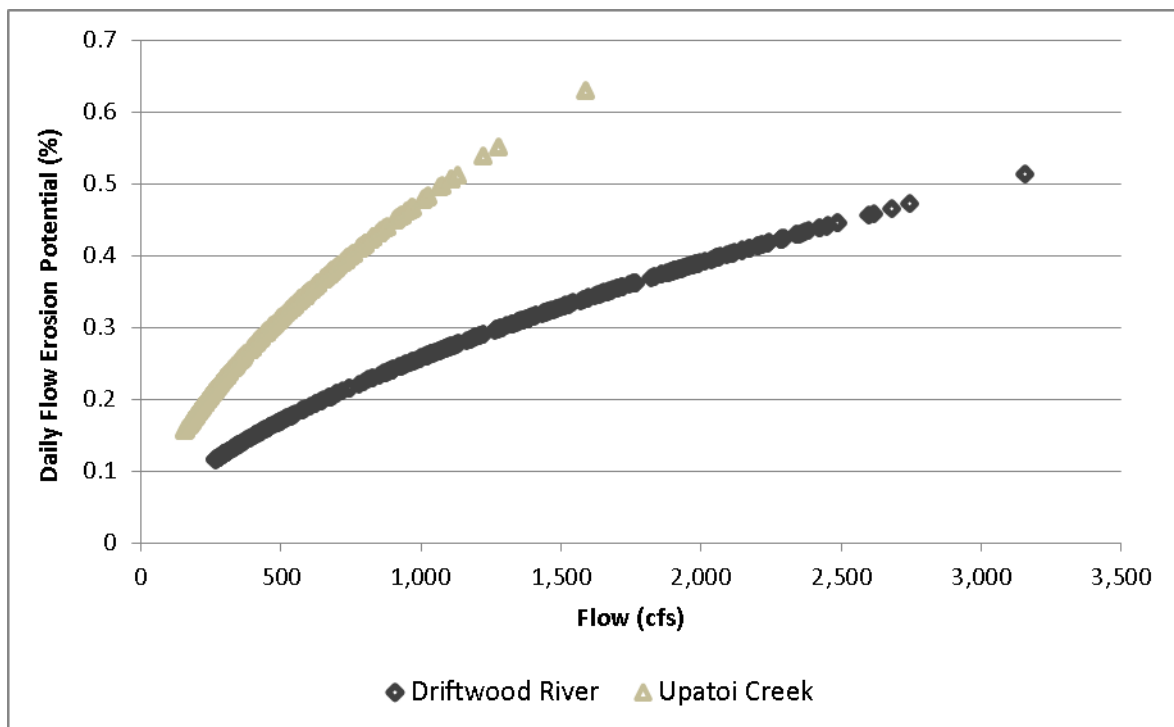
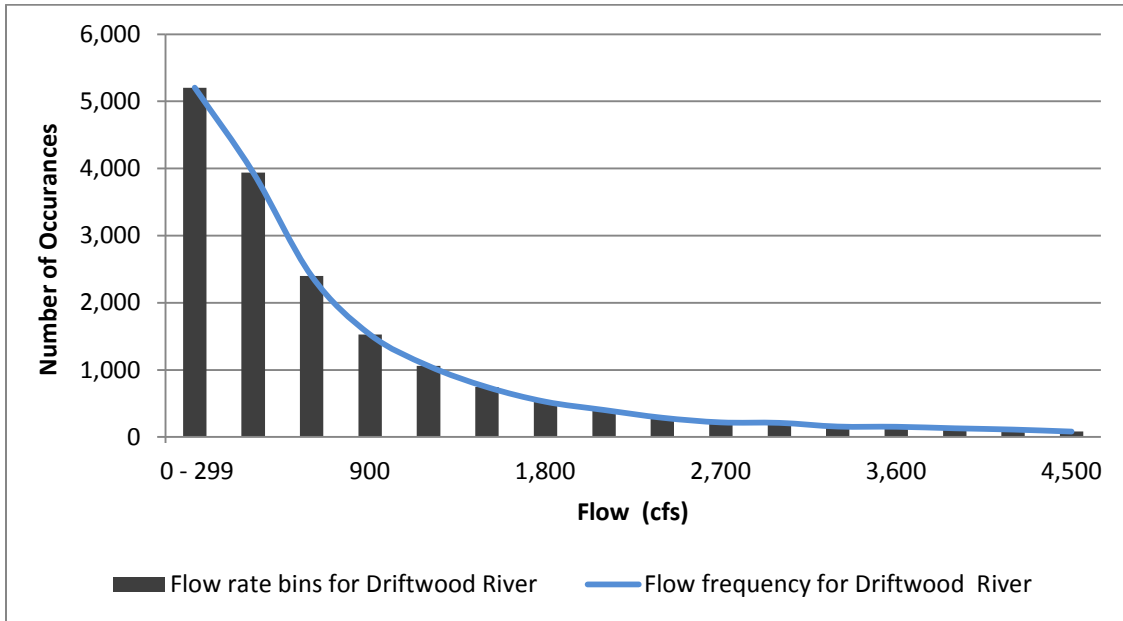


Figure 8.1. Percent DFEP curves for Driftwood River and Upatoi Creek.

A site-specific daily erosion rate was estimated by multiplying the previously determined bank erosion rates (BERs) with the flow induced erosion potential for each day, DFEP. Likewise, a site-specific daily sediment load was predicted by multiplying the previously determined sediment loads with the DFEP for each day. Thus, the Total Daily Sediment Load (TDSL) of the entire reach was calculated by summing together the daily sediment load values for each streambank location. Figure 8.2 displays the relationship between number of flow events and discharge. Discharges were grouped into flow rate bins at 300 cfs increments. Both rivers experienced a greater occurrence of events at low to moderate flows. In a study by Wolman and Miller (1960), on an annual basis, the greatest contribution of sediment transport occurred at low to moderate flow events. Similar to these findings, the greatest contribution of streambank erosion occurred at low to moderate flow events for Driftwood River over a 49-year period and for Upatoi Creek over a 44-year period of record (Figure 8.3).

a)



b)

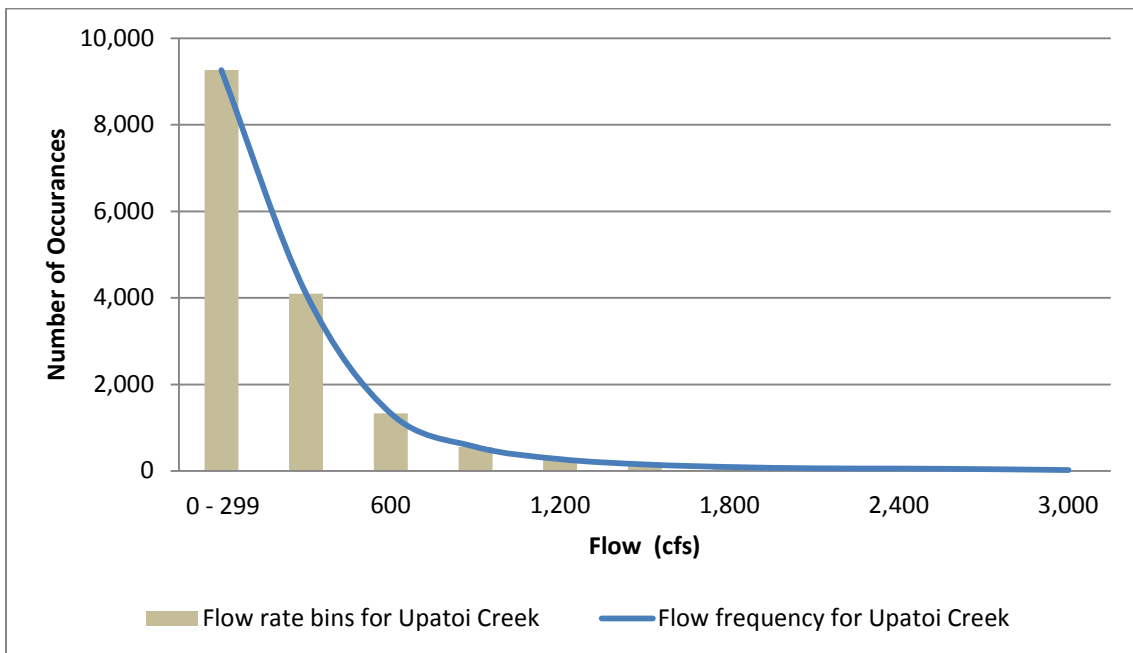
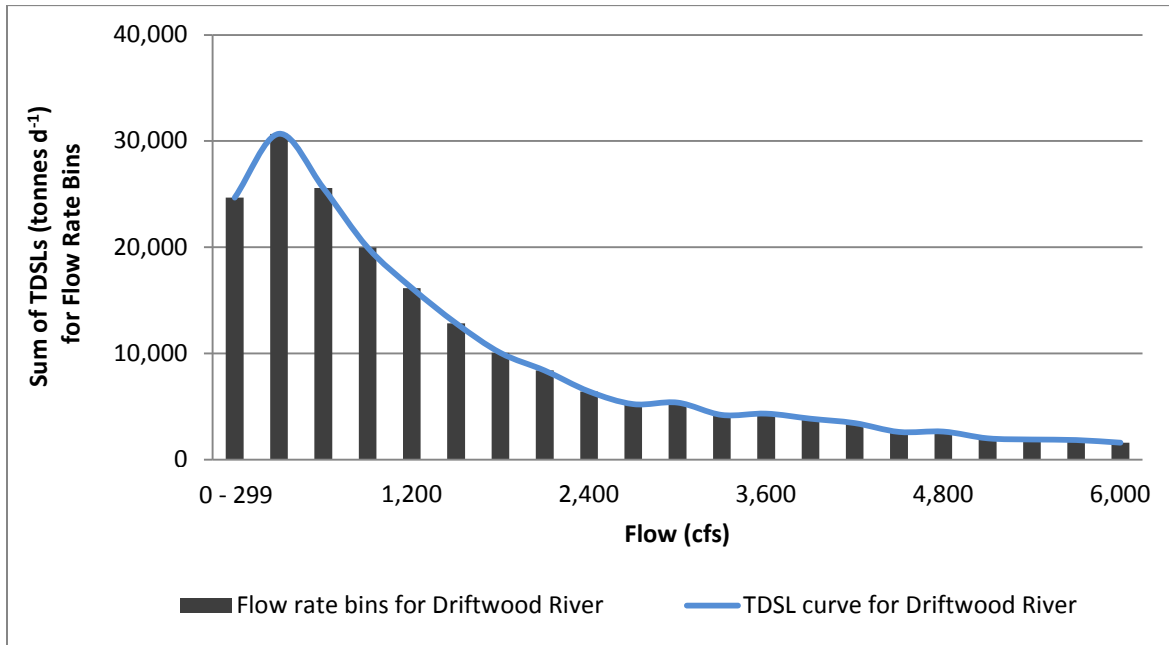


Figure 8.2. Frequency of flow occurrences over a) 49-year period (1942 – 1991) of USGS discharge data for Driftwood River and b) 44-year period (1969 – 2012) of USGS discharge data for Upatoi Creek. Flow rates were grouped into bins at 300 cfs increments (e.g. 0 – 299 cfs).

a)



b)

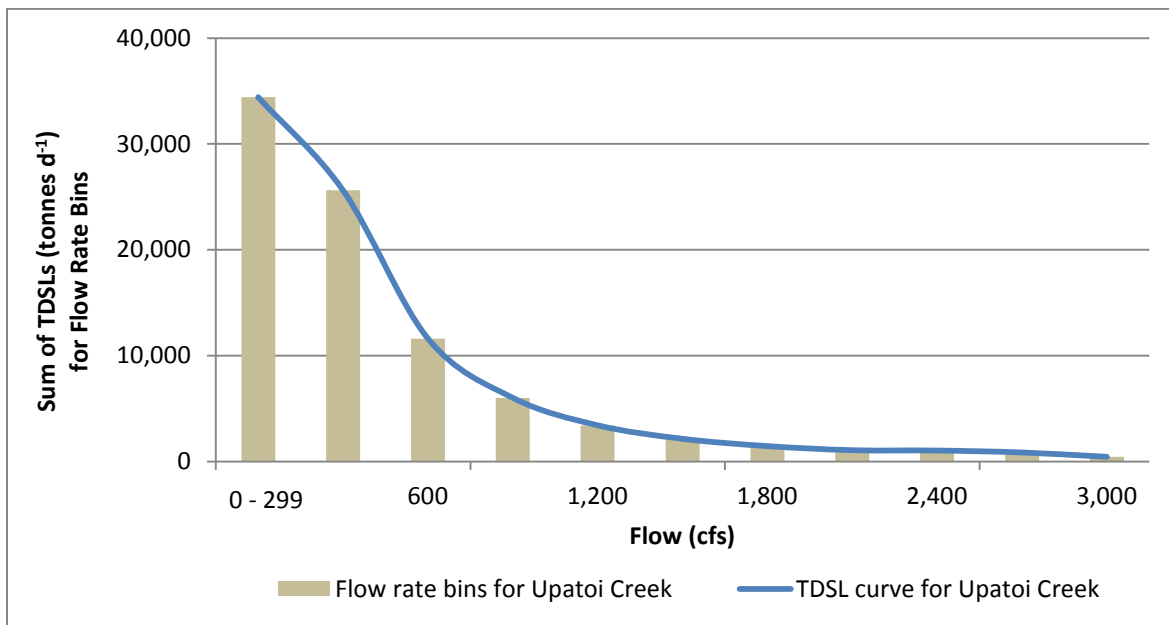


Figure 8.3. Summation of TDSL values by flow rate bins over a) 49-year period (1942 – 1991) of USGS discharge data for Driftwood River and b) 44-year period (1969 – 2012) of USGS discharge data for Upatoi Creek. Flow rates were grouped into bins at 300 cfs increments (e.g. 0 – 299 cfs).

### 8.1.1 Sediment Load Curve

USGS rating curves are developed to predict stream discharge based on the height (stage) of water in a gage station (NOAA, 2014). Based on this concept, a sediment load curve for streambank erosion was developed to estimate TDSL values based on daily flow rates (Figure 8.4). Once this curve has been developed for a river system, it can be used along with discharge data to predict daily sediment loads. As with the USGS rating curve, the sediment load curve may shift over time resulting from changes in the river system, such as streambank erodibility and stream erosivity, or within the watershed such as changes in land use practices (NOAA, 2014). This curve can be employed as input to hydrologic models and as a component of TMDL development.

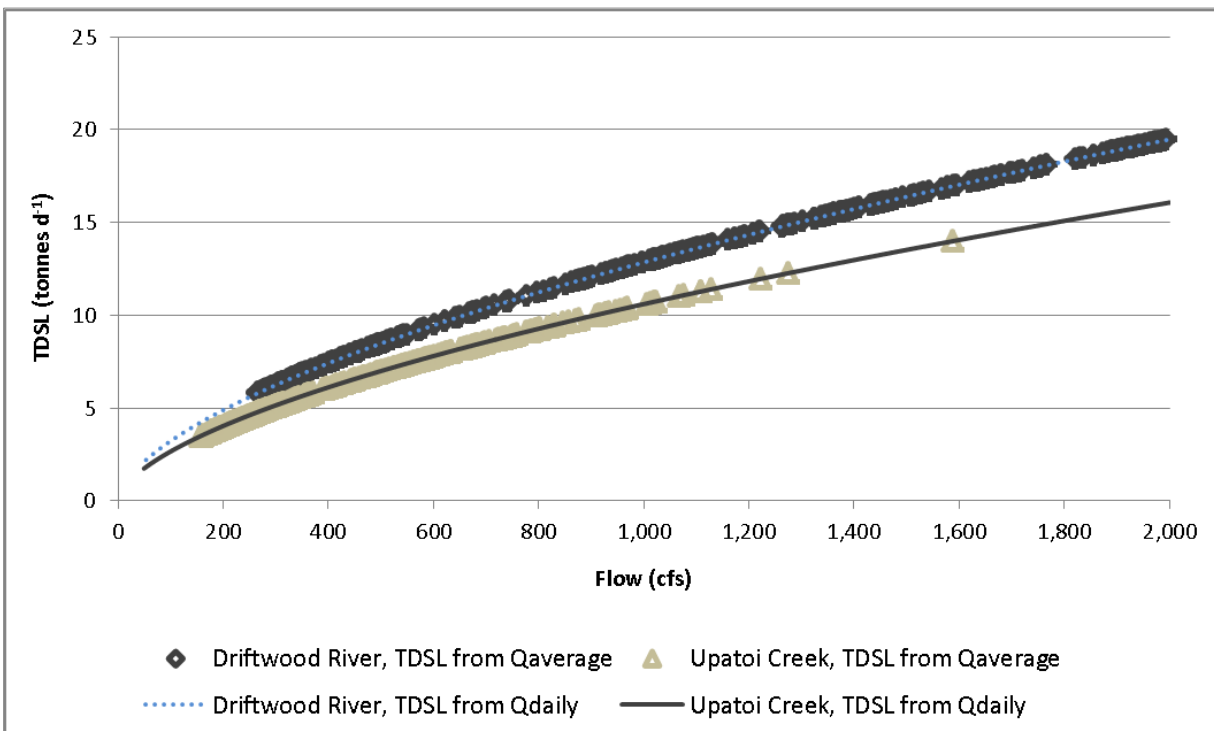


Figure 8.4. Relationship between time-averaged daily flow rates and total daily sediment loads for Driftwood River and Upatoi Creek.

### 8.1.2 Estimating DFEPs Using an Excess-flow Approach

Several erosion prediction models, such as BSTEM and SWAT, use the excess shear stress approach (eq. 1) to predict streambank erosion rates (Neitsch et al., 2009; Simon et al., 2009). Based on this approach, the initiation of fluvial erosion is dependent on a detachment threshold termed critical shear stress. Erosion does not occur if the average boundary shear stress is below the critical limit. A study on the middle Sacramento River in California employed aerial photography and in-field erosion measurements to assess the impact of stream power on lateral migration rates (Larsen et al., 2006). Regression analysis displayed a strong linear relationship between both parameters. Furthermore, a higher statistical relationship was found when including a discharge threshold. After the threshold was applied to the regression analysis, higher erosion rates were estimated at high flow events.

This threshold concept was applied to the DFEP protocol in order to determine its impact on the TDSL estimates for Upatoi Creek. Based on the LER equation (eq. 2), the critical limit would be associated with a flow rate. Low flow rates were assumed to have no erosive potential and therefore excluded from this analysis by estimating an average baseflow discharge ( $Q_{bf}$ ). This threshold value was selected based on time-averaged daily baseflow estimates from HYSEP, a hydrograph separation program developed by the USGS (Sloto and Crouse, 1996). The program's local minimum algorithm was used to separate the baseflow component from the total streamflow (Figure 8.5). Baseflow values are impacted by small- and large-scale variations such as seasonal and climatic conditions. Therefore, long-term average values should be utilized as inputs into the HYSEP program to reduce the influence of outliers caused by temporal variations (Sloto and Crouse, 1996). Thus, to estimate  $Q_{bf}$ , a time-averaged annual hydrograph was input into HYSEP.

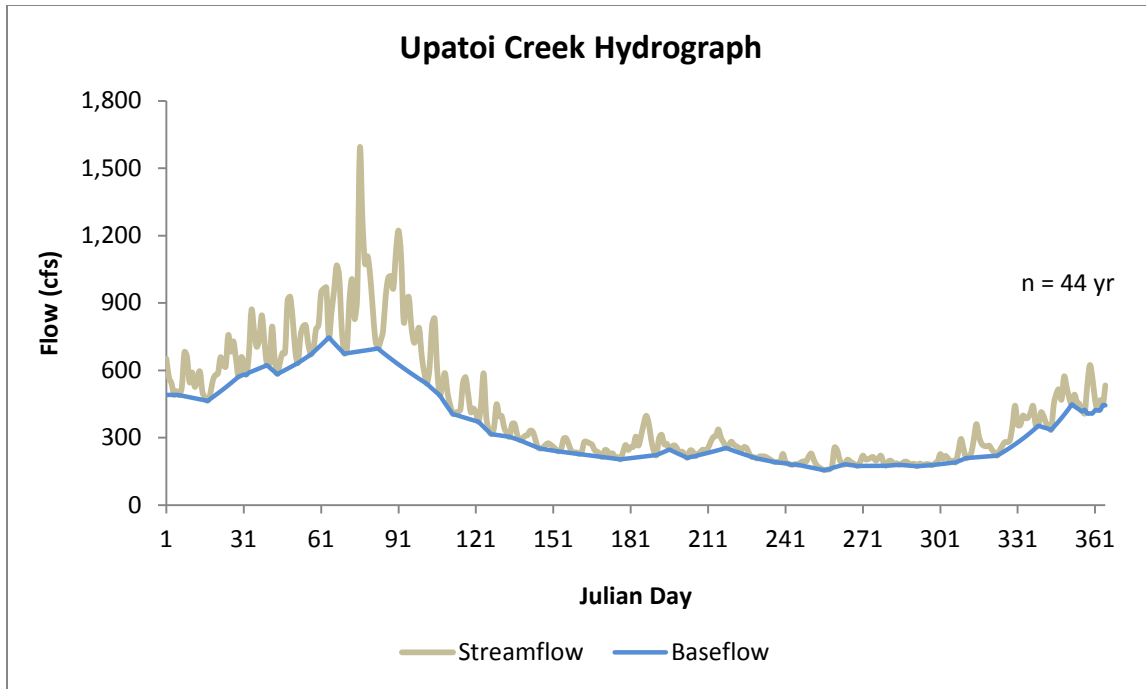


Figure 8.5. Time-averaged annual hydrograph, separated into the baseflow component, for a 44-year period (1969 – 2012) of USGS discharge data for Upatoi Creek.

Over a 44-year period, the average annual baseflow using HYSEP was 350 cfs for Upatoi Creek. This numerical value was selected as the streambank erosion threshold,  $Q_{bf}$ . On an average annual basis, 88% of all discharge values less than 350 cfs occurred between the months of May and November (Figure 8.6). Consequently, the DFEPs for all discharges less than 350 cfs ( $<Q_{bf}$ ) were assigned a value of zero resulting in daily bank erosion rate estimates of  $0 \text{ m d}^{-1}$  (Figure 8.7). Because of this numerical threshold, 65% of TDSL estimates based on daily discharge values were changed to  $0 \text{ t d}^{-1}$ . Conversely, DFEPs for discharges greater than  $Q_{bf}$  were calculated by subtracting the baseflow discharge from the

individual time-averaged daily discharges ( $Q_i - Q_{bf}$ ). The resultant excess flow values were used in the LER equation and DFEPs were estimated using the same protocol as the all-Q approach:

$$LER_i / \sum_{i=1}^{365} LER_i.$$

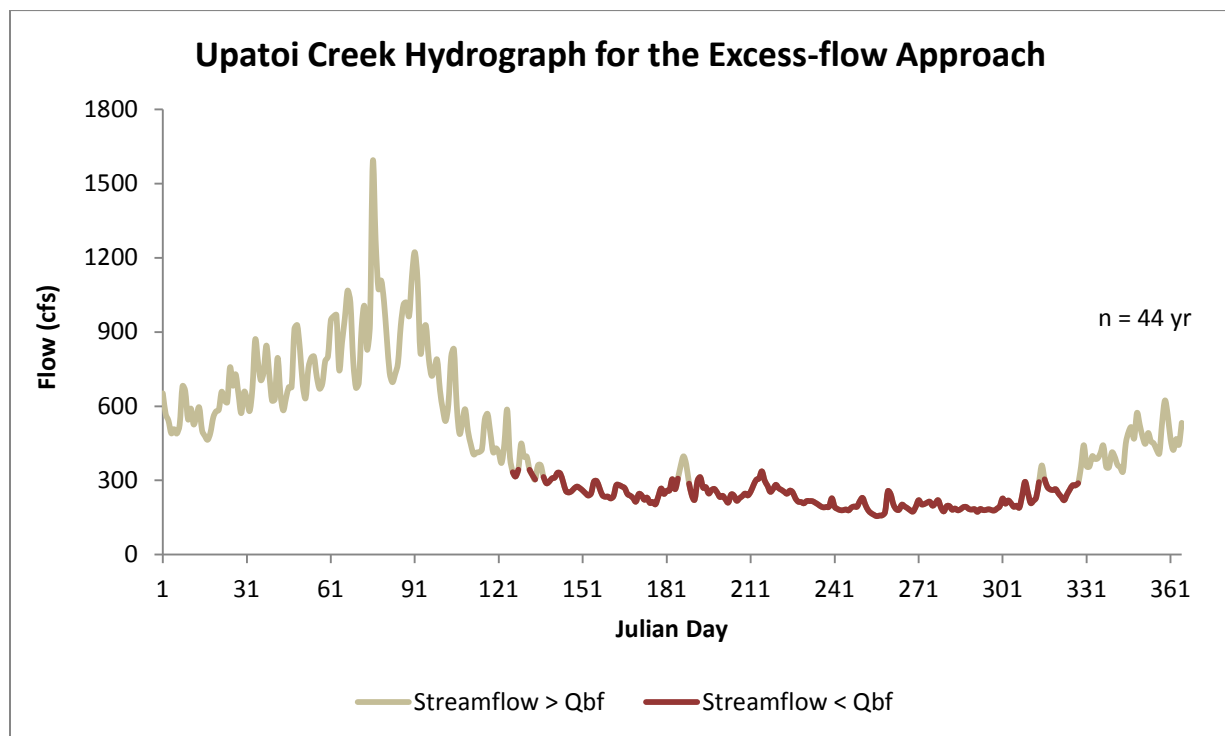


Figure 8.6. Time-averaged annual hydrograph, highlighting flows less than  $Q_{bf}$ , for a 44-year period (1969 – 2012) of USGS discharge data for Upatoi Creek

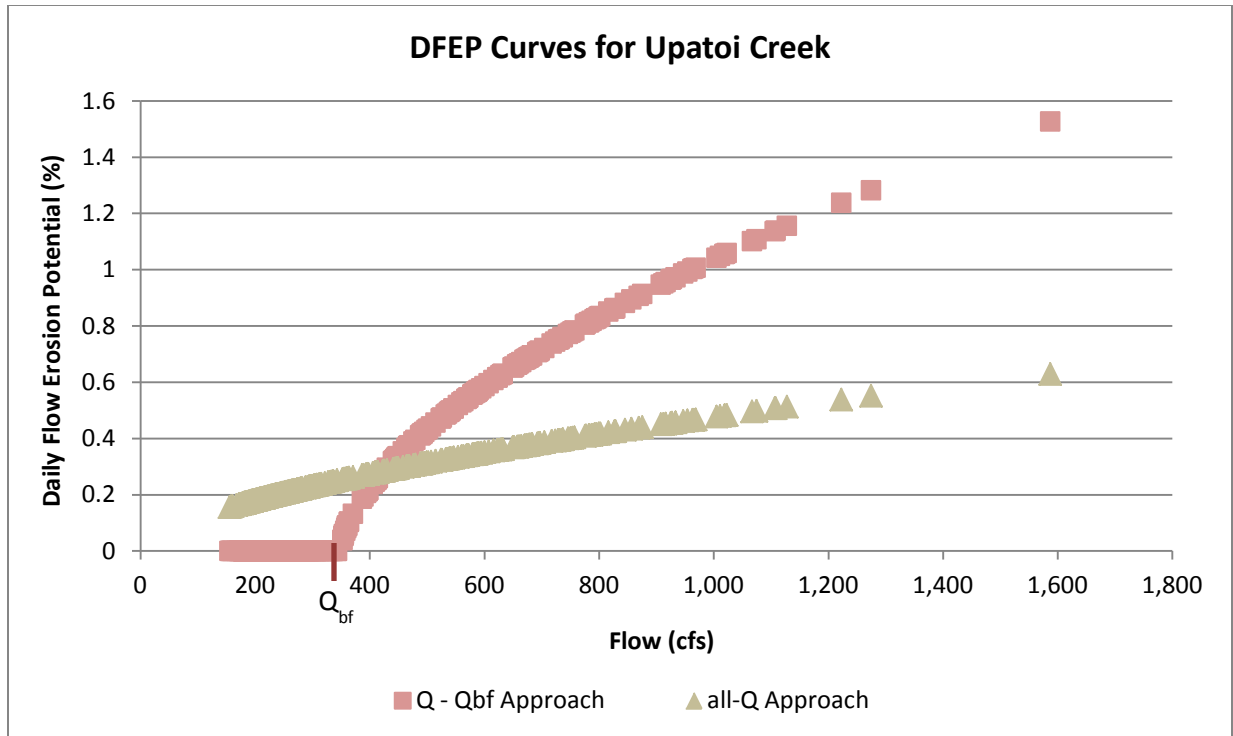


Figure 8.7. Comparison of Percent Daily Flow Erosion Potential (DFEP) curves using the excess-flow ( $Q - Q_{bf}$ ) and all-flow approaches (all-Q) for Upatoi Creek.

Similar to the findings of Larsen et al. (2006), after the  $Q_{bf}$  was applied, the sediment load distribution shifted upward resulting in higher sediment loads at higher flow events (Figure 8.8). This positive shift in the sediment load curve is explained by the stream-specific erosion potential coefficient, which increased from 0.168 to 0.474 after the excess-flow approach was utilized for Upatoi Creek. As illustrated in Figure 8.9, the greatest contribution of sediment loading shifted from low to moderate flow events.

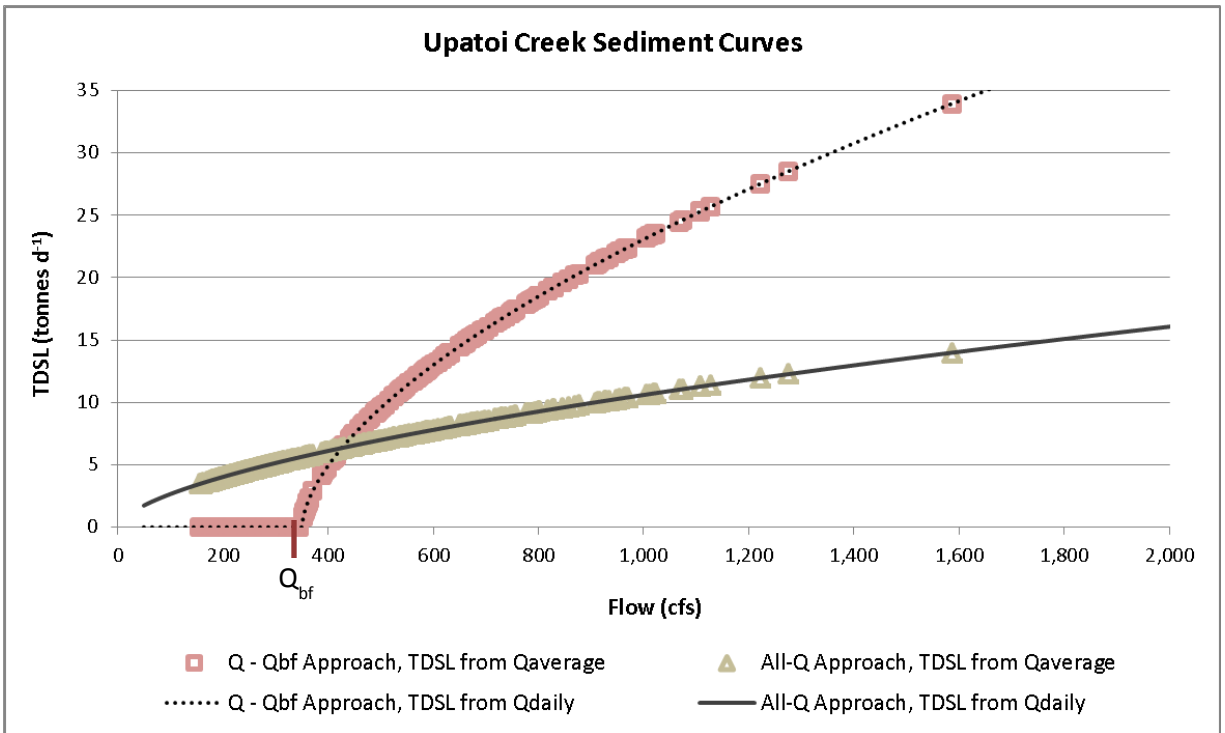


Figure 8.8. A comparison of sediment loading curves for Upatoi Creek using the excess-flow ( $Q - Q_{bf}$ ) and all-flow (all-Q) approaches.

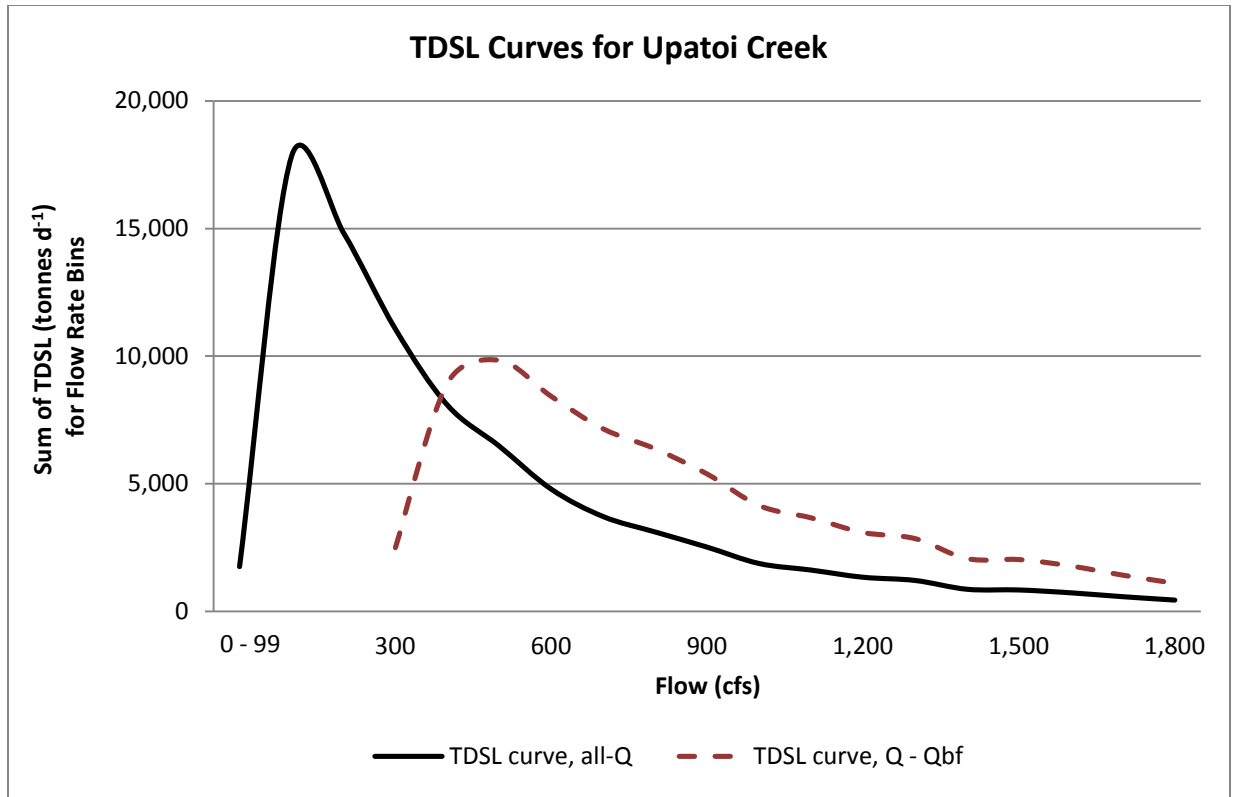


Figure 8.9. TDSL summation curves by flow rate bins over a 44-year period (1969 – 2012) of USGS discharge data for Upatoi Creek using the excess-flow and all-flow approaches. Flow rates were grouped into bins at 100 cfs increments (e.g. 0 – 99 cfs).

## 8.2 Calculation of TMDLs for Streambank Erosion

TDSLs can be used to calculate a numerical sediment TMDL for streambank erosion by incorporating these values into the Maximum Daily Limit (MDL) equation (eq. 3), a long-term average approach devised by the USEPA. This statistical approach assumes a log-normal distribution. Plotting USGS discharge data against number of occurrences displays a log-normal distribution for both study sites (Figures 8.2). First, equation 2 was used to predict daily lateral erosion rates (LERs) based on USGS daily flow data over a 49-year period for Driftwood River and a 44-year period for Upatoi Creek. Second, an erosion potential coefficient was empirically-derived from the data (Evans et al., 2003). The AVGWLF model uses watershed characteristics, such as percent developed land, animal density, and area-weighted curve number, to calculate the erosion potential coefficient,  $a$  (eq. 2). Therefore, an erosion potential coefficient was derived for this study to fit the daily LER values to the trend previously established for sediment load estimates based on average-annual discharge values (Figure 8.4). As a result, the daily LER values were multiplied by the stream-specific erosion potential coefficient. Third, the estimated total daily sediment loads were statistically analyzed to determine a long-term average, standard deviation, and coefficient of variation. Last, these statistical values along with a z-score were input into eq. 3 in order to estimate the TMDL in tonnes per day. Furthermore, the flow rate at which the TMDL was exceeded can be identified over the time period of interest.

Table 8.1 shows the results for Upatoi Creek and Driftwood River using the USEPA-devised MDL equation. The Driftwood River had greater variability in flow rates which resulted in a higher coefficient of variation. The TMDL for streambank erosion was  $66 \text{ t d}^{-1}$  for the 22.5 km section of Driftwood River and  $24 \text{ t d}^{-1}$  for the 20.4 km section of Upatoi Creek. Furthermore, the flow rate above which the TMDL was exceeded occurs at 15,117 cfs for Driftwood River and 3,912 cfs for Upatoi Creek. Driftwood River had a higher long-term average (LTA) flow rate resulting in a higher LTA sediment load, because of the power relationship between flow and lateral erosion (eq. 2). The Driftwood River drains a watershed

area of 2,746 km<sup>2</sup> while Upatoi Creek drains a watershed area of 886 km<sup>2</sup>. Therefore, the larger watershed area of Driftwood River results in higher average discharges. Based on USGS flow data, the MDL for the Driftwood River was exceeded 0.3% over a 49-year period in comparison to 0.5% over a 44-year period for Upatoi Creek.

These values of streambank erosion need to be added to estimates of overland flow erosion to get the true sediment loading rates of river systems (USEPA, 1999). Additionally, total sediment load values for streambank erosion should be included in the calculation of sediment TMDLs to create a more robust plan for restoring impaired streams back to acceptable water quality standards (Borah et al., 2006).

Table 8.1. TMDL results for Driftwood River and Upatoi Creek using the MDL equation.

| Variable                      | Driftwood River | Upatoi Creek |
|-------------------------------|-----------------|--------------|
| LTA TSL, t d <sup>-1</sup>    | 12.1            | 5.7          |
| LTA Q, cfs                    | 909             | 355          |
| St Dev, t d <sup>-1</sup>     | 9.5             | 3.6          |
| CV                            | 0.8             | 0.6          |
| z                             | 2.778           | 2.778        |
| TMDL, t d <sup>-1</sup>       | 66              | 24           |
| TMDL Q, cfs                   | 15,117          | 3,912        |
| Erosion Potential Coefficient | 0.204           | 0.168        |
| Count                         | 17,885          | 16,060       |
| Occurrence, %                 | 0.3             | 0.5          |

### 8.2.1 Impact of Scale on the TMDL

A 1.6 km section of Driftwood River, 7% of the total reach length, was analyzed to assess the impact of scale on the TMDL results. The LTA sediment load decreased to  $1.0 \text{ t d}^{-1}$  and the TMDL for streambank erosion decreased to  $5.4 \text{ t d}^{-1}$ , approximately 8% of the total reach erosion rate. However, the LTA and TMDL flow rates were equivalent to the original results for the entire reach. Consequently, scale impacted the selection of streambank locations with varying mBEHI and NBS scores resulting in dissimilar BERs and TSLs, while flow rates were held constant for the entire reach and therefore not impacted by scale. This finding is significant because the flow rate at which the TMDL is reached is not dependent on the reach length.

### 8.2.2 Impact of Stream Restoration on TMDLs

An analysis was performed to assess the impact of stream restoration projects on the sediment TMDL. For Upatoi Creek, the TSL was reduced by 26.8% after the highest 1% of normalized TSL values, equivalent to 1% of the total bank length, were given the lowest possible BER. Using eq. 3, if the TMDL was not recalculated after these streambank locations were restored, the flow rate at which the TMDL was exceeded would increase from 3,192 to 6,579 cfs (Table 8.2). This reduced the occurrence rate of TMDL flow events from 0.5% to 0.1%. Thus, after restoration efforts are completed, the TMDL will be exceeded approximately five times less often.

Table 8.2. Impact of stream restoration on the TMDL for Upatoi Creek.

| Variable                      | Upatoi Creek |
|-------------------------------|--------------|
| LTA TSL, $t\ d^{-1}$          | 5.7          |
| St Dev, $t\ d^{-1}$           | 3.6          |
| CV                            | 0.6          |
| z                             | 2.778        |
| TMDL, $t\ d^{-1}$             | 24           |
| TMDL Q, cfs                   | 6,579        |
| Erosion Potential Coefficient | 0.123        |
| Count                         | 16,060       |
| Occurrence, %                 | 0.1          |

### 8.2.3 TMDL Using the Excess-flow Approach

Previously reported TMDL values were calculated under the assumption that all flow rates produced erosion (all-Q). Based on the excess shear stress approach, streambank erosion begins when a threshold is exceeded. The excess-flow ( $Q - Q_{bf}$ ) approach was applied to the MDL analysis in order to identify its impact on the TMDL estimate for Upatoi Creek. This approach estimated a long-term average sediment load similar to the LTA from the all-Q approach. However, values for the statistical variables used in the MDL equation differed (Table 8.3). The coefficient of variation and standard deviation were greater for the excess-flow approach, because TDSL estimates had a wider range over the 44-years of discharge data,  $0 - 236\ t\ d^{-1}$ . In comparison, the TDSL estimates ranged from  $2 - 84\ t\ d^{-1}$  for the all-flow analysis. As a result, the excess-flow approach produced a TMDL 3.6 times greater than the all-Q approach. Consequently, incorporating an erosion threshold similar to the excess shear stress approach will significantly impact the sediment TMDL.

Table 8.3. TMDL results using the excess-flow approach for Upatoi Creek.

| Variable                      | Upatoi Creek |
|-------------------------------|--------------|
| LTA TSL, $t\ d^{-1}$          | 5.7          |
| St Dev, $t\ d^{-1}$           | 11.5         |
| CV                            | 2.0          |
| z                             | 2.778        |
| TMDL, $t\ d^{-1}$             | 87           |
| TMDL Q, cfs                   | 6,283        |
| Erosion Potential Coefficient | 0.474        |
| Count                         | 16,060       |
| Occurrence, %                 | .2           |

### 8.3 TMDL Limitations

For this study, the method of estimating TDSLs was based on the streambank erosion routine component of the AVGWLF model (eq. 2). This Lateral Erosion Rate (LER) equation uses a power function to establish a relationship between discharges and erosion rates. The 0.6 power factor was obtained from an extensive literature review of global meander migration rates and corresponding average bankfull discharges (Rutherford, 2002). As a result, this relationship is only valid when estimating erosion rates at bankfull discharge. However, the AVGWLF model utilizes the power relationship to predict lateral erosion rates using mean monthly discharges. In this study, the relationship was used to estimate streambank erosion rates for all USGS discharge data. Consequently, the 0.6 power factor may not be valid for all discharge values. Excluding lower flow rates from the analysis resulted in a greater annual contribution of DFEPs at higher flow rates. Consequently, the greatest contribution of sediment loading shifted from low to moderate flow events. Results from the

excess-flow analysis showed a significant impact on the TMDL calculation. Further research should be focused on whether or not a discharge threshold should be used for TDSL estimation and if the 0.6 power factor is appropriate for the entire flow regime.

The MDL equation is a statistical approach that account for the variability of flow rates and sediment loads by incorporating non-daily data to calculate a daily limit. This approach is not restricted to reference conditions. Therefore, if the equation is applied to an impaired body of water, the resultant maximum daily limit will be for the impaired condition. Rather the MDL calculation should be performed on TDSL estimates from a reference stream in order to complete a comparative analysis. TDSL estimates for the impaired waterbody can be used to determine the flow rate at which the impaired stream exceeds the reference MDL. This information can then be used to create a sediment TMDL for the impaired condition. It should also be noted that the MDL equation was developed for stream impairments that are influenced by high flow events. This is the underlying concept behind calculating a maximum limit based on a selected recurrence interval (i.e. z-score). Therefore, if the MDL equation is used to calculate sediment TMDLs, it should be employed on stream reaches that are impaired by excess sediment loads due to high flow events, such as streambank erosion.

## Chapter 9: Conclusion

The Streambank Video Mapping System (SVMS), Bank Assessment for Non-point source Consequences of Sediment (BANCS) model, and Maximum Daily Limit (MDL) equation were integrated into a novel methodology for 1) collecting streambank footage and channel measurements 2) estimating bank erosion rates and sediment loads 3) identifying locations with high recession rates and 4) developing sediment TMDLs for streambank erosion. In previous studies, the SVMS proved beneficial to the collection of georeferenced video footage and channel dimension measurements (Candlish, 2010; Connell, 2012; McConkey, 2010; Swinson, 2012). For this study, the SVMS was used to collect continuous second by second channel width measurements, GPS position, and georeferenced video footage of streambank condition.

Video mapping surveys on two river reaches, a 22.5 km section of Driftwood River and a 20.4 km section of Upatoi Creek, were conducted to demonstrate this new methodology. A modified version of the Bank Erosion Hazard Index (mBEHI) was developed based on previous work by Connell (2012) in order to conduct a completely ocular assessment of streambank erodibility from bank condition parameters. The radius of curvature to width ratio, a channel pattern approach, was used to estimate Near Bank Stress (NBS). Site-specific bank erosion rates were graphically estimated using values of mBEHI and NBS along with the North Carolina Piedmont region bank erosion prediction curves. Additionally, sediment loading rates for the entire reach were estimated by incorporating bank height, length, and soil bulk density. Values were thematically mapped using ArcGIS to visually identify streambank locations with high erosion rates. Driftwood River had an estimated total sediment load (TSL) per unit stream length of  $222 \text{ t yr}^{-1} \text{ km}^{-1}$  with 13% of the reach rated as very high erosion susceptibility (mBEHI), and 89.7% rated as very low stream erosivity (NBS). In comparison, Upatoi Creek had an estimated TSL per unit stream length of  $109 \text{ t yr}^{-1} \text{ km}^{-1}$ , with 5% of the reach receiving a very high

erosion susceptibility rating, and 83.0% receiving a very low erosivity rating. Annual sediment loads were converted to daily loads by calculating the flow induced erosion potentials for each calendar day based on USGS flow data. Total Daily Sediment Load (TDSL) estimates were used as inputs to the MDL equation as a means of statistically calculating the sediment TMDL for streambank erosion. For Driftwood River, the TMDL was calculated as  $66 \text{ t d}^{-1}$  occurring at a flow rate of 15,117 cfs. For Upatoi Creek, the TMDL was calculated as  $24 \text{ t d}^{-1}$  occurring at a flow rate of 3,912 cfs.

The annual TSL values were comparable to loading rates published in the literature. Throughout this study, it was unclear how to handle the estimation of erosion rates at locations with depositional features, such as the inside bank of sharp meander bends, because the BANCS model does not distinguish between erosional and depositional areas. Therefore, assuming no erosion occurred on the bank with an adjacent depositional feature, the annual predicted TSL decreased by less than 1% of the total TSL for both Driftwood River and Upatoi Creek. Consequently, the bank erosion prediction was analyzed using an erosion rate of  $0 \text{ m yr}^{-1}$  on the inside of sharp meander bends.

The BANCS model does describe bank locations as either a straight reach or outside of bend. Assuming that bank erosion occurred on only one channel bank for both straight and meandering sections, the annual TSL for Upatoi Creek decreased by 34 – 47% depending on which bank was designated as eroding. Therefore models, such as SWAT, would greatly underestimate the sediment loading rate of a river system by making the assumption that erosion only occurs along one bank (Neitsch et al., 2009).

Driftwood River had a total annual sediment load greater than two times that of Upatoi Creek. From the video interpretation, it was determined that poor riparian vegetation and a low percentage of surface protection resulted in the higher loading rates. As a result, it's important to take into account the streambank condition of a river system. The AVGWLF streambank erosion routine predicts

streambank erosion as a function of flow rate and watershed characteristics (Evans et al., 2003).

Including a component of bank condition in the model would generate more accurate estimations. It should be noted that the 0.6 power factor used to convert annual TSL predictions to daily TSLs may not be the most appropriate value. However, it currently is the best available relationship between discharge and bank erosion rates based on a global review of the literature by Rutherford (2000) and its use in the AVGWLF model as part of the streambank erosion routine (Evans et al., 2003).

Despite these various assumptions, this new methodology provides a great link between watershed-scale data collection, assessment, and analysis. Since streambank and channel conditions can vary over several stream miles due to the heterogeneity of erodibility and erosivity parameters, site-specific data should be used to estimate erosion rates for an entire reach rather than extrapolating between individual streambank measurements. These site-specific results can then be mapped using ArcGIS to identify bank locations with the highest erosion rates and prioritize restoration efforts. This methodology provides a great step forward in predicting the amount of sediment loading originating from the in-channel process of streambank erosion, especially when a direct field measurement is too expensive, difficult, time consuming or access is limited.

## Chapter 10: Recommendations

### 10.1 Future Work

There are a couple components of this new integrated methodology that could be refined in future research. The site-specific radius of curvature ( $R_c$ ) calculation used in this study can provide beneficial information about stream erosivity such as the location in a meander bend that is expected to experience the greatest near bank stress. Adjusting the river width factor is a simple method for selecting the upstream and downstream GPS endpoints used in the  $R_c$  calculation. However, the BANCS model calculates the radius of curvature ( $R_c$ ) for a meander bend by drawing a circle using three points: 1) the apex of a bend 2) the upstream point of curvature and 3) the downstream point of curvature (Rosgen, 2009). The radius of the resultant circle is the  $R_c$ , which applies to the entire outside bend of a meander (i.e. from the upstream to downstream point of curvature). Thus, the site-specific  $R_c$  calculation could be modified to better reflect the radius of curvature definition used in the BANCS model by determining meander bend inflection points (i.e. point of curvature) and selecting these locations as the upstream and downstream GPS endpoints.

The laser distance sensor output was filtered to remove exceedingly large or small values using a simple conditional statement. A more sophisticated filter may need to be devised in order to smooth out the distance measurements even further, because large changes were still evident between consecutive measurements. Furthermore, a visual assessment of the video footage may provide meaningful information about the reason for measurement dissimilarities such as sensor obstructions and depositional features (i.e. islands and bars).

Future research using the BANCS model should also specify how streambank locations are selected (i.e. one bank or both banks). Not stating this information may result in erroneous interpretations of predicted sediment load values. For this study, a significant reduction in the total

annual sediment load was predicted when assuming bank erosion occurred on only one channel bank. As a result, estimated sediment loading rates reported in the literature may be significantly higher if studies are only predicting erosion for one bank.

## **10.2 Data Collection and Analysis**

The timing of a stream survey is important to the SVMS data collection process. Surveys should not be conducted during high flow period since portions of the bank may be underwater. Furthermore, high river velocities may result in video footage being collected at a rate that is too fast for the viewer to accurately assess. For wide rivers a “leaf off” survey should be conducted to prevent hindrances to the visual evaluation of streambank condition such as shadows and vegetative overhangs.

For both river surveys, two kayaks were used to collect redundant bank footage and distance measurements. For small streams, both kayaks can float the center line of the stream channel. However, for wider streams it is necessary to have one kayak focusing on the left bank and the other on the right bank. This will reduce the impact of distance on the ocular assessment.

Before the video footage is interpreted, an observer should be trained to make ocular estimates by calibrating the eye. This can be accomplished by watching small sections of footage with predetermined mBEHI index scores. Video footage may be watched by different observers to speed up the ocular assessment and reduce mental fatigue for sections of stream greater than 10 km (Connell, 2012). In order to maintain scoring consistency, the same viewer should evaluate the same parameter, both left and right bank, for the entire survey.

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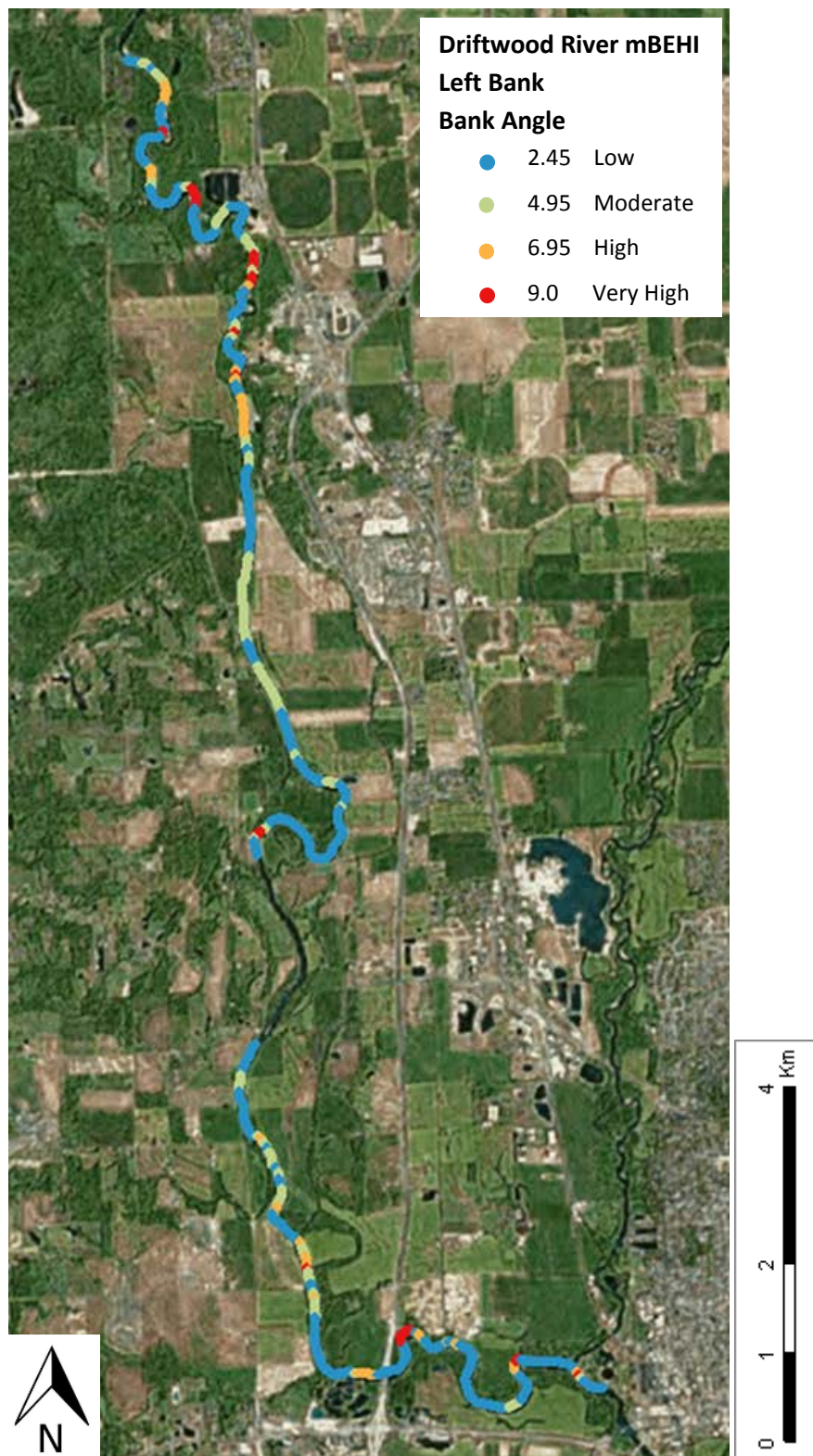
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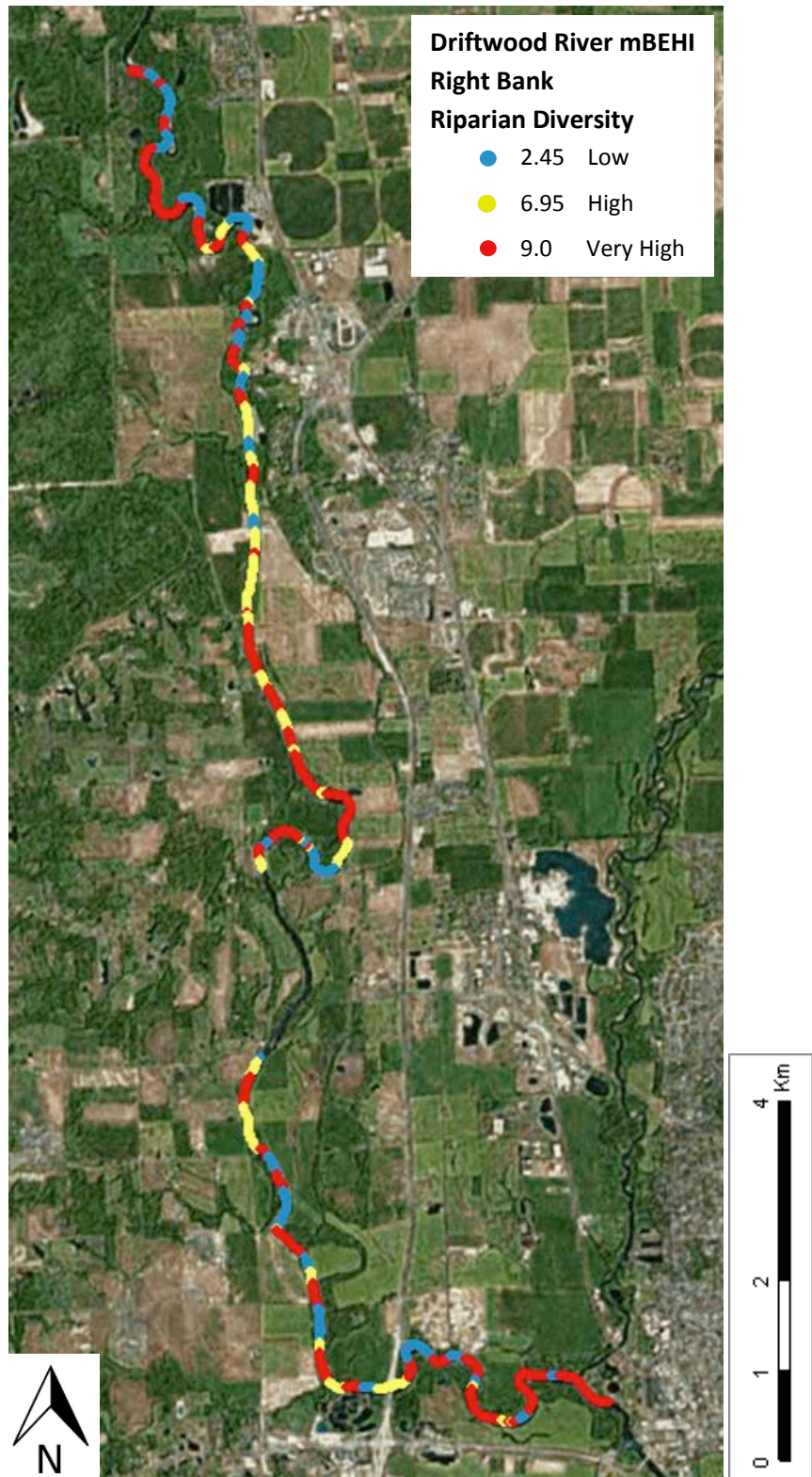
## Appendices

## Appendix A

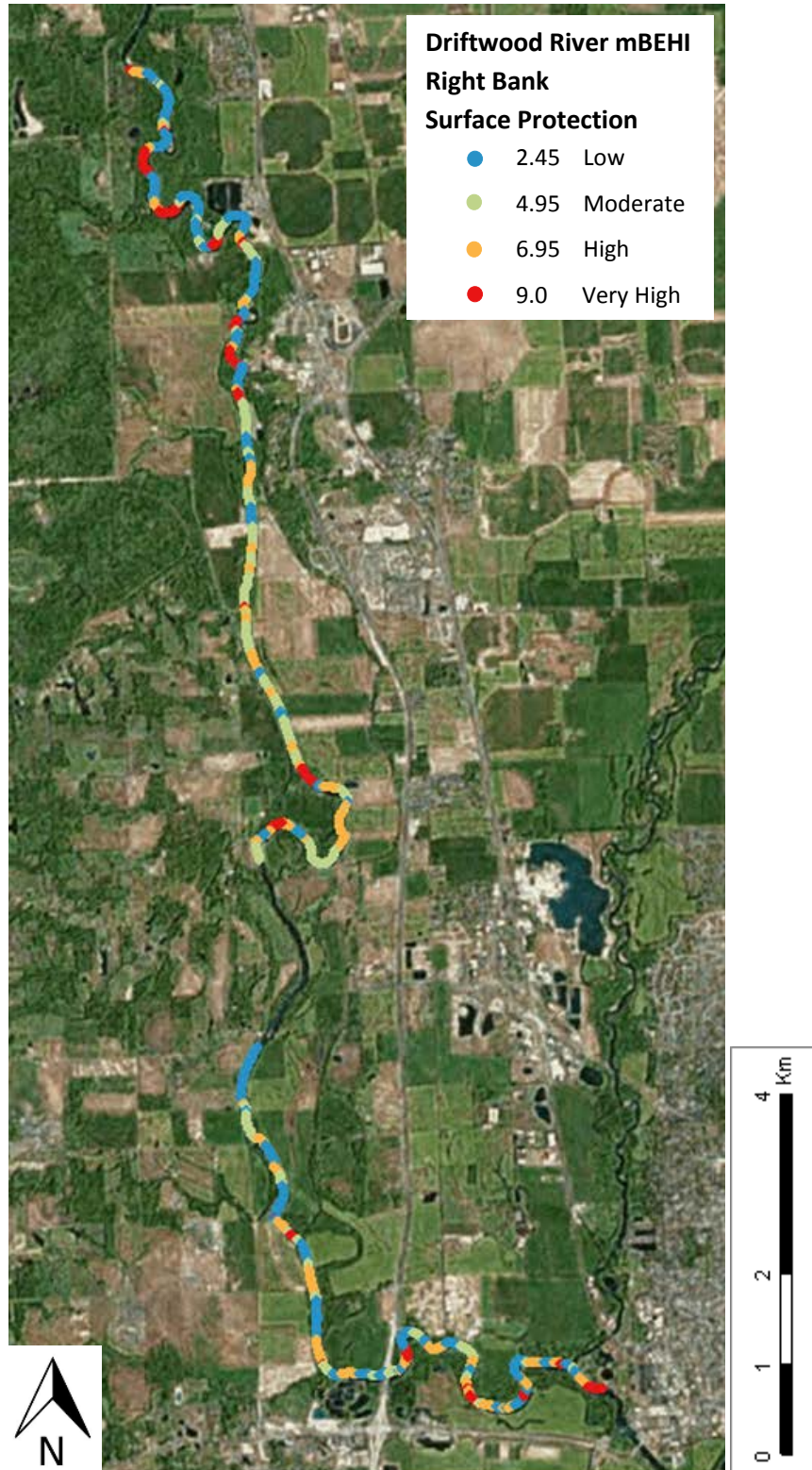




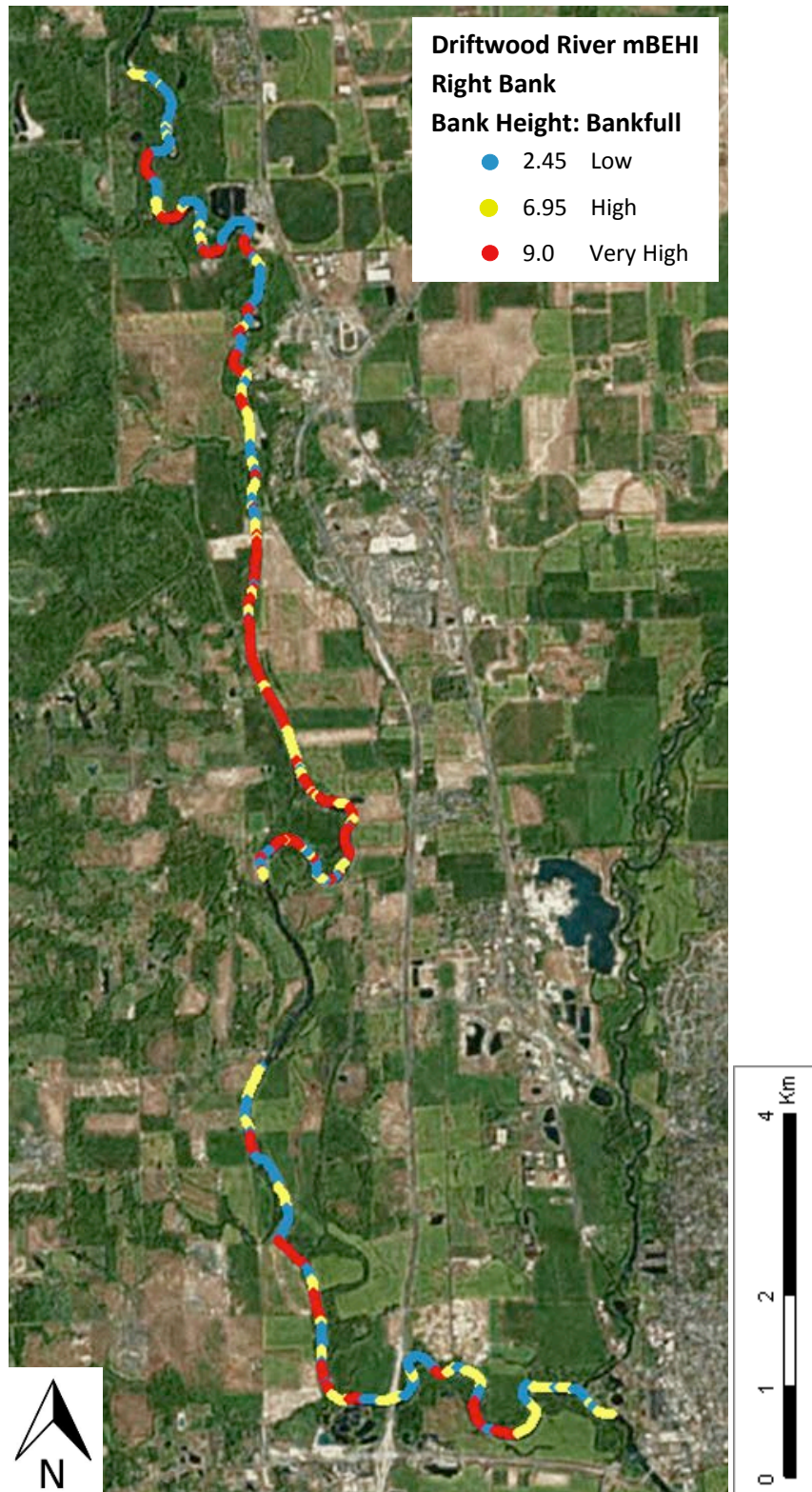


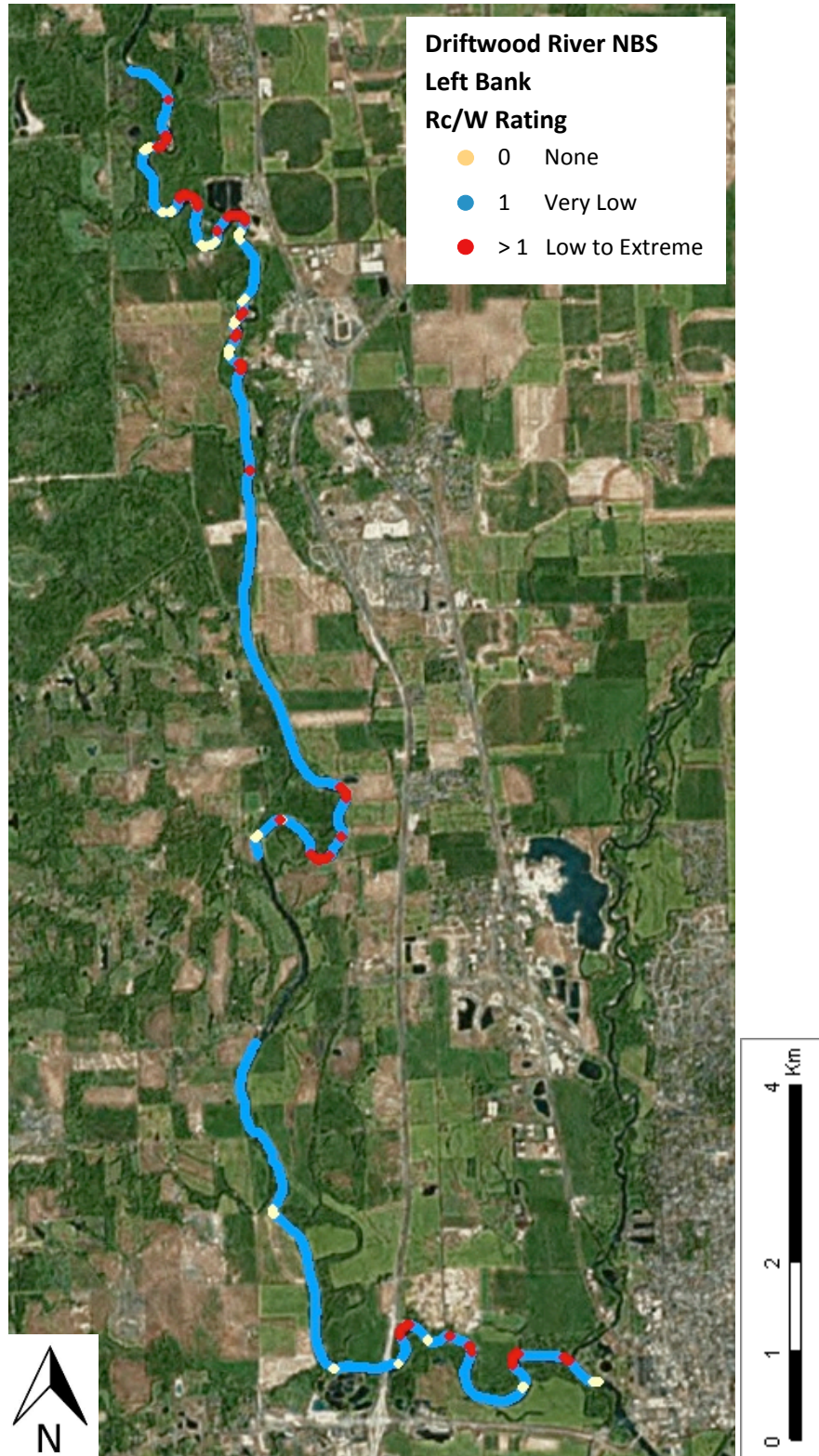




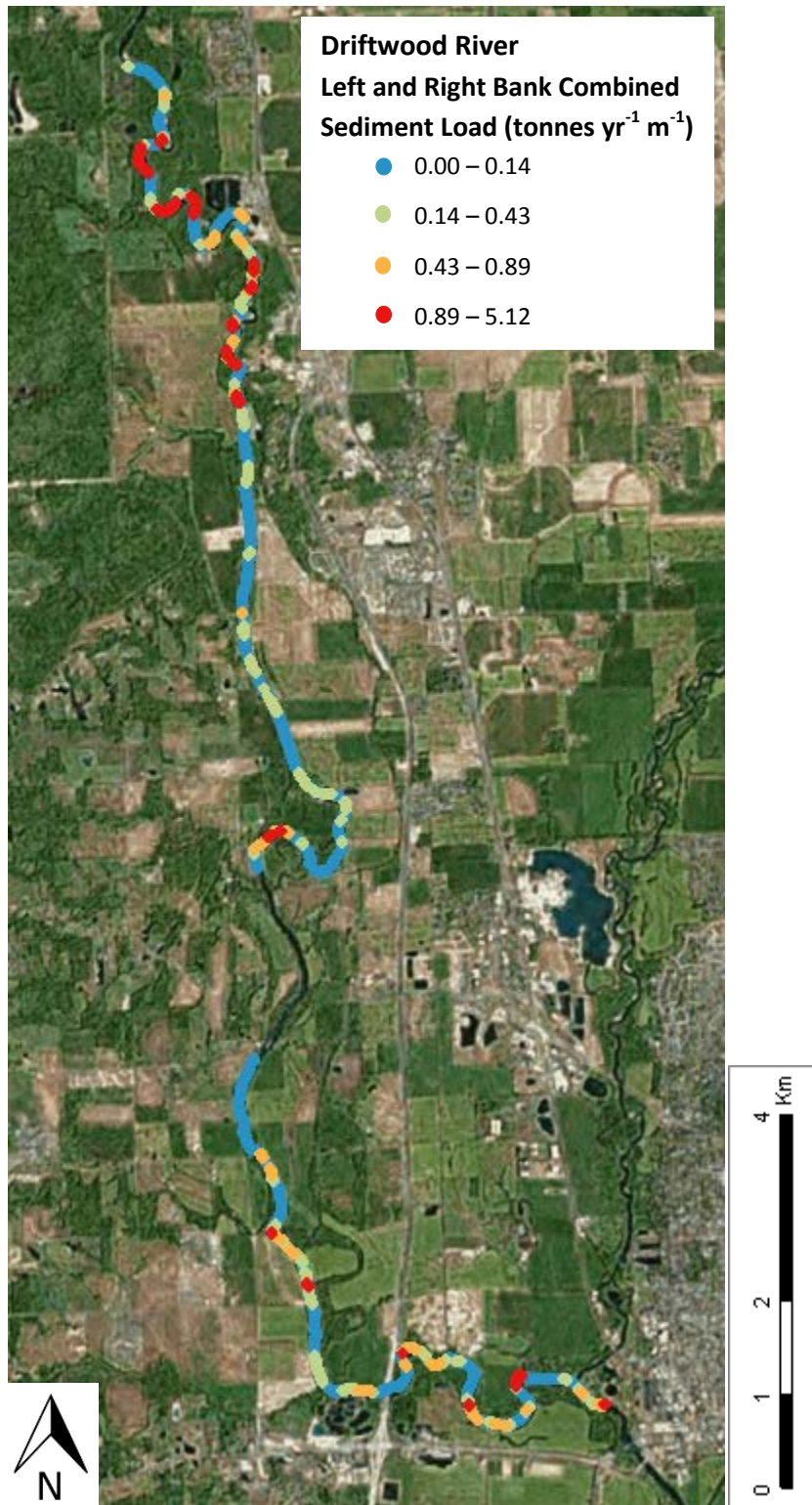




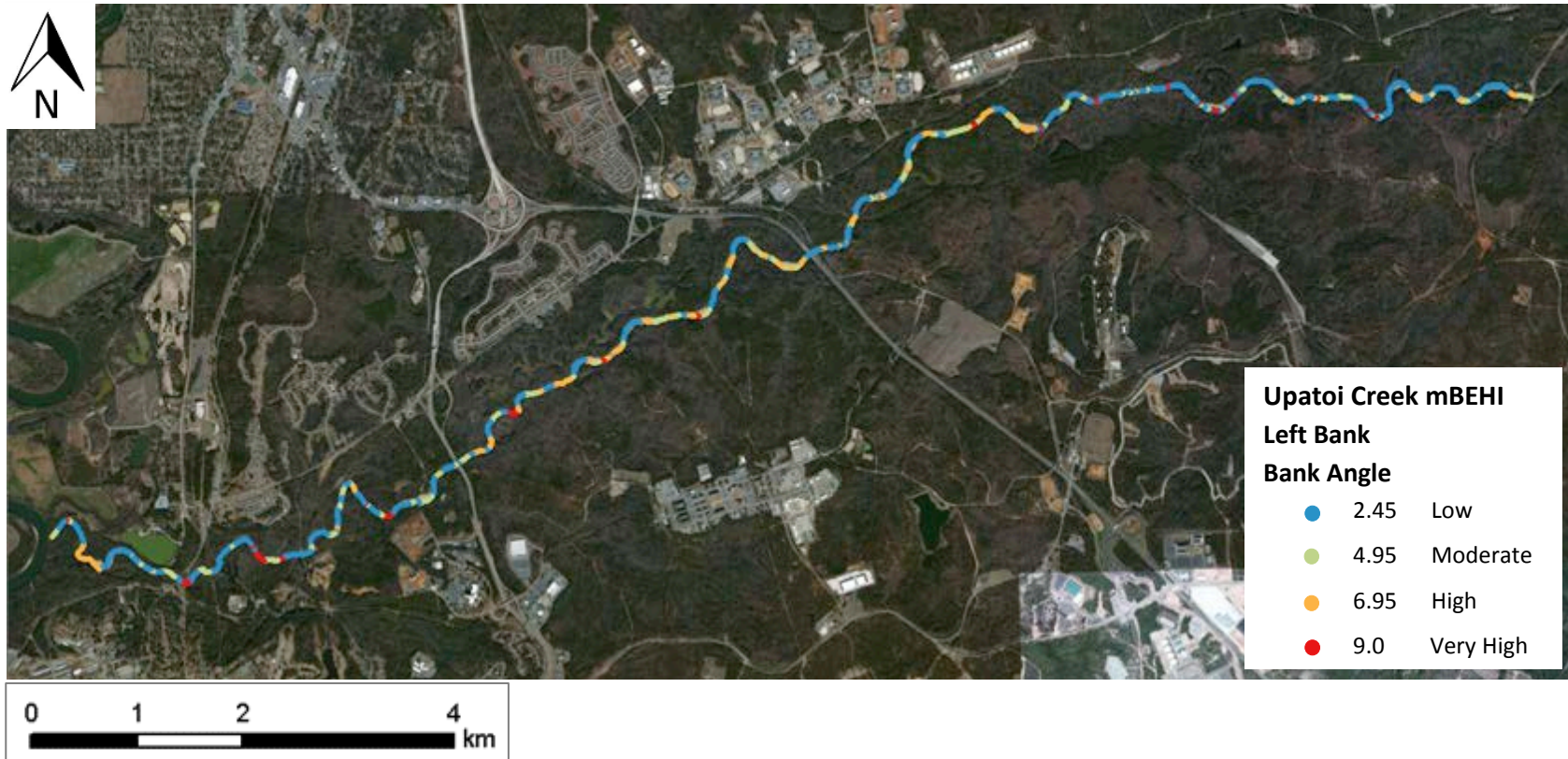




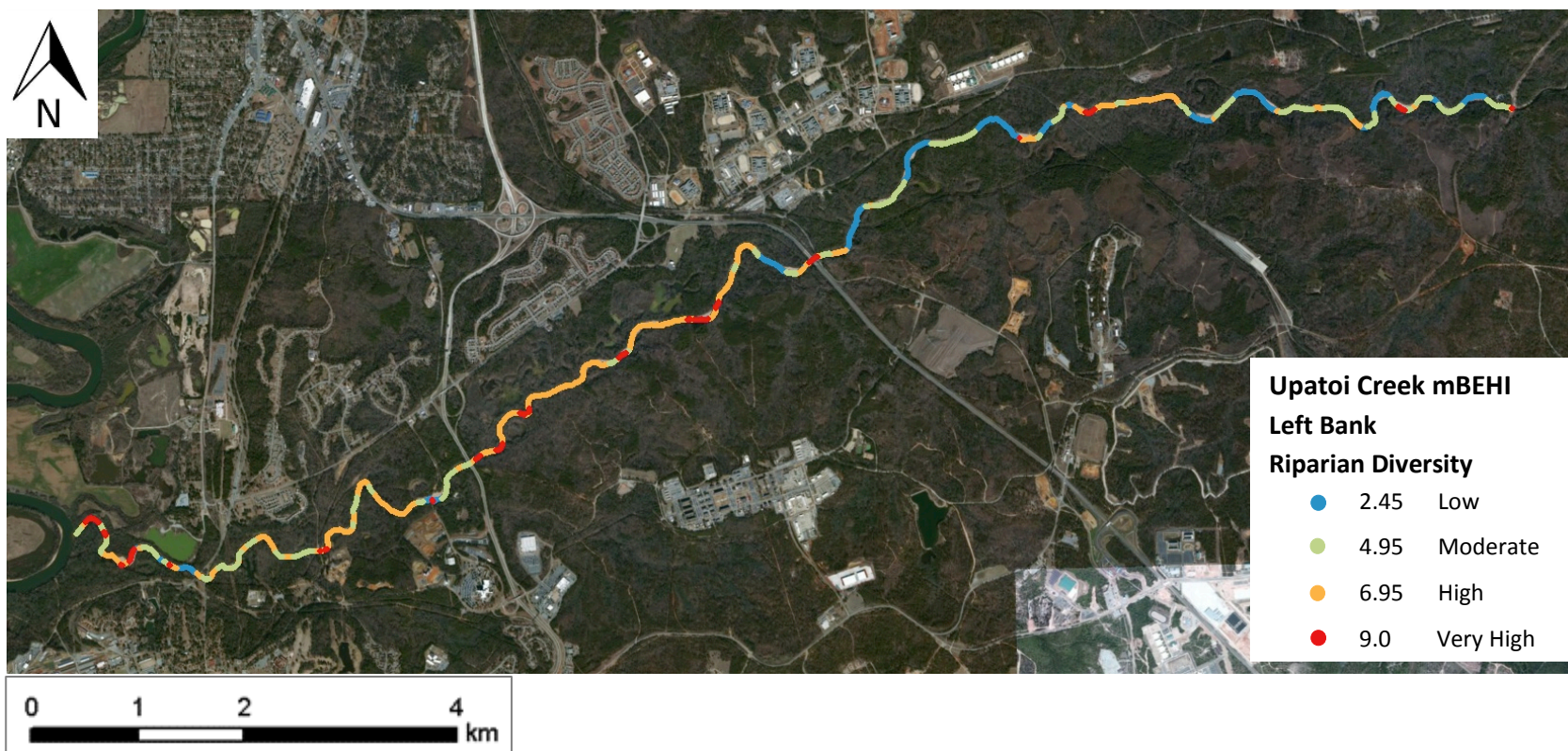


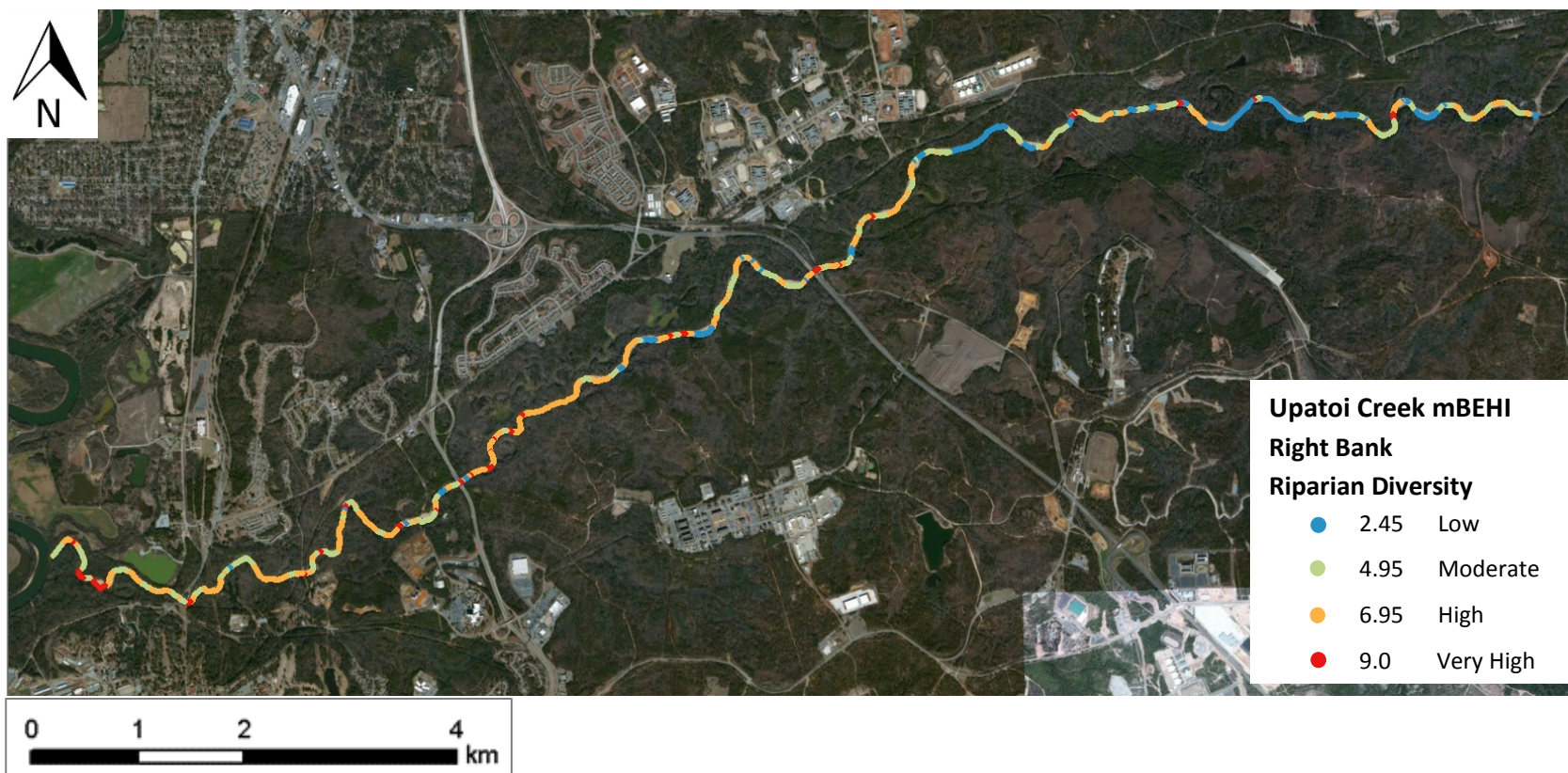


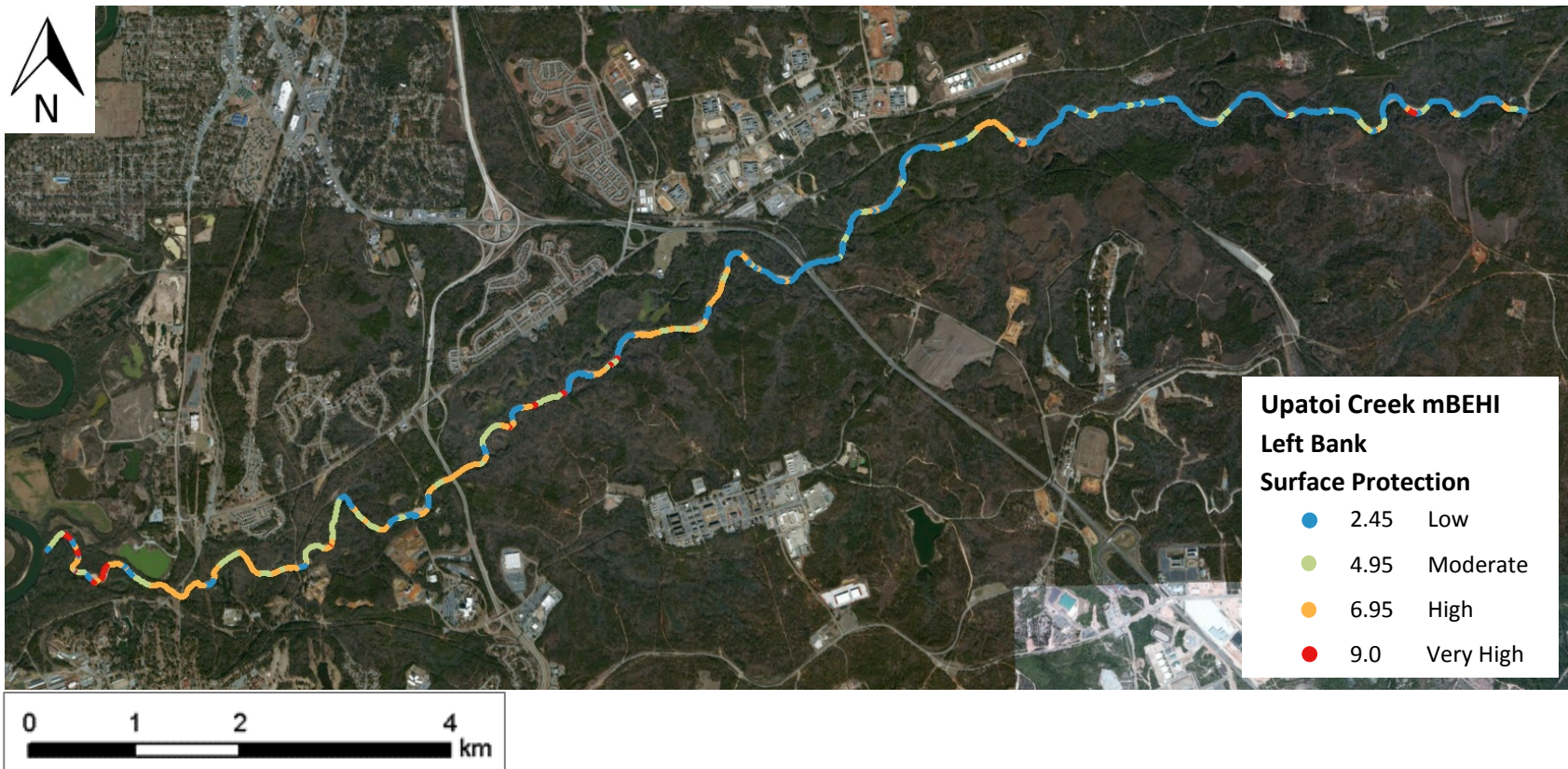
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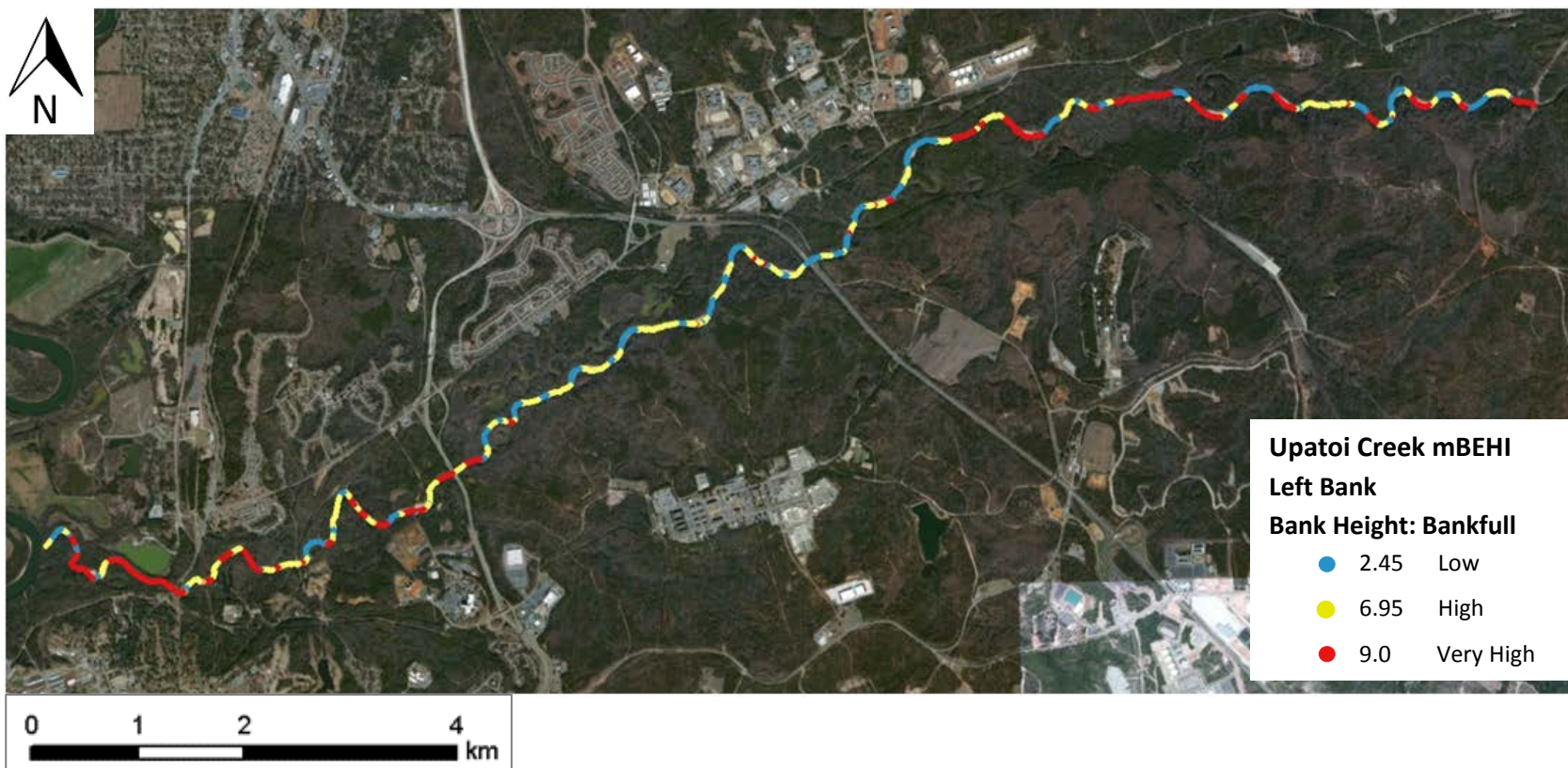


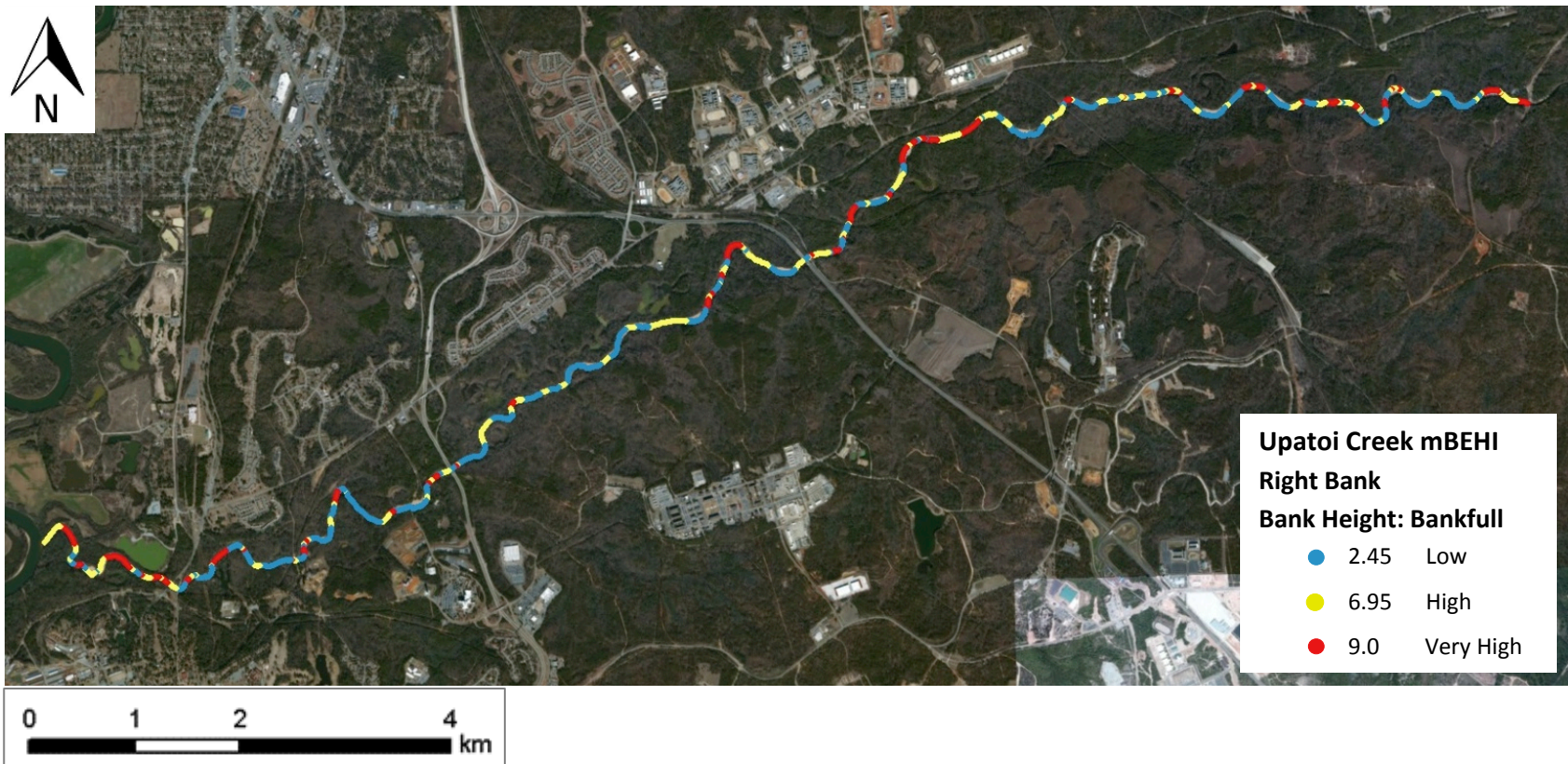




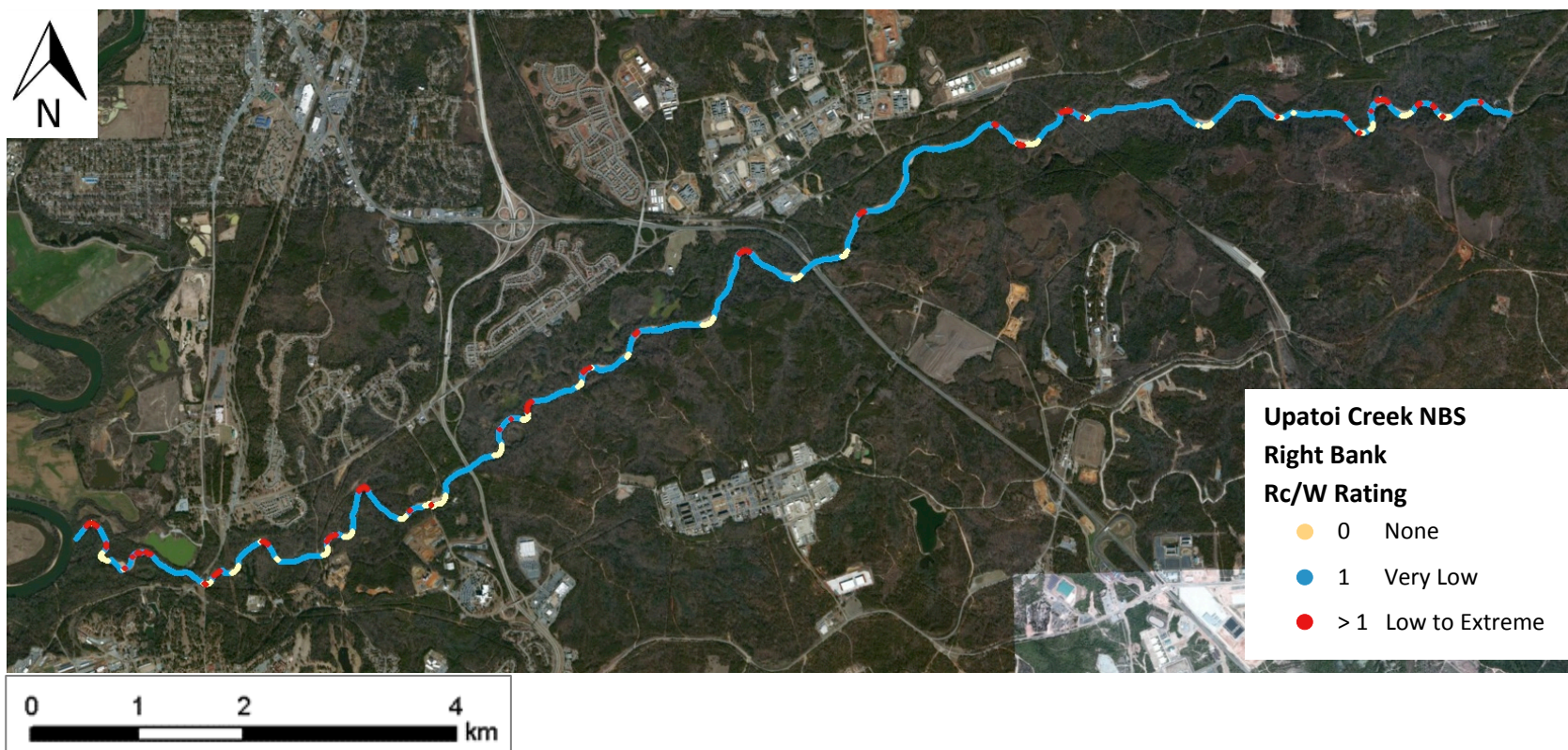






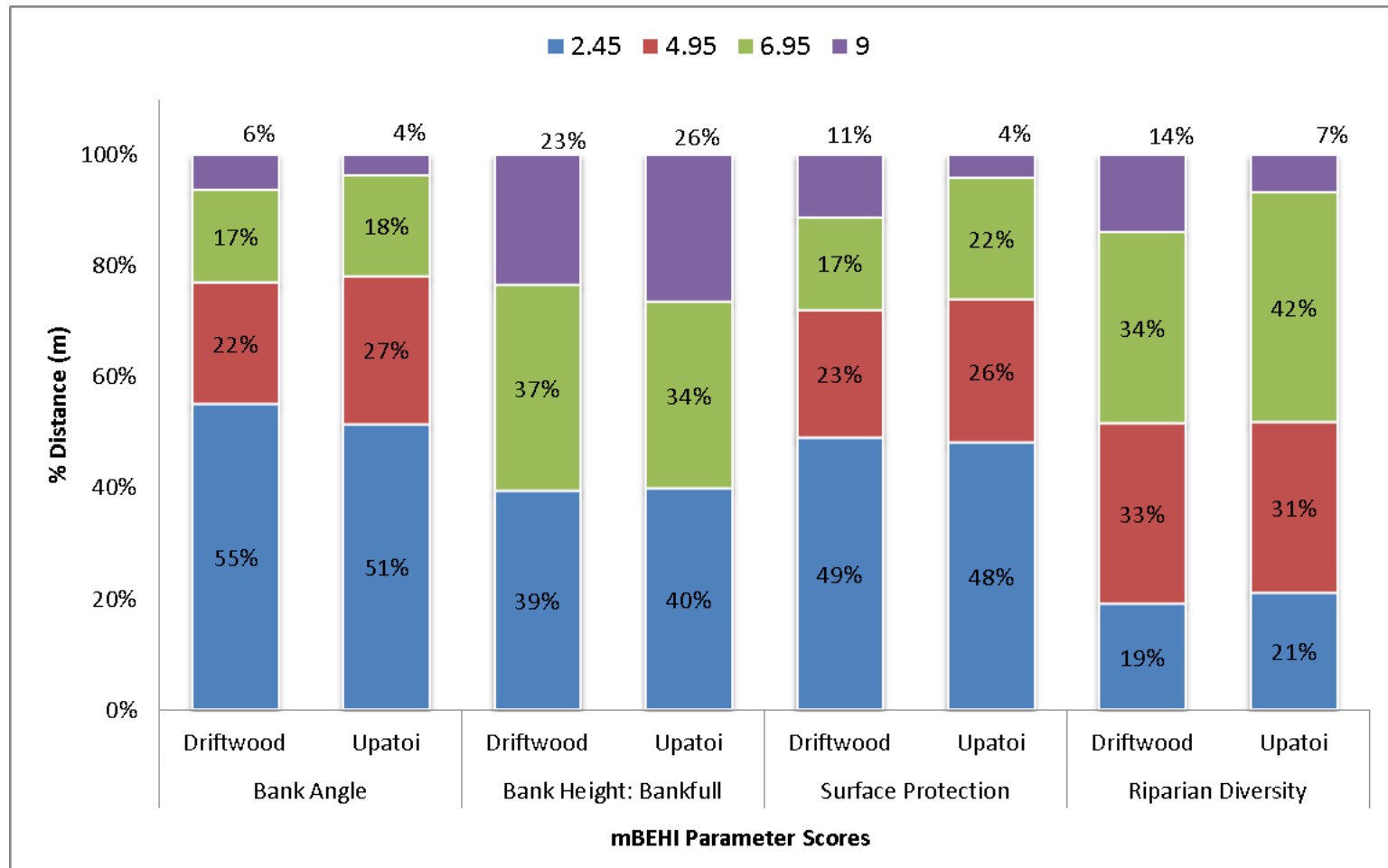


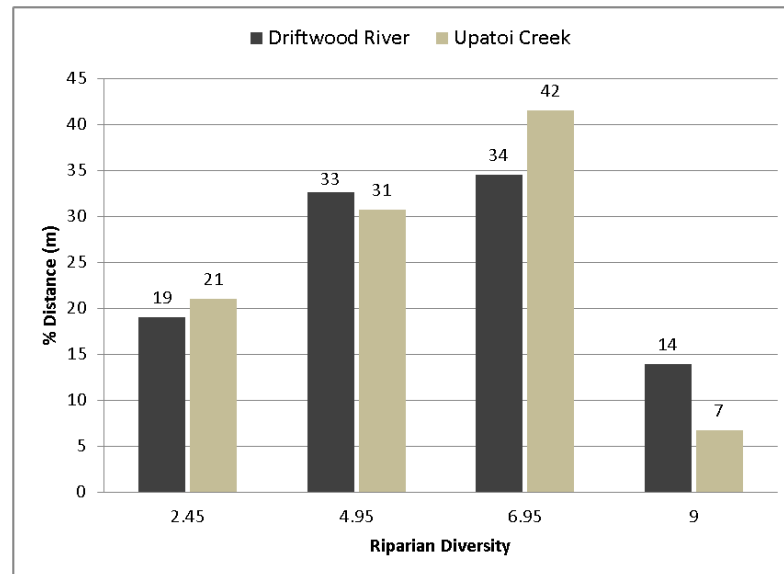
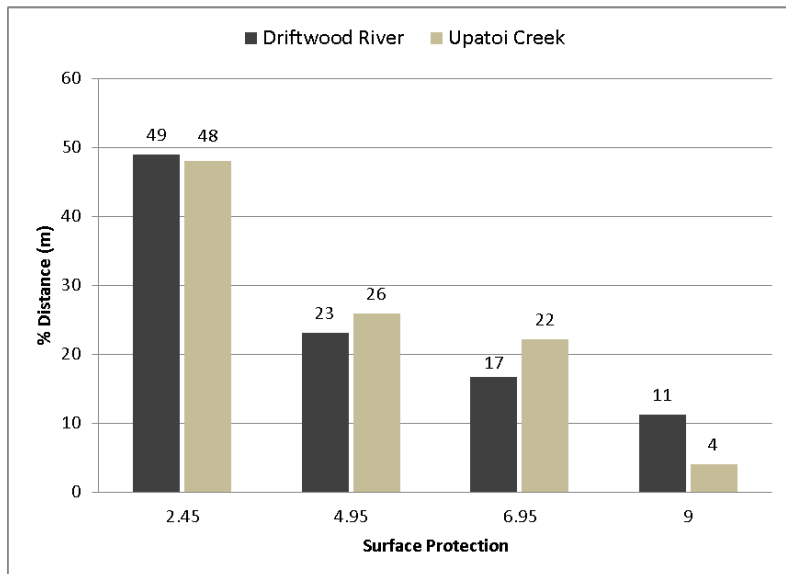
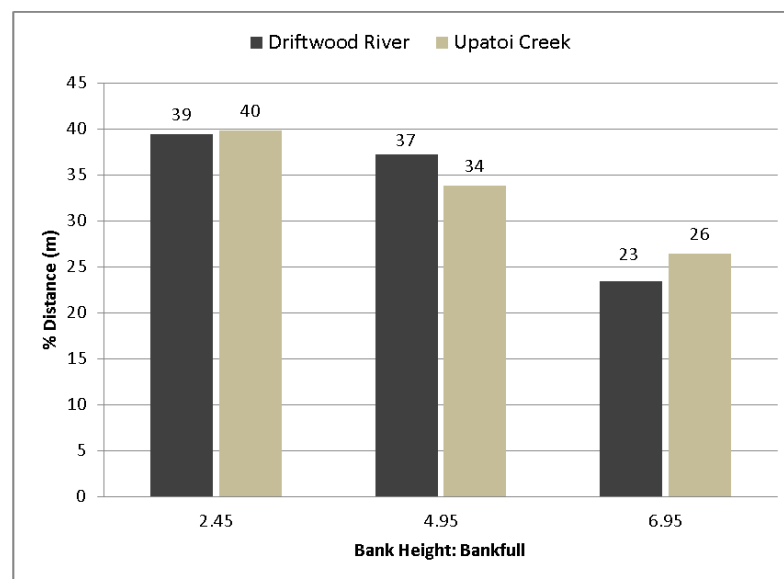
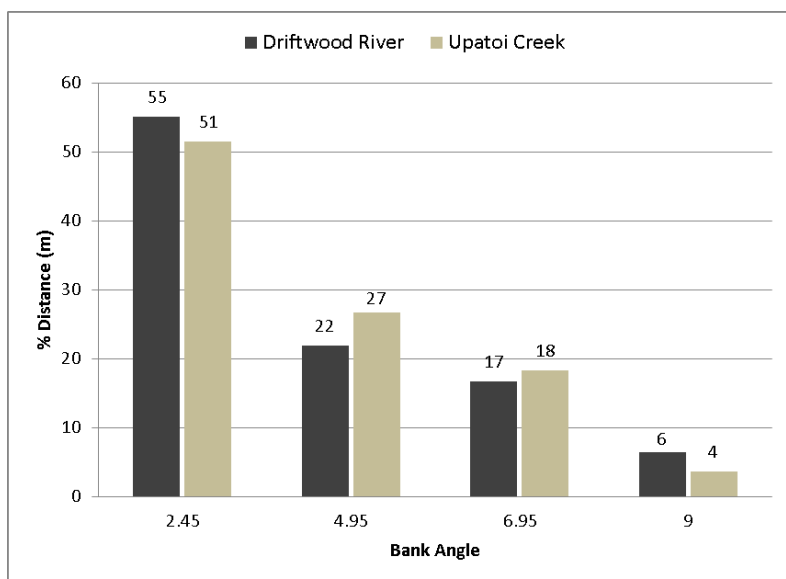


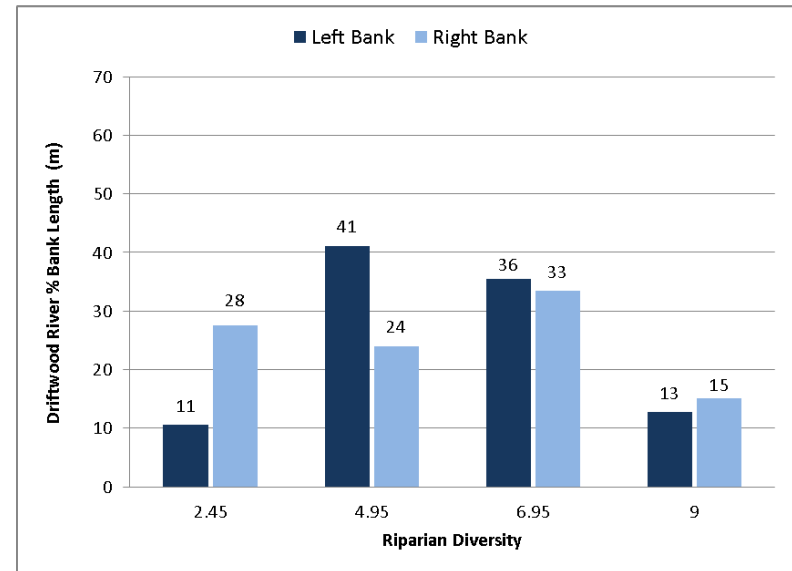
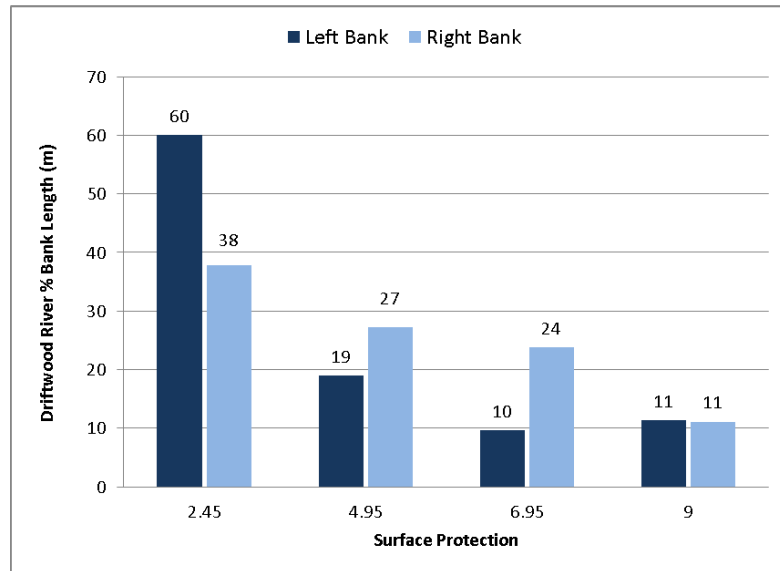
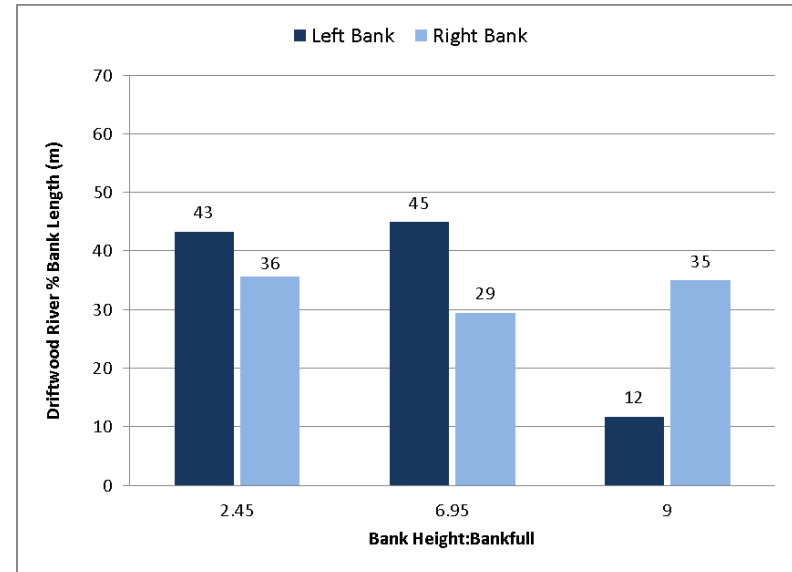
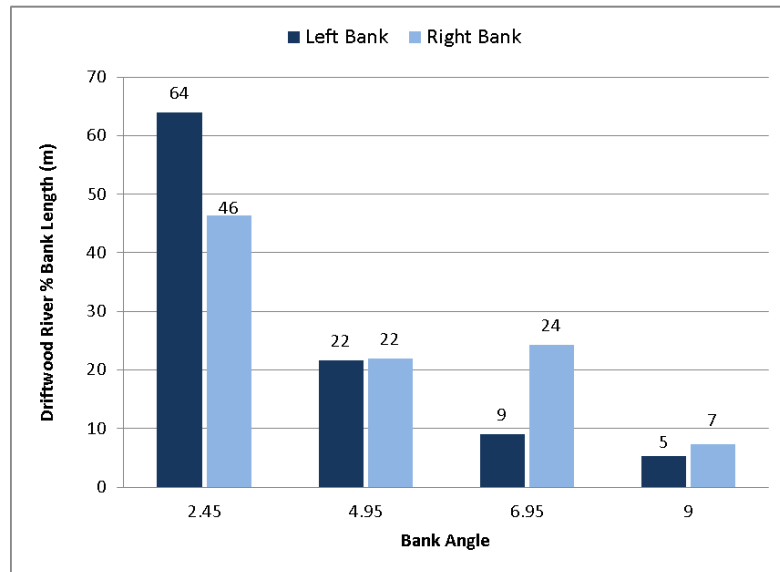


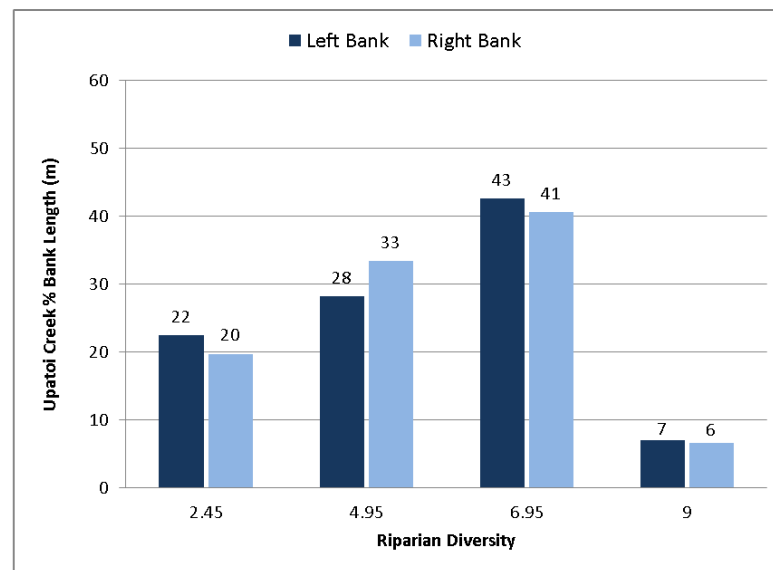
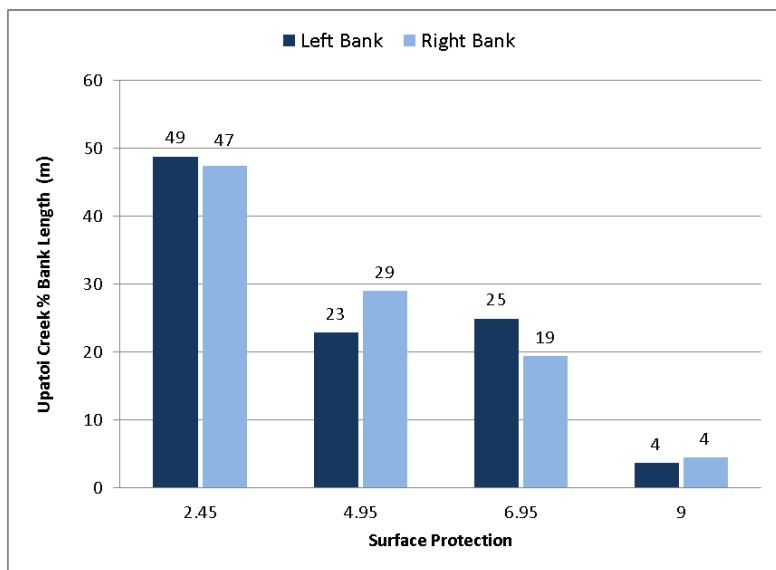
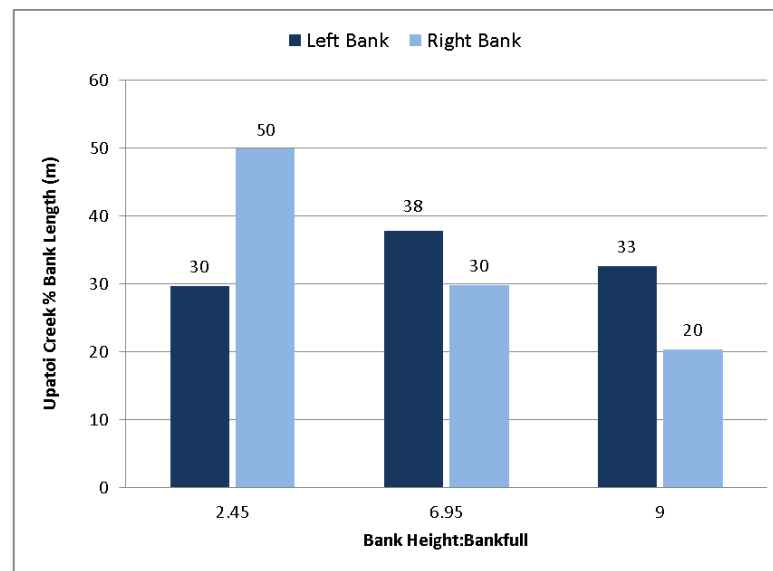
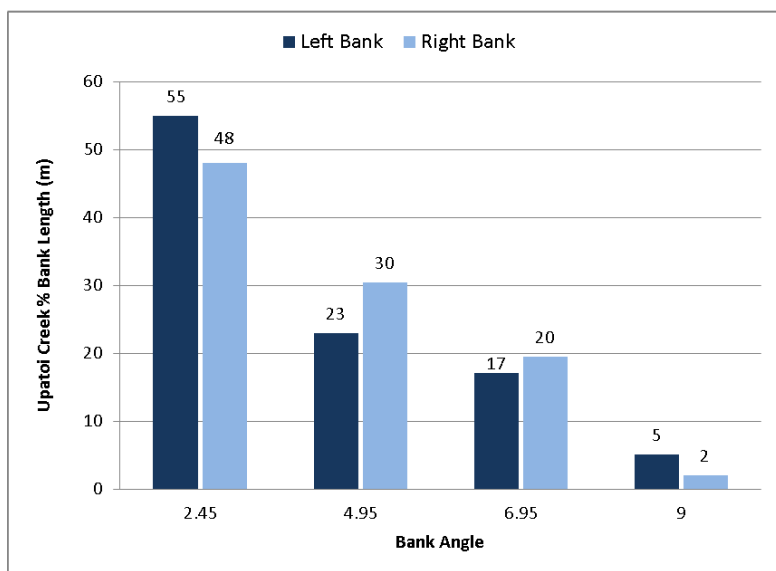


# Appendix C









## **Vita**

Kelsey Hensley was born in Texas and resided in the Lone Star state until graduating from high school. She attended the State University of New York – College of Environmental Science and Forestry in Syracuse, New York where she earned a Bachelor of Science Degree in Environmental Science in May, 2009. Subsequently, she worked as a Knoxville – Knox County CAC AmeriCorps member on the Water Quality in Knoxville, TN. After successfully completing a two-year term, she continued her education as a Master's student in Biosystems Engineering in 2012. During her graduate career she worked as a research assistant under Dr. Paul Ayers.