5-2010

Georeferenced Riverine Habitat Mapping in the Big South Fork National River and Recreation Area

James Bryan McConkey
The University of Tennessee, conk@utk.edu

To the Graduate Council:

I am submitting herewith a thesis written by James Bryan McConkey entitled "Georeferenced Riverine Habitat Mapping in the Big South Fork National River and Recreation Area." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Paul D. Ayers, Major Professor

We have read this thesis and recommend its acceptance:

John S. Schwartz, John B. Wilkerson

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by James Bryan McConkey entitled "Georeferenced Riverine Habitat Mapping in the Big South Fork National River and Recreation Area." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering.

Paul Ayers, Major Professor

We have read this thesis
and recommend its acceptance:

John Schwartz

John Wilkerson

Accepted for the Council:

Carolyn R. Hodges
Vice Provost and Dean of the Graduate School

GEOREFERENCED RIVERINE HABITAT MAPPING IN THE BIG SOUTH FORK NATIONAL RIVER AND RECREATION AREA

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

James Bryan McConkey
May 2010

Acknowledgements

I would like to thank my adviser, Paul Ayers, for giving me the opportunity to work on such an enjoyable project and for the guidance to see it through to completion. I also express my gratitude to John Schwartz and John Wilkerson for their time and valuable input while serving on my committee.

Thanks to the National Park Service, particularly Steve Bakaletz, Elena Robisch, and Ray Albright for their support and funding for this project. I also acknowledge Matt and Julie Hudson for their support and friendship throughout my research.

I thank Margaret Taylor for her guidance through university requirements, Craig Wagoner for fabricating custom parts, David Smith for electronics soldering skills, Tim Prather for GIS knowledge and maps, and Ann Reed and Arnold Saxton for statistics support.

This project would not have been possible without the help of J.R. Candlish, Ken Swinson, Adam Duncan, Alex McLemore, Steve Krajewski, and Kun Liu. I truly enjoyed the long hours in the field with you all.

I want to thank my beautiful wife, Marissa, for enduring late night study sessions, critiquing repetitive presentations, and giving me the encouragement I needed to do my best work on this project. I also thank my parents, Bill and Donna McConkey, for encouraging me to chase my dreams and further my education. The support of my family made my college experience memorable and fun.

Abstract

This project describes the development of a river habitat map of the Big South Fork National River and Recreation Area (BISO NRRA) using GPS-based video mapping and image georeferencing techniques. The Big South Fork of the Cumberland River and major tributaries have been floated and mapped with GPS, sonar, and georeferenced under and above water video cameras. Video footage is interpreted for physical bedforms and compiled in an ArcGIS attribute table that can be queried for species specific habitat location.

Underwater video mapping system (UVMS) bedform data includes river characteristic (pool, riffle, run), substrate (bedrock, fines/sand, gravel, cobble, and boulder), embeddedness, sonar depth, rugosity, and sinuosity. The Clear Fork River and New River (3^{rd} order streams), White Oak Creek and North White Oak Creek (2^{nd} order streams), and the Big South Fork of the Cumberland River, a 4^{th} order stream are compared based on the EPA Qualitative Habitat Evaluation Index (QHEI).

Relationships between bedform parameters are evident in UVMS data, and large boulder substrate was predicted with 67% accuracy based on sonar depth and river characteristic. The rugosity metric can indicate the location of other habitat characteristics, such as large woody debris and riverbed drop-offs. Embeddedness distribution was modeled using SAS based on UVMS data. The linear, quadratic, and non-linear models poorly fit the embeddedness distribution, with R-squared values of 0.37, 0.42, and 0.33 respectively.

Traditional river habitat assessment methods vary in scale from stream length categorization based on satellite imagery and topographic maps (kilometer resolution), to aquatic microhabitat inventory by biologists (0.1 m resolution). Typically, reach scale (10 m resolution) and mesoscale (1 m resolution) studies are limited by accessibility and man-hours in the field. The underwater video mapping system (UVMS) allows for stream scale habitat quantification with mesoscale resolution. Kayak or canoe based UVMS can map river habitat inaccessible from land. Georeferenced river characteristic and substrate video can be evaluated by biologists in the lab, reducing time and labor required for field studies. One limitation of UVMS is that underwater bedform data is recorded only in the thalweg, the deepest continuous line along a watercourse.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

The Big South Fork National River and Recreation Area (BISO NRRA) encompasses 526 km^2 (125,000 acres) of the Cumberland Plateau and 130 km (81 miles) of navigable waterways. The BISO NRRA was established by the U.S. Congress in 1974 granting ownership and management of the land to the National Park Service (NPS). The park boundaries protect 39% of the watershed of the Big South Fork of the Cumberland River. Of the BISO primary tributaries, the NRRA protects 5% of the Clear Fork River watershed and 2% of the New River watershed (NPS, 2008). The park is a relatively pristine wilderness, primarily forestland and sparsely populated, but the river system suffers from pollution of past mining operations, forest logging, all terrain vehicle (ATV) traffic, oil and gas production roads, and watershed development outside the park boundaries (Massey, 2008). The Big South Fork of the Cumberland River is a 73 km (45.3 miles) fourth order stream sourced by third order streams, Clear Fork River, 32 km (19.9 miles), and the New River, 14.3 km (8.9 miles) based on the Strahler number of stream classification (GSA, 2009). Two second order tributaries to the Big South Fork are also analyzed in this study, North White Oak Creek, 9.8 km (6.1 miles) and White Oak Creek, 4.5 km (2.8 miles). The total river distance mapped is detailed in Figure 1. Stream scale habitat maps are generated from either a biological or geologic perspective; 'top-down' or 'bottom-up' approaches, respectively. By the top-down biological approach, aquatic fauna are inventoried and then physical habitat is examined to explain

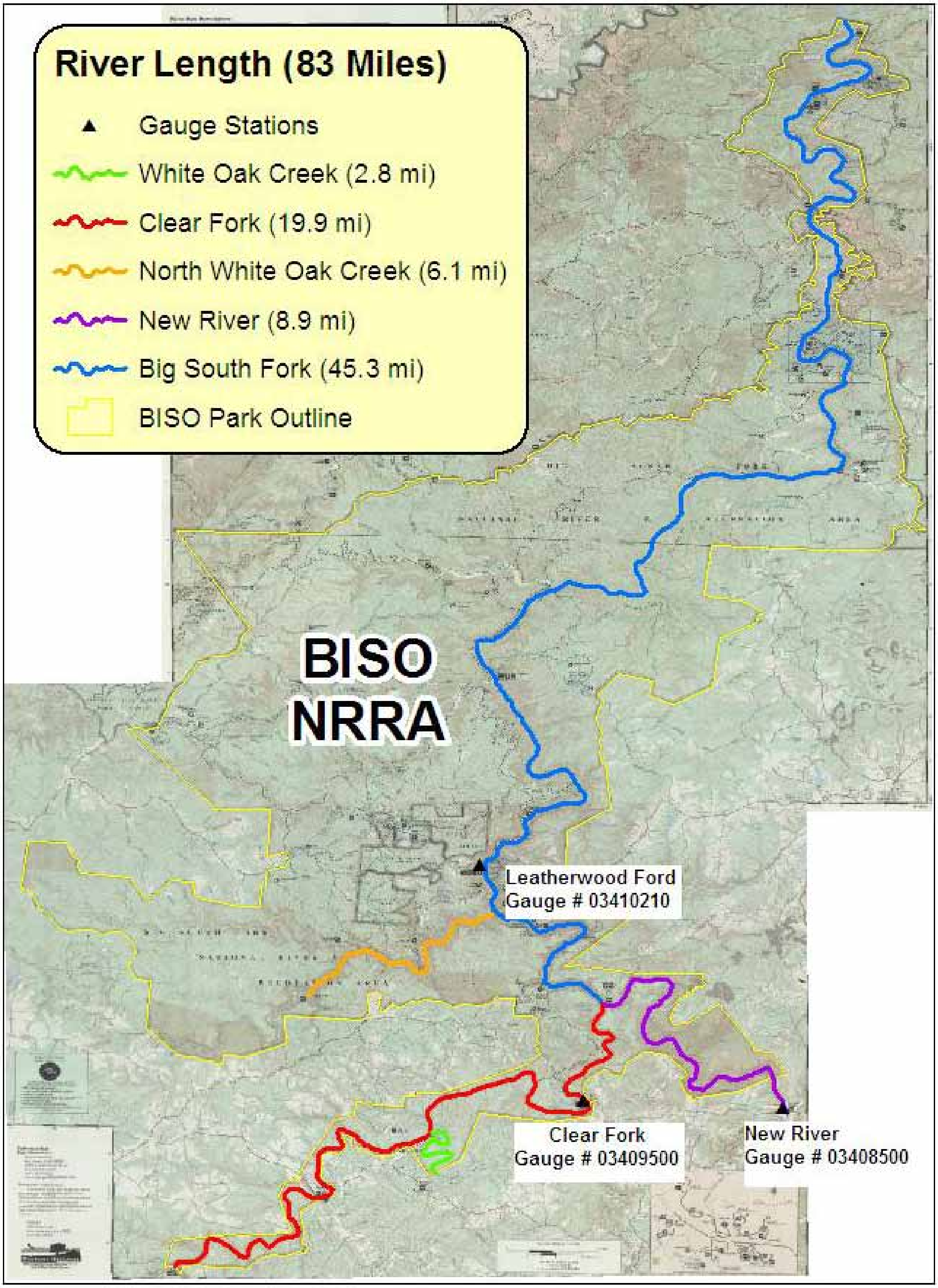

Figure 1: Big South Fork NRRA river miles

spatial distribution of biota (Newson and Newson, 2000). This study uses the bottom-up geomorphological approach, where biotic patterns could be predicted from empirical data describing the physical hydrologic environment.

Accurate physical descriptions of riverine features are important to environmental management agencies for habitat classification and management strategy. Physical bedform data such as river characteristic, substrate particle size, embeddedness, water depth, flow rate, sinuosity, and rugosity are used to define specific river habitats at the mesoscale level. Because habitat characteristics are dynamic in a natural river, it is important to know not only what types of physical habitat exist in a river system, but also exactly where along the river specific combinations of features are located. "Data collected in comprehensive, statistically based surveys are needed to evaluate habitat restoration and improvement programs and to monitor changes resulting from management decisions" (Dolloff et al., 1997).

In 2004, a new method of mapping mussel habitat was developed and tested in the BISO NRRA (Fiscor, 2005). An underwater video mapping system (UVMS) was used to record riverine morphological characteristics and combined with differentially corrected geographic positioning system (DGPS) information. This mapping system can be used to classify transitions in physical bedform data for understanding aquatic biota habitat suitability. UVMS data encompassing an entire riverine national park can be used for qualitative habitat studies along the river thalweg. Pools do not have a discernible thalweg, so the centerline of the stream is mapped in pools. A UVMS database with mesoscale habitat resolution of an entire river system can be used for statistically predicting distribution of fine sediment particles throughout a river system, or modeling of physical bedforms based on river system parameters.

1.2 Objectives

- Use underwater video mapping system (UVMS) to create comprehensive riverscape data of the navigable rivers within the boundaries of the Big South Fork National River and Recreation Area.
- Modify the EPA qualitative habitat evaluation index (QHEI) for use with UVMS data. Measure QHEI scores on representative reaches and stream segments, then compare to overall river length score.
- Analyze UVMS data for trends and relationships among riverscape features.
- Create a statistical model to predict embeddedness location and severity based on UVMS data.

Chapter 2: Literature Review

2.1 Mapping Techniques

There are various established methods of riverine habitat classification. Techniques vary in scale and accuracy, from stream classification using remote sensing and topographic maps to time and labor intensive microhabitat field surveys.

Frissell et al. (1986) proposed spatial and temporal scale metrics for hierarchical organization of stream systems into successively lower levels: stream (10^3 m), segment (10^2 m), reach (10^1 m), pool/riffle (10^0 m), and microhabitat (10^{-1} m) subsystems (GSA, 2009). A segment is the distance between two stream junctions, stable at 10^6-10^5 year timescale. A reach is more subjective, with boundaries defined by changes in gradient, local side-slopes, valley floor width, riparian vegetation, and bank material, stable over 10^4-10^3 years. The pool/riffle level is characterized by bed topography, water surface slope, depth, and velocity patterns, stable over 10^2-10^1 years. Finally, the microhabitat level has homogeneous substrate, water depth, and velocity, habitat changes seasonally on a 10^1-10^0 year timescale. Hydrologic flow levels must be considered in habitat interpretation. Riffle and pool forms are artifacts of flood events. At low flow only fine sediment and organic materials are transported, but at high flow pools are zones of convergent flow and bed scour, while riffles are zones of divergent flow and deposition of bedload. Biotic fauna are determined by physical bedforms, and "physical features that control microhabitat distribution can be seen to control invertebrate distributions" (Frissell et al., 1986).

Newson and Newson (2000) also address the problem of scale in stream ecosystem classification. Riverine habitat is a complex combination of physical, chemical, and biological factors. Currently, management decisions are made at a larger scale than the habitat data collected. "Given the promise of the physical biotope approach, its logical extension in predictive mode is via the hierarchical concepts shared by freshwater ecologists and geomorphologists; however, there is little agreement on scale terminology, hierarchical principles and, above all, a truly geomorphological channel classification, based on reaches, into which mesoscale habitat typologies could be fed" (Newson and Newson, 2000). The mesoscale approach, similar to reach scale classification, "varies across the active channel width and at channel length intervals that are small multiples of channel width" (Newson and Newson, 2000). Geomorphologists have proved that habitat hydrology patterns are closely controlled by the morphological units and substrate materials of the channel.

The Rosgen habitat classification technique (Rosgen, 1994) uses aerial photography and topographic maps to identify valley features, and then verifies the ready-scale classification through a field-based approach using width-to-depth ratio, sinuosity, entrenchment ratio, and channel material from field measurements (Bain and Stevenson, 1999). Substrate identification is performed visually at intervals across the width of the river perpendicular to flow. Embeddedness is evaluated at the thalweg or center of the river channel only. Combining data from remote sensing and field surveys, a river is classified as one of nine categories in the Rosgen Level II reach type classification table (Rosgen, 1994). Substrate composition is evaluated using a modified

Wentworth scale into sand/fines, small gravel, large gravel, cobble, small boulder, large boulder, or bedrock. Embeddedness, a measure of fine sediment surrounding substrate particles, and the primary substrate type in heterogeneous substrate are classified by percentage categories (Bain and Stevenson, 1999).

Marcus et al. (2003) used high spatial resolution hyperspectral (HSRH) imagery to map in-stream habitats, depth, and woody debris in third and fifth order streams in the northern Yellowstone region. Identification of habitat morphology such as pools, riffles, runs, and glides, water depth, and the presence of woody debris are all determined from the spectral signal read from one meter accuracy pixels. Imagery was collected using a helicopter flying 600 meters above the ground with a sensor measuring 128 contiguous bands covering the visible to shortwave-infrared portion of the spectrum (Marcus et al., 2003). Identification requires an unobstructed view of the stream, and depth measurements require clear water where the stream bed is visible through the water surface. Results of this study were validated using ground-truth polygons mapped by field teams. Because of the subjectivity of field mapping transitional areas among habitat regions, a two meter buffer zone was used in HSRH habitat identification. Visual analysis of HSRH generated maps suggest this is a viable habitat classification approach, and discrepancies from field validation were attributed to ground-truth subjectivity and lack of coordination between aerial and field teams because the imagery was not georeferenced.

Hilderbrand et al. (1999) GIS mapped stream channel features in an 870 meter reach of Stony Creek in western Virginia by stringing a 30 meter measuring tape parallel to the stream in sections. This line represented the y-axis of a coordinate system, and perpendicular measurements into the channel represented the x-axis. River characteristics were represented in a Cartesian grid and located by relative compass bearing. The coordinate locations of pools, riffles, and runs were then converted into a GIS map of the stream using Arc Info (Hilderbrand et al., 1999).

Zimmerman (2003) modified a walking method, the Basinwide Visual Estimation Technique (BVET) (Dolloff et al., 1993), to map mussel habitat using a boat in the Clinch River, Virginia. The river was divided into habitat units, and the data gathered was unit length, stream width, substrate composition, embeddedness, riparian land use, bank erosion potential, and mean unit depth. GPS was used to collect the lat/long coordinates at the start and end of each unit. Substrate was visually evaluated and depth was measured with a wading rod. The river was floated in a zigzag pattern where possible. Potential stressors such as bridges, abandoned mine lands, and wastewater discharges were located on a GIS map and distance weighted relative to the study areas. A habitat risk assessment model was developed based on the data (Zimmerman, 2003).

Williams, et al. (2004) evaluated the BVET as a method of estimating abundance of fish populations in small streams. It was noted that although the BVET has been adopted by numerous government agencies for monitoring stream biota, many of the assumptions used by the BVET cannot be met because of unsuitable conditions. Lack of bed control structures, variability in flow regimes, and lack of consistency among observers are listed as difficulties to using the BVET method for comprehensive river habitat assessment (Williams et al., 2004).

Fiscor (2005) used canoe based UVMS to map potential habitat for five species of endangered mussels known to exist in the Big South Fork. Georeferenced physical bedform features were queried for habitat suitability of the endangered mussels over the 27.8 km (17.3 miles) of river reaches that were mapped in this study. Habitat data were categorized for suitability for each mussel species as optimal, suboptimal, marginal, and non-suitable based on river characteristic, substrate, embeddedness, and water depth. Predicted habitat areas were compared to known locations of mussel populations from a previous inventory of Big South Fork endangered mussels habitat (Bakaletz, 1991). "Bakaletz found a total of nine mussel sites for the five endangered species within the three river reaches mapped in this study. The UVMS method indicated optimum, suboptimum, or marginal mussel habitat in the vicinity of eight out of these nine areas" (Fiscor, 2005).

Rodgers (2008) analyzed data from the kayak based UVMS map of Abrams Creek in the Great Smoky Mountains National Park. The UVMS substrate interpretation was compared to traditional pebble count methods of substrate identification and a control method of laying a frame on the creek bottom and identifying all particles within. The UVMS system was used to record substrate images by following a straight line along the thalweg and also a 45-degree angle crosswise pattern across the creek. The UVMS method of substrate identification produced comparable results to the pebble count and the frame control methods, differing statistically by overestimating the number of particles in gravel beds versus the other methods. He also concluded that "underwater video mapping proved to be a much quicker method for obtaining substrate data for long stream reaches when performing visual estimation for post processing" (Rogers, 2008).

Flug et al. (1998) used sonar to map river depth of six transects of the Green River in Utah. The six transects were irregularly spaced over a distance of 1.5 km (1 mile). The sonar recorded depth measurements at three second intervals. A flat bottom boat with an outboard jet engine was used to compensate for shallow water across the study region. River width measurements were made on foot using a standard hip-chain. These measurements were indicated to the sonar operator and encrypted into the sonar measurements to correspond with depth measurements. Traditional transect survey methods require a fixed reference cable perpendicular to flow, but this sonar survey depended on the skills of the boat pilot for straight and perpendicular transects. Repeatability was measured by conducting four passes at each transect location and comparing individual depth values to corresponding average depth values. Average standard deviation (SD) was 0.12 m for an average depth of 1.3 m, having a coefficient of variation (CV) of 10%. Measurements in shallow water near the bank were excluded, and the SD improved to 0.05 m and a CV of 4.7%. Sonar depth measurements were compared to traditional surveys for two other dates at a common transect location. Most variability was in the shallow water near the bank, partially attributed to differences in flow volume for the different days. "The ability to replicate sonar measurements from one traverse to another, as well as comparing sonar collected data to more traditionally measured methods, however, is shown to be quite good" (Flug et al., 1998).

Dolloff et al. (1997) compared the basinwide visual estimation technique (BVET) and the representative reach estimation technique (RRET) for habitat evaluation at the watershed scale at three small watersheds in the Appalachian Mountains. Both techniques are walking methods and require river accessibility on foot. For the BVET evaluation, visual habitat observations were made comprehensively for 8.7 km, 5.5 km, and 6.7 km reaches in three different watersheds. Habitat type (pool, riffle, or cascade), hip-chain distance along thalweg from start point, estimated habitat area, average and maximum depth, and large woody debris (LWD) counts were visually identified and physically subsampled for calibration. The RRET is based on the assumption that a trained biologist can select stream sections with habitats representative of the whole watershed. Three 100 meter representative reaches in each of the three watersheds were extensively measured for pools, riffles, and cascades, habitat surface area, depth, and amount of LWD. Dolloff et al. (1997) regarded the BVET estimates as more accurately depicting number and location of different habitat types. Estimates of total habitat area were similar for the two techniques, but the proportions, numbers, and average sizes of habitat types were different. The RRET failed to record less common cascade habitat in one watershed, resulting in uncharacteristically high areas of pool and riffle. It was concluded, "to expect a single reach to reflect the characteristics of an entire stream is unrealistic, unless that reach approaches the length of the stream" (Dolloff et al., 1997).

Frappier and Eckert (2007) surveyed 142 segments from minimally impacted streams using the Environmental Protection Agency's (EPA) Environmental Monitoring and Assessment Program (EMAP) protocol. Five approaches for habitat prediction, based on discriminant function, linear regression, ordination, and nearest neighbor analyses, were compared to the EMAP for accuracy. Separate linear regression models for each habitat predictor gave the highest accuracy of habitat prediction, and the best model had an error of 27%. Minimum transect length was 150 m. Physical habitat variables modeled were wetted width, angle of each bank, undercut length, bankfull channel width and height above water surface, canopy cover, embeddedness, substrate particle size, and depth (Frappier and Eckert, 2007).

2.2 River Habitat Health Index

Both physical and chemical factors are critical to the suitability of a riverine habitat to support aquatic biodiversity. There are several indices currently in use to quantify physical habitat features of river systems. This study focuses entirely on empirical physical data for habitat interpretation.

Rankin (1989) developed a Qualitative Habitat Evaluation Index (QHEI) based on substrate, instream cover, channel morphology, riparian and bank condition, pool and riffle quality, and gradient. Because the QHEI was designed to quantify physical characteristics, Ohio streams that were minimally impacted by chemical water quality were selected for the study. A Chi-square test was used to determine if the QHEI metrics correlated to calculations of the Index of Biotic Integrity (IBI) based on fish counts (Rankin, 1989; Kerans and Karr, 1994). Results of the study are as follows from the Mississinewa Watershed final report:

> QHEI values for the 10 study sites ranged from 29 to 86. The strongest correlation of parameters was between QHEI value and channel

morphology, and between QHEI values and stream gradient, indicating that the single greatest factors affecting QHEI values seems to be the degree of ditching to the stream, which removes natural sinuosity, increases bank slope and can increase stream gradient. The presence and quality of pool and riffle zones was determined to be the next most important factor in determining the QHEI value. Accordingly, the two sites with the lowest QHEI values had the lowest channel and gradient scores, and had very low pool/riffle quality scores. It was also found that the site with the lowest QHEI value was also determined to have the lowest substrate score as it exhibited high levels of silt and embeddedness (Reber et al., 2002).

An and Choi (2003) used the QHEI to describe the physical portion of an Index of Biological Integrity (IBI) when evaluating the effect of habitat modification on ecosystem health in the Keum River, Korea. The river was evaluated for fish assemblages, chemical contamination, and physical habitat quality before and after a dam construction project. The habitat degradation was determined to be primarily as a result of physical habitat modification, because the QHEI had the most influential score in the overall IBI. Seven physical factors were selected from the EPA QHEI: substrate, canopy cover, channel alteration, river characteristic ratio, bank vegetation, streamside cover, and riparian vegetative zone width. QHEI values changed from "Fair" to "Very Poor" on a scale of good, fair, poor, very poor, with the worst scores occurring nearest the dam (An and Choi, 2003).

Bryce et al. (1999) outlined a holistic approach to evaluate the condition of aquatic habitats. Physical factors that directly affect aquatic biota are: water quality, flow regime, physical habitat, food and energy sources, and biotic interactions. The study was confined to the Mid-Appalachian ecoregion. Streams in forested areas with roads absent from the riparian zone and minimal human activity in the watershed were used as reference for natural variation and biotic assemblages. Watersheds were compared and ranked from relatively undisturbed to highly disturbed based on map analysis, aerial photo interpretation, and site visits for stream physical habitat data and riparian zone information. Stream reach length was measured as 40 times the mean wetted channel width. For each stream reach, physical habitat measurements were taken across eleven evenly spaced transects, including: channel morphology (bankfull width, depth, shoreline habitat complexity, and instream fish habitat), substrate type and size, riparian vegetation cover, aquatic macrophytes, woody debris, and human alterations to channel and riparian zone. Water chemistry samples were taken at the midpoint of the stream reaches, and macroinvertebrate samples were taken at nine transects. Physical, chemical, and benthic stress indicators correlated with ecoregion factors such as topography, prevalence of economically valued natural resources, and human population density. Ridge ecoregion streams had the lowest risk scores (53% low to moderate risk) with small, forested headwater watersheds. Western Alleghany Plateau ecoregion had a mosaic of farm and forest land use with significant oil drilling and coal mining, with 78% stream length in high risk category. Because of urbanization, agriculture, and stream channelization, valley streams scored the worst with 96% in high risk category (Bryce et al., 1999).

Barbour et al. (1999) developed the rapid bioassessment protocol (RBP) with the EPA. The RBP uses extensive data gathered from biological surveys, chemical monitoring, and visual physical habitat assessment. Sampling reaches are categorized into high gradient or low gradient streams and physical habitat assessment parameters are adjusted accordingly. All parameters are evaluated and rated on a numerical scale of 0 to 20 for each sampling reach. The ratings are then totaled and compared to a reference condition to provide a final habitat ranking. Scores increase as habitat quality increases. The ten parameters measured are: epifaunal substrate/available cover, embeddedness, velocity/depth combinations, sediment deposition, channel flow status, channel alteration, frequency of riffles and/or frequency of bends (sinuosity), bank stability, bank vegetative protection, and riparian vegetative zone width. The actual habitat assessment process involves rating these 10 parameters as optimal, suboptimal, marginal, or poor (Barbour, 1999).

Kaufmann et al. (1999) working in support of the Environmental Monitoring and Assessment Program (EMAP) (EPA, 2008) provides guidance for calculating indices of physical habitat in wadeable streams. Variance among streams was compared with variance between repeat stream visits. Quantitative metrics were divided into two groups, flow-sensitive and flow independent. Integrated metrics such as mean substrate diameter were very precise, and features sensitive to differences in flow stage, such as riffle/pool and width/depth ratios tended to be imprecise. Several field habitat survey methods employed by EMAP were analyzed, and visual assessments such as the RBP (Barbour, 1999) were determined imprecise as related to field validation. Seven physical habitat attributes important in influencing stream ecology were identified: stream size/channel dimensions, gradient, substrate size and type, habitat complexity and cover, riparian vegetation cover and structure, anthropogenic alterations, and channel-riparian interaction (Kaufmann et al., 1999).

2.3 Rugosity

Rugosity is defined as the variations or amplitude in the height of a surface (Bain and Stevenson, 1999). Rugosity is commonly measured in the field by measuring the length of a chain draped across a rough surface, then measuring the straight length of the same chain (Wolman, 1954). Shumway (2007) used underwater video mapping to quantify habitat complexity in a freshwater lake. Substrate quadrants were videoed at depth by a self contained underwater breathing apparatus (SCUBA) diver, and these images were evaluated for light intensity (light to dark) indicating surface rugosity. Optical intensity values were compared to traditional surface topographic rugosity surveys in each quadrant by a length of chain conforming to the substrate profile versus a string stretched taught across the span. Rugosity and optical intensity were positively correlated, and both methods significantly differentiated between sand, intermediates, and rock substrates (Shumway, 2007).

Brock (2004) performed an aerial light detection and ranging (LIDAR) rugosity study of several coral reefs in Florida. The LIDAR scanned 130-m reef transects at approximately 0.8 m spacing. "The relative horizontal point-positioning precision, highly significant to the analysis of topographic complexity presented below, is on the order of

10 cm or less" (Brock et al., 2004). Average rugosity values ranged from 1.017 to 1.10 for a 60-130 m coral reef transect.

Wolman (1954) describes an established approach to rugosity calculation for a river reach. In a desired stream reach, a grid was established and walked to gather 100 representative substrate samples. Each particle diameter is measured and rugosity levels were established based on the number of measurements that fall in defined categories, such as the Wentworth scale. This method is compared to sieving and weighing substrate samples at systematic locations across a reach for representative particle size averaging. Rugosity is then calculated based on median particle diameters at the sampling sites (Wolman, 1954).

Rugosity measurements are based on river bottom physical phenomena at various scales. Reach scale rugosity can be calculated from systematic sonar depth measurements, as in this study, or extrapolated from representative substrate measurements in the field. Some hands-on physical approaches to rugosity are draping a chain across the substrate and pebble count methods, such as point-count and sieving and weighing various sizes of representative substrate particles.

2.4 Sinuosity

Sinuosity is a ratio measure of the length of a river path versus a straight line distance. Sedimentation, bed load, and gradient are determinant factors in river bend formation. The rivers in this study are low sinuosity rivers, with overall sinuosity scores less than 3.5 (Bridge et al., 1986).

Smith (1998) demonstrated through modeling meandering channels that sediment transport and the slope of the floodplain were the dominant influences that led to channel migration and bend formation (Smith, 1998). Experiments were conducted in a small flume with a mix of earth and clay. Water was introduced without an initial bend at a constant bankfull level. Moist sediment was arranged in heaps at the stream head and eroded gradually into the stream. Sediment levels were maintained to promote channel instability without causing the stream to overflow its banks. It was determined that "given a sufficient slope and sediment supply, any of the experimental mixes having enough cohesion to maintain a well defined, single thread channel, were likely to produce high sinuosity bends" (Smith, 1998).

Stolum (1996) shows with model simulations that the meandering process self organizes the river morphology into a critical state characterized by fractal geometry (Stolum, 1996). The processes of river meandering described in this study are repeated in all rivers regardless of magnitude and across all scale levels within a river, an indicator of fractal patterns. Sinuosity is caused by two opposing planform processes; lateral migration increases sinuosity, and cutoffs reduce sinuosity. Rivers in the mathematical model fluctuate between tendencies toward an ordered state, with a straight line being the most ordered state a river can possibly take, and a chaotic state defined by the formation of ox-bow bends. A cutoff is the formation of an ox-bow lake where the sinuous bend is removed from the river channel through erosion of the point bar. In the model, the opposing processes self-organize into a steady state sinuosity of 3.14, or pi, the sinuosity of a circle (Stolum, 1996).

Bridge et al. (1986), studies a low sinuosity (less than 3) river using a combination of aerial photography and field research to map migration of point bars and islands. Islands are measured to form through sediment accretion, lengthening at a rate up to 2 m (6.5 ft) per year, and widening at a rate of 1 m (3.3 ft) per year. Channel segments abandoned by a cutoff require a century to fill. The substrate was primarily sand and gravel in this study, and the larger particles accumulated in the thalweg. The spatial distribution of the bed material did not change appreciably during the two year study. Suspended sediment load was primarily sand. Core samples of point bars indicate fining upwards in layers, from large gravel, increasingly large sand particles, to a layer of peat and silt on top (Bridge et al., 1986).

2.5 Summary

There is great variation among riverine habitat mapping techniques. It is agreed that important physical predictors of habitat locations are found at the mesoscale level, but biotic suitability prediction requires an understanding of watershed scale geomorphology. Most studies use remote sensing or topographic maps for large scale stream classification and random sampling of reaches inside the stream system for field validation (Frissell et al., 1986). Habitats found at randomly sampled reaches are often extrapolated to represent biological diversity of the entire stream system, with questionable accuracy. Aquatic habitat classification does not have to be species specific, because the relative complexity of physical habitat is a proven indicator of biotic diversity. Habitat quality of stream systems in different geographic locations can be compared based on empirical physical features when grouped into similar scale categories. Habitat complexity and biotic suitability can be modeled with the right parameters. The EPA QHEI is an established method of physical habitat quality quantification. The QHEI has been applied to compare representative reaches in various river ecosystems, but has never before been applied to an entire river system, such as the Big South Fork and tributaries.

Stream habitat classification at the mesoscale (1 m) level has traditionally been based on representative reach extrapolation (Frissell et al., 1986), or by comprehensive walking surveys such as the BVET (Dolloff et al., 1993). UVMS is the only kayak/canoe habitat mapping method to generate a comprehensive physical habitat map of an entire river system at the mesoscale level. Randomly selected reaches are assumed to represent the habitat potential of the entire stream system. Often researchers' availability of "random" reaches is limited by river accessibility. Habitat classification methods that consider hierarchical scale metrics usually use remote sensing combined with field research to extrapolate mesoscale habitat maps. The advantage to RRET and BVET analysis is detail that varies along the river transect and describes the persistence of pool/riffle bedform data, and substrate heterogeneity perpendicular to flow (Frissell et al., 1986). Disadvantages include time intensive field surveys by biologists trained in habitat identification, and the uncertainty of extrapolating data to represent an entire riverine ecosystem. A distinct advantage of UVMS data over other habitat identification methods is speed and efficiency in creating comprehensive stream-length sonar depth data and georeferenced water surface and substrate video that can be reviewed by experts in the lab. UVMS creates a permanent record of base flow habitat characteristics that can be shared and interpreted by different researchers with different interests.

The sonar depth measurements have been tested and proven accurate and efficient. The visual observation method of substrate identification using lasers for scale reference is accurate compared to established quadrant survey and point count methods. The only limitation of UVMS as compared to representative reach survey is data collection in the thalweg only.

Chapter 3: Equipment

The type of river habitat targeted for study defines the underwater video mapping system (UVMS) platform used for mapping. Deep water substrate is outside the range of flush mounted video cameras in the kayak, and the canoe is unsuitable for negotiating class III+ whitewater rapids (AWSC, 1998). If the kayak passes over a deep pool, the substrate is often concealed from view by turbidity. If the canoe is used, the submersible video camera on a reel records all deepwater substrate, but some large rapids must be portaged that could be ran using a kayak. Therefore the dominant river characteristic chooses the UVMS platform. Safety equipment such as personal floatation devices (PFD) and helmets are used as recommended by the National Park Service (NPS), as well as a medical first-aid kit and river rescue throw ropes.

3.1 Canoe UVMS Platform

The canoe UVMS platform (Figure 2) is built on an Old Town Guide 147 canoe. Video is captured using two Ocean Systems Deep Blue color underwater video cameras each with 75m (250 ft) of tether cable, I-Theater personal cinema glasses video eyewear, and two DriveData DR3 digital video recorders (DVR). The canoe UVMS requires two operators, one in the bow with a double-blade kayak paddle and 12 Volt trolling motor, and one in the stern wearing the video glasses attached to the submersible video camera on a reel. The submersible camera is weighted, and includes an aluminum tailfin and waterproof flashlights for illumination at depth, or two waterproof lasers mounted

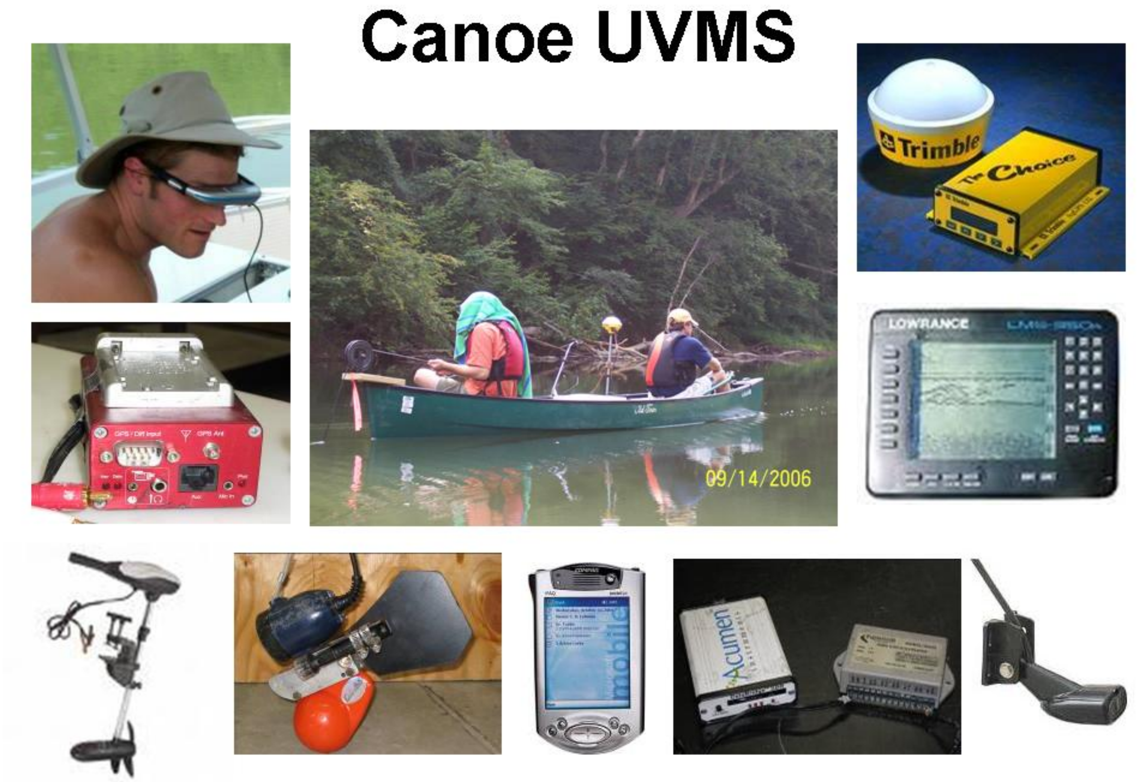

Figure 2: Canoe UVMS hardware pictures

parallel 10 cm (4 inch) apart for scale comparison. Sonar depth is recorded using a Lowrance LMS-350a sonar depth transducer mounted on a Tite Lok 5798 hinged transducer mount. GPS location is measured using a Trimble Ag132 GPS receiver with Omnistar satellite-based differential correction (DGPS) (Trimble Navigation Limited, 2009). Power for the trolling motor is supplied by a 12 Volt deep cycle marine battery.

3.2 Kayak UVMS Platform

The kayak UVMS platform (Figure 3) is mounted on a Wilderness Systems Tarpon 100 sit-on-top 3-meter (10-foot) kayak. There are three waterproof cameras, one Ocean Systems Deep Blue camera mounted on the bow to capture above water video, and

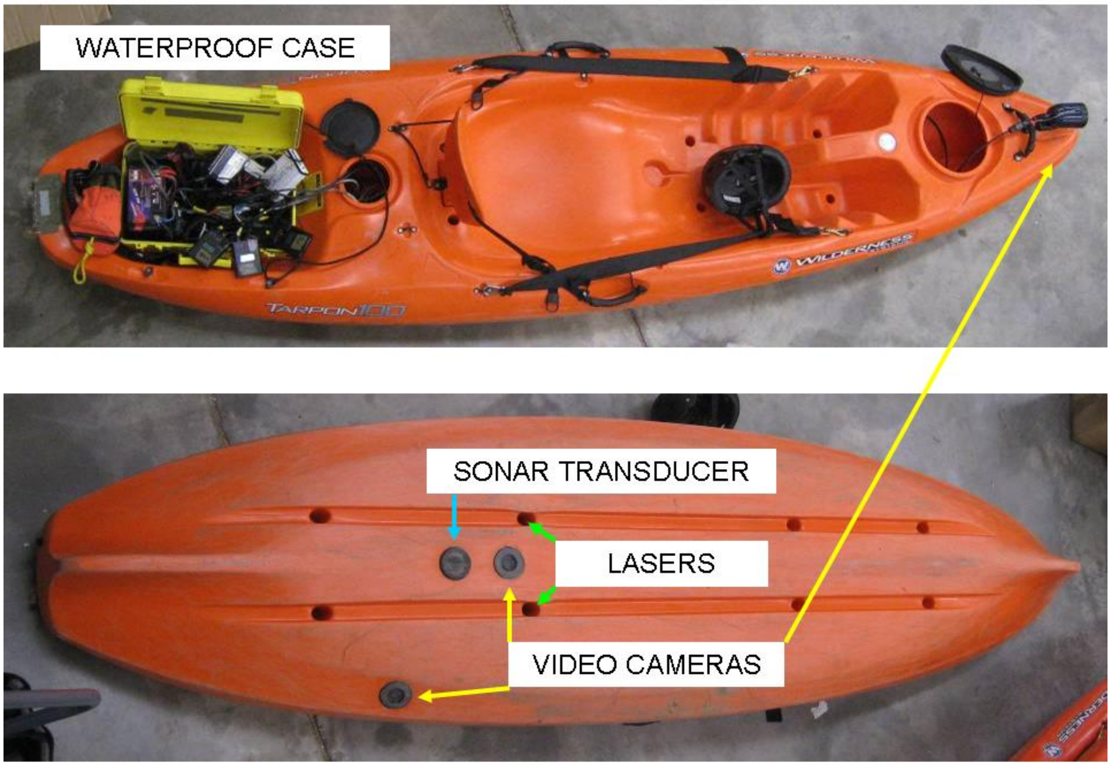

Figure 3: Kayak UVMS hardware pictures

two DropShot 20/20 through-hull color underwater video cameras that record substrate from two angles, perpendicular and offset 30 degrees. The offset video camera is useful when the water is too shallow or the velocity is too high for the bottom camera. Two Spyder II Pro red 300mW waterproof laser pointers are parallel mounted 20 cm (7.75 inch) apart perpendicular to the river bottom for use in substrate scale estimation.

3.3 UVMS Hardware Configuration

Sonar depth is measured using a customized Cruz-Pro ATU-120S shallow water sonar transducer with 15 cm to 13 m (0.5 to 44 ft) operational range. GPS position is provided using a Garmin 18x OEM PC GPS receiver with wide area augmentation system (WAAS) differential correction (FAA, 2007). Water sensitive electronics are protected by a Pelican 1500 waterproof case (Figure 4).

Video footage is synchronized with the global positioning system (GPS) location using a Red Hen Systems VMS 200 GPS modem in both the canoe and kayak UVMS platform (Figure 5). The location from the GPS receiver is translated into digital audio and stored on the audio track of the video footage using DriveData DR3 DVRs moving pictures expert group 2 format (mpeg-2) and SanDisk 8 giga-byte (GB) compact flash (CF) cards in file allocation table 32 (FAT-32) format. GPS audio and video are function tested in the field using a DriveData 2.5 inch liquid crystal display (LCD) monitor before recording data. One 8-GB CF card can store approximately 4 hours of video in long-playing (LP) format. GPS and sonar signals are output as $GPRMC and $SDDBT National Marine Electronics Association (NMEA) sentences respectively. These are

Figure 4: Battery, VMS-200, NMEA combiner, SDR, and 3 DVR recorders

combined by a Noland Engineering Model NM42 NMEA multiplexer and stored on a SanDisk 1-GB compact flash card (FAT format) by an Acumen Databridge serial data recorder (SDR) datalogger. Power for the UVMS system is supplied by an Odyssey PC625 12V motorcycle battery (14.8 amp hours). A backup positional tracklog is recorded using a Garmin 60CSx handheld GPS receiver with a Gilsson external GPS antenna. Backup hardware, extra data cards, cables, and lunch are stored in another waterproof case on a second kayak.

Electronic components throughout the boat were assembled with recommended standard (RS-232) 9-pin serial connectors. Data transfers on pins 2 and 3, and pin 5 is ground (Appendix)(SGI, 2009). All hardware was programmed to communicate at 4800 baud. Data acquisition and transmission rate was set to 1 Hz whenever possible. SDR 1GB CF card was formatted FAT, and 8GB DVR CF cards were FAT 32 format. DVR video recorders were set to "line-in" audio and mpeg-2 record format. GPS data was recorded on the NMEA 0183 $GPRMC stream and was differentially corrected GPS (DGPS) using WAAS or the OmniSTAR satellite when available (NMEA, 1995; FAA, 2007).

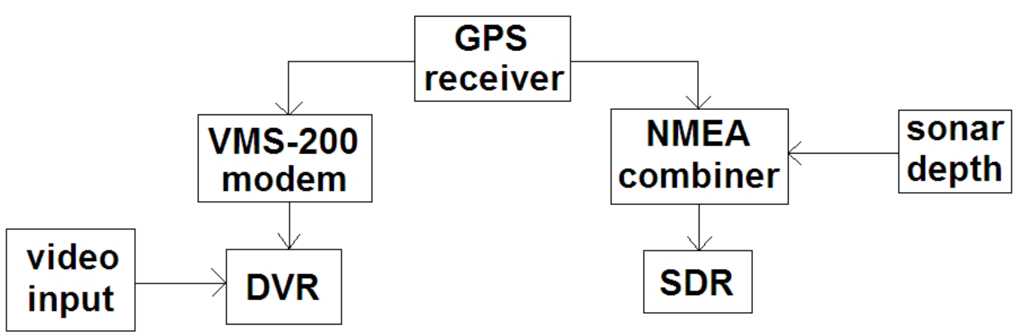

Figure 5: UVMS hardware configuration

Chapter 4: Attribute Acquisition and Analysis

4.1 River Video Mapping

River flowrates were surveyed at United States Geological Survey (USGS) gauge stations for expedition planning (Figure 6) (NOAA, 2007; USGS, 2007-2009). National Oceanic and Atmospheric Association (NOAA) weather forecasts were also an important consideration (NOAA, 2007). River levels were ideally mapped at median annual base flow, approximately 2.83-14.16 cubic meters per second (100-500 cfs). Tributaries that are not gauged, such as North White Oak Creek, were ran at significantly higher downstream gauge levels. Spikes in flowrate from a rain event were avoided because elevated turbidity reduced video visibility. The Leatherwood Ford gauge # 03410210 was used for Big South Fork flowrates, the Clear Fork gauge # 03409500 was used for Clear Fork River flowrates, and the New River gauge # 03408500 was used for New River flowrates (Figure 1). Inclement weather and personnel availability resulted in some mapping expeditions at less than desirable levels.

Compact flash cards (8GB) were replaced in the DVRs every 3-1/2—4 hours because of memory limitations. DVRs were stopped and restarted when scouting or portaging rapids, or stopping for lunch. It took thirteen mapping day trips and one overnight to complete the underwater video mapping system (UVMS) map of the 130 km (81 miles) of river system thalweg in the BISO NRRA (Table 1). The river thalweg is the deepest continuous line along a watercourse (Armantrout, 1998).

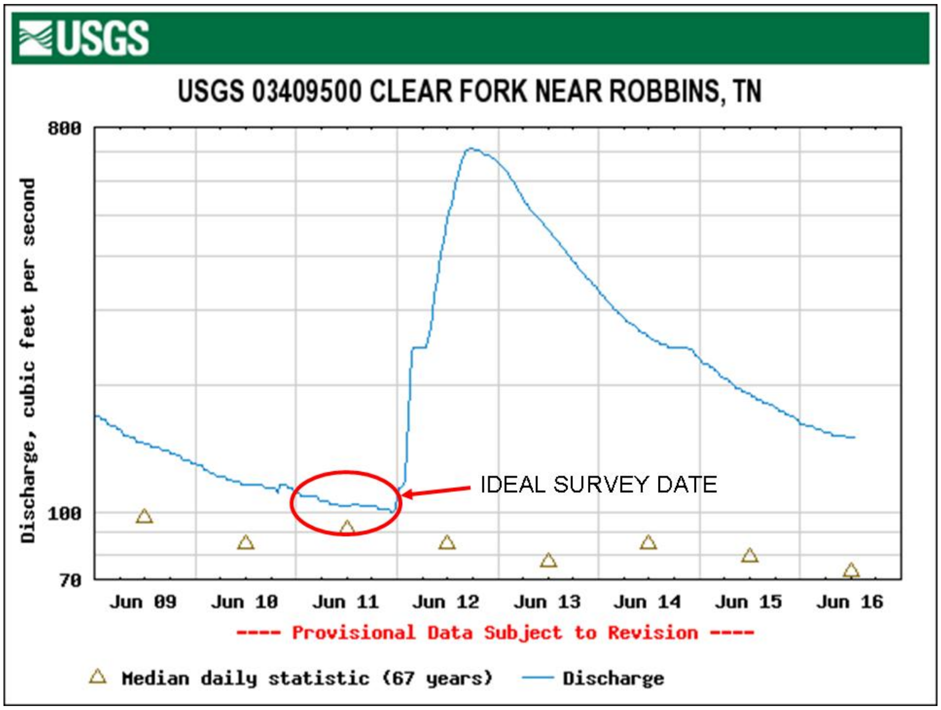

Figure 6: USGS river flowrate gauge data

Table 1: BISO NRRA mapping trips

Date	River	Put In	Take Out	km	Miles	Rapids	Vessel	cfs	Gauge
10/20/2005	Big South Fork	Station Camp	Big Island	6.4	4	II	Canoe	62	Leatherwood
10/21/2005	Big South Fork	Big Island	Bear Creek	16.1	10	II	Canoe	61	Leatherwood
7/18/2006	Big South Fork	O&W Bridge	Leatherwood	3.7	2.3	II-III	Kayak	128	Leatherwood
7/2/2009	Big South Fork	Leatherwood	Station Camp	12.6	7.8	I-II	Canoe	194	Leatherwood
9/3/2009	Big South Fork	Confluence	O&W Bridge	7.6	4.7	III-IV	Kayak	113	Leatherwood
9/11/2009	Big South Fork	Yamacraw	Alum Ford	8.5	5.3	I-II	Canoe	171	Leatherwood
10/21/2009	Big South Fork	Alum Ford	Big Creek	7.2	4.5	I	Canoe	1300	Leatherwood
10/22/2009	Big South Fork	Bear Creek	Yamacraw	7.9	4.9	IV	Canoe	1050	Leatherwood
4/5/2004	Clear Fork	Peter's Bridge	Brewster Bridge	4.8	3	II-III	Kayak	146	Clear Fork
6/2/2009	Clear Fork	Brewster Bridge	Burnt Mill Bridge	17.1	10.6	II	Kayak	126	Clear Fork
6/9/2009	Clear Fork	Burnt Mill Bridge	Confluence	6.3	3.9	II	Kayak	147	Clear Fork
6/29/2009	New River	New River Bridge	Confluence	14.3	8.9	II-III	Kayak	170	New River
3/31/2009	North White Oak	Zenith	Leatherwood	12.2	7.6	II	Kayak	3050	Leatherwood
4/30/2009	White Oak Creek	Horseshoe Bend	Burnt Mill Bridge	5.8	3.6	II	Kayak	303	Clear Fork
				130.5	81.1				

4.2 UVMS Data Processing

In the lab, the video data was converted to mpeg-2 format using the DriveData DVR software. The mpeg-2 files were georeferenced in ArcMAP using the RedHen Systems GeoVideo software. Sonar depth as $SDDBT and GPS as $GPRMC NMEA sentences were combined by the NMEA multiplexer and stored on the Acumen SDR datalogger. GPS and sonar data were sorted and combined in Microsoft Excel spreadsheet format and georeferenced in ArcMAP. Above water and underwater GeoVideo shapefile attribute tables were spatially joined to the sonar shapefiles based on GPS proximity. Combined shapefiles were exported as MS Excel files, and distance, rugosity, and sinuosity were calculated. Final shapefiles with all UVMS parameters were merged to create whole river maps, and a comprehensive park wide UVMS map describing the entire BISO NRRA river system.

4.2.1 Distance between GPS points

GPS data is broadcast in decimal degree format based on the World Geodetic System of 1984 (WGS84) elliptical earth model (NOAA, 2009). Distance between GPS points is calculated using equation 1 (Wilkerson, 2009):

$$DISTANCE = \sqrt{(((Lat1 - Lat2) * 110946)^2 + ((Lon1 - Lon2) * 111319 * \cos((Lat1 * \pi)/180))^2)} \qquad \textbf{(1)}$$

Distance = Distance between GPS coordinate points in meters

Lat = Latitude in decimal degrees

Lon = Longitude in decimal degrees

The great circle Northing along a meridian measures 110,946 meters for 1 degree change in latitude. The great circle Easting along a parallel measures 111,319 meters for

1 degree change in longitude. The distance equation includes the cosine of the latitude angle in radians to compensate for diminishing meridian widths from the equator to the poles.

The GPS distance value is useful in quantifying habitat queries, because kayak velocity is consistently higher in riffles than in pools. The trolling motor creates a nearly constant 0.7 meter/second (1.5 mph) velocity throughout pools, and the maximum speed of a kayak in a riffle is 3.7 meters/second (8.3 mph). When quantifying bedform data, a maximum distance of 4 meters per data point was used for attribute interpretations. Distance values contained in one data point that are not representative of visual characterization were removed, such as the 700+ meter portage around the class IV Devil's Jump rapid (AWSC, 1998). Unfiltered distance data is used to calculate river mile. Habitat quantification differences between data point summation and distance summation are largest for river characteristic data. Amount of pools decreases 5% in the Clear Fork River, while riffles increase 2% and runs increase 3% (Figure 7).

4.2.2 Sonar Depth

Sonar depth soundings are recorded at a variable frequency based on depth and return signal strength (Van den Berg, 2008). Sonar data was recorded at approximately 1 Hz in this study from two different sonar transducers, a custom Cruz-Pro ATU-120S and a Lowrance LMS-350a. The Lowrance sonar transducer resolution was limited in shallow water and returned zero value depth data at water depths shallower than 0.5 meter (1.5 ft) (Figure 8). The sonar transducer custom made for this project by Cruz-Pro had an operating range of 0.23 to 10.5 meters (0.75 to 35 ft). Water depth shallower than

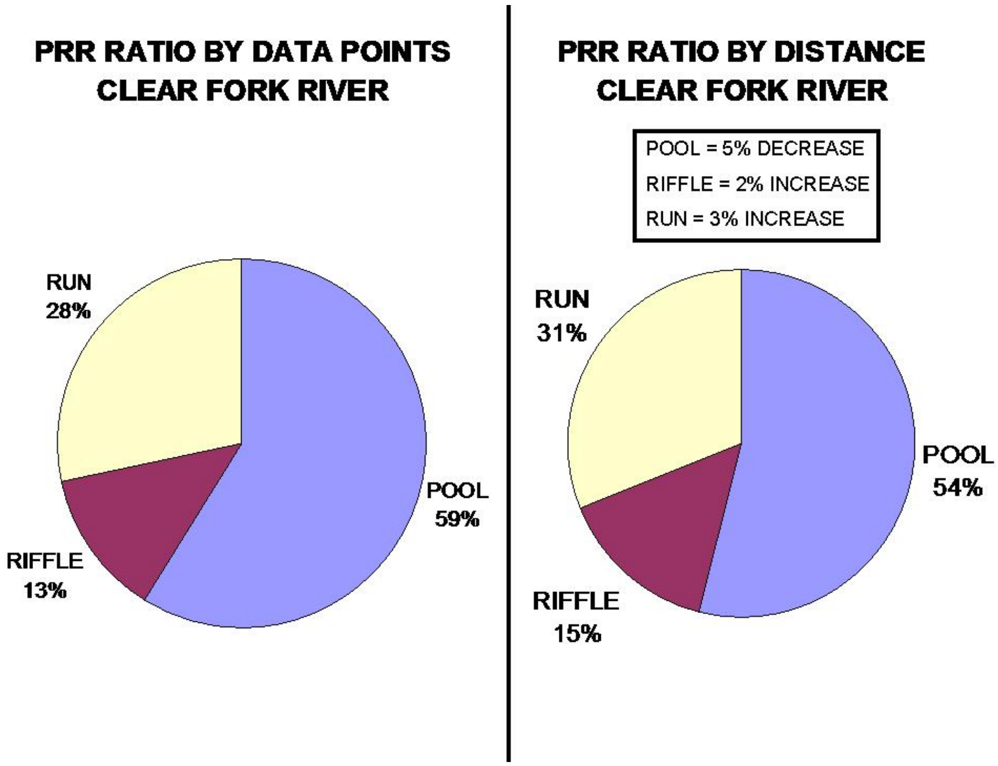

Figure 7: River characteristic summary—data points vs. distance

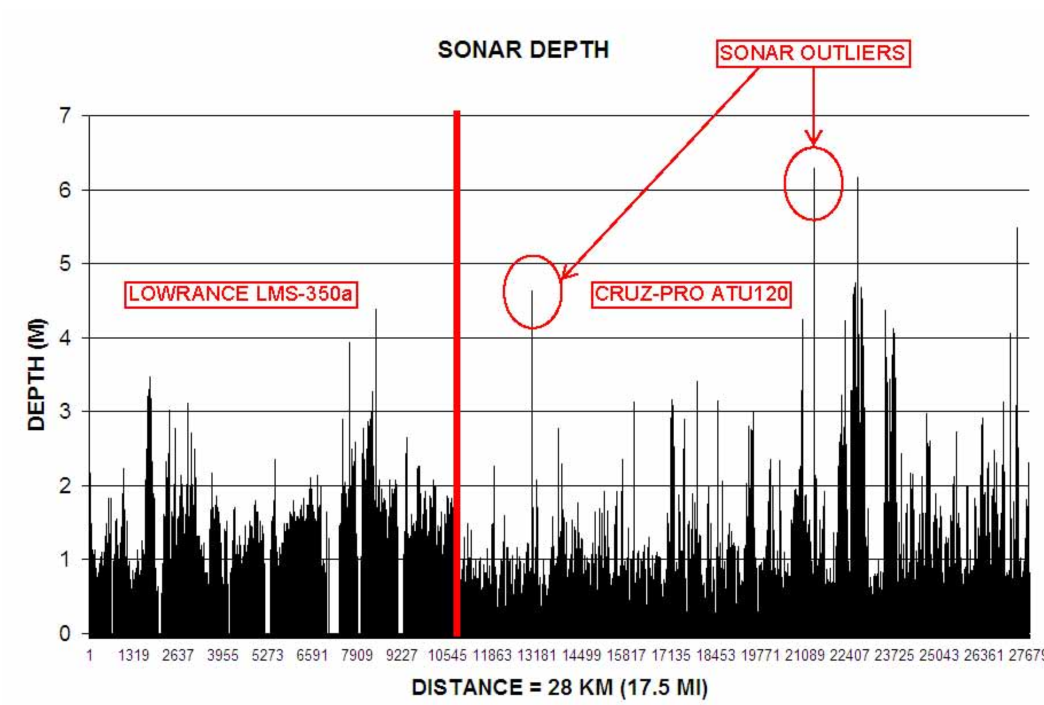

Figure 8: Comparison of Lowrance and Cruz-Pro sonar transducers

0.23 meters (0.75 ft) returned zero value depth data. These differences in sensitivity are apparent graphically (Figure 8).

The Lowrance depth sounder was used to map the upper section of the Clear Fork River, and the Cruz-Pro depth sounder was used for the following two lower sections. More zero value depths are recorded by the Lowrance sonar unit, shown as gaps in the sonar graph (Figure 8), because of insufficient shallow water sensitivity. Average depth differences are attributed to different flowrates for sections ran on different dates. The upper section was mapped at 434 cfs, while the lower two sections were mapped at 126 and 118 cfs at the Clear Fork gauge. Outlier depth values occur occasionally with both sensors, but are obvious as a single thin spike on the depth graph and do not significantly influence rugosity averaging. All UVMS data can be mapped thematically across the entire river system, such as this sonar depth map detailing the relative water depths of the BISO NRRA (Figure 9). The background map is a National Geographic Trails Illustrated topographic park map (NGS, 2007).

4.2.3 Rugosity

Rugosity is a measure of variations in height amplitude of a surface. It is commonly measured by the length of a chain conforming to a rough surface divided by the straight line length between the start and end points of the chain (Kuffner et al., 2007). In this study rugosity is calculated from sonar soundings at each GPS point using equation 2:

$$Rugosity = \frac{\sqrt{Distance^2 + \Delta Depth^2}}{Distance} \qquad \textbf{(2)}$$

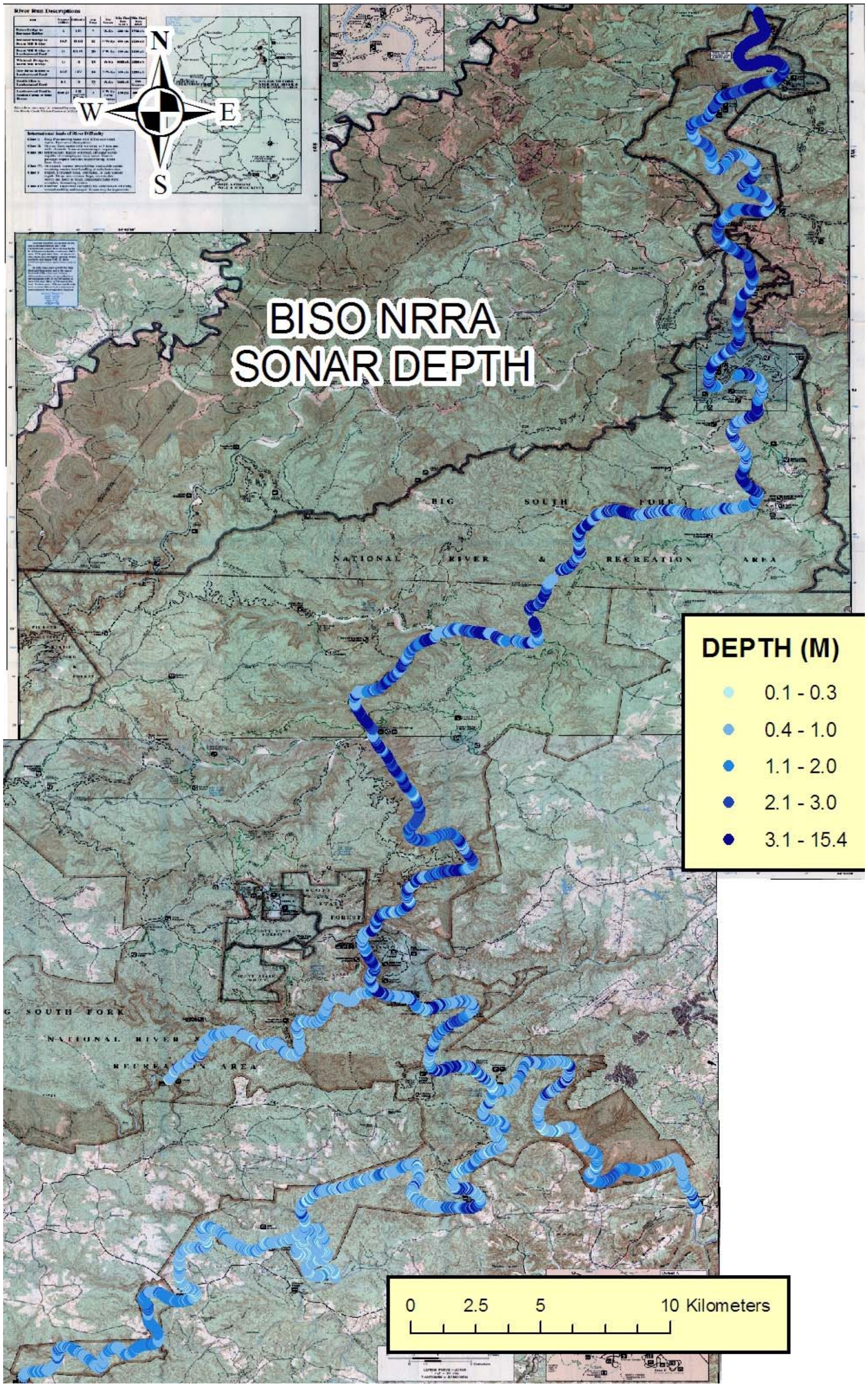

Figure 9: Sonar depth map of BISO NRRA river system

Distance = distance between GPS coordinate points in meters

ΔDepth = changes in water depth in meters from GPS point to point

Rugosity is a unitless number based on distance between GPS measurements and differences between corresponding sonar depth soundings (Figure 10).

The point to point amplitude of rugosity values is erratic because of the sensitivity of the sonar sensor to rapid changes in amplitude. Rugosity at each point is averaged over 100 data points, 50 upstream points and 50 downstream points, to smooth the rugosity values while maintaining the predictive indicators of substrate amplitude. Although distances between GPS points vary with velocity, the average distance between points is approximately 1 meter, and a 100 point segment is indicative of a 100 meter stream reach. Representative reaches and stream segments are recommended to be at least 100 meters, but vary based on natural breaks used to start and stop river sections (Dolloff et al., 1997). Average UVMS velocities are approximately 1 meter/second.

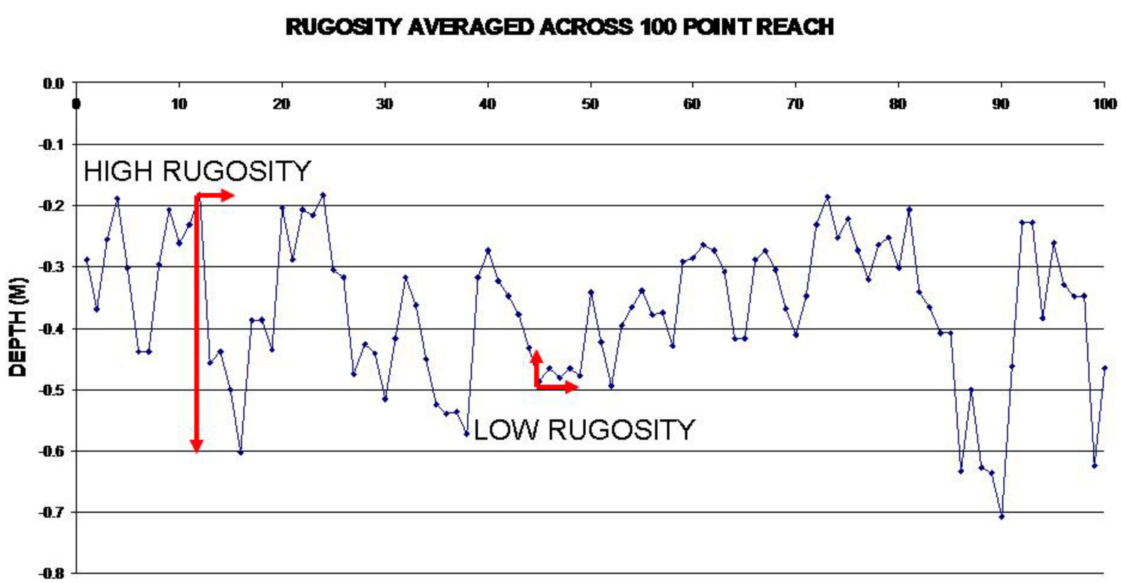

Figure 10: Depth vs. Distance describing rugosity

Rugosity graph peaks reliably indicate bedform characteristics such as drop-offs, large boulder fields, and even large woody debris (Figure 11).

The peaks indicating the large boulder field and the drop-off in Figure 9 are abnormally high for the rugosity equation parameters. When paddling over a pool or large boulder field, the depth sounder sometimes returned zero value depths across steeply sloped transitions, ascending and descending, caused by either a limitation in the speed of computational adjustment in the sonar transducer, or a misdirected return sonar signal. Although the rugosity peaks are uncharacteristically high, the peaks still indicate the location of rugose bedform phenomena. As water depths increase in drop-offs and

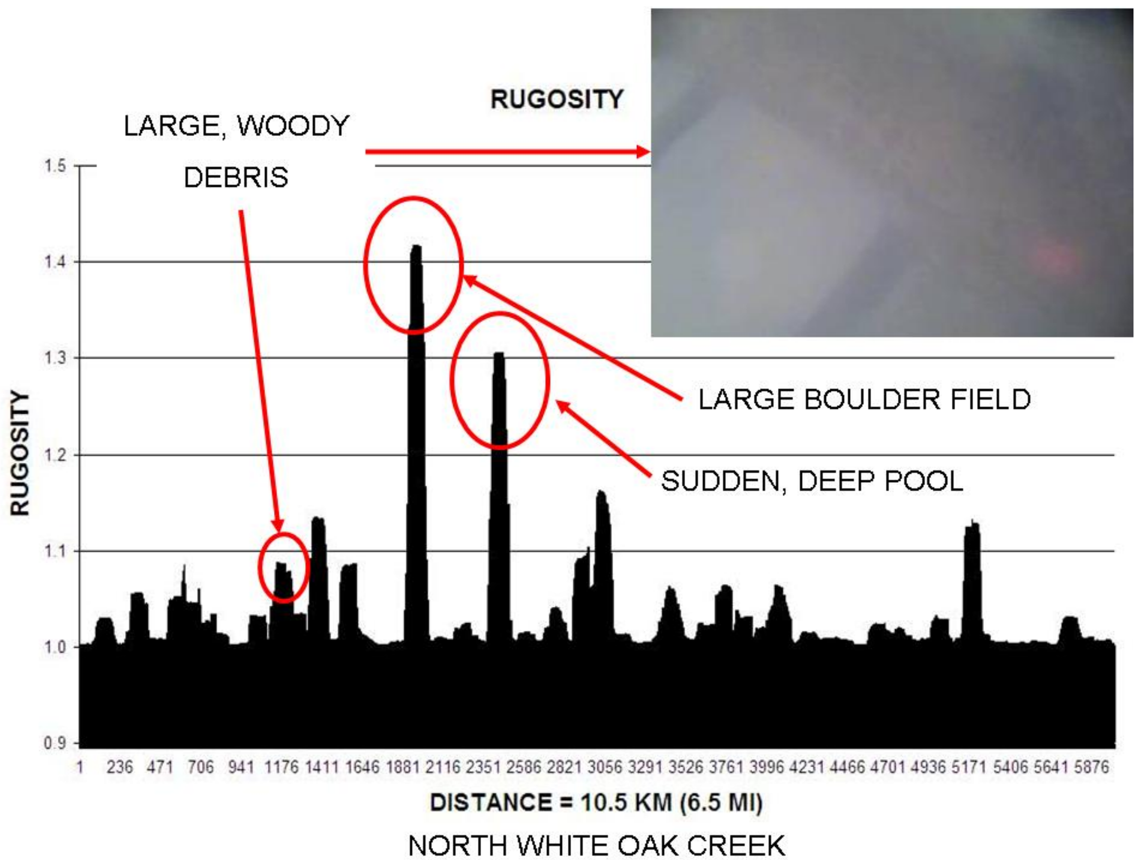

Figure 11: Video substrate verification of rugosity peaks

large boulder fields, rugosity peak amplitude increases with the depth difference between river bottom depth and zero depth sonar errors. In Figure 12, the dark bands indicate areas of high rugosity, and the light color bands indicate a more uniform bottom contour. Dark bands on a rugosity map can indicate the presence of large boulder fields, drop-offs, and ledges.

The rugosity metric taken directly from the equation output from point to point is too erratic to allow thematic predictions of rugose bedform phenomena such as dropoffs, large woody debris, and large boulders. Each rugosity value recorded in the database is an average of the 50 points upstream and 50 points downstream, and the flattening effect of this averaging improves the visual representation of the rugosity value over the length of the stream. The distance between points increases as velocity increases. Therefore, the distance represented by the 100 data points averaged for rugosity is not the same from point to point. It is approximately 100 meters. Rugosity was examined by averaging over exactly 100 meters, 50 upstream and 50 downstream. This strategy does not appreciable change the thematic predictive ability of the metric. Averaging rugosity over 100 meters instead of 100 points introduces a non-uniform flattening effect into the rugosity data because each rugosity value is an average of a variable number of data points, approximately 100 in number. Rugosity was averaged over 100 points in this study because of inconsistency in comparison between rugosity data at different locations when averaged over 100 meters.

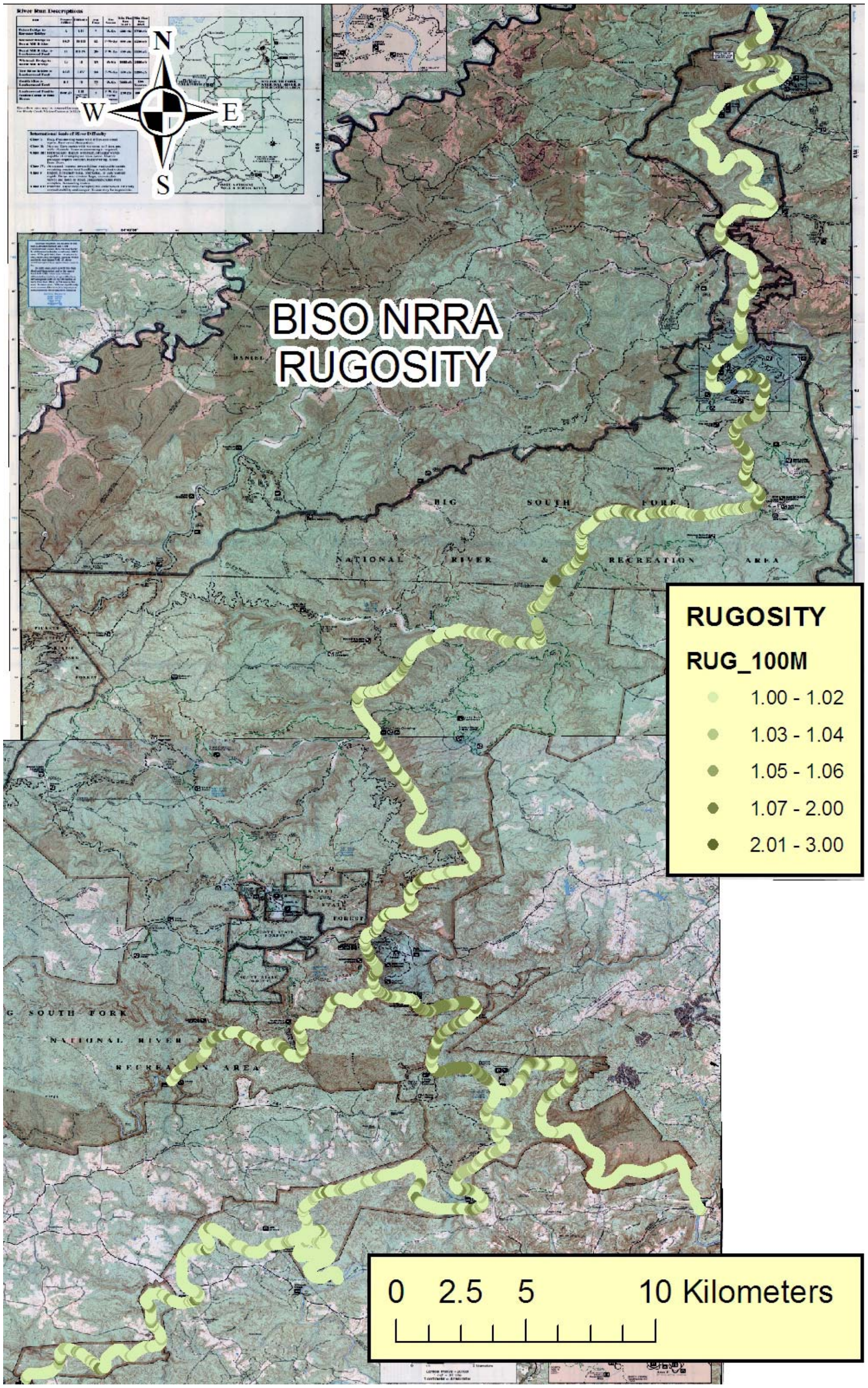

Figure 12: Rugosity Map of BISO NRRA river system

4.2.4 Sinuosity

Sinuosity is the total distance of a river course divided by the shortest possible path, a straight line (Armantrout, 1998). High sinuosity values indicate meandering in the course of a river channel. Sinuosity is calculated using equation 3:

$$Sinuosity = \frac{\Sigma(DistanceU) + \Sigma(DistanceD)}{\sqrt{(((LatU - LatD)*110946)^2 + ((LonU - LonD)*111319*\cos((Lat*\pi)/180))^2)}} \quad \textbf{(3)}$$

DistanceU = sum of distances between GPS points upriver

DistanceD = sum of distances between GPS points downriver

LatU, LatD = Latitude coordinates, upriver and downriver, in decimal degrees

LonU, LonD = Longitude coordinates, upriver and downriver, in decimal degrees

Sinuosity is zero from point to point by GPS distance, so it has been averaged over 100 points (50 upstream and 50 downstream) for reach scale metrics and 1000 points (500 upstream and 500 downstream) for stream scale metrics. Intuitively, sinuosity increases as it is measured over a greater distance. Average thalweg sinuosity on a reach scale is similar for all five rivers. Average stream scale sinuosity better indicates the overall meandering of each river, as compared to a sinuosity measurement taken on the entire length of each river in the BISO NRRA (Figure 13). White Oak Creek has the highest overall sinuosity score, and is the most meandering river in the BISO NRRA. In a thematic map of sinuosity the sharpest bends in a river correspond with darkening colors, measured from stream scale sinuosity values (Figure 14).

The dark bands in Figure 15 indicate high sinuosity values, measured over 1000 points and 100 points, or approximately 1 km and 100 meters, respectively. Reach scale sinuosity indicates meandering of the thalweg within the river channel. Relatively

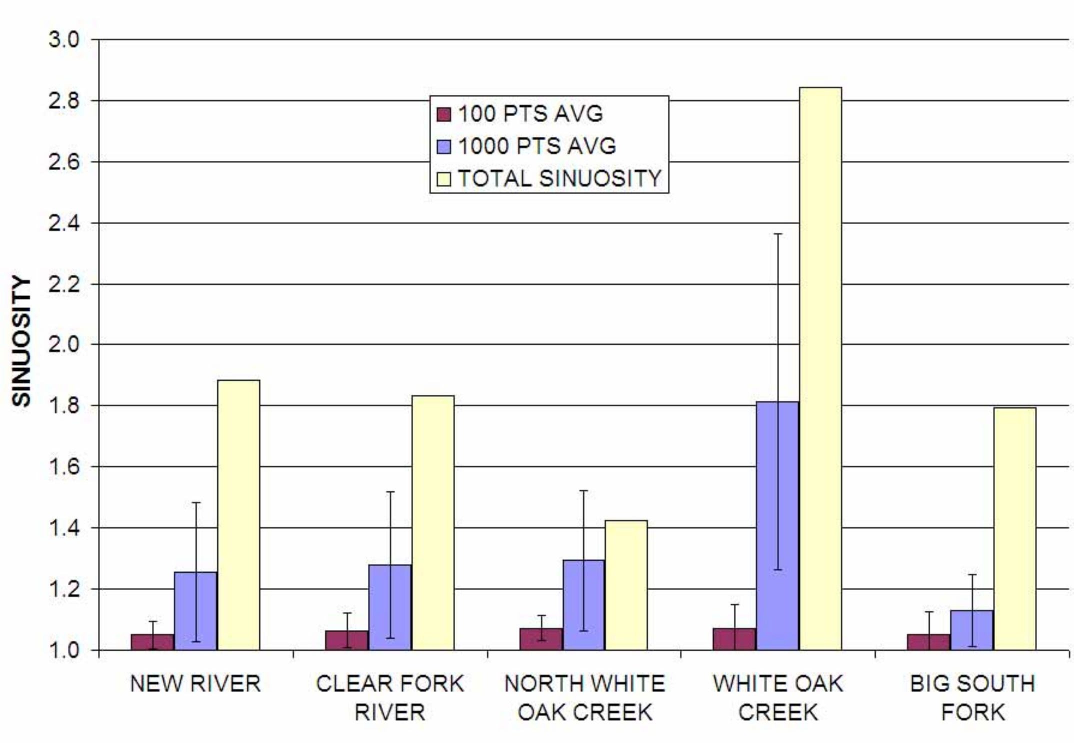

Figure 13: 100 pts average, 1000 pts average, and total sinuosity

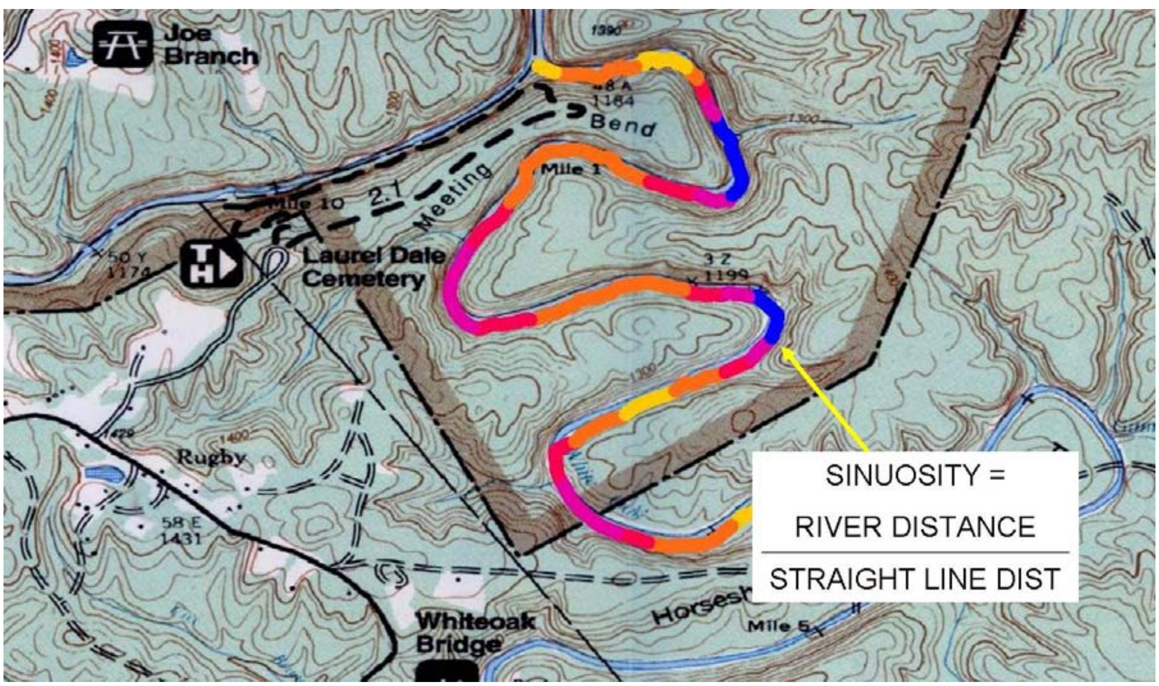

Figure 14: White Oak Creek sinuosity on topographic map

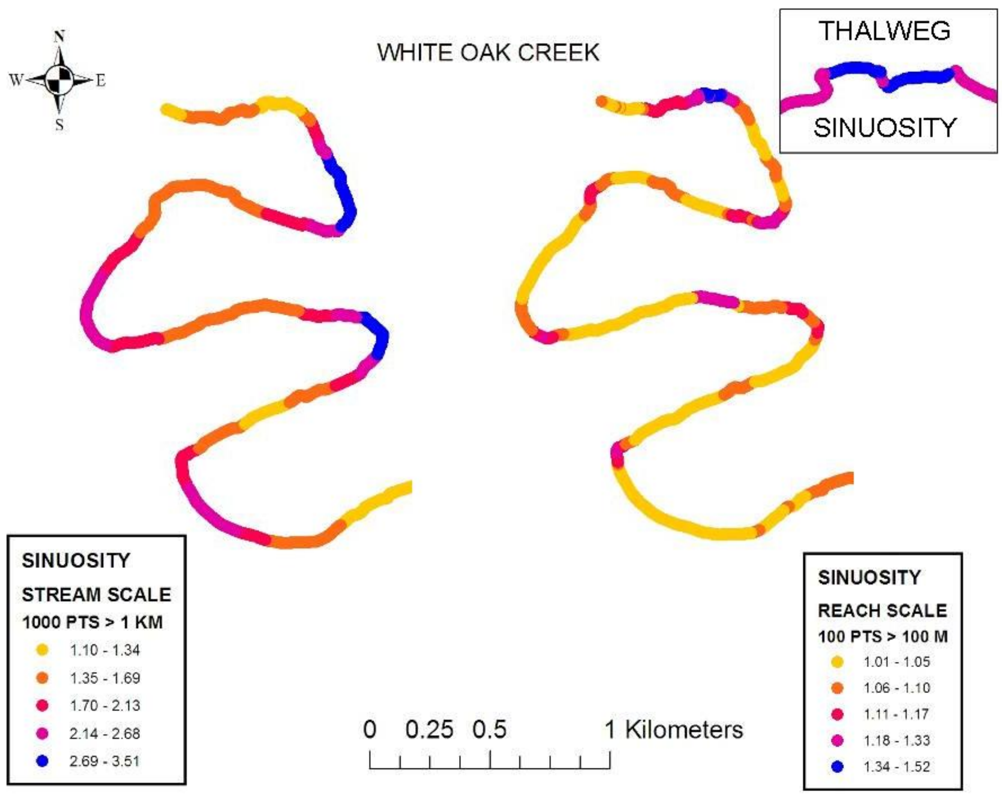

Figure 15: Stream scale vs. reach scale sinuosity

straight river channel segments can have high sinuosity values when analyzed on a 100 point scale because sinuosity is measured in the thalweg, which can meander widely around obstacles to flow. Stream scale sinuosity corresponds to river meandering, verifiable against regional topographic maps (Figure 14).

Sinuosity represents the sum distance between 50 or 500 points upstream and downstream of a single data point. Velocity is variable from point to point, and the distance between points increases with an increase in velocity. Therefore, 100 points does not equal 100 meters, and 1000 points does not equal 1 kilometer. The approximations in sinuosity calculations are a simplification based on the structure of the data set. It is preferable to calculate sinuosity values for exactly 100 and 1000 meters regardless of the number of data points. However, the following figures indicate that this approximation in sinuosity values accurately indicates the actual river conditions on the ground and is sufficient for predictive representation as a bedform metric. The four large peaks in this sinuosity graph of White Oak Creek (Figure 16) correspond to the four major switchbacks pictured in the course of White Oak Creek (Figure 14). This demonstrates that the numerical stream scale sinuosity metric is an accurate indicator of river channel meander.

Dark bands in Figure 17 indicate sharp bends and switchbacks in a river course. This park wide thematic sinuosity map is based on the stream scale sinuosity metric, where sinuosity is calculated over 1000 data points to approximate 1 kilometer (0.62 mile) distance.

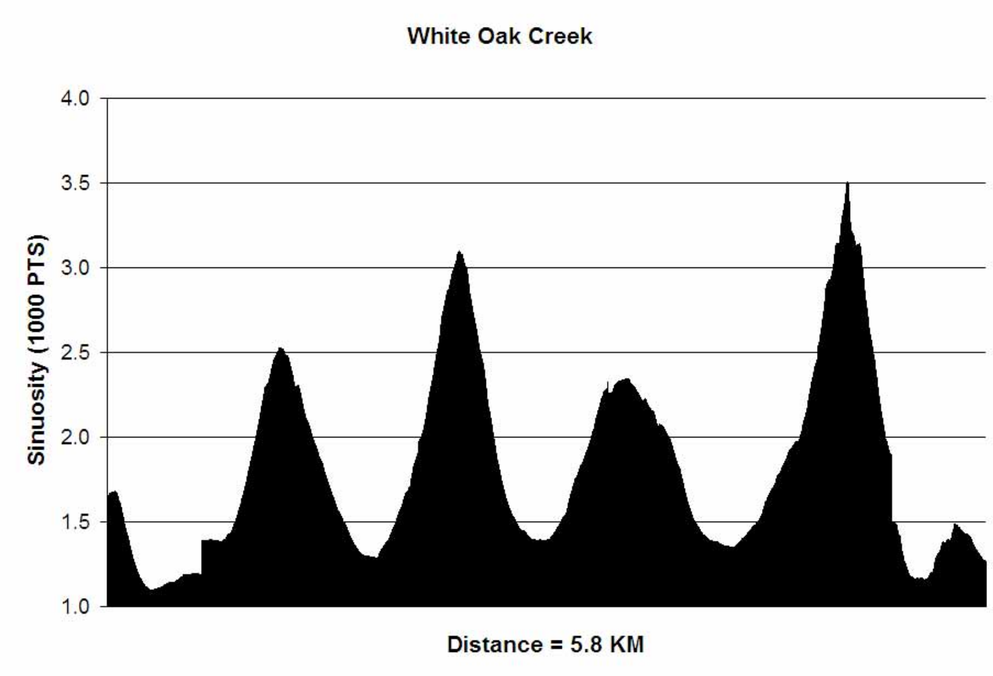

Figure 16: Sinuosity graph indicates bends in White Oak Creek

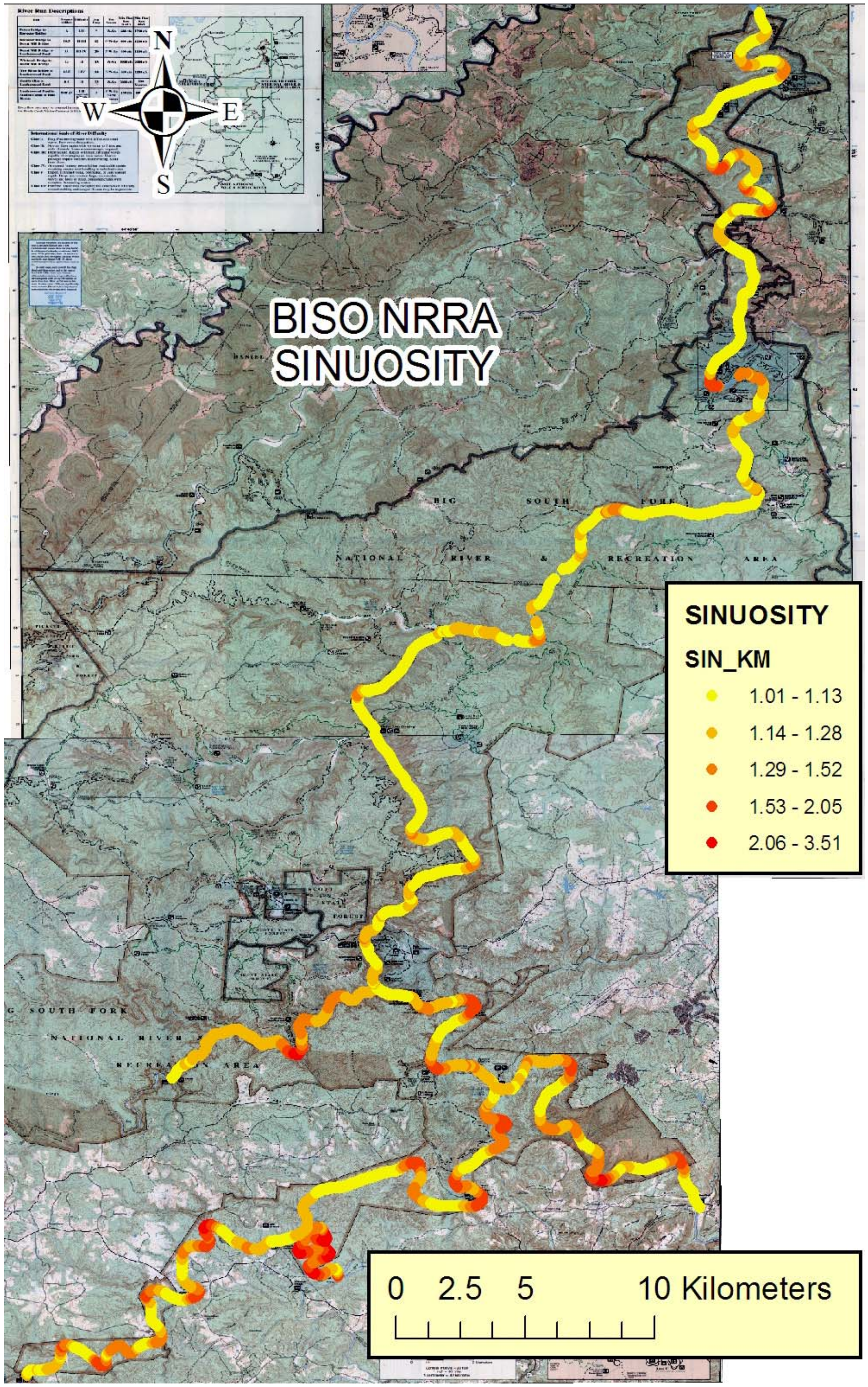

Figure 17: Stream scale sinuosity map of BISO NRRA

4.3 Video interpretation and analysis

The georeferenced video footage was reviewed in the lab to identify river characteristic, substrate, and embeddedness transitions. Multiple reviewers inventoried different sections of the river system because of the volume of data and years of data acquisition. A single reviewer for all video is preferable to minimize reviewer subjectivity of bedform interpretation.

4.3.1 River Characteristic:

Water surface bedforms were identified based on the following definitions (Armantrout, 1998) (Figure 18):

- Pool—no surface turbulence or definable thalweg, deeper than aquatic habitats immediately above and below it
- Run—little to no surface agitation, waves, or turbulence, no major flow obstructions, approximately uniform flow
- Riffle—small hydraulic jumps over rough bed material causing small ripples, waves, and eddies. Rapids and cascades were also included in this category, having very turbulent waters with exposed substrates dominated by large boulders and rocks.

A five second transitional buffer rule is applied during video interpretation because of the video speed and the diversity of physical bedforms. Bedform changes less than 5-second duration were not identified. Water surface characteristics vary seasonally based on river flow (Hilderbrand et al., 1999), and flow data for the mapping date is accessible on the USGS real-time water data website (USGS, 2007-2009). All reaches are mapped

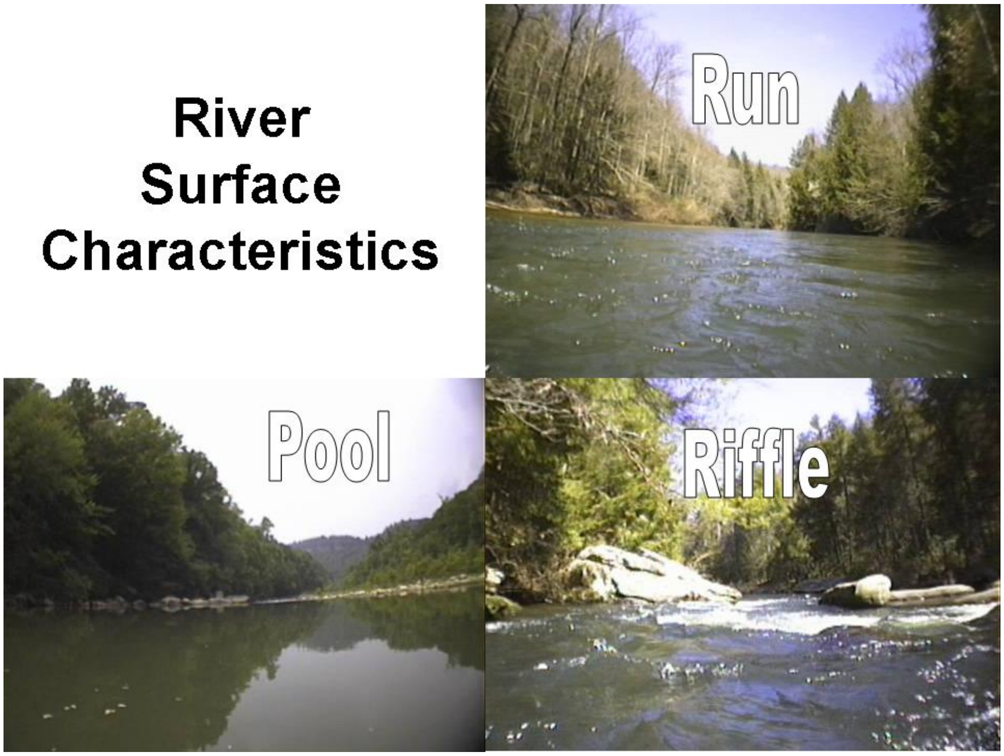

Figure 18: River characteristic frame captures

at mean annual base flow, with approximately 2.83-14.15 cubic meters per second (100-500 cfs) the ideal target mapping flow rate.

River characteristics are quantified by distance ratios for five rivers surveyed inside the BISO NRRA (Figure 19). Greater percentage of riffles indicates a higher gradient stream, while more pools indicate a lower gradient stream. The length of the pool river characteristic is another metric that may be relevant to aquatic habitat analysis. The pools of the BISO NRRA have been quantified and thematically mapped (Figure 20). The longest unbroken pools occur in the northernmost section of the Big South Fork River where it flows out of the park boundaries and into Lake Cumberland. However, as in the case of the Big South Fork and New River, much of the river can be low gradient,

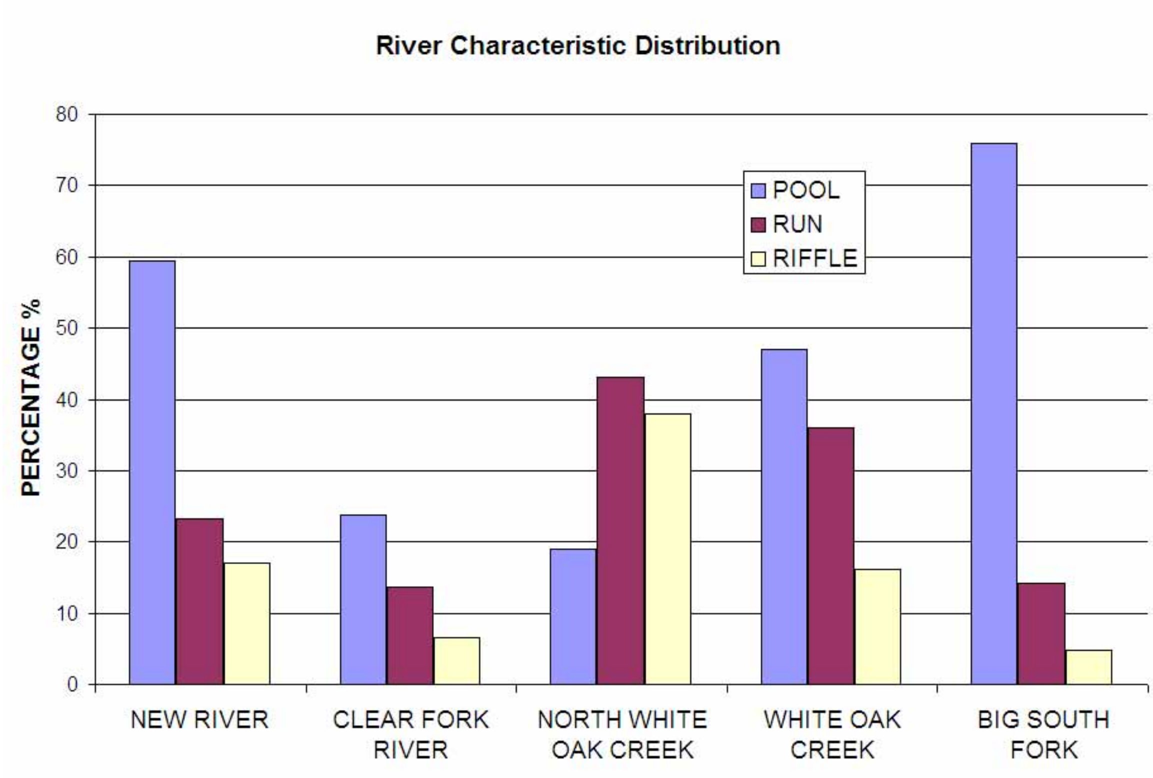

Figure 19: River characteristic distributions in BISO NRRA

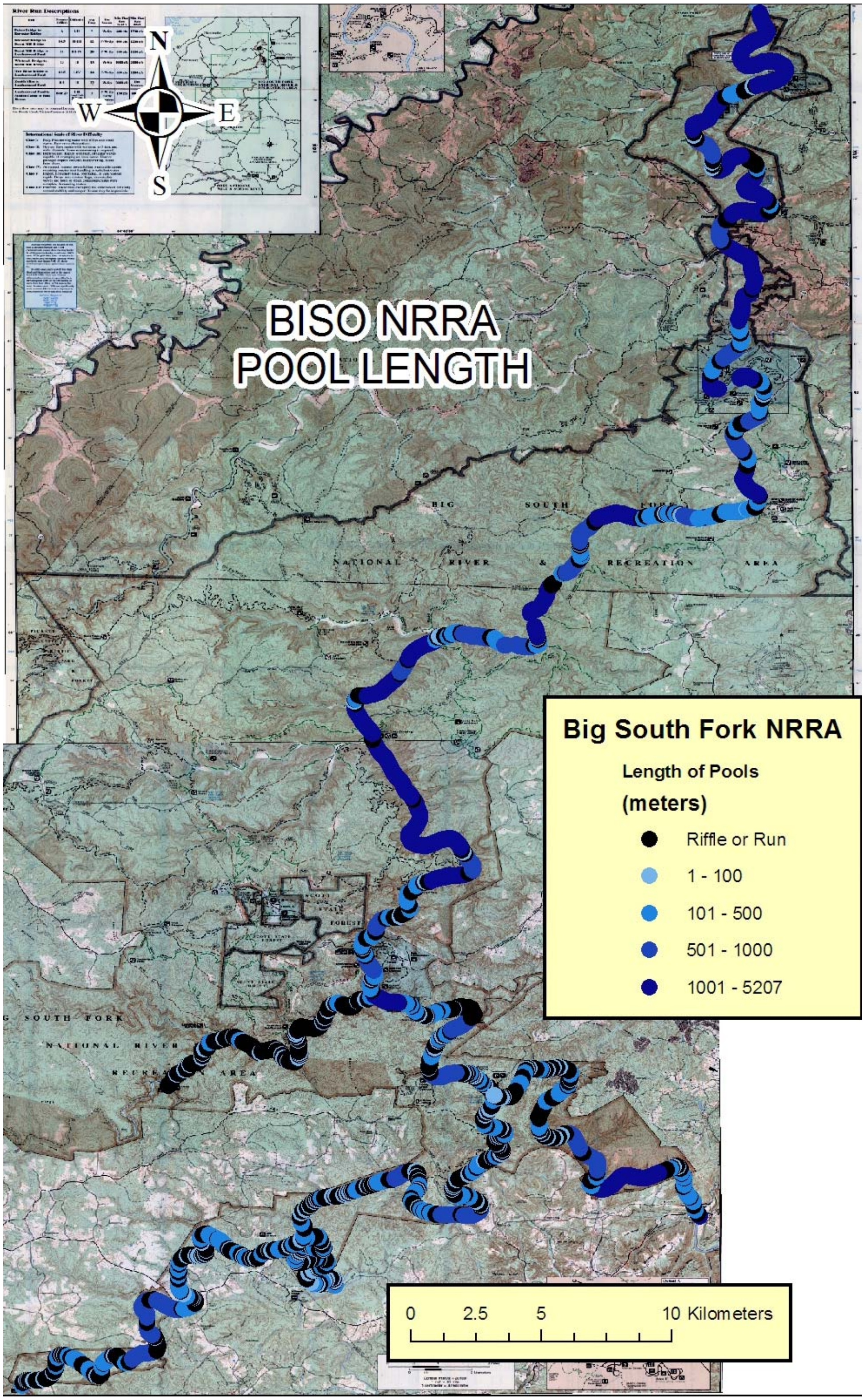

Figure 20: Pool length map of BISO NRRA

with a high gradient section that contains much of the overall elevation change in the stream.

River characteristic distributions are visible in Figure 21, a thematic map of pools, riffles, and runs of the BISO NRRA. River segments that are primarily pools indicate lower gradient and slower moving water, and segments with mostly riffles and runs indicate higher gradient and faster water velocity. Average gradients were calculated based on a 10-meter resolution Digital Elevation Model downloaded from the USDA NRCS Geospatial Data Gateway (USDA NRCS, 2009). Overall gradient change between the beginning and end points of the rivers inside the boundaries of the BISO NRRA is displayed in Table 2. Obviously, gradient changes dramatically throughout the course of a river and Table 2 only indicates overall elevation drop of the mapped sections of the BISO NRRA river system.

4.3.2 Substrate

Substrate was classified into seven categories of particle size using a modified Wentworth scale (Armantrout, 1998) (Table 3 and Figure 22).

In 2005, 25-acre landslide from a closed and reclaimed coal strip mine upstream of the New River caused extreme turbidity and sedimentation levels dangerous to aquatic habitat (Barker, 2005). Because of this landslide, and erosion from ATV trails and logging operations (Massey, 2008), low visibility from excessive turbidity in the New River prevented underwater video substrate and embeddedness characterization. Underwater habitat information for the New River was unavailable in this study. Substrate distributions were compared for the remaining four rivers surveyed (Figure 23).

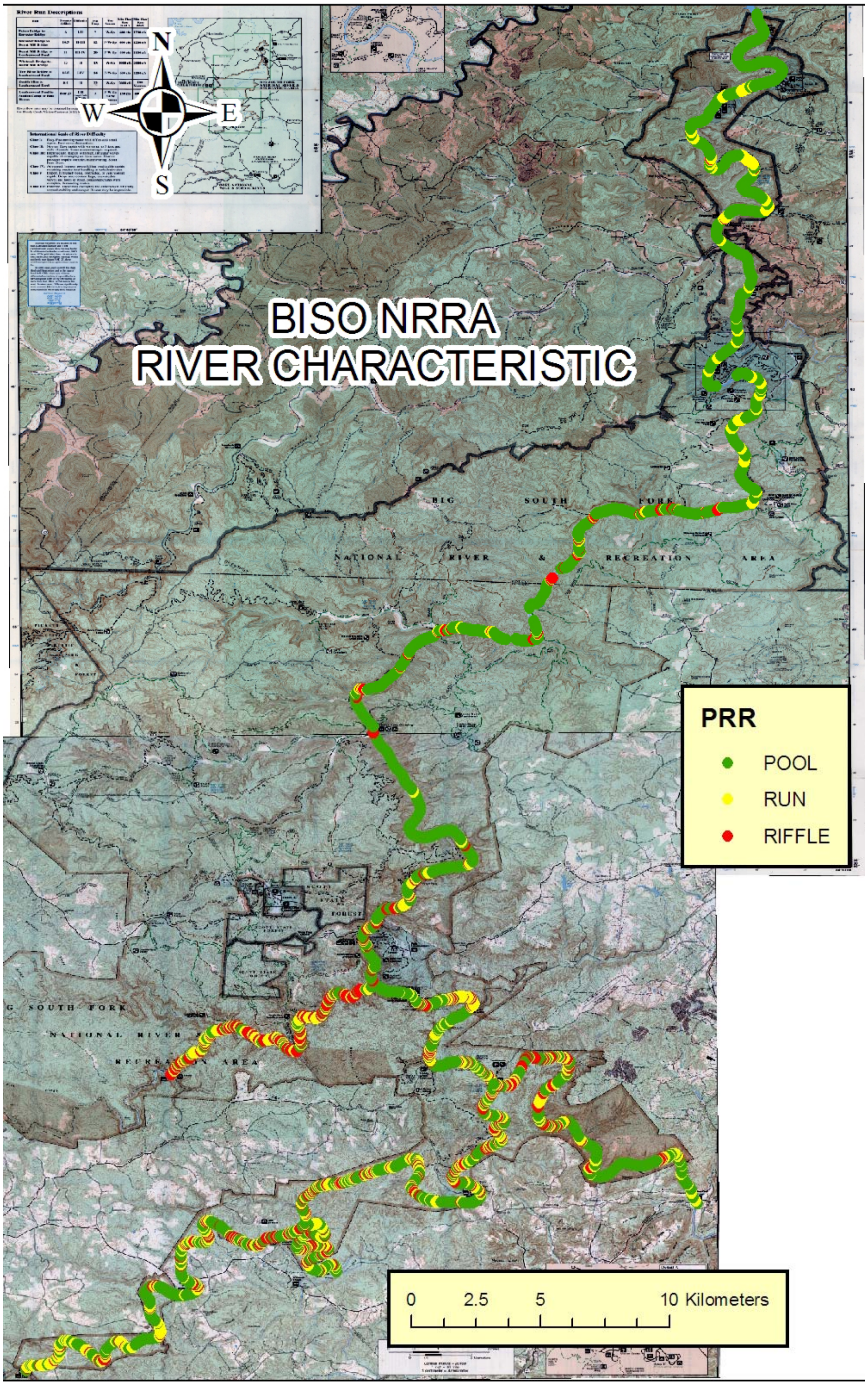

Figure 21: River characteristic map of BISO NRRA

Table 2: Average gradient of BISO NRRA Rivers

River	Start Elevation (meters)	End Elevation (meters)	Drop (meters)	Run Length (meters)	Average Gradient	Conventional Gradient (ft per mile)
Big South Fork Cumberland River	310	220	90	72903	0.12%	6.5
North White Oak Creek	324	275	49	9817	0.50%	26.4
White Oak Creek	371	355	16	4506	0.36%	18.7
Clear Fork River	382	310	73	32026	0.23%	12.0
New River	334	310	25	14323	0.17%	9.2

Table 3: Modified Wentworth scale for substrate classification

Substrate	Description
Bedrock	Unbroken Rock Surface
Fines/Sand	Particles < 0.25 cm (0.1 inch)
Small Gravel	Rocks 0.25—1.0 cm (0.1—0.4 inch)
Large Gravel	Rocks 1.0—10 cm (0.4—4 inch)
Cobble	Rocks 10—30 cm (4—12 inch)
Small Boulder	Rocks 30—60 cm (12—24 inch)
Large Boulder	Rocks > 60 cm (24 inch)

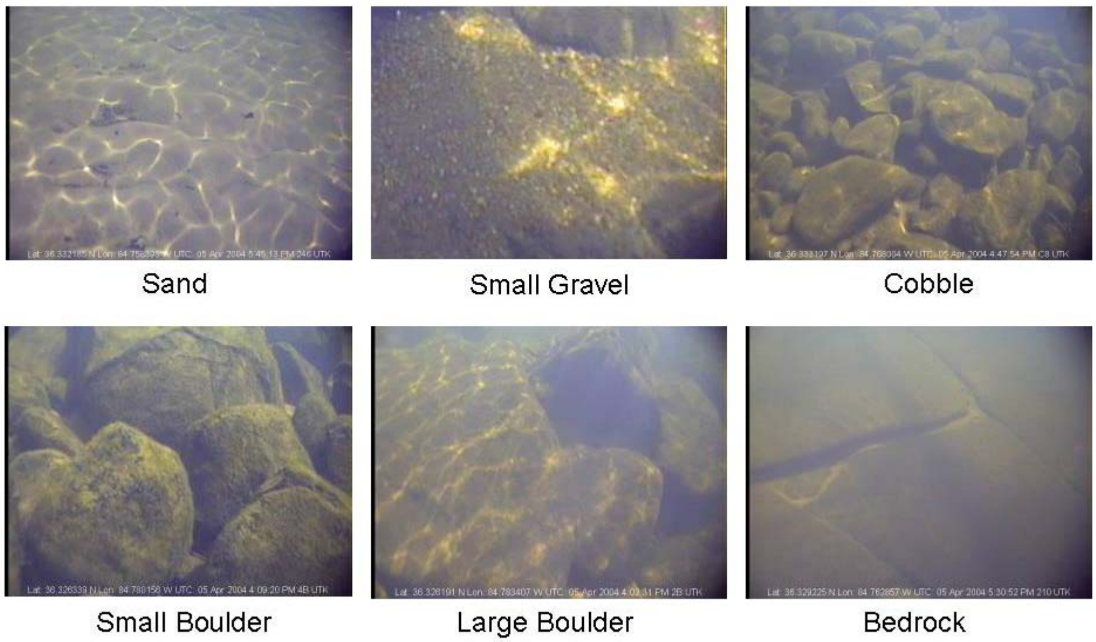

Figure 22: Substrate video frame capture examples

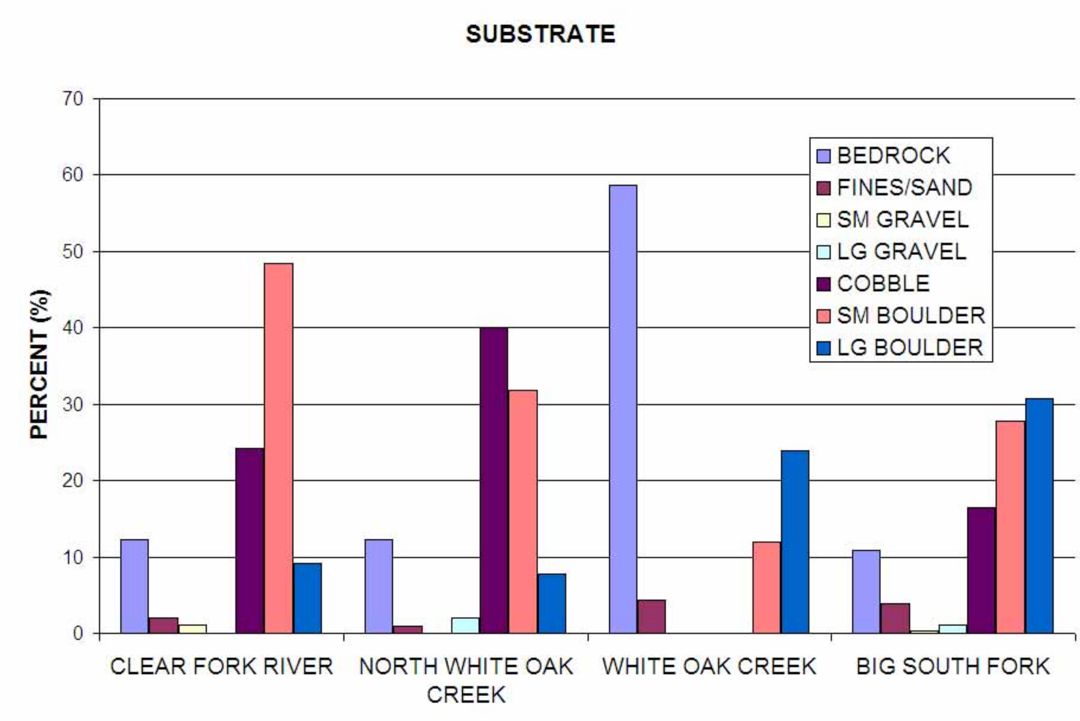

Figure 23: Substrate distribution for four BISO NRRA rivers

White Oak Creek has primarily bedrock substrate. North White Oak Creek and Clear Fork River have mostly small boulder and cobble substrate. The Big South Fork River has mainly small and large boulder substrate. However, these are the dominant substrate types by percent coverage of the thalweg video image. The video footage can be reviewed for heterogeneity to describe secondary substrate types, such as gravel or sand lying between boulders. In this study, dominant substrate types were identified based on a causative river mechanics relationship between substrate and other bedforms. There are trends in substrate particle distribution. Cobblestones are usually found in shallower water, and large boulders and fine particles are usually found in deep pools (Figure 24). Rodgers (2008) observed that large boulders are not interpreted in shallow water in UVMS data because the thalweg flows between large boulders if the water shallower than the diameter of a boulder.

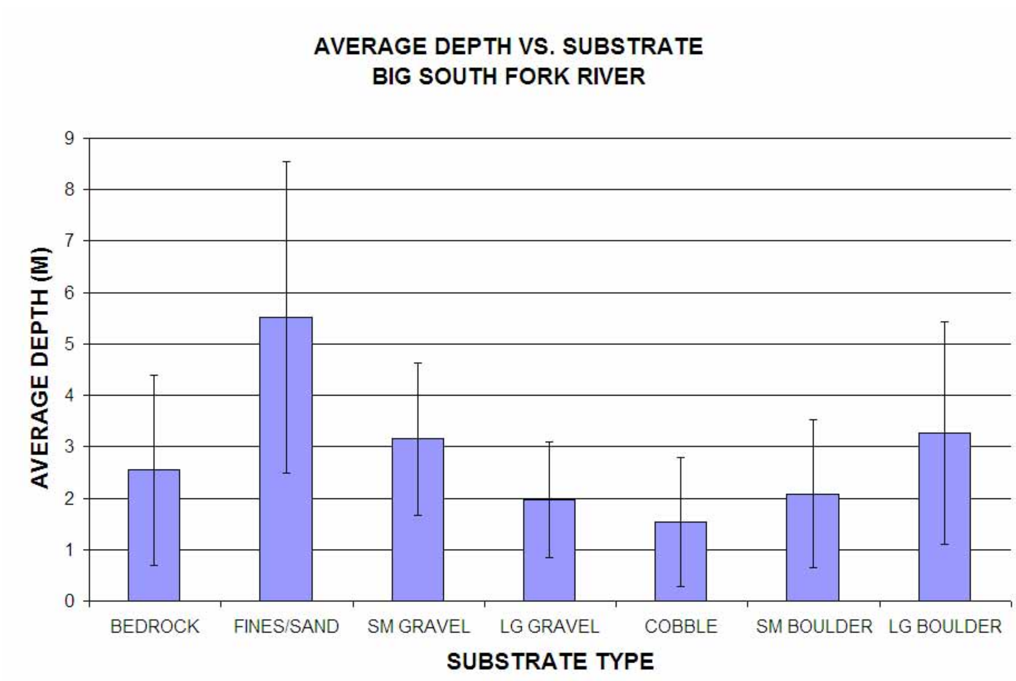

Figure 24: Average depth by substrate type in Big South Fork River

A novel comparison of river depth distribution is possible using the GPS river distance measurements and the sonar depth data. Sonar soundings are sorted by descending depth and plotted at five percent intervals of the total river length. The Big South Fork River has a maximum water depth of 15 meters (50 ft). The Big South Fork River is a 4th order stream and 50% of its running length within the BISO NRRA boundaries is greater than 2 meters (6.5 ft) deep. Clear Fork River and New River are 3rd order streams with maximum depth soundings around 6 meters (20 ft). North White Oak Creek and White Oak Creek are 2nd order streams. The maximum depth of North White Oak Creek is 5.5 meters (18 ft), and White Oak Creek is the shortest and shallowest with maximum depth less than 2 meters (6.5 ft). On the sonar depth distribution diagram, the descending depth versus river distance graphs stack and group in accordance with stream order rankings (Figure 25).

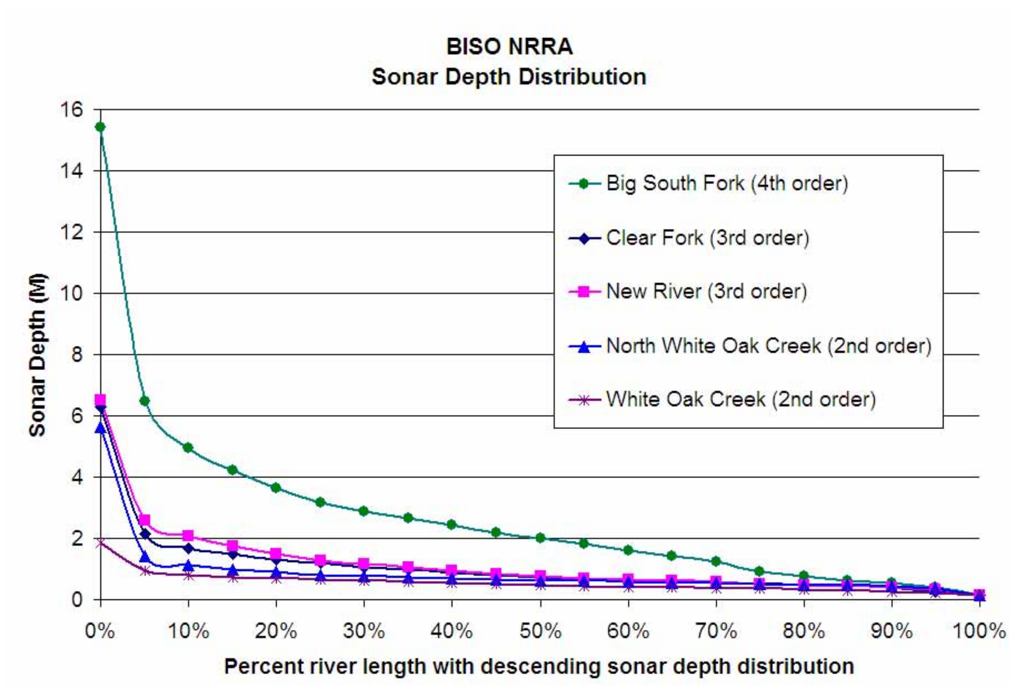

Figure 25: BISO rivers comparison, sonar depth distributions

The lighter color bands in Figure 26 indicate small substrate particle size, such as fines/sand and gravel. The dark bands indicate larger substrate particles, such as boulders. Black areas indicate an absence of substrate data, either because of a portage or high turbidity, as in the case of New River which has a high amount of suspended fine particles from erosion.

<u>4.3.3 Embeddedness</u>

Embeddedness is defined as the degree that substrate particles are surrounded or covered with fine sediment (Bain and Stevenson, 1999). In the event bedrock substrate, embeddedness is evaluated based on the severity of fine particulate accumulation on the surface and in the cracks of the bedrock. Embeddedness was categorized into four percentile ranges: 0-25%, 25-50%, 50-75%, and 75-100% in accordance with the Bain and Stevenson visual estimation method along the river thalweg (Bain and Stevenson, 1999) (Figure 27).

Embeddedness ratios are similarly compared for four BISO rivers. The high bars in the 0-25% embedded category indicate that the Clear Fork River, North White Oak Creek, and White Oak Creek are all clean rivers with low sedimentation. These three rivers flow from a protected watershed, highly forested with little development (NPS, 2008). The Big South Fork River has much higher sedimentation levels than the other three, 63% of the substrate is over 50% embedded (Figure 28). The BISO is a 4th order stream transitioning into Lake Cumberland, and is compared to 2nd and 3rd order streams, with a large amount of sediment flowing in from the New River. These are possible explanatory factors for increased sedimentation in the Big South Fork River.

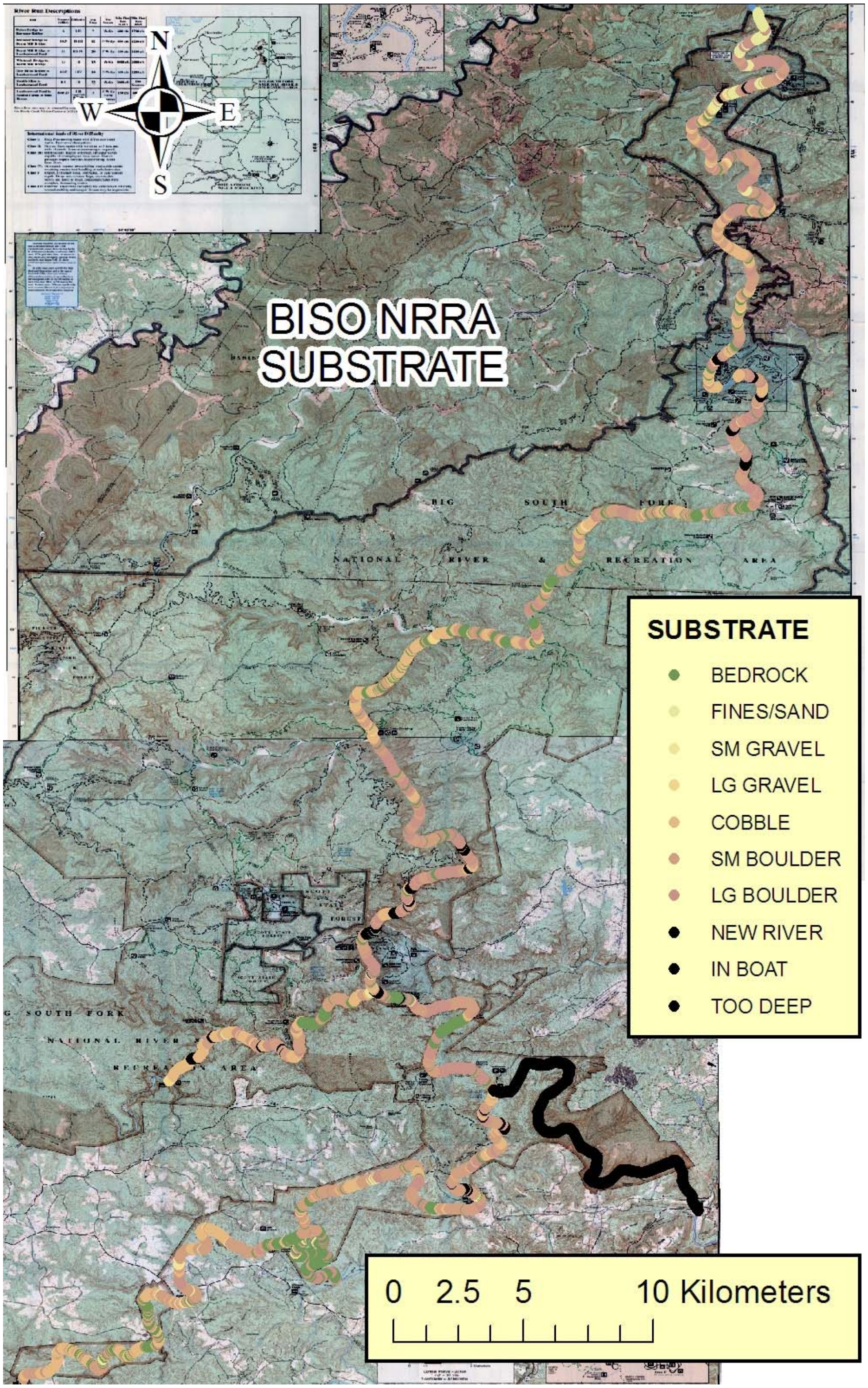

Figure 26: Substrate map of BISO NRRA

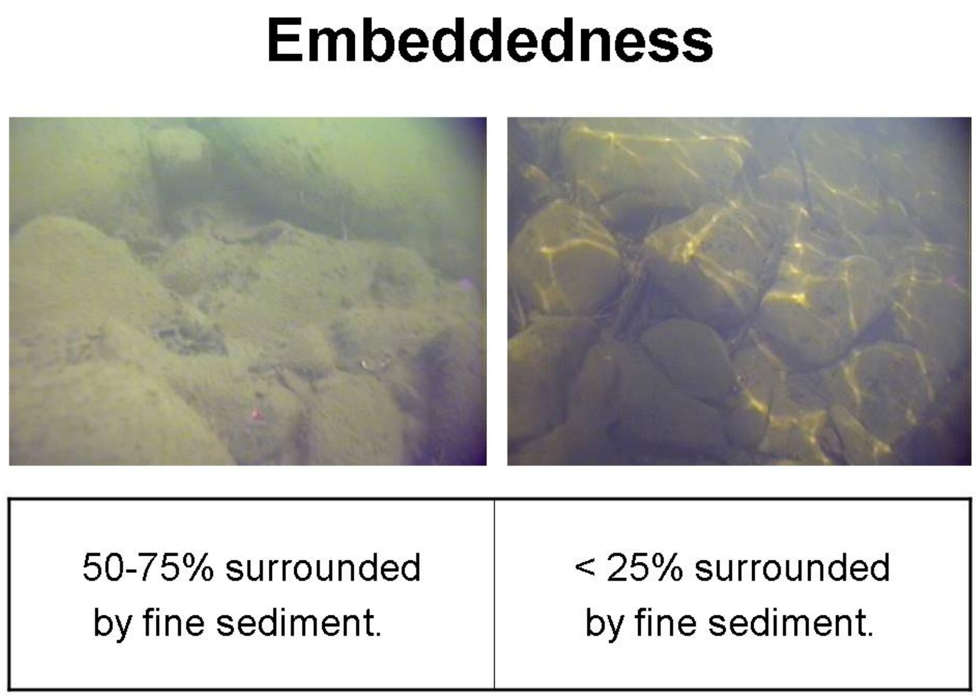

Figure 27: Embeddedness images percentage classification

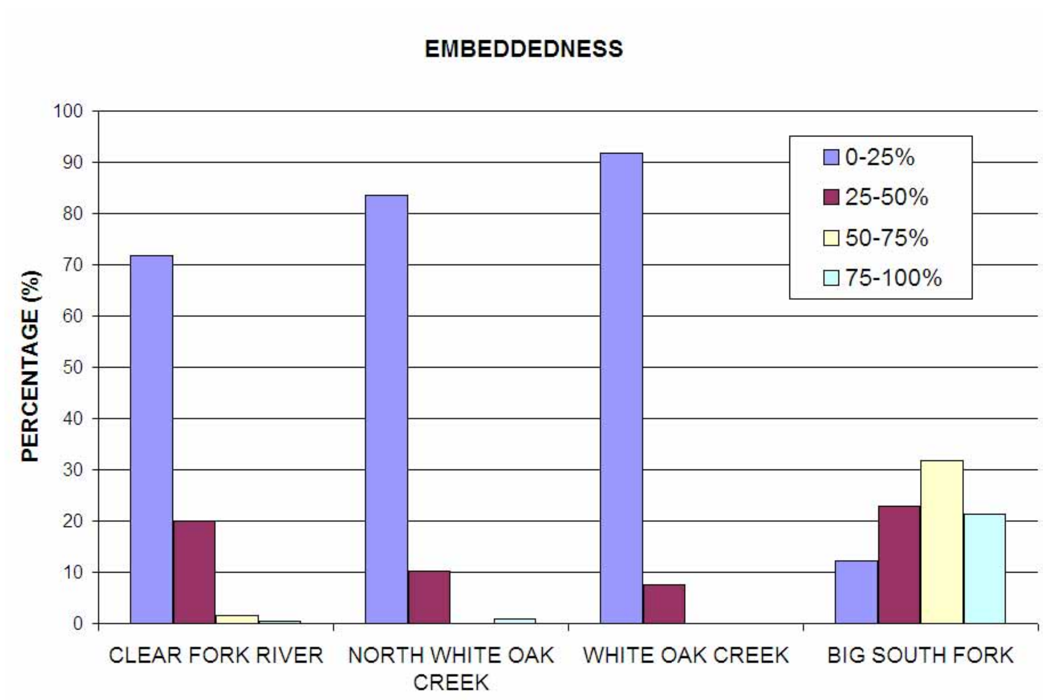

Figure 28: Embeddedness distribution for four BISO NRRA rivers

Embeddedness is a function of water velocity, among other factors. Sediment transport is high when water velocity is high, and sediment aggrades when channel width increases and water velocity decreases (Julien, 2002), such as when river characteristic transitions from riffle or run to pool. The accumulation of fine particles in the river system is accordingly describable by water depth, because the transition from riffle or run to pool corresponds with an increase in water depth. Embeddedness increase correlates with water depth in all rivers mapped in the BISO NRRA (Figure 29).

This same phenomenon is reflected by plotting river characteristic against embeddedness (Figure 30). The highest percentage of riffles corresponds with the 0-25% embeddedness category, and pools with the 50-100% embeddedness ranges. Higher water velocities carry fine sediment particles and deposit those particles when the flow slows down and dissipates into pools. The locations of pools, deep water, and high embeddedness levels correspond in UVMS thematic maps, such as in the Big South Fork River (Figure 31).

In Figure 32, light color bands indicate river segments with less than 50% embeddedness of substrate particles. Dark bands indicate river segments with substrate more than 50% embedded. Typically, sediment particles are swept through high gradient riffles and runs, and then deposited in slower flowing, deep pools.

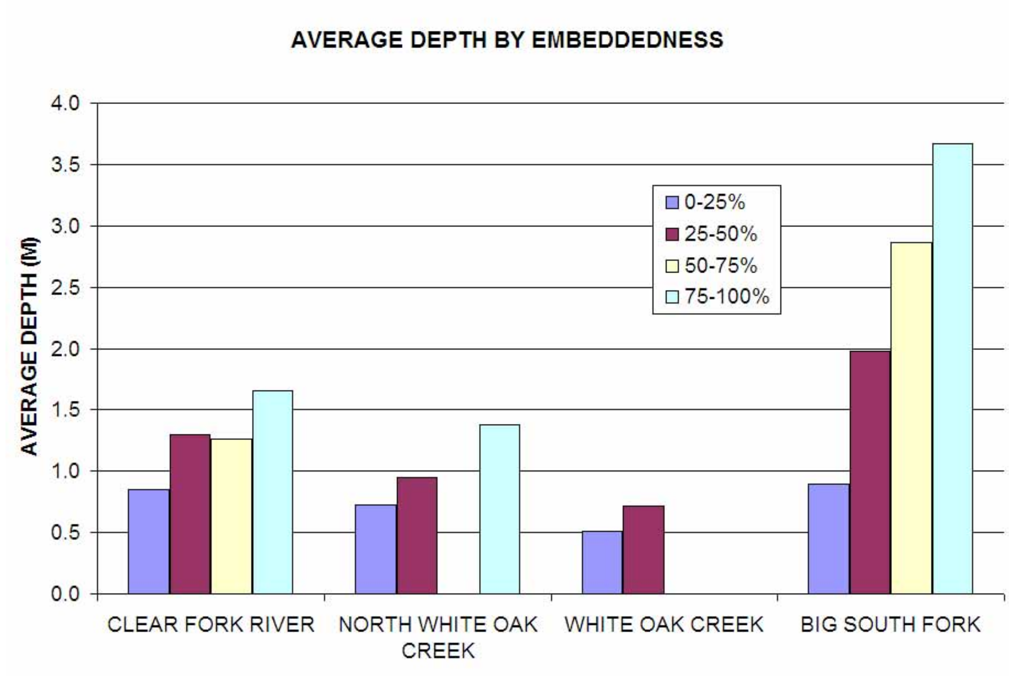

Figure 29: Average depth by embeddedness percentage

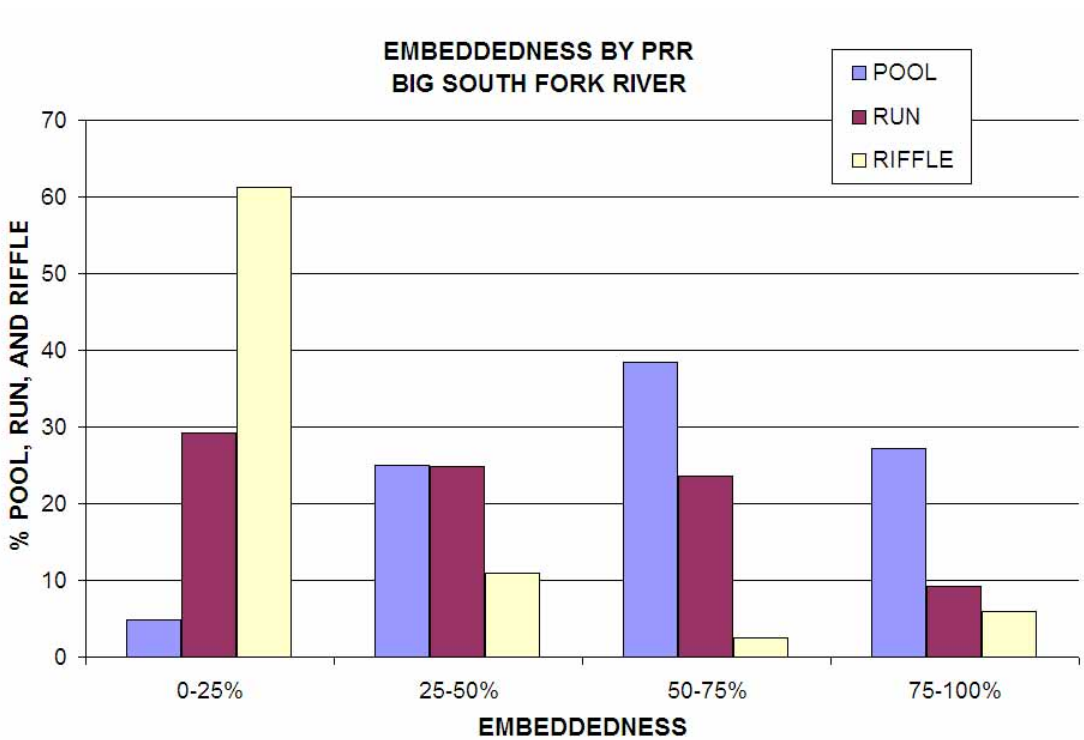

Figure 30: Embeddedness distribution vs. river characteristic

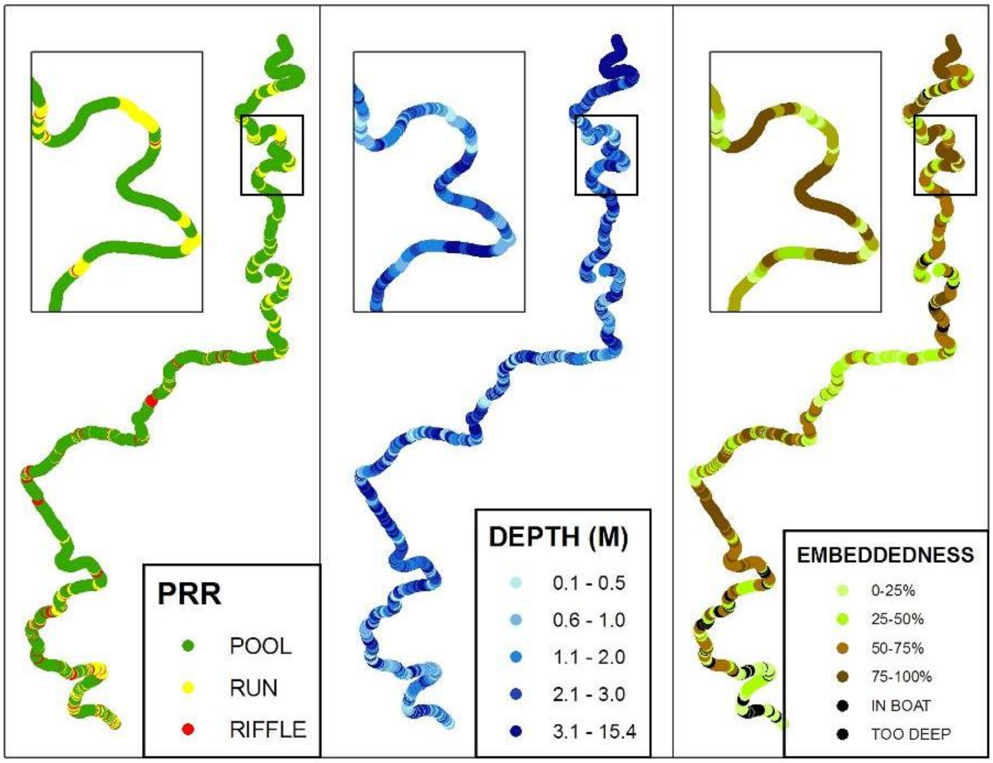

Figure 31: Big South Fork River characteristic, depth, and embeddedness

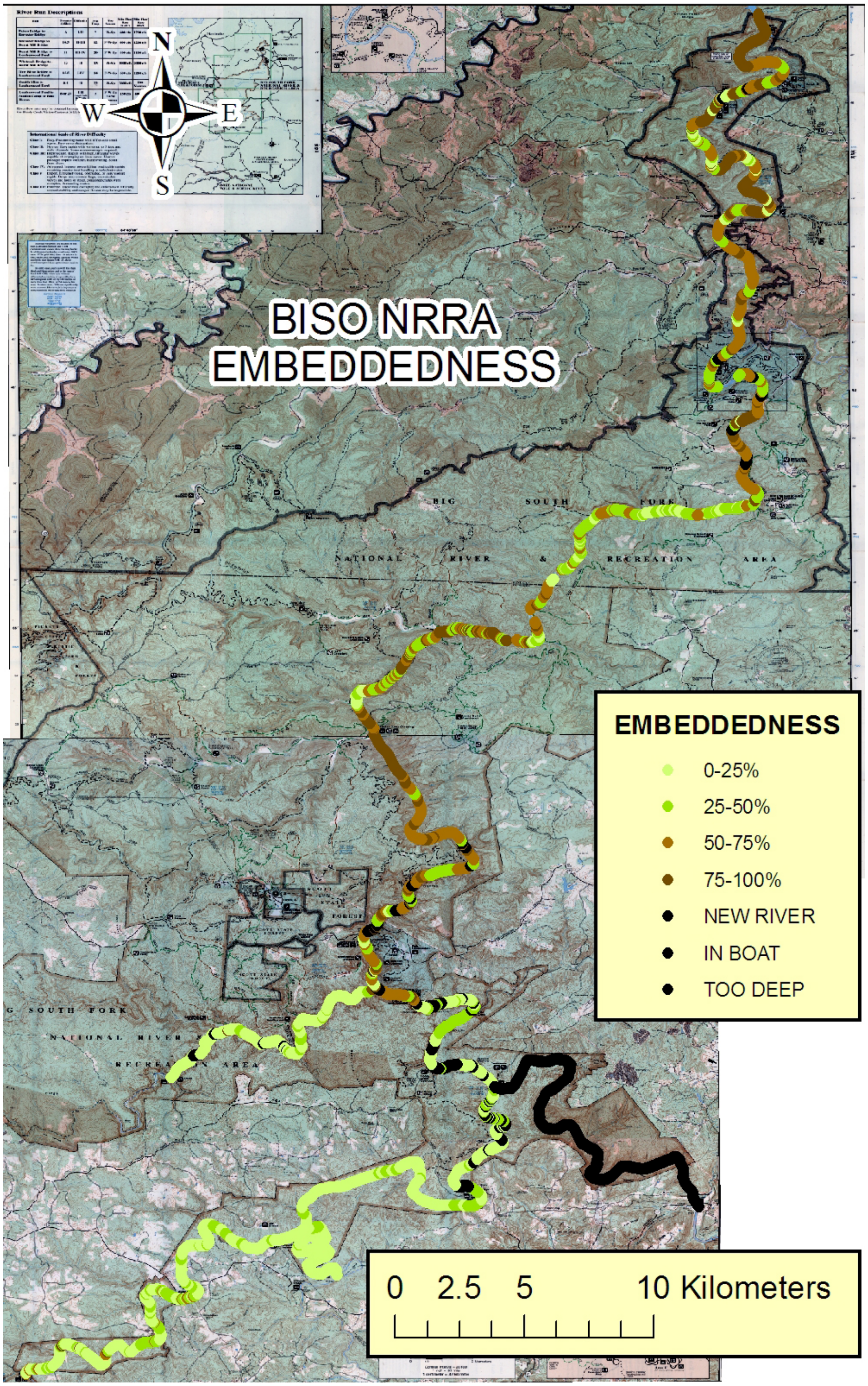

Figure 32: Embeddedness distribution of BISO NRRA

Chapter 5: Quantification of River Attributes

5.1 Qualitative Habitat Evaluation Index

The EPA Qualitative Habitat Evaluation Index (QHEI) is a checklist with many categories of physical criteria that can be obtained from underwater video mapping system (UVMS) data (Rankin, 1989). The QHEI assigns weighted values to each of 19 physical habitat features, and produces a single comparative value indicating biotic integrity, with the highest scoring river the healthiest (Table 4). Eight of the nineteen criteria that suit UVMS data were selected to create a UVMS QHEI on a 31 point scale. Substrate score is assigned based on the highest quantity occurrence in the segment evaluated. Another metric adds points based on the number of substrate types present. A point is added if a majority of substrate is less than 25% embedded, and points are subtracted when embeddedness levels exceed 50%. Increasing point values are added for higher sinuosity segments based on maximum reach or stream scale sinuosity values, for evaluation of reach and stream segments respectively. If pools are present, points are added based on the maximum depth of the pool. Higher points are added for deeper riffles, or runs if no riffles are present. Points are added for substrate stability in riffles, such as cobblestones or larger particles. Clean riffles with low embeddedness values add points, and highly embedded riffles subtract a point (Table 4).

Clear Fork, North White Oak Creek, White Oak Creek, and Big South Fork were evaluated using the UVMS QHEI. New River was omitted because of absence of substrate data. Two reaches of 100 consecutive data points and two stream segments of

Table 4: UVMS QHEI categories and point values (Reber et al., 2002)

Dominant Substrate	
LG Boulder	10
SM Boulder	9
Cobble	8
Gravel	7
Bedrock	5
Fines/Sand	4

Number of Types	
# Types > 4	2
# Types < 4	0

Embeddedness	
0—25%	1
25—75%	0
50—75%	-1
75—100%	-2

Sinuosity (Max)	
High (> 2.5)	4
Mod (1.5-2.5)	3
Low (< 1.5)	2
None (~1)	1

Pool Max Depth	
Depth > 1 m	6
0.7—1 m	4
0.4—0.7 m	2
Depth < 0.4 m	1
No Pool	0

Riffle/Run Depth	
> 0.1 m (Max > 0.5 m)	4
> 0.1 m (Max < 0.5 m)	3
0.05—0.1 m	1
< 0.05 No Riffle	0

Riffle/Run Substrate	
Stable (Cobble+)	2
Mod Stable (Gravel)	1
Unstable (Fines/Sand)	0
No Riffle/Run	0

Riffle/Run Embeddedness	
0—25%	2
25—75%	1
50—75%	0
75—100%	-1
No Riffle/Run	0

1000 consecutive data points were selected in each river using a random number generator (Haahr, 2009). The entire database for each river was also evaluated for UVMS QHEI metrics. Scores were typically high on the 31 point scale, with the lowest reach scores occurring in Big South Fork, mainly because of high embeddedness. UVMS QHEI scores were highest when the entire river length was assessed. The large differences between reach scale habitat quality scores and the whole river score support the Dolloff (1997) study that questioned the validity of representative reach habitat classification (Figure 33).

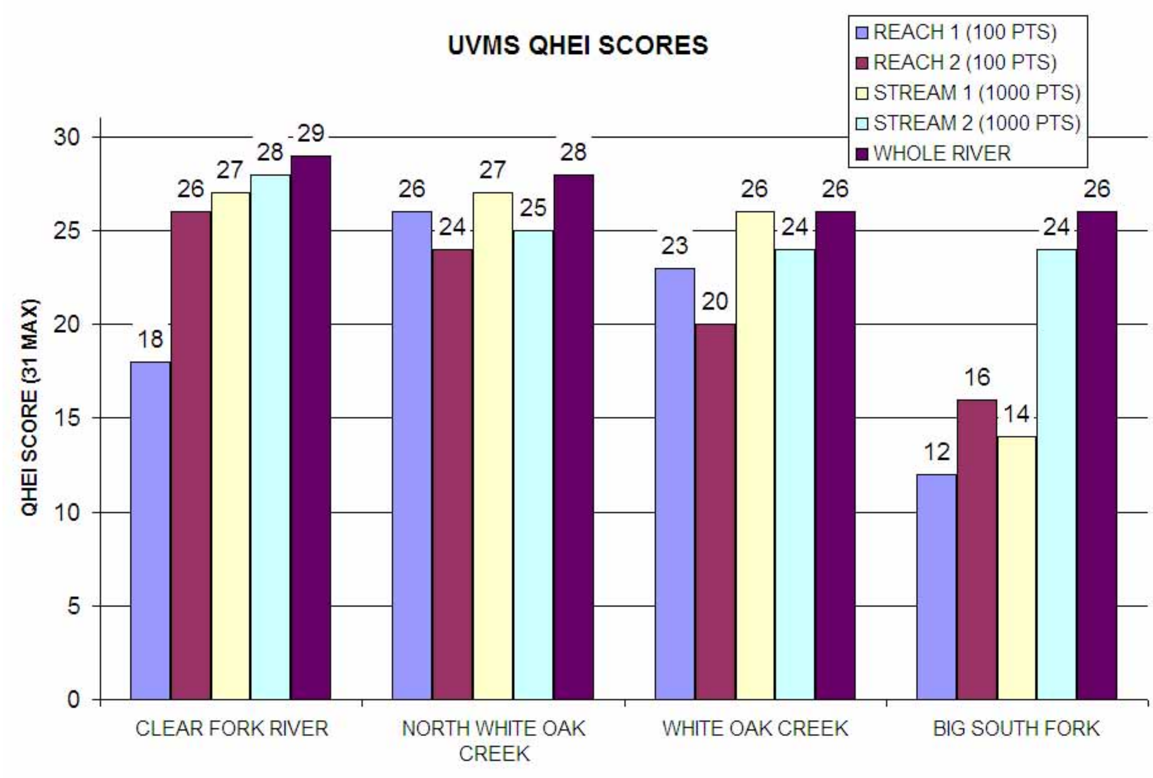

Figure 33: UVMS QHEI scores compared across 4 BISO rivers

5.2 UVMS Multivariate Regression Modeling

Underwater habitat characteristics are the most difficult to survey in the field using traditional methods. However, the movement of both large and small sedimentary particles are described by other physical features of a river system (Julien, 2002) that are observable above water. UVMS data could be a valuable tool for predictive modeling of species specific habitat location in a river system. Embeddedness was modeled using SAS software (SAS Instute Inc., 2008) to predict sediment distribution based on river characteristic and depth. River characteristic was divided into ordinal categories of 1, 2, and 3, respectively, based on ascending surface turbulence, and modeled as continuous variables. Linear regression equation 4 was produced using SAS for predicting severity of embeddedness:

$$Embeddedness = 2.43 + 0.25(Depth) - 0.50(RiverCharacteristic) \qquad \textbf{(4)}$$

Embeddedness = percentile categories 0-25%, 25-50%, 50-75%, and 75-100%, modeled as 1, 2, 3, and 4, respectively

River Characteristic = pool, riffle, and run modeled as 1, 2, and 3, respectively

Depth = water depth in meters

A linear-quadratic model was also produced to test non-linear relationship between embeddedness categories. The following polynomial model was used for linear-quadratic regression (equation 5).

$$\begin{aligned} Embeddedness &= 2.39 + 0.62(Depth) - 0.033(Depth^2) - 0.97(RiverCharacteristic) \\ &+ 0.17(RiverCharacteristic^2) - 0.09(Depth * RiverCharacteristic) \end{aligned} \qquad \textbf{(5)}$$

River Characteristic = pool, riffle, and run modeled as 1, 2, and 3, respectively

Depth = water depth in meters

Mixed model analysis of variance tested differences in embeddedness categories, and least squares means were compared using least significant difference mean separation (Table 5).

Each category of embeddedness was significantly different at $P < 0.05$. The UVMS data is normally distributed with the Kolmogorov-Smirnov fit statistic $D = 0.083$ and $P < 0.01$. The R-squared value of the equation was 0.39, so this linear model only predicts 39% of the variation of embeddedness distribution across the four rivers mapped in the Big South Fork NRRA. A Pearson correlation analysis tested linear correlation between dependent variable embeddedness and independent UVMS variables depth,

Table 5: Embeddedness categories ANOVA and LSD mean separation

Embeddedness Level	Estimate	Error	Group
0-25%	0.89	0.017	D
25-50%	1.98	0.013	C
50-75%	2.87	0.011	B
75-100%	3.67	0.013	A

river characteristic, rugosity, sinuosity, and substrate. Only variables that explained more than 10% of the linear variation in embeddedness were included in the model (Table 6).

Best-fit coefficients and exponents were determined using SAS non-linear model procedure "proc nlin" to minimize sum of squares error (SAS Instute Inc., 2008). Equation 5 summed the river characteristic and depth parameters, and equation 6 multiplied the parameters:

$$Embeddedness = 0.66(RiverCharacteristic^{-2.28}) + 1.50(Depth^{0.35}) \qquad \textbf{(6)}$$

$$Embeddedness = 2.15(RiverCharacteristic^{-0.39})(Depth^{0.27}) \qquad \textbf{(7)}$$

River Characteristic = pool, riffle, and run modeled as 1, 2, and 3, respectively

Depth = water depth in meters

R-squared values are 0.32 for equation 6 and 0.33 for equation 7. These values are only slightly better than random guessing, which has an R-squared value of 0.25. River characteristic and embeddedness are ordinal categorical variables modeled as

Table 6: Embeddedness Predictor Correlation Coefficients

UVMS Independent Variable	Pearson Correlation Coefficient	Embeddedness Linear Variation Explained
Depth	0.34	11.85%
River Characteristic	-0.43	18.54%
Rugosity	-0.17	2.75%
Sinuosity	-0.04	0.13%
Substrate Size	0.12	1.41%

continuous variables. The continuous model output was adjusted by assigning output value ranges to ordinal embeddedness categories. Output values less than 1.5 were assigned to the 0-25% embeddedness category. Values greater than 1.5 and less than 2.5 were assigned to the 25-50% category. Values greater than 2.5 and less than 3.5 were assigned to the 50-75% category. And values greater than 3.5 were assigned to the 75-100% category.

Embeddedness percentiles were explored as non-linear ordinal categories and modeled using SAS linear regression. The model explained less embeddedness variation when embeddedness was a non-linear input and R-squared decreased to 0.28.

All models underestimated the 0-25% and 75-100% embeddedness levels, and overestimated the 25-50% and 50-75% embeddedness levels. Embeddedness models were evaluated for accuracy by subtracting the predicted value from the actual embeddedness value. The models' predictions were correct with approximately 34% accuracy, as compared to 25% accuracy from random guessing.

Embeddedness levels were modeled for the Big South Fork of the Cumberland River from the head at the confluence of Clear Fork River and New River, to the Northern park boundary by Big Creek. The linear regression model explained 28% of the variation in embeddedness levels with an R-squared value of 0.28, and the quadratic model had and R-squared value of 0.30.

The predictive value of these equations is low for several reasons. Water velocity is a key parameter that influences the accumulation and distribution of fine sediment particles. Pools, runs, and riffles are the most descriptive UVMS metric of water velocity, but the classification of the river characteristic categories is ordinal rather than continuous. Water velocity is a combination of discharge, bankfull channel width, channelization, and gradient (Julien, 2002). A model based on UVMS data created from continuous parameters such as gradient and channel width, along with sonar depth, and compared to field measured embeddedness ranking would provide better predictive accuracy.

<u>5.3 Substrate prediction based on rugosity and sonar depth</u>

Rugosity can be used as a predictor of large boulder substrate location in a river system. Since large boulder influences rugosity values and are mapped in water deeper than the boulder diameter, a habitat query of the Big South Fork River was examined for above average rugosity (rugosity > 1.06) and deeper than average water depth (depth > 3 meters). The substrate type that fit these search criteria was 67% large boulder as compared to 31% randomly occurring large boulder substrate distribution (Figure 34 and Figure 35).

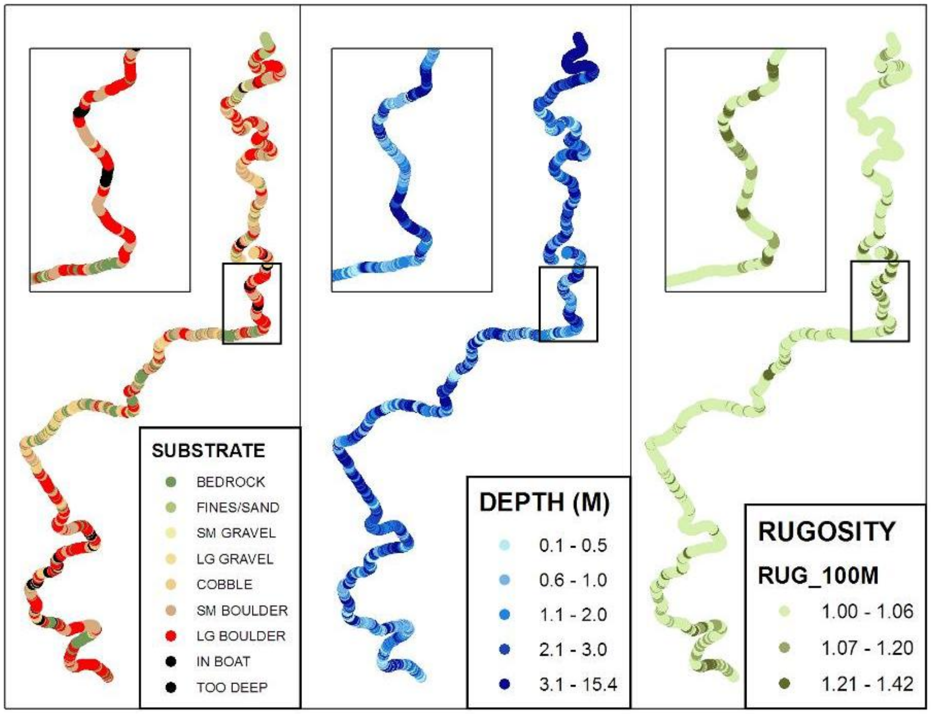

Figure 34: Large boulder substrate compared to sonar depth and rugosity

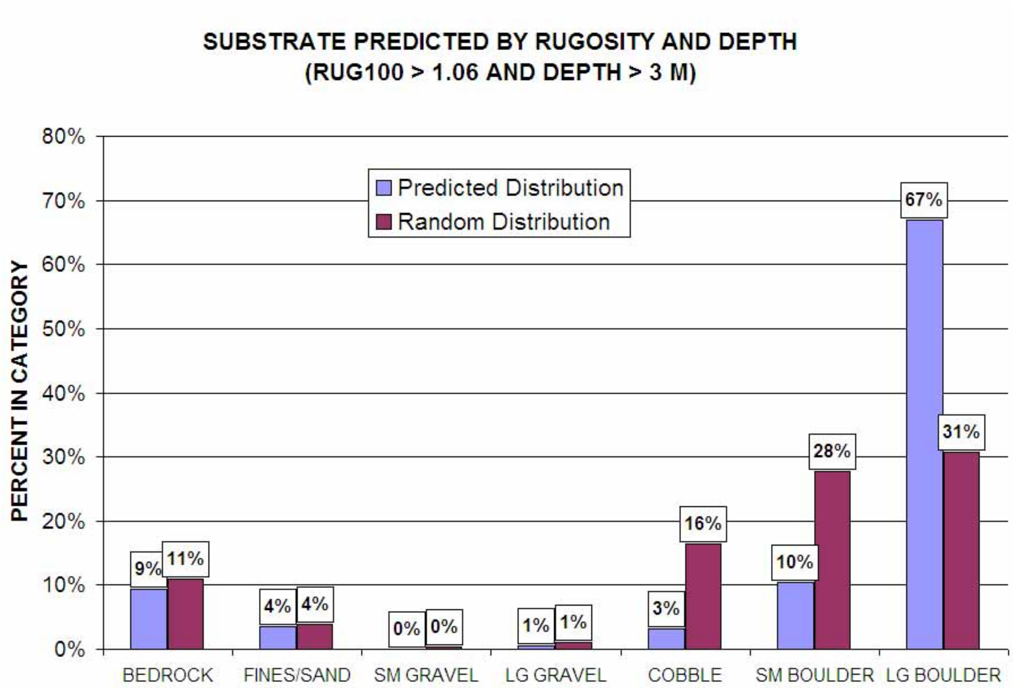

Figure 35: Large boulder substrate location predicted by sonar depth and rugosity

Chapter 6: Conclusions

The entire navigable watercourse of the Big South Fork National River and Recreation Area (BISO NRRA) was mapped using an underwater video mapping system (UVMS). Sonar data and georeferenced video was collected along the river thalweg, the deepest continuous line along the watercourse. The underwater video mapping system (UVMS) database contains mesoscale habitat data including GPS coordinates, water depth, river characteristics, dominant substrate type, embeddedness, sinuosity, and rugosity.

The EPA Qualitative Habitat Evaluation Index (QHEI) was modified to accommodate UVMS data. The Big South Fork River, Clear Fork River, North White Oak Creek, and White Oak Creek were evaluated and scored on the QHEI scale. Four randomly selected segments, two reach scale and two stream scale, were QHEI tested, and the scores were compared to a total river length QHEI score for accuracy. The overall QHEI health of the four rivers was very good, based on selected EPA physical indicators of river health. The modified QHEI scores ranged from 26 to 29 out of an ideal 31 points. The lowest scores came from random representative reach evaluation, indicating that representative reach habitat evaluation was not indicative of overall river habitat health in this study.

Linear, quadratic, and non-linear models were creating using SAS software (SAS Instute Inc., 2008) to predict embeddedness based on river characteristics and sonar depth. The model results were marginally better than random embeddedness estimation. The linear model fit the embeddedness data with an R-squared value of 0.39, the quadratic model had an R-squared value of 0.42, and the two non-linear models had R-squared values of 0.32 and 0.33.

The distribution of bedform data has been shown to follow trends, and can be used to predict locations of unknown parameters in the field. The sonar transducer lacked the signal frequency to discriminate small substrate particles, but the rugosity calculations indicated the location of large boulder substrate with 67% accuracy as compared to a 31% natural large boulder distribution.

UVMS data were thematically mapped for visual interpretation of habitat locations and bedform trends. In the Clear Fork River thematic map (Figure 36), the darker bands indicating high embeddedness correspond to the pool areas on the river characteristic chart, as well as the deep sections of the sonar depth chart. This embeddedness distribution is intuitively correct because the fine particles settle out as the water energy dissipates into the deep pool regions.

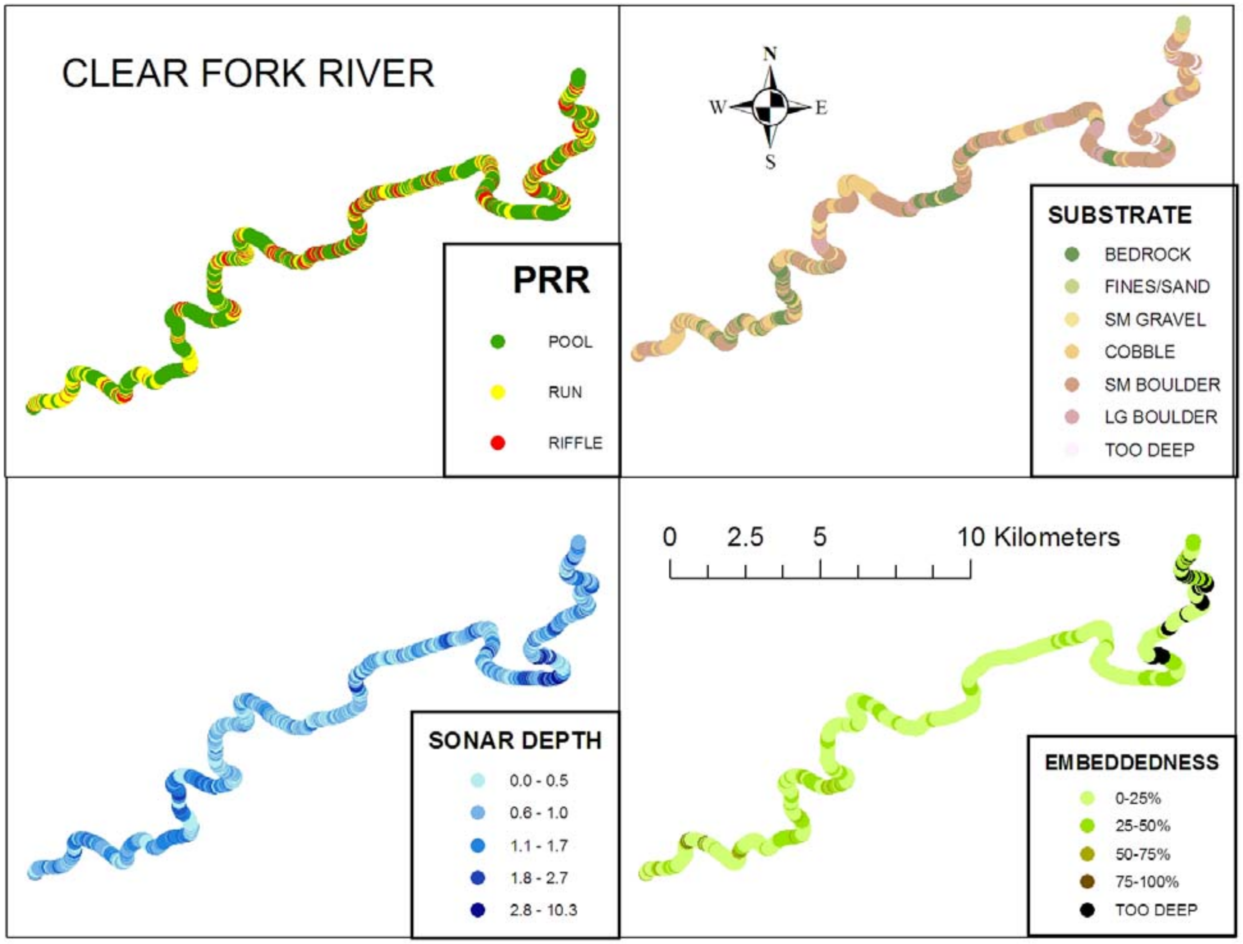

Figure 36: River characteristic, substrate, depth, and embeddedness

Chapter 7: Recommendations

The underwater mapping system (UVMS) is a novel and efficient method of gathering bedform data. UVMS is useful for conducting aquatic habitat suitability surveys. UVMS data has been queried for endangered mussels and minnow habitat preferences in the Big South Fork NRRA and the Obed Wild and Scenic River systems. Physical bedform features required for proliferation of aquatic biota are supplied by biologists, and the UVMS recorded bedforms are searched for corresponding habitat information and location. UVMS data is ideally suited to be used with species specific biological preferences to generate georeferenced habitat maps for endangered or invasive species. Sonar rugosity and GPS based sinuosity are calculated without observer subjectivity. UVMS data is getting closer to representing the complex variability of riverine ecosystems as new sensors are added to the UVMS platform.

Commercially available sonar rangefinders with NMEA output will record stream width. An acoustic Doppler current profiler (ADCP) or an electromagnetic fluid velocity sensor could differentiate water velocity profiles from the GPS velocity of the kayak or canoe (Teledyne RD Instruments, 2009). A LIDAR scan or a one meter resolution DEM raster could supply elevations for gradient data. UVMS mapping technique has been changed to include transects every 50 meters as used on the Driftwood River in Indiana in September 2009. UVMS gains the ability to describe how bedforms change perpendicular to flow, as well as create a three dimensional (3-D) sonar model of channelization, by including regularly spaced transects at the expense of time in the field.

UVMS can statistically compare river bedform changes in a temporal frame of reference by creating a reference condition database for river system impact from management decisions, such as watershed development or the construction of a dam.

List of References

An, K.-G. and S.-S. Choi 2003. An assessment of aquatic ecosystem health in a temperate watershed using the Index of Biological Integrity. *Journal of Environmental Science and Health* A38(6): 1115-1130.

Armantrout, N. B. 1998. Glossary of aquatic habitat inventory terminology. Bethesda, MD: American Fisheries Society.

AWSC (American Whitewater Safety Committee). 1998. International Scale of River Difficulty. www.americanwhitewater.org. Accessed 2009.

Bain, M. B. and N. J. Stevenson, Eds. 1999. Aquatic habitat assessment: common methods. Bethesda, MD: American Fisheries Society.

Bakaletz, S. 1991. Mussel survey of the Big South Fork National River and Recreation Area. Thesis. Cookeville, TN: Tennessee Technological University, Department of Biology.

Barbour, M. T., J. Gerritsen, B.D. Snyder, and J.B. Stribling 1999. Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish, Second Edition. EPA 841-B-99-002. U.S. Environmental Protection Agency. Office of Water. Washington, D.C.

Barker, S. 2005. Slippery slope: Landslide at steep reclaimed strip-mine site brings reclamation problems into forefront. Knoxville News Sentinel. http://www.knoxnews.com/news/2005/mar/09/slippery-slope/. Accessed November 11, 2009.

Bridge, J. S., N. D. Smith, F. Trent, S. L. Gabel, and P. Bernstein 1986. Sedimentology and morphology of a low sinuosity river. *Sedimentology* 33: 851-870.

Brock, J. C., C. W. Wright, T. D. Clayton, and A. Nayegandhi 2004. LIDAR optical rugosity of coral reefs in Biscayne National Park, Florida. *Coral Reefs* 23: 48-59.

Bryce, S. A., D. P. Larsen, R. M. Hughes, and P. R. Kaufmann 1999. Assessing relative risks to aquatic ecosystems: a mid-Appalachian case study. *Journal of the American Water Resources Association* 35(1): 23-36.

Dolloff, C. A., D. G. Hankin, and G. H. Reeves Southeastern Forest Experimental Station. 1993. Basinwide estimation of habitat and fish populations in streams. General Technical Report SE-83. U. S. Dept. of Agriculture. Forest Service. Southeastern Forest Experimental Station. Asheville, NC.

Dolloff, C. A., H. E. Jennings, and M. D. Owen 1997. A comparison of basinwide and representative reach habitat survey techniques in three southern appalachian watersheds. *North American Journal of Fisheries Management* 17: 339-347.

EPA (United States Environmental Protection Agency). 2008. Environmental Monitoring and Assessment Program. http://www.epa.gov/emap/index.html. Accessed 11 June 2009.

FAA (Federal Aviation Administration). 2007. Global navigation satellite systems. http://www.faa.gov. Accessed 6 March 2009.

Fiscor, A. J. 2005. Mussel habitat mapping in the Big South Fork National River and Recreation Area (BISO). MS Thesis. Knoxville, TN: The University of Tennessee, Department of Biosystems Engineering.

Flug, M., H. Seitz, and J. Scott 1998. Measurement of stream channel habitat using sonar. *Regul. Rivers: Res. Mgmt.* 14: 511-517.

Frappier, B. and R. T. Eckert 2007. A new index of habitat alteration and a comparison of approaches to predict stream habitat conditions. *Freshwater Biology* 52: 2009-2020.
Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley 1986. A hierarchical framework for stream habitat classification: Viewing streams in a watershed context. *Environmental Management* 10(2): 199-214.
GSA (Geological Society of America). 2009. The Geological Society of America Bulletin. http://www.geosociety.org/. Accessed October 19, 2009.
Haahr, M. 2009. Random.org true random number service. www.random.org. Accessed November 15, 2009.
Hilderbrand, R. H., A. D. Lemly, and C. A. Dolloff 1999. Habitat sequencing and the importance of discharge in inferences. *North American Journal of Fisheries Management* 19(1): 198-202.
Julien, P. Y. 2002. River Mechanics. New York: Cambridge University Press.
Kaufmann, P. R., P. Levine, E. G. Robison, C. Seeliger, and D. V. Peck. 1999. *Quantifying Physical Habitat in Wadeable Streams*. EPA/620/R-99/003. U.S. Environmental Protection Agency. Washington, D.C.
Kerans, B. L. and J. L. Karr 1994. A benthic index of biotic integrity (B-IBI) for rivers of the Tennessee Valley *Ecological Applications* 4(4): 768-785.
Kuffner, I. B., J. C. Brock, R. Grober-Dunsmore, V. E. Bonito, T. D. Hickey, and C. W. Wright 2007. Relationships between reef fish communities and remotely sensed rugosity measurements in Biscayne National Park, Florida, USA. *Environ Biol Fish* 78: 71-82.
Marcus, W. A., C. J. Legleiter, R. J. Aspinall, J. W. Boardman, and R. L. Crabtree 2003. High spatial resolution hyperspectral mapping of in-stream habitats, depths, and woody debris in mountain streams. *Geomorphology* 55: 363–380.
Massey, M. P. 2008. Use of the AnnAGNPS pollutant loading model for prediction of sediment yields in a mountainous Cumberland Plateau region: correlations with the stream bed sediment characteristics. MS Thesis. Knoxville, TN: The University of Tennessee, Department of Environmental Engineering.
Newson, M. D. and C. L. Newson 2000. Geomorphology, ecology and river channel habitat: mesoscale approaches to basin-scale challenges. *Progress in Physical Geography* 24(2): 195-217.
NGS (National Geographic Society). 2007. Big South Fork National Recreation Area Trail Map # 241. Evergreen, CO: National Geographic Maps.
NMEA (National Marine Electronics Association). 1995. NMEA 0183 Standard for Interfacing Marine Electronic Devices. Version 2.1: 22-23, 28, 34-35
NOAA (National Oceanic and Atmospheric Administration). 2007. National Weather Service Enhanced Radar Images. http://radar.weather.gov/. Accessed October 22, 2009.
NOAA (National Oceanic and Atmospheric Administration). 2009. NGS FAQs. http://www.ngs.noaa.gov/faq.shtml#WGS84. Accessed November 9, 2009.
NPS (National Park Service). 2008. Big South Fork National River and Recreation Area. http://www.nps.gov/biso. Accessed 6 January 2009.

Rankin, E. T. 1989. The Qualitative Habitat Evaluation Index (QHEI): Rationale, Methods, and Application. Columbus, OH: Environmental Protection Agency. 6 November.

Reber, J. M., M. Guebert, E. R. Squiers, R. Reber, and J. Sweeten 2002. Land Use and Sediment Loading in the Mississinewa Watershed. *Taylor University Watershed Use and Stream Water Attribute Study*.

Rogers, J. S. 2008. Comparison of underwater video mapping and pebble count measurements in determining stream channel substrate. MS Thesis. Knoxville: University of Tennessee, Department of Wildlife and Fisheries.

Rosgen, D. L. 1994. A classification of natural rivers. *Catena* 22: 169-199.

SAS Instute Inc. 2008. SAS/Stat Users Guide. Version 9.2. Cary, NC.

SGI (Silicone Graphics Inc.). 2009. DB-9 Pinouts for RS-232 and RS-422 Protocols. http://techpubs.sgi.com/library/tpl/cgi-bin/getdoc.cgi?coll=0650&db=bks&fname=/SGI_EndUser/MSB3xx_UG/ch07.html. Accessed July 16, 2009.

Shumway, C. A. 2007. Quantifying habitat complexity in aquatic ecosystems. *Freshwater Biology* 52: 1065-1076.

Smith, C. E. 1998. Modeling high sinuosity meanders in a small flume. *Geomorphology* 25: 19-30.

Stolum, H.-H. 1996. River meandering as a self-organization process. *Science* 271: 1710-1713.

Teledyne RD Instruments. 2009. StreamPro ADCP. http://www.rdinstruments.com/streampro.aspx. Accessed June 16, 2009.

Trimble Navigation Limited. 2009. GPS Tutorial. http://www.trimble.com/gps/index.shtml. Accessed November 23, 2009.

USDA NRCS (United States Department of Agriculture National Resources Conservation Service). 2009. Geospatial Data Gateway. http://datagateway.nrcs.usda.gov/. Accessed November 9, 2009.

USGS (United States Geological Survey). 2007-2009. USGS Real-Time Water Data for Tennessee. http://waterdata.usgs.gov/tn/nwis/uv. Accessed 09 June 2009.

Van den Berg, B. 2008. Personal Communication. Shallow water NMEA 0183 active depth transducer. October 5, 2008.

Wilkerson, J. 2009. Personal Communication. GPS distance calculation equation.

Williams, L. R., M. L. Warren, S. B. Adams, J. L. Arvai, and C. M. Taylor 2004. Basin Visual Estimation Technique (BVET) and Representative Reach Approaches to Wadeable Stream Surveys:

Methodological Limitations and Future Directions. *Fisheries* 29(8): 12-22.

Wolman, M. G. 1954. A method of sampling coarse river bed material. *American Geophysical Union Transactions* 35(6): 951-956.

Zimmerman, L. L. 2003. Propagation of juvenile freshwater mussels (Bivalvia: Unionidae) and assessment of habitat suitability for restoration of mussels in the Clinch River, Virginia. MS Thesis. Blacksburg, VA: Virginia Polytechnic Institute and State University, Department of Fisheries and Wildlife Sciences.

Appendix

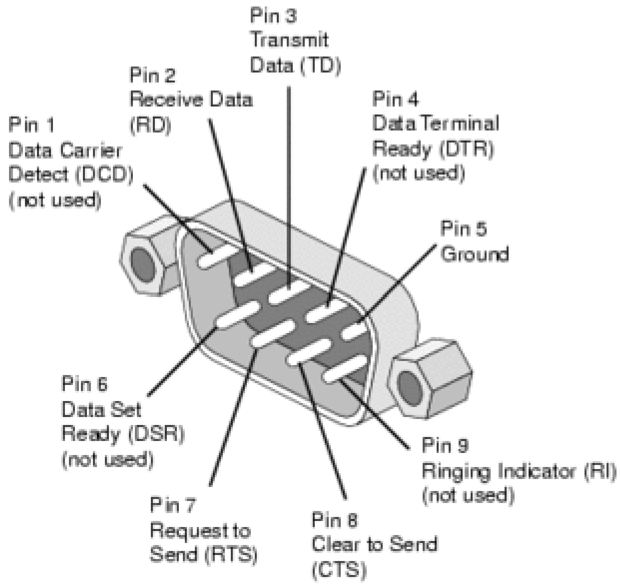

Figure 37: RS-232 Diagram (SGI, 2009)

STREAM__Barren Creek E____________ RM____ DATE6/17/02 RIVER CODE ______________ **QHEI SCORE: 55**

LOCATION__Wheeling Pike & 650 E_______________ CREW:_Reber, Diehl_________________

1) SUBSTRATE (CHECK ONLY TWO SUBSTRATE TYPE BOXES; CHECK ALL TYPES PRESENT): **SUBSTRATE SCORE: 14**

TYPE — POOL RIFFLE — POOL RIFFLE — **SUBSTRATE QUALITY**

☐ ☐ BLDER/SLABS [10] ____ ____ ■ ☐ GRAVEL [7] ____ ____ **Substrate Origin (Check all)** — **Silt Cover (Check one)**
☐ ☐ BOULDER [9] ____ ____ ■ ☐ SAND [6] ____ ____ ☐ LIMESTONE [1] ☐ RIP/RAP [0] ☐ SILT HEAVY [-2]
☐ ☐ COBBLE [8] ____ ____ ☐ ☐ BEDROCK [5] ____ ____ ■ TILLS [1] ☐ HARDPAN [0] ■ SILT MODERATE[-1]
☐ ☐ HARDPAN [4] ____ ____ ☐ ☐ DETRITUS [3] ____ ____ ☐ SANDSTONE [0] ☐ SILT NORMAL [0]
☐ ☐ MUCK [2] ____ ____ ☐ ☐ ARTIFIC. [0] ____ ____ ☐ SHALE [-1] ☐ SILT FREE [1]

TOTAL NUMBER OF SUBSTRATE TYPES: ■ >4 [2] ☐ <4 [0] ☐ COAL FINES [-2] **EXTENT OF EMBEDDNESS** (CHECK ONE)
☐ EXTENSIVE [-2] ■ MODERATE [-1]

NOTE: (Ignore sludge that originates from point-sources; score is based on natural sources) ☐ LOW [0] ☐ NONE [1]

COMMENTS________________________________

COVER SCORE: 13

2) INSTREAM COVER — **AMOUNT** (CHECK ONLY 1 OR CHECK 2 AND AVG.)

TYPE (CHECK *ALL* THAT APPLY)
☐ EXTENSIVE > 75% [11]
■ UNDERCUT BANKS [1] ☐ DEEP POOLS [2] ☐ OXBOWS [1] ■ MODERATE 25-75% [7]
■ OVERHANGING VEGETATION [1] ■ ROOTWADS [1] ■ AQUATIC MACROPHYTES [1] ☐ SPARSE 5-25% [3]
■ SHALLOWS (IN SLOW WATER) [1] ■ BOULDERS [1] ☐ LOGS OR WOODY DEBRIS [1] ☐ NEARLY ABSENT <5% [1]

COMMENTS________________________________

3) CHANNEL MORPHOLOGY: (CHECK ONLY ONE PER CATEGORY OR CHECK 2 AND AVERAGE) **CHANNEL: 10**

SINUOSITY	DEVELOPMENT	CHANNELIZATION	STABILITY	MODIFICATIONS/OTHER	
☐ HIGH [4]	☐ EXCELLENT [7]	☐ NONE [6]	☐ HIGH [3]	☐ SNAGGING	☐ IMPOUND.
☐ MODERATE [3]	☐ GOOD [5]	☐ RECOVERED [4]	■ MODERATE [2]	☐ RELOCATION	☐ ISLANDS
■ LOW [2]	■ FAIR [3]	■ RECOVERING [3]	☐ LOW [1]	☐ CANOPY REMOVAL	☐ LEVEED
☐ NONE [1]	☐ POOR [1]	☐ RECENT OR NO RECOVERY [1]		■ DREDGING	☐ BANK SHAPING
				☐ ONE SIDE CHANNEL MODIFICATIONS	

COMMENTS________________________________

4) RIPARIAN ZONE AND BANK EROSION (CHECK ONE BOX PER BANK OR CHECK 2 AND AVG PER BANK) **RIPARIAN: 6**

river right looking downstream

RIPARIAN WIDTH — L R (Per Bank)	EROSION/RUNOFF - FLOODPLAIN QUALITY — L R (Most Predominant Per Bank)	L R (Per Bank)	BANK EROSION — L R
■ ☐ WIDE>50m [4]	☐ ☐ FOREST, SWAMP [3]	☐ ☐ URBAN OR INDUSTRIAL [0]	☐ ☐ NONE OR LITTLE [3]
☐ ☐ MODERATE 10-50m [3]	☐ ☐ OPEN PASTURE/ROWCROP [0]	☐ ☐ SHRUB OR OLD FIELD [2]	■ ■ MODERATE [2]
☐ ■ NARROW 5-10m [2]	■ ■ RESID.,PARK,NEW FIELD [1]	☐ ☐ CONSERV. TILLAGE [1]	☐ ☐ HEAVY OR SEVERE [1]
☐ ☐ VERY NARROW 1-5m [1]	☐ ☐ FENCED PASTURE [1]	☐ ☐ MINING/CONSTRUCTION [0]	
☐ ☐ NONE [0]			

COMMENTS________________________________

5) POOL/GLIDE AND RIFFLE/RUN QUALITY **POOL: 6**

MAX DEPTH (CHECK 1)	MORPHOLOGY (CHECK 1)	POOL/RUN/RIFFLE CURRENT VELOCITY (CHECK ALL THAT APPLY)	
☐ >1m [6]		☐ TORRENTIAL [-1]	☐ EDDIES [1]
■ 0.7-1m [4]	☐ POOL WIDTH > RIFFLE WIDTH [2]	☐ FAST [1]	☐ INTERSTITIAL [-1]
☐ 0.4-0.7m [2]	■ POOL WIDTH = RIFFLE WIDTH [1]	☐ MODERATE [1]	☐ INTERMITTENT [-2]
☐ <0.4m [1]	☐ POOL WIDTH < RIFFLE WIDTH [0]	■ SLOW [1]	☐ NO POOL [0]
☐ <0.2m [Pool = 0]			

COMMENTS________________________________

RIFFLE: 0

RIFFLE/RUN DEPTH	RIFFLE/RUN SUBSTRATE	RIFFLE/RUN EMBEDDEDNESS
☐ GENERALLY > 10cm, MAX>50cm [4]	☐ STABLE (e.g. Cobble, Boulder) [2]	☐ EXTENSIVE [-1]
☐ GENERALLY > 10cm, MAX<50cm [3]	☐ MOD. STABLE (e.g. Pea Gravel) [1]	☐ MODERATE [0]
☐ GENERALLY 5-10cm [1]	☐ UNSTABLE (Gravel, Sand) [0]	☐ LOW [1]
☐ GENERALLY < 5cm [Riffle = 0]		☐ NONE [2] ■ NO RIFFLE [0]

COMMENTS________________________________

6) GRADIENT (feet/mile):_5feet/mile_ %POOL:____0____ %RIFFLE:____0____ %RUN:___100___ **GRADIENT: 6**

Section 4: Page 12 of 20

Figure 38: Sample EPA QHEI Checklist

Vita

James Bryan McConkey was born in Athens, TN. After graduating from Baylor High School in Chattanooga, TN in 1996, he earned a Bachelor's Degree in Mechanical Engineering from the University of Tennessee in May, 2001. He worked for 7 years as a TN licensed general contractor and managed an apartment complex with marina. He then returned to the University of Tennessee in January 2008 for his Master's Degree in Biosystems Engineering.