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Analysis of Georeferenced Sonar-Based Thalweg and Cross-Sectional River Depth Profile Measurements

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I am submitting herewith a thesis written by Kenneth Wray Swinson entitled "Analysis of Georeferenced Sonar-Based Thalweg and Cross-Sectional River Depth Profile Measurements." 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.

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Analysis of Georeferenced Sonar-Based Thalweg and Cross-Sectional River Depth Profile Measurements

A Thesis Presented for the

Master of Science

Degree

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Kenneth Wray Swinson

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Abstract

Depth is a physical river characteristic that is important for habitat classification, river health analysis, and hydrologic/hydraulic modeling. Recent studies have shown that sonar can be an accurate way of measuring river depth, when compared to traditional techniques, but more study is necessary. The main objective of this research was to evaluate the utility of the CruzPro ATU120S and the Lowrance LMS-350A sonar depth units as tools for collecting river depth measurements along longitudinal (thalweg) and cross-sectional profiles. This included analyzing and evaluating the georeferenced commercially available sonar units for accuracy, precision, and response time under controlled lab and river test conditions. The CruzPro sonar unit is capable of accurately measuring dynamic depths greater than 0.5 m with average absolute percent error (AAPE) and average root mean square error (RMSE) values less than 8.9% and 0.08 m, respectively. Cross-sectional profile mapping utilizing sonar yielded RMSE values from 0.01 to 0.06 m and AAPE values from 2.06% to 4.23% at depths greater than 0.5 m. Sonar mapping systems were successful at collecting thalweg and cross-sectional depth profiles on the Driftwood River. A thalweg depth comparison between the two sonar units yielded no statistically significant difference in measured depths. Maximum cross-sectional depth and the cross-sectional area of a river were predicted using thalweg depth and river width with $R^2$ values of 0.49 and 0.69, respectively. Georeferenced sonar is an excellent tool for collecting large-scale accurate river depth in relatively short amounts of time as compared to traditional methods.
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Chapter 1: Introduction

1.1 Background

Depth is a physical river characteristic that is necessary for many river analyses. Depth profiles are important for habitat classification, river health analysis, and hydrologic/hydraulic modeling (Fiscor, 2005; Maddock, 1999; Platts et al., 1983). Aquatic species habitats are defined by depth with distinctive communities living at different depths in the water column. Inger and Chin (1962) described the different communities of cyprinids in a small Borneo stream; a surface community which tends to consist of small silvery species with upward facing mouths, a mid-water community of larger silvery fishes streamlined with terminal mouths, and a bottom dwelling community of drab colored fishes with dorsally humped profiles and ventrally positioned mouths (Figure 1). Many river assessment models that evaluate indicator species or assess river health require depth inputs and river cross-sectional areas, which require multiple depth measurements (Maddock, 1999). Hydraulic models such as River2D and HEC-RAS use elevations or depths to predict river flows, velocities, sediment transport, and water quality (University of Alberta, 2008; USACE, 2011).
Current methods for acquiring depth profiles, specifically cross-sectional river profiles, are expensive, time consuming, and require a great deal of man-power or specialized tools and training. The traditional method of physically measuring the depth of the river with a surveying rod (stadia) or a weighted rope is the most common and widely accepted. This method requires the conversion of hand collected data to digital format, which is time consuming and can cause errors. Several people are required to collect the depths; with the process being time and labor
intensive. River depth can be difficult to measure and several bias or errors of physically measuring depth can occur. The largest issue is with most researchers choosing to collect data in the warmer months and not during flood events or annual high flows, which severally limits the data. Remote areas of rivers are also difficult to study, and seldom surveyed. Data bias can occur when individuals make a conscious or unconscious choice to not wade into deeper water to collect depth measurements. Simple errors of leaning on measuring poles for stability when collecting depth measurements can also occur.

Newer methods such as spectral or optical imagery, light detection and ranging systems (LiDAR), and sonar have been tested for collecting river depth (Marcus et al., 2003; Kinzel et al., 2007; Flug et al., 1998). Spectral and optical imagery do not measure the depth, but estimates it several ways such as multiple regression equations or models based on physically collected data (Marcus and Fonstad, 2008). These techniques require specialized equipment that must be flown over the river in favorable weather, which is expensive. Spectral and optical image data can be limited by river visibility from the air and shadows. The technology has limitations collecting deeper depths because light must penetrate to the bottom of the stream. The accuracy of these techniques is variable with $R^2$ values ranging from 0.28 to 0.99 (Marcus and Fonstad, 2008).

Airborne LiDAR, also known as laser altimetry, is used for mapping topography and have recently been used to collect bathymetry (underwater depth) (Kinzel et al., 2007). These LiDAR systems are very specialized, limited in number, and are mounted to planes. The LiDAR system works by sending pulses from a laser and measuring the time of the surface backscatter(s). Very accurate global positioning systems (GPS) and airplane attitude (pitch, yaw, and roll) are required to calculate the sensors position and determine the depths of the river.
LiDARs ability to collect bathymetry is limited by the clarity and depth of the water (Kinzel et al., 2007).

Sonar (sound navigation and ranging) has been used extensively in military, commercial, and civilian applications to estimate the depth of water. However, sonar has not been utilized on a large scale to collect river data. Military use of sonar began during World Wars I and II, and was primarily used for navigation, communication, and enemy detection (Urick, 1975). Military, commercial, and civilian use of sonar has been mostly for navigation to identify deeper water where ships can travel and to produce seafloor and large river bottom depth maps. Flug et al. (1998) has shown that sonar systems can be an effective means of collecting river data. The use of sonar would allow for faster more intensive large scale river depth collection in short periods of time. River depth is dynamic and changes over time and georeferenced sonar would allow for more frequent and easily repeatable surveys that are cost effective. More testing is necessary to evaluate the use of sonar for river depth data.
1.2 Objectives

The main objective of this research was to evaluate the utility of a sonar depth sensor as a tool for collecting river depth and more specifically to:

1) Analyze and evaluate the CruzPro sonar unit for accuracy, precision, and response time under controlled lab and river test conditions,

2) Evaluate a kayak-mounted sonar system as a cross-sectional river mapping tool and compare depth sensor output to the traditional method for accuracy and precision,

3) Compare thalweg profiles to analyze the depth sensor for accuracy and precision,

4) Develop continuous thalweg and cross-sectional depth profiles for the Driftwood River using a Canoe- and Kayak-mounted Sonar-based GPS Mapping System (CSMS and KSMS) to collect georeferenced river depth measurements,

5) Implement sonar depth as a tool for measuring thalweg and cross-sectional depth profiles and demonstrate its utility,

6) Compare Lowrance LMS-350A sonar to CruzPro ATU120S sonar for depth accuracy,

7) Generate a maximum depth model to observe how well thalweg depth predicts maximum depth,

8) Generate a cross-sectional area model to observe how well thalweg depth and river width predict a river's cross-sectional area,

9) Compare cross-sectional profile spacing on a river for collecting river data,
Chapter 2: Literature Review

2.1 River Depth Importance

River depth is used extensively for river health assessment, riverine habitat classification, modeling river systems, and estimating river variables such as velocity and flow (Barbour et al., 1999; Kaufmann et al., 1998). There are many different methods for collecting the depth of rivers based on the river location and data implementation.

Platts et al. (1983) described the importance of depth in evaluating fish cover, assessing pool quality, assessing fish environments, and evaluating stream, riparian, and biotic conditions. They define stream depth as “the vertical height of the water column from the existing water surface level to the channel bottom measured in tenths of feet (0.03 m).” The stream shore depth is important for young fish and can be an effective way of evaluating land use activities that could modify the stream bank or stream bottom morphology and is “…measured at the shoreline or at the edge of a bank overhanging the shoreline (Platts et al., 1983).” Average depth calculation techniques are described when streamflow data is and is not present. Depth measurements are important to determine stream velocities and cross-sectional area, and have been incorporated into several habitat models designed to indicate fish standing crops (quantity, total weight, biomass or energy content), and to assist in evaluating impacts from land management activities. Several bias or errors of physically measuring depth data are described. The largest issue is with most researchers choosing to collect data in the warmer months and not during flood events or annual high flows, which severely limits the data. Data bias can occur when individuals make a conscious or unconscious choice to not wade into deeper water to
collect depth measurements. Simple errors of leaning on measuring poles for stability when collecting depth measurements can also occur.

Maddock (1999) discusses the importance of measuring physical habitat parameters for evaluating river health. The indicators for describing river health include the ecological status, water quality, hydrology, geomorphology and availability of physical habitat. Maddock (1999) states “assessing physical habitat is an important member of this suite of indicators.” A suitable living space for a given species is required for that species to reside there, and this can be defined by physical habitat parameters. The productivity of any stream system is likely to be determined by four key factors, one of which is the physical structure of the channel. Depth is one of the important factors for broad scale and microhabitat assessment. The challenge of performing large scale assessments with sufficient detail is pointed out. The article states that physical habitat is determined by an interaction between geomorphology and hydrology. Maddock (1999) emphasizes improvements in the data collection process by stating; “the development of new technologies particularly relating to survey methods should help improve the speed and level of detail attainable by physical habitat assessments. These methods will provide the necessary information required for the development of the two-and three-dimensional physical and hydraulic habitat models.” He further mentions that the “combination of Sonar and differentially corrected GPS (DGPS) has been demonstrated to be effective in characterizing the precise physical habitat of individual reaches and is likely to improve understanding of the system attributes that control biological diversity and river health (Maddock, 1999).”

Rosgen (1994) states that stream pattern morphology is directly influenced by channel width, depth, velocity, discharge, channel slope, channel material roughness, sediment size, and sediment load. The variables are all interconnected, so a change in one will influence changes in
another. Because of this connection, the measurable variables, such as depth, should be used as stream classification criteria. Rosgen (1994) proposes a classification technique that divides rivers into 7 major stream type categories that differ in width-to-depth ratio, entrenchment, gradient, and sinuosity in different landforms. He also uses the field measured width-to-depth ratio, along with other parameters, for verification.

An extensive list of river assessment techniques, including river models, which use depth measurements as an integral part of the analysis exist can be found. Bedoya et al. (2009) shows how different states use models that incorporate different depth variables, such as mean depth, thalweg depth, and width-depth ratio. Fiscor (2005) used depth as one of his five primary habitat attributes for mapping freshwater mussel habitats. The QUAlity Simulation Along Rivers (QUASAR) model uses multiple depth measurements in calculations to simulate dynamic flow behavior and river water quality (Whitehead et al., 1997).

2.2 River Depth Measurement

2.2.1 Traditional Method

Traditional depth collection techniques are still the most common techniques used for collecting river depth and cross-sectional depth data. This method is outlined by several different groups including the United States Geological Survey (USGS) (1976) in the National Handbook of Recommended Methods for Water-Data Acquisition, the Texas Water Resources Institute (under the USGS) in Techniques of Water-Resources Investigations (Buchanan and Somers, 2010), and the United States Department of Agriculture Forest Service in Stream Channel Reference Sites: An Illustrated Guide to Field Technique (Harrelson et al., 1994).
Location and distance information is determined from surveying instruments and the river width is divided into increments for multiple cross-sectional depth measurements.

The determination of depth is known as sounding and is most commonly done mechanically (Buchanan and Somers, 2010). River surveyors are required to wade across the river with a handheld survey rod to gather water depth, or negotiate the cross-section by a boat guided by a cable marked with river width increments, or use a cable system suspended above the river that the surveyor is attached onto and can drop a heavy weight attached to a cable into the water and record the cable length manually (US Geological Survey, 1976). These collection techniques are accepted as the most accurate way of measuring river depth.

2.2.2 Remote Sensing

Remote sensing techniques such as optical or spectral imaging and LiDAR systems for acquiring river depth and other habitat parameters have seen expanded use in the past two decades (Marcus and Fonstad, 2008). These techniques require specialized equipment to be flown over the river and can estimate depth on a sub-meter level or over large areas. Marcus and Fonstad (2007) assert that most of the studies that use these technologies are proof-of-concept at local or reach scales and the use of the technology needs to be expanded.

Marcus et al. (2003) evaluated the potential of 1-m resolution, 128-band hyperspectral imagery for mapping depths in third and fifth order streams in the northern Yellowstone region. A stepwise multiple regression was used to determine the relationship strength between depth and spectral reflectance. Then equations where developed for estimating depths throughout the stream. Eight in-stream habitats (high- and low-gradient riffles, eddy drop zones, standing water, rough-water runs, runs, glides, and pools) were classified by surface turbulence. Depth
was isolated as the primary driver of observed spectral reflectance on the images, so depth could be estimated.

This technique of measuring depths generated $R^2$ values ranging from 28% for runs and glides in third order reaches to 99% for glides in fifth order reaches (Marcus et al., 2003). The less accurate depth estimates obtained from smaller streams was attributed to the increase in a wide range of depths and surface turbulences on a single pixel. The authors concluded that the high accuracies achieved indicate that high spatial resolution hyperspectral (HSRH) imagery can be a powerful tool for watershed-wide mapping and modeling of streams. However, the use of HSRH imagery for stream mapping is limited by the need for clear water, no tree cover obscuring the stream, and the availability of airborne hyperspectral sensors. The aerial imagery in the study was not georeferenced and would be an obstacle if wanting to integrate the classification maps into GIS analyses with other data layers.

Light detection and ranging or laser-induced direction and ranging (LiDAR) systems work by sending pulses from a laser and measuring the time of the surface backscatter(s) (Kinzel et al., 2007; Charlton et al., 2003). Very accurate GPS and airplane attitude (pitch, yaw, and roll) are required to calculate the sensors position and determine the depths of the river. Kinzel et al. (2007) evaluated LiDAR for the collection of shallow depths (< 1.0 m) in braided, sand-bedded river. The National Aeronautics and Space Administration’s Experimental Advanced Airborne Research LiDAR (NASA EAARL) was the system tested due to its advances with water-penetrating capabilities. The study was conducted on two river reaches in Nebraska in 2002 and 2005. The LiDAR measurements were computed with a terrestrial algorithm and compared to ground-truth GPS point measurements. The root mean square errors of the depth measurements taken on submerged sand in two different areas were 0.18 m and 0.24 m. These measurements
were deeper than the actual depth. Because the LiDAR’s laser pulse travels slower in water (0.11 m/ns) than in air (0.15 m/ns) the depth will be calculated as 0.04 m/ns deeper or 1.36 m for every 1 m of actual depth if the pulse is assumed to be through air. This is why an algorithm was developed for the bathymetric (underwater depth) data. LiDAR’s ability to collect bathymetry is limited by the visibility, clarity, and depth of the water (Kinzel et al., 2007).

2.2.3 Sonar

Sonar (Sound Navigation and Ranging) systems use sound propagation through water for measurements or communication (Bureau of Ships, 1965). The earliest references to underwater sound are from Leonardo da Vinci, who noted that ships could be heard at great distances through a tube partially submerged in water (Urick, 1975). The development of present day sonar systems began in the late 19th century and was advanced by World Wars I and II. Post war advances in electronics generated the expanded use of sonar systems such as side-scan sonar and fish finders. The discovery of transduction, conversion of electricity to sound and vice versa, was an integral step in development of the sonar systems used today. Sound is a pressure wave and the pressure change caused by sound on certain types of crystal pairs will cause an electrical charge across them, which is called piezoelectricity. Devices that accomplish this are referred to as transducers. Hydrophones are transducers that convert sound into electricity and projectors are transducers that convert electricity into sound. These are the two main parts of active sonar systems (Urick, 1975).

There are two types of sonar systems passive and active. Passive sonar systems listen for sounds generated by the target and are used for communication, telemetry, control applications and distance finding. Active sonar systems generate a sound (pulse) that bounces off the target,
and the sound returns to the system as an echo. The amount of time it takes for the echo to return can be used to calculate the distance and is called echo-ranging (Urick, 1975).

Flug et al. (1998) evaluated an off-the-shelf sonar sounder system as an efficient and low cost technique for measuring depth in a large river cross-section. The operating range for the sonar was from 0.6-450 m with a precision of 0.1 m. The portable sonar equipment system was mounted on a boat and used to record water depths directly onto a laptop computer. The boat was positioned at specific distances from the shore via a cable to acquire positioned depth measurements and data was collected from repeated cross-sectional passes. The boat mounted sonar system was evaluated to determine its precision and the precision of the field data collection technique. Validation results from two different sites gave an average sample standard deviation (S.D.) of 0.12 m for the complete cross-sections, with a coefficient of variation of 10%. When validation was done neglecting the shallow water stream bank depths (less 0.6 m), data yielded an average sample S.D. of 0.05 m, with a coefficient of variation below 5%. The sonar system accuracy was assessed by comparing to traditionally surveyed transect data from a regularly gauged site. The average mean squared deviation of 46.0 cm$^2$ was acquired using only water depth measurements greater than 0.6 m. The procedure proved to be a reliable, accurate, safe, quick, and economic method to record river depths for stream habitat studies.

Fiscor (2005) conducted river mapping with a canoe based underwater video mapping system (UVMS) to locate potential habitat for five endangered mussel species within the Big South Fork National River and Recreation Area (BISO). Fiscor used the Lowrance LMS-350A sonar unit for depth measurement and found during simple tests that it reads 0.18 m (0.6 ft) greater than the actual depth when in fresh water and is unreliable at depths less than 0.5 m (1.6 ft). Multiple river reaches were categorized by their average and maximum depth, flow
characteristics, and substrate composition. Depth maps were created in GIS to assist in creating mussel species specific habitat maps and assessing mussel habitat suitability.

McConkey (2010) utilized a canoe- and kayak-based UVMS for habitat mapping in the Big South Fork National River and Recreation Area (BISO NRRA). The system collected georeferenced sonar-depth data that was used to calculate rugosity. The GPS and depth point-to-point data was used for the rugosity calculations and averaged over 100 data points. McConkey (2010) defines rugosity as “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).” The rugosity was used as an indicator for identifying large boulder fields with 67% accuracy. Depth and rugosity maps were created for the BISO NRRA system (McConkey, 2010).

2.3 Thalweg and Cross-sectional Depth

2.3.1 Thalweg Depth

The term “thalweg” is often defined as the deepest continuous path along a river. The following are different ways in which “thalweg” has been defined:

“Even where the channel is straight it is usual for the thalweg, or line of maximum depth, to wander back and forth from near one bank to the other.” (Leopold et al., 1964, pp. 281-282)

“The thalweg of a river is the line which marks the deepest channel.” (Olson, 1970, pp. 81)

“More direct measures from cross-sectional measurements include evaluation of changes in mean bed elevation and thalweg elevation, the deepest point in a given cross-section.” (Mossa and Konwinski, 1997)
“As a result the course of the deepest ‘thread’ of flowing water, a course known as the *thalweg*, is more zigzag than the center line of the channel.” (Pielou, 1998, pp. 128)

“The ‘thalweg’ is simply the deepest portion of the channel or cross-section.” (Kaufmann et al., 1999)

“The thalweg or, deepest path of water along a stream,…” (Bartley and Rutherfurd, 2002)

“Typically, at any cross section in a channel, there will be a portion of the flow along the deepest part of the channel (called the *thalweg*) that is moving the fastest.” (Ward and Trimble, 2004, pp. 172)

“Thalweg profiling involves surveying the streambed elevation along the deepest portion of the stream (the thalweg) to produce a two-dimensional, longitudinal profile of streambed elevations.” (Mossop and Bradford, 2006)

“A thalweg is defined as the line joining the lowest points of the gully.” (Thommeret et al., 2010)

Although these are all acceptable ways of defining “thalweg” they are not practical when attempting to navigate a river by boat. Hyde (1912) discusses the use of thalweg as it pertains to international law and the use of rivers as boundaries. He states the definition of thalweg as “the downway, or the course followed by vessels of the largest tonnage in descending the river. That course frequently, if not commonly, corresponds with the deepest channel. It may, however, for special reasons take a different path” (Hyde, 1912). Because the operator of a boat or vessel does not know exactly where the deepest part of the river is they have to make a logical guess of its location. This research uses this method of identifying the thalweg of a river. Therefore the thalweg is frequently not at the deepest part of the cross-section of a river, although it is usually close. So in this paper the thalweg is more analogous to a predicted thalweg when used with the common definition.
2.3.2 Cross-sectional Depth

Cross-sections of a river are the paths across a river that are perpendicular to the flow (Harrelson et al., 1994, pp. 15). Pavelsky and Smith (2008) define river flow width, which is where a cross-section would be measured, as the shortest cross-sectional distance from water’s edge to water’s edge, orthogonal to the river channel. Rhoads et al. (2003) identified cross-sections that encompass the geomorphological diversity of a reach from detailed topographic mapping using an electronic total station. Each cross-section was aligned orthogonal to the local channel direction. Although these practices for collecting cross-sections are similar, there are situations when the cross-sections would be different. When surveying a river and its’ floodplain, cross-sections can extend onto dry land. Depth measurements or river bed elevations are collected at specific intervals and noticeable breaks in slope along a cross-section depending on the river or defined cross-sectional width. The depth between these points is interpolated to produce a continuous cross-sectional profile. These profiles allow for the wetted perimeter of the river to be calculated. The wetted perimeter is an important river characteristic that if often utilized for estimating a river’s minimum allowable flow and for predicting areas of suitable habitat (Gergel et al., 2002).

2.3.3 Utility of a Cross-section

Cross-sections are a valuable tool in river hydrologic studies and essential for calculations involving flow, velocity, depth, area, and river width. These variables are all important in the relationship that flow (Q) is equal to velocity (v) times cross-sectional area (A), where the area is calculated from the river width and multiple depth points along a cross-section (Buchanan and Somers, 2010; Pavelsky and Smith, 2008). This relationship is utilized by the
USGS to estimate streamflow data by river stage relationships. River stage refers to the water-surface elevation above a fixed reference point that may not correspond directly to water depth and is unique to each streamgaging site (Deacon et al., 2001).

Several programs use some form of cross-sections in analysis of hydrologic/hydraulic or habitat modeling. Some programs such as the RivWidth software calculate river widths from remotely sensed data for the use in hydraulic modeling (Pavelsky and Smith, 2008). Cross-sections along with many other parameters are utilized in programs such as River2D and HEC-RAS for hydraulic modeling. Clark et al. (2008) used River2D for identifying suitable fish habitat and Mouton et al. (2006) used HEC-RAS and CASiMiR for fish habitat modeling. Merwade et al. (2005) presented a GIS-based approach for producing the thalweg and a 3D mesh to support river hydraulic modeling using a channel boundary, an arbitrary centerline, and 3D measurement points of river bathymetry with a boat-mounted acoustic depth sounder.

2.4 Summary

River depth is a necessary parameter that must be measured to obtain quality river assessments. The current measurement techniques can be improved on to make depth data collection faster and easier while maintaining accuracy near the traditional methods. The depth estimation techniques of HSRH and LiDAR do not appear to have an adequate precision for the data requirements of most river assessments. Flug et al. (1998) has shown that sonar depth is a valid way of measuring river cross-sectional depth and have the potential for large scale and accurate depth measurements. The sonar depth measuring technique used by Flug et al. (1998) still confined the operator to land based operations that needs to be addressed for more large scale assessments, and the data quality can be improved with advancements in technology.
Merwade et al. (2005) has shown that point based river depth data can be utilized in hydraulic modeling. Several of the measuring errors and data collection gaps that Platts et al. (1983) describe can be alleviated when sonar depth sensors are mounted to watercraft such as kayaks, canoes, or boats. Fiscor (2005) conducted successful river depth data using canoe mounted sonar for mussel habitat maps. More research on fast and accurate depth data collection with sonar depth sensors is necessary to make river assessments easier and more cost effective.
Chapter 3: Materials and Methods

3.1 Equipment

A Canoe- or Kayak-mounted Sonar-based GPS Mapping System (CSMS or KSMS) was utilized for data collection. The system was mounted on a canoe or kayak depending on the section of river floated. Canoes are suitable for floating on larger bodies of water that are deeper and have minimal water velocity, while kayaks are capable of navigating shallower rivers with fast moving water and rapids that can be technical to navigate. A CruzPro ATU120S Shallow Water Active Depth Transducer was mounted on the kayak and a Lowrance LMS-350A Sonar Unit was mounted on the canoe (CruzPro Ltd., 2009; Lowrance Electronics Inc., 2008).

3.1.1 Depth Sensors

The LMS-350A wide screen sonar unit, manufactured by Lowrance Electronics Inc. (2008), can integrate GPS and display real-time depth and/or position graphs. The LMS-350A’s transducer operates at a frequency of 192 kHz with a 20 degree cone angle (beam width) and measures down to 305 m (1500 ft) with a 3 cm (0.1 ft) resolution. Sonar data is serially transmitted (National Marine Electronics Association (NMEA) 0183, $SDDBT sentence, 4800 baud) approximately every two seconds (Lowrance Electronic Inc., 1993).

The CruzPro ATU120S specialized shallow water active depth transducer, manufactured by CruzPro Ltd. (2009), transmits (NMEA-0183, $SDDBT sentence, 4800 baud rate) every second. The CruzPro ATU120ST is the same unit with a water temperature sensor. The shallow water depth sensor is accurate from 0.15- 13.4 m (0.5- 44 ft) with a 3 mm (0.01 ft) resolution. The sensors operating frequency is 120 kHz and has a cone angle of 38 degrees. The data output
can be damped to smooth the data or prevent fast fluctuations. The damping value ranges from zero (none) to 99, with a default value of zero (CruzPro Ltd., 2009).

These sonar units have transducers that generate sound pulses at different cone angles for measuring the depth. These sound waves spread out into the water in a cone shaped beam and if the beam contacts a flat perpendicular surface it would reflect off of a circular area called the field of view. An example of the two cone angles from the sonar units with different field of view diameters can be seen in Figure 2 and a plot of the field of view and field of view diameter versus depth in Figure 3. Although a large range of depths could be present in the field of view, the sonar units use digital signal processing for calculating depth (CruzPro Ltd., 2011).
Figure 2. Difference in the field of view and field of view diameters from the two transducer cone angles
3.1.2 Global Positioning System (GPS)

A Trimble AgGPS 114/132 receiver was used on the canoe- and kayak-mounted systems to collect OmniSTAR satellite-based differential GPS position data. Both units output real-time sub-meter positions and 0.16 kph (0.1 mph) velocity accuracy measurements (Trimble Navigation Limited, 2000; Trimble Navigation Limited, 2001). A Garmin 18x OEM PC GPS unit with Wide Area Augmentation System (WAAS) differential correction was sometimes utilized on the kayak system. The unit can achieve less than 15 meter accuracy with Standard
Positioning Service (SPS) and less than 3 meter accuracy with WAAS, and the velocity accuracy is 0.19 kph (0.12 mph) for both (Garmin International, Inc., 2008). Both GPS units output at 1 Hz with a 4800 baud rate on NMEA-0183 $GPGGA and $GPRMC sentences. Georeferenced depth is important for identifying the precise locations of the measurements and enables the data to be mapped and easily located.

3.1.3 Collection System

The sonar-based mapping system can be placed on a Wilderness Systems Tarpon 100 sit-on-top kayak that is 3.05 m (10 ft) long or an Old Town Guide 147 canoe that is 4.45 m (14 ft 7 in.) long. The CruzPro sonar transducer was flush mounted to the bottom of the kayak just behind the seat. All of the systems components were housed in a waterproof Underwater Kinetics UltraCase model 613 or 716 attached to the back of the kayak. The Trimble or Garmin GPS unit was mounted to the top of the storage case. The Lowrance LMS-350a sonar transducer was mounted to the side of the canoe using a Tite Lok 5798 hinged transducer mount. The Trimble GPS unit was mounted to a pole to elevate it in the middle of the canoe for better reception. The system was housed in a waterproof storage case set in the middle of the canoe. A multiplexer was used to combine the outputs from the GPS and the sonar and then stored onto a compact flash (CF) card by a serial data recorder (SDR). The Kayak-mounted Sonar-based GPS Mapping System (KSMS) is shown in Figure 4 and the Canoe-mounted Sonar-based GPS Mapping System (CSMS) in Figure 5. A flow chart of the system is shown in Figure 6.
Figure 4. The Kayak-mounted Sonar-based GPS Mapping System is shown with components.
Figure 5. The Canoe-mounted Sonar-based GPS Mapping System is shown with components.

Figure 6. Flow chart of data collection system.

3.1.4 Safety Emphasis

While kayaking and canoeing the river, personal floatation devices (PFD) were worn at all times. Medical first-aid kits and river rescue throw ropes were carried in the boats at all times. The use of boats for surveying rivers eliminated the need for individuals to wade across the river in potentially dangerous areas when fast moving currents were present. River depth locations
were able to be collected in deeper and faster flowing sections of the river. The physical depth measurements where collected in slow moving, pool sections of the river.


3.2 Studies Conducted

This chapter is a summary of the studies conducted with the detailed procedures in the following chapters. Table 1 shows the location of the tests and which sonar units were utilized for conducting the study.

Table 1. Location of river tests and the sonar unit(s) utilized

<table>
<thead>
<tr>
<th>Test/ River Section</th>
<th>Depth Transducer</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of Tennessee Pool</td>
<td>CruzPro</td>
</tr>
<tr>
<td>Citico Creek, TN</td>
<td>X</td>
</tr>
<tr>
<td>Driftwood River, IN</td>
<td>X</td>
</tr>
<tr>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Obed River (OBRI), TN</td>
<td>X</td>
</tr>
<tr>
<td>Station Camp in the Big South Fork National River and Recreation Area (BISO), TN</td>
<td>X</td>
</tr>
</tbody>
</table>

3.2.1 Controlled Sensor Tests

Controlled field and lab tests were conducted to assess the sonar depth sensors accuracy, precision, and response time. These are important parameters to determine because the variability of depths and the rates at which they change are not uniform in the field. Accuracy is defined as the absence of error. Precision is defined as the ability of the instrument to produce a similar response under the same conditions. Response time is defined as the amount of time until the sensor responds to a change. The response time was calculated as a time constant from a step input. A suitable test site on Citico Creek was used to perform several of the field tests. The slow moving section of the river had suitable depths and bed form changes for the various
tests. Several tests were also performed in an Olympic sized swimming pool at the University of Tennessee at Knoxville (UTK) to generate a more controlled environment.

3.2.1.1 Static Tests

The kayak mounted depth sensor was placed in Citico Creek at a specific depth and a time series of data was collected to see if the sensor maintained the same output. Several depth increments were tested to acquire the accuracy of the sensor at different depths. These same tests were done in the UTK pool and compared to the field data. These tests were used to assess the accuracy and precision of the sensor and the percent error, root mean square error, and standard deviation for the data was calculated.

3.2.1.2 Vertical Movement Tests

Vertical movement tests were conducted at the UTK pool. The depth sensor was positioned at a specific depth and then moved to different depths while data was being collected. Times were noted when the sensor crossed specific depths that were measured physically with a stadia rod and marked. This test was performed twice, once descending and once ascending in the water column. The vertical movement tests were performed to assess the precision and response time of the sensor.

3.2.1.3 Horizontal Movement Tests

3.2.1.3.1 Uniform Depth

The kayak mounted depth sensor was moved over a level section of the UTK pool at a slow (0.5 m/s) and fast (1.5 m/s) rate of speed. This test was to evaluate the effect of the kayak moving on the depth output of the sensor. The absolute percent error, root mean square error, and standard deviation of the measurements were calculated.
3.2.1.3.2 Changing Depth

The kayak mounted depth sensor moved from the shallow end of the UTK pool to the deep end of the pool and back while the sonar continuously measured depth. Specific times where noted when the sensor passed over marked depth locations that were physically measured. This experiment was used to test the sensors accuracy, precision, and response time. The percent error, root mean square error, and standard deviation for the marked depth locations were calculated. The time interval between when the kayak crossed the marked depth and when the sensor output is the same value was recorded as the “depth delay”. The average time delay was calculated for all the marked depths.

3.2.1.3.3 Reaction to Objects

These tests assessed the sensors response time to changing depth and how it is affected by objects in the sonar cone. The kayak mounted depth sensor was moved over a level substrate surface in the UTK pool and passed over objects of different shape placed on the bottom. The physically measured depths before, during, and after the object were compared to the sensors values. The time constant for the sensor when it crossed the object was calculated. The percent error, root mean square error, and standard deviation for the depth along the object were calculated.

3.2.1.3.4 Vertical Structure Interference

The depth sensor was tested to evaluate how it handled vertical structures and depth changes. The sensor was positioned in the UTK pool at varying distances from the pool wall to see if the depth output would change as it approached or moved away from the wall. The sensor was also placed directly over the vertical transition of depth along an object with a time series of
data collected to evaluate how the sensor handles the depth transition. The percent error, root mean square error, and standard deviation for the depth with the vertical interference were calculated.

3.2.1.4 River Cross-section Evaluation Tests

Several cross-sections were collected on Citico Creek using the traditional method and the kayak mounted depth system. The sonar depth output was compared to a physical measurement at the same location. The overall cross-sectional profile was also compared between the two methods. These cross-sections were compared for accuracy and precision. Several cross-sections were conducted with the kayak rocking side-to-side to evaluate how the kayak movements affect the sensor readings. Slight and severe degrees of rocking were assessed. The percent error, root mean square error, and standard deviation for the cross-sections were calculated.

3.2.2 River Data Analysis

3.2.2.1 Thalweg Comparison

Citico Creek is located in the Cherokee National Forest in Tennessee. It is a mountain stream that starts from several small streams at the top of a mountain and flows down into Tellico Lake. A 14.6 km (nine mile) road-side reach of Citico Creek was run twice in a five day period at comparable flows. Because of the shallow nature of the creek, only the shallow water depth sensor was used on this reach. The georeferenced sonar depth data collected was analyzed for depth sensor accuracy and precision. The percent error, root mean square error, and standard deviation for the three runs were calculated.
3.2.2 Sonar-Based GPS Mapping System Implementation

The Driftwood River study area consisted of an 18 mile reach starting from the confluence of the Big Blue River and Sugar Creek in Indiana. Only small tributaries flow into the Driftwood River until it joins with the Flat Rock River forming the East Fork of the White River at Columbus, Indiana. Georeferenced thalweg sonar depth measurements were collected along the entire length of the river with the KSMS. River cross-sections perpendicular to the flow of the river were run at approximate 15, 20, and 60 m spacing along the entire river reach using the canoe-mounted sonar-based GPS mapping system. Most of the 448 cross-sections are at 60 m spacing. Thalweg and cross-sectional depth profiles were generated for the Driftwood River with the data. A thalweg depth comparison was performed between the CruzPro and Lowrance sonar units. Maximum depth models were developed to observe how well thalweg depth and river width can be used to predict maximum depth. Cross-sectional area models were developed to predict the cross-sectional area of the river given the thalweg depth and river width. A cross-sectional profile positioning comparison was performed to assess if there were significant differences between 15, 20, and 60 m spacing. These assessments were performed to demonstrate the implementation of sonar-based mapping system as a tool for measuring cross-sectional profiles.
Chapter 4: Controlled Sensor Tests

The controlled sensor tests were conducted with the CruzPro ATU120S sonar unit. The CruzPro default data damping value of zero was used for data smoothing on all tests unless otherwise specified (CruzPro Ltd., 2009). Controlled lab and river test data were analyzed for depth measurement accuracy, precision, and response time. The depth sensor outputs the measured depth as a positive value, but the depth will be displayed as a negative value for the purposes of showing substrate surfaces for the proper perspective.

4.1 Static Tests

4.1.1 Objective

Static tests were performed on the CruzPro sonar unit to assess the accuracy and precision of the depth measurement. The device’s manual states that the unit is accurate from 0.15-13.4 m (0.5-44 ft) with a 3 mm (0.01 ft) resolution (CruzPro Ltd., 2009).

4.1.2 Data Collection

The shallow water depth sensor was positioned at varying depths for two minute intervals, yielding approximately 120 data points, while depth data was collected. A stadia rod was used to physically measure the depth at each location. This was done both in the University of Tennessee Knoxville (UTK) swimming pool and at Citico Creek, located within the Citico Creek Wilderness and Cherokee National Forest in Monroe County, TN (35.48356° N, 84.12179° W). Depths ranged from 0.15 to 5.46 m (0.5-17.9 ft), with the deeper depths
achievable only in the pool. Due to the changing bottom gradient of the UTK pool the depths of 4.45 and 4.72 m were on a sloped (14.6%) surface.

4.1.3 Results

Figure 7 shows the results of the pool test plotted against a one-to-one line, where the X-axis displays the physically measured depth (PMD) and the Y-axis shows the sonar measured depths collected over the two minute time interval. The average depth is labeled for each point and one standard deviation (SD) for each sample of data is shown.

Figure 7. Static UTK pool test results comparing the sonar depth measurements to physically measured depths
The depth measurements of the sonar unit below 0.30 m are substantially different from the PMD. The sonar measurements between 0.30 and 0.46 m have larger SDs with the average measured depth higher than the PMD. From 0.46 to 1.86 m the depth sensor measures the depth with the average depth very close to the PMD. The sensor was held under the water for these tests with the pool depth of 1.24 m and it is possible the sonar pulses could be reflected from the water surface or pool walls at the lower depths. In a communiqué with the manufacturing company it was stated that the higher depth errors could be due to the pulse coming back so soon that the transducer is still ringing (sending sonar pulse) and the receiver cannot register the return signal (B. van den Berg, personal communication, 2011). Therefore later, possibly reflected, pulses would be registered and a deeper depth would be calculated. When the sonar is not confined, especially by the dense rectangular walls of the pool, a 0 m depth would be output. This was observed in sonar river depth measurements and discussed further in section 6.3.

The 4.45 and 4.72 m measurements were on the sloped bottom section of the UTK pool and the sonar output a larger range of depths. These variations could be due to the rocking of the sensor. The sonar was positioned over the center of the deep end of the UTK pool for the 5.49 m test and compares very well to the PMD. A summary of the average, standard deviation, average absolute percent error (AAPE) and root mean square error (RMSE) for each series of sensor measured depth are shown in Table 2 and 3.

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Physically Measured Depth (m)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>Average (m)</td>
<td>1.66</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.01</td>
</tr>
<tr>
<td>AAPE</td>
<td>2073.02</td>
</tr>
<tr>
<td>RMSE (m)</td>
<td>1.58</td>
</tr>
</tbody>
</table>
Table 3. Sonar measured depth statistics for static pool tests (continued)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>PMD 0.84</th>
<th>PMD 0.91</th>
<th>PMD 0.91</th>
<th>PMD 1.07</th>
<th>PMD 1.22</th>
<th>PMD 1.31</th>
<th>PMD 1.37</th>
<th>PMD 1.37</th>
<th>PMD 1.85</th>
<th>PMD 4.45</th>
<th>PMD 4.72</th>
<th>PMD 5.49</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (m)</td>
<td>0.87</td>
<td>0.91</td>
<td>0.91</td>
<td>1.09</td>
<td>1.23</td>
<td>1.33</td>
<td>1.38</td>
<td>1.38</td>
<td>1.86</td>
<td>3.95</td>
<td>4.44</td>
<td>5.46</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>1.21</td>
<td>0.99</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>AAPE</td>
<td>3.95</td>
<td>1.39</td>
<td>0.88</td>
<td>2.24</td>
<td>0.99</td>
<td>1.59</td>
<td>0.61</td>
<td>1.00</td>
<td>0.57</td>
<td>12.08</td>
<td>5.98</td>
<td>0.40</td>
</tr>
<tr>
<td>RMSE (m)</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>0.03</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.01</td>
<td>1.31</td>
<td>1.02</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The results from the test at Citico Creek are shown in Figure 8 plotted against a one-to-one line, where the X-axis displays the PMD and the Y-axis shows the sonar measured depths collected over the time interval. The average depth is labeled for each point and one SD for each sample of data is shown.

![Figure 8. Static test results from Citico Creek comparing the sonar depth measurements to physically measured depths](image-url)
All the depths above 0.50 m are measured very close to the PMD with very small SDs. The sonar measured depths below 0.50 m have many different variations. The three 0.15 PMD have three different data sets; one is all zeros, one is close to the PMD with a high SD, and one is over half a meter off with a small SD. Even though one SD bar goes below zero, no negative depth value were collected. The PMDs of 0.23 (1), 0.34, 0.35, 0.44 are very close to the PMD with small SDs. Several of the points have large SDs and they all have a higher average measured depth. The large errors at the 0.15 m PMD (0.77 m measured) and the 0.30 m PMD (0.97 m measured) could be a result of the previously discussed error of the transducer still ringing causing reflected pulses to be detected. A summary of the average, standard deviation, average absolute percent error and root mean square error (RMSE) for each series of sensor measured depth are shown in Table 4 and 5.

Table 4. Sonar measured depth statistics for static tests at Citico Creek, TN

<table>
<thead>
<tr>
<th>Statistics</th>
<th>0.15</th>
<th>0.15</th>
<th>0.15</th>
<th>0.23</th>
<th>0.23</th>
<th>0.29</th>
<th>0.30</th>
<th>0.34</th>
<th>0.35</th>
<th>0.44</th>
<th>0.46</th>
<th>0.47</th>
<th>0.50</th>
<th>0.53</th>
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</thead>
<tbody>
<tr>
<td>Average (m)</td>
<td>0.00</td>
<td>0.18</td>
<td>0.77</td>
<td>0.23</td>
<td>0.33</td>
<td>0.30</td>
<td>0.97</td>
<td>0.34</td>
<td>0.32</td>
<td>0.45</td>
<td>0.64</td>
<td>0.39</td>
<td>0.49</td>
<td>0.55</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.00</td>
<td>0.26</td>
<td>0.02</td>
<td>0.01</td>
<td>0.25</td>
<td>0.18</td>
<td>0.14</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.11</td>
<td>0.05</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>AAPE</td>
<td>100.00</td>
<td>128.30</td>
<td>405.25</td>
<td>4.22</td>
<td>71.82</td>
<td>35.69</td>
<td>216.60</td>
<td>4.24</td>
<td>8.52</td>
<td>3.32</td>
<td>39.67</td>
<td>17.86</td>
<td>4.26</td>
<td>3.17</td>
</tr>
<tr>
<td>RMSE (m)</td>
<td>0.15</td>
<td>0.26</td>
<td>0.62</td>
<td>0.01</td>
<td>0.27</td>
<td>0.18</td>
<td>0.68</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.21</td>
<td>0.10</td>
<td>0.02</td>
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</table>

Table 5. Sonar measured depth statistics for static tests at Citico Creek, TN (continued)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>0.61</th>
<th>0.66</th>
<th>0.76</th>
<th>0.78</th>
<th>0.87</th>
<th>0.91</th>
<th>0.93</th>
<th>1.07</th>
<th>1.07</th>
<th>1.13</th>
<th>1.22</th>
<th>1.37</th>
<th>1.52</th>
<th>1.68</th>
<th>1.83</th>
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<tbody>
<tr>
<td>Average (m)</td>
<td>0.62</td>
<td>0.66</td>
<td>0.76</td>
<td>0.76</td>
<td>0.93</td>
<td>0.92</td>
<td>0.96</td>
<td>1.09</td>
<td>1.08</td>
<td>1.15</td>
<td>1.22</td>
<td>1.39</td>
<td>1.57</td>
<td>1.69</td>
<td>1.84</td>
</tr>
<tr>
<td>Standard Deviation (m)</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>AAPE</td>
<td>2.38</td>
<td>2.21</td>
<td>1.35</td>
<td>2.47</td>
<td>7.12</td>
<td>1.03</td>
<td>3.20</td>
<td>2.65</td>
<td>1.97</td>
<td>2.38</td>
<td>0.77</td>
<td>1.47</td>
<td>2.71</td>
<td>1.12</td>
<td>0.89</td>
</tr>
<tr>
<td>RMSE (m)</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
<td>0.06</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.02</td>
</tr>
</tbody>
</table>
4.1.4 Conclusions

Over the calibrated range the depth sensor can accurately measure river depths greater than 0.5 m with an overall average absolute percent error of 2.42% and an average RMSE of 0.03 m, but has errors when the depth is shallower. For depths less than 0.5 m the average absolute percent error is 316.85% and the average RMSE is 0.50 m. Table 6 shows a summary of the statistics from the UTK pool and the Citico Creek tests.

Table 6. Summary of sonar measured depth statistics from the UTK pool and Citico Creek, TN tests

<table>
<thead>
<tr>
<th>Statistic</th>
<th>UT Pool</th>
<th>Citico Creek</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Less than 0.5 m</td>
<td>Greater than 0.5 m</td>
</tr>
<tr>
<td></td>
<td>Less than 0.5 m</td>
<td>Greater than 0.5 m</td>
</tr>
<tr>
<td>Average AAPE (%)</td>
<td>547.41</td>
<td>2.33</td>
</tr>
<tr>
<td>Average RMSE (m)</td>
<td>0.78</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>86.29</td>
<td>2.42</td>
</tr>
<tr>
<td></td>
<td>0.21</td>
<td>0.03</td>
</tr>
</tbody>
</table>

The Citico Creek field test shows that the sensor is capable of measuring shallower depths in a river than in the UTK pool, this could be due to the substrate type, where Citico Creek has a sandy and gravel bottom and the pool is solid concrete. Field tests show that the sensor is capable of measuring depths down to 0.15 m, although there are errors and the SDs for depths less than 0.5 m can be high. This confirms the manual’s minimum stated measurable depth for the sensor. The manual states that the resolution of the sensor is 0.003 m (0.01 ft), but the output data from the senor only goes to two decimal places, so the resolution would be limited to 0.01 m. The sensor does output depth in feet to two decimal places, which could be converted to produce the 0.003 m resolution stated. When conducting field tests, a stadia rod with 0.01 ft increments was used to measure the physical depth and measuring to that resolution was difficult in the moving water. Although the sensor could be capable at measuring depth with this resolution, it does not seem practical for the depth measurement to have this precision in
such a dynamic environment, especially because changes in depth of 0.003 m would not be important.

4.2 Vertical Movement Tests

4.2.1 Objective

The vertical movement tests were performed to assess the precision and response time of the sensor. These tests are important for assessing the sensors ability to accurately measure river depth’s rate of change. The tests will indicate if the thalweg and cross-sectional rugosity in a river can be accurately measured with sonar.

4.2.2 Data Collection and Analysis

The depth sensor started from a depth of 1.22 m and was slowly lowered and raised in the UTK pool while a time series of data was taken. Times were noted when the sensor crossed specific depths that were measured physically with a stadia rod and marked. For analysis, each sensor value needed to be compared to a physically measured depth, therefore for each second of sonar depth between the PMD, a PMD was interpolated for comparison.

4.2.3 Results

The result from the descending vertical movement test is shown in Figure 9. The sensor started from a depth of 1.22 m and descended to a depth of 0 m in 31 seconds.
Figure 9. Sonar measured depth as the depth decreases in the UTK pool

The average absolute percent error between the sonar and the PMD for the descending depth measurements is 61.3% and the RMSE is 0.33 m. When only considering depths greater than 0.4 m the average absolute percent error and RMSE are improved to 8.9% and 0.07 m, respectively. The errors at depths less than 0.4 m could be a result of the previously discussed error of the transducer still ringing causing reflected pulses to be detected and greater depths calculated.

The result from the ascending vertical movement test is shown in Figure 10. The sensor started from a depth of 0 m and ascended to a depth of 1.22 m in 29 seconds.
Figure 10. Sonar measured depth as the depth increases in the UTK pool

The average absolute percent error for the ascending sonar measurements is 390.6% and the RMSE is 0.71 m. The sensor measured depths greater than 0.5 m with an average absolute percent error and RMSE of 7.6% and 0.08 m, respectively. The errors at depths less than 0.5 m could be a result of the previously discussed error of the transducer still ringing causing reflected pulses to be detected and greater depths calculated.

4.2.4 Conclusions

The depth sensor has the ability to measure depths greater than 0.5 m both descending and ascending at an average vertical velocity of 0.04 m/s. When the depth was decreasing the
sensor was able to measure shallower depths before the sensors measurements became irregular at about 0.35 m. When the depth was increasing the sensor had irregular measurements until about a depth of 0.35 m when the sensor slowly approached the correct depth. The sensor continually responded to the changing depth and measured it well above 0.5 m depths considering the potential errors with slowly moving a depth sensor and identifying the time of exact physical depths.

4.3 Horizontal Movement Test with Uniform Depth

4.3.1 Objective

The horizontal movement test with a uniform depth was performed to evaluate the measurement error of the sonar unit moving horizontally at different velocities. This test is important to assess how the sensor measures a constant depth while moving. The test was conducted at two speeds to identify if there was a substantial effect in the sonar measurements. The slow speed represented the speed the kayak-mounted and canoe-mounted depth sensors experience in pool sections of a river, while the fast represented speeds experienced in runs and riffles.

4.3.2 Data Collection

The shallow water depth sensor was moved over a level section of the UTK pool at a slow and fast rate of speed. The slow speed was approximately 0.5 m/s (1.1 mph) and the fast speed was approximately 1.5 m/s (3.4 mph). A stadia rod was used to physically measure the depth of the pool.
4.3.3 Results

The results of the sonar measurements from a slow moving horizontal test with a uniform depth are shown in Figure 11. The PMD was 1.24 m and the average measured depth from the sonar was 1.28 m with a SD of 0.01 m. The average absolute percent error of the sonar is 3.38% and the RMSE is 0.04 m.

![Graph showing sonar measurements from a horizontal movement with a uniform depth at a slow speed in the UTK pool.](image)

Figure 11. Sonar measurements from a horizontal movement with a uniform depth at a slow speed in the UTK pool

The results of the sonar measurements from a fast moving horizontal test with a uniform depth are shown in Figure 12. The PMD was 1.24 m and the average measured depth from the
sonar was 1.29 m with a SD of 0.01 m. The average absolute percent error of the sonar is 4.09% and the RMSE is 0.05 m.

![Graph showing sonar measurements from a horizontal movement with a uniform depth at a fast speed in the UTK pool.]

4.3.4 Conclusions

The sonar measured the depth with an average absolute percent error less than 4.09% when it was moving in water with a constant depth. During the slow and fast moving tests the average depths only varied by 0.01 m and the SDs were both 0.01 m. The sonar measured depths varied from the physically measured depth by only 0.04 m for the slow test and 0.05 m for the fast test.
4.4 Horizontal Movement Test with Changing Depth

4.4.1 Objective

The horizontal movement test with a changing depth was performed to evaluate the effect of the sonar unit moving on how it measures a changing depth and if there is any delay. This test is important to assess how the sensor measures depth changes that are likely to occur in rivers. Thalweg and cross-sectional depths along a river will constantly be changing and this test simulates these depth changes.

4.4.2 Data Collection and Analysis

The kayak mounted depth sensor moved from the shallow end of the UTK pool to the deep end of the pool and back at approximately 0.25 m/s (0.56 mph) while the depth sensor collected data. Specific times where noted when the sensor passed over marked depth locations that were physically measured with a stadia rod. For analysis, each sensor value needed to be compared to a physically measured depth, therefore for each second of sonar depth between the PMD, a PMD was interpolated for comparison. When calculating the depth delay, the time between when the sensor passes a depth and the sensor outputs the depth, only the actual PMDs between the start and stop were used. Because the same depth is not always measured, half a second was used for when the PMD occurred between two sonar measured depths. When collecting the physically measured depths for the sloped surface an error occurred with one depth point that was not discovered until later. The UTK pool bottom has a consistent 14.6% slope where the test was run, but one point was well out of this trend. The error either occurred from measuring in the wrong location or from recording the depth incorrectly. A best fit point has been filled in for the error and these points can be seen in Figure 13.
4.4.3 Results

The results from the horizontal movement test with changing depth are shown in Figure 13. The sensor moved from a depth of 1.57 m to a depth of 4.67 m and back on a sloped surface. When the sensor was measuring the depth increase the average absolute percent error was 2.36\% and the RMSE is 0.08 m. When the sensor was measuring the depth decrease the average absolute percent error was 1.66\% and the RMSE is 0.06 m.

Figure 13. Sonar measured depth from horizontal movement test with changing depth in the UTK pool
The average depth delay for the sensor measuring the depth increase is 1.17 seconds and for the depth decrease is 0.75 seconds. An example of the depth delay calculation is shown in Figure 14.

![Figure 14. Example of depth delay for sonar measured depth increase](image)

### 4.4.4 Conclusions

The sonar measured the increasing and decreasing depth changes with an average absolute percent error less than 2.36%. The test displayed that even physically measuring the depth can lead to errors. Both increasing and decreasing average depth delays were very short with the delay for measuring depth increase 0.42 seconds longer. These relatively short times
could simply be from errors in the sensors position and not entirely from a slow reaction speed. There are also potential one second delays due to the output of the GPS unit and the sonar unit outputting data every second.

4.5 Horizontal Movement Test- Reaction to Objects

4.5.1 Objective

The horizontal movement test with the sonar moving over different sized objects was performed to evaluate the sensors response time to changing depth and how it is affected by objects in the sonar cone. This test was performed to assess how the sensor would respond to depth changes that occur in a river; such as rock cliffs and large woody debris.

4.5.2 Data Collection and Analysis

The depth sensor was moved over a level substrate surface with a depth of 1.39 m in the UTK pool and passed over 0.51 m tall benches placed on the bottom. The benches were constructed of a PVC frame and dense decking material for the tops. The benches were positioned to create different lengths for the sensor to pass over. The bench dimensions are shown in Figure 15 and a summary of bench configurations with dimensions are shown in Table 7. The 4.67 m long bench test was performed at three different damping values to compare how this setting effects the depth measurement. The damping value is a user modifiable setting on the depth sensor that prevents fast fluctuations in the sonar measurements. A damping value of zero means there is no damping and the value can be set as high as 100. The average time constant for each damping value was calculated from the UTK pool bottom to the bench and from the bench to the pool bottom. The physically measured depths over the bench were compared to the
sensors values for each bench configuration. The 1.12 m long bench test was run at a slow (0.5 m/s) and a fast (1.5 m/s) speed.

![Dimensions of benches used for reaction to objects test](image)

Figure 15. Dimensions of benches used for reaction to objects test

<table>
<thead>
<tr>
<th>Bench Dimensions</th>
<th>1 Bench</th>
<th>2 Benches</th>
<th>3 Benches</th>
<th>2 Benches Long</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
<td>0.56</td>
<td>1.12</td>
<td>1.68</td>
<td>4.67</td>
</tr>
<tr>
<td>Width (m)</td>
<td>2.34</td>
<td>2.34</td>
<td>2.34</td>
<td>1.12</td>
</tr>
</tbody>
</table>

### 4.5.3 Results and Conclusions

#### 4.5.3.1 Damping Value Comparison Results

The results from the 4.67 m long bench tests are shown in Figure 16, 17, and 18 for the damping values of 0, 3, and 20, respectively. The sonar set to a damping value of zero had an average time constant of zero seconds for both going from the UTK pool bottom to the bench
and from the bench to the pool bottom. Note that a few measurements recorded the depth to the bottom of the pool and not the bench. This will be discussed in section 4.5.3.4. The sonar set to a damping value of three had an average time constant of 5.4 seconds from the pool bottom to the bench and an average time constant of 2.2 seconds from the bench to the bottom. The sonar set to a damping value of 20 had an average time constant greater than 16 seconds from the pool bottom to the bench and an average time constant greater than 19 seconds from the bench to the bottom.

Figure 16. The 4.67 m long bench test with damping value of zero
Figure 17. The 4.67 m long bench test with damping value of three
Figure 18. The 4.67 m long bench test with damping value of 20

### 4.5.3.2 Damping Value Comparison Conclusions

The damping value has a substantial effect on the depth measurement from the sonar unit. The damping value of zero allows for the sensor to measure changing depth values with little or no delay, while the damping value of three causes the depth measurements to change slowly and the damping value of 20 causes extreme time delays. These tests show that if sudden changes in depth want to be recorded accurately then the damping value should be set to zero.
4.5.3.3 Damping Value of Zero Results

The zero damping value test with a 4.67 m long bench is shown in Figure 16. The average depth over the bench was 0.94 m with a SD of 0.14 m and the physically measured depth of the bench was 0.88 m. The average absolute percent error for the sonar measured depth over the bench is 7.49\% and the RMSE is 0.16 m.

The test with a 1.68 m long bench is shown in Figure 19. The average depth over the bench was 0.92 m with a SD of 0.13 m. The average absolute percent error for the sonar measured depth over the bench is 5.98\% and the RMSE is 0.14 m.

Figure 19. The 1.68 m long bench test with damping value of zero
The test with a 1.12 m long bench with a slow speed of approximately 0.5 m/s is shown in Figure 20. The average depth over the bench was 1.01 m with a SD of 0.22 m. The average absolute percent error for the sonar measured depth over the bench is 15.48% and the RMSE is 0.25 m.

Figure 20. The slow speed 1.12 m long bench test with damping value of zero

The test with a 1.12 m long bench with a fast speed of approximately 1.5 m/s is shown in Figure 21. The average depth over the bench was 0.97 m with a SD of 0.19 m. The average absolute percent error for the sonar measured depth over the bench is 10.34% and the RMSE is 0.20 m.
Figure 21. The fast speed 1.12 m long bench test with damping value of zero

The test with a 0.56 m long bench is shown in Figure 22. The average depth over the bench was 0.99 m with a SD of 0.20 m. The average absolute percent error for the sonar measured depth over the bench is 12.60% and the RMSE is 0.22 m.
4.5.3.4 Damping Value of Zero Conclusions

A summary of all the statistics calculated for each bench configuration with the average values for all tests is shown in Table 8. Several of the bench configurations have instances when the sensor is over the bench but it measures the depth to the bottom of the pool. Figure 23 shows the configuration when two or more benches were pushed together at the bottom of the pool and the gaps that could allow the sensor to measure through the bench to the bottom. When these instances are removed, assuming that the sonar was measuring to the bottom, all of the calculated statistics for the bench measurements improve substantially. A summary the improved statistics
calculated for each test with the average values for all tests are shown in Table 9, along with the number of points removed. The average depth is improved by 0.07 m with a standard deviation of 0.02 m. The improved average depth over the bench of 0.90 m is only 0.02 m off from the measured value of 0.88 m.

Table 8. Summary of sonar measured depth statistics from damping value of zero tests

<table>
<thead>
<tr>
<th>Test</th>
<th>Ave. Depth (m)</th>
<th>SD (m)</th>
<th>AAPE (%)</th>
<th>RMSE (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.67 m Long Bench</td>
<td>-0.94</td>
<td>0.14</td>
<td>7.49</td>
<td>0.16</td>
</tr>
<tr>
<td>1.68 m Long Bench</td>
<td>-0.92</td>
<td>0.13</td>
<td>5.98</td>
<td>0.14</td>
</tr>
<tr>
<td>1.12 m Long Bench Slow</td>
<td>-1.01</td>
<td>0.22</td>
<td>15.48</td>
<td>0.25</td>
</tr>
<tr>
<td>1.12 m Long Bench Fast</td>
<td>-0.97</td>
<td>0.19</td>
<td>10.34</td>
<td>0.20</td>
</tr>
<tr>
<td>0.56 m Long Bench</td>
<td>-0.99</td>
<td>0.20</td>
<td>12.60</td>
<td>0.22</td>
</tr>
<tr>
<td>Average</td>
<td>-0.97</td>
<td>0.18</td>
<td>10.38</td>
<td>0.19</td>
</tr>
</tbody>
</table>
Figure 23. Two benches together showing gaps that potentially caused the sonar to measure the bottom depth instead of the bench depth.

Table 9. Summary of sonar measured depth statistics from damping value of zero tests with assumed errors removed

<table>
<thead>
<tr>
<th>Test</th>
<th>Ave. Depth (m)</th>
<th>SD (m)</th>
<th>AAPE (%)</th>
<th>RMSE (m)</th>
<th>Points Removed</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.67 m Long Bench</td>
<td>-0.90</td>
<td>0.03</td>
<td>3.06</td>
<td>0.04</td>
<td>4</td>
</tr>
<tr>
<td>1.68 m Long Bench</td>
<td>-0.89</td>
<td>0.02</td>
<td>2.26</td>
<td>0.02</td>
<td>3</td>
</tr>
<tr>
<td>1.12 m Long Bench Slow</td>
<td>-0.90</td>
<td>0.02</td>
<td>2.40</td>
<td>0.02</td>
<td>4</td>
</tr>
<tr>
<td>1.12 m Long Bench Fast</td>
<td>-0.90</td>
<td>0.02</td>
<td>2.22</td>
<td>0.02</td>
<td>2</td>
</tr>
<tr>
<td>0.56 m Long Bench</td>
<td>-0.91</td>
<td>0.01</td>
<td>3.11</td>
<td>0.03</td>
<td>2</td>
</tr>
<tr>
<td>Average</td>
<td>-0.90</td>
<td>0.02</td>
<td>2.61</td>
<td>0.03</td>
<td>Total : 15</td>
</tr>
</tbody>
</table>
4.6 Horizontal Movement Test- Vertical Structure Interference

4.6.1 Objective

The vertical structure interference tests were performed to evaluate the sonar’s depth measurement to a sudden depth transition and when a vertical structure is in the sonar cone. These tests assess how the sensor reacts to rocks and other objects that it will encounter when collecting river depth.

4.6.2 Data Collection

The sensor was positioned in the UTK pool at varying distances from the wall to see if the depth output would change as it approached or moved away from the wall. This was conducted at a constant depth of 1.37 m. The sensor was also placed directly over the vertical transition of depth along a submerged object with a two minute time series of data collected. This was conducted three times for comparison.

4.6.3 Results

The results from the wall distance test are shown in Figure 24. The average depth for all distances is 1.42 m with a SD of 0.01 m. The PMD of 1.37 m is not shown in Figure 24 because it is 0.05 m less than the average measured sonar depth. The average absolute percent error was 3.46% and the RMSE was 0.05 m for all distances.
The results from the submerged object vertical transition test are shown as a box plot in Figure 25. The physically measured depth to the object was 0.84 m and to the bottom was 1.37 m. The three tests have a total of 350 points collected with 203 (58%) measuring bench (<0.9 m), 114 (33%) measuring the bottom (>1.3 m), and 33 (9%) measuring depths in-between. Table 10 shows a summary of the average depth, standard deviation, maximum and minimum depth for each test.
Figure 25. Vertical interference tests along the edge of a submerged object

Table 10. Summary of sonar measured depth statistics calculated from submerged object tests

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Depth (m)</td>
<td>0.89</td>
<td>0.84</td>
<td>1.35</td>
</tr>
<tr>
<td>SD (m)</td>
<td>0.05</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>Maximum Depth (m)</td>
<td>1.19</td>
<td>1.37</td>
<td>1.39</td>
</tr>
<tr>
<td>Minimum Depth (m)</td>
<td>0.86</td>
<td>0.80</td>
<td>0.83</td>
</tr>
</tbody>
</table>
4.6.4 Conclusions

The vertical structure interference wall distance test shows that the wall has little to no effect on the sonar’s measurement of the depth. There was only a slightly larger variation in the depth measurements at distances less than 0.5 m from the wall, but the overall variation was only 0.03 m.

The vertical interference tests along the edge of a submerged object exhibited much more variation on sonar depth measurements. Tests 1 and 2 appear to measure the depth to the bench more than to the bottom and test 3 measured the depth to the bottom more. These differences can be attributed to the sonar moving slightly over the edge of the object. The interesting result from these tests is that the sonar will measure depths between the top of the object and the bottom of the pool that are not actually present. This is because the sensor is using sound pulse responses from the object and the bottom to calculate a depth. These instances are rare because the average over the two minute interval for tests 1 and 2 are 0.89 and 0.84 m, which is about the depth to the actual object, and the average depth of test 3 is 1.35 m, which is about the depth to the bottom.
Chapter 5: River Cross-section Evaluation

5.1 Objective

The objective of this study was to evaluate the Kayak-mounted Sonar-based GPS Mapping System (KSMS) for use as a cross-sectional river mapping tool. The sonar measured depth was compared to the tradition method of collecting river cross-sections. These cross-sections were compared for accuracy and precision.

5.2 Study Area

Citico Creek is a mountain stream that starts from several small streams in the Citico Creek Wilderness and flows through the Cherokee National Forest in Monroe County, TN into Tellico Lake. A long pool section of the river near Young Branch Horse Camp (35.48356° N, 84.12179° W) was used for the study. Citico Creek is shown in Figure 26, with the testing section highlighted.
Figure 26. Map of Citico Creek cross-section locations at 35.48356° N, 84.12179° W
5.3 Data Collection

Three cross-sections were mapped at Citico Creek, an extra-shallow, shallow, and deep, on 3 August 2010 using the traditional method and the KSMS. Each cross-section demonstrates different depth profiles with different maximum depths. The cross-sections were profiled first using the traditional method, collecting depths at 1 m intervals or when a significant depth change occurred. The kayak-mounted depth system then mapped the cross-section ten times; five from river left to river right and five from river right to river left. One side of the extra-shallow cross-section was too shallow for the kayak to float, so the kayak-mounted depth system’s cross-sections do not go all the way across the river. Figure 27 shows the traditional method and Figure 28 shows the kayak mounted depth system collecting cross-sectional depth profiles on Citico Creek.
Figure 27. Cross-sectional depth profile collection using the traditional method on Citico Creek, TN
5.4 Data Processing

Each depth point from the kayak system has a GPS point associated with it. There are positional errors with the multiple kayak paths and the accuracy of the GPS, so not all the calculated river widths are the same. When the back of the kayak touches the edge of the water the sonar and GPS units are one meter from the edge and this distance is added to both ends of every cross-section and set at a depth of zero. The kayak depth points were normalized with the traditional methods measured river width for depth point comparison. The normalized kayak
cross-sections where then joined to the traditional survey points based on the closest point in ArcGIS. Only these points and their averages over the ten passes were compared in the analysis for cross-sectional profile accuracy.

5.5 Results

Figure 29 and Figure 30 display the results for the extra-shallow cross-sectional depth tests with a comparison of the average depth from the ten passes against the survey depth and a standard deviation plot of the ten passes. Figure 29 shows the one side of the extra-shallow cross-section that was too shallow for the kayak to float. The extra-shallow cross-section had 24 points for comparison with a maximum survey depth of 0.53 m, and the maximum depth for the averaged sonar data of 0.56 m. The survey data had an average depth of 0.33 m, while the average sonar data had an average depth of 0.37 m with an average SD of 0.17 m. The root mean square error (RMSE) and average absolute percent error (AAPE) between the survey and average sonar data is 0.11 m and 31.92%, respectively. When all survey depths below 0.5 m are omitted (18 points), as suggested by previous studies, the RMSE and AAPE improve substantially to 0.01 m and 2.06%, respectively.
Figure 29. Comparison of extra-shallow cross-sectional profiles from averaged sonar depth and survey depth at Citico Creek, TN
Figure 30. Sonar’s extra-shallow cross-sectional depth standard deviation plot from 10 passes at Citico Creek, TN

Figure 31 and Figure 32 display the results for the shallow cross-sectional depth tests with a comparison of the average depth from the ten passes against the survey depth and a standard deviation plot of the ten passes. The shallow cross-section had 29 points for comparison with a maximum survey depth of 1.05 m, and the maximum depth for the averaged sonar data of 1.00 m. The survey data had an average depth of 0.60 m, while the average sonar data had an average depth of 0.61 m with an average SD of 0.05 m. The RMSE and AAPE between the survey and average sonar data are 0.09 m and 29.53%, respectively. When all survey depths
below 0.5 m are omitted (7 points), as suggested by previous studies, the RMSE and AAPE improve to 0.03 m and 3.83%, respectively.

Figure 31. Comparison of shallow cross-sectional profiles from averaged sonar depth and survey depth at Citico Creek, TN
Figure 32. Sonar’s shallow cross-section depth standard deviation plot from 10 passes at Citico Creek, TN

Figure 33 and Figure 34 display the results for the deep cross-sectional depth tests with a comparison of the average depth from the ten passes against the survey depth and a standard deviation plot of the ten passes. The shallow cross-section had 27 points for comparison with a maximum survey depth of 1.47 m, and the maximum depth for the averaged sonar data of 1.47 m. The survey data had an average depth of 0.95 m, while the average sonar data had an average depth of 0.98 m with an average SD of 0.11 m. The RMSE and AAPE between the survey and average sonar data are 0.10 m and 13.66%, respectively. When all survey depths below 0.5 m are
omitted (5 points), as suggested by previous studies, the RMSE and AAPE improve to 0.06 m and 4.23%, respectively. When collecting the surveyed depth measurements a submerged log, commonly referred to as large woody debris (LWD), was noted and depth points were taken just before, over, and just after the log.

Figure 33. Comparison of deep cross-sectional profiles from averaged sonar depth and survey depth at Citico Creek, TN
5.6 Conclusions

These results show that the sonar measured river depths greater than 0.5 m with average absolute percent errors less than 4.23%. The extra-shallow cross-section had the most variability especially when the depth was less than 0.5 m. When measurements for depths less than 0.5 m were removed the RMSE and AAPE were improved on all cross-sections. The LWD that was marked using the traditional survey method in the deep cross-section was not identified with the sonar and this could be due to the sonar measurement not being taken directly over the log.
because each measurement is only taken every second. The traditional methods 1 m increment depth measurements may not have measured the LWD either, because it was only 0.3 m wide. The LWD was identified because a person was physically standing in the river and had to step over the log, enabling it to be easily identified and marked.

The sonar’s greatest deviations from the surveyed depths are along the more substantial depth changes. The higher standard deviations along these depth changes could be a result of the GPS and kayak operator’s positional accuracy especially when considering the river widths were normalized. Figure 35 shows a short segment of one cross-section and the distribution of depth locations from each pass with reference to the surveyed depth locations. From this figure it can be seen that it is possible when joining the sonar depth points to the survey depth points that they could be, at most, about 0.5 m away.

A previous cross-sectional evaluation study using sonar was conducted by Flug et al. (1998) on a much wider river (~100 m) using a 5 m long flat boat. The survey and sonar depth measurements were collected at static 5 m intervals. The river had a maximum depth of approximately 2.25 m and the cross-section was only collected four times with sonar. Flug et al. (1998) reported an average SD of 0.12 m, which was improved to 0.05 m when only depths greater than 0.6 m were utilized. When comparing the survey data to the sonar data at depths greater than 0.6 m, Flug et al. (1998) reported a mean squared deviation of 46 cm$^2$. The deep cross-section is the most similar for comparing results to the ones from this study. The average SD of the deep cross-section was 0.11 m. The mean squared error (deviation) for the deep cross-section was 96.9 cm$^2$, which improved to 31.5 cm$^2$ when only depths greater than 0.5 m were considered. A significant difference between the cross-sections collected for the Flug et al. (1998) study and for this study is that the depth was collected continuously with a moving boat.
producing depth measurements approximately 1 m apart that were not attempted to be positioned at the exact same location every time. The KSMS system also produced more depth points for substantially narrower cross-sections.
Figure 35. A short segment of one cross-section showing the distribution of sonar depth locations from the 10 passes with respect to the survey depth locations
Chapter 6: Thalweg Comparison

6.1 Objective

The thalweg comparison was conducted to analyze the depth sensor for accuracy and precision. The test was performed to assess the Kayak-mounted Sonar-based GPS Mapping Systems (KSMS) ability to collect continuous thalweg profiles for a river.

6.2 Study Area

Citico Creek is located in the Cherokee National Forest in Monroe County, Tennessee. The thalweg profiles were collected along a 14.6 km (nine mile) section of Citico Creek from just below Jake Best campground (35.456° N, 84.119° W) to an embayment of Tellico Lake (35.536° N, 84.106° W. The KSMS depth mapped reach of Citico Creek is shown in Figure 36.
Figure 36. Thalweg depth collected section on Citico Creek, TN for comparison from 35.456° N, 84.119° W to 35.536° N, 84.106° W

6.3 Data Collection and Depth Values

A 14.6 km road-side reach of Citico Creek was run on 30 July 2009 and on 3 April 2009 at comparable flows. Sonar depth data was collected using the KSMS for both passes down Citico Creek. The kayak sits 0.08 m (0.25 ft) in the water. This is the distance from the water surface to the bottom of the sensor and is added to each depth reading. When the reading is 0 m, the depth value is set at 0.15 m; this is the assumed average value for all depths too shallow to measure. This is because when the sensor outputs a 0 m depth, the depth could be between 0.08
and 0.23 m, assuming the kayak does not become beached. The two runs down Citico Creek have variations in the GPS positions due to the kayak’s movement down the creek and GPS errors. For this reason the GPS depth points were joined in ArcGIS by closest point within a buffer set at 10 m. This distance was selected based on kayak path variations and potential GPS errors. This potentially allowed for a GPS point from run 2 to be joined to multiple points in run 1. Run 1 had approximately 12,528 points while run 2 had 13,854 and when joined 10792 points were kept with an average distance of 1.97 m. Sixty six percent of the points (7081 points) were joined at a distance of less than 2 m. Several of the points not joined were because GPS was lost for several short sections along the river due to satellite availability and canopy coverage.

6.4 Results

The average depth from run 1 was 0.72 m and from run 2 was 0.74 m, both with a SD of 0.35 m. The average absolute percent error (AAPE) between the two runs was 29.2% and the root mean square error (RMSE) was 0.23 m. A comparison between the two runs plotted on a one-to-one line is shown in Figure 37. The X-axis is the depth from the first run and the Y-axis is the depth from the second run. If the depths collected from each run were exactly the same they would be on the one-to-one line. When collecting the depth data there were a total of 1098 points that were originally 0 m measured depths that were estimated to be 0.15 m. When these points are removed the AAPE and RMSE are improved to 19.3% and 0.20 m, respectively. A thalweg depth profile was generated from both kayak depth mapping runs and is shown in Figure 38. A detailed thalweg profile from 9.5 to 10 km is shown in Figure 39.
Figure 37. Sonar measured depth comparison between 2 runs on Citico Creek
Figure 38. The thalweg depth profiles from both kayak mapping runs on Citico Creek, TN
Figure 39. The thalweg depth profile from both runs on Citico Creek, TN from 9.5 to 10 km
6.5 Conclusions

The results show that the KSMS is capable of producing consistent thalweg depth profiles with multiple passes of a river. There is some variation in the sonar measured depths between the two kayak runs, but a lot of the variation is probably due to kayak and GPS positional errors.

The depth comparison figure shows two arms extending out from the one-to-one line between 0.5 m and 1.0 m on both the X- and Y-axes. These points, shown in Figure 40, were identified as having a difference in depth greater than 0.75 m. Figure 41 shows these 172 points and their locations on the Citico Creek section. There was no substantial positional error identified at these locations with an average distance of only 1.82 m between the two runs. Slight variations in the kayaks positioning of the presumed thalweg could cause the substantial depth differences especially if the section is more channelized and the thalweg scour is more pronounced or if the kayak cuts toward the inside curve of a bend in the river.
Figure 40. Sonar measured depth comparison with depth differences greater than 0.75 m highlighted.
Figure 41. Red points indicate locations of measured depth differences between the two sonar depth mapping runs greater than 0.75 m along Citico Creek, TN
Chapter 7: Sonar-based GPS Mapping System Implementation

7.1 Objective

The objective of this study was to use the Canoe- and Kayak-mounted Sonar-based GPS Mapping Systems (CSMS and KSMS) to collect georeferenced river depth measurements on the Driftwood River in Indiana. The depth data was utilized to generate thalweg and cross-sectional depth profiles, to compare sonar measured thalweg depths between the CSMS and KSMS, to develop a maximum depth model, and to develop a cross-sectional area model. The Lowrance LMS-350A was utilized in the canoe system and the CruzPro ATU120S in the kayak system. A comparison of river cross-sectional positioning was conducted on 15, 20, and 60 m spaced cross-sections.

7.2 Study Area and Data Collection

The Driftwood River study area in Indiana consists of a 29 kilometer (18 mile) reach starting from the confluence of the Big Blue River and Sugar Creek (39.351° N, 85.990° W). Only small tributaries flow into the Driftwood River until it joins with the Flat Rock River forming the East Fork of the White River at Columbus, Indiana (39.204° N, 85.929° W) (Figure 42). The Driftwood River is a wide (~40 m) and shallow (~1 m) river with a low gradient and only a few small riffles.
Figure 42. Location of Driftwood River, IN from 39.351° N, 85.990° W to 39.204° N, 85.929° W
The Driftwood River study was conducted from the 17 to 19 September 2009 using the KSMS and CSMS. The average streamflow for the days the river data was collected was 379 cfs (USGS, 2004-2011). Georeferenced thalweg sonar depth measurements were collected along the entire stretch of the river with the CSMS. River cross-sections perpendicular to the flow of the river were ran at approximate 60 m spacing along the entire river reach with the kayak-mounted system. Intensive cross-sectional measurements at 15 and 20 m spacing were collected at two locations. An example of the GPS data collected from both systems is shown in Figure 43. The light blue points are from the CSMS and the black points are from the KSMS. Each cross-section was cut out from the KSMS data based on noted times when paddling the river and if necessary, edited based on position.

Figure 43. Example of GPS data collected on the Driftwood River, IN
7.3 Data Processing and Organization

The data was processed extensively in Excel and ArcGIS to create a condensed database of the important information. A maximum cross-sectional depth, thalweg depth, and thalweg depth CS (from cross-section) was identified for each cross-section. Maximum cross-sectional depth and thalweg depth CS are from the kayak, while thalweg depth is from the canoe (Figure 44). The river width and cross-sectional area were calculated for each cross-section. When the back of the kayak touches the edge of the water the sonar and GPS units are one meter from the edge and this distance is added to both ends of every cross-section and set at a depth of zero.

Figure 44. Identification of depth points from the thalweg and cross-sectional profile mapping data sets
7.4 Depth Values

The depth sensors are only valid for depths greater than 0.15 m (0.5 ft) (CruzPro) and 0.40 m (1.3 ft) (Lowrance). When the depth is less than these values the sensor output a depth of 0. Very rarely when the depth is less than 0.15 m the CruzPro sensor will output a very large depth that is not reasonable as described in section 4.1.3. The error only occurred 24 out of approximately 75,000 points (0.03%). These 24 values were assumed to be 0 m depth readings. As previously described in section 6.3 the kayak depths have 0.08 m added and 0 m readings were set at 0.15 m. The Lowrance depth sensor is adjustable and is set approximately 0.08 m below the water surface. All of the Lowrance depth readings have 0.08 m added to them.

7.5 Individual Study Results and Conclusions

7.5.1 Thalweg Depth Profile Results

The thalweg depth profile for the Driftwood River was generated using the depth data from the canoe setup with the Lowrance LMS-350a. Figure 45 shows the thalweg depth profile of the Driftwood River starting at the confluence of the Big Blue River and Sugar Creek (mile 0) until it flows into the Flat Rock River (mile 18) forming the East Fork of the White River. A thematic map of thalweg depth was generated and is shown in Figure 46. The average thalweg depth of the Driftwood River is 0.96 m (3.15 ft) and the maximum depth is 6.52 m (21.39 ft).
Figure 45. Driftwood River, IN thalweg depth profile
Figure 46. Depth map of the Driftwood River, IN
7.5.2 Thalweg Depth Profile Conclusions

The CSMS was successful at collecting a thalweg depth profile for the entire Driftwood River with 31,407 data points collected. A total of 7,453 depth values (23.7%) were less than the Lowrance sonar can measure and were assumed to be a depth of 0.15 m. A thalweg depth profile for the river and a thematic map of the depth was successfully created and allows for the identification of shallow and deep sections of the river.

7.5.3 Cross-Sectional Depth Profile Results

During the study 448 cross-sections were collected with the KSMS. It is possible to develop a cross-sectional depth profile for each cross-section; an example using cross-section 239 is shown in Figure 47. The cross-sections enabled the identification of the maximum depth and the calculation of river width, cross-sectional area, and average velocity. It would also be possible to calculate the wetted perimeter of the cross-section. The river width was calculated for each of the 448 cross-sections as a straight line distance from the endpoints of each cross-section.

The average calculated river width for the Driftwood River was 40.23 m, with a maximum width of 78.10 m and a minimum width of 7.47 m. The area of each cross-section was calculated by a summation of the point to point area between each depth point. The average cross-sectional area for the river is 38.64 m$^3$, with a maximum of 133.86 m$^3$ and a minimum of 3.60 m$^3$. The Driftwood River flow can be estimated from two United States Geological Survey (USGS) gages that are located near the confluence of the Driftwood and Flatrock Rivers. The estimated Driftwood River flow can be calculated by subtracting the flow at the Flatrock River gage from the flow at the East Fork White River gage, which can be seen in Figure 48. The average flow for the days the river data was collected was 10.73 m$^3$/s (379 cfs) (USGS, 2004-2011). The
average velocity of each cross-section can be calculated with this information and the average velocity of the Driftwood River was 0.38 m/s, with a maximum of 2.98 m/s and a minimum of 0.08 m/s. Thematic maps were created for each of the river features and are shown in Figure 49 through Figure 51.

Figure 47. Cross-sectional profile generated for cross-section 239 on the Driftwood River, IN
Figure 48. Location of streamflow gages used to estimate the flow of the Driftwood River, IN
Figure 49. Thematic map of cross-sectional area for the Driftwood River, IN
Figure 50. Thematic map of river width for the Driftwood River, IN
Figure 51. Thematic map of average cross-sectional velocity for the Driftwood River, IN
7.5.4 Cross-Sectional Depth Profile Conclusions

The KSMS successfully collected 448 cross-sections on the Driftwood River. The data can be used to generate cross-sectional profiles for any of the cross-sections mapped. The data enabled the identification of the maximum cross-sectional depth and the calculation of river width, cross-sectional area, and average velocity. Thematic maps were able to be generated for each of the river attributes.

7.5.5 Thalweg Depth Comparison between Sonar Units Results

A comparison between the CruzPro (KSMS) and Lowrance (CSMS) sonar units was conducted using the river collected data. The closest depth to the thalweg line made by the canoe in the cross-section was identified as the thalweg depth CS (Figure 44). These two points were compared to see if there is a significant difference between the measured depths from the two sonar units. Figure 52 shows a comparison of the two thalweg depth values plotted against a one-to-one line. The data follows the line well with some natural variation, which is expected, especially since the depth values are not at the exact same location. A paired t-test was run on the thalweg depth and thalweg depth CS to see if the means differ. All of the recorded zero values were removed from both columns of data for this analysis. The mean thalweg depth from the Lowrance was 1.25 m, with a standard deviation of 0.70 m, and the mean thalweg depth from the CruzPro was 1.26 m, with a standard deviation of 0.66 m. The results from the test, the calculated t-value was 0.55 and the t-critical value was 3.29, show that the means for the two sonar units are not significantly different at an alpha level of 0.001.
Figure 52. Thalweg depth comparison between the CSMS and KSMS

7.5.6 Thalweg Depth Comparison Conclusions

The thalweg depth comparison shows that there is not a statistically significant difference between the thalweg depth values collected from the CruzPro and Lowrance sonar units. The CruzPro sonar unit is accurate to shallower depths and will be used for further analysis.

7.5.7 Maximum Depth Model Results

The thalweg depth values measured by the KSMS were utilized to generate a model that would predict the maximum cross-sectional depth. The maximum cross-sectional depth was
identified from each of the 448 cross-sections. The thalweg depth versus the maximum cross-sectional depth is plotted in Figure 53. The average absolute error between the thalweg depth and the actual maximum CS depth is 0.48 m, with an average percent error of 21.5%. Figure 53 shows that all the depth points are on or above the 1-to-1 line, therefore maximum cross-sectional depth is always greater than the thalweg depth.

![Figure 53. Thalweg depth from KSMS versus maximum cross-sectional depth](image)

The maximum cross-sectional depth can be estimated as a function of the thalweg depth. A predicted depth ratio (PDR) variable was generated and multiplied by the thalweg depth to create a linear model that estimates the maximum cross-sectional depth. A good estimator of the
PDR is the average percent error between the thalweg depth and the maximum cross-sectional depth.

The model to predict maximum cross-sectional depth ($D_m$) based on thalweg depth ($D_t$) is:

$$D_m = \text{PDR} \times D_t$$  \hspace{1cm} \text{Equation 1}

where

$D_m$ = maximum depth of cross-section (m)

PDR = predicted depth ratio

$D_t$ = thalweg depth (m)

If the average percent error added to 1 is used as the PDR and substituted into the equation, it becomes:

$$D_m = 1.215 \times D_t$$

Figure 54 shows the model predicted values in relation to the original data. The linear maximum depth model has an $R^2$ value of 0.36 signifying that 36% of the total variation of the maximum depth is explained by the variation in the thalweg depth. The average absolute error is 0.40 m, the average absolute percent error (AAPE) is 24.6%, and the root mean squared error (RMSE) is 0.63 m. Considering the natural variation in the river bed-form of rivers, the model predicts the maximum depth reasonably well. The issue with this model is that as the thalweg depth increases the predicted maximum depth separates from the observed trend. This is due to the PDR not being a constant value, but actually decreasing as the thalweg depth increases.

Figure 55 shows how the PDR approaches one, which means that as a river becomes deeper the thalweg depth and the maximum depth become the same. This explains the commonly used definition of thalweg; for large rivers the thalweg depth is the maximum cross-sectional depth.
Figure 54. Linear maximum depth model for the Driftwood River, IN
A logarithmic regression line was fit through the predicted depth ratio data in Excel (Figure 55). The equation for the PDR is:

\[ PDR = -0.249 \ln D_t + 1.278 \]  

\text{Equation 2}

Because it is known that the maximum depth will never be less than the thalweg depth, this equation becomes invalid at a thalweg depth of approximately 3.0 m. Therefore the range of the PDR equation is set for thalweg depths between 0 and 3.0 m and all greater depths the PDR is 1. The modified maximum depth model from equation 1 is now:

\[ D_m = -0.249 \ln D_t + 1.278 \times D_t \]  

\text{Equation 3}
The predicted maximum depth is shown in relation to the measured data in Figure 56. The non-linear maximum depth model has an $R^2$ of 0.43, an average absolute error of 0.36 m, an AAPE of 21.9%, and the RMSE is 0.59 m. All of these values are improved from the linear model and the predicted maximum depth better follows the observed trend.

![Figure 56. Modified maximum depth model output](image)

When river width values are collected along with the thalweg depth a multiple regression can be used to predict the maximum cross-sectional depth. The PDR value is significantly reduced and can be made a constant because the river width variable compensates for the
variation. The multiple regression model to predict maximum cross-sectional depth based on thalweg depth was calculated to be:

\[ D_m = 1.02 \times D_t + 0.01 \times RW \]  \hspace{1cm} \text{Equation 4}

where

\( RW = \text{river width (m)} \)

The predicted maximum depth is shown in relation to the measured data in Figure 57. The maximum depth multiple linear regression model has an \( R^2 \) of 0.49, an average absolute error of 0.36 m, an AAPE of 23.6\%, and the RMSE is 0.56 m. This model has a more dynamic prediction of the maximum depth which is similar to the measured data. This model has an improved \( R^2 \) and RMSE with no change in the average absolute error, and a slightly higher AAPE.
7.5.8 Maximum Depth Model Conclusions

The results from the maximum depth model analysis show that the maximum depth can be predicted as a function of the thalweg depth or the thalweg depth and river width. The linear model with a constant PDR is very simple and predicts the maximum depth fairly well especially at shallower depths. The constant PDR value causes the model to predict higher maximum depth values as the thalweg depth increases. This model would probably have to be modified depending on the type of river that it is used on because the PDR value would most likely change with river type.
The non-linear maximum depth model has improvements in the predicted maximum depth especially at the higher thalweg depths. The PDR was identified to approach one as the thalweg depth increased and this model compensated for the change. The non-linear maximum depth model is not dimensionally homogeneous, which makes it less intuitive. This model would be more applicable to many different rivers because it is reasonable to assume that the PDR will approach one as the thalweg depth increases. More analysis would be necessary to identify how it changes in different river systems.

The maximum depth multiple linear regression model predicts the maximum cross-sectional depth the best, but requires the added input of river width. The model is dimensionally homogeneous and is more intuitive because it is logical that the river width would have an impact on the maximum depth. The PDR is a much smaller constant value and it is reasonable to assume that it would become one above a certain thalweg depth and at this point the river width would not have an impact on the maximum depth. Further analysis especially on larger river would need to be performed to identify when this occurred.

7.5.9 Cross-Sectional Area Model Results

The cross-sectional area of the river was modeled based on the thalweg depth and river width. Predicting the cross-sectional area of a river allows for the cross-sectional area and the average river velocity, when flow data is available, to be estimated at any point along the river. The cross-sectional area of a river can be thought of as a function of the river width and depth. This study collected the thalweg depth so it was used along with a constant to predict the cross-sectional area. Excel was used to fit a linear model to the river width multiplied by the thalweg
depth versus the calculated cross-sectional area. Figure 58 shows this plotted with the best fit linear regression model. This cross-sectional area model is:

\[ A_{CS} = 0.824 \times D_t \times RW \]

where

\[ A_{CS} = \text{area of cross-section (m}^2\text{)} \]

The results from this model plotted versus the calculated areas with a one-to-one line are shown in Figure 59. The cross-sectional area linear regression model has an \( R^2 \) of 0.56, an average absolute error of 9.34 m\(^2\), an AAPE of 24.5\%, and the RMSE is 12.96 m\(^2\).
An alternative way to estimate the cross-sectional area is to incorporate the river width and mean cross-sectional depth into the prediction. The river width divided by the mean cross-sectional depth is commonly referred to as the width to depth ratio when using bankfull values (Rosgen, 1994). The mean depth is calculated by dividing the cross-sectional river area by the river width. Therefore the mean depth multiplied by the river width can be used to predict the cross-sectional area. The cross-sectional area model using the river width and mean depth is:

$$A_{CS} = D_{avg} \times RW$$

Equation 5

where

$$D_{avg} = \text{mean depth (m)}$$
Because the mean depth cannot be measured it has to be estimated and the thalweg depth was used to do this. The mean depth was calculated for the 448 cross-sections using the calculated cross-sectional area and river width. Figure 60 shows the mean depth plotted against the thalweg depth. A linear regression model was fit through the data to predict the mean cross-sectional depth using the thalweg depth and the equation is:

\[ PD_{avg} = 0.565 \times D_t + 0.369 \]  

Equation 6

where

\[ PD_{avg} = \text{predicted mean depth (m)} \]

Figure 60. Mean depth plotted versus the thalweg depth with a linear regression model fit to the data
The mean depth linear regression model has an $R^2$ of 0.66, an average absolute error of 0.20 m, an AAPE of 22.1%, and the RMSE is 0.28 m. The predicted mean depth model from Equation 6 can be substituted for the mean depth in Equation 5 to produce a model to predict the cross-sectional area using the thalweg depth and river width and is shown below.

$$A_{CS} = 0.565 \cdot D_t + 0.369 \cdot RW$$

Equation 7

The results from cross-sectional model using the predicted mean depth form the thalweg depth are plotted versus the calculated areas with a one-to-one line in Figure 61. The cross-sectional area model using the predicted mean depth and river width has an $R^2$ of 0.69, an average absolute error of 7.88 $m^2$, an AAPE of 22.1%, and the RMSE is 10.89 $m^2$. All of these values are improved from the linear model.
7.5.10 Cross-Sectional Area Model Conclusions

The linear cross-sectional area model is a simple way of estimating the cross-sectional area of a river utilizing the thalweg depth and river width. Although this model produces good results the thalweg depth is not conventionally used in river cross-sectional area analysis and the constant value would probably have to be modified depending on the river type. The cross-sectional area of a river is more commonly associated with the mean cross-sectional depth and river width. The thalweg depth was used to predict the mean cross-sectional depth and incorporated into an equation using the mean depth and river width to predict the cross-sectional area. The cross-sectional area model using the predicted mean depth improved the prediction of the cross-sectional area. The model using the mean depth and river width to predict the cross-sectional area should be valid on all rivers, but the model used to predict the mean depth would have to be further analyzed if it were to be used on other rivers.

7.5.11 Cross-Sectional Positioning Comparison Results

Two intensive cross-section spacing samples were collected along different sections of the river; 13 at approximate 15 m spacing and 10 at approximate 20 m spacing. T-tests were performed on the three measured values from the mapping systems, the thalweg depth, maximum cross-sectional depth, and river width, for the intensive spacing versus the regular 60 m spacing to analyze if there was a significant difference.

The 15 m spaced cross-sections were made into two sample; one with all 13 cross-sections at 15 m spacing and another with four at 60 m spacing, using the first, fifth, ninth, and thirteenth cross-sections. The 15 m spaced cross-sections were first analyzed to see if there was a difference in variance. An F-test was performed on the two samples for each of the river
attributes with the results shown in Figure 62. All F-tests were performed with an alpha of 0.001 to create a 99.9% confidence level. For all three attributes the calculated F is less than the critical F value and the P value is greater than alpha, therefore the hypothesis can be accepted that the variances are the same.

The variances are equal therefore a two sample t-test assuming equal variances was performed on the river attributes and the results are shown in Figure 62. All the t-tests were performed with an alpha of 0.001 to create a 99.9% confidence level. For all three attributes the calculated t is less than the critical t value and the P value is greater than alpha, therefore the hypothesis can be accepted that the means are the same.
### Thalweg Depth

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### Maximum Depth

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<td><strong>Variance</strong></td>
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<td>0.67</td>
<td><strong>Variance</strong></td>
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<td>0.67</td>
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<tr>
<td><strong>Observations</strong></td>
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<td><strong>Observations</strong></td>
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<td>df</td>
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<td><strong>F</strong></td>
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<td>P(F&lt;=f) one-tail</td>
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<tr>
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<td>P(T&lt;=t) one-tail</td>
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</tr>
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<td>F</td>
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<td><strong>t Critical one-tail</strong></td>
<td>3.73</td>
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</tr>
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<td></td>
<td></td>
<td><strong>P(T&lt;=t) two-tail</strong></td>
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<td></td>
</tr>
<tr>
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<td></td>
<td></td>
<td><strong>t Critical two-tail</strong></td>
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### River Width

<table>
<thead>
<tr>
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<tbody>
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<td>25.92</td>
<td><strong>Mean</strong></td>
<td>26.24</td>
<td>25.92</td>
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<td>19.47</td>
<td><strong>Variance</strong></td>
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<td>19.47</td>
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<td><strong>Observations</strong></td>
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<td>13</td>
<td><strong>Observations</strong></td>
<td>4</td>
<td>13</td>
</tr>
<tr>
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<tr>
<td><strong>F</strong></td>
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<td><strong>Hypothesized Mean Difference</strong></td>
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<td></td>
</tr>
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<td>P(T&lt;=t) one-tail</td>
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<td><strong>t Critical one-tail</strong></td>
<td>3.73</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td><strong>P(T&lt;=t) two-tail</strong></td>
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<td></td>
<td><strong>t Critical two-tail</strong></td>
<td>4.07</td>
<td></td>
</tr>
</tbody>
</table>

Figure 62. Summary tables for the calculated statistics of the 15 m intensive cross-sectional study
The 20 m spaced cross-sections were made into two sample; one with all 10 cross-sections at 20 m spacing and another with four at 60 m spacing, using the first, fifth, ninth, and thirteenth cross-sections. The 20 m spaced cross-sections were first analyzed to see if there was a difference in variance. An F-test was performed on the two samples for each of the river attributes with the results shown in Figure 63. All F-tests were performed with an alpha of 0.001 to create a 99.9% confidence level. For all three attributes the calculated F is less than the critical F value and the P value is greater than alpha, therefore the hypothesis can be accepted that the variances are the same.

The variances are equal therefore a two sample t-test assuming equal variances was performed on the river attributes and the results are shown in Figure 62. All the t-tests were performed with an alpha of 0.001 to create a 99.9% confidence level. For all three attributes the calculated t is less than the critical t value and the P value is greater than alpha, therefore the hypothesis can be accepted that the means are the same.
### Thalweg Depth

<table>
<thead>
<tr>
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</thead>
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<tr>
<td><strong>Variance</strong></td>
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<td>0.16</td>
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</tr>
<tr>
<td><strong>df</strong></td>
<td>3</td>
<td>9</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>1.21</td>
<td></td>
</tr>
<tr>
<td><strong>P(F&lt;=f) one-tail</strong></td>
<td>0.36</td>
<td></td>
</tr>
<tr>
<td><strong>F Critical one-tail</strong></td>
<td>13.90</td>
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### Maximum Depth

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<tbody>
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<td>1.56</td>
</tr>
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</tr>
<tr>
<td><strong>df</strong></td>
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</tr>
<tr>
<td><strong>F</strong></td>
<td>1.25</td>
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</tr>
<tr>
<td><strong>P(F&lt;=f) one-tail</strong></td>
<td>0.35</td>
<td></td>
</tr>
<tr>
<td><strong>F Critical one-tail</strong></td>
<td>13.90</td>
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</tr>
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</table>

### River Width

<table>
<thead>
<tr>
<th></th>
<th>15 m</th>
<th>60 m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mean</strong></td>
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<td>39.07</td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>10.80</td>
<td>7.03</td>
</tr>
<tr>
<td><strong>Observations</strong></td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td><strong>df</strong></td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td><strong>F</strong></td>
<td>1.54</td>
<td></td>
</tr>
<tr>
<td><strong>P(F&lt;=f) one-tail</strong></td>
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<td><strong>F Critical one-tail</strong></td>
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<table>
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<tbody>
<tr>
<td><strong>Mean</strong></td>
<td>39.21</td>
<td>39.07</td>
</tr>
<tr>
<td><strong>Variance</strong></td>
<td>10.80</td>
<td>7.03</td>
</tr>
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<td><strong>Observations</strong></td>
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<td>4</td>
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<td><strong>Pooled Variance</strong></td>
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<td><strong>Hypothesized Mean Difference</strong></td>
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<tr>
<td><strong>df</strong></td>
<td>12</td>
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<td><strong>t Stat</strong></td>
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<tr>
<td><strong>P(T&lt;=t) one-tail</strong></td>
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<td><strong>t Critical one-tail</strong></td>
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</tr>
<tr>
<td><strong>t Critical two-tail</strong></td>
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</table>

Figure 63. Summary tables for the calculated statistics of the 20 m intensive cross-sectional study
7.5.12 Cross-Sectional Positioning Comparison Conclusions

The results from the cross-sectional position comparison study show that there is no significant difference between collecting cross-sectional river profiles at 15 m or 20 m spacing than at 60 m spacing. There was no significant difference in the means or variances of the thalweg depth, maximum cross-sectional depth, and river width.

7.6 Field Data Collection Time

The study data was collected over a three day period using two kayaks and one canoe. The kayaks spent 26.2 water-hours (the amount of time the kayak was on the water) collecting the data. It took the canoe only 11 water-hours to collect all the thalweg data. If only one boat collects the thalweg depth of a river and estimates the other variables, the time required to collect the data could be reduced by more than half. Estimating the maximum cross-sectional depth with the model would also produce values for any point on the river and not at 60 m intervals. Even more time would be saved when considering the traditional method would have taken a significantly longer time and possibly required more people.

7.7 Conclusions

The project was successful at using a Canoe- and Kayak-mounted Sonar-based GPS Mapping System (CSMS and KSMS) to collect georeferenced river depth measurements on the Driftwood River in Indiana. The depth data was used to develop a thalweg profile with an average thalweg depth of 0.96 m (3.2 ft) and a maximum depth of 6.52 m (21.4 ft). The KSMS successfully collected 448 cross-sectional depth profiles for the Driftwood River. The cross-
sections were used to identify the maximum cross-sectional depth, and to calculate the river width, cross-sectional area, and the average cross-sectional velocity. Thematic river maps were generated for these attributes to visually display where the differences are located. The thalweg depth comparison between the two sonar units showed that there is no significant difference in measured thalweg depth.

The maximum depth of a cross-section can be predicted using the thalweg depth with an $R^2$ of 0.43, an average absolute error of 0.36 m, an AAPE of 21.9%, and a RMSE of 0.59 m. When predicting the maximum depth of a cross-section using the thalweg depth and river width the $R^2$ improves to 0.49 and RMSE improves to 0.56 m. It was found that the predicted depth ratio of a river decreases with river depth and settles at a value of 1. Although it can be assumed that for all rivers the PDR value will approach 1, the equations generated might not be valid for all river types. The maximum depth model allows for estimation of the maximum cross-sectional depth at any location on the river from a measured thalweg depth by either mapping system.

The cross-sectional area of a river can be predicted using a basic linear regression using the river width and thalweg depth with an $R^2$ of 0.56, an average absolute error of 9.34 m$^2$, an AAPE of 24.5%, and the RMSE is 12.96 m$^2$. This model would have to be modified to be used on other river types, because the calculated constant would probably be different. Using the predicted mean depth and river with to model the cross-sectional area of the river improves the prediction with an $R^2$ of 0.69, an average absolute error of 7.88 m$^2$, an AAPE of 22.1%, and the RMSE is 10.89 m$^2$. The model using the mean depth and river width to predict the cross-sectional area should be valid on all rivers, but further investigation would be necessary to calibrate the model to different river types. The cross-sectional area model allows for estimation
of any cross-sectional area at any location along the river with measured thalweg depth and river width data and with flow data allows for average velocity estimations.

The results from the cross-sectional position comparison study show that there is no statistically significant difference in the means or variances of the thalweg depth, maximum cross-sectional depth, and river width collected at 15 m or 20 m spacing than at 60 m spacing. The study shows that boat mounted sonar can be used to collect large scale river depth data. These techniques can significantly reduce the amount of time necessary to collect river depth data and reduce the costs of performing large river surveys. Remote river sections not easily accessed by foot could possibly be floated to acquire data that was previously unobtainable by traditional collection methods.
Chapter 8: Conclusions

The studies conducted demonstrate that the Kayak-mounted Sonar-based GPS Mapping System (KSMS) and the Canoe-mounted Sonar-based GPS Mapping System (CSMS) can be used to collect river depth data. The CruzPro shallow water depth sensor can accurately measure depths greater than 0.5 m with an overall average absolute percent error of 2.38% and an average RMSE of 0.03 m, but has errors when the depth is shallower. The Citico Creek field test shows that the sensor is capable of measuring shallower depths in a river than in the UTK pool, this could be due to the substrate type, where Citico Creek has a sandy and gravel bottom and the pool is solid concrete. Field tests show that the sensor is capable of measuring depths down to 0.15 m, although there are errors and the SDs for depths less than 0.5 m can be high. The horizontal moving tests showed that the sonar units measure constant and changing depths very well while moving. The reaction to objects tests established that a damping value of zero (no damping) should be used to collect river depth values.

These results from the river cross-section evaluation test shows that the sonar measures the cross-sectional river profile very well at depths greater than 0.5 m. The sonar’s greatest deviations from the surveyed depths are along the more substantial depth changes. The results confirmed a previous cross-sectional evaluation study using sonar conducted by Flug et al. (1998) and showed improvements in the accuracy and resolution of the sonar depth data.

The thalweg depth comparison results show that the KSMS is capable of producing consistent thalweg depth profiles with multiple passes of a river. There is some variation in the thalweg depth profiles which can be contributed to navigational errors by the kayak operator and a portion of the variations between surveys is due to GPS positional errors.
The sonar-based GPS mapping system implementation studies demonstrate a variety of river depth mapping applications that the systems can be applied. The two sonar units implemented in the depth surveys did not show statistically significant differences in the depths measured. Thalweg and cross-sectional depth profiles of a river can be completed accurately and in substantially shorter amounts of time than other survey methods. River maps can be created for river attributes such as thalweg depth, river width, cross-sectional area, and average cross-sectional velocity. The results from the cross-sectional position comparison study show that there is no significant difference in the means of the thalweg depth, maximum cross-sectional depth, and river width between collecting cross-sectional river profiles at 15 m or 20 m spacing than at 60 m spacing.

A linear maximum depth model was generated that predicted the maximum cross-sectional depth of a river using the thalweg depth with an $R^2$ value of 0.36, an average absolute error of 0.40 m, an average absolute percent error (AAPE) of 24.6%, and a root mean squared error (RMSE) of 0.63 m. A non-linear maximum depth model was generated using the thalweg depth with an $R^2$ of 0.43, an average absolute error of 0.36 m, an AAPE of 21.9%, and a RMSE of 0.59 m. A maximum depth multiple linear regression model was generated using the thalweg depth and river width with an $R^2$ of 0.49, an average absolute error of 0.36 m, an AAPE of 23.6%, and a RMSE of 0.56 m.

A cross-sectional area linear regression model was generated that used the thalweg depth and river width to predict the cross-sectional area of a river with an $R^2$ of 0.56, an average absolute error of 9.34 m$^2$, an AAPE of 24.5%, and a RMSE of 12.96 m$^2$. A cross-sectional area model was generated using the predicted mean depth (from the thalweg depth) and the river
width with an $R^2$ of 0.69, an average absolute error of 7.88 m$^2$, an AAPE of 22.1%, and a RMSE of 10.89 m$^2$.

The long term thalweg studies analyzed the thalweg depth profiles on a three mile section of the Cumberland River in Scott County, Tennessee. The results suggest that the thalweg river depth was changing between 2004 and 2006 and remained stable from 2006 through 2011. The changing thalweg river depth profile could be attributed to a substantially higher peak streamflow event that occurred in 2004. A similarly high peak streamflow has not occurred since that time and the thalweg depth profile has remained constant in recent years. Because the streamflows were not consistent throughout the study period, the flow could have been a factor in the different thalweg depth profiles. The results from the 2004 and 2005 survey comparison suggest that streamflow affected the thalweg river depth with a statistically significant difference between the mean thalweg depths. The last four survey years did not have a statistically significant difference between the mean thalweg depths, but no conclusion can be made at this time due to the streamflow data has yet to be confirmed by the USGS.
Chapter 9: Recommendations

The use of Canoe- and Kayak-mounted Sonar-based GPS Mapping Systems (CSMS and KSMS) is an accurate and efficient way of collecting river depth data. Thalweg and cross-sectional river depth profiles can be collected using these mapping systems. The river attributes collected with the systems can be used to predict maximum cross-sectional depths, cross-sectional areas, and average velocities at any point along a river that has been mapped. River maps can be generated with any of the river attributes to help visualize and locate what is occurring on the river. The ease and quickness of using a mapping system can allow for more river studies to be conducted, on larger river sections, and they have the ability to map remote areas. The KSMS and CSMS are limited to use on rivers that have a sufficient amount of water flow for boat navigation.

It is important for the canoe or kayak operator to be observant when navigating the river, so that thalweg and cross-sectional depths are correctly collected. Cutting the corners on river bends and not maintaining a straight path can affect the quality of the data collected. When depths less than 0.5 m are identified and the specific depth data is required, more intensive traditional surveys are recommended. The collecting of river width data with distance sensors while floating the thalweg of the river would allow for better data collection and allow models to be more accurate.

More intensive sensor tests can be performed on the sonar units in both the pool and river. Multiple tests utilizing different sized objects of different densities both static and moving would be useful. Tests with different object in parts of the sonar cone would show how they could affect the sonar depth measurements.
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Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.


Vita

Kenneth Wray Swinson was born in San Bernardino, California and moved to Tennessee when he was 10 years old. He graduated from Farragut High School and attended the University of Tennessee, Knoxville where he earned a Bachelor’s Degree in Biosystems Engineering in May, 2009. During his academic tenure he worked as a research assistant under Dr. Paul Ayers and had an internship at Strata-G, LLC. Ken continued his education as a Master’s student in Biosystems Engineering in 2009.