Title: Mapping Lake Sturgeon *Acipenser fulvescens* spawning habitat in the Upper Tennessee River using side scan sonar

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Abstract

The Lake Sturgeon *Acipenser fulvescens* is a fish species that was once dispersed widely throughout the Mississippi River drainage but was largely extirpated from the southern portions of its range by overfishing and habitat degradation. There is an ongoing restoration effort to reestablish the Lake Sturgeon to rivers of the Southeastern United States. Reintroduced juvenile Lake Sturgeon now occupy several reservoirs along the Upper Tennessee River that are separated from each other by hydroelectric dams. To complete their life history, Lake Sturgeon will migrate upriver from reservoir habitats to more lotic habitats and spawn over coarse rocky substrate, even in the tailwaters of impassable dams. We mapped the substrate of four tailwaters that may be future Lake Sturgeon spawning locations using low-cost, consumer-grade side scan sonar and a GIS. We used video imagery collected from random locations within the mapped areas to validate our digitization of sonar imagery. We calculated the area of four substrate classes displayed in the maps to assess the suitability of each of the tailwaters for Lake Sturgeon spawning. The best spawning substrate (unembedded, coarse, rocky substrate 6 – 25 cm in diameter) comprised 17.0 – 30.5% of the total area mapped at each dam, while the least suitable substrate class (fine sediment <0.2 cm in diameter) comprised 6.2 – 30.7% of the mapped areas. Our results suggest any future spawning events by Lake Sturgeon below each of these dams are likely to encounter some suitable spawning substrate patches, while management opportunities exist to supplement other tailwater areas with suitable spawning substrate.

Introduction

In North America, there are ten extant species of Acipenseriforme fishes (Cech and Doroshov 2004). Seven of the ten species are considered vulnerable, threatened, or endangered by the IUCN (2015) and most have been afforded state or federal protections in the U.S. (Birstein 1993; Jelks et al. 2008). Factors contributing to their widespread decline include degradation of habitat by pollution, loss of connectivity to spawning grounds, and overexploitation (Billard and Lecointre 2001). The Lake Sturgeon *Acipenser fulvescens* historically occurred in large rivers and lakes of the Mississippi River, Great Lakes, and Hudson Bay drainages (USA) (Harkness and Dymond 1961; Scott and Crossman 1973; Becker 1983; Etnier and Starnes 1993). This species is potamodromous and only inhabits freshwater (Boreman 1997). The Lake Sturgeon is believed to be largely extirpated from the southern reaches of the Mississippi River, where numbers may have been low prior to anthropogenic alterations to the populations (Etnier and Starnes 1993; Williamson 2003). Over 150,000 juvenile Lake Sturgeon have been released in rivers across the Southeast since 2000, and ongoing monitoring efforts are tracking Lake Sturgeon movement and growth (M. Cantrell, U.S. Fish and Wildlife Service, unpublished data). One of the major objectives of this reintroduction effort is to facilitate the resurgence of successful natural spawning and recruitment of Lake Sturgeon in the Tennessee River.

Lake Sturgeon spawning migrations appear to be largely triggered by rising springtime water temperatures (Bruch and Binkowski 2002). In many river systems occupied by Lake Sturgeon, the river is fractured by dams that are likely to be impassable by migrating Lake Sturgeon (Auer 1996). However, Lake Sturgeon have been found to successfully spawn in the tailwaters immediately downstream of dams that they cannot surmount (LaHaye et al. 1992; McKinley et al. 1998; Caswell et al. 2004). The fertilized eggs are adhesive, so it is advantageous for Lake Sturgeon to spawn over coarse rocky substrate (Auer and Baker 2002). The open interstitial spaces between rocks provide cover for developing embryos, and larger particles are less likely to be dislodged by high water flows which may reduce exposure of the embryos to predation and physicochemical stressors (Threader et al. 1998).

When the reintroduced Tennessee River Lake Sturgeon reach sexual maturity, they will attempt spawning migrations. When this occurs, many of the fish will encounter one of four large hydroelectric dams on the Upper Tennessee River (Fort Loudoun, Watts Bar, Chickamauga, and Nickajack dams) and some may attempt to spawn in the tailwaters below those dams. To assess the suitability of these four tailwaters for future Lake Sturgeon spawning events, we collected and processed side scan sonar imagery of the riverbed in the tailwaters using consumer-grade fish finder units (Kaeser and Litts 2010). We used the sonar imagery and reference video imagery to create predictive maps of the substrate in the tailwaters. Our objectives were to 1) classify the substrate found in the tailwaters and score the substrate using the Lake Sturgeon HSM, and 2) to estimate the total area of each class at each dam. Using those estimations, we then assessed the suitability of each tailwater for future Lake Sturgeon spawning events.

<A>Methods

Study sites.—We conducted sonar surveys of the tailwaters immediately downstream of the four upstream-most dams on the mainstem Tennessee River, listed here in order from upstream to downstream: Fort Loudoun dam, Watts Bar dam, Chickamauga dam, and Nickajack dam (Figure 1). For the purposes of this study, we refer to the tailwater sites by the name of the dam immediately upstream, although the site is actually a part of the next reservoir downstream (e.g., what we refer to as the Fort Loudoun tailwater is a part of Watts Bar reservoir, etc.). Fort Loudoun dam is located on the Tennessee River in Loudoun County, Tennessee (35.791 ^{o}N, 84.243 ^{o}W). The dam was closed in 1943, and contains four hydroelectric generating units with a combined capacity of 162 MW. The dam measures 37.19 m tall by 1277.11 m wide. Watts Bar dam is located at the boundary between Meigs and Rhea Counties, Tennessee (35.621 ^{o}N, 84.782 ^{o}W). Watts Bar dam was completed in 1943, and contains 5 hydroelectric generating units with a combined capacity of 182 MW. Watts Bar dam is 34.14 m tall and 902.21 m wide. Chickamauga dam is located in Hamilton County, Tennessee (35.105 ^{o}N, 85.229 ^{o}W). Chickamauga dam was closed in 1940, and houses four hydroelectric generating units with a combined capacity of 199 MW. The dam is 39.32 m tall by 1767.84 m wide. The descriptive information for each of the dams was accessed at the Tennessee Valley Authority’s website (available online at https://www.tva.gov/Energy/Our-Power-System/Hydroelectric/).

Each survey consisted of parallel transects using a total sonar beam width of 76.2 m. Each transect began as close to the dam as conditions allowed, and continued downstream for approximately two river kilometers (RKM). Our sonar surveys of each tailwater were completed between 10 May 2015 and 26 May 2015, when flows had subsided from the higher spring releases.

Sonar imagery collection.—We utilized the sonar imagery collection and geoprocessing procedure developed by Kaeser and Litts (2008; 2010) and Kaeser et al. (2013) with some modification for sonar imagery collection and processing. We collected the sonar imagery of the substrate in each tailwater from approximately 25 m from the base of each dam to approximately 2 RKM downstream in parallel, longitudinal transects. We utilized both the side scan sonar and global positioning system (GPS) capabilities of a Humminbird® 1199ci HD SI fishfinder unit (Johnson Outdoors Marine Electronics, Racine, WI). We made the decision to utilize the GPS data from the Humminbird unit after preliminary tests had demonstrated the accuracy of the Humminbird unit when compared to GPS data collected at the same test locations with a Garmin® GPSmap 76CS handheld GPS unit (Garmin International, Inc., Olathe, KS). All of the surveys were conducted in a 4.62 m aluminum johnboat with a 60 hp Yamaha® outboard jet motor (Yamaha Corporation, Hamamatsu, Japan). We used a custom-built, adjustable aluminum arm to mount the sonar transducer in the bow of the boat, where the sonar imagery would not be affected by propeller wash (Figure 2). As the GPS data is collected from the Humminbird® unit and not the sonar transducer, all of the final sonar imagery products are displayed approximately 4 m upstream of their true physical location.

To collect the sonar imagery, we set the side scan sonar to a beam width of 38.1 m to each side. We set the sonar frequency to 455 kHz. We used the default screen scroll speed. We programmed an interval timer alarm to sound when small overlaps in the scrolling imagery occurred before we began image collection at each site. We used intervals of 18 – 27 s, which were determined by environmental conditions at the tailwater at the time of survey (e.g., the current flow conditions at each dam and the number of personnel and equipment in the boat). We also ensured that the unit was continuously collecting trackpoints, which are waypoints collected at 3-s intervals. Once the settings were finalized, we began the first downstream transect to collect the sonar imagery. We began the first transect at each tailwater positioned so that one of the banks of the river was evident in the sonar imagery. We would position the boat as close as conditions safely allowed to the dam, then turn downstream and allow the sonar imagery collected during the turn to clear. After the image was aligned with the direction of the boat, we began capturing sequential, overlapping sonar images of thetransect and saved them to a removable 32 GB memory card. We proceeded downstream for each transect, maneuvering the boat along the contours of the river and avoiding obstacles when necessary. We referenced the waypoints marked on the map screen of the Humminbird® unit periodically when the transects were in open water in an attempt to maintain equal width between transects and ensure the most even sonar cover of the width of the river. Once the entire width of the tailwater had been covered by a series of parallel transects, we exported all of the waypoint and trackpoint GPS data to the memory card for processing into sonar image mosaics.

Sonar data processing.—To process the individual sonar images into mosaics for each transect, we first batch-clipped the sonar imagery using the program IrfanView (Irfan

Skilijan 2015) to remove the extraneous collar saved with the sonar imagery when captured. We then uploaded the waypoints associated with each of the image captures to ArcMap 10.0 (ESRI, Redlands, CA). The waypoints were converted to Universal Transverse Mercator (UTM) projection and displayed for inspection. We next uploaded the trackpoints collected during the surveys and transformed them to UTM as well. We deleted the trackpoints collected during the positioning of the boat between each transect, so that we had a series of waypoints associated with the sonar images and the trackpoints that defined the path of the boat as it collected the sonar imagery for each transect. We then created a trackline from the trackpoints using the B-spline function in the ET GeoWizards add-on (ET SpatialTechniques, Pretoria, South Africa) in ArcMap.

We used the 'sonar tools' toolbox in ArcGIS 10.0 (available for download online at http://www.fws.gov/panamacity/sonartools.html) to process the raw sonar images into georeferenced sonar image mosaics. We processed each transect individually. First, we used the sonar tools to batch identify the overlap points in each sequential image, and then stitched the images together at the overlap points to generate an image mosaic. Next, we generated a control point network with the associated trackline and waypoint information for that transect, which we applied to the raw sonar image mosaic to georeference the imagery. We saved the spatially-explicit georeferenced sonar image mosaics for each transect as individual raster layers for display adjusting for improved clarity and the digitization process.

Ground data collection and processing.—Once we had created the georeferenced sonar image mosaics for each of the transects completed at each tailwater, we loaded all of the raster layers into ArcMap over a National Agriculture Imagery Program (USDA 2014) orthoimage of the tailwater (natural color, 1 m ground sample distance, 6 m horizontal accuracy). We then digitized by hand a polygon that encircled all of the area mapped by the sonar survey transects bounded by the river bank displayed in the NAIP image, to create a single polygon encompassing the entire area mapped by the sonar surveys at each tailwater. With this polygon, we used the random point generator tool in ArcMap to randomly generate 50 points within the polygon outlining the area mapped. We set a buffer of 20 m radius around each point to reduce overlap of the points and ensure we could collect reference data at each point from a boat that was likely to be moving continuously during ground data collection. We converted the location data of each point at each tailwater from UTM to GPS coordinates, and revisited each tailwater to collect reference ground data of the substrate (Congalton and Plourde 2002).

We went to each of the 50 randomized points located in each tailwater and deployed a SplashCam® Deep Blue Pro underwater camera system (Ocean Systems, Inc., Everett, WA) to record video imagery of the substrate at each point. We saved all of the imagery recorded at each point with a Sony® DCR-DVD203 HandyCam (Sony Corporation, Tokyo, Japan). We reviewed the images captured at each of the locations on a computer in a laboratory setting, so that we could slow down and rewind the images to ensure accurate classification of the substrate at each location. We utilized a classification scheme that we developed from a combination of our observations of tailwaters at Douglas and Cherokee dams, made prior to our sonar surveys when the releases from the dams were minimal and exposed much of the substrate immediately below the dams, and including classes of substrate we expected to encounter (Table 1).

Substrate classification and assessment.—We began with an initial classification scheme that contained 10 classes of substrate (Table 1). Additionally, we attempted to define the classes such that if we were unable to generate sonar image maps of sufficient resolution to accurately interpret the various classes from the sonar imagery, we could collapse the original substrate classes into fewer more broadly defined classifications. We conducted analog image interpretation and digitization of the various substrate classes listed in Table 1 (Narumalani et al. 2002). We conducted all of the digitization at the raster resolution scale (1:939). We made decisions about classifying the substrate patches based on the intensity of the sonar reflection (brighter images indicating harder substrate) and texture of nearby sonar imagery. We used different colors corresponding to each of the classes listed in Table 1, and digitized all patches as separate polygon shapefile layers.

We assigned the original ten substrate classes used in the digitization and video image classification scores of 1 – 4 based on the scoring in the Lake Sturgeon HSM, to assign biological relevance to the substrate classes and simplify validation. Once we had completed digitizing patches of substrate following the classification scheme in Table 1, we overlaid the waypoint data and associated substrate classifications of the ground data reference points. We calculated an accuracy assessment of the first substrate maps by generating an error matrix. Given the low accuracy values found in our error matrix, we created second editions of the substrate maps using four more broadly defined substrate classes and scores from (Table 2). We reclassified the substrate observed in the ground data video imagery into the four classes of substrate from the HSM and then overlaid the ground data on the georeferenced sonar image mosaics. We then completed a second analog digitization of the substrate, using the four substrate classes displayed in the sonar imagery and in the video imagery. We used the sonar imagery as a guide to identify boundaries among the four substrate patches. As we used both the reference ground data and the sonar imagery in creating the second edition maps, we did not calculate a second error matrix. All of the ground data points were contained in polygons of their respective substrate type.

<A>Results

<B>First edition substrate maps

We generated georeferenced sonar image mosaics for each transect conducted at each of the four dams. We used between 6 and 9 transects to cover the width of the river at each dam, and while the coverage was imperfect, the gaps in the sonar imagery from either gaps in the coverage of the transects or errors in the image processing procedures were of a small enough area to not interfere with the digitization process (Figure 3). We digitized the substrate patches we observed in the sonar imagery using polygons corresponding to the substrate classifications listed in Table 1 (Figure 4). We digitized substrate patches across transects where needed, and used underlying transects to interpret substrate present in the data gaps of some transects, particularly when the overlaying image had lost resolution at the edges of the transect. Our first interpretations of the sonar maps suggested that fine substrate particles (< 0.2 mm diameter; indicated on each map in beige) were the predominant substrate at each of the dams. We observed that bedrock was present immediately below each of the dams

After we digitized the complete mapped area at each of the four dams, we overlaid the ground reference data over the collected polygons of substrate patches to assess the accuracy of our digitization. We compared the data in the attribute table for the reference points to the digitized patch underneath the point, and recorded both our classifications of the substrate type from the sonar imagery and our classifications of the substrate in the video imagery. We input this information into an error matrix to calculate our accuracy as overall accuracy, producer's accuracy, and user's accuracy (Congalton and Plourde 2002). Our overall accuracy ranged from 29% for the first digitization of the substrate at Watts Bar tailwater to 38% for the first digitization of the substrate at Fort Loudoun (Table 3). The accuracy results trended upward in the order of maps digitized, with the lowest accuracy in the map we digitized first and the highest accuracy in the map we digitized last. These low accuracy measurements led us to attempt a second edition of the maps which incorporated both the ground reference data and the sonar imagery in the digitization process.

<B>Second edition substrate maps

When we developed substrate maps the second time, we overlaid the groundtruthing data points on the georeferenced but unclassified sonar image mosaics. We then digitized new polygons using the underlying sonar imagery to inform our delineation of the boundaries among the patches of the four substrate classes found in the video imagery. The second edition of the substrate maps showed similar patterns to what we observed in the first edition maps: at the base of the dam, there was an area of bedrock, and towards the downstream end of the mapped areas there appeared to be an increase in the finer sediment classes (Figure 5).

Once we had generated the second edition substrate maps, we used the area calculator function in ArcMap to assess the total area (in square meters) of each of the four substrate classes at each of the four dams (Figure 6a). As the river width increased at the more downstream tailwaters, we adjusted for total area mapped in the 2 RKM survey locations by calculating the area of each substrate patch as a percentage of the total area mapped at that dam (Figure 6b). We visually assessed the charts for trends in the areas of the substrate classes. There is an upstream-to-downstream increasing trend in the total area of the best spawning substrate (cobble-boulder) across the tailwaters even when total width of the river is taken into consideration.

<A>Discussion

We utilized a process of collecting side scan sonar imagery and GPS data that has been recently developed to take advantage of the falling costs of consumer grade sonar equipment marketed towards recreational anglers. This low-cost option allowed us to overcome several hurdles typical of sonar projects to map underwater habitat. While sonar mapping of aquatic habitat is not a brand new methodology, many side scan sonar units were developed to conduct benthic habitat mapping of marine environments, and the equipment and software required to process the imagery can be prohibitively expensive or developed for use in deeper environments than those we encountered in the tailwaters we surveyed (Cochrane and Lafferty 2002; Lathrop et al. 2006; Brown and Collier 2008; Venteris and May 2014). Additionally, the use of underwater camera systems to collect reference data (e.g., Kaeser et al. 2012) significantly improves on the time required for data collection over the use of SCUBA/snorkel surveys (e.g. Powers et al. 2015) or sediment dredging (e.g., Lathrop et al. 2006; Venteris and May 2014), at a cost of physical examination of the substrate for classification. The complete procedure detailed here was relatively quick, requiring approximately one day in the field to collect the sonar and reference imagery for each dam, and approximately three days to process and interpret the sonar and reference imagery for each tailwater. We anticipate the processing time to reduce considerably as we continue to utilize this procedure for substrate mapping, and the tradeoff between resolution in imagery classification and speed of data collection and processing makes the procedure we used a valuable exploratory tool for classifying benthic habitat.

The overall goal of this project was to assess at some scale the substrate in the dam tailwaters we mapped so that we could judge how appropriate the tailwaters were for future Lake Sturgeon spawning events. After our first attempt at interpreting the sonar imagery, our initial accuracy estimates were inadequate (29-38%). We attribute this to differences between the resolution of the imagery we collected and the resolution necessary to utilize our initial, fine scale classification scheme. As our initial accuracy measurements were unacceptable, we revised our techniques by including video imagery to increase our confidence in our substrate interpretation and digitization results. Subsequently, by collapsing our original, uninformative substrate classification scheme into the final coarse scale version, and using a hybrid approach to creating the substrate maps presented in Figure 5, we improved our ability to describe the available substrates in Tennessee River tailwater environments, while simultaneously streamlining our assessment of suitable spawning habitat for Lake Sturgeon.

As we have generated a census of the available substrate at these dams, we did not require statistical testing to interpolate results. We noted that cobble-boulder substrate area was greater in the tailwaters of the two most downstream dams, Chickamauga and Nickajack. Annual resampling efforts have found that larger, older Lake Sturgeon appear to inhabit the reservoirs below Chickamauga and Nickajack dams relative to the reservoirs downstream of Watts Bar and Fort Loudoun dams (M. Cantrell, U.S. Fish and Wildlife Service, unpublished data). This is likely an artifact of the reintroduction process, as the majority of Lake Sturgeon have been reintroduced into Fort Loudoun reservoir near Knoxville, TN, upstream of Fort Loudoun dam. We believe that the Lake Sturgeon have slowly moved downstream from the reintroduction location, so that the fish that have made it the farthest from the reintroduction point (i.e., to Nickajack and Guntersville reservoirs, downstream of Chickamauga and Nickajack dams, respectively) are likely to be the oldest fish. As older fish are typically larger, these Lake Sturgeon are also the ones likely to reach reproductive maturity and attempt spawning first (Becker 1984). Our results suggest that if that scenario became reality, the Lake Sturgeon that aggregated in the tailwaters below Chickamauga and Nickajack dams would encounter the greatest areas of high quality spawning substrate. The conditions we have presented in our maps here suggest that those first early spawning attempts by Lake Sturgeon in the Tennessee River would be bolstered by the availability of suitable spawning substrate in the tailwaters of those two dams.

Once aggregations of reproductively mature Lake Sturgeon have been found, management actions can be taken to further augment successful reproduction. The construction of artificial spawning reefs, a management tool that has been used with success to augment Lake Sturgeon spawning and recruitment in other systems, may be useful in the continued support of natural Lake Sturgeon recruitment to the Tennessee River (LaHaye et al. 1992; Johnson et al. 2006; Roseman et al. 2011; Bouckaert et al. 2014; McLean et al. 2015). Artificial reefs can be developed in areas where reproductively mature Lake Sturgeon aggregate and the relevant water conditions are suitable for spawning. As we did not find significant differences at a coarse scale in the overall area of optimal spawning substrate among the dam tailwaters we surveyed, we recommend continued monitoring of these tailwaters and other potential migration barriers in the Tennessee River system for the presence of Lake Sturgeon when water conditions are suitable for spawning. Once an area has been found to support spawning Lake Sturgeon, further management actions, such mapping of the substrate at finer resolutions and the construction of artificial reefs can then be taken. The data we have provided here represent a baseline assessment of the substrate across these tailwaters where future Lake Sturgeon spawning events may occur. This information should be incorporated into the planning of any artificial spawning reef construction efforts.

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Tables

Table 1. Initial classification scheme used when digitizing substrate patches in the first edition substrate maps and video reference imagery.

Substrate	Characterization	Spawning Habitat Score
Bedrock	> 75% exposed bedrock	2
Mixed Rocky	≤ 50% coarse + fine matrix	3
Rocky Coarse	Discernible individual particles > 25 cm diameter	4
Rocky Fine	Particles 25 > x > 1 cm diameter	4
Riprap	Artificially placed bank stabilizing rock	4
Fine	> 75% sand, silt, clay particles ≤2 mm	1
Biological	Algae, aquatic macrophytes, zebra mussel reefs	1
Anthropogenic	Anthropogenic substrate, not riprap (e.g. concrete)	1
No Data/Sonar Shadow	No sonar image data	
No Data - Dam	No image at beginning of transect	

Table 2. Final substrate classification scheme.

Particle	Size (cm diameter)	Score
Cobble-Boulder	6 – 25	Highest
Gravel	0.2 – 6	
Bedrock	>25	
Fine	<0.2	Lowest

Table 3. Error matrices comparing the agreement between the first edition substrate maps and the ground reference imagery. The classifications (1-4) correspond to the scores assigned the various substrate types in Table 1.

Fort Loudoun	1	2	3	4	Row Total
1	5	2	0	0	7
2	5	5	6	0	16
3	1	0	2	0	3
4	1	5	4	0	10
Column Total	12	12	12	0	36

Fort Loudoun	Producer's Accuracy	User's Accuracy	Overall Accuracy
1	0.42	0.71	0.33
2	0.42	0.31	
3	0.17	0.67	
4	1	0	

Watts Bar	1	2	3	4	Row Total
1	1	2	1	0	4
2	1	2	0	0	3
3	1	1	2	0	4
4	1	9	0	0	10
Column Total	4	14	3	0	21

Watts Bar	Producer's Accuracy	User's Accuracy	Overall Accuracy
1	0.25	0.5	0.24
2	0.14	0.67	
3	0.67	0.5	
4	0	0	

Chickamauga	1	2	3	4	Row Total
1	4	6	3	4	17
2	4	0	0	0	4
3	3	0	2	1	6
4	1	9	0	9	19
Column Total	12	15	5	14	46

Chickamauga	Producer's Accuracy	User's Accuracy	Overall Accuracy
1	0.33	0.24	0.33
2	0	0	
3	0.40	0.33	
4	0.64	0.47	

Nickajack	1	2	3	4	Row Total
1	4	3	0	0	7
2	0	0	0	1	1
3	3	1	2	0	6
4	9	14	1	10	34
Column Total	16	18	3	11	48

Nickajack	Producer's Accuracy	User's Accuracy	Overall Accuracy
1	0.25	0.57	0.33
2	0	0	
3	0.67	0.33	
4	0.91	0.29	

Figure Captions.

Figure 1. Map showing location of TVA hydroelectric dams on the Upper Tennessee, French Broad, and Holston Rivers. The four dams where we conducted sonar surveys are Fort Loudoun, Watts Bar, Chickamauga, and Nickajack dams.

Figure 2. The sonar transducer arm we fabricated. The arm allowed us to place the sonar transducer in the bow of the boat, which reduced the interference of the propeller wash on the final sonar imagery. The transducer is removable, and the arm is adjustable for depth as well as raised out of the water for travel at speed in the boat. Photo credit: Todd Amacker.

Figure 3. The sonar image mosaics for each transect conducted at each dam. We conducted multiple parallel downstream transects at each dam to cover the width of the river with 78.2 m sonar width passes. Dams are shown clockwise from top left: Fort Loudoun dam, Watts Bar dam, Chickamauga dam, Nickajack dam. All four maps displayed at 1:17000 scale, and the direction has been adjusted to orient the upstream portion of the image at the top.

Figure 4. First edition substrate maps. Each map was digitized by hand at the raster resolution using the classification scheme outlined in Table 1. Dams are shown clockwise from top left: Fort Loudoun dam, Watts Bar dam, Chickamauga dam, Nickajack dam. All four maps displayed at 1:17000 scale, and the direction has been adjusted to orient the upstream portion of the image at the top.

Figure 5. Second edition of substrate maps. These maps were digitized using the classification scheme in Table 2. Dams are shown clockwise from top left: Fort Loudoun dam, Watts Bar dam, Chickamauga dam, Nickajack dam. All four maps displayed at 1:17000 scale, and the direction has been adjusted to orient the upstream portion of the image at the top.

Figure 6. Areal measurements of the various substrate classes identified in the second edition maps developed using both the sonar and ground reference imagery at each tailwater. A) the total area of each class at each tailwater; B) the area of each substrate class as a percentage of the total area mapped at each tailwater.

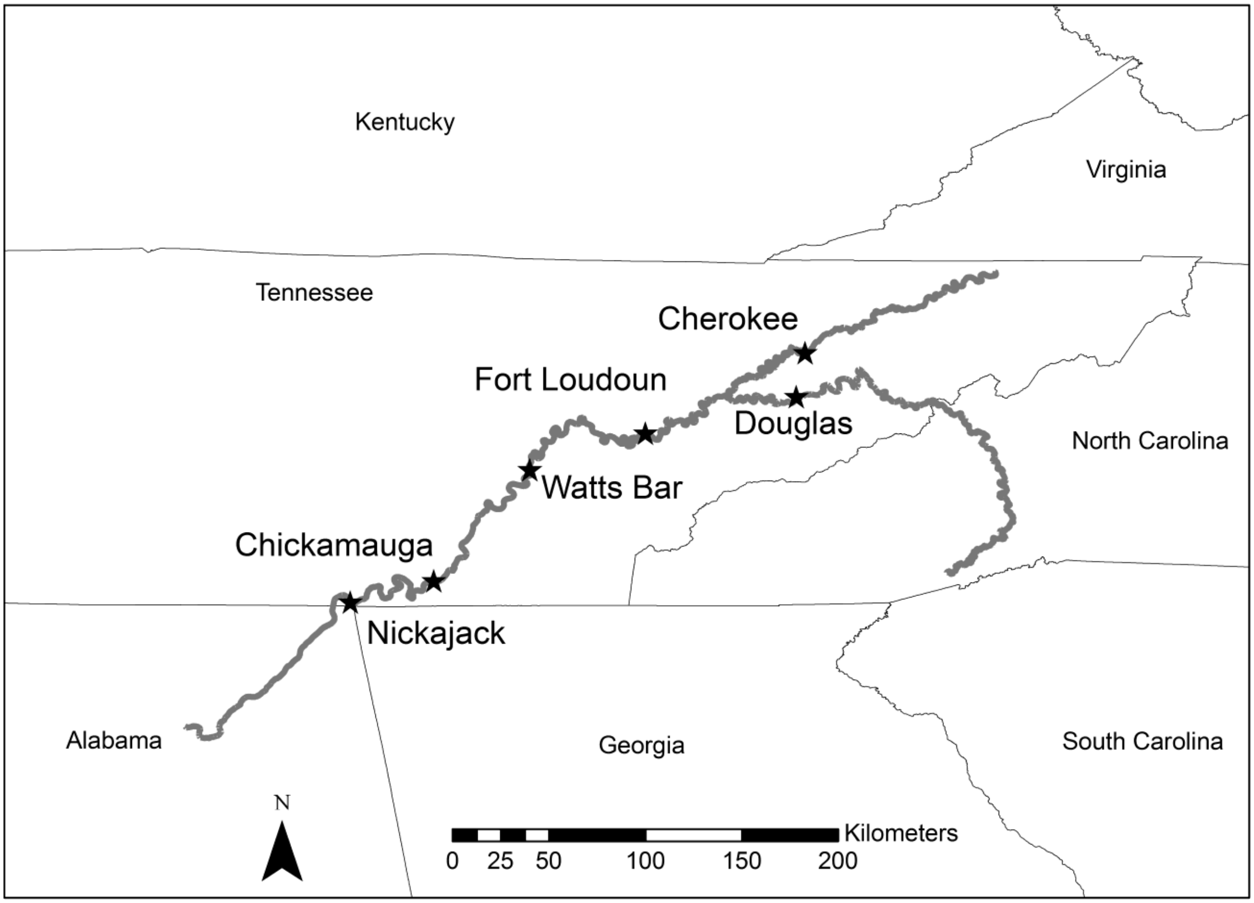

Kentucky
Virginia
Tennessee
Cherokee
Fort Loudoun
Douglas
North Carolina
Watts Bar
Chickamauga
Nickajack
Alabama
Georgia
South Carolina
N
Kilometers
0 25 50 100 150 200

Figure 1.

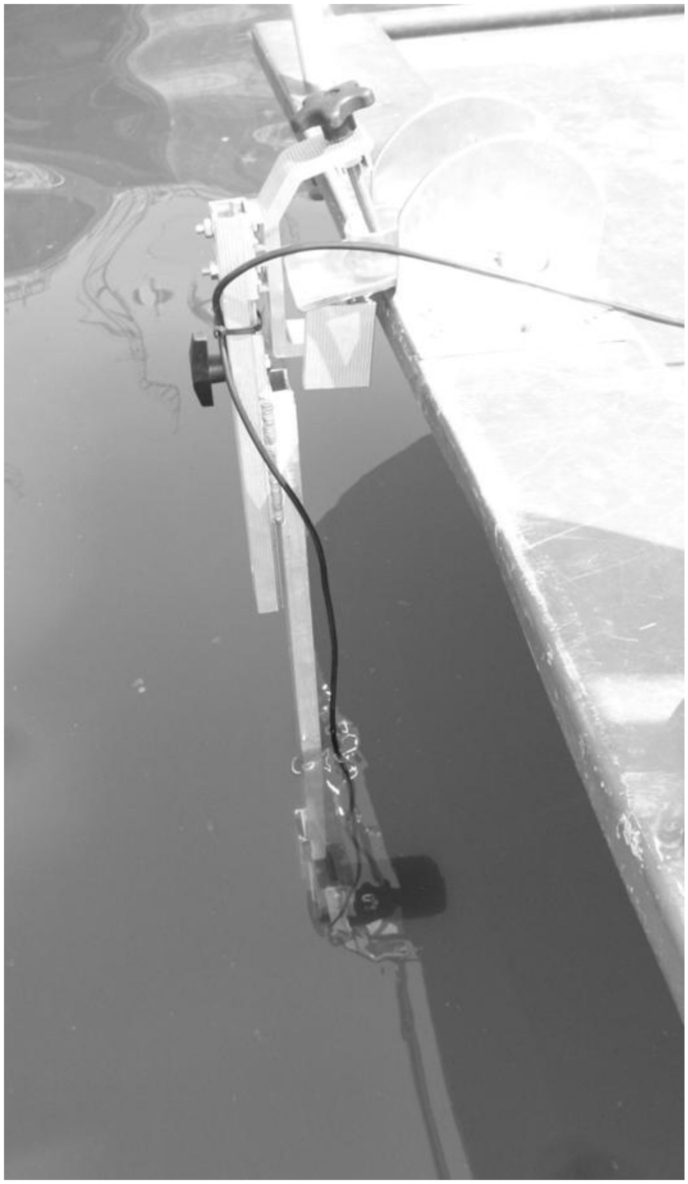


Figure 2.

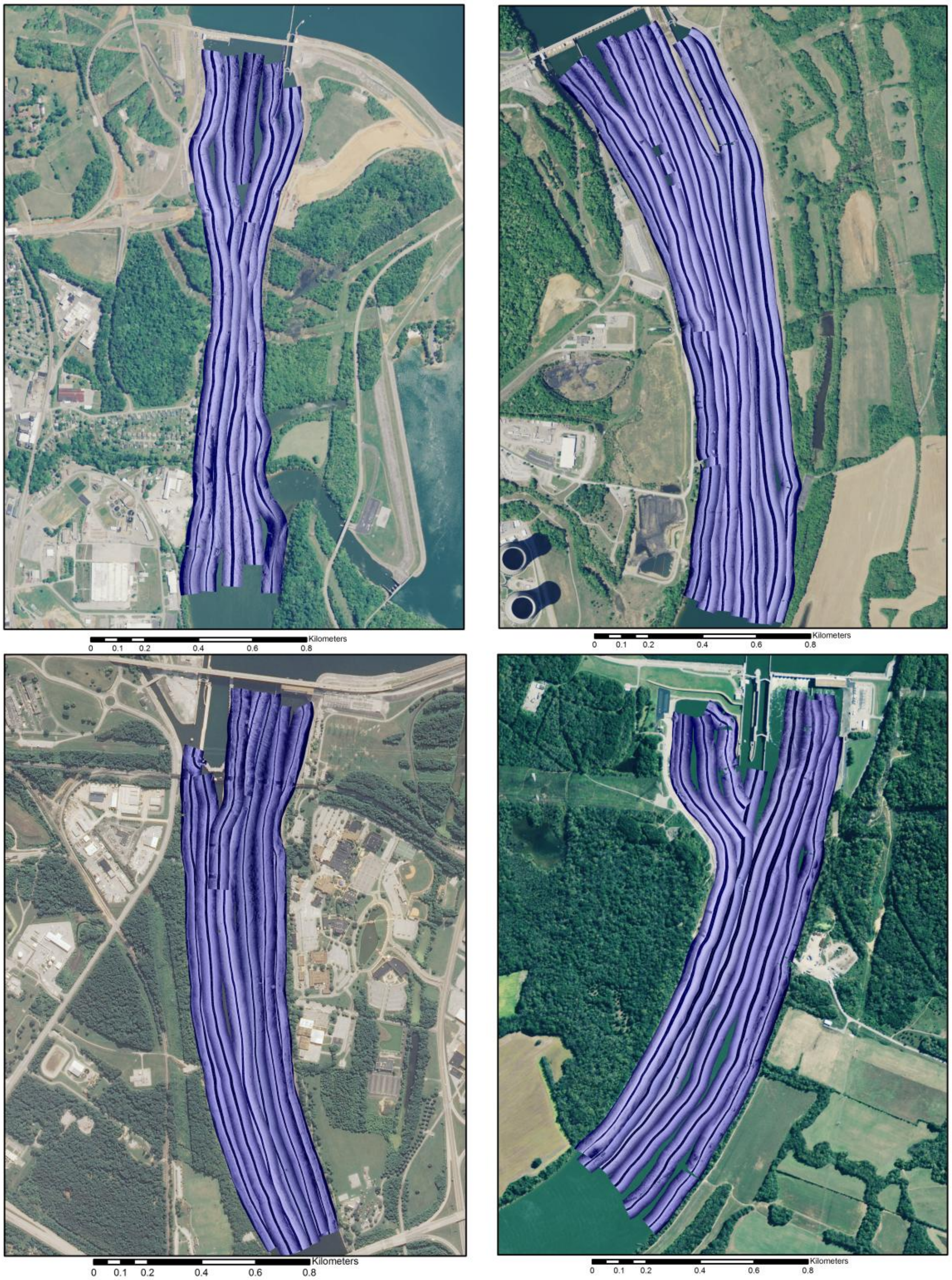

0 0.1 0.2 0.4 0.6 0.8 Kilometers
0 0.1 0.2 0.4 0.6 0.8 Kilometers
0 0.1 0.2 0.4 0.6 0.8 Kilometers
0 0.1 0.2 0.4 0.6 0.8 Kilometers

Figure 3.

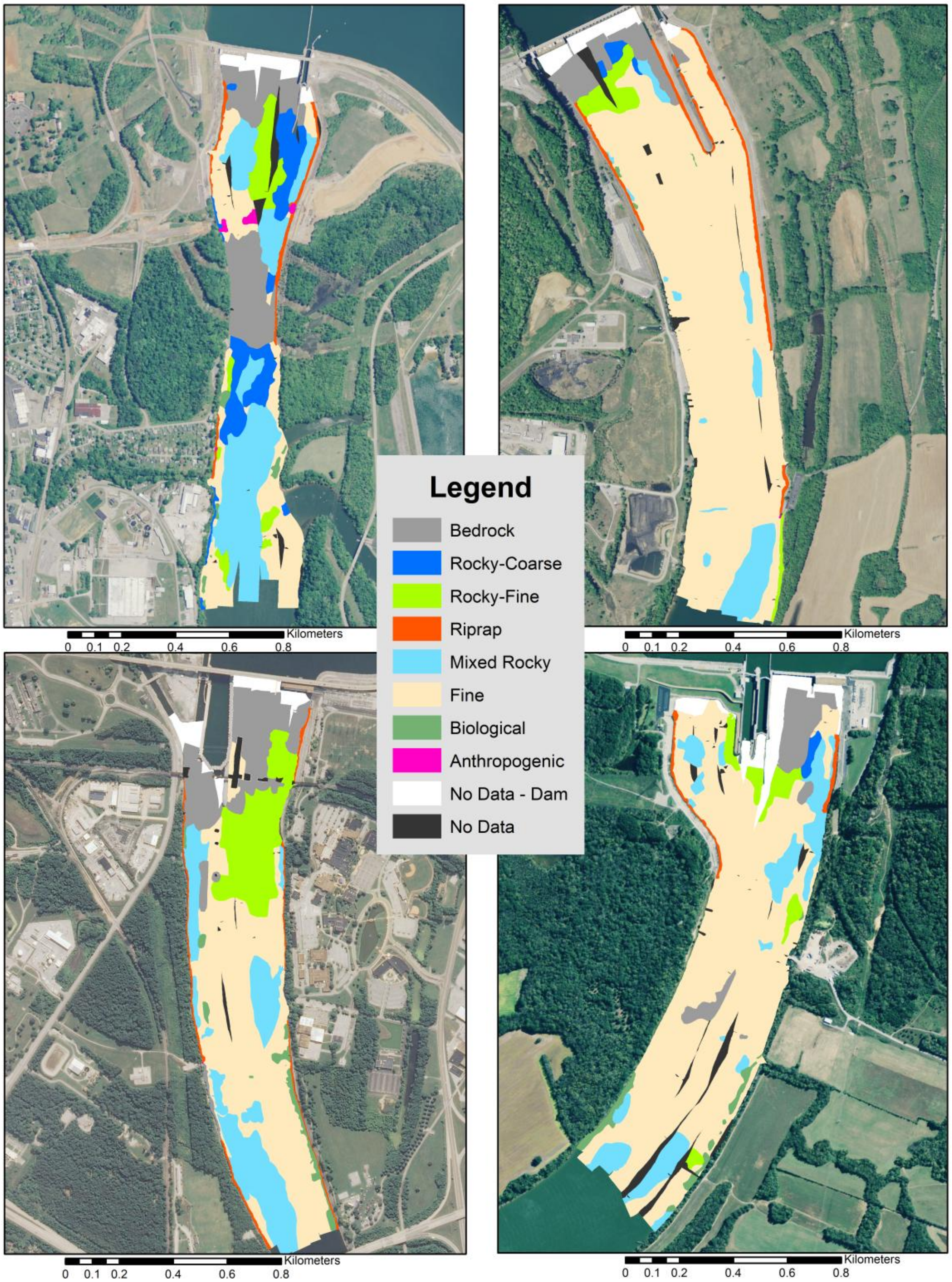

Legend
Bedrock
Rocky-Coarse
Rocky-Fine
Riprap
Mixed Rocky
Fine
Biological
Anthropogenic
No Data - Dam
No Data
Kilometers
0 0.1 0.2 0.4 0.6 0.8

Figure 4.

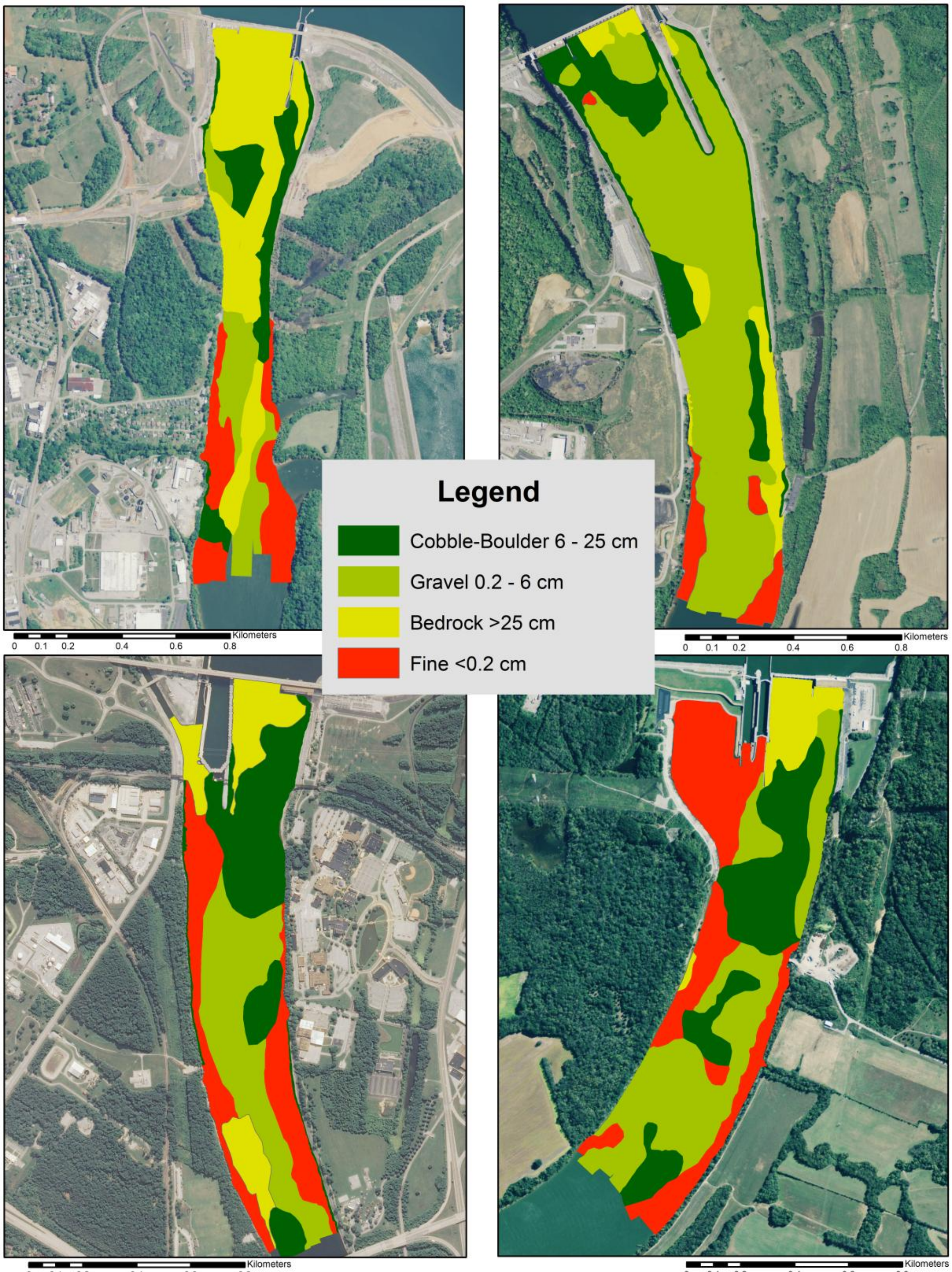
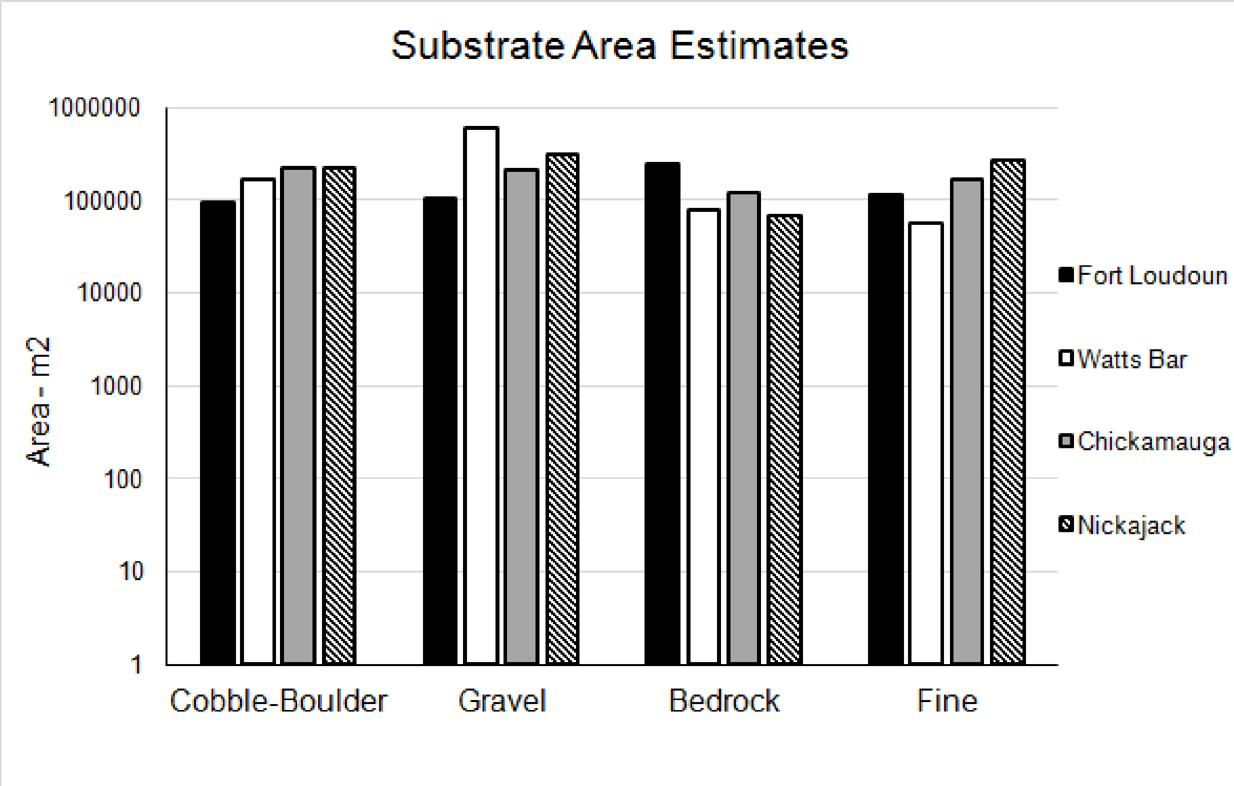

Legend
Cobble-Boulder 6 - 25 cm
Gravel 0.2 - 6 cm
Bedrock >25 cm
Fine <0.2 cm
Kilometers
0 0.1 0.2 0.4 0.6 0.8

Figure 5.



Substrate Area Estimates
1000000
100000
10000
1000
100
10
1
Area - m2
Cobble-Boulder
Gravel
Bedrock
Fine
Fort Loudoun
Watts Bar
Chickamauga
Nickajack

Figure 6A.

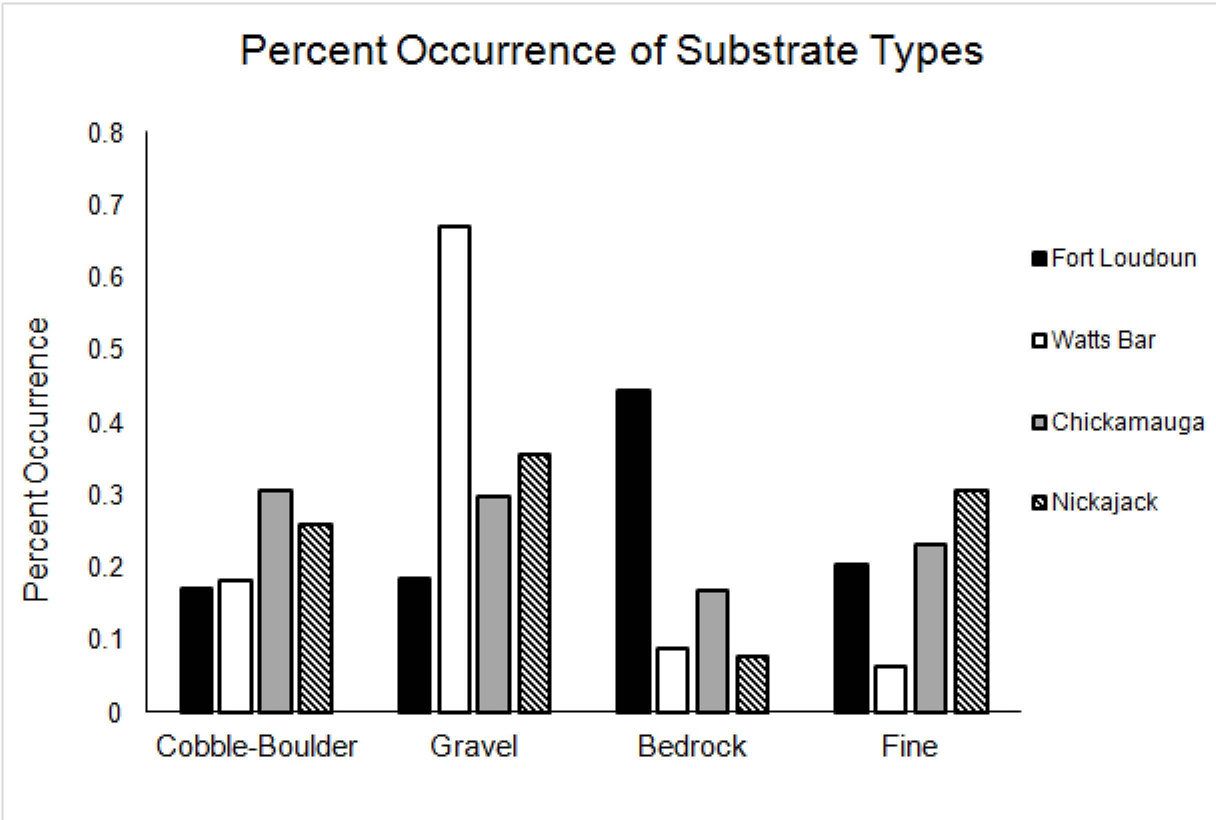

Percent Occurrence of Substrate Types
Percent Occurrence
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Cobble-Boulder
Gravel
Bedrock
Fine
Fort Loudoun
Watts Bar
Chickamauga
Nickajack

Figure 6B.