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ARTICLE

Mapping Lake Sturgeon 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 separated from each other by hydroelectric dams along the upper Tennessee River. 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. Using low-cost, consumer-grade, side-scan sonar and a GIS, we mapped the substrate of four tailwaters that may be future spawning locations for Lake Sturgeon. 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 evaluate that aspect of the suitability of each of the tailwaters for Lake Sturgeon spawning. The revised maps showed that 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 tailwater, 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 that 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 tailwater areas with suitable spawning substrate.

In North America, there are 10 extant species of acipenseriform fishes (Cech and Doroshov 2004). Seven of the 10 species are considered vulnerable, threatened, or endangered by the International Union for Conservation of Nature and Natural Resources (IUCN 2015) and most have been afforded state or federal protections in the United States (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, Laurentian Great Lakes, and Hudson Bay drainages (Harkness and Dymond 1961; Scott and Crossman 1973; Becker 1983; Etnier and Starnes 1993). 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). A multiagency effort, which includes annual releases of age-0 Lake Sturgeon (minimum TL, 15.24 cm) sourced from the Wolf River, Wisconsin, is ongoing to restore the Lake Sturgeon to its historic range in the southeastern United States. More than 150,000 juvenile Lake Sturgeon have been released in rivers across the Southeast since 2000, and the majority of these fish were reintroduced to the upper Tennessee River (M. Cantrell, U.S. Fish and Wildlife Service, unpublished data). A key objective 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 are largely triggered by rising springtime water temperatures (Bruch and Binkowski

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2002). In many river systems occupied by Lake Sturgeon, the river is fractured by dams that are likely impassable by migrating Lake Sturgeon (Auer 1996a). When the reintroduced Tennessee River Lake Sturgeon reach sexual maturity, they will attempt spawning migrations upstream from the reservoirs. When this occurs, many of the fish will encounter small and large dams, including four large hydroelectric dams on the main channel of the upper Tennessee River (Fort Loudoun, Watts Bar, Chickamauga, and Nickajack dams). Some of the reproductively mature Lake Sturgeon may attempt to spawn in the tailwaters below these hydroelectric dams in a manner similar to Lake Sturgeon in other river systems (e.g., LaHaye et al. 1992; McKinley et al. 1998; Caswell et al. 2004).

In their habitat suitability model (HSM) for Lake Sturgeon, Threader et al. (1998) identified four habitat variables that contribute to spawning habitat suitability for this species: water temperature, water velocity, substrate, and depth. Of these four variables, temperature, velocity, and depth will be governed largely by the hydroelectric management schedules at the large dams and recent river flows and environmental factors at the small dams at the time of the future migrations. Indeed, Lake Sturgeon spawning effectiveness and recruitment have been positively affected by alterations to flow management regimes in other systems (e.g., Auer 1996b). The remaining variable is substrate. Artificial spawning reefs have been constructed by hydroelectric producers and fisheries managers to augment Lake Sturgeon spawning events below hydroelectric dams in other systems (Johnson et al. 2006; Dumont et al. 2011; Bouckaert et al. 2014). In light of this, we set out to document the type and areas of substrate in the tailwaters directly below the four upper Tennessee River hydroelectric dams. To assess the suitability of these four tailwaters for Lake Sturgeon spawning, we collected and processed side-scan sonar imagery of the riverbed using a consumer-grade fish finder unit (Kaeser and Litts 2010). We used sonar imagery, reference video imagery, and their associated GPS coordinates in a GIS to create maps of the substrate in the tailwaters. Our objectives were to (1) classify and score the substrate found in the tailwaters using the Lake Sturgeon HSM (Threader et al. 1998), and (2) estimate the total area of each substrate class at each dam. This information will serve as a baseline assessment of the suitability of the substrate in these tailwaters for future Lake Sturgeon spawning events.

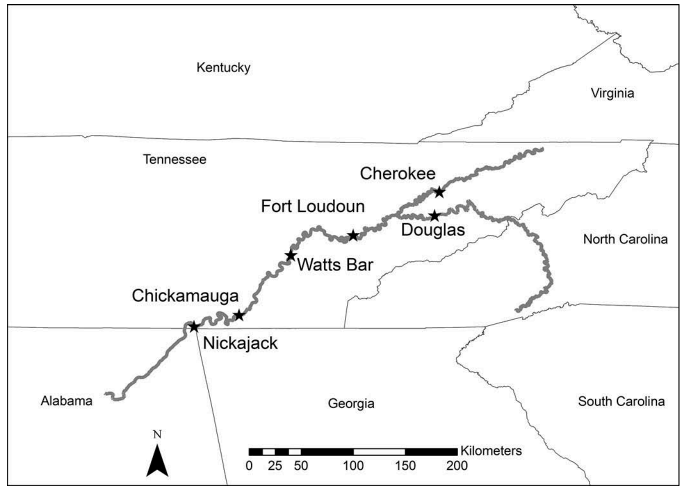

FIGURE 1. Location of Tennessee Valley Authority hydroelectric dams on the upper Tennessee, French Broad, and Holston rivers. The four dams where we conducted sonar surveys are Fort Loudoun, Watts Bar, Chickamauga, and Nickajack dams.

METHODS

*Study sites.—*We conducted sonar surveys of the tailwaters immediately downstream from the four upstream-most dams on the main-stem 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). Fort Loudoun Dam is located on the Tennessee River in Loudoun County, Tennessee (35.791°N, 84.243°W). The dam was completed in 1943 and contains four hydroelectric generating units with a combined capacity of 162 MW. The dam measures 37 m tall by 1,277 m wide. Watts Bar Dam is located at the boundary between Meigs and Rhea counties, Tennessee (35.621°N, 84.782°W). Watts Bar dam was completed in 1943 and contains five hydroelectric generating units with a combined capacity of 182 MW. Watts Bar Dam is 34 m tall and 902 m wide. Chickamauga Dam is located in Hamilton County, Tennessee (35.105°N, 85.229°W), and was completed in 1940. Chickamauga Dam houses four hydroelectric generating units with a combined capacity of 199 MW. The dam is 39 m tall by 1,767 m wide. Nickajack Dam is located in Marion County, Tennessee (35.004°N, 85.919°W). The dam was completed in 1967 and generates 105 MW of electricity from four generating units. Nickajack Dam is 24.70 m tall by 1,148.18 m wide. The descriptive information for each of the dams is available at the Tennessee Valley Authority's Web site (https://www.tva.gov/Energy/Our-Power-System/Hydroelectric/).

Each survey consisted of parallel downstream 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. Our sonar surveys of each tailwater were completed between May 10 and May 26, 2015, when flows had subsided from the higher spring releases.

*Sonar imagery collection.—*We used the sonar imagery collection and geoprocessing procedure developed by Kaeser and Litts (2008, 2010) and Kaeser et al. (2013) with some modification. We used the GPS data from the fish finder unit as this streamlined the data collection process after preliminary tests confirmed its accuracy when compared with GPS data collected at the same test locations using a handheld GPS unit. We conducted all of the surveys in a 4.62-m, aluminum johnboat equipped with a 60-hp outboard jet motor. 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 are collected from the sonar screen unit and not the sonar transducer, all of the final sonar imagery products are displayed approximately 4 m upstream from their true physical location. A discrepancy at this small scale is acceptable given the coarse mapping resolution and large areas mapped.

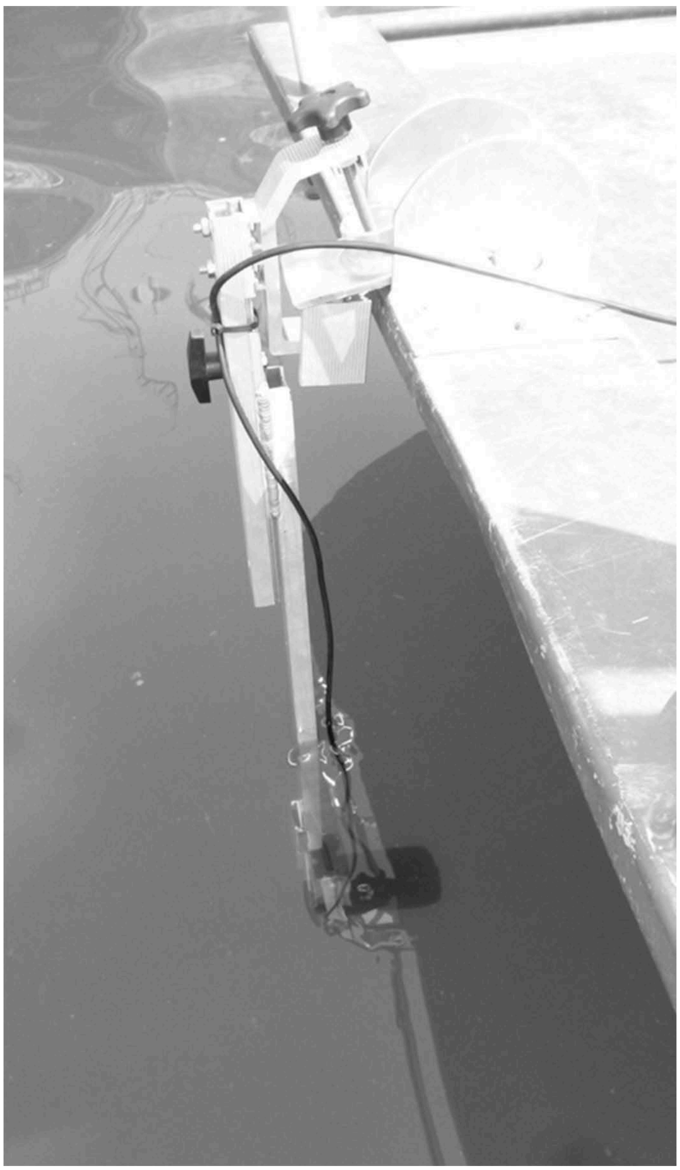

FIGURE 2. The bow-mounted sonar transducer arm. The transducer is removable, and the arm is adjustable for depth as well as capable of being raised out of the water for travel at speed. (Photo credit: Todd Amacker.)

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 (www.irfanview.com/) 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, California). 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 and 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.—We loaded the relevant georeferenced sonar imagery raster layers into ArcMap over a National Agriculture Imagery Program (NAIP; USDA 2014) orthoimage of each tailwater (natural color, 1 m ground sample distance, 6 m horizontal accuracy). We digitized a polygon that bounded all of the mapped substrate area bounded by the riverbank displayed in the NAIP image at the raster resolution scale (1:939), and then used the random point generator tool in ArcMap to randomly generate 50 points within the polygon outlining the area mapped (Congalton and Plourde 2002). We chose a sample size of 50 reference points in light of the logistical requirements of revisiting the sites and the time required for operating the underwater camera system effectively. We set a radius of 20 m around each point as a buffer to reduce overlap among the points and to ensure that we could collect reference data at each point from a boat, which was likely to be moving continuously during ground data collection. We converted the location data of each point at each tailwater from Universal Transverse Mercator to GPS coordinates and revisited each tailwater to collect reference ground data of the substrate.

Substrate classification and assessment.—We began with an initial classification scheme that contained 10 classes of substrate (Table 1). We defined 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 employed a holistic decision-making process to classify the substrate patches based on the intensity of the sonar reflection (brighter images indicating harder substrate) and texture of nearby sonar imagery. While we attempted more rigorous automated classification techniques (unsupervised and supervised), the sonar imagery produced with this method does not contain the necessary data for the automated classification tools to perform.

We assigned the original 10 substrate classes used in the digitization and video image classification scores of 1–4 based on the scoring in the Lake Sturgeon HSM to contribute

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	

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 waypoints and associated substrate classifications of the ground data reference points. We calculated an accuracy assessment of the first substrate maps by generating simple error matrices that compared the classification of the substrate below each reference point from the sonar image digitization to the substrate classification assigned from the video reference imagery. In response to low accuracy rates, we created second editions of the substrate maps using four, more broadly defined substrate classes and scores (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 both the sonar image mosaics and the reclassified video imagery. We used the sonar imagery as a guide to identify boundaries among patches of the four substrate classes. 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.

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

RESULTS

First-Edition Substrate Maps

The substrate maps we generated using the first classification scheme are shown in Figure 3. The first-edition maps indicated fine substrate particles (<0.2 mm diameter; shown 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. Our overall accuracy ranged from 29% to 33% for the first digitization of the substrate using the initial classifications (Table 3). Given this high rate of error, we do not report areal measurements of the substrate classes used in these maps here.

Second-Edition Substrate Maps

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 4). The total areas (m^2) of each of the four substrate types at each of the dams are displayed in Table 4. The area of each substrate type as a percent of the total area mapped at each of the dams is shown in Figure 5. Of the four substrate types indicated on the map, bedrock (embedded particles >25 cm in diameter, displayed in yellow) was the predominant substrate in the Fort Loudoun Dam tailwater, comprising 44.3% of the total area mapped. Gravel (particles 0.2–6 cm in diameter, displayed in light green) was the predominant substrate type below Watts Bar Dam and comprised 67.0% of the substrate. Of the four tailwaters mapped, Chickamauga Dam exhibited the greatest area of cobble–boulder substrate (the optimal Lake Sturgeon spawning substrate, 6–25 cm in diameter, indicated by dark green) as a percentage of the total area mapped at 30.5%. However, there was a more even distribution of each of the four substrate types in the tailwater below Chickamauga Dam, and gravel substrate covered 29.6% of the area mapped. Gravel was the predominant substrate type and covered 35.6% of the tailwater below Nickajack Dam, which also exhibited the greatest coverage of fine particles (<0.2 cm diameter, displayed in red) at 30.7%. When we visually assessed the trends displayed in Figure 5, we noted that there was an increasing trend in the total area of the best spawning substrate (cobble–boulder) between Fort Loudoun Dam, the upstream tailwater, and Chickamauga and Nickajack dams, the downstream tailwaters, even when total width of the river was taken into consideration.

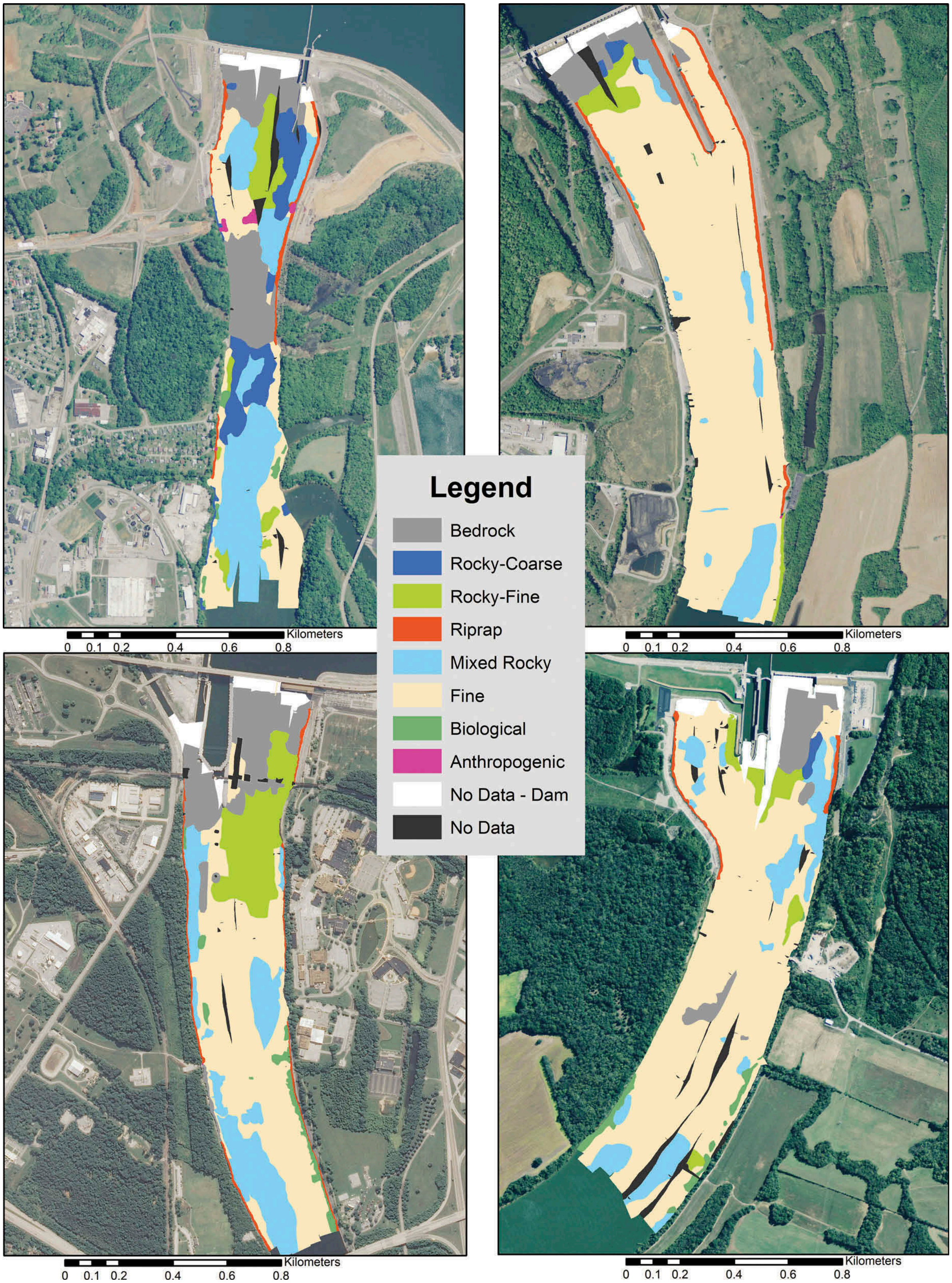

FIGURE 3. First-edition substrate maps. We digitized each map by hand at the raster resolution using the classification scheme outlined in Table 1. Dams are shown clockwise from top left: Fort Loudoun Dam (upper left), Watts Bar Dam (upper right), Chickamauga Dam (lower right), and Nickajack Dam (lower left). All four maps are displayed at 1:17000 scale, and the maps are oriented so that the upstream portion of the tailwater is at the top of the image.

TABLE 3. Accuracy of first-edition substrate maps for each of the four dams mapped as the percent agreement between digitized substrate patches and reference imagery.

Dam	Overall accuracy (%)
Fort Loudoun	33
Watts Bar	24
Chickamauga	33
Nickajack	33

DISCUSSION

The overall goal of this project was to describe the distribution of four size-classes of substrate in four Tennessee Valley Authority tailwaters to assess the suitability of these areas for future Lake Sturgeon spawning events. After our first attempt at interpreting the sonar imagery, our initial accuracy rates (29–33%) were inadequate. Future research using the techniques we have detailed here will benefit from revising the collection of the ground imagery. A stratified random sampling design (e.g., balance-acceptance sampling: Roberston et al. 2013), which avoids the issue of "clumping" reference locations and can account for differing areal measurements of the various substrate classes in addition to a larger sample size of reference points, will greatly improve the accuracy of future mapping studies. We attribute our low initial accuracy 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 technique by including the video imagery in the second digitization procedure to improve our confidence in the results at a cost of consuming the reference data in map generation without reserving additional reference data to assess the accuracy of the second-edition maps. This is why we did not report accuracy measures such as the results of additional error matrices. Using this hybrid approach, we improved our ability to describe the available substrates among upper 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 from 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, Tennessee, upstream from Fort Loudoun Dam. We think that the Lake Sturgeon have 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 1983). Our results suggest that if that scenario becomes 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 will be supported by the relatively greater availability of suitable spawning substrate in the tailwaters of those two dams.

To date, spawning by reintroduced Lake Sturgeon in the Tennessee River has not been documented. Once aggregations of reproductively mature Lake Sturgeon have been found, management actions can be taken to further augment successful reproduction. Our assessment will aid future management attempts to identify tailwater areas for artificial spawning reef installation. The construction of artificial spawning reefs, a management tool that has been used with success to augment Lake Sturgeon spawning in other systems, may support 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 dramatic 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 as mapping the substrate at finer resolutions and constructing artificial reefs can then be undertaken. Future high-resolution substrate mapping efforts will also benefit from assessing seasonal differences in the distribution of substrate in response to dam management schedules, which may be a confounding factor in substrate surveys of tailwaters. The data we have provided here represent a baseline assessment of the substrate across these tailwaters where future Lake Sturgeon spawning events may occur. Water velocity, temperature, and depth all play critical roles in governing Lake Sturgeon spawning and these factors should be considered in dam management schedules, providing another avenue of support for future Lake Sturgeon recruitment.

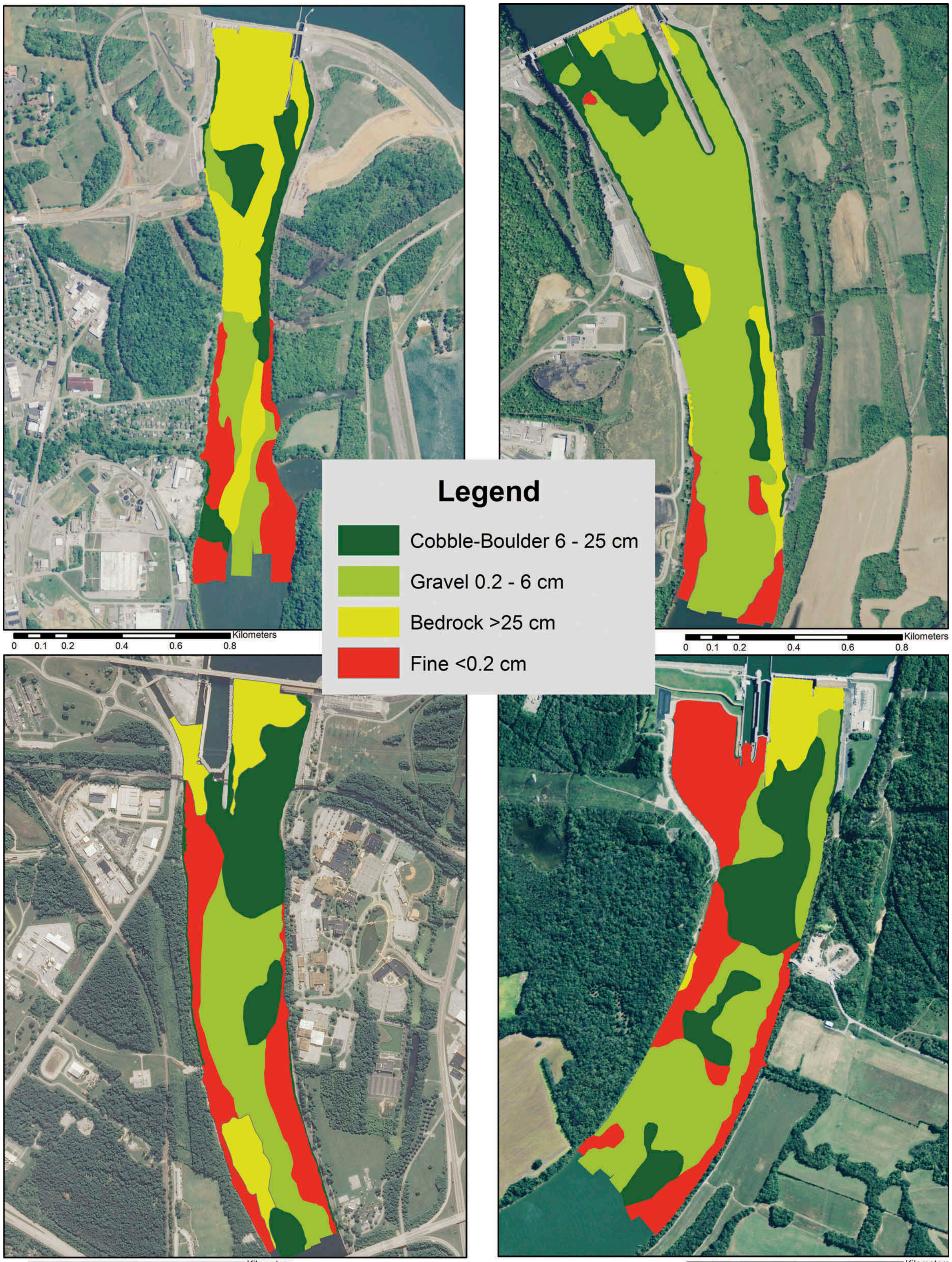

FIGURE 4. Second-edition substrate maps. The classification scheme used in the digitization of these maps is detailed in Table 2. Dams are shown clockwise from top left: Fort Loudoun Dam (upper left), Watts Bar Dam (upper right), Chickamauga Dam (lower right), Nickajack Dam (lower left). All four maps are displayed at 1:17000 scale, and the maps are oriented so that the upstream portion of the tailwater is at the top of the image.

TABLE 4. Total area (m^2) of each substrate type at each dam calculated from the second-edition substrate maps.

Dam	Cobble–boulder	Gravel	Bedrock	Fine	Total
Fort Loudoun	94,429.2	101,673.7	246,252.6	113,608.1	555,963.6
Watts Bar	163,131.5	605,106.2	78,464.6	55,861.6	902,563.9
Chickamauga	216,603.5	210,083.0	119,593.5	164,631.6	710,911.6
Nickajack	220,524.2	303,475.1	66,797.9	261,346.3	852,143.5

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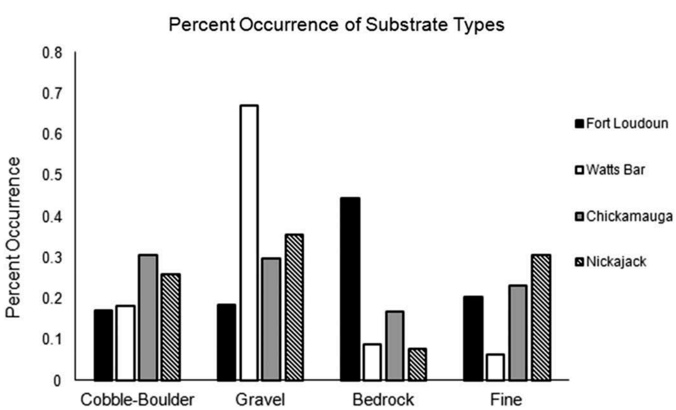

FIGURE 5. Areal measurements of the various substrate classes identified in the second-edition maps as a percentage of the total area of the tailwater mapped.

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