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ARTICLE

Quantification of Walleye Spawning Substrate in a Northern Minnesota River using Side-Scan Sonar

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Abstract
Evaluating aquatic habitats is an important component of many ecological studies and natural resource assessments, but traditional habitat evaluations are time and labor intensive and do not provide continuous data. Side-scan sonar (SSS) can provide a low-cost method that collects continuous aquatic habitat data. We used SSS mapping to quantify suitable spawning substrate available to Walleye *Sander vitreus* during the 2015 spring spawning migration in a 10.8-km reach of the Tamarac River, Minnesota. The SSS map had 78.0% agreement with reference points classified in the field, and the proportion of reference points predicted as suitable using the SSS map was not significantly different than the proportion of reference points observed to be suitable. Suitable substrate for Walleye spawning comprised 8.4% (26,392 m^2) of the total area mapped. The estimated number of females that suitable substrate could support was lower than the number that likely migrate up the Tamarac River and suggests that access to spawning substrate may sometimes limit reproductive success. This study demonstrates that a relatively inexpensive SSS unit can be used to efficiently map aquatic habitat while acquiring quantitative and qualitative data.

The assessment of aquatic habitats provides useful information for a variety of ecological applications. Assessing the components of abiotic habitat present in a system, and where specific conditions occur, yields insight into biotic community structure and locations where certain taxa are likely to be found (Knapp et al. 1998; Jackson et al. 2001; Bornette and Puijalon 2011). Further, locating suitable habitat aids in estimating the ability of certain taxa to grow, develop, survive, and reproduce (Knapp et al. 1998; Jackson et al. 2001; Hafs et al. 2014). The availability of suitable spawning habitat is an important component of reproduction in fish, with reduced quantity and quality of spawning habitat linked to reduced egg deposition, egg survival, age-0 abundance, and recruitment to the adult population (Johnson 1961; Dombeck et al. 1984; Knapp et al. 1998).

Traditionally, river habitat has been evaluated and mapped using techniques that consist of taking measurements visually or physically at discrete points, transects, or grids throughout the river (e.g., Wright et al. 1981; Fitzpatrick et al. 1998; Maddock 1999; Hafs and Gagen 2010). These techniques can require extensive time and effort in the field and result in a trade-off between the level of detail and the size of the area being mapped (Maddock 1999). Furthermore, traditional techniques typically do not produce continuous data; thus, areas not evaluated must be inferred from areas that have been evaluated. The evaluations may also be limited by environmental conditions, including water depth and transparency.

Techniques have been developed that use relatively inexpensive recreational side-scan sonar (SSS) units and GIS software to effectively map and evaluate freshwater habitats (Kaeser and Litts 2008, 2010; Kaeser et al. 2013). Side-scan sonar provides continuous

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data and is not limited by deep or turbid water. Previous freshwater SSS studies have evaluated and/or quantified variables, including sedimentation (Manley and Singer 2008), large woody debris (Kaeser and Litts 2008), substrate type (Kaeser and Litts 2010; Kaeser et al. 2013), fish abundance (Barton 2000), and fish spawning habitat (Edsall et al. 1989; Walker and Alford 2016). One of the most recent SSS studies mapped and accurately classified spawning habitat for Walleye *Sander vitreus* in Wisconsin lakes (Richter et al. 2016). When using SSS to evaluate substrate type in freshwater habitats, the reported overall accuracy ranges from 29% to 93% (Kaeser et al. 2013; Richter et al. 2016; Walker and Alford 2016). Kaeser and Litts (2010) reported time in the field for data collection when river mapping using SSS to be 11 min/km and total map production time to be ~3 h/km, which was about one tenth of the time required when using transect-based techniques. Although these studies suggest that SSS has distinct advantages when mapping freshwater habitats, not all studies in the literature provide accuracy assessments and studies that produce SSS maps directed toward a specific management interest remain sparse. Thus, studies evaluating SSS habitat mapping techniques for freshwater fish in systems with varying morphology are necessary to test the broad applicability of the technique and inform future researchers.

Mapping spawning habitat requires an understanding of the environmental variables that constitute suitable spawning habitat. The U.S. Fish and Wildlife Service synthesizes habitat suitability indices for many game and nongame species based on compiled literature and expert reviews (Schamberger et al. 1982). The habitat suitability index constructed for Walleyes suggests that the quality and quantity of suitable substrate is one of the primary factors affecting reproductive success (McMahon et al. 1984). The substrates most suitable for Walleye spawning are those with diameters between 2.0 and 250.0 mm (McMahon et al. 1984), which are categorized as gravel, pebble, and cobble using the sediment classification scheme from Wentworth (1922).

Egg production in female Walleyes is proportional to body mass, with a typical production of 60,000 eggs/kg (Nickum 1986) and a mean egg diameter of 2.0 mm (Smith 1941; Colby et al. 1979). The stacking of eggs has been shown to reduce fertilization rates in laboratory settings (Moore 2003) and would likely increase the chance of transport and ensuing siltation, abrasion, and predation, which are the presumed causes for reduced egg survival on finer substrates (Bozek et al. 2011). Literature estimates of Walleye egg densities range from 65 to 7,047 eggs/m^2 (Johnson 1961; Corbett and Powles 1986; Manny et al. 2007).

The Walleye fishery of the Red Lakes, Minnesota, is economically important and supports popular recreational and commercial fisheries. For example, combined recreational and commercial harvest exceeded 770,000 Walleyes in 2015 (Brown and Kennedy 2016). The fishery is currently near record-high levels of Walleye abundance and is completely supported by natural reproduction (Kennedy 2016). Although spawning migrations have only been quantified in the Tamarac River, the largest tributary to Upper Red Lake, it is presumed (based on local knowledge) that this tributary supports the largest Walleye spawning migration. A hatchery was previously operated at the Tamarac River, where the mean Walleye catch between 1932 and 1979 was 203,066 individuals, with catch reaching as many as 646,161 fish (Groshens 2000). However, these collections did not capture the entire duration of the migration because nets were often disabled once holding pens were filled to capacity, and therefore the true migration size was larger. Hatchery operations at the Tamarac River, which provided total catch data, have been suspended since 1979, but annual electrofishing surveys are currently conducted during spawning migrations. The mean electrofishing survey catch rate over the last 10 years was 638 Walleye/h (Brown and Kennedy 2016).

The magnitude of historic migrations and current electrofishing catch rates provide evidence to suggest that the Tamarac River may be an important component of Red Lakes Walleye reproduction. Two previous cursory evaluations by Minnesota Department of Natural Resources staff have been conducted to assess Walleye reproduction in the Tamarac River (Fraune and Scidmore 1963; Groshens 2000). However, reproductive success in the Tamarac River is largely unknown and in-depth assessments on the quantity and quality of spawning habitat in the river are lacking.

The ability to acquire accurate and continuous substrate data regardless of water depth or clarity makes SSS mapping an ideal technique to describe and quantify Walleye spawning substrate in the Tamarac River. Our objectives were to (1) quantify suitable Walleye spawning substrate in the 10.8-km reach accessible to Walleyes in the Tamarac River during spring 2015, (2) assess the accuracy of the SSS map, (3) estimate the number of females that could be supported by available suitable substrate, and (4) evaluate the implications.

METHODS

Study site.—The Red Lakes cover 116,550 hectares and comprise the largest body of water contained within Minnesota borders (Figure 1). The Tamarac River is the main tributary to the upper basin of the Red Lakes and flows 34.9 km into the northeastern corner of the basin (Groshens 2000). The river's drainage encompasses 815 km^2, including a portion of a 1,295-km^2 peat bog, the largest in the lower 48 states (Groshens 2000). The drainage is primarily wetlands, but approximately 35% of the watershed is forested (Groshens 2000). The river has a low gradient with substrates ranging from silt to cobble but is dominated by silt and sand (Fraune and Scidmore 1963; Groshens 2000). Water depths near the mouth can exceed 3 m, but the majority of the river is typically 1 m deep. Beaver *Castor canadensis* dams are common in the river and have blocked Walleye migrations in the past (Fraune and Scidmore 1963; Groshens 2000). This study focused on the 10.8-km reach from the river mouth up to a large beaver dam (Figure 1).

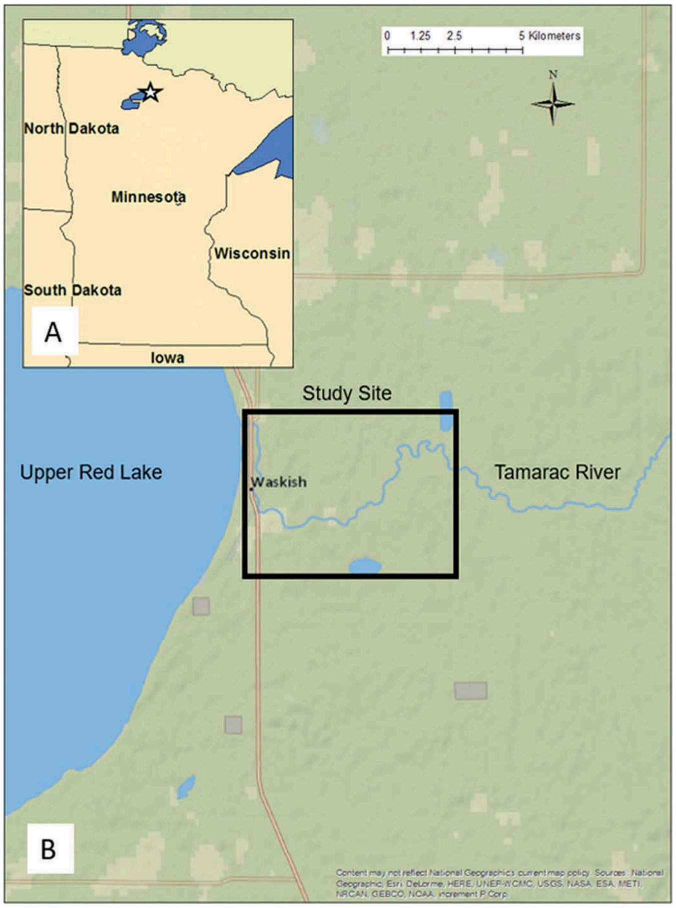

FIGURE 1. Maps showing **(A)** the location of the Tamarac River (marked with a star) within Minnesota and **(B)** the Tamarac River with the study site outlined in black.

Sonar survey.—A recreational-grade Humminbird 1199ci HD sonar unit (cost ~US$2,000) was used to collect sonar images, with a bow-mounted transducer to eliminate the effect of prop wash. All sonar images of the Tamarac River riverbed were collected in the same day during the fall of 2015. A frequency of 455 kHz was used following setting recommendations in Kaeser et al. (2013). We used a wide range setting of 36.6 m per side because obstacles (e.g., beaver caches, deadhead logs, and overhanging trees) in the river often did not allow travel down the center of the river, and this range setting ensured bank-to-bank coverage when the boat had to be guided down either bank. We chose not to use the "water contour" setting on the SSS unit because we were unhappy with the results and felt it made sonar signatures difficult to interpret.

Sonar images were taken moving downstream from the upstreammost portion of the study area, where boat and fish passage were inhibited by a large beaver dam, to the mouth of the river (Figure 1). Because fish passage was inhibited by the beaver dam, the mapped section of the river represents the entire reach available to Walleyes during the spring 2015 spawning migration. Sonar "snapshots" and associated GPS waypoints were taken such that each image overlapped the previous one to ensure complete coverage of the river and a continuous sonar image of the riverbed similar to methods described by Kaeser and Litts (2010). The boat was positioned as close to stream center as possible and speed was kept between 5 and 8 km/h following methods described by Kaeser and Litts (2010) and Kaeser et al. (2013).

Reference points.—Reference points were established during late spring of 2015 using a rough grid pattern. Substrate was classified every 10 paces at approximately 25, 50, and 75% of the stream's width in the upstreammost 1.6 km of the study area. This section of the river was chosen because the water depth allowed for the collection of the highest number of reference points and was presumed to have the most heterogeneous substrate composition in the study reach based on previous investigations (Fraune and Scidmore 1963; Groshens 2000). Suitable Walleye spawning habitat was defined as having a predominant substrate with diameters ≥ 2 mm, and unsuitable habitat was defined as having a predominant substrate with diameters < 2 mm. McMahon et al. (1984) suggested that substrates with diameters between 2 and 250 mm were the most suitable substrates for Walleye spawning, but given that the Tamarac River is a low-gradient stream located in a large peat bog, it is unlikely to contain substrates with diameters > 250 mm. This was supported both by observations from the investigators for this study and previous assessments of the river (Fraune and Scidmore 1963; Groshens 2000). Therefore, a maximum threshold for suitable substrate diameter was not necessary.

At each reference point, substrate was identified as being suitable or unsuitable for Walleye spawning and a GPS waypoint was taken using a Garmin eTrex 20 GPS unit. Substrate class was determined by touch and rotation of a wooden rod. If there was uncertainty as to which category the substrate should be assigned to using this method, a small sample was retrieved with a shovel, placed on a ruler, and visually assessed to determine if mean particle diameter was ≥ 2 mm.

Map production.—Each raw sonar "snapshot" was manually processed to remove all metadata and the area displaying the water column, and areas of no data were not displayed in the map (Figure 2). Metadata and the area displaying the water column were removed by cropping these areas out of the sonar image. Areas outside the river channel were not displayed by setting the value of these pixels to not be displayed in ArcGIS (Environmental Systems Research Institute [ESRI]). After images were processed, they were georeferenced using control point matrices in AcrGIS 10.3. All georeferencing, digitization, and delineations in this study were conducted using Universal Transverse Mercator Zone 15 and the 1984 World Geodetic System datum.

An iterative process was used to select the number of control points to use per image, where the number of control points was increased until the addition of control points provided minimal change to the geometry of the sonar image after georeferencing.

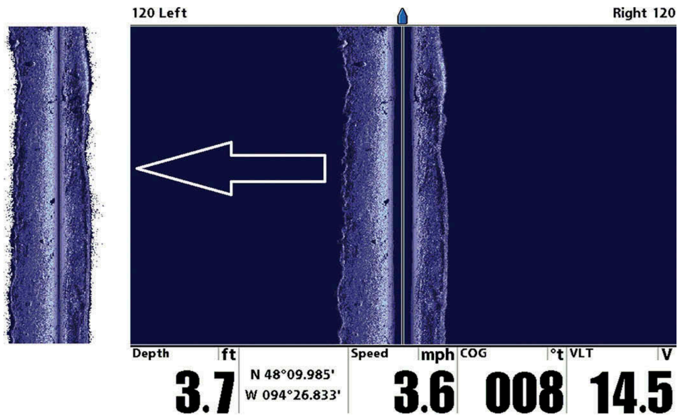

FIGURE 2. Demonstration of the removal of metadata and no-data areas from the raw sonar image (right panel) to produce a sonar image ready for georeferencing (left panel).

Fourteen control points were used to georeference each image, with control point matrices consisting of six control points along each bank and one at both the upstream and downstream edge of the sonar image (Figure 3). Control points for sonar images were generated from GPS waypoints recorded by the SSS at the time each snapshot was taken and by then generating control points at equal intervals along both the edges of the sonar image and the river edges on the world imagery layer provided by ESRI in ArcGIS, which provided imagery with a resolution of < 0.3 m at our study site (ESRI 2016). After georeferencing, images were mosaicked so that the overlapping area in the upstream image overlaid the downstream image.

The recent emergence of software for processing sonar videos and images to produce maps provides a means to reduce map production time greatly. However, limited work has been done to assess maps produced using such software. Therefore, the choice to process and georeference individual sonar images was made because previous studies with robust accuracy assessments have used the "snapshot" approach for map production (e.g., Kaeser and Litts 2008, 2010; Kaeser et al. 2013).

The length of river typically represented by sonar images was 36.9 m (mean). At this scale, river curvature was generally uniform and spline transformation was used based on how control point matrices were generated (Figure 3) and its low root mean squared error. All sonar images captured in the reference site were georeferenced to facilitate the assessment of accuracy. To reduce processing time, the remaining sonar images were assessed in their raw form and only images containing areas of both suitable and unsuitable substrates were georeferenced. When images contained only one classification of substrate, the entire riverbed represented by that image was assigned to that substrate class. River boundaries were digitized using the world imagery layer provided by ESRI (2016).

The amount of time necessary to conduct the field survey, process images, and georeference images per kilometer of river mapped was calculated to provide an estimate of the mean time

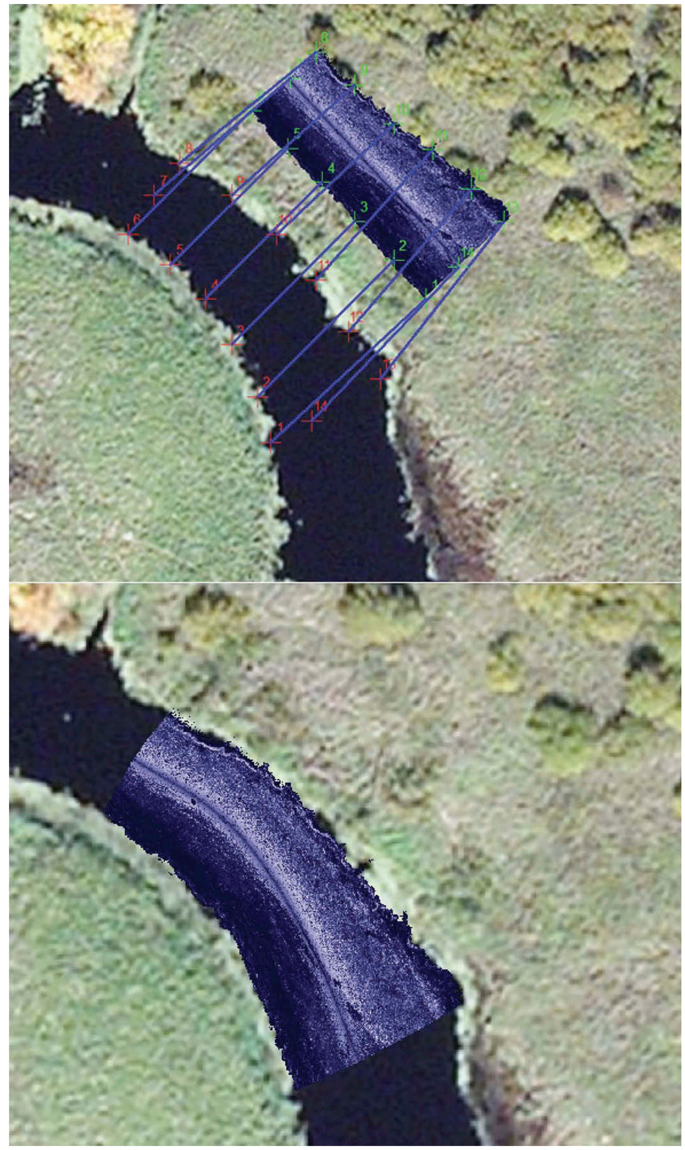

FIGURE 3. Sonar image with its control point matrix (top panel) being transformed and georeferenced into its geospatial location (bottom panel).

required for each process. Image processing and georeferencing times were calculated on a subset of sonar images near the end of map making. Because the subsets were taken near the end of the map-making process, these times represent map production time for somebody who is familiar with this process. Novice map producers would likely experience a higher production time associated with the learning curve for this technique.

Prior to mapping the Tamarac River, the ability to interpret sonar signatures and accurately classify substrates was attained by examining the signatures of substrates that were confirmed visually or physically in water bodies with a variety of substrate types. Sonar signatures from previous studies were also examined. Sonar signatures were assessed following methods similar to those described by Kaeser and Litts (2010), which used intensity of return, texture, and pattern to differentiate between substrate classes (Figure 4).

Substrates in sonar images from the Tamarac River were classified using the simple binary classification scheme used for reference data, either suitable or unsuitable habitat for Walleye spawning. Areas containing suitable habitat were digitized and saved as an ESRI shapefile. This shapefile was merged with the digitized river boundary to produce a layer with two polygons, one representing suitable substrate and one representing unsuitable substrate. From this layer the total area (m^2) and percent area of the river containing suitable substrate were calculated for the mapped area as a whole and for each 0.5-km reach using the "calculate geometry" tool in ArcGIS. Based on classification scheme, GPS accuracy, and river width, a minimum mapping unit of 78.5 m^2 was used (Kaeser and Litts 2010).

Accuracy assessment.—During the spring and summer of 2015 the Tamarac River discharge was low due to low precipitation in the watershed, so shifts in substrate composition between the collection of reference points and the sonar survey are unlikely. Reference points representing suitable substrate were "clipped" from the suitable substrate polygon on the SSS map to assess the ability to predict the correct substrate class using the SSS map. The number of reference points representing suitable substrate that were predicted correctly and incorrectly was calculated using the number of reference points contained in the clipped polygon and the total number of suitable reference points. This same procedure was followed for reference points representing unsuitable substrate. These data were entered in an error matrix used to calculate overall, user's, and producer's accuracies. Producer's accuracy (omission errors) was calculated as the proportion of reference points in a category that were classified correctly using the SSS map (Congalton 2005). User's accuracy (commission errors) was calculated as the proportion of points from the SSS map in a category that were classified correctly (Congalton 2005). Overall accuracy was the proportion of all reference points that were classified correctly. Misclassified reference points were assessed to evaluate if spatial accuracy of the GPS unit and/or SSS map were likely sources of misclassification. This was performed using the "spatial join" and "buffer" tools in ArcGIS to calculate the distance from misclassified points to polygons that would have classified them correctly and to calculate the area of a 3.0-m buffer (manufacturer reported accuracy of GPS unit) that overlapped a polygon that would have resulted in a correct classification.

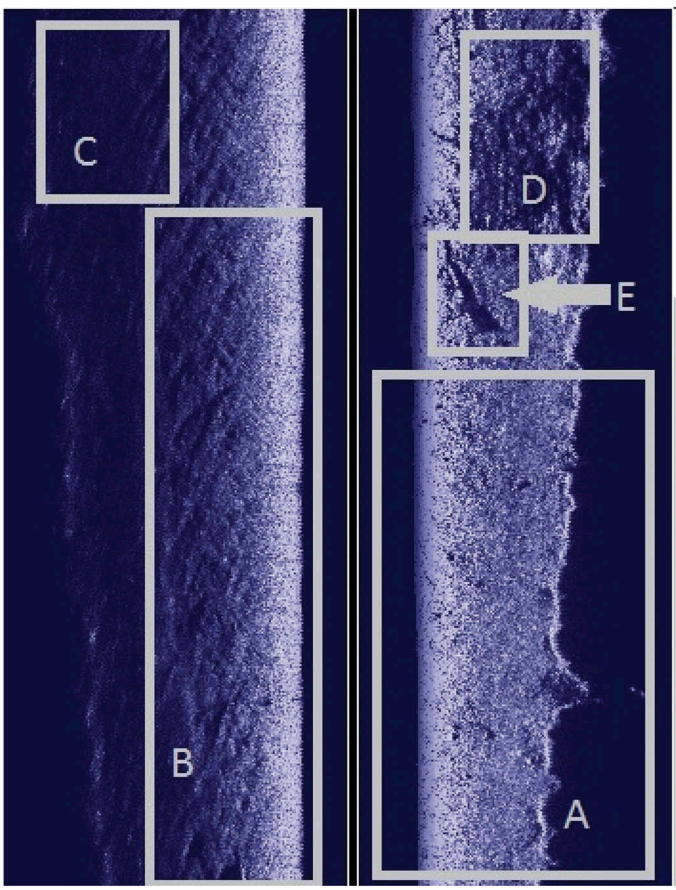

FIGURE 4. Image displaying sonar signatures of **(A)** coarse suitable substrate, **(B)** unsuitable substrate exhibiting ripples indicative of sand, **(C)** unsuitable very fine silt substrate, **(D)** a beaver cache, and **(E)** a single large deadhead log.

Egg deposition.—The maximum egg density from literature sources of 7,047 eggs/m^2 (Manny et al. 2007), the egg production of females in the Tamarac River, and the estimated area of suitable substrate was used to calculate the number of female Walleyes that could likely be supported by the suitable substrate that was accessible in 2015. Egg production of female Walleyes in the Tamarac River was estimated using egg production of 60,000 eggs/kg (Nickum 1986) and the mean mass of female Walleyes in the Tamarac River. Mean mass of female Walleyes migrating up the river was calculated from fish captured in overnight fyke-net sets, which were made every third day during the 2014 and 2015 spawning migrations. All female Walleyes were measured for total length and a subsample was weighed to establish a length–weight relationship following methods described by Anderson and Neumann (1996).

The number of females that could be supported by the suitable substrate that was accessible in 2015 was divided by the mean percentage of female fish in spawning migrations from 2005 to 2015 (9.7%; Brown and Kennedy 2016). This estimate was then used to project the total migration size (male and female) that could be supported. We compared the estimated number of females that could be supported in 2015 to the mean and maximum number of females that were trapped while migrating into the Tamarac River historically and to the mean number of mature females in the Red Lakes during the last 10 years as presented in Brown and Kennedy (2016).

Statistics.—Overall accuracy with a 95% confidence interval, user's accuracies, and producer's accuracies were calculated using an error matrix for the SSS map (Congalton 1991; Congalton and Green 2009). The ability of SSS to predict substrate type better than random was determined by performing a Kappa analysis (Congalton 1991; Congalton and Green 2009). Pearson's chi-square tests were used to assess non-site-specific accuracy (i.e., proportions of each substrate without a spatial aspect) and producer's and user's accuracies between substrate types. Assessment of possible bias towards either class when delineating transitions from one substrate type to another was conducted with Wilcoxon rank-sum tests (Hollander and Wolfe 1999). All statistical tests were performed using Program R (R Core Team 2014).

RESULTS

Habitat Map

We mapped 10.8 km of the river, over which 293 sonar snapshots were taken containing 315,275 m^2 of riverbed. The estimated total area of substrate classified as suitable for Walleye spawning using the SSS map was 26,398 m^2, which was 8.4% of the total riverbed. Georeferencing was the most time intensive process of sonar map production (228 min/km), followed by image processing (16.9 min/km). The SSS field survey required two people and was the least time intensive process in map production (9.4 min/km). The summation of these processes provided an estimated total map production time of 254.3 min/km.

Using the SSS map, 26 polygons were delineated as suitable spawning substrate, ranging in size from 98.6 to 3,047.8 m^2 (median = 733.6 m^2). The reach with the largest quantity of suitable substrate was between river kilometer (rkm) 3.5 and rkm 4.0 (measured from the mouth of the Tamarac River at Upper Red Lake) and contained 3,386 m^2 of suitable substrate, which was 16.5% of the total area of that reach (Figure 5). The highest percentage of suitable substrate (34.1%) occurred between rkm 10.0 and rkm 10.5 (Figure 5). No suitable substrate was identified in the downstreammost 2.5 km of the river.

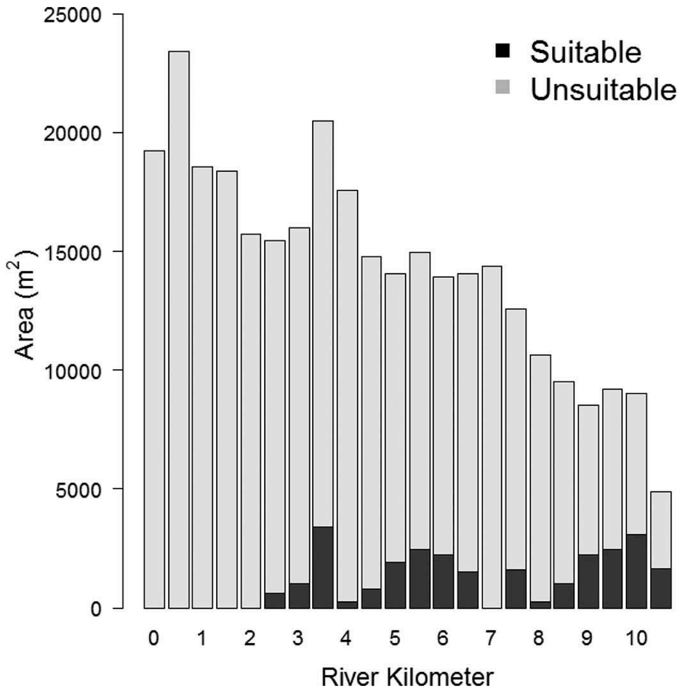

FIGURE 5. Area (m^2) of suitable and unsuitable substrates in each 0.5-km reach in the downstreammost 10.8 km of the Tamarac River (the last bar represents 0.3 km instead of 0.5 km). River kilometers are measured from the mouth of the Tamarac River at Upper Red Lake.

Accuracy Assessment

We classified substrate in the field at 598 points in the reference reach, with 220 points representing suitable substrate and 378 points representing unsuitable substrate for Walleye spawning. Eight polygons representing suitable substrate ranging from 98.6 to 3,047.8 m^2 (median = 589.6) were mapped in the reference reach. Only one polygon delineated as suitable substrate did not contain suitable substrate reference points. This was the smallest polygon (98.6 m^2) and had two suitable substrate reference points 0.09 and 0.26 m outside the border, well within the 3.0-m error level of the GPS unit.

The ability to predict substrate type at reference points was significantly better than random (K = 0.54, 95% CI = 0.47–0.61, P < 0.001) and had moderate agreement with reference points (Landis and Koch 1977). The percent of reference points classified as suitable using the SSS map (41.8%) was not significantly higher than observed in reference data (36.8%; χ^2 = 3.37, df = 1, P = 0.066), which suggests non-site-specific accuracy was high. Producer's accuracy was similar for both substrate types at 76.8% and 78.6% for suitable and unsuitable substrate, respectively (χ^2 = 0.16, df = 1, P = 0.692). Conversely, user's accuracy was significantly lower for suitable substrate (67.6%) than unsuitable (85.3%; χ^2 = 25.61, df = 1, P < 0.001). Overall accuracy for the SSS map was 78.0% (95% CI = 72.4–85.4; Table 1).

The majority (67.4%) of misclassifications occurred in close proximity (<3.0 m) to polygons that would have classified them correctly (Figure 6). The median distance to the correct classification polygons for suitable points misclassified using the SSS map was 2.6 m (interquartile range [IQR] = 0.7–6.9 m) and 1.6 m (IQR = 0.8–2.9 m) for misclassified unsuitable points. The median distance of correctly classified points to a SSS-delineated substrate transition (6.6 m) was significantly higher than the median distance of misclassified points (1.8 m), which indicated misclassifications were frequently associated with substrate transitions (W = 48,085, P < 0.001). For misclassified points, the median area of the 3.0-m buffer overlapping polygons with the correct classification for suitable and unsuitable points was 8.7 m^2 (IQR = 4.9–11.6 m^2) and 7.4 m^2 (IQR = 3.8–11.3 m^2), respectively. Neither the distance to, nor the area of buffer overlapping the correct classification polygon were significantly different between substrate classes (W = 2,453, P = 0.07; W = 907, P = 0.53, respectively).

Egg Deposition

The length–weight equation for female Walleyes captured in the Tamarac River was generated from 113 fish and applied to a

TABLE 1. Error matrix for the side-scan sonar map produced for the Tamarac River displaying overall, user's, and producer's accuracies.

Classified data	Reference data: Suitable	Reference data: Unsuitable	Total	User's accuracy
Suitable	169	81	250	67.6%
Unsuitable	51	297	348	85.3%
Total	220	378	598	
Producer's accuracy	76.8%	78.6%		Overall accuracy = 78.0%

total of 168 female Walleyes. The mean mass of female Walleyes that migrated up the Tamarac River was 1.03 kg and would thus produce 62,089 eggs/female. Using these estimates, it would require egg deposition from 2,996 female Walleyes to reach maximum reported egg densities on suitable substrate and would therefore require a total migration size of 30,888 fish. The number of females that suitable substrate could support represented 0.4% of the mature females in the system (most recent 10-year average) and was smaller than the mean (9,297 fish) and maximum (24,167 fish) number of females that migrated the river historically (1932–1979; Minnesota Department of Natural Resource, unpublished data).

DISCUSSION

Map Production

The use of SSS enabled the acquisition of substrate data for the entire 10.8-km study site in less than 2 h and provided accuracy high enough to quantify suitable spawning substrate. Further, the SSS map provided continuous habitat data, which is not produced using traditional transect- or grid-based techniques. Sonar images in this study were individually processed and provided the benefit of not displaying areas without data outside the river channel. This made the generation of control points for sonar images simpler and enhanced the aesthetics of the SSS map. One significant drawback to individually processing images is increased processing time. Removal of metadata, no-data areas, and water column pixels for individual images comprised a significant portion of the processing time associated with map production in this study and is not logistically feasible for large-scale assessments.

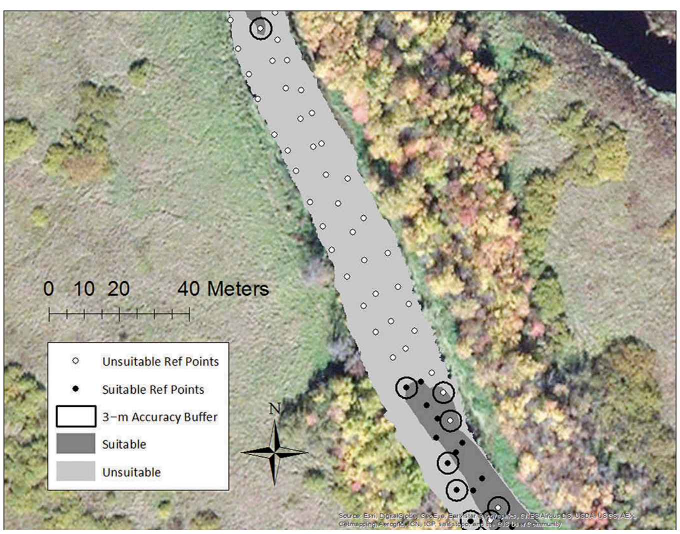

FIGURE 6. Substrate map with suitable and unsuitable reference points and delineated polygons. The 3-m buffers are shown to demonstrate the proximity of misclassifications to a polygon with the correct classification.

In SSS images from units like the one used in this study, the areas near the nadir are compressed to display the water column. This creates a distorted image of the river bottom, which effects spatial accuracy. This distortion occurs whether or not pixels representing the water column are left in the sonar image. We believed that errors resulting from removing the water column were less than those that would be introduced by classifying the pixels representing the water column as substrate. For mapping applications in which the water column makes up a small portion of the sonar images, the error of classifying pixels representing the water column as substrate is minimized.

Map Accuracy

The simple classification scheme (i.e., binary) in this study likely contributed to the relatively high accuracy (78%) compared with previous SSS studies using more complex classification schemes (Kaeser and Litts 2010; Kaeser et al. 2013; Richter et al. 2016). It is intuitive that accuracy is diminished as the classification scheme becomes more complex. Therefore, when selecting a classification scheme for a SSS map one should consider the objectives of the assessment and what classification scheme best fulfills those objectives while minimizing complexity.

The majority (67.4%) of misclassified points occurred less than 3.0 m from the correct polygon class, which provides evidence to suggest that the major sources of misclassification were the spatial accuracy associated with the SSS map and GPS unit. This likely resulted in the reported overall accuracy (78%) being lower than the true sonar classification accuracy because a portion of these points considered misclassified were likely correctly classified by their sonar signature. The use of a more accurate GPS unit would have presumably resulted in higher accuracy by eliminating misclassifications due to spatial uncertainty. To avoid this uncertainty in future SSS mapping studies, researchers should consider collecting reference data with more accurate GPS units. An inability to accurately define transitions between suitable and unsuitable substrates, particularly transitions from sand to gravel, which had similar sonar signatures, was likely another major contributor to classification errors. This is similar to findings from Kaeser and Litts (2010), who reported sand and gravel having similar sonar signatures and suggested that distinction between fine rocky substrate and sand was "a noteworthy source of misclassification".

Egg Deposition

The historic mean Walleye catches recorded during hatchery operations are likely smaller than the current migrations considering those estimates did not include the entire migration. Further, in the last 10 years the Red Lakes' fishery has had high spawning stock biomass (mean = 6.2 kg/ha), the highest population estimate on record (22 million Walleyes ≥ age 2), and Tamarac River electrofishing catch rates of up to 919 Walleyes/h (Brown and Kennedy 2016). Natural mortality during this time period has been high, reaching over 50% in 2013 (Brown and Kennedy 2016). High abundance and high natural mortality provide supporting evidence that the population may be near its carrying capacity and, therefore, is not likely to have been larger during the 47 years when the total catches were reported by hatchery operators.

Considering that the Tamarac River is a major tributary, it is likely that the proportion of mature females in the system that migrate the river is higher than the proportion of mature females that suitable substrate could have supported in 2015 (0.4%). Further, the estimated number of female Walleyes that suitable substrate could have supported (2,996 fish) was lower than the number that migrated the river historically (mean = 9,297; maximum = 24,167 fish). Therefore, the number of females currently migrating the river is likely much higher than what suitable substrate could support.

Egg deposition from many more females than what the available suitable substrate could support would either result in eggs being deposited on unsuitable substrate, which has been shown to reduce survival (McMahon et al. 1984), or in having much higher egg densities on suitable substrate. How high egg densities affect Walleye egg survival and development in situ has not been evaluated, but stacking of eggs has been shown to reduce fertilization rates in laboratory settings (Moore 2003) and would likely increase the chance of transport that results in siltation and abrasion. High egg densities may also reduce the amount of oxygen available to eggs by reducing the area of the water–egg interface where gasses are exchanged, which is relevant considering that the Tamarac River drains from a large bog, where incoming water is known to be low in dissolved oxygen.

The presumed occurrence of egg densities on suitable substrate that are much higher than previously observed (and speculation as to why high egg densities could negatively affect egg survival) and/or egg deposition on unsuitable substrate provide evidence that the amount of suitable spawning substrate available during the time of this study may be a limiting factor for Walleye reproduction in the Tamarac River during a typical year. While spawning substrate is not the only factor that affects the reproductive success of Walleyes, it is one of the most important (McMahon et al. 1984) and it may be one of the most significant factors limiting reproductive success of Walleye spawning in the Tamarac River.

Both previous assessments of Walleye reproduction in the river stated that Walleye movement upriver was eventually inhibited by the presence of beaver dams and that the majority of suitable substrate occurred upstream of where the beaver dam was located during this study. Therefore, it is likely that the quantity of suitable spawning substrate accessible to Walleyes varies annually and is highly influenced by the size and location of beaver dams in combination with flow conditions. Downstream from the beaver dam location in this study, the river transitions from a mostly wooded area to open bog, with many fewer trees near the riverbanks, and eventually to areas of human development. Therefore, a beaver dam occurring further downstream of the beaver dam that limited fish passage in this study is unlikely, and the area of suitable substrate we quantified is likely near the minimum of what would be accessible to Walleyes in a given year.

Implications

Substrate mapping using SSS provided an effective tool for the acquisition of continuous substrate data, which provided additional information to officials managing this fishery. The use of SSS to effectively evaluate spawning habitat for Walleyes in a lotic system was demonstrated in this study and has also recently been used to successfully evaluate Walleye spawning habitat in lentic systems (Richter et al. 2016). This illustrates that SSS could be a powerful tool in a variety of systems to aid in Walleye management. The manual processing of images and georeferencing in this study was very time intensive, and future researchers may want to consider using sonar video processing software to reduce map production time. However, maps produced from sonar videos have not been well studied and accuracy assessments of maps produced using such software should also be conducted.

While this study suggests that beaver dams limiting access to spawning substrate may have negative effects on spawning success in the Tamarac River during a typical year, the Red Lakes Walleye population and fishery are currently thriving. Thus, as long as the fishery maintains its current productive status, limited access to spawning substrate in the Tamarac River is not reason for management concern. However, if the population should become imperiled, managers should consider monitoring the river for the presence of beaver dams and remove them prior to spawning migrations to provide Walleyes access to additional suitable spawning substrate.

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