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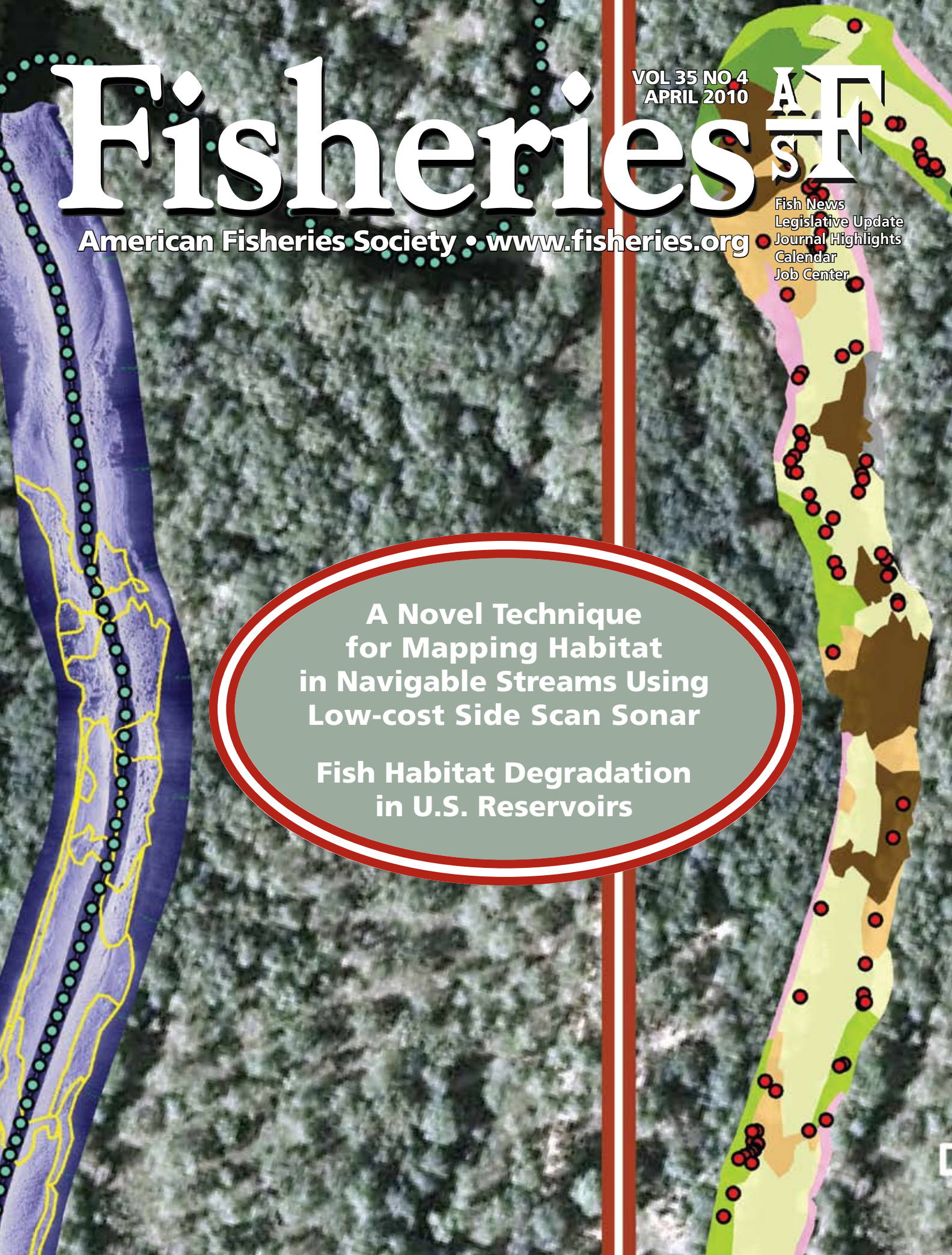

A Novel Technique for Mapping Habitat in Navigable Streams Using Low-cost Side Scan Sonar

Fish Habitat Degradation in U.S. Reservoirs

Fisheries

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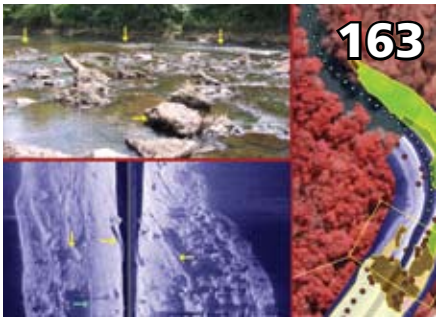

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COVER: Aerial image of an Ichawaynochaway Creek reach with the survey boat track, sonar image map layer, and digitized substrate boundaries added (left panel). Classified substrate polygons and large woody debris interpreted from sonar imagery are displayed for the same reach (right panel).
CREDIT: Adam Kaeser

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FEATURE:
FISH HABITAT

Kaeser demonstrates the execution of a 1-person sonar survey from a small watercraft on a small stream in southwest Georgia.

A Novel Technique for Mapping Habitat in Navigable Streams Using Low-cost Side Scan Sonar

ABSTRACT: An inexpensive and rapid technique for mapping instream habitat of navigable rivers is needed by natural resource professionals. Unlike more expensive side scan sonar devices, the Humminbird Side Imaging system employs a boat-mounted transducer enabling the survey of shallow, rocky streams. This device can be used to obtain high resolution, georeferenced images of underwater habitat. We developed a technique employing geographic information systems (GIS) to transform raw sonar images to fit the configuration of a stream channel. The end product is a GIS layer that can be interpreted to map instream habitat. We demonstrated this approach by mapping substrate and large woody debris in a southwest Georgia stream, and evaluated the technique through a comprehensive accuracy assessment. An overall classification accuracy of 77% was observed for substrate mapping and sonar estimates of large woody debris were correlated ($r^2 = 0.79$) with actual wood abundance. Sonar mapping generated estimates of reach and substrate area comparable to a traditional field approach, and reduced the time investment by 90%. Applications for high resolution habitat maps are widespread and numerous; the ability to produce these maps at low cost is now within the grasp of researchers and managers alike.

Nueva técnica para mapeo de hábitat en ríos navegables mediante escáner sonar de bajo costo

RESUMEN: Los estudiosos de los recursos naturales requieren de una técnica rápida y económica para mapear hábitats en ríos navegables. A diferencia de la mayoría de los escáneres sonares, el sistema de imágenes Humminbird® emplea un transductor montable en una embarcación que permite hacer sondeos en ríos rocosos y someros. Este dispositivo puede utilizarse para obtener imágenes subacuáticas del hábitat, de alta resolución y geo-referenciadas. Se desarrolló una técnica que emplea información de los Sistemas de Información Geográfica (SIG) para transformar las imágenes originales de sonar de forma tal que se ajusten a la configuración de los canales fluviales. El producto final es una capa de SIG que puede ser interpretada para mapear hábitats en los ríos. Este enfoque se demuestra mediante el mapeo del sustrato y escombros de madera en un río del suroeste de Georgia, y también se evaluó su precisión. En cuanto al mapeo del sustrato se observó una precisión del 77% y la estimación realizada mediante el sonar de la abundancia de los escombros de madera se correlacionó con la abundancia real de la madera ($r^2 = 0.79$). Los mapeos con sonar generaron estimaciones tanto de alcance como de área de sustrato, comparables con los obtenidos con los enfoques tradicionales, y redujeron el tiempo de las operaciones en un 90%. Las aplicaciones de mapas de hábitat de alta resolución son variadas y numerosas; la habilidad de producir estos mapas a un bajo costo se encuentra en este momento al alcance tanto de investigadores como de manejadores.

Adam J. Kaeser, and Thomas L. Litts

Kaeser is an aquatic ecologist and Litts is a GIS specialist with the Georgia Department of Natural Resources, Wildlife Resources Division. Kaeser can be contacted at adam.kaeser@dnr.state.ga.us.

INTRODUCTION

Fish habitat encompasses the variety of physical, biological, and chemical features of the environment that sustain individuals, populations, and assemblages (Hubert and Bergersen 1999). Fishes relate to habitat across a variety of spatial and temporal scales, from the microhabitat patch of an individual brook trout (*Salvelinus fontinalis*) redd to the stream network inhabited by an entire population. The health and biotic potential of fish populations are intimately linked to the integrity of their habitat across these scales (Barbour and Stribling 1991; Roth et al. 1996). The loss, degradation, and fragmentation of aquatic habitats have widely imperiled fishes (Leidy and Moyle 1998; Dudgeon et al. 2006; Jelks et al. 2008), and there is an urgent need to identify, protect, restore, and enhance fish habitat throughout the United States. This need is exemplified in the core mission of the National Fish Habitat Action Plan (NFHAP), a contemporary initiative focusing on fish and habitat conservation efforts nationwide (www.fishhabitat.org).

The research and management of stream fish habitat across landscapes poses a number of challenges. Traditionally, stream ecologists have focused on smaller, wadeable systems and finer spatial scales (e.g., the stream reach), extrapolating site-specific information to a broader context (Fisher and Rahel 2004; Marcus and Fonstad 2008). At coarse scales, and in larger and more turbid systems, traditional approaches can become costly and may not provide a continuous perspective of the riverine landscape. Though terrestrial landscape ecology has flourished using spatial technologies to reveal patterns and processes at broad scales, the investigation of riverine landscapes has lagged behind (Wiens 2002), perhaps for want of analogous tools and techniques. To enable ecological investigations at scales relevant to the life history of stream fishes (Fausch et al. 2002; Lowe et al. 2006), and to support the nationwide conservation of fish habitat, a multiscale, riverscape perspective is necessary, as are the tools, methods, and training to facilitate this approach.

Over the past two decades spatial technologies such as global positioning systems (GPS), geographic information systems (GIS), and remote sensing have become pervasive tools used to map land cover (Frissell et al. 1986; Poole 2002; Meyer et al. 2005), channel geomorphology (Gilvear and Bryant 2003; Mollot and Bilby 2008), and other features that directly or indirectly influence fish habitat (Fisher and Rahel 2004; Laba et al. 2008). Imagery captured with space and airborne, passive sensor systems (e.g., Ikonos, aerial photography) are frequently used as the principal input, or foundation for such studies at a wide range of resolutions (~30 cm to 1 km) and map scales (large to small).

For aquatic environments, low-altitude deployment of both passive and active sensor systems is increasing as advanced remote sensing technology enables the detection and visualization of underwater habitat. Recent demonstrations include bathymetric lidar (Charlton et al. 2003), radar measurement of discharge (Costa et al. 2000), thermal infrared mapping of stream temperature (Torgersen et al. 2001), and the mapping of geomorphic channel structure and large woody debris using hyperspectral imagery (Marcus et al. 2003; Jones et al. 2007; Marcus and Fonstad 2008). However, these approaches are generally expensive, demand rigorous logistical planning, require highly specialized technical personnel, and can be hindered by environmental factors such as canopy cover, water depth, and turbidity (Legleiter et al. 2004; Marcus and Fonstad 2008). Financial considerations aside, such limitations preclude the widespread use of these technologies in a vast number of turbid and deep stream systems.

Waterborne hydroacoustic technology provides an alternative to aerial remote sensing of habitat in a host of aquatic systems. For example, side scan sonar (SSS) has been used for decades to detect and map benthic features of marine and deep freshwater systems (Newton and Stefanon 1975; Fish and Carr 1990, 2001; Prada et al. 2008). Traditional SSS is, however, expensive and typically involves towing an underwater sensor (i.e., towfish), limiting its use in relatively shallow freshwater systems. Examples of freshwater applications include Edsall et al. (1989), Anima et al. (2007), Laustrup et al. (2007), and Manley and Singer (2008).

In 2005 Humminbird® released the 900-series Side Imaging (SI) system, an inexpensive (~$2,000) side scan sonar device. The SI system employs a small, boat-mounted transducer that enables surveys in shallow, rocky streams. This device is capable of producing very high resolution (<10 cm) imagery revealing substrate, large woody debris, and depth—all critical components of instream habitat. Recognizing the potential of the SI system, we have worked to develop rapid, flexible, and cost-effective techniques to acquire and geoprocess sonar imagery for use in the production of large-scale, classified habitat and image maps in riverine landscapes.

In this study our objectives were (1) to demonstrate a technique that uses the Humminbird® SI system to map and classify habitat (substrate, LWD, depth) in a small navigable stream, (2) to evaluate the technique through a comprehensive map accuracy assessment, and (3) to compare the results and time investments of sonar-based vs. traditional approaches to instream habitat assessment.

METHODS

Study area

In this study we examined Ichawaynochaway Creek, a low gradient (<0.001% slope) tributary to the lower Flint River on the Gulf Coastal Plain of southwestern Georgia (Figure 1). This stream was selected because high flows during winter and spring permit navigation, and low flows typically experienced during summer permit wading and snorkeling for ground truth surveys. Ichawaynochaway Creek is comprised of sandy runs, rocky shoals, and portions of channel incised into, and flanked by, Ocala limestone outcrops and dense tree canopies. Additional geographic and hydrologic descriptions for this system may be found in Palik et al. (1998), Golladay and Battle (2002), and Golladay et al. (2004).

Procedures for data acquisition, map production, and assessment

(a) Sonar data acquisition

We employed a Humminbird® 981c SI system to obtain sonar data during a high discharge event. High flows were targeted in order to image habitat within the bankfull channel. The sonar survey was completed in 3.5 hours on 8 April 2008. The SI system was connected to a WAAS-enabled Garmin GPSMAP® 76 GPS to provide coordinate information for image capture locations. The sonar transducer was positioned in front of a small johnboat via a custom mount and set at an operating frequency of 455 kHz. The side beam range was set to 24.4 m (80 ft.) per side. The GPS antenna was also positioned near the transducer to maximize image capture location accuracy. Consecutive, overlapping sonar images and associated coordinate data were recorded to the SI system while navigating downstream at ~8.0 km/h (5 mph) and maintaining a mid-channel position. Additional

Figure 1. Location of study area in southwest Georgia. Dashed line points to upstream head of mapped reach.

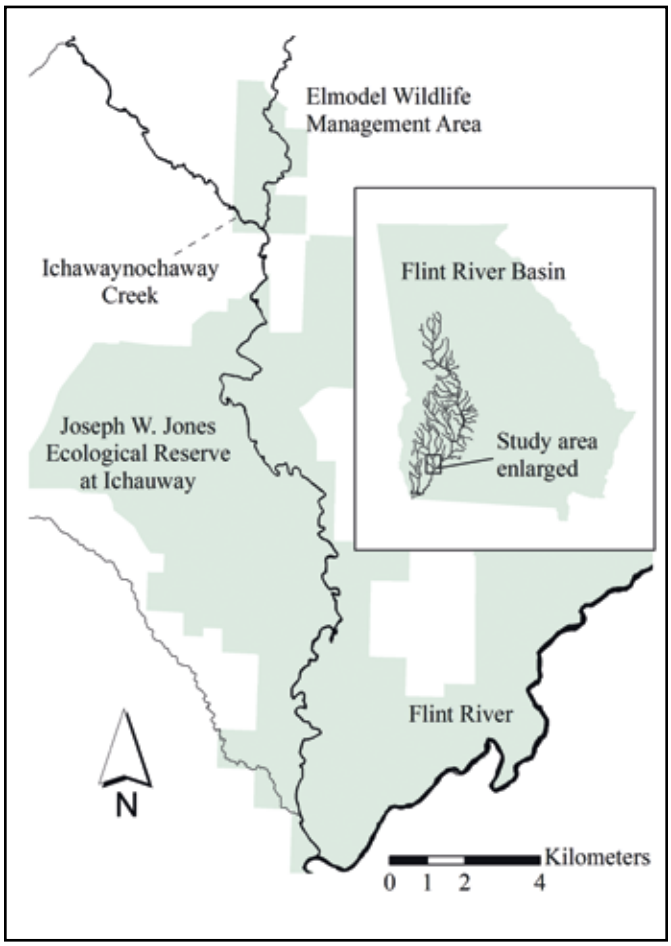


Table 1. Classification scheme and associated definitions developed for the Ichawaynochaway Creek substrate map.

Substrate Class	Acronym	Definition
Sandy	S	≥ 75% of area composed of particles < 2 mm diameter (sand, silt, clay or fine organic detritus).
Rocky fine	Rf	> 25% of area composed of rocks > 2 mm, but < 500 mm diameter across the longest axis.
Rocky boulder	Rb	An area ≥ MMU that includes ≥ 3 boulders, each ≥ 500 mm diameter across longest axis, each boulder within 1.5 meters of the next adjacent boulder. Any area meeting these criteria, regardless of underlying substrate, is classified Rb.
Limerock fine	Lf	≥ 75% of area composed of limestone as bedrock or an outcropping with relatively smooth texture (not fractured into blocks ≥ 500 mm diameter).
Limerock boulder	Lb	≥ 75% of area composed of limestone fractured into blocks ≥ 500 mm diameter across longest axis and meeting the spatial arrangement criteria of Rb.
Unsure sandy	US	Any area of the sonar map difficult to classify due to poor image resolution, but suspected to be predominantly sandy due to stream channel context.
Unsure rocky	UR	Any area of the sonar map difficult to classify due to poor image resolution, but suspected to be predominantly rocky due to stream channel context.

geographic coordinates and stream depth data were recorded to the GPS device at 3-s intervals.

(b) Sonar data processing

We employed Environmental Systems Research Institute's (ESRI) GIS software and the IrfanView graphic viewer to transform raw sonar images into sonar image maps (SIMs) with real world coordinates (e.g., Universal Transverse Mercator [UTM]). ArcView 3.2 (ESRI) and IrfanView were used to process the raw sonar images, a step that involved image collar removal, image cropping at user identified image overlap points, and the generation of raw sonar image mosaics. The resultant mosaics consisted of 10–12 individual images, each representing ~400–500 m of stream reach. Mosaics were saved as raw JPEG (.jpg) images.

Field-collected GPS waypoint and track data were imported into ArcView 3.2, reviewed, and saved as ESRI shapefiles. These shapefiles were processed using custom algorithms written in the Avenue scripting language to derive robust image-to-ground control point networks for each raw image mosaic. Each image mosaic control network contained between 300 and 360 control points and was stored as a space-delimited text file (.txt) for use in image transformation.

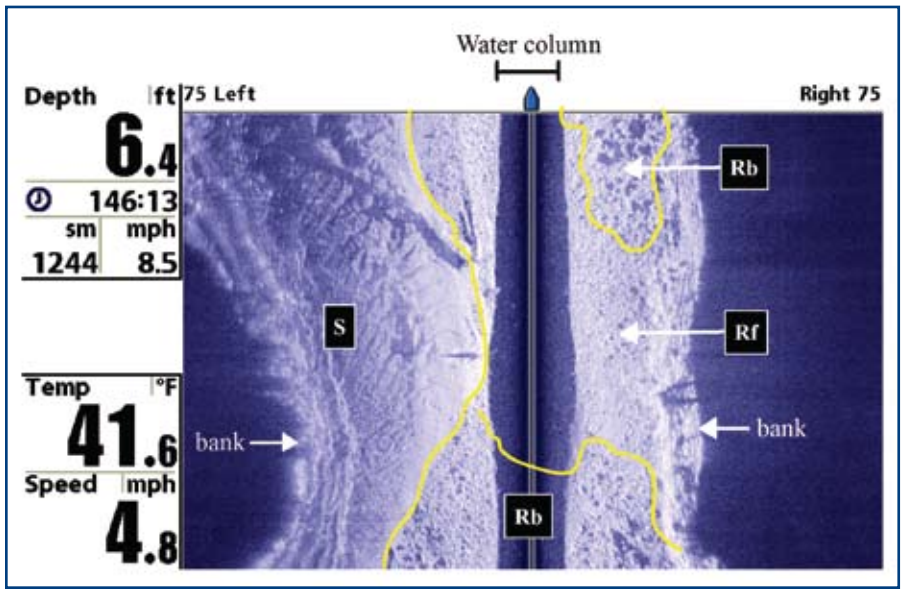
Transformation of raw image mosaics to SIMs was completed using the georeferencing tools available in ESRI's ArcGIS 9.2 (ArcView level) software. Image mosaics were opened in ArcGIS and their corresponding control point network files were loaded as link tables. A SPLINE transformation was applied to the link table, which consistently resulted in a solution with a low total root mean square error (RMSE) of ±0.01 m or less due to the nature of the transformation type (ESRI 2008). The rectify command was used to transform raw image mosaics into SIM files using the SPLINE transformation solution, cubic convolution resampling, and an output ground pixel resolution of 10 cm. The SIM files were saved as JPEG (.jpg) images with corresponding world files registered to UTM Zone 16 and cast on the North American Datum of 1983 (NAD83).

(c) Habitat map production

A minimum map unit (MMU) and classification scheme were defined during on-site inspection of sonar images in portions of Ichawaynochaway Creek upstream of the mapped area, prior to map production. We identified a MMU of 28 m^2, an area equal to a circle with a 3-m radius. The classification scheme included five predominant, surficial substrate classes: sandy (S), rocky fine (Rf), rocky boulder (Rb), limerock fine (Lf), and limerock boulder (Lb; Table 1). To ensure mutual exclusivity of the classification scheme, areas containing < 75% limerock in combination with other rocky substrates defaulted to either Rf or Rb according to class definitions. The classification scheme was also hierarchical by design. For example, Lf could be combined with Rf to constitute a single, fine-textured rock class, and Lb could be combined with Rb to constitute a single, coarse-textured rock class. An additional unsure class was established to account for areas of the SIM that were poorly resolved. Unsure areas were presumptively assigned a predominantly sandy (US) or predominantly rocky (UR) classification based on their stream channel context.

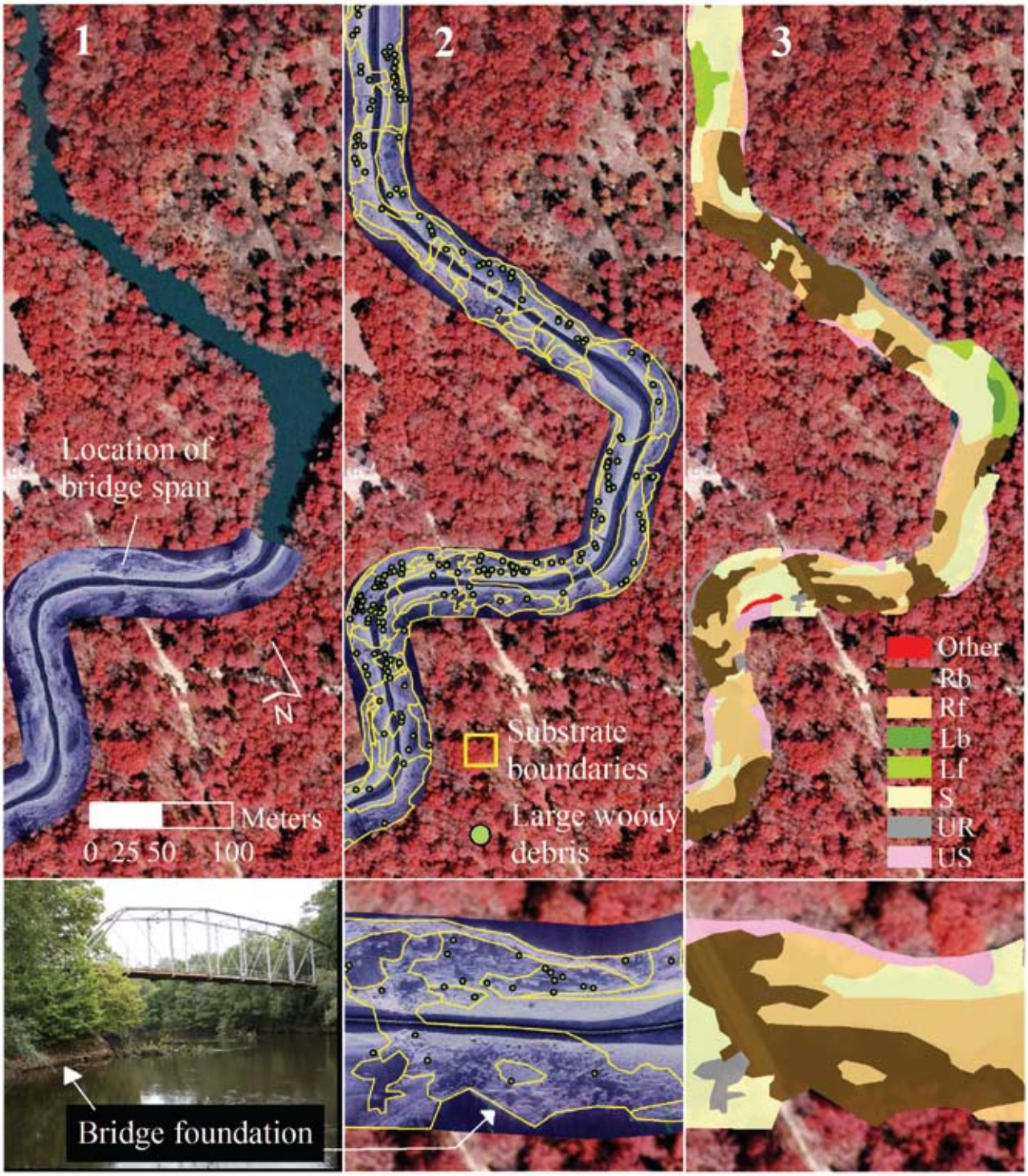
Rectified sonar imagery was rendered in ArcGIS 9.2 at the raster resolution scale (~1:375) to digitize stream banks and substrate class boundaries. During digitization, areas of uniform sonar signature ≥ MMU were uniquely delineated (Figure 2).

Figure 2. Raw sonar image from Ichawaynochaway Creek annotated to identify key habitat features. Image width is 150 feet. The water column appears as a dark area in the center of the image. Yellow lines have been drawn to illustrate the apparent boundaries between the following substrate classes: S = sandy, Rb = rocky boulder, and Rf = rocky fine areas. Stream banks are revealed as abrupt margins within the image.



Slant range correction was not performed on raw sonar imagery to correct distortion near the image center (Fish and Carr 1990), therefore substrates observed adjacent to the water column were interpreted as extending to the center of the image. All areas bound by digitized lines were converted to polygons and assigned a substrate class (Figure 3).

Figure 3. Evolution of a sonar-based habitat map. Panel 1 displays an aerial infrared image of Ichawaynochaway Creek with transformed sonar imagery added as a layer. In Panel 2 substrate boundaries and large woody debris layers have been added. Panel 3 displays only the classified substrate polygons. Legend acronyms refer to the following substrate classes: Rb = rocky boulder, Rf = rocky fine, Lb = limerock boulder, Lf = limerock fine, S = sandy, UR = unsure rocky, and US = unsure sandy. Bridge photograph shows the irregular foundation that appears in the adjacent sonar image, and some of the rocky boulder substrate mapped in this area. Layer transparency reveals the proper position of the bridge above the sonar image foundation. Aerial infrared imagery provided courtesy of the Joseph W. Jones Ecological Research Center at Ichauway.



In Kaeser and Litts (2008) we assessed large woody debris (LWD) using raw (i.e., untransformed) sonar imagery obtained in Ichawaynochaway Creek. To compare our ability to map and quantify LWD from transformed sonar imagery generated during this study, we digitized and enumerated wood in segments on the SIMs that matched our former study reaches (Figure 3).

(d) Map accuracy assessment

Several methods were employed to evaluate the habitat map and validate the mapping technique. To assess the dimensional accuracy of transformed imagery, we identified a set of fixed objects in the SIMs to locate and measure in the field. This set included 21 logs and the abutments of 3 unique bridges. Logs were typically oriented parallel to the stream channel (evaluating image y-dimension), and bridge abutments were oriented perpendicularly to the channel (evaluating image x-dimension). Actual log lengths were measured in the field with a tape and bridge spans were measured with a Nikon ProStaff Laser 440 rangefinder and compared to measurements made from SIMs with the ArcMap ruler tool.

To evaluate the overall classification or thematic accuracy of the substrate map, a sample of reference sites was selected. We randomly assigned points (n = 492) to substrate polygons (71 points per class, except UR which received 66 points) using the Random Point Generator, v. 1.3 extension for ArcView 3.x to serve as reference data collection sites (www.jennessent.com/arcview/random_points.htm). Sample points were randomly placed within reference polygons at a minimum distance of 3 m from polygon edges to reduce the risk of incorrectly locating a point in an adjacent polygon due to combined GPS and map position error.

Reference sites were visited 16–20 June 2008 with a field crew of three persons operating two boats, each equipped with a GPS device. One device was a WAAS-enabled Trimble Recon unit (Transplant CF GPS receiver, 2–5 m accuracy) (TransplantComputing 2002), and the other a LandMark Systems component GPS system that included a TDS Nomad data logger and WAAS-enabled, Hemisphere GPS Crescent antenna capable of achieving < 2 m accuracy under canopy cover (Hemisphere GPS 2007). Use of two boats enabled the crew to operate independently to confirm point locations. Once located, snorkeling was conducted to inspect and classify the substrate within a 3-m radius around the point (i.e., the sample site). Some points (n = 11) were skipped because they were too deep to survey without a dive team; 5 points could not be located due to poor satellite reception during the ground truth survey. Map classification data were not in hand during reference data collection.

Error matrices and conventional classification accuracy statistics were computed using reference data (Congalton and Green 1999). The standard error matrix was normalized, an iterative proportional fitting procedure that allows individual cell values within the matrix to be directly compared regardless of differences in sample size, and Kappa analysis performed using MARGFIT (Congalton 1991). Reference data for unsure areas were analyzed separately. Areal map accuracy was estimated as the total area of all map polygons

Preparing to dive and inspect a reference site during the Ichawaynochaway Creek map accuracy assessment.

that included a correctly classified reference site, divided by the total area of all map polygons visited during reference data collection.

Our ability to assess classification accuracy was potentially confounded by the positional (i.e., horizontal) accuracy of the source SIMs and the GPS accuracy experienced during reference site location. To assess horizontal accuracy of the SIMs according to National Standard for Spatial Data Accuracy guidelines (FGDC 1998), we calculated root mean square error (RMSEr) using the coordinates of 18 fixed objects (logs and bridges) measured from the SIMs against their "true" locations recorded in the field with the Nomad GPS.

(e) Comparison of habitat assessment approaches

To determine whether sonar mapping yielded estimates of substrate composition and LWD comparable to a traditional, transect-based approach, we sampled 7 randomly selected reaches, each ~500 m long, during low water periods in summer 2007 (Kaeser and Litts 2008). Transects perpendicular to the stream channel were established at 20-m intervals within each reach. Along each transect, bankfull channel width and the length covered by either sandy or rocky substrate were visually assessed by snorkeling and recorded. We classified the predominant surficial substrate according to the scheme employed during sonar map production. Reach area was calculated from transect data as the mean bankfull channel width multiplied by reach length. For each reach, the total transect length covered by each substrate class was summarized, converted to a proportion of the total length assessed, and multiplied by reach area to yield an estimate of substrate class area.

Reach and substrate class areas corresponding to field survey reaches were subset from the completed substrate map and summarized in ArcGIS. The total sandy area in each reach = S + US classes, and total rocky area = Rf + Rb + Lf + Lb + UR classes. The two assessment methods (sonar and transect) were compared following the method described by Bland and Altman (1986). Large woody debris was sampled and the data analyzed as described in Kaeser and Litts (2008).

To compare the overall efficiency of sonar mapping with the transect-based approach, we maintained a detailed record of time invested during each step in the project.

RESULTS AND DISCUSSION

Map Statistics

Twenty-seven kilometers of lower Ichawaynochaway Creek were mapped. Four substrate classes constituted 89% of the mapped area: sandy (40%), rocky fine (22%), rocky boulder (15%), and limerock fine (12%). The least common substrate was limerock boulder (4%). Unsure areas constituted 7% of the total map area (US = 5%, UR = 2%).

The 101-ha map exhibited a high level of detail and heterogeneity. The map consisted of 1,199 substrate polygons ranging in area from 28 m^2 to 33,000 m^2. The majority of polygons (83%) were small (<1,000 m^2); all substrate classes were represented in this area category. Few polygons (n = 12) exceeded one hectare (> 10,000 m^2) in size; only contiguous sandy, rocky fine, or limerock fine classes were represented in this category.

Mean depth of Ichawaynochaway Creek during the sonar survey was 3.05 m (SD = 1.13, range 0.6–8.6 m, n = 3,307). Recommended transducer altitude (i.e., height above the substrate) during surveys is typically 10–20% of the range setting (Fish and Carr 1990). Mean altitude of the sonar transducer during our survey was 12.5% of the range setting. In this study we did not conduct additional analyses of the depth records obtained, but these data might be used to geographically model and map the distribution of channel geomorphic units (riffle, run, pool) throughout the study system.

Map Accuracy

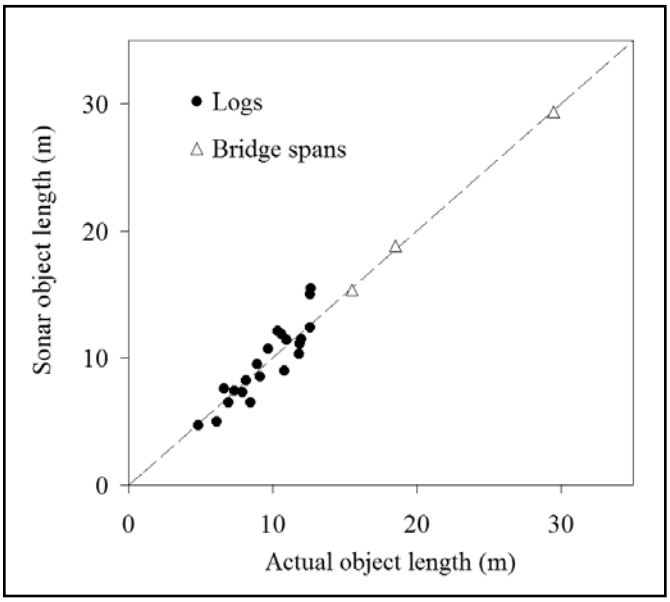
Several types of error potentially affect the overall accuracy of a completed habitat map. Dimensional, or geometric, errors may have been introduced during the transformation of raw sonar image mosaics into SIMs. The dimensions of fixed objects in the field were, however, similar to SIM dimensions; the mean difference between measurements was 0.87 m (SD = 0.78; Figure 4). These results and the high degree of fit of transformed imagery to the apparent stream channel provided ample evidence that the processing techniques we employed effectively corrected image dimensionality.

Overall classification accuracy for the Ichawaynochaway Creek map was 77% (Table 2). This statistic represents the proportion of correctly classified sites visited during reference data collection (Congalton and Green 1999). Normalized accuracy of the map was 76%, similar to overall accuracy because roughly equal numbers of reference sites were visited in each class (Table 3). Producer's accuracy, a statistic that represents the map maker's ability to correctly identify substrates appearing in the map, ranged from 69–83%. Producer's accuracy was lowest for the rocky fine class and highest for sandy areas. User's accuracy, a statistic that describes the proportion of classified areas on the map that are correct in the field, ranged from 61–90%. User's accuracy was highest for sandy areas, the most abundant substrate mapped in lower Ichawaynochaway Creek, and lowest for limerock boulder, the least abundant substrate class. Kappa analysis on the error matrix yielded a KHAT statistic of 0.71 (Variance = 0.0008) and Z statistic of 25.0 indicating the map classification was significantly better than random.

A large proportion of misclassifications were the result of confusion between rocky boulder and limerock boulder, and rocky fine and limerock fine classes. Such mistakes were anticipated and difficult to avoid given that these substrate pairs exhibited similar appearance in the sonar imagery. One way to handle this confusion is to collapse the substrate pairs into a single fine-textured rocky class, and a single coarse-textured rocky class. Doing so increases the overall Ichawaynochaway Creek map accuracy to 86%.

Another source of misclassification was the confusion of limerock boulder and limerock fine, and rocky fine and rocky boulder classes. A review of the sonar image map revealed that some of these mistakes could have been avoided by paying closer attention to (1) the manner in which discrete boundaries were imposed in zones of transition between the classes, and (2) the effect of image compression in areas near

Figure 4. Length of objects measured in sonar imagery versus actual length of these same objects located in the field. Dashed line (y = x) represents equality between measurements.



the center of the image (Fish and Carr 1990). Issues related to classification in areas of continuous transition are inherent to map accuracy assessments (Congalton and Green 1999; Meyer and White 2007). Slant range correction, an additional processing step that effectively removes the water column appearing in raw sonar imagery, might facilitate discrimination of substrates in the near-field portion of imagery, yet our results demonstrate high accuracy without undertaking this step.

Another noteworthy source of misclassification in the map was the confusion of sandy and rocky fine areas. Several areas classified as sandy in the map were actually covered by gravel substrate (i.e., Rf; particle diameter ~5–15 mm). These particles were below the stated transverse resolution (63.5 mm) of the SI system (Humminbird® 2005). Transverse resolution is the ability to discriminate two objects in close proximity that are aligned parallel to the path of the boat (Fish and Carr 1990). In effect, gravel and sand exhibited similar signature in the SIMs, a phenomenon that was likely accentuated in both the near-field and far-field portions of the sonar image. At broader perspectives, however, sandy areas often exhibited rippled or dune-like patterns (e.g., Kendall et al. 2005), features that helped to discriminate sand from fine rocky substrate in many instances. We recommend that particular attention be devoted to reducing/resolving this confusion if the project goal is to identify fine rocky areas such as gravel beds.

Table 2. Standard error matrix and associated statistics for the Ichawaynochaway Creek substrate map classification.

Classified data	Reference site data (field data)					Row total	User's accuracy
	S	Rf	Rb	Lf	Lb		
S	60	6	1	0	0	67	90%
Rf	8	54	2	5	0	69	78%
Rb	0	8	59	1	3	71	83%
Lf	4	7	1	51	8	71	72%
Lb	0	3	16	8	42	69	61%
Column total	72	78	79	65	53	347	
Producer's accuracy	83%	69%	75%	79%	79%		Overall accuracy 77%

The gray, diagonal elements of the matrix contain the correct classification for each substrate type.

Unsure areas were primarily mapped as narrow polygons extending along the margins of the stream, where sonar shadows or far-field distortion affected the quality of sonar data. The majority of these areas were classified unsure sandy (US) in the Ichawaynochaway Creek map. User's accuracy for US areas was 85%, indicating this class could be lumped with S, thereby reducing the total unsure area in the map. On the other hand, only 56% of unsure rocky (UR) areas were confirmed rocky during reference data collection. We attribute the misclassification of many UR areas to a false impression of rocky texture produced by groups of cypress knees and submerged woody debris often encountered in these parts of the stream channel. For practical purposes, special attention could be devoted to unsure areas during ground truth work to fill in such data gaps if deemed important.

Table 3. Normalized error matrix for the Ichawaynochaway Creek substrate map classification.

Classified data	Reference site data (field data)				
	S	Rf	Rb	Lf	Lb
S	0.849	0.096	0.025	0.013	0.017
Rf	0.107	0.718	0.038	0.123	0.015
Rb	0.005	0.097	0.780	0.029	0.090
Lf	0.036	0.063	0.014	0.728	0.160
Lb	0.004	0.026	0.143	0.108	0.719
Normalized accuracy = 76%					

The gray, diagonal elements of the matrix contain the correct classification percentages for each substrate type.

Given the potential for sediment redistribution, an important consideration when planning and executing a mapping study is the period of time that elapses between sonar and ground truth surveys. We do not believe that sediment redistribution was a major factor affecting the classification accuracy results of this study, however, as the sonar survey was conducted during the last high flow event of spring 2008, and no additional high flow events occurred during the brief, two-month period between sonar and ground truth surveys. Qualitative, yet extensive comparisons of mapped to actual

sediment distribution patterns in Ichawaynochaway Creek indicated that little change had occurred between surveys in this low gradient system.

The positional, or horizontal error (RMSEr) of the source SIMs was estimated at ±5.95 m. This result has important implications for the classification accuracy of the substrate map and suggests that buffering reference data sites at 3 m from polygon edges was insufficient to safeguard against GPS error in this study. Some reference data sites may have been incorrectly co-registered with their corresponding map locations thereby conservatively biasing (i.e., depressing) the classification accuracy estimate (Foody 2008). In future studies, we recommend that both the internal polygon buffer distance used to safeguard against co-registration errors and the radius used to define the MMU are greater than or equal to the least stated accuracy of the GPS equipment used (e.g., in this study- 5 m).

The overall classification accuracy statistic provides one perspective on map accuracy. During assessment, an equivalent number of reference sites were examined from each substrate class, yet some classes were represented by small polygons comprising a small proportion of the total area mapped (e.g., Lb). Thus, the overall classification accuracy statistic does not represent the total area of the map that is correctly classified. By examining accuracy in terms of polygon area, we estimated areal map accuracy at 86% (Table 4). Collapsing Rf and Lf into a single fine-textured rocky class, and Rb and Lb into a single coarse-textured rocky class increases areal map accuracy to 92%. This analysis assumes that the area of an entire polygon was classified correctly if the reference site was deemed correct, and vice versa for incorrectly classified sites. We believe this is a reasonable assumption given that substrates were delineated by a single interpreter and assigned a class according to image signature similarities.

COMPARISON OF METHODS

Sonar habitat mapping generated estimates of physical habitat similar to the traditional, transect-based approach. Sonar map estimates of bankfull channel area were comparable and ~10–15% greater than field estimates (Figure 5). We attribute these differences to the conduct of the sonar survey during a discharge that exceeded what we identified in the field as bankfull channel width. Sonar estimates of sandy and rocky substrate were typically within 30% of estimates generated by the transect-based method, although the relationship was more variable than that of bankfull channel area. Additional variation in these estimates was expected given that the transect method sampled only a fraction of the substrate present in a reach. In addition, some sediment redistribution may have occurred between the transect surveys (summer 2007) and the sonar survey (spring 2008) thereby increasing variation among estimates.

Estimates of LWD from 2008 SIMs were more accurate than estimates made from raw sonar imagery (obtained 2007) in all Ichawaynochaway Creek study reaches (Kaeser and Litts 2008); however, we were still unable to identify all of the wood present within a stream reach by sonar inspection (Figure 6). We believe more wood was visible in imagery obtained during the 2008 survey because we relocated the sonar transducer to the front of the boat, thus eliminating distortion caused by propeller turbulence. We do not believe that redistribution of LWD was a factor affecting these results, as few high flows and no flood events occurred between field ground truth and sonar surveys. SIM estimates of wood were correlated (r^2 = 0.79) with actual Ichawaynochaway Creek wood counts obtained during ground truth surveys. These results indicate that transformed sonar imagery (SIMs) may also serve as a reliable source of information on wood distribution and abundance (Kaeser and Litts 2008).

Sonar habitat mapping required substantially less time (~3 h/km) to complete than the traditional, transect-based approach (~30 h/km) (Table 5). Although accuracy assessment requires additional time, this investment could be greatly reduced in future efforts by eliminating some elements (e.g., fixed object measurement), and by assigning reference sites to areas of the map near access points instead of throughout an entire study area. Image preparation time (10 min/km) was significantly reduced in this study by the use of custom software and the program IrfanView relative to investments (63 min/km) described in Kaeser and Litts (2008).

CONCLUSION

The technique demonstrated here represents a rapid, inexpensive, and accurate method of creating high resolution, spatially detailed maps of continuous, instream habitat

Table 4. Areal accuracy of classified polygons examined during the field assessment study.

Polygon class	Total polygons visited	Area of polygons visited (ha)	Area classified correctly[1] (ha)	% Area classified correctly
S	59	19.0	18.6	98%
Rf	63	10.8	8.7	81%
Rb	71	9.4	9.1	97%
Lf	58	7.2	5.2	72%
Lb	62	3.8	2.2	58%
UR	64	1.6	0.9	54%
US	65	2.0	1.6	81%
Total	442*	53.7	46.3	Areal map accuracy (46.3/53.7) = 86%

[1] This statistic assumes that the entire area enclosed within a polygon was classified correctly if the actual substrate within a 3-m radius examined matched the assigned classification, and likewise assumes that the entire area of the polygon was incorrect if the examined area did not match the classification.

* Fewer polygons were visited than reference sites because some large polygons contained more than 1 reference site.

Figure 5. Reach and substrate area estimated from the sonar image map and from transect data obtained in the field. Dashed line (y = x) represents equality between measurements (*n* = 7 reaches).

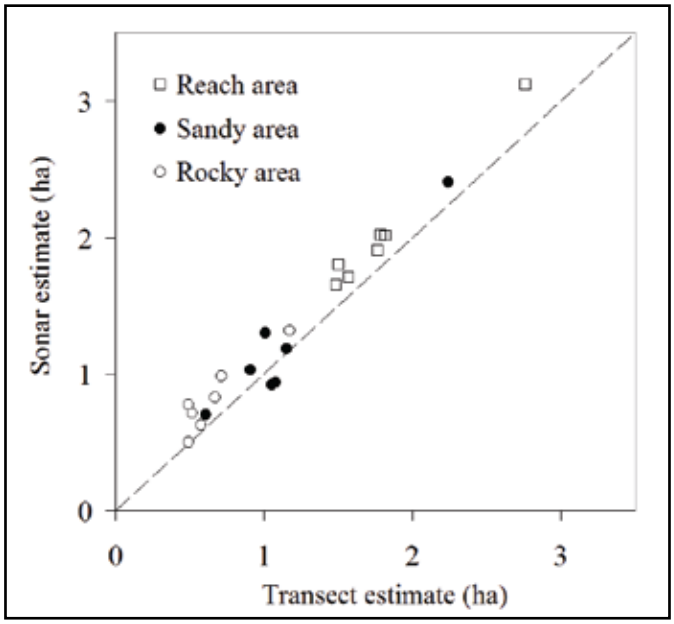
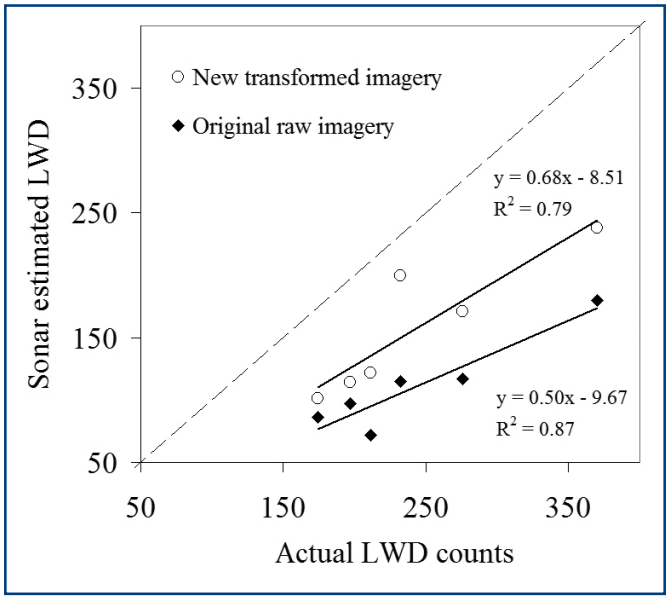


Figure 6. Sonar estimates of large woody debris (LWD) versus actual counts obtained from field surveys in Ichawaynochaway Creek. Open circles represent counts made from sonar image maps (front-mounted transducer), and black diamonds represent counts made from raw, untransformed imagery (rear-mounted transducer). Dashed line (y = x) represents equality between counts of LWD.



across broad aquatic landscapes. Sonar mapping provides a comparable and effective substitute for the labor intensive, traditional field assessment of several key habitat variables. Sonar mapping is not only more efficient, but the information generated is geospatially referenced at a level of detail that is difficult, if not impossible to achieve with traditional methods. By providing a means to visualize whole-channel, underwater features, sonar mapping overcomes limitations of traditional approaches in deep, turbid, and/or non-wadeable systems characteristic of the Southeast Coastal Plain and elsewhere. From a practical standpoint, this technique can be performed using software readily available to researchers and managers with a limited amount of training and expertise.

Within the GIS environment, information contained in these maps can be integrated with a wide variety of data layers providing new ways to examine patterns and processes occurring in aquatic landscapes. Applications of sonar habitat maps include studies of habitat-organism relationships, the identification or prediction of critical habitat, the association of land cover and instream habitat, and the monitoring of change over time.

Table 5. Time invested during steps of the sonar habitat mapping process (accuracy assessment not included*).

Sonar mapping step	Details	Time invested (min/km)
Sonar data capture	Boat survey	11
Data processing	Image preparation	10
	Georeferencing/geotransformation	41
Map production	Substrate boundary digitization	43
	Substrate classification and review	20
	Large woody debris digitization	30
Total		155

*Comprehensive map accuracy assessment (2 persons examined ~500 reference sites, each 28 m^2, plus fixed object measurement) required an additional 275 min/km to complete.

Like all assessment techniques, sonar mapping is not applicable to some types of ecological investigation and aquatic systems. In this study we identified several limitations of the technique such as the loss of data due to sonar shadowing and range resolution effects, and potential difficulties associated with discriminating between substrate types. The quality of sonar data is directly related to careful mission planning, proper execution, and the conditions experienced both during the survey and those fixed by stream morphology (e.g., gradient, sinuosity, channel confinement). The quality of the habitat map will, in turn, depend on the quality of the sonar data and the experience of the person developing the map.

This study represents a critical first step towards evaluating a technique for using low-cost side scan sonar to map habitat. This flexible technique can be adapted to map shoreline or benthic habitat in a variety of lentic or large lotic systems, and we are currently leading investigations in larger rivers. Although we used both ArcView 3.2 and ArcGIS 9.2 to process imagery in this study, we recently developed tools that function exclusively within the ArcGIS 9.2+ platform. These new tools have greatly reduced the processing time investment from 51 min/km (this study) to 12 min/km. We hope that this research and the availability of these tools encourage researchers and managers to consider mapping, monitoring, and assessing aquatic habitat with low-cost side scan sonar. Future research should evaluate sonar mapping in a variety of systems to explore the effective boundaries of this promising remote sensing technique.

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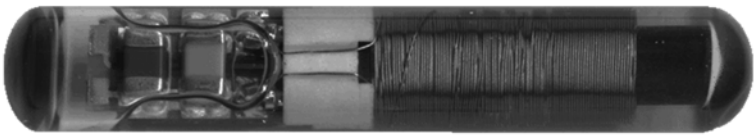

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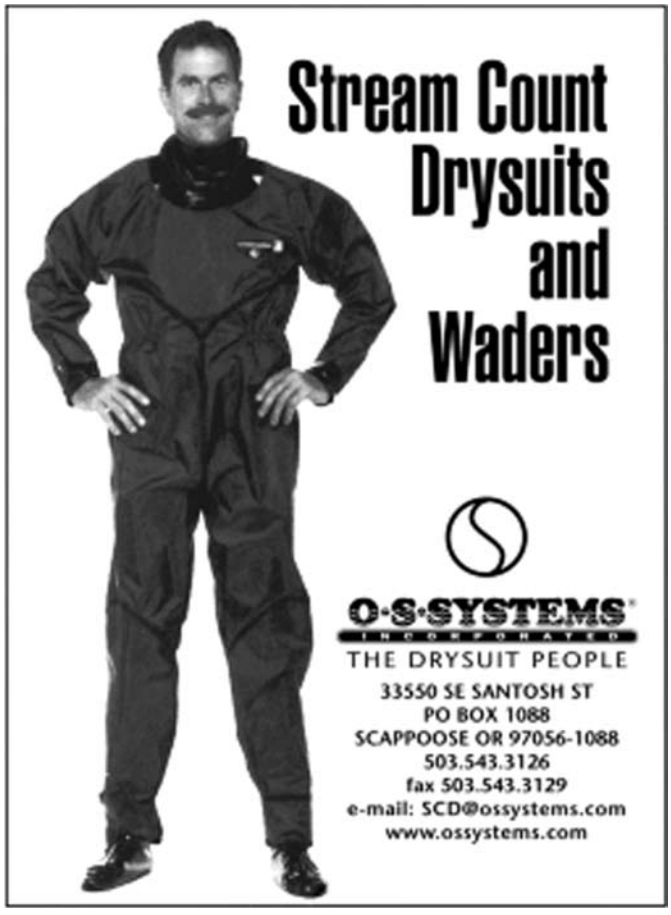

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