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USING LOW-COST SIDE-SCAN SONAR FOR BENTHIC MAPPING THROUGHOUT THE LOWER FLINT RIVER, GEORGIA, USA

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ABSTRACT

An efficient, low-cost approach for mapping habitat features in navigable streams is needed to support the research and management of aquatic ecosystems at the landscape level. We developed a method that uses high-resolution (455 kHz) side-scan sonar imagery obtained with the inexpensive (~$2000) Humminbird® Side Imaging system and ArcGIS to produce sonar image maps (SIMs) used to interpret and map habitat features such as substrates and large woody debris, in addition to continuously recording depth along the survey route. This method was recently demonstrated and evaluated in several small streams in southwestern Georgia (30–50 m width, 40 km mapped). To evaluate the feasibility of this method for mapping substrate and depth in larger rivers and over greater spatial extents, we conducted a sonar survey and generated SIMs for 124 km of the lower Flint River (85–140 m width). We interpreted the SIMs to digitize and classify substrate and bank boundaries. To assess classification accuracy, we visually inspected substrate at randomly assigned reference locations. A comparison of reference and map data revealed an overall classification accuracy of 84%. These results were consistent with previous findings and indicate that low-cost side-scan sonar is also an effective mapping tool for larger rivers. The sonar survey did, however, result in more missing and unsure substrate data and a lower map accuracy for fine-textured substrates than previously achieved when mapping smaller streams. We found a strong, positive relationship ($r^2 = 0.89$) between the sonar range and the proportion of unsure substrate in the map, suggesting that a multi-pass, parallel-transect sonar survey could be used to maintain high-image resolution when stream widths exceed 100 m and/or obstructions, such as islands, are encountered. Applications for sonar-based habitat maps are widespread and numerous. The ability to produce these maps efficiently at low-cost is within the grasp of researchers and managers alike.

KEY WORDS: habitat mapping; side-scan sonar; remote sensing; substrate

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INTRODUCTION

Landscape-level habitat data are extremely valuable to those involved with the research and management of aquatic systems. The characterization of underwater habitat features at the landscape scale is, however, notably difficult and costly, especially in non-wadeable, turbid systems. In recent years, several sophisticated airborne techniques, such as LIDAR and thermal infrared systems, have been demonstrated to map riparian and subsurface features (Torgersen *et al*., 2001; Charlton *et al*., 2003; Hohenthal *et al*., 2011). For these remote sensing techniques, depth and turbidity significantly affect data quality, whereas the overall cost and need for technically specialized personnel limit the number of opportunities where these techniques are feasible (Legleiter *et al*., 2004; Marcus and Fonstad, 2008).

Side-scan sonar (SSS), first developed in the 1960s, provides an alternative method for remotely sensing underwater habitat features. SSS transmits and receives reflected acoustic signals (i.e. backscatter); backscatter intensity is translated to produce a two-dimensional image of the underwater landscape (Fish and Carr, 1990). Although a variety of factors influence the performance of SSS, reliable sonar data can be obtained in deep and turbid environments.

SSS has traditionally been used to locate sunken vessels, for charting navigational channels, and characterizing benthic substrates, primarily in marine or otherwise open, deep water systems (Newton and Stefanon, 1975; Hobbs, 1986; Prada *et al*., 2008). In such environments, a transducer is towed at depth by a moving vessel during data capture. This configuration limits the use of SSS in shallow and otherwise hazardous aquatic systems where rocks or debris could damage the towfish apparatus. Moreover, traditional SSS systems are expensive, require expertise to operate and specialized software to process sonar imagery. These factors have presumably limited access to and application of SSS in inland aquatic systems. Several examples of freshwater applications of SSS include the mapping of potential lake trout and sturgeon spawning habitat by Edsall *et al*. (1989) and Laustrup *et al*. (2007), respectively, and the mapping of

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substrates and benthic morphology by Anima *et al.* (2007) and Manley and Singer (2008).

In 2005, Humminbird® released the Side Imaging system, an inexpensive (~$2000) SSS device that operates at high frequencies (455 or 800 kHz) to produce high-resolution (10-cm pixel) imagery of underwater landscapes. The SI system uses a small, boat-mounted transducer enabling surveys in shallow, rocky streams. Over the last few years, we have worked to develop and evaluate a complete method for data acquisition, image processing and production of classified maps of habitat features in navigable, inland waterways using the Humminbird® SI system. We first demonstrated a low-cost approach to mapping large woody debris and submerged logs (Kaeser and Litts, 2008) and then demonstrated and evaluated the mapping of substrate, bank boundaries and depth throughout 27 km of lower Ichawaynochaway Creek (mean width = 38 m), a major tributary to the lower Flint River in southwestern Georgia (Kaeser and Litts, 2010). The next step in our evaluation of this method was to investigate scalability. In this study, our primary objectives were to demonstrate and to evaluate the effectiveness of low-cost sonar mapping of habitat features in a larger river and over a larger spatial extent than previously demonstrated using the single-pass survey approach. We hypothesized that a single-pass approach would yield imagery of sufficient resolution to map features in the lower Flint River with accuracy comparable with that achieved during the mapping of Ichawaynochaway Creek, but that the use of higher range settings would result in greater proportions of unsure areas in downstream (i.e. wider) reaches of the river map.

An important, potential limitation of SSS examined in this study involves the relationship between sonar range and transverse resolution. Transverse resolution, also called target separation, is the ability to distinguish two objects (e.g. two rocks) that lie parallel to the boat path as separate objects (Fish and Carr, 1990). At a fixed frequency (e.g. 455 kHz), increasing sonar ranges leads to decreasing transverse resolution due to horizontal beam spreading, an effect that is magnified in the far-field or near-edge portions of the sonar image (Fish and Carr, 1990). The resulting decline in image resolution can hinder the ability to discriminate and accurately classify features in far-field portions of an image. As a river widens, however, the sonar range must be increased to image the entire river channel when conducting a single-pass survey. Thus, the selection of range setting is a practical issue when planning a sonar survey, with trade-offs between efficiency (i.e. single or multiple pass) and image resolution. A goal of this study was to define a relationship between the sonar range and the proportion of poorly resolved areas in the SIM that could be referenced when planning future sonar missions in streams of varying widths.

A second motivation for development of the lower Flint River map came from several initiatives focused on conservation and restoration of the following riverine fish species: shoal bass *Micropterus cataractae*, gulf sturgeon *Acipenser oxyrinchus desotoi* and Alabama shad *Alosa alabamae*. The first two species associate with coarse rocky or bedrock substrate during critical phases of their life histories (Fox *et al*., 2000; Wheeler and Allen, 2003; Stormer and Maceina 2009); these substrates can be distinguished from unconsolidated, finer substrates using the Humminbird® SI system (Kaeser and Litts, 2010). An accurate and spatially explicit inventory of habitat in the lower Flint River was lacking, and identified as a high-conservation priority. Thus, the secondary objectives of this study were to survey and describe the longitudinal distribution and abundance of rocky substrates throughout the lower Flint River and to render this information in a geographic information system in an accessible format for future studies of fish habitat associations.

METHODS

Study area

Our study area encompassed the lower 124 km of the Flint River, from the Flint River Dam in Albany to a downstream point near the city of Bainbridge, GA, where the river flows into Lake Seminole (Figure 1). The lower Flint River is a sixth-order river with a mean width of 96 m and mean daily discharge of 180 m^3 s^{-1} [United States Geologic Survey (USGS, 2010) water data, gauge 02353000]. The lower Flint River is characterized by a stable, deeply incised channel flanked by steep sandy banks and limestone outcrops. In many areas, the channel is perched on an underlying bedrock layer of Ocala limestone that confines the Upper Floridan Aquifer (Brown and Smith, 2001; Hicks and Opsahl, 2002). To facilitate steamboat navigation, the Army Corps of Engineers historically dredged and channelized numerous shallow, rocky areas (i.e. shoals) interspersed throughout the lower Flint River (Mueller, 1990). Several man-made and natural islands ($n = 40$) are located along the river creating secondary channels, many of which are navigable during high discharge events. Additional geographic and hydrologic descriptions for this system can be found in the Flint River Basin Management Plan (Georgia Environmental Protection Division, 1997).

The lower Flint River was ideally suited for an investigation of the scalability of our mapping method; substrate composition was similar to Ichawaynochaway Creek, allowing us to use a similar substrate classification scheme and to compare classification accuracy results between substrate maps produced by the same map maker. In addition, the mean width of the lower river varies from

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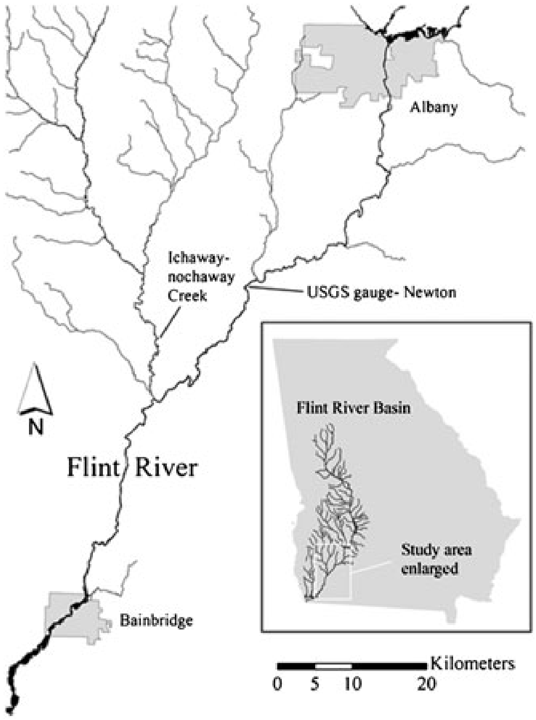

Figure 1. Location of the lower Flint River in southwestern Georgia. Map study area extends from the Flint River dam in Albany (RKM 121) to below the city of Bainbridge (RKM 0). Inset identifies the location of the study area with respect to the entire Flint River Basin. The USGS gauging station in Newton is located in RKM 65.

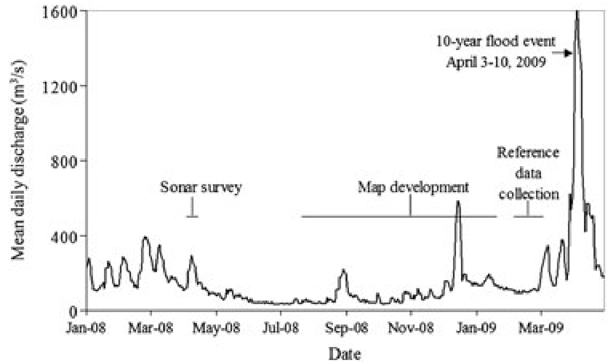

Figure 2. Flint River mean daily discharge ($m^3\ s^{-1}$) during phases of the study as observed at USGS gauge 02353000 in Newton, Georgia. Project phases are labeled for reference purposes.

approximately 100 to 150 m over its longitudinal course, allowing us to investigate the influence of range setting on image resolution and the resulting proportions of poorly resolved or unsure areas in the developed map.

Procedures for map production

Sonar survey. We used a Humminbird® 981c SI system to acquire sonar imagery of the Flint River during a high discharge event in April 2008 (Figure 2). High flows offered favorable conditions for navigation and imaging of the entire, inundated river channel with a single pass. During imaging, the sonar transducer was positioned in front of a johnboat using a custom mount. The SI system was networked to a WAAS-enabled Garmin GPSMAP® 76 unit to provide both geographic coordinates (i.e. waypoints) for image capture locations and track-point coordinates with depth measurements along the survey route every three seconds. The side beam range was adjusted between 48.8 m (160 ft) per side and 70.1 m (230 ft) per side to accommodate longitudinal changes in river width (Table I). Consecutive, overlapping sonar 'snapshot' images and associated coordinates were recorded to the SI system while maintaining a constant speed and mid-channel position. The sonar survey was completed in 4 days.

Sonar data processing. Raw sonar images were transformed into SIMs with real-world coordinates (e.g. Universal Transverse Mercator) using Environmental Systems Research Institute's (ESRI) GIS software and the IrfanView graphic viewer. 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 approximately 400–500 m of stream reach. Mosaics were saved as 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 that contained between 300 and 360 control points for each raw image mosaic.

The transformation of the raw image mosaics to SIMs was completed using the georeferencing tools available in ESRI's ArcGIS 9.2 software. Image mosaics were opened in ArcGIS, and their corresponding control point networks 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)

Table I. Details of the April 2008 sonar survey

Sonar survey date	RKM	Portion of map	River stage Newton (m)[a]	Range setting (m per side)
4/6/2008	99 to 65	upper	8.9	49
4/7/2008	65 to 63	upper	9.3	49
4/7/2008	63 to 36	lower	9.3	52–55
4/10/2008	121 to 99	upper	10.0	49
4/10/2008	36 to 24	lower	10.0	55
4/16/2008	24 to −2	lower	7.5	58–70

[a]The Flint River Newton gauge (USGS 02353000) is located within RKM 65, the approximate midpoint of the study area.

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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 georeferenced JPEG (.jpg) images with corresponding world files registered to Universal Transverse Mercator Zone 16 and cast on the North American Datum of 1983 (NAD83).

The decision to convert images from raw image .bmp format to mosaic image JPEG format was driven by file size and hardware limitations. Before adopting the conversion, dozens of images were converted and visually compared with source images. Inspection was conducted by overlaying .bmp and corresponding .jpg images in ArcGIS 9.2 and visually comparing at a variety levels from full image to pixel-level views. At no level did we detect a visual shift in how a pixel or feature was rendered on screen. Because our method incorporates heads-up visual interpretation and digitizing on the computer screen, the conversion was adopted.

Map production. The minimum mapping unit (MMU) and the classification scheme for the lower Flint River map were defined through the on-site inspection of printed sonar images in portions of the river during low-flow conditions, before map production. We identified an MMU of 314 m^2, an area equal to a circle with a 10-m radius. SIMs were rendered in ArcGIS 9.2 at the raster resolution scale (~1:375), a scale at which features are readily discerned, to digitize river bank and substrate class boundaries. The digitization of banks was primarily based on the SIMs; however, Digital Orthographic Quarter Quadrangle imagery obtained during leaf-off conditions in 1999 was used to digitize bank boundaries when they were beyond sonar range. Substrate boundaries were manually digitized around areas of uniform sonar signature ≥MMU by visual interpretation of the SIMs. Slant range correction, a post-processing procedure that removes the water column from raw sonar images, was not performed; therefore, substrates observed adjacent to the water column were interpreted as properly extending to the center of the image. Digitized lines were converted to polygons and assigned a substrate class. The substrate classification scheme included six predominant, surficial substrate classes: sandy (S), rocky fine (Rf), rocky boulder (Rb), limerock fine (Lf), limerock boulder (Lb) and mixed rocky (Mx; Table II). These classes were defined on the basis of material composition and particle size. Sonar images were interpreted using texture, tone, shape, pattern and association to distinguish and classify substrate polygons (Figure 3).

An additional unsure class was included in the scheme to account for poorly resolved areas of the SIMs. Unsure areas were presumptively classified as either predominately sandy (US) or predominately rocky (UR) on the basis of image texture and in-stream context (Table II). Areas of missing image data were classified as either sonar shadow (SS) or no data (No) to differentiate sources of data loss. Sonar shadows are dark areas appearing behind any solid objects, such as bridge abutments, that protrude into the water column. Such objects reflect acoustic signals back to the

Table II. Classification scheme and associated definitions developed for the lower Flint River 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 three or more boulders, each ≥500 mm diameter across longest axis, each boulder within 1.5 m 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
Mixed rocky	Mx	An area comprising two or more substrates classes (at least one being rocky) arranged such that no homogeneous portion is ≥MMU
Unsure sandy	US	An area of the sonar map difficult to classify due to reduced image resolution, suspected to be predominantly sandy
Unsure rocky	UR	An area of the sonar map difficult to classify due to reduced image resolution, suspected to be of predominantly rocky composition
Sonar shadow	SS	An area of the sonar map within range that was not imaged because the sonar signal was blocked by reflective object(s)
No data	No	An area of the sonar map beyond sonar range but within the boundaries of the river channel
Island	Isl	Any area of land wholly contained within the river channel that is surrounded by water during typical winter or spring discharge

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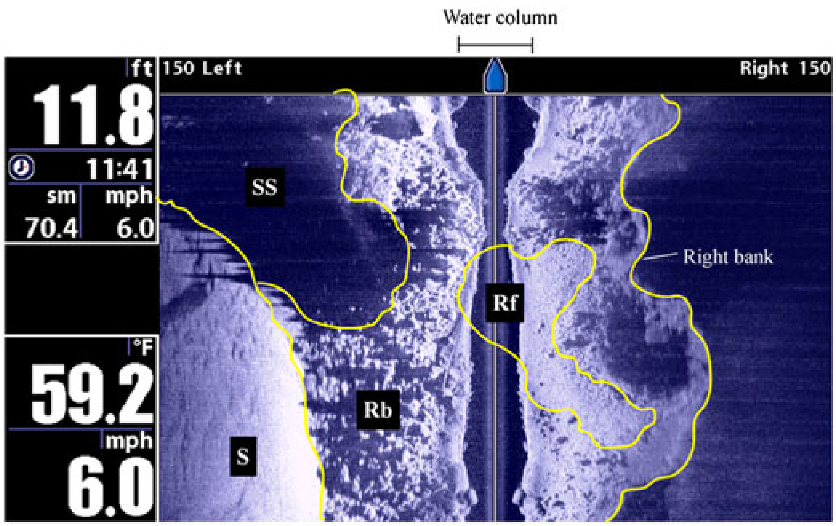

Figure 3. Raw sonar image annotated to identify key features. Total image width is 91 m (300 ft). The water column appears as a dark area in the center of the image. Yellow lines have been drawn to illustrate the apparent boundaries between a few of the substrate classes appearing in the image: S, sandy; SS, sonar shadow; Rf, rocky fine; Rb, rocky boulder. The right river bank appears in the image, but the left bank was out of sonar range. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

transducer, preventing those signals from 'imaging' areas beyond them. The no data class represented portions of the inundated river channel that were beyond sonar range and not imaged during the survey. Any area within the river channel that was not inundated during the sonar survey was delineated and classified as an island (Isl).

The digitization of bank and substrate boundaries and substrate classification was initially conducted by T. Tracy, an intern who was trained by A. Kaeser but had no prior experience developing sonar-based maps. The draft map was then inspected and edited by A. Kaeser. Given the potential for differences in maps made by different individuals, the review and editing of the map by A. Kaeser was required to directly compare the classification accuracy of the lower Flint River map to the accuracy of the Ichawaynochaway Creek map. Lastly, a point shapefile representing the mid-channel survey route and associated depth observations was added to the map. The map was completed January 2009 and comprised a continuous substrate polygon layer, a layer representing the channel margins (banks) and a layer representing mid-channel depth observations throughout the study reach (Figure 4). To illustrate longitudinal trends in substrate composition and depth throughout the lower Flint River, we divided the map into 124 contiguous reaches, each 1 km long, and extracted and summarized map data for each reach.

Map accuracy assessment

To evaluate substrate classification accuracy, we selected a sample of reference sites from the map. Points ($n = 385$) were randomly assigned to substrate polygons (55 points per class) in the upper half of the map [river kilometer (RKM) 122 to 63]. Points were similarly assigned to the lower half of the map (RKM 63 to −2) to obtain a paired data set used to evaluate differences in classification accuracy between upper and lower portions of the map. The map was divided into two reaches according to range settings (49 vs 52–70 m per side) used during the sonar survey (Table I). All points were buffered at 8 m from polygon edges to reduce co-registration error (i.e. locating points in an incorrect polygon due to GPS and map position error) and to avoid locating points in areas of transition between substrate patches (Kaeser and Litts, 2010). Because of time constraints and feasibility, we did not inspect reference sites from three classes: mixed rocky, sonar shadow and no data.

Reference sites within the upper half of the study reach were visited February 2009 during a period of unusually low, stable and non-turbid conditions in the river (Figure 2). During assessment, the boat operator navigated to each reference point using both a WAAS-enabled Trimble Recon unit (Transplant CF GPS receiver, 2–5 m accuracy) and a Garmin GPSmap 76Cx device (~5 m accuracy). The crew anchored the boat in position over the point and lowered a submersible Aqua-Vu® drop camera to inspect substrate near the point (i.e. the reference site). The camera was connected to a television, which enabled the crew to visually assess and classify the actual substrate present at each site. The drop camera was deployed off both sides and around the bow of the boat and panned to provide a view of substrate within an area approximately 8 m^2. Wherever possible, the crew used a 3.7-m-long metal pole to prod and scrape the substrate beneath the boat. This procedure provided additional tactile and auditory information on substrate hardness, texture

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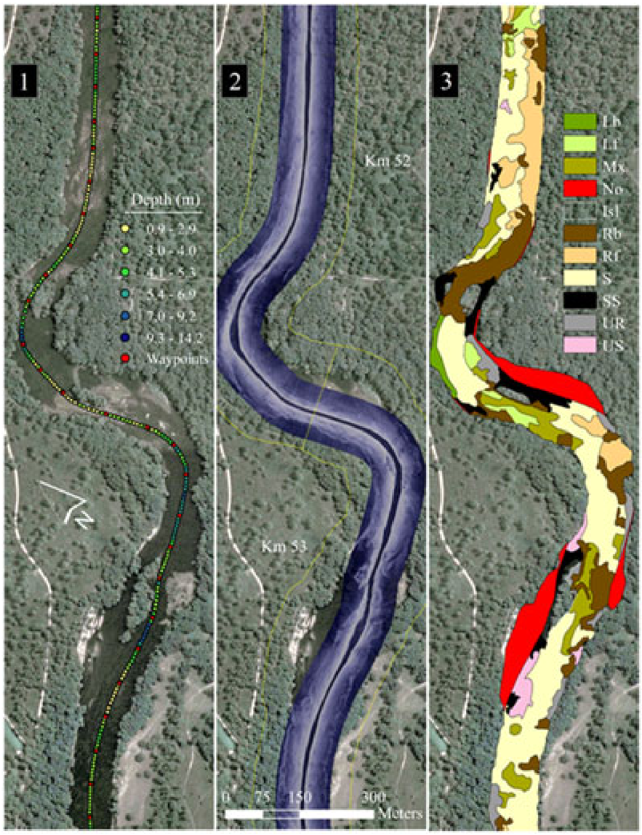

Figure 4. Multiple layers of the sonar-based habitat map for RKM 52–53 of the lower Flint River. Panel 1 displays a 2007 National Agriculture Inventory Program aerial photograph of the river channel during low water conditions revealing shallow rocky areas and several islands. Projected track and waypoints reveal the actual course taken during the sonar survey (track points classified using Jenk's natural breaks and assigned a color corresponding to depth). Panel 2 displays the geotransformed sonar imagery added as a layer to the map (scale 1:6000). Panel 3 displays the classified substrate polygons. Polygons were digitized by sonar image interpretation at a scale of approximately 1:375. Substrate acronyms correspond to classes defined in Table II. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

and thickness. The actual substrate classification for each reference site was determined by the crew and recorded. Information on map substrate classification was not in hand during the field assessment. A few reference sites were not assessed because they were either too deep for visual inspection or too swift for anchoring the boat.

Reference data collection was halted in early March 2009 when two consecutive high-flow events elevated river turbidity, preventing inspection with the drop camera (Figure 2). Shortly thereafter, a 10-year flood event occurred on the lower Flint River, leading us to abandon all additional reference data collection efforts because of the potential for fine sediment redistribution. As a result, several reference sites were not visited in the upper half of the map from the classes US, UR and Lb. No reference sites were visited in the lower half of the study area, preventing an assessment of classification accuracy for this portion of the map.

An error matrix and conventional classification accuracy statistics were computed using classified and 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. Given that similar classification schemes and identical map makers were used during the production of the Flint River and Ichawaynochaway Creek maps, normalization also permitted direct comparison between error matrices to assess the relative effect of sonar range on substrate classification accuracy. Kappa analysis was performed using MARGFIT (Congalton, 1991) to determine if the Flint River map classification was better than random, and a paired-comparison Z statistic was calculated to determine if the overall classification accuracy in the Flint River map differed statistically from classification accuracy achieved in the Ichawaynochaway Creek map (Congalton and Green, 1999; Kaeser and Litts, 2010). Reference data for the unsure area classes were analyzed separately.

To evaluate the statistical relationship between the sonar range and the proportion of poorly resolved (i.e. unsure) areas in the SIMs, we subdivided the map into sections according to the range setting used during the sonar survey. The proportion of unsure area in each section was calculated as the areal sum of all unsure polygons (US + UR) divided by the total area of all polygons in the section. Polygons of the class no data (No) were not included in area computations. The linear relationship between the sonar range and the proportion of unsure area was assessed using weighted, least squares regression using the area of the map scanned at each range setting as the weighting factor (SAS, 2001).

To assess the positional (i.e. horizontal) accuracy of the SIMs according to National Standard for Spatial Data Accuracy guidelines (FGDC, 1998), we calculated the $RMSE_r$ using the coordinates of 32 fixed objects (e.g. exposed boulders and cypress tree trunks). Coordinates were recorded in the field with a WAAS-enabled Trimble Recon unit during the reference data collection period. Coordinates for these objects were compared with coordinates for apparent object position in the SIMs.

RESULTS AND DISCUSSION

Map statistics

The completed map encompassed 124 km and 1191 ha of the lower Flint River. The map exhibited a high level of heterogeneity and detail and consisted of 3050 polygons ranging in area from 314 to 1 230 000 m^2. Three substrate classes constituted 67% of the map area: sandy (40%), limerock fine (17%) and rocky boulder (10%). Rocky fine

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and mixed rocky constituted 6% and 5% of the map area, respectively. The least common substrate class in the map was limerock boulder (4%). Unsure areas constituted 10% of the mapped area (6% unsure sandy and 4% unsure rocky), and 6.5% of the map was missing data (4% no data + 2% sonar shadow). Islands represented the remaining approximately 1% of the map area.

Average mid-channel depth of the Flint River during the sonar survey was 4.34 m (SD = 1.65, range = 0.8–17.8 m, n = 23 131 observations). Recommended transducer altitude (i.e. height above the substrate) during surveys is typically 10% to 20% of the range setting (Fish and Carr, 1990); mean altitude during the survey was 8.2%. Stream discharge was relatively consistent over the sonar survey period. Among survey dates, the river stage fluctuated only 0.76 m at the gauging station in Newton (Table I).

Map accuracy and mapping efficiency

The overall classification accuracy for the upper half of the Flint River map was 84% (Table III). This statistic represents the proportion of correctly classified sites visited during reference data collection (Congalton and Green, 1999). Producer's accuracy, a statistic that represents the ability of the map maker to correctly identify substrates appearing in the SIMs, ranged from 77% to 96%. Producer's accuracy was highest for limerock boulder areas and lowest for rocky fine. User's accuracy, a statistic that represents the proportion of classified areas on the map that are correct in the field, ranged from 72% to 100%. User's accuracy was highest for limerock boulder and rocky boulder classes and lowest for rocky fine. The normalized accuracy of the map was 81%, slightly lower than the overall accuracy because fewer reference sites were visited for classes exhibiting the highest accuracies (e.g. Lb and Rb; Table IV). Kappa analysis on the normalized error matrix produced a KHAT statistic of 0.80 (variance = 0.0010) and a Z statistic of 29.0, indicating that the map classification was significantly better than random.

Table IV. Normalized error matrix for the lower Flint River substrate map classification

	Reference site data (field data)				
Classified data	S	Rf	Rb	Lf	Lb
S	0.746	0.108	0.007	0.132	0.006
Rf	0.127	0.720	0.067	0.080	0.006
Rb	0.037	0.038	0.889	0.011	0.024
Lf	0.074	0.118	0.024	0.763	0.021
Lb	0.015	0.016	0.012	0.014	0.943
Normalized accuracy = 81%					

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

A comparison of normalized classification accuracy results from the Flint River map to results from the Ichawaynochaway Creek map provided insight on the effectiveness of using our method to map substrates in a larger river. Overall accuracy was 7% greater in the Flint River sonar map, and normalized accuracy was 5% greater than achieved in the Ichawaynochaway Creek map. A Kappa analysis for the pairwise comparison of the Flint River and Ichawaynochaway Creek error matrices yielded a Z statistic of 2.55, indicating a statistically significant difference in mapping accuracy between the Flint River and the Ichawaynochaway Creek sonar maps. The paired Z statistic, only slightly above the significant value 1.96, reflected only a moderate improvement in accuracy in the Flint River map (Congalton, 1991).

A large proportion of the classification errors made in the Flint River map were the result of confusion among the three, fine-textured substrate classes: S, Rf and Lf. Similar mistakes were made during the classification of Ichawaynochaway Creek substrate and were expected in the Flint River map because of the resemblance of these substrates in the SIMs (Kaeser and Litts, 2010). In general, the error rates associated with fine-textured substrates were similar between studies, indicating that the use of range settings

Table III. Standard error matrix and associated statistics for the lower Flint River substrate map classification

	Reference site data (field data)						
Classified data	S	Rf	Rb	Lf	Lb	Row total	User's accuracy (%)
S	38	5	0	7	0	50	76
Rf	6	36	4	4	0	50	72
Rb	1	1	46	0	1	49	94
Lf	3	5	1	39	1	49	80
Lb	0	0	0	0	47	47	100
Column total	48	47	51	50	49	245	
Producer's accuracy (%)	79	77	90	78	96		Overall accuracy, 84

Substrate acronyms are defined in Table II. The gray, diagonal elements of the matrix contain the correct classifications for each substrate type.

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approximately two times greater than those used during the Ichawaynochaway Creek sonar survey did not diminish our ability to accurately discriminate among fine substrate classes in the upper half of the Flint River map. Although some of the misclassifications in the Ichawaynochaway Creek map were related to the occurrence of gravel substrate (Kaeser and Litts, 2010), we did not encounter any gravel substrate during reference data collection in the lower Flint River. Thus, this study did not provide training opportunities for discrimination of this substrate type.

One misclassification that occurred more frequently in the Flint River map than in the Ichawaynochaway Creek map was the confusion of S and Lf areas (+12% S:Lf and +4% Lf:S substitution errors). These two classes were best discriminated in the Flint River on the basis of tone and broad scale patterns such as fractures, which were relatively common to the Lf class, and dunes or ripples, which were common to the S class. Although some misclassifications were likely the direct result of our failure to distinguish between the two substrates, we also discovered another potential source of error during field collection of reference data. Several reference sites were identified as S by visual inspection, yet prodding and scraping with the metal pole revealed that only a thin veneer of sand was covering solid Lf substrate. Although flows were generally low and stable between sonar imaging and reference data collection, a period of 9 months had passed and one notably high discharge event had occurred (December 2008; Figure 2). We suspect that some change in the surficial distribution of S and Lf classes occurred during this period, possibly resulting in some classification errors.

Considering the potential for fine sediment redistribution and the confounding effects of such changes on the assessment of map accuracy, we justified abandoning reference data collection for the lower half of the Flint River map after the 10-year flood event of April 2009. Post-flood efforts to inspect sites could have generated both type I and type II errors with no ability to differentiate such errors from those actually attributable to image interpretation (Fielding and Bell, 1997). Although unpredictable, the possibility of stochastic events like floods that can rearrange patterns of substrate deposition should be considered when planning and executing a mapping project.

Our ability to discriminate coarse-textured substrate classes (i.e. Rb and Lb) generally improved in the lower Flint River relative to Ichawaynochaway Creek. Accuracy improvements were at least partially attributable to the natural morphology and distribution of the two classes in the Flint River. Unlike the distribution of Lb in Ichawaynochaway Creek, which often overlapped or was adjacent to Rb, Lb substrate in the lower Flint River occupied discrete outcrops frequently occurring along the margins of the channel. Outcrops of Lb were often composed of large, massive boulders that were more discernable than the patches of Lb that occurred in Ichawaynochaway Creek. These natural differences enhanced our ability to discriminate between Rb and Lb in the Flint River map.

Classification accuracy for Lb was 100% according to matrix statistics; however, several of the unsure polygons (7 of 32) visited during reference data collection were, in fact, Lb substrate. Given that unsure polygons were frequently delineated along the margins of the river channel, it is likely that several Lb outcroppings were assigned to an unsure class. In addition, the buffering of reference points at 8 m from adjacent substrate classes biased against the inspection of narrow (i.e. <8 m wide), near-bank polygons. For practical purposes, additional time could be devoted to verifying Lb along lower Flint River channel margins as the class is often partially exposed during low water conditions and easy to visually inspect.

A greater overall proportion of the Flint River map was classified as unsure than was classified as unsure in the Ichawaynochaway Creek map (10% vs 6%, respectively; Kaeser and Litts, 2010). In both maps, poorly resolved areas (US and UR) were primarily mapped as narrow polygons extending along the river channel margins, where far-field distortion or sonar shadows affected the quality of sonar data. We attribute the increased proportion of unsure area in the Flint River map to far-field distortion, an effect that was particularly evident in the downstream portions of the map where sonar ranges exceeded 50 m per side. We observed a strong, linear relationship ($r^2 = 0.89$) between the sonar range and the proportion of unsure area in the map (US + UR classes; Figure 5).

These results provide a practical rule of thumb for the selection of range settings when planning a sonar mission. Assuming a goal of 6% unsure area or less, our results suggest an effective range threshold that is approximately 49 m (160 ft) per side at the 455-kHz operational frequency. In rivers that exceed this threshold (i.e. those >100 m wide), it is possible to mitigate the effects of far-field distortion and maintain the high-image resolution necessary for accurate substrate class discrimination by taking a multiple-pass, parallel-transect approach using reduced range settings to image portions of the channel.

A small investment of additional field time could have reduced the extent of missing data (No + SS) in the Flint River map. For example, scanning all of the secondary channels formed around islands would have reduced the quantity of missing data by 37% (28 ha). Figure 4 portrays a reach of the lower Flint River containing four small islands where a multi-pass approach could have been used to reduce data loss.

The Flint River SIM showed improvements in positional or horizontal accuracy (RMSEr = ±4.6 m; compiled to meet

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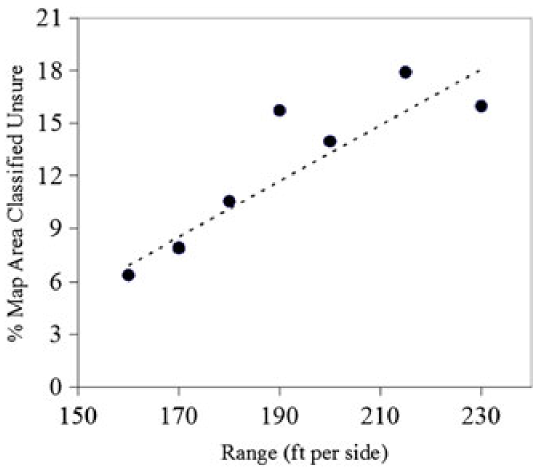

Figure 5. Relationship between sonar range (feet per side) and percentage of unsure area in the completed lower Flint River sonar habitat map. Line fitted to the data represents the weighted regression analysis of both variables, using the total area of the map scanned at each range setting to serve as the weighting factor.

7.04 m horizontal accuracy at the 90% CI) compared with the Ichawaynochaway Creek sonar map (±5.95 m; compiled to meet 9.03 m horizontal accuracy at the 90% CI; Kaeser and Litts, 2010), indicating that mapping at the scale of a medium-sized river resulted in better positional accuracy. We attribute this result to the increased width of the lower Flint River channel favoring good satellite reception, whereas the comparably narrow Ichawaynochaway Creek channel was prone to canyon and canopy effects that interfered with GPS signal reception during both the sonar survey and the reference data collection. The positional accuracy of the Flint River SIMs suggests that the 8-m buffer distance applied to reference data points was a sufficient and conservative safeguard against coregistration errors in the field. The use of a larger reference point buffer in the Flint River map likely contributed to the moderate improvements in overall mapping accuracy reported in this study. Considering the positional error inherent in this map, users interested in studying species–habitat relationships using location data obtained in the field with GPS devices should consider the use of distance-based rather than classification-based approaches to spatial analyses (Conner *et al*., 2003).

Sonar habitat mapping of the Flint River required approximately 1.5 h km^{-1} to complete as follows: sonar survey, 11 min km^{-1}; image geoprocessing, 12 min km^{-1}; bank and substrate boundary digitization, 43 min km^{-1}; and substrate classification and review, 20 min km^{-1}. The time invested (per km) on the Flint River map was approximately 30% lower than that invested during the mapping of comparable habitat elements in Ichawaynochaway Creek because several additional image processing steps were automated. The accuracy assessment of the upper half of the Flint River map involved a two- to three-person crew working for 5 days, requiring a total of 96 man-hours to complete.

Although we used ArcView 3.2 and ArcGIS 9.2 to process imagery in this study, our tools have since been updated to perform exclusively at the ArcGIS 9 or 10 level. In addition, our methodology has been further automated and streamlined, reducing image geoprocessing investments to approximately 3 min km^{-1}.

Longitudinal trends in substrate and depth

Several trends in lower Flint River substrate composition and depth were revealed by extracting and summarizing map data on a per-kilometer basis. Below the Flint River dam, a hydropower facility, fine-textured, limestone bedrock predominated, and sandy areas were notably absent (Figure 6). Sand constituted an increasing proportion of channel substrate with increasing distance from the dam. This pattern is consistent with the known effects of dams and is related to restrictions on the downstream supply of fine sediments that deposit in the reservoir above the dam and increased scouring of sediments from the channel below the dam by hydropeaking operations (Ward, 1998; Stanford and Ward, 2001). In the lower Flint River, sand generally replaces limerock fine as the predominant substrate along a gradient of distance from the Albany dam.

From RKM 103 to just above Newton, GA (RKM 68), the Flint River deepens and limerock bluffs (i.e. outcrops of Lb) become prominent along the river banks. The Flint River from Newton to just below the confluence with Ichawaynochaway Creek (RKM 41) is shallower than average and is dominated by an extensive patchwork of shoals composed of coarse rocky substrate (Rb, Rf and Mx classes). The area below Ichawaynochaway Creek to Bainbridge (RKM 0) is slightly deeper than average, composed primarily of sand with limestone boulder outcroppings along the banks. As the river approaches Bainbridge and Lake Seminole, it becomes wider, more lacustrine and depositional, a likely reason for the predominance of sandy substrate in this reach.

CONCLUSIONS

Low-cost sonar habitat mapping provides a rapid, inexpensive and accurate method for mapping continuous, underwater habitat features at larger spatial scales and in larger river systems than previously demonstrated. Accuracy assessment results suggest that a one-pass sonar survey approach may be sufficient for the discrimination of substrate classes similar to those examined in this study using range settings up to approximately 49 m per side. The high mapping accuracies achieved for coarse, rocky substrate, particularly the rocky boulder class, indicates that the completed Flint River map

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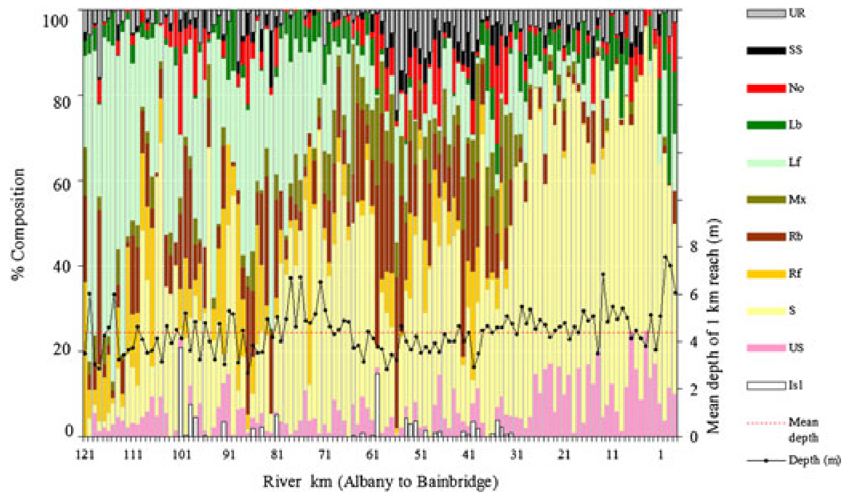

Figure 6. Proportional composition of 1-km reaches of the lower Flint River from Albany (km 121) to Bainbridge (km 0). Acronyms correspond to the following map classifications: UR, unsure rocky; SS, sonar shadow; No, no data; Lb, limerock boulder; Lf, limerock fine; Mx, mixed rocky; Rb, rocky boulder; Rf, rocky fine; S, sandy; US, unsure sandy; ISL = island. Black circles represent average mid-channel depth (m) of each reach observed during the sonar survey ($n = \sim 120$ observations per reach). Dashed red line represents the overall mean river depth observed during the survey. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

may serve as a comprehensive and reliable source of habitat information for the future research and management of several species of conservation concern. Attention should be devoted to the issue of change in substrate deposition over time to assess the practical, future utility of the sonar-based map in this river system.

In this study, we identified several sources of classification error and potential limitations inherent in using low-cost SSS to map habitat features. Given the fundamental importance of visual interpretation of sonar imagery for mapping, we suggest that users seek training opportunities to improve their ability to match actual substrate patterns in a study system with corresponding sonar image signatures. The quality of a sonar-based map will likely depend on both the quality of the sonar data and the experience and aptitudes of the person developing the map. We believe that inspection and minor editing by a more experienced map maker in this study likely improved the overall accuracy of the final map and should be considered when appropriate. Future research should investigate the effect that modest training and mapping experience has on the accuracy and congruence of maps produced by different makers. To improve map products and to provide the information necessary for sound map applications, we also strongly recommend that projects include an accuracy assessment component.

Although sonar-based habitat maps can be created quickly, the timing of accuracy assessment should consider the timing of high flow events and the potential for redistribution of substrates. Obtaining statistically viable reference data using a probabilistic approach (i.e. points randomly assigned to substrate polygons) is a worthy consideration, yet in many cases random assignment must wait until the classified substrate map has been completed. Obtaining reference data during our sonar survey, for example, was impossible because of high, turbid water conditions. The drop-camera approach used during this study proved to be an effective means for reference data collection, but only during a protracted, low-flow period of opportunity.

To adopt a continuous view and integrated approach to the research and management of riverscapes (Fausch *et al.*, 2002; Wiens, 2002), aquatic resource professionals need tools and techniques that are widely available and affordable and provide detailed, landscape-level information. Low-cost sonar habitat mapping provides a means to efficiently image and map the underwater landscape, and GIS provides the platform necessary to integrate this information with other spatial data sets to yield powerful analytical possibilities. Applications of sonar habitat maps include studies of habitat–organism relationships, the identification of critical habitat and modeling of habitat suitability, the association of land use or hydrology with physical instream habitat and the monitoring of change over time. Given the alarming rate of habitat loss and modification worldwide, we hope that this research and these tools will be used to support habitat conservation and to improve our ecological understanding of the complex yet elegant structure and function of aquatic ecosystems.

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