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Benthic Mapping Using Sonar, Video Transects, and an Innovative Approach to Accuracy Assessment: A Characterization of Bottom Features in the Georgia Bight

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ABSTRACT

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Benthic maps provide the spatial framework for many science and management activities in coastal areas such as identification and protection of fish distributions and associated habitat as well as for monitoring changes in benthos and fish communities. To meet this need at Gray's Reef National Marine Sanctuary off the Georgia, U.S.A., coast, we created fine-scale benthic maps by visual interpretation of sonar imagery within a geographic information system. The major bottom types in the sanctuary—flat sand, rippled sand, hard bottom that is sparsely colonized with sessile invertebrates, and densely colonized hard bottom—were delineated through combined analysis of backscatter from side-scan sonar, bathymetry from multibeam sonar, scuba surveys, and video transects. Maps showed that unconsolidated sediments cover 75% of the bottom of this region; 8% occurs as flat sand plains with obvious burrowing and reworking of surface material by mobile benthic invertebrates, whereas 67% occurs as rippled sand without such fauna. The rest of the sanctuary consists of limestone bottom in two types of formations; either flat, sparsely colonized regions (25% of the sanctuary's total area) or as vertical ledges that are densely colonized with a diverse fauna of sessile invertebrates (<1%). Despite their limited area, these 0.5–2-m-tall ledge features harbor the majority of the sanctuary's biodiversity and biomass of both sessile invertebrates as well as ichthyofauna. A modified accuracy assessment procedure was used to account for spatial autocorrelation in the validation data and to separate thematic from positional accuracy. Overall thematic accuracy of maps is 95% for those areas of the map in which thematic accuracy and positional accuracy could be separated (87% of the mapped area). This fine-scale characterization provides a benthic inventory for a marine sanctuary and novel methods for mapping using sonar and accuracy assessment using transects.

ADDITIONAL INDEX WORDS: *Gray's Reef, live bottom, thematic accuracy, georeferenced video, spatial autocorrelation, variogram.*

INTRODUCTION

Gray's Reef, designated as a National Marine Sanctuary in 1981, encompasses a 58-km^2 area of sand and limestone bottom located 27 km off the coast of Georgia. It was selected as a sanctuary in part because of the complex mosaic of habitats in the area including sand plains, caves, scarps, and rocky overhangs (Fig. 1) that support a diverse assemblage of organisms including approximately 150 species of fish, 200 species of invertebrates, and 65 species of macroalgae (KENNEDY, 1993). Despite a wealth of investigations on the natural resources of the biota and benthic features of Gray's Reef, only coarse benthic maps of the area have been produced (*e.g.,* a minimum mapping unit of 0.5 km^2 or larger). Natural resource managers require a more detailed baseline characterization to support the many responsibilities of sanctuary staff including marine ecosystem management, education, and research. An understanding of the distribution of benthic habitats provides the spatial framework within which to properly address spatially explicit research and management goals such as identifying and protecting essential fish habitat. A fine-scale baseline characterization is also the first step in monitoring temporal changes in the Gray's Reef seascape and understanding more about the dynamic nature of a region of the continental shelf frequently impacted by hurricanes.

Aerial photography or satellite based mapping techniques

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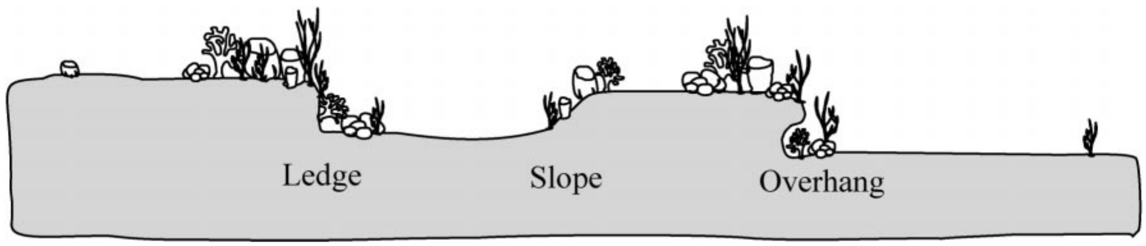

Figure 1. Example cross section of bottom features in GRNMS. High densities of sessile invertebrates occur on or near limestone ledges or other changes in bathymetry.

cannot be used to map benthic features in this region of the continental shelf because of moderate turbidity and 20–30-m water depths. In addition, mapping a large bottom area that lies a moderate distance offshore prevents extensive collection of independent sets of "point" observations that are typically used for validation of remote sensing data during map production as well as for accuracy assessment once maps are completed. Recently, acoustic imaging has emerged as a valuable tool for natural resource managers and researchers that require comprehensive maps of bottom features but are unable to use aerial photography or satellite remote sensing technology because of water depth or turbidity (BLONDEL and MURTON, 1997; CLARKE, MAYER, and WELLS, 1996; PRATSON and EDWARDS, 1996). We used a combination of these sonar technologies to enable benthic mapping in the moderately deep, turbid water of the sanctuary along with video transects rather than scattered point observations to facilitate collection of ground validation and accuracy assessment data.

Once maps are produced, proper measurement of thematic accuracy using transect data requires modification of typical accuracy assessment procedures used for point data because of a combination of spatial autocorrelation inherent to neighboring points along transects, the presence of habitat heterogeneity at a scale finer than the minimum mapping unit (MMU), and potential misalignment of accuracy assessment and map data. Positional error of maps and/or accuracy assessment data can result in conservative bias (*i.e.,* map accuracy is underestimated) when standard accuracy assessment procedures are used (VERBYLA and HAMMOND, 1995). Accuracy assessment data is often collected at a finer spatial scale than mapped polygons and must be cautiously applied within the context of the MMU. Positive spatial autocorrelation, the condition where nearby samples tend to have similar values, is common for ecological variables such as habitat classification and, if uncorrected, can have an adverse impact on statistical tests (LEGENDRE, 1993). Positive autocorrelation violates the assumption of independence and biases statistical tests by effectively overestimating the true sample size (AUBRY and DEBOUZIE, 2000). Steps must therefore be taken to ensure that points for accuracy assessment are far enough apart such that they are statistically independent.

Given these considerations, we mapped benthic habitats of the sanctuary using a custom geographic information system (GIS) application and combined analysis of backscatter from side-scan sonar, bathymetry from multibeam sonar, and video transects. Thematic accuracy was evaluated using a novel application of georeferenced video frames collected along transects and geostatistics to select accuracy assessment sites that met the assumption of statistical independence.

METHODS

Benthic maps of Gray's Reef National Marine Sanctuary (GRNMS) were created by visual interpretation of sonar imagery using the Habitat Digitizer 3.0 extension (KENDALL *et al.,* 2001) for ArcView 3.2. The Methods section has been divided into the following subsections to describe map production: creating sonar mosaics, collecting ground validation and accuracy assessment data, developing the habitat classification scheme, digitizing benthic maps, and assessing thematic accuracy.

Creating Sonar Mosaics

From June 26 to July 4, 2001, side-scan sonar data were acquired by the NOAA Ship Whiting using Isis Sonar (v5.0) acquisition software (Triton Elics International, Inc., Watsonville, California) and a Klein 5500 side-scan system. Data were collected along north-south (N-S) as well as east-west (E-W) tracklines each with 100% coverage of the sanctuary respectively such that two backscatter mosaics could be created, one for each of the trackline orientations. Data were collected along lines that crossed the entire sanctuary. Each long transect line was acquired in several 200-megabyte segments to facilitate later data reduction and manipulation. Swath width for each segment was approximately 150 m with 10%–30% overlap between adjacent lines. The backscatter data were archived onto DLT-III tapes onboard ship as *.xtf files and then restored and processed on a segment by segment basis at the Skidaway Institute of Oceanography (SKIO) with Isis Sonar (v5.88). The bottom tracking was adjusted manually in order to accurately follow the morphology of the seafloor, and the water column was removed. Navigation data was smoothed to remove jumps in time or unrealistic changes in speed. Time-varied gain (TVG) was applied to all files. The TVG curve was locked down on a segment showing the full range of backscatter values in the image and kept constant for the mosaicking procedure. Ship position was recorded using Differential Global Positioning System

(DGPS). Each segment was corrected for layback using a best-fit approximation to the multibeam bathymetry. The horizontal layback ranged from 0 to 31 m and averaged approximately 20 m. The output resolution for the processed segments was 0.25 m per pixel. The line segments were saved in UTM zone 17 coordinates and uploaded to Delph Map (v2.8) for mosaicking.

In Delph Map, the lines were added to the mosaic segment by segment. In regions of overlap for segments on adjacent lines, the best image for feature detection was visually selected before segments were merged into a single image. The image was exported as a GeoTiff file. Horizontal accuracy of the two backscatter mosaics (N-S and E-W oriented tracklines) was estimated to be ~10 m.

Multibeam bathymetry data were acquired using a Reson Seabat 8101 multibeam echosounder (Goleta, CA) that was hull-mounted on Whiting's Launch 1005. Data were collected along E-W tracklines using ISIS Sonar software (v5.59), processed in CARIS Hydrographic Information System and Hydrographic Data Cleaning System (v4.3.2), and mosaicked in Mapinfo. Pixel size in the final mosaic was 2 m, and horizontal accuracy was estimated to be 5 m.

Collecting Ground Validation and Accuracy Assessment Data

Following preliminary evaluation of the backscatter mosaics, bathymetry, and historical ground truth data, individual dive sites and transects were selected for typological validation in the field by scuba and towed video to enable visual interpretation of sonar signatures. Site selection for four dives was focused on spots in the sanctuary with backscatter signatures that were representative of large areas in the sonar mosaics. This allowed *in situ* characterization and photography of the main bottom types in the sanctuary. The area surveyed within the sanctuary was maximized by limiting the number of time consuming scuba surveys in favor of using video transects that allowed rapid survey of large areas. Eight transects were selected to cross as many representative sonar signatures as possible occurring in different depths and parts of the sanctuary. A camera mounted on a minibat allowed tow speeds of several knots. In addition to the eight video transects that were used for ground validation, four more transects were conducted and used solely for measuring thematic accuracy. Unlike the transects collected for ground truth data, the four transects for accuracy assessment were each assigned a random starting location on one side of the sanctuary, were conducted along parallel track lines to prevent overlap, and spanned the length of the sanctuary. This resulted in an unbiased sample of bottom types from which to identify accuracy assessment points. The eight video transects for ground truth data and the four randomly located transects for use in accuracy assessment were laid out to cover 37 and 24 linear km, respectively. Navigating to field sites was accomplished by uploading geographic coordinates from the sonar mosaic into a shipboard Global Positioning System (GPS) for dives and transect starting points.

For all transects, the video camera was downward pointing and averaged approximately 2 m above the substrate. A time stamp, ship velocity, tow cable length, geographic coordinates, overall depth, and depth of the minibat were recorded with the video. This allowed the horizontal position of individual frames of video to be estimated to within 5–10 m of their true position. The speed of the boat and frequency of GPS fixes resulted in georeferenced frames of imagery every 6–14 m. At each GPS fix, the percent cover of sessile benthic organisms was quantified by freezing the video frame and using a grid overlaid onto the television monitor.

Over 200 digital still photos were acquired from a variety of perspectives from vertical to horizontal during the four dives. All dives were between 20 and 23 m depth. Two dives, conducted in areas with homogeneous, soft backscatter signatures, revealed the bottom to be a flat sand plain with many epibenthic and infaunal invertebrates present (latitude 31.40932, longitude −80.86893; and latitude 31.41245, longitude −80.91633). The other two dives were conducted on sites with more variable backscatter signatures and ledges evident in the bathymetry, one of which consisted of a densely colonized ledge with a vertical elevation of 2 m (latitude 31.39624, longitude −80.88998). In the basin extending away from the foot of the ledge were colonized hard bottom patches interspersed with rippled sand areas. Extending away from the top of the ledge was very sparsely colonized hard bottom with no vertical relief. The fourth dive site consisted of a small ledge with less than 0.5 m vertical elevation (latitude 31.38164, longitude −80.88581). The ledge itself was densely colonized but with only sparse colonization extending away from the top of the ledge and a large area of rippled sand extending away from the foot of the ledge. The observations and images acquired at these four dive sites were used to aid with interpretation of other areas with similar backscatter signatures, to help develop the classification scheme described in the next section, to provide horizontal and oblique photographic examples of classification types, and for understanding how the frames of downward-pointing video would appear from other perspectives.

Developing the Habitat Classification Scheme

We created a two-tiered classification scheme to define benthic features visible in the sonar data. The specific categories and structure of the classification scheme were driven by several factors. The map requirements of GRNMS staff for science and management were of primary concern; however, the MMU, spatial resolution, positional accuracy, and other limitations associated with the sonar data constrained the possible classifications. Based on the resolution of the sonar data and extent of the area to be mapped, an MMU of 10 by 10 m was selected. Previous research in the area indicates that a few bottom types dominate the region including sand, ledges, and live bottom. Because of the limited data available, thematic categories were only qualitative in initial studies of the area (Henry and Giles, 1979; Hunt, 1974). Later, scuba observations and benthic quadrats were used to establish quantitative classifications for some hard bottom areas that were denoted as sparse, with 1%–25% of the bottom colonized; moderate, with 26%–50% of the bottom colonized; or dense, with 50% or greater area of the substrate colonized

(PARKER, CHESTER, and NELSON, 1994). In order to evaluate the ecological relevance of these quartile-based categories and possibly select more appropriate quantitative criteria for benthic classification, we analyzed our video data of bottom features and compared it to the sonar imagery. To accomplish this, the percent colonization values for each of the georeferenced frames of the video transects were overlayed onto the sonar mosaic. This comparison also allowed us to determine if bottom features identifiable on video have specific bathymetry and backscatter signatures that allow them to be reliably and consistently interpreted.

Based on this combined examination of the georeferenced video data overlayed onto the sonar imagery (backscatter and bathymetry), it was deemed possible to consistently identify four bottom types from the available data: sand plain, rippled sand, sparsely colonized hard bottom, and densely colonized (ledges) hard bottom. A two-tier classification scheme was created around these categories that defines bottom types within two major groups: unconsolidated sediment and colonized hard bottom. A general description, list of sonar characteristics used for identification, example photograph, and example backscatter image are provided for each of the four bottom types.

CLASSIFICATION SCHEME

Unconsolidated Sediment

These bottom types consist of loose sand or small shell fragments with less than 1% of the area colonized by sessile invertebrates attached to the benthos such as sponges or corals. There is a clear boundary in sonar signatures between sites with even the sparsest of colonization and those with none. No mud is found within the project area. Subcategories are sand plain and rippled sand.

Sand Plain

General Description: This bottom type consists of stable sand deposits in a region with no sudden changes in relief (Fig. 2). Grain size appears to be smaller than areas with rippled sand. Sediment thickness is variable but may be only a few centimeters overlying flat limestone. Bioturbation is visible from polychaetes, echinoderms, and burrowing fishes and ranges from reworking of surface material to mound building and other excavations.

Sonar Characteristics: Sand plains have only gradual changes in bathymetry and a very homogenous backscatter signature. The northwest to southeast oriented features of low backscatter (dark signal) separated by rippled sand in Figure 3 were observed to have no sessile benthic colonizers and were simply flat sand areas. Similarly, during a scuba survey, a large area of dark backscatter and low bathymetric relief found in the northwest region of the sanctuary was also found to be flat sand with no colonization by sessile benthic invertebrates.

Figure 2. Sand plain. The image was acquired by a diver from an oblique perspective approximately 0.5 m above the substrate. The black spots in the image are 1–2-cm-diameter holes of infauna.

Rippled Sand

General Description: This bottom type is composed of sediment with regular ridges or ripples (Fig. 4). The ridges generally run along a north-south axis in this region due to the orientation of waves and tidal currents. These sand ripples are 6–10 cm in height from crest to trough and are 40–60 cm in length from crest to crest. Troughs are often dominated by coarser material such as shell fragments, while crests are composed primarily of sand.

Sonar Characteristics: Rippled sand was easily observed and discriminated from all other bottom types using only the N-S backscatter mosaic. Specifically, the regular pattern of strong and weak sonar returns corresponding to the surface orientation of the sand waves to the sonar pulses was clearly visible. This regular interval is evident in the lower-central region of Figure 3. The width of the alternating hard and soft sonar returns matches the wavelength of rippled sand measured *in situ.* Interestingly, this bottom type was much more difficult to discriminate from sand plain in the E-W mosaic because of the geometry of the sonar beam angle and the N-S orientation of the sand waves. Bathymetry for these areas is constant or gently sloping with no areas of sudden change.

Colonized Hard Bottom

General Description: This bottom type consists of exposed limestone substrate that is colonized with an assemblage of sessile benthic organisms such as soft corals, sponges, and tunicates. Density of colonization may be from sparse to continuous. The limestone may be flat with little vertical relief

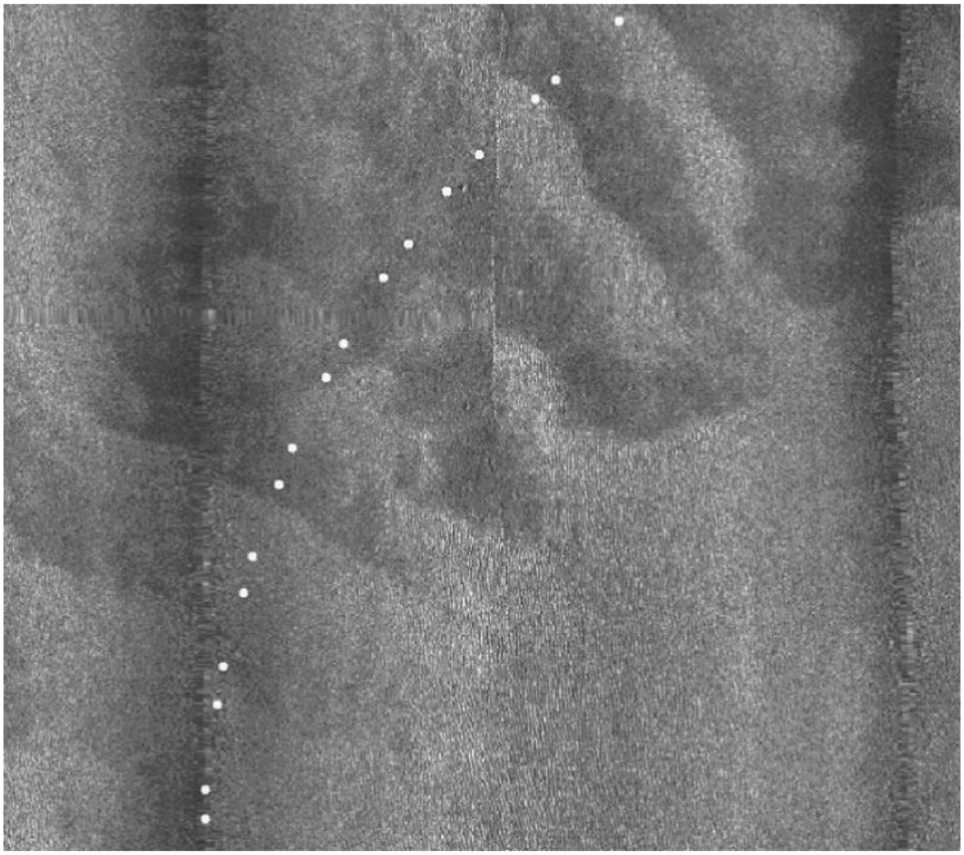

Figure 3. Segment of the N-S side-scan sonar mosaic 180 by 160 m centered at UTM17; 3474237N 511595E. Dots are geocoded video frames used to confirm that the bottom is all sand in this figure with no sessile benthic colonizers despite the differences in backscatter signatures.

or include ledges, overhangs, and other rapid changes in bathymetry. Subcategories are sparsely and densely colonized hard bottom.

Sparsely Colonized Hard Bottom

General Description: This bottom type consists of partially exposed limestone substrate that is colonized with a sparse assemblage of sessile benthic organisms (Fig. 5). Between 1% and 60% of the bottom area is colonized, although the majority of the video frames with colonization have only between 1% and 20% coverage of sessile benthic organisms. A thin veneer of sand 1–2-cm thick covers much of the bottom but is thin or ephemeral enough to allow sessile benthic organisms to attach to the limestone. This bottom type covers large contiguous areas of very low relief.

Sonar Characteristics: This bottom type has only gradual changes in relief but highly variable backscatter signatures as a result of changes in density and type of benthic colonizers, bottom composition, and roughness.

Densely Colonized Hard Bottom

General Description: This bottom type consists of exposed limestone that is colonized with a nearly continuous coverage of sessile benthic organisms such as soft corals, sponges, and tunicates (Fig. 6). Typically, only ledges and other areas of high relief have sufficiently exposed limestone to be densely colonized as observed on video transects. Percent cover measurements of the bottom in the video frame analysis indicated that these areas had at least 60% coverage of sessile benthic organisms and in several cases achieved 100% coverage. The more abrupt the change in relief, the more dense the colonization of sessile organisms. In contrast, flat limestone typically has only a sparse colonization of sessile invertebrates rarely approaching 60% coverage. Ledges typically have a vertical relief of 0.5 m up to 2 m.

Sonar Characteristics: Densely colonized ledges were most easily identified using bathymetry, although they are clearly evident in backscatter imagery as well. The precise vertical resolution of the multibeam bathymetry made identification of even small ledges (<0.5 m) a simple task. Backscatter shadows due to relative geometry of ledges and sonar beams allowed excellent visualization of these features (Fig. 7). Sand ripples present in the basin adjacent to the foot of many ledges (Fig. 7) aided in their identification.

As noted previously, patterns in the local variability of backscatter and bathymetry aided greatly with interpretation of bottom types. To better visualize the different areas

Figure 4. Rippled sand. The image was acquired by a diver from an oblique perspective approximately 0.5 m above the substrate. Ripple crests are approximately 0.5 m apart.

Figure 6. Densely colonized hard bottom. The image was acquired by a diver from a horizontal perspective approximately 2 m above the substrate at the base of the ledge. Elevation under this ledge is approximately 0.3 m, and the total ledge height is approximately 2 m.

Figure 5. Sparsely colonized hard bottom. The image was acquired by a diver from an oblique perspective approximately 1.5 m above the substrate. The branching organisms pictured are approximately 10–20 cm tall.

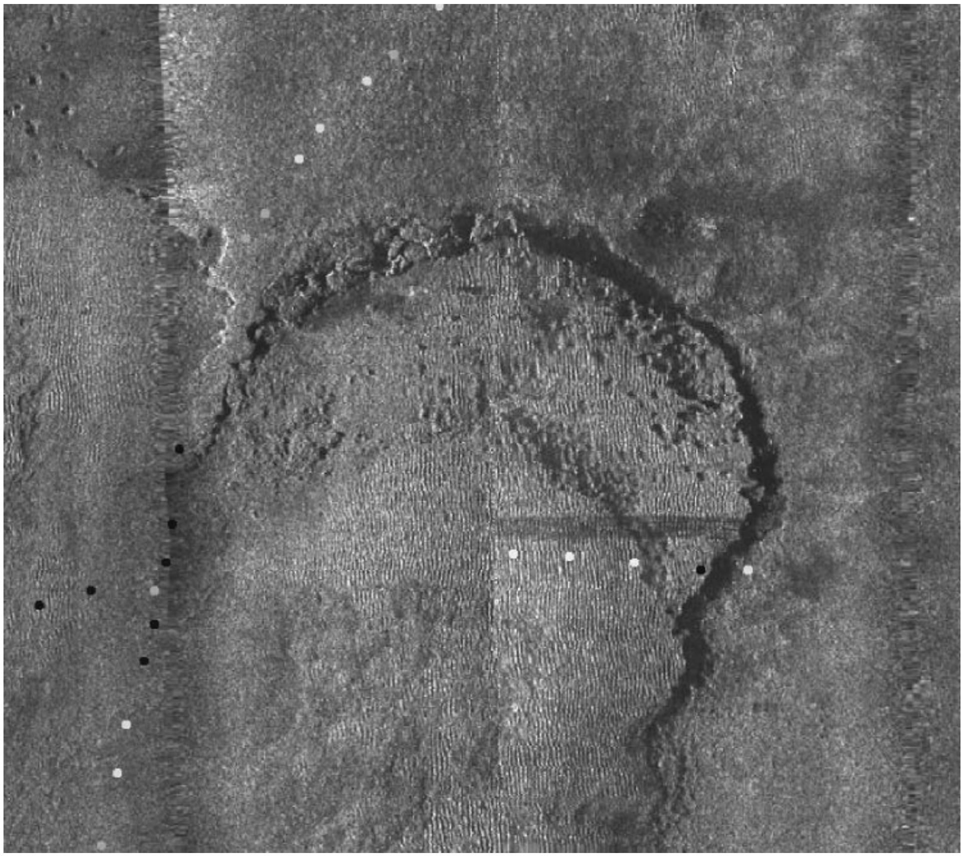

Figure 7. Segment of the N-S side-scan sonar mosaic 175 by 155 m centered at UTM17; 3473522N 510460E. The dots denote geolocated video frames used to identify a variety of features over heterogeneous bottom.

with specific variance signatures, the sonar data was converted into two derived products. First, a grid displaying backscatter variance was created. Using the original N-S backscatter grid, standard deviation of backscatter values for all grid cells within 3 m of each original grid cell was calculated using a moving window approach. The resulting grid was created with the same resolution as the raw backscatter data, or 0.25 m. The 3-m radius of analysis was selected to include a neighborhood of backscatter pixels that maximized visualization of rippled sand areas. Comparison of this new grid with the other data sources showed that rippled sand areas have a characteristic variance in backscatter due to the regularly occurring pattern of high and low sonar returns that occurs with the same periodicity as the crests and troughs of sand waves (~50 cm). Areas of sand plain and those directly beneath the sonar fish (*i.e.,* the nadir line) had low variance in backscatter signatures, whereas sparsely colonized areas had highly heterogeneous values.

Next, a grid of bathymetric variance was created based on the multibeam data using a similar process to distinguish ledges from flat areas. Using the original 2-m bathymetry grid, standard deviation of the depth values for all grid cells within 6 m of each 2-m grid cell was calculated and used to create a map of depth variability. The 6-m radius of analysis was selected to include a neighborhood of cells in deviation calculations that was consistent with the MMU and sufficiently resolved to identify the narrow ledge habitat. This approach resulted in high values for cells on or near ledges and low values for cells surrounded by flat bottom.

Digitizing Benthic Maps

Bottom features were mapped directly in a GIS. The georeferenced ground truth data, bathymetry, N-S and E-W oriented backscatter mosaics, along with the variance grids were loaded into ArcView (v3.2) with the Habitat Digitizer (v3.0) extension activated (KENDALL *et al.,* 2001). The MMU restriction in the Habitat Digitizer was set to 100 m^2. Digitizing scale was set to 1:1,000 in the Habitat Digitizer. Preliminary evaluation of the sonar imagery indicated that at this scale, boundaries of all the bottom types in the classification scheme could be readily identified. At 1:1,000 scale, the individual pixels of the backscatter mosaic are just discernable; therefore, additional zoom does not improve resolution, interpretability, or line placement.

Using the Habitat Digitizer, polygon boundaries were delineated around backscatter signatures in the N-S sonar mosaic corresponding to bottom types in the classification scheme. All lines were digitized on this single backscatter image since there were small positional inconsistencies among sonar mosaics. Feature delineation was often accomplished by first digitizing a large polygon such as a sand plain and then appending new polygons to the initial polygon or splitting out smaller polygons within. Each new polygon was attributed with the appropriate bottom designation according to the classification scheme. The positional accuracy of polygon boundaries is similar to that of the N-S mosaic since delineation was performed directly on the digital imagery. By alternating between the two backscatter mosaics, variance grids, and the ground truth data from georeferenced video frames, the edges of benthic types in the classification scheme could be easily interpreted. Additional collateral information available including previously completed benthic maps, dives, and video transects (excluding the accuracy assessment transects) were also used to assist with feature delineation and assignment of thematic attributes.

A first draft of the benthic maps was then presented for review to local experts at SKIO in Savannah, Georgia. Review session participants included members of the local research and management community. The draft maps then underwent final QA/QC and were saved as ArcView shapefiles. Thematic accuracy was assessed for these final maps.

Assessing Thematic Accuracy

Accuracy was quantitatively evaluated for two of the four bottom types that were mapped, namely, sparsely colonized live bottom and unconsolidated sediment. All bottom types could not be quantitatively evaluated because of limitations of the accuracy assessment data set. Unconsolidated sediment could be readily discriminated from colonized frames in the video data; however, rippled versus flat sand could not. As a result, accuracy of map delineations was measured at the most general level of the classification scheme for the unconsolidated sediment categories. In addition, densely colonized live bottom comprised less than 1% of the mapped area and similarly was found to be in only a fraction of 1% of the video frames used for accuracy assessment. This low sample size prevented statistically robust evaluation of this classification, although qualitative assessment of densely colonized sites is considered.

The accuracy assessment data set was collected in August 2002, 13 months after the sonar data were obtained. This short time interval and lack of major storms during this period minimized the possibility that sediment could have shifted and habitat types changed significantly in the project area between the time of acquisition of the sonar data and collection of the accuracy assessment data.

Spatial versus thematic accuracy can be difficult to disentangle. We minimized problems associated with misalignment of map and reference data as well as mismatch between the scale of video data and the MMU by following a specialized accuracy assessment procedure. Following previous studies that have used transect data for accuracy assessment (*e.g.,* MULLER *et al.,* 1998), we eliminated accuracy assessment sites in both the transect data and the benthic map based on the combined potential positional error of these two data sources. The maximum combined error was estimated to be 15–20 m. Specifically, the benthic habitat map was rasterized (2.5-m cell size), and individual pixels were removed from the accuracy assessment process if any pixels within a 20-m diameter around each cell contained a different habitat type. This step removed 13% of the overall map area. Similarly, individual video frames were removed from the analysis if the previous and subsequent video frames along the transect did not have the same habitat type. Three geocoded video frames in a row cover approximately 20 m. This step removed 570 (21%) out of 2,694 data frames. This resulted in areas being included in the accuracy assessment only if they exhibited relatively homogeneous bottom types at the scale of the positional accuracy of the source data and MMU. Although this technique minimizes the impact of spatial misalignment on the assessment of thematic accuracy, it also reduces the scope of inference to those portions of the map that were not removed because of small-scale heterogeneity.

Problems associated with autocorrelation of accuracy assessment points along a transect were eliminated by analyzing the spatial autocorrelation structure of the transect data and selecting points for accuracy assessment that were far enough apart along the transects such that the assumption of statistical independence was met. First, Geary's C and Moran's I statistics were calculated to test for the presence of significant spatial autocorrelation. Moran's I is the "standard" autocorrelation statistic and provides a global (*i.e.,* across the study area) test of spatial autocorrelation. Geary's C is more sensitive to autocorrelation within small neighborhoods. Since both tests showed highly significant ($p < 0.001$) positive autocorrelation, the following procedures were used to determine the minimum distance required between video frames to select independent samples from the transect data: (1) The empirical variogram was calculated for the video transect data to describe the decrease in relatedness between pairs of points as a function of distance between them. A spherical variogram model (line in Fig. 8) was fit to the empirical variogram (points in Fig. 8). Variogram parameters for video transect data were nugget = 58, partial sill = 132, and range (m) = 150. (2) The range parameter of this model represents the distance at which autocorrelation becomes negligible. Pairs of points separated by a distance greater than the range can be considered essentially independent. The spherical model was chosen based on the observed pattern of the empirical variogram and because it is the only model that provides a precise nonarbitrary estimate of the range. (3) Based on the calculated range, video frames were selected for accuracy assessment at intervals of 150 m.

Bottom type recorded for each selected series of three adjacent video frames was overlaid onto the benthic maps and compared against the classification assigned during visual interpretation. After comparing the map classification to each video site, an error matrix was produced displaying both errors of inclusion and exclusion. In addition, overall accuracy, user's and producer's accuracy, and the kappa statistic (measure of map accuracy relative to a map with classifications randomly assigned expressed as a percent) are reported (CONGALTON, 1991). Although the video survey design was a random start systematic sample, estimates of kappa and its

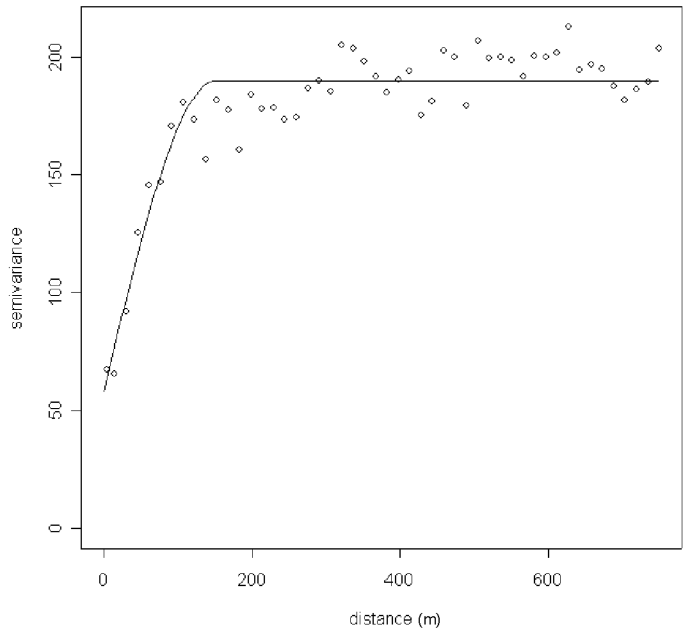

Figure 8. Semivariogram based on colonization values for accuracy assessment transects. Points are the empirical variogram, points are the modeled variogram, and distance units are in meters.

standard error are based on formulas for random multinomial samples. STEHMAN (1992) shows, however, that the bias in the estimate of kappa for a systematic survey is negligible. Bias in the standard error of kappa is harder to predict, as it depends on the extent to which any periodicity in the underlying map matches the period of the systematic sample.

RESULTS

The seafloor within GRNMS is largely flat and featureless with depths ranging between 14 and 21 m with an average depth of 18 m. A summary of the area for each of the bottom types reveals that unconsolidated sediments dominate the bottom of this region, covering 75% of the total area, and that colonized hard bottom occurs over 25% of the bottom. Densely colonized ledges, which harbor much of the biodiversity of the sanctuary, account for only a fraction of 1% of the total area (Table 1). This 1% of the bottom attributed as densely colonized bottom was spread among 447 sites primarily in the central and south-central portions of the sanctuary.

Overall map accuracy was excellent at 94.8%. Both unconsolidated sediment and sparsely colonized bottom had a high thematic accuracy (Table 2). User's and producer's accuracy were both above 90% for the evaluated categories. The kappa statistic was 0.88 ± 0.04 (SE) indicating significantly better than random prediction accuracy ($p < 0.001$). However, because of the specialized procedure used here, the scope of inference for this accuracy assessment is limited to those regions of the map that did not display fine-scale spatial heterogeneity, or 87% of the mapped area. Without the buffering procedure that we used to disentangle spatial and thematic accuracy, overall accuracy was still quite acceptable at 82.7%.

In addition, note that the error matrix contains comparisons for unconsolidated sediment and sparsely colonized hard bottom only. Recall that because of the small area of densely colonized hard bottom (0.6% of the mapped area) and the limits of the video transect data, insufficient samples were available for quantitative accuracy assessment. Only 17 out of the

Table 1. *Summary of the number and area of polygons for each map category. Total area mapped is slightly larger than the extent of the sanctuary since the sonar data extended slightly beyond the sanctuary boundaries.*

Classification	No. Polygons	Area (km²)	% of Area
Flat sand	1,538	4.7	8
Rippled sand	1,516	40.0	67
Sparsely colonized live bottom	1,181	14.9	25
Densely colonized live bottom	447	0.4	<1
Totals	4,682	60	100

Table 2. *Error matrix. Numbers in the matrix indicate class coincidence, (U) indicates user's accuracy, and (P) indicates producer's accuracy based on analysis of 135 points.*

	Habitat Type Observed on Video	
Mapped Habitat Type	Unconsolidated Sediment	Sparsely Colonized Hard Bottom
Unconsolidated Sediment	88 96.7% (U) 95.7% (P)	3
Sparsely Colonized Hard Bottom	4	40 90.9% (U) 93.0% (P)

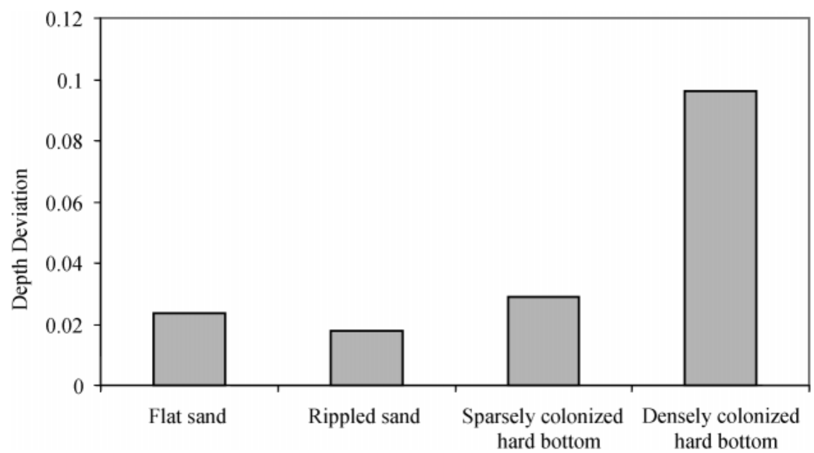

Figure 9. Mean standard deviation of depth for pixels within each polygon type.

2694 video frames (0.6%) were classified as densely colonized hard bottom. Ideally, this problem could be eliminated by stratifying the collection of accuracy assessment data according to bottom types once an initial map of the area has been produced; unfortunately, logistics prevented such an arrangement from being possible here. The 17 video frames classified as densely colonized live bottom occurred in two clusters, both of which crossed or occurred near areas mapped as such within the spatial accuracies of these data. In addition, one site that was classified as densely colonized in the benthic map was crossed by a transect but not scored as densely colonized in the video. Five additional polygons attributed as densely colonized were visited in the field in May 2003 and were confirmed to have that habitat type since maps were produced. Unfortunately, eight points do not constitute a statistically robust sample size to determine if densely colonized live bottom was successfully interpreted. Because this is an important classification, an alternative metric for evaluating the delineation of densely colonized habitat was explored. Recall that bathymetric variance was used to aid in delineation of thematic classes. Sand plains, rippled sand, and sparsely colonized hard bottom were all defined in part by very low or no change in bathymetry. According to the classification scheme, only densely colonized hard bottom, which mainly occurs on or near ledges, has high slope or sudden changes in bathymetry. One way to simply confirm that polygons labeled as densely colonized encompassed areas of high depth relief and those labeled as sand or sparsely colonized covered areas of low relief is to examine the average bathymetric deviation of polygons labeled with each classification. Figure 9 shows that polygons labeled as densely colonized had much higher depth variance than those labeled other categories. Because bathymetric variance was used to aid in delineation of polygon boundaries, this analysis simply confirms that densely colonized polygons were successfully digitized to encompass areas of significant depth relief. This provides additional, qualitative validation that this important bottom type was correctly delineated; however, only through additional fieldwork, including random site visits, can quantitative evaluation of user's and producer's accuracy be accomplished for all classifications.

Table 3. *Area of different habitat types within Grays Reef National Marine Sanctuary from the current study and two previous studies.*

	Current Study	Hunt (1974) in Parker *et al.* (1994)	Georgia DNR in Hopkinson *et al.* (1991)
Sand	75%	18%	53%
Some colonization/live bottom	25%	58%	13%
Dense or moderate colonization/ledge habitat	0.6%	24%	34%

DISCUSSION

Previous researchers estimated that 18% of the GRNMS bottom was covered with sand, 58% consisted of live bottom, and another 24% was ledge habitat (Table 3; Hunt, 1974; Parker, Chester, and Nelson, 1994). Another study, citing a Georgia Department of Natural Resources map, estimated that 53% of the bottom was bare sand, 13% was sparsely colonized live bottom, and the remaining 34% was moderately colonized hard bottom (Hopkinson *et al.,* 1991). These estimates were based on the limited point assessments, grab samples, and sonar technology available during previous decades. The differences between the areas tabulated are in part influenced by the lack of rigorous quantitative criteria for map categories, differences in definitions between classifications, and some amount of real change that occurred in the region's habitats during the time period between creation of the two maps.

In comparison, this study found three-quarters (75%) of the GRNMS bottom was sand, 25% showed some colonization, and only 0.6% was densely colonized. As noted previously, differences in classification categories and resolution make it difficult to quantitatively compare the categories among different studies; however, two general observation can be made. First, the percentage of bottom classified as sand is clearly greater in the current study than in previous reports. Second, only a very small fraction of the sanctuary consists of densely colonized ledges. Certainly, changes have occurred in the relative proportions of the different benthic types in the study area since the first assessment of Gray's Reef in 1974. Such changes are due to a combination of gradual sediment transport processes as well as brief but severe storm events such as hurricanes. The relative importance of these influences in erosion and deposition of sand is poorly understood in this region and should be the focus of further study. Only now, with the advent of more advanced sonar technologies and the map and protocol devised here, has a fine-scale baseline been established against which future assessments can be compared.

Additional areas of research that should be explored to provide a more complete assessment of habitats within GRNMS include directed assessment of densely colonized hard bottom to quantify the accuracy of delineations for this important bottom type. In addition, *in situ* benthic characterization will allow differences within the four mapped categories to be quantified. For example, the 447 polygons attributed as densely colonized hard bottom are not identical habitats but could not be further characterized using the sonar data. Measuring the differences in ledge height, colonization density, and composition of fish and invertebrate assemblages using scuba at randomly sampled ledge sites will provide a greater understanding of the variability in these important benthic structures for the Georgia bight and southeastern shelf communities.

The accuracy assessment demonstrates that the habitat maps successfully differentiate between unconsolidated sediment and colonized bottom for a large majority of the area mapped. The strong spatial autocorrelation apparent in the variogram of the video transect data underscores the importance of accounting for this common phenomenon. Although a variety of approaches to correcting for autocorrelation exist (DALE and FORTIN, 2002), the method described here is simple and effective. Positional inaccuracies and rarity of densely colonized habitat prevented accuracy assessment within areas of fine-scale habitat heterogeneity and densely colonized regions, although qualitative evidence indicates that this bottom type was correctly delineated. The fact that overall map accuracy increased substantially when the buffer was applied suggests that our approach was effective in separating the effects of positional from thematic inaccuracy. The results of our modified accuracy assessment procedure indicates that the benthic maps of GRNMS have a very high degree of thematic accuracy and are suitable for a variety of management and research applications.

CONCLUSIONS

The majority of the seafloor on the continental shelf lies beyond the detection limits of aerial or satellite mapping technologies because of water depth and/or turbidity. The approach and mix of technologies used for this mapping project can be easily adapted and applied to produce accurate maps of many such areas. The software we used allows creation of a customized classification scheme and delineation of maps with specific scale and resolution characteristics. The video transect approach to collection of field data requires a modified procedure for accuracy assessment but maximizes the spatial area that can be covered during field operations in deeper water. The use of both backscatter and bathymetric variance provides more insightful visualization of benthic features during interpretation than the use of raw sonar values alone and will ultimately be the key to automated classification techniques.

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