Integrating remote sensing products and GIS tools to support marine spatial management in West Hawai`i

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ABSTRACT: Marine protected areas (MPAs) represent a form of spatial management, and geospatial information on living marine resources and associated habitat is extremely important to support best management practices in a spatially discrete MPA. Benthic habitat maps provide georeferenced information on the geomorphic structure and biological cover types in the marine environment. This information supports an enhanced understanding of ecosystem function and species habitat utilization patterns. Benthic habitat maps are most useful for marine management and spatial planning purposes when they are created at a scale that is relevant to management actions. We sought to improve the resolution of existing benthic habitat maps created during a regional mapping effort in Hawai`i. Our results complemented these existing regional maps and provided more detailed, finer-scale habitat maps for a network of MPAs in West Hawai`i. The map products created during this study allow local planners and managers to extract information at a spatial scale relevant to the discrete management units, and appropriate for local marine management efforts on the Kona Coast. The resultant benthic habitat maps were integrated in a geographic information system (GIS) that also included aerial imagery, underwater video, MPA regulations, summarized ecological data and other relevant and spatially explicit information. The integration of the benthic habitat maps with additional "value added" geospatial information into a dynamic GIS provide a decision support tool with pertinent marine resource information available in one central location and support the application of a spatial approach to the management of marine resources. Further, this work can serve as a case study to demonstrate the integration of remote sensing products and GIS tools at a fine spatial scale relevant to local-level marine spatial planning and management efforts.

Keywords: Marine spatial planning, marine management, benthic habitat mapping, marine protected area, GIS, remote sensing, Hawai`i

INTRODUCTION

Coral reefs are one of the most ecologically important ecosystems on Earth (Connell 1978) and provide economic, biological and cultural resources that supports the livelihood of millions of coastal residents (Wilkinson 1999). Global degradation of coral reefs is occurring rapidly as a result of direct anthropogenic stresses and global climate change (Jackson 1997; Pandolfi et al. 2003; Hoegh-Gulberg et al. 2007). It is predicted that without effective management actions in the next 20 – 40 years, close to 60 percent of the coral reefs on our planet will be considerably degraded (Wilkinson 1994). Coastal managers must embrace new and innovative ways that are cost-effective, time-efficient, and repeatable to address these issues affecting the marine environment.

Geospatial Technology in the Marine Realm

Remote sensing was first utilized to study and map coral reef ecosystems using the Landsat multispectral sensor in 1975 (Smith et al. 1975). A few years later, Lyzenga (1978) applied remote sensing techniques to map water depth and benthic features in the marine environment. Since these early applications of remote sensing in a coral reef environment, the technology and capabilities of remote sensors have greatly advanced (Andrefouet et al. 2003; 2004; Hamel et al. 2010). The recent expansion in the use of remotely sensed imagery is partially driven by the fact that monitoring coral reefs through field surveys can prove to be difficult due to the considerable amount of time and resources necessary to collect in-situ data (Hedley et al. 2004). The coupling of remote sensing and GIS technology to produce benthic habitat maps has been a valuable step in developing spatial management tools for coral reef conservation actions (Monaco et al. 2001; 2007; Friedlander et al. 2003). Providing coral reef managers with benthic habitat maps and other geoinformatic products can greatly assist in forms of spatial management, such as marine protected area design and evaluation (Friedlander et al. 2007; Haddak et al. 1996; Kendall et al. 2004; Pittman et al. 2007).

The Value of Benthic Habitat Maps to Marine Spatial Management

Benthic habitat is a major determinant of fish assemblage structure in the marine environment. Fish assemblage structure has been found to vary significantly between benthic habitat types in Hawai`i (Friedlander et al. 1998). To address these habitat related differences in fish assemblage structure, the use of benthic habitat classes as strata - for a stratified random sampling design - can result in a more effective sampling strategy (Friedlander et al. 2003a; 2007). As a result, benthic habitat maps provide useful information for planning sampling design for research or monitoring efforts (Sladek-Nowlis and Friedlander 2004). This methodology has been used in other coral reef fish studies (Appeldorn et al. 2003; Christensen et al. 2003; Friedlander et al. 2003b) to guide the sampling design and account for variation in fish abundance that may be influenced by the benthic substrate present at the site.

In addition, documenting the location of habitats in an MPA can provide insight into the species distribution in the area and the level of habitat connectivity (Kendall et al. 2004). For instance, Gillanders et al. (2003) highlighted the value of studying habitat connectivity between adult and juvenile habitat to better understand the nursery role of certain coastal areas. MPA design and evaluation can be guided by a better understanding of fish-habitat interactions and juvenile and adult habitat connectivity (Christensen et al. 2003; Friedlander et al. 2003b). Benthic habitat maps can be used to help incorporate a diverse mosaic of habitats in an MPA to meet such goals as conserving biodiversity (Roberts et al. 2001) or protecting critical nursery habitat (Gillanders et al. 2003).

Scientists and managers can extract more valuable information from sampling efforts when using ecologically relevant benthic habitat maps, resulting in a better understanding of fish-habitat utilization patterns. For instance, Appeldoorn et al. (2003) used benthic habitat maps to study the effects of habitat connectivity on the spatial distribution of fish communities in Columbia, resulting in recommendations for MPA design that encompassed critical nursery and spawning areas. In addition, Franklin et al. (2002) found that GIS assisted in the visualization of spatially linked benthic habitat types and fish habitat utilization patterns in the Florida Keys.

Producing habitat maps at a scale relevant to local management

Scale is an important consideration during the interpretation of remotely sensed imagery (Arnold et al. 1997). Coral reef communities demonstrate habitat heterogeneity across several spatial scales, from centimeters to kilometers (Hochberg et al. 2003). Benthic habitat maps can assist in the management of coral reef ecosystems on a variety of scales. However, the mapping of coral reef habitats should proceed at a scale that is relevant to the management unit (Stevens et al. 2002; 2004). Although MPAs are often designed to meet global-scale conservation goals of preserving biodiversity, these management units are often represented by small, discrete geographic areas and are managed at a local-scale. As a result, regional, national or global scale remotely sensed data is often too coarse to be relevant to management at these local scales.

The most appropriate spatial scale for benthic habitat mapping aimed to assist in management efforts in Hawai`i is at the local scale resulting in a large scale map. The NOAA National Ocean Service (NOS) Biogeography Branch benthic maps were produced at a scale of 1:6000 and were created during a national mapping effort to inform management at a national scale (Coyne et al. 2003). Marine Life Conservation Districts (MLCDs) were designed by the State of Hawai`i, Department of Land and Natural Resources (DLNR) to conserve and replenish marine resources. The MLCDs represent one type of marine protected area presently used in the management of marine resources in Hawai`i, and these MPAs range in geographic extent from approximately 14 ha to 127 ha. The NOAA benthic habitat maps have been successfully applied to evaluate MPA design and function in Hawai`i at a regional-level (Friedlander et al. 2007). However, when focusing a study at one particular local-scale site (e.g., a small MPA, such as Hanauma Bay – 41 ha), a higher level of map detail may be necessary to address research questions.

Research objectives

The first objective was to develop benthic habitat maps at a scale relevant to local marine management efforts in Hawai`i MLCDs. In order to maintain continuity and contribute to the larger NOAA mapping effort, the classification scheme created by NOAA and the Hawai`i coral reef community

was used in this study. The scale and minimum mapping unit (MMU) were modified to reflect our objective of mapping MPAs at a scale relevant to local management. This research effort was not aimed at comparing our local mapping effort to the larger NOAA effort, but focused on enhancing the benthic habitat map products in Hawai`i for better management of local MPAs.

Geospatial information on living marine resources and associated habitat is extremely important to support best management practices in a spatially discrete area. The second objective was to integrate the benthic habitat maps with additional "value added" geospatial information into a dynamic GIS, using geospatial tools available to the public. This GIS database will provide a decision support tool with pertinent marine resource information available in one central location, and allow managers to apply a spatial approach to the management of marine resources.

STUDY SITES

The study sites for this research were located at four Marine Life Conservation Districts on the Kona Coast of the Island of Hawai`i. The four study sites were Lapakahi, Waialea Bay, Old Kona Airport and Kealakekua Bay (Table1, Figure 1, Figure 2).

Table 1: Summary of Marine Life Conservation Districts on the Kona Coast of Hawai`i Island.

MLCD name	Established	Legislation	Total area (ha)
Lapakahi	1979	HAR 13-33	59.1
Waialea Bay	1985	HAR 13-35	14.0
Old Kona Airport	1992	HAR 13-37	87.8
Kealakekua Bay	1969	HAR 13-29	127.0

Figure 1: Marine Life Conservation District (MLCD) locations on the Kona Coast of Hawai`i Island. Map insets denote MLCD boundaries and subzones.
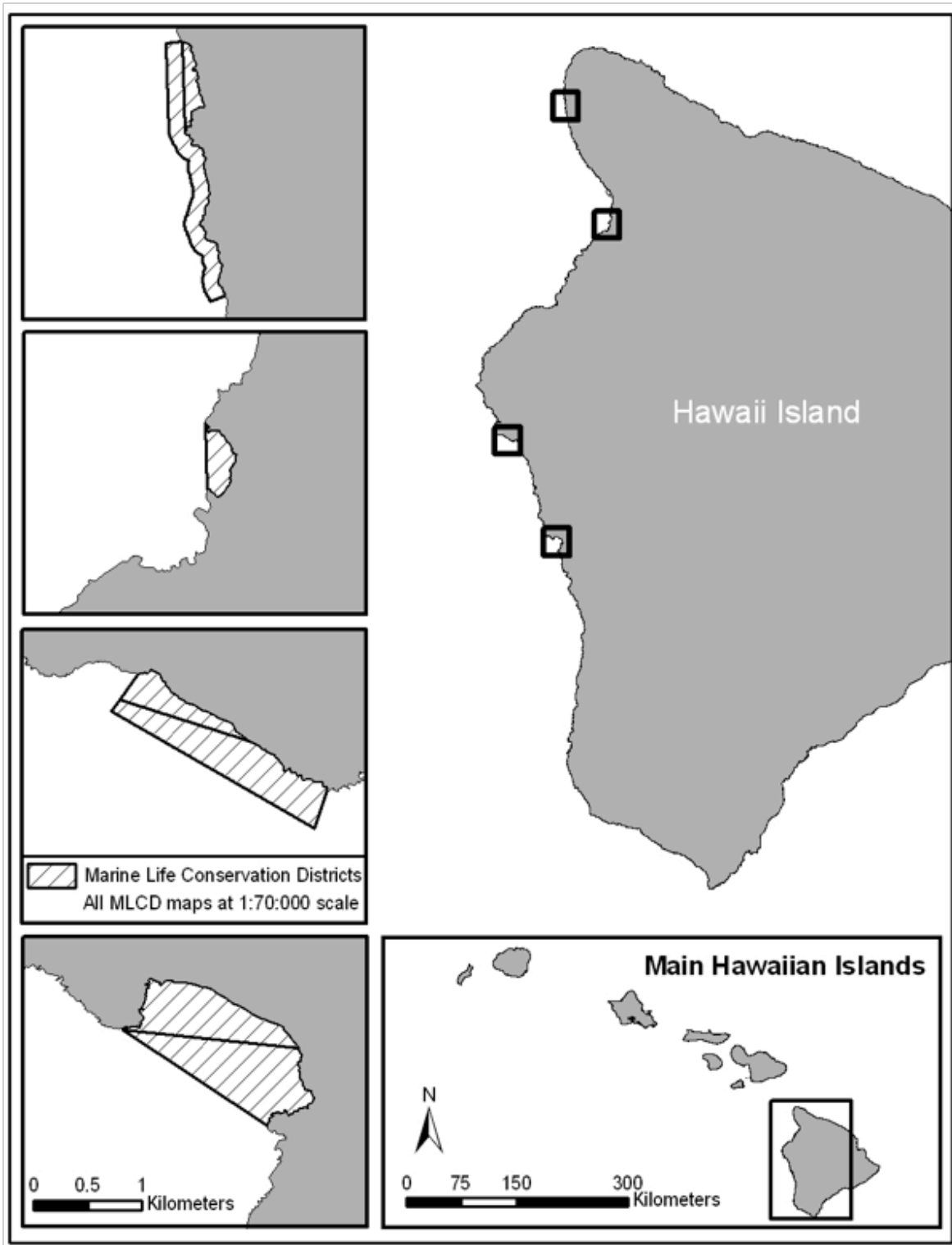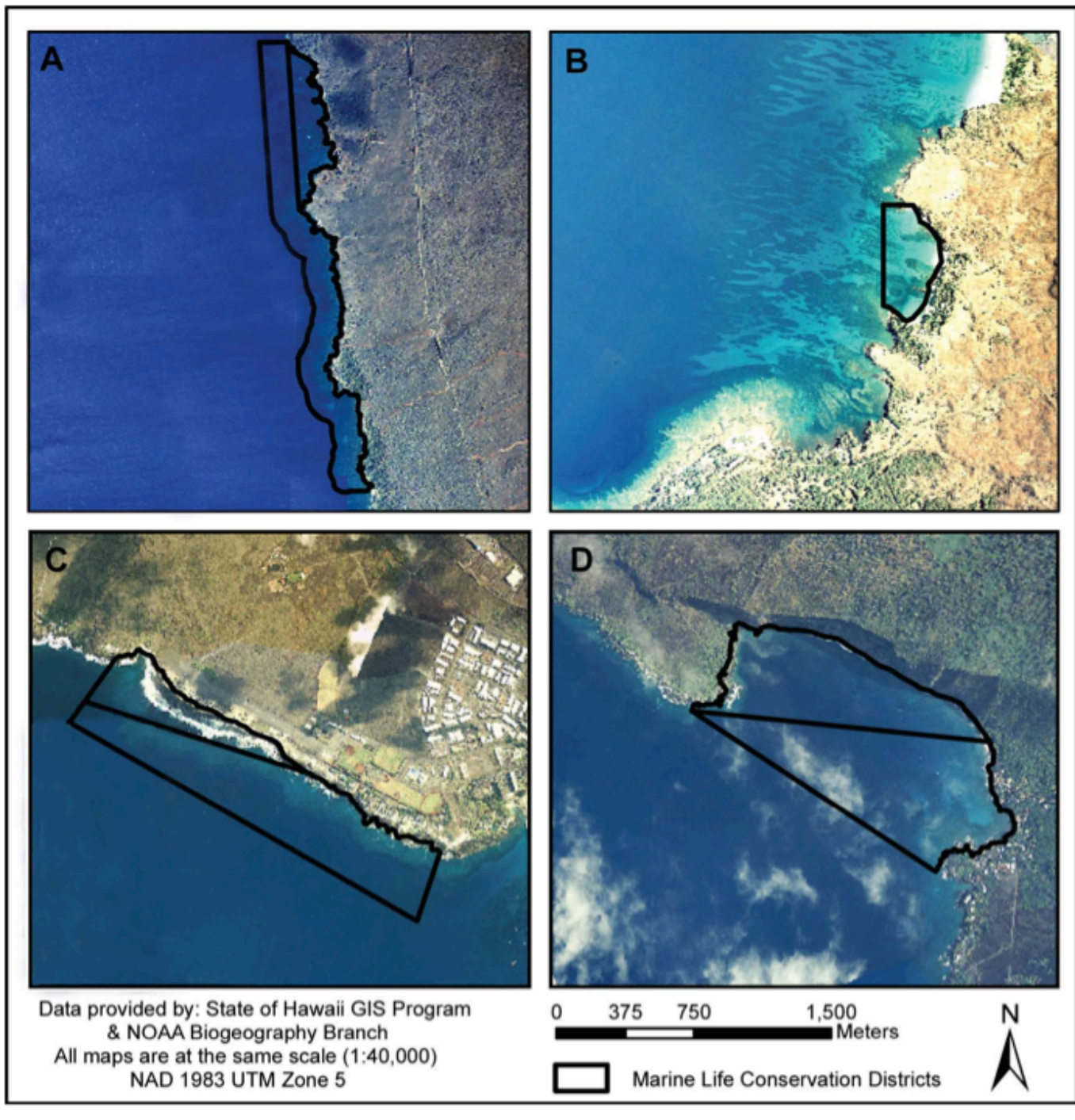
Figure 2: Aerial imagery of MLCD study sites on the Island of Hawaii (a) Lapakahi; (b) Waialea Bay; (c) Old Kona Airport; and (d) Kealakekua Bay.

Data provided by: State of Hawaii GIS Program & NOAA Biogeography Branch
All maps are at the same scale (1:40,000)
NAD 1983 UTM Zone 5

Marine Life Conservation Districts

The Lapakahi MLCD is the northern most study site on the Kona Coast, and was established in 1979 to conserve 59.1 ha of marine area adjoining a state park. The adjacent Lapakahi State Historical Park features ruins of the ancient fishing village of Koai`e, dating back to the 1300s. This location shelters shallow water boulder habitat that shifts with increasing depth to predominantly colonized volcanic rock and sand patch habitats. The diversity of habitat types and complexities at this location support a high diversity of fish species. Waialea Bay is a 14.0 ha MLCD that was established in 1985. This bay contains habitats consisting of sandy bottom and coral colonized on volcanic rock. Old Kona Airport MLCD was established in 1992 and is just northwest of Kailua-Kona. This 87.8 ha protected area shelters colonized volcanic rock in the shallows, with an adjoining steep drop off with high coral cover. Kealakekua MLCD was established in 1969 and is the southernmost MLCD on the Kona Coast. This 127.0 ha MLCD encompasses shallow areas that are characterized by high coral cover, very steep drop offs, extensive sandy bottom, and protects a high diversity and biomass of reef fish.

GEOSPATIAL DATA

In 2000, the NOAA Operation Centers aircraft along with National Geodetic Survey cameras and personnel acquired color aerial photographs at 1:24,000 scale for portions of the main Hawaiian Islands. Diapositives were scanned at 500 dots per inch (DPI), producing 1 meter by 1 meter spatial resolution (pixels) TIF files, which were then orthorectified. The data products used in this study were the color aerial photographs taken along Hawai`i Island's leeward (Kona) coastline by the NOAA effort, and distributed as mosaiced images in Universal Transverse Mercator (UTM) Zone 5, North American Datum (NAD) 83 (Coyne et al. 2003). In 2007, the separation of biological cover and geomorphic structure represented a significant evolution of the previous versions of the classification schemes developed for mapping of the in the Hawaiian Islands (Battista et al. 2007). The major product of this effort was a series of GIS-based benthic habitat maps that were characterized by a high degree of spatial and thematic accuracy (Anderson 2002; Coyne et al. 2003; Battista et al. 2007) (Figure 3).

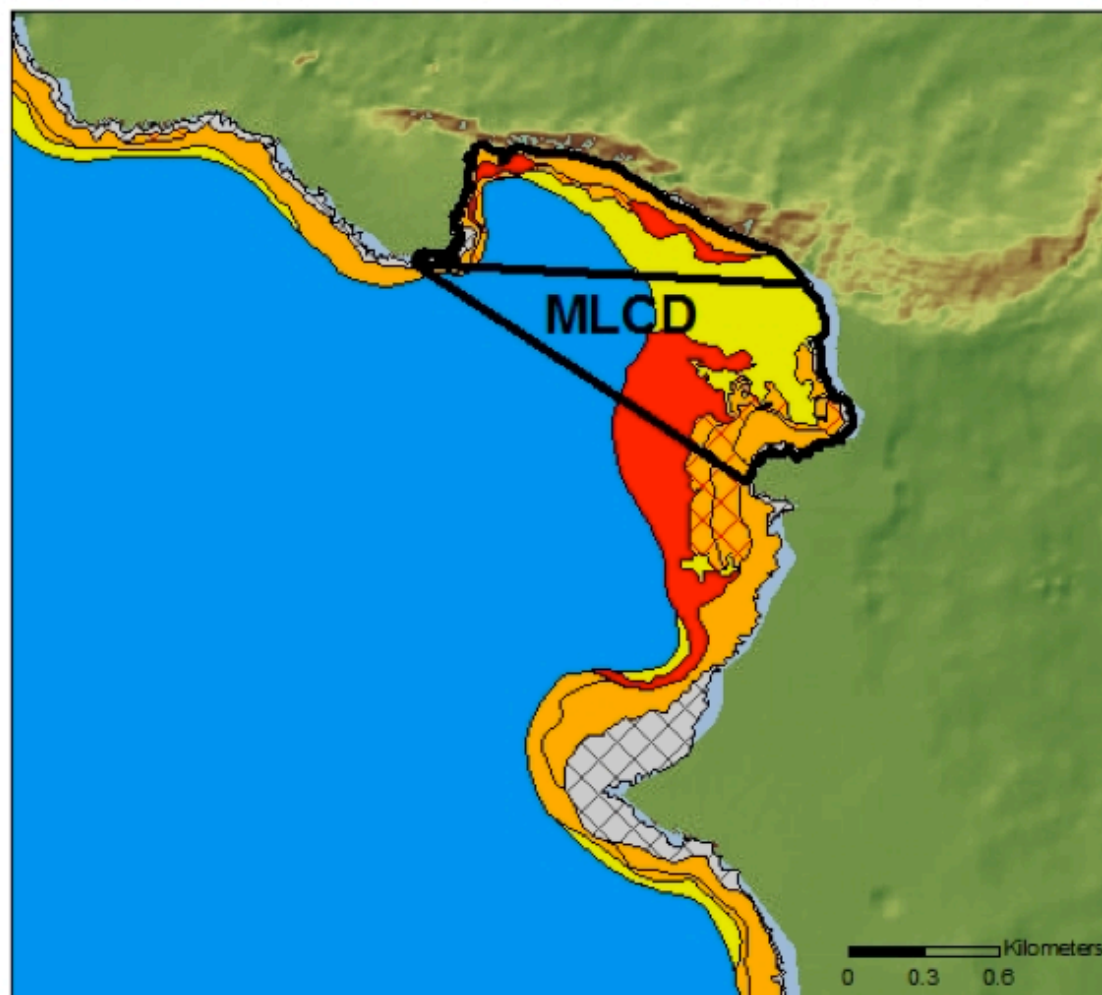Additional ancillary GIS data sets were used to develop the benthic maps; the data was downloaded from the State of Hawai`i Office of Planning's web site, or retrieved from the Hawai`i Division of Aquatic Resources (DAR). These data sets included the coastline for Hawai`i Island and the boundaries for Marine Life Conservation Districts. All data sets were converted to UTM Zone 5, NAD 1983 using the Hawai`i Datum and Projections extension (created by Stone in 2002) for Environmental Systems Research Institute, Inc.'s (ESRI) ArcView. Any other GIS data files utilized in this study were created in ArcView using the Habitat Digitizer Extension (created by NOAA/NOS), Random Point Generator Extension (created by Jenness in 2001), and the Hot Potato Extension (created by McVay in 1998).

METHODOLOGY

In 1999, the NOAA Biogeography Branch began a coral reef research effort aimed at mapping, assessing, inventorying, and monitoring U.S. coral reef ecosystems (Monaco et al. 2001). As a component of this, NOAA developed a hierarchical classification scheme for benthic habitats which defined benthic communities using two attributes: large geographic "zones" and smaller "habitats" (Coyne et al. 2003). The classification scheme defined thirteen "zones" and twenty-seven distinct "habitats" that can be identified using visual interpretation of aerial photography and other types of remote sensed imagery. Several factors were considered for the development of the classification scheme, including: input from the management community; existing scheme's used elsewhere in the Pacific; and knowledge from NOAA's previous coral reef mapping efforts in the Caribbean and Florida Keys (Coyne et al. 2003). In order to maintain continuity and contribute to the larger NOAA mapping effort the classification scheme created by NOAA was used as a model for delineating marine habitat types in this study.

A GIS extension was developed by NOAA to assist with the mapping of the benthic habitats in the U.S. Virgin Islands and Puerto Rico, and was also used by NOAA for its mapping efforts in Hawai`i (Kendall et al. 2001). The extension was developed to assist users in visually interpreting georeferenced imagery, such as aerial photography or satellite imagery. The interface of the tool allows the image interpreter to rapidly identify and assign attributes to polygons, and also allows the user to create or modify new hierarchical classification schemes. The NOAA Habitat Digitizer extension that was used in this

Figure 3: NOAA Biogeography Branch biological cover benthic habitat map using updated 2007 classification scheme.

study is available at no cost, and can be downloaded on the NOAA CCMA Shallow-water benthic habitat maps website (NOAA 2010).

Image Classification

The minimum mapping unit (MMU) is the smallest cartographic entity that is mapped in an image, and is associated with the scale of the data and the immediate spatial context (Congalton and Green 1999). The spatial scale of 1:6000 utilized by NOAA for mapping of coral ecosystems present on the Mainland U.S. (e.g., Florida) was ideal for those marine areas since they cover a much larger region than Hawai`i. NOAA noted that for its mapping objectives in the Florida Keys and Caribbean, little information was gained relative to the effort that would have been required to produce maps at a finer scale (Anderson et al. 2002). On the other hand, Hawai`i resource managers have expressed an interest in "higher resolution" benthic habitat maps around the state (Walsh pers. com). A MMU was chosen for this study to attempt to address the need for more detailed, fine-scale, benthic habitat maps to provide decision support for marine spatial management at a local scale. This research effort was not aimed at comparing our local mapping effort to the larger NOAA effort, but focused on enhancing the benthic habitat map products in Hawai`i to support spatial management of local MPAs.

The benthic habitat polygons were manually delineated from aerial photographs by photo-interpretation and heads-up digitizing methods. To ensure that the photointerpretor had a consistent level of detail, the 1:2,000 scale was "locked" using the habitat digitizer extension, and was used consistently during the digitizing process (Coyne et al. 2003). As a result, the benthic habitat maps produced by this study were digitized at a scale of 1:2,000, with a MMU of 0.10 ha.

Accuracy Assessment

Map quality information is provided to the user through thematic classification accuracy assessments (Stehman 1997). The thematic classification accuracy is generally obtained by choosing reference locations that are independent of training locations and comparing the classifications of the reference locations to the

classification on the map (Mumby and Green 2002). Thus, field assessment is a critical step in correctly classifying the benthic habitats present at the study site (Stehman 1997), especially when mapping ecological assemblages (Mumby et al. 1997).

The accuracy of the maps produced for this study was assessed in order to ensure that the benthic habitats in the aerial photos were classified with a high level of accuracy. The Random Point Generator Extension v 1.1 was utilized to create stratified random points within each classified polygon. These randomly generated ground control points (GCP) were converted to the geographic coordinate system for input into a GPS. Fifty points (50) were generated for each of the habitat classes, but the number of points actually assessed in the field varied in each habitat due to inaccessibility because of high surf and limited boat access. One hundred thirteen (113) random accuracy assessment points were generated and validated in the field.

At the respective GPS point, the depth at each GCP was recorded using a depth sounder, and field notes were recorded at each site. The benthic habitat at that location was noted and later entered into the error matrix to assess the thematic accuracy of the maps. The error matrix is a tool to organize data in order to statistically analyze and interpret thematic classification accuracy (Stehman 1997). The error matrix is an important step in the process of assessing the accuracy of the classified image and provides an effective way to present the accuracy assessment (Naesset 1996). The matrix is represented by rows and columns that correspond to an individual benthic habitat class, with each cell containing the total sample sites for that particular habitat class (Mumby and Green 2000).

The user's and producer's accuracy was also derived from the error matrix and used to determine distinct levels of accuracy for each benthic habitat class. The user's accuracy is dependent upon actual field verification and thus errors of commission (Naesset 1996). Errors of commission are considered errors of inclusion and occur when an area is included in a habitat class when it did not belong in that particular habitat class (Congalton and Green 1999). For example, user's accuracy represents the probability of an area classified as aggregated coral on

the map is in fact aggregated coral in-situ. The producer's accuracy represents the probability that a particular habitat class is classified correctly from the imagery. The producer's accuracy is dependent upon accurate image interpretation and so it is based on errors of omission. The overall accuracy is calculated by adding the correctly classified accuracy assessment points and dividing by the total number of accuracy assessment points collected (Congalton and Green 1999).

"Value Added" Geospatial Information

In this study, hot links were created utilizing the Hot Potato extension downloaded from the ESRI website. The MLCD polygons for Lapakahi, Waialea Bay, Old Kona Airport, and Kealakekua Bay were all hotlinked to State of Hawai`i, Division of Aquatic Resources (DAR) regulations and boundary description. These polygons were also hotlinked to Adobe Acrobat PDF files that contain additional quantitative and qualitative data obtained from DAR, Washington State University, and the University of Hawai`i at Hilo. In addition, video clips of Lapakahi and Kealakekua Bay were edited from underwater digital video footage provided by DAR. Fifty to sixty second clips of these sites illustrated the benthic habitat and fish assemblage characteristics of the general area.

RESULTS

Benthic Habitat Map Accuracy Assessment

Accuracy assessment points collected in the field were used as reference data to compare to the habitats classified from the imagery. Accuracy of the benthic habitat maps was quantified for each of the habitat classes (Table 2). The 113 accuracy assessment points were entered into the error matrix (Table 3). The user's accuracy for the habitat maps produced for the MLCDs ranged in value from 83-96%. Uncolonized volcanic rock had the highest user's accuracy of 96%. The lowest user's accuracy values were for patch reef, and scattered coral and rock in unconsolidated sediment habitat classes. For the classified aggregated coral habitat only 30 of the 36 sites were found to be aggregated coral during field accuracy assessment, but 26 of the 27 uncolonized volcanic rock habitats were found to be correctly classified.

The producer's accuracy for the habitat classes ranged from 71-100%. In the case of the colonized volcanic rock sites (71%), the habitat was visually difficult to distinguish during image interpretation between some of the aggregated patch habitat. Scattered coral rock in unconsolidated sediment presented no difficulty during photointerpretation with a producer's accuracy of 100%. The overall accuracy of the benthic habitat maps produced in this study was 88%.

"Value Added" Geospatial Information

All GIS data and remote sensing products were integrated into GIS to create a comprehensive marine spatial database for MLCDs on the Kona Coast of Hawai`i (Table 4). Baseline GIS information used to assist in the creation of the benthic habitat maps included polygon shapefiles of the Hawai`i Island coastline, MLCD boundaries, and the aerial photographs. The ArcView Project file contained point themes of GPS locations of select DAR coral reef sampling sites as well as random points generated for field accuracy assessment. Depths recorded at each random point were added to the associated table for the accuracy assessment points. Hotlinks to each MLCD polygon provided Adobe PDF files with aerial photographs of each MLCD that denoted the boundaries and sub-zones of each protected area. Each MLCD also had hotlinks to a PDF document of the pertinent State of Hawai`i, Division of Aquatic Resources regulations, and a site description from the DAR website. In addition, Kealakekua Bay and Lapakahi MLCD had GPS locations linked to underwater video clips and summarized coral reef fish and benthic data.

DISCUSSION

Benthic Habitat Mapping

For coastal management, numerous issues could arise if managers make decisions and enforce rules based on a habitat map of unknown accuracy. Coral reefs are often comprised of a mosaic of habitat types, and the issue of accuracy is amplified when habitat types are very heterogeneous (Guisan and Zimmermann 2000). Considering all of the potential problems and issues that could arise from inaccurate maps, the accuracy

Table 2: Number of accuracy assessment points (AA) visited in the field by benthic habitat class for all Marine Life Conservation Districts.

Benthic habitat type	Habitat code	No. of AA
Uncolonized volcanic rock/boulder	UV	30
Colonized volcanic rock/boulder	CV	17
Scattered coral/rock in unconsolidated sediment	SC	16
Aggregated patch reef	PR	32
Sand	SA	18

Table 3: Accuracy assessment points summarized in an error matrix by habitat type. The user's (UA) and producer's accuracy (PA) is detailed for each habitat class and overall accuracy is provided.*

	SA	PR	SC	CV	UV	Total	UA
SA	15	0	0	1	1	17	88%
PR	0	30	0	4	2	36	83%
SC	3	0	16	0	0	19	84%
CV	0	1	0	12	1	14	86%
UV	0	1	0	0	26	27	96%
Total	18	32	16	17	30	113	
PA	83%	94%	100%	71%	87%	15%	99
						Overall	88%

* Habitat codes summarized in error matrix are as follows: SA=Sand, PR=Aggregated patch reef, SC=Scattered coral rock in unconsolidated sediment, CV=Colonized volcanic rock/boulder, UV=Uncolonized volcanic rock/boulder.

Table 4: Summary of ancillary GIS data sets and remote sensing products integrated into GIS database.

Data set	Geometry	Type	Source
GPS locations of accuracy assessment points	point	.shp file	project
Field notes from accuracy assessment	point	.shp file	project
GPS locations of coral reef sampling sites	point	.shp file	DAR
Summarized data from coral reef sampling	n/a	.pdf	UH/DAR
Hotlinked underwater video clip of	n/a	.avi file	DAR
MLCD boundary and subzones	polygon	.shp file	DBEDT
State of Hawai`i MLCD regulations	n/a	.pdf	DAR
State of Hawai`i MLCD site description	n/a	.pdf	DAR
State of Hawai`i MLCD site photograph	n/a	.pdf	DAR
Aerial photographs	n/a	.tif	NOAA
Benthic habitat maps (1:6,000)	polygon	.shp file	NOAA
Benthic habitat maps (1:2,000)	polygon	polygon	Project
Island of Hawai`i	polygon	.shp file	DBEDT

assessment of tropical coastal resource maps is somewhat rare (Mumby and Green 2000). When creating coral reef maps without field data for a reference, or using a preexisting habitat classification scheme, the classes used may not be suitable, resulting in the production of inaccurate maps (Mumby 2000). Without providing an accuracy assessment of a benthic habitat map, the value of the map to marine spatial planning and management actions may be uncertain.

Providing coastal managers with accurate benthic habitat maps can greatly contribute to best management practices (Monaco et al. 2001), with the appropriateness of maps produced for coastal applications being evaluated by the manager based on the accuracy statistics provided in the error matrix. The overall accuracy of the benthic habitat maps produced in this study was 88%, which is within the 85% suggested accuracy range acceptable for confident use for management purposes. The overall accuracy of the habitat maps produced was within this range and therefore may be used with a degree of certainty. However, the accuracy necessary for a benthic habitat map is dependent on the specific use for the map. This is an important point, and it should again be emphasized that managers must take into consideration the acceptability of the user's, producer's and overall accuracy of the maps before using these map products. For instance, a manager may need a different level of map accuracy for planning a stratified sampling design in comparison to calculating the area of coral habitat within a marine protected area.

The user's accuracy for the habitat classes evaluated in this study ranged from 83-96%. The user's accuracy can provide a relevant measure of accuracy for management applications for a specific habitat class (Mumby and Green 2000). If a manager was interested in obtaining an approximate area of seagrass bed habitat in an MPA, a benthic habitat map could be used to calculate this area. By also incorporating the user's accuracy value for the seagrass habitat class, the manager could also get a general idea of the error associated with that particular habitat class.

Geoinformation Technology for Marine Spatial Management

The products derived from geospatial technologies support informed decision making with respect to marine spatial planning and management. In this study, GIS was utilized to archive these benthic habitat maps derived from remotely sensed imagery and store pertinent value-added ecological and human dimension information. The benthic habitat maps and a dynamic GIS can provide a robust analytical tool and source of spatially referenced information. This spatial (GIS) database can provide resource managers and coastal planners in Hawai`i with comprehensive information about an MPA that has traditionally been difficult to access, because such information can be located in many different agencies and institutions.

Marine Spatial Management Applications for Benthic Habitat Maps

The integration of benthic habitat maps and geospatial information can provide scientists and managers with a valuable tool to support coastal management actions. For example, Franklin et al. (2002) produced benthic habitat maps in the Tortugas region of the Caribbean, and these maps products were applied to assist in the characterization of essential fish habitat and also used to formulate recommendations for the citing of three new MPAs in the region. In addition, Christensen et al. (2003) utilized the NOAA benthic habitat maps created for Puerto Rico to plan a stratified random sampling design. This sampling design accounted for variation in fish abundance that was influenced by the benthic substrate present at the site, and allowed for broad-scale patterns in fish assemblage structure to be analyzed at geographic scales commensurate with management decisions. Similarly, Friedlander et al. (2002) also used benthic habitat maps to guide sampling design, but further extended the use of these habitat maps by incorporating them into discussions with local fisherman to gain traditional ecological knowledge of the study site. At the end of this study, benthic habitat map products were integrated with the biological and sociological information to assist with evaluating the efficacy of the current Seaflower Biosphere Reserve and guide the planning of future protected areas in the region (Appeldorn et al. 2003; Friedlander et al. 2003b).

CONCLUSIONS

The first objective was to develop benthic habitat maps at a scale relevant to local marine management efforts in Hawai`i. We sought to improve the resolution of existing habitat maps created during a regional mapping effort in Hawai`i. Our results complement the existing maps and provide more detailed, fine-scale habitat maps for select Hawai`i MPAs. The map products derived from this study will allow local managers to extract information at a scale relevant to local marine management efforts in Hawai`i. Moreover, the integration of benthic habitat maps with geospatial information will provide a better understanding of coral reef ecosystems and a solid foundation for spatial management in the study area. It is anticipated that the benthic habitat maps and GIS project database created by this study will continue to assist in local level of management of coral reefs in West Hawai`i.

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