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A Benthic Terrain Classification Scheme for American Samoa

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Coral reef ecosystems, the most varied on earth, continually face destruction from anthropogenic and natural threats. The U.S. Coral Reef Task Force seeks to characterize and map priority coral reef ecosystems in the U.S./Trust Territories by 2009. Building upon NOAA Biogeography shallow-water classifications based on Ikonos imagery, presented here are new methods, based on acoustic data, for classifying benthic terrain below 30 m, around Tutuila, American Samoa. The result is a new classification scheme

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for American Samoa that extends and improves the NOAA Biogeography scheme, which, although developed for Pacific island nations and territories, is only applicable to a maximum depth of 30 m, due to the limitations of satellite imagery. The scheme may be suitable for developing habitat maps pinpointing high biodiversity around coral reefs throughout the western Pacific.

Keywords terrain analysis, bathymetry, benthic habitat, marine GIS, American Samoa, corals

The high productivity of coral reef ecosystems demands a quantifiable analysis of the complexity and diversity present there. Many people depend on the resources and services that coral reef ecosystems provide, and the direct connection with adjacent coastal ecosystems is important to increasing coastal populations (Culliton 1998). Natural and anthropogenic processes threaten natural and cultural resources in these areas in the form of storms, global warming, sea water level rise, disease, over-fishing, ship grounding, sediment runoff, trade in coral and live reef species, marine debris, invasive species, security training activities, offshore oil and gas exploration, and coral bleaching (Miller and Crosby 1998; Evans et al. 2002). Although corals can recover from natural disasters, their ecosystems may not bounce back in the face of destructive anthropogenic threats (Miller and Crosby 1998; Weier 2001; Green et al. 1999).

The U.S. Coral Reef Task Force (CRTF) was established by NOAA in June 1998 as an overseer of coral reef protection. The CRTF Mapping and Information Working Group has a goal to characterize and map all priority shallow water (<30 m) coral reefs and deep water (>30 m) coral reef systems in the U.S. and Trust Territories by 2009 (Evans et al. 2002). Until 2001, U.S. coral reefs were not mapped at a resolution useful enough for assessing and managing resources (i.e., multibeam bathymetry at 5-m horizontal resolution or lower and extensive underwater video and photography along transects). The work described here is a first step in meeting that objective for coral reef systems around the island of Tutuila, American Samoa.

As growing populations flock to coastal homes, residents, resource managers, researchers, scientists and other professionals alike are becoming more aware of the importance of marine environments and their resources. To protect such environments there is a need for documenting baseline information about them on an ecosystem level, for long-term monitoring, and for estimating the geographic extent of critical habitats. With this in mind, the National Oceanic and Atmospheric Administration's (NOAA) Biogeography Program turned to the use of satellite imagery to delineate potential benthic habitats within coastal regions down to about 30 m (e.g., Monaco et al. 2005) using a habitat classification scheme that is coral centric. By using heads-up digitizing to analyze Ikonos imagery, airborne color aerial photography, and airborne hyperspectral imagery, researchers have successfully classified habitats in much of the shallow water regions around the coastal U.S. and Territories (i.e., Puerto Rico and the U.S. Virgin Islands, Northwest Hawaiian Islands, Monterey Bay, American Samoa, the Commonwealth of the Northern Mariana Islands, Guam) (Buja et al. 2002; Coyne et al. 2001, 2002a, 2002b; NCCOS 2005).

Scientists and researchers are extending their understanding to regions deeper than 30 m in order to protect and monitor coral reef ecosystems, some of the most varied on earth. To locate and study resources associated with particular terrains, it is necessary to map benthic terrain at a fine-scale. New data collection and mapping techniques are required to extend the shallow water classifications for potential habitats in deeper water, at this fine-scale. The methods and results presented here explain a way to classify benthic terrains in 30 to 150 m depths with a 1 to 2 m resolution. These terrains provide information, based on an integration of marine data into a geographic information system (GIS), which scientists may use to identify areas of high biodiversity and species' potential habitats. Use and furtherance of the GIS and the resulting benthic terrain classification may lead to more efficient management of marine protected areas, simpler decision making with the use of more detailed, extensive, and accurate science, advancements in marine and coastal research, and improvements on georeferenced marine mapping (e.g., Wright and Bartlett 2000; Valavanis 2002). In this case, layers (i.e., multibeam bathymetry, slope, bathymetric position index (at multiple scales), and rugosity) were combined in a GIS and assessed with unique algorithms to produce classification maps.

A significant ongoing goal in seafloor exploration is to define a common classification scheme that all characterization studies can use effectively and efficiently. The development of a common classification scheme would make sharing results and data easier. However, in this effort there is an understanding among researchers, scientists, and managers that the use of a single, common classification scheme applicable to all environments is not a reality yet. The seafloor mapping community is striving for such a scheme at regional and local levels (http://www.ngu.no/geohab, Marine Geological and Biological Habitat Mapping Network). The contribution of this study is that it presents such a scheme specifically for American Samoa, at depths of 30–150 m. This extends and improves the NOAA Biogeography scheme, which, although developed for Pacific island nations and territories, is only applicable to a maximum depth of 30 m, due to the limitations of satellite imagery.

Review of Seafloor Classification Approaches: Multibeam and Visual Data

Most benthic terrain classification studies have relied primarily on analysis and interpretation of multibeam bathymetry. They also had access to some kind of visually-observed survey data (e.g., transect video, still photos, grab samples, etc.) to make qualitative and/or quantitative inferences. Multibeam backscatter (i.e., the intensity of the acoustic returns) has been used as well but is a separate issue, not discussed here, due to the greater complexities in processing acoustic strength versus travel time, and of interpreting seafloor sediment types and inhomogeneities in subbottom layers (as explained in Zhou and Chen 2005).

Greene et al. (1999) developed a successful classification scheme for fish habitats offshore of Central California. It was recently updated in Greene et al. 2005 and describes broad classes such as megahabitats (based on depth and general physiographic boundaries), meso/macrohabitats (based on scale), seafloor slope, seafloor complexity, and geologic units. The scheme continues with more detailed habitat characteristics interpreted from video, still photos or direct observation via SCUBA. They are macro/microhabitats (based on observed small-scale seafloor features), seafloor slope (estimated from in situ surveys), and seafloor complexity (estimated rugosity).

Weiss (2001) made a unique classification scheme for understanding watershed metrics by using a topographic position and landform analysis. To form a topographic position index (TPI), he used algorithms that perform an analysis on each grid cell in an elevation model. Each grid cell is assigned a TPI value that indicates its position (higher than, lower than, or the same elevation) in the overall landscape. By combining TPI with slope position, Weiss (2001) found methods to apply a landform classification scheme to watersheds around Mt. Hood, Oregon, USA, and the west slope of the Oregon Cascades. The scheme includes 10 landform classes: canyons, deeply incised streams; midslope drainages, shallow valleys; upland drainages, headwaters; U-shape valleys; plains; open slopes; upper slopes, mesas; local ridges/hills in valleys, midslope ridges, small hills in plains; mountain tops, high ridges. Weiss (2001) considered two scales of landforms in order to incorporate structures found within broad landscapes. His techniques are well suited to benthic classifications that serve as a predictor for habitat suitability and biodiversity (Guisan et al. 1999).

Iampietro and Kvitek (2002) derived descriptive grids from multibeam bathymetry to quantify seafloor habitats for the nearshore environment of the entire Monterey peninsula in central California, USA, with GIS. They followed Weiss's (2001) methods to develop TPI grids that, at a fine-scale, can describe micro- and macroscale habitats while, at a broad-scale, can describe meso- and megascale habitats. Another derivative of bathymetry that they applied was rugosity. Rugosity is a measure of roughness or bumpiness (classified as high, medium, and low) that is quantified with a ratio of surface area to planar area.

Coops et al. (1998) further developed and tested procedures to predict topographic position from digital elevation models for species mapping. In this study, topographic position is a "loosely defined variable" that attempts to describe topography with spatial relationships. Quantitative assessments of such terrains are rarely reported. Topographic position can help researchers understand how patterns, processes, and species are spatially related. While qualitative analyses can describe processes on slopes at different scales, a quantitative assessment determines primary units within the context of a process. Depending on the scale of the landscape in interest, more or fewer divisions of topographic position may be quantified. This overview describes a landscape classification scheme by Speight (1990). Speight (1990) defined morphology types with eleven different classes: crests, depressions (open and closed), flats, slopes (upper, mid, lower and simple), ridges, and hillocks. The topographic position analysis in this study incorporates local relief, elevation percentile, plan and profile curvature, slope, and variance threshold. After defining crests, depressions, flats and slopes, the study goes further to define the more detailed classes. Unfortunately, the study does not attempt to subdivide the depressions into open and closed though the classification scheme recognizes the need for the distinction. Also, because of their fine scale complexity, hillocks and ridges were not quantified (Coops et al. 1998).

Some historical studies have taken approaches to relate topographic features with populations of particular species. Schmal et al. (2003) used multibeam bathymetric maps to guide submersibles that allowed the researchers to identify detailed biotopes and species within geomorphic zones (e.g., coral species zones within midshelf banks <36 m depth, or within banks <50 m depth, or on the soft bottom). The bathymetry served as an effective base layer in a GIS to use for their investigation. Another study that effectively related species to their habitat locations used side scan sonar mosaics to find the relationship between population abundance and the benthoscape (undersea landscapes; Zajac et al. 2003). With the use of backscatter imagery, they classified large scale benthoscapes such as muddy sands, fine sands and muds, boulder, cobble and outcrop, sand wave fields, and mixed. They paid close attention to transitions between benthoscapes where infaunal populations were readily identified at a finer scale.

The approach taken in the current study takes into consideration the many applications of many types of data that are used for benthic habitat mapping (e.g., Hall et al. 1999). Most often there is a need for a baseline of information. Usually, the baseline, or framework, used for a habitat study is a basic data set that describes the surficial characteristics of the seafloor in some useful fashion (Dartnell and Gardner 2004). Then, based on what the seafloor looks like, a biologist, geologist, ecologist, geophysicist, or other interested party will supplement that framework with specific data sets. A biologist may add a layer of information about amount of relief or the thickness of sediments. A geologist may add data revealing sediment size or rock type. Depending on the interest of the research, different layers of information are needed. Therefore, a method has been developed here that results in separate data sets that may be combined at different scales and in different combinations to serve as a baseline of information for researchers, scientists, and managers. But as explained in the next section, we combine this with the satellite based approach NOAA Biogeography, considering and extending their classifications into a new classification scheme for Pacific island deepwater habitats.

Existing NOAA Biogeography Approach: Satellite Imagery

NOAA's Biogeography Program developed a classification scheme for benthic habitats throughout the Pacific Islands (Coyne et al. 2002b), based on high-resolution Ikonos satellite imagery, in order to meet the needs of resource managers and scientists. This extends the approaches described in the previous section because with the synoptic coverage of satellite imagery, it allows greater areas of the seafloor to be classified. The drawback here, of course, is that it is only good to 30 m in clear waters. A hierarchical classification was chosen to define and delineate habitats and was influenced by management requests, the existing classification schemes, past knowledge of mapping coral reefs, the minimum mapping unit, quantitative data, and limitations of the imagery (Coyne et al. 2002b). Their hierarchical scheme uses two categories of classes (zones and habitats) thereby allowing the user to expand and collapse the scheme. Zones describe a benthic community's location. Habitats, which occur within zones, are based on geomorphologic structure and biological cover type. The structure and cover component are then further divided into major and detailed levels resulting in a GIS polygon habitat map product with each polygon populated with one zone and four habitat attributes. The structural component of the maps is divided into four major and seventeen detailed designations. The biological cover component is divided into nine major designations with each subdivided into four density classes. Classes that were determined to be undetectable from the imagery were not included in the scheme. This approach was first developed by the Caribbean Fishery Management Council (Coyne et al. 2002b; Christensen et al. 2003) and subsequently refined for use in Hawaii and the U.S. Pacific Territories.

In these maps, polygon boundaries are visually interpreted and manually delineated on computer screen based of the color, texture, and relative location of the feature in the remotely sensed imagery. Extensive field observations are conducted to determine habitat types in areas where uncertainty existed in the visual interpretation of the imagery, where gradients exist through habitat types or where habitat diversity is highly heterogeneous.

Field surveys were also conducted to acquire ground truth needed to establish a statistically robust assessment of the thematic accuracy of these products (Congalton 1991; Rosenfield et al. 1982; Cohen 1960; Ma and Redmond 1995; Hudson and Ramm 1987). This statistical treatment generates overall accuracy, Kappa and Tau statistics, as well as user and producer accuracy of the thematic content of the map products at both the major and detailed level of the classification scheme. Accuracy of the zone attribute was not tested. Ikonos satellite imagery was used to generate all of these map products for the coral reefs of American Samoa. The overall thematic accuracy was greater the 85% (Kappa and Tau >0.85) at the major level of the classification scheme and greater than 75% (Kappa and Tau >0.75) for the detailed level of the classification scheme, but again, only for a maximum depth of 30 m.

The classification scheme introduced in this article bridges the multibeam approaches of the previous section with the satellite-based approach of NOAA Biogeography. Using those earlier approaches, we effectively take the NOAA scheme into deeper water. A primary objective of the current study was to extend this existing classification below 30 m, the reach of what is viewable and classifiable in Ikonos imagery.

Study Site and its Threats

American Samoa, a small, remote territory in the heart of the South Pacific, is the only U.S. territory south of the equator and consists of about 197 km^2 of land cover. It lies about 14^o south of the equator, about 4,700 km southwest of Honolulu, Hawaii (Figure 1). It neighbors the independent nation of (western) Samoa as the eastern portion of the Samoan archipelago. American Samoa's five volcanic islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two coral atolls (Rose and Swains) are surrounded by true tropical reefs, which are extremely rare in U.S. waters.

The coral reef ecosystems around American Samoa are being threatened by natural and adverse anthropogenic patterns and processes (Evans et al. 2002). For example, coral bleaching events related to sea temperature rise have increased in the region, including a particularly destructive event in 1994 (FBNMS 2004). An infestation of crown-of-thorns starfish killed vast amounts of coral in the late 1970s owing to their habits of eating live coral (Craig 2002). In addition, coral around the South Pacific islands are threatened annually by tropical cyclones. American Samoa suffered from the effects of hurricane Ofa in 1990, hurricane Val in 1991, and most recently hurricane Heta in January 2004 (Craig 2002; FBNMS 2004; FEMA 2004). Anthropogenic threats such as gill netting, spear fishing, poison and dynamite fishing, nonpoint pollution and cumulative impacts challenge and stunt coral reef recovery from natural disasters (ASG: DOC 2004).

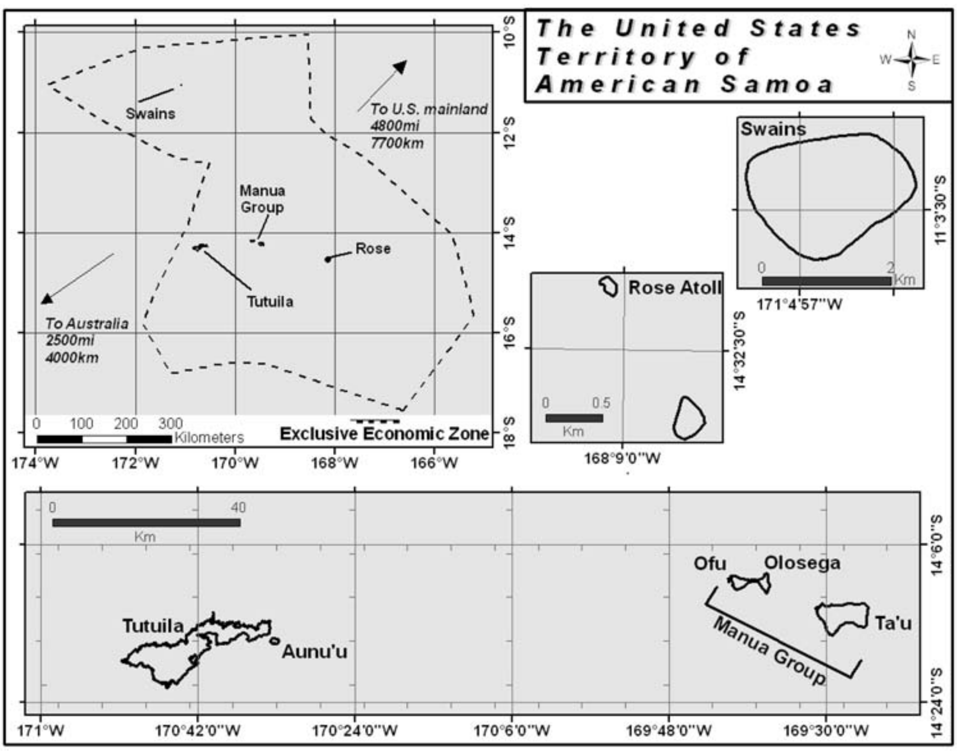

Figure 1. Location Map of American Samoa, a U.S. Territory that is home to priority coral reefs that are part of the National Action Plan to Conserve Coral Reefs. American Samoa is part of the Samoan archipelago and is comprised of five volcanic islands and two coral atolls.

Deep Water (30 m–200 m) Data Collection for This Study

Extensive data have been collected in American Samoa since 2001, including multibeam bathymetry, towed diver videos, accuracy assessment photography, field notes, and information from a rebreather dive (Wright 2002; Wright et al. 2002). Multibeam mapping systems allow surveyors to collect bathymetry by ensonifying massive areas of the seafloor with high accuracy (e.g., Blondel and Murton 1997; Mayer et al. 2000). Scores of acoustic beams form a swath that fans out up to several times the water depth. Multibeam mapping systems are set up on research vessels that navigate across the study area making real-time adjustments for sound velocity, heave, roll, pitch, and speed (3–12 knots) (e.g., Blondel and Murton 1997). Most modern multibeam mapping systems also collect backscatter data which are often useful for classifying seafloor bottom characteristics (e.g., sediments versus lava flows).

The first scientific surveys of depths beyond 30 m in coral reef ecosystems around American Samoa collected bathymetric data from 3 to 160 m depth in 2001 and 2002 with the University of South Florida's Kongsberg Simrad EM3000, 300 kHz, multibeam mapping system (Wright et al. 2002; Wright 2002). The 2001 survey collected bathymetry and backscatter for Fagatele Bay National Marine Sanctuary (FBNMS), part of the National Park, Pago Pago Harbor, the western portion of Taema Bank, and Faga'itua Bay (Figure 2). Sites surveyed in November 2002 are eastern Taema Bank, Coconut Point, Fagatele Bay, and Vatia Bay (Figure 2).

The NOAA Coral Reef Ecosystem Division (CRED), part of the Pacific Island Fisheries Science Center (PIFSC), conducted surveys in February/March 2002 and February/March 2004. CRED towed diver video (0–25 m), deeper (20–100 m) towed photographic and video data, and single beam/bottom classification data resulting from the 2002 surveys were used for this analysis. Extensive multibeam (bathymetry and

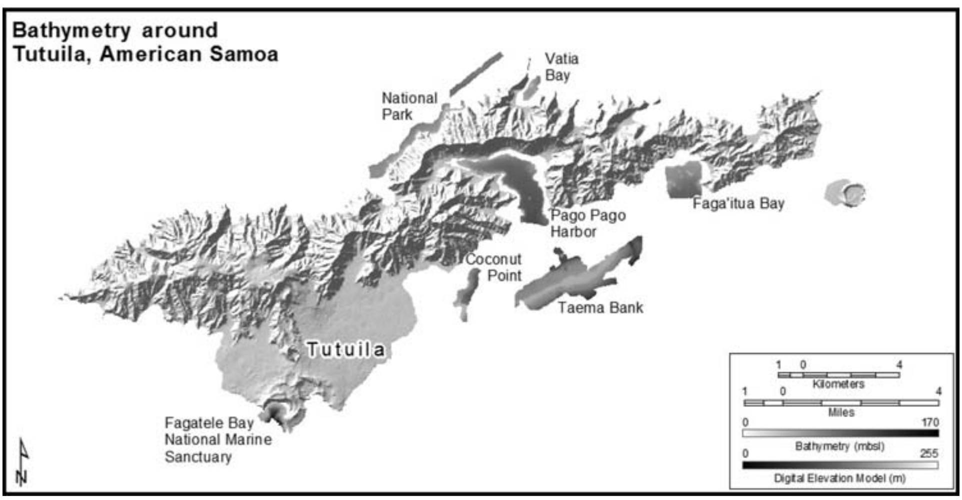

Figure 2. Location of high-resolution multibeam bathymetry surveys around Tutuila, American Samoa (1-m horizontal spatial resolution and ±1-m vertical accuracy for all areas except for the National Park where data were collected at 2-m resolution with a vertical accuracy of ∼±5 m). Projection: Geographic, WGS84. Bathymetry was collected in April and May of 2001 and November of 2002 with the Kongsberg Simrad EM3000 (http://dusk.geo.orst.edu/djl/samoa).

backscatter) and video data were also collected in early 2004, but it was not possible to incorporate these data here. These multibeam bathymetric data are now available online at http://www.pifsc.noaa.gov/cred/hmapping.

Data Analysis and Processing

Bathymetry

The 300 kHz multibeam bathymetry data from the 2001 and November 2002 surveys were used for analysis, after postprocessing, as a 3-column XYZ ASCII file with positive depth values based on a mean low low water datum at full resolution of the Kongsberg Simrad EM3000 system. For Fagatele Bay, Coconut Point and Taema (Eastern), the XYZ bathymetry was gridded at 1m spacing in MB-System (Caress et al. 1996). MB-System outputs grids in the format of Generic Mapping Tools (GMT) for a UNIX environment. GMT is a public suite of tools used to manipulate tabular, time-series, and gridded data sets, and to display these data in appropriate formats for data analysis (Wessel and Smith 1991). Then the GMT grids were converted to a format compatible with Arc/INFO® using a suite of tools called ArcGMT (Wright et al. 1998). For Taema Bank (Western), the XYZ data were gridded with Fledermaus and exported as an ArcView ASCII file, then converted to a grid with ArcToolbox. After importing the grids into the Arc/INFO® raster grid format, algorithms were run in ArcGIS™ to calculate derivatives.

Bathymetric Derivatives: Bathymetric Position Index, Slope

First, positive depth values were converted to negative. Slope, or the measure of steepness first-order derivative, was simply derived using the ArcGIS™ spatial analyst extension's surface analysis. Output slope values (raster grids) are derived for each cell as the maximum rate of change from the cell to its neighbor.

Bathymetric Position Index (BPI) is a second-order derivative (as it is derived from the first derivative, slope) of bathymetry as modified from topographic position index as defined in Weiss (2001) and Iampietro and Kvitek (2002). BPI was derived as a measure of where a georeferenced location, with a defined elevation, is relative to the overall landscape. The derivation involves evaluating elevation differences between a focal point and the mean elevation of the surrounding cells within a user defined rectangle, annulus, or circle.

For example, where a user has an elevation grid that has 1 m resolution, he/she may choose to analyze the grid with an annulus. The annulus, having an inner radius of 2 units and an outer radius of 4 units, would be used to analyze spatially each grid cell in comparison to its neighboring cells that fall within that annulus (Figure 3).

BPI was calculated in the ArcGIS™ raster calculator using the focal mean calculation described above; the resulting grid values are converted to integers to minimize the storage size of the grid and to simplify symbolization (Algorithm 1).

Algorithm 1 creates a BPI grid using bathymetry and user defined radii:

scalefactor = outer radius in map units multiplied by bathymetric data resolution,
irad = inner radius of annulus in cells,
orad = outer radius of annulus in cells,
bathy = bathymetric grid, and
rad = radius (if using circle instead of annulus).

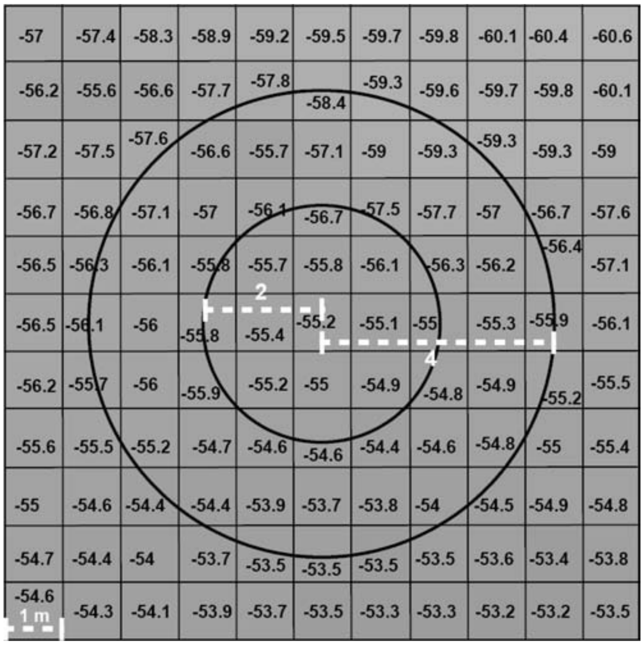

Figure 3. Example of the variables used to derive bathymetric position index (BPI) from bathymetry. The grid cells here (1 m resolution) represent bathymetry as negative values. The annulus has an outer radius of 4 and an inner radius of 2. Therefore the BPI scalefactor is 4 (outer radius multiplied by bathymetry resolution).

$$\mathrm{BPI}\langle scalefactor\rangle = \mathrm{int}((bathy - \mathrm{focalmean}(bathy, \mathrm{annulus}, irad, orad)) + 0.5)$$
or
$$\mathrm{BPI}\langle scalefactor\rangle = \mathrm{int}((bathy\text{—}\mathrm{focalmean}(bathy, \mathrm{circle}, rad)) + 0.5)$$

The cells in the output grid are assigned values within a range of positive and negative numbers (Figure 4). The 0.5 is added before the integer conversion and is meant to force floating point values, regardless of the sign of the value, to round up if the value has a decimal of greater than.5 and to round down if the value has a decimal of less than.5. The variable is not necessary if a user chooses to allow the floating point values to be rounded downward consistently for positive and negative values.

A negative value represents a cell that is lower than its neighboring cells (valleys). A positive value represents a cell that is higher than its neighboring cells (ridges). Larger numbers represent benthic features that differ greatly from surrounding areas (such as sharp peaks, pits or valleys). Flat areas or areas with a constant slope produce near-zero values.

In this example, the cells with a value of 1 are higher than those with the value of 0, and the values of 2 are higher than the others (Figure 5). The diagonally linear pattern of cells with the value of 1 starting from the top, left corner of the grid may represent a crest in the benthoscape. Furthermore, the grid cells with values of 2 along that pattern may be narrow crests on top of the larger crest. Also, notice that the other groups of BPI values of 1 may represent small mounts within the benthoscape. The values of 0 are all flat areas or constant slopes. Whether they are flats or slopes would be determined in another algorithm that considers slope along with BPI. This derivation is discussed in the development of classification scheme for American Samoa section. This example does not include negative

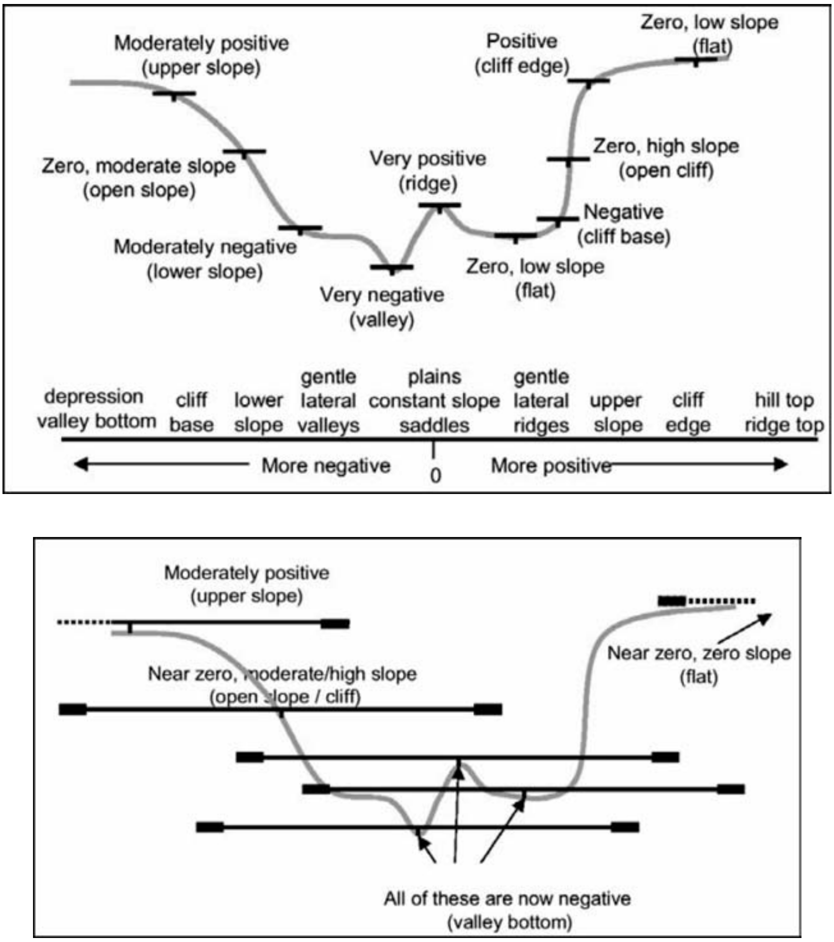

Figure 4. A description of the resulting bathymetric position index (BPI) values that are derived from bathymetry. These are based on a topographic position index by Weiss (2001). Top describes fine scale BPI values. Bottom describes broad scale BPI values. (Courtesy of Weiss 2001.)

BPI values. If negative values were present in this grid sample, they would represent patterns of depressions. The scalefactor of the resulting grid is 4, where scalefactor is the resolution multiplied by the outer radius.

The results of BPI are scale dependent; different scales identify fine or broad benthic features. To achieve the best BPI zone and structure classifications several large and small-scale grids were created for each study site. The fine scale grids were created with scalefactors of 10, 20, and 30, and the broad scale grids were created with scalefactors of 50, 70, 125, and 250. BPI⟨20⟩ and BPI⟨250⟩ were used to classify Fagatele Bay and Taema Bank. These scalefactors were chosen because, at these sites, the small seascape features (distance between relatively small ridges) are, on average, about 20 m across; the large seascape features (e.g., the distance across the deep channel on the west end of Taema Bank and the length of the peninsula in Fagatele Bay) are about 250 m across. This is based on close examination of the bathymetry prior to the BPI calculation, especially in the Fledermaus 3-D visualization system. For Coconut Point, features of interest were

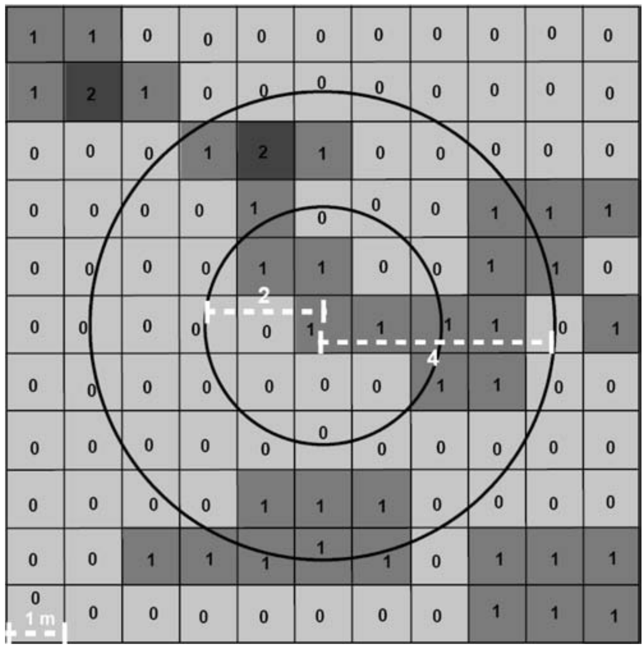

Figure 5. Example of the variables used to derive bathymetric position index (BPI) from bathymetry. The grid cells represent a derived BPI grid. Negative values are lower than their neighbors. Positive values are higher than their neighbors. Values of zero are flat areas or areas with constant slope.

identified from about 10 m to 70 m across, so BPI⟨10⟩ and BPI⟨70⟩ were used. See Tables 1 and 2 for the values used to derive BPI for each study site.

Prior to the classification of the final zones and structures, BPI was standardized. Conclusions about the structure of the overall seascape can be made with spatial analysis by applying an algorithm that combines standardized BPI grids of different scales with slope and bathymetry. In Arc/INFO® GRID, the final algorithms for classifying BPI zones and structures are based on combined broad scale and fine scale standardized BPI grids, slope, and depth.

Rugosity Analysis

The rugosity analysis resulted in descriptive maps that help identify areas with potentially high biodiversity. Rugosity describes topographic roughness with a surface area to planar

Table 1
Parameters used for calculating fine scale bathymetric position index grids

Study site	Resolution (meters)	circle, annulus, or rectangle	Radius	Fine scalefactor
Fagatele Bay	1	Circle	20	20
Coconut Point	1	Circle	10	10
Taema Bank 2002 (Eastern)	1	Circle	20	20
Taema Bank 2001 (Western)	1	Circle	20	20

Table 2
Parameters used for calculating broad scale bathymetric position index grids

Study site	Resolution (meters)	circle, annulus, or rectangle	Irad	Orad	Broad scalefactor
Fagatele Bay	3	Annulus	16	83	250
Coconut Point	1	Circle		70	70
Taema Bank 2002 (Eastern)	3	Annulus	16	83	250
Taema Bank 2001 (Western)	3	Annulus	16	83	250

area ratio. Rugosity was derived with the ArcView® Surface Area from Elevation Grids extension (Jenness 2003) using a 3×3 neighborhood analysis to calculate surface area based on a 3-D interpretation of cells' elevations. Rugosity values near one indicate flat, smooth locations; higher values indicate areas of high-relief. Rugosity calculated using this technique is highly correlated with slope. The highest rugosity values show a relationship with the high slope and lower rugosity with low slope. Rugosity classifications extend the classes used by CRED for habitat complexity in their 2002 towed-diver surveys. The classes were assigned with the following standard deviation divisions in ArcView® 3.3: Very High (>3 std. dev.), High (2–3 std. dev.), Medium High (1–2 std. dev.), Medium (0–1 std. dev.), Medium Low (Mean), Low (−1–0 std. dev.). Rugosity can be associated with attributes recorded during dives and with comments and attributes recorded in accuracy assessment surveys conducted in 2001 (Figure 6). From qualitative analysis, the derived rugosity grid and the towed-diver surveys are not directly related. However, from this type of comparison, divers may possibly standardize their observations among different divers in order to collect less subjective information about the environment.

Development of Classification Scheme for American Samoa

Since postprocessing of the 2001 and 2002 data was completed during the initial phase of this study, only these multibeam bathymetry data were used to classify the seafloor on the basis of bathymetric position index (BPI) and rugosity. The methods developed were based on the topographic position index algorithms of Guisan et al. (1999), Weiss (2001) and Iampietro and Kvitek (2002) and the rugosity algorithm of Jenness (2003) as applied in Iampietro and Kvitek (2002). Their application to American Samoa bathymetry is the first extension of existing shallow water benthic classification to depths beyond 30 m. (Figure 7).

Spatial analysis was used to derive, from the original bathymetry, indices of slope and multiple scales of BPI (i.e., BPI zones and structures). The resulting derivative grids were combined with a new algorithm to develop final products: BPI zones, BPI structures and rugosity classification maps for the study sites. The maps introduce the first deepwater benthic classification scheme for American Samoa that may also be extended to other coral reef systems. The mapping steps for the classifications, including the classification scheme, are summarized in the flowchart in Figure 8. The process identifies four BPI zones and 13 structure classes.

The algorithm that combines these data sets uses standard deviation units where 1 standard deviation is 100 grid value units; slope and depth values are defined by the user.

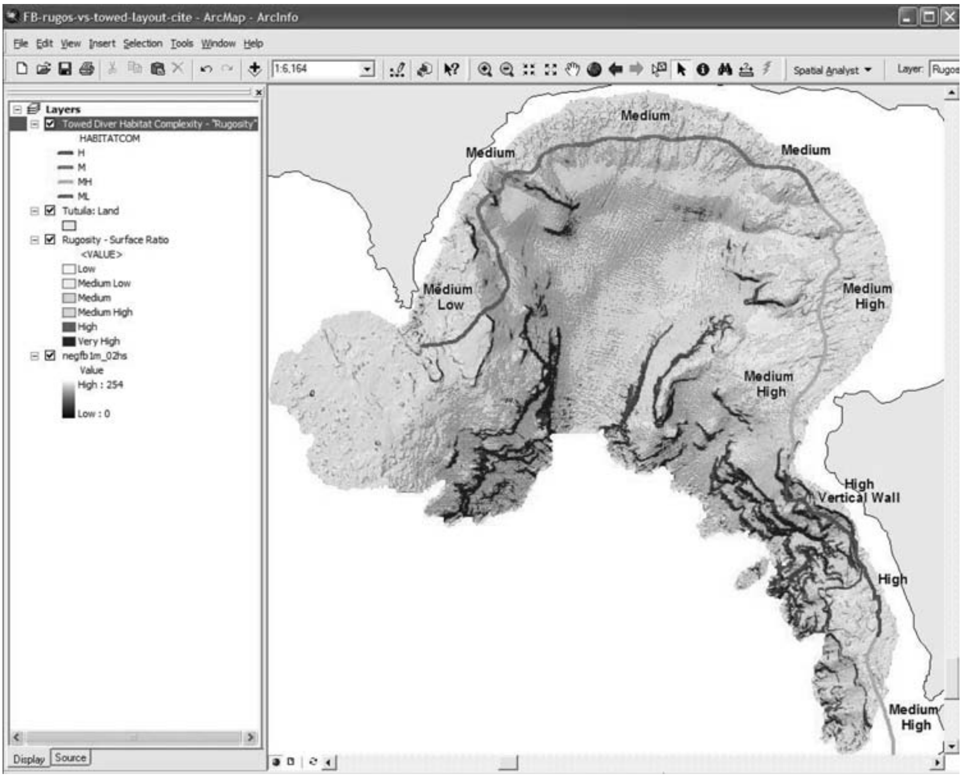

Figure 6. Rugosity derived in ArcView® 3.3 and towed-diver video transects symbolized by habitat complexity observations. Transects overlaid on rugosity grid shows the relationship between the two data sets.

The algorithms for BPI zones and structures use different combinations of the grids. The following is an example of how BPI zones were derived (Algorithm 2).

Algorithm 2 creates an output grid classified by BPI zones by combining the attributes of BPI and slope:

B-BPI = broad scale BPI grid,
out_zones = name of the output grid,
slope = the slope grid derived from bathymetry, and
gentle = the user defined slope value indicating a gentle slope.

If ($B\text{-}BPI >= 100$) $out\_zones = 1$,
else if ($B\text{-}BPI <= -100$) $out\_zones = 2$,
else if ($B\text{-}BPI > -100$ and $B\text{-}BPI < 100$ and $slope <= gentle$) $out\_zones = 3$,
else if ($B\text{-}BPI > -100$ and $B\text{-}BPI < 100$ and $slope > gentle$) $out\_zones = 4$.

The unique numbers assigned to classes in algorithm 2 are the following, as defined in the classification scheme for BPI zones: (1) Crests, (2) Depressions, (3) Flats, and (4) Slopes.

Structures were derived with a similar algorithm as that used for BPI zones, however both scales of BPI were considered in order to pinpoint finer features. Also, the variable of depth was added to identify different flat structures that may represent different habitats. The decision tree below shows the path of decisions that the algorithm uses to derive

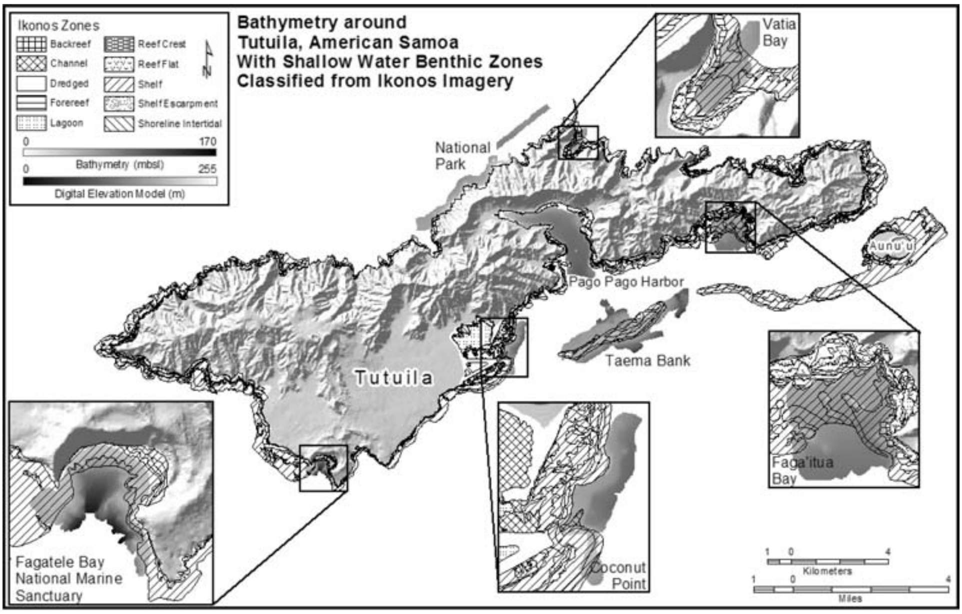

Figure 7. The amount of overlap that exists between NOAA Biogeography habitat classifications that were made using Ikonos imagery and the coverage of multibeam bathymetry as of 2002.

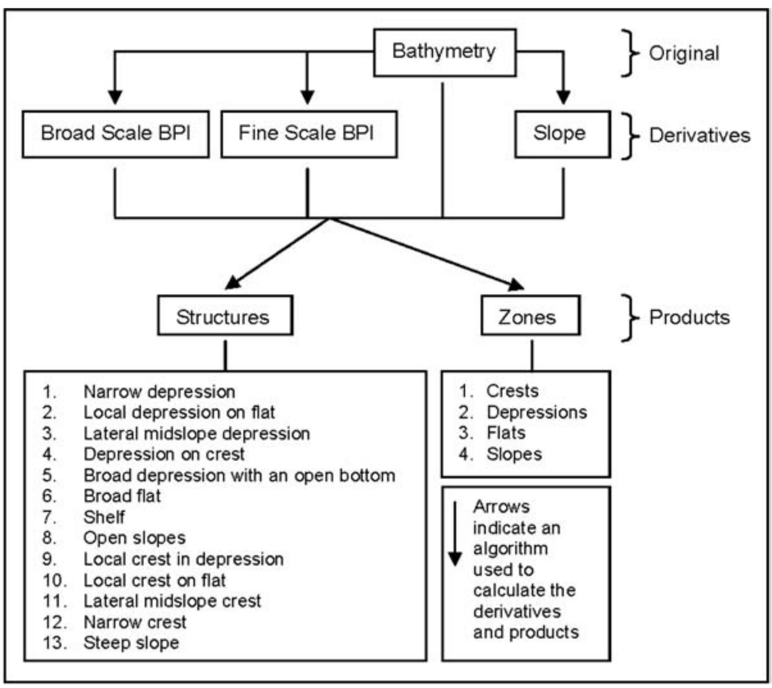

Figure 8. A flowchart showing the data sets used to derive BPI zones and structures.

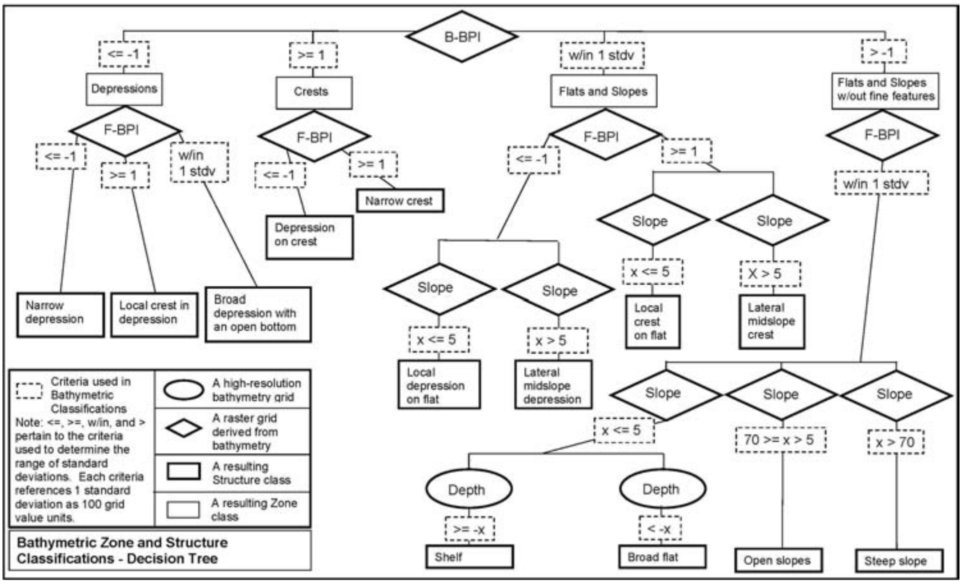

Figure 9. A flowchart of the decisions made by the algorithms that derive zone and structure classes from broad scale bathymetric position index (B-BPI), fine scale BPI (F-BPI), slope and depth.

structure classes (Figure 9). The algorithm assigns a unique number to each of the 13 structures. The unique numbers assigned to classes are the following, as defined in the classification scheme for structures: (1) Narrow depression, (2) Local depression on flat, (3) Lateral midslope depression, (4) Depression on crest, (5) Broad depression with an open bottom, (6) Broad flat, (7) Shelf, (8) Open slopes, (9) Local crest in depression, (10) Local crest on flat, (11) Lateral midslope crest, (12) Narrow crest, and (13) Steep slope.

Specific values for slope and depth are sensitive to interpretation at specific study sites. Each study site has a unique composition of depth and slope ranges. The methods are best applied where slope and depth values are considered on the condition of transition zone locations and the presence of two or more significant depth ranges within the study site. In order to develop a uniform classification for all the American Samoa study sites, common values that are suitable for sites around Tutuila were used in the classification algorithms. Gentle slopes were defined 5° and steep slopes were defined as 70°. A depth of −22 m was used to define the difference between shelves and broad flats. These slopes and depths were determined using 3-D visualization in Interactive Visualization System's Fledermaus software.

Multiple schemes were reviewed to aid in the development of classifications for the reefs of American Samoa (Coops et al. 1998; Dartnell and Gardner 2004; Greene et al. 1999; Iampietro and Kvitek 2002; Schmal et al. 2003; Speight 1990; Zajac et al. 2003; White et al. 2003; Greene et al. 2005). Weiss's (2001) landform scheme is also valuable as it classifies slope position and landform types as predictors of habitat suitability, community composition, and species distribution. In this study, similar landform classes are interpreted only to describe the seafloor and as a baseline for future habitat studies, given the availability of future data on species counts and distributions. The terminology used in the classification scheme (for zones) presented here is well-matched with the NOAA/NOS Biogeography

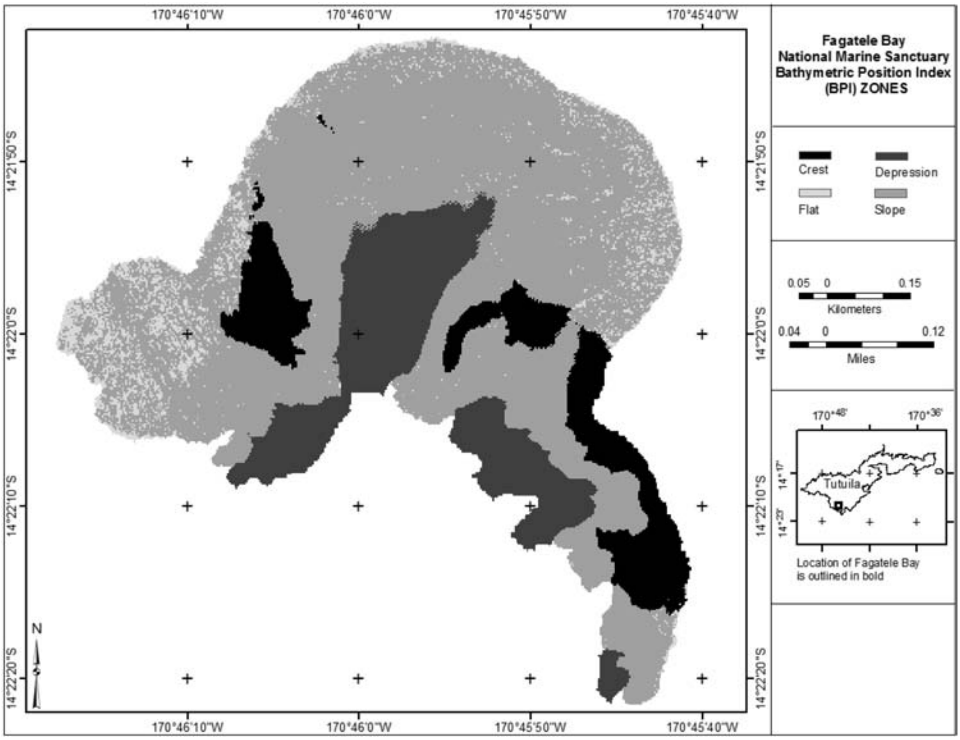

Figure 10. BPI Zones for Fagatele Bay National Marine Sanctuary.

Program's scheme for shallow water classifications (NWHI 2003). This biogeography scheme is being extended into deeper water by scientists at CRED are working primarily with multibeam and underwater video data (Rooney and Miller pers. comm. 2004) in 20–200 m water depths. The NOAA/NOS classification schemes, the Weiss (2001) landform scheme, and the Speight (1990) scheme, were closely analyzed to develop agreeable terms for the BPI zones and structures that extend below 30 m depth around American Samoa.

In this scheme, *broad* refers to seafloor characteristics defined by broad scale BPI grids and *fine* refers to seafloor characteristics defined by fine scale BPI grids. BPI has been described in more detail in the data analysis section.

Classification Scheme for BPI Zones

A surficial characteristic of the seafloor based on a BPI value range at a broad scale and on slope values.

1. Crests—High points in the terrain where there are positive bathymetric position index values greater than one standard deviation from the mean in the positive direction
2. Depressions—Low points in the terrain where there are negative bathymetric position index values greater than one standard deviation from the mean in the negative direction

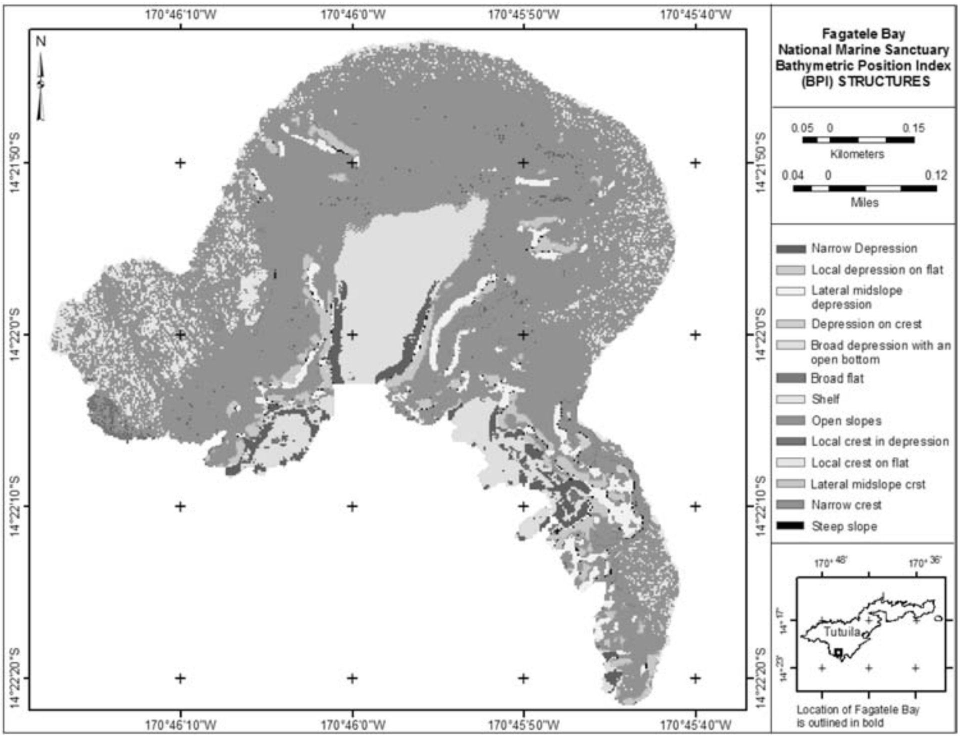

Figure 11. Structures for Fagatele Bay National Marine Fisheries.

3. Flats—Flat points in the terrain where there are near zero bathymetric position index values that are within one standard deviation of the mean. Flats have a slope that is $<=5^\circ$.
4. Slopes—Sloping points in the terrain where there are near zero bathymetric position index values that are within one standard deviation of the mean. Slopes have a slope that is $>5^\circ$. Slopes are otherwise called escarpments in the NOAA/NOS classification scheme.

Classification Scheme for Structures

A surficial characteristic of the seafloor based on a BPI value range at a combined fine scale and broad scale, on slope values and on depth.

1. Narrow depression—A depression where both fine and broad features within the terrain are lower than their surroundings.
2. Local depression on flat—A fine scale depression within a broader flat terrain.
3. Lateral midslope depression—fine scale depression that laterally incises a slope.
4. Depression on crest—A fine scale depression within a crested terrain.
5. Broad depression with an open bottom—A broad scale depression with a U-shape where any nested, fine scale features are flat or have constant slope.
6. Broad flat—A broad flat area where the terrain contains few, nested, fine scale features.

7. Shelf—A broad flat area where the terrain contains few, nested, fine scale features. A shelf is shallower than 22 m depth. (This depth value was decided on based on 3-D visualization and the NOAA/NOS classification scheme (NWHI 2003)). The NOAA/NOS scheme defines a shelf as ending between 20 and 30 m depth.
8. Open slopes—A constant slope where the slope values are between 5° and 70° and there are few, nested, fine scale features within the broader terrain.
9. Local crest in depression—A fine scale crest within a broader depressed terrain.
10. Local crest on flat—A fine scale crest within a broader flat terrain.
11. Lateral midslope crest—A fine scale crest that laterally divides a slope. This often looks like a ledge in the middle of a slope.
12. Narrow crest—A crest where both fine and broad features within the terrain are higher than their surroundings.
13. Steep slope—An open slope with a slope value greater than 70°.

Discussion

The classification developed in this study is the first for deepwater environments in American Samoa and should make a critical contribution to benthic habitat mapping in the Pacific. It gives a unique picture of coral reef environments on two different scales. The descriptive name of each class in the scheme provides users a way to recognize patterns of terrain based on zones and structures. The classification uses general terms that can apply to coral reef environments as seen by scientists with several different interests (e.g., biological habitats, coral disturbance after natural disasters, algae growth, and marine mammal distribution). By using general descriptions of the zones and structures based on the analytical procedures described in this article, researchers and scientists may view coral reef environments with the focus of most specialties. The classifications advantageously use several data sets to describe basic features of the coral reef environment. The basic descriptions, using standard language among other classifications schemes, allow the classifications to be used for qualitative analyses or for quantitative analyses. The quantitative nature would be accomplished from raster calculations to determine spatial statistics within and among the classes. One disadvantage to the classification is that the scheme does not incorporate shape of features. For instance, if a crest is linear it should be recognizable by sight as a linear ridge. However, the classification scheme will not indicate the difference between a group of crests that form a linear ridge and a group that forms a mound. The same challenge exists for classifying patterns of depressions (e.g., channels vs. holes).

The classification does not provide a complete description of benthic habitats, but adds to the resources that may be used in an integrated GIS. By using multibeam bathymetry and derivative data sets to describe the structures of the seafloor, researchers have a better idea of how to combine the data in a fashion that will answer important scientific questions. While the resulting data sets (BPI zones, structures, and rugosity) each provide a unique picture of the benthic environment, a combined analysis may reveal more, important information. Researchers at CRED are using the data sets in an integrated GIS in order to make products that may be used by working scientists and managers. The integration of marine data in GIS provides a means for advancing marine and coastal research, science and management, georeferenced mapping, modeling and decision making (e.g., Wright and Bartlett 2000; Valavanis 2002; Greene et al., 2005). The integration of the unique data sets in a GIS will allow researchers and scientists to query the data based on any combination of all of the available data sets. For example, a habitat for a particular fish may be indicated by depths between 30 and 45 meters, where many small crests and depressions are interlaced at a fine scale, having high rugosity. A user can query all the data sets at one time within the integrated GIS in order to create a new data set that includes only the habitats that meet those criteria. Also, a user may merge data sets for adjacent areas to make a regional analysis, or a user may choose to make a simple qualitative analysis of all the data sets in order to plan sampling locations for in situ data collection.

The data analyzed in a GIS are validated when combined with in situ data sets. Such groundtruthing (e.g., video collection, still photos, diver rugosity measurements) was collected in the shallow waters (<30 m) around Tutuila in February/March 2002 and 2004 and along the west coast of Saipan in the Commonwealth of the Northern Mariana Islands in December 2004. Currently, scientists at CRED are analyzing the in situ data in order to make a more informed accuracy assessment of the data sets derived in this study. The method and classification scheme were tested with the bathymetry from the Saipan anchorage area (Figure 12). Resulting BPI grids were made for zones and for structures using the classification scheme discussed in this article. The underwater videos were classified using a scheme developed for optical validations data around coral reef ecosystems in Pacific Island regions. The scheme does not match the one presented in this article, but the results are promising, as they qualitatively present an immediate association between the BPI structures and underwater video classifications. For example,

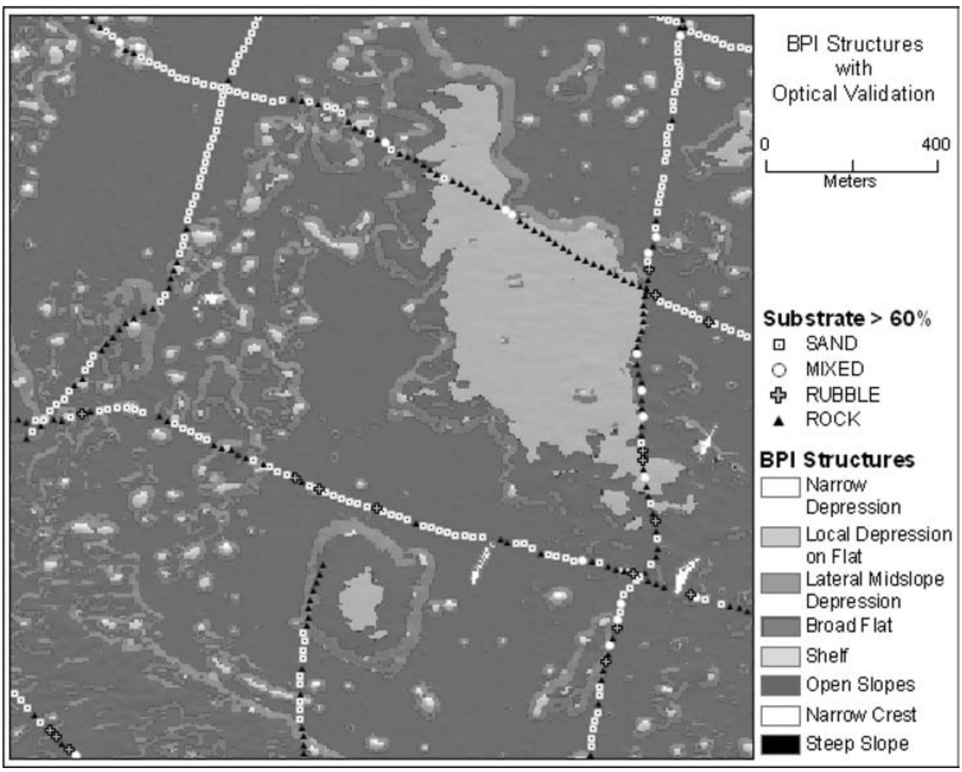

Figure 12. BPI Structures overlaid with optical validation. This is a sample from the Saipan anchorage data set that was surveyed by CRED in 2003 and 2004. The structures were derived from a bathymetric grid (5-m pixel size), and the optical validation represents interpretations of videos from a towed underwater video camera-sled. A qualitative assessment validates a pattern of associations between substrates and BPI structures.

where raised features outlined by open slopes (e.g., shelves) are characterized in the BPI structures the videos were classified as hard bottom (e.g., rock). Likewise, where broad flats are located the videos reveal unconsolidated (e.g., sand) substrate. The open slopes and other transitional areas (e.g., narrow crests and lateral midslope features) often correspond with mixed substrates or rubble. This analysis is continuing to find relationships between BPI zones/structures and percentages of living cover (e.g., Coralline Algae, Scleractinian Coral, Macroalgae), scale of relief (i.e., five categories ranging from less than 0.5 m–> 3.0 m), and number/size of cavities noted in the frame (e.g., few small and many large cavities, many small cavities). The analysis is evolving into a product that will validate interpolations of coral cover and substrate type across the region; it will eventually provide a prototype habitat map and methods that may be applied to other Pacific Island regions.

Additionally, during CRED's mission in early 2004, a complete backscatter data set was collected and is, as of August 2005, available for download at http://www.nmfs.hawaii.edu/cred/hmapping/hmap_data.php. The backscatter is an enormous asset to determining potential benthic habitats. By incorporating it in the GIS, patterns of the types and/or composition of substrate may be exposed within each zone, structure and rugosity class. Our scheme will be further validated by recent Pisces V submersible dives to Fagatele Bay and Taema Bank on Hawaii Undersea Research Lab cruise KOK0510, along with the accompanying statistical validation, July 2005 (Wright 2005; http://dusk.geo.orst.edu/djl/samoa/ hurl).

All of the analytical procedures used for the classifications in this study have been encapsulated into a convenient GIS desktop tool called the Benthic Terrain Modeler (BTM; Rinehart et al. 2004; http://www.csc.noaa.gov/products/btm). This ArcGIS 8. × / 9.× extension was jointly developed by researchers at Oregon State University and the NOAA Coastal Services Center. It should allow the user to replicate the procedures on the bathymetry used in this study (now permanently archived and publicly available at http://dusk.geo.orst.edu/djl/samoa), on CRED datasets, or on the user's own dataset. The BTM will allow users to apply the classification scheme used in this study for Tutuila on their own coral reef bathymetry. The user may use the default classification scheme, as described in this article, or may develop or insert other schemes in XML format (Rinehart et al. 2004). The benthic mapping methods may potentially be applied to other study sites around American Samoa and to coral reef ecosystems across the Pacific and in the Caribbean. The application of the methods to extend shallow water classifications will be fairly easy with the use of the BTM.

Conclusion

The study was a success in reaching its goals: (1) methods were developed for benthic mapping and applied to three sites around American Samoa, (2) a new classification scheme was developed introducing the concepts of BPI zones at a broad resolution (depressions, slopes, flats, crests) and structures (finer features within zones) around the study sites and supplemented by measures of rugosity, where complex features may be hosting high biodiversity; and (3) visual survey information was used as initial validation for the resulting classifications.

Bathymetry, BPI, slope, and rugosity were combined with spatial analysis to develop methods for creating a classification for deep water (>30 m) benthic zones and rugosity around American Samoa. The methods were based on components of studies that classified shallow water coral reef systems, terrestrial landforms, but also the satellite-based (Ikonos) classification of NOAA Biogeography for Pacific islands. From these shallow water classifications, only the zones, at a macro habitat level (Greene et al. 1999) were suitable for extension to deep water sites. The methods used for the deep water benthic zone and rugosity classifications around American Samoa extend the classifications for shallow waters around the territory.

As American Samoa is an archipelago of mostly submerged volcanoes, its shoreline is flanked by fringing reefs that plunge into deep water. This dramatic topography, combined with a tropical climate, creates a complex coral reef ecosystem that supports thousands of species. BPI zones, structures and rugosity provide a framework for planning scientific surveys that will give a better understanding of species-habitat relationships and possibly for establishing and monitoring marine protected areas. Future studies include the work of NOAA CRED in interpreting additional extensive towed video footage around Tutuila, as well as Saipan, to further validate our classification scheme and assess its utility to other islands beyond Samoa, and the analysis of Pisces V submersible dive videography just collected in July 2005 on Hawaii Undersea Reserch Lab cruise KOK0510. As the results become available, they will provide a tool for statistical analysis along video transects and for areas interpolated between them. The statistical results may help to define a more automated process for using bathymetric derivatives (e.g., BPI zones, structures, rugosity, texture) to create habitat classifications.

The classifications resulting from the methods in this study, when combined with associated marine life information, are tools for designing management programs for the Fagatele Bay National Marine Sanctuary, the National Park of American Samoa, and other marine reserves in the territory. They are a baseline of information for policy makers and managers to establish a wider and more effective network of marine protection throughout the Pacific contributing also to a national and global investigation of the world's marine and coastal environment.

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