Majuro Atoll, Republic of the Marshall Islands
Coral Reef Ecosystems Mapping Report

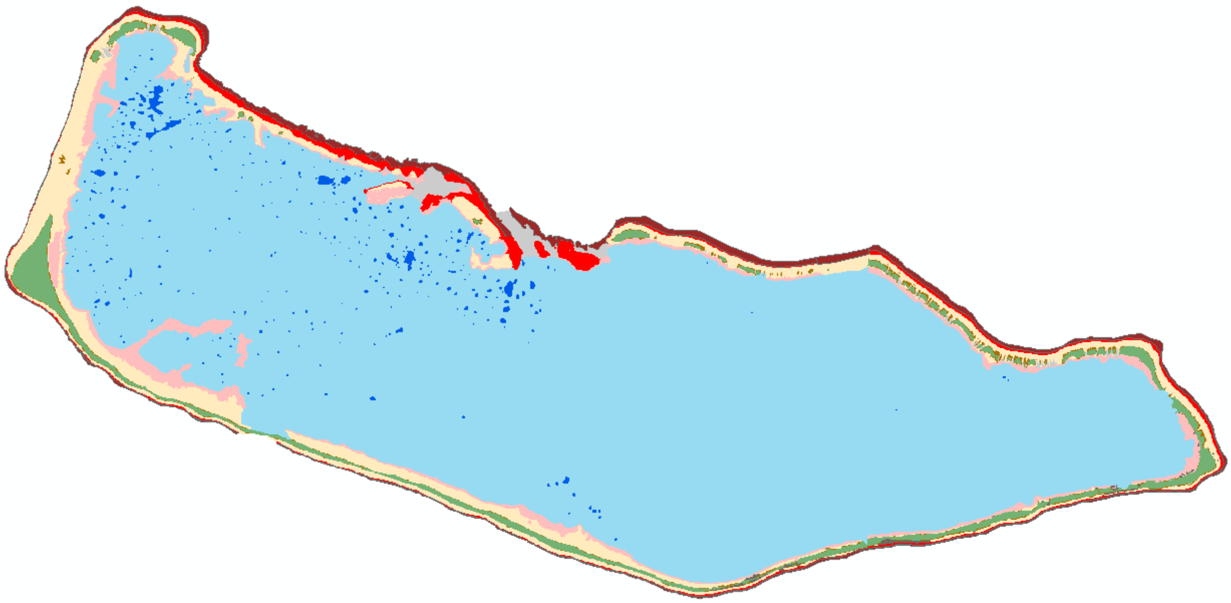

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TABLE OF CONTENTS

List of Tables

List of Figures

Abstract

Digital maps of the coral reef ecosystem (<~30m deep) of Majuro Atoll, Republic of the Marshall Islands, were created through visual interpretation of remote sensing imagery. Digital Globe's Quickbird II satellite images were acquired between 2004 and 2006 and georeferenced to within 1.6 m of their true positions. Reef ecosystem features were digitized directly into a GIS at a display scale of 1:4000 using a minimum feature size of 1000 m^2. Benthic features were categorized according to a classification scheme with attributes including zone (location, such as lagoon or forereef, etc.), structure (bottom type, such as sand or patch reef, etc.) and percent hard bottom. Ground validation of habitat features was conducted at 311 sites in 2009. Resulting maps consisted of 1829 features covering 366 km^2. Results demonstrate that reef zones occurred in a typical progression of narrow bands from offshore, though forereef, reef flat, shoreline, land, backreef, and lagoon habitats. Lagoon was the largest zone mapped and covered nearly 80% of the atoll, although much of it was too deep to have structures identified from the satellite imagery. Dominant habitat structures by area were pavement and aggregate reef, which covered 29% and 18% of the mapped structures, respectively. Based on the number of features, individual and aggregated patch reefs comprised over 40% of the features mapped. Products include GIS based maps, field videos and pictures, satellite imagery, PDF atlas, and this summary report. Maps and associated data can be used to support science and management activities on Majuro reef ecosystems including inventory, monitoring, conservation, and sustainable development applications.

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1. Introduction

1.1 Mapping coral reef ecosystems under the US Coral Reef Task Force

The United States Coral Reef Task Force (USCRTF) was established in 1998 by Presidential Executive Order 13089 to lead efforts to preserve and protect coral reef ecosystems in the United States, U.S. Territories, and associated States. The USCRTF has noted that current, accurate, and consistent maps of coral reef ecosystems are essential for preservation and management. With comprehensive maps and habitat assessments, coral reef managers can be more effective in designing and implementing a variety of conservation measures, including:

- Long-term monitoring programs with accurate baselines from which to track changes;
- Sustainable development of the coastal zone and place-based conservation measures, such as marine protected areas (MPAs); and
- Targeted research to better understand the oceanographic and ecological processes affecting coral reef ecosystem health.

The objective of the Majuro, Republic of the Marshall Islands, mapping project was to generate a benthic habitat map of the shallow water reef ecosystems of the Atoll (Figure 1). Standard benthic habitat mapping techniques (see section 2.5) were used to generate a benthic habitat map of its shallow-water (~0-30 m deep) coral reef ecosystems.

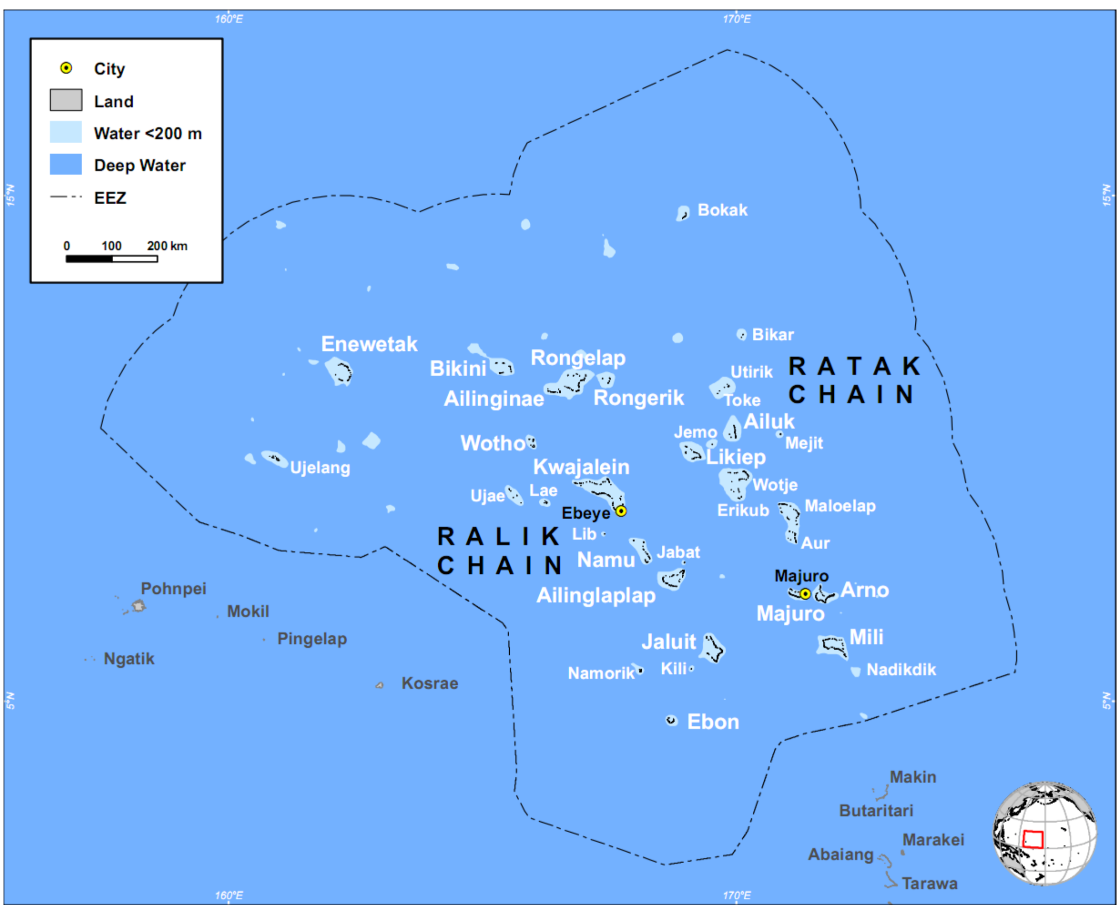

Figure 1. Location of the Marshall Islands and Majuro Atoll. Map Source: K. Buja, in Beger et al. 2008.

1.2 Background, geology, and marine habitats of Majuro Atoll

The Republic of the Marshall Islands consists of 2 island chains and 29 coral atolls totalling more than 1200 islands and islets (Beger et al. 2008)(Figure 1). Part of Micronesia, the islands are located near the equator in the Pacific Ocean roughly halfway between the State of Hawaii and Australia. The islands today are the gradual products of volcanic eruption, subsidence, and coral reef formation over many millions of years. The islands first emerged ~70 million years ago from volcanic hotspots south of the equator. As the Pacific Plate moved off the hotspots to the northwest, the tall volcanic islands began to sink under their own weight. At the same time, corals and other reef building organisms began to colonize and grow around the shallow island coast. Over the millenia, the islands completed their gradual sink as the corals continued their growth upwards in the shallows, gradually forming circular or irregularly shaped lagoons surrounded by reefs and eventually small islands of accumulated coral sands.

Majuro Atoll, the focus of this assessment, is located at 7°7′N 171°11′E. The oblong atoll is approximately 12 km across north to south, 40 km long east to west, and has a perimeter length of ~100 km. Tides are semi-diurnal with a spring range of 1.6 m. It is the capital of the Marshall Islands and is home to nearly half the population of the country (30,000 at Majuro Atoll). Despite relatively greater development compared to other atolls nearby, Majuro still has many relatively pristine reef areas, especially along the northern and western quadrants. Evidence of human impacts to reef ecosystems that are visible in satellite imagery are mostly along the eastern and southeastern quadrants where development is greatest. These impacts include mining the reef flat for construction material, dredging for anchorages, building of seawalls and piers, and several filled in areas. Key natural disturbances are storms, crown-of-thorns starfish and coral bleaching.

1. Methods

2.1 Overview of Map Production

NOAA's Biogeography Branch has been mapping coral reef ecosystems throughout US States and Territories in the Pacific, Atlantic, and Caribbean regions since 1999 at a variety of island types and geological settings. The program has used a suite of broadly consistent mapping techniques that have evolved to take advantage of technological improvements, such as improved satellite data sources, and can be customized to meet the varying needs of regional projects with different financial support. Typical steps in these mapping projects that can be utilized depending on project scope include:

- Acquisition of remote sensing imagery
- Development of a classification scheme
- Selection of mapping parameters
- Draft feature delineation
- Selection of field validation sites
- Field validation
- Final feature delineation*
- QAQC of final map products and metadata

*Many map projects are assessed for thematic accuracy following this stage. Due to limited funds and limited local field support, it was not possible to conduct an accuracy assessment at Majuro.

2.2 Remote sensing imagery

Benthic habitats were visually interpreted from Digital Globe's Quickbird II (QB2) commercial satellite imagery collected between 2004 and 2006. The satellite collects a four-channel multispectral image (blue, green, red, and near infra-red colors) at 2.44 m spatial resolution as well as a panchromatic image (black and white) at 0.61 m resolution. NOAA fused these images to create "pansharpened" scenes for mapping that have the high spatial resolution of the panchromatic image and the colors of the multispectral image. Three partially overlapping scenes covered the atoll (Figure 2). Where overlapping imagery occurred, the most recent scene with clear views of the seafloor was used.

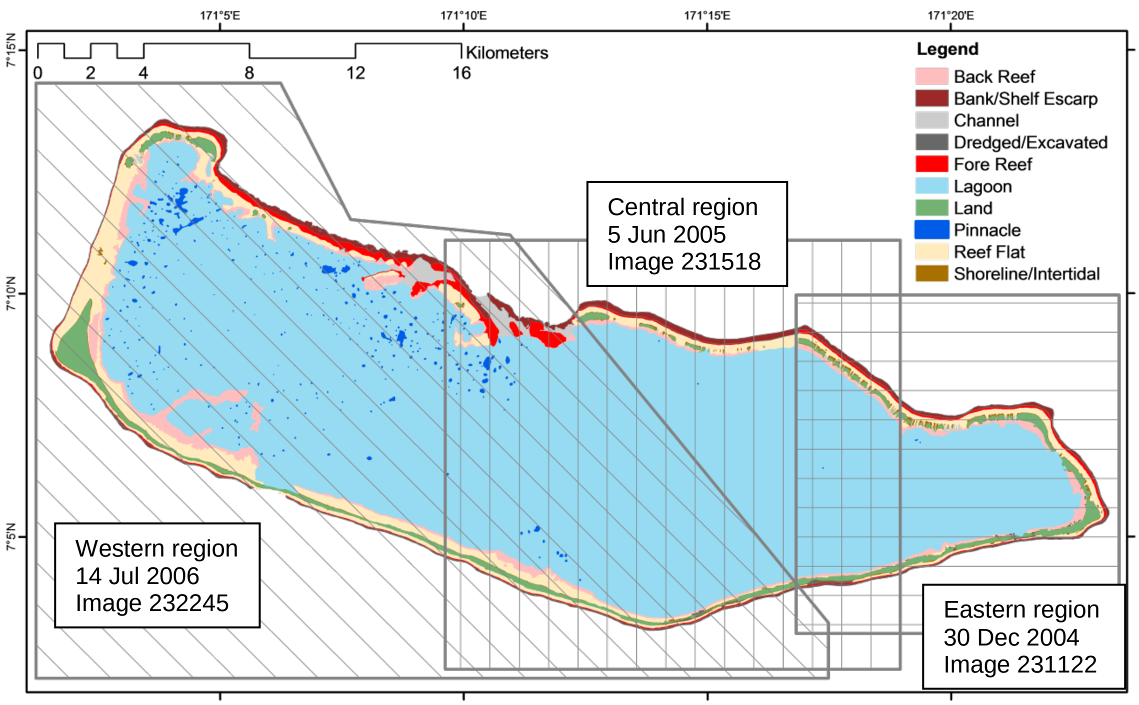

Figure 2. Footprints and acquisition dates of the three QB2 scenes overlaid on zone map of Majuro

Satellite data was orthorectified by NOAA to improve its positional accuracy. Survey-grade GPS measurements were taken at 21 features around the atoll that were visible in the satellite images. Using the field positions, in addition to satellite orientation data provided by Digital Globe, each satellite scene was positioned to +/- 1.6 m (CEP 95) of its true position.

2.3 Benthic Habitat Classification Scheme

Benthic maps are created by drawing boundaries between different bottom types that are visible in remote sensing imagery on a computer monitor using a mouse or digitizing pad, a process known as "on-screen" digitizing. Bottom types are described using a habitat classification scheme. Classification schemes for use in a variety of coral reef ecosystems and mapping approaches have been developed by the NOAA Biogeography Branch in consultation with many Federal, State and local partners (e.g. Kendall et al. 2001, Battista et al. 2007, Zitello et al. 2009, and Kendall and Poti (Eds) 2011). A scheme was customized for use at Majuro to capture local reef formations and was also simplified, compared to other schemes, to meet the constraints of the limited field work that was possible with this project.

Several considerations informed development of the classification scheme. Habitat classes must be visible and interpretable from remote sensing imagery. Adequate field validation must be conducted to ground-truth habitats as they appear in remote sensing imagery. Classes must be mutually exclusive and contained in a boundary no smaller than the minimum mapping unit (described in Section 2.4). Schemes that have been developed by the NOAA Biogeography Branch have included up to 5 attributes:

- Zone: Refers to each benthic feature's location in relation to the shoreline and the shelf edge and does not address substrate or cover types found within it.
- Geomorphologic Structure: Refers to predominant physical composition of the feature and does not address location.
- Biological Cover: Refers to what is colonizing benthic features. (Not used at Majuro)
- Coral Cover: Refers to percent cover of both hard and soft corals within four broad intervals. (Not used at Majuro)
- Percent Hardbottom: Refers to the proportion of a feature occupied by hard substrate.

Three attributes were used in this mapping project, including zone, geomorphological structure, and percent hard bottom. Biological cover and coral cover were not mapped for two reasons. First, accurately mapping cover is only possible by visiting a large number of field sites. Despite plans for local boat support, mechanical issues prevented completion of the full scope of scheduled surveys. The limited field surveys that were conducted for this project, however, revealed several areas with identical signatures in the remote sensing imagery, with identical zone and structure attributes, that differed markedly in dominant cover. Cover for patch reefs on pinnacles was notably variable as was cover on pavement (Images 1 - 2). These differences can only be discerned and mapped for the whole atoll with a much larger amount of field effort than was possible in this study. Second, cover was not mapped due to the length of time between acquisition of satellite images (2004), field work (2009), and map production (2011). Cover is the most ephemeral of the habitat classes and can change significantly over the span of ~5 years or even more rapidly in response to acute storms or wave events. In several areas around the atoll there are cases where cover appeared to have changed (and even a few cases of altered structure and zone) in successive satellite images and again by the time field surveys were conducted. These changes reduce both the capability and relevance of mapping cover.

Only a basic description of zone and structure categories used in Majuro mapping is provided here. For more detailed explanations and example images of each classification category, please refer to other recent NOAA Biogeography Branch mapping reports (e.g. Kendall et al. 2001, Battista et al. 2007, Zitello et al. 2009, and Kendall and Poti (Eds) 2011).

Images 1 and 2. Pavement at low tide. Image at right has extensive coverage of macroalgae and live coral whereas the image at left has only a thin turf algae.

<u>Description of Zones</u> (Blue text box)

Eleven mutually exclusive zones were identified, from land to deep ocean, corresponding to typical atoll geomorphology. These zones included: *Land, Shoreline Intertidal, Reef Flat, Lagoon, Back Reef, Fore Reef, Bank/Shelf, Bank/Shelf Escarpment, Channel, Pinnacle, Dredged/Excavated,* and *Unknown*. Figure 3 illustrates zone types across a typical cross-section of the atoll. Zone refers only to each benthic community's location and does not address substrate or structure types that are found within. For example, the *Lagoon* zone may include patch reefs, sand, and reef rubble; however, these are considered structural elements that may or may not occur within the lagoon zone and therefore, are not used to define it.

Land

Terrestrial features at or above the spring high tide line.

Shoreline Intertidal

Area between the spring high tide line (or landward edge of emergent vegetation when present) and lowest spring tide level. Emergent segments of reefs are excluded from this zone and instead are defined below as *Reef flat*. Typically, this zone is narrow due to steep beach faces or rock outcrops that dominate the land/sea interface. While present island-wide, the feature is often too narrow to be mapped due to the scale of the imagery.

Lagoon

Shallow area (relative to the deep water outside the atoll) inside the atoll surrounded by the *Back Reef*. This zone is typically protected from the high-energy waves commonly experienced on the *Bank/Shelf* and *Reef Crest* zones.

Reef Flat

Shallow area of very low relief that is exposed at low tide between the *Shoreline Intertidal* zone and the *fore reef* or *back reef*. Inside the atoll, this zone is well protected from the high-energy waves commonly experienced on the *reef flat* outside the atoll. The position of the seaward edge of the reef flat was often concealed beneath wave swash in the satellite imagery of Majuro and was approximated.

Back Reef

Area on the inside of an atoll sloping inward from the *Shoreline Intertidal* zone or *Reef Flat* down to the seaward edge of the *Lagoon* floor.

Fore Reef

Area along the seaward edge of the *Reef Flat* that slopes into deeper water to the landward edge of the *Bank/Shelf Escarpment*. Features not associated with an emergent *Reef Flat* but still having a seaward-facing slope that is significantly greater than the slope of the *Bank/Shelf* are also designated as *Fore Reef*.

Bank/Shelf

Deeper water area (relative to the shallow water in a lagoon or reef flat) extending offshore from the seaward edge of the *Fore Reef* or shoreline to the beginning of the escarpment where the insular shelf drops off into deep, oceanic water. Due to its steep sides, this zone is almost non-existent around Majuro Atoll and occurs only in the region of north/central channel into the lagoon.

Bank/Shelf Escarpment
This zone begins on the seaward edge of the *Fore Reef* around most of Majuro, where depth increases rapidly into deep, oceanic water and exceeds the depth limit of satellite imagery. This zone is intended to capture the outside of the atoll as its sides descend into deep waters of the open ocean. Due to limited boat availability, very little ground validation was conducted in this zone.

Channel
Naturally occurring channels in the seafloor that often cut across several other zones.

Dredged/Excavated
Area in which natural geomorphology is disrupted or altered by excavation or dredging.

Pinnacle
High relief features occurring in the *Lagoon* that are separated from backreef features by the deeper waters of the lagoon. Pinnacles are typically capped by coral reef or hard bottom structures.

Unknown
Zone indistinguishable due to cloud cover, gaps in imagery, or other interference in satellite data.

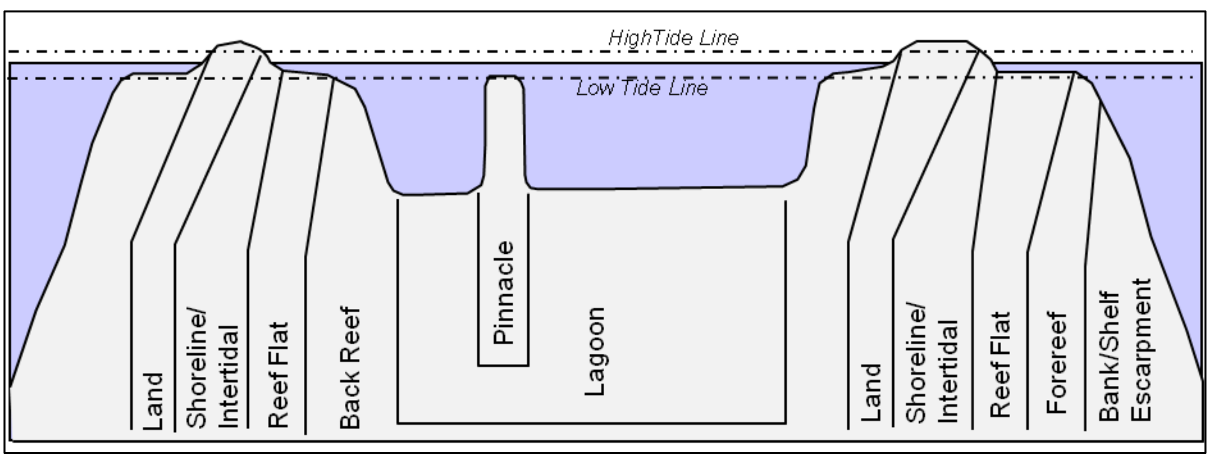

Figure 3. Cross-section of zones through the atoll. Horizontal and vertical scales are variable and for illustration purposes only. Due to space constraints, zones located seaward of land are labeled on the right-hand side of the figure and zones inside the atoll are labeled on the left-hand side. Zones not appearing in the figure are *Channel*, *Dredged/excavated*, and *Unknown*.

<u>Description of Geomorphological Structures</u> (Red text box)
Fourteen distinct and non-overlapping geomorphologic structures could be mapped by visual interpretation of satellite imagery. Structure refers only to predominant physical composition of the feature and does not address location (see Zone for shore to shelf edge location). The structure types are defined in a collapsible hierarchy ranging from four major classes (*Coral Reef and Hardbottom*, *Unconsolidated Substrate*, *Other Delineations*, and *Unknown*), to fifteen detailed classes listed and defined below.

Coral Reef and Hardbottom
Solid substrates, including bedrock, boulders, and reef building organisms. A thin veneer of sediment may be present. Detailed classes within this category include: *Aggregate Reef, Individual Patch Reef, Aggregated Patch Reefs, Spur and Groove, Pavement, Pavement with Sand Channels, Reef Rubble,* and *Rock/Boulder*.

Aggregate Reef
Continuous, high-relief coral formation of variable shapes lacking sand channels of *Spur and Groove*. Includes linear coral formations that are oriented parallel to shore or the shelf edge. This class is used for such commonly referred to terms as linear reef, fore reef or fringing reef.

Individual Patch Reef
Patch reefs are coral formations that are isolated from other coral reef formations by bare sand, seagrass, or other habitats, and that have no organized structural axis relative to the contours of the shore or shelf edge. They are characterized by an often circular or oblong shape with a vertical relief of one meter or more in relation to the surrounding seafloor. *Individual Patch Reefs* are larger than or equal to the *minimum mapping unit* (MMU).

Aggregated Patch Reefs
These features have the same defining characteristics as an *Individual Patch Reef.* However, this class refers to clustered patch reefs that individually are too small (less than the MMU) or are too close together to map separately. Where aggregated patch reefs share sand halos, the halo is included in the polygon.

Spur and Groove
This structure has alternating sand and coral formations that are oriented perpendicular to the shore or fore reef. The coral formations (spurs) of this feature typically have a high vertical relief relative to pavement with sand channels and are separated from each other by 1-5 meters of sand or hardbottom (grooves), although the height and width of these elements may vary considerably. This habitat type typically occurs in the *Fore Reef* or *Bank/Shelf Escarpment* zone.

Pavement
Flat, low-relief, solid rock in broad areas often with partial coverage of sand, algae, hard coral, gorgonians, zooanthids or other sessile invertebrates.

Pavement with Sand Channels
Areas of pavement with alternating sand/surge channel formations that are oriented perpendicular to the shore or *Bank/Shelf Escarpment*. The sand/surge channels of this feature have low vertical relief relative to *Spur and Groove* formations. This habitat type occurs in areas exposed to moderate wave surge, such as the *Bank/Shelf* zone.

Reef Rubble
Dead, unstable coral rubble often colonized with turf, filamentous, calcareous, or encrusting macroalgae. This habitat often occurs landward of well developed reef formations in the *Reef Crest, Back Reef* or *Reef Flat* zones due to storm waves piling up dead coral. *Reef Rubble* can also occur in offshore areas due to diseased or physically impacted reef communities.

Rock/Boulder
Large, irregularly shaped carbonate blocks or volcanic rock often extending offshore from the island bedrock or headlands. Can also occur as aggregations of loose rock fragments that have been detached and transported from their native beds. Individual boulders often range in diameter from 0.25 – 3 m.

Unconsolidated Substrate
Areas of the seafloor consisting of small, unattached or uncemented particles with less than 10% cover of large stable substrate. Detailed structure classes of softbottom include *Sand, Sand with Scattered Coral and Rock* and *Seagrass*.

Sand
Coarse sediment typically found in areas exposed to currents or wave energy.

Sand with Scattered Coral and Rock
Primarily sand bottom with scattered rocks or small, isolated coral heads that are too small to be delineated individually (i.e. smaller than individual patch reefs). If the density of small coral heads is greater than 10% of the entire polygon, this structure type is described as *Aggregated Patch Reefs*.

Seagrass
Primarily sand bottom colonized by seagrass of variable density and patchiness.

Other Delineations
Any other type of structure not classified as *Coral Reef and Hardbottom* or *Unconsolidated Substrate*. Usually related to the terrestrial environment and/or anthropogenic activity. Detailed structure classes include *Land* and *Artificial*.

Land
Terrestrial features at or near the spring high tide line.

Artificial
Man-made habitats such as submerged wrecks, large piers, and submerged portions of rip-rap jetties, breakwaters or seawalls.

Unknown
Major structure indistinguishable due to data gaps from turbidity, cloud cover, water depth, or other interference with an interpretable signature of the seafloor.

Unknown
Detailed structure indistinguishable as above.

Description of Percent Hardbottom **(Green text box)**
Seven classes were used to denote the approximate proportion of each polygon occupied by hard bottom substrate. A polygon encompassing several patch reefs that were too small to be delineated individually is actually comprised of some area of patch reefs and some background structure such as sand. This category includes both "living" hard bottom such as patch reefs, as well as "abiotic" features such as pavement and rock/boulder. This attribute can be used to estimate the combined amount of coral reef and hard bottom around the island based on the area of each polygon.

<10%
Used for all sand and sand with scattered coral and rock polygons.

10-30%
Used for some aggregated patch reef polygons and other discontinuous features.

30-50%
Used for some aggregated patch reef polygons and other discontinuous features.

50-70%
Used for some aggregated patch reef polygons and other discontinuous features.

70-90%
Used for some aggregated patch reef polygons, pavement, and other discontinuous features.

90-100%
Used for most individual patch reef, pavement, aggregate reef polygons, and other continuous features.

2.4 Mapping Parameters

A key parameter selected at the beginning of the mapping process is the *minimum mapping unit* (MMU). The MMU denotes the size of the smallest habitat feature that can be delineated by an individual polygon. Time constraints and resolution of remote sensing imagery prevent mapping of every individual patch reef, small seagrass patch, and other small habitat features. Instead, only larger habitat features can be efficiently mapped. Several efforts have been undertaken that examined the effectiveness and utility of mapping at various MMUs (e.g. Kendall and Miller 2007, Kendall and Miller 2010, Kendall et al. 2011). Selecting an appropriate MMU requires several considerations, including, but not limited to: ability to accurately interpret features in the imagery, needs of the scientific and management communities, and time constraints needed to efficiently delineate features and complete map production. Given the goals and constraints of the Majuro mapping project, an MMU of 1000 m^2 was selected.

Another key parameter selected prior to mapping is the scale at which the on-screen digitizing will be performed. This refers to the appearance and size (how zoomed in) of the remote sensing image on the computer monitor at the time polygons are drawn. Zooming in to fine scales and close up views of remote sensing images allows detailed edges to be followed closely, but is time consuming. Zooming out to broad scales makes habitat features appear smaller on the screen resulting in less detailed habitat boundaries but more rapid map production. A moderate level of zoom is often best to balance the trade-offs in polygon detail and production speed and is selected based on resolution of the remote sensing imagery, width of typical polygon features, the classification scheme, and MMU. For this project, a digitizing scale of 1:4000 was used for all polygon delineation.

2.5 Draft Feature Delineation

All benthic habitats were mapped from the shoreline to a depth where features were no longer visible in remote sensing imagery (~30 meters). This task was accomplished using visual interpretation and digitizing in ArcGIS facilitated by the Habitat Digitizer Extension developed by NOS (http://biogeo.nos.noaa.gov/products/apps/digitizer/). The ArcGIS extension allows for a custom habitat classification scheme to be developed based on the user's needs. It provides the option of setting the digitizing scale and MMU size and alerts the photo interpreter when these parameters are exceeded.

A first draft coral reef habitat map was produced directly in ArcGIS format by drawing boundaries around all features that could be identified by visual inspection of the satellite imagery. Polygon boundaries were drawn by a mapping specialist around features in the imagery with colors and textures thought to be associated with categories in the classification scheme. This first draft map includes all zones, geomorphologic structure and percent hard bottom attributes.

2.6 Field Validation

During the initial delineation of habitat polygons, the technician identified areas that were, 1) thought to be representative of typical cross-sections of atoll features, and 2) indicated where uncertainty existed in the visual interpretation of any attributes in the classification scheme. These positions were uploaded to a GPS. During field work at Majuro in September 2009, 311 positions were surveyed to determine the "ground truth" of actual features appearing in the imagery. Trimble GEO XH hand-held GPS units were used for all field work. Habitat attribute information was collected in the field on hard-copy data sheets and digitally using a GPS data logger. The benthic habitat assessments were made in the field by hiking to many sites at low tide, kayaking, swimming, or boating to sites, and using a glass bottom look box, free diving, video drop camera or observing from the surface. Digital photography, video files, and notes about each site were saved for later analysis during development of second-draft habitat maps. At the end of each field day, the data was downloaded from the GPS and differentially post-processed to the Majuro CORS base station (www.ga.gov.au/geodesy/slm/spslcmp/marshall.jsp) to improve positional accuracy. The GPS file was then converted to an ArcGIS shape file for display with satellite imagery and draft maps.

Image 3. Example of GPS field validation at rock/boulder structure.

2.7 Final Feature Delineation

Habitat maps were then revised in the GIS based on field observations. Polygon boundaries and classification attributes were reviewed and modified as needed in a second draft of the habitat map using overlays of the field GPS data, examination of field pictures and videos, and review of the remote sensing imagery.

2.8 QA/QC and Metadata

The GIS map product generated during this work was closely examined in several ways to ensure quality. A final pan-through of completed maps overlaid on the imagery was conducted to eliminate obvious errors in zone, structure, and percent hard bottom attributes. More subtle errors, such as multipart, overlapping, sliver, and void polygons were identified and corrected using ArcGIS geodatabase and topology options and quality control procedures developed at NOAA. Adjacent polygons with identical classification attributes were identified and merged. Polygons were evaluated for complete entries in the attribute table. Polygons were queried for impossible attribute combinations (e.g. Sand with greater than 10% hard bottom). Once all QA/QC steps were completed, the final map was saved in an ArcGIS database and used for calculation of summary statistics for the results section of this report.

Benthic habitat maps, field validation data, and remote sensing products were documented according to Federal Executive Order 12906. Metadata records were created which detailed field sampling dates, datum, projections, processing steps, field records, and any other pertinent information.

3. Results

3.1 Summary of Mapped Features

A total of 1829 features covering 366 km^2 were mapped at Majuro, including 11 km^2 of land and 288 km^2 of deep unknown areas in the central lagoon. Due to the large size of the atoll and small details provided in the GIS, the maps are not shown in their entirety in this report. Instead, examples of the GIS map products displaying the zones and detailed geomorphologic structure are shown for only a small portion of the atoll (Figure 4). The whole set of GIS map products are displayed comprehensively in a separate PDF atlas available on-line. The real value of the map products lies not in the simple examples and brief summary report produced here, but rather in the application of the atlas and GIS maps themselves.

In discussing the results, it should first be noted that some features have changed since the satellite images were collected that are the basis of this mapping project. Individual satellite scenes were acquired over a two year period beginning in 2004. Field surveys were conducted three years later in September 2009, and final maps are now available in 2012. There were clear changes visible in some parts of the remote sensing imagery alone. These were confirmed during site visits and were especially evident in channels and back reefs on the north side of the atoll where sand and rubble piles had shifted. Overall habitat composition is the same, but exact boundaries and extents of some features has changed.

3.2 Extent of Zones and Structures

Zones mapped at Majuro reflect typical atoll morphology in the Marshall Islands (Holthus et al. 1992, Xue 1997)(Figure 4). All zones circled the entire atoll but were quite narrow, only 10 to a few hundred meters wide. Zones were

Image 4. Example of Forereef zone, spur and groove structure.

somewhat wider on the east and west sides of the atoll. Forty-nine islands or islets were mapped around Majuro. The lagoon was by far the largest zone by area, comprising nearly 80% of the atoll. Reef flat was the next largest zone and covered 7.5% of the atoll. Zones with the largest number of features were back reef (677 polygons) and pinnacles (432), with most of the shallow pinnacles occurring in the western half of the lagoon. Due to the high quality imagery, most pinnacles were mapped, however, some were at the edge of, or partly under, clouds and certain others were simply too deep to appear in satellite images. These will have to be mapped from multibeam bathymetry data sources since the lagoon reaches depths of nearly 70 m in places (Kruger and Kumar 2008).

Table 1. Summary of Zones Mapped at Majuro.

Zone	Number of Polygons	Area (km^2)	Area (%)
Back Reef	677	13.6	3.7%
Bank/Shelf Escarp.	15	8.4	2.3%
Channel	60	3.1	0.9%
Dredged/Excavated	35	0.5	0.1%
Fore Reef	28	7.7	2.1%
Lagoon	3	289.1	79.0%
Land	49	11.3	3.1%
Pinnacle	432	3	0.8%
Reef Flat	225	27.5	7.5%
Shoreline/Intertidal	305	2	0.6%
TOTALS	1829	366.2	100%

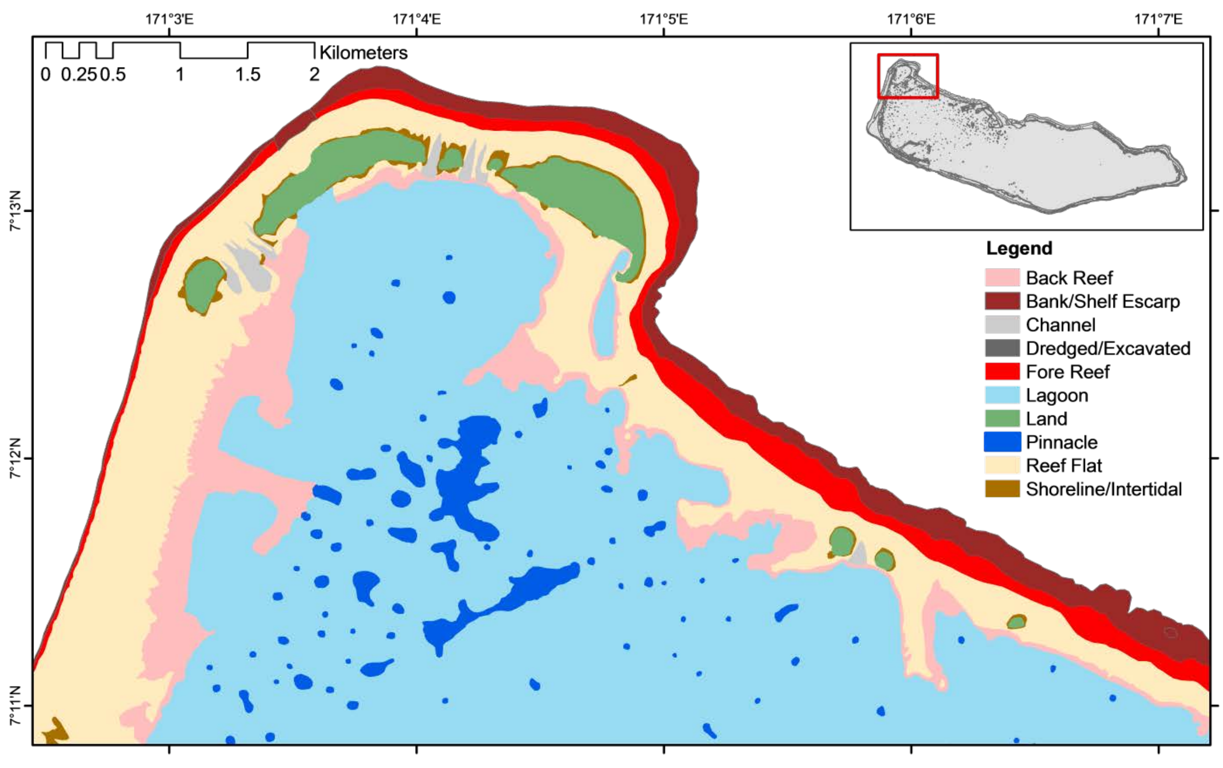

Figure 4. Example of zones map from NW corner of Majuro.

Major geomorphological structures in the classification scheme include coral reef/hard bottom and unconsolidated substrate. Of the total 73.9 km^2 of coral reef ecosystem mapped (excludes 12 polygons classified as "unknown", including the large central lagoon region), 77% were coral reef and hard bottom, 8% were unconsolidated substrate, and 15% were other delineations such as "land" (Table 2).

Major Structure	Number of Polygons	Area (km^2)	Area (%)
Coral Reef/Hard Bottom	1359	56.7	76.8%
Other Delineations	58	11.3	15.3%
Unconsolidated Substrate	400	5.8	7.9%
TOTALS	1817	73.9	100%

Table 2. Summary of Major Structures Mapped at Majuro. Excludes 12 polygons classified as "unknown" including the large central lagoon.

Similarly, a GIS area summary was tabulated for Detailed Geomorphologic Structure. Of the total 73.9 km^2 of coral reef ecosystem mapped (excludes 12 polygons classified as "unknown" including the large central lagoon region), the largest proportion (29%) was "pavement" followed by "aggregate reef" (18%) with other bottom types making up smaller proportions (Table 3)(Figure 5). Common combinations of zone and structure around the atoll included pavement on reef flats, spur and groove on fore reefs, aggregate reefs on back reefs, rubble in channels, and patch reefs on pinnacles.

Detailed Structure	Number of Polygons	Area (km^2)	Area (%)
Aggregate Reef	172	13.5	18.3%
Artificial	9	0.0	0.1%
Land	49	11.3	15.3%
Individual Patch Reef	352	1.3	1.8%
Aggregated Patch Reefs	394	8.2	11.1%
Pav. w/ Sand Channels	4	0.7	1.0%
Pavement	90	21.5	29.1%
Reef Rubble	138	3.7	5.0%
Rock/Boulder	198	1.9	2.5%
Sand	209	3.4	4.6%
Sand w/ Scattered Coral and Rock	163	2.3	3.1%
Seagrass	28	0.1	0.2%
Spur and Groove	11	6.0	8.1%
TOTALS	1817	73.9	100%

Table 3. Summary of Detailed Structures Mapped at Majuro. Excludes 12 polygons classified as "unknown" including the large central lagoon.

Other Pacific atolls that have been mapped using the same approach include Swains and Rose in American Samoa, and Palmyra, south of Hawaii. These three atolls are much smaller geologic features that together could easily fit into the Majuro lagoon (Swains is 3 km across with 29 polygons, Rose is 4 km across with 61 polygons, and Palmyra is 22 km across with 477 polygons, compared to Majuro at 40 km across with 1870 polygons). Despite smaller size and variable feature width, all had generally similar zonation and progression of structure types in cross-section.

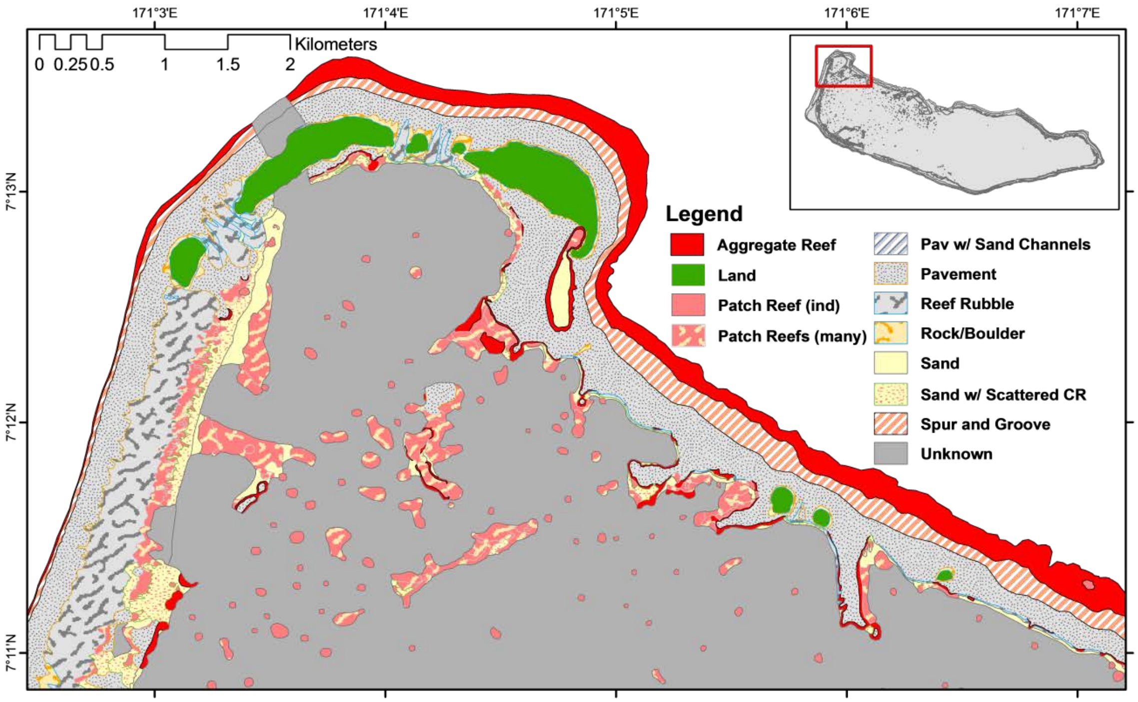

Figure 5. Example of detailed structures map from NW corner of Majuro.

4. Next steps

Benthic maps are foundational tools for monitoring, conservation, development planning, stock assessments and other activities that can be placed into greater spatial context. Maps produced in this project, in GIS and PDF atlas formats (Edwards et al. 2012), satellite imagery, videos, and pictures taken in the field are all available at the NOAA Biogeography Branch website (http://ccma.nos.noaa.gov/ecosystems/coralreef/majuro_mapping.aspx) and can be used to support a variety of coastal management activities identified as important in Majuro (Beger et al. 2008). The approach documented here can be used to map other atolls and seamounts throughout the Marshall Islands. Priority could be given to those more heavily populated or with particular development pressures or those with key conservation or monitoring programs (e.g. Ailinglaplap, Ailuk, Arno, Bikini, Jaluit, Kwagelain, Mili, Rongelap).

An assessment of thematic accuracy of the Majuro Atoll benthic habitat map has <u>not</u> yet been conducted, but is an important part of the map making and validation process (Congalton 1991). Field surveys for accuracy assessment were planned as part of the original project scope but had to be eliminated. This was due to the unavoidable loss of local boat support on all but a few days of planned field work. Boat mechanical issues and lack of back-up options on a remote Pacific Island resulted in >50% reduction in survey efficiency. As a result, the severely reduced field operations were devoted entirely to conducting a subset of planned ground truth surveys to aid map creation at the expense of collecting any independent data for accuracy assessment.

While the vast majority of shallow water (< ~ 30m) reef ecosystem features were mapped in this project, some small areas were obscured by cloud cover and could not be mapped. Apart from the shallow back reef and pinnacle habitats in the lagoon, the majority of the interior of the atoll could not be mapped from the satellite imagery due to water depth. Extensive bathymetric surveys have been conducted by SOPAC using multibeam sonar covering much of the lagoon floor (Figure 6)(Kruger and Kumar 2008). Resulting images could be visually interpreted using the same habitat classification scheme as was used here to produce a more comprehensive map of lagoon habitats.

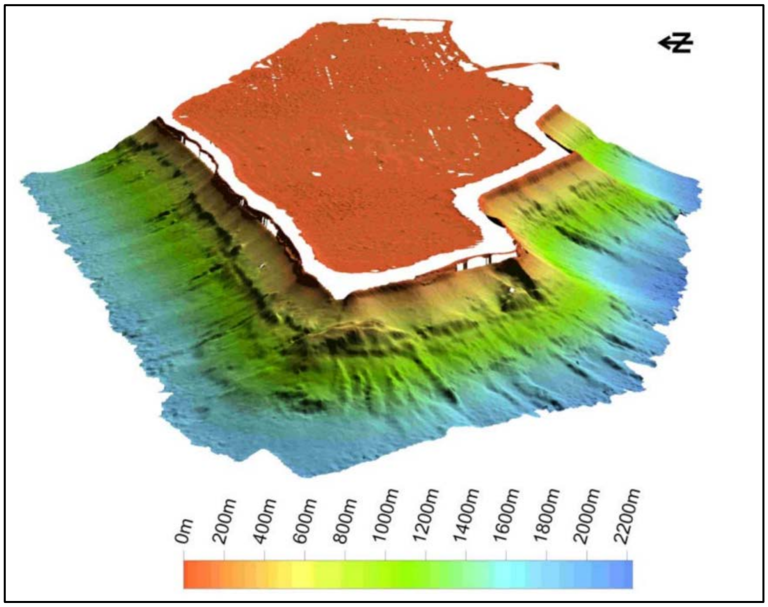

Figure 6. Three dimensional perspective image of Majuro bathymetry looking west. Reproduced here with permission from J. Kruger (SOPAC, Kruger and Kumar 2008).

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