A SPATIO-TEMPORAL ANALYSIS OF THE BENTHIC HABITAT ON ROSE ATOLL, AMERICAN SAMOA IN RESPONSE TO THE REMOVAL OF THE GROUNDED JIN SHIANG FA FISHING VESSEL DEBRIS

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This thesis is dedicated to my beautiful mother, Debra Barrera, and my father, James Roberson. They both inspired me to pursue my dreams of exploring the underwater world and becoming an intelligent and independent woman and scientist. It’s impossible to thank them adequately for all of their sacrifices and unconditional love.

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List of Tables

Table 1. The two sensors on the IKONOS-2 satellite, their respective spectral bands, and the spectral band ranges. ................................................................................................................................. 25

Table 2. The two sensors on the WorldView-2 satellite, their respective spectral bands, and the spectral band ranges. ................................................................................................................................. 29

Table 3. The data sets that were used to derive each of the three benthic habitat maps for Rose Atoll. The three maps represent the benthic habitat for Rose Atoll before (2004) debris removal, during (2006) debris removal, and after (2010) debris removal of shipwreck debris left from the Jin Shiang Fa fishing vessel. ................................................................................................................................. 53

Table 4. The final y-intercept equations and $R^2$ values of the five spectral bands of the selected ROI. Each spectral band was compared to the depth (NIR band). ................................................................. 59

Table 5. The $R^2$ values of the 12 spectral band combinations. A low $R^2$ value means there is more sun glint in the image, where a high $R^2$ value means there is less sun glint in the image. ............... 62

Table 6. The $R^2$ values of the 12 spectral band combinations for 5 depth bins (<30m, <25m, <20m, <15m, <10m). A comparison of 5 depth bins was performed in order to test the hypothesis whether the accuracy of the derived bathymetry changed in response to the area of the WorldView-2 satellite image for Rose Atoll. ................................................................................................................................. 64

Table 7. The eight geomorphological features that were derived from the two bathymetric data sets for the 2006 and 2010 benthic habitat maps. (Source: Costa, B. M., Bauer, L. J., Battista, T. A., Mueller, P. W., & Monaco, M. E. (2009). Moderate-Depth Benthic Habitats of St. John, US Virgin Islands.) ................................................................. 67

Table 8. The percent and accumulative eigenvalues for each original geomorphic layer (2006). The PCA identified the top 3 Principal Components as the layers that contributed the most variance to the seafloor structure in the 2006 bathymetric data set (highlighted). ......................................................... 73

Table 9. Percent of variance contributed by each original geomorphic layer (2006). The top 3 Principal Components that contribute the most to the variance in seafloor structure (highlighted) are: Slope, Curvature, and Plan Curvature ................................................................................................................................. 74
Table 10. The percent and accumulative eigenvalues for each original geomorphic layer (2010). The PCA identified the top 3 Principal Components as the layers that contributed the most variance to the seafloor structure in the 2010 bathymetric data set (highlighted). ........................................ 74

Table 11. Percent of variance contributed by each original geomorphic layer (2010). The top 3 Principal Components that contribute the most to the variance in seafloor structure (highlighted) are: Rugosity, Curvature, and Plan Curvature. ........................................................................................................ 75

Table 12. An example of five classified images analyzed in Excel. The classifications Soft Coral, Sediment, Invertebrate, Tape/Wand, and Unclassifiable were omitted in the analysis and were not used to derive the benthic habitat maps for 2006 and 2010. In this table, Hard Coral takes priority over Coralline Algae in image 3 and Coralline Algae take priority over Turf Algae in image. Then, 1 of 3 percentage bins (10-<50%, 50-<90%, and 90-100%) was assigned to each image. .................................................................................................................................................. 78

Table 13. The classifications that were used for the signature file for the supervised classification of the benthic habitat for the 2006 benthic habitat maps, and the number of sample points used per classification ........................................................................................................... 79

Table 14. The classifications that were used in the signature file for the supervised classification of the benthic habitat for the 2010 benthic habitat maps, and the number of sample points used per classification ........................................................................................................... 80

Table 15. The area (km$^2$) of each dominant cover type in each year ................................................ 93

Table 16. The areas (km$^2$) for the Percentage of Dominant Cover Types ........................................ 94
List of Figures

Figure 1. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Biological Cover of the seafloor. This benthic habitat map could be used by a researcher to determine the total percentage coral at a site, for instance. (Source: CREP. (n.d.). Hawaii Big island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/). ................................................................. 3

Figure 2. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Benthic Cover of the seafloor. This benthic habitat map could be used by project managers, such as engineers, to determine where it would be best to construct an underwater cable, for instance. (Source: CREP. (n.d.). Hawaii Big island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/). ........................................................................ 4

Figure 3. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Substrate of the seafloor. (Source: CREP. (n.d.). Hawaii Big Island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/). ........................................................................... 5


Figure 5. The first benthic habitat map for Rose Atoll created in 2004 by NOAA’s NCCOS Biogeography Team. The benthic habitat is divided into 19 Cover Types, which were derived from a 4 meter resolution, multispectral IKONOS-2 satellite image. (Source: NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.). ................................................. 10

Figure 6. The second benthic habitat map for Rose Atoll created in 2004 by NOAA’s NCCOS Biogeography Team. The benthic habitat is divided into 13 Structure Types, which were also derived from a 4 meter resolution, multispectral IKONOS-2 satellite image. (Source: NCCOS,


Figure 8. A 4 meter resolution, multispectral WorldView-2 satellite image of Rose Atoll, showing the two small islets on the eastern side. (Source: CREP servers with special permission).

Figure 9. The dense vegetation on Rose Island and the shallow reef flat that surrounds it. (Source: Information for the timeline was retrieved from USFWS. (n.d.). About the Refuge - Rose Atoll - U.S. Fish and Wildlife Service. Retrieved June 07, 2017, from https://www.fws.gov/refuge/Rose_Atoll/about.html).

Figure 10. The boundary of the Rose Atoll National Wildlife Refuge, which was established in 1973. This map was retrieved from NOAA’s National Marine Sanctuary of American Samoa website. (Source: NOAA. (2014, January 24). Muliāva (Rose Atoll and Vailulu’u Seamount). Retrieved June 07, 2017, from http://americansamoa.noaa.gov/about/location.html).


Figure 17. This is an example of a multispectral IKONOS-2 satellite image of Bora Bora, French Polynesia (resolution unknown). The resolution of this image is not as fine as the WorldView-2 image. (Source: Satellite Imaging Corp. (n.d.). IKONOS Satellite Image Gallery. Retrieved June 07, 2017, from http://www.satimagingcorp.com/gallery/ikonos/). ................................................................. 27


Figure 19. An example of a WorldView-2 satellite image. This is a 0.5 meter resolution image of the Great Barrier Reef, and the shallow coral reefs (brown areas) are very high-resolution. (Source: Kramer, H. J. (2002). WorldView-2. Retrieved June 07, 2017, from https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-2). .... 30

Figure 20. An illustration of how multibeam bathymetry is acquired using a multibeam echo sounder attached to the hull of a NOAA research vessel (left). Acoustic (sound) waves are emitted from the multibeam echo sounder, and the amount of time that it takes for the sound wave to return to the vessel is used to determine the water depth. The water depth is then used to map the seafloor. This concept is similar to echolocation that bats and odontocetes (toothed whales) use to determine the position of objects (right). (Source: James, S. N. (n.d.). Filling in the Gaps – Part II. Retrieved June 07, 2017, from https://schmidtocean.org/cruise-log-post/filling-in-the-gaps-part-ii/). .............................................................................. 32
Figure 21. An example of multibeam bathymetry around the coasts of the Main Hawaiian Islands from the perspective of the Island of Hawai‘i (Big Island). *(Source: (n.d.). OCN 201 Lab Picts. Retrieved June 07, 2017, from https://windward.hawaii.edu/facstaff/miliefsky-m/OCN%20201%20Lab/Picts/).* ................................................................. 33

Figure 22. An illustration of the three techniques that have been used to acquire bathymetric data (water depth). From left to right, lead line surveys have the least accuracy while multibeam echo sounders have the highest accuracy. *(Source: United States Office of Coast Survey. (n.d.). Title. Retrieved June 07, 2017, from https://www.nauticalcharts.noaa.gov/mcd/learnnc_surveytechniques.html).* .................. 34


Figure 24. A 1 meter resolution benthic image of the coral reef on Rose Atoll acquired on March 18, 2015 during a towed diver survey. Crustose coralline algae is noticeable pink. *(Source: CREP server with special permission).* ................................................................. 36

Figure 25. Assessment sites assigned to Cocos Lagoon, Guam in a stratified random sampling technique. The goal is to have an even distribution of assessment sites over the entire area. *(Source: NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.)*. 38


Figure 30. The SCUBA gear and towboard equipment that each NOAA-certified, trained SCUBA diver has in order to perform towed diver surveys (top) and an illustration of a towed diver survey (bottom). *(Source: NOAA CREP. (n.d.). Survey Methods. Retrieved June 07, 2017, from https://www.pifsc.noaa.gov/cred/survey_methods.php#habitat_mapping).* ........................................... 42


Figure 32. The home page of CoralNet BETA, formerly CoralNet. *(Source: UCSD. (n.d.). CoralNet BETA. Retrieved June 08, 2017, from https://coralnet.ucsd.edu/).* ................................................................. 45

Figure 33. The 4 meter resolution, multispectral IKONOS-2 satellite image of Rose Atoll, AS that was used by NOAA’s NCCOS Biogeography Team to derive the benthic habitat in their 2005 publication. *(Source: CREP server with special permission).* ................................................................. 49


Figure 35. An aerial view of the NOAA Ship *Hi‘ialakai* off the coast of Oahu, Hawai‘i. The AHl research vessel (smaller, red boat) can be seen secured to the ship. *(Source: NOAA OMAO. (2017, March 27). Marine Operations. Retrieved June 07, 2017, from https://www.omao.noaa.gov/learn/marine-operations/ships/hiialakai).* ......................... 51

Figure 36. The entire 2 meter resolution, multispectral (8 band) WorldView-2 satellite image that was used to derived the benthic habitat map for Rose Atoll for 2010. The image was acquired on December 6, 2009 and later purchased by NOAA for benthic habitat mapping. *(Source: CREP server with special permission).* ..................................................................................... 53

Figure 38. This image shows the two data sets that were merged together to create one single data set (Source: NOAA CREP. (2010). Rose Atoll: Bathymetry. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/american-samoa/rose-atoll/rose-atoll-bathymetry/). ................................................................. 56

Figure 39. The two single beam bathymetric data sets that were used to validate the bathymetry derived from the WorldView-2 satellite images for the 2010 benthic habitat map. The land masses for the two islets on Rose Atoll are masked out (Step 1). (Source: CREP servers with special permission.) ........................................................................................................ 58

Figure 40. A graphical representation of the “de-glinting” method used in Hedley et al., 2005 to remove sun glint from satellite imagery. A linear regression is performed between the NIR band brightness (representing depth) and the visible bands (Coastal Blue, Blue, Green, Yellow, Red) using a sample set of pixels (ROI) from the image. The $R^2$ value of each visible band in the ROI is analyzed, and the coefficients of the slope-intercept equation are applied to the other pixels in the image. (Source: Hedley, J. D., Harborne, A. R., & Mumby, P. J. (2005). Technical note: Simple and robust removal of sun glint for mapping shallow-water benthos. International Journal of Remote Sensing, 26(10), 2107-2112.) ....................... 61

Figure 41. The results of the Hedley et al. method. The same 2 meter resolution, multispectral WorldView-2 satellite image of Rose Atoll, AS. The original “glinted” image (left) before applying the Hedley equation, and the “de-glinted” image (right) after applying the Hedley equation to the BandMath in ENVI 5.0. The “de-glinted” image (right) is now corrected for atmospheric distortion, and the sun glint over the water is removed. (Source: CREP servers with special permission). ......................................................................................... 61

Figure 42. The final 5 meter resolution bathymetry map for Rose Atoll. The bathymetry was used to derive the benthic habitat maps for 2006. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers). ......................................................................................... 65

Figure 43. The final 2 meter resolution bathymetry map for Rose Atoll. The bathymetry was used to derive the benthic habitat maps for 2010. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers). ......................................................................................... 66

Figure 44. The Mean Depth, Standard Deviation of Depth, Slope, and Slope of Slope that were used to derive the benthic habitat maps for Rose Atoll for 2006. The dark scar in the western side of the atoll is the site of the Jin Shiang Fa ship shipwreck. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers)......................................................................................... 69
Figure 45. The Rugosity, Curvature, Plan Curvature, and Profile Curvature that were used to derive the benthic habitat maps for Rose Atoll for 2006. The dark scar in the western side of the atoll is the site of the Jin Shiang Fa shipwreck. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).

Figure 46. The Mean Depth, Standard Deviation of Depth, Slope, and Slope of Slope that were used to derive the benthic habitat maps for Rose Atoll for 2010. The dark scar in the western side of the atoll is less noticeable. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).

Figure 47. The Rugosity, Curvature, Plan Curvature, and Profile Curvature that were used to derive the benthic habitat maps for Rose Atoll for 2010. The dark scar in the western side of the atoll is less noticeable. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).

Figure 48. An example of a benthic image of Rose Atoll with 10 randomly assigned points superimposed on the image (purple circles). Each point was manually classified using one of four functional group codes: CORAL = Hard Coral, CCA = Crustose Coralline Algae, MA = Macroalgae, or TURF = Turf Algae. (Source: This image was gathered from CREP servers with special permission).


Figure 50. Dominant Cover Types on Rose Atoll during 2004. Four dominant habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with data from in situ benthic habitat assessments conducted in 2004. The large scar in the western bank of the reef flat is the site of the Jin Shiang Fa shipwreck. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i, with data from NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.).

Figure 51. Dominant Cover Types on Rose Atoll during 2006. Five dominant habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with in situ benthic imagery acquired during March 2006. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i with data from CREP servers).
Figure 52. Dominant Cover Types on Rose Atoll during 2006. Four dominant habitat types were derived from multispectral WorldView-2 satellite imagery and validated with in situ benthic imagery acquired during March 2010. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i with data from CREP servers). ................................................................. 85

Figure 53. Percentages of Dominant Cover Types on Rose Atoll during 2004. Nine habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with data from in situ benthic habitat assessments conducted in 2004. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i with data from NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.). ................................................................. 86

Figure 54. Percentages of Dominant Cover Types on Rose Atoll during 2006. Ten habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with in situ benthic imagery acquired during March 2006. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i with data from CREP servers). ................................................................. 87

Figure 55. Percentages of Dominant Cover Types on Rose Atoll during 2010. Seven habitat types were derived from multispectral WorldView-2 satellite imagery and validated with in situ benthic imagery acquired during March 2010. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i with data from CREP servers). ................................................................. 88

Figure 56. The level of confidence in the supervised classification of the ten derived habitat types in Figure 54. This map shows high confidence (green) in the derived habitat types across the reef flat and slope environment and low confidence (red) in the lagoon. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i). ................................................................. 89

Figure 57. The level of confidence in the supervised classification of the seven derived habitat types in Figure 55. This map shows very high confidence (green) in the derived habitat types across the reef flat and slope environment and low confidence (red) in the lagoon. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i). ................................................................. 90
List of Abbreviations

NOAA – National Atmospheric and Oceanic Administration
NWHi – Northwestern Hawaiian Islands
PRIAs – Pacific Remote Island Areas
DOC – Department of Commerce
OMAO – Office of Marine and Aviation Operations
NMFS – National Marine Fisheries Service
NOS – National Ocean Service
OAR – Office of Oceanic and Atmospheric Research
NWS – National Weather Service
NESDIS – National Environmental Satellite, Data, and Information Service
PIFSC – Pacific Islands Fisheries Science Center
CREP – Coral Reef Ecosystem Program, formerly the Coral Reef Ecosystem Division (CRED)
HMRG – Hawaiʻi Mapping Research Group
CRCP – Coral Reef Conservation Program
UH Mānoa – University of Hawaiʻi at Mānoa
SOEST – School of Ocean and Earth Science and Technology
HIGP – Hawaiʻi Institute of Geophysics and Planetology
PIBHMC – Pacific Islands Benthic Habitat Mapping Center
AHI – Acoustic Habitat Investigator
MNM – Marine National Monument
NCCOS – National Centers for Coastal Ocean Science
USFWS – United States Fish and Wildlife Service
NPFC – National Pollution Funds Center
USCG – United States Coast Guard
HURL – Hawaiʻi Undersea Research Laboratory
ASRAMP – American Samoa Reef Assessment and Monitoring Program
Table of Contents

Acknowledgements .................................................................................................................. iii
List of Tables ............................................................................................................................ iv
List of Figures ............................................................................................................................ vi
List of Abbreviations .................................................................................................................. xiv

Chapter 1: Introduction ................................................................................................................. 1

1.1 Thesis Outline ..................................................................................................................... 1

1.2 Background ......................................................................................................................... 1
1.2.1 NOAA and UH Mānoa Partnerships in Benthic Habitat Mapping ............................... 7
1.2.2 Benthic Habitat Mapping for Rose Atoll ...................................................................... 9

1.3 Introduction to the Research Study ...................................................................................... 12
1.3.1 Setting ........................................................................................................................... 12
1.3.2 Study Area and a Brief History ..................................................................................... 17
1.3.3 Purpose and Objectives ................................................................................................. 20
1.3.4 Significance .................................................................................................................... 20

Chapter 2: Review of Literature .................................................................................................. 21

2.1 Background ......................................................................................................................... 21
2.1.1 Spatial Distribution of Coral Reefs .............................................................................. 22
2.1.2 Threats to Coral Reefs and Benthic Habitat Mapping ............................................... 23

2.2 Data Types in the Benthic Habitat Maps in this Research Study ........................................ 23
2.2.1 Multispectral Satellite Imagery ................................................................................... 24
2.2.2 Multibeam and Single Beam Bathymetry .......................................................... 31
2.2.3 Benthic Imagery (Ground Truth Data) .......................................................... 36
2.3 Benthic Imagery Analysis Techniques .................................................................. 43
  2.3.1 Manual Analysis ............................................................................................... 43
  2.3.2 Automated and Semi-Automated Analysis ...................................................... 44
  2.3.3 Accuracy of Manual, Automated, and Semi-Automated Techniques .......... 46
2.4 Conclusion .............................................................................................................. 47

Chapter 3: Methods ..................................................................................................... 48
  3.1 Data Collected for the 2004 Benthic Habitat Maps ........................................... 48
  3.2 Data Collected for the 2006 Benthic Habitat Maps ........................................... 50
  3.3 Data Collected for the 2010 Benthic Habitat Maps ........................................... 52
  3.4 Data Analysis: Benthic Habitat Mapping Procedure ........................................ 54
    3.4.1 Derivate Bathymetry ....................................................................................... 54
    3.4.1.1 Georectify the Satellite Imagery .............................................................. 57
    3.4.1.2 Examine the Ground Truth Data ............................................................ 57
    3.4.1.3 Convert DNs and Reflectance to TOA radiance ....................................... 58
    3.4.1.4 Analyze a Set of Sample Pixels ................................................................. 59
    3.4.1.5 “De-glint” the Satellite Image ................................................................. 60
    3.4.1.6 Compare the Derived Bathymetry to the In Situ Bathymetry ................. 62
    3.4.1.7 Extract the Derived Bathymetry .............................................................. 63
    3.4.2 Derive Geomorphological Features .............................................................. 66
    3.4.3 Perform a Principal Component Analysis (PCA) ........................................ 73
3.4.4 Derive the Benthic Habitat ................................................................. 75
  3.4.4.1 Analyze the Benthic Imagery (Ground Truth Data) ..................... 75
  3.4.4.2 Create the Benthic Habitat Maps .................................................. 78
    3.4.4.2.1 Georectify the Ground Truth Data ...................................... 78
    3.4.4.2.2 Create Signature Files for Classification ................................. 79
    3.4.4.2.3 Perform a Supervised Classification ...................................... 80
    3.4.4.2.4 Optically Validate the Benthic Habitat ................................... 81
    3.4.4.2.5 Apply a Minimum Mapping Unit (MMU) .................................. 82
    3.4.4.2.6 Finalize the Derived Benthic Habitat Maps ............................. 82

Chapter 4: Spatio-Temporal Analysis ............................................................. 91
  4.1 Spatial and Temporal Differences in the Dominant Cover Types .......... 91
  4.2 Spatial and Temporal Differences in the Percentages of Dominant Cover Types .... 94

Chapter 5: Conclusion and Future Research ................................................. 98
  5.1 Research Summary ............................................................................. 98
  5.2 Limitations of the Research ............................................................... 99
  5.3 Research Implications ....................................................................... 100
  5.4 Management Implications .................................................................. 101
  5.5 Opportunities for Future Research ...................................................... 101

References ................................................................................................. 103
Chapter 1. Introduction

The chapter provides background information about the main theme of this research study, which is benthic habitat mapping. The research conducted in this study, a brief history of the study area, and the objectives and significance of this research study are also provided.

1.1 Thesis Outline

This thesis is divided into five chapters. Chapter 1 gives a background about benthic habitat mapping and introduces the research study, the study area, and the purpose and objectives. Chapter 2 is a review of literature related to coral reef ecosystems, the types of data used in this research study, and techniques for analyzing benthic imagery. Chapter 3 explains the data that were gathered and the mapping procedure that was followed to derive the benthic habitat maps for 2004, 2006, and 2010. The derived bathymetry, derived geomorphic layers, and the derived benthic habitat maps are all shown in this chapter. Chapter 4 discusses the results from the derived benthic habitat maps and the spatial and temporal differences in 2004, 2006, and 2010. Chapter 5 summarizes the results and discusses the significance of the findings for future considerations.

1.2 Background

Benthic habitat maps are used to refer to anything that occurs under a body of water. They are also referred to as underwater maps, seafloor maps, seabed maps, or habitat maps, and they are not to be confused with nautical charts. Nautical charts are created for navigation whereas
benthic habitat maps are not. A benthic habitat map is derived from multiple types of data including satellite or aerial imagery, acoustic surveys such as bathymetry and backscatter imagery, and benthic imagery (underwater photos). Derivatives, such as geomorphology data, are derived from bathymetry and backscatter imagery and are also used to derive benthic habitat maps. Benthic habitat maps help researchers and natural resource managers visualize the different types of habitats underwater, such as coral reef ecosystems, and they are used in decision-making. Figures 1-3 are some examples of derived benthic habitat maps of the coral reef ecosystem in West Hawai‘i. These maps are used by researchers and natural resource managers to assess and monitor the state of coral reefs in the U.S. These maps are often requested by managers and used to make better-informed decisions about the protection of endangered and threatened coral reefs in the U.S. and the area of current and potential coral reef habitats.
Figure 1. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Biological Cover of the seafloor. This benthic habitat map could be used by a researcher to determine the total percentage coral at a site, for instance. (Source: CREP. (n.d.). Hawaii Big island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/).
Figure 2. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Benthic Cover of the seafloor. This benthic habitat map could be used by project managers, such as engineers, to determine where it would be best to construct an underwater cable, for instance. (Source: CREP. (n.d.). Hawaii Big island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/).
Figure 3. An example of a benthic habitat map of West Hawai‘i, which show the Dominant Substrate of the seafloor. (Source: CREP. (n.d.). Hawaii Big Island: Benthic Habitat Maps. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/main-hawaiian-islands/hawaii-big-island/hawaii-habitat/).
At the forefront of benthic habitat mapping in the U.S. is the National Oceanic and Atmospheric Administration (NOAA). NOAA conducts biennial benthic surveys (underwater surveys) and ecological assessments around the coastal U.S. in order to derive accurate and up-to-date benthic habitat maps of coral reef ecosystems. Scientists at NOAA’s Daniel K. Inouye Regional Center on Ford Island in Honolulu, Hawai‘i, and researchers from the University of Hawai‘i at Mānoa (UH Mānoa) are leading the way in benthic habitat mapping for NOAA’s Pacific Islands Region (Figure 4).

1.2.1 NOAA and UH Mānoa Partnerships in Benthic Habitat Mapping

NOAA is a federal entity under the Department of Commerce (DOC) that includes 6 Line Offices: the Office of Marine and Aviation Operations (OMAO), the National Marine Fisheries Service (NMFS), the National Ocean Service (NOS), the Office of Oceanic and Atmospheric Research (OAR), the National Weather Service (NWS), and the National Environmental Satellite, Data, and Information Service (NESDIS). Under the NMFS Line Office, commonly known as NOAA Fisheries, the management, conservation, and protection of living marine resource within the United States’ Exclusive Economic Zone (3 to 200 miles offshore) is the responsibility of 5 main regions: the Alaska Region, the Greater Atlantic Region, the Pacific Islands Region, the Southeast and Caribbean Region, and the West Coast Region. The responsibility of managing, conserving, and protecting the Pacific Islands Region is held by the Pacific Islands Fisheries Science Center (PIFSC) on Ford Island, Honolulu, Hawai‘i. The benthic habitat map products used for the Pacific Islands Region are completed by the Coral Reef Ecosystem Program (CREP), formerly the Coral Reef Ecosystem Division (CRED), which was initiated by NOAA Fisheries in 2001. CREP is mostly funded by the Coral Reef Conservation Program (CRCP), which is a collaborative partnership between multiple NOAA offices and programs that are involved in the monitoring and management of coral reef ecosystems across the world. The study sites of projects funded by CRCP cover 7 U.S. states and territories, remote uninhabited islands, and the Pacific Freely Associated States with coral reefs. Within CREP is where this research study and thesis were completed.

CREP is located in the newly-built Inouye Regional Center on Ford Island in Honolulu, Hawai‘i, combining all of the Pacific Islands Region Line Offices into one location and allowing
access and collaboration between researchers. CREP is divided into seven teams: the Benthic Ecology and Monitoring Team, the Data Management Team, the Ecospatial Information Team, the Fish Ecology and Monitoring Team, the International Capacity Building Team, the Ocean and Climate Change Team, and the Operations and Marine Debris Team. In addition, each team has a dedicated webpage on the NOAA Fisheries website at https://www.pifsc.noaa.gov/cred/.

On the Ecospatial Information Team’s webpage at https://www.pifsc.noaa.gov/cred/ecospatial_information.php, for example, the public can learn about CREP’s collaboration with NOAA’s Biogeography Branch in Silver Spring, Maryland, benthic habitat mapping techniques in the Pacific Islands Region, CREP’s mapping methods, and CREP’s partnerships with the Hawai‘i Mapping Research Group (HMRG) within the UH Mānoa’s School of Ocean and Earth Science and Technology (SOEST) and the Hawai‘i Institute of Geophysics and Planetology (HIGP). This research study was completed as a Graduate Assistant (GA) in CREP’s Ecospatial Information Team and in collaboration with the Benthic Ecology and Monitoring Team, the Data Management Team, and the Fish Ecology and Monitoring Team.

HMRG is a research and operational group, currently found at http://www.soest.hawaii.edu/HMRG/cms/, which has specialized in seafloor mapping technology development and mapping services over the past 25 years. All of the data collected and processed by CREP and HMRG for the Pacific Islands Region are available on the Pacific Islands Benthic Habitat Mapping Center (PIBHMC) website, which is currently found at https://www.soest.Hawaiʻi.edu/pibhmc/cms/. PIBHMC personnel support seafloor mapping missions on the NOAA Hi‘ialakai and Oscar Elton Sette (two, 224-foot oceanographic research vessels operated by NOAA’s OMAO), as well as operate NOAA Fisheries’ 25-foot R/V AHI
(Acoustic Habitat Investigator). For each island in the Pacific Islands Region, there are various data products that can be found on the PIBHMC website, including satellite or aerial imagery, bathymetry, geomorphology layers, and benthic imagery. The bathymetry and benthic imagery, for example, are used as ground truth data to validate benthic habitat maps in CREP. The validated benthic habitat maps are then published on the PIBHMC website for public access, and they are used by the general public, instructors, researchers, and managers as instructional, research, and decision-making tools. The overall goal of this research study is to contribute accurate and meaningful benthic habitat maps of Rose Atoll, American Samoa to the PIBHMC website and also contribute a thesis for a Master’s degree to the University of Hawai‘i at Mānoa’s Geography Department.

1.2.2 Benthic Habitat Mapping for Rose Atoll

One location where CREP’s mapping efforts are ongoing and would directly benefit from the derived benthic habitat maps in this research study is on Rose Atoll, American Samoa. Rose Atoll is a Marine National Monument (MNM) that has one of the most pristine and remote coral reef ecosystems in the world (Peck, 2016; Rodgers et al., 1993). Although a remote location, Rose Atoll has experienced vessel groundings on the surrounding reef flat, such as the well-known vessel grounding of the Jin Shiang Fa fishing vessel in 1993 (Section 1.3.2). The impacts of this vessel grounding can be assessed and monitored using benthic habitat maps, but only two benthic habitat maps have been derived for Rose Atoll. In 2004, NOAA’s National Centers for Coastal Ocean Science (NCCOS) Biogeography Team created two benthic habitat maps for Rose Atoll (Figures 5-6).
Figure 5. The first benthic habitat map for Rose Atoll created in 2004 by NOAA’s NCCOS Biogeography Team. The benthic habitat is divided into 19 Cover Types, which were derived from a 4 meter resolution, multispectral IKONOS-2 satellite image. (Source: NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.).
The first map (Figure 5) showed the dominant cover types on Rose Atoll, and the second map (Figure 6) showed the structure types of the seafloor. The lack of benthic habitat maps for Rose Atoll was a driving force behind this research study. In order to better understand the changes that have occurred to the coral reef ecosystem on Rose Atoll in response to this disaster, and better manage the resources effectively, additional benthic habitat maps need to be derived.

Figure 6. The second benthic habitat map for Rose Atoll created in 2004 by NOAA’s NCCOS Biogeography Team. The benthic habitat is divided into 13 Structure Types, which were also derived from a 4 meter resolution, multispectral IKONOS-2 satellite image. (Source: NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.)
1.3 Introduction to the Research Study

This thesis sets out to provide comprehensive benthic habitat maps of Rose Atoll, in order to compare them to the two benthic habitat maps derived by NOAA’s NCCOS Biogeography Team and assess the changes in the coral reef ecosystem over space and time.

1.3.1 Setting


American Samoa is where this research study was focused. Samoa is a small archipelago in the South Pacific Ocean that is separated into Samoa and American Samoa (Figure 7). American Samoa is southeast of Western Samoa and consists of two uninhabited coral atolls (Rose and Swain’s Atolls) and five volcanic islands (Tutuila, Ta’u, Ofu, Olosega, Aunu’u, and Nu’utele). A small coral atoll, known as Rose Atoll, is where the data gathered in this research study were acquired from.
Rose Atoll is a diamond-shaped coral atoll located at 14°32’S 168°08’W. It is the easternmost atoll of American Samoa and the southernmost U.S. protected area (Rodgers et al., 1993). A shallow reef flat surrounds Rose atoll and two small, uninhabited islets (Figure 8). Rose Island covers an area of about 17 acres, has dense vegetation (Figure 9) and a maximum elevation of about 3 meters, but Sand Island varies in shape and size in response to tides and wave action (USFWS, n.d.). Therefore, Sand Island has no permanent land area or elevation (USFWS, n.d.). Rose Atoll protects an inner lagoon area of about 2 kilometers (1.2 miles) wide and about 30 meters (100 feet) deep, and a small channel is in the northern corner that connects the lagoon with the ocean (USFWS, n.d.). Hundreds of migratory birds that traverse across the Pacific Ocean land on Rose and Sand Islands, and many endemic, marine organisms thrive in the coral reef ecosystem that makes us the reef flat. This is the reason Rose Atoll was established as a National Wildlife Refuge in 1973 (Figure 10) and then as a Marine National Monument in 2009 (Figure 11) (USFWS, n.d.).

The two islets support rare species of shearwaters, terns, and nesting petrels, while the shallow reef flat supports rare species of reefs sharks and giant clams (Rodgers et al., 1993). Crustose coralline algae dominates the coral reef ecosystem that makes up the shallow reef flat, instead of hermatypic (reef-building, hard calcareous) corals, but this attribute is unique to “coral” atolls in the central Pacific Ocean (Green, 1997). Both, crustose coralline algae and reef-building corals play an importance role in the architecture of coral reef ecosystems (Johnson, 2016), and this is why they are both analyzed in this research study.
Figure 8. A 4 meter resolution, multispectral WorldView-2 satellite image of Rose Atoll, showing the two small islets on the eastern side. (Source: CREP servers with special permission).

Figure 9. The dense vegetation on Rose Island and the shallow reef flat that surrounds it. (Source: Information for the timeline was retrieved from USFWS. (n.d.). About the Refuge - Rose Atoll - U.S. Fish and Wildlife Service. Retrieved June 07, 2017, from https://www.fws.gov/refuge/Rose_Atoll/about.html).
Figure 10. The boundary of the Rose Atoll National Wildlife Refuge, which was established in 1973. This map was retrieved from NOAA’s National Marine Sanctuary of American Samoa website. (Source: NOAA. (2014, January 24). Muliāva (Rose Atoll and Vailulu’u Seamount). Retrieved June 07, 2017, from http://americansamoa.noaa.gov/about/location.html).
1.3.2 Study Area and a Brief History

The shallow reef flat along the western side of Rose Atoll is the specific area under study. This was the area of the vessel grounding of the *Jin Shiang Fa* fishing vessel in October 1993, about 20 years after Rose Atoll was established as a National Wildlife Refuge (Figure 12-13).


**Figure 13.** An image of the shipwreck acquired on November 6, 1993 by the USFWS, about a month after the event. (*Source: Green, A., Burgett, J., Molina, M., Palawski, D., & Gabrielson, P. (1997). The impact of a ship grounding and associated fuel spill at Rose Atoll National Wildlife Refuge, American Samoa. Report to US Fish and Wildlife Service, Pacific Islands Ecoregion, Honolulu, Hawai‘i.*).
On 24, 1993, a 137-foot, 275-ton Taiwanese longline fishing vessel, the *Jin Shiang Fa*, ran aground on the western bank of Rose Atoll, gouging two 40-meter scars into the coral reef and spilling an estimated 100,000 gallons of diesel fuel, 500 gallons of lubricant oil, and 2,500 pounds of ammonia over the coral reef (Green 1997; Capune, 1995). The oil slick covered the coral reef, and tides moved it across the atoll, suffocating and killing crustose coralline algae and reef-building corals (USFWS 2001; Green 1997). The vessel had grounded because of human negligence (the helm was unmanned at the time), and the vessel was abandoned by the boat crew and the Chinese government for about six years (Green, 1997). As the abandoned vessel sat on the reef flat, large amounts of iron from the corroding hull and other parts slowly leached into the water (USFWS 2001; Green, 1997). The iron functioned as a fertilizer and encouraged invasive blue-green and red algae to proliferate in this time and replace the crustose coralline algae and reef-building corals that were destroyed (Green, 1997).

Then, in 1999, funds were allocated by the Chinese government to remove the vessel debris, but the Chinese government ran out of funds soon after before all of the debris could be removed (USFWS, n.d.). Over the next 14 years, the remaining vessel debris was removed by the U.S. Coast Guard (USCG), Pacific Strike Team, U.S. Fish and Wildlife Service (USFWS), American Samoan Government, National Pollution Funds Center (NPFC), Hawai’i Undersea Research Laboratory (HURL), and NOAA (Figure 14), and research studies were simultaneously conducted. Research studies conducted by the USCG and USFWS, from 1993 to 2001, described the physical and chemical disturbances to the coral reef ecosystem, and the studies found that about one-third of the coral reef was destroyed and early algal-blooms were dominating the coral reef (USFWS, 2001; Green, 1997; Capune 1995). Then, in 2004, the two benthic habitat
maps were derived by NOAA’s NCCOS Biogeography Team.

In this research study, *in situ* (in the field) data that were acquired during March 2006 and March 2010, as part of ASRAMP research cruises, were available. The *in situ* data were benthic images, and the images were used to derive benthic habitat maps for 2006 and 2010. The 2006 and 2010 benthic habitat maps derived are similar to the map derived in 2004 by NOAA’s NCCOS Biogeography Team, and they were all compared to each other in a spatial and temporal analysis.

![A Brief History of Rose Atoll](image)

1.3.3 Purpose and Objectives

The purpose of this research study was to assess the changes that have occurred to the coral reef ecosystem on Rose Atoll in response to the Jin Shiang Fa vessel debris. In order to accomplish this, two objectives were met. The first objective was to derive comprehensive benthic habitat maps for Rose Atoll for 2004, 2006, and 2010. The second objective was to perform a spatio-temporal analysis of the benthic habitat during the three time frames using the derived maps.

1.3.4 Significance

The derived benthic habitat maps for Rose Atoll for 2006 and 2010 will show two major characteristics: Biological Cover Types and Percentages of Biological Cover Types. These two characteristics are very important in assessing and monitoring coral reef ecosystems, and therefore, the derived benthic habitat maps will contribute to the management of shallow water coral reef ecosystems in the Pacific. The derived benthic habitat maps will also be shared on the PIBHMC website and internally in CREP, and this will allow researchers to use the information in their own analyses of the coral reef ecosystem on Rose Atoll.
Chapter 2. Review of Literature

The purpose of this chapter is to provide background information about the importance of benthic habitat mapping for coral reef ecosystem conservation. This chapter also provides examples of the different types of remote sensing and \textit{in situ} data that were used to derive benthic habitat maps in this research study for Rose Atoll, and literature related to the analysis of remote sensing data in terrestrial and marine ecosystems is discussed.

2.1 Background

Coral reefs ecosystems (Figure 15) provide many natural resources to humans that can be translated into a value of more than $33$ billion per year, in the form of shore protection, marine fisheries, tourism, medicines, and cosmetic products (Climate, Carbon, and Coral Reefs, 2010). Coral reefs are also the second largest contributor to Earth’s biodiversity (Knowlton \textit{et al.}, 2010), second to rainforests, and are ironically considered the “rainforests of the sea.” These underwater rainforests provide ecological services and serve as biodiversity hotspots that contribute to our health and well-being, and therefore, coral reefs need to be studied and protected.

### 2.1.1 Spatial Distribution of Coral Reefs

Corals consist of both shallow water and deep water corals. Shallow water corals are some of the less isolated and easily accessible corals and are found at depths of less than 50 meters in water about 20 degrees C (Lindner et al., 2008). Deep water corals are the more isolated and less accessible corals and are found at depths exceeding 6300 meters and in water around 4 degrees C (Cairns, 2007; Freiwald, 2002; Roberts 2009). Deep water corals are still found in shallow water areas, but they are more tolerant of deeper depths and no sunlight than shallow water corals. Major advancements in remote sensing technology, such as Remotely Operated Vehicles (ROVs), Unmanned Aircraft Systems (UASs), unmanned submersibles, have made access to deep sea corals easier, which have increased the discovery and study of these difficult to access organisms as well as the threats to these ecosystems.
2.1.2 Threats to Coral Reefs and Benthic Habitat Mapping

Corals are fragile organisms that are impacted by natural stressors and anthropogenic stressors (Hughes et al., 1990; Chumkiew et al., 2011, Hallock, 2005). Natural stressors include climate changes brought on by El Nino and La Nina events. Anthropogenic stressors include wasteful fishing practices, oil spills, industrial and agricultural runoff, increased greenhouse emissions, and deep-sea oil mining, and sometimes we may not initially relate these to stressors as threats to corals. Anthropogenic stressors indirectly and directly change the water quality and clarity, making it difficult for corals to survive. One example of an anthropogenic stressor is the effects of greenhouse gases on corals. Increased greenhouse gas emissions in the atmosphere contribute to increasing ocean temperature, which causes corals to bleach (lose their photosynthetic zooxanthellae) and eventually die from starvation (Mónaco et al., 2012). In order to assess the impacts that anthropogenic stressors have on fragile coral reef ecosystems, benthic habitat maps need to be created, and the creation of one map requires different types of data.

2.2 Data Types in the Benthic Habitat Maps in this Research Study

The derived benthic habitat maps created in this research study consist of three different types of data: multispectral satellite imagery (which was used first to derive bathymetry, or water depths), multibeam and single beam bathymetry (which were used second as ground-truth data to validate the derived bathymetry), and benthic imagery (which was used last to validate the derived benthic habitat in the final steps). The most important aspect of the multispectral satellite imagery was the resolution of the imagery, because the accuracy of all of
the derivatives (derived bathymetry, derived geomorphological features, and derived benthic habitat) depended on high-resolution satellite imagery. The most important aspect of the multibeam and single beam bathymetry was to make sure there were enough data points evenly distributed across Rose Atoll, because the validation and accuracy of the derived bathymetry depended on an even distribution of ground-truth data across the study area. Lastly, the most important aspects of the benthic imagery were the image resolution, color balance, and accurate classification, because the validation of the derived benthic habitat relied on the image quality and accurate classification assigned to each image in the post-processing steps.

2.2.1 Multispectral Satellite Imagery

The satellite imagery that was used to derive the benthic habitat maps for 2004 and 2006 were two multispectral IKONOS-2 satellite images, while the imagery that was used to create the derived benthic habitat map for 2010 was a multispectral WorldView-2 satellite image. The IKONOS-2 satellite (Figure 16), also referred to as the IKONOS satellite, was the first commercially available high-resolution satellite that was launched into orbit on September 24, 1999 from Vandenberg Air Force Base, California (Satellite Imaging Corporation, 2017; Space Imaging, 2000). The satellite (now decommissioned) was operated by DigitalGlobe and consisted of two sensors that were capable of capturing 3.28 meters multispectral imagery (4 standard colors: Blue, Green, Red, and Near-Infrared) and 0.82 meter panchromatic imagery (Black and White) at nadir, or directly below the sensors, (Space Imaging, 2000) (Table 1).

Table 1. The two sensors on the IKONOS-2 satellite, their respective spectral bands, and the spectral band ranges.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Spectral Bands</th>
<th>Spectral Band Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral</td>
<td>Band 1 = Blue</td>
<td>445 – 516 µm</td>
</tr>
<tr>
<td></td>
<td>Band 2 = Green</td>
<td>506 – 595 µm</td>
</tr>
<tr>
<td></td>
<td>Band 3 = Red</td>
<td>632 – 698 µm</td>
</tr>
<tr>
<td></td>
<td>Band 4 = NIR</td>
<td>757 – 853 µm</td>
</tr>
<tr>
<td>Panchromatic</td>
<td>Pan</td>
<td>757 – 853 µm</td>
</tr>
</tbody>
</table>
Additionally, the image swath, or area of coverage, that was captured by the sensors was about 128 square kilometers (11.3 kilometers swath width) at nadir (Space Imaging, 2000), which is equivalent to about 32,000 acres or 50 square miles. This area is about three-fifths the area of American Samoa or about half the area of Honolulu, Hawai‘i. Imagery from the IKONOS-2 satellite had an accuracy of 9 meters (DigitalGlobe Press Releases, 2014), which was improved in future commercially available satellites. IKONOS-2 satellite imagery is still used for a variety of purposes, including to map urban and rural areas (Agüera et al., 2008; Greenhill et al., 2003), natural resource management (Gillespie et al., 2008; Dechka et al., 2002), agriculture and forestry analysis (Pu and Landry, 2012; Chubey et al., 2006), disaster management (Van der Sande et al., 2003; Van Westen, 2000), tax analysis (Monmonier, 2004; Rundquist et al., 2002), mining (Li-jun, et al., 2016), construction (Cai, et al., 2016), engineering (Al-Khudhairy et al., 2005), and change detection (Hofmann and Bekkarnayeva, 2017; Niemeyer and Canty, 2003). In addition, the Satellite Imaging Corporation has purchased IKONOS-2 satellite imagery of areas around the world for use in media and motion pictures, and the high-resolution aspect of the IKONOS-2 satellite sensors make the imagery popular in homeland security, coastal monitoring, 3D Digital Terrain Models (DTMs), and Digital Elevation Model (DEM) (Satellite Imaging Corporation, 2017). Figure 17 is an example of an IKONOS-2 satellite image of Bora Bora, French Polynesia, which could be used to derive the benthic habitat of the coral reef.
Figure 17. This is an example of a multispectral IKONOS-2 satellite image of Bora Bora, French Polynesia (resolution unknown). The resolution of this image is not as fine as the WorldView-2 image. (Source: Satellite Imaging Corp. (n.d.). IKONOS Satellite Image Gallery. Retrieved June 07, 2017, from http://www.satimagingcorp.com/gallery/ikonos/).
The WorldView-2 satellite (Figure 18) is another, more improved, satellite also operated by DigitalGlobe. The WorldView-2 satellite is the most spectrally diverse, commercial satellite, which was launched into orbit on October 8, 2009 from Vandenberg Air Force Base, California (Satellite Imaging Corporation, 2017). The satellite consists of two sensors that are capable of capturing 1.85 meters 8-band multispectral imagery (4 standard colors: Red, Blue, Green, Near-Infrared 1, and 4 new colors: Red Edge, Coastal, Yellow, Near-Infrared 2) and 0.46 meter panchromatic imagery (black and white) at nadir (Satellite Imaging Corporation, 2017) (Table 2).

Table 2. The two sensors on the WorldView-2 satellite, their respective spectral bands, and the spectral band ranges.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Spectral Bands</th>
<th>Spectral Band Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multispectral</td>
<td>Band 1 = Coastal Blue</td>
<td>400 – 450 nm</td>
</tr>
<tr>
<td></td>
<td>Band 2 = Blue</td>
<td>450 – 510 nm</td>
</tr>
<tr>
<td></td>
<td>Band 3 = Green</td>
<td>510 – 580 nm</td>
</tr>
<tr>
<td></td>
<td>Band 4 = Yellow</td>
<td>585 – 625 nm</td>
</tr>
<tr>
<td></td>
<td>Band 5 = Red</td>
<td>630 – 690 nm</td>
</tr>
<tr>
<td></td>
<td>Band 6 = Red Edge</td>
<td>705 – 745 nm</td>
</tr>
<tr>
<td></td>
<td>Band 7 = NIR1</td>
<td>770 – 895 nm</td>
</tr>
<tr>
<td></td>
<td>Band 8 = NIR2</td>
<td>860 – 1040 nm</td>
</tr>
<tr>
<td>Panchromatic</td>
<td>Pan</td>
<td>450 – 800 nm</td>
</tr>
</tbody>
</table>

The image swath that can be covered by the WorldView-2 satellite is about 269 square kilometers (16.4 kilometers swatch width) at nadir (WorldView-2 Datasheet, 2017), which is equivalent to about 66,500 acres or about 104 square miles. An area of 104 square miles is equivalent to the area of Saint Kitts and Nevis in the Caribbean, which is the eighth smallest country by area in the world (Rosenberg, 2017). The WorldView-2 satellite is the first of its kind to collect spatial imagery via a paintbrush-like sweeping motion at an altitude of about 770 kilometers (Spatial Imaging Corporation, 2017). The back and forth sweeping motion allows the satellite to collect very large sets of imagery in a single pass, roughly 1 million square kilometer images per day, which allows the satellite to revisit areas more than once and provide the most same-day image sweeps of any commercial high-resolution satellite (Satellite Imaging Corporation, 2017). Additionally, WorldView-2 satellite imagery has been demonstrated to be less than 3.5 meters accurate (WorldView-2 Datasheet, 2017; DigitalGlobe Press Releases,
2014), which is important in small scale analyses, such as precise change detection (de Alwis Pitts and So, 2017; Tian et al., 2014) and fine-scale mapping (Kaszta et al., 2017; Rapinel et al., 2014). Figure 19 is an example of a WorldView-2 image of the Great Barrier Reef, which could also be used to derive the benthic habitat.

Figure 19. An example of a WorldView-2 satellite image. This is a 0.5 meter resolution image of the Great Barrier Reef, and the shallow coral reefs (brown areas) are very high-resolution. (Source: Kramer, H. J. (2002). WorldView-2. Retrieved June 07, 2017, from https://directory.eoportal.org/web/eoportal/satellite-missions/v-w-x-y-z/worldview-2).
The IKONOS-2 satellite image that was used by NOAA’s NCCOS Biogeography Team to create the 2004 benthic habitat maps for Rose Atoll is described in Chapter 3. The IKONOS-2 satellite image that was used in this research study to create the 2006 benthic habitat maps used the same IKONOS-2 satellite image, because it was the only image available during this time. Finally, the WorldView-2 satellite image that was used to create the 2010 benthic habitat maps is described in Chapter 3.

2.2.2 Multibeam and Single Beam Bathymetry

Multibeam and single beam bathymetry data sets were used to validate the IKONOS-2-derived bathymetry for the 2006 benthic habitat map and the WorldView-2-derived bathymetry for the 2010 benthic habitat map, respectively. The multibeam and single beam bathymetry data sets served as ground truth data that were used to validate the accuracy of the satellite-derived bathymetry data sets. Multibeam bathymetry is simply water depth data that is collected using sound waves emitted by a multibeam echo sounder (Figure 20), which is a type of sonar that is mounted to the hull of large ships and used to map the seafloor (De Moustier and Matsumoto, 1993). Multibeam echo sounders were developed in the 1970s and are one of the most accurate ways to acquire high-resolution bathymetric data, however, the accuracy of the bathymetric data decreases with depth, beam width, and tile angle of the beam (Svarog, 2002). In order to acquire accurate, high-resolution multibeam bathymetry from both shallow and deep depths, multibeam echo sounders can be used at higher frequencies up to 450 kHz to map shallow coastal water and the continental shelf, or at lower frequencies down to 12 kHz to map the deep ocean (Beaman, n.d.). The multibeam echo sounder also tracks and records the
position of the vessel and the vessel motion (i.e. gyro heading, heave, pitch and roll) in order to produce highly accurate bathymetry (Beaman, n.d.). Furthermore, a multibeam echosounder gets its name from the multiple beams, or soundings, that are emitted in a swath-like pattern over the seafloor, which allow a vessel to collect bathymetry over a larger area with greater overlap (NOAA, 2015). The highly accurate, high-resolution bathymetry acquired from a multibeam echo sounder is a very dense data set that can be used to generate spectacular 3D depth models (Figure 21), which are valuable in natural resource management and coastal mapping.

Figure 20. An illustration of how multibeam bathymetry is acquired using a multibeam echo sounder attached to the hull of a NOAA research vessel (left). Acoustic (sound) waves are emitted from the multibeam echo sounder, and the amount of time that it takes for the sound wave to return to the vessel is used to determine the water depth. The water depth is then used to map the seafloor. This concept is similar to echolocation that bats and odontocetes (toothed whales) use to determine the position of objects (right). (Source: James, S. N. (n.d.). Filling in the Gaps – Part II. Retrieved June 07, 2017, from https://schmidtocean.org/cruise-log-post/filling-in-the-gaps-part-ii/).
Single beam bathymetry, on the other hand, is another type of bathymetric data that is acquired using an older type of sonar known as a single beam echo sounder (Figure 22).

Single beam echo sounders came into use between the 1940s and 1980s to eliminate the use of lead line surveys that were used to measure depth soundings (U.S. Office of Coast Survey, n.d.). A single beam echo sounder gets its name from the single beam that is emitted over the seafloor, resulting in a less dense data set (Alvarado, 2011). The fact that single beam bathymetric data is less dense than multibeam bathymetric data means that the features of the seafloor are more generalized than detailed, and singlebeam bathymetry is not ideal for
Figure 22. An illustration of the three techniques that have been used to acquire bathymetric data (water depth). From left to right, lead line surveys have the least accuracy while multibeam echo sounders have the highest accuracy. (Source: United States Office of Coast Survey. (n.d.). Title. Retrieved June 07, 2017, from https://www.nauticalcharts.noaa.gov/mcd/learnnc_surveytechniques.html).

generating spectacular 3D depth models. Singlebeam echo sounders also cover a narrower swath than multibeam bathymetry (Figure 23), but single beam echo sounders track and record the vessel position and movements just like multibeam echo sounders do. In this research study, singlebeam bathymetry was the only bathymetric data available to validate the WorldView-2-derived bathymetry for the 2010 benthic habitat map.
NOAA’s NCCOS Biogeography Team did not derive bathymetry or geomorphological features of the seafloor from the IKONOS-2 satellite image. Instead the benthic habitat was derived directly from the satellite image using object-based classification (NCCOS, 2005). This method was not used in this research study to derive benthic habitat for 2006 and 2010, because it was very difficult to assign a single pixel value to classify all of the corals, macroalgae, and turf algae. Instead, bathymetry was derived from the satellite images and from there the benthic habitat was derived. Furthermore, the multibeam bathymetry that was used to validate the IKONOS-2-derived bathymetry for 2006 and the single beam bathymetry that was used to validate the WorldView-2-derived bathymetry for 2010 are described Chapter 3.

2.2.3 Benthic Imagery (Ground Truth Data)

Figure 24. A 1 meter resolution benthic image of the coral reef on Rose Atoll acquired on March 18, 2015 during a towed diver survey. Crustose coralline algae is noticeable pink. (Source: CREP server with special permission).
Benthic images are simply photos of the seafloor (Figure 24) that are used as ground truth data in benthic habitat mapping, in order to validate benthic habitat classifications derived from other data sets (González-Rivero 2014; Beijbom 2012; Monaco, 2012; Costa, 2009; NCCOS, 2005; Kenyon et al., 2004). Benthic images are collected during benthic habitat assessments, which can be conducted using trained divers, Remotely Operate Vehicles (ROVs), or manned submersibles. Descriptive and visual data are collected during benthic habitat assessments, but in some cases, both types of data are not always collected. In this research, the ground truth data was both descriptive and visual, but the collection techniques were not the same for the three years. Two different techniques were used by NOAA’s NCCOS Biogeography Branch and by CREP to acquire the benthic imagery that was gathered for this research study.

NOAA’s NCCOS Biogeography Team used a stratified random sampling method to conduct benthic habitat assessments of Rose Atoll in 2004, in order to validate the benthic habitat derived from the IKONOS-2 satellite imagery (NCCOS, 2005). This means that after the benthic habitat was derived from the IKONOS-2 satellite image in the lab, assessment sites for the collection of benthic images were selected randomly within each habitat type and spectral signatures of the satellite image (NCCOS, 2005; Congalton, 1991). This selection process (Figure 25) was performed on a computer. The GPS coordinates of the assessment sites were saved,
Figure 25. Assessment sites assigned to Cocos Lagoon, Guam in a stratified random sampling technique. The goal is to have an even distribution of assessment sites over the entire area. (Source: NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.).

and the sites were visited and marked in the field using a drop weight (NCCOS, 2005). Three benthic habitat assessments were made at each site: (1) the area within 1 square meter around the weight was surveyed, and site ID and depth were recorded, (2) the most common habitat type within a 7 meter radius around the weight was identified, and (3) the second most common habitat type within the same 7 meter radius was identified (NCCOS, 2005). Additionally, in order to eliminate bias in the accuracy assessment process, an independent team conducted the site assessments (NCCOS, 2005). All of the data collected from the assessment sites were descriptive site data, and no benthic images were collected or classified as in the 2006 and 2010 benthic habitat maps. The images in Figures 26-29 were used in the NCCOS literature to describe the habitat types derived from the IKONOS-2 satellite image.


CREP used a different technique to acquire benthic images of Rose Atoll, which were used for the 2006 and 2010 benthic habitat maps. The benthic images were collected via towed diver surveys (Figure 30) during the American Samoa Reef Assessment and Monitoring Program (ASRAMP) research cruises in 2006 and 2010. Towed diver surveys are a technique used by CREP since 2002 to acquire accurate, high-resolution (1 meter resolution) benthic images, which are used to verify the benthic habitat derived from other data sets (Ferguson et al., 2016; NOAA PIFSC, n.d.). During a towed diver survey, two NOAA-certified, trained SCUBA divers hover about 1 meter from the seafloor and are slowly towed (with 60 meters of tow line) along the seafloor at a rate of about 0.89 meters per second (about 2 miles per hour) (Ferguson et al., 2016). The two divers each hold on to a towboard device, which is a large board that has been equipped the following: a downward-facing Canon™ EOS-50D² digital still camera enclosed in a Sexton™ waterproof housing, a forward-facing GoPro® Hero 3+ Silver Edition HD digital video camera in a waterproof housing, a clipboard with StarBoard™ waterproof vinyl sheets, gauges for depth, time, and pressure, and two Ikelite™ DS-50 or 51 strobes affixed to the bottom. The downward-facing camera is set to take pictures of the seafloor every 15 seconds while the two divers are towed by the boat about 200 meters along the seafloor (Ferguson et al., 2016). All of the benthic images that are acquired from towed diver surveys are processed in a photo software program known as Picasa before classification by an analyst, in order to correct for the color and image brightness lost at deep depths (Ferguson et al., 2016). The benthic images acquired from Rose Atoll in 2006 and 2010 are explained in Chapter 3.
Figure 30. The SCUBA gear and towboard equipment that each NOAA-certified, trained SCUBA diver has in order to perform towed diver surveys (top) and an illustration of a towed diver survey (bottom). (Source: NOAA CREP. (n.d.). Survey Methods. Retrieved June 07, 2017, from https://www.pifsc.noaa.gov/cred/survey_methods.php#habitat_mapping).
2.3 Benthic Imagery Analysis Techniques

In benthic habitat mapping, benthic imagery serves as some of the most important ground truth data. Ground truth data is used to validate the habitat types that are derived from other data sets, like satellite imagery. Benthic images are analyzed and classified according to a standardized classification scheme, which is developed simultaneously when creating a benthic habitat map. CREP has several classification schemes for classifying benthic images, but this process is moving toward being more standardized across NOAA. Recently, the Coastal and Marine Ecological Classification Standard (CMECS) has released a national classification scheme that will be incorporated into all NOAA benthic habitat maps in the future (NatureServe, n.d.).

In benthic habitat mapping, benthic imagery is classified in one of two ways: manually or automatically.

2.3.1 Manual Analysis

In manual analysis, benthic images are individually classified by a coral analyst on a computer monitor, using image analysis software and a classification scheme (previously determined). There is a variety of image analysis software programs that are used to analyze benthic imagery today, and many software programs are offered by underwater cameras manufacturers. The image analysis software that is currently used in CREP to analyze benthic imagery is known as Coral Point Count with Excel Extensions 4.1, or CPCe, (Kohler and Gill, 2006) (Figure 31). CPCe is a Windows-based,
image analysis software that is provided as freeware by the National Coral Reef Institute (NCRI). CPCe is used by scientific institutions and researchers to analyze large data sets of benthic imagery, in order to determine the amount of habitat cover in the entire dataset (Kohler and Gill, 2006). The data can then be exported and analyzed in MS Excel.

Let’s use an example data set of 10,000 benthic images, which is the approximate number of images that are classified in CREP from an ASRAMP data set. In CPCe, each benthic image is uploaded and superimposed with randomly assigned points. The number of points per image is determined by a number of factors, including the analyst’s capabilities, the quality of the images, and the overall purpose of the benthic habitat map. Once all of the images in a data set have superimposed points on them, they are saved as individual JPEG files. This process saves the images and the points together, which can be used in the future for evaluations and calibrations between analysts. The manual analysis process ideally takes about 250 days (about 8 months) to complete for a dataset of about 10,000 images (Beijbom et al., 2012). This estimate assumes that a coral analyst analyzes benthic images at a rate of approximately 40 images per day and also has other work projects (Beijbom et al., 2012). Manual analysis of benthic imagery is an arduous and exhaustive process, because an analyst is staring at a computer monitor for hours (Beijbom et al., 2015; Beijbom et al., 2012), and this explains the current popularity of automated and semi-automated analysis techniques.

2.3.2 Automated and Semi-Automated Analyses

In automated and semi-automated analyses, benthic images are classified completely by a computer (automated), or partially by a computer (semi-automated). Just like with manual
image analysis, there is also a variety of software programs that are used to automate this process. A semi-automated, online program that is currently being tested in CREP is a program known as CoralNet (Beijbom et al., 2012) (Figure 32). CoralNet is an online data repository and classification program for benthic imagery that was developed in 2012 by UCSD Ph.D. student Oscar Beijbom. CoralNet was released in 2012 and has evolved into an updated version known as CoralNet Beta (Beijbom et al., 2015). CoralNet Beta allows scientific institutions and researchers to directly upload a small subset of benthic imagery to the online program and train the program’s algorithms (Beijbom et al., 2015; Beijbom et al., 2012). The algorithms are then used to analyze the remaining subset of imagery.

Let’s use the same example of 10,000 benthic images. The same 10,000 images can be analyzed in about one day with an automation program, such as CoralNet (Beijbom et al., 2012). This program has the potential to significantly increase an analyst’s capacity to analyze large subsets of benthic imagery, which increase the validity of benthic habitat maps. There has been a lot of improvements in automated and semi-automated analysis techniques (Stokes and Deane, 2009, Aguzzi et al., 2011, and Shihavuddin et al., 2013), because the principles and theories of computer-assisted analysis have been around for a long time.

Automated and semi-automated image analyses, collectively referred to as Computer Image Analysis (CIA), were developed in the early 1960s, using the principles of a Support Vector Machine (SVM)(Noble, 2006). A SVM is founded on the theory of Computer Learning,
also referred to as the Vapnik-Chervonenkis theory, VC theory, or theory of Statistical Learning (Bousquet et al., 2004; Noble, 2006). These theories collectively attempt to explain the learning process of a computer in a mathematical or statistical respect. The principles stipulate that in order for a computer to learn how to analyze data, a subset of analyzed data must be provided to the computer (Beijbom, et al., 2012; Noble, 2006; Bousquet et al., 2004). In benthic imagery analysis, this means that a subset of benthic photos that have already been analyzed must be provided to the computer, in order to analyze the remaining images. Throughout the 1960s and 70s, SVMs became more sophisticated in the types of patterns that they could detect, and they became popular in many professional fields for predicting events (Noble, 2006; Andrew, 2000). SVMs have been used to predict bankruptcy (Min and Lee, 2005; Fan and Palaniswami, 2000), analyze credit risk (Yu et al., 2010; Yu and Cao, 2009), forecast finances (Cao and Tay, 2001), classify cancer tissue (Furey et al., 2000), and in mathematics (Tian et al., 2012).

2.3.3 Accuracy of Manual, Automated, and Semi-Automated Techniques

Thus far, the manual analysis of benthic imagery is most accurate method, because every image is personally inspected during analysis. However, with automated and semi-automated analysis, the accuracy can vary, because each image in the subset that is analyzed by the computer’s trained algorithms is not personally inspected after analysis. Other factors, such as the quality of the imagery in the training subset and the number of images available for each category of habitat can significantly affect the accuracy of the results (Beijbom et al., 2012). In the example of CoralNet, the accuracy of the computer analysis is provided to researchers in terms of kappa statistics and a confusion matrix (Beijbom et al., 2012). For the purpose of this
research study, however, all of the benthic imagery that was gathered was manually analyzed, in order to ensure that each image was accurate.

2.4 Conclusion

After reading this chapter, it’s clear to see how many types of data go into creating a benthic habitat map. In many cases, one of these data types may be unavailable or inaccessible, and this leads to methodologies to work around that issue. In this research study, there were difficulties in trying to gather enough data to create accurate and meaningful benthic habitat maps for Rose Atoll, and these difficulties were overcome by incorporating data from different Sources and different years. The three derived benthic habitat maps were named according to the three collection dates of the benthic imagery: 2004, 2006, and 2010. Therefore, in the remaining 3 chapters of this thesis, the three maps are referenced as the “2004 Benthic Habitat Map”, “2006 Benthic Habitat Map”, and “2010 Benthic Habitat Map”.

Chapter 3. Methods

The focus of this chapter is to describe the data in each of the three benthic habitat maps and also explain the methods that were used to derive bathymetry from multispectral satellite imagery, derive geomorphological features of the seafloor from bathymetry, perform a Principal Component Analysis (PCA) on the geomorphic layers, and finally, classify the benthic habitat. All of the data were gathered from either the PIBHMC website or internal CREP servers with special permissions, and throughout this chapter, each subsection references the location from where the data were gathered.

3.1 Data Collected for the 2004 Benthic Habitat Maps

The 2004 benthic habitat map of Rose Atoll was already completed and gathered from a 2005 publication by NOAA’s NCCOS Biogeography Team (NCCOS, 2005). The benthic habitat map was created with two data sets: 1) an IKONOS-2 satellite image and 2) descriptive data about the benthic habitat during field assessments.

The first data set was a 4 meter resolution, multispectral IKONOS-2 satellite image (Figure 33), which was acquired on March 5, 2002 by GeoEye (now known as DigitalGlobe). The image was purchased by NOAA’s NCCOS Biogeography Team for benthic habitat mapping, and the image was made available on internal CREP servers. The image was corrected for geometric distortions, which are distortions in an image that can be caused by the perspective of the satellite sensor optics, the motion of the platform, the curvature and rotation of the Earth, the altitude, attitude, and velocity of the platform, or the terrain relief (Richards and Richards,
The correction for this distortion was accomplished in ArcGIS in which the image was projected in the correct coordinate system WGS 84 UTM Zone 2S (the Universal Transverse Mercator zone for American Samoa) by NOAA’s NCCOS Biogeography Team. The second data set was descriptive data from benthic habitat assessment sites, which were acquired by NOAA’s NCCOS Biogeography Team in 2004. These data are not included in the 2005 publication, but the shapefiles for the published benthic habitat map were found online. The attribute data from these shapefiles were used in this research study to calculate area of each benthic habitat types: Coral, Coralline Algae, Macroalgae, and Turf Algae.

Figure 33. The 4 meter resolution, multispectral IKONOS-2 satellite image of Rose Atoll, AS that was used by NOAA’s NCCOS Biogeography Team to derive the benthic habitat in their 2005 publication. (Source: CREP server with special permission).
3.2 Data Collected for the 2006 Benthic Habitat Maps

The 2006 benthic habitat maps were derived using three types of data: (1) an IKONOS-2 satellite image, (2) multibeam bathymetry, and (3) benthic imagery. The first data set was the same 4 meter resolution, multispectral IKONOS-2 satellite image that was used in the NCCOS 2005 publication (Figure 33). The same satellite image was used in this map, because there were no other satellite images available in CREP during 2006. The second data set was 5 meter resolution, multibeam bathymetry of the slope environments and inner lagoon of Rose Atoll (Figure 34). This data was acquired from February to March 2006, aboard CREP’s Acoustic Habitat Investigator (AHI) research vessel, which is launched from the NOAA Ship *Hi’ialakai* (Figure 35).

The *Hi‘ialakai* is a 224 foot, oceanographic research vessel operated by the NOAA OMAO and is the only federally commissioned research vessel in the U.S. used for ocean exploration, coral reef ecosystem mapping, and fish stock and coral reef health surveys (Marine Operation, 2017). The ship is equipped with a 30 kHz Simrad EM300 sonar, which was used to collect deep sea multibeam bathymetry around Rose Atoll in 2006. The *AHI* is a 25 foot research vessel that is launched from the NOAA Ship *Hi‘ialakai* in order to conduct shallow water coral reef surveys (NOAA PIFSC, n.d). The *AHI* is equipped with a 240 kHz Reson 8101ER sonar, which was used to collect shallow water multibeam bathymetry of the outer slopes and inner lagoon areas of Rose Atoll in 2006. The *AHI* is mostly used by CREP for seafloor mapping, and the vessel is equipped with three survey sensors in total: (1) a 240 kHz Reson 8101ER multi-beam sonar which
provided bathymetry and imagery, (2) a TSS/Applanix POS/MV Model 320 which measured position, velocity, attitude, and heading, and (3) a Seabird SBE 19 CTD which measured sound velocity profiles (NOAA PIFSC, n.d.). The third data set was benthic imagery collected around the slope environment and inner lagoon of Rose Atoll in March 2006 via towed diver surveys during the ASRAMP research cruise. The benthic images used in this map were similar to the image in Figure 24. A total of 1,845, 1 meter resolution benthic images were used to validate the derived benthic habitat classification for the 2006 benthic habitat map.

3.3 Data Collected for the 2010 Benthic Habitat Maps

The 2010 benthic habitat maps were derived using three types of data: (1) a WorldView-2 satellite image, (2) single beam bathymetry, and (3) benthic imagery. The first data set was a 2 meter resolution, multispectral (8 band) WorldView-2 satellite image of Rose Atoll (Figure 36), which was acquired on Dec 6, 2009 by DigitalGlobe. The third data set was benthic imagery collected around the slope environment and inner lagoon of Rose Atoll during March 2010 via towed diver surveys. These images are also similar to the image in Figure 24. A total of 652, 1 meter resolution benthic images were used to validate the derived benthic habitat classification for the 2010 benthic habitat map. Finally, Table 3 shows the data sets that were used to derive each of the three benthic habitat maps, and to clarify, the 2004 benthic habitat map was retrieved from a 2005 NCCOS publication (NCCOS, 2005), whereas the 2006 and 2010 benthic habitat maps were created during this research study.
Figure 36. The entire 2 meter resolution, multispectral (8 band) WorldView-2 satellite image that was used to derived the benthic habitat map for Rose Atoll for 2010. The image was acquired on December 6, 2009 and later purchased by NOAA for benthic habitat mapping. (Source: CREP server with special permission).

Table 3. The data sets that were used to derive each of the three benthic habitat maps for Rose Atoll. The three maps represent the benthic habitat for Rose Atoll before (2004) debris removal, during (2006) debris removal, and after (2010) debris removal of shipwreck debris left from the Jin Shiang Fa fishing vessel.

<table>
<thead>
<tr>
<th>2004 Benthic Habitat Maps</th>
<th>2006 Benthic Habitat Maps</th>
<th>2010 Benthic Habitat Maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>IKONOS-2 satellite imagery</td>
<td>IKONOS-2 satellite imagery</td>
<td>WordView-2 satellite imagery</td>
</tr>
<tr>
<td>Benthic habitat assessments (descriptive data)</td>
<td>Multibeam bathymetry</td>
<td>Single beam bathymetry</td>
</tr>
<tr>
<td></td>
<td>Benthic imagery</td>
<td>Benthic imagery</td>
</tr>
</tbody>
</table>
3.4 Data Analysis: Benthic Habitat Mapping Procedure

To reiterate, only the 2006 and 2010 benthic habitat maps were derived for Rose Atoll in this research study. The 2004 benthic habitat maps were retrieved from a 2005 NCCOS publication (NCCOS, 2005). Subsections 3.4.1-3.4.4 describe the procedure that was used to derive benthic habitat maps for Rose Atoll for 2006 and 2010.

3.4.1 Derive Bathymetry

The first step in the benthic habitat mapping procedure was to derive bathymetry (water depth) from the two satellite images. For the 2006 benthic habitat map, bathymetry was previously derived from the IKONOS-2 satellite image by CREP, and this bathymetry was merged with multibeam bathymetry to create seamless bathymetry for Rose Atoll (Figure 37). Figure 38 shows the two sources of bathymetry that were used to create one seamless bathymetric product.
Figure 38. This image shows the two data sets that were merged together to create one single data set (Source: NOAA CREP. (2010). Rose Atoll: Bathymetry. Retrieved June 07, 2017, from http://www.soest.hawaii.edu/pibhmc/cms/data-by-location/american-samoa/rose-atoll/rose-atoll-bathymetry/).

For the 2010 benthic habitat map, there was no bathymetry on PIBHMC, and therefore the bathymetry needed to be derived from the WorldView-2 satellite image in. The procedure to derive bathymetry from the WorldView-2 satellite image was adapted from methods developed by CREP’s Ecospatial Team to derive bathymetry from WorldView-2 satellite imagery (Ehses and Rooney, 2015). The process involved 7 steps: 1) Georectify the satellite image and extract any clouds, land masses, boats, and waves, 2) Examine the ground truth data, 3) Convert the digital numbers (DNs) and reflectance to Top of Atmosphere (TOA) radiance, 4) Create and examine a
set of sample pixels, 5) Remove the sun glint from the satellite image ("de-glint" the image), 6) Compare the derived depths to the ground truth data, and 7) Extract the bathymetry values from the final “de-glinted” image and perform an error analysis.

3.4.1.1 Georectify the Satellite Imagery

In step 1, the image was opened in ArcGIS and projected in the correct coordinate system for Rose Atoll (UTM Zone 2S). The two islets on Rose Atoll, clouds, and nearshore waves were masked out using the Create Feature Class tool and Extract by Mask tool. The final image was then saved as a TIFF (Tag Image File Format) file, in order to be opened in another program.

3.4.1.2 Examine the Ground Truth Data

In step 2, the ground truth data was examined and projected in the correct coordinate system for Rose Atoll. The ground truth data were 2012 and 2015 NMEA GPS single beam bathymetry data sets, which consisted of 26,629 and 33,045 GPS points, respectively (Figure 39). Data points for 0-30 meters were extracted, and the two data sets were merged into one dataset. The Subset Features tool in ArcGIS was used to separate the entire data set into two subsets: one for the Model Builder and one for Error Analysis.

________________________

1 National Marine Electronics Association
Figure 39. The two single beam bathymetric data sets that were used to validate the bathymetry derived from the WorldView-2 satellite images for the 2010 benthic habitat map. The land masses for the two islets on Rose Atoll are masked out (Step 1). (Source: CREP servers with special permission.)

3.4.1.3 Convert DNs and Reflectance to TOA radiance

In step 3, the georectified TIFF file was opened in Environment for Visualizing Images (ENVI) 5.0, an image analysis software, and the Red, Green, and Blue (RGB) bands were assigned to Bands 5, 3, and 2, respectively. The digital number and reflectance values of all of the 8 bands were converted to TOA radiance using the equation below (Equation (1)), in order to atmospherically correct the image. The Absolute Calibration Factor and the Effective Bandwidth are data that were found in the metadata for the WorldView-2 satellite image.

\[
\text{TOA Radiance} = \text{Absolute Calibration Factor} \times \text{Effective Bandwidth} \tag{1}
\]
3.4.1.4 Analyze a Set of Sample Pixels

In step 4, the spectral radiances of 5 of the 8 bands (Band 1 = Coastal Blue, Band 2 = Blue, Band 3 = Green, Band 4 = Yellow, Band 5 = Red) were analyzed in response to the depth (Band 6 = NIR1), in order to “de-glint” the image in the next step. In order to do this, a sample set of pixels, also known as a Region of Interest (ROI), were selected from the image. The ROI was required to have no visible sun glint and a homogenous bottom type (no underwater substrate or interferences). Then, a Linear Regression in MS Excel was performed on each band versus the depth (NIR1 band) in MS Excel, using scatterplots and the RSQ function. The correlation ($R^2$ value) between the depth band (NIR1 band) and each of the colored bands (Coastal Blue, Blue, Green, Yellow, and Red) was a measure of the amount of sun glint in the ROI. A low $R^2$ value indicated a weak correlation between the depth band (NIR1 band) and colored band, which meant there was less sun glint in the ROI (a favorable ROI). A high $R^2$ value indicated a strong correlation between the depth band (NIR1 band) and colored band, which meant there was more sun glint in the ROI (an unfavorable ROI). About 20 ROIs were chosen, and the ROI with the lowest $R^2$ values for the 5 bands (Table 4) was chosen to use in the following step to “de-glint” the WorldView-2 satellite image.

<table>
<thead>
<tr>
<th>Spectral Band</th>
<th>y-intercept Equation</th>
<th>$R^2$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Band 1 = Coastal Blue</td>
<td>$y = 0.1733x + 24.205$</td>
<td>0.16</td>
</tr>
<tr>
<td>Band 2 = Blue</td>
<td>$y = 1.5357x + 58.254$</td>
<td>0.56</td>
</tr>
<tr>
<td>Band 3 = Green</td>
<td>$y = 1.639x + 25.72$</td>
<td>0.60</td>
</tr>
<tr>
<td>Band 4 = Yellow</td>
<td>$y = 0.9008x + 18.235$</td>
<td>0.20</td>
</tr>
<tr>
<td>Band 5 = Red</td>
<td>$y = 1.6036x + 5.6159$</td>
<td>0.89</td>
</tr>
</tbody>
</table>
3.4.1.5 “De-glint” the Satellite Image

In step 5, the coefficients from the y-intercept equation of each of the 5 bands (Table 4) were applied to the BandMath of the satellite image in ENVI. The coefficients were plugged into the equation below (Equation (2)), which is derived from Hedley et al., 2005, in order to remove the sun glint in satellite imagery for mapping shallow water benthic habitats. In the equation, the regression slope \( b_i \) is multiplied by the difference between the pixel NIR value \( R_{\text{NIR}} \) and the ambient NIR level \( \text{Min}_{\text{NIR}} \), and is subtracted from the pixel value in band \( i \) \( R_i \) to give the “de-glinted” pixel value of band \( i \) \( R_i' \). The \( \text{Min}_{\text{NIR}} \) is the NIR value that is expected from a pixel in the image with no sun glint, and this value was retrieved from the minimum NIR value found in the ROI. A graphical representation of the method is also shown in Figure 40, and the results from the Hedley et al. method are shown in Figure 41.

\[ R_i' = R_i - b_i (R_{\text{NIR}} - \text{Min}_{\text{NIR}}) \]
Figure 40. A graphical representation of the “de-glinting” method used in Hedley et al., 2005 to remove sun glint from satellite imagery. A linear regression is performed between the NIR band brightness (representing depth) and the visible bands (Coastal Blue, Blue, Green, Yellow, Red) using a sample set of pixels (ROI) from the image. The $R^2$ value of each visible band in the ROI is analyzed, and the coefficients of the slope-intercept equation are applied to the other pixels in the image. (Source: Hedley, J. D., Harborne, A. R., & Mumby, P. J. (2005). Technical note: Simple and robust removal of sun glint for mapping shallow-water benthos. International Journal of Remote Sensing, 26(10), 2107-2112.).

Figure 41. The results of the Hedley et al. method. The same 2 meter resolution, multispectral WorldView-2 satellite image of Rose Atoll, AS. The original "glinted" image (left) before applying the Hedley equation, and the “de-glinted” image (right) after applying the Hedley equation to the BandMath in ENVI 5.0. The “de-glinted” image (right) is now corrected for atmospheric distortion, and the sun glint over the water is removed. (Source: CREP servers with special permission).
3.4.1.6 Compare the Derived Bathymetry to the *In Situ* Bathymetry

After the *Hedley et al.* method was applied to the WorldView-2 satellite image, the image was saved as a GeoTIFF file. The GeoTIFF and the Model Builder subset were opened in ArcGIS. The Extract Multi Values to Points tool was used to extract the values from the GeoTIFF and add them to the attribute table of the Model Builder subset. The Table to Excel tool was used to convert the attribute table into an MS Excel spreadsheet. In MS Excel, a Regression Analysis was performed on the GeoTIFF values (derived bathymetry) and the Model Builder values (*in situ* bathymetry) for 12 spectral band combinations, and the $R^2$ values were compared (Table 5). A

<table>
<thead>
<tr>
<th>#</th>
<th>Spectral Band Combination</th>
<th>$R^2$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coastal Blue/Blue</td>
<td>0.54</td>
</tr>
<tr>
<td>2</td>
<td>Coastal Blue/Green</td>
<td>0.59</td>
</tr>
<tr>
<td>3</td>
<td>Coastal Blue/Yellow</td>
<td>0.42</td>
</tr>
<tr>
<td>4</td>
<td>Coastal Blue/Red</td>
<td>0.45</td>
</tr>
<tr>
<td>5</td>
<td>Blue/Green</td>
<td>0.59</td>
</tr>
<tr>
<td>6</td>
<td>Blue/Yellow</td>
<td>0.54</td>
</tr>
<tr>
<td>7</td>
<td>Blue/Red</td>
<td>0.54</td>
</tr>
<tr>
<td>8</td>
<td>Green/Yellow</td>
<td>0.61</td>
</tr>
<tr>
<td>9</td>
<td>Green/Red</td>
<td>0.61</td>
</tr>
<tr>
<td>10</td>
<td>Yellow/Red</td>
<td>0.28</td>
</tr>
<tr>
<td>11</td>
<td>Coastal Blue/Blue/Green/Yellow/Red</td>
<td>0.62</td>
</tr>
<tr>
<td>12</td>
<td>Coastal Blue/Blue/Green/Yellow</td>
<td>0.63</td>
</tr>
</tbody>
</table>

Table 5. The $R^2$ values of the 12 spectral band combinations. A low $R^2$ value means there is more sun glint in the image, where a high $R^2$ value means there is less sun glint in the image.
low \( R^2 \) value indicated a weak correlation between the derived bathymetry and \textit{in situ} bathymetry, which meant the derived bathymetry was less reliable. On the other hand, a high \( R^2 \) value indicated a strong correlation between the derived bathymetry values and the \textit{in situ} bathymetry, which meant the derived bathymetry was more reliable. An ideal \( R^2 \) value in benthic habitat mapping would be between 0.7 and 0.8, but a higher \( R^2 \) values depends on image quality and ROI preference (Hedley \textit{et al.}, 2005). The spectral band combination with the highest \( R^2 \) value was selected (Combination 12), and the \textit{Coefficients} from the Regression Analysis were applied to the image once more using an additive version of the Hedley \textit{et al.} method (Equation (3)). In the Equation 3, the spectral value \((D)\) is the sum of the Intercept \((a)\) and of the chosen spectral band combination plus the product of the regression slopes of the Coastal Blue, Blue, Green, and Yellow spectral bands \((x_1, x_2, x_3, x_4)\) and the spectral bands \((b_1, b_2, b_3, b_4)\). The following equation was applied to the BandMath of the satellite image in ENVI 5.0:

\[
D = a + (x_1)(b_1) + (x_2)(b_2) + (x_3)(b_3) + (x_4)(b_4)
\]

of the chosen spectral band combination plus the product of the regression slopes of the Coastal Blue, Blue, Green, and Yellow spectral bands \((x_1, x_2, x_3, x_4)\) and the spectral bands \((b_1, b_2, b_3, b_4)\). The following equation was applied to the BandMath of the satellite image in ENVI 5.0:

\[
D = 41.78708634 + (1.628932709*b_1) + (-0.418721129*b_2) + (0.647833516*b_3) + (-0.464801337*b_4), \text{ where } b_1 = \text{Coastal Blue}, b_2 = \text{Blue}, b_3 = \text{Green}, \text{ and } b_4 = \text{Yellow}.
\]

3.4.1.7 Extract the Derived Bathymetry

In step 7, the bathymetry was derived and an error analysis was performed. The final “de-glinted” image was saved as a GeoTIFF, and the derived bathymetry values were added to the
attribute table of the Error Analysis subset of the NMEA GPS single beam bathymetry, using the Extract Multi Values to Points tool in ArcGIS. The attribute table was extracted as an Excel spreadsheet using the Table to Excel tool, and a Regression Analysis in MS Excel was performed on the derived bathymetry and the single beam bathymetry. In order to check if the accuracy of the derived bathymetry was affected by the area of the WorldView-2 satellite image, 4 additional depth bins (<25 meters, <20 meters, <15 meters, <10 meters) were analyzed as well (Table 6). As in step 6, the $R^2$ values of the 12 spectral band combinations were compared.

Table 6. The $R^2$ values of the 12 spectral band combinations for 5 depth bins (<30m, <25m, <20m, <15m, <10m). A comparison of 5 depth bins was performed in order to test the hypothesis whether the accuracy of the derived bathymetry changed in response to the area of the WorldView-2 satellite image for Rose Atoll.

<table>
<thead>
<tr>
<th>#</th>
<th>Spectral Band Combination</th>
<th>$R^2$ value (&lt;30 m)</th>
<th>$R^2$ value (&lt;25 m)</th>
<th>$R^2$ value (&lt;20 m)</th>
<th>$R^2$ value (&lt;15 m)</th>
<th>$R^2$ value (&lt;10 m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coastal Blue/Blue</td>
<td>0.54</td>
<td>0.56</td>
<td>0.53</td>
<td>0.46</td>
<td>0.30</td>
</tr>
<tr>
<td>2</td>
<td>Coastal Blue/Green</td>
<td>0.59</td>
<td>0.64</td>
<td>0.69</td>
<td>0.71</td>
<td>0.64</td>
</tr>
<tr>
<td>3</td>
<td>Coastal Blue/Yellow</td>
<td>0.42</td>
<td>0.45</td>
<td>0.46</td>
<td>0.42</td>
<td>0.36</td>
</tr>
<tr>
<td>4</td>
<td>Coastal Blue/Red</td>
<td>0.45</td>
<td>0.49</td>
<td>0.52</td>
<td>0.51</td>
<td>0.48</td>
</tr>
<tr>
<td>5</td>
<td>Blue/Green</td>
<td>0.59</td>
<td>0.64</td>
<td>0.67</td>
<td>0.68</td>
<td>0.61</td>
</tr>
<tr>
<td>6</td>
<td>Blue/Yellow</td>
<td>0.54</td>
<td>0.56</td>
<td>0.55</td>
<td>0.50</td>
<td>0.37</td>
</tr>
<tr>
<td>7</td>
<td>Blue/Red</td>
<td>0.54</td>
<td>0.57</td>
<td>0.56</td>
<td>0.52</td>
<td>0.40</td>
</tr>
<tr>
<td>8</td>
<td>Green/Yellow</td>
<td>0.61</td>
<td>0.66</td>
<td>0.69</td>
<td>0.69</td>
<td>0.57</td>
</tr>
<tr>
<td>9</td>
<td>Green/Red</td>
<td>0.61</td>
<td>0.66</td>
<td>0.69</td>
<td>0.68</td>
<td>0.52</td>
</tr>
<tr>
<td>10</td>
<td>Yellow/Red</td>
<td>0.30</td>
<td>0.33</td>
<td>0.42</td>
<td>0.55</td>
<td>0.71</td>
</tr>
<tr>
<td>11</td>
<td>Coastal Blue/Blue/Green/Yellow/Red</td>
<td>0.62</td>
<td>0.69</td>
<td>0.72</td>
<td>0.69</td>
<td>0.49</td>
</tr>
<tr>
<td>12</td>
<td>Coastal Blue/Blue/Green/Yellow</td>
<td>0.63</td>
<td>0.69</td>
<td>0.73</td>
<td>0.70</td>
<td>0.51</td>
</tr>
</tbody>
</table>
The results in Table 5-6, were the best results after 5 repetitions of steps 1-7. The final results in Table 6 show that the WorldView-2-derived bathymetry had a 63% correlation with the *in situ* single beam bathymetry for the 0-30 meter study area. In the final part of this step, the “de-glinted” image was opened in ArcGIS, and any derived bathymetric values of less than or equal to 0 were removed from the raster, using the Raster Calculator. Then, the Filter tool was used to perform a low pass filter in order to smooth the entire bathymetric raster and reduce the significance of anomalous cells (using a 3 x 3 cell neighborhood). The final derived bathymetry for Rose Atoll for 2006 and 2010 are shown in Figures 42 and 43, respectively.

![Bathymetry Derived from Multispectral IKONOS-2 Satellite Imagery by NOAA CREP's Ecospatial Team (2006)](image)

**Figure 42.** The final 5 meter resolution bathymetry map for Rose Atoll. The bathymetry was used to derive the benthic habitat maps for 2006. *(Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).*
Figure 43. The final 2 meter resolution bathymetry map for Rose Atoll. The bathymetry was used to derive the benthic habitat maps for 2010. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).

3.4.2 Derive Geomorphological Features

With the two bathymetric data sets for the 2006 and 2010 maps, the next step was to derive eight geomorphological features of the seafloor (Costa et al., 2009) (Table 7), in order to derive shallow water benthic habitat maps for the U.S. Virgin Islands. This step was performed in ArcGIS, using Spatial Analyst and 3D Analyst tools from the Benthic Terrain Modeler (BTM) 3.0 Toolbox and ArcToolbox. The BTM 3.0 Toolbox is a free, downloadable
Table 7. The eight geomorphological features that were derived from the two bathymetric data sets for the 2006 and 2010 benthic habitat maps. (Source: Costa, B. M., Bauer, L. J., Battista, T. A., Mueller, P. W., & Monaco, M. E. (2009). Moderate-Depth Benthic Habitats of St. John, US Virgin Islands.).

<table>
<thead>
<tr>
<th>Geomorphological Feature</th>
<th>Dataset</th>
<th>Unit</th>
<th>Description</th>
<th>Tool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Depth</td>
<td></td>
<td>Meters</td>
<td>The average water depth. Used a 3 x 3 cell neighborhood.</td>
<td>Spatial Analyst</td>
</tr>
<tr>
<td>Standard Deviation of Depth</td>
<td></td>
<td>Meters</td>
<td>The dispersion of water depth values from the mean water depth. Used a 3 x 3 cell neighborhood.</td>
<td>Spatial Analyst</td>
</tr>
<tr>
<td>Slope</td>
<td></td>
<td>Degrees</td>
<td>The maximum rate of change in the slope between a cell and its neighbor cells. Used a 3 x 3 cell neighborhood.</td>
<td>Spatial Analyst</td>
</tr>
<tr>
<td>Slope of Slope</td>
<td></td>
<td>Degrees of degrees</td>
<td>The maximum rate of maximum slope change between a cell and its neighbor cells. Used a 3 x 3 cell neighborhood.</td>
<td>Spatial Analyst</td>
</tr>
<tr>
<td>Rugosity</td>
<td></td>
<td>Ration value</td>
<td>The ratio of surface area to planar area. Used a 3 x 3 cell neighborhood.</td>
<td>Rugosity function in the BTM</td>
</tr>
<tr>
<td>Curvature</td>
<td></td>
<td>1/100 z units</td>
<td>The rate of change in the curvature across the seafloor surface, highlighting ridges, crests, and valleys. Used a 3 x 3 cell neighborhood.</td>
<td>3D Analyst</td>
</tr>
<tr>
<td>Plan Curvature</td>
<td></td>
<td>1/100 z units</td>
<td>The curvature of the seafloor surface perpendicular to the slope direction. Used a 3 x 3 cell neighborhood.</td>
<td>3D Analyst</td>
</tr>
<tr>
<td>Profile Curvature</td>
<td></td>
<td>1/100 z units</td>
<td>The curvature of the seafloor surface parallel to the slope direction. Used a 3 x 3 cell neighborhood.</td>
<td>3D Analyst</td>
</tr>
</tbody>
</table>
ArcGIS application\(^2\), which is a suite of tools used by ocean and coastal scientists, and resource managers to analyze bathymetric data and classify benthic habitats (Wright et al., 2012; Wright et al., 2005). The eight derived geomorphological features for Rose Atoll for 2006 are shown in Figures 44-45, and for 2010, they are shown in Figure 46-47. The derived geomorphological features provided information about the characterization of the seafloor surface (Pittman et al., 2009), and they were used to help derive the benthic habitat of the shallow water coral reef on Rose Atoll. The eight layers were subsequently stacked in ArcGIS into a single raster layer for each year, and this raster layer was used in the next step.

\(^2\) Benthic Terrain Modeler (BTM) 3.0 was downloaded from https://www.arcgis.com/home/item.html?id=b0d0be66fd33440d97e8c83d220e7926
Figure 44. The Mean Depth, Standard Deviation of Depth, Slope, and Slope of Slope that were used to derive the benthic habitat maps for Rose Atoll for 2006. The dark scar in the western side of the atoll is the site of the Jin Shiang Fa shipwreck. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).
Figure 45. The Rugosity, Curvature, Plan Curvature, and Profile Curvature that were used to derive the benthic habitat maps for Rose Atoll for 2006. The dark scar in the western side of the atoll is the site of the Jin Shiang Fa shipwreck. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).
Figure 46. The Mean Depth, Standard Deviation of Depth, Slope, and Slope of Slope that were used to derive the benthic habitat maps for Rose Atoll for 2010. The dark scar in the western side of the atoll is less noticeable. *(Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).*
Figure 47. The Rugosity, Curvature, Plan Curvature, and Profile Curvature that were used to derive the benthic habitat maps for Rose Atoll for 2010. The dark scar in the western side of the atoll is less noticeable. (Source: Map created in ArcGIS for Desktop with data from PIBHMC and CREP servers).
3.4.3 Perform a Principal Component Analysis (PCA)

A Principal Component Analysis (PCA) was performed on the stacked geomorphological features for the two years in order to determine which features contributed most to the variance in the seafloor structure (Costa et al., 2009; Lillesand and Kiefer, 2000). A PCA is widely used in remote sensing, computer vision, and machine learning to reduce redundancy in one’s data and find the “principal components”, the data that contribute most to the variation in the entire data set, in terms of covariance, correlation, eigenvalues, eigenvectors, and percent variance (Hossain, 2017; Pyatykh and et al., 2013; Fauvel and Benediktsson, 2009; Li and Yeh, 1998; Fung and LeDrew, 1987; Byrne et al., 1980). Tables 9 and 10 show the Percent and Accumulative Eigenvalues (Variance) for each original geomorphic layer, and Tables 9 and 11 show the geomorphic layers that contributed the most to the top 3 Principal Components.

Table 8. The percent and accumulative eigenvalues for each original geomorphic layer (2006). The PCA identified the top 3 Principal Components as the layers that contributed the most variance to the seafloor structure in the 2006 bathymetric data set (highlighted).

<table>
<thead>
<tr>
<th>PCA Layer</th>
<th>Eigenvaule</th>
<th>% of Variance</th>
<th>Accum. % of Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.30E+02</td>
<td>62.4619</td>
<td>62.4619</td>
</tr>
<tr>
<td>2</td>
<td>3.89E+01</td>
<td>18.6724</td>
<td>81.1343</td>
</tr>
<tr>
<td>3</td>
<td>2.52E+01</td>
<td>12.1076</td>
<td>93.2419</td>
</tr>
<tr>
<td>4</td>
<td>1.09E+01</td>
<td>5.2158</td>
<td>98.4577</td>
</tr>
<tr>
<td>5</td>
<td>3.19E+00</td>
<td>1.5334</td>
<td>99.9912</td>
</tr>
<tr>
<td>6</td>
<td>1.79E-02</td>
<td>0.0086</td>
<td>99.9997</td>
</tr>
<tr>
<td>7</td>
<td>5.49E-04</td>
<td>0.0003</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>8.09E-15</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 9. Percent of variance contributed by each original geomorphic layer (2006). The top 3 Principal Components that contribute the most to the variance in seafloor structure (highlighted) are: Slope, Curvature, and Plan Curvature.

<table>
<thead>
<tr>
<th>PCA Layer</th>
<th>Mean Depth</th>
<th>SD Depth</th>
<th>Slope</th>
<th>Slope of Slope</th>
<th>Rugosity</th>
<th>Curvature</th>
<th>Plan Curvature</th>
<th>Profile Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.71</td>
<td>1.79</td>
<td>96.15</td>
<td>1.13</td>
<td>0.23</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.09</td>
<td>0.00</td>
<td>0.00</td>
<td>0.60</td>
<td>0.00</td>
<td>98.19</td>
<td>1.12</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.01</td>
<td>0.00</td>
<td>1.12</td>
<td>98.88</td>
<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>9.98</td>
<td>0.37</td>
<td>0.45</td>
<td>88.45</td>
<td>0.06</td>
<td>0.69</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>89.07</td>
<td>0.00</td>
<td>1.31</td>
<td>9.59</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>0.08</td>
<td>64.87</td>
<td>1.29</td>
<td>0.11</td>
<td>0.31</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
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<tr>
<td>7</td>
<td>0.07</td>
<td>20.62</td>
<td>0.09</td>
<td>0.12</td>
<td>45.76</td>
<td>0.00</td>
<td>0.00</td>
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<td>8</td>
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<td>0.70</td>
<td>0.00</td>
<td>53.63</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
</tr>
</tbody>
</table>

Table 10. The percent and accumulative eigenvalues for each original geomorphic layer (2010). The PCA identified the top 3 Principal Components as the layers that contributed the most variance to the seafloor structure in the 2010 bathymetric data set (highlighted).

<table>
<thead>
<tr>
<th>PCA Layer</th>
<th>Eigenvalue</th>
<th>% of Variance</th>
<th>Accum. % of Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.90E+02</td>
<td>52.7005</td>
<td>52.7005</td>
</tr>
<tr>
<td>2</td>
<td>1.86E+02</td>
<td>33.9232</td>
<td>86.6238</td>
</tr>
<tr>
<td>3</td>
<td>3.62E+01</td>
<td>6.5769</td>
<td>93.2007</td>
</tr>
<tr>
<td>4</td>
<td>2.84E+01</td>
<td>5.1701</td>
<td>98.3708</td>
</tr>
<tr>
<td>5</td>
<td>8.94E+00</td>
<td>1.6267</td>
<td>99.9975</td>
</tr>
<tr>
<td>6</td>
<td>1.26E-02</td>
<td>0.0023</td>
<td>99.9997</td>
</tr>
<tr>
<td>7</td>
<td>1.46E-03</td>
<td>0.0003</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>5.41E-13</td>
<td>0</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 11. Percent of variance contributed by each original geomorphic layer (2010). The top 3 Principal Components that contribute the most to the variance in seafloor structure (highlighted) are: Rugosity, Curvature, and Plan Curvature.

<table>
<thead>
<tr>
<th>PCA Layer</th>
<th>Mean Depth</th>
<th>SD Depth</th>
<th>Slope</th>
<th>Slope of Slope</th>
<th>Rugosity</th>
<th>Curvature</th>
<th>Plan Curvature</th>
<th>Profile Curvature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.02</td>
<td>1.40</td>
<td>0.09</td>
<td>0.42</td>
<td>98.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>0.00</td>
<td>0.02</td>
<td>0.00</td>
<td>0.12</td>
<td>0.00</td>
<td>98.76</td>
<td>1.11</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
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<td>0.00</td>
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<td>0.00</td>
<td>1.10</td>
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<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>11.28</td>
<td>0.07</td>
<td>87.46</td>
<td>1.05</td>
<td>0.14</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>0.21</td>
<td>87.13</td>
<td>0.00</td>
<td>11.88</td>
<td>0.78</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>65.74</td>
<td>0.11</td>
<td>0.79</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
</tr>
<tr>
<td>7</td>
<td>23.22</td>
<td>0.01</td>
<td>43.29</td>
<td>0.07</td>
<td>0.07</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
</tr>
<tr>
<td>8</td>
<td>10.82</td>
<td>0.04</td>
<td>55.76</td>
<td>0.02</td>
<td>0.02</td>
<td>0.00</td>
<td>0.00</td>
<td>33.33</td>
</tr>
</tbody>
</table>

3.4.4 Derive the Benthic Habitat

A supervised classification was performed on the 2006 and 2010 PCA rasters, using classified benthic images acquired in 2006 and 2010 as ground truth data. In order to perform the supervised classification, the first step was to classify the raw benthic imagery from the ASRAMP research cruises from 2006 and 2010.

3.4.4.1 Analyze the Benthic Imagery (Ground Truth Data)

The 1,845 benthic images that were acquire during March 2006, and the 652 benthic images that were acquired during March 2010 were manually classified by trained coral analysts according to a predetermined classification scheme. A broad classification scheme to functional group (Hard Coral, Coralline Algae, Macroalgae, and Turf Algae) was determined. The term “hard coral” included all calcareous, reef-building corals, which help build the calcium carbonate skeleton of the reef. Hard corals are also referred to as stony corals, and all hard
corals are in the phylum Cnidarian and Order Scleractinia. Some of the hard corals found on Rose Atoll included *Favia, Acropora, Porites, Montipora, Astreopora, Montastrea*, and *Pocillopora*. The term “coralline algae” referred to the distinctively pink and red encrusting macroalgae, which also cements the reef together and contributes to the architecture (Johnson, 2016). Crustose coralline belong to the division Rhodophyta and are in the order Corallinales. The term “macroalgae” means seaweed, and this functional group included upright and encrusting red algae, brown algae, and green algae. The term “turf algae” broadly referred to the delicate grass-like structures that were attached to substrate.

*Figure 48.* An example of a benthic image of Rose Atoll with 10 randomly assigned points superimposed on the image (purple circles). Each point was manually classified using one of four functional group codes: CORAL = Hard Coral, CCA = Crustose Coralline Algae, MA=Macroalgae, or TURF = Turf Algae. *(Source: This image was gathered from CREP servers with special permission).*
The images were all manually classified in a program known as Coral Point Count with Excel Extensions, or CPCe, using a total of 10 randomly assigned points that were superimposed onto each image in CPCe (Figure 48). The data were then exported into an MS Excel Spreadsheet. In MS Excel, labels were given to each image based on the most dominant cover type (Table 12). Hard coral was given first priority, coralline algae were given second priority, macroalgae were given third priority, and turf algae were given fourth priority in labeling. This meant that if an image had an equal classification of Hard Coral and Turf Algae, for example, then the image was classified as having a majority of Hard Coral. The number of similar classifications for the 10 points in one image were added together and then divided by 10 (the total number of points). This resulted in a percentage of each classification for every image. Based on that percentage, the Dominant Cover Type and Percentage of Dominant Cover Type were determined for each image. The category for Percentage of Dominant Cover Type was divided into three percentage bins: 10-<50%, 50-<90%, and 90-100%, and only one bin was assigned to every image. After this analysis was complete, the spreadsheet was saved and the classifications were ready to be used for a supervised classification.
Table 12. An example of five classified images analyzed in Excel. The classifications Soft Coral, Sediment, Invertebrate, Tape/Wand, and Unclassifiable were omitted in the analysis and were not used to derive the benthic habitat maps for 2006 and 2010. In this table, Hard Coral takes priority over Coralline Algae in image 3 and Coralline Algae take priority over Turf Algae in image. Then, 1 of 3 percentage bins (10-<50%, 50-<90%, and 90-100%) was assigned to each image.

<table>
<thead>
<tr>
<th>Image</th>
<th>Hard Coral</th>
<th>Coralline Algae</th>
<th>Macroalgae</th>
<th>Turf Algae</th>
<th>Dominant Cover Type</th>
<th>Percentage of Dominant Cover Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>10</td>
<td>50</td>
<td>0</td>
<td>Macroalgae</td>
<td>50-&lt;90%</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>30</td>
<td>0</td>
<td>30</td>
<td>Coralline Algae</td>
<td>10-&lt;50%</td>
</tr>
<tr>
<td>3</td>
<td>30</td>
<td>30</td>
<td>20</td>
<td>30</td>
<td>Hard Coral</td>
<td>10-&lt;50%</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>40</td>
<td>Turf Algae</td>
<td>10-&lt;50%</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>80</td>
<td>10</td>
<td>0</td>
<td>Coralline Algae</td>
<td>90-100%</td>
</tr>
</tbody>
</table>

3.4.4.2 Create the Benthic Habitat Maps

Subsections 3.4.4.2.1-3.4.4.2.6 are the last six steps that were taken to create the final benthic habitat maps for Rose Atoll for 2006 and 2010. These steps were all completed in ArcGIS, and the six steps took about two months’ time.

3.4.4.2.1 Georectify the Ground Truth Data

The Excel spreadsheets containing the ground truth data for 2006 and 2010 were opened in ArcGIS and projected in the correct coordinate system for American Samoa (UTM Zone 2S). This step was taken to ensure that the ground truth data aligned with the PCA raster data sets for 2006 and 2010.
3.4.4.2.2 Create Signature Files for Classification

A signature file was created for each category used in the Dominant Cover Type (Coral, Coralline Algae, Marcoalgae, and Turf Algae), and for each percentage bin used in the Percentage of Dominant Cover Type (10-%50%, 50-%90%, and 90-100%), using the Image Classification Toolbar (or the Create Signatures tool in ArcToolbox). The PCA raster data set for each year was used to create a signature file, and Tables 13 and 14 show the number of classifications that were used for each signature file. A specific number of sample points from each data set were selected for each signature file, which was determined by the total number of classifications available in the data set.

Table 13. The classifications that were used for the signature file for the supervised classification of the benthic habitat for the 2006 benthic habitat maps, and the number of sample points used per classification.

<table>
<thead>
<tr>
<th>Classifications used in Signature File</th>
<th>Number of Sample Points Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral 10-%50%</td>
<td>20</td>
</tr>
<tr>
<td>Coral 50-%90%</td>
<td>20</td>
</tr>
<tr>
<td>Coralline Algae 10-%50%</td>
<td>20</td>
</tr>
<tr>
<td>Coralline Algae 50-%90%</td>
<td>20</td>
</tr>
<tr>
<td>Coralline Algae 90-100%</td>
<td>20</td>
</tr>
<tr>
<td>Macroalgae 50-%90%</td>
<td>12</td>
</tr>
<tr>
<td>Turf 10-%50%</td>
<td>25</td>
</tr>
<tr>
<td>Turf 50-%90%</td>
<td>25</td>
</tr>
<tr>
<td>Turf 90-100%</td>
<td>25</td>
</tr>
<tr>
<td>Sediment</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 14. The classifications that were used in the signature file for the supervised classification of the benthic habitat for the 2010 benthic habitat maps, and the number of sample points used per classification.

<table>
<thead>
<tr>
<th>Classifications used in Signature File</th>
<th>Number of Sample Points Used</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral 10-&lt;50%</td>
<td>20</td>
</tr>
<tr>
<td>Coral 50-&lt;90%</td>
<td>20</td>
</tr>
<tr>
<td>Coralline Algae 10-&lt;50%</td>
<td>20</td>
</tr>
<tr>
<td>Coralline Algae 50-&lt;90%</td>
<td>20</td>
</tr>
<tr>
<td>Macroalgae 50-&lt;90%</td>
<td>20</td>
</tr>
<tr>
<td>Turf 10-&lt;50%</td>
<td>20</td>
</tr>
<tr>
<td>Turf 50-&lt;90%</td>
<td>20</td>
</tr>
</tbody>
</table>

3.4.4.2.3 Perform a Supervised Classification

The signature file from each PCA image was then used to perform a supervised classification, with a Maximum Likelihood Classification (MLC), from the Image Classification Toolbar. The MLC tool in ArcGIS is based on the following two assumptions: 1) The sample cells (pixels) selected for each category are normally distributed and 2) Bayes’ theorem of decision making (ESRI, n.d.). The tool assigns each cell (pixel) a classification based on the variance and covariances of the categories in the signature file (ESRI, n.d.). The MLC method is used in remote sensing to classify imagery for urban and agricultural land use, for example, when ground truth data is available or when the imagery can be easily classified into categories (Bruzzone and Prieto, 2001; Stefanov, 2001; Paola and Schowengerd, 1995). If ground truth data is not available or categories cannot be easily classified from the image, then an unsupervised classification method is considered.

In addition to the MLC raster output, a confidence raster was created from the MLC tool. The confidence raster was used to assess the accuracy of the supervised classification and is
showed in Chapter 4, for 2006 and 2010. A Majority Filter was then performed on each MLC raster, using the Majority Filter tool and a 3 x 3 cell neighborhood (8 contiguous, surrounding cells). This tool was used to classify the benthic habitat of each cell (pixel) based on the majority classification of the contiguous cells surrounding one cell, which was a method used classify cells in the MLC raster without a classification (Figure 49).

![Figure 49](image)

**Figure 49.** A Majority Filter that was applied to a raster data set using a filter of the closest 8 cells (contiguous, surround cells) around each cell. *(Source: ESRI. (n.d.). Majority Filter. Retrieved June 07, 2017, from http://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/majority-filter.htm).*

### 3.4.4.2.4 Optically Validate the Benthic Habitat

The raster data sets were converted to polygons (using the Raster to Polygon tool), and the benthic imagery was used to optically validate the derived benthic habitat from the MLC method. Each classification was examined and the polygons that were incorrectly classified from the MLC method and Majority Filter were manually corrected using the Editor Toolbar. This was the most time consuming process in the Benthic Habitat Mapping Procedure, and it took about 2 days to examine all of the ground truth data for each map. Once completed, the area of each polygon in each map was examined.
3.4.4.2.5 Apply a Minimum Mapping Unit (MMU)

The attribute table for each map was used to examine the area of each polygon, and the Editor Toolbar was used to omit polygons with an area less than a Minimum Mapping Unit (MMU) of 25 meters squared (5 x 5 meters). A MMU of 25 meters squared was used for the 2006 and 2010 benthic habitat maps, in order to generalize the habitats types for both years to a comparable scale in the analysis in Chapter 4. In remote sensing, a MMU is used to characterize a particular terrestrial or underwater landscape or habitat (Thomas, 2016; Homer et al., 2001), and the MMU size is based on, both the data resolution and the purpose of the map (Rutchey, K., & Godin, 2009; Saura, 2002). A MMU of 25 meters squared removed a large amount of polygons (about 100,000 in each data set), which significantly lessened the processing time for the next step.

3.4.4.2.6 Finalize the Derived Benthic Habitat Maps

The remaining polygons in each data set were dissolved (using the Dissolve tool) in order to eliminate borders between the same habitat types and create a unified polygon. The dissolved polygons were then smoothed (using the Smooth Polygon tool), in order to soften the sharp edges of the polygons and give the habitat types a more realistic shape. ArcGIS completed this step in about 5 hours, because of the large amount of polygons in each data set. Once the smoothing completed, the habitat types were converted back to raster data sets at a 5 meter resolution (using the Polygon to Raster tool). The final benthic habitat maps for 2004, 2006, and 2010 have a resolution of 5 x 5 meters and are presented in the following order: by “Dominant Cover Types” for 2004 (Figure 50), 2006 (Figure 51), and 2010 (Figure 52), and then by
“Percentages of Dominant Cover Types” for 2004 (Figure 53), 2006 (Figure 54), and 2010 (Figure 55). The last two figures show the confidence levels for the derived benthic habitat maps for 2006 (Figure 56) and 2010 (Figure 57).

Figure 50. Dominant Cover Types on Rose Atoll during 2004. Four dominant habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with data from in situ benthic habitat assessments conducted in 2004. The large scar in the western bank of the reef flat is the site of the Jin Shiang Fa shipwreck. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i, with data from NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.).
Figure 51. Dominant Cover Types on Rose Atoll during 2006. Five dominant habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with in situ benthic imagery acquired during March 2006. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i with data from CREP servers).
Figure 52. Dominant Cover Types on Rose Atoll during 2006. Four dominant habitat types were derived from multispectral WorldView-2 satellite imagery and validated with \textit{in situ} benthic imagery acquired during March 2010. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i with data from CREP servers).
Figure 53. Percentages of Dominant Cover Types on Rose Atoll during 2004. Nine habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with data from in situ benthic habitat assessments conducted in 2004. *(Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i with data from NCCOS, N. (2005). Atlas of the shallow water benthic habitats of American Samoa, Guam, and the Commonwealth of the Northern Marianas Islands. NOAA Tech. Memo. NOS NCCOS, 8.)*
Figure 54. Percentages of Dominant Cover Types on Rose Atoll during 2006. Ten habitat types were derived from multispectral IKONOS-2 satellite imagery and validated with in situ benthic imagery acquired during March 2006. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i with data from CREP servers).
Figure 55. Percentages of Dominant Cover Types on Rose Atoll during 2010. Seven habitat types were derived from multispectral WorldView-2 satellite imagery and validated with in situ benthic imagery acquired during March 2010. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai’i with data from CREP servers).
Figure 56. The level of confidence in the supervised classification of the ten derived habitat types in Figure 54. This map shows high confidence (green) in the derived habitat types across the reef flat and slope environment and low confidence (red) in the lagoon. (Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i).
Figure 57. The level of confidence in the supervised classification of the seven derived habitat types in Figure 55. This map shows very high confidence (green) in the derived habitat types across the reef flat and slope environment and low confidence (red) in the lagoon. *(Map created in ArcGIS for Desktop in NOAA’s Coral Reef Ecosystem Program in the Inouye Regional Center on Ford Island, Honolulu, Hawai‘i).*
Chapter 4. Spatio-Temporal Analysis

This chapter discusses the spatial and temporal differences in the “Dominant Cover Types” and the “Percentages of Dominant Cover Types” from the derived benthic habitat maps for 2004, 2006, and 2010.

4.1 Spatial and Temporal Differences in the Dominant Cover Types

In a visual comparison between the three derived benthic habitat maps for “Dominant Cover Types” in Figures 50-52, a change in the distribution of the four most abundant cover types can be seen over the entire atoll and over the vessel grounding site on the western side. In 2004 (Figure 50), for example, macroalgae-dominated the ship grounding site on the western side of the reef flat and the rim of the lagoon. This macroalgae-dominated area could be attributed to the 30 tons of vessel debris that remained corroding on the reef flat. The iron that leaked into the water from the corroding hull acted as a fertilizer, and the iron allowed invasive blue-green and red algae to dominate the damaged reef flat (Green, 1997).

In the derived benthic habitat map for 2006 (Figure 51), however, the western side of the reef flat and the rim of the lagoon seemed to have recovered since the removal of 30 tons of vessel debris in 2004 (Figure 14). The vessel grounding site consisted of almost all coral and coralline algae. The quick recovery of the coral reef ecosystem in these areas shows that the corroding hull and other debris influenced the growth of invasive macroalgae and therefore decreased the health of the coral reef ecosystem. The confidence level in the derived benthic habitat (Figure 56) is lower for the lagoon and slope environment, but the confidence is very
high for the reef flat and middle of the lagoon. This means that the derived benthic habitat for the reef flat is more reliable than the derived benthic habitat for the lagoon and slope environment. The low confidence in the lagoon and slope environment could have been caused by more than one factor, such as the quality of the satellite imagery, or the lack of benthic imagery acquired in these two areas. Therefore, the confidence of the derived benthic habitat could be improved in the future using better satellite imagery and more benthic imagery in these two areas.

In 2010 (Figure 52), the macroalgae cover increased in the vessel grounding area and the lagoon, while the rim of the lagoon was composed on more coralline algae. Turf algae were not abundant in the lagoon like it was in 2004. The reef flat is also dominated by hard, reef-building corals, whereas in 2004, the reef flat consisted of a mix of hard, reef-building corals, coralline algae, and turf algae. The shift seen in the derived benthic habitat map for 2010 in a more coral-dominated reef flat shows that the coral reef ecosystem is recovering rapidly in response to the vessel debris removal in 2004 and 2007. Although the derived benthic habitat for 2010 shows more coverage of coralline algae and macroalgae in the lagoon, the confidence level in the derived benthic habitat is low in the lagoon compared to the confidence level on the reef flat (Figure 57). This means that the derived benthic habitat for the entire lagoon is unreliable, but the confidence level could be improved in the future using the same two suggestions as applied to the 2006 derived benthic habitat maps.

In a statistical comparison between the three derived benthic habitat maps for Dominant Cover Types, the changes in the distribution of the four most abundant cover types over the entire atoll can be assessed more easily (Table 15).
Table 15. The areas (km$^2$) of the four most abundant biological cover types that composed the benthic habitat of Rose Atoll in 2004, 2006, and 2010. The areas were calculated in ArcGIS.

<table>
<thead>
<tr>
<th>Dominant Cover Types</th>
<th>2004 (Area in km$^2$)</th>
<th>2006 (Area in km$^2$)</th>
<th>2010 (Area in km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral</td>
<td>1.64</td>
<td>3.01</td>
<td>4.16</td>
</tr>
<tr>
<td>Coralline Algae</td>
<td>2.58</td>
<td>0.42</td>
<td>0.42</td>
</tr>
<tr>
<td>Macroalgae</td>
<td>1.33</td>
<td>0.06</td>
<td>0.69</td>
</tr>
<tr>
<td>Turf Algae</td>
<td>0.57</td>
<td>1.90</td>
<td>0.07</td>
</tr>
</tbody>
</table>

In 2004, the benthic habitat was comprised of 1.64 km$^2$ of coral cover, 2.58 km$^2$ of coralline algae cover, 1.33 km$^2$ of macroalgae cover, and 0.57 km$^2$ of turf algae cover. In 2006, the benthic habitat was composed of 3.01 km$^2$ of coral cover, 0.42 km$^2$ of coralline algae cover, 0.06 km$^2$ of macroalgae cover, and 1.90 km$^2$ of turf algae cover. In 2010, the benthic habitat consisted of 4.16 km$^2$ of coral cover, 0.42 km$^2$ of coralline algae cover, 0.69 km$^2$ of macroalgae cover, and 0.07 km$^2$ of turf algae cover. In sum, the most abundant biological cover type in 2004, 2006, and 2010 were coralline algae, hard corals, and hard corals, respectively, while the least abundant biological cover types were turf algae, macroalgae, and turf algae, respectively.

Overall, the net change in coral cover from 2004 to 2010 was positive, the net change in coralline algae cover was negative, the net change in macroalgae cover was negative, and the net change in turf algae cover was negative. These results show a shift from an algae-dominated reef to a coral-dominated reef, suggesting that the conditions on the reef flat and in the vessel grounding areas are very suitable for reef-building corals. These results also suggest that the coral reef ecosystem on Rose Atoll is recovering very quickly since the complete removal of the *Jin Shiang Fa* vessel debris in 2007 (Figure 14), and the iron from the corroding hull and other pieces no longer inhibits coral and coralline algae growth.
### 4.2 Spatial and Temporal Differences in the Percentages of Dominant Cover Types

Table 16. The areas (km²) of the percentages of the most abundant biological cover types that composed the benthic habitat of Rose Atoll in 2004, 2006, and 2010. The areas were calculated in ArcGIS.

<table>
<thead>
<tr>
<th>Dominant Cover Types</th>
<th>2004 (Area in km²)</th>
<th>2006 (Area in km²)</th>
<th>2010 (Area in km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coral 10-&lt;50%</td>
<td>1.54</td>
<td>2.83</td>
<td>2.88</td>
</tr>
<tr>
<td>Coral 50-&lt;90%</td>
<td>0.10</td>
<td>0.57</td>
<td>1.28</td>
</tr>
<tr>
<td>Coral 90-100%</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Coralline Algae 10-&lt;50%</td>
<td>2.22</td>
<td>0.39</td>
<td>0.07</td>
</tr>
<tr>
<td>Coralline Algae 50-&lt;90%</td>
<td>0.26</td>
<td>0.22</td>
<td>0.35</td>
</tr>
<tr>
<td>Coralline Algae 90-100%</td>
<td>0.10</td>
<td>0.07</td>
<td>-</td>
</tr>
<tr>
<td>Macroalgae 10-&lt;50%</td>
<td>1.29</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Macroalgae 50-&lt;90%</td>
<td>0.03</td>
<td>0.09</td>
<td>0.69</td>
</tr>
<tr>
<td>Macroalgae 90-100%</td>
<td>0.01</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turf Algae 10-&lt;50%</td>
<td>-</td>
<td>1.44</td>
<td>0.03</td>
</tr>
<tr>
<td>Turf Algae 50-&lt;90%</td>
<td>0.57</td>
<td>0.24</td>
<td>0.04</td>
</tr>
<tr>
<td>Turf Algae 90-100%</td>
<td>-</td>
<td>0.40</td>
<td>-</td>
</tr>
</tbody>
</table>

The percentages of the most abundant biological cover types were also calculated, in order to assess smaller changes in the coral cover, crustose coralline cover, macroalgae cover, and turf algae cover. In a visual comparison of the percentages of the derived cover types for 2004, 2006, and 2010 (Figures 53-55), changes are visible as well. In 2004, 2006, and 2010, for example, the coral cover type predominantly consisted of 10-<50% of hard, reef-building corals. In 2004 and 2006, the coralline algae cover type predominantly consisted of 10-<50% of crustose coralline algae, but in 2010, the coralline algae cover type predominantly consisted of 50-<90% of crustose coralline algae. In 2004, the macroalgae cover type predominantly consisted of 10-<50% of upright and encrusting macroalgae, and then in 2006 and 2010, the
percentage increased to 50-<90%. Finally, the turf algae cover type predominantly consisted of 50-<90% of turf algae in 2004 and 2010, but in 2006, the turf algae cover type mainly composed of 10-<50% of turf algae.

From 2004 and 2006, 30 tons of vessel debris were removed from the western side of the reef flat (Figure 14), and the changes in the benthic habitat show a shift from a coralline algae-dominated ecosystem to a coral-dominated ecosystem. This shift is supported by the increase in total coral cover from 1.64 km$^2$ in 2004 to 3.40 km$^2$ in 2006, an increase of 1.76 km$^2$, and by the significant decrease in the total coralline algae cover from 2.58 km$^2$ in 2004 to 0.68 km$^2$, a loss of 1.90 km$^2$ of coralline algae. From 2004 and 2006, the total macroalgae area also decreased by 1.24 km$^2$, from 1.33 km$^2$ in 2004 to 0.09 km$^2$ in 2006. One explanation for the decrease in the macroalgae cover type can be the removal of the corroding vessel debris, which supported invasive macroalgae growth and inhibited new coral growth. Another change seen in the benthic habitat is the increase in the turf algae cover from 0.57 km$^2$ in 2004 to 2.08 km$^2$ in 2006, a significant increase of 1.51 km$^2$. However, in 2004, the turf algae cover type mainly consisted of 50-<90% turf algae, and then in 2006, the turf algae cover type was mainly 10-<50% of turf algae. The coverage of 50-<90% of turf algae in 2006 decreased to 0.25 km$^2$, which means that the benthic habitat was covered by a smaller percentage of turf algae after the removal of vessel debris.

From 2006 to 2010, the final 2 tons of vessel debris were removed from the reef flat (Figure 14), and this can be assessed in the derived benthic habitat maps. The coral cover type remained the most abundant cover type in 2010, as the total area increased by 0.76 km$^2$, from 3.40 km$^2$ in 2006 to 4.26 km$^2$ in 2010. The increase in coral cover is seen in the 50-<90% coral cover type.
in 2006 and 2010, from 0.57 km$^2$ in 2006 to 1.28 km$^2$ in 2010, and this increase supports the conclusion that the coral reef ecosystem is recovering rapidly in response to the removal of all of the vessel debris. Also, the conclusion that the algae-dominated ecosystem is shifting to a coral-dominated ecosystem is supported by the decline in the total coralline algae cover type from 2006 to 2010, from a total area of 0.68 km$^2$ in 2006 to a total area of 0.42 km$^2$ in 2010. In 2006, the coralline algae cover type was consisted mainly of 10-<50% cover, but in 2010, the coralline algae cover type consisted mainly of 50-<90%. Although this shows that a higher percentage of coralline algae were classified in the coralline algae cover type, the percentage of 90-100% coralline algae was not derived in the 2010 benthic habitat map as it was in the 2006 benthic habitat map. The area of the only macroalgae cover type of 50-<90% also increased by 0.60 km$^2$ from 2006 to 2010, from 0.09 km$^2$ in 2006 to 0.69 km$^2$ in 2010. However, the macroalgae cover in the derived benthic habitat maps for 2010 is concentrated in the lagoon and the vessel grounding site, which also have low confidence levels (Figure 57). The low confidence level suggests that the derived benthic habitat in these two areas in less reliable, and therefore, the area of the macroalgae cover type may be less than was actually derived.

Finally, a significant decrease was seen in the percentages of the turf algae cover type. In 2006, the turf algae cover type mainly consisted of 10-<50% turf algae, at 1.44 km$^2$, but in 2010, the 10-<50% turf algae cover type declined to 0.03 km$^2$, a difference of 1.41 km$^2$.

This spatial and temporal analysis helps support three conclusions, that 1) the restoration of Rose Atoll was indeed successful, 2) the vessel debris did indeed negatively impact hard coral and coralline algae growth on Rose Atoll, and 3) the coral reef on Rose Atoll showed a rapid recovery and a shift in the dominant benthic habitat between 2004 and 2010, in response to
the vessel debris removal. The significant findings from the spatial and temporal analysis that support these three conclusions are summarized in Chapter 5, and future research opportunities to build upon this analysis and research study are discussed as well.
Chapter 5. Conclusion and Future Research

The goal of this chapter is to refocus the purpose of this research study, summarize the main findings from the spatio-temporal analysis, and lead to the implications of the findings. This chapter also includes the limitations of the research study and future research opportunities.

5.1 Research Summary

This research study provided an assessment of the spatial and temporal differences in the benthic habitat of Rose Atoll during three years, 2004, 2006, and 2010, in response to debris removal of the grounded Jin Shiang Fa fishing vessel. The significant findings that support the conclusions made in Chapter 4 were:

1) Reef-building corals and coralline algae in the location of the Jin Shiang Fa vessel grounding made a positive recovery between 2004 and 2010, dominating the macroalgae and turf algae species.

2) Reef-building corals and coralline algae over the entire atoll made a positive recovery as well during the three years, dominating the macroalgae and turf algae species.

3) Overall, the coral reef ecosystem of Rose Atoll shifted from a coralline algae-dominated ecosystem in 2004 to a coral-dominated ecosystem by 2006. This timeframe corresponds to the removal of nearly 273 tons of vessel debris since 1993 (Figure 14).
5.2 Limitations of the Research

The goal of this section is to first acknowledge the limitations of this research study before leading into the implications of the findings and discussing opportunities for future research. The reason for acknowledging the limitations of the research study is to understand how constraints in the data and the methods impacted or influenced the spatio-temporal analysis and the interpretation of the findings.

One important limitation of this research study was the naming convention for the derived maps, which influenced the spatio-temporal analysis. In 2004, for example, the maps were derived using IKONOS-2 satellite imagery acquired in 2002 and benthic habitat assessments conducted in 2004. When looking at the two derived maps for 2004 in Figures 50 and 53, the titles imply that all of the data were collected during 2004 when in fact, this was not the case. Instead, the maps were titled based only on the collection year of the in situ data (the benthic images). This method was used to label all of the maps in this research study in order to remain consistent in the titles and the spatio-temporal analysis. The reason for this method of naming the maps was because the in situ data were the most important data in this research study and in benthic habitat mapping in general (Eugenio et al., 2015; Kendall et al., 2005; Mumby et al., 1997). Without in situ data to use for ground truthing, the derived maps in this research and in any other benthic habitat mapping project would be inaccurate and thus unreliable. This was one limitation of the research study that could have been approached differently, such as naming the maps based on the acquisition date of the satellite images, for example. This would have also influenced the dates used in the spatio-temporal analysis.

Another limitation of this research study was the lack of data for Rose Atoll in general. The
data in this research study were the only available data, which limited the spatio-temporal analysis to a three year timeframe. The different satellite images for Rose Atoll also influenced the methods to derive benthic habitat, which impacted the confidence levels of the supervised classification for 2006 (Figure 56) and 2010 (Figure 57). However, the software programs that were used to analyze the satellite images (ENVI), and derive the bathymetry, geomorphological features, and the benthic habitat (ArcGIS) were kept consistent. This helped rule out any inconsistencies in the derived maps that may have been caused by different software programs.

These limitations influenced both, the naming of the derived benthic habitat maps and the spatio-temporal analysis, which is why they are worth noting before leading to the implications of this research study.

5.3 Research Implications

So what do these findings mean? What difference do they make? Who might be interested in these results? These are the questions that this section will attempt to answer. First and foremost, these findings imply that the coral reef ecosystem on Rose Atoll has fully recovered, and the benthic habitat is more suitable for coral growth more so now than before. The rapid coral growth, which surpassed the growth of coralline algae, implies that the presence of high amounts of iron from the corroding vessel debris did in fact decrease the water quality and negatively influence coral growth. Secondly, the difference that these findings make is in the continued monitoring and management of the coral reef ecosystem of Rose Atoll. Since these findings show that Rose Atoll has recovered and the restoration efforts have been successful, future restoration is no longer necessary. However, future assessment and monitoring is
necessary, and these findings support the claim that Rose Atoll is a very unique and precious natural resource that requires monitoring and management. Thirdly, these findings will be most helpful to the agencies that are involved in the continuous monitoring and management of Rose Atoll, including the American Samoan Government, USFWS, USCG, and NOAA.

**5.4 Management Implications**

The findings in this research study support the implication that the Restoration Plan developed by the USFWS and American Samoan Government in 2001 to remove the vessel debris and restore the reef back to its original state was successful. The findings also support the implication that the ecological assessments and benthic surveys conducted by NOAA during its biennial RAMP research cruises were successful in providing sufficient data for Rose Atoll. The purpose of NOAA’s RAMP cruises is to assess and monitor the coral reef ecosystems in the Pacific, including Rose Atoll, and that is exactly what this research study accomplished. Therefore, these two implications lead to the conclusion that while continued management is necessary for the conservation of Rose Atoll’s precious coral reef, the continued removal of debris and restoration is no longer necessary.

**5.5 Opportunities for Future Research**

This research study leaves the door open for many research questions and future research opportunities. The most apparent research opportunity that this research study would benefit from is the comparison of a spatio-temporal analysis of Rose Atoll using more current data, since the most current data in this study was from 2010. NOAA has since conducted biennial
RAMP research studies since 2010, but these data are currently backlogged, unavailable or inaccessible. In addition, there is a lack of available satellite imagery and bathymetric data for Rose Atoll beyond 2010, and locating and using more current remote sensing data is a great research opportunity.

Another research opportunity that could build upon this research study and contribute to benthic habitat mapping in general is research and development of a standardized methodology to derive benthic habitat from satellite imagery. As mentioned in Chapter 3, the methods used in this research study to derive benthic habitat from satellite imagery were adapted from methods developed by formed CREP employees, and the methods and literature were very much appreciated. However, remote sensing technologies are rapidly evolving, and the amount of remote sensing data that acquired is rapidly increasing. Therefore, in order to process and analyze these large data sets and generate benthic habitat maps, there needs to be rapidly evolving methodologies as well. Methodology research and development will always be beneficial to benthic habitat mapping as long as remote sensing technologies evolve and improve.

As this research study has shown, there are many potential research opportunities that could build upon the spatio-temporal analysis performed for Rose Atoll for the three years. Further study in the spatial and temporal difference in the coral reef on Rose Atoll since 2010 and in methods research and development will indeed be useful in the management and conservation of Rose Atoll and coral reefs in the Pacific.
References


