SHORELINE CHANGE AT MAÑAGAHA, SAIPAN

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1. INTRODUCTION

1.1 Shoreline change

The coastlines of the world are the focus of population growth and urban development this century. It is projected that approximately 2.65 billion people will be living within the coastal zone by 2025. More than half of all Americans now live on or close to the coast with population density expected to increase. Within the Pacific Basin, population growth can increase the economic incentive to develop more land. On islands, this results in development pressures along the shoreline and into the active beach system.

Chronic erosion of the shoreline increases resource and population vulnerability to inundation by storm surge, tsunami, and sea-level rise. As population increases along the coastline, the need to understand the highly dynamic coastal region becomes more important. The majority of shoreline change studies have been prompted by realization that coastal erosion threatens private property, public infrastructure, and natural ecosystems (National Academy Study, 1990). Improved understanding of detailed erosion patterns provides managers with a basis for planning appropriate coastal development and resource management, thus improving community resiliency and sustainability. Lack of robust physical processes modeling means that analysis of historical shoreline trends provides a practical, relatively affordable method of predicting future erosion hazards (National Academy Study, 1990).

Typically, studies compile and analyze historic and modern shoreline position data to inform planning and policy about past shoreline variability. The methods used are designed to record, analyze, and predict patterns of shoreline change. These are largely dictated by the physical characteristics of the shoreline being studied and the type and quantity of shoreline position data available.

1.2 Study site

Mañagaha islet, 3 km off the coast of Saipan, Commonwealth of the Northern Mariana Islands is used here as the geographic context to review shoreline change literature, assess available shoreline position data, select an appropriate analysis methodology, develop a descriptive/predictive model of shoreline processes, and describe
the historical pattern of shoreline change. Improved understanding of shoreline change at Mañagaha will establish an improved basis for evaluating management options available to authorities.

Mañagaha and its surrounding waters were established as the Mañagaha Marine Conservation Area in 2000 with a unique combination of important marine, flora and fauna, economic, and cultural resources. Since 1996, severe coastal erosion along the northeast, east and southeast sandy shoreline has resulted in felled trees, undermined day-use concrete structures and eroded walking paths. These existing hazards pose health and safety risks to users accessing the sandy beaches of these areas and impact an endangered bird nesting habitat. Managers and planners need information about the changing shoreline in order to manage potential hazards to visitor safety and to plan mitigation efforts to minimize impact of continued coastal erosion on environmental resources.

Figure 1. Erosion at Mañagaha. Erosion along the eastern and southeastern shoreline of Mañagaha has already destroyed a day-use pavilion, eroded the trail and felled trees. Managers are concerned for visitor safety.
1.3 Research goal

The goal of this study is to quantify shoreline change around Mañagaha using available data about past shoreline position variability to calculate shoreline change rates around the island and identify erosion hazard areas. Managers can use the identified erosion hazard areas in planning for potential impacts of erosion on the environmental resources and access to those areas by local residents and visitors.

To achieve this goal, Mañagaha is described from environmental, historic and economic perspectives. Previous studies and reports on and about erosion on the island are presented. Methods to identify, process and analyze high-resolution historical aerial imagery, satellite imagery, field collected beach profiles, and photographs will be reviewed from relevant shoreline change literature and from shoreline change analyses in analogous locations in the Pacific Basin. Data collected is first presented qualitatively, then processed, the shoreline selected and digitized and sampled alongshore. Single transect (ST) and polynomial methods (PX and PXT) are used to analyze historical shoreline position data around Mañagaha and calculate a rate at each shoreline measurement location. A robust rate uncertainty at the 95% confidence interval is calculated at each location that incorporates shoreline position and model uncertainties. The results of the historical shoreline change analysis are presented and discussed to help local authorities develop an appropriate short-term shoreline management strategy at this important economic, cultural and natural resource.

1.4 Thesis structure

The remainder of this thesis is structured into sections. Section two provides a site description of the island environment, the management context in which decisions about use and access to Mañagaha are made, and the cultural and economic roles the island occupies in Saipan and the Commonwealth. Section three explores the erosion problem on Mañagaha, the removal of shoreline debris in 1995 and prior work and studies that document the erosion. Section three reviews existing methods to construct a shoreline change analysis using available data, processing techniques, shoreline definitions, sampling techniques, measurement and position uncertainty definitions and a shoreline change rate calculation method.
Section five outlines methods and results developed for Mañagaha using aerial and satellite imagery, field-collected beach profiles, prior work and image and statistical processing software. Results are presented in tabula format and as projected hazard zones on a map of the island. Section six discusses and summarizes the shoreline change analysis results around the island. These are placed within the context of the goals of this thesis and the larger body of shoreline change studies.
2. SITE DESCRIPTION

2.1 Environmental setting

Saipan is located within the Commonwealth of the Northern Marianas Islands (CNMI) in the low western latitudes (~15° N) of the Pacific Ocean (Figure 1). Mañagaha is a four ha sandy cay within Tanapag Lagoon, 2.7 km west of Garapan, Saipan (Figure 2). Tanapag Lagoon extends along the West coast of Saipan, ~3.5 km at its widest point in the north and narrowing to the south. It possesses a typical fringing reef morphology defined by a broad and shallow reef flat, a reef crest and a steep reef front. The reef crest is located about 600 m to the west and northwest of Mañagaha and significantly attenuates open ocean wave energy from the west, north, and south. The reef flat is

Figure 2. Saipan location map. Saipan is located within the Commonwealth of the Northern Marianas Islands
Mañagaha is composed of poorly sorted carbonate sediment with a median grain size of 1.6 mm (Cloud et al., 1956). Outcrops of beachrock are exposed at lower low tide at many locations around the island. It is most apparent at the east and southeast exposures where the beachrock intersects remaining sandy beach. 1946 imagery (Appendix A) reveals beachrock along the north and northwest shore that has since been covered with sand. While there is no detailed geologic information of the interior of Mañagaha (i.e. no sediment or rock cores), WWII era bunkers and emplacements and the above-mentioned 1946 aerial imagery indicates large-scale earth (high albedo, probably sand) moving has taken place to reshape the island. The reshaping of the island was perhaps for construction and fortification following invasion of Saipan by American forces in 1945. The change in island shape may also be a result of undocumented impacts of the Aleutian tsunami of April 1, 1946, though no damage is reported on Saipan.
(Hoffman, 1950). It is speculated that a limestone basement likely underlies much of the island and acted as an anchor to sediment during island formation (Cloud et al., 1956; USACE, 2001).

Saipan and Mañagaha lie at the convergence of the Asiatic Monsoon belt and the northeast trade winds belt. Trade winds blow 70% of the year dominantly from the east to east-northeast and are strongest January through May during the dry season. Annually on Saipan, trade winds blow approximately 13 - 18 km/hr 40% of the year, 20 - 30 km/hr 26% of the year, and 4% of the year wind speeds are greater than 30 km/hr (USACE, 2004). Light and variable wind conditions tend to occur during the wet season of July through December. Storm/typhoon winds are more likely between April and November.

Mañagaha has a unique wave climate due to its location in Tanapag lagoon and position relative to Saipan. The fringing reef along the western coast of Saipan buffers the island from direct open ocean swell. The island of Saipan buffers Mañagaha from the majority of trade wind generated swell. Large typhoon and storm generated swell as well as infrequent southwest swell does impact Mañagaha as well as the Saipan coast. Figure 4 shows common swell (blue) and wind (orange) direction during a typical year. Lifeguards at Mañagaha describe swell from the west and north that wrap into the lagoon through the harbor entrance to the southwest. These swells can produce high run-up during high tide that overtop the wide flat beach on the northwest end of the island and penetrate the vegetation line. For the most part, trade wind generated, short period waves exist during the majority of the year with periodic storm induced waves usually attenuated by the fringing reef potentially impacting Saipan and Mañagaha significantly (USACE, 2001). Since 1945, there have been an
average of three large tropical storms pass within 300 nm of Saipan annually (Minton and Palmer, 2006). There are four principal types of wave energy that potentially directly impact the Mañagaha shoreline: 1) Trade wind generated waves from the east and northeast that cross Tanapag Lagoon; 2) Wave energy from open ocean/deep water swells crossing the fringing reef from the north, west or southwest; 3) Infrequent north wind generated waves and currents running south; 4) Tropical storm and cyclone waves.

Tides at Saipan are semi-diurnal with two high and two low tides each 24-hour period. The mean tide range at Saipan is 0.4 m (CO-OPS, 2012) with a mean higher high water elevation of 0.2 m and a lower low water elevation of -0.4 m relative to mean sea level (USACE, 2001).

### 2.2 Management of the island

The island and the surrounding waters were designated a marine protected area (MPA) in 2000 under Public Law 12-12 as the Mañagaha Marine Conservation Area. The protected area designation expands, refines and updates the Mañagaha Marine Park management plan of 1985 (CRMO, 1985). The marine park sought to identify and expand compatible uses of the island following designation as a U.S. National Historic site in 1984. The purpose of Public Law 12-12 and the goals of current management are to protect the island and its surrounding marine environment for the continued use and enjoyment of visitor and residents (Schroer, 2005).

The Department of Land and Natural Resources (DLNR) holds management authority of the Mañagaha Marine Conservation Area. The Division of Fish and Wildlife (DFW) are responsible for the Mañagaha Marine Conservation Area management plan required through PL 12-12. Through the plan, DFW are tasked with managing habitats and wildlife within the protected area, working with the other permitting agencies and organizations that have permitting authority over various uses of Mañagaha. The Coastal Resource Management Office (CRMO) manages coastal resources and any activity impacting those, such as the sole concession provider on the island. Because Mañagaha is entirely comprised of coastal resources, the CRMO works with the DFW in concurrence for permitted activities that potentially impact any habitat, flora or fauna on the island.
In practice, two rangers hired by the Board of Public Lands are stationed on the island everyday to monitor visitor arrivals and concession activities and enforce the regulations of the conservation area. The DFW sends officers and staff to the island to collect data and monitor wildlife, fish and habitats, maintain signage and investigate reports of regulations violations or concerns by visitors and rangers. CRMO staff visit the island to monitor the impact to existing coastal resources such as beaches, permitted structures, water quality and commercial activities. Together with the Department of Environmental Quality, CRMO staff are responsible for monitoring, investigating impacts to, and permitting any use potentially affecting water quality around the island. Because coastal erosion affects coastal resources and activities conducted on the island the CRMO has established a monitoring plan around the island.

Coastal erosion on Mañagaha has eroded walking paths, felled trees and exposed beachrock, potentially endangering visitors. An endangered shorebird nesting habitat is impacted in the northwest portion of the island where nests located in the sandy dune are being destroyed by attacking waves. The permitted sole commercial concession on the island (Tasi Tours and Transportation, Inc.) would also like to avoid any visitor’s having a negative experience, potentially impacting business revenue. Any remediation of the effects of coastal erosion for users requires action by the DFW and CRMO and should address both the concerns of businesses reliant on the island and impacts to the flora and fauna being encroached upon.

2.3 Economic role of Mañagaha

Mañagaha is an important asset to the economy of Saipan and the CNMI. The island is the most visited attraction by foreign tourists in the Commonwealth of the Northern Marianas Islands (CNMI). The island is used as a tourist activities staging area and recreation base for visitors of all types, foreign and local, by providing sandy shore access to the surrounding reefs, concessions services, SCUBA and snorkel rental and transportation to and from the island regularly. It is the most visited marine protected area (MPA) in the CNMI, generating approximately $21 million of the total $42.31 million in tourist revenue generated from activities in and associated with MPAs (Van Beukering, 2006; Saladores, 8/9/2000). Tourist revenue includes all commercial activity (money
spent by tourists to engage in an activity) where the protected area is a focal point or associated with the activity being carried out. These include conservation area focused snorkel tours, scuba diving and concession activities as well as stop-overs by motor boat activities near the island such as parasailing and jet skiing, that use the area peripherally. In addition to these economic activities tourists who visit the island pay a landing fee of $5 each, grossing over $1 million per year (Dones, 8/8/2006) that goes into a trust account intended to pay for management, maintenance and regulation enforcement of the conservation area (Shroer, 2005). The account is regularly redirected to other projects (Dones, 8/8/2006).

2.4 Cultural role of Mañagaha

The island is important to the Carolinians of Saipan. It continues to be used as a gathering place for Fiighiló or burning of objects close to the deceased in a small fire during Firowrowa (funeral) ceremonies (Schroer, 2005; Sablan, 2003; Russell, 1998) and for the collection of medicinal herbs and plants with more than 28 species found on the island (Schroer, 2005; Sablan, 2003). There are four day-use pavilions about the island used by local and foreign visitors regularly. The island has a large statue commemorating Aghurubw, the Carolinian navigator that lead a small group of Carolinian settlers by voyaging canoe to settle on Mañagaha in 1815 ‘for many years’ (CRMO, 1985). These settlers planted many of the medicinal plants found there today (Shroer, 2005). When the Carolinian settlers arrived in Saipan, few Chamorro were left on the island following Spanish colonial banishment of all Saipan Chamorro to Guam 31 years earlier (Russell, 1998).

There is no record or archeological evidence of permanent settlement on Mañagaha since the Carolinian group moved to Saipan. This is due to a lack of written history, displacement of the Chamorro population and extensive earth movement and natural sediment transport on the island that would erase delicate archeological evidence. Fresh water resources on the island would not likely support a large population. The Japanese moved into the Marianas Islands in 1914 and used most of the flat areas of Saipan island to grow sugarcane. Mañagaha became a strategic location to defend the harbor entrance from invasion. West of the island, patch reefs were removed to make a
seaplane runway. The pier at Mañagaha was likely built by the Japanese military to fortify the island and facilitate seaplane support.

During WWII, Mañagaha (referred to then as Maniagassa) was the stage for the final fight in the battle of Saipan. Shelled heavily during the invasion, it was taken in a single hour on July 13, 1944 and occupied for the remainder of the war (Hoffman, 1950). It is from this period of occupation by the Japanese and then the U.S. military that the wrecks of ships, airplanes, barges and a significant amount of smaller debris can be found scattered in the area. Two mooring buoys within the conservation area mark WWII era Japanese and American military airplane wrecks for SCUBA diving tours. On land, several disused bunkers of both Japanese and American military origin, several pillboxes and metal debris attract visitors using the walking trail around the island (Figure 2).
3. SHORELINE CHANGE AT MAÑAGAHA

3.1 The removal of debris

In May of 1995, in response to concerns about visitor safety by tour companies and the Coastal Resource Management Office (CRMO), World War II (WWII) era disintegrating metal structures and other debris along the shoreline were removed from the south and southeast portions of the island (see figure 5). The wrecks in the southwest ‘corner’ of the island were the largest items removed and thereafter became the focal point of erosion. There was no study conducted prior to debris removal to evaluate the potential impacts on the stability of the shoreline or the marine park (USACE, 2001).

Figure 5. 1987 aerial photograph showing three areas of debris removal. A barge, the Samsung wreck (indicated with blue arrow) was the largest structure removed. Prior to removal, the disintegrating wrecks presented a safety hazard to beach and ocean users.

Following wreck removal and the onset of rapid coastal erosion (See Existing Conditions) CRMO requested help from the USACE as structures were threatened by coastal erosion. Various mitigation efforts were investigated including construction of
breakwaters or other hardened structures on or near the island. The USACE examined the problem using profiles along the eastern and southern shoreline over a four-year period (1997 – 2001). They concluded that the wrecks were acting as hard points along the shoreline, creating a depositional environment by interrupting alongshore currents and protecting the immediate shoreline from direct wave attack (USACE, 2001). With the removal of the wrecks, the accreted land and sandy shoreline is again exposed to dominant alongshore currents and wave attack.

### 3.2 Shoreline change definitions

When discussing shoreline change along a portion of coast, it is important to understand the difference between various terms used. Shoreline change is the movement

![Figure 6. Shoreline photo locations around Mañagaha.](image)

### Photo locations

- Figure 7
- Figure 8
- Figure 9
- Figure 10
of the shoreline landward or seaward from a point of reference. Typically this point of reference is a previous position, however in shoreline change studies, an arbitrary onshore or offshore location (a baseline) is created and used (see Section 4). Coastal erosion refers to the landward migration of the coast. At a sandy shoreline, this means that the beach is moving landward in conjunction with the vegetation line, causing beach erosion and land loss. Coastal erosion does not necessarily imply beach loss.

A sandy beach relies on a source of sediment in the system supplied from onshore, offshore, and along-shore especially during episodic events such as storms or high waves. When the waves overtop the beach or migrate the beach face and swash into the backshore, the wave action erodes or undercuts vegetation to draw upon the stored sand in the backshore. When sediment is not available or accessible because it is naturally limited in supply or impounded (e.g. behind a seawall), beach erosion may result since the beach is starved for a source of sediment, especially during episodic events. Beach loss occurs when no sediment is available to replenish the beach.

3.3 Existing conditions – coastal erosion on Mañagaha

Coastal erosion on Mañagaha is reported by the local concessionaire as early as June of 1996 following wreck removal (Agulto and Yuknavage, 2006). Since then erosion has continued and resulted in coastal erosion and the exposure of beachrock, beach narrowing and

Figure 7. Photos of land loss and beach loss in 2001. The erosion scarp approximately 3 feet high and being further undercut next to the pedestrian path that has eroded since. Note the vegetation on the scarp together with felled trees along the shore indicating past vegetation extent. (photo: USACE, 2001)
Figure 8. Exposed beachrock as a result of beach erosion (a) restricts safe ocean entry and exist for visitors. If algal growth occurs on the surface, footing may become dangerous. Felled trees (b) interrupt alongshore access. Note that the beach is preserved. (photos: UH, 2007)

Figure 9. Day-use shelter or pala pala (left) in 1999 (photo: CRMO staff, 1999 from USACE, 2001) is being undermined by erosion. The same structure in 2001 (right) is completely lost (photo: USACE, 2001).

Figure 10. The northwest portion of the island is the main activity concession area, where the majority of visitors go and where the beach is widest (left and right, in the distance). Erosion is apparent along the western coast as the beach narrows nearing the landing pier (right). Photos: UH, 2007
steepening, felling of trees, the destruction of a portion of the pedestrian path and the collapse of a *pala pala*.

Erosion is most apparent on the northeast, east and southeast portions of the island (Figures 8 - 10). There is beach erosion impacting the west shore, on the north side of a concrete walkway connecting the landing pier to the island (Figure 10a). The majority of erosion (save at the landing pier) is situated away from the main tourist concessions in the northwest (Figure 10b). This has the upside of relatively lower pedestrian traffic volume being exposed to changing potential hazards such as tripping and falling on eroded walking paths, off steep sloped scarps, over fallen trees, on algae covered beachrock and exposed debris in addition to the normal marine recreation related hazards. The downside of being out of the high traffic areas is that aid services in the event of serious injury are further away. Of course, potential hazards existed prior to WWII debris removal, specifically those resulting from debris itself.

### 3.4 Prior work

This study follows the work of the U.S. Army Corps of Engineers (USACE) Honolulu Engineering District (2001) and Coastal Resource Management Office (CRMO) staff that document erosion along the east, southeast and southern shoreline of Mañagaha since the removal of WWII era relics and debris from shoreline. The 2001 USACE report recommended further study of the physical processes such as wave, current and sediment studies coupled with numerical and physical models to understand sediment processes and distribution that influence the position of the shoreline and “help determine optimal placement and likely impacts of any remediation measures”. They also recommend further monitoring of the shoreline that CRMO staff continued with biannual and post-storm beach surveys around the island from 2003 through 2005 (Agulto and Yuknavage, 2006). The DFW is tasked with wildlife and habitat management responsibilities outlined in the Mañagaha Marine Conservation Area (Shroer, 2005; PL 12-12). The CRMO is concerned with visitor safety using island facilities (the eroding pedestrian path, collapsed *pala pala*, safe shoreline access) Both management agencies seek to understand the extent of erosion to-date, identify areas of potential erosion in the future and mitigate the effects of current and future erosion to protect the health and
safety of visitors to the island while preserving the environmental and cultural resources that make the island unique and important.

The USACE (2001) study was requested by local resource managers to provide information of coastal processes, provide alternatives to stabilize the shoreline erosion, and protect threatened structures on Mañagaha. The report provides environmental information, photo documentation and series of beach profile line locations that quantify the extent of erosion to 2001. The study is an initial investigation into erosion at Mañagaha. The study finds that the removed WWII era wrecks from along the east and south east acted as hard points along the shoreline dissipating wave and current energy in a portion of the island dominated by trade wind and wave conditions. Since removal, over 100 ft of sandy shoreline has been lost since 1997 from the most severely affected areas while small amounts of accretion have occurred in other areas.

The study also investigated whether the erosion at Mañagaha may be the result of works by the USACE in 1994 to deepen the shipping channel that lies 1.5 km to the south of the island. The study found it highly unlikely that the erosion at Mañagaha could be the result of deepening the channel by 4 m.

Agulto and Yuknavage (2006) present the need for a robust method to examine historical shoreline change at Mañagaha. The work documents the extent of erosion to date using beach profiles around the island. They also present a relevant chronology of events affecting Mañagaha:

- Sept 1984 Mañagaha registered as a National historic site
- Dec 1995 HPO permits the removal of 5 wrecks. CRM Program Agencies/CPA/EFC/Samsung decide that four wrecks need removal
- April 1996 removal commences
- May 1996 barge removal complete
- June 1996 remaining metal shards and some erosion is noticed by DEQ lab staff during sampling
- August 1996 investigation of erosion requested by CRM
- April 1997 more erosion reported
- Jan 1998 erosion appears to have stabilized
- April 1999: Rep Heinz Hofshneider requests assessment of Saipan lagoon dredging impact. CRMO, Peter Barlas says Saipan channel dredging is the major culprit. Pala Pala damage and downed trees are shown by a survey of the area.
- May 1999 Governor Pedro Tenorio call for action to save Mañagaha
- 1999 Dredging commences in the channel south of Mañagaha
• March 2000 ACOE and CRMO state that Mañagaha should be allowed to stabilize naturally.
• Jan 2001 Mañagaha erosion study distributed
• CRMO provides NAD83 coordinates of the Mañagaha Protected Marine area. Mañagaha is thought to be recovering. No action will be taken towards constructing a breakwater
• Nov 2003 beach at profile 4 is near gone

Using 9 beach profiles collected by CRMO staff and photographs over a three-year period (2002 – 2005), they track migration of the beach face of Mañagaha bi-annually and post storm events. They document the effects of coastal erosion along the northeast, east and southeast of the island as it undermined trees, and causes the collapse of a pala pala. On the southwest side of the island, erosion caused structural damage to the landing pier. At the same time the northwest portion of the shoreline was accreting. Coastal erosion is also documented threatening nesting habitat used by the endangered shearwater bird. The plotted profile data are included as appendix B.
4. METHODS

A sandy beach at a shoreline is the result of multiple dynamic physical processes that interact at several spatial and temporal scales. Changes in the long-term (decades, centuries) or short-term (minutes, hours, days) represent the interaction of these processes as they seek equilibrium. Coastal engineers develop mechanical and numerical models of these physical processes using scaled models of the near shore and basin morphology, field-deployed instruments such as current and pressure meters, and modeling programs with the goal to understand changes in the position of the shoreline. While these efforts can add a significant amount of knowledge about the study area, the budget for such efforts and the expertise to collect and process the data and interpret the results are not always available or justified. Where there is a lack of access to physical and numerical models of physical processes, a historical shoreline change analysis study provides a practical and relatively affordable method to quantify shoreline position changes and identify possible future erosion hazard areas (National Research Council, 1990).

Historical shoreline change analysis methods rely on a variety of historical shoreline position data. These can be extracted from old topographic sheets (T-sheets) and surveys, remotely sensed data such as vertical aerial photography, satellite data (natural color and other), and LiDAR data, modern ground-based kinematic GPS surveys, spot elevations and surveyed beach profiles (Boak and Turner, 2005). The quantity,
quality, resolution and sources of shoreline position data act as constraints in deciding an
appropriate shoreline change study method to use (Moore, 2000). Moore (2000) discusses
multiple techniques to map shorelines based on available data, desired accuracy,
processing time and equipment. Moore includes a discussion of mixing mapping
techniques and derived shorelines and analyzing change within a GIS. The author finds
that soft copy photogrammetry integrated into a GIS, such as used by Coyne et al. (1999)
and Fletcher et al. (2003), the most thorough and expensive method to map shoreline
change. She recommends a method that balances cost (time and money) with the timeline
of the project and the desired output (product type and accuracy). Moore provides a set
of recommendations to successfully complete a shoreline mapping project: 1) select an
appropriate technique to map the shoreline. 2) when possible use GPS rather than NOS
topographic sheets (T-sheets) and T-sheets rather than USGS quadrangles. 3) if using
historical maps, assess their accuracy. 4) use the highest quality vertical aerial
photographs. 5) use the largest scale photography available, at least 1:20000. 6) choose a
shoreline proxy that is well characterized by your mapping technique (e.g. top of dune
should be used as the shoreline only if the mapping method accounts for relief
displacement). 7) account for uncertainties in the shoreline proxy chosen (e.g. seasonal
variation, effect of storms on the shoreline position). 8) account for short-term variation
in the position of the shoreline proxy. 9) preform an overall error assessment and
calculate an overall error estimate.

This study adapts historical shoreline change analysis methods from Fletcher et al.
(2003) and Coyne et al. (1999) that use the crest of the beach toe as shoreline change
reference feature. Shore-normal shoreline measurement locations (transects) are located
approximately every 20 m alongshore and a robust uncertainty statistic is developed as in
Fletcher et al. (2003) and Romine et al. (2009). Genz et al. (2007) provide an overview of
common methods used to calculate shoreline change rates while Frazier et al. (2009) and
Genz et al. (2009) introduce a new set of methods. Figure 1 outlines the methodology
and workflow of the shoreline change analysis adapted for use in this study and provides
an outline for the following section of this chapter.
4.1 Image data identification

Numerous agencies including the United States Geological Survey (USGS), National Oceanic and Atmospheric Administration (NOAA), Federal Emergency Management Agency (FEMA), states, local governments and private parties collect aerial and satellite imagery for resource evaluation, charting, mapping and planning. Vertical aerial photography is collected using aircraft equipped with calibrated, geometrically stable, horizontally mounted cameras. Mobilization and calibration costs may be significant. As a result, most collection efforts are organized as surveys with flight line maps for planning large area, continuous acquisition of overlapping coverage. High-resolution vertical aerial photography is recommended by FEMA for shoreline change studies because they provide historic continuous shoreline coverage (Crowell et al., 1991).

Satellite imagery such as those from Digital Globe™ Quickbird™ and Worldview-2™ sensors provide large scene collection at a resolution (> 0.6 m) that is comparable to processed vertical aerial images and quality (color bands and bit-depth) to delineate shoreline features visually on-screen. The imagery vendor typically provides a level of processing that corrects for at-sensor and ground level conditions based on the costs and resources required (accurate GPS data and possibly elevation data) that may be available for the desired area (cheaper to process) or need to be collected and processed (more labor intensive, i.e. expensive).

High-resolution vertical aerial shoreline surveys and satellite imagery provide continuous along-shore position information about features on the beach at the moment the camera captured the image. They chronicle the dynamic physical processes such as along-shore sediment transport, tides, and wave setup that result in the shoreline position at the moment the image is acquired. The use of aerial imagery as a primary data resource in historical shoreline studies is recommended by the Federal Emergency Management Agency – FEMA as a source for shoreline position data (Crowell et al., 1991).

Coyne et al. (1999) and Fletcher et al. (2003) employed a general set of guidelines to select imagery appropriate for historical shoreline change analysis. Imagery that, when scanned, is of sufficient scale and quality to delineate the proxy of the shoreline change reference feature while maintaining a workflow for island scale photogrammetric studies. They identify historic and modern imagery that is 1:16000 or larger with preference
given to larger scale, tonally balanced stereo imagery of contiguous portions of the coastline. Stereo coverage provides complete overlap of the ground, aiding in image rectification using control points and passpoints between imagery and in identifying the shoreline change reference feature in the processed image maps (discussed in the following sections).

The shoreline proxy refers to a morphological feature or visible indicator that represents a shoreline definition. In the field, morphological features such as the crest of the beach toe, the wetted/dry sand line and the seaward edge of vegetation represent the interaction of physical processes and the beach over time. The crest of the beach toe represents the instantaneous low water mark (LWM) (Romine et al., 2009), the highest swash of incoming waves creates the temporary wetted/dry line and the highest wash of the annual highest waves tend to define the vegetation line. On image base maps, the shoreline proxy may be visible as a distinct color or tone change in the image, although not necessarily. The definition, identification, and uncertainty associated with locating the shoreline proxy in the field and on imagery is discussed in later sections.

### 4.2 Image Processing

Unprocessed aerial photos and satellite images, while qualitatively interesting do not support accurate quantitative measurement due to the shape of the lens, distance of the film plate or processors from lens (Camera Focal Length) and the altitude of the airplane above the ground. The use of high-resolution vertical aerial photography as a mapping tool in shoreline change analysis is possible because there are published methods of removing the distortion introduced by the camera and platform (airplane or satellite). Implemented to minimize errors, image rectification can transform vertical aerial imagery from multiple sources, different cameras, resolutions and scales to a common referenced map-quality projection. Once in a common projection, the shoreline positions may be compared (Crowell et al., 1991; Thieler and Danforth, 1994; Coyne et al., 1999; Fletcher et al., 2003).

To rectify an image data source, whether aerial or satellite, a reference image, mosaic, map or database may be used. Ground control points (GCPs) are points that a user or routine identifies with a reference coordinate and a corresponding image.
coordinate. Care is taken to identify points and locations common to the reference and image-to-be-rectified that are at ground level (to avoid the effect of parallax, apparent in low altitude aerial imagery). Thieler and Danforth (1994) introduce computer aided soft-copy photogrammetric techniques to rapidly process multiple images and greatly shorten the time it takes to process imagery of a stretch of coast and extract a shoreline. Coyne et al. (1999) bring rectification methods into the Pacific region and adapt Thieler and Danforth (1994) to map continuous portions of shoreline along the Oahu coastline. Coyne uses camera information and aero-triangulation to rectify modern and historic imagery to a common datum (WGS84 (1993) zone 4). Aerotriangulation is a rectification method that uses tiepoints (also known as passpoints) to establish a relationship between frames and ground control points (using differential global positioning points (DGPS) in their case) located within each frame of imagery. Historical imagery is corrected using ground control points collected from processed modern imagery when DGPS locations are not identifiable in the imagery.

4.3 The shoreline change reference feature

The shoreline change reference feature (SCRF) or shoreline indicator is the proxy of the land water boundary used to indicate the position of the shoreline. It represents the shoreline position in each map data set used. In historical shoreline change analysis, a consistent definition of the shoreline and its visible proxy is required to calculate a rate of shoreline change (Crowell et al., 1991; Moore, 2000).

Boak and Turner (2005) provide a summary of many SCRFs used in shoreline studies. They delineate two types of shoreline indicators, feature and datum based. Feature based shorelines are those that represent a geomorphic feature visible on the beach itself. Datum based shorelines (Figure 12, features K and G) represent the intersection of a vertical tide datum (usually statistically derived from tidal station data) with a digital terrain model (DTM) of the beach. Datum based shoreline definitions lack proxies and cannot be found in the field during beach profiling efforts (beach profiling is discussed below). Boak and Turner found 45 examples of shoreline indicators in literature, 4 of which were datum based. 35 of the remaining 41 are based on visually discernable features such as high swash, a debris line or man-made structure while the
last 6 are extracted from imagery using image processing techniques and are not necessarily visible to the human eye. Figure 12 indicates many commonly referred to

**KEY**

A Seawall edge  
B Vegetation Line  
C Berm crest  
D Storm/debris line  
E An old high tide water level  
F Previous high tide water level  
G mean high water (tidal datum)  
H Wet/dry line or runup maxima  
I Instantaneous water line  
K Mean lower low water line (tidal datum)  
L Beach toe/crest of beach step or maximum drawback of shorebreak waves

Figure 12. Selected shoreline change reference features (SCRFs). Located along a beach profile fronting a seawall (top) and not (bottom) (modified after Boak and Turner, 2005). Note that the presence of a seawall replaces proxies of several SCRFs and requires additional research to evaluate the definition of the SCRFs present (such as the vegetation line (B)).

SCRFs in profile view. Boak and Turner found that the high water line (HWL) as the most widely used as well as the most widely varying in definition. They found considerable variation between HWL definitions in the literature; often the HWL was defined as the tone change on the beach face (foreshore of the beach) left by the maximum run up from a preceding high tide. In Figure 12, features D, E, F, and H have been used as proxies for the HWL in literature.

The toe of the beach is described by Bauer and Allen (1995) as a quasi-equilibrium step feature marking the base of the foreshore of the beach and created by vortexes as breaking waves swash up and retreat down the foreshore (Figure 12, feature L). It is commonly characterized along the profile of a beach as two slope changes, one
at the crest of the toe and another at the base. During the flood tide, the step is evolved landward with a retreat of the step face landward. During an ebb tide, the step evolves seaward with material from the foreshore that collapses down the slope.

The crest of the toe or beach step crest is identified in the field using Bauer and Allen (1995)’s description. It is a geomorphic feature indicating the low water mark (Fletcher et al., 2003; Romine et al., 2009) usually visible as the first slope change and significant step seaward of the land/water interface. It can be identified in a beach profile as a ‘step’. A beach profile (Figure 12) is a surveyed line from a stable control point across the beach towards the water, usually perpendicular to the shoreline. Beach profiles used by Coyne et al. (1999), Fletcher et al. (2003) and Romine et al., 2009 are collected using electronic theodolite, laser, and telescoping rods with mounted reflecting prisms. Precise angles and distances are processed to calculate exact elevations at features of interest (see Figure 12 and Appendix A). Methods used by CRMO staff on Mañagaha replace the electronic theodolite with a plane table, manual theodolite and measuring rod and yield similar results albeit at a slower pace and lower accuracy. A collection of points along an azimuth from the control point perpendicular to the beach creates a profile of the beach.

In high-resolution aerial and satellite imagery, the crest of the beach toe is indicated by a tone change in the water column (Figure 13) immediately offshore of the land/water boundary. This is due to the change in water depth associated with the toe feature (Coyne et al., 1999). The high albedo of many carbonate sand beaches including those at Mañagaha mean that many shoreline proxies, such as previously wetted sand indicating a HWL are not always identifiable (Coyne et al., 1999) nor represent a a consistent definition of shoreline through time (e.g. a cultivated vegetation line that no longer represents annual reoccurring high wave extents).

In developing their shoreline change analysis method in Hawaii, Coyne et al. (1999) use beach profiles collected over a complete tidal cycle to test the sensitivity of three shoreline definitions proxies using beach profiling: the HWL, the LWM and the vegetation line. The HWL proxy is the highest reach of the waves and visible in the field on the beach face as a tone change in the sand at the highest swash of the waves. The LWM proxy is the crest of the beach toe. It is visible in the field as a slope change as the
base of the foreshore, at the maximum draw-back of the waves. The vegetation line proxy is the seaward extent of stable vegetation growth and visible as such in the field.

They find that the toe of the beach is less sensitive to tidal variation in position than the high water line based on beach profile data. Importantly for historical shoreline change analysis, they conclude that the toe of the beach is the more appropriate indicator of the shoreline position because it is less sensitive to tidal variation and is more readily visible on high albedo carbonate beaches, particularly on black and white (monochromatic) historic imagery where the contrast of the beaches can be high. Fletcher et al. (2003) also use the toe of the beach as the SCRF and identify the crest of the toe on

![Figure 13. Identifying the crest of the beach toe in imagery (orange dash line on left image, orange dot on right diagrams). The toe is indicated by a tone change in the water column due to a change in water depth (profile A). It is sometimes a subtle feature landward of and close (~0.1 m) to the sand/rock interface (profile B).](image)

gray-scale and color imagery from 1949 through 2002 around Maui, Hawaii. Romine et al. (2009) uses the toe as the geomorphic proxy of the low water mark (LWM) around Oahu, Hawaii in their historical shoreline change study. Romine et al. (2009) follows Coyne et al. (1999) and Fletcher et al. (2003) and choose not use the vegetation line as the SCRF. They found that the vegetation line is not an appropriate indicator of shoreline variability where it is artificially influenced through cultivation, maintenance and grooming.
When selecting imagery to include in historical shoreline change analysis, the feature of interest must be visible in each image database prior to processing (Crowell et al., 1991; Coyne et al., 1999; Moore, 2000; Fletcher et al., 2003). Processed imagery is visually interrogated to locate and manually digitize the shoreline change reference feature proxy on-screen (Figure 13, left). The tone and contrast of the imagery can be adjusted to maximize visibility of the feature as it is digitized along the shore and across mosaicked imagery bounds (Coyne et al., 1999). The resulting digital shoreline represents the historical shoreline position of the date of imagery.

4.4 Casting Transects

A stable reference location is required to measure change in the position of the shoreline. A baseline acts as that stable location. Baselines are constructed parallel to the general trend of all of the compiled digitized shorelines such that transects cast perpendicular to the baseline run through each shoreline as shore-normal as possible. Transects are shoreline measurement locations along the shoreline. Transects are cast from baselines and run through the digitized shoreline (Figure 14, right). The distance from the baseline along the transect, to intersect each shoreline is recorded as a table of distances organized by transect number and the date of the shoreline intersected.

4.5 Uncertainty Analysis

It does not take long while studying the shoreline using aerial photography, beach profiles, or simply sitting on the beach to appreciate the temporal and spatial variability of the shoreline. Tidal changes, recent storms and seasonal beach trends exist in the background of any single recorded shoreline position. They operate continuously and result in any single shoreline representing a snapshot of the beach morphology as a result of these processes. The final calculated shoreline change rate, as a derived product of these positions will include this variability. It is important to identify, calculate and include these uncertainties in the shoreline change model to ensure that the calculated rates reflect shoreline position trends rather than short-term variability (Romine et al., 2009). Following Coyne et al., 1999 and Fletcher et al., 2003, two groups of uncertainties are identified: position uncertainties and measurement uncertainties.
Position uncertainties are associated with the position of the shoreline at the moment the imagery was collected. As described above, this moment lays within the context of physical processes that occur on time-scales from tidal to seasonal fluctuations reflecting dominant, recurring wind and wave driven current patterns. Measurement uncertainties are associated with delineating the position of the shoreline in the data source. These include rectification error, digitizing error, pixel size of the processed map data, plotting errors on topographic charts and field identification of the high water line associated with topographic charts. Romine et al. (2009) follow and develop Fletcher et al., 2003 to identify the probability distribution for each error process. The total positional uncertainty equation

\[ U_t = \pm \sqrt{Er^2 + Ed^2 + Ep^2 + Etd^2 + Ets^2 + Ec^2 + Es^2} \]

where \( Er \) = rectification error, \( Ed \) = digitizing error, \( Ep \) = pixel error, \( Ets \) = error plotting on a T-sheet, \( Etd \) = tidal fluctuation error, \( Es \) = seasonal error, and \( Ec \) = error in field identification of MHWL and low water line (Genz et al., 2007). Effectively, the total positional error (\( Ut \)) uncertainty for each shoreline position represents the confidence in the shoreline position as identified by the feature on the beach. It is applied as a weight for each shoreline position in shoreline change models that use weighted regression methods (Romine et al., 2009).

### 4.6 Shoreline Analysis – rate calculation

The shoreline change rate characterizes the trend in the position of the shoreline over time. It is used to represent the statistical trend of the shoreline position over time (Figure 13). There are two general types of shoreline change rate calculation methods: single transect and polynomial methods. Coyne et al. (1999) and Fletcher et al. (2003) both use single transect methods. Coyne et al. (1999) use the end point rate (EPR) method for their final shoreline change rate statistic. Fletcher et al. (2003) also calculate the EPR and also use the reweighted least squares regression (RLS) method around Maui, Hawaii.
Genz et al. (2007) develop criteria to help select an appropriate rate calculation method based on how well the analyst understands uncertainty in their methodology (quantified most major sources of error) and how many shoreline positions (data points) are analyzed. Methods sample along-shore using transects cast from arbitrary onshore or offshore baselines that intersect digitized historical shorelines. Plots of distances from the baseline along each transect to each historical shoreline position are generated (See Figure 14). Distance is plotted on the y-axis; time is plotted on the x-axis; historical shoreline distances from the baseline are plotted as points. Methods used to derive a trend in the position of the shoreline through time fall into three general categories: single transect methods, non-acceleration polynomial methods and polynomial methods with acceleration.

Single transect (ST) methods to calculate shoreline change rates assume discrete information about the shorelines at each transect location. Genz et al., 2007 review statistical methods commonly used on historical shoreline data to calculate rates of change. Fletcher et al., 2003, Miller et al., 2003, Romine et al. 2009 use the WLS method.
around the Hawaiian Islands to calculate the long-term shoreline change rate. The WLS method is a linear regression method that incorporates the calculated total positional, root mean square error (RMSE) of each shoreline position into the linear regression function. The RMSE weights the influence of each shoreline position in calculating the linear regression trend. The slope of the trend is the shoreline change rate.

Genz et al. (2009) and Frazier et al. (2009) introduce and develop polynomial shoreline change rate calculation methods. ST methods statistically over-fit the model to the data by using only the data as a single transect location to derive a shoreline change rate (Frazier et al., 2009). Effectively, this means that ST methods ignore physical processes like alongshore currents and tides that affect position of the shoreline at adjacent transect locations along an entire beach similarly. Polynomial (PX) methods build polynomial models of variations in the alongshore shoreline change rates using a finite linear combination of a mathematical basis function (Romine et al., 2009). They model data from all transects along a whole or portion of beach with as few parameters as possible to calculate a rate at any single transect location. Three types of basis functions are used: Legendre polynomials (LX), trigonometric functions (RX), and empirical orthogonal functions (EX). Each basis function of polynomial methods can also be combined with an orthogonal function to model shoreline change rate variation through time (T). The three polynomial methods including the temporal component are referred to as PXT methods. PXT methods reveal acceleration or deceleration in the rate of shoreline change over time.

These methods differ significantly from the methods employed by Coyne et al. (1999) and Fletcher et al. (2003) by combining adjacent transects (shoreline position data) on a beach that behave similarly. This effectively reduces errors calculated by the rate model by reducing the number of parameters used to fit the combined data points. These methods imply that physical processes that affect shoreline position at any given time occur at a scale larger than a single transect and that the shoreline positions and shoreline change rates at each transect are related (Romine et al., 2009). As alongshore distance from a given transect increases, an exponential decay function is incorporated into the polynomial model to represent the decreasing influence of that transect data on the polynomial model.
The six polynomial methods: LX, RX, EX, LXT, RXT and EXT provide additional information about shoreline change spatially and temporally while reducing model uncertainty. This increases the signal (shoreline change) to noise (uncertainty) ratio along a shoreline. In order to provide managers with the best information possible about shoreline change along a beach and plan for future erosion hazards the ‘best’ polynomial method is selected as the method with lowest errors and highest percentage of statistically significant rates calculated.

Rates calculated using single transect (ST) methods tend to produce higher rate uncertainties than polynomial methods as discussed above. Polynomial methods provide a tool to understand shoreline change from the perspective of the entire beach (PX) and over time (PXT). Romine et al. (2009)
5. A SHORELINE CHANGE ANALYSIS OF MAÑAGAHA

5.1 Identification of Imagery

Vertical aerial photography of Mañagaha was collected from the USGS, NOS and NOAA. Table 1 summarizes data source information and visual assessment of the data and Figure 15 shows coverage of the island in the identified imagery. When selecting imagery, particular attention was paid to the beach tone and color depth specifically for shoreline reference feature identification. The toe of the beach is visible in each image selected for analysis. 1945 and 1946 imagery dates are unknown. Oblique images dated November, 1945 (Cloud et al., 1956) show Mañagaha in the background in a similar modified condition as shown in the undated 1946 photo found for this study. This helps constrain 1945 imagery to a collection date towards the early part of the year. A digital line graph (DLG), a scanned topographic map (1:25000) and an Electronic Navigation Chart (ENC) also contained coverage of Mañagaha. Each of these data were reviewed and checked using the pier located on the west side of Mañagaha as well as general island shape, characterization of the surrounding reef (ENC specifically) and any specific features.

The DLG was obtained in ESRI shape file format from the USGS through the Geocommunity™ online data download website. The digital lines indicate the pier, tourist concession area including building footprints, management zones, vegetation extent and an outline of the island. The DLG metadata gives an April 2003 data compilation date. The shoreline definition is a datum based mean sea level. The extent of the island is not consistent with imagery from 1999 or 2004, the closest years. The shape indicates an extent of the island prior to WWII wreck removal with a sand spit-like feature in the southeast end of the island. The pier is also scaled incorrectly (too short) while other features (building footprint appear correctly scaled. All features are offset to the west approximately 13 meters. Manual attempts to rectify the vector locations using control points on stable features visible in satellite imagery (2004 and 2006 data) did produce acceptable results. However, on the re-referenced data, the eastward shoreline extends over beachrock, indicating again that the data source for the vectors is probably before wreck removal. No information on the sheet indicates an imagery date. The DLG
shoreline was discarded from analysis because of poor quality; suspected inconsistent shoreline data sources and incomplete metadata.

Figure 15. Identified and processed vertical aerial photos and satellite imagery (Mañagaha portions). Dates are unknown for 1945 and 1946 imagery. 1987 image collected on Feb 6. 1996 image collected on June 12. 1999 image collected on February 19. 2004 image collected on April 25.
The topographic map was obtained in digital format from the CRMO in Saipan and delivered on disk in TIFF format. Metadata indicated that the coastline boundary represents a zero contour of mean high water and all data is derived from aerial photographic sources dated 1968-1970 and surveys during 1963. A search through USGS archives in Honolulu and through the National Archive Map and Photo collection for the original imagery returned no imagery from 1968-1970. In the map, Mañagaha is misplaced 800 m to the northwest. Indicated reef features do not correspond to existing reef structure and the pier is absent. After investigating possible georeferencing issues from the source data (A scanned paper map and no metadata indicating georeferencing method or accuracy – assumed poor), the topographic map was deemed poor quality for inclusion in the shoreline change analysis.

The ENC file is commonly used by mariners on their approach to land and indicates aids to navigation, soundings, reefs, and land. The ENC file for this portion of Saipan (ENC 81076) indicates a 2004 last update date. No date is indicated for source information such as the outline of Mañagaha or Saipan Harbor. The outline of Saipan includes the pier and the wreck of the barge in the southeast of the island is evident.

<table>
<thead>
<tr>
<th>Date</th>
<th>Data type</th>
<th>Data source</th>
<th>Approx. scale</th>
<th>Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>unkown, 1945</td>
<td>air photo</td>
<td>Navy archives/CRMO USGS</td>
<td>1: 10,000</td>
<td>fair</td>
</tr>
<tr>
<td>early 1946</td>
<td>air photo</td>
<td>USGS</td>
<td>1: 10,000</td>
<td>good</td>
</tr>
<tr>
<td>Feb 6, 1987</td>
<td>air photo</td>
<td>NOAA/NOS</td>
<td>1: 10,000</td>
<td>good</td>
</tr>
<tr>
<td>June 12, 1996</td>
<td>air photo</td>
<td>NOAA</td>
<td>1: 10,000</td>
<td>good</td>
</tr>
<tr>
<td>Feb 19, 1999</td>
<td>air photo</td>
<td>NOAA</td>
<td>1: 12,000</td>
<td>good</td>
</tr>
<tr>
<td>April 25, 2004</td>
<td>satellite image</td>
<td>IKONOS/USGS</td>
<td>1: 50,000</td>
<td>good</td>
</tr>
<tr>
<td>March 23, 2005</td>
<td>satellite image</td>
<td>DG/Dept of Agriculture</td>
<td>1: 50,000</td>
<td>good</td>
</tr>
<tr>
<td>April 5, 2006</td>
<td>satellite image</td>
<td>DG/NOAA</td>
<td>1: 50,000</td>
<td>good</td>
</tr>
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<td>DLG</td>
<td>USGS</td>
<td>1: 24,000</td>
<td>poor</td>
</tr>
<tr>
<td>before 1995</td>
<td>topographic map</td>
<td>CRMO</td>
<td>1: 24,000</td>
<td>poor</td>
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<td>Unknown</td>
<td>ENC</td>
<td>CRMO</td>
<td>1: 7,500</td>
<td>poor</td>
</tr>
</tbody>
</table>

Table 1. Shoreline data sources for Mañagaha. Data source deemed to be of poor quality were not included in analysis. March 23, 2005 is removed from analysis due to the closeness in date to coverage in 2004 and 2006.
While the position of the island is correct, the ENC is considered a poor resource for a shoreline position since no date is indicated.

5.2 A qualitative assessment of the selected imagery

A qualitative assessment of imagery selected for analysis guides the reader through changes in the shoreline through time. The imagery is included in Appendix A and referred to here by the year of acquisition. The island appears in the 1945 imagery with a large sand beach around the island. The beach appears wider along the north and south sides of the island and noticeably thinner south of the pier on the west. The concrete landing pier is on the west side of the island and was originally constructed by the Japanese prior to WWII (Management Plan, 1985). Sediment is apparent in the water columns around the island. The location of structures is unknown at this date although Japanese military did have several structures and bunkers in place (Management Plan, 1985). Vegetation cover of the interior of the island appears complete.

In the 1946 imagery the island shape has been drastically altered and appears to have more of a circular formation. The large sandy beach is significantly narrowed, most notably in the upper northwest portion of the island where beachrock appears along the length of beach. The southeast shoreline position is seaward of present, out to the seaward extent of the removed wreck. The reason for the drastic change in the shape is unexplained. Following the US invasion of Saipan, the island was used by the US military and evidence of earth moving and buildings in the northeast portion of the island are visible. A seaplane runway lies to the northeast of the island and many of the wrecks in the surrounding waters are Japanese and American military seaplanes and pieces. The island may have been used to service or support these operations. Vegetation appears to be destroyed at spots around the island compared with 1945 imagery due to bombardment during the invasion of Saipan and subsequent occupation and building construction. The 1945 and 1946 images were acquired from the USGS and originally collected by the U.S. Department of the Army.

The island appears in the 1987 imagery to have resumed a more elongated shape similar to the 1945 image. Sandy beach is apparent in the northwest portion of the island and a sand lobe extends seaward to include the WWII era wrecks in the southeast portion.
of the island. An L-shaped concessions services building built in 1984 (Management Plan, 1985) is visible along the north of the island behind the wide beach as well as several pala pala landward of the pier and along the shoreline. The 1996 image shows additional structures and the walking trail around the island is visible along the southeast edge of vegetation. The 1999 image follows removal of the WWII wreckage and a narrowing of the beach along the south shore and at the southeastern ‘corner’ is apparent. 1987, 1996 and 1999 imagery was collected by the national oceanographic survey (NOS) of NOAA. Erosion continues into the 2004 and 2006 imagery along the southeast portion of the island with vegetation retreating and the walking trail apparently eroded. The beach is significantly narrowed along the east and southeast shores in the 2004 IKONOS image. The 2006 Digital Globe™ satellite image also shows narrow sandy beach along the same shores. This image has good tone and color balance as well as low water reflectance. It was acquired from the national oceanographic and atmospheric administration (NOAA).

5.3 Rectification of Aerial Imagery

Contact prints of the image frames from NOAA were received scanned at multiple resolutions from 600 - 900 pixels per square inch (ppi) resulting in different pixel sizes. 1946 imagery was scanned at 900 dpi to assure Scanned images were corrected using PCI Geomatics OrthoEngine, a commercially available image processing software package. A polynomial was selected as the most appropriate rectification method. Five ground control points were selected between the reference image and each aerial photo or additional satellite image. Care was taken to locate the same features in each dataset and select points as close to the island and as close to a zero elevation as possible.

The reference data source for image georeferencing was the March 2005 QuickBird satellite image mosaic with published RMS uncertainty of 13.5 m and a resolution of 0.54 m for the whole scene. The calculated root mean square error of the differences between control point locations and polynomial modeled locations ranged from 2.06 m to 0.86 m. These errors are relative to the 2005 reference image and contribute to the total position uncertainty calculation for each shoreline position as the rectification error ($E_r$).
5.4 Digitizing the shoreline positions

The low water mark (LWM) was used as the shoreline position based on the morphological proxy of the crest of the toe of the beach (Coyne et al., 1996; Fletcher et al., 2003; Romine et al., 2009). Processed image base maps from 1945, 1946, 1987, 1996, 1999, 2004 and 2006 were digitized on-screen using computer software-based histogram resampling to visually locate the tone change denoting the crest of the toe feature (see Figure 13). Figure 16 is a compilation of each digitized shoreline displayed on the 2006 image base map.
5.5 Casting transects

Shoreline positions are sampled approximately every 20 meters alongshore by casting transects from manually digitized offshore baselines that run parallel to the trend of the shoreline positions around the island. Thirty-four transects were cast around the island (Figure 17) and provide a regular sample of historic shorelines that form the raw data for the shoreline rate calculation.

Figure 17. Transects around Mañagaha. Transects are the shoreline measurement locations that intersect and record the distance from the baseline to each shoreline position. 34 Transects are used at Mañagaha.

5.6 Beach profiling

During fieldwork in March of 2007, beach profiles were collected at referenced locations around Mañagaha (Figure 18) to characterize beach morphology. Old lines no
longer occupied are shown as black dashed lines, still used locations are shown with red lines and three new profiles were established during 2007 fieldwork (gold lines). Stable features such as buildings or mature trees in the backshore were used as reference points to orient shore-normal profiles across the beach. Eight profile locations were surveyed using a Leica TC407 Total Station, tripod, telescoping stadia rod, and reflecting prisms. Shoreline features were recorded along each profile line (Figure 19) including the position of the base and crest of the toe of the beach, the edge of sand if the beach is intersected with beachrock, the wet/dry sand line and the berm crest or scarp face. Recording points at slope changes along the profile characterized the geomorphology of the beach.

The staff of the Coastal Resource Management Office of Saipan provided beach profile data collected between 2002 and 2006 at eight locations around the island, six of those sites were still occupied as of fieldwork in May of 2007. The profiles were collected seasonally and following storm events. Figure 20 is an example profile collected by CRMO staff from 2002 – 2006. Profiles were collected using a tripod mounted Berger level and Jacob staff. The red line is the profile line in Figure 20 plotted

Figure 18. Beach profile locations around Mañagaha

Figure 20.
for comparison. CRMO field staff record a start point from a control point and then move directly seaward to the berm crest or erosion scarp at the top of the beach face.

![Profile: Site 1](image)

Figure 19. UH site 1 beach profile data collected on March 9, 2007. Morphology of the beach is recorded as elevation changes. Features are noted with crosses. The reference point (0 m distance) is the start point with an elevation of 0 m.

The data is poorly annotated with only a berm crest (BC) indicated. No other features are recorded in field notes. The method ignored most common geomorphic

![Site 1 Profile](image)

Figure 20. Site 1 profile data example collected by CRMO staff. UH fieldwork data of the same site (red line and Figure 19). Triangles indicate post storm profile dates. CRMO staff noted the reference point (0 m distance, 0 m elevation) and the berm crest feature also as 0 m elevation. Without more feature data noted, the CRMO profile data was used only to calculate the seasonal uncertainty ($E_s$) using the variability of the berm crest feature.
changes of the beach and significant beach features (see Figure 12). Appendix B includes all beach profile data received from the CRMO and collected during fieldwork in March of 2007. Because of the lack of annotated features other than the berm crest in the CRMO profile data, it is used in this study only to estimate the seasonal uncertainty (Es) of the shoreline location.

5.7 Uncertainties

Uncertainties in the measurement of the shoreline on image base maps and those associated with position of the shoreline in nature are summarized in Table 3. The 2-sigma, 95% confidence interval is used when calculating uncertainties. The total position uncertainty (Ut) is calculated with the following equation modified from Genz et al. (2007)

\[ U_t = \pm \sqrt{E_r^2 + E_d^2 + E_p^2 + E_t^2 + E_s^2} \]

where \( E_r = \) rectification error, \( E_d = \) digitizing error, \( E_p = \) pixel error, \( E_t = \) tidal fluctuation error, and \( E_s = \) seasonal error. Errors in field identification of MHWL and low water line (Ec) and those associated with plotting on a topographic sheet (Ets) do not apply to the Mañagaha study since no topographic sheet is used for shoreline positions.

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<th>( E_d )</th>
<th>( E_p )</th>
<th>( E_t )</th>
<th>( E_s )</th>
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Table 2. Shoreline position uncertainties. Shoreline measurement and position uncertainties and calculated total position uncertainties for each shoreline position at Mañagaha.
Rectification uncertainty (Er) uses the square root of the sum of the squares of the differences between the positions of the control points located on the original reference imagery (2004) and on the processed image from the rectification procedure. Digitizing error (Ed) is an estimated value of error associated with visually interpreting and digitizing the shoreline on an image map. It is based on image scale and quality and user experience. At Mañagaha, the shoreline on each dataset was digitized several times and the Ed value calculated for each image map source is the standard deviation of the differences. The pixel size (Ep) is based on the scanned resolution of the aerial photo or collected satellite image and image processing (rectification). The tidal uncertainty (Et) is based on fieldwork that measured the horizontal migration of the crest of the toe over a complete tidal cycle. The error in shoreline position due to seasonal variability (Es) is calculated from the beach profile data from the CRMO over a four-year period. The profile data is divided by date into winter (Nov - Mar) and summer (Apr - Oct) at each profile site. The Es is calculated as the standard deviation of the differences of the mean summer and winter horizontal positions of the berm crest, the single feature that is regularly annotated in the CRMO profile data.

5.8 Calculating shoreline change

Following methods and scripting used by Genz et al. (2007) and Frazer et al. (2009) and Genz et al. (2009), shoreline positions weighted by their total position uncertainty (Ut) are used to calculate the trend of shoreline change through time using single transect (ST) and polynomial (PX and PXT) methods. Shorelines from 1945 and 1946 were excluded from the analysis because they represent a state of the shoreline prior to wreck emplacement and therefore represent a difference physical setting of the beach system at Mañagaha. The intent of this study is to understand shoreline change at Mañagaha since wreck removal in 1995. The 1987 shoreline is included in the first set of results to characterize shoreline change from the beach state at the time of wreck removal to the most recent shoreline position. The rates are also calculated with 1987 removed (1996 – 2006) to reveal potential erosion hazard areas should the trend continue. Rates are calculated using 1987 through 2006 position data. Rates are calculated using the ST
method weighted least squares (WLS) and polynomial methods with acceleration (PXT) and without (PX). Results are shown in Table 4.

The EX method has the largest percentage of significant rates (uncertainty < calculated rate) and is chosen to calculate the shoreline change rate for the island of Mañagaha. Erosion rates are plotted around the island in Figure 21 as positive rates.

Negative shoreline change rates in Table 3 indicate erosion. To identify potential erosion.

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<th>Polynomial Modeling (m/yr)</th>
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Table 3. Shoreline change rates calculated using ST and PX methods. The single-transect method, S-T(WLS), uses weighted least squares at each transect and does not incorporate shoreline data from neighboring transects. The 95% confidence interval (column 3: S-T CI95) indicates that most rates using this method are not statistically significant (CI95 > 1). Polynomial methods (LX, RX, and EX) and their rate uncertainties (CI95) utilize all shoreline data along the beach to calculate a rate at any transect (columns 4 – 9). This increases statistical significance. EX was found to have the least uncertainty. Erosion is negative and accretion is positive.
hazard areas, the EX rates are multiplied by a factor of 10 to represent a 10 year hazard projection. Figure 22 shows the result projected from the 2006 vegetation line. The dashed line represents the projected landward extent of the beach. The red area is the uncertainty in the projected line position – the hazard area. The projected hazard area at transects 21 and 22 appears angular and unnatural in Figure 22. This is due in part to the orientation of these two transects and to the significant reorientation of the shoreline at

Figure 21. EX shoreline change rates around Mañagaha (1987 – 2006). Negative rates indicate accretion, positive, erosion.
that location (particularly 21). The orientation of the two transects has the effect that
when extended landward the effect of projecting the vegetation line 38.8 m (3.88 m/yr x
10 yrs) at transect 21 in that direction causes a spatial overlap with transect 22 which is
projected 12.3 m. The result is an acute angle in the projected vector as it is reaches the
difference in the projected distances (26.5 m). When locating the baselines from which

Figure 22. EX 10-yr projected shoreline position (dashed line). The red band is the 95%
confidence (red band) on 2006 Quickbird. Note that as a result of the location and
orientation of transect 21, the predicted shoreline position appears as an indent relative
to general trend of the island’s shoreline. This is due in part to the chosen location of
the transect (perpendicular to the trend of historical shorelines) and in part to the re-
orientation of the shoreline at this location following debris removal in 1996 compared
with the present shoreline.

the transects are cast, the general orientation of the shoreline is approximated from all of
the shoreline positions. The orientation of the shoreline at this section of beach (transects
21 – 22) has changed significantly over time. To change the orientation so that the two
transects do not intersect risks sampling the shoreline more obliquely than necessary and miscategorizing the shoreline position.

The EXT polynomial method was used on 1996–2006 shoreline data of Mañagaha to model shoreline change rates both spatially and temporally. The 1996-2006 time period represents shoreline change since wreck removal and the EXT method reveals recent changes in the trend of shoreline change rates. Rate changes through time are characterized as slope changes in the line. EXT was also used on 1987–2006 data to

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<tr>
<td>22</td>
<td>3.93</td>
<td>1.97</td>
<td>3.79</td>
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<td>23</td>
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<td>3.07</td>
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<td>-0.27</td>
<td>1.09</td>
</tr>
<tr>
<td>24</td>
<td>1.51</td>
<td>4.06</td>
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<td>0.13</td>
<td>-1.11</td>
<td>1.47</td>
</tr>
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<td>25</td>
<td>0.52</td>
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<td>0.50</td>
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<tr>
<td>26</td>
<td>0.30</td>
<td>5.26</td>
<td>-0.15</td>
<td>0.01</td>
<td>6.67</td>
<td>1.34</td>
</tr>
<tr>
<td>27</td>
<td>0.13</td>
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<td>0.01</td>
<td>4.07</td>
<td>0.82</td>
</tr>
<tr>
<td>28</td>
<td>0.23</td>
<td>2.24</td>
<td>0.05</td>
<td>0.00</td>
<td>2.64</td>
<td>0.58</td>
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<tr>
<td>29</td>
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<td>0.11</td>
<td>0.01</td>
<td>1.80</td>
<td>0.43</td>
</tr>
<tr>
<td>30</td>
<td>0.73</td>
<td>3.53</td>
<td>0.41</td>
<td>0.03</td>
<td>4.54</td>
<td>0.99</td>
</tr>
<tr>
<td>31</td>
<td>1.01</td>
<td>2.28</td>
<td>0.82</td>
<td>0.07</td>
<td>2.52</td>
<td>0.77</td>
</tr>
<tr>
<td>32</td>
<td>1.07</td>
<td>0.65</td>
<td>0.97</td>
<td>0.08</td>
<td>1.24</td>
<td>0.39</td>
</tr>
<tr>
<td>33</td>
<td>0.59</td>
<td>1.09</td>
<td>0.47</td>
<td>0.04</td>
<td>1.75</td>
<td>0.40</td>
</tr>
<tr>
<td>34</td>
<td>0.45</td>
<td>0.31</td>
<td>0.41</td>
<td>0.03</td>
<td>0.46</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Table 4. Results using EXT on 1996–2006 shoreline data. EXT models shoreline change rates through time. The rate is calculated at the latest shoreline (2006). The EX and ST method results are included for comparison.
compare to EX results using the same data (see Appendix C – Shoreline history plots EX and EXT). EXT results calculated at 2006 are shown in Table 5 with EX and ST (WLS) recalculated for 1996 – 2006 for comparison purposes.
6.0 DISCUSSION AND CONCLUSIONS

6.1 Research summary

Results of the historical shoreline change analysis of Mañagaha can be used to describe conditions around the island. The island can be subset into four regions (Figure 23) that reflect the general behavior of the shoreline with the removal of the wrecks in 1995:

- Region 1) accretion of a broad sand plain (NW, transects 6-10);
- Region 2) generally eroding shoreline (NE to E, orange, transects 11-24);
- Region 3) quasi-stable shoreline (SW to S, yellow transects 25-34); and
- Region 4) eroding shoreline north of the pier (W, tan, transects 1-5).

Figure 23. Shoreline change by region. Four regions and representative shoreline position plots characterize Mañagaha shoreline change 1987 – 2006. Note that erosion is +/positive and accretion is -/negative in the plots.
Region 1 is characterized by a broad sandy beach backed by a cultivated vegetation boundary. The shoreline in this area has accreted with the removal of debris at an average rate of $1.41 \pm 0.30$ m/yr. Region 2 is dominated by alongshore sediment transport. The wreck and debris removal particularly affect this region where these hard points apparently diffused alongshore transport. Since 1987 the region has experienced an average erosion rate of $1.14 \pm 0.22$ m/yr. It is in this region that erosion hazards exist (Figure 22) that impact native vegetation and the shorebird nesting sites within the no-entry management area (Figure 3). Region 3 is characterized by quasi-stability to moderate accretion. The removal of wrecks and debris appear to have initially caused erosion in this region, however since 1999, accretion has occurred possibly due to sediment transport alongshore from region 2. As a result, the average shoreline change rate in region 2 indicates slight insignificant (uncertainty $>$ rate) accretion at a rate of $0.05 \pm 0.23$ m/yr. The 2007 (UH profile) crest of the toe position reflects the 2006 shoreline position in this region and may indicate a stabilization of the shoreline there. Region 4 is experiencing moderate erosion since 1987 at an average rate of $0.58 \pm 0.22$ m/yr. The behavior of the shoreline in this region indicates that it is starved of sediment. The landing pier to the south blocks sediment transport from region 3 while the accretion of region 1 may be blocking alongshore transport from that region south.

Calculated shoreline change rates using WLS, and EX indicate erosion along the east and southeast portions of the shoreline at transects 11 through 24. This corresponds to the removal of the WWII relics from the area and implies that they had a stabilizing effect on the position of the shoreline until they were removed. Polynomial methods with acceleration (EXT) indicate by a change in the slope of the rate that the amount of erosion has slowed since 2004.

The endangered shearwater nesting site in the northeast of the island is adjacent to a planned leach field for the septic system on the island. Erosion hazards identified in this study imply that the nesting site will continue to be impacted. To protect the nesting site, managers will need to mitigate the impact of the erosion hazard either by providing migration space landward of the nesting site, where the leach field is planned or by stabilizing the shoreline.
It appears likely that the existing erosion hazard is an expression of the island finding an equilibrium state that existed prior to debris and wreck emplacement. This is shown by coastal erosion reported and documented in the field since wreck removal and in this historical shoreline change analysis. The pier on the island is still maintained and will continue to be so while the island remains a significant tourist attraction and driver of the local economy. While decision makers and resource managers identify impacts to infrastructure and natural resources associated with shoreline erosion (falling trees, eroding pathways, impacted bird habitat) since wreck removal, the context of that erosion implies that in the long term, an equilibrium shoreline position will be reached.

6.2 Research implications

There is a continuum of needs from decision makers and planners that must balance the immediate needs and concerns of the tour operators and visitors with the natural variability of the shoreline. Structures being undermined are unsafe, pedestrian paths that terminate on eroded bluffs with fallen trees lead to liability on the part of the tour operator. Coastal erosion at Mañagaha is a natural process of shoreline change in the wake of human impact on the shoreline. Historical shoreline change analysis at Mañagaha provides statistically significant information about that change around the island. Erosion hazard areas identified from this analysis provide information and guidance to resource managers and decision makers about where to focus time and effort to mitigate impacts to visitor safety while preserving environmental resources as they adapt to the changing shoreline. Better understanding the historical variability in the shoreline position can guide plans for the future protection of the area and ensure enjoyment of this unique valuable resource by the people of Saipan and visitors alike as mandated by Public Law.

In an effort to mitigate coastal erosion to protect development, engineered structures have been used to replace the protection offered by a sandy coastline. Around the world, where large population growth too close to the shoreline intersects natural shoreline variability, the shoreline tends to be sacrificed to the economic value of the structures impacted. Large engineering projects to stabilize or nourish eroding sections of beach (e.g. seawalls and beach nourishment) are expensive. While their implementation
will have a questionable effect on the long term sustainability of the island as a natural resource, they will most likely lead to a loss of sandy beach in the face of rising sea levels and negatively impact the visitor industry dollars that they are intended to preserve.

### 6.3 Opportunities for future research

Local and regional scale sea level rise may impact island stability and the accuracy of predicted erosion hazards. Sea levels also vary with changes in trade wind activity, the El Niño/ La Niña cycle, seasonally and tidally. Guam, also in the Marianas Islands chain experienced 8.45 mm/yr sea level rise between 1993 and 2006. More research is needed to tie local shoreline processes into sea level rise. At Mañagaha, the impact of sea level rise appears to fall within the signal marked by wreck removal. To map the response of shoreline to sea level rise, enough data (shoreline positions) would be needed to exceed the noise of shorter term (e.g. seasonal) processes and local scale changes to the physics of the beach system that tends to dominate current shoreline studies. In this respect, Mañagaha may pose a difficult study site.
APPENDIX A Imagery of Mañagaha

Image from Navy archives date unknown in 1945.
Image from USGS date unknown in 1946.
Image from NOAA/NOS dated Feb 6, 1987.
Image from NOAA dated June 12, 1996.
Image from NOAA dated February 19, 1996.
APPENDIX B Beach profile locations around Mañagaha.
# PROFILE LOCATION DESCRIPTIONS

<table>
<thead>
<tr>
<th>ID</th>
<th>LOCATION</th>
<th>LINE-UP</th>
<th>BRP</th>
<th>FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>SITE 1</td>
<td>Red pavilion on the SE corner of Managaha. Azimuth = 196°</td>
<td>the north wall of the covered area</td>
<td>north base of the corner of most landward, north cement pillar</td>
<td>north base of the corner of second most landward, north cement pillar</td>
</tr>
<tr>
<td>SITE 3</td>
<td>low lying cement channel on ground located on the east side of the island in between the N and S points of the eastern shoreline. Cement channel is located approx. 4m landward of the coastal path. NOTE: grass may be covering this location. Azimuth = 138°</td>
<td>the inside face of the north side of the channel. Profile shoots directly through to palms at the top of the scarp. Trunks of palms are ~1m apart</td>
<td>back, inside north face of the cement channel</td>
<td>front, inside north face of the cement channel</td>
</tr>
<tr>
<td>SITE 4</td>
<td>concrete bunker on ENE side of Island. Bunker is directly off of the landward side of coastal path. Azimuth = 137°</td>
<td>the outside, N facing wall that defines the roof of the bunker</td>
<td>top, N, landward and outside corner of the bunker roof</td>
<td>N, seaward and outside corner at the bottom of bunker roof</td>
</tr>
<tr>
<td>SITE 5</td>
<td>concrete bunker on ENE side of Island. Bunker is directly off of the landward side of coastal path. Azimuth = 70°</td>
<td>uses only the 70 degree azimuth angle shot from the BRP of site 4</td>
<td>top, N, landward and outside corner of the bunker roof</td>
<td>line has only two points, the BRP and the TOP OF SCARP</td>
</tr>
<tr>
<td>SITE 7</td>
<td>second pavilion E from the main building. Pavilion borders the W boundary of the bird sanctuary. Azimuth = 85°</td>
<td>the 2 concrete pillars located on the NW end of the covered pavilion</td>
<td>seaward base of the most landward pillar located on the NW side of the pavilion</td>
<td>seaward base of the most seaward pillar located on the NW side of the pavilion</td>
</tr>
<tr>
<td>SITE 8b</td>
<td>located off the N side of the main structure on the NW side of the island. Azimuth = 24°</td>
<td>uses two trees off the NNW of the main building</td>
<td>seaward base of the most landward tree</td>
<td>Seaward base of the most seaward tree</td>
</tr>
<tr>
<td>SITE 8</td>
<td>two ironwood trees that line up of the NW corner of the main building. Azimuth = 324°</td>
<td>the base of two ironwood trees</td>
<td>seaward base of the most landward tree</td>
<td>Seaward base of the most seaward tree</td>
</tr>
<tr>
<td>SITE NP</td>
<td>cluster of palms of four palms on the west side of the island approx 45m N of the pier. There is a temporary covered area here with a yellow canopy. directly behind and north of the line. Azimuth = 274°</td>
<td>use the two south most palms that create a line directly off shore</td>
<td>seaward base of the most landward palm</td>
<td>Seaward base of the most seaward palm</td>
</tr>
<tr>
<td>SITE SP</td>
<td>pavilion just S of the pier. Line is located N of large concrete block on beach and S of metal debris just off shore Azimuth = 231°</td>
<td>the 2 concrete pillars located on the S end of the covered pavilion</td>
<td>seaward base of the most landward pillar located on the S side of the pavilion</td>
<td>seaward base of the most seaward pillar located on the S side of the pavilion</td>
</tr>
</tbody>
</table>
### Profile Line Checklist
**Beach Morphological Features**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Onshore:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Back Reference Point</td>
<td>Fixed survey reference point, mauka online</td>
<td>BRP</td>
</tr>
<tr>
<td>Front Reference Point</td>
<td>Fixed survey reference point, makai online</td>
<td>FRP</td>
</tr>
<tr>
<td>Side Reference Point</td>
<td>Fixed survey reference point, offline</td>
<td>SRP</td>
</tr>
<tr>
<td>Numbered Reference Point</td>
<td>Fixed survey reference point (number)</td>
<td>RP#</td>
</tr>
<tr>
<td>GPS Location</td>
<td>GPS surveyed point</td>
<td>GPS</td>
</tr>
<tr>
<td>Start Of Line</td>
<td>(Coastal Structures) i.e. coastal paths (landward and seaward)</td>
<td>SOL</td>
</tr>
<tr>
<td>(Dune Crest)</td>
<td>May be covered by vegetation. May be more than one</td>
<td>(DC)</td>
</tr>
<tr>
<td>Vegetation Line</td>
<td>Note type of vegetation (i.e. naupaka, grass, etc.)</td>
<td>VL</td>
</tr>
<tr>
<td>(Debris Line)</td>
<td>Notable last storm/high-wave deposition</td>
<td>(DL)</td>
</tr>
<tr>
<td>Berm Crest</td>
<td>Notable Break in Slope on Foreshore. May be more than one</td>
<td>BC</td>
</tr>
<tr>
<td>Wet/Dry Line</td>
<td>Highest swash of last tidal cycle. Good to know at what period of tide cycle survey is being conducted in order to find Wet/Dry line.</td>
<td>WD</td>
</tr>
<tr>
<td>High Swash</td>
<td>Highest runup at survey time, associated with set waves</td>
<td>HS</td>
</tr>
<tr>
<td>Sea Level</td>
<td>Mean sea level</td>
<td>SL</td>
</tr>
<tr>
<td>Step Crest</td>
<td></td>
<td>SC</td>
</tr>
<tr>
<td>Step Base</td>
<td></td>
<td>SB</td>
</tr>
<tr>
<td>Toe of Beach</td>
<td>(if no step exists)</td>
<td>TB</td>
</tr>
<tr>
<td><strong>Offshore:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sand</td>
<td></td>
<td>S</td>
</tr>
<tr>
<td>Ripples</td>
<td>Get crest, trough if possible</td>
<td>(RP)</td>
</tr>
<tr>
<td>Beachrock</td>
<td></td>
<td>(BR)</td>
</tr>
<tr>
<td>Rock</td>
<td></td>
<td>R</td>
</tr>
<tr>
<td>Coral Head</td>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Rock/Sand</td>
<td></td>
<td>R/S</td>
</tr>
<tr>
<td>Sand/Rock</td>
<td></td>
<td>S/R</td>
</tr>
<tr>
<td>Bar</td>
<td>Offshore bar- crest, trough</td>
<td>BAR</td>
</tr>
<tr>
<td>End of Line</td>
<td></td>
<td>EOL</td>
</tr>
</tbody>
</table>

> Features in parentheses may not exist or be observed at a given survey
> Some may occur more than once at a given site.
> Beachrock may be found onshore within beachface.
> Vegetation clumps, walls, revetements, beachrock ridges, sand channels, sand fields, coral heads

![A Typical Beach Profile](image-url)
UH March 9, 2007 fieldwork collected beach profile data
CRMO beach profile data with UH collected profile shown in red
SITE 6 PROFILE

SITE 6 PROFILE (Nov-Mar)

SITE 6 PROFILE (Apr-Oct)
APPENDIX C Shoreline History Plots using EX 1987-2006

EX: Transect #1

EX = 0.23087 ± 0.090275 m/yr (2σ)

EX: Transect #2

EX = 0.3038 ± 0.14135 m/yr (2σ)

EX: Transect #3

EX = 0.37469 ± 0.15712 m/yr (2σ)

EX: Transect #4

EX = 0.7889 ± 0.30325 m/yr (2σ)

EX: Transect #5

EX = 0.92364 ± 0.44042 m/yr (2σ)

EX: Transect #6

EX = -1.4664 ± 0.54518 m/yr (2σ)

EX: Transect #7

EX = -2.3758 ± 0.38613 m/yr (2σ)

EX: Transect #8

EX = -1.8051 ± 0.31235 m/yr (2σ)

EX: Transect #9

EX = -1.1699 ± 0.18889 m/yr (2σ)

EX: Transect #10

EX = -0.21363 ± 0.043396 m/yr (2σ)

EX: Transect #11

EX = 0.49956 ± 0.080848 m/yr (2σ)

EX: Transect #12

EX = 0.427 ± 0.088774 m/yr (2σ)

EX: Transect #13

EX = 0.47897 ± 0.11341 m/yr (2σ)

EX: Transect #14

EX = 0.71297 ± 0.18525 m/yr (2σ)

EX: Transect #15

EX = 0.36171 ± 0.591607 m/yr (2σ)
### Time-Shoreline Position (m)

<table>
<thead>
<tr>
<th>Transect</th>
<th>Rate (m/yr) ± Error (σ/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect #16</td>
<td>0.57818 ± 0.094283 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #17</td>
<td>0.64925 ± 0.10511 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #18</td>
<td>0.95863 ± 0.15522 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #19</td>
<td>1.7474 ± 0.31442 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #20</td>
<td>2.6034 ± 0.42375 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #21</td>
<td>3.8766 ± 0.63537 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #22</td>
<td>1.2324 ± 0.33822 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #23</td>
<td>0.94416 ± 0.28646 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #24</td>
<td>0.74777 ± 0.12067 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #25</td>
<td>-0.1985 ± 0.18037 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #26</td>
<td>-0.65853 ± 0.3049 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #27</td>
<td>-0.52549 ± 0.23258 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #28</td>
<td>-0.52742 ± 0.26467 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #29</td>
<td>-0.17094 ± 0.10953 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #30</td>
<td>-0.20946 ± 0.20378 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #31</td>
<td>-0.036584 ± 0.20365 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #32</td>
<td>0.11872 ± 0.16005 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #33</td>
<td>0.64393 ± 0.19829 m/yr (2σ)</td>
</tr>
<tr>
<td>Transect #34</td>
<td>0.15685 ± 0.16005 m/yr (2σ)</td>
</tr>
</tbody>
</table>
Shoreline History Plots using EXT 1987 - 2006

EXT: Transect #1

EXT: Transect #2

EXT: Transect #3

EXT: Transect #4

EXT: Transect #5

EXT: Transect #6

EXT: Transect #7

EXT: Transect #8

EXT: Transect #9

EXT: Transect #10

EXT: Transect #11

EXT: Transect #12

EXT: Transect #13

EXT: Transect #14

EXT: Transect #15
APPENDIX D A guided literature review

This review is structured to discuss the important literature pertaining to historical shoreline change at Mañagaha. A brief outline is provided:

- Intro
- Site Description
  - Cultural
    - History
      - Scott Russell: Tiempon I Manmofo’na: Ancient Chamorro Culture and History in the Northern Marianas Islands. And: From Arabwal to Ashes: A Brief History of Garapan Village 1818-1945
    - Traditional Use
  - Geology
- History
  - Mañagaha was referred to as Maniagassa Island by the US military and was captured from the Japanese in 1 hour by the U.S Army on July 13, 1944 as the final mission in the Saipan campaign (D-day June 15, 1944).
- WWII
  - Anthropogenic and structure placement – US Army (now US Navy)
      - document aerial imagery from 1945 showing a pier/wharf but no evidence of breakwaters or seawalls.
      - 1946 US Army aerial image of island indicates massive earth movement to reshape island into circle shape
- Current use
Marine reserve

Tourism on the island
- Economic value of tourism focused there
  - Existing conditions and prior work–
    - Agulto and Yuknavage, 2006
    - USACE Honolulu District, 2001

Erosion
- Beachrock exposure
- Trail eroding
- Trees falling
- Tourist injury liability
- Injure business

Methods
- Image Processing
  - Crowell et al., 1991
    - raise the issues of using aerial photos for mapping shorelines
  - Thieler and Danforth, 1994 and Moore, 2000
    - Discuss methods to correct issues
  - Coyne et al., 1999
    - Incorporate Thieler and Danforth into a methodology to correct imagery and mosaic it together for continuous coverage
  - Moore, 2000 makes recommendations for a successful shoreline mapping project.
  - Fletcher et al., 2003
    - Update Coyne et al and use Moore recommendations by using processed mosaics as control point resources for older aerial imagery

Shoreline change reference feature
- Shoreline definition
  - Types – geomorphological and datum based
    - Boak and Turner, 2005
  - High water line vs toe (low water mark)
    - Coyne et al., 1999
      - comparison of seasonal variability
      - visibility on white carbonate sand beaches
    - Bauer and Allen, 1995
      - Toe definition
  - Do not use the Vegetation Line
    - Fletcher et al., 2003
    - Romine et al., 2009
  - Feature used elsewhere in Pacific
Analogous to Hawaii

- Coyne et al., 1999
- Fletcher et al., 2003
- Romine et al., 2009

Shoreline change rate calculation
- Cast transects to sample shoreline
- Uncertainty Analysis
  - Coyne et al., 1999
  - Fletcher et al., 2003
  - Romine et al., 2009
- Method choice
  - Single Transect methods
    - Incorporates the position uncertainty statistic as an estimation of confidence
      - Romine et al., 2009 for justification
      - Genz et al., 2007 for method selection
  - Polynomial Methods
    - Uses all shoreline data at all transects on a beach
    - Allows spatial and temporal variation of the shoreline change rate
      - Frazier et al., 2009 and Genz et al., 2009 for methods
      - Romine et al., 2009 for application and interpretation
  - Compatible with other studies
    - Review of many methods
      - Genz et al., 2007

History and Cultural use of Mañagaha


Russell, 1984 is used as a reference for the history Mañagaha as the first landing place of the first Carolinian migrants to Saipan led by Chief Aghurubw. Placing Mañagaha within the historical context of Saipan history for the first time.

Russell’s report No. 19 begins with the arrival of Carolinians at Mañagaha (called Ghalaghal in Carolinian) led by Chief Aghurubw. Their canoe voyage, and subsequent habitation of Saipan represents a well-defined cultural influence on modern Saipan and establishes one of the two historical contexts in which Mañagaha is specifically
mentioned prior to World War II. Mañagaha is the landing place and memorial burial site of Chief Aghurubw. The group lived on Mañagaha for approximately 15 years. Today, there is a statue of his likeness on the island to commemorate his role in Carolinian Saipan history. The majority of the book describes lifestyles within Garapan (now the Capitol of Saipan) and its changing façade as the economy of Saipan changed. The influence of colonizing powers, the Spanish, Japanese, on the lives of the Saipan Chamorro the Saipan Carolinians that live there is well documented in photographs, tax records and recounted family stories that author mines for a version of what society looked liked during this period.


Provides a history of Saipan prior to the arrival of Chief Aghurubw from the Caroline Islands. When Chief Aghurubw arrived there were few Sapian Chamorro people living on the island, having been banished from their home by the Spanish rulers. The history of Saipan Chamorro and Carolinian’s is intertwined from this point when the Chamorro returned to Saipan to find it inhabited by the Carolinians.

The history and use of Mañagaha and Saipan are intertwined. The archeological and physical remnants of the Chamorro of Saipan discussed by Scott Russell follows publications by archeologists Alexander Spoehr and Fred Reinman on work done in the 1950’s and 60’s excavating sites both on Saipan, Rota and Tinian. These provide a version of Chamorro history prior to western discovery by Magellan in 1521 and Spanish rule of Saipan (1818 – 1891). Their Saipan history includes analysis of archeological sites but exempts most local oral knowledge. This is the result of the indigenous Chamorro populations of Saipan (and Tinian) being forcibly removed from these islands by the Spanish in 1689 to Guam following conquest of the northern islands.

Sablan, 2003 is used as reference for cultural use of Mañagaha by the Saipan Carolinian community currently.

Sablan describes the ritual of Fiighiló or burning of objects close to the deceased during Firowrowa ceremonies in a small fire. He describes the unobtrusive nature of the practice on the environment, that the objects were completely consumed in the small fire that is then completely exhausted and dispersed.


This is used as reference of the role of Mañagaha (referred to as Maniagassa during World War 2). The recount of the island places the earliest photography of Mañagaha used in this study from 1945 and 1946 in the timeline of the military occupation of Saipan and Mañagaha. The island is described as an apostrophe shape, 300 yards long and 250 yards wide. This also describes the island’s appearance in the 1945 image used in this study while the 1946 image, also found for this study reveals that the shape of the island was significantly more round.

Hoffman recounts the military operation to take the island on July 13, 1944. The operation was the last battle of the Battle for Saipan that began on June 15, 1944. The change in shape is unexplained in Hoffman, 1950 since it occurred after the war was over. No other documents or military records were found that would give the reason for the earth works necessary to change the change of the island so drastically.

**Prior Work**


This presents the need for a robust method to examine historical shoreline change at Mañagaha. The presentation summarizes previous work (USACE study) and recommendations (USGS) then provides the baseline for decisions about what to do to manage erosion there. The data collected by the CRMO and which was indicated in this presentation was also included in this study where applicable.
This presentation and provided document gives a chronology of events affecting Mañagaha and presents the results of Coastal Resource Management Office personnel efforts to document the extent of observed erosion along the Mañagaha shoreline.

- Sept 1984 Mañagaha registered as a National historic site
- Dec 1995 HPO permits the removal of 5 wrecks. CRM Program Agencies/CPA/EFC/Samsung decide that four wrecks need removal
- April 1996 removal commences
- May 1996 barge removal complete
- June 1996 remaining metal shards and some erosion is noticed by DEQ lab staff during sampling
- August 1996 investigation of erosion requested by CRM
- April 1997 more erosion reported
- Jan 1998 erosion appears to have stabilized
- April 1999: Rep Heinz Hofshneider requests assessment of Saipan lagoon dredging impact. CRMO, Peter Barlas says Saipan channel dredging is the major culprit. Pala Pala damage and downed trees are shown by a survey of the area.
- May 1999 Governor Pedro Tenorio call for action to save Mañagaha
- 1999 Dredging commences in the channel south of Mañagaha
- March 2000 ACOE and CRMO state that Mañagaha should be allowed to stabilize naturally.
- Jan 2001 Mañagaha erosion study distributed
- CRMO provides NAD83 coordinates of the Mañagaha Protected Marine area. Mañagaha is thought to be recovering. No action will be taken towards constructing a breakwater
- Nov 2003 beach at profile 4 is near gone

Using 9 beach profiles collected by CRMO staff and photographs over a three-year period (2002 – 2005), they track migration of the shoreline of Mañagaha bi-annually. In the northeast, east and southeast of the island it undermined trees, and caused the collapse of day-use facilities. Erosion also began threatening nesting habitat used by the endangered shearwater bird. On the southwest side of the island, erosion caused structural damage to the landing pier. At the same time the northwest portion of the shoreline was accreting. Plotted profile data are included in the appendix and

This is referenced for context, placing the management of the island within the preservation context while also being developed as the economic resource it is today. The document also places management authority with the CRMO as the permitting agency.

This management plan, updated in 2005, is the organizing document that identifies the Coastal Resource Management Office (CRMO) as the organizing and permitting entity in concert with the Dept. of Fish and Wildlife, Dept. of Natural Resources, Marianas Visitors Bureau, Dept. of Public Safety and Boating Safety, Historic Preservation office, Division of Environmental Quality and the CNMI Legislature managing use of the island. The management plan also charges the CRMO with developing the Park for economic purposes while preserving the environmental, cultural and historic resources on and around the island for the people of Saipan and the CNMI. This follows Mañagaha being designated in 1984 as a U.S. National Historic Site because of the WW2 era relics around and on the island.


This resource is used as reference for the management plan of the island and the cultural, historic, flora and fauna found on Mañagaha. It provides the regulatory context that this study falls within.

This plan updates the 1985 Mañagaha Island Marine Park Management Plan following Public Law 12-12 passed in August of 2000 establishing the Mañagaha Marine Conservation Area. The plan was developed by the Division of Fish and Wildlife (DFW). The Department of Land and Natural Resources (DLNR) is the managing entity responsible for organizing and streamlining permitting interests in the island among all the permitting entities that have mandates over various uses of and conservation responsibilities for resources in the area. The management plan specifically identifies the CRMO as the permitting agency in concert with the DWF for economic activity on the Mañagaha, including the concession activities, while preserving the conservation interests on and around the island for the people of Saipan and the CNMI. The management plan organizes the myriad of various commercial activities being conducted on and around the island by establishing management zones and permitting that attempt
to manage the island and surrounding waters to preserve the cultural, historic, marine, flora and fauna identified. The 28 species of medicinal plants are cited as planted by locals of Carolinian decent with the statue of Chief Aghurubw representing their arrival in the islands in the late 1800’s. The plan establishes an exclusive concession permit scheme and user fee base. The concession permit allows a single vendor to operate from the island on a 5 yr competitively bid permit. The fee base provides direct revenue for the Commonwealth documentation of users of the island for management. Currently, the concession permit is held by Tasi Tours, Inc.


This Minton and Palmer, 2006 report are the source for storm frequency and variability in the region of Saipan.

Storms have potentially significant effect on islands with respect to flooding, erosion, and damage to structures, crops, and vegetation. They may result in storm surge, severe rainfall, and wind. Saipan is adjacent to the cyclone breeding ground of the western Pacific. Cyclone activity in the region of Saipan is affected by decadal variation and the El Niño-Southern Oscillation (ENSO). ENSO refers to variations in the water surface temperature in the eastern Pacific Ocean and in the air surface temperature in the western Pacific. During ENSO, warmer waters migrate toward the central Pacific increasing the frequency and strength of storms that have the potential to target Saipan. Following ENSO the cyclone breeding ground moves west into the Mariana Islands region resulting in storm strength that is relatively low when in the vicinity of Saipan and tends to increase as it moves away.

Since 1970 an average of 3 cyclones per year passes within 300 nautical miles of Saipan. Decadal variation has caused cyclones in the 70’s to be less frequent than in the 80’s and 90’s. July through December is the period in which cyclones are most common.

Since 1945:

- 186 cyclones passed within 120 nautical miles of Saipan
• 8 (4.3%) tropical depressions
• 40 (21.5%) tropical storms
• 138 (74.2%) typhoons
• 44 (31.9%) super typhoons
• 11 super typhoons passed within 120 nm
• 1990 very high storm frequency

US Army Corps of Engineers Honolulu Division, 2001. Mañagaha Island Erosion Study CNMI.

This report provides this study with technical information about erosion at Mañagaha. This study also encourages further study of the erosion problem which.

The Army Corps was requested by local resource managers to provide information of coastal processes, provide alternatives to stabilize the shoreline erosion, and protect threatened structures on Mañagaha. The report provides environmental information, photo documentation and series of beach profile line locations that quantify the extent to erosion to 2001. The study is an initial investigation into erosion at Mañagaha. The study finds that the removed WWII era wrecks from along the east and south east acted as hard points along the shoreline dissipating wave and current energy in a portion of the island dominated by trade wind and wave conditions. Since their removal, over 100 ft of sandy shoreline has been lost since 1997 from the most severely affected areas while small amounts of accretion have occurred in other areas.

There are three types of wind patterns that affect Mañagaha. E-NE trades (45%, 10.5 mph), slack winds or variable light winds, and typhoons. The tides at Mañagaha fluctuate around 1.5 ft. The waves environment include trade wind waves, low-pressure system waves and storm waves.

The report postulates that Mañagaha is anchored on a coral outcrop and formed from sand accretion due to wind, waves and currents. They also suggest that coarse, unworked limestone rock and debris found around the island and in surrounding waters is likely the remains of dredging for seaplane runways to the east of the island and shipping channels to the south.

For the Mañagaha study, this report is used for the wind speed numbers and as an information resource for possible data sources of aerial imagery and factors contributing to shoreline change at Mañagaha besides the removal of the WWII era wrecks along the shoreline.

This study examines chronic erosion at American Memorial Park on Saipan. They beach profiling from 1996 – 1999 and 2004 and aerial imagery from 1948 – 1985 to quantify changes in the shoreline. They find high variability in the shoreline of the park with up to 300 feet of erosion recorded at one location and 5 feet of accretion at another. They identify several factors contributing to the erosion: small wind waves, storm swell, continued health of eel grass beds immediately offshore (that may trap sediment offshore) and continued shoreline development to the east that retards or blocks sediment transport from that direction.

**Methods**


Crowell et al. (1991) is used here as a processing tutorial legitimization of including aerial photography in shoreline change analysis. This study summarizes the best photogrammetric and error analysis methods up to publication date.

In this second of a two part series on mapping historical shoreline change, Crowell et al. (1991) discuss mapping and accuracy the shoreline for the Federal Emergency Management Agency (FEMA) at a national level. This study marks the nationalization of soft-copy photogrammetry to construct hi-quality base maps to be included in shoreline change analysis. They discuss the inherent distortions and sources of error associated with using aerial imagery to map the shoreline. These include errors due to ground elevations (terrain), camera geometry, film plate, and airplane tilt. They summarize a simple correction method using ground control points of known map coordinates located on stable features visible in the imagery and on topographic charts
(T-sheets) to fit imagery and correct for the effects of these sources of error. They discuss the need to track error throughout the mapping process to assess final map quality. The final error statistic can be derived from the processed imagery based on check points, with the root mean square error as an conservative approximation of the difference between the modeled ‘correct’ positions on the corrected aerial photo and a source map. They endorse a single statistic to analyze and predict shoreline position. The authors describe errors associated with processing imagery and provide a framework for estimating and documenting sources of error and recommend a final error statistic that reflects the processing steps required and nature of the feature being mapped (in their case, the high water line). They suggest a simple root mean square error calculation that assumes that each source of error is independent.


Thieler and Danforth (1995) provide the first comprehensive analytical and conceptual framework to process large quantities of aerial imagery and map sources. They summarize many cartographic and photogrammetric relationships and processing techniques that are at the foundation of extracting high quality shoreline position data from vertical aerial photographs and existing map data. They develop a computer-based image processing technique to process multiple aerial images using an array of control and tie points and camera information and simultaneously correct errors due to camera projection and re-project the images into a common map projection. The Mañagaha study employs these methods using PCI Geomatics software for image processing.

High quality is defined as low error in image and map processing using a robust error method based on input data accuracy and checkpoints. The techniques and procedures they outline and discuss operate on digitized aerial imagery and maps that may contain distortions and errors from the media and environment in which they were stored until digitized. The basic steps to process imagery, i.e. to understand and build relationships between image space(s) and object space are given. These steps are interchangeable depending on the image processing software’s ability to integrate
multiple steps into a workflow. The authors present them as: (1) Establish a control network of points visible in the aerial photograph(s) that can be located on the ground and geographic coordinates measured or calculated from a known source (map or already processed imagery). (2) Build a relationship between the aerial camera and image space using fiducial marks on each photo and between the photos and the ‘ground’ using passpoints (or tiepoints). (3) Remove distortions due to the shape of the lens (radial lens distortion – idealized), distance of film plate to the lens (Camera Focal Length – CFL), and distortions of the media or scan of the aerial photograph. The camera calibration report contains a systematic assessment of camera geometry and values for fiducial marks on the film plate, the radial lens distortion and the CFL. In the absence of a published report, simplistic assumptions can be tested about the CFL, while the scale of the image and a visual assessment of the photo quality will help identify image distortion due to poor lens quality or media irregularities. Poor lens quality and media irregularities will impact step 1 and 2 errors and overall confidence in the processed image. (4) Relative and absolute orientation of the imagery. Relative orientation is performed during passpoint and control point collection (step 1). Absolute orientation solves for the attitude of the aerial camera (camera station) at each exposure using an aerotriangulation adjustment based on the ground control points of the control network in step 1. Steps (5) and (6) involve solving for each pixel location through single ray intersection to the control point coordinate system. If elevations of the ground object are known, the effect of terrain displacement can be integrated. If they are not, this remains a source of error in the derived feature positions as they appear on the new, processed image map (this can be significant in areas of high terrain variation, such as coastal bluffs and escarpments).


For the Mañagaha study, Coyne et al., 1999 brings historical shoreline change analysis into the Pacific Island context, provides an analogous context in the Pacific Basin for shoreline change analysis methodology including an uncertainty analysis and tests the sensitivity of three shoreline proxies. She finds the toe as a more appropriate shoreline
change reference feature for shoreline change analysis of beaches around Oahu, Hawaii. Mañagaha also has carbonate beaches of high albedo and reflectivity with relatively clear water near-shore. Available data of Mañagaha did not reveal a proxy of the high water line visible in each image, especially in older (1945/1946) imagery where image quality is low and beach area contrast is high. The toe of the beach proxy of a tone change in the water column is readily identified in each image. The use of Mañagaha as a tourist recreation site has resulted in the human alteration of the vegetation line by raking fallen leaves and seeds as well as cleaning of the beach face slope of small debris deposited by the last high tide waves.

Coyne et al. (1999) adapts Theiler and Danforth (1995) to process scanned 1949 and 1996 vertical aerial photography of four stretches of coastline along the island of Oahu, HI. Using available camera information, fiducial marks, differential GPS (DGPS) locations visible on the 1996 imagery and tiepoints (passpoints) between the photos to process image pixel values into the UTM WGS84 (1993) zone 4 datum using a cubic convolution resampling method of the single ray intersection values of each image pixel to produce a 0.5 m output resolution processed image. Their mosaic process uses ‘cutlines’ located by the user on each image to identify areas of each image to include in the mosaic. The goal of mosaicking together processed imagery is to identify and retain those areas of each processed image with the least error, to create a continuous shoreline coverage of the best portions of each image. This provides a large accurate base map for shoreline extraction (identify and digitize onscreen) and to use for control point extraction in 1949 image processing where historical imagery may not contain features used in the DGPS survey. Coyne et al. (1999) also develops the systematic uncertainty analysis discussed by Crowell et al. (1991) using repeated sampling techniques and fieldwork to conservatively estimate uncertainties to calculate a final root mean square error statistic which calculated rates of change are compared to


Moore, 2000 is used in this study as a reference set of guidelines and recommendations for sorting through data sources by aerial/satellite image availability,
quality, scale and project goals. The Mañagaha study is limited in available data mainly due to its location in the Pacific and the costs associated with moving airplane and air survey equipment into the area.

Moore (2000) discusses multiple techniques to map shorelines based on available data, desired accuracy, processing time and equipment. Moore includes a discussion of mixing mapping techniques and derived shorelines and analyzing change within a GIS. She finds that soft copy photogrammetry integrated into a GIS, such as used by Coyne et al., 1999 and Fletcher et al., 2003, the most thorough and expensive method to map shoreline change. She recommends a method that balances cost (time and money) with the timeline of the project and the desired output (product type and accuracy). Moore provides a set of recommendations to successfully complete a shoreline mapping project: 1) select an appropriate technique to map the shoreline. 2) when possible use GPS rather than NOS topographic sheets (T-sheets) and T-sheets rather than USGS quadrangles. 3) if using historical maps, assess their accuracy. 4) use the highest quality vertical aerial photographs. 5) use the largest scale photography available, at least 1:20000. 6) choose a shoreline proxy that is well characterized by your mapping technique (e.g. top of dune should be used as the shoreline only if the mapping method accounts for relief displacement). 7) account for uncertainties in the shoreline proxy chosen (e.g. seasonal variation, effect of storms on the shoreline position). 8) account for short-term variation in the position of the shoreline proxy. 9) perform an overall error assessment and calculate an overall error estimate.


The historical shoreline analysis of Mañagaha adapts image processing, uncertainty analysis method descriptions from Fletcher et al. (2003).

Fletcher et al., 2003 build upon the softcopy photogrammetric and GIS method around the island of Maui, Hawaii and incorporate 10 m USGS digital elevation models (DEMs) into the rectification process: orthorectification - to correct horizontal displacement of stable vertical features like boulder outcrops and cliffs backing sandy
beach in the imagery. They use DGPS control points and collected tiepoints on their most recent imagery (1997 vertical aerial imagery) as input to the aerotriangulation and absolute adjustment. Similar to Coyne et al., 1999 they use a 4 pixel cubic convolution resampling method during the image processing to produce 0.5 m resolution orthophotos. The inclusion of a DEM during processing results in lower rectification errors for each set of imagery and the final orthophoto mosaic since horizontal displacement due to terrain can be assessed in control point and tiepoint locations (using the DEM). With orthorectification errors (root mean square) below 2 m for processed imagery, Fletcher et al. is able to use the constructed more accurate orthophoto mosaics as base maps for processing older aerial imagery, extending the resources available for control point extraction beyond what is visible in recent imagery.

Fletcher et al. (2003) develops a robust uncertainty analysis that attempts to quantify all errors potentially affecting the position of the shoreline. Their methodology is based on repeat sampling and field techniques first outlined by Crowell et al. (1999) and adapted to Hawaiian beaches by Coyne et al. (1999). Fletcher et al. (2003) assess the 1 sigma uncertainty of a shoreline position using the root mean square of the sources of error. They identify two types of uncertainty sources, positional and measurement. Positional uncertainties are associated the position of the toe in nature (seasonal and tidal variability) while measurement uncertainties are associated with the measurement of the feature on processed imagery or map data (topographic sheet scale, and rectification errors, digitization, pixel size).


For the Mañagaha study, Boak and Turner (2005) provide background and relevant literature references about the different possible shoreline data sources available to extract shoreline features from and a broad review of shoreline change reference features used in shoreline studies. They find that the high water line (HWL) is the most common feature mapped. However what is actually identified on the image/ground to represent the HWL varies widely across studies.
Boak and Turner (2005) provide a summary of many SCRFs used in shoreline studies. They delineate 2 types of shoreline indicator, feature and datum based. Feature based shorelines are those that represent a geomorphic feature visible on the beach itself. Datum based shorelines represent the intersection of a vertical tide datum (usually statistically derived from tidal station data) with a digital terrain model (DTM) of the beach. They found 45 examples of shoreline indicators in literature, 4 of which were datum based. 35 of the remaining 41 are based on visually discernable features such as high swash, a debris line or man-made structure while the last 6 are extracted from imagery using image processing techniques and are not necessarily visible to the human eye. The high water line (HWL) was found to be the most common shoreline indicator used. With considerable variation between definitions they found in the literature, when present, often the HWL was defined as the tone change on the beach face (foreshore of the beach) left by the maximum run up from a preceding high tide. Boak and Turner provide a summary table of shoreline indicators reported, how it is identified, its generic name, comments, source of data, the extraction technique to digitize the feature, and the referenced studies. They also review and describe the broad range of data sources including aerial photography, beach surveys, GPS, remote sensing platforms such as hyperspectral/multispectral imaging video imaging, microwave sensors, and light detection and ranging technology (LiDAR) found in literature to characterize the shoreline. They discuss the identification of the shoreline as involving two stages. The first is the definition and selection of shoreline indicator to act as the proxy for the land-water interface. The second stage involves identifying the shoreline in the available data source.


On Mañagaha, Bauer and Allen, 1995 provide the geomorphologic description of the toe of the beach and how it forms. During fieldwork on the island in 2007, the toe was identified in the field and recorded in beach profiles around the island using a total station and telescoping rod and prism. The toe was also tracked at a single location on the island over a complete tidal cycle using a stake and tape to mark its position during tidal
extremes. This exercise provides a field collected horizontal uncertainty in the beach toe position as it is recorded in the aerial photography. This uncertainty in position is carried forward through analysis and becomes a component in the shoreline change rate uncertainty.

Bauer and Allen, 1995 examine the formation and occurrence of the beach toe, or step, in the morphodynamics of the beach system. The toe is described as a quasi-equilibrium step feature marking the base of the foreshore of the beach and created by vortexes as breaking approaching waves swash up and retreat down the foreshore. It is commonly characterized along the profile of a beach as two slope changes, one at the crest of the toe and another at the base. During the flood tide, the step is evolved landward with a retreat of the step face landward. During an ebb tide, the step evolves seaward with material from the foreshore that collapses down the slope.


This text advocates the use of historical shoreline change analysis where there is a lack of access to physical and numerical models of physical processes. It also advocates the inclusion of rate data on Federal Insurance Rate Maps that are created by the Federal Emergency Management Agency (FEMA).

In this book, the National Academy of Science incorporates knowledge from the broad consensus of coastal science and existing management programs (like the Coastal Zone Management program) to help bring attention to the fact that development along the coastline is increasing and populations are moving into a dynamic zone that changes rapidly. They provide information and guidance about coastal processes, shoreline change and coastal engineering to inform the reader (decision makers, resource managers and planners). Their goal is to bring knowledge and good examples into the policy realm on a national, state and local level so that ad hoc management of the shoreline is replaced with programs that identify and recognize interests, responsibilities and opportunities to manage development of the coastline as a resource.

Genz et al. (2007) reviews statistical methods to derive shoreline change rates from historical shoreline position data. It is used in this study of Mañagaha to select a single transect (ST method – see Genz et al. (2009)) rate calculation method. At Mañagaha the contributions to a final uncertainty in the shoreline position are quantified. However, we do not understand the impact that storms that pass near the island have on the shoreline position in the past, Genz et al. 2007 suggests that the reweighted least-squares regression (WRLS), weighted least absolute deviation (WLAD) or weighted least squares (WLS) method. WLAD is not chosen because of the possibility that multiple valid solutions (rates) being calculated from a dataset. While two rates may be valid statistically, a solution of two, possibly very different rates at a single location, may distract from the intent of a shoreline change analysis’ goal of providing tools for decision makers and planners. At Mañagaha, WLS and WRLS are both calculated using all data.

Genz et al. (2007) review established shoreline change rate calculation methods and introduce a new set of methods that incorporate shoreline position uncertainties. The end point rate (EPR) used by Coyne et al. (1999) and included in Fletcher et al. (2003). The re-weighted least (linear) squares (RLS) method is used by Fletcher et al. (2003) and smoothed alongshore to produce their annual erosion hazard rate.

Genz et al. develop selection criteria to help select an appropriate rate calculation method based on how well the analyst understands uncertainty in their methodology (quantified most major sources of error). They test methods using hindcasting and forecasting of known shoreline positions and then perform the same using synthetic data. Removing storm influenced shoreline positions (those that are from data from north shore Maui collected following a storm – up to a month) made little difference in rate calculations at many locations. This indicates that removing shorelines collected close to storms is not necessary in many cases in Hawaii.
EPR is calculated using only shoreline positions (usually the earliest and latest) and is the difference in position divided by the time between the positions. The main disadvantage of this method is that ignores uncertainty, that if either of the 2 positions are have error associated with them the calculated rate will be inaccurate. Reweighted least squares (RLS) uses a 2-step method. First, a least median of squares regression is run on all the shoreline data to identify outliers (those outside of a cutoff value) and then computes an ordinary least squares regression on the remaining points. The advantage of this method is that it is robust and can identify up to 50% of the data as outliers. It works well with large datasets of many shorelines. With few shorelines, it risks throwing out good data because they are identified as outliers. RLS also ignores uncertainties in the shoreline positions.

The weighted least squares (WLS) method is described by Genz et al. (2007) as incorporating shoreline position uncertainties into the regression analysis so that a shore position is with a high uncertainty is weighted less (influences the calculation of the regression less). If the uncertainties were all the same, it would an ordinary least squares regression. Similar to RLS, reweighted weighted Least squares (WRLS) incorporates a two step process using the least median of squares to identify outliers, and then incorporates positional uncertainties as the WLS method does to calculate the trend based on the weighted remaining data.

They also introduce a binning method that identifies transects where the behavior of the beach through time is similar. Indistinguishable rates indicate littoral or sublittoral cells (a unit or subunit of a beach that shares sediment) and are assigned one rate based on all those shoreline positions. This method is introduced here as a way to increase the signal to noise ratio of the data by combining transects of data that behave similarly together for analysis. It is tested on Maui, Hawaii where sediment transport has been studied and found similar littoral cell structures.

Romine et al. (2009) is used at Mañagaha as the source for position and measurement uncertainty definitions and as guidance. They also use the toe as the geomorphic proxy of the low water mark (LWM) that is also used at Mañagaha.

Romine et al. (2009) present single transect (ST) and polynomial (PX) shoreline change rates for the beaches of southeast Oahu, Hawaii. These are calculated using recently developed polynomial methods developed by Frazer et al. (2009) and Genz et al. (2009) to assist coastal managers in planning for erosion hazards. This study also provides an example for interpreting results from these new rate calculation methods. They strongly advocate including shoreline position uncertainties in erosion rate calculations as a metric of confidence that the results are significantly different from the noise associated with natural variability in the position of the shoreline.


Both single transect (ST) and polynomial methods (PX methods and EXT) are calculated at Mañagaha. These methods and the mathematical code necessary to run them give historical shoreline change studies another set of tools that significantly add to the value of the results.

In these companion papers, Frazer et al. (2009) and Genz et al. (2009) developed polynomial shoreline change rate calculation methods (PX and PXT) that include the alongshore variation of shoreline change rates in their models. These methods build polynomial models in the alongshore direction using linear combinations of mathematical basis functions. Polynomial methods employ data from all transects along a beach to calculate a rate at any single location. Polynomial methods can also model variation through time (T). These methods provide a single rate calculation at each transect location just as single transect (ST) methods like WLS and RLS. However, unlike ST, the
calculation includes data from all transects on a beach which reduces model over-fit and distributes model uncertainty over many transects. Polynomial acceleration methods can provide important information about changes in the shoreline change rate through time (acceleration and deceleration).

Polynomial methods use one of three types of basis functions to build a model for the alongshore variation of rates. Generalized least squares regression (GLS) is used in each method to calculate the parameters of the model. GLS incorporates the uncertainty ($U_t$) of each shoreline position as a weight for each shoreline’s influence on the model. LXT uses Legendre polynomials as the basis functions. RXT utilizes trigonometric functions (e.g., sines and cosines) as the basis functions. EXT, utilizes empirical orthogonal functions as the basis functions of the shoreline data of all transects on a beach.

ST methods regard transects as independent measurement locations. Polynomial methods assume that larger scale processes, such as sediment transport affect adjacent transects on a beach similarly. As a result of this binning of data, the uncertainties associated with the rates calculated using the polynomial methods are invariably lower than with the ST method because they use all of the data on a beach to calculate the rates. As a result, polynomial methods using basis functions produce statistically significant rates at a higher percentage of transects than ST.
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