Changes to Bermuda's marine environment since Lt. Hurd's survey of 1789-1797:

learning from the past to enhance conservation awareness

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Above all, I would like to thank Lt. Thomas Hurd, for his meticulous charts, which have surprised even the most cynical of scientists with their accuracy, and have provided a glimpse into a part of Bermuda's history its people have not yet seen.

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Abstract

It is beneficial to have long-term baseline data when setting conservation goals for the protection of marine habitats. Otherwise there is a danger that declining habitats will be mistakenly considered healthy, and therefore not in need of resource management. This report describes my analysis of a nautical survey completed by Lt. Thomas Hurd during the years of 1789-1797, which I compared to aerial photos taken in 1997 in order to provide an ecological baseline to guide conservation and restoration activites on the island of Bermuda. The goal of this study was to determine the positive or negative effects resulting from altering the marine environment, as well as the social or cultural factors that drove these alterations to occur. It is hoped that a better understanding of the implications of these changes will help policymakers to better confront present-day environmental issues.

This study utilized a Geographic Information System (GIS) to digitize the features on Hurd's survey to enable precise mathematical analyses of habitat modification. Overlay analyses were performed using digitized feature to determine how much reef area was lost due to (1) channel dredging and (2) the construction of the airport in Castle Harbour. Pond and wetland features present on Hurd's survey were also digitally compared to maps of modern-day features to determine overall losses in area and extent. Quantitative and qualitative analyses were also performed on several other sections of the island of Bermuda, where anthropogenic disturbances were known to occur. These locations include the City of Hamilton, the islands in the Great Sound, Morgan's Point (a former U.S. naval base), and Ireland Island, site of the Royal Naval Dockyard. Depth points and current flow presented on the survey were also digitized, enabling the creation

of a high-resolution map of the bathymetry and physical oceanography of the Bermuda platform.

Results showed that in total, ship channel construction necessitated removal of nearly 45 ha of reef, many times unnecessarily due to improper planning of channel location. Further, the large-scale degradation that occurred in Castle Harbour due to the construction of the airfield was found to have dredged and infilled 238 ha of reef, ten times more reef than estimated in a previous study. Area of natural wetland features was found to decrease by 58% from the 169.69 ha originally surveyed by Hurd, resulting in an overall loss of 22 natural features. However, this study illustrates that there exist opportunities to restore and create new wetland and mangrove forest habitats, and also proved that man-made wetland habitats can prosper under favourable conditions.

1.0. Introduction

One of the most difficult problems associated with the conservation and effective management of marine habitats is how to define what is natural and what is not. This problem arises from a deficiency of long-term baseline data with which to compare to present day communities, and is compounded by a mind-set present in every generation that what was present in their childhood was natural. The danger is that habitats or animal populations that are slowly in decline may be mistakenly considered healthy, and therefore are not in need of resource management. Defining what is natural versus what was changed due to human activity is an issue on Bermuda as much as it is elsewhere.

Bermuda is a semi-tropical island 56 km^2 in size; located in the western north Atlantic 1000 km southeast of Cape Hatteras, North Carolina (Hayward et al., 1981). While Bermuda has excellent records of the social, political, and economical events that have taken place ever since colonization in1609, historical accounts of Bermuda's marine environment have not always been collected, and when kept were often focused on inconsequential aspects of the natural world, were species specific, or were lost for a host of reasons. Fortunately, for conservationists and historians alike, one of these lost records was recently re-discovered by the British Hydrographer's Office. This document is a remarkable set of maritime survey charts completed between the years of 1789 and 1797 by Lieutenant Thomas Hurd, and supplemented by topographical work by Captain Andrew Durnford of the Royal Engineers, with help from Naval Lieutenant Andrew Evans (Figure 1). In 2008, the first version of the original chart ever seen in Bermuda was provided to the Bermuda Maritime Museum (now the National Museum of Bermuda). Although others had charted Bermuda's waters as well, the Hurd survey is unique in its

extreme accuracy and representation of the whole of the Bermuda Platform, including the complex reef system that covers it. The chart was so accurate that there was concern during the 19th century that the map would be used as a navigational tool for anyone attempting to invade the Island. For this reason the map was hidden for many years with later copies having false channels and ambiguous markings drawn in. Hurd's survey would have been the standard for navigation at the time, but the changed made in later nautical charts caused quality and accuracy to diminish, as evidenced by the present nautical map which generalizes large reef sections and marks swaths of area as "unsurveyed", a complete divergence from the meticulous details seen on Hurd's survey (Figure 2).

1.1. The extraordinary survey of Lt. Thomas Hurd

Hurd and Evans began their surveying expedition in 1789, under request by the King of England, George III. The goals of the survey were to record all of Bermuda's hydrographic features such as reefs, water depth, tidal information, main navigational features and pilotage around the island, specifically through the northern reef expanses (Webb, 2008). The survey was also commissioned to determine Bermuda's strategic potential, since Bermuda was well positioned to replace the harbours on the East Coast of the United States lost by Britain during the Revolutionary War (Webb, 2008).

Hurd surveyed Bermuda's reefs and islands to amazing accuracy, especially considering what technology would have been available at the time. Surveys were carried out using triangulation from various land-based survey stations (Webb, 2008). Hurd's equipment list included tools for triangulation and navigation, such as: a brass sextant (used for determining latitude), a theodolite (used to measure horizontal and

vertical angles), a compass, a telescope "for observing Jupiter's satellites", deep-sea and hand lead lines, and a water glass for observing underwater features (Webb, 2008). Hurd conducted his surveys on a six-oared cutter with mast and sails, and a crew that included a local slave, James Darrell, who knew the natural channels around the island well, and was granted freedom for his help with conducting the surveys (Webb, 2008).

In 1794, Admiral George Murray, commander of the North American Station, visited Bermuda, and was delighted when he found Hurd ready to pilot him through the reefs to the sheltered shores of Grassy Bay off Ireland Island, where Hurd proposed a ship-refitting basin (Various Writers, 1997). Admiral Murray saw Bermuda's potential as a naval post (a potential that was later realized with the construction of the Dockyard, and later the US base), and urged the need to adopt it as a base for any vessels sailing within his station (Various Writers, 1997). Hurd was promoted to Commander for his efforts, and was ordered to erect channel buoys (charted on the survey), which he did in turn to extend his surveys (Various Writers, 1997). Hurd completed his survey in 1797, and then returned to England to draw out the map work. The map was finished in 1801, and upon completion measured 12' wide by 6' tall (Various Writers, 1997). In 1808, Hurd was successfully appointed the Second Hydrographer to the Royal Navy (Various Writers, 1997).

1.2. Bermuda's unique environment: a long history of conservation

Since its early history, Bermuda has had a reputation of making sound conservation decisions. In 1616, Bermuda introduced the first conservation law in the New World, limiting the capture of the endemic Bermuda petrel, or cahow (*Pterodroma cahow)*. This legislation came at a time when the cahow was already driven to near

extinction. However, it still resonated as a useful example for later years, when preventative laws were introduced limiting the hunting of sea turtles in 1620, and restricting the capture of pilchards and fry to be used only for bait or food, and not for oil.

As Bermuda developed, the agricultural industry floundered, as exports could not match those of the larger, fertile, Caribbean islands when Bermuda had restricted amounts of arable land. In the late 1600's, Bermuda became conscious of the value of its strategic location, and shifted its economic focus from agriculture to the sea, taking advantage of its central location to connect the emerging North American economy with that of the bountiful Caribbean islands. This decision initiated Bermuda's long maritime association, and, by becoming more reliant on the sea and all it offered as a means of travel, driving a rich shipbuilding industry, a source of food, and a source of exportable goods such as salt, Bermuda prospered.

Bermudians have always depended on the sea to for recreational and commercial pursuits, but the marine ecosystem of Bermuda would not be so rich in diversity if it weren't for its location and for the positive marine management decisions that have been made over the last few decades. The high biodiversity of Bermuda's marine ecosystem is unique for an island at such high latitude. Bermuda's climate is mild and semi-tropical because of warm water eddies that spiral in from the Gulf Stream, creating an environment suitable for growth of tropical marine species such as reef corals (UNESCO, 1998). Coral reefs are a vital habitat for thousands of plant and animal species, and also provide a great amount of structural support, acting to dissipate wave action during storms, protecting the coastline and providing up to 1.1 billion dollars' worth of benefits every year (van Beukering et al. 2009). Coral reefs are in turn reliant on neighbouring

seagrass meadows and mangrove forests, which provide habitat for juvenile reef fish, and help to cycle nutrients throughout shallow waters. The plants and animals that rely on these three habitats also support a variety of commercial and recreational pursuits, such as fishing, and diving, which both locals and tourists enjoy.

Bermuda's reef system is not only unique in its location, being the northernmost coral reefs in the world, but also stands out in its resilience to the kinds of environmental stress that have decimated reefs in the Caribbean over the past three decades (Wilkinson, 2004). Caribbean corals live in temperatures that are high all year round, whereas Bermuda experiences cooler winter temperatures. Therefore, Caribbean reefs have been more greatly affected by bleaching events due to ocean warming, as well as epidemics of coral disease. Caribbean reefs are also composed of only one dominant coral genus (*Acropora sp.)* whereas Bermuda has five abundant species from three dominating genera (*Diploria labyrinthiformis, Diploria strigosa, Porites astreoides, Montastraea cavernosa*, and *Montastraea frankesi*). Therefore, if one dominant species in Bermuda suffers from high mortality, another coral species can act to fulfill a similar ecological role until the affected species recovers. Caribbean reefs appear to lack such functional redundancy.

Anthropogenic and natural disturbances to the marine environment of the Caribbean are also more difficult to manage than are Bermuda's, as the Caribbean reef system is much larger in extent, and is held under legislation from many different countries. Protection of the reef can vary from place to place, and it is much harder to determine what reef areas need to be protected, or determine where enforcement or compliance from locals is lacking. Since Bermuda's reefs only extend a short distance, resource managers and scientists are able to isolate key habitats such as fish spawning

grounds, and protect them. Bermuda has therefore been able to make some important environmental decisions that have prevented a lot of the degradation seen in the Caribbean. For example, fish pots were banned in Bermuda in the early 1990's, and many commercial species have been steadily increasing in population since (Hayward et al. 1981). Many species of fish and benthic organisms are also protected within the whole of the economic exclusion zone of Bermuda. For this reason, the Bermuda platform in its entirety can be considered a marine protected area for these organisms.

Because of their resiliency during times when other reefs have been devastated by disease or bleaching, and the many conservation laws imposed on the marine environment, Bermuda's reefs may be considered a paradigm for Caribbean reef management. Therefore future plans to manipulate or indirectly effect Bermuda's marine environment should be carefully considered, since the marine environment is as an exceptionally important resource, and one of the few healthy reef systems in the Atlantic.

1.3. Using Hurd's survey to increase conservation awareness in Bermuda

Hurd's chart is a unique representation of Bermuda's past. Due to its accuracy and completeness, the chart provides historical documentation of the landmarks and landforms present in Bermuda's marine environment at that time - one that can be used to compare against features present today. Comparisons of the distribution of islands, reef structures, and marine habitats present today to those charted during Hurd's nine-year surveying expedition are beneficial, as they show how Bermuda's diverse habitats have changed during the last two hundred years. This study thoroughly analyzes the marine habitats charted on the Hurd survey, and executes comparisons of these critical habitats between both time periods. For this study, I mapped the marine habitats, islands, and

wetlands present on the Hurd map, and overlaid these features with the aerial photos commissioned by the Bermuda Zoological Society in 1997 using Geographic Information Systems (GIS) to determine how the distribution of marine habitats in Bermuda has changed over the past two hundred years. Historical background has been provided when appropriate to support how and why changes were done, and whether these changes were natural or anthropogenic in origin. Thorough comparisons were performed on certain regions of the island that are well known as having been heavily impacted by anthropogenic influence.

Through these comparisons, I intended to document and understand how humans and natural processes have influenced and changed Bermuda's marine environment, and also to discover whether or not the communities we study today have persisted throughout time and are present in their natural state relative to 1797. Assessing the changes that occurred in the past two hundred years will help conservationists to better restore degraded environments to a natural state, and provide new knowledge to apply to present options for restoration and management. It will also provide insight into how resilient Bermuda's various habitats are over the long-term, and help to better understand what local cultural, social, or environmental phenomena influence change.

2.0. Methods

The Hurd survey was provided as digital images of three separate map pieces by Dr. Edward Harris of the National Museum of Bermuda. These three digital images were merged into one continuous image by LookBermuda Ltd.. The merged Hurd digital image was then geo-referenced using ArcGIS 9.3 (ESRI, Redlands, CA, USA) by linking

control points on distinct reef features apparent in it to the same features in the georeferenced 1997 aerial photomosaic created by the Bermuda Zoological Society.

Features of the Hurd map were manually traced onto various digital map layers in ArcMap. Digitization was accomplished at a scale of 1:2500 for small features such as reefs, and 1:5000 for land features. The following layers were manually digitized where needed for comparisons, using Hurd's original legend descriptions as a guide:

- breakers,
- breakers exposed at low tide,
- reefs,
- land,
- land based water features,
- depth points (fathoms),
- currents,
- Reefs needed for mathematical analysis

Over 30,000 depth sounding reference points were also manually digitized, and these points were converted into a vector based triangulated irregular network (TIN) to clearly display the bathymetry of the Bermuda Platform at a high resolution (Figure 3). Current speed and direction was also mapped by Hurd, and these details were also transferred to the GIS map manually..

The digitized layers were overlaid on several different charts and photographic mosaic maps from different periods, in order to perform different analyses and cross reference results. The details of this process are expanded upon in later sections. The reef polygons derived from the 1997 aerial photograph were digitized by Dr. Thaddeus

Murdoch (Bermuda Zoological Society). The Bermuda Government Department of Conservation Services (DCS) provided the land polygons derived from the 1997 aerial. DCS also provided the Navigational Chart used to determine modern channel locations, as well as aerial photographs of the land taken in the 1940's, a digital, geo-referenced copy of the Savage survey of 1899, and digital map layers of extant pond and wetland features.

Historical research was performed to determine why, how, and when certain changes occurred. Research was accomplished by performing literature searches, as well as through personal communication from local sources that are cited throughout the text.

2.1. Sources of Error and Error Determination

When utilizing secondary geographic sources like drawn maps to compare against primary sources such as aerial photographs, there is bound to be some amount of error. The technology available to Hurd in the 1700's would have produced errors due to differences in how a person used the equipment or how the equipment reacted to changes in temperature or humidity. Technology today allows much more advanced mapping techniques to be used. Thus, comparing maps made using today's technology against historical maps is bound to result in variations in the features observed. Underwater features, for example, were mapped by Hurd using a waterglass, which would allow the detection of deeper features, and differentiation between reef types. Conversely, the aerial photographs are more difficult to use for differentiating reef types, and only show what is directly under the surface of the water. These differences between techniques, mean that some deeper features that Hurd may have spotted could have been overlooked when mapping reefs from the aerial mosaic. for example at the eastern end of the island,

where water quality is low and reefs are difficult to identify on the aerial image, but are clearly defined on the Hurd survey.

Errors can also be made during the process of geo-referencing. Geo-referencing of the Hurd map was done as conservatively as possible, using only the most necessary control points to minimize distortion and stretching, and to retain the integrity of the original survey. For this reason, in cases where large areas were being compared, it was sometimes more meaningful and revealing to compare features by eye rather than by mathematical analysis.

Despite the known difficulties in comparing the maps, error between Hurd's survey and the 1997 images was determined in the region of Castle Harbour. 32 random points were placed on land or reef features surrounding Castle Harbour. At each random location, distance between Hurd's drawn line and the 1997 line were recorded. An average distance of 27.4 m +/- 22.7 m was then determined from this process.

3.0. Results and Discussions for Areas of Interest

3.1. Bermuda's Waterways and Ship Channels

"*The numerous rocks reefs and shoals surrounding these islands render the crossing their latitudes in the night, or the making them at any time in hazey weather rather hazardous but this difficulty will soon vanish when the Nautical Survey on which I was several years employed shall be published and made known"*

-Thomas Hurd, 1801

Bermuda's reefs have always been treacherous to traverse by any ocean going vessel. The island was founded and colonized by shipwreck survivors, and as of now,

nearly 500 shipwrecks have been found in the waters surrounding Bermuda. This staggering number has little to do with the story of the Bermuda Triangle, and is due to the intricacies and complex geomorphology of Bermuda's reef system. The island is surrounded by a 100km belt of shallow (less than six feet deep) reefs, and the total reef area is estimated to be around 500km^2. There are few natural channels that pass through the lagoonal reef system, and only two natural channels pass through the rim reef to the open sea, one south of Castle Harbour and one east of St. George's. Bermuda is also a very small island in an isolated stretch of the Atlantic Ocean, creating an obstacle in the path of navigators. This is why so many ships have collided with Bermuda's reefs, even as recently as 2006, when a cruise ship ran aground in the Great Sound. Another recent shipwreck, the Mari Boeing, necessitated blasting of 100 acres of reef in 1978 to free the vessel, leaving a sandy, desolate flat in her wake, which has yet to recover ecologically (Sarkis, 1999, Thaddeus Murdoch unpublished data).

3.1.1. The North and South Channels

The ship channels that intersect the Northern lagoon of the Bermuda Platform are essential to Bermuda's people, as they are the lifelines that bring food and goods from abroad, as well as many tourists to the island. Throughout history, the channels also underwent a great deal of military use, as British and American vessels both frequented Bermuda's strategic waters throughout times of war.

Part of Hurd's commission to survey Bermuda's waters was to find a suitable channel through the northern expanses of Bermuda's reef system. This alternative passage was desired due to the difficulties of piloting a sailing vessel through the eastern channels, the Narrows, which Hurd discovered, and the channels leading into St.

George's Harbour, during times when winds blew from the east through to the southwest. The only alternative presented before Hurd's survey was to use the eastern channels was to travel through Castle Harbour, and through to the open ocean on the south shore of Bermuda, but this route through to the south entrances of Castle Harbour was not safe, due to the many obstacles such as reefs, underwater rocks, small islands, and boilers which impeded travel throughout the Harbour. The necessity of finding alternate passage was proven when the "Cerebus" was lost in 1783, after colliding with a reef adjacent to Castle Island near the southwest opening of the Harbour.

During the period that Hurd completed his survey, ships were smaller, lighter, and drew less water than modern ones, which meant natural channels and breaks could be used with great advantage. Hurd did find many natural reef breaks throughout the northern reef expanse that he considered viable for passage, but he also remarked in a report that the channels are exceedingly intricate, and should only be used by small vessels or in the presence of an experienced pilot (Jones, 1941). Therefore, the pursuit of a larger channel through the reef was still indispensable.

While completing his survey work, Hurd did find a suitable path through the northern reef expanse, through natural breaks to the east of North Rock. The channel he marks on the survey never reaches a shallower depth than six fathoms, but it is narrow in several locations, and is bordered by the rim reef, which is generally less than 10 feet deep. The channel past North Rock presented significant difficulty for navigation, but was the only then viable passage for larger vessels to come through if they could not pass through from the east. Because of this, Hurd himself only allowed one of his pilots to know its exact location, and suggested that publications made of his survey after its

original printing should not show the channel, in case the survey fell into the wrong hands (Jones, 1941).

Even though the North Rock Channel Hurd discovered was a solution for larger ships to pass northerly during variable easterly conditions, as the island grew economically, there was a need for ships to navigate throughout the Lagoon from St. George's to Hamilton. The reefs in the Lagoon presented a problem, and vessels needed a channel that could be accessible during any condition for any sized ships, and so it still became necessary to dredge channels very early in Bermuda's maritime history. The first channel that was dredged in Bermuda's waters was one parallel to the north shore of the island, referred to in this text as the South Channel, in 1795 (Figure 4). This occurred around the time Hamilton was being established as a town, and provided a route from the safe haven of Murray's Anchorage to the burgeoning urban centre of Hamilton. The channels around St. George's were dredged later, in the early 1920's (see section 3.2). The Narrows and Town Cut were dredged to create a wider passageway that was easier to navigate between St. George's, Murray's Anchorage, and the open sea. The newest and largest channel is the Northern Channel (Figure 4), which passes through reefs in the northern part of the lagoon, to Grassy Bay in the west, and as it is 42 feet deep, supports ships with a larger draught than the South (the older) Channel. The South Channel is far too shallow for post-Panamax Cruise ships, which are anticipated to run aground there. This channel was dredged during the Second World War, when the US base was established at Morgan's Point. The decision to create a channel that entered Grassy Bay from the north also necessitated the natural channel that passed through Stag Rocks (Figure 4) into the Great Sound to be replaced by a new eastwards channel named

Dundonald Channel that was dredged through the reefs (Figure 4C), passing through to Morgan's Point. This was required to lessen the angle of the curve between the North Channel and the channel passing into the Great Sound.

3.1.2. The channels entering Hamilton Harbour

The channels entering Hamilton Harbour have been altered several times over the course of the past two centuries (Figure 5). Hurd's survey shows a channel passing between Long Island and Agassiz Island, south of where Two Rock passage cuts through. The channel Hurd marked is 10 feet deep at its shallowest point, but it makes use of a natural gap through the islands. After entering the harbour, the channel is marked as curving steeply up to the gap where Two Rock now progresses. This curve would likely be a hazard for modern vessels, which are too large to turn that swiftly. If Hurd's original channel had simply been deepened, then the island chain eastwards (Spectacle Island, Butterfield Rock, and World's End Island) would have had to be blasted as well to reduce the curve. Two Rock passage simply passes above this island chain, although some reef did have to be dredged, and Mowbray Island was reduced to a small islet (Figure 5).

Before Two Rock was blasted in 1933, another channel was made through Timlin's Narrows, just north of Hinson's Island (Figure 5), to accommodate ships with a draught of up to 14 feet (Teddy Tucker, pers. comm.). Timlin's Narrows is an ideal location for a channel, as it is up to five fathoms (30 feet) on each side, and the narrow strip of reef in the channel was 3 fathoms (18 feet) at its shallowest. The drawback of this channel was that ships would have had to travel a long way around the islands in the Great Sound to reach it. Ships on this path would also pass over a cluster of reefs 3

fathoms deep in the Great Sound, which although suitable for ships with a draught of 14 feet, would not be able to accommodate larger modern vessels. \

For this study, the channels around Bermuda were further analyzed to determine the reef and land area lost due to the dredging and construction of the channels. As impact studies were not required for marine construction until recent times, it was previously unknown how much damage channel dredging has done to Bermuda's reef habitats. By analyzing the North and South Channels, Two-Rock Passage, and the Narrows Channel in this section, and Town Cut in the next section, this study hopes to provide information that can be used to guide development of future channel expansion.

3.1.3. Methods

In order to obtain an estimate of the reef area lost due to channel construction, a buffer of 100 m around the center of the North and South ship channels and the Narrows Channel was created that corresponded to the width of the channels present today (Figure 4). The buffer width was derived from the width of Dundonald Channel. From there, an overlay analysis was performed to extract the reef area from the Hurd map that intersected the current channel area.

The determination of reef and land area lost due to the construction of Two Rock Passage was performed using the same methods as for the North and South Channels. Again, a buffer of 100 m was placed around Two-Rock Passage and the corresponding channel entering Hamilton Harbour (Figure 4). An overlay analysis was used to determine reef and land area displaced during the construction process in 1933.

3.1.4. Results

The results show that in total (according to Hurd), the North and South Channels, together with the Narrows Channel, Dundonald Channel, and Two Rock Passage, displaced 39.44 ha of reef. 0.54 ha of land was also lost due solely to the construction of Two-Rock passage into the harbour.

As previously mentioned, since ship traffic is vital to Bermuda's existence, the removal of reef for channel construction could be excused. However, the ill placement of these channels negates the positive benefits that result from ship traffic when benthic communities are concerned. The North Channel was placed attentively to avoid many large reef structures, likely resulting in easier and more economically viable construction, and to give a wide berth to smaller reef obstacles interspersed throughout the lagoon. It also takes advantage of the large open basin of Murray's Anchorage, and a natural channel that passes through the southern part of White Flats (Figure 4). However, the excavation of the North Channel also necessitated the removal of 31.77 ha reef from the Stag Rocks to create Dundonald Channel (Figure 4). This was because the curve that ships would have had to navigate when entering the Great Sound from the North Channel was too sharp for ships to be able to pass through if using the older natural reef pass. Hurd's map shows the older channel to be three fathoms deep. From observing the direction that the North Channel enters Grassy Bay (Figure 4), it can be determined that the Channel could have passed through the older natural pass if the Channel had been dredged slightly straighter where it passes north of Ireland Island, and Stag Rocks could have been spared. Dredging the older channel to make it deeper would also have been quicker and cheaper than blasting reefs.

The Southern Channel also unnecessarily displaced 1.18 ha of reef, as it was blasted through a reef expanse called Crawl Flat just south of Bailey's Bay Flats (Figure 4) though there is a suitable detour that passing through no reef at all. The channel through Crawl Flat could easily have passed above the reef on the north side, instead of through the crook of the reef, as this reef flat is surrounded by sufficiently deep water on all sides. Many ships today actually pass through the north instead of through the channel, by cutting the curve to the west of Shelly Bay Shoals (personal observation). The sandy expanse north of Crawl Flat is an adequate depth of 6 fathoms (36 ft).

Two Rock passage was, in the authors opinion, well placed, minimizing the need for large ships to turn sharply in the harbour, and shortening the distance traveled, while also disrupting the least amount of reef area (Figure 4).

3.1.5. Implications and Recommendations

Although the construction of Bermuda's ship channels did displace reefs, it is unlikely that the engineers constructing the channels would have had enough awareness of the structure of the reef system to be able to plan channels around them. Especially in the case of the South Channel, which was dredged in 1795, engineers would likely have gone along the most direct route, blasting reefs where alternatives could not be easily seen. With the technology and aerial images available today, any future plans for expansion of the channel system could be based around the reef structures, taking every square meter of reef that is likely to be displaced into account. This is a technological advantage that would have been unavailable, but likely of great interest, to navigators and engineers throughout the last two centuries. In present times, we also hold much more value in our reef system, as we understand and acknowledge the importance of the

ecology of these structures. For navigators in past centuries, reefs would have simply been a danger and a threat when piloting around the island.

Besides utilizing technology to our advantage, we must also fully utilize the knowledge that we currently possess regarding the effects of dredging and ship passage on benthic communities. Plans to expand ship channels must be carefully scrutinized, as both dredging channels and increasing ship traffic within them can re-suspend excessive amounts of sediment. Sediment can smother corals, causing mortality (Price, 2006; Rogers, 1990; Torres et al., 2001), and can have detrimental effects on other benthic communities such as seagrass meadows (Price, 2006; Rogers, 1990). Although many of Bermuda's near channel reef communities are composed of more sediment-tolerant branching hard coral species (Murdoch et al., 2008), which have less difficulty eradicating sediments because of their morphology (Rogers, 1990), currents and tidal fluctuations can cause excess sediment deposition in regions downstream of the initial source of sediment suspension. For example, some reef passes through the outer rim reefs have been observed to be much more turbid than other rim locations, likely due to the flow of lagoonal water through them (T. Murdoch, pers. comm.). Excess concentrations of suspended sediments can also cause mortality in fish, as it can clog fish gills and create interference in the visual cues some fish species rely on for prey detection (Price, 2006). Excess sediment suspension could be reduced by prohibiting the passage of larger vessels in the South Channel, which is much shallower than the North Channel.

By looking closely at the reefs present on the Hurd map, and analyzing the configuration of channels passing through the reefs, it can be concluded that the channels were not planned optimally to minimize damage to the reef environment, likely due to

technological and engineering difficulties of that era. Hopefully, with the new technologies we now have available, and with the knowledge we have of how the indirect effects of alterations to the environment such as dredging and increased shipping traffic will ultimately effect Bermuda's marine and coastal habitats, future stakeholders will be able to make decisions that better protect the condition of Bermuda's marine environment.

3.2. St. George's Parish, Town Cut, and Ferry Reach

St. George's Parish is the easternmost Parish on Bermuda, consisting of most of the islands and land surrounding Castle Harbour. St. George's consists of the main island of St. George's, St. David's, Tucker's Town, Coney Island, and all the islands within St. George's Harbour. The Town of St. George's was the first permanent settlement on the island in 1612.

On Hurd's survey, the Parish is composed of 129 islands, of which less than a dozen show signs of habitation. The Town of St. George's is the only developed town centre on Hurd's survey. The Town was accessed from the east end of St. George's Harbour, through a pass between Paget and Smith's Islands. Hurd marks two channels with a depth of 18 feet that pass over the reefs east of Smith's Island that lead into this pass. Like many of the channels Hurd marks on his survey, these would have been adequate for passage of smaller sailing ships, given the right conditions. Because this was the only route into St. George's, the waterway was very well protected, overlooked by three forts: Fort Popple, on St. David's Island; Paget Fort, on Paget Island; and Smith's Fort, on Governor's Island (Harris, 2001). After 1823, Fort Cunningham was erected, causing the use of Paget Fort and Fort Popple to be redundant (Harris, 2001).

The Narrows channel, referred to as Hurd's Channel in old navigational records, was the most important navigational discovery made by Hurd while he was undertaking his surveys. The Narrows channel passes from the anchorage of Jervis's Roadsted (Five Fathom Hole) northward to the large basin of Murray's Anchorage (Figure 6). The Narrows channel remains the only channel that offers safe passage for larger ships along the eastern end of the island, and remains an important access route from St. George's to Murray's Anchorage and the channels beyond. As the channel passed "within half a gunshot of the shore" (Thomas Hurd, in Jones, 1941), the Narrows was also a well-protected waterway, guarded by Fort St. Catherine's, and Alexandra Battery.

Town Cut, which is the main channel into St. George's Harbour used today, was evidently not heavily used during Hurd's time, as the channel was shallow, sinuous, and only 20 m wide.

As the first settlement on the island, St. George's was where the seat of parliament was first established. However, in the late 1700's, when Hurd conducted his surveys, Crow Lane (Hamilton Harbour) and the Great Sound were on their way to becoming the major ports for the island. This led to Hamilton becoming established as a port city in 1790, eventually overtaking St. George's in importance after it became the seat of parliament in 1815 (Hayward, 1910). When Hamilton became the capital, St. George's began to lose pace economically. Luckily, when larger steamships began to frequent the island, St. George's found a chance to re-establish its importance in the maritime community. The newly opened Panama Canal, which was first used for passage in 1914, meant more steamships were frequenting the waters around Bermuda in need of a place to re-coal on the way to the Canal (Hayward, 1910). Bermuda was conveniently placed,

allowing ships to avoid taking the 520-mile detour to Newport News on the East Coast of the United States (Hayward, 1910). Since Hamilton was further from the open ocean, and was a smaller port than St. George's, it was thought steamships would have a greater advantage re-coaling in St. George's (Hayward, 1910). Therefore, the decision was made to create a better waterway into St. George's Harbour, and proposals were put forward to either deepen the existing channel south of Paget Island, or widen and dredge Town Cut. The latter occurred in the 1920's, establishing the main waterway present today (Figure 6).

When Town Cut was dredged in the 1920's, its increased use necessitated the two islands on the south side of the cut (Higg's Island, and Horseshoe Island to the west) to be joined to prevent a vacuum of water pulling ships out of the cut through the passage between the islands (McCallan, 1948). Therefore, on moderns maps, Higg's island exists is one larger island. When Town Cut was dredged, the Narrows Channel was also widened to allow larger ships a northern passage. The decision to widen and deepen Town Cut instead of simply deepening the channel south of Paget Island was likely made because the curve in the channel south of Paget Island was too severe for large ships to turn, and even smaller ships often had to be "warped" through the channel by pulling ropes from the shore.

Today, the Town of St. George's is a World Heritage Site under UNESCO, whose streets and buildings have therefore not changed much in design since they were built. The heritage status imposed on the city also prevents urban development from engulfing the city and the historical structures within.

As with the other channels that cross Bermuda's waters, impact studies were not done to determine the amount of reef that would be damaged by dredging. This study determined the area of reef and land that were dredged in order to widen Town Cut.

3.2.1Methods

A buffer of 50 m was created around the length of the Town Cut Channel (Figure 6). The buffer size was determined by the present width of the channel. An overlay analysis was then performed to determine what regions were directly affected by the location of the channel. Total area of reef, flat scattered with patch reefs, and land affected by the placement of Town Cut were then calculated.

3.2.2. Results

In the process of widening Town Cut, according to Hurd, 5.48 ha of reef was removed, as well as 0.98 ha land, and a further 2.84 ha of sandy flat scattered with patch reefs.

The amount of reef and land that needed to be removed in order for the channel to be widened was likely thought a small price to pay for revitalizing the town of St. George's to once again become an active port.

3.2.3. Implications and recommendations

The decision to dredge Town Cut was economically driven; one that revitalized the Town at a small expense to the environment. St. George's quickly re-established itself as a major port based on its proximity to the open ocean, an advantage that is still utilized today. As current ship channels could come under consideration for expansion

due to the increasing size and draught of cruise ships, it would be important to consider that St. George's proximity to deep waters would necessitate less dredging to expand the channels entering St. George's Harbour, rather than expanding the entire lagoonal channel system. In the last few decades, St. George's has been a popular tourist destination, where cruise ships frequent in the summer months, but as many of the cruise ships that visit Bermuda are larger Panamax or even post-Panamax, they are unable to manage the passage into St. George's, and now frequent Dockyard instead, which can accommodate these vessels.

Presently, it is possible that history may repeat itself as the Town of St. George's has seen fewer visitors than in years before due to the loss of cruise ships docking in the Harbour. This has led to a heated debate regarding whether Town Cut should be re-dredged. Some residents have voiced concern over the terrestrial habitat that would be damaged, but the small area of land adjacent to the channel could be very easily mitigated. Coral reefs are not as easily mitigated, and dredging Town Cut in place of the longer channel systems throughout the lagoon would prevent the loss of a much greater magnitude of reef area. If Town Cut is re-dredged, it is the hope of the residents of St. George's that the Town will once again become a bustling harbour.

3.3. Castle Harbour

Castle Harbour is a large semi-enclosed body of water at the eastern end of Bermuda, bordered on the north side by Longbird Island, St. David's Island, and Cooper's Island (now collectively the Kindley Field Airstrip), and on the western side by Walsingham and Tucker's Town (Figure 7). In Hurd's time, the western sand flats of the Harbour were used as an anchorage when ships could not pass through the eastern

channels, as the many surrounding islands would have allowed it protection from waves and storms. The Harbour would also likely have had a low sea water retention time, promoting the flow of fresh sea water through the Harbour, and promoting the growth of hundreds of small coral reefs and expansive seagrass meadows. The islands and features around and in the Harbour are currently considered some of the most historically, environmentally, and culturally important features in Bermuda. Around the perimeter of the Harbour, lie forts, the cave structures of Walsingham, and the nature reserve of Nonsuch Island, which has been restored to exemplify Bermuda's natural environment as it appeared before human settlement. Castle Harbour is also well known for its long history of environmental degradation due to human interference.

Castle Harbour's history of anthropogenic perturbations began in 1871 with the construction of the causeway (Figure 7; Hayward, 1910). Prior to the construction of this link between Longbird Island and the mainland (which occurred concurrently with the construction of the bridge between Longbird Island and St. George's Island), St. George's islanders were reliant on a ferry system between Ferry Reach and Coney Island, which utilized flat wooden barges that could accommodate horses and carriages. The causeway was built across advantageously positioned islands and the long peninsula of Longbird Island in order to span the channel. However, one might question the decision at that time to not build a bridge over the existing ferry connection from Coney Island. The author can only speculate that any consideration of building a link here would have been opposed, as at that time sailing ships would still be traveling through Ferry Reach to gain access to Murray's Anchorage on the north shore when eastern winds would hinder the passage of ships through the eastern channels. Building a bridge tall enough at Coney

Island to accommodate these vessels would have been very difficult. Additionally, Ferry Reach may also have been considered too exposed to hurricanes and strong winter storms for a bridge to be built there. As there would have been several ways of gaining access to Castle Harbour from the north, the loss of one throughway between Grotto Bay and Longbird Island would have not been a deficit. Similiarly, although the causeway would have restricted water flow, which can limit nutrient flow and cause sediment to settle and smother corals, it likely did not restrict it enough to cause great detriment to in-harbour benthic communities, as naturalists up to 30 years later reported no damage to coral reefs in the region (Flood et al., 2005).

After the construction of the causeway, Castle Harbour was unmodified until the second quarter of the 20th century. When World War Two began, Bermuda supported the allied war effort by supplying soldiers and acting as a vital stepping stone for allied forces crossing the Atlantic. The United States government, in discussion with the United Kingdom, saw Bermuda as a strategic base as enemy fleets could be detected long before they reached American shores. The United States government therefore requested an anchorage at St. George's, and use of the Brothers Islands (known today as "Morgan's Point') in the Great Sound to build a base for ships and seaplanes. However, when the deal was re-visited, the demands changed to a request for 1.5 square miles of land on the western part of the island for use as an air base. The Governor intervened, and it was compromised that a naval base would be established on Brothers Islands as previously discussed, but the airfield would be built at the eastern end of the island, at St. David's. The airfield was created by joining Longbird, St. David's, and Cooper's Islands and by infilling land perpendicular to the islands to place a missile storage facility, altogether, an

undertaking that required dredging nearly three square kilometres of coral reef, sand, and rock from Castle Harbour to infill 200 ha of land (Figure 8). Although many residents were displaced during these operations from the islands in Castle Harbour, many more would have been relocated had the airport been placed in the western parishes, as the Americans attempted to negotiate.

The dredging and infilling required for the construction of the airport caused the degradation of many benthic communities in Castle Harbour (Flood et al., 2005). The newly infilled island blocked off the northern channels to Castle Harbour, preventing adequate exchange and flow of water, and creating a body of water with little mixing, and a greater retention time. Therefore, Castle Harbour became a very turbid environment (Flood et al., 2005), producing a great amount of sediment stress on coral communities in the affected region, and creating a largely unstable, unsuitable environment for reef-building corals to grow. More than 70 years later, the water quality remains low, compounded by the decision in 1971 to dump bulk waste such as motor vehicle parts, appliances, and metal, into a reclaimed dump site on the northern rim of the harbour, adjacent to the civil air terminal (Flood et al., 2005). Ash blocks (ash stabilized into concrete) from the waste incinerator are also dumped into the harbour, further degrading the environment (Flood et al., 2005). Castle Harbour still today continues to be a primary example of how anthropogenic changes can completely alter the function and structure of a habitat, and how the consequences of such a decision can resonate for decades after the change occurred.

3.3.1. Methods

To determine total reef area lost due to dredging and infilling, a polygon was created of the areas in Castle Harbour that were either dredged or filled in. This was accomplished by mapping the highly visible dredge line from the 1997 aerial photograph, and combining this polygon with a polygon of the present day island configuration. The land polygons of the Hurd survey were overlaid with this polygon, and overlapping sections were clipped, resulting in a polygon consisting solely of infilled or dredged regions (Figure 8). Reef features from the Hurd survey that were contained within this polygon were selected, and the area of reef within the polygon was calculated.

3.3.2. Results

Up until this study, it was difficult to estimate how much reef area was in Castle Harbour prior to the airfield development. A previous study by Smith in 1999 demonstrated reef loss by analyzing black and white aerial photos, estimating a loss of 24.4 ha of reef due to the construction of the airport (Smith, 1999), but analysis of the Hurd map refuted these results, revealing that Castle Harbour contained 254 ha more reef area than it does presently. Areas that were directly infilled or dredged were compared to Hurd's map, revealing that approximately 238 ha of reefs, and a further 16.6 ha of sandy flat scattered by patch reefs were displaced by either dredging or infilling during airport construction (Figure 7). In total 658 reefs were removed during dredging operations, and a further 31 reefs were partially destroyed or directly impacted. Therefore, even if previous estimates were based only on reef regions that were directly affected, and discounted the areas scattered with patch reefs, a significant underestimation in the area

of the reefs that were found within Castle Harbour prior to airfield construction was made, likely due to the difficulty of differentiating reef features on the black and white photos.

3.3.3. Implications and recommendations

Despite all of the human perturbations to Castle Harbour, the decision to use Bermuda as a defensive base by the Americans protected Bermuda from the possibility of invasion by enemy forces, and when the war was over, the airport also greatly contributed to Bermuda's growing tourism industry, and its economy. Despite the losses afforded to local landowners, who freely gave their land away, Bermuda gained a civil airfield that was built free of charge by allowing the United States residency on the island, and were paid $60 m a year for housing the naval and air bases. The airport became a new gateway for travelers and locals when it opened for commercial flights, the first of which was in 1946. Prior to Kindley Field's construction, Bermuda was accessible only by boat or seaplane (a civil airport for sea planes was based at Darrell's Island, see section 3.4.), the latter of which became less popular as landplanes grew to be faster and more user-friendly. It can also be argued that although the construction of the airport caused damage to the environment, this damage is compounded by the continued use of Castle Harbour as a dump, creating greater environmental impacts, and inhibiting the possibility of natural habitat restoration.

The reef structures in Castle Harbour have a reduced extent to what Hurd surveyed in the 1700's, but Castle Harbour now provides a compelling case study for how habitats can be altered for decades due to human manipulation, and also provides a glimpse of how the environment will react if we cause the same degradation to occur

again. It provides an opportunity to minimize such damage from occurring when we are faced with new planning decisions, knowing how such altercations affect the environment.

3.4. The City of Hamilton, Hamilton Harbour, and Great Sound Islands

Hamilton's history as a city began around the time that Hurd was completing his surveys. In 1790, merchants from the Western and Central parishes petitioned to acquire 145 acres of land on which they could establish the Town of Hamilton, reserving the harbourfront land for a wharf. In 1793, Hamilton, along with St. George's, was incorporated by Parliament, and as previously mentioned, Hamilton replaced St. George's as the seat of Parliament in 1815. In 1897 when the Hamilton Cathedral (Church of England) was completed, the Town became the City of Hamilton.

Since Hamilton was barely established when Hurd was surveying the islands, it can be presumed that what is present on Hurd's map is Hamilton in an unspoiled form, so a thorough comparison can be drawn. Hurd's map shows similar features to the present day map (Figure 9), most notably Pitt's Bay, which has only been altered to accommodate a marina and boat club. Albuoy's Point has been modified to accommodate ferry docks and parkland, by filling in the western inlet of the land jutting into the harbour. The rest of the coastline shows alterations simply from coastal development, decreasing the rugosity of the coast to a defined line. The development trend continues east, curving around the southern side of the harbour through Crow Lane. The eastern most tip of the harbour, named Bond Bay, has been increased in area, by joining three smaller bays into one, likely to accommodate more space for boat moorings (Figure 9). Ducks Island, a small island covered in mangroves at the center of Bond Bay,

appears on the Hurd map as part of a larger piece of land that projects into the harbour from the southern side of Crow Lane.

In the harbour, many of the smaller islands appear close in structure to their 1790's counterparts (Figure 10). The most notable changes in the cluster of islands just before the harbour occur near Two-Rock Passage, blasted in 1933 to accommodate larger ships that were entering the harbour. Mowbray's Island has been drastically reduced in size, and is now an islet marking the eastern extent of the opening to Two-Rock passage. Further along from the entrance to the harbour, throughout the chain of larger islands ending with the dot of Pearl Island in the middle of the Great Sound, there are more modifications that have occurred. Many of the larger islands here (Hawkins, Hinson, Marshall) are all presently habitated, but despite undergoing development, their morphologies today are very similar to their 1700's counterparts (Figure 10). Many of the islands here, for example Nelly's Island, Port's Island, and Burt Island, seem to have dramatically different coastlines presently from what Hurd surveyed (Figure 10). However, I attribute some of these differences to error on Hurd's map (or errors in Durnford's topographical supplement), because the coastlines of these islands appear natural in nature, and there are no signs of infill or reclamation occurring. I believe Hurd may have overemphasized some of the coastline features, and deemphasized others. South of these islands, Darrell Island (Tucker's Island on Hurd's survey) is found; the former station of the Royal Air Force, used until 1948 as an airport for seaplanes that brought freight and travelers between Europe and the Americas. Darrell Island has therefore undergone changes to accommodate a hanger, and seaplane docks. When these structures were torn down, the topology of the island was again reformed. The island is

now a location used by camp groups in the summer months, and the derelict airport facility is boarded up and surrounded by fencing. Many of the islands in the Harbour and Sound were also used as base camps for convicts and Boer War prisoners sent to Bermuda to construct the Dockyard.

Today Hamilton is a prosperous city with a wealth of shops, businesses, and governmental buildings and a skyline that constantly changes to reflect the city's growth as an urban centre. The roads encircling the Harbour are some of the busiest roads in all of Bermuda, carrying more than 12,000 workers, or 40% of Bermuda's total working population, into the city (Corporation of Hamilton, 2005). Only recently has the City of Hamilton drafted plans to alter the appearance of the harbourfront, and the coastline, which, as stated before, has gone almost unchanged for two hundred years.

3.4.1. Implications and Recommendations

Hamilton has grown into a densely populated and developed city centre, which inevitably has led to increased pollution in Hamilton Harbour (Hayward et al., 1981). Oil and fluid leaks from ships, surface run-off of road contaminants such as oil from vehicles, sediment made by ships that clouds the Harbour waters, littering, and the use of antifouling paint on boats are just a few of numerous sources of pollution that have a negative effect on benthic communities in Hamilton Harbour. The main causes of most chemical pollution in aquatic systems such as Hamilton Harbour are urbanization, coastal development, and shipping traffic.

With debate open regarding the future of Hamilton's waterfront, it will be possible to create a more sustainable city design and review current sources of pollution with an aim of decreasing fouling of the Harbour. For example, it may be possible to

introduce a plan that requires less movement of ships once in the harbour, reducing sediment movement in the water column. Utilizing modern green technologies to power new developments in the city could reduce the need for energy produced by the oil burning power plant located outside Hamilton, decreasing air pollution in the vicinity, and supporting the increased energy expenditure of a rising commercial and residential population.

Some improvements have already been made in the Harbour. For example, the concentration of the anti-foulant chemical tributyl tin (TBT), in the Harbour has been reduced since a ban on its use (Connelly et al., 2001). Ships using the waterways and harbours of Bermuda are also prohibited from dumping waste such as sewage, garbage, and coal unless permission is granted to do so.

Relative to many other port cities in the world, Hamilton is not a source of high concentrations of, or particularly toxic pollution. However, Bermuda's small size necessitates proper resource and pollutant management. By understanding the environmental impacts of a growing city and how Hamilton has changed over the past two hundred years, it should be possible to plan to remedy current sources of pollution, and better manage resource use in the city for more sustainable growth.

3.5. Morgan's Point

Morgan's Point was originally not a point of land jutting into the Great Sound, but instead a group of islands called "The Brothers" (Figure 11). The circumference of each island was dominated by patch reefs, with small reefs found in the channels between the islands. Altogether, Hurd charted 1.08 ha of reef around the islands, and a further 15 ha of sandy flat scattered with patch reefs. The islands underwent land reclamation around

their perimeters to create what is now known as Morgan's Point, connected to the mainland of Southampton Parish by a man-made causeway.

The islands were converted into this state by the US government for use as a naval base for military ships and seaplanes. This occured at the same time that St. David's Island was commissioned to become the Kindley Field airbase. When the islands were joined together, the landmass increased in area from 0.192 km^2 to 0.279 km^2. The Savage survey from 1899 shows that there was a quarry on the western island, but no houses on either the western or the eastern island, implying that the construction of the naval base did not displace any local residents.

Some of the features of the Brothers Islands were retained in the conversion process (Figure 11). For example, the extension of land forming the northern rim of the inlet to the north of the point appears to have been constructed utilizing existing islets. The eastern point of Morgan's Point has also retained the morphology of the easternmost Brother Island.

While the naval base was in use, it was not uncommon to see soldiers with rifles lining the shoreline, cautioning mariner's to avoid docking (Robert Fisher, pers. comm.). Shipments of surplus goods to the soldiers stationed there often ended up being dumped into Southampton Pond (Al Demoura, pers. comm.), contributing to the use of that pond as dump (the pond is now completely infilled, and covered with a golf driving range (see section 3.7.2.)). The dumping of surplus goods did however provide locals in the area with many new clothing, food, and other household items (Al Demoura, pers. comm.).

Now a derelict site, Morgan's Point could be in many ways considered an ecological tragedy. When the soldiers left, the environmental damage done to the land

and nearshore habitats were not remediated. Derelict buildings and structures remain, as do large pieces of metal and machine parts, and other dangerous goods such as fuel, sewage, and chemicals. The reefs that were present around the Brothers Islands on Hurd's survey are nearly all gone, save for a small reef of 0.5 ha located south of the eastern most point of the Western Brother Island (Figure 11). Colonies of sea rods and branching hard corals are also found living on the rocks that border the foundation of the Point (personal observation). The extant flora is composed mainly of invasive species, with casuarinas dominating the landscape (personal observation).

However, one region of Morgan's Point shows ecological promise. On the north side of the land, a small inlet was made as a safe harbour for boats (Figure 11). Today the coastline of this man-made inlet is dominated by mangroves, and acts as a miniature estuary that provides habitat for herons, crustaceans, mollusks, and small fishes (personal observation). The mangroves, although found along most of the inlet coastline, are 6-8 feet in height, and must be young trees that grew after the base was abandoned in the early 1990's. Mangrove forests are efficient at cycling nutrients between coral reefs and seagrass meadows and are also critical habitats for juvenile reef fish, which eventually leave and live as adults out on the coral reefs. It is therefore possible that this inlet is acting as a nursery for commercial fish species. This small mangrove forest exemplifies that human perturbations may inadvertently benefit the environment, and that a small change in coastline formation can positively benefit the marine environment when marinas or small harbours are permitted to be constructed.

3.5.1. Implications and recommendations

In the near future, Morgan's Point may be re-developed in order to support a hotel and golf course development, and the mangrove forest may be negatively affected during the rumoured development process. As mangrove forests have declined in size and extent on Bermuda, mainly due to the infilling of many ponds and swamps (see section 3.7) and coastal development, this small loss of mangrove habitat should be avoided if possible. In contrast, it is recommended that instead of removing mangrove forest habitats, future coastline developments here and elsewhere on the island should attempt to include as much potential mangrove habitat as possible, since mangrove habitats such as inlets and estuaries provide protection from wave energy and storms, and help expedite sediment deposition. This slows coastal erosion, protecting sea walls and other coastal features. Since Morgan's Point is in an open basin, protection such as that offered by mangrove forests would help prevent damage or degradation that could occur to developments because of these factors.

3.6. Ireland Island and the Royal Naval Dockyard

The year 2009 marks Bermuda's 400th anniversary of settlement. Coincidentally, 2009 also marks the 200th anniversary of the Royal Naval Dockyard on Ireland Island, which was established in 1809. Bermuda has always been utilized as a strategic military base, as it lies between the two great powers of the United States and England. For this reason many fortifications are found scattered on the island, some dating from the time of settlement. The largest and most monumental fortification however, was the Royal Naval Dockyard.

In 1801, Thomas Hurd wrote about Bermuda's strategic potential to the British Admiralty, exclaiming that the islands "*appeared to be placed by Nature as a checque [sic] or guard to the whole Western Hemisphere and their surrounding shoals intended not only as a barrier against the encroachment of the Ocean but as a strong natural defense for the protection of its possessors against an invading enemy*". He mentions Bermuda as a good replacement for the ports in Halifax, as besides being accessible during all seasons, Bermuda was also less liable for attack because of its position, and could afford the same services of shipbuilding, repairing, and storage that could Halifax. When Hurd originally conducted his marine surveys, he proposed that a refitting basin be should be placed in Grassy Bay, which lies east of the northwestern island in Bermuda: Ireland Island (Various Writers, 1997). A letter from Captain Penrose (who was sent to Bermuda to determine the safety and defenses of the anchorages Hurd had discovered) to Admiral Murray in 1795 stressed the possibility of fortifying Ireland Island and Grassy Bay. Penrose wrote that Ireland Island was not highly populated, and would provide suitable land for construction of a garrison (Various Writers, 1997). Hurd surveyed Ireland Island as it was before it was established as a naval base (Figure 12).

In the 19th century, Ireland Island was seen as a strategic place for a military base because it is surrounded on every side by large expanses of treacherous reef except on the eastern side, where the safe anchorage of Grassy Bay is found. Ireland Island overlooks the Great Sound as well as the northern and western extents of the Bermuda reef platform (Figure 12).

In 1808, Vice Admiral Sir John Warren submitted a report for the creation of the Dockyard, which led to the acquisition of Ireland Island, and two smaller islands to the

southwest, Boaz and Watford, by the British government in 1809. Harrington Sound was also considered as a location for the base, as it was a sheltered harbour, and accessible only by the entrance through Flatt's Inlet. In the end however, the defensive position of Ireland Island made it a stronger candidate, even though the rock was tougher to work through, being composed of the hard stone that also created the Walsingham cave formations (Livingston, 1944). In 1809, the Royal Naval Lands, and the Dockyards on Ireland Island were established, and after many years of work, the main structures of the keep, the fortifications, the Commissioner's House, and the Casemates barracks, were completed by the mid 1800's.

Obviously, many of the changes to Ireland Island that can be seen since Hurd completed his survey are due to the construction of the Dockyard facilities. Many coastal features retain in a similar morphology to that which Hurd surveyed as the construction of the Dockyard appears to have utilized many natural features, possibly due to the difficulties of working with the hard limestone. For example, the boat slip found in the North Basin appears to have been formed from a small inlet, and the arm of the South Basin was built over a foundation of reef (Figure 12). The reefs surrounding the immediate coast of Ireland Island also do not appear to have been modified, perhaps because they formed a natural defense against attacking ships. The only break in this defense was a natural channel along the northwestern coast of Ireland Island, a narrow, winding channel leading to Hogfish Cut. Therefore, in 1896 the channel leading to the Dockyards was blocked by a decommissioned ship, the Vixen, off Daniel's Island, west of Somerset to prevent a breach in the defensive strategy of the Dockyards (Berg and Berg, 1990).

Ireland Island was also modified by excavating two cuts through the island. One cut, known as Cockburn's Cut, was made south of the Dockyard Proper (Figure 12) to inhibit enemy access to the Dockyard by land. By cutting at this location and placing a bridge, British soldiers stationed here would have had complete control over who gained access to the Dockyard Proper.

The second cut was made through the south end of the island into an enclosed marine pond called "The Lagoon". The Lagoon was enclosed during the time that the Dockyard was in use, but soon after it was realized that by enclosing the Lagoon, the water became stagnant, forming a breeding ground for disease carrying mosquitoes. Therefore, an opening was created through to the northern shore of Ireland Island, and another cut at the southern end of The Lagoon was re-opened with the gap bridged for the road located there.

Further investigation of The Lagoon presents the possibility that by enclosing the inlet, and by cutting through the western part of the lagoon, an ideal habitat was inadvertently created for the growth of a mangrove swamp. Presently in this lagoon, mangroves thrive along the entire coastline and a high abundance of propogules, or mangrove seedpods, dot the shallow waters. This area would not have supported this type of growth if it were not for the decision to enclose it, as there would be more wave energy entering the lagoon, hindering mangrove growth. As in the inlet of Morgan's Point, this anthropogenic disturbance has again inadvertently created a very healthy habitat for mangroves. As mentioned previously, since mangroves across Bermuda have suffered from loss of suitable habitat due to the infilling of many ponds and marshes, any extant mangrove habitats, or potential habitats, no matter how small, must be preserved.

Decommissioned in 1951, the Dockyard fell into a state of disrepair, due to neglect and damage from passing storms. In the 1980's when tourism was on the rise, Dockyard was revitalized, and the original buildings were restored to accommodate shops and local artisans. The keep area was also converted into the Bermuda Maritime Museum. A cruise ship pier was built in 1990, with a second pier completed in 2009, and as it can accommodate some of the larger post-Panamax ships that Hamilton and St. George's cannot, Dockyard currently receives frequent visits from cruise ships during the summer season.

3.6.1. Implications and recommendations

The Royal Naval Dockyard today is a site of national heritage, which showcases the island's relationship with Britain, and where archaeologists continue to discover remnants of Bermuda's military history. Unfortunately, the circumference of the Dockyard is now littered with garbage and construction waste, mostly sourced from the Sallyport waste facility. A sewage treatment plant along the north coast of the island, in the middle of Dockyard proper, was built in the 1990's. The treatment plant is used to handle the sewage produced by cruise ships visiting the Dockyard, as ships are prohibited from dumping sewage into Bermuda's waterways. The sewage is partially treated and macerated, and is disposed of through deep-bore holes through the limestone foundation. In Florida these bore-holes reach depths of more than 1000 ft, but in Bermuda many are 50 ft with some reaching only 150 ft, likely endangering near shore communities (Dr. Thaddeus Murdoch, pers. comm.). In the late 1990's, an artificial beach and snorkel park was constructed on the northeast tip of Ireland Island, which actually did little to enhance

the reef environment, as the dredging increased sediment flux on adjacent reefs (personal observation).

Hopefully in the future, the waste that litters the coastline will be cleaned up, and the delicate reef habitats surrounding the islands will be protected. Until recently the reefs appear to have been relatively unharmed.

3.7. Ponds and Wetlands

Bermuda's extant wetlands are diverse habitats, boasting many native and endemic species of plants and animals. They are represented as mainly brackish and marine features, and the few that are considered freshwater experience fluctuations in salinity due to the influx of seawater during exceedingly high tides or storm surge. Local wetlands are key habitats for migrating birds, and dozens of different species have been observed at several locations during migration season.

Bermuda's wetlands, marshes and ponds are only a modest representation of the features that were present two hundred years ago. Hurd's survey marks a remarkable 45 water features across the island totaling 169.69 ha. Presently, only 9 of these features remain in their original morphology, but 23 wetland features are found in Bermuda today (not counting concrete or lined ponds such as those in golf courses), comprising just 71.62 ha, a loss of 58% (Table 1).

There are many reasons why wetlands were infilled or reduced by such great extent. Some ponds were filled in to remove potential mosquito breeding grounds. In the earlier part of the 20th century, Bermuda was stricken with malaria and yellow-fever that were spread by marsh-breeding mosquitos. In many cases, ponds were filled in with trash, a cultural tradition begun by the early settlers and continued until the waste depot

was built in the 1960's. Depositing refuse into ponds was the most convenient way of removing waste, mainly because there was no manageable way of moving trash to one central location until automobiles were introduced in the 1940's, but this also removed a vector of disease by removing the mosquito breeding grounds at a low cost.

There were also physical reasons for infilling or controlling the extent of some pond features. Since many of Bermuda's wetlands are greatly influenced by tides, flooding was often an issue. This was the case in Pembroke Parish, where flooding events proved too unpredictable; leading to the decision to control the flow of water by building a canal system. As wetlands were not considered desirable neighbours, due to the distinctive odour the activity of bacteria within them produced, draining wetlands also increased the desirability of surrounding neighbourhoods.

Wetlands were also infilled to create productive land that could be used for agriculture. The soft bottom quality and constant inundantion of Bermuda’s wetlands meant that surrounding land was extremely fertile, excellent for agriculture, notably celery cultivation (Hayward et al., 1981). The eastern border of Warwick Pond was filled for a celery farm, and a now extinct pond in Southampton was famed for the high quality celery grown around it (Al Demoura, pers. comm.). Unfortunately, the soft peat that formed such fertile land was in many cases impossible to build upon. Although some wetlands were reclaimed to support urban growth, especially in Pembroke, where the marsh complex infringed on the north side of the City of Hamilton, not all these attempts were successful, as no amount of infill could stabilize the ground enough for construction.

The following sections expand on the history and morphology of pond and wetland features found in each Parish, beginning at the west end. This study aimed to determine whether or not there are opportunities for wetland restoration, or potential for the development of new wetlands, such as with the mangrove habitats at Morgan's Point and on Ireland Island. The size and location of ponds that Hurd surveyed, as well as the natural features remaining today, are summarized in Table 1 along with changes in wetland area. Figure 13 depicts the wetlands present on Hurd's survey, and Figure 14 depicts these wetlands relative to the 1997 aerial photomosaic, with notes referring to modification or destruction of wetland features. Wetlands present on the Hurd survey but not on modern aerials were given names by the author, which are shown in Figure 13 and are distinguished in the text by apostrophes.

3.7.1. Sandy's Parish

In the westernmost parish of the Island, Sandy's Parish, there are no wetlands marked on Hurd's survey. Presently however, there are two ponds, both of which rest on marshy substrate adjacent to Somerset Long Bay. Upon closer inspection, Somerset Long Bay today appears to have gained landmass in the mouth of the basin since 1798, which is the opposite of what would have been thought to occur naturally due to erosion and sea-level rise. Hurd's survey shows a long sloping beach that today is stable ground. The shoreline likely accreted seawards in the past two hundred years due to the presence of a coastal mangrove forest that is no longer there (Teddy Tucker, pers. comm.). Sediment deposition mediated by the mangrove swamp would have created a stable coastline and led to gradual shoreline accretion.

This answers the question of how the shoreline changed, but neglects to answer the question of how the ponds formed. The northern pond, named Pitman's Pond, is an artifical feature, dredged by the man for whom the pond is named for, who wanted to create a small private harbour. He was declined permission to cut the pond through to the sea, and therefore left it as a pond feature (Teddy Tucker, pers. comm.). In the last decade, the National Trust purchased this pond during the "Buy Back Bermuda" campaign.

The original southern pond was filled as a garbage dump and restored by dredging. This pond was non-prominent swamp feature prior to being filled, and was often dry except during periods of very high tide (Teddy Tucker, pers. comm.). The author's hypothesis regarding the original formation of the southern pond here is that it formed in a similar fashion to the ponds found in extant Pembroke Marsh. The mangrove swamp may have been cleared away and in filled, to remove possible mosquito breeding grounds. If this was the case, the filling of the swamp may have simply compressed the peat, causing upwelling of underground water into new pond habitats. When new ponds were accidentally created this way, residents probably resorted to dumping garbage into the ponds to fill the ponds, as in other wetlands around the island (although this was not accomplished in Pembroke Marsh, as the area was too large, and there were insufficient amounts of in fill available). As the pond was used as a dumping ground for trash and later restored, it must have been dredged deeper into the peat marsh than it was naturally, creating a larger, deeper pond than the original.

Naturalists restored these ponds recently to what was considered their natural state, but they are probably habitats that are truly anthropogenic in origin.

3.7.2. Southampton Parish

In Southampton, six ponds are marked clearly on the Hurd map. In the western part of the parish, there were four pond features. Evan's Bay Pond is the first pond found when traveling easterly, and is named for the bay to which it lies adjacent. Further east, Hurd marks a large (4.26 ha) water feature, "Southampton Pond", which is centrally located between the north and south shore, and is found southwest of Buck Island. "Southampton Pond" is neighboured to the east by a smaller feature of 0.139 ha: "East Southampton Pond". Continuing eastwards, Seymour's Pond is found where Middle Road meets South Road. In the eastern part of the parish, approaching the border with Warwick, two more ponds were found parallel to the coastline adjacent to Horseshoe Bay. "Horseshoe Pond" stretched from Port Royal Cove eastwards to where Eastdale Lane presently runs. "East Horseshoe Pond" was a smaller feature found approximately half way between Horseshoe Bay and Chaplin Bay.

Evan's Bay Pond and Seymours Pond remain, while "Southampton Pond" has been in filled and replaced by industrial buildings and a golf driving range. Previously, this pond was a productive saltwater marsh, whose fertile border was used for agriculture, specifically a celery farm. The pond was also neighboured by a cow pasture, and bulrushes and other plants from the pond were used for hay and bedding for the animals (Al Demoura, pers. comm.). When Americans occupied Morgan's Point during the 1940's, the marsh was used primarily as a garbage dump, for surplus goods and provisions acquired by the base. For residents in this area, the dump actually provided many necessities: food, clothing, and other goods that were unused and disposed of by the soldiers. Canals were built to drain the marshland, and it was then in-filled with

sediment, and covered with grass. A golf driving range is currently located there. As little as 6-10 inches of soil cover the former dumpsite, and in a heavy rain, the field still floods (Al Demoura, pers. comm.).

The two features adjacent to Horseshoe Bay are now encompassed by South Shore Park, which runs from Port Royal Cove to Warwick Long Bay. The pond features are no longer present; however the soft ground does shape a small valley where the ponds were located. The area is dominated by scrubland leading to the sandy shoreline. The wetland is easily seen from the public parking lot of Horseshoe Bay Beach. Adjacent to the walkway to the beach one can also see a drainage channel leading into the wetland. The close proximity of these two ponds to the ocean and the high rates of erosion of the south shore coast likely contributed to natural drainage of the ponds.

3.7.3. Warwick Parish

When Hurd surveyed Bermuda, there were three pond features in Warwick Parish. All save for Warwick Pond has now disappeared.

The smallest pond feature in the parish, "South Warwick Pond", was adjacent to the easternmost end of Warwick Long Bay Beach near the junction of what is now South Road and Warwick Lane. This small wetland feature has been built over by residential developments, but the fertile soil has also supported the development of several agricultural fields in the area.

North of "South Warwick Pond" is where "West Warwick Pond" is found on Hurd's survey. The pond was three times the size of Warwick Pond, and if present today would reach from Greendale Lane in the west to Khyber Pass in the east. A few remnants of this pond remain; the most prominent of these being Jack's Pond, which

forms part of Higg's Nature Reserve, restored by the Bermuda National Trust and opened in 2008. The land here is low-lying and soft, but was in filled as a garbage dump and developed to support commercial structures, a post office, and a playing field. The Railway Trail nature trail runs along the south border of the former wetland.

To the east of "West Warwick Pond" on Hurd's survey is Warwick Pond, the only extant pond feature in Warwick, and Bermuda's second largest freshwater pond feature after Spittal Pond (Thomas, 2004). The eastern tip of the pond has been reclaimed as agricultural land, reducing the size of the pond by 0.26 ha, and the pond, a Bermuda National Trust nature reserve, is surrounded by woodland.

3.7.4. Paget Parish

Paget Parish is shown to only have two ponds on the Hurd map. One is at the base of Crow Lane, "Crow Lane Pond", and is now covered by a guest house and boat club.

The other is Paget Marsh, obtained by the Bermuda National Trust and Bermuda Audubon Society in 1965 for protection. The marsh was restored to the Bermuda Palmetto swamp it was in pre-colonial times (Thomas, 2004) by returning populations of native and endemic flora that had been out-competed by introduced populations of shrubs and small trees since the 1600s (Thomas, 2004). In the center of the marsh, a small pond has been restored from use as a garbage dump, and is now nearly completely overtaken by mangrove trees. Paget Marsh is now one of the true natural examples of how Bermuda's wetland biodiversity appeared before settlement.

3.7.5. Pembroke Parish

During the 1700's, Pembroke Parish contained more wetland than any other, totaling 37.2 ha in area. This network of wetland covered area from the estuary in Mill Creek, and through five wetland features to the easternmost wetland feature. The land occupied by wetland on Hurd's survey borders present day Marsh Folly Road to the northeast. The southern border would have ended at what is now the north side of the City of Hamilton, edging along Canal Street and North Road. Excess water that drained from the larger eastern features created a freshwater stream that ran to Mill Creek (Thomas, 2004), where there was a large, dense, mangrove swamp (Teddy Tucker, pers. comm.; Thomas, 2004). Coring of the peat layer in Pembroke Marsh has shown that before humans arrived on the island, it consisted of a dense cedar marsh, though later descriptions of the region suggest trees were sparse throughout the wetlands (Thomas, 2004). The wetland system was also home to two now extinct endemic gastropod species (Thomas, 2004).

Currently, the Pembroke Marsh complex is an extreme paradigm of wetland degradation in Bermuda. What was once a network of freshwater and marine habitats consisting of marshland, a freshwater stream, and the Mill Creek estuary, is now represented by a drainage canal, and two pond features in the east. In place of the marshes are now stretches of reclaimed land made into residential plots, industrial land, and a waste depot, which is adjacent to the extant pond and nature reserve.

The canal system was built in 1837, when Governor Lefroy drained the Pembroke Marsh due to constant flooding into neighbouring regions, which were quickly being developed. A sluice gate was built at the western end to prevent the entry of salt water,

but allow controlled draining of freshwater from the system. Although this was an engineering success, the attempt to extend the canal through to the eastern marsh in 1840 did not perform as well, and therefore has created many problems throughout the system.

The easternmost marsh comprises a region known as Marsh Folly that was never successfully reclaimed for land. Since other wetlands of the Pembroke Marsh complex were in filled successfully, attempts were made to achieve the same ambition in the eastern marsh. However, the marsh here was very old, which led to the creation of a deep peat layer. Efforts to infill the marsh simply compressed the peat like sponge full of water, creating the pond features that are present here today.

Since the reclamation of this marsh failed, it became a prime candidate for a dumping ground following the ban on dumping waste into wetlands. By 1970, all of Bermuda's refuse was deposited here, and the dump was used until as recently as 1994. The dump was covered in a layer of sediment, but toxins and pollutants continue to drain into the canal and marshlands, degrading the entire downstream watershed from the dumpsite (Thomas, 2004).

Considering the environmental value of intact wetlands such as Paget Marsh, this brackish environment would no doubt have been an important habitat for many native migratory bird species, aquatic animals, and endemic flora such as the palmetto and cedar. Although there is no possibility of returning the region to it's full former glory, the northern part of the canal has retained relatively high biodiversity, giving one hope that if downstream communities become less polluted and are cleaned up, re-colonization of lost species may occur throughout the canal system.

3.7.6. Devonshire Parish

To the east of Pembroke lies Devonshire Parish, once known as Brackish Pond for the reason that it was dominated by the marshland of that name. Like Pembroke Marsh, Brackish Pond was dominated by Bermuda Cedar trees, until 1914 when a fire engulfed many of them (Thomas, 2004). The symbolization used on Hurd's survey suggests that what was called Brackish Pond, but now called Devonshire Marsh, was two large pond features, with a small separating margin of area marked as marshland.

Today, Devonshire Marsh contains a number of ditch ponds, which have been constructed to aid drainage of the marsh and contain the highest diversity of freshwater life on the island, so conversely to Hurd's survey the majority of the area is now marshland dominated by grasses and shrubs instead of pond (personal observation). This marshland still encompasses near to its former area, bordering Vesey Street and Parson's Lane (both of which occur on the Hurd map) to the north, Middle Road to the south, and Orange Valley Road to the west. Much of the edge of the wetland has been reclaimed for industrial, recreational, or agricultural purposes, but a 10 acre section has been designated to two nature reserves, Firefly Nature Reserve and Freer Cox Nature Reserve. Land reclamation and drainage led to a decrease in pond area from what was charted by Hurd.

Besides Brackish Pond, Devonshire also houses some remnants of other wetland features that appear on the Hurd survey. Directly to the north of Hungry Bay, Hurd's map shows a wetland about 50 m wide at its widest point and 500 m long, stretching from where present day Kent Avenue runs. Few buildings have been erected on top of the former marshland, as the ground is quite soft and susceptible to flooding after a rainstorm. On the western edge of the former wetland, there is a drainage channel

leading from under the ground into the wooded area adjacent to Hungry Bay (Camden Marsh).

Hungry Bay is shown on Hurd's survey as being more enclosed and protected than it is now, as the severity of recent hurricane events have caused a great amount of coastal erosion in the bay, cutting an island at the western tip of the southern land projection. Hurd also marks the Hungry Bay mangrove swamp as smaller in area than it is presently. One would assume this is due to growth of the swamp over the past 200 years, but there is also evidence to suggest that a mangrove dieback occurred a few hundred years ago due to expedited sea-level rise. Mangrove peat is very sensitive to sea-level changes, and a study by Ellison (1993) determined that there was a correlation between peat density at Hungry Bay and the change in sea-level. The results of the study insinuate that if mangrove peat cannot accumulate enough to accommodate a rise in sea-level, then the mangroves are liable to die back (Ellison et al., 1993). With rising sea-level predicted for the next century, it is possible that another greater die back will occur, possibly decimating the mangrove population of Bermuda, including the distinctive forest in Hungry Bay. As the abundance of mangrove swamp has already decreased significantly from the amount present prior to the degradation of Bermuda's wetlands, if attempts are not made now to preserve these habitats, they may well disappear altogether.

Further east of the Hungry Bay Pond, on the border between Devonshire and Smith's Parish, there is another large wetland near Collector's Hill mapped on Hurd's survey ("Collector's Hill Wetland"). This water feature is now represented by Cloverdale Pond, and the two pond features present in the E.T. Gibbons Nature Reserve located to the west of the former wetland, just north of Devonshire Fort. The original

wetland was 900 m long by 110 m at its widest point, covering an area of 5.36 ha. With nearly twice the area of Spittal Pond, and a similarly unique coastline, it would likely have supported an astounding diversity of life. The wetland is also charted on the Savage survey of 1899 as marshland surrounding one larger pond feature, Cloverdale Pond. Cloverdale Pond is still the largest remaining feature of that wetland present today, but had to be dredged out after being used as a garbage dump (Hayward et al., 1981). The parkland surrounding these features is low lying and the ground is soft, indicating the location of the wetland. A grocery store, several restaurants, residential lots, and agricultural land have replaced much of this presumably once distinct habitat.

3.7.7. Smith's Parish

Crossing over into Smith's Parish brings us to the Spittal Pond nature reserve. This pond is considered Bermuda's largest freshwater feature. However, technically its proximity to the sea causes variations in salinity due to salt spray from wave action. Spittal Pond is a popular nature trail where it is possible to see a glimpse of not only Bermuda's geological past by examining the fossilized corals and leaves embedded in the rocky surfaces, but also Bermudian history. Spittal Pond is well known for being the home of the rock where a Spanish or possibly Portugese sailor carved his initials and the date he arrived there, 1543, the earliest known visitor.

Hurd's survey shows Spittal Pond as one large water feature, but Spittal Pond today actually consists of two ponds, one larger natural feature, and a smaller manmade pond to the south called the Bird Pond (an excellent spot to view herons and other waterfowl). Prior to its restoration as a nature reserve, Spittal Pond had many uses, from

agriculture to rifle practice (on the Savage survey the western portion of the reserve is marked as a shooting range).

3.7.8. Hamilton Parish

The next parish in an easterly direction is Hamilton, where some of the largest wetland features in present-day Bermuda are found. At the southern end of Hamilton Parish, south of Harrington Sound, are Mangrove Lake, Trott's Pond, and many other smaller water features. Traveling counter clockwise around Harrington Sound, one comes across the sinkhole pond formations that form the Walsingham Nature Reserve. North of Walsingham, there is a wetland adjacent to Bailey's Bay shown on the Hurd survey but no longer present. On the north side of Harrington Sound, one encounters another sinkhole pond, Davis Pond, and 0.3 km west, two wetlands adjacent to Shelly Bay.

Mangrove Lake, the largest marine lake in Bermuda, appears to have retained its original morphology, but the modern aerials seem to show it as "compressed" from the east and west compared to Hurd's survey (a loss in area of 4.25 ha). This is because the mangrove swamp present here increased in density over the last two hundred years. From 1900 to 1980, Mangrove Lake decreased in area by 1.13 ha (Hayward et al., 1981) due to increases in the density of peat, so if that figure is extrapolated over two hundred years, enough peat would have accumulated to offset this change in area. According to Hurd's survey, Mangrove Lake was open to the Atlantic Ocean on its southern border. The darker yellow colour Hurd gives the sand suggests that this waterway was enclosed but inundated during storms or high tides. This presents more evidence to the hypothesis that Diamondback Terrapins (*Malaclemys terrapin*), which are native to the southern US,

are native to Bermuda. Before this discovery, Mangrove Lake was not considered as an original habitat for these reptiles because it is an enclosed water feature, although it is one of only two ponds in which they are found (Mark Outerbridge, pers. comm.). The observation that the lake was previously open to the ocean supports the hypothesis that the terrapins originally settled in the brackish environment there, as they would not have had to traverse land to reach the mangrove swamp in which they inhabit. The sandbar between the lake and ocean would also be an ideal nesting habitat for the terrapins; a habitat that has been substituted by sand traps on the Mid-Ocean Golf course, which have likely inadvertently led to the persistence of this native reptile in Mangrove Lake and Trott's Pond.

To the east of Mangrove Lake, Trott's Pond is the only other local pond supporting a population of native Diamondback Terrapins, and is another water hazard on the Mid-Ocean Golf Course. Trott's Pond is larger on Hurd's survey by 2.93 ha, mostly due to the presence of two peninsulas on the southern boundary, which have been grown over by mangrove trees. The eastern peninsula has also been reduced in size due to the construction of South Road.

Golf course water features have not yet been considered in this report, however, a trail of three wetland features north of Trott's Pond that appear on the Hurd survey have been modified or restored as water features on the Mid-Ocean Golf Course. The course also features some artificial ponds, but these are beyond the scope of this report. The natural ponds are the only natural golf course ponds, with regards to Hurd's survey, on the island.

West of Mangrove Lake (technically in Smith's Parish but included here), Hurd mapped four smaller water features that are not present on current maps, having been infilled and replaced with residential zones and playing fields. The most northern of the four ("Mangrove Lake West Pond A")would be found at the junction of Harrington Sound Road and Rocky Ridge Road. The pond just south of this at the corner of Somersall Road and Harrington Sound Road, Angel's Grotto North Pond (Hayward et al., 1981) is now a large playing field. Heading southeast, the third pond ("C") would have been located in what is now a wooded area bordered by houses on Somersall Road, Somersall Lane, South Road, and South Breakers Road. The last pond ("D") in the chain is hidden below the cricket pitch of the Cleveland Cricket Club.

The distinct habitats of Walsingham Nature Reserve are found northeast of Trott's Pond, towards Bailey's Bay. The reserve is unique for the network of underwater caves contained within, and for the geological and historical value of the limestone formations that shape the region. The ponds found within this nature reserve are sinkholes, formed by the collapse of smaller caves that then filled up with seawater. These ponds are very high in marine animal diversity, boasting a wide variety of sponges as well as native algaes (Thomas, 2004), as well as larger vertebrates such as sea turtles, which travel into the pond using the vast cave system.

Walsingham Pond appears on the Hurd map as two distinct features, 949 m^2 and 3070 m^2 in area, but on modern maps, it is a large 7900 m^2 pond, neighboured by a much smaller 264 m^2 pond. I hypothesize that this was an error on Hurd's survey, as later maps, including the Savage survey of 1899, show Walsingham Pond and West Walsingham Pond in the same configuration as they are presently in. The error might

have been due to the complexity of the formations at Walsingham, as the coastline of Walsingham Pond on Hurd's survey is featureless and smooth, and may have been greatly generalized. Likewise, the size of the pond may have been underestimated due to the thickets of mangroves and other coastal flora surrounding the pond.

Three smaller ponds appear to the west of Walsingham Pond on Hurd's survey, all of which remain intact on the present day aerials. Deep Blue, to the north of Walsingham Pond, also appears as it did on Hurd's survey.

North of Walsingham, Hurd's map shows a 3899 m^2 wetland east of Bailey's Bay. This feature was a well-developed mangrove swamp, until it was destroyed during the past 60 years when other ponds were infilled for fears of creating mosquito breeding grounds (Hayward et al., 1981). The wetland is now filled with native species, such as Bermudian palmettos and red mangroves, as well as fast growing cane grass, and casuarinas. The former wetland is part of Wilkinson Memorial Park, adjacent to a portion of the railway trail leading to Coney Island, and has great potential to be restored back into a mangrove and palmetto swamp.

West of these wetland features on the north side of Harrington Sound, Davis Pond is found to be present on both the Hurd map and modern maps. Davis Pond is a sinkhole, formed by a collapsed cave, and is a striking feature hidden away behind the brush bordering the Shelly Bay Marketplace. The pond is a natural feature surrounded by red mangroves, buttonwood, and casuarinas, and is present on both the Savage survey, and the 1940's aerial photos. Standing at the edge of the pond, schools of endemic Bream (*Diplodus bermudensis)* and Yellowfin Mojarra (*Gerres cinereus)* are visible in the

shallows. Davis Pond is likely connected through underwater caves to the north shore for these fish to have migrated here.

North East of Flatt's Village, 0.3 km west of Davis Pond and adjacent to Shelly Bay, Hurd's survey marks two wetlands: one northeast of Shelly Bay, and one east. The north wetland was used as a garbage dump, but was reclaimed by the National Trust, and is now encompassed by the Shelly Bay Nature Reserve. It is a dense red mangrove marsh, which is inundated by tides. The eastern wetland is mainly gone, except for a few low-lying areas comprised of marsh grasses and shrubs. If present today, the eastern wetland would stretch from the playground at Shelly Bay Beach, and across North Shore Road, curving to the southwest. There is a stand of black mangroves adjacent to the playground where the northern edge of the pond would have been. Across North Shore Road, behind the bus shelter that lies directly across from the Shelly Bay beach parking lot, there is also a small area of marshland covered by red mangroves.

3.7.9. St. George's Parish

In St. George's Parish, there are few natural ponds corresponding to the 1700's. Hurd's survey shows five wetland features across the Parish: Coney Island Pond, Lover's Lake on St. George's Island, Coot Pond near Fort St. Catherine's, Paget Island Pond, and St. David's Marsh on St. David's Island.

Before the Causeway connecting the mainland to Longbird Island and the bridge connecting Longbird Island to St. George's Island were built, Coney Island was the main thoroughfare for people traveling from St. George's to the mainland, by way of a ferry that traversed from Ferry Point on St. George's Island. On Hurd's survey, the pond appears to be enclosed by land as it is a dark blue colour similar to other pond features on

the map, but a large crease in the map makes it difficult to tell conclusively if this is so. Coney Island itself appears to be connected to the mainland by two bridges, linking an islet in between. The Bermuda Railway passed through Coney Island when it ran between 1932 and 1948, crossing the northern rim of the pond and over Ferry Reach. Presently, the pond is a uniform round shape, rather than pear shaped as on the Hurd map. The western border of the pond is crossed by the former railway tracks, so it is likely that the morphology of the pond and inlet were altered during this process.

Lover's Lake, in the Ferry Reach nature reserve at the western end of St. George's Island, is an inland saltwater pond fringed with black mangrove trees. It is the same morphology as it is on Hurd's map, as well as both the Savage survey and the 1940's aerial. Lover's Lake was a breeding ground for mosquitoes that carried yellow-fever, a disease which caused the deaths of 230 soldiers stationed at nearby Martello Tower in the 1850's.

Coot Pond is adjacent to Tobacco Bay at the east end of St. George's Island. On Hurd's survey, Coot Pond is fully enclosed by land, but the Savage survey of 1899 and all subsequent surveys and aerials show Coot Pond to be open to the northwest. There is little chance Hurd was mistaken, as he does not mark the feature or the land around it, ambiguously. Coot Pond is a karst feature, shaped by the dissolution of the underlying layer of limestone, so it is likely that significant erosion opened the bay. The opening was also dredged so that boats could moor in Coot Pond, which is very shallow, but sheltered.

On St. David's Island, there was a large pond feature marked on its south side, towards the island's center. Hurd distinguishes it as marshland that is connected to the

sea by a sandy stretch, as Mangrove Lake was. It is likely that this marsh would be under the influence of the tides, and would have a fresh influx of seawater throughout after a high tide. This marsh was destroyed when land was reclaimed for the airport, as in the 1940's aerial image this marsh was evidently still present right before the airport was constructed. It rests hidden under the main runway of the airfield, almost exactly where planes touch down on the runway when landing from the east.

There was also a small pond on Paget Island, which remains today as part of Paget Island Park, adjacent to Fort Cunningham. The pond is no longer enclosed however, as a small canal leading into the pond was created so small boats could moor there (Dr. Thaddeus Murdoch, pers. comm.).

There is another pond in St. George's that is present on modern maps, but not found in any form on the Hurd survey. Bartram's Pond, in the Stoke's Point Nature Reserve, St. George's is today perceived as a restored wetland that was previously filled with refuse. However, there is little evidence to validate this claim. The pond does not appear on the Savage survey or the 1940 aerial photos. Bartram's Pond is locally known as a pond that was restored from use as a dump, but in reality this is a man-made pond (Outerbridge et al. 2007). The ground was likely low lying and soft, and dug for use as a garbage dump. Being in close proximity to the sea, it probably filled with sea-water after it was dredged deeper in 1983.

3.7.10. Implications and Recommendations

Through the examination of how the distribution and morphology of Bermuda's wetlands have changed over the past two hundred years, it is possible to imagine the consequences of a dramatic loss of wetlands in Bermuda, which were never abundant

even historically. It is critical to understand the cultural and social issues that led to the disappearance of many of these habitats in order to conserve and protect them. Though some of Bermuda's wetlands were removed for reasons concerning human health, others were used as garbage dumps (granted this would have been the simplest solution before the arrival of automobiles to the island), or were drained to make room for urban expansion and development. Despite restoration efforts, 33% of Bermuda's wetlands still remain to be mitigated. This study presents several suggestions for mitigating this loss, presenting several examples from our findings.

In areas where wetlands have been built over, restoration is an unrealistic goal. However, remnants of some wetlands remain in national parkland, which would be possible to restore. A wetland of this nature is Bailey's Bay Pond, which was a productive mangrove swamp prior to being in filled in the 1940's. It is now overgrown with invasive plant species. Some other extinct wetlands are under open green space that is privately owned, such as playing fields, golf courses, and residential gardens. Many of the restored wetlands in Bermuda were privately owned, prior to being purchased during public campaigns known as "Buy Back Bermuda" in which the Bermuda National Trust and the Bermuda Audubon Society purchased these lots and initiated restoration. These undeveloped grassy regions that sit atop historic wetlands are primary candidates for restoration. Most of these wetlands are covered by very little sediment (less than 15 cm), and are inundated during periods of heavy rain. These wetlands include Southampton Pond, Hungry Bay Pond, and sections of Pembroke Marsh.

Another block to habitat restoration is wetlands which are highly polluted, hindering restoration. The region most affected by this issue is the Pembroke Marsh

complex, now composed of a polluted drainage canal and two pond features. The most pressing issue in this region is the proximity of the canal to nearby houses, which have septic tanks adjacent to the canal, and could possibly leach sewage into the water. These houses could be placed onto a sewer grid that connected to that of the nearby City of Hamilton, in order to decrease pollution, and facilitate natural habitat restoration.

Finally, another way to mitigate wetland loss would be to create new wetland habitat. The great success of the two inadvertently created mangrove forests permits the possibility for developers to incorporate these habitats into their developments, to encourage growth of mangrove trees. This could be accomplished through the creation of small inlets in the shoreline, or by creating docks and marinas that decrease water turbulence and shelter bays, so mangrove growth along shorelines can be promoted.

It is impossible to know precisely what biota was lost or what effects the loss of these environments has truly cost the island in biodiversity. However, from the effects that we are aware of, such as the extinction of endemic species, the loss of vital coastline and marsh habitat, and the pollution present in the current watersheds, it is evident that Bermuda must ensure remaining areas are protected under legislation and action as protected area, while invoking more research on restoring and conserving these distinct habitats. Bermuda's various environmental groups and researchers have embarked on some immense restoration projects, and have been able to return many of Bermuda's wetlands back to their original state, or akin to it, but past and future efforts will not succeed unless there is cooperation among all island residents to keep the wetlands pristine.

4.0. Conclusions

This study has looked at Hurd's survey at a relatively superficial level, evaluating what has changed based on what appears on multiple map sources. However, there is still much that can be learned from examination of the 200 yr old charts. For example, having mapped the depth points, it would be highly beneficial for benthic ecologists, oceanographers, and meteorologists to model the bathymetry of the Platform from the depth points digitized during this study, as depth information available today is at a much lower resolution than that which Hurd charted. The information provided on current flow would also help supplement what is known about the physical oceanography of the Bermuda Platform. Other biological indices of change would also be fascinating to explore to provide evidence that would support what Hurd charted. For example, exploring core samples for peat to determine locations of mangrove swamps, coring near shore reefs to see how ship channel construction affected reef composition, or relating sea-level rise and erosion rates to miniscule changes in the coastline.

Regarding Bermuda's ponds and wetlands, it should be possible to better manage and restore both present and potential wetland habitats by using information gathered from Hurd's survey. For example, Davis Pond is an extraordinary natural feature that should not be overlooked by conservationists, as it could be explored in greater detail to determine more about the ecology of this habitat, to help better understand tidal marine ponds in Bermuda as a whole. An opportunity for restoration is also present in the overgrown and reclaimed swamp east of Bailey's Bay. Though destroyed in the last five decades, it still has the potential to again be restored to a vibrant wetland. Bermuda's mangroves also have potential to be restored because the extent of mangrove forests has

greatly declined due to habitat loss over the past two centuries. These critical fish habitats could be remediated in the future with minimal effort. Coastal developers should take advantage of the natural protection these maritime forests afford, and incorporate suitable mangrove habitat throughout the development process. Increasing the extent of mangrove forest could also help compensate for the recent loss of seagrass meadows across the Platform (Murdoch et al., 2007), as these habitats provide reciprocal benefits such as nutrient cycling, and habitats for juvenile fish such as groupers and snappers as well as macroinvertebrates such as bivalves and lobsters. Previously, seagrass meadows compensated for the reduced extent of mangrove forests across the island, but as both habitats are now experiencing declines, it is pertinent to preserve both habitats, and increase their extent. Since Bermuda's coastline is constantly undergoing development, integrating mangrove forests into the coastline is an ideal solution for both developers and conservationists. Morgan's Point and the Ireland Island Lagoon are paradigms for how successful a mangrove forest can be in an anthropogenically-altered environment.

As discussed previously, Bermuda's reefs have enjoyed many advantages over Caribbean reefs, insinuating that reefs here are worthy of strong protection, enforcement and legislation to maintain the resiliency of the platform. However, human activities such as dredging place Bermuda's reefs at risk, no matter what their status is compared to global reef systems. Studying Hurd's survey reveals that previous physical degradation of reefs in Castle Harbour was far greater than previously estimated. This report also shows that the placement of ship channels could have almost entirely avoided damage to any reefs, had their conservation been part of the overall channel development

strategy. As discussed earlier, small-scale degradation of the Platform, such as that which occurs for channel creation, actually translates to large-scale degradation of the reefs, as the effects of suspended sediments and effluents from ships during travel across the lagoon can spread to far reaches of the platform.

The most important lesson arising from evaluating Hurd's survey remains that studying the past can reveal insight into ecosystems that would be impossible if only studying the habitats that are present today. Hurd's survey has helped to reveal what features were natural during that period. By understanding how the marine habitats of Bermuda have changed over the past two hundred years, stakeholders and policy makers can develop better strategies for conservation and restoration. One shouldn't regret or forget the past, but one should learn about the past and use this knowledge to guide how one's activites in the present will affect the future for all of us.

TABLES

Table 1. Area of pond and wetland features present on the Hurd survey and the area of the 1997 representatives. N/E denotes a non-existent feature on that survey.

Wetland name	Area in 1797 (ha)	Area in 1997 (ha)	Change in area (ha)
Evan's Bay Pond	0.80	0.71	-0.09
Southampton Pond	4.26	N/E	4.26
East Southampton Pond	0.14	N/E	0.14
Seymour's Pond	0.181	0.14	-0.041
Horseshoe Pond	2.15	N/E	2.15
East Horseshoe Pond	0.12	N/E	0.12
South Warwick Pond	0.42	N/E	0.42
Warwick Pond	1.55	1.28	-0.27
West Warwick Pond	6.06	N/E	6.06
Paget Marsh	7.13	10.1	2.97
Crow Lane Pond	1.09	N/E	1.09
Pembroke Marsh Complex	37.20	1.36	-35.84
(A)	0.27	N/E	0.27
(B)	5.18	N/E	5.18
(C)	0.65	N/E	0.65
(D)	7.41	N/E	7.41
(E)	23.70	1.36	-22.34
Brackish Pond West and East	30.80	35.60	4.8
Hungry Bay Pond	1.44	N/E	1.44
Collector's Hill Pond*	5.36	0.26	-5.1
Spittal Pond	3.58	4.07	0.49
Mangrove Lake	14.0	9.75	-4.25
West Mangrove Lake Pond A	0.40	N/E	0.4
Angel's Grotto North Pond	0.58	N/E	0.58
West Mangrove Lake Pond C	0.24	N/E	0.24
West Mangrove Lake Pond D	0.24	N/E	0.24
Mid Ocean South Pond	0.45	0.49	0.04
Trott's Pond	5.87	2.94	-2.93
Mid Ocean East Pond	0.36	0.33	-0.03
Mid Ocean North Pond	0.77	0.74	-0.03
Shelly Bay Pond North	1.05	N/E	1.05
Shelly Bay Pond South	0.94	N/E	0.94
Davis Pond	0.092	0.18	0.088
Walsingham Pond	0.31	0.79	0.48
Walsingham Pond West	0.095	0.03	-0.065
Walsingham Top Pond	0.10	(joined) 0.297	+0.087
Walsingham Middle Pond	0.11		
Walsingham Bottom Pond	0.06	0.03	-0.03
Deep Blue (Walsingham)	0.16	0.05	-0.11
Bailey's Bay Pond	0.39	N/E	0.39
Coney Island Pond	0.50	0.46	-0.04
Lover's Lake	0.43	0.38	-0.05
Coot Pond**	0.91	N/E	0.91
Paget Island Pond	0.19	0.27	0.08
St. David's Marsh	1.95	N/E	1.95
TOTALS	**169.69**	**71.62**	**-98.07**

FIGURES

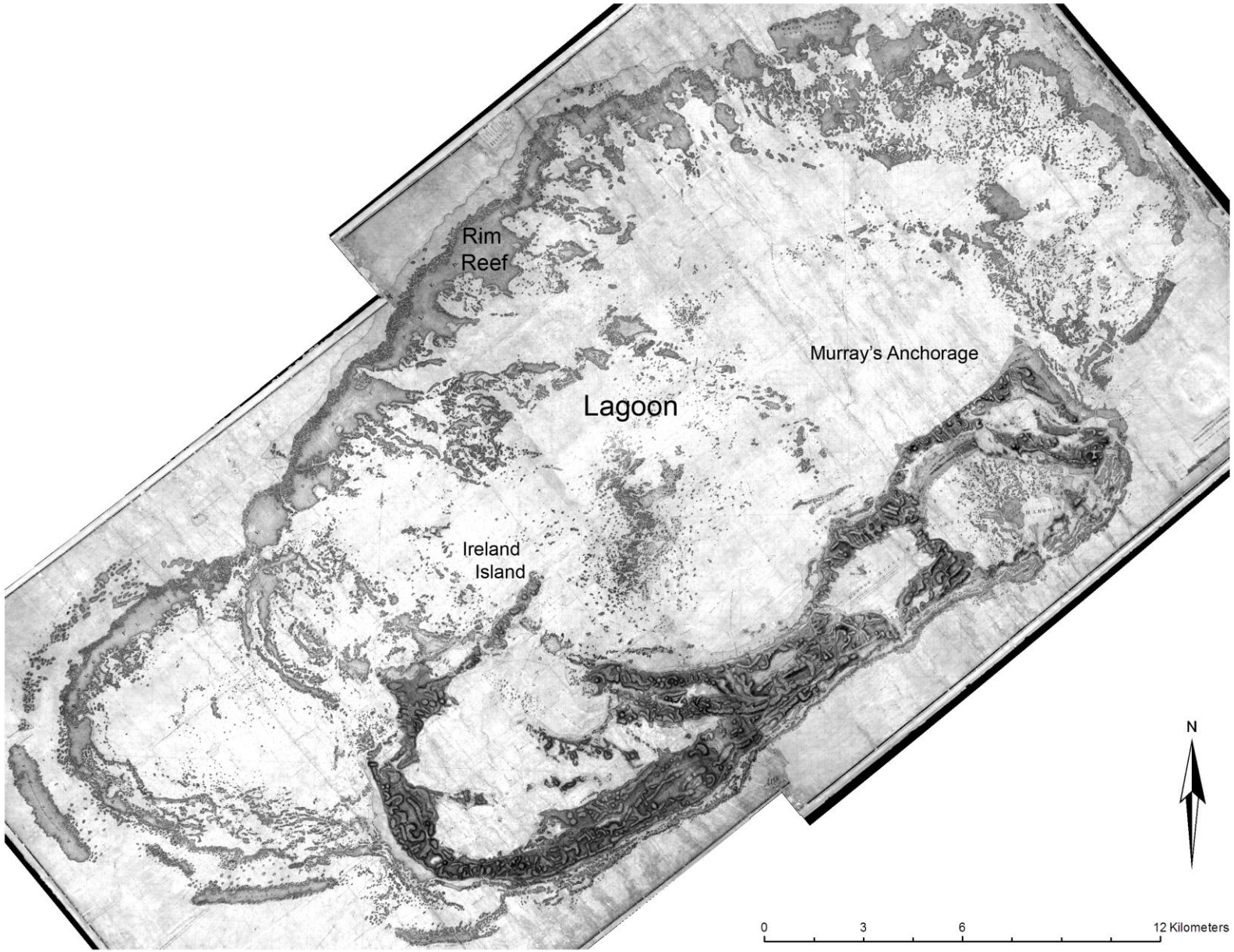
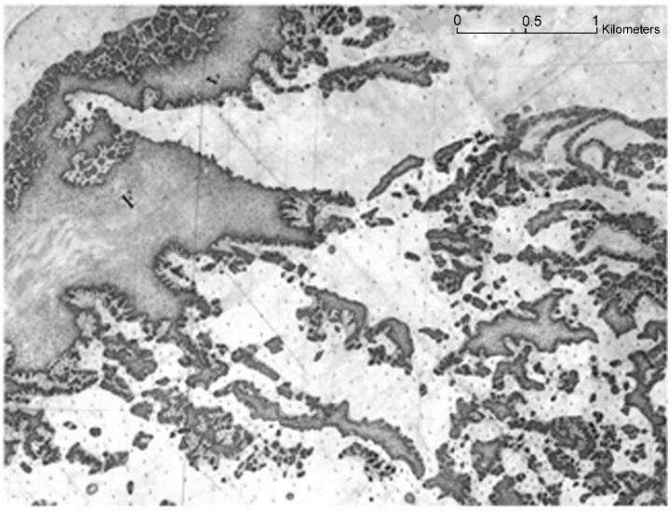
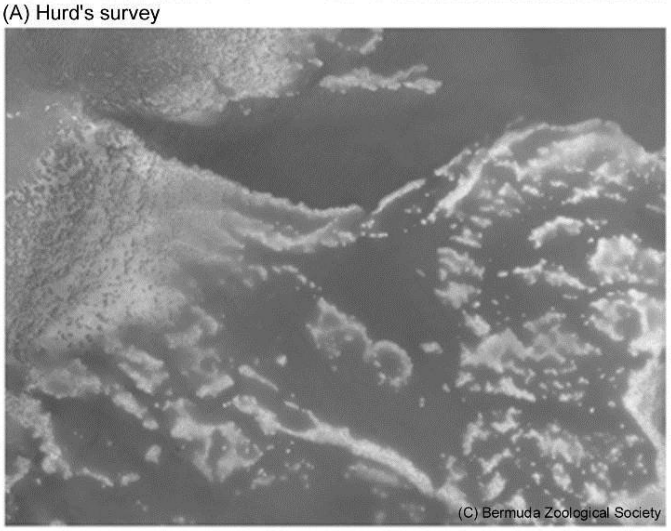


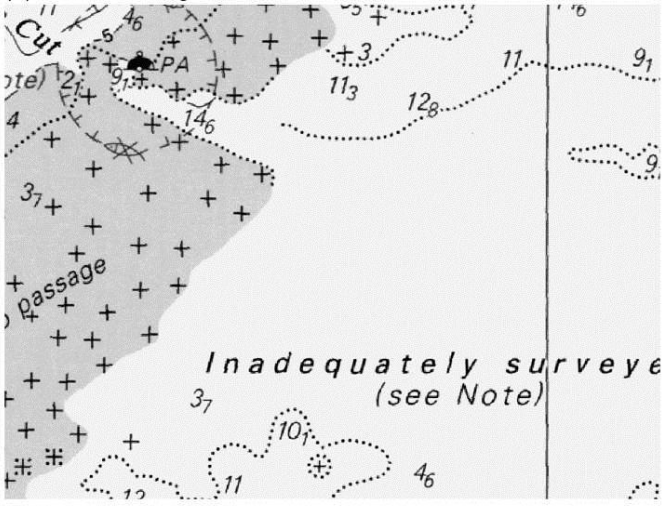
Figure 1. Thomas Hurd's complete survey of Bermuda, 1789-1797.



(A) Hurd's survey



(B) 1997 aerial image



(C) Modern nautical chart

Figure 2. Comparison of detail on Hurd's survey (A), 1997 aerial images (B), and a modern nautical chart (C).

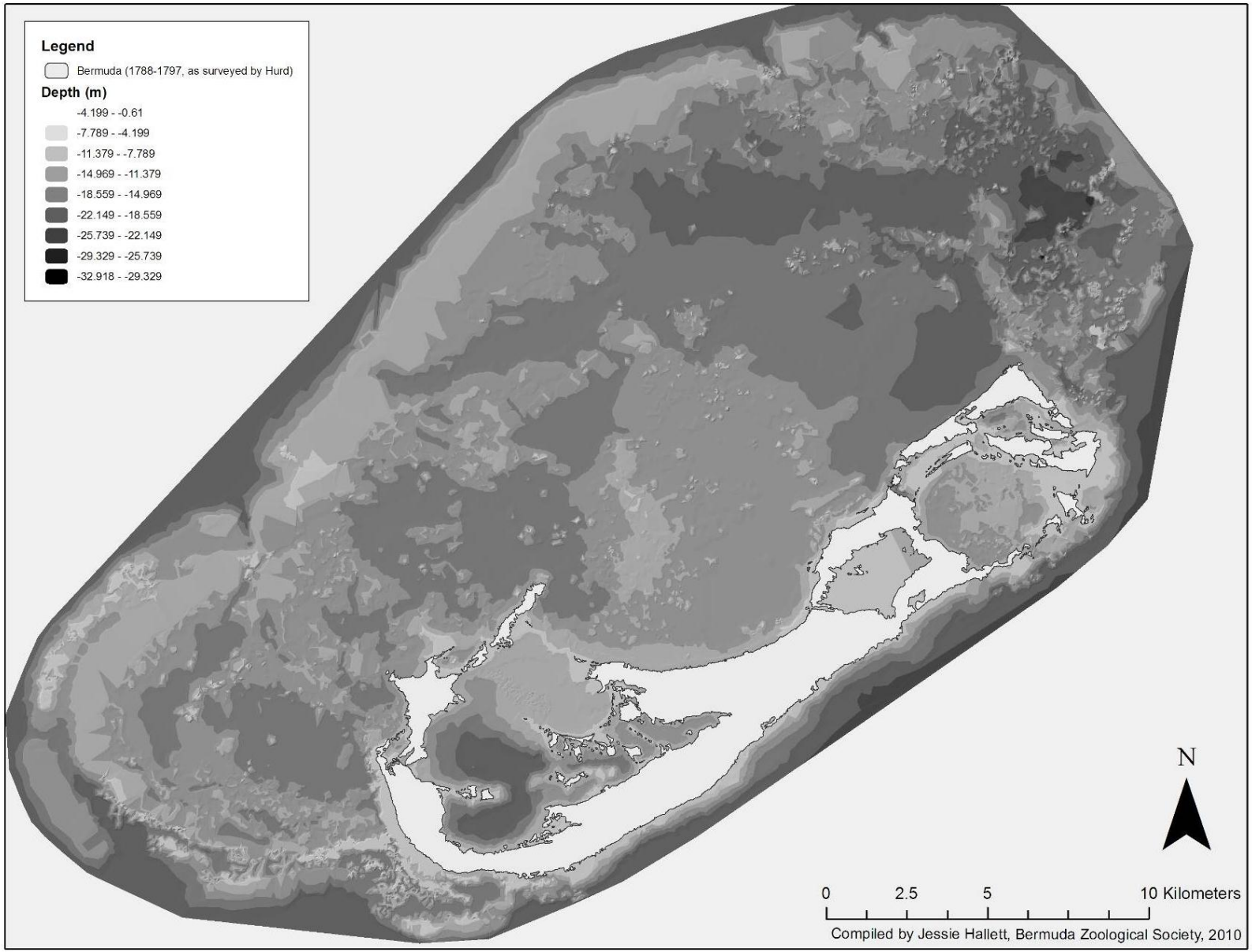


Figure 3. A triangulated irregular network (TIN) depicting depths in metres around the island of Bermuda, based on over 30,000 mapped depth points derived from Hurd's chart.

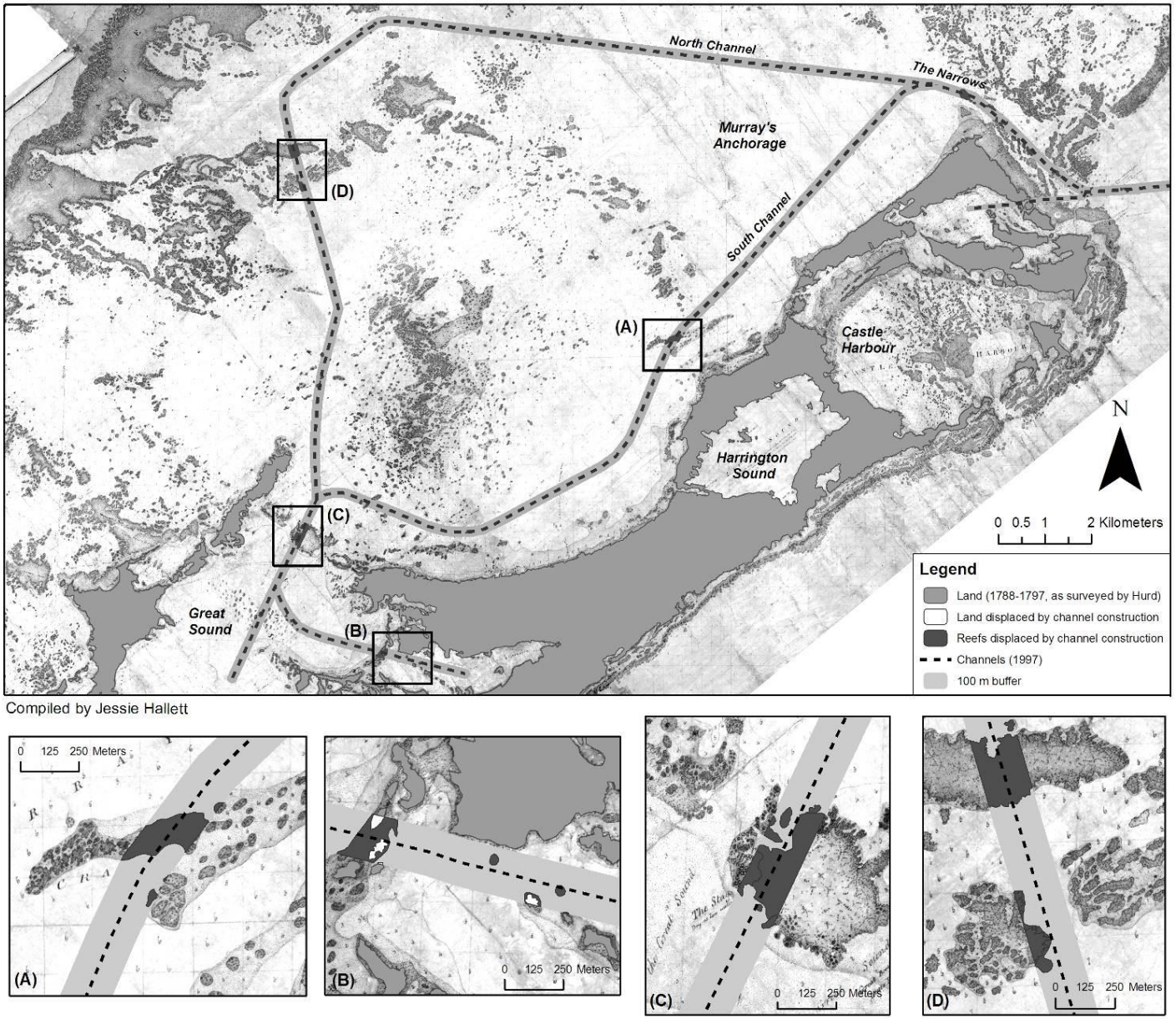


Figure 4. Shipping channels dredged around Bermuda. Insets show damage to reefs at Crawl Flat (A), Two-Rock Passage (B), Stag Rocks and Dundonald Channel(C), Crescent (D).

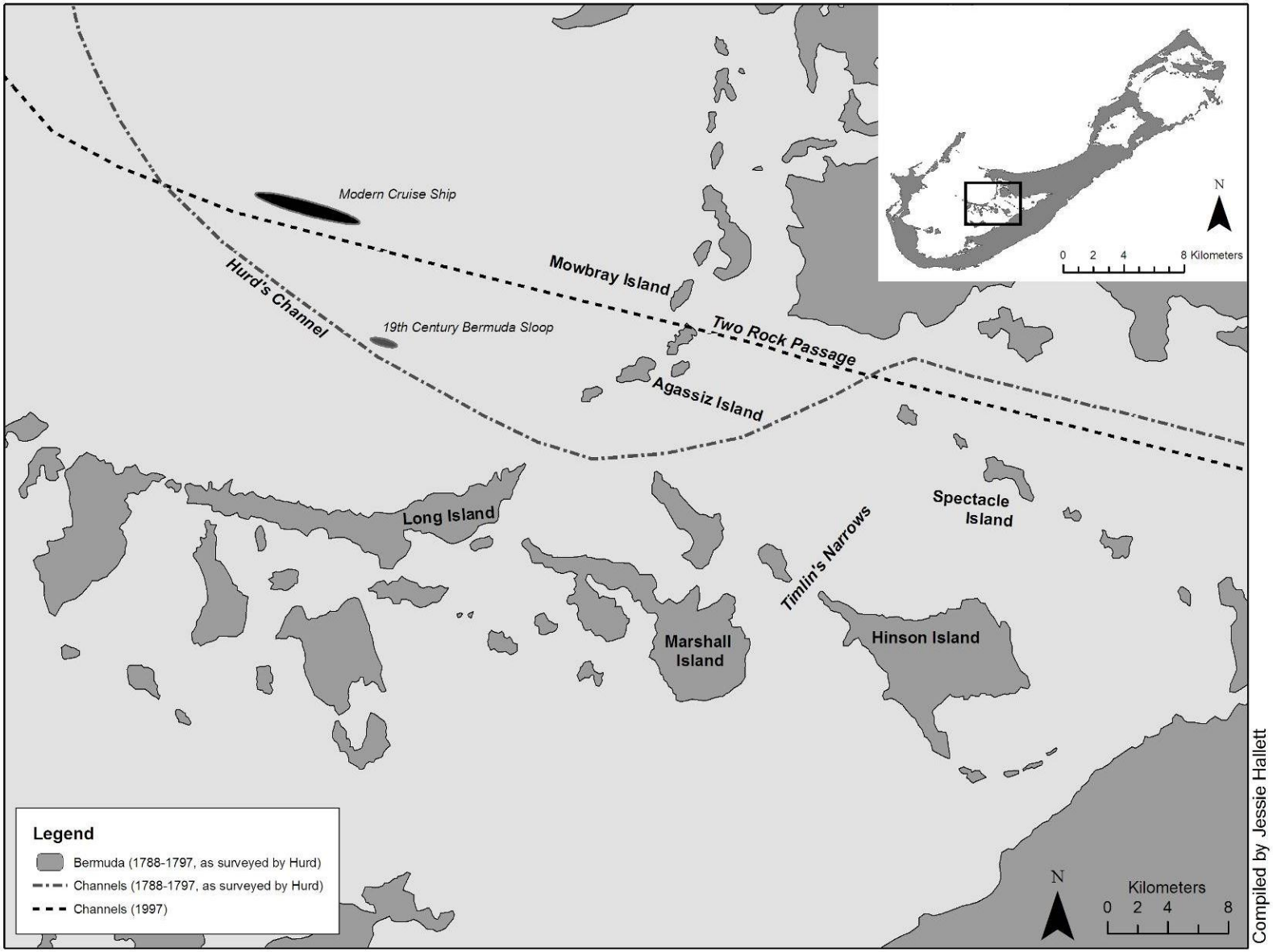


Figure 5. Historical and modern channels entering Hamilton Harbour.

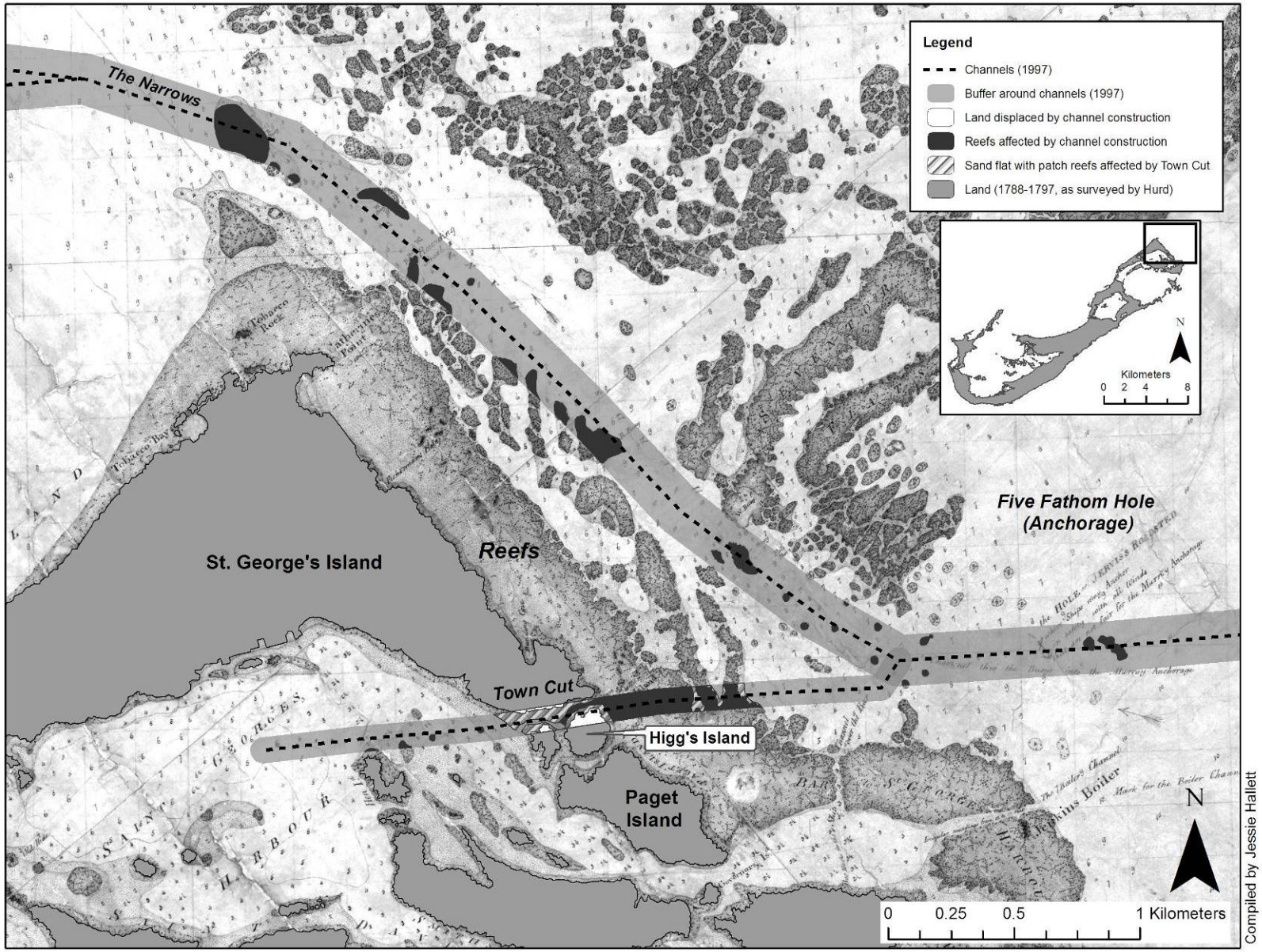
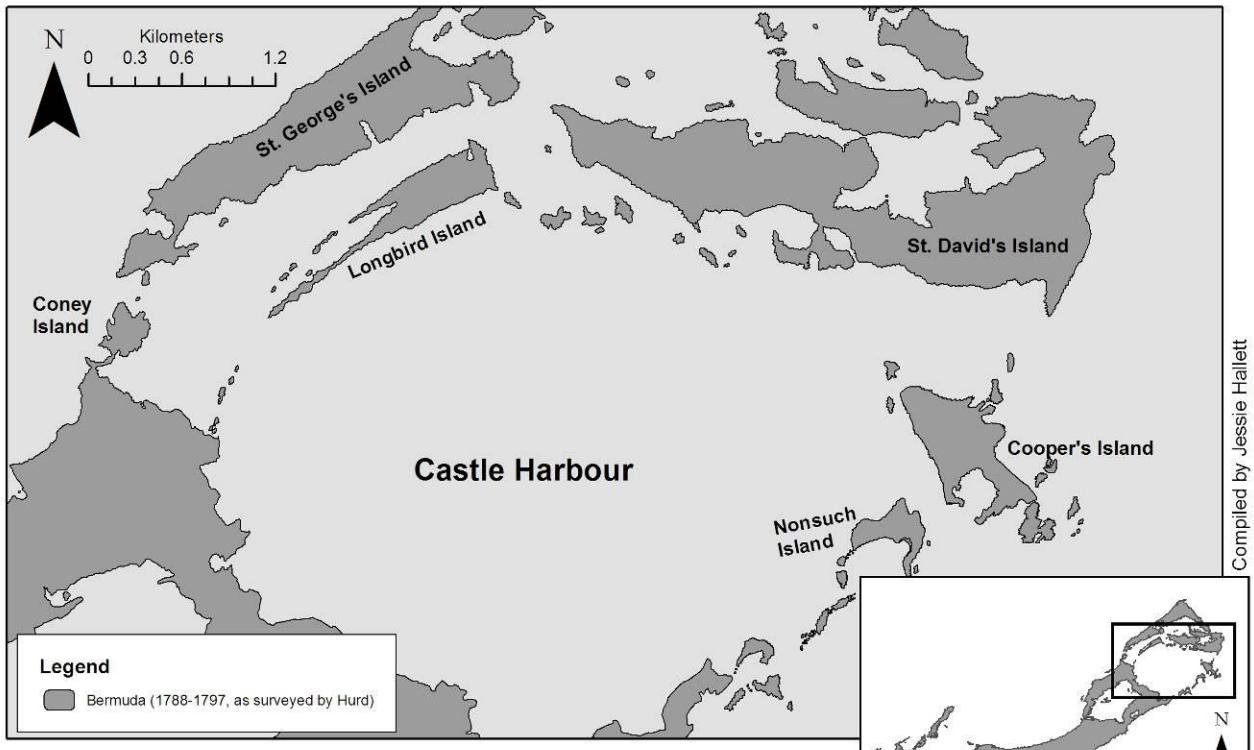
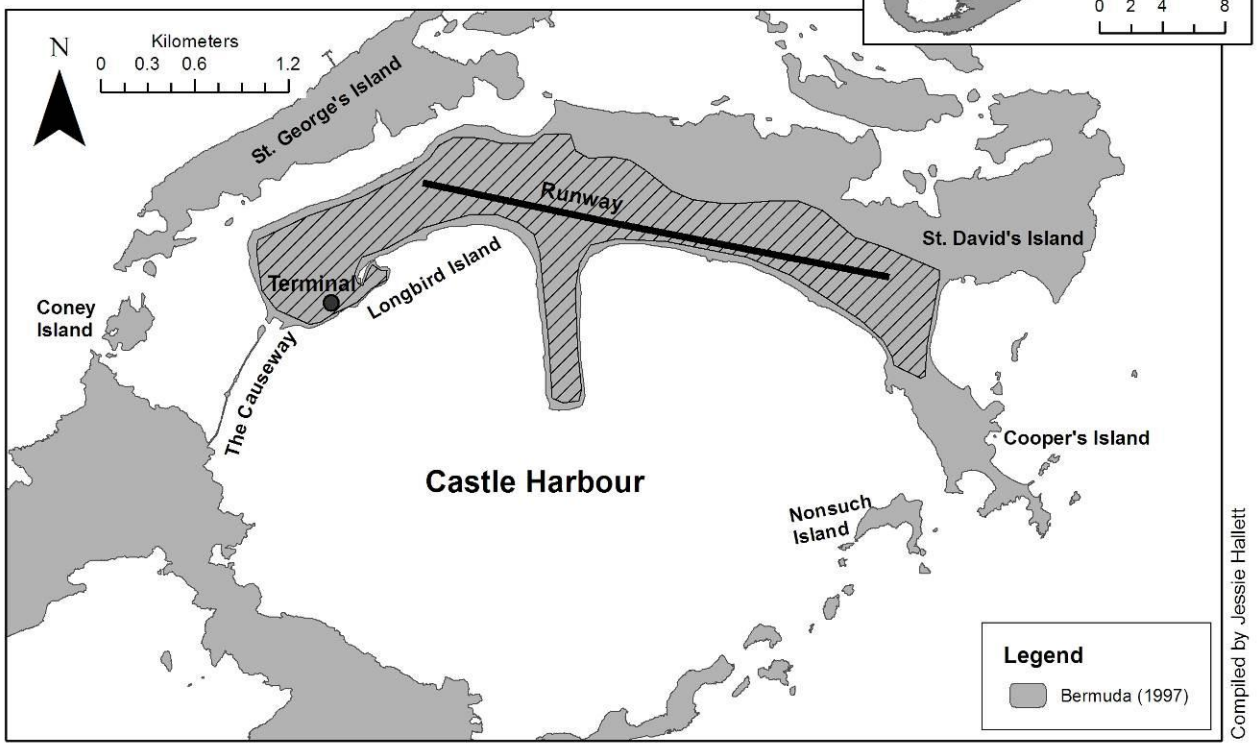


Figure 6. The channels around and entering St. George's Harbour.



1788-1797: Land and islands surrounding Castle Harbour.



1997 overlay of land. Kindley Field Airstrip, currently the civil airfield, is cross hatched.

Figure 7. Digitized versions of the features in and around Castle Harbour as charted by Hurd (top) and as in the 1997 aerial images (bottom).

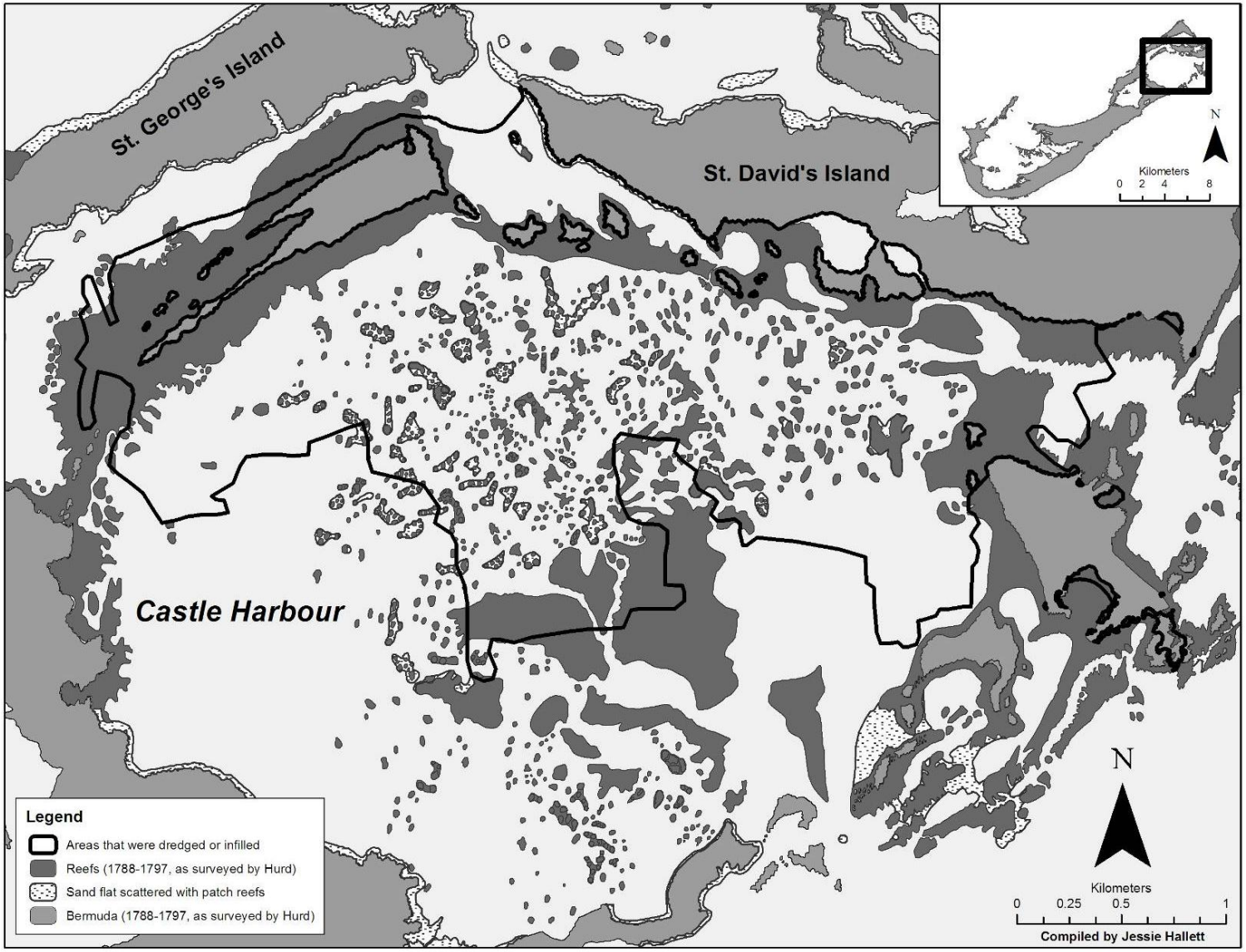


Figure 8. Digitized version of the reefs and land in and around Castle Harbour charted by Hurd. The black line surrounds features affected by dredging or infilling during airfield construction during the 1940's.

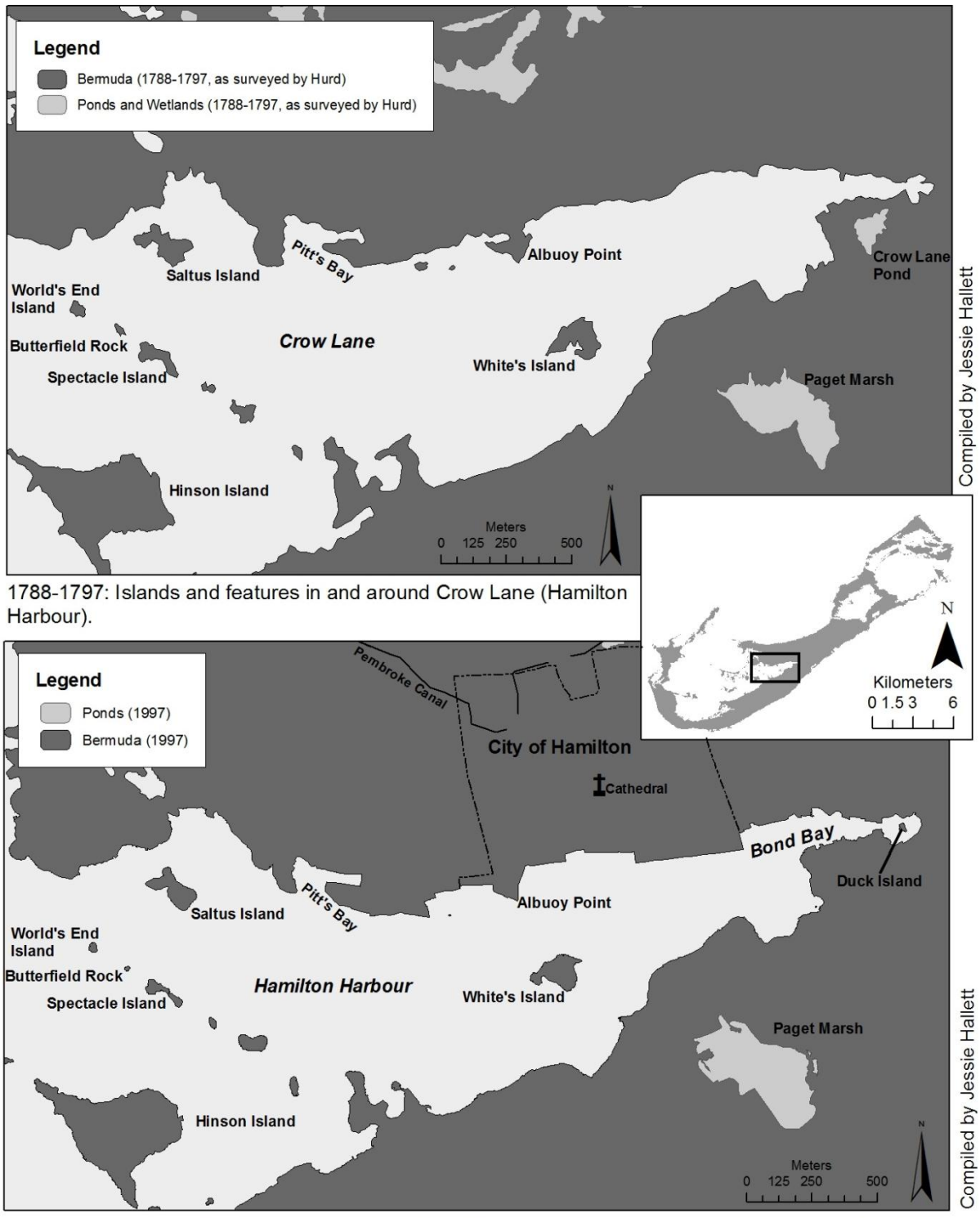


Figure 9. The City of Hamilton as surveyed by Lt. Thomas Hurd (top) and as it appears on 1997 aerial images (bottom).

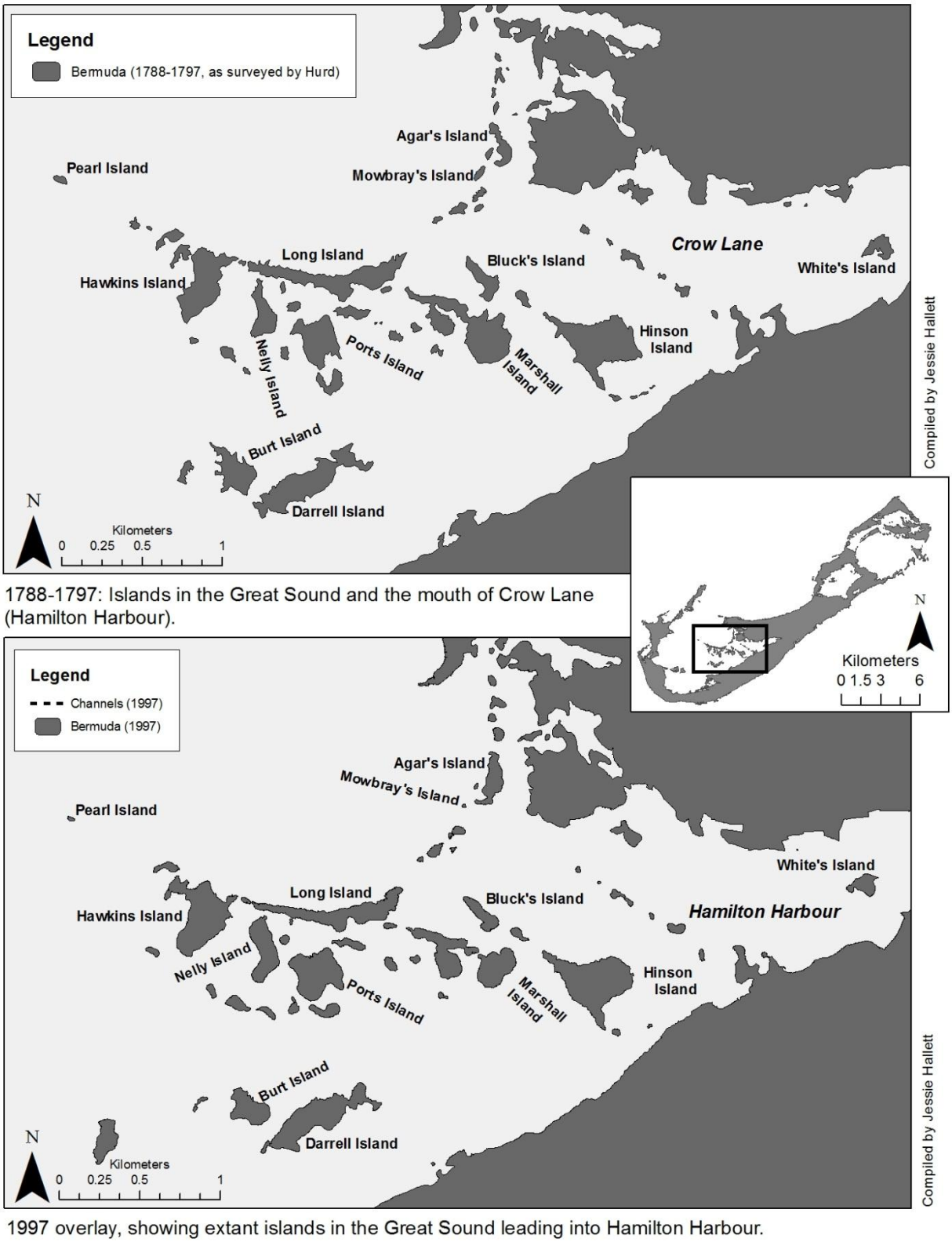
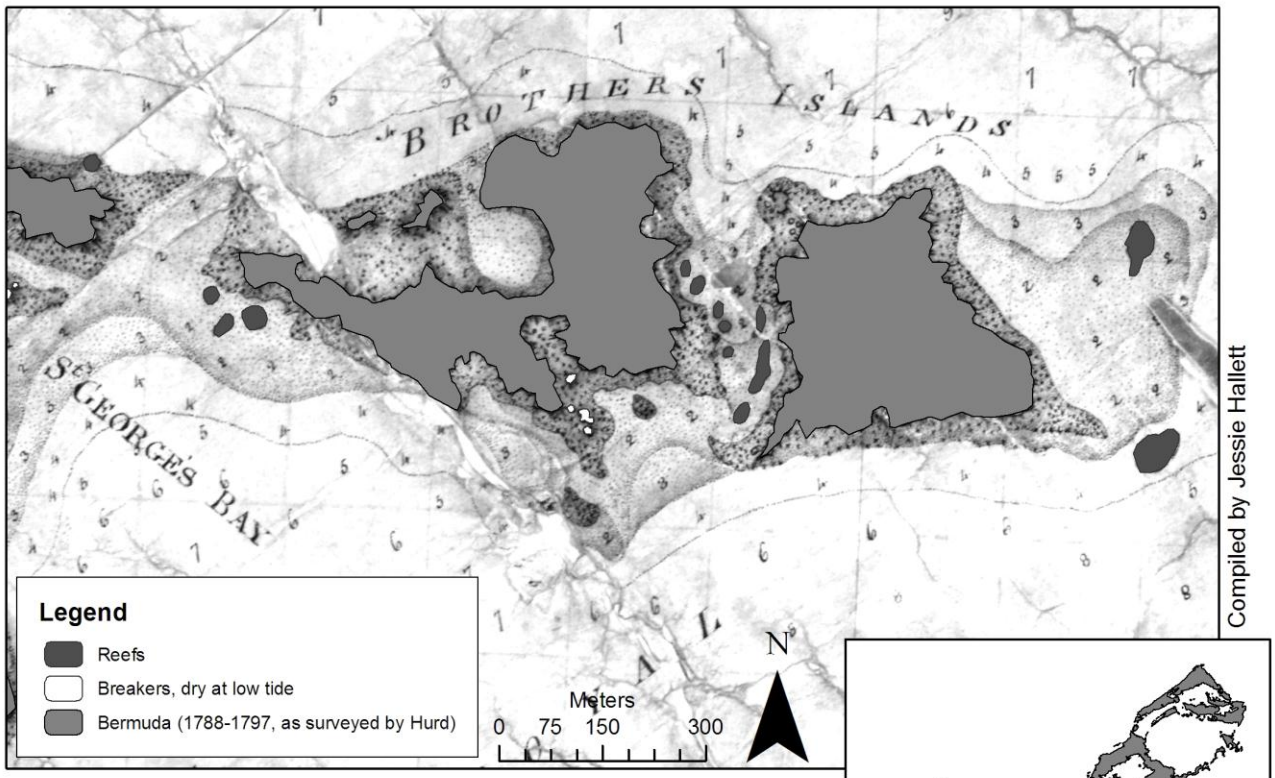
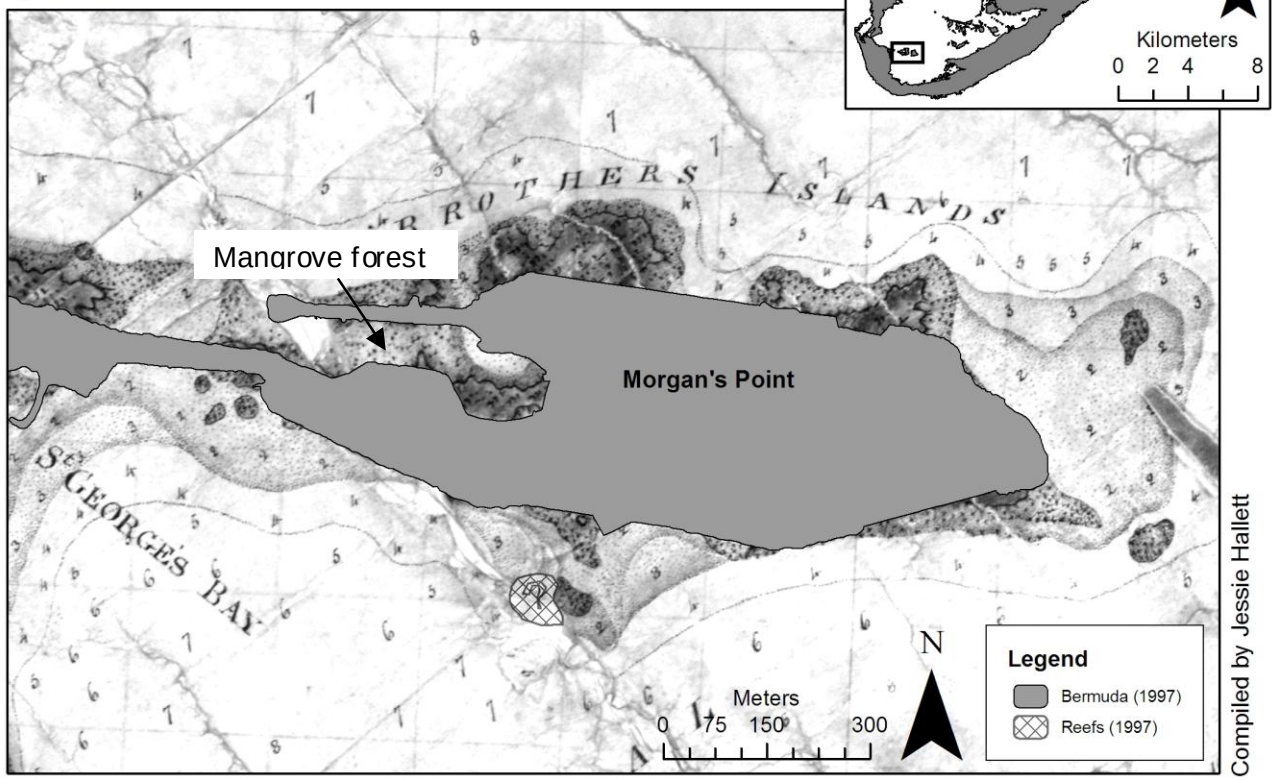


Figure 10. The islands in Hamilton Harbour and Crow Lane as surveyed by Lt. Thomas Hurd (top) and as they appear on 1997 aerial images (bottom).

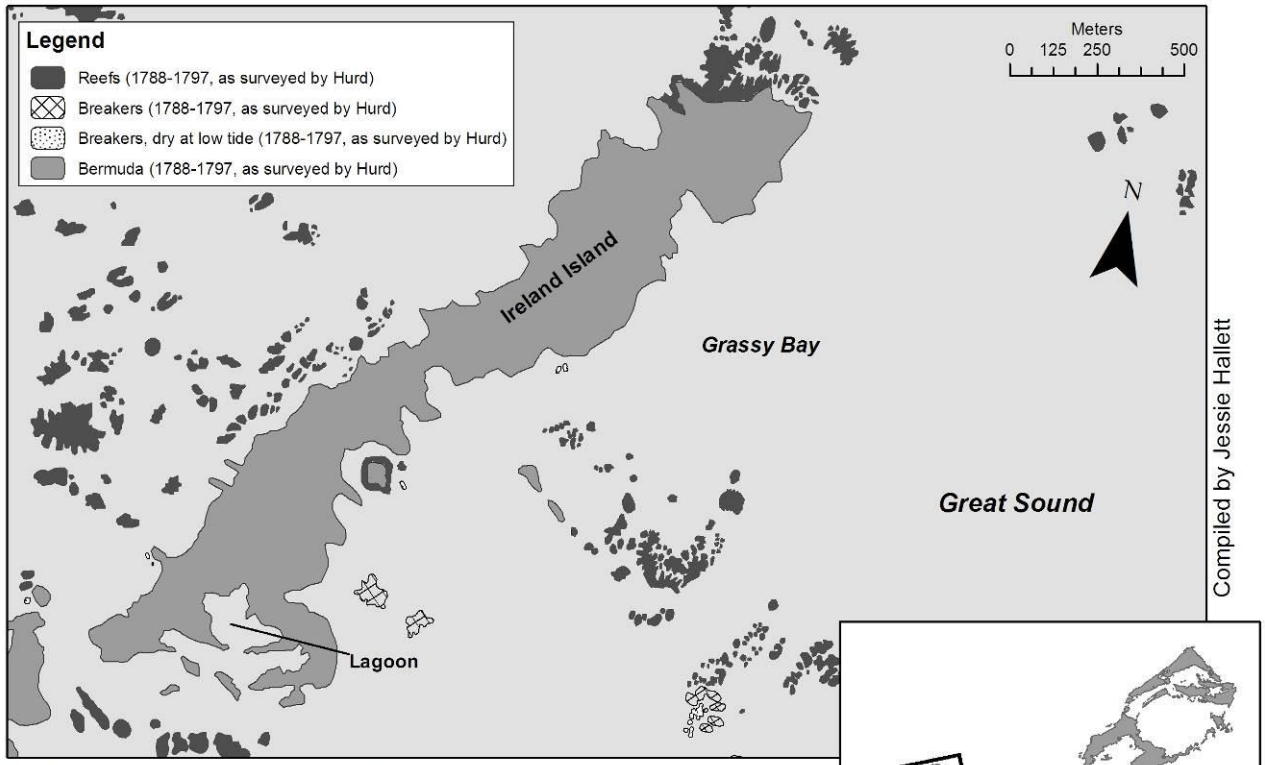


1788-1797: Brothers Islands and surrounding reef features as surveyed by Thomas Hurd.

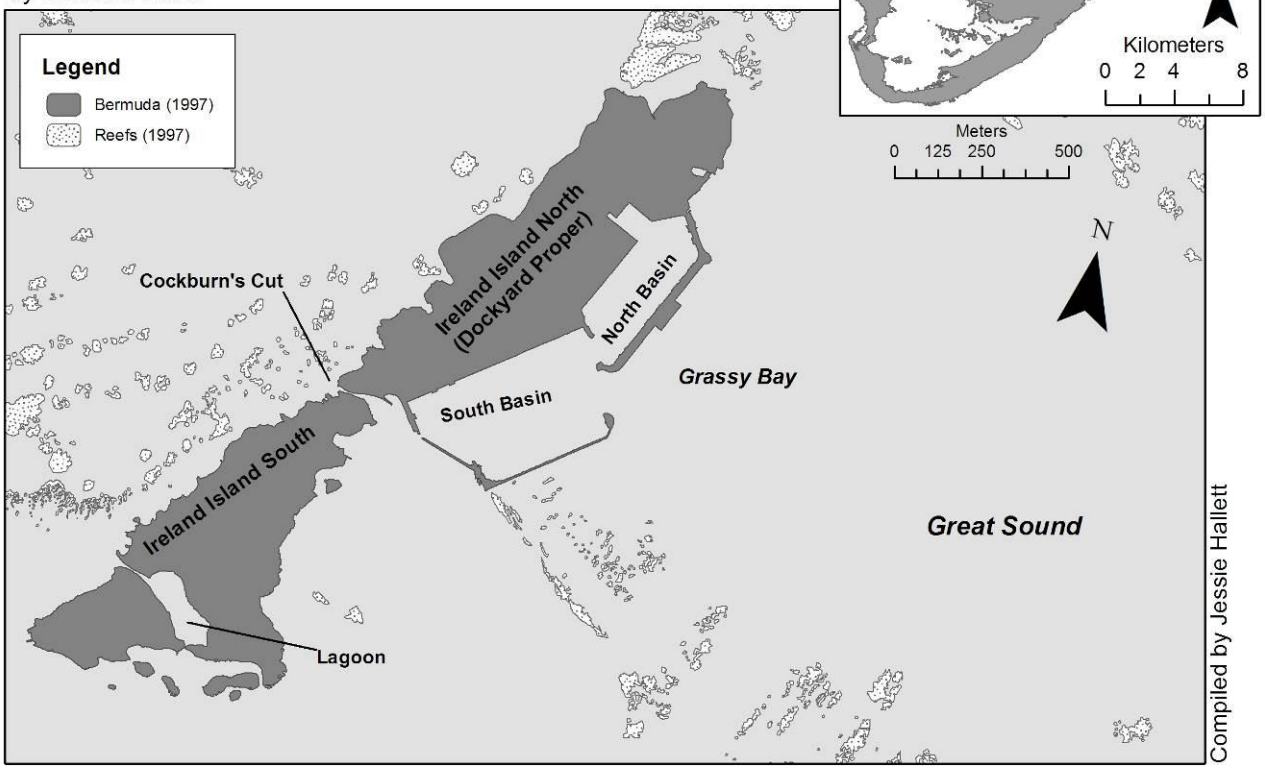


1997 overlay, showing Morgan's Point and extant reef features.

Figure 11. The Brothers Islands charted by Hurd (top) and in 1997 (bottom), now known as Morgan's Point.



1788-1797: Ireland Island, and the surrounding reef structures mapped by Thomas Hurd.



1997 overlay, showing changes to the morphology of Ireland Island due to construction of the Dockyards, and the extant reef structures.

Figure 12. Ireland Island as charted by Hurd (top), and on the 1997 aerial (bottom) after construction of the Royal Naval Dockyard in the 1890's.

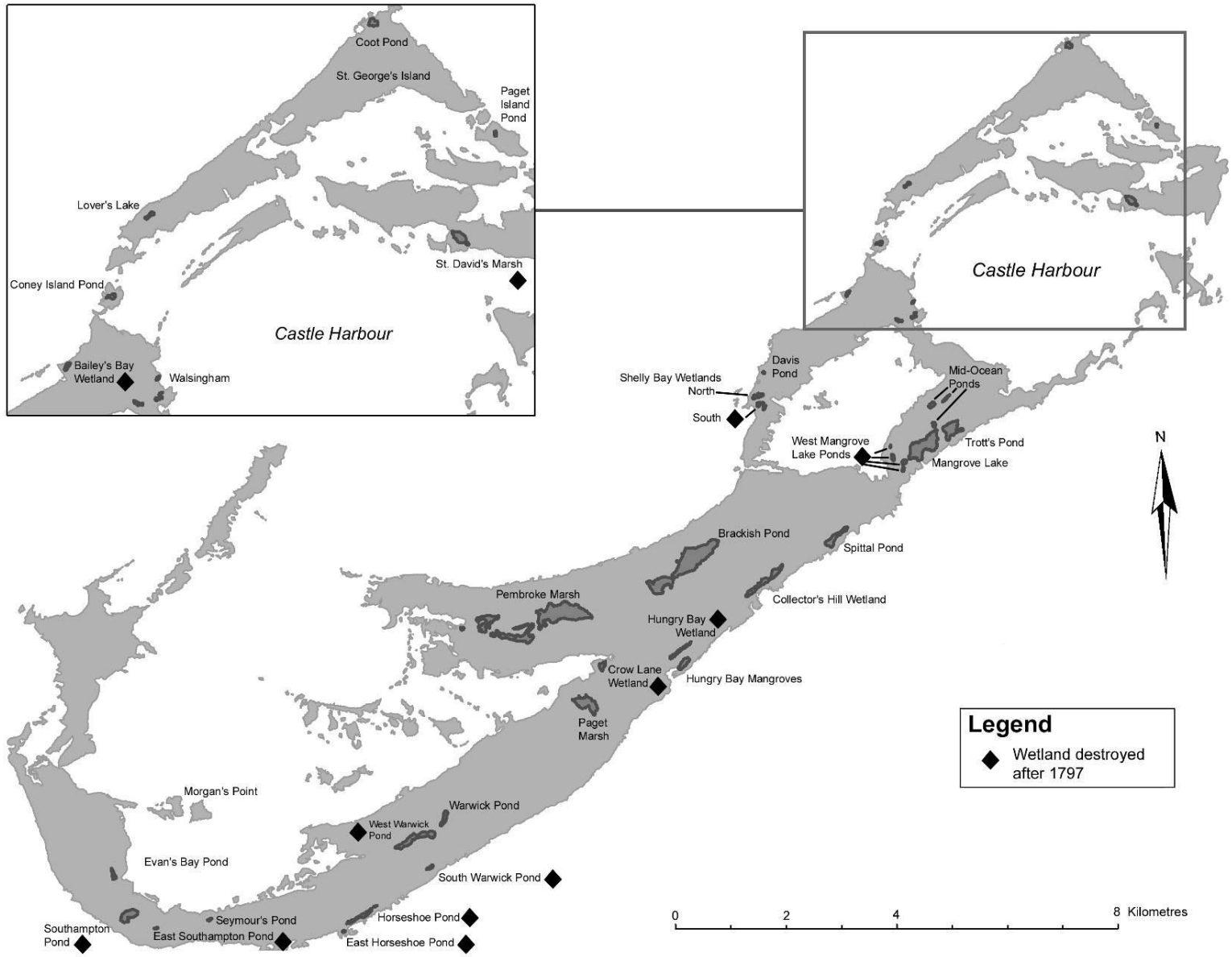


Figure 13. Wetland features charted by Thomas Hurd, 1788-1797.

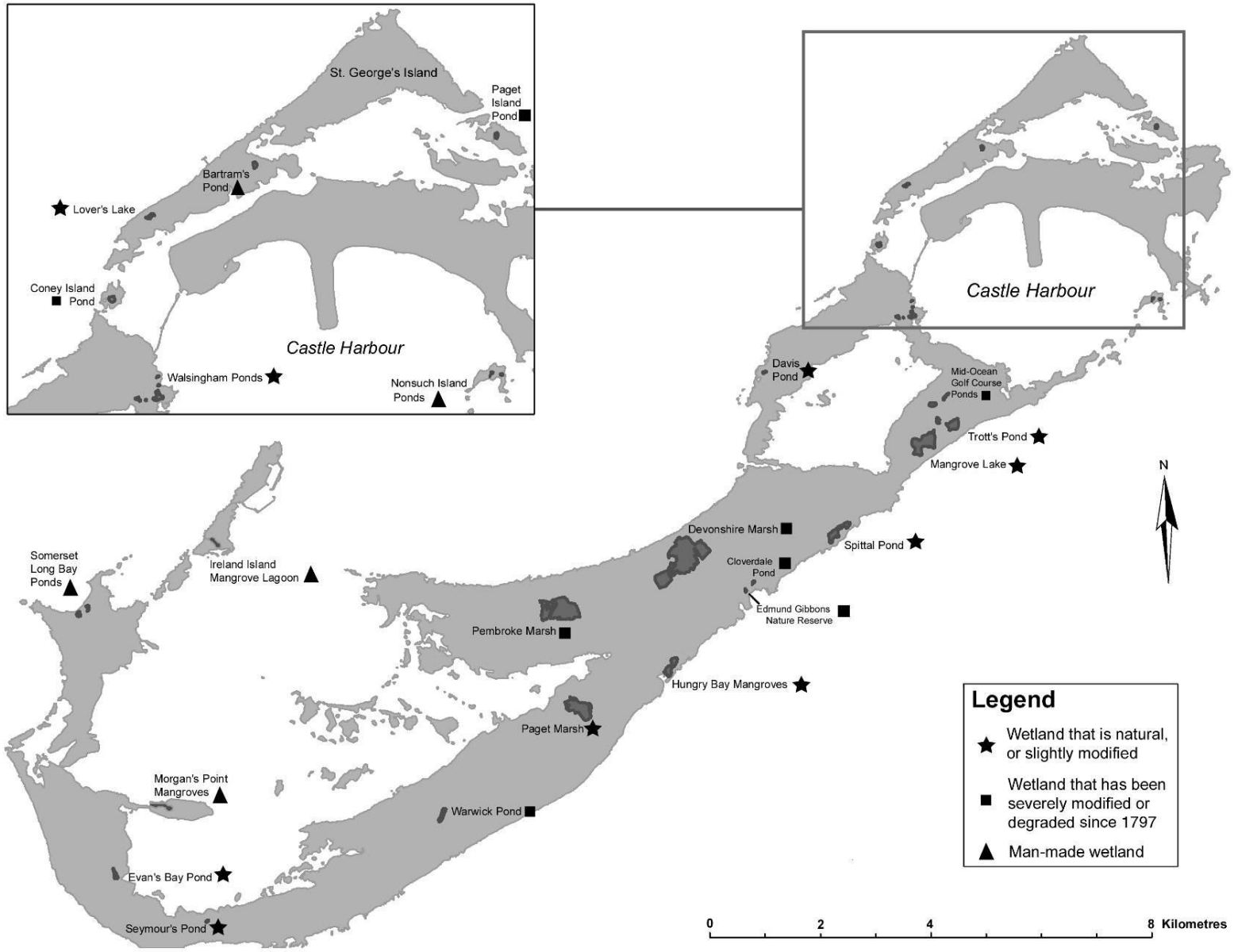


Figure 14. Wetlands charted from the 1997 aerial photomosaic.

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