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A two-part process for assessing the adequacy of hydrographic surveys and nautical chart coverage

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A TWO-PART PROCESS FOR ASSESSING THE ADEQUACY OF HYDROGRAPHIC SURVEYS AND NAUTICAL CHART COVERAGE

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DEDICATION

This is work is dedicated to God and to my mother Victoria Azuike who supported me each step of the way.

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ABSTRACT

A TWO-PART PROCESS FOR ASSESSING THE ADEQUACY OF HYDROGRAPHIC SURVEYS AND NAUTICAL CHART COVERAGE

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University of New Hampshire, December, 2012

IHO Publication C-55 contains information about the progress of hydrographic surveying and nautical charting for littoral states. Listed primarily as percent coverage, it is difficult to use this information to determine: 1) if the current level of surveying or charting is adequate or in need of action, or 2) can be used to compare different locations. An analysis methodology has been developed to assess the adequacy of hydrographic surveying and nautical charting coverage. Indications of chart adequacy as depicted on charts or sailing directions are spatially correlated with significant maritime areas associated with navigational/national interest. However, an analysis based solely on these datasets is limited without access to the current depth information. Publically-available, multi-spectral satellite imagery can be used to derive estimates of bathymetry and provide information in previously unsurveyed areas. Preliminary results show that multi-spectral satellite remote sensing is potentially beneficial as a reconnaissance tool prior to a hydrographic survey.

I. INTRODUCTION

The oceans of the world cover about 75 percent of the earth and have since the advent of human civilization played an important role in the development of nations (NRC, 2003). The successful use of the sea has defined the prosperity of littoral states that employed the sea for movement of goods and services, exploration and exploitation of natural resources and recreation (NRC, 2003). These activities have hinged on the successful avoidance of dangers such as wrecks, shoals, shifting shorelines, pipelines, and submarine cables prevalent in these waters (NOAA Coast Pilot 5, 2010).

Nautical charts are charts specifically designed to meet the requirements of marine navigation showing depths of water, nature of bottom, elevations and characteristics of the coast (IHO, 1994). They constitute the main navigational tool for sailors, fishermen, and other mariners. These charts depict the locations of dangers and ensure the safety of navigation within the oceans of the world (IHO, 2005). Thus, they are vital for the success of the activities within these waters and instrumental to the wealth of a nation that depends on the ocean for its economic survival. However, most of the coastal nations around the world do not have adequately surveyed nautical charts according to IHO standards. Most of their charts have areas showing pecked (estimated) and discontinuous shorelines, and low density of soundings indicating lack of data. A good number of these charts have positions marked as PA (Approximate Position), PD (Position Doubtful) and have caution notes warning of uncharted shoals. The uncertainty of these marked positions makes them unreliable for avoiding danger and so shows that the areas have not been adequately surveyed to ensure safety of navigation.

1.1 IHO Publication C-55

The International Hydrographic Organization (IHO) publishes the status of Hydrographic Surveying and Nautical Charting Worldwide document. IHO Publication No. 55 (C-55) is issued by the IHO to show the extent of hydrographic surveying and nautical charting, worldwide. The aim of C-55 is to provide base data for governments as they consider the best ways of implementing the responsibilities set out in Chapter V, Regulation 9, of the Safety of Life at Sea (SOLAS) (IHO, 2004). C-55 is used by the IHO to identify and help prioritize requirements for progressing modern surveys and chart production. The compilation of the hydrographic database is focused on identifying gaps in hydrographic data. A major challenge in global data compilation is obtaining hydrographic, charting and maritime safety information from developing countries.

IHO C-55 assesses available national hydrographic data using the IHO standards for hydrographic surveys (IHO S-44) criteria and other methodical classification of hydrographic data sources (IHO, 2004). The resulting report includes three classes: adequately surveyed areas, areas requiring survey at a larger scale and areas that have never been systematically surveyed. This classification provides only the extent for each area in terms of national percentage coverage and has limited application when used to determine high priority areas that are in need of hydrographic surveys and improved nautical charts.

IHO C-55 indicates that many coastal states lack the capacity to plan and implement a prioritized survey program. IHO also recognizes that "relatively few IHO countries have satisfactory arrangements in place to ensure that surveys are carried out" (Ward, 2012). In particular, C-55 identifies gaps in the hydrographic data for major areas in the Caribbean Sea, the coastal waters of West Africa, the Indian Ocean and adjacent seas.

1.2 Charting and Nautical Information

The primary mission of a hydrographic office (HO) is to provide necessary information required by a mariner to safely navigate his vessel (IHO, 2011). This information is usually provided in the form of paper nautical charts, Electronic Navigational Charts (ENCs), sailing directions and other publications that enable a mariner to make informed decisions required for safe navigation. The main document used for navigation is the nautical chart, which is a graphic representation of the ocean waters and adjoining coastal regions designed to meet the requirements of marine navigation (IHO, 2005). It contains information on water depth, shorelines, aids and hazards to navigation, and other information necessary for safe navigation. Sailing Directions are route planning manuals that describe in more detail the navigational features of the coastal area and port approaches, and provide detailed country information for safe navigation in the area. This information includes hazard and warning systems, pilotage requirements; and search and rescue requirements. There are other information provided by the chart and nautical publications that give an indication of the accuracy of the hydrographic data from which the chart was compiled. These are usually shown in the form of symbols, character type and positive warnings. Also available on the charts and in nautical publications are maritime significant areas, which are areas defined by how they are used by a nation.

Information on the adequacy of charted information includes symbols, abbreviations and warnings that are used to inform mariners regarding the level of confidence that should be given to data on a nautical chart. This information is derived both from the nautical chart and sailing directions or any other nautical publication that may be issued from time to time by a maritime administrative agency. The rules for using these symbols and warnings are published by the IHO. However, some HOs have country-specific symbols and warnings. In practice, the type and number of symbols that are used to warn about the inadequacies or inaccuracy of a hydrographic data and the dangers they portend depend on the national HO's charting standards, and the judgment of the cartographer.

"Maritime significant area" is a term used in this study to describe sea areas of navigational importance that help to maintain sea lines of communication in support of commerce and other economic activities, such as ports, harbors, navigational channels, anchorages. Maritime significant areas also comprise areas of cultural and natural importance as defined by a nation, such as marine protected areas (MPA), military restricted areas, and areas for exploration and exploitation of natural resources. They are defined based on the current usage and needs of the nation. Thus, the extent or status of an area may change with time regardless of any hydrographic update.

1.3 Study Goal

The primary goal of this study is to develop a process that a hydrographic office can use, without access to costly sources of information, to analyze a nautical chart to determine:

1) The adequacy of current information required for safe navigation.

2) Priority areas that are in need of new hydrographic surveys and improved nautical charting.

1.4 Study Approach

A two-part approach is proposed whereby a nautical chart is first analyzed in terms of what is contained solely in chart-related information. The initial analysis is further improved using readily available remote sensing imagery.

The results of this study are intended for the use of countries that have limited resources. The recommended process to assess and prioritize existing nautical charts will enable them to focus their resources in areas with highest priority in need of hydrographic surveys and improved nautical charts.

1.5 Methodology

This study describes a process for evaluating the adequacy of a given navigational chart, and prioritizing sea areas for survey or resurvey. The primary focus of the process is on the chart adequacy information and maritime significant areas available on nautical charts and sailing directions. The process identifies and prioritizes areas that require survey within a chart. The nautical charts of the territorial waters of Belize and Nigeria were used to develop this process. From the C-55, both countries were identified as having gaps in their hydrographic data.

Two procedures were developed. The first procedure focused on chart adequacy information and maritime significant areas available on nautical charts and sailing directions. An evaluation of the adequacy of hydrographic surveying and nautical charting coverage based on a standardized analysis and assessment methodology revealed that one of the limitations in this procedure is that the source data are sometimes out of date. The second procedure addresses this issue by using optically-derived bathymetry to update the depth area layer in the chart adequacy evaluation with the most recently available satellite information. This procedure provides a bathymetric estimate in unsurveyed areas, and indicates any major discrepancies between present depths and the chart's soundings.

The procedure requires the involvement of an expert assessment (e.g., an experienced mariner) on the relative importance of the chart adequacy information in terms of safety-of-navigation for typical vessels that sail in the charted area. Although the assessment is subjective, the robustness of the evaluation was confirmed by a sensitivity test. Chart adequacy information was evaluated based on five evaluation criteria (classes): reliability diagram, chart quality symbols/indicators, doubtful danger markings, survey completeness and depth area. A weighted percentage was then assigned to each chart adequacy class based on their assessed importance in the navigation of a vessel. Each class was sub-divided into elements that can be used to assess the adequacy of the chart for navigation. For example, the source diagram class has A1, B1, B2, B3 and B4 as its elements. Each element of a chart adequacy class was digitized into a feature polygon in *ArcMap*. The feature polygon was then converted into a raster grid using "polygon to raster conversion" tool in *ArcMap*. Each element was numerically rated by the degree of danger it poses to the safety of navigation, on a scale of 1 to 5, where a value of 1 is equal to the least danger to the safety of navigation, and a value of 5 is the most dangerous to the safety of navigation. These values were assigned to each element using the "reclassify tool" where the digital number (DN) value for each element was assigned the rated value. The chart adequacy classes were then summed together to give the chart adequacy score for each area. This was implemented using the "weighted sum" tool in *ArcGIS* spatial analyst. The assumption is that the sum of the chart adequacy classes for each area has a linear relationship to the chart adequacy score for the area. This is expressed by the equation:

Chart adequacy score = [(Depth area * Assigned %) + (Source diagram * Assigned %) + (Chart completeness * Assigned %) + (Doubtful danger * Assigned %) + (Chart quality * Assigned %)]

Maritime significant areas were evaluated based on two main classes: navigational significant and other significant areas. The navigation significant areas are sea areas such as channels, anchorages, shipping routes. Other significant areas are area of national and cultural importance which are delineated specifically for other reasons other than safety of navigation but can be impacted by the transit of shipping traffic through the area. A percentage weight is assigned to each class based on the importance of each area to a country. Each maritime significant area class is divided into elements according to the use of the area. For example the navigation significant areas have channels, anchorage areas,..etc., as elements. Each element is rated based on its importance to a nation. This may be based on the navigation importance in terms of safe conduct of the vessel or the impact shipping traffic has on the area (i.e. pollution to the environment). This rating is on a score of "0" to "1" depending on the requirements of a nation. For this study, only country specific information from the charts and sailing directions were used. These sources of information had only information on navigation significant areas such as channels, ports, and anchorage areas. No information such as Marine Protected Areas (MPAs), fishing grounds, etc. were shown the charts that were evaluated. Also, based on the available information, it was not possible to develop an objective rate of each element of the navigation significant area in terms of order of importance. Consequently for this study, the classes of the maritime significant areas are rated based on a Boolean logic. Areas that are important to navigation are rated as "1" and all other areas are rated as "0". Each class was digitized into a feature polygon and converted to a raster grid using "Polygon to Raster conversion" tool in *ArcMap.* The resulting raster grids were assigned their rated values using the "raster reclassify" tool in *ArcGIS Spatial Analyst.* These classes are later summed together into a maritime significant area class layer.

Areas on the chart are then prioritized for survey by intersecting the chart adequacy layer and the maritime significant area layer (one layer was multiplied by the other) using the "raster calculator" tool (*Spatial Analyst, ArcMap*). The results of the intersection will yield priority areas on a scale of "0" to "5". Where "0" are areas having the lowest priority for survey and "5" are areas having the highest priority for survey. The result was classified into three priority groups; low, medium, and high.

1.6 Data Sources and Study Sites

The sites selected for the study are the Escravos River and coastal region in Nigeria, and the Big Creek coastal region in Belize (Figure1.1). Nigeria is located in West Africa between latitude 4° and 15° north and longitude 3° and 13° east; Belize is located on the northeastern coast of Central America. The two countries were identified by the C-55 document as having significant gaps in their hydrographic data. Also, in order to determine the best-performing algorithm in the second part of the study, bathymetry-extraction algorithms were evaluated in a well-controlled test site. The northern coast of Cape Ann, Massachusetts, U.S.A was used for the test site. The area was selected because of its proximity to the University of New Hampshire (UNH) and the availability of a recent Airborne LIDAR Bathymetry (ALB) survey, which was used as a reference data set.

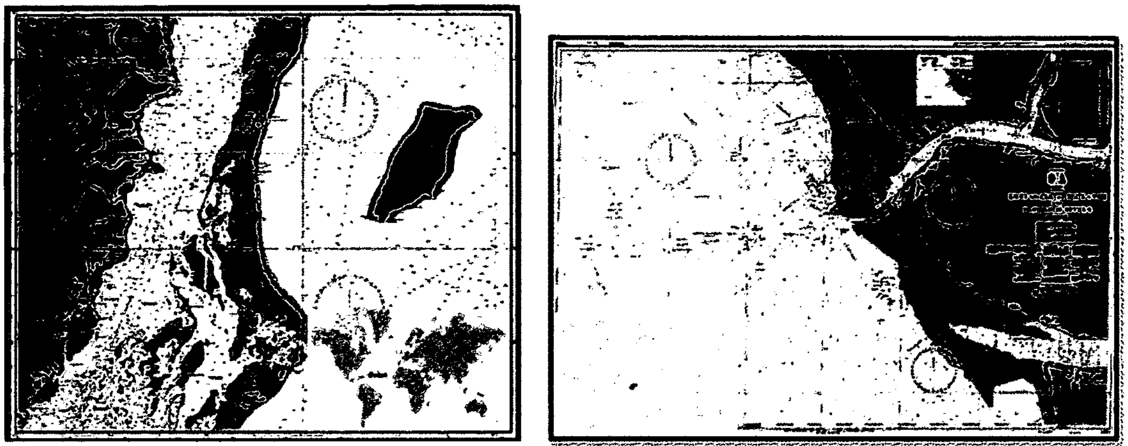


Figure 1.1 – British Admiralty (BA) Chart 1797 (Monkey River to Colson Point, Belize) and Chart 3321(Entrances to Escravos and Forcados River, Nigeria). Inset showing the location of the study sites.

The first part of the study was based on information from the chart and sailing directions only. The second part of the study used Landsat satellite images to infer bathymetry. The Landsat images covering the two study site were down loaded from the United States' Geological Survey (USGS) public web archives (http://earthexplorer .usgs.gov/).

II. CHART ADEQUACY AND COMPLETENESS INFORMATION

The adequacy of a nautical chart is dependent on the accuracy of the hydrographic survey data used to compile the chart (IHO 2011) and the skill of the cartographer compiling the chart. The cartographer considers a wide variety of issues in the making of a nautical chart, such as the type of vessel plying the area, the navigation practice of the mariners, the nature of potential dangers and the quality of the hydrographic survey data. The chart maker takes any limitation in the data sources into account when compiling the chart by including symbols and warnings to reflect the inadequacies in the hydrographic survey data (IHO, 2011). All efforts in making the chart are made to draw the attention of the mariner to possible dangers to navigation such as shoals and wrecks. The type and number of symbols to warn about the inadequacies or inaccuracy of a hydrographic data and the dangers they portray depend on the agency's charting standards and the judgment of the cartographer. In the method presented here, the chart adequacy and completeness information can be evaluated by five main data classes: zone of confidence and source diagram, chart quality symbols/indicators, doubtful danger markings, survey completeness, and navigation significant depths.

2.1 Category of Zone of Confidence (CATZOC) and Source Diagrams

Charts are compiled from a variety of surveys and other data sources such as aerial photography etc. As a result of differences in survey technology, data collection techniques and procedures used in surveys from which a chart is compiled, the resulting survey data have varying degrees of uncertainty. These uncertainties in survey data are usually classified and depicted on the chart using reliability diagrams. The reliability diagrams are typically imbedded in the chart and used to inform mariners about the quality of the survey data shown on the chart. Two types of reliability diagram are normally used depending on the HO producing the chart: CATZOC and source diagram.

2.1.1 Category of zone of confidence (CATZOC)

The CATZOC is a qualitative assessment of the hydrographic survey data and charting standard used to compile a chart. It is displayed as a diagram on a chart to show the quality of the survey data (Smith, 2005). Sea areas are classified based on an estimation of the total error budget of the depicted depth and positional errors. From the seafloor coverage assessment, the detection level of all significant seafloor features can be determined. A major drawback of CATZOC is that the date of survey is not shown (Heeley, 2003). The survey date is vital information for mariners especially when navigating in unstable seafloor areas. Table 2.1 summarizes the six CATZOC categories. CATZOC A1 signifies an exceptionally high degree of hydrographic surveying normally employed for navigational critical areas such as harbor areas and approaches to harbor or similar areas (NSC, 2010). CATZOC A2 indicates a high standard of survey used for main shipping routes and approaches to harbor. CATZOC B represents a lower standard of survey than A2 and implies that full bottom coverage was not achieved. Therefore the area might have significant features or objects on the seafloor that have not been detected or shown on the nautical chart. CATZOC B is normally used over the open ocean areas. CATZOC C and D indicate very low survey standards and completeness and are collected on an opportunity basis with no controlled methodical approach during the data collection. CATZOC U is used to show areas where the quality of the bathymetric data is yet to be assessed (NCS, 2010). Currently, CATZOC diagrams are not presented in many navigational charts. Although IHO has recently adopted the CATZOC as valuable product (IHO,1996) most HOs, such as NOAA in the United States, prefer using source diagrams (Heeley, 2003) and the UKHO only apply them on electronic charts (Parker, 2003). CATZOC and source diagram cannot be used simultaneously on the same chart.

TABLE 2.1: CATZOC Categories and their Standards (NCS, 2010)

CATZOC	**Positional Accuracy**	**Depth Accuracy**	**Seafloor Coverage**
A1	± 5 m	= 0. 50 m + 1%d	All significant seafloor features detected
A2	± 20 m	= 1.00 m + 2%d	All significant seafloor features detected
B	± 50 m	= 1.00 m + 2%d	Uncharted features hazardous to surface navigation are not expected but may exist
C	± 500 m	= 2.00 m + 5%d	Depth anomalies may be expected
D	Worse than ZOC C	Worse than ZOC C	Large depth anomalies may be expected
U	Unassessed – the quality of the bathymetric data are yet to be assessed		

2.1.2 Source diagram

A source diagram is a diagram imbedded in the chart that references the coverage, survey period and survey technology on which a chart was compiled. The source diagram provides information about the origin, scale and spatial limits of the hydrographic data used to prepare the chart (IHO, 2011). It gives an indirect indication of the quality of data. Effective use of a source diagram requires a good comprehension of past and current hydrographic surveying practices (Heeley, 2003). From the date of survey, the technical methods used in the hydrographic survey can be deduced. This type of knowledge provides an indication of the accuracy of the equipment used for the survey and the expected level of detection of significant seafloor features (Heeley, 2003). The scale of survey gives some indication of the thoroughness and the line spacing for controlled surveys (IHO, 2011). The survey date on the source diagram is grouped into periods in order to represent the accuracy of measurements and survey standards typical to that time period as shown in Table 2.2. It is important to note that proliferation and adoption of survey technology differs between countries. While some countries easily implement new technologies, others are slower in doing so. The table below represents survey technology periods in the United States and may not be applicable to other countries. It is not uncommon to find in charts, especially from countries that lack resources, surveys from the beginning of the 20th century and even earlier. These surveys were often carried by countries that colonized those areas and have not been updated since.

TABLE 2.2: Typical Periods Mentioned in a Source Diagrams (Nos, 1992)

Period	Survey technology	Horizontal accuracy	Depth accuracy	Seafloor Coverage	Classification
Pre 1940	Lead line, Optical position fixing	100-500 m	0.2 m at depth less than 20m	Partial bottom coverage	B4
1940-1969	Single beam echo sounder, Optical position fixing	100-500 m	0.2 m	Partial bottom coverage	B3
1970-1989	Single beam echo sounder, Electronic positioning, side scan sonar	10-50 m	0.2 m	Partial bottom coverage	B2
1991-present	Single beam echo sounder, differential GPS positioning	>0.5 m	0.2 m	Partial bottom coverage	B1
1991-present	Multibeam, differential GPS positioning	>0.5 m	0.2 m	Full bottom coverage	A

2.2 Chart Quality Symbols/Indicators

Chart quality symbols/indicators are cartographic symbols on a chart that supplement depth information and are used to draw attention to the dangers inaccurate depth data portend (IHO, 2011). The chart quality symbols are expected to be clear and conspicuous so that they can easily be seen (IHO, 2011). Chart quality symbols include depth contours, broken depth contours, coastlines and broken coastlines.

2.2.1 Depth contours and broken depth contours

Depth contours are line features connecting points of equal water depth on a chart (IHO, 1994). They represent the shape of the seafloor at the time of the survey. However, when the cartographer is not confident about the quality of the source data, the depth contours are broken (i.e., black dash lines). These broken contours are used to draw attention to inadequacies in the survey data (IHO, 2011). Broken depth contour may be used either with fine upright soundings or widely spaced normal soundings. When used in conjunction with shallow water blue tint they indicate that the extent of the shallow water area is not precisely known (IHO, 2011).

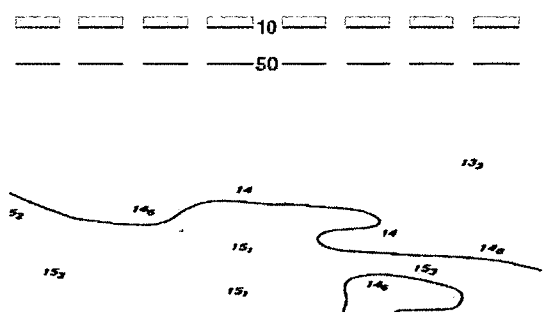


Figure 2.1 Examples of broken depth contours (top) and depth contours (bottom).

2.2.2 Coastlines and broken coastline

A coastline is where the shore and water meet (IHO, 1994). On the chart, they represent the land-water boundary at a selected vertical datum. These features are usually drawn at the mean high water mark or at the mean water line (Mean Sea Level) if the tide range is not significant (IHO, 1994). Similar to a depth contour, an adequately surveyed coastline is represented by a continuous bold line. When there is a lack of confidence in the positional accuracy of the charted coastline, they are represented with broken black lines. These broken coastline symbol indicate to the mariners that the coastline has not been surveyed or is inadequately surveyed. In cases that a surveyed coastline is applied to a nautical chart from smaller scale source or charts, the coastline will also be indicated as a broken coastline.

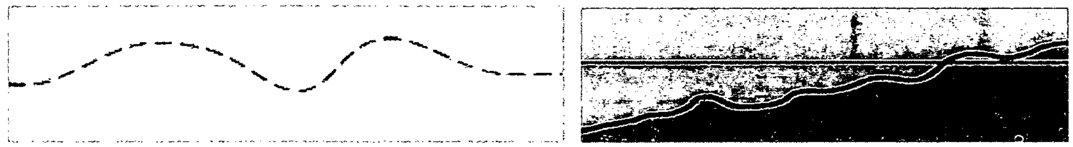


Figure 2.2 Coastline (right) and broken coastline (left).

2.2.3 Slanted and fine upright (hairline) sounding

As specified in IHO INT1, sounding on a nautical chart standard are usually shown as slanting numbers. However, when a charted sounding is produced from a less accurate source (e.g., derived from leadline survey) the less accurate depth is shown as hairline/ upright sounding (IHO, 2011). In order to give a complete picture of the seafloor, the most current survey for each sea areas is used. In cases that the most current survey or the only available survey data for a particular sea area is inadequate and less accurate than other areas with more accurate survey, the less accurate information will be depicted as fine upright sounding on a chart.

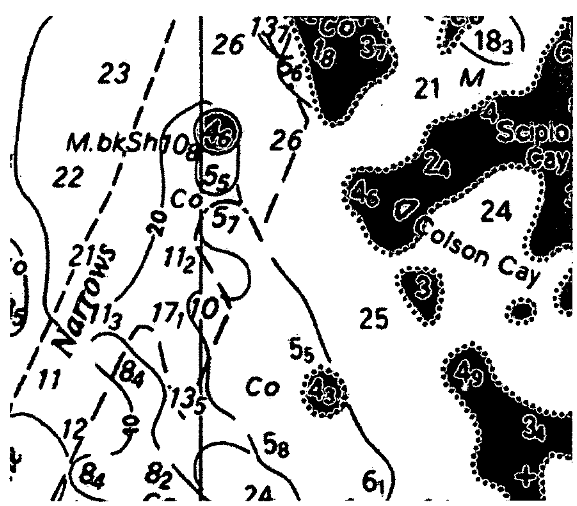


Figure 2.3 Slanted and fine upright soundings in a chart.

2.3 Doubtful Danger Abbreviations

A Doubtful danger abbreviation is used to indicate the positional or depth inaccuracies of features in a nautical chart (IHO, 2011). Where the positional or depth accuracy of a feature within a survey is beyond the error margin for the required order of survey, doubtful position abbreviations are used to draw the attention of chart users to this fact. The doubtful danger abbreviations are shown in italics on the chart.

2.3.1 Position approximate (PA)

PA indicates that the position of a wreck, shoal etc has either not been accurately determined or does not remain fixed (IHO, 1994). Position Approximate marking is typically applied to a feature when the margin of error is greater than 30 m (NOS, 1992).

2.3.2 Position doubtful (PD)

PD indicates that a wreck, shoal, etc has been reported in various positions, but has not yet been verified in any survey means (IHO, 1994). Position Doubtful marking are typically applied when reports to the hydrographic organization are made by observation from mariners on board a non-hydrographic surveys vessel, such as fishing boat or cruise ships.

2.3.3 Existence doubtful (ED)

ED is used to warn mariners of the existence of rocks, shoal etc., the actual existence of which has not been established (IHO, 1994). However, mariners are expected to navigate with caution in the vicinity.

2.3.4 Sounding doubtful (SD)

SD indicates that the depth shown over a rock, shoal etc may be less than indicated (IHO, 1994)

2.4 Chart Completeness

2.4.1 Soundings

Soundings are measured or charted depths of water (IHO, 1994) and are among the most important information on a chart. Soundings on a nautical chart are shoal biased depth information of the seafloor (IHO, 2011). Soundings are derived from survey data collected by various technologies (including, leadline, sonar or LIDAR). They are shown for the entire sea area where available data exists. Depth soundings are even found in very deep places because an absence of soundings suggests sparse or inadequate data. In cases of placement conflict between soundings, the deeper soundings are eliminated in favor of shoal soundings. Sufficient number of soundings (not more than 30 mm between soundings irrespective of chart scale) is retained to show the full range of the depth and allow mariner determine their position by sounding (IHO, 2011). Soundings are drawn as point features. However, the distribution of the soundings, their depth values and the font style can be segmented into areas.

2.4.2 Distribution of sounding

The distribution of soundings can be considered to be an approximate indication of the level completeness of a survey. Evenly distributed soundings show that a systematic methodological procedure has been used to collect the data and may likely have a high level of completeness. However, when the soundings are sparse with blank spaces, the sounding may be from non-hydrographic survey sources and the level of completeness will be poor. The distribution of soundings for a given area however depends on the terrain characteristics of the seafloor. U.S. conventions for sounding spacing are described here. Other nations conventions may vary somewhat although the usually follow similar patterns. In flat and evenly sloping areas, soundings are evenly spaced (not placed closer than 15-30 mm between soundings irrespective of chart scale) and gradually become wider as depth increases (NOS, 1992). In places of irregular seafloors that are characterized by large abrupt variation in depth, the soundings are denser and irregularly displayed on the chart to depict the nature of the seabed. Denser soundings (at least 6 mm apart) are used to draw attention to potentially dangerous areas (NOS, 1992). The selection of soundings ensures that the overall topography of the sea floor is presented in an accurate and complete manner that is easily understood by mariners. Lines of soundings show regularly spaced ensonified areas on the chart with the spacing depending on the survey line spacing. In areas of many features with morphological relief in shallow waters, such as coral areas, it becomes impossible to find every significant obstruction in the area. This area will be shown as a poorly surveyed area and have a positive warning of incomplete survey.

Least depth soundings over features delineated by contours are selected first since they are often associated with hazardous shoal areas. These soundings, usually called "critical soundings," represent the least depths in proximity to known or potential navigational routes (NOS, 1992). Critical soundings are spaced close together to increase the amount of detail presented to the mariner, but are not placed closer than 6 mm to each other on the chart irrespective of the chart scale (NOS, 1992). Supportive soundings are soundings that provide additional information about the shape of the seafloor and show changes in bottom slope away from shoals or deeps (NOS, 1992). They are useful in determining a vessel's position by line of sounding. Supportive soundings can also be used to show the character of significantly deep areas. They are selected only after critical sounding have been placed on the chart. The spacing distance between supportive sounding and the critical soundings should be at least 10 mm apart. Fill soundings are used to depict relatively flat areas and deep areas between shoals that are not covered by supportive soundings. They are used to complete the picture of the seafloor. The spacing between fill soundings is from 15 mm to 30 mm. (NOS, 1992). In spite of the above, it is almost impossible to determine which soundings are fill, critical or support sounding on a chart. Therefore, sparely dense area and blank spaces will be generally regarded as having poor chart completeness.

2.4.3 Chart completeness warnings

Chart completeness warnings and cautionary notes are used to draw the attention of mariners to certain areas that pose a greater degree of risks to navigation which may otherwise not be obvious to them (IHO, 2011). These types of warnings include 'unsurveyed areas', 'incomplete survey', 'inadequate survey' and 'see note'. In areas that are considered dangerous for vessels to enter, bold dashed black lines may be used in conjunction with these warnings to give a very positive form of warning (IHO, 2011).

a. Unsurveyed areas: Unsurveyed area warnings are used to show areas on the chart where there is no existing data derived from any controlled systematic survey (1HO, 1994). These include places having only soundings with lines of passage and isolated ship reports. Unsurveyed areas are depicted on a chart as wide blank areas which may have "Unsurveyed" written. The unsurveyed area warnings are used mostly to draw attention to unsurveyed areas amongst surveyed areas. Although wide blank areas are generally considered to be unsurveyed, bold dashed black line are used to depict the extent of the unsurveyed area that is considered dangerous.

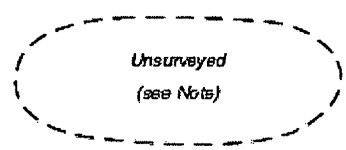


Figure 2.4 An example to an unsurveyed area warning in a chart.

a) Incomplete survey and inadequately area warning: Incomplete survey and inadequately surveyed area warnings are used to draw the attention of mariners to areas on the chart where there are insufficient hydrographic data to identify underwater features that may constitute a danger to navigation (IHO, 2011). These warnings are normally used in cases that the depth measurements are based on older leadline surveys or on reconnaissance surveys and non-hydrographic surveys, such as seismic surveys. These types of surveys do not sufficiently identify all shoals that may exist between lines of sounding and the selected soundings may not have been shoal biased. Incomplete survey and inadequately surveyed areas may be shown on a chart with the limits marked with bold dashed black lines around the warning. In areas with large space between the soundings, these warnings are typically used in the available spaces on the chart to indicate that the general area is inadequately surveyed (IHO, 2011). Upright soundings or slanting soundings with broken contour lines are also used to indicate an area that is inadequately surveyed.

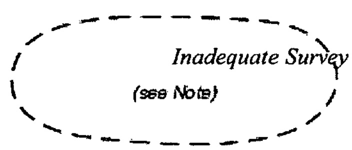


Figure 2.5 An example to an inadequate survey warning in a chart.

2.5 Extraction of Relevant Hydrographic Information

Charts of the study areas were scanned using a "contex scanner" to convert the paper charts to TIF raster format. The rasterized charts were exported to *ArcGIS*. The charts were then geo-referenced. This was done by digitizing pixels corresponding to features with known spatial coordinates of known points (control points). All the geo-referenced charts had a total RMSE of < 0.5 pixel. Chart adequacy class information was identified on the chart and a layer was created for each class in *ArcCatalog*. Each class of information on the chart was then extracted by digitizing (manually tracing) out the information into its layer in *ArcMap* using the digitizing tool.

2.5.1 Source diagram

For both study areas, the source diagrams were scanned and overlaid on the chart. The overlaid raster image was imported into *ArcGIS.* This overlay aided in showing the extent of each hydrographic survey from which the chart was compiled. Hydrographic surveys on the charts were classified based on the NOAA classification of survey periods (see Table 2.2). Surveys from the same period were grouped together under the same classification. For chart 1797 from Belize, the source diagram and the classification results (B2, B3 and B4) are given in Table 2.3. Though survey "h & j" ended in 1991 which borders with the B1 class, the survey was classified as B2. The reason for this classification decision is based on the assumption that the survey technology has not changed during the course of the survey. BA Chart 1797 with overlaid source diagram and the source diagram classification results are shown in Figure 2.6. The source diagram and the classification result (B1, B2, B3, and B4) for BA Chart 3321 are given in Table 2.4. Despite the fact that survey "c" was in 2004, it was classified as B1 rather than A1 because full bottom coverage could not be ascertained from the survey and is considered unlikely. BA Chart 3321from Nigeria with overlaid source diagram and the source diagram classification results are shown in Figure 2.7. Using the digitizing tool in *ArcMap*, each classification result was digitized into a layer.

TABLE 2.3: Source Diagram Classification of Survey Areas (BA Chart 1797)

Survey	Time of survey	Classification
a	1988	B2
b & j	1974	B2
c	1958	B3
e & j	1922	B4
f & j	1834-1840	B4
g & j	1840	B4
h & j	1988-1991	B2
i & j	Unknown date	B4

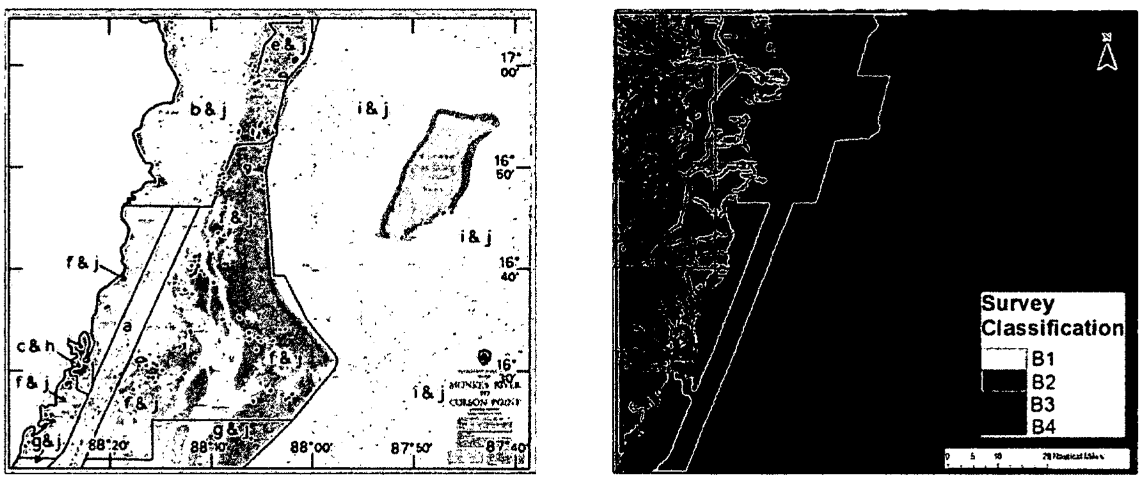


Figure 2.6 Source diagram classification: (left) BA Chart 1797 overlaid with the source diagram and (right) the classification results.

TABLE 2.4: Source Diagram Classification of Survey Areas (BA Chart 3321)

Survey	Time of survey	Classification
a	1984-89	B2
b	1968	B3
c	2004	B1
d	1975-1977	B2
e	1938-1968	B4
f	1910-1913	B4
g	unknown	B4

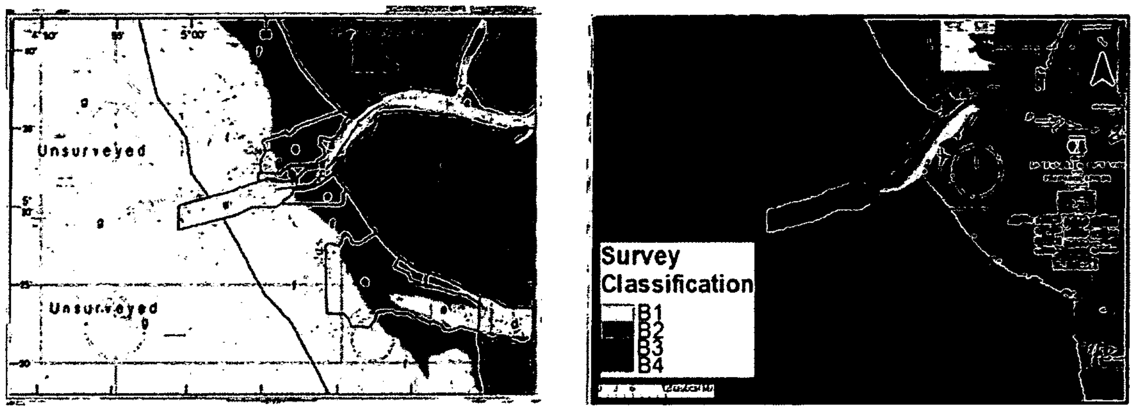


Figure 2.7 Source diagram classification: (left) BA Chart 3321 overlaid with the source diagram and (right) the classification results.

2.5.2 Slanting and Upright soundings

The spatial extent of sea areas covered by marked slanting and upright soundings were identified as separate polygons for BA Chart 1797 and BA Chart 3321.This process involved assigning an area that was covered by slanted and upright soundings. These areas were then digitized as a chart quality layer in *ArcMap* as shown in figures 2.8 and 2.9, respectively.

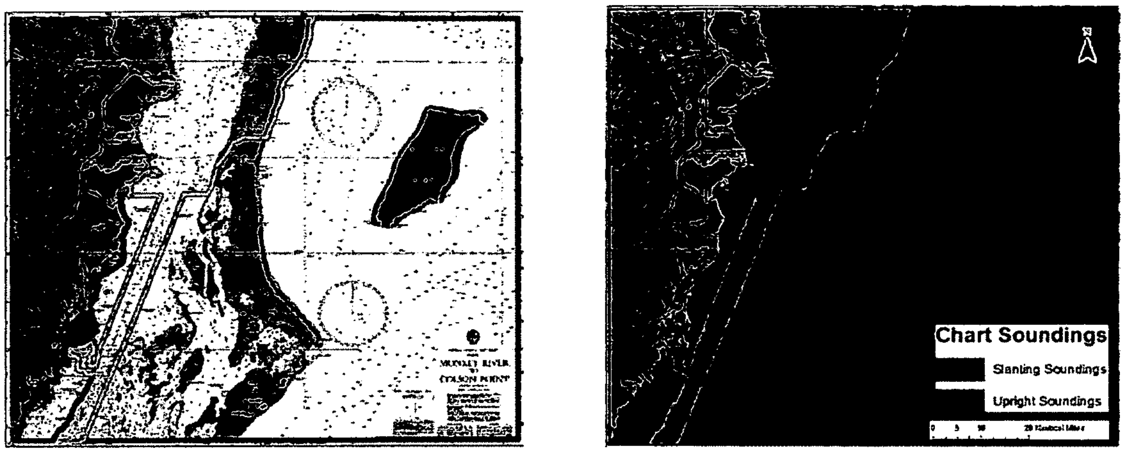


Figure 2.8 Slanting and upright soundings: (left) BA Chart 1797 showing areas of slanting an upright depth sounding and (right) polygons showing areas of slanting an upright depth sounding.

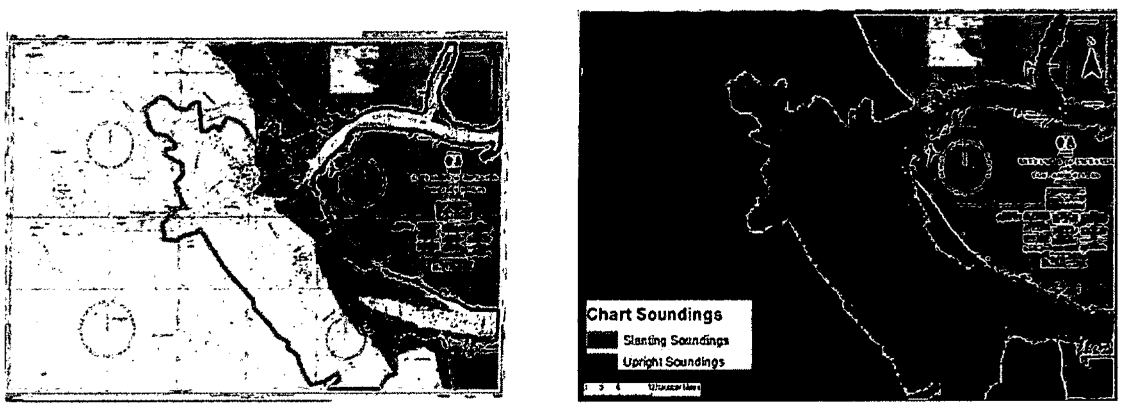


Figure 2.9 Slanting and upright soundings: (left) BA Chart 3321 showing areas of slanting an upright depth sounding and (right) polygons showing areas of slanting an upright depth sounding.

2.5.3 Chart completeness

a) Incomplete survey warning: Incomplete survey warning is used in available spaces on the BA Chart 1797 to indicate that the general area is inadequately surveyed as shown in figure 2.10. The spatial extent of the sea area referred to by the incomplete survey warning is extracted from the chart by digitizing (Manually tracing out) the extent using the *ArcMap* polygon digitizing tool. Areas containing upright soundings which also refer to incomplete survey are included as part of the incomplete survey class. Areas containing slanting depth soundings within the general extent of the incomplete survey warning which refers to a complete survey area are excluded from the polygon. The boundary limits of the incomplete survey warnings are defined by the extent of the area having regular sounding indicting that a form of systematic survey has taken place. In BA Chart 3321, there is no incomplete survey warning on the chart. However, slanting soundings between the broken contour lines refer to incomplete or inadequate survey.

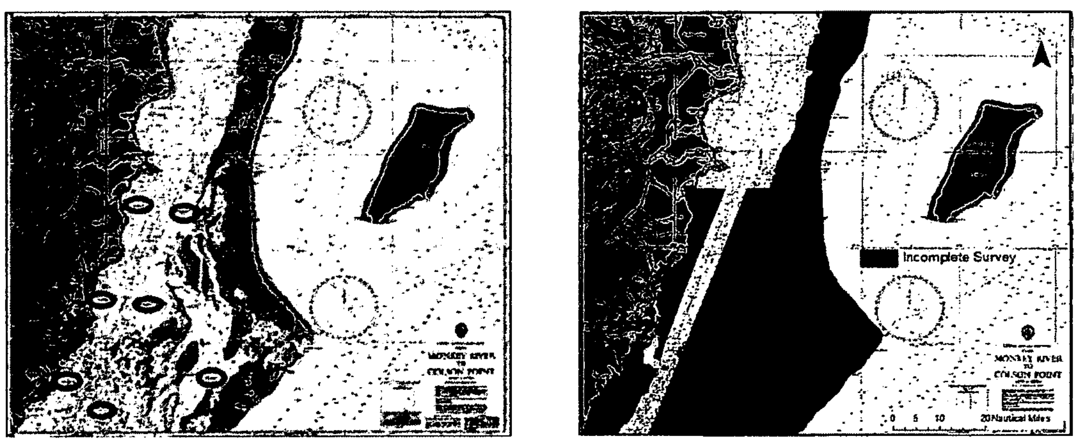


Figure 2.10 Incomplete survey: (left) BA Chart 1797 showing general area of incomplete survey and (right) polygons showing areas of incomplete survey.

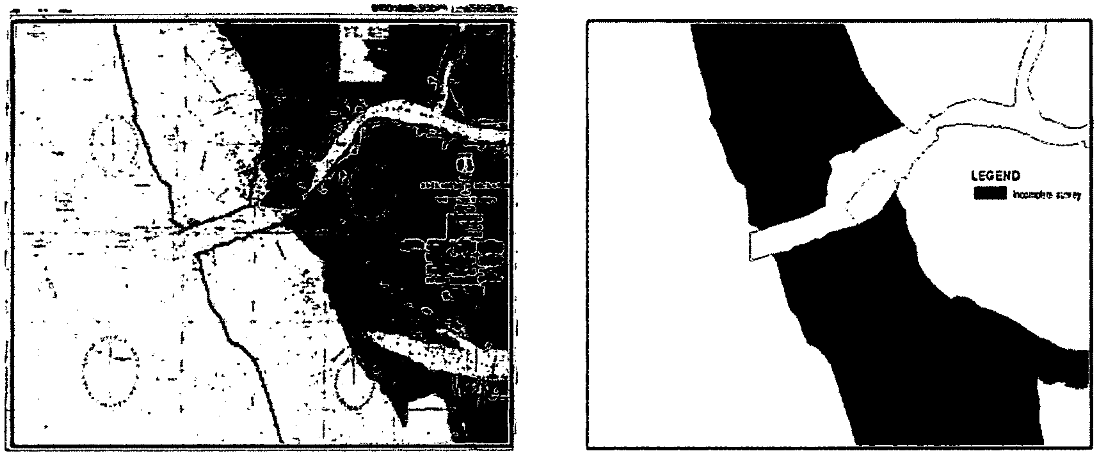


Figure 2.11 Incomplete survey: (left) BA Chart 3321 showing general area of incomplete survey and (right) polygons showing areas of incomplete survey.

b) Unsurveyed area: Isolated lines of soundings and blank spaces in BA Chart 1797 indicate that the sea area has not been systematically surveyed and show a poor level of survey completeness. The spatial extent of this area on the chart is extracted as shown in figure 2.12. For BA Chart 3321, unsurveyed warning is used in the available space to show the area is unsurveyed. However the boundary limits of the unsurveyed areas are defined by the extent of isolated lines of soundings and blank spaces on the chart. The extent of the unsurveyed area by the mouth of the Escravos River was depicted based on the information from the National Geospatial Intelligence Agency (NGA) sailing directions, which mentions several unsurveyed areas at the river mouth as shown in figure 2.13. The remaining area of the chart area is assumed to have good survey completeness (more of acceptable survey completeness) within the limits of the accuracy of the survey. It should be noted that this does not mean the all significant obstructions in the "good survey completeness" area have been identified.

> Vessels should approach the mouth of the Escravos River with caution due to several unsurveyed areas lying off the coast in this vicinity.
>
> 2.20 Koko (6°00'N., 5°28'E.) (World Port Index No. 46140) is situated on the N bank of the river. It is a large settlement and extends for about 1 mile along the shore. The main

Figure 2.12 Extract from the NGA sailing direction showing where several unsurveyed areas at the mouth of Escravos channel are mentioned.

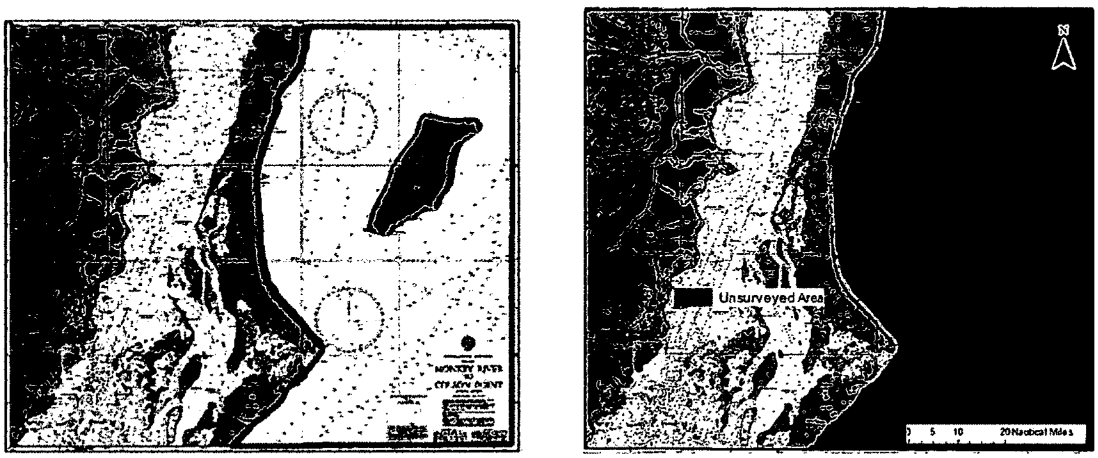


Figure 2.13 Unsurveyed area: (left) BA Chart 1779 showing the isolated lines of soundings and blank spaces (right) polygon showing unsurveyed area.

Figure 2.14 Unsurveyed area: (left) BA Chart 3321 showing area of unsurveyed warning, isolated lines of soundings and blank spaces (right) polygon showing unsurveyed area.

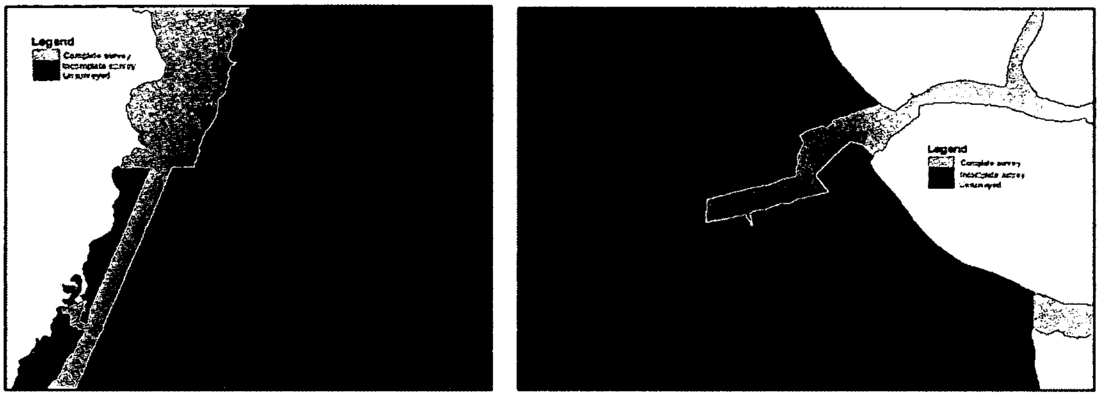


Figure 2.15 Survey completeness: (left) BA Chart 1797 and (right) 3321 showing poor and good survey completeness.

2.5.4 Doubtful danger abbreviation

The positions of two wrecks on BA chart 1797 were marked with PA. In this study, where doubtful danger abbreviations are located between soundings, the PA points were designated using a 500m buffer zone (see figure 2.16). For chart 3321, the position of two drying heights and two PA wrecks were also marked with a 500 m-buffer as shown in figure 2.17. In charts, ED, SD or reported feature were not seen and not used in the current chart adequacy process. It is important to note that ED, SD or reported feature should be processed the same way as a PA feature.

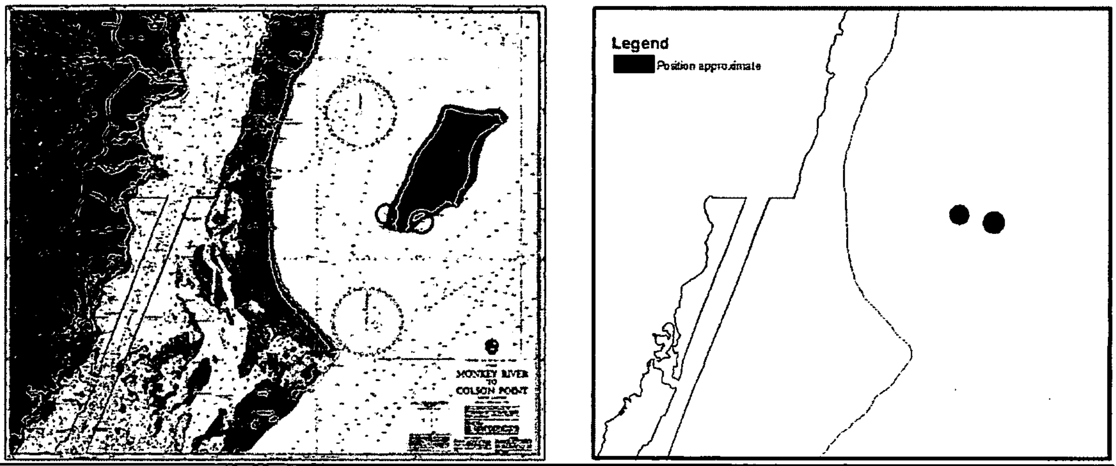


Figure 2.16 Position approximate: (left) BA Chart 1797 showing area of wrecks marked with *PA* (red circle) and (right) doubtful danger abbreviations class.

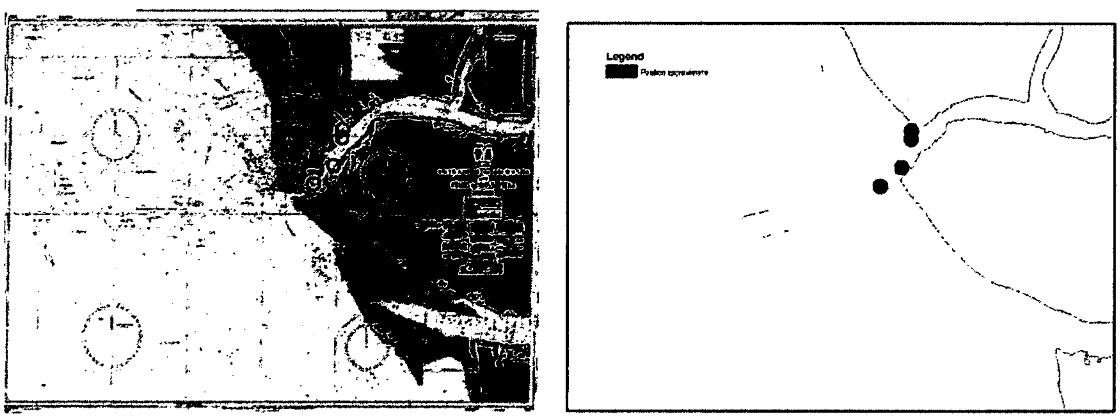


Figure 2.17 Position approximate: (left) BA Chart 1797 showing area of wrecks marked with *PA* (red circle) and (right) doubtful danger abbreviations class.

2.5.5 Depth areas

Depth areas were classified based on the type of vessels using the sea area covered by the chart. In BA chart 1797, it is noted that the harbor was dredged to 7 m (fig 2.18). Thus, it could be deduced that vessels entering Big Creek port are expected to have a draft less than 7 m. Vessels are not expected to operate in areas less than 1m of depth. The inner channel has an average depth of about 15 m, i.e., vessels with less than 15 m drafts are expected to navigate safely within channel. The 40 m contour is based on the maximum expected draft for any vessel which is 40 m (IHO, 2008). Based on these navigational depth areas, the chart was classified into four (4) depth areas: 1 - 7m, 7 - 15m, 15 - 40m, and >40 m (Table 2.5). The navigational significant depth area classification results for BA Chart 1797 are shown in Figure 2.19.

For chart 3321, the depth of the mouth of the navigation channel near the entrances of the Escravos and Forcados channel is about 5 m (Fig 2.20). The Escravos oil terminal has two single buoy loading moorings with depths 20 m and 30 m. It can be deduced that only vessels drawing less than 20 m can have access to these locations. Based on the above, the chart is classified into four (4) depth areas: 1 - 5m, 5 - 30 m, 30 - 40m, and >40 m (Table 2.6). The navigational significant depth area classification results for BA Chart 3321 are shown in Figure 2.21.

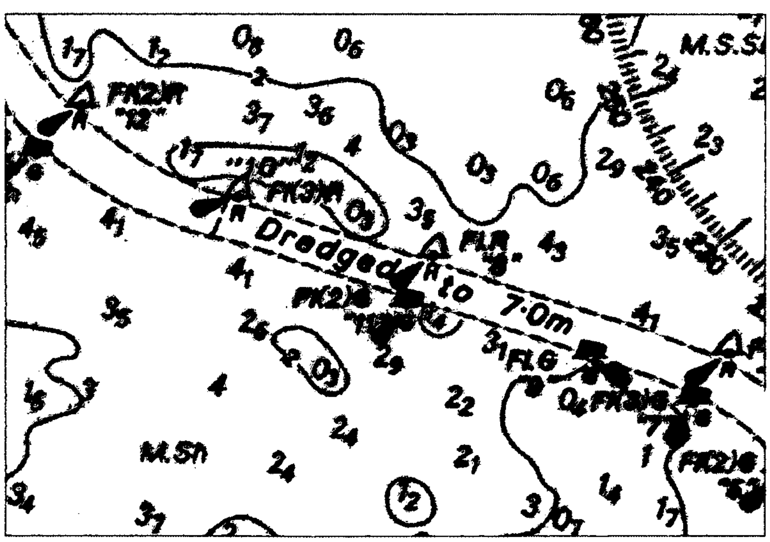


Figure 2.18 Extract of BA Chart 1797 showing the channel dredged to 7 m.

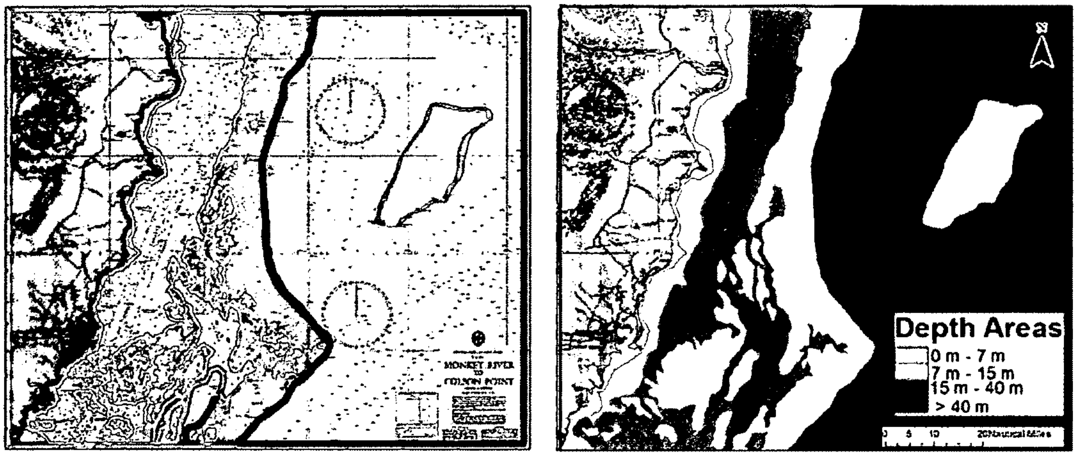


Figure 2.19 Navigational significant contours (left) BA Chart 1797 with the navigational significant depth area classification.

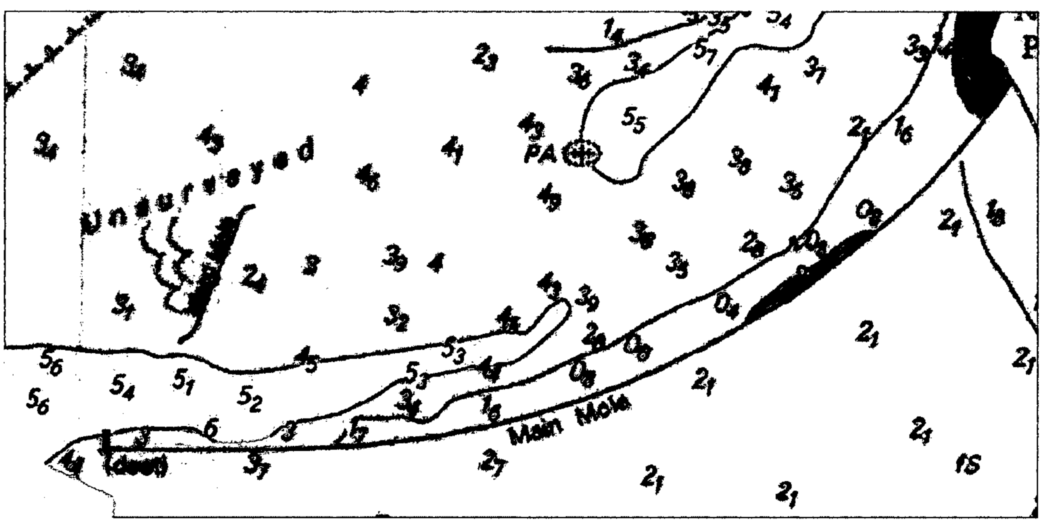


Figure 2.20 Extract of BA Chart 3321 showing charted depths at the mouth of the Escravos River entrance.

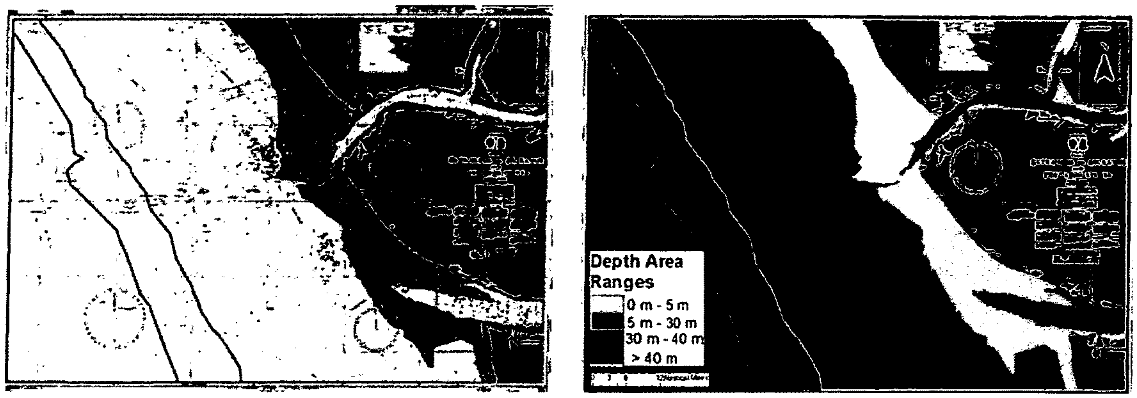


Figure 2.21 Navigational significant contours: (left) BA Chart 3321 with the navigational significant depth area classification.

III. MARITIME SIGNIFICANT AREAS

The second rating scale for prioritizing marine areas within the chart is based on maritime significant areas. These areas were prioritized based on their navigational importance as they help to maintain lines of communications in support of commerce and other economic activities, such as ports, harbors, navigational channels and roadsteads/anchorages. Maritime significant areas also comprise areas of cultural and natural importance as defined by a nation, such as marine protected areas (MPA), military restricted areas, and areas for exploration of natural resources. Prioritizing these maritime areas may not coincide with the priorities of other nations or maritime users. In contrast to chart adequacy evaluation in which the adequacy score is based on the survey accuracy and coverage represented in the chart, marine significant areas are based on the current usage and needs of the nation. Thus, the coverage and priority of an area may change with time regardless of any hydrographic update. In the context of nautical charting and safety to navigation, the maritime significant areas are divided into navigational significant areas and 'Other' maritime significant areas. In this study, only navigation significant areas will be considered for the priority rating.

3.1 Navigational Significant Areas

3.1.1 Ports/harbors

A port is defined as "a place provided with terminal and transfer facilities for loading and discharging cargo or passengers, usually located in a harbor" (IHO, 1994). Harbors are defined as natural or artificially improved bodies of water providing protection for vessels and generally anchorage and docking facilities (IHO, 1994). Ports are usually located within a harbor and their navigable depth usually depends upon the draft of vessels that visit the port. A deep-water port must be able to accommodate very large ships that may reach 290 m in length, width of 33 m and a draft of 12m (Dasguputa, 2011). Port facilities and harbors are shown on a chart to reflect their actual geometric shape especially on a large scale chart. Figure 3.1 is a schematic example for a pier (port facility symbolize by the T shaped structure) within the tidal harbor (the tides rises and falls freely within the harbor).

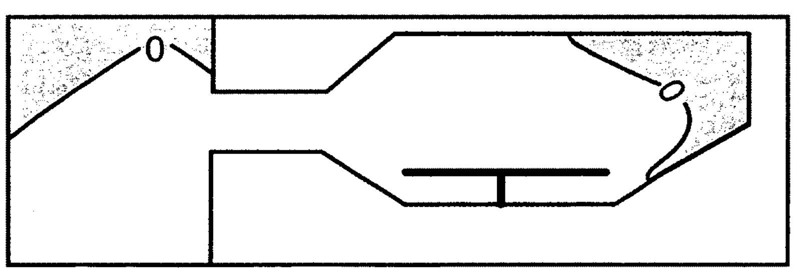


Figure 3.1 An example of a pier within a tidal harbor on a chart. The pier is the T shape black structure while the rest of the area symbolizes the harbor (IHO, 2011).

3.1.2 Navigational channels

Navigational channels are that part of a body of water (sometimes dredged) deep enough for navigation through an area otherwise not navigable (IHO, 1994). The channels are typically marked with a buoy system that defines the limits of the channel within which it is safe to navigate (Fig 3.2). Broken black lines are often used with buoy symbols to mark the limits of the channel on a chart (IHO, 1994). However, not all channels are marked. Unmarked channels are shown on the chart with maritime limiting broken black line which defines their boundary. Depending on the nature of the seafloor, channels may be dredged to maintain their intended depth.

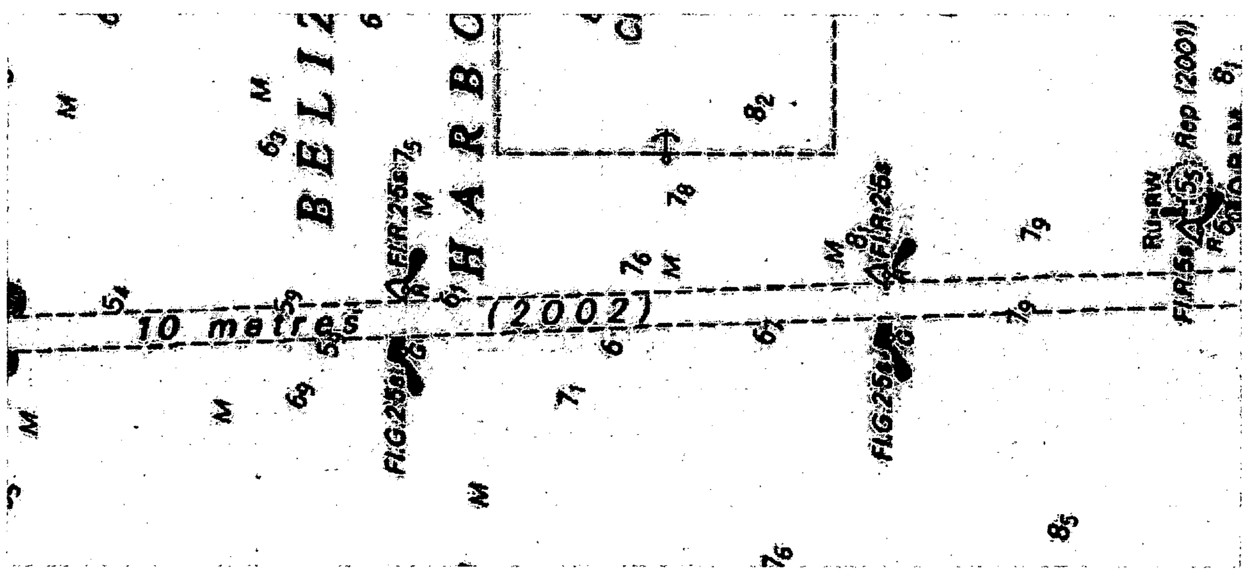


Figure 3.2 An example of a navigation channel marked by a buoyage system on a BA Chart 522.

3.1.3 Anchorage /Roadsteads

Anchorages are areas where ships can anchor or may anchor (IHO, 1994). They are usually located in sheltered bays or portions of the sea adjacent to a harbor where vessels may lie in safety at anchor until allowed into the harbor. Natural anchorages offer protection from winds. An anchorage is typically shown on the chart with anchor symbol. An anchorage area normally has its boundary defined by a dashed black line overlying anchors at intervals with an anchorage symbol in the middle. The type of vessels allowed to anchor in a particular anchorage may be indicated on the chart by inserting the vessel type beside the anchorage symbol (Figure 3.3). Roadsteads are areas near the shore, where vessels can anchor in safety; usually a shallow indentation in the coast (IHO, 1994). They are usually open anchorages (Cockcroft and Lameijer, 2004). In some waters, transiting of an area is allowed but anchoring is prohibited. This is mainly to prevent fouling and probable destruction of infrastructure such as oil pipe line or objects of national importance like archeological sites. A line of T- shaped dashes pointing inwards towards the area in question with a cross overlaid on an anchor at regular intervals is used to mark the boundary of the area when anchoring is prohibited (Figure 3.4).

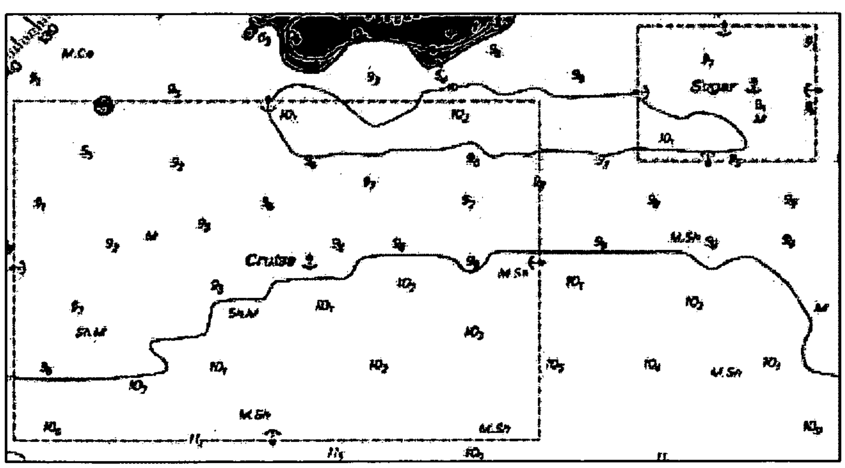


Figure 3.3 Anchorage area symbol (BA chart 522).

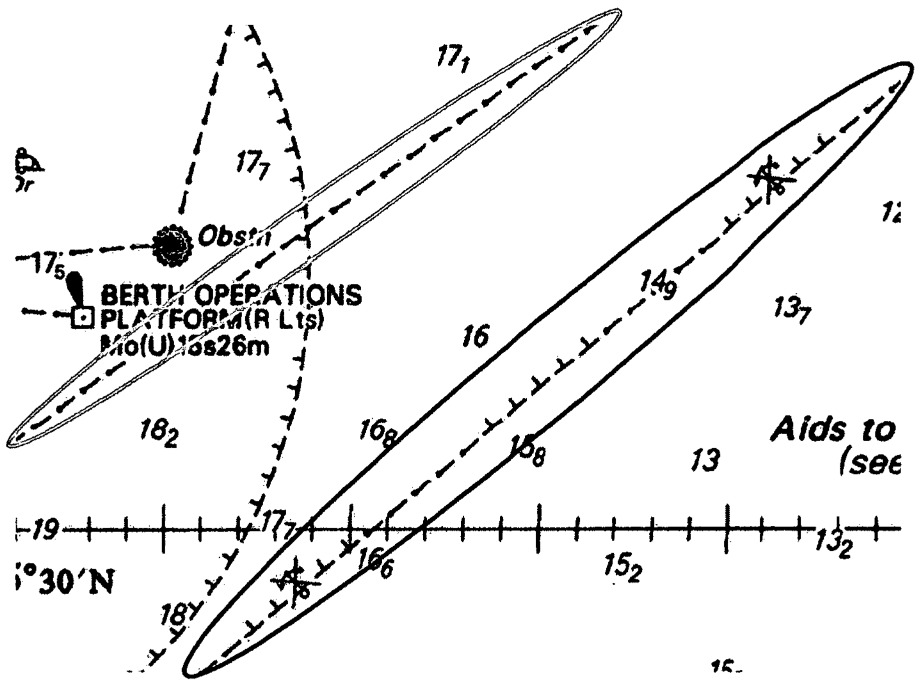


Figure 3.4 Showing the anchorage prohibited symbol (circled in red) in the vicinity of oil pipe lines (circled in blue) and rigs (BA Chart 3321).

3.2 Other Significant Maritime Areas

3.2.1 Marine protected areas and particularly sensitive sea areas

MPA are areas within the maritime area where protective, conservation, restorative or precautionary measures, consistent with international law have been instituted for the purpose of protecting and conserving species, habitat, ecosystems or ecological processes of the marine environment. A Particularly Sensitive Sea Area (PSSA) is defined as "an area that needs special protection through action by IMO because of its significance for the recognized ecological, socio-economic or scientific reasons and because it may be vulnerable to damage by international shipping (IMO A.982 (24)). These areas can be located in the open ocean or in the coastal areas. MPA's are marine areas that are already affected or potentially will be affected by development, pollution, overfishing and natural events that have put a strain on the health of the coastal and maritime ecosystem. MPA include submerged cultural resources that reflect a nation's maritime history, natural biological communities, habitats ecosystems and renewable living resources. A common goal of MPAs is to provide recreation and economic opportunities and sustain critical resources for future generation.

3.2.2 Fishing grounds and fishing zones

Fishing grounds are marine areas in which fishing is frequently carried on, while fishing zones are offshore areas in which exclusive fishing rights and management are held by the coastal nation (IHO, 1994). At times, countries delineate fishing grounds on a chart and restrict fishing in the waters. The restrictions may range from a permanent restriction or a seasonal restriction to a fishing permit restriction. For example, fishing trawlers are restricted from some fishing grounds to prevent unfavorable competition with local fishermen fishing with ordinary nets. Hydrographic data is usually required in fishing grounds for habitat mapping and to prevent fishing vessels running aground, damaging the fish habitat or fouling their net by underwater obstructions. Fishing grounds are not normally charted, but fishing prohibited areas are always charted. The typical symbol for a restricted fishing area is a cross overlaid on a fish (Figure 3.5).

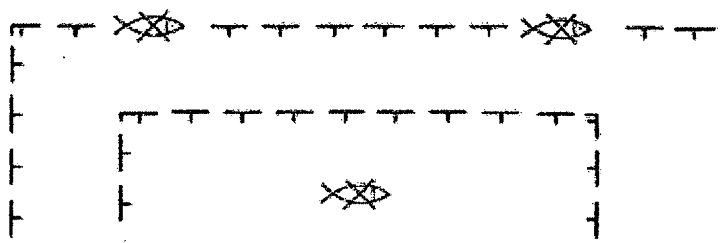


Figure 3.5 Chart symbols for a fishing prohibited area (INT Chart 1).

3.2.3 Defense areas

These are strategic marine areas where military and policing activities take place. Defense areas include explosives dumping grounds, military practice areas and submarine exercise areas. Others are strategic areas or sea routes that enable effective policing of a nation's territorial waters in support of anti-smuggling and illegal immigration law enforcement. When passage is prohibited in a defense area, the limits are marked on a chart with T- shaped dashes pointing towards the area in question. Positive warning like "entry prohibited", "submarine exercise areas" or mine symbols may be used to further draw the attention of the mariner to the area (IHO INT Chart 1).

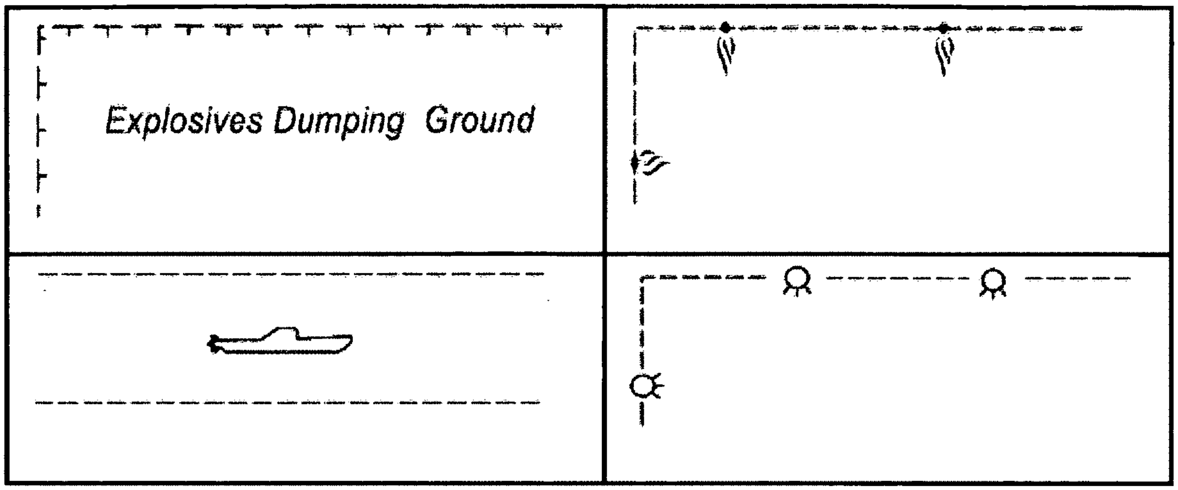


Figure 3.6 Chart symbols for activities in military restricted areas: (top left) explosive dumping ground (top right) firing danger area (bottom left) submarine transit lane and exercise area (IHO INT Chart 1)

3.2.4 Recreational areas

Recreational areas are marine areas for water recreation, such as scuba diving, snorkeling, recreational fishing, or surfing. It should be noted that many marine recreational areas are MPAs, where leisure activities are allowed. Activities within the area are closely monitored to prevent damage to the environment. Recreation areas may or may not be marked on a chart.

3.2.5 Offshore mineral development areas

These are offshore areas where mineral exploration and other exploitation activities take place. Offshore mineral development areas can range from very shallow intertidal areas to depth of about 3000 m, which is about the maximum operational depth of today's equipment (Tanaka et al., 2004). These areas may be shown on the chart, especially if they have infrastructure that may obstruct marine traffic flow, such as pipelines and rigs.

Anchoring is usually prohibited in the vicinity these infrastructure and the area is delineated with an anchorage prohibited delineating marks as shown in Figure 3.4.

3.3 Extraction of Maritime Significant Areas

Similar to the rating procedure of chart adequacy information classes, maritime significant areas rating was also conducted using the BA Charts 1797 (Big Creek approach, Belize) and BA Chart 3321 (Escravos approach, Nigeria) and their sailing directions. The Maritime significant areas category gives an indication of how sea areas are used, thus, areas that directly support the safe conduct of shipping traffic will have a higher rating in the evaluation. Navigational significant areas such as the channel, anchorage area and anchorages prohibited areas were extracted based on the available information on the chart and sailing directions. A layer was created for each maritime significant area class in *ArcCatalog*. Each identified significant sea area was traced out into its class layer in *ArcMap*.

3.3.1 Navigational channel

On BA Chart 1979, two channels are noticeable. The first is small channel leading to Big Creek port. This channel has well-defined boundaries with a region "B" buoyage system with green port hand buoys and red starboard hand buoys according to the sailing directions (fig 3.7). Also on BA chart 1797, a geographic zone named the "Inner Channel" defines the lagoon/channel between the Belize mainland coast and the reef system. A navigational channel within the "Inner Channel" is only partially defined by dashed black lines in the central and southern part of the chart. The channel boundaries were extrapolated in the northern part based on average depth of the maritime limits of the channel in the southern part of the chart that ranges between 14 to 22 m (fig 3.8).

Figure 3.7 Big creek channel: (left) BA Chart 1797 showing the channel into Big Creek marked with buoys. (right) polygon showing the extracted channel.

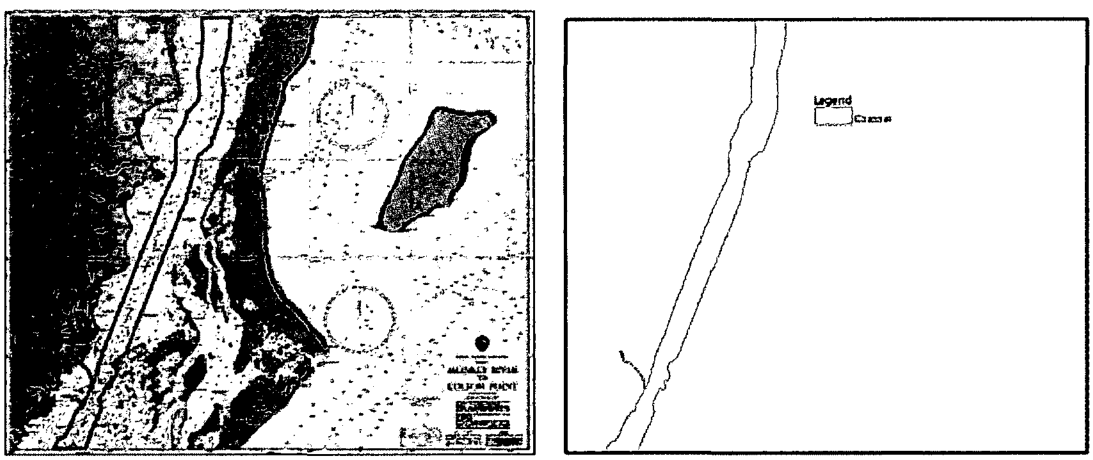
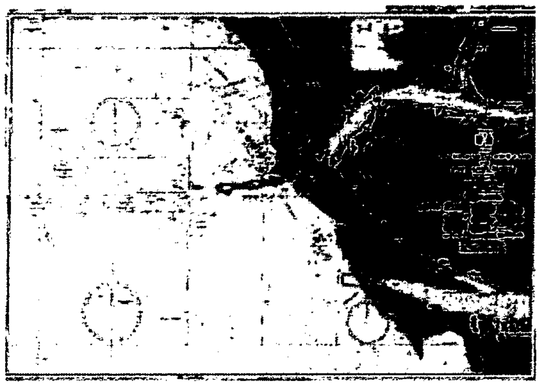


Figure 3.8 The Inner Channel: (left) BA Chart 1797 showing the Inner channel represented with a red line, (right) polygon showing the extracted channels.

For BA chart 3321, no channel limits were marked on the chart. However, the NGA sailing directions state that the channel is within the 5 m depth contours. Although there are areas shallower than 5 m within the Escravos and Forcados River channels (Figure

2.21) and separate the channels into two parts, the channels were digitized out to the navigation significant area layer as a continuous feature (Figure 3.9).



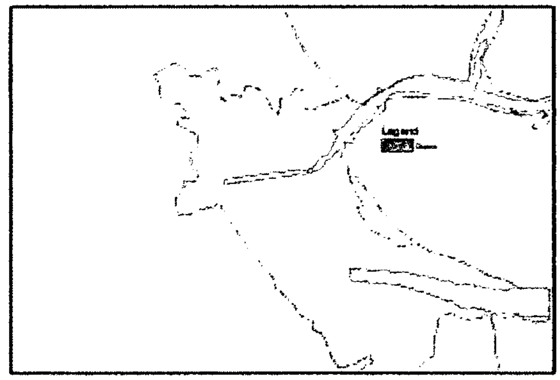


Figure 3.9 Escravos and Forcados channels: (left) BA Chart 3321 showing the channels represented with a green line, (right) polygon showing the extracted navigation channels.

3.3.2 Anchorage

The Big Creek anchorage area (BA Chart 1797) is shown with an anchor symbol without any marked boundaries. However, the NGA sailing directions defined the anchorage boundary as follows: "vessels may anchor within the 10 m contour line 0.3 Nm south of Placentia point." This does not give the exact limits of the anchorage. For this study, the limits the anchorage area were based on the anchor symbol on the chart to the boundary of the marked channel having the east and west boundaries as the 5 and 10 m contour line, respectively. Furthermore, another anchorage symbol is shown at the entrance of the Big Creek channel. However, the boundary of this area was not shown on the chart or mentioned in the sailing directions. The polygons for both anchoring areas as shown in figure 3.10.

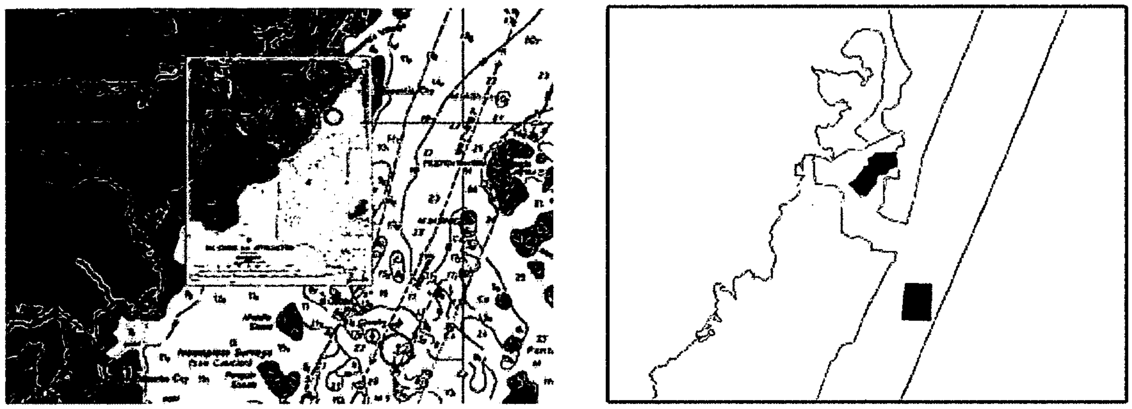


Figure 3.10 Big Creek anchorage areas: (left) BA Chart 1797 showing the anchorage symbol represented within a red circle, (right) polygon showing the extracted anchorage area.

The anchorage area near the Escravos Channel (BA Chart 3321) is marked near the Escravos oil terminal (Figure 3.11). The extent of the anchorage was not shown on the chart and not mentioned in the sailing directions. In addition, anchorage prohibited areas are also shown on the chart (fig 3.12). These areas that contain oil and gas pipelines infrastructure that is located on and below the seafloor. The restriction is based on the possible environmental disaster from a damaged pipeline due to anchoring. Although this area also has offshore mineral development significant areas, only the navigation significant areas were considered in this study.

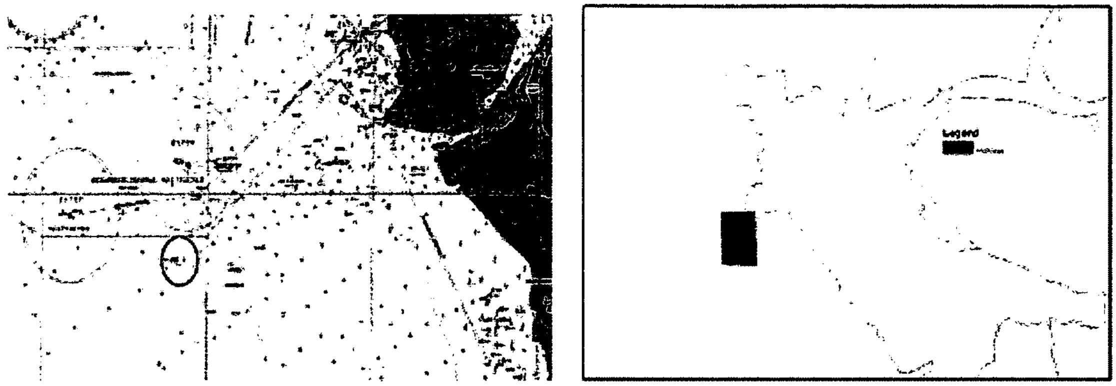


Figure 3.11 Escravos anchorage areas: (left) BA Chart 3321 showing the anchorage symbol represented within a red circle, (right) polygon showing the extracted anchorage area.

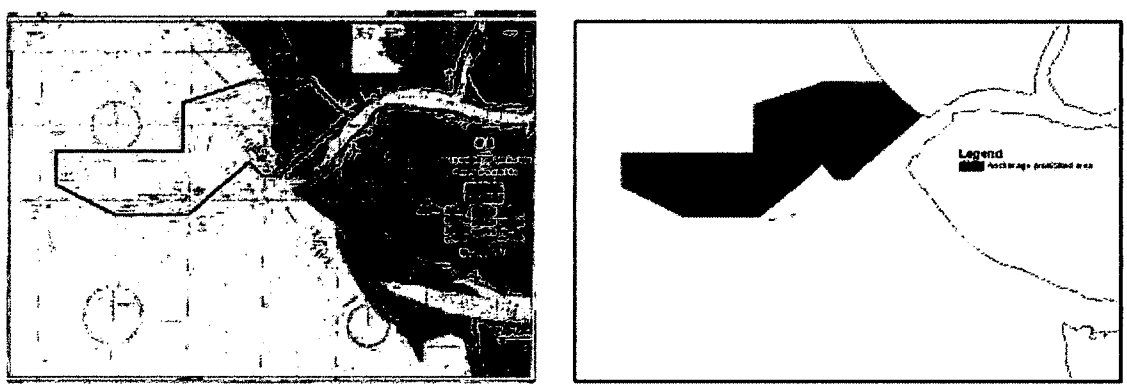


Figure 3.12 Escravos anchorage prohibited area: (left) BA Chart 3321 showing the anchorage prohibited area represented with a red line. (right) polygon showing the extracted anchorage prohibited area.

IV. PRIORITIZING MARITME SIGNIFICANT AREAS

4.1 Rating of Chart Adequacy Information Classes

The Chart adequacy and completeness information scale was evaluated based on five (5) criteria: zone of confidence or source diagram (Section 2.1), chart quality symbols/indicators (Section 2.2), doubtful danger markings (Section 2.3), survey completeness (Section 2.4) and navigation significant depths (Section 2.4). Each class was further divided into various elements that are related to chart adequacy for safe navigation.

A weighted percentage was allocated to each class based on the assessed importance of each class in deciding a safe route for a voyage. In plotting a track, the mariner evaluates all available information required to make a successful voyage. In doing this, he or she considers information in order of relative importance. For example, the depth on a chart is very important as it tells the mariner where a vessel can and cannot go in with respect to his draft. So if its draft is more than the charted depth it cannot go in that direction. While PA on a wreck is important, it will not stop a vessel from going through the area; rather the vessel will navigate with particular caution in the vicinity of danger. From this example, it can be assessed that depth is a more important consideration than "PA" in the navigation of the vessel.

Furthermore, each element of a chart adequacy information class was numerically rated by the degree of danger it poses to the safety of navigation, ranging from least danger to the safety of navigation (1) to the most danger to the safety of navigation (5). An example is the source diagram class which has A1, B1, B2, B3 and B4 as its elements. A1 is recent (1991-Present) survey collected with 100% seafloor coverage using RTK positioning. While B3 (1940-1961) is an older single beam survey that used optical systems for positioning. A1 poses less danger to shipping traffic because its currency, high positional accuracy and 100% coverage than B3 which has a relatively poor positioning and not all significant features have been identified. Subsequently, a rating of the source diagram will give A1 a lower rating than B3 because it poses less danger to safety of navigation.

This procedure involved an expert assessment by an experienced mariner on the relative importance of the chart adequacy information in the conduct of a vessel. Though the assessment is subjective, the robustness of the evaluation was further confirmed by a sensitivity test. The sensitivity test appraised how the variability in assigned weights and rating affected the chart adequacy assessment. The Chart adequacy information class ratings are summarized in Table 4.1.

4.2 Depth Area

The Depth area was considered the most important criteria in determining the adequacy of a chart for navigation. As the mariner plans the vessel route through an area, a major consideration is the water depth in relation to the vessel's draft. From expert assessment, the navigation significant depth criterion was given a weight of 50%. The ranges 1 to 7m (5), 7 to 15m (4) and 15 to 40m (3) elements in the depth class were rated according to the danger the depth range within the class poses to navigation. This is based on the assumption that the probability of a vessel to run aground increases with decreasing depth. Also, changes in the sea floor will likely reduce under keel clearance in shallow waters than in deep waters. The area of water depths greater than 40 m was rated as 1 because of its low hazard potential, as no ship draft is expected to be deeper than 40m.

4.3 Source Diagram

The source diagram class was classified based on the period of survey. The source diagram class serves as a qualitative accuracy estimate of the survey. Thus, its influence in determining the adequacy of a chart for navigation is considered second to the depth class and was given a weight of 20%. The elements of the source diagram class were rated as: A1 (1), B1 (2), B2 (3), B3 (4) and B4 (5).

4.3.1 Chart completeness

Chart completeness was classified based on thoroughness of the survey. While some areas in a chart were considered complete within this class, it cannot be ascertained from the chart or sailing directions if all major obstructions that may pose a danger to navigation were identified. Accordingly, chart completeness was considered to have limited reliability in determining the adequacy of a chart for navigation and was given a weight of 15%. The elements complete, incomplete survey and unsurveyed areas were rated 2, 4 and 5, respectively.

4.3.2 Doubtful danger

Doubtful danger class was classified based on the positional or depth uncertainty of soundings and other hydrographic features. The class usually covers a small area and is considered of limited influence in determining the adequacy of a chart for navigation. Accordingly, the class was given a weight of 5%. The class elements "PA" and "SD" are rated as '4' because of their known existence, but their position is in doubt. "ED" is rated as '5' because its existence is also in doubt.

4.3.3 Chart quality symbols

The chart quality symbol class provides information on the quality of the sounding data. These symbols are useful in warning mariners of the available data accuracy. The use of the chart quality symbols is relatively subjective, giving room to some level of inconsistency. Accordingly, the class is considered to be of limited use in determining the adequacy of chart for navigation and is given a weight of 10%. The elements of the class slanting and upright soundings are rated 2 and 5, respectively.

TABLE 4.1 Chart Adequacy Areas Scores

Class	Weight	Element	Assigned Rating	Score
Depth Area	50%	Deep waters	1	0.5
		Moderate deep	3	1.5
		Shallow	4	2.0
		Very shallow	5	2.5
Source diagram	20%	A1	1	0.2
		B1	2	0.4
		B2	3	0.6
		B3	4	0.8
		B4	5	1.0
Chart completeness	15%	Complete	2	0.3
		Incomplete	4	0.6
		Unsurveyed	5	0.75
Doubtful danger	5%	PA	4	0.2
		SD	4	0.2
		ED	5	0.25
		Reported	5	0.25
Chart quality symbols	10%	Slanting	2	0.2
		Upright	5	0.5

4.4 Study Results of the Chart Adequacy Classes

In order to assess the chart adequacy for navigation, the class layers were compiled together into one layer based on the assigned weights and the rating factor of each element within the class. Using *ArcGIS*, the classes were summed together using a weighted overlay table. By expert assessment, the resulting marine areas were rated "not adequate (4.2-5.0)", "low (3.6- 4.2)", "moderate (2.9-3.6)" and "high adequacy (1-2.9)" based on manual classification method derived from empirical observation of BA chart 1797 and 3321 (Table 4.2). Areas scored "not adequate" were usually unsurveyed or incomplete survey areas and places with lead line survey. By visual observation, the score of "not adequate" areas range from 4.2 -5.0. Low adequacy areas have the same characteristics as "not adequate" areas but occur in comparatively deeper waters than "not adequate" areas. The low adequacy areas were observed to have scores ranging from 3.6 - 4.2. Moderate adequacy characterizes areas that were systematically surveyed using echosounders (pre-1990 echosounders). They occurred in areas with score values ranging from 2.9 to 3.6. High adequacy describes areas that were systematically surveyed using modern survey equipment with high accuracy (Multibeam sonar and RTK GPS) and where observed to have values ranging from 0 to 2.9 (Table 4.2). However, unsurveyed or incomplete survey areas may have a moderate or high adequacy if the depths of the survey areas are greater than 40 m. Also, it is important to note that the chart adequacy results consider only the surveying perspective and not the marine significant areas (no geo-political considerations).

TABLE 4.2 – Scores for Chart Adequacy Classification

Adequacy Rating Category	**Score Range**
Not adequate	4.2 – 5.0
Low	3.6 – 4.2
Moderate	2.9 -3.6
High	< 2.9

The study results show that 21% (1277 km^2) of the total marine area (5933km^2) in BA Chart 1797 of Belize and 27% (571km^2) of the total marine area (2112 km^2) in BA Chart 3321 of Nigeria are rated as "not adequate". The adequacy score results for BA Chart 1797 are presented in Figure 4.1, where 4% (225 km^2) are rated as low, 12% (3408 km^2) are rated as moderate, and 63% (3743 km^2) are rated as high (Table 4.3). The chart adequacy score results for BA Chart 3321 are presented in Figure 4.2, where 41% (875 km^2) are rated as low, 10% (201 km^2) are rated as moderate ,and 22% (465 km^2) are ranked as high (Table 4.4). Some unsurveyed areas east of the Great Barrier Reef within BA chart 1797 and areas about 20 Nm off the coast of BA chart 3321 were ranked as moderate and high adequacy for navigation. The reason for this ranking is that the seafloor is more than 40 m deep and is not considered a danger to mariners. However, there is still a possibility of unidentified objects projecting from the seafloor which may be hazardous to vessels.

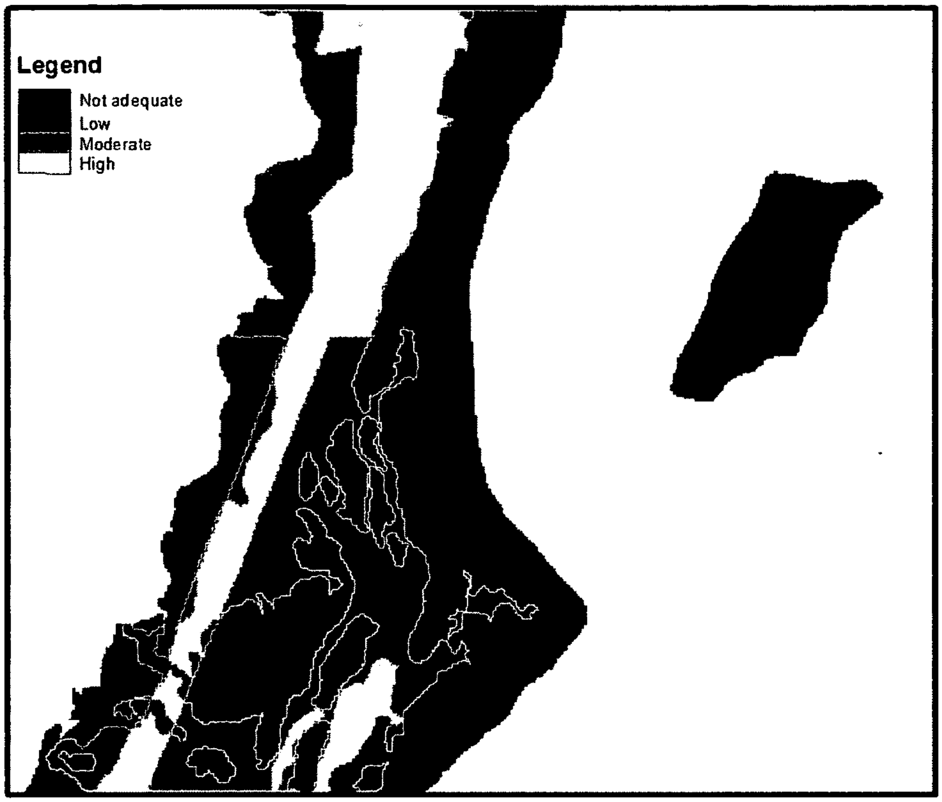


Figure 4.1 Chart adequacy ratings for BA Chart 1979.

TABLE 4.3 Chart Adequacy Ratings for BA Chart 1979 as Percentage of the Total Marine Area.

Adequacy rating	Coverage area (km^2)	Percentage (%)
Not adequate	1277	21
Low	225	4
Moderate	689	12
High	3743	63
Total area	5933	100

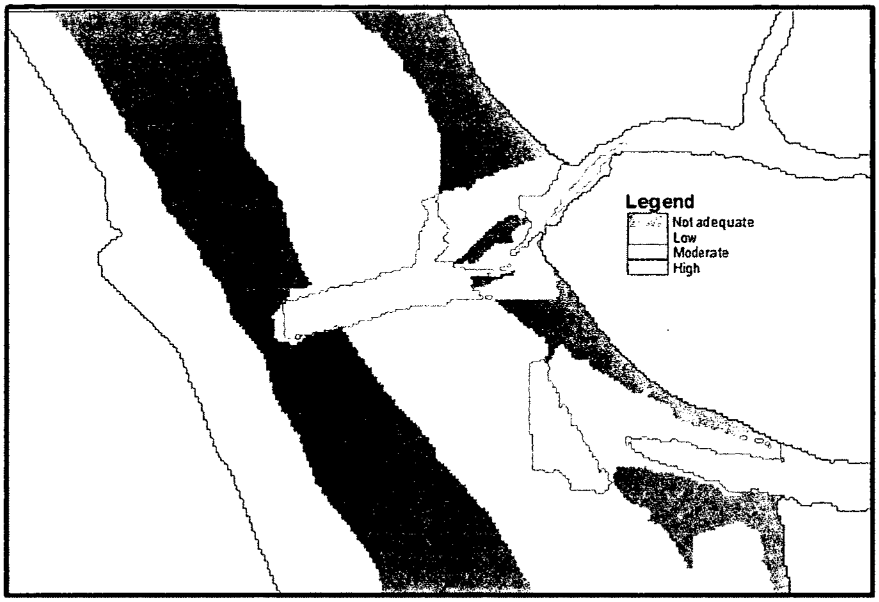


Figure 4.2 Chart Adequacy rating for BA Chart 3321.

TABLE 4.4 Chart Adequacy Areas for BA Chart 3321 as Percentage of the Total Marine Area.

Adequacy Rating	Coverage area (SqKm)	Percentage (%)
Not adequate	571	27
Low	875	41
Moderate	201	10
High	465	22
Total	2112	100

4.5 Rating of Maritime Significant Areas

Maritime significant areas were evaluated based on two main classes: navigational significant (Section 3.1) and other significant areas (Section 3.2). A percentage weight is assigned to each class based on the importance of each area to a country. Each maritime significant area class is divided into elements according to the use of the area. For example the navigation significant areas have channels, anchorage areas, etc. as elements. Each element is rated based on its importance to a nation. This may be based on the importance of the element in terms of safety of navigation or the impact shipping traffic has on the area (i.e., pollution to the environment). This rating is on a score of "0" to "1" depending on the requirements of a nation (Table 4.5). The weights and ratings can be changed according to the requirements of individual nations.

In this study, only information on navigation significant areas such as channels, ports, and anchorage areas were available in the data sources (charts and sailing direction). Information on other significant areas such as MPA's, fishing grounds etc was not available. Also, the existing information was insufficient to enable rating of each element of the navigation significant area in order of importance. Consequently, only the navigation significant areas classes were considered and were rated based on a Boolean logic. Areas that are important to navigation are rated as "1" and all other areas are rated as "0" (Table 4.6).

4.5.1 Navigation significant areas

Navigation significant areas are areas that are of pilotage importance to a mariner. These areas include ports, harbors, channels and anchorages. In this study, each element was rated based on their importance to safe navigation and in maintaining sea lines of communication between ports. All elements in this study were considered important to safe navigation of vessels and are weighed at 100%. As a result, each area within the class was considered important to navigation and is rated 1.

4.5.2 Other significant areas

Marine areas that have less significance in term of safety-of-navigation were classified as other significant areas. These areas were not considered in this study and were rated as 0 (Table 4.5). However, if these areas area marked on the chart or mentioned in the sailing direction, they will be evaluated as shown in Table 4.6.

TABLE 4.5 Study Rating of Maritime Significant Area Class

Class	Weight	Element	Assigned Rating	Rating Score
Navigation significant	100%	Port/Harbor	1	1
		Channel	1	1
		Anchorage/Roadstead	1	1
		Anchorage prohibited area	1	1
other significant	25%	Marine protected area	0	1
		Offshore mineral development area	0	1
		Fishing ground	0	1
		Other sea areas	0	1

TABLE 4.6 Maritime Significant Area Class Rating Scores

Class	Weight	Element	Assigned Rating	Score
Navigation significant	75 %	Port/Harbor	0.9	0.68
		Channel	0.9	0.68
		Anchorage/Roadstead	0.7	0.58
		Anchorage prohibited area	0.6	0.45
other significant	25%	Marine protected area	0.9	0.23
		Offshore mineral development area	0.6	0.15
		Fishing ground	0.5	0.13
		Other sea areas	0.1	0.03

4.6 Study Results of the Maritime Significant Area Class

To assess the navigation importance of the maritime significant areas, both classes were compiled into one layer using *ArcGIS*. The resulting marine areas were separated as navigation (1) and other (0) significant areas. The study results show that 6% (352 km^2) of the total marine area (5933km^2) in BA Chart 1797 of Belize (Table 4.6) and 21% (441 km^2) of the total marine area (2112 km^2) in BA Chart 3321 of Nigeria (Table 4.7) are ranked as "navigational significant". The rating results for BA Chart 1797 and BA Chart 3321 are presented in Figures 4.3 and 4.4, respectively.

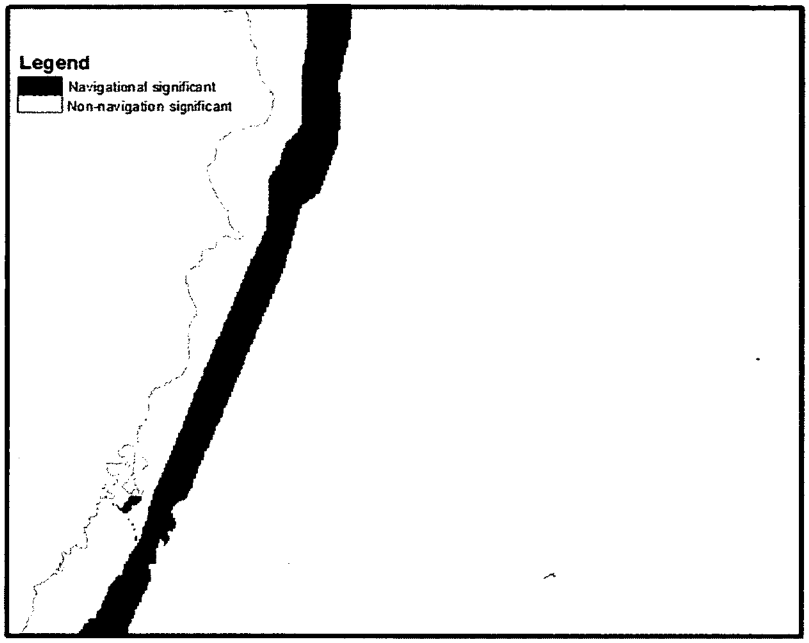


Figure 4.3 Maritime significant area class rating for BA Chart 1979 implemented in *ArcGIS*. The area is classified into navigation significant and other significant areas

TABLE 4.7 Percentage Coverage Of Maritime Significant Area for BA Chart 1797

Area	Coverage area (km^2)	Percentage (%)
Navigation significant	352	6
Other significant	5638	94
Total	5933	100

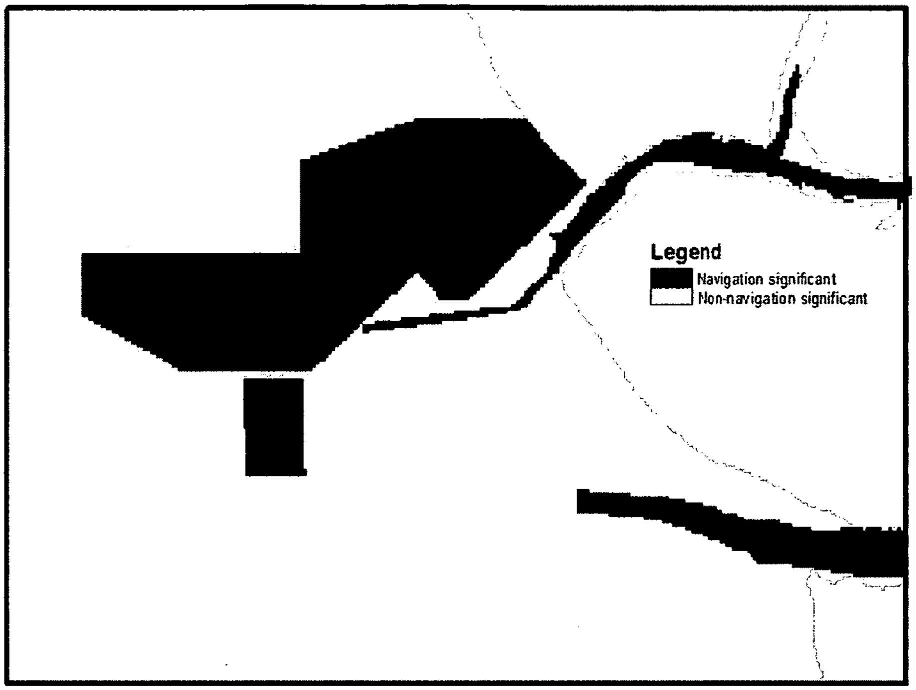


Figure 4.4 Navigation significant area class rating for BA Chart 3321 implemented in *ArcGIS*. The area is classified into navigation and other areas

TABLE 4.8 Percentage Coverage Of Maritime Significant Area for BA Chart 3321

Area	Coverage area (km^2)	Percentage (%)
Navigational significant	441	21
Other	1671	79
Total	2112	100

4.7 Hydrographic Survey Priority Maps

Priority maps that identify areas that require attention were produced based on the chart adequacy rating (Fig. 4.1 and 4.2) and the maritime significant areas rating (Fig 4.3 and 4.4). These two layers were multiplied using a raster calculator (*Spatial Analyst, ArcMap*). The priority maps are to be used by the operator for identifying the marine areas that should be surveyed in order to improve the overall adequacy of the chart. The priority maps are produced in two steps. First, the results of the cross- referencing are presented as a numerical value ranging from 0 to 5 (Fig 4.5 and 4.6), where areas with the higher scores have a higher priority for survey while areas with lower scores have a lower priority for survey. Second, the priority maps are re-classified to three main classes of low, medium and high priority areas. The priority classification is based on visual inspection of the numeric values of the priority areas in the charts (Tables 4.8 and 4.9). The numeric number ranges that define these patterns are used to prioritize the chart. Although this classification step is subjective and the value ranges between the medium and high priority can by defined uniquely for each chart, the priority classes are comparable between different charts and provide a visualization tool that simplifies decision making. Maps of the priority classes are shown in Figures 4.7 and 4.8. All areas with a numeric value of "0" in BA Chart 1797 and BA Chart 3321 were classified as "low priority". The low priority class is indicative of the other no significant areas. Areas with a numeric value range of 0.1 to 2.8 in BA Chart 1797 and 0.1 to 3.9 in BA Chart 3321 were classified as "medium priority". Areas with a numeric value range of 2.9 to 5.0 in BA Chart 1797 and 4.0 to 5.0 in BA Chart 3321 were classified as "high priority".

The procedure results identified that only 1% of the total marine area in chart 1797 (Table 4.10) and 6% of the total marine area in BA Chart 3321 (Table 4.11) were classified as a "high priority" area. A hydrographic survey over the high priority areas would result in improved safety of navigation. In BA Chart 1797, most areas of high priority occurred at the shallow areas of the Inner channel and the anchorage area south of point Palencia. Although most of the areas around the Belize barrier reef system and the Glover reef island were ranked "not adequate" and "low adequacy" for navigation, the areas were classified as low priority. This classification is primarily because the areas are within the other significant areas. The high priority areas in BA Chart 3321 are located mainly within the anchorage prohibited areas and in some parts of Escravos and Forcados channels. Large areas of the BA Chart 3321 were classified with high priority because of oil exploration activities and the attendant network of oil pipe lines which produced a large area of anchorage prohibited area that was rated "1".The anchorage prohibited areas in BA Chart 3321 have not been surveyed recently (since 1913) compared to Escravos (2004) and Forcados (1977) channels.

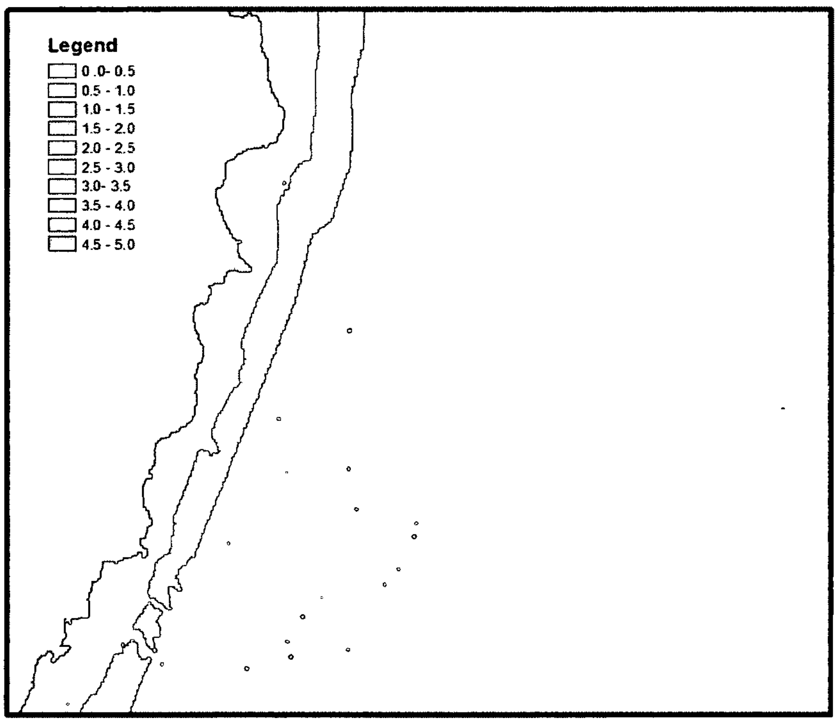


Figure 4.5 Numeric value representation of the priority map of BA Chart 1797.

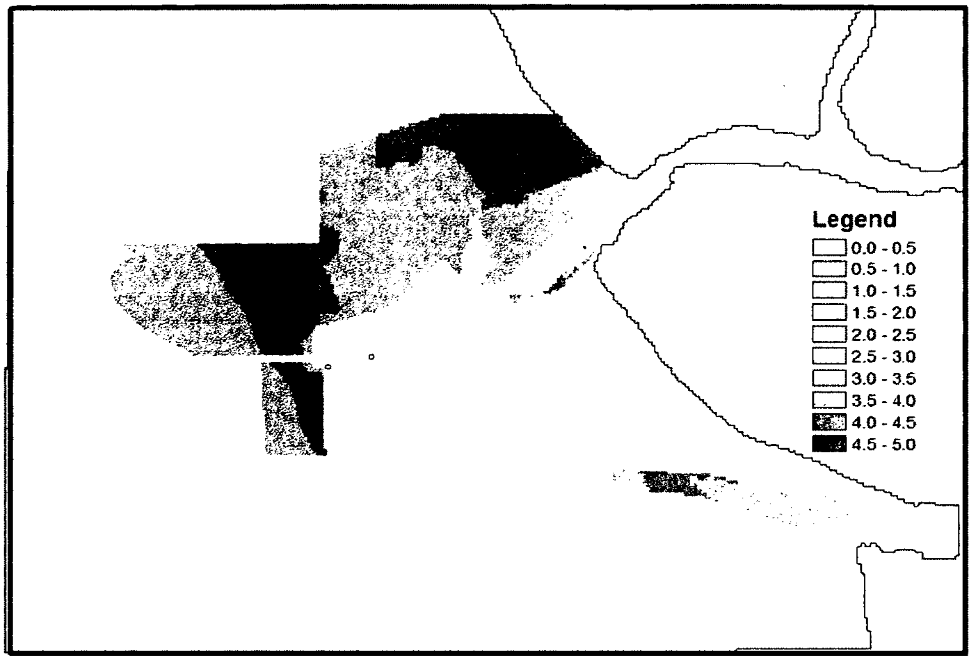


Figure 4.6 Numeric value representation of the priority map rating of BA Chart 3321.

TABLE 4.9 Priority Rating for BA Chart 1797

Priority Rating	**Value Range**
High priority	2.8 – 5.0
Medium priority	0 – 2.8
Low priority	0

TABLE 4.10 Priority Rating for BA Chart 3321

Priority Ranking	**Value Range**
High priority	3.9 – 5.0
Medium priority	0 – 3.9
Low priority	0

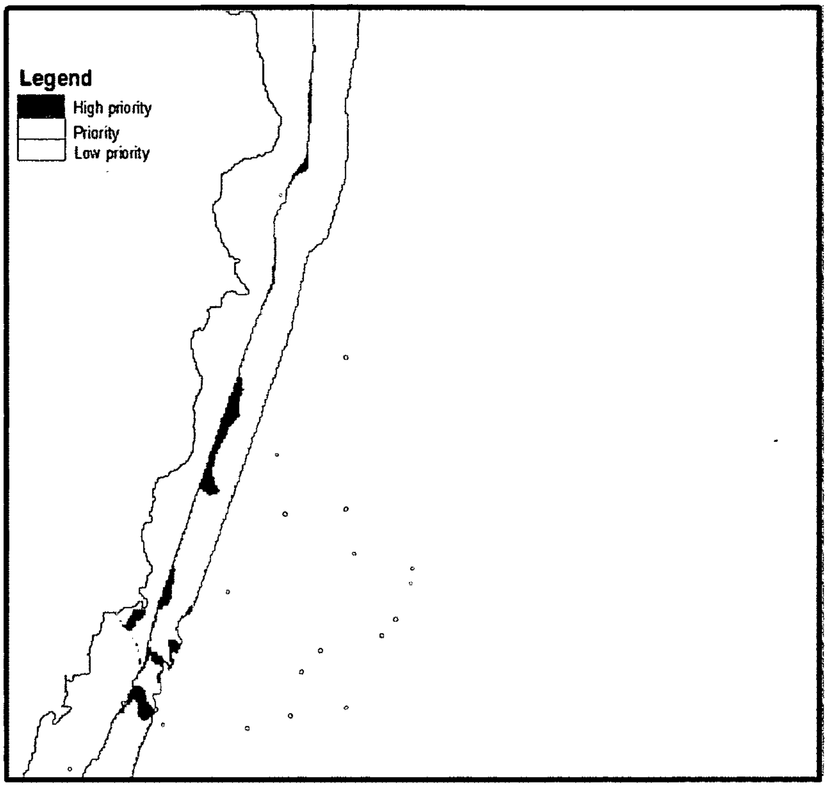


Figure 4.7 BA Chart 1797 prioritized areas for hydrographic survey.

TABLE 4.11 Prioritized Coverage of BA Chart 1797 for Survey

Area	Coverage area (km^2)	Percentage (%)
High priority	38	1
Medium Priority	309	6
Low priority	5186	93
Total	5933	100

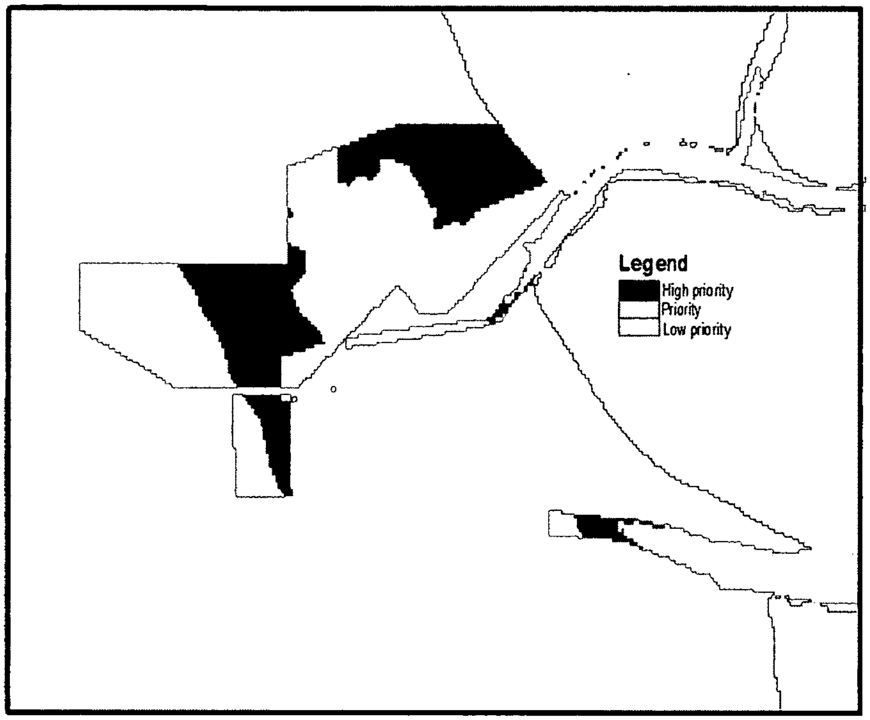


Figure 4.8 Numeric value representation of the priority map of BA chart 3321.

TABLE 4.12 Prioritized Coverage of BA Chart 3321 for Survey

Area	Coverage area (km^2)	Percentage
High priority	129	6
Medium Priority	309	15
Low priority	1674	79
Total	2112	100

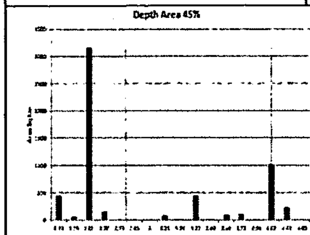
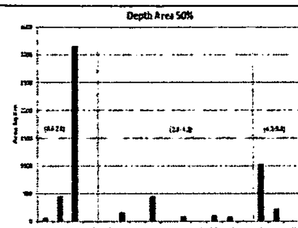
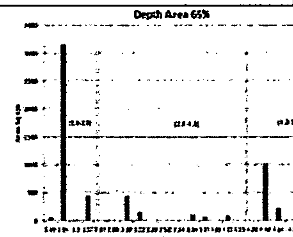
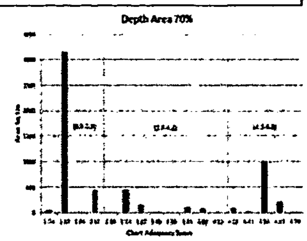
4.8 Sensitivity Analysis

The robustness of the chart adequacy procedure was evaluated by conducting a sensitivity analysis (SA) to examine the variability of the results as an outcome of altering the input parameters (weights) over a predetermined range. In this study, the SA is used to understand the stability of the chart adequacy result. Small variations in weight should result in modest changes in the chart adequacy result. Based on expert knowledge, initial nominal weights of 55%, 20%, 20% and 5% were assigned as weights of the four different criteria (Depth area, Chart Completeness, reliability diagram and Doubtful danger) layers, respectively (section 4.4). The weights were varied within a range of up to +/- 20%, with varying intervals depending on the criteria. As the weight for a given layer is varied, the weights of other layers were adjusted to add up to 100% while maintaining a relative weight ratio between the remaining layers (Salteli et al. 2000). In this sensitivity test the chart quality symbols were lumped into the chart completeness layer. Based on visual inspection of the result histograms, the weights at which the areas cross the preselected chart adequacy thresholds of 0.0-2.8 (High), 2.8-4.2 (Moderate), and 4.2-5.0 (Low) were determined from the result histogram (Table 4.13). Table 4.14 presents the resulting maps for chart 1797 from all range tests with respect to the original threshold and provides an easy-to-interpret structure, where the weight values are in the Layer column.

The sensitivity results show that there is an inverse relationship between the depth area layer to the reliability diagram and chart completeness layers. As the weight of the depth layer decreases to 50%, more are reported as adequately charted. Similarly, more areas are reported as adequately charted when either the reliability diagram or the chart completeness layers are valued above 20%. All the criteria layers where stable when varied by +/- 10%.

One of the conclusions from the SA result is that while the linear addition of weights used in the chart adequacy computation provided reasonable results, its effectiveness depended on choosing appropriate chart adequacy thresholds values. A more robust chart adequacy computation method may be developed for this process.

TABLE 4.13 Chart Adequacy Sensitivity Test Chart

Depth Area Layer			
45%	50%	65%	70%
			
Reliability Diagram			
10%	15%	30%	35%

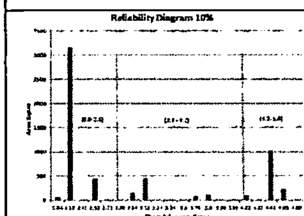
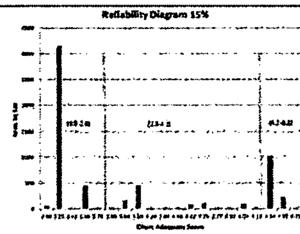
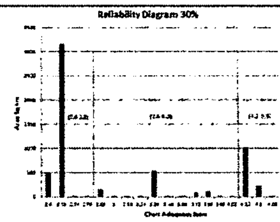
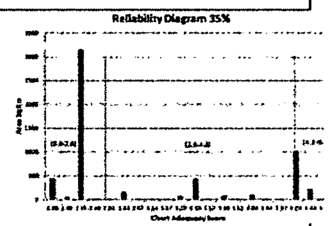

			

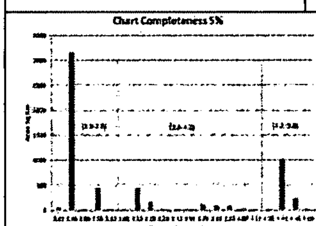
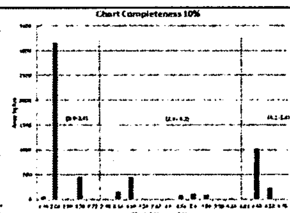
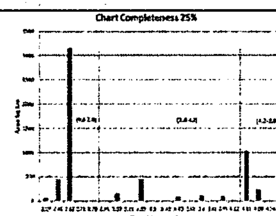
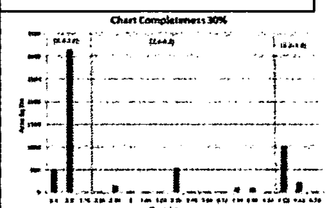
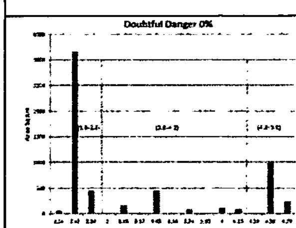
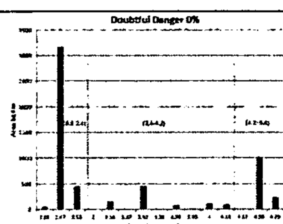
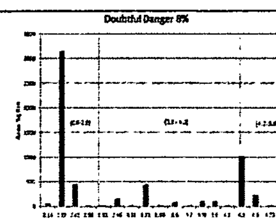
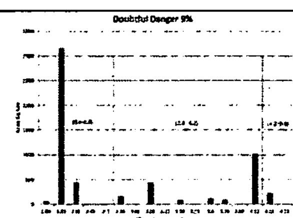
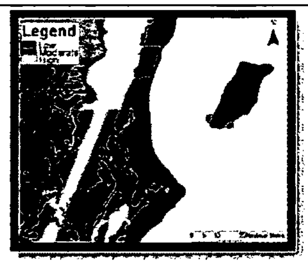
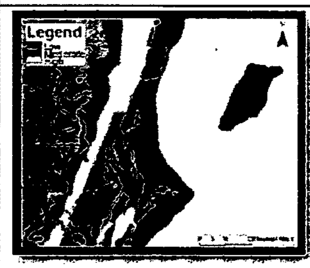
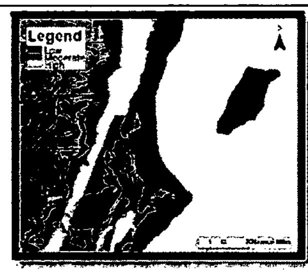
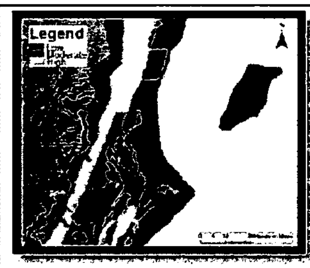
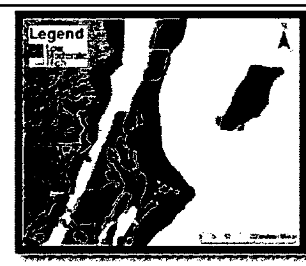
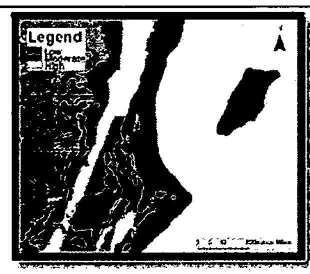
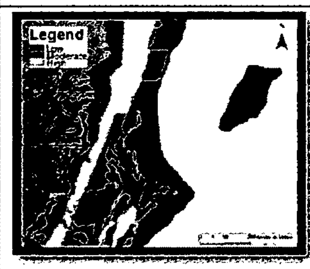
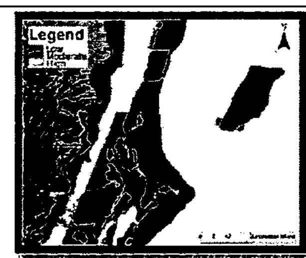
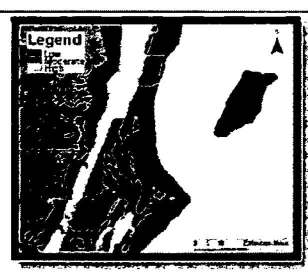
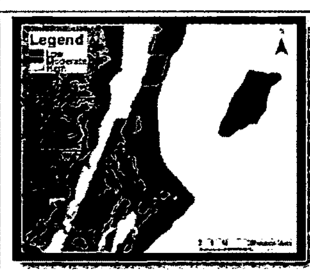
Chart Completeness			
5%	10%	25%	30%
			
Doubtful Danger			
0%	1%	8%	9%
			

TABLE 4.14 Chart Adequacy Sensitivity Test Spatial Area Diagram

Layer	45%	50% -65%	70%
Depth Area			
Layer	10%	15%- 30%	35%
Reliability Diagram			
Layer	5%	10% -25%	30%
Chart Complete ness			
Layer	0%	1% -8%	9%
Doubtful Danger			

4.9 Discussion

This study set out with the aim of developing a procedure for evaluating the adequacy of nautical charts for navigation, and to develop a procedure that can be used to prioritize marine areas within the chart that require a hydrographic survey. The study was based on information available from current charts and published sailing directions. In most cases, these are the primary sources of information regarding the adequacy of current nautical charts for a developing country. The procedure was able to rate marine areas in terms of the adequacy for safe navigation. Furthermore, the procedure was able to identify and prioritize areas that would improve the chart adequacy. In this study, approximately 1% of the marine area in BA Chart 1797 (5933 km^2) and 6% of the marine area in BA Chart 3321 (2112 km^2) were classified as "high priority" for further surveys. In both charts, the majority of the navigation significant areas were ranked as "medium priority". Accordingly, this procedure was able to prioritize marine areas within a chart for hydrographic surveys, and improved nautical charts. The procedure is not confined to the BA charts and can use other sources, such as the NOAA charts and the coastal pilot.

The robustness of this procedure mainly depends on a number of factors including, the source layers used (zone of confidence or source diagram, chart quality symbols/indicators, doubtful danger markings, survey completeness, navigation significant depths and navigational significant areas). For example, the groupings of the survey periods in the source diagram provide some indication of the accuracy of measurements and survey standards that were used. However, it is difficult to determine the survey equipment and instruments used for a particular survey. Also, the conclusions from the sensitivity analysis recommended that though the linear addition of weights used in the chart adequacy computation provided reasonable results, a more robust chart adequacy computation method may be developed for this process.

There are other factors that limit the effectiveness of this procedure. The dates of the surveys and when the chart or sailing direction was published is important. However, the scaling of data in the production of nautical charts leads to the loss of details and resolution of soundings. Many of the soundings collected during a hydrographic survey are omitted in the chart production process. As a result, significantly less information is available for analysis when determining chart adequacy for navigation and prioritization of survey. Further, there is the danger of prioritizing the wrong areas for survey. Also, there is a possibility that significant features are lost in the data due to the reduction of soundings used to produce the chart. This shortcoming makes any up-to-date, high resolution and easily available data a viable option for checking the accuracy of the charts for navigation.

In this study, not all the navigation significant areas were well-defined. Some information on the chart and in the sailing directions was not clear, and the extent of their area could not be clearly delineated. For example, the extent of the anchorage area for the anchorage in BA chart 3321 was not shown on the chart or mentioned in the sailing directions. Another example is the maritime extent of the northern part of the inner channel in BA chart 1797, which is also not provided by the chart or the sailing directions.

Some additional activities could be conducted that could improve the outcome of the procedure. One is to contact national maritime administration to inquire about information which is not available on the chart or the sailing directions. This includes information such as traffic density, nature of seafloor, economic importance, national defense, environmental consideration etc. Knowing about this will enable a more realistic rating of the maritime significant area, and a better prioritization of the sea areas for survey is achieved. Other possible means would be to incorporate source data from publically available digital information on the traffic density from the automatic identification system (AIS) or satellite-based remote sensing data.

V. OPTICALLY DERIVED BATHYMETRY

5.1 Principles of Ocean Remote Sensing

Since the 1970's, satellite remote sensing technology has been adopted as a possible technique in the collection of bathymetric data (Jensen, 2007). The wide area coverage, repeatability and easy availability of satellite remote sensing data have made this technology a desirable alternative in mapping areas that conventional ship-mounted and towed sonar systems cannot access. The ability of light to penetrate the water column provides the fundamental principle for inferring water depth using this technology. Understanding the interaction of light with the atmosphere, the water column, the seafloor and the system hardware components used to collect reflected radiation plays an important role in extracting bathymetric data from satellite images (Jensen, 2007). However, it is important to note that this reflected energy is a function of the interactions of the solar radiation with air-water interface, atmospheric scattering and the biological constituents in the water column (Morel et al., 1977). The radiation reflected from the sea surface, seafloor and the water column is captured by the sensor in the satellite platform using an optical detector. A typical multispectral sensor contains several detectors, where each detector can capture a broad spectral range (70 to 150 nm) from the visible to the infrared portions of the electromagnetic spectrum. It is also possible for a single detector (i.e. Charged Coupled Device) to record multiple spectral channels, when operated as a line scanner or by using a Bayer filter.

The light transmittance through the water column varies as a function of wavelength. The spectral range of the sunlight that is able to penetrate the water is typically between 350 nm (ultraviolet-blue) to 700 nm (red), depending on the water clarity and the water depth (Jerlov, 1976; Mobley, 2004). Sunlight at wavelengths greater than 700 nm (infrared) is limited in its ability to penetrate the water column to any appreciable depth. Typically, satellite channels in the near-infrared ranges (780 to 900 nm) are used to delineate land/water boundary in coastal environments (Robinson, 2004).

The ocean is not composed from only pure water. It contains various amounts of dissolved and particulate material that vary spatially and temporally within the water column. Close to the coast, the run-off from land and re-suspension of sediments due to the shallow depths and the breaking waves are noticeable. There is a gradual seaward decrease of dissolved and suspended particulate material due to the reduced import from land sources. These materials influence the optical properties of the ocean water and impose several limiting factors on the derivation of water depth using satellite imagery (Holden and LeDrew, 2001).

As the light emitted from the sun, downwelling irradiance, interacts with the water surface interface, an amount of the incident light energy is reflected back to the atmosphere. The amount of light reflected back depends on the transmitted wavelength and the angle of incidence to the water surface (Mobley, 2004; Jerlov, 1976). The rest of the transmitted light penetrates the water column and interacts with particles and dissolved matter in the water that cause some of the incident light to be absorbed and scattered (Jensen, 2007). This results in a light intensity loss that depends on the water attenuation and the turbidity of the water column. The intensity loss through the water column is wavelength dependent and can be modeled as an exponential function of the diffuse attenuation coefficient, $K(\lambda)$ and depth, z (Jerlov, 1976; Mobley, 2004).

The decrease in the intensity of the downwelling irradiance, $E_d(\lambda ,z)$ with depth is expressed by Beer's law:

$$E_d(\lambda ,z) = E_d(\lambda ,0) \cdot e^{(-Kz)} \quad [5.1]$$

Where $E_d(\lambda ,0)$ and $E_d(\lambda ,z)$ are the downwelling irradiance just above the surface and at a depth z, respectively. The Beer's law can be further modified to account for the contribution from each wavelength and changing downwelling irradiance at various depths (Mobley et al., 2004).

$$E_d(\lambda ,z) = E_d(\lambda ,0) \cdot e^{-\int_0^z k(z)dz} \qquad [5.2]$$

Rearranging the equation yields the attenuation coefficient:

$$\mathrm{K(z)} = -\frac{1}{E(z)}\frac{dE(z)}{dz} \qquad [5.3]$$

In remote sensing, radiance measurements are conducted. The radiance is reflected irradiance that is captured within the field of view of the detector and has units of

$W \cdot sr^{-1} \cdot m^{-2}$. The observed radiance in shallow waters is expressed as (Philpot, 1989; Maritorena et al., 1994):

$$L_{obs} = L_b e^{-2K(\lambda) \cdot z} + L_w \quad [5.4]$$

where L_{obs} is the radiance observed at the sensor's detector, L_b is the radiance contribution from the bottom, and L_w is the observed radiance over optically deep water with no bottom contribution. As a result of L_w, only a subset of the spectral range from the downwelling irradiance reaches the bottom and is reflected back.

In addition to calculating the observed radiance, the diffuse attenuation coefficient is used to characterize water bodies based on their water clarity. Jerlov (1976) characterized water clarity in order to distinguish between water types based on the spectral profile of the diffuse attenuation coefficient. He classified the ocean waters into five different oceanic water types (I, IA, IB, II and III) and five coastal water types (1, 3, 5, 7, 9) as a function of attenuation coefficient (Fig 5.1). A low value in each group indicates clear waters and high value indicate turbid waters. In the case of oceanic waters, the water clarity ranges from extremely clear water (Type I) to increasingly turbid waters having greater attenuation and greater amounts of organic constituents (Type III). Similarly for coastal waters, type 1 is clearest and type 9 is most turbid. The dominant material in the Jerlov oceanic waters is typically the phytoplankton that predominates in the open ocean, whereas color dissolved organic matter (CDOM) and terrigenous particles dominate the optical properties in the Jerlov coastal waters. The Jerlov classification scheme represents a quantitative way of checking water clarity and replaces the traditional secchi disk which is subjective.

According to figure 5.1, light with wavelengths around 470 nm (Blue) has the lowest attenuation coefficient in ocean waters. Thus, blue channels in satellite imagery will have the deepest penetration in the ocean waters. In the case of coastal waters, which are considered more turbid than the oceanic waters, the lowest attenuation coefficient is at wavelengths around 530 nm (Green). Shallow water bathymetry mapping is typically conducted over coastal waters. Clearer water conditions may exist along the coast of islands (Case II/III). However, these conditions also vary from oceanic to coastal depending on the season (algae bloom) and weather conditions (storms). In this study, bathymetry will be extracted from satellite data of the upwelling radiance from the seafloor that is not completely attenuated by the water column (equation 5.4).

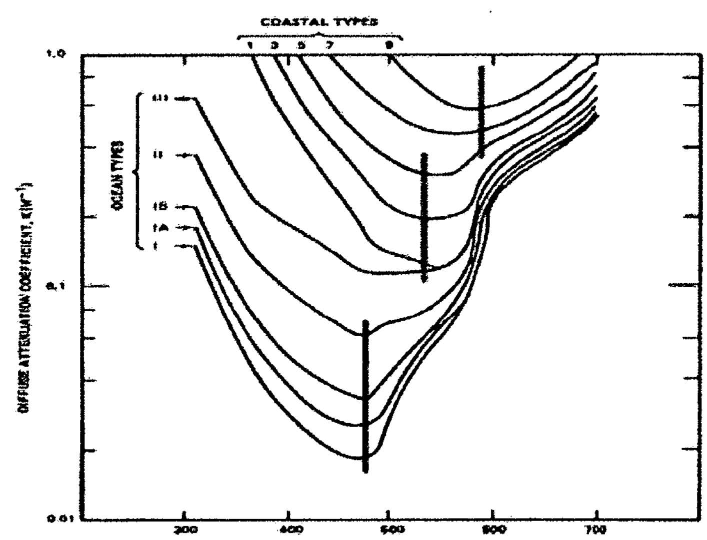


Figure 5.1 Jerlov's water classification scheme, where the typical diffuse attenuation coefficients of different water types are plotted as a function of wavelength (Jerlov, 1976)

5.2 Bathymetry from Optical Remote Sensing

Several models have been developed for the determination of bathymetry from satellite images. These models are typically from two approaches: 1) The linear approach, which focuses on the inversion of the radiative transfer equation of electromagnetic radiation. This method is based on the fact that light attenuates exponentially with depth in water (Lyzenga, 1978; Philpot, 1989); 2) The ratio method approach, which derives bathymetry based on the ratio of two bands (Dierssen et al., 2003; Stumpf et al, 2003). Based on the challenges to derive the diffuse attenuation coefficients, this study focused only on algorithms from the ratio method approach:

5.2.1 Linear transform approach

The linear transform approach uses the radiative transfer equation based on Beer's Law (Lyzenga, 1978). In order to derive the bathymetry, the method requires knowledge of the optical properties (e.g., diffuse attenuation coefficient and bottom reflectance) of the water body in a given image. The linear transform approach assumes that water is vertically homogenous (uniformly mixed), and that the optical properties of the water column and bottom are constant within the image scene. Based on the Beer's law, Lyzenga (1978) derived the relationship of the observed radiance, $L_{obs}(\lambda_i)$, to the water depth, z, and the bottom radiance for a single wavelength band, $L_b(\lambda_i)$, which is described as:

$$L_{obs}(\lambda_i) = [L_b(\lambda_i) - L_w(\lambda_i)] \cdot e^{-2K \cdot z} + L_w(\lambda_i) \quad [5.5]$$

Where $L_w(\lambda_i)$, is the radiance of the water column and K is the diffuse attenuation coefficient. Lyzenga (1978) assumed that the diffuse attenuation coefficient of the upwelling radiance is equal to the diffuse attenuation coefficient of the downwelling radiance. In order to derive the bathymetry, the optical property values of the water column and the seafloor need to be determined:

$$z = -\frac{1}{2K} \cdot ln\left(\frac{L_{obs}(\lambda_i) - L_w(\lambda_i)}{L_b(\lambda_i) - L_w(\lambda_i)}\right) = -\frac{1}{2K} \cdot [ln(L_{obs}(\lambda_i) - L_w(\lambda_i)) - ln(L_b(\lambda_i) - L_w(\lambda_i))] \quad [5.6]$$

Philpot (1989) emphasized the challenge to retrieve accurate values for the water column and the seafloor optical properties. As a result, accurate depth values are hard to achieve. In order to extract bathymetry using only the observed radiance, $L_{obs}(\lambda_i)$, and the radiance of the water column, $L_w(\lambda_i)$, Lyzenga (1985) suggested an over-determined approach using two or more bands. In the case of two bands (band i and band j), three constants (a_o, a_i and a_j) are needed to derive a linear solution for depth:

$$z = a_0 + a_i X_i + a_j X_j \quad [5.7]$$

Where

$$X_i = ln(L_{obs}(\lambda_i) - L_w(\lambda_i))$$

These site specific constants are used as correctors for the optical properties and are derived by multiple linear regressions of sampled pixels. The log transform is used to linearize the deep water corrected radiance to depth, as the radiance is assumed to attenuate with depth (Haibn et al, 2008). The major drawback of this model is that it requires three tunable variables (a_o, a_i and a_j) and deep water conditions for retrieving $L_w(\lambda_i)$ and $L_w(\lambda_j)$. The water depth accuracies from linear transform approach vary due to changes in the reflective properties of the bottom substrates (Green et al, 2000).

5.2.2 Ratio transform approach

The ratio transform approach utilizes two bands to reduce the number of parameters required to infer depth. This requires less empirical tuning and therefore a more robust algorithm than the linear transform approach (Stumpf et al., 2003). Assuming a uniform mixture in the water column, the ratio of two bands will maintain a near-constant attenuation value that is the difference of the diffuse attenuation coefficient at two different wavelengths. The concept for both algorithms using the ratio approach is that bottom radiance of one channel will decay faster with depth than the other band (Dierssen et al., 2003; Stumpf et al., 2003). As a result, the ratio between the two bands will increase as depth increases.

Dierssen et al (2003) used a band difference concept to derive bathymetry in turbid waters. Dierssen et al (2003) found in her study area (Lee Stocking Island, Bahamas) that a strong attenuation in the red band and a relatively weak attenuation in the green band will produce a ratio that is correlated with the bathymetry. She supported her conclusions by showing a linear relationship between her green/red (555 nm/ 670 nm) ratio results to single-beam depth measurements and formulated the following linear relationship:

$$z = c_1 \cdot [ln(L_{obs}(\lambda_i)) - ln(L_{obs}(\lambda_j))] + c_2 = c_1 \cdot ln\left(\frac{L_{obs}(\lambda_i)}{L_{obs}(\lambda_j)}\right) + c_2 \quad [5.8]$$

Where c_1 and c_2 are the gain and offset constant that are empirically defined.

Stumpf et al. (2003) used a log ratio concept, where the bathymetry was extracted from a natural log ratio between the blue and green bands. The green band attenuates faster with depth than the blue band. The Stumpf et al. (2003) algorithm is able to remove the errors associated with varying albedo because both bands are typically affected in a smilar way. Accordingly, the change in ratio between bands is affected more by depth than by bottom albedo (Stumpf et al., 2003). Depth can then be derived using:

$$z = m_1 \cdot [ln(L_{obs}(\lambda_i))/ln(L_{obs}(\lambda_j))] - m_0 = m_1 \left(\frac{ln(nL_{obs}(\lambda_i))}{ln(nL_{obs}(\lambda_j))}\right) - m_0 \quad [5.9]$$

Where m_1 is the tunable constant to scale the ratio to depth, n is a fixed constant for all areas and m_o is the offset for a depth of 0 m (Z=0). The value of n is chosen to ensure that the logarithm will be positive under all circumstances and the ratio will produce a linear response.

It is important to note that both approaches are site specific. Each satellite image, even over the same site, requires different constants and optical properties. In this study, only the ratio transform algorithms will be evaluated. This is because the ratio transform algorithms involve fewer constants and do not require prior knowledge of the optical properties (i.e., diffuse attenuation coefficient and bottom reflectance) of the water body to determine bathymetry.

5.3 Datasets

5.3.1 Geographic Settings

The test site for the procedure development is located on the southern coasts of Plum Island, MA and the northern coasts of Cape Ann, MA (Figure 5.1). The length of the test site is 34 km and its substrates vary from sand and mud to sediments containing shells and rocky outcrops. The area is a low-energy wave environment with a tidal range of about 2.5 m. The physiographic structure along the shore lines and inner shelf are controlled by the structure of the underlying bedrock formation (Barnhardt et al., 2007). To the north of the test site, the Merrimack River discharges sediments into the Gulf of Maine. The sediments are then transported in the southeasterly direction by alongshore currents generated by strong waves (Barnhardt et al., 2007), thus, leading to constant morphological changes. The Landsat image selected for this study was collected at 15:16 GMT just before the end of high tide on the 27th of September 2000.

Figure 5.2 RGB Landsat image of the test site (Collection date: September 27, 2000)

5.3.2 Reference dataset

An Airborne LIDAR Bathymetry (ALB) dataset was used as a reference dataset to validate the optically-derived bathymetry from the Landsat image. The ALB dataset was collected by the US Army Corps of Engineers (USACE) using the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) systems (Figure 5.3). According to the metadata, the data has a horizontal accuracy of 3m (2sigma) and a vertical accuracy of 30cm (2sigma). The spot spacing of the laser measurements was 5 X 5 m^2 with a horizontal accuracy of about 3 m and vertical accuracy of 15 cm (Wozencraft and Lillycrop, 2003). The laser measurements were horizontally referenced to NAD 83 with NAD 83 ellipsoid heights. The ALB laser measurements were loaded into the *ArcMap* project and gridded to a surface at the Landsat image resolution of 28.5 m × 28.5 m. The depths of the Lidar data are used to test the linearity of the satellite derived bathymetry algorithms and chart depth.

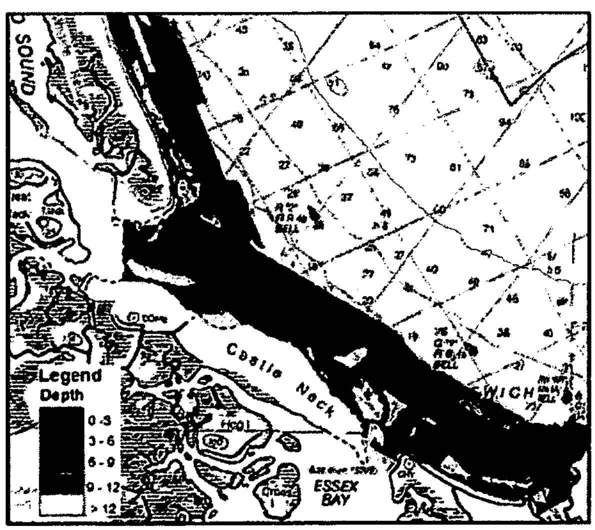


Figure 5.3 The Lidar dataset gridded at 28.5m resolution

5.3.3 Nautical chart

Although this process is intended to validate the chart depths, some of the soundings were used to reference the optic-driven bathymetry to the chart datum. In the U.S. test site, chart soundings from two NOAA charts were used for referencing: 1) NOAA chart 13279 'Ipswich Bay to Gloucester Harbor' (scale 1:20,000) and 2) NOAA chart 13278 'Portsmouth to Cape Ann' (scale 1:80,000). The horizontal datum for both charts is North American Datum (NAD) of 1983, and a Mercator projection is used. Depth soundings are in feet and are vertically referenced to the Mean Lower Low Water (MLLW) tidal datum. The hydrographic survey in the areas covering the test site was collected between 1940 and 1969 by the National Ocean Service (NOS). The survey used single beam echo sounder and primarily visual aids for positioning achieving partial bottom coverage.

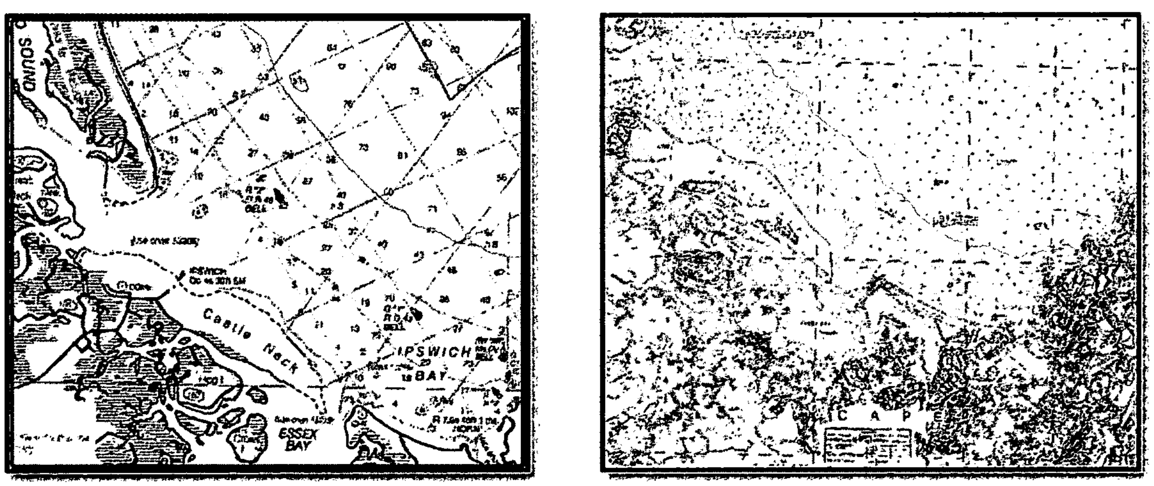


Figure 5.4. Extract of (Left) NOAA Chart 13278 (Portsmouth to Cape Ann; chart scale: 1:80,000) and (right) NOAA Chart 13279 (Ipswich Bay to Gloucester Harbor, 1:20,000) showing the study area.

5.3.4 Landsat imagery

Landsat imagery was selected as the input imagery for the optic-derived bathymetry procedure. The coverage repeatability and its availability in public archives (http://earthexplorer.usgs.gov/) make this satellite imagery ideal as a source dataset for the procedure. The Landsat 7 satellite is an earth observation satellite operated by the United States Geological Survey. The satellite is a sun synchronous satellite operating in an orbit 705 km above the earth (Jensen, 1996). It is designed to collect imagery from the earth in a swath 185 km wide as it passes overhead. It carries a single nadir- pointing instrument, the Enhanced Thematic Mapper plus (ETM+) with eight band multispectral scanning radiometer capable of producing images of up to 28.5 m resolution. The large swath of the Landsat imagery can potentially cover nautical charts of the scale of 1:50,000 to 1:60,000 with a single image. While the Landsat ETM+ imagery has fairly coarse spatial resolution, the 30 m ground sample distance (GSD) is significantly smaller than the maximum allowable spacing between charted soundings of 300 m (in ground distance) of the scale of charts used in the study. For this study only four out of the eight bands were investigated (Table 5.1).The Landsat image selected for this study was collected at 1516 GMT at high tide on the 27th of September 2000. The Landsat ortho-rectified images are referenced to WGS 84 and have a positional uncertainty better than 50 m.

TABLE 5 1. Landsat Spectral Bands used in the Study

Spectral region	Spectral bands (nm) Landsat-7
Blue	450-520
Green	530-610
Red	630-690
Near Infrared (NIR)	780-900

5.4 Optically-Derived Bathymetry Procedure

The Stumpf et al. (2003) and Dierssen et al. (2003) bathymetry-extraction algorithms were both evaluated over a well-controlled environment. The goals of the algorithm evaluation were: 1) to determine the algorithm performance as a function of bands, 2) to evaluate the use of spatial filters in improving the pre-processing procedure, 3) to estimate the use of chart soundings to vertically constraint the algorithm results, and 4) to evaluate the error sources in the optically-derived bathymetry product. The algorithm evaluation included two bands combinations (Blue/Green, Green/Red) and the use of spatial filters in pre-processing procedures. The bathymetry models from a Landsat image were compared to a reference dataset.

The optically-derived bathymetry procedure includes the selection of the appropriate satellite bands, bathymetry algorithms, and spatial filters. The key steps in the procedure can be grouped into: pre-processing, water separation, spatial filtering, applying the bathymetry algorithms and referencing the bathymetry to the chart's datum. The test site was used to select between the different options within each step and validate the final bathymetric product.

5.4.1 Pre-processing

Based on the charts geographic location, a search was conducted in the USGS archives (http://earthexplorer.usgs.gov/) for available imagery collected by Landsat 5 and Landsat 7. After reviewing the different scenes in a quicklook view (Figure 5.5), only images with minimum cloud coverage (0% to 10 %) and very little sun glint were chosen. These images were downloaded from the website into the *ArcMap* project, where the bands of the image were stored separately in a TIF format.

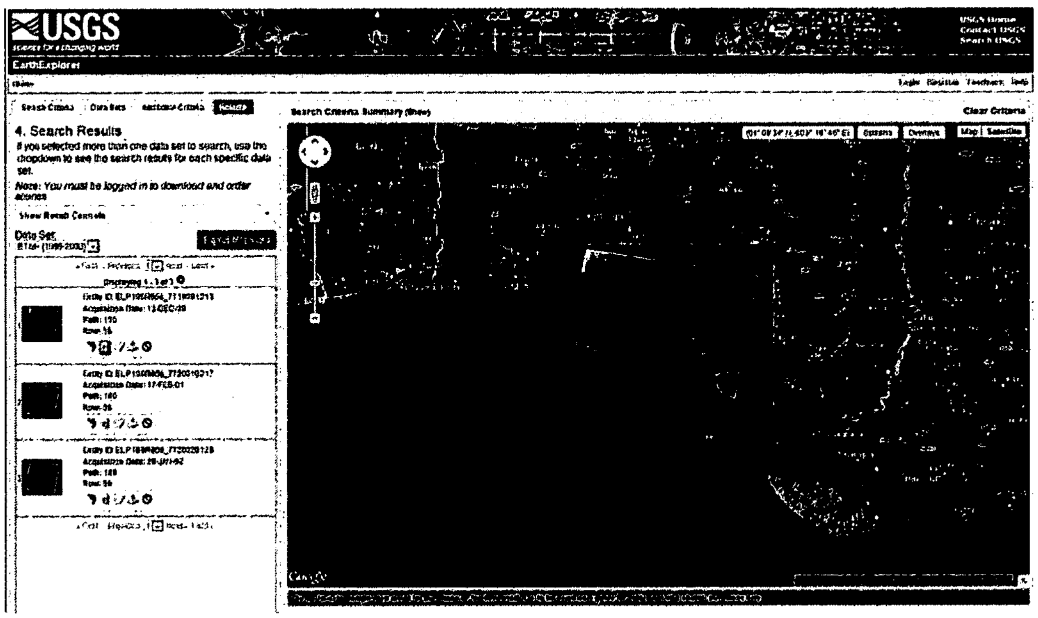


Figure 5.5 Search result from USGS website

5.4.2 Water separation

Due to the optical characteristics of water that are close to opaque in the near infrared (NIR) range, the water appears dark in the IR band. The dark (low digital values) of the NIR band are in contrast to the dry land areas that are appear bright (high digital values). As a result, the histogram of the NIR band over a coastal area is bi-modal (a digital value distribution of land and a digital value distribution of the water). In this study, a threshold value between the two distributions was used for separating land from water in the NIR band. This operation was conducted using the ***Raster Calculator*** tool in *ArcMap*. Figure 5.6 illustrates the separation of the land area from water.

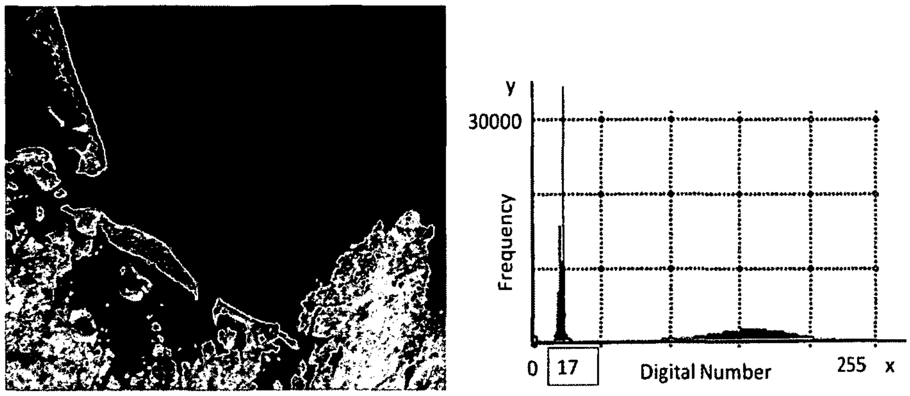


Figure 5.6. Near-infrared image of the test site (left). The NIR image histogram showing the Land-Water threshold (right). For the near-infrared image, the land-water threshold was determined to be 17, thus, any digital number greater than 17 is considered land.

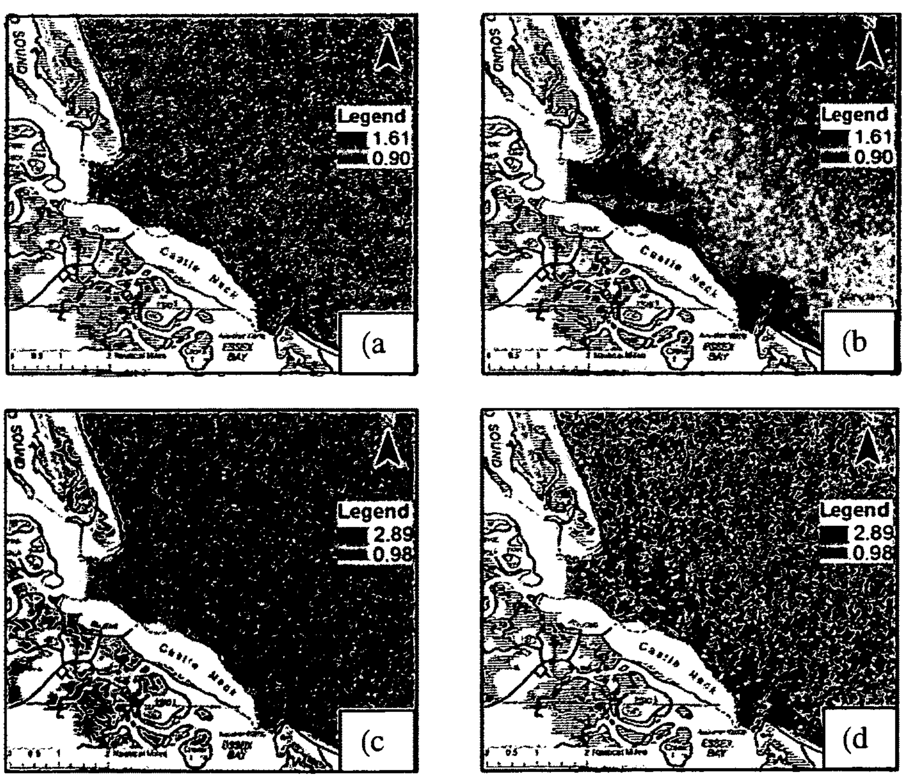
5.4.3 Spatial filtering

The water area was converted into a polygon shapefile using the ***Raster to Feature*** conversion tool in *ArcMap*. The polygon was subsequently used to extract the study area from the red, green and blue (RGB) bands of the satellite images (Figure 5.7). The subset RGB was saved without any filtering. Thereafter, a low-pass spatial filter was applied to the images. The low-pass filters are used to smooth the image and remove speckle created by the data compression process. This was performed using the ***Extract by Mask*** and ***Filter*** tools in *ArcMap*.

Figure 5.7 Extracted and filtered images of blue (left), green (center) and red (right) bands of the test site.

5.4.4 Applying the bathymetry algorithms

The Stumpf et al. (2003) and Dierssen et al. (2000) algorithms were used to generate models of the blue/green and green/red bands for the unfiltered and filtered images. This resulted in eight possible procedure configurations (Fig 5.8).



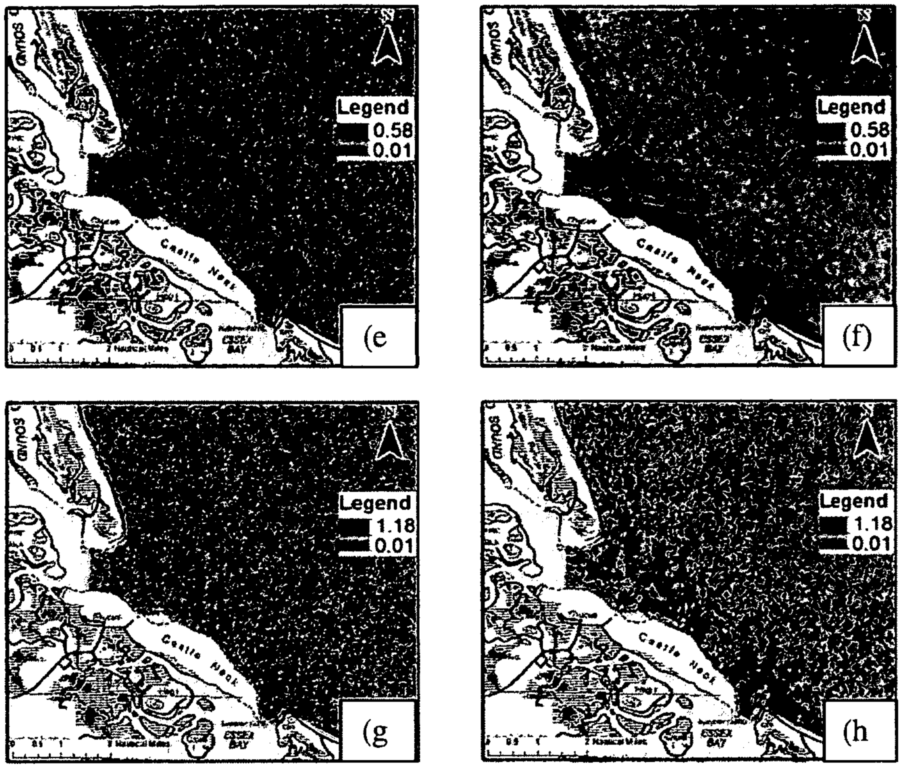


Figure 5.8 Stumpf algorithm result for unfiltered (a) and filtered (b) blue/green bands; and unfiltered (c) and filtered (d) green/red bands. Dierssen algorithm result for unfiltered (e) and filtered (f) blue/green bands; and for unfiltered (g) and filtered (h) green/red bands.

5.4.5 Referencing the bathymetry to the chart's datum

The referencing step includes three sub-steps using *ArcMap* and *MS Excel*:

a) Selecting reference soundings: In order to calculate the gain and offset values (Equations 5.8 and 5.9), the algorithm results were compared and correlated to the chart soundings. Typically, the two main considerations for selecting reference soundings are 1) the source diagram that indicates the survey period and the survey technology and 2) visual correlation between the optically-driven bathymetry and the chart's contours and soundings. In this study, where different procedure configurations are investigated to validate that the chart's soundings are reliable enough for the empirical calculations, the depth soundings were compared to the ALB reference dataset.

b) Identifying the extinction depth – The algorithm model results were compared to the Lidar dataset and chart soundings at co-incident points based on the location of the chart's soundings. The sampled depths in the area overlapping between all three datasets were grouped to extremely shallow (0.0 m - 0.5 m), shallow (0.5 -3.5 m), intermediate (3.5- 6.5 m) depths with respect to the MLLW tidal datum (Figure 5.9).

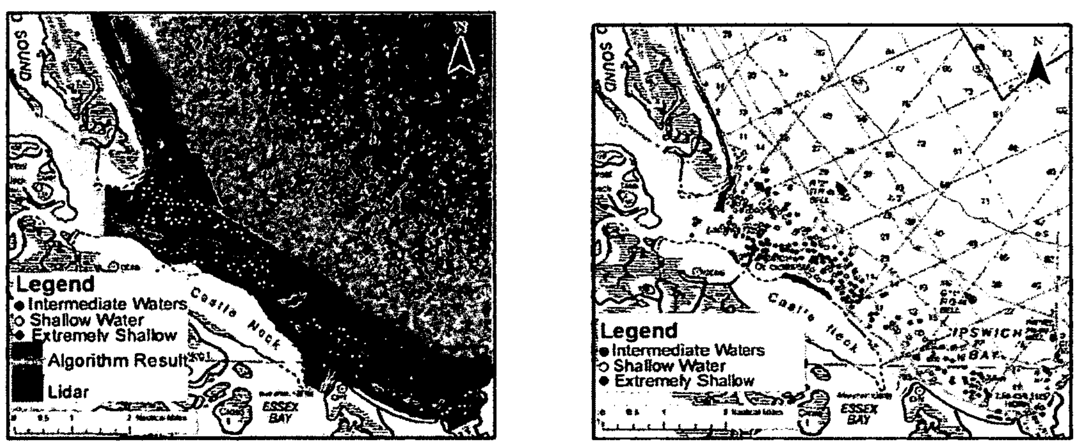


Figure 5.9 Sample points in the extremely shallow, shallow and intermediate depth areas.

In deeper waters, where only the chart soundings and the optical-driven bathymetry were available, the sampled depths were grouped to visible seafloor morphology (0 m – 6 m), suspended sediment (6 m - 25 m) and optically-deep areas (> 25 m) (Figure 5.10). Multiple depth measurements from the optically-derived bathymetry and ALB bathymetry datasets with the same chart sounding depth were averaged into a single value.

Figure 5.10 Sample points in the optically deep, sediment plume and clear bathymetry.

The averaged values of the optically-driven bathymetry were plotted against the chart soundings and the ALB bathymetry. This was to identify the depth of extinction, which is the boundary between visible seafloor morphology and the suspended sediment area and/or the optically-deep area. Based on a visual inspection of the depth measurements, other depth boundaries were also determined.

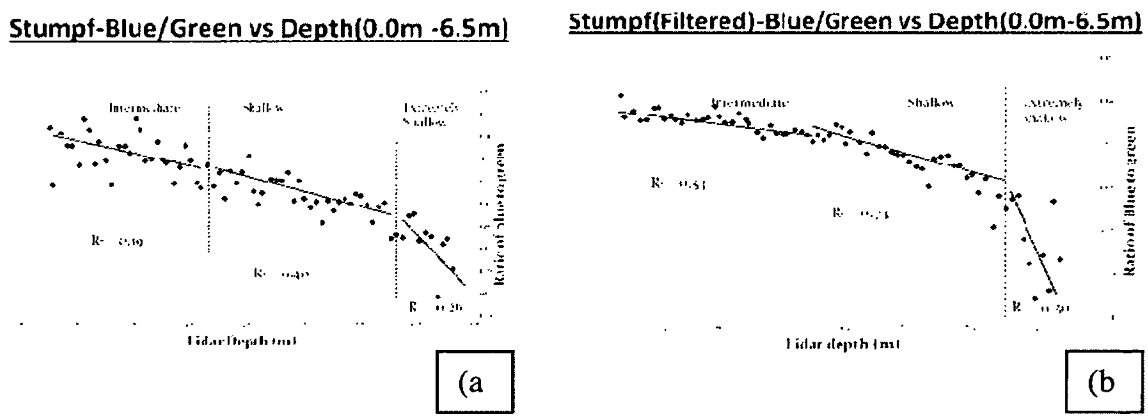
<u>Statistical analysis</u> - The extinction depth is the maximum depth that the light can penetrate the water and defines the depth limit of the algorithm. A statistical analysis, namely calculating the correlation coefficient, was used to indicate the linearity between the datasets. A linear trend line fit was applied to each depth group, where the R^2 (Pearson correlation coefficient), and the gain and offset were calculated. Based on the R^2 result, the best procedure configuration was selected.

5.5 Test Results

For purposes of this study, the best procedure configuration was selected based on the highest R^2 result. In addition, the chart soundings were validated as a referencing data source by comparing to the ALB reference dataset.

5.5.1 Comparison of the algorithm results to the ALB dataset

Since the chart soundings are shoal biased, the algorithm results were compared to the ALB dataset to assess the algorithm's performance by evaluating the linearity of the results to the reference dataset. Visually, the blue/green band ratio with a low-pass filter for both algorithms (Figures 5.8b and 5.8f) showed more clearly morphological features. Empirically (Figure 5.11; Table 5.2), the linear regression coefficient between the green/blue band ration in the shallow and intermediate depth regions improve by 0.3 to 0.35 by using the low-pass filter. Both algorithms (Stumpf and Dierssen) provide very similar linear regression results after applying the low-pass filter.



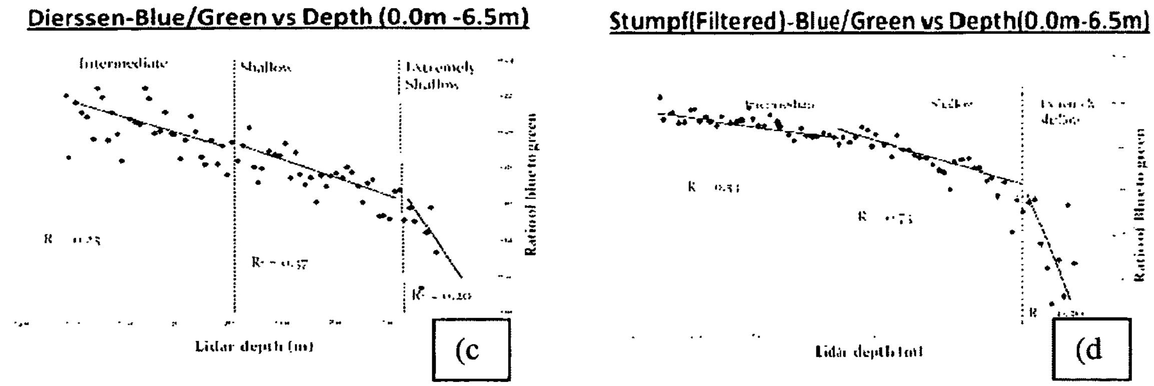


Figure 5.11 Plots of the Stumpf algorithm results compared to Lidar for unfiltered (a) and filtered (b) blue/green band ratio. Plots of the Dierssen algorithm results compared to Lidar for unfiltered (c) and filtered (d) blue/green band ratio.

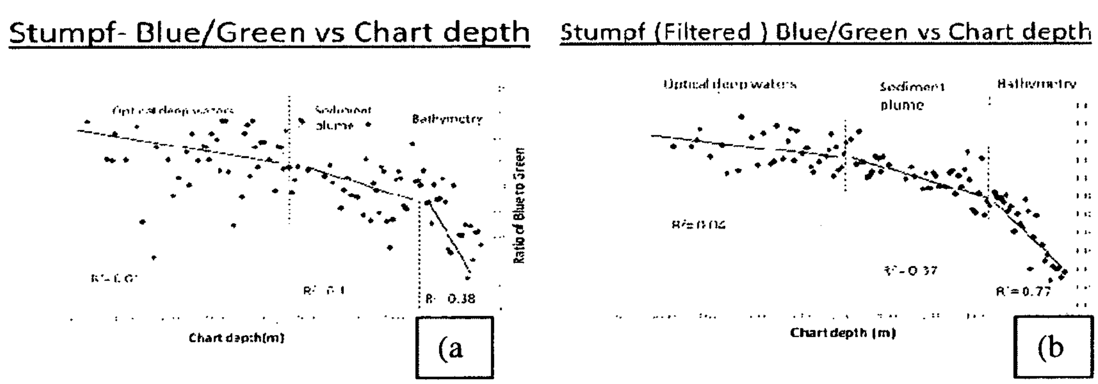
TABLE 5.2 Summary of R^2 values from the Algorithm Linear Regression Results

	Unfiltered			Lowpass Filtered		
Algorithm	Extremely Shallow	Shallow	Intermediate	Extremely Shallow	Shallow	Intermediate
Stumpf	0.26	0.40	0.19	0.30	0.73	0.53
Dierssen	0.20	0.37	0.23	0.29	0.73	0.53

The comparison results between the bathymetry from the different procedure configurations and the ALB dataset showed that the lowpass-filtered Blue/green Stumpf algorithm performed the best based on the linear regression coefficient R^2 at extremely shallow, shallow and intermediate depths (Table 5.2). It is important to note that the correlation values were very low (0.20 - 0.30) for all procedure configurations at extremely shallow waters. The low performance of the algorithms at extremely shallow depths may be attributed to poor water clarity as a result of wave action in the surf zone.

5.5.2 Comparison of the algorithm results to chart soundings

After validating the algorithm results with the ALB dataset, the algorithm model results for blue/green bands were compared to the nautical chart (Figures 5.12). The extinction depth in all the configurations was around 6 m below MLLW. The linear regression coefficient in the areas overlapping the ALB dataset (Bathymetry waters) showed high correlation values, where the best performing configuration (lowpass-filtered Blue/green Stumpf algorithm) yielded R^2=0.77. In deeper waters than the extinction depth (sediment plume waters), the algorithm has a poor linear regression coefficient (R^2=0.30). The reason for the poor linear regression coefficient is that the returning signal is scattering from only the water column (i.e., the sediments in the water column become the dominant signal). The algorithm results in the seaward direction represent a reduction in the concentration of the suspended sediments and not an increase in depth. Outside of the sediment plume (optically deep waters) the plot shows no correlation (R^2<0.04) with the chart soundings.



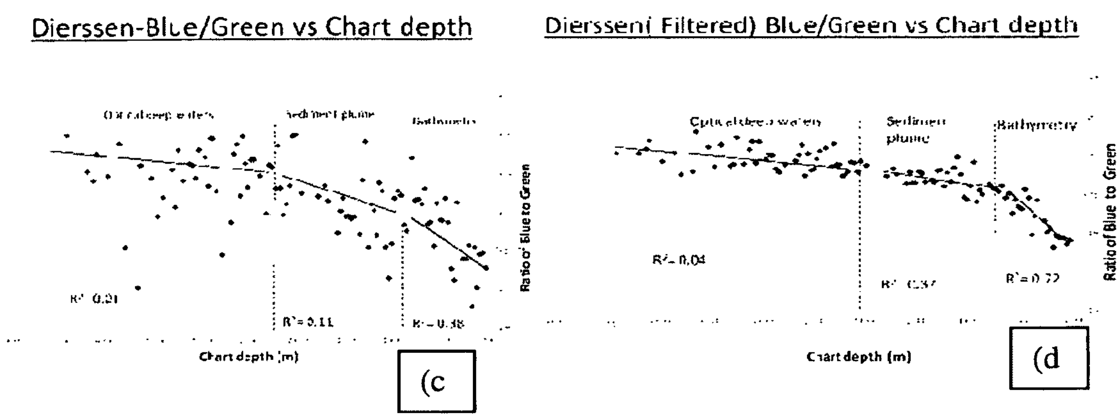


Figure 5.12 Plot of Stumpf algorithms compared to chart soundings for unfiltered (a) and filtered (b) blue/green band ratio. Plot of Dierssen algorithms compared to chart soundings for unfiltered (c) and filtered (d) blue/green band ratio.

TABLE 5.3 Summary of the Algorithm Linear Regression (R^2) Results with respect to the Chart Soundings

Algorithm	Unfiltered			Lowpass Filtered		
	Bathymetry	Mud Plume	Optically Deep	Bathymetry	Mud Plume	Optically Deep
Stumpf	0.49	0.16	0.005	0.77	0.37	0.04
Dierssen	0.38	0.11	0.003	0.72	0.37	0.04

5.5.3 Vertical difference

As a final validation for the use of chart soundings for referencing, a comparison was made between the chart soundings and the ALB dataset. The comparison results showed a high linear regression coefficient ($R^2 = 0.80$). This also indicated that the seafloor has been fairly stable between the hydrographic survey of the study area (1940-1969), the ALB survey (2005) and Landsat image (2000). The computed offset was 27.78 m, which is consistent (within estimated uncertainties of the ALB data and chart soundings) with the MLLW – NAD 83 (CORS 96) datum offset 28.33 m for the project site calculated using VDatum.

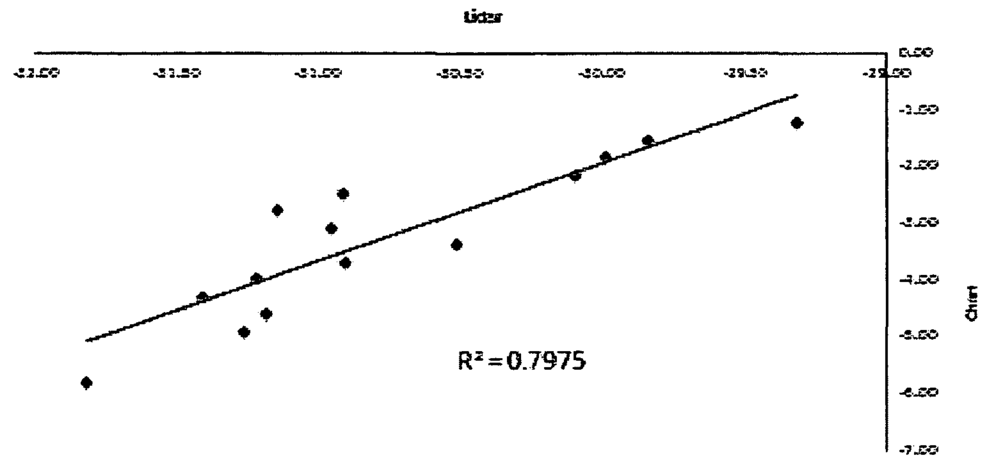


Figure 5.13 Plot of chart soundings compared to the ALB dataset

The linear transform below converted the algorithm output to actual depths, referenced to the chart datum, MLLW:

$$y = 233.68\,x + 260.05 \quad [5.10]$$

where y is the charted depth referenced to MLLW, x is the Stumpf algorithm result, 233.68 is the gain, m_0 , and 260.05 is the offset, m_1. The optically derived-bathymetric surface referenced to MLLW was compared to the ALB dataset to evaluate the depth difference (Figure 5.14, right image). The mean depth difference was 0.304 m; the standard deviation was 1.83 m while the root mean square error was 1.856 m.

Table 5.4: Results of Comparison of Satellite-Derived Bathymetry against ALB Dataset

RMSE (m)	1.856
Mean difference, μ (m)	0.304
Standard deviation, σ (m)	1.83

The result showed that in most areas the depth differences were between 0m and 2 m. Only in a few local areas was the difference in depth greater than 4 m. This high difference may be due to turbulence caused by along shore currents and/or waves moving over features with steep (Figure 5.14, left image). It seems that the seafloor around these steep features is of channels within a sandy seafloor or rocky outcrops and boulder glacial deposits in the vicinity of flat lying sediments. In both cases, there is the potential of sediment being suspended over the feature and increasing the turbidity of the water. However, it is impossible to determine if the turbulence is caused by the wave unless the height of waves at the time of image collection is known. Another reason for the high differences between the datasets was observed in the northwest part of the study site at water depths greater than 6m, which is about the depth of extinction for the image. The high vertical differences may also be caused by changes to the seafloor morphology over time considering the time difference between the data collection times of the ALB and satellite images. Furthermore, errors in the geo-referencing of the two datasets may contribute to vertical differences.

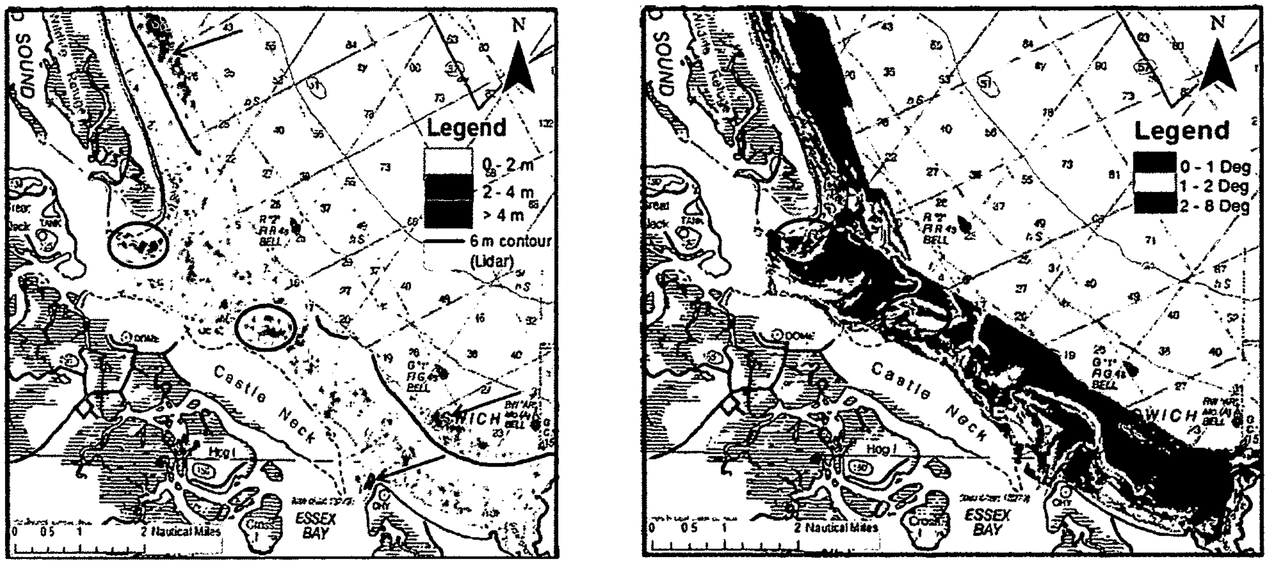


Figure 5.14 Vertical difference results between the optically derived bathymetry and the ALB dataset (right) and the slope map of the study area based on the ALB dataset (left). The red circles indicate the locations of high depth difference.

5.5.4 Procedure evaluation conclusions

The configuration that was selected in the procedure included the use of the Stumpf algorithm with a blue/green band ratio and a low-pass spatial filter applied to the bands. This configuration was selected based on the empirical results. It is important to note that the water clarity is a key factor in the procedure that limits the depth in which the procedure can perform successfully. Also, the selection of the sounding based on the algorithm results is a key factor for referencing the bathymetry to the chart's vertical datum. Other environmental factors are the presence of cloud and sea-surface glint in the satellite image and will be discussed in the next chapter.

VI. OPTICALLY DERIVED BATHYMETRY FOR CHART ADEQUACY

6.1 Update of the Depth Layer

The highest ranking procedure configurations selected for deriving bathymetry and comparing to the chart depth is the lowpass-filtered Blue/green Stumpf algorithm This configuration is based on the R^2 correlation values from the comparison of the different procedure configurations in a controlled environment (ALB reference dataset). In addition, it was established that the chart soundings are a suitable constraint to reference the optically-derived bathymetric dataset. The highest ranking procedure configuration was used to produce shallow-water bathymetry in the coastal waters of Nigeria and Belize. These two sites were selected based on the IHO publication C-55 (IHO, 2004) that identified the nautical charts of Nigeria and Belize as containing gaps in their hydrographic data.

The source diagrams (Figure 6.1) that indicate the survey date and sometimes the survey technology for the charts covering Nigeria (Chart 3321) and Belize (Chart 1797) showed that only a small portion of the chart was surveyed in the last 50 years (areas a, b, c and d in Nigeria and areas a and b in Belize). In addition, other areas have not been surveyed more than a 100 years or have been inadequately surveyed or not been systematically surveyed (areas b, f and g in Nigeria and areas b, c, e, f, g and i in Belize). The goals of using optically-driven bathymetry are:

1) Identify shoal areas that are not indicated on the chart – What is not on the chart?

2) Monitor coastal changes of the seafloor since the last survey used to generate the soundings for the chart – What areas have changed since the last survey?

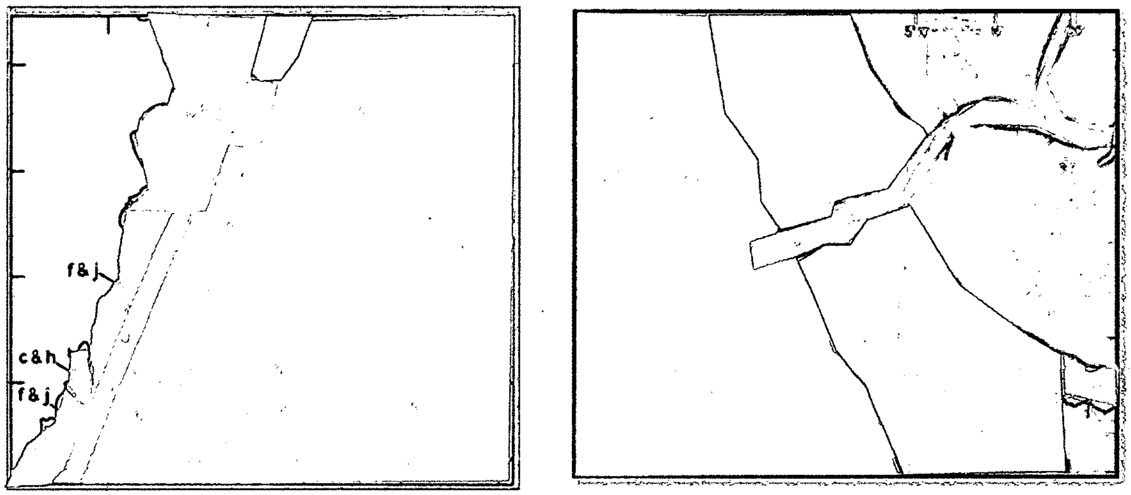


Figure 6.1 The Admiralty charts 1797(Left) and 3321(Right) overlaid with source diagram. The source diagram is color coded to show the periods of surveys used to compile the chart over the last 50 years (green), 100 years (yellow) and 150 year (red).

From the GIS chart adequacy classification of the chart and sailing direction, the depth area class had the highest influence (55%) in determining the adequacy of a sea area for navigation. Furthermore, the depth area ranges were determined from charted depth information, which is as old as the last survey for the area. The optical-derived bathymetry provides current depth information used to update the depth area class, especially in unsurveyed areas. This is subsequently applied to the chart adequacy evaluation process to provide a more updated chart adequacy and hydrographic priority map.

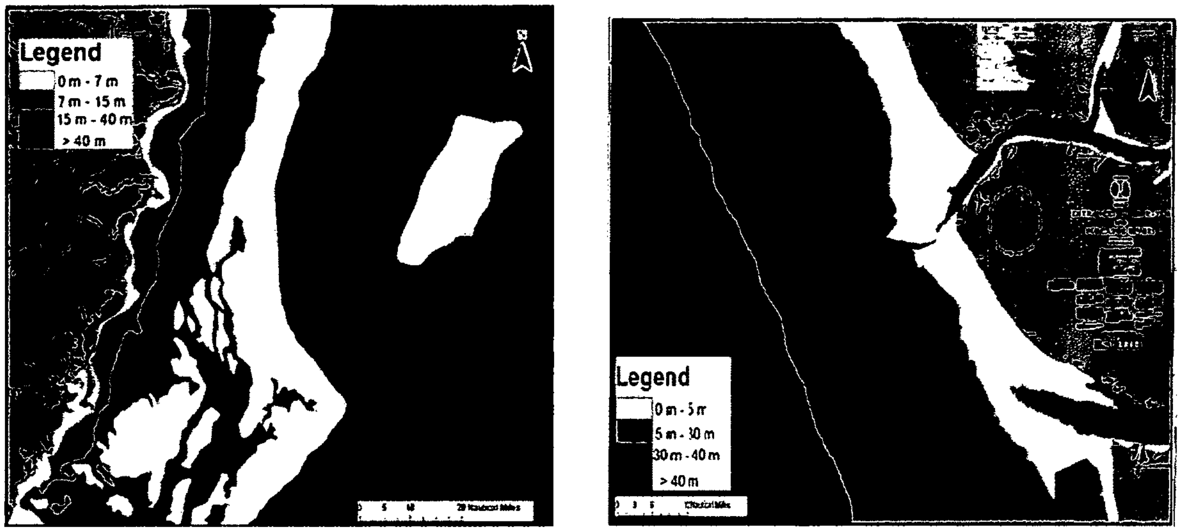


Figure 6.2 Depth area class for Belize (Left) and Nigeria (Right) with depth information derived from charts and sailing direction.

6.2 Nigeria Study Site

6.2.1 Geographic setting

The Nigeria study site is the Escravos area south west of the Niger delta. The area has a coastline of about 67 km and has substrates mainly of sand and mud. The Escravos area is relatively high-wave environment with a tidal range of about 2.2 m. The wave action forces a strong littoral current in the northwest direction. This spawns active sandy beaches and barriers systems on the coast. The Escravos and Forcados Rivers discharge sediments into the area which are then transported northwards by the alongshore current (Major-Mora et al, 1976). Typically for river deltas, it is expected to find changes in the bathymetry of the Escravos and Forcados Rivers.

6.2.2 Landsat imagery

The most-recent Landsat image that covers the Escravos area was downloaded from the USGS website. The Landsat image was collected on the 17th of February 2001 at 09:47 GMT (Figure 6.3). The Landsat ortho-rectified bands are referenced to WGS 84 datum and have a positional uncertainty better than 50 m. The image is characterized by a small amount of cloud cover (< 10%). The cloud cover mainly affected the land area of the image and the southern coastline. The cloud cover was removed by sampling the cloud and removing the image pixels that fell within the cloud digital number (DN) range. This was done using the Raster Calculator in ArcGIS.

Figure 6.3 RGB Landsat image of Escravos, Nigeria with cloud cover.

6.2.3 Nautical chart

The Escravos study area is the area covered in the BA chart 3321 (Figure 6.4). The vertical datum of the chart soundings which was used to reference the optical-derived bathymetry is the lowest astronomical tide (LAT) with units of meters. The chart was published in 2000 with a scale of 1:60,000. The horizontal datum of the chart is WGS 84 and a Mercator projection is used. Survey periods noted in the chart range between 1910 and 2004. The historic surveys (> 50 years) were carried out by the Nigerian ports authority and Nigeria Marine surveys, while the more recent surveys (2004) are from commercial surveys.

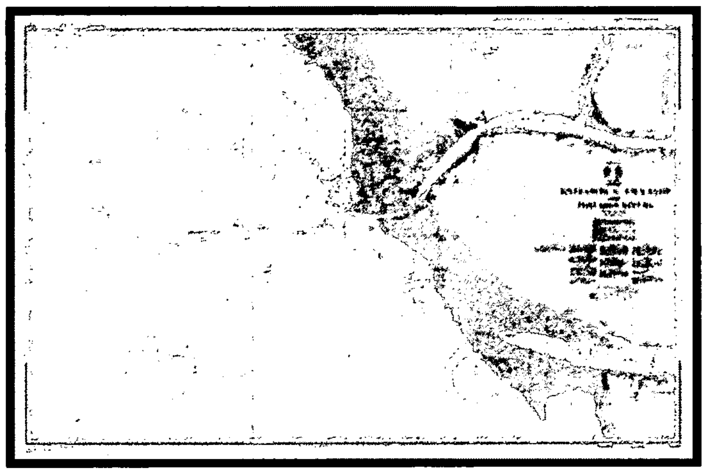


Figure 6.4 BA Chart 3321 (Chart scale: 1:60,000)

6.2.4 <u>Optically-derived bathymetry procedure</u>

The same bathymetric procedure that was defined in the New England test site was used to derive bathymetry in the Escravos (Nigeria) study area. However, the pre-processing procedure (water separation) was slightly different as a result of cloud cover in the Escravos image. In infrared band, it was noticeable that cloud cover was also over the water (Figure 6.5). In order to remove the cloud, the digital number (DN) range of the cloud cover, instead of land, was used to determine the water separation boundary. Unfortunately, areas beneath the cloud cover could not be inferred. Using the blue and green bands without cloud cover, a filtered Stumpf algorithm procedure configuration was generated (Figure 6.6).

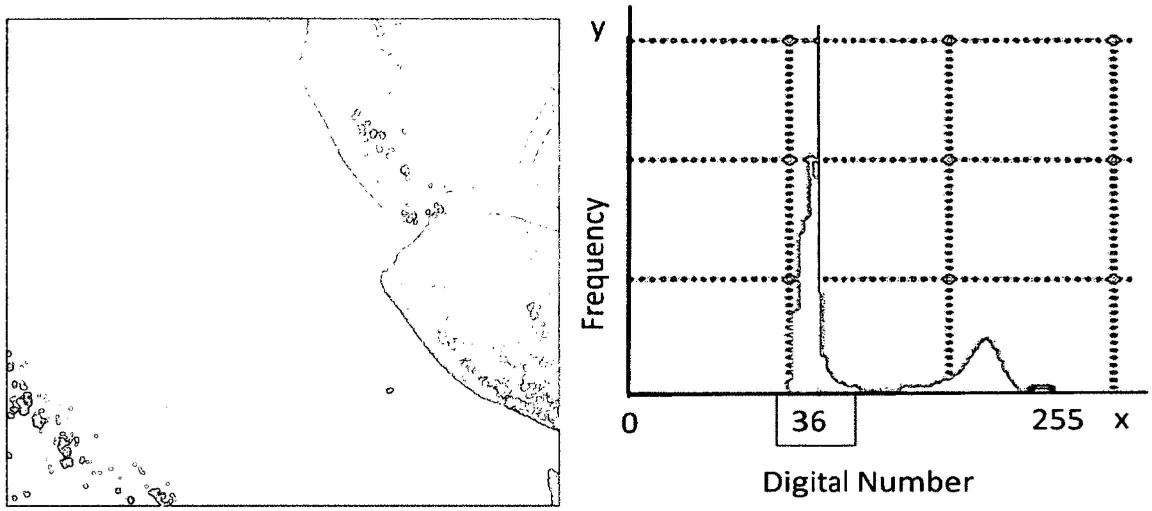


Figure 6.5. Near-infrared image of the Escravos area (left). The NIR image histogram showing the Land/Cloud-Water threshold (right). For the near-infrared image, the cloud-water threshold was determined to be 36, thus, any digital number greater than 36 is considered cloud or land.

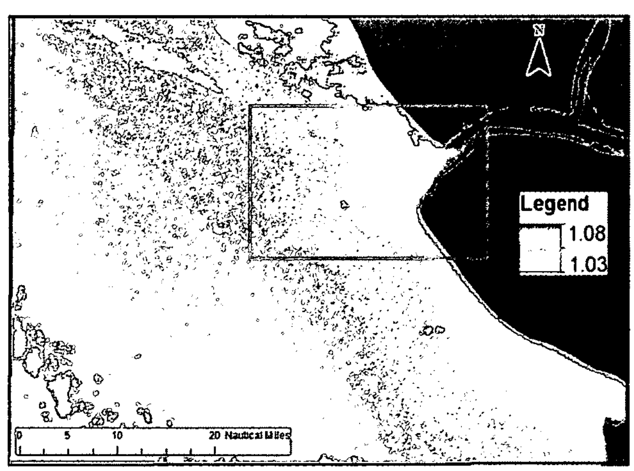


Figure 6.6 Filtered Stumpf algorithm result.

The resulting bathymetry was referenced to the LAT using the chart soundings. Although the chart was compiled from a number of old surveys, the algorithm result showed areas of seafloor stability when compared to the same locations on the chart (shown in red box). Soundings were selected from this area to calculate the gain and offset (Figure 6.6).

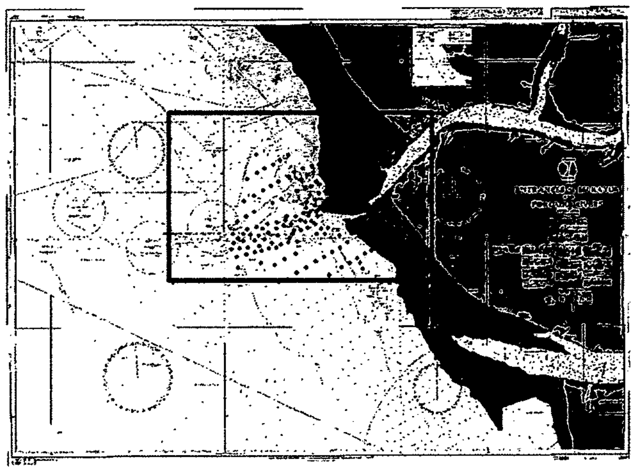


Figure 6.7 BA Chart 3321 showing area from which chart soundings were selected to calculate the gain and offset of the optical-driven bathymetry (red box).

The filtered Stumpf blue/green algorithm result was compared to the chart, and a linear regression was applied. The resulting plot showed a good correlation ($R^2 = 0.83$) between the algorithm result and chart within visible bathymetry areas. The calculated extinction depth for the image was calculated at about 6 m below the LAT 0 m contour line (Figure 6.7). Deeper areas (sediment plume waters and optically deep waters) showed no correlation ($R^2 = 0.03$).

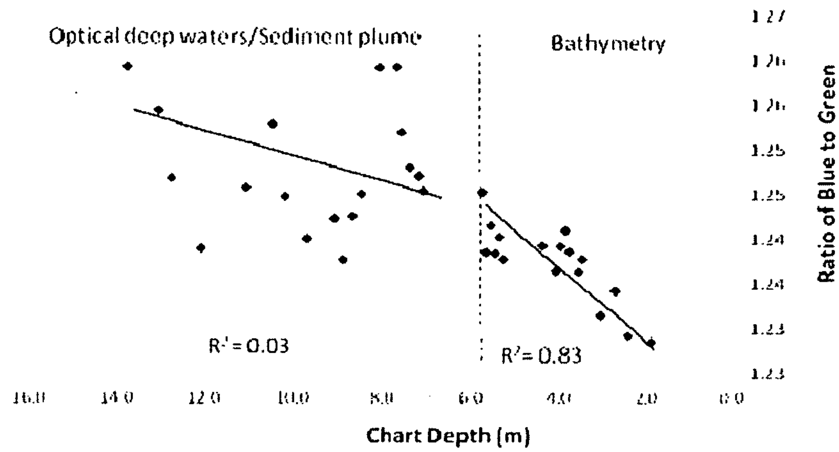


Figure 6.8 Plot of Stumpf algorithms compared to chart soundings for filtered blue/green band ratio.

A bathymetric surface (Figure 6.8 left) was generated by applying a gain, m_0, and offset, m_1, using the following equation:

$$y = -225.22\,x + 275.67 \quad [6.1]$$

where y is the optically-derived bathymetric model referenced to LAT, x is the Stumpf algorithm result, m_0 is -225.22 and m_1 is 275.67 is. To determine the stability (i.e., change in time of the bathymetry) of the area, a 5 m contour line generated from the optically derived bathymetry (red line) was compared to the 5 m contour line on the chart (Figure 6.8 right).

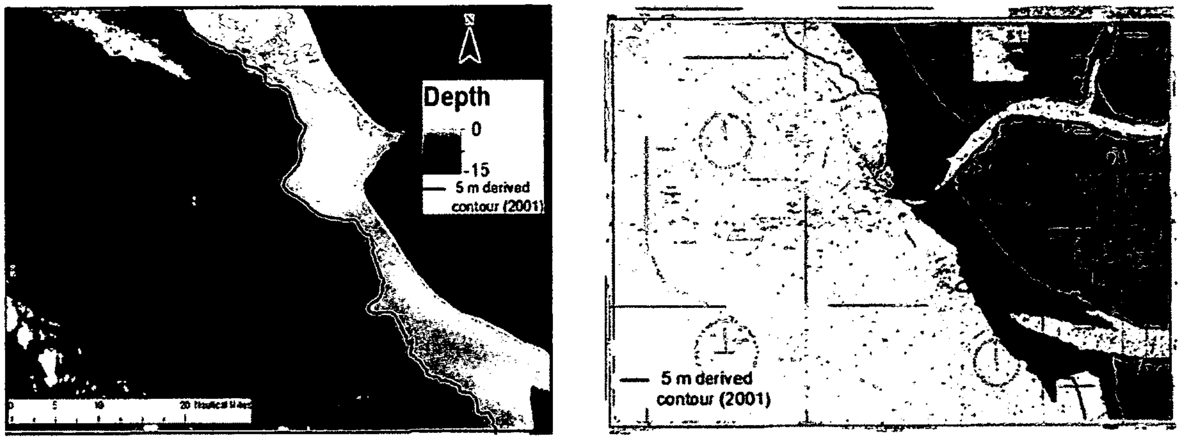


Figure 6.9 Optically derived bathymetry for Escravos area (left) and Admiralty chart 3321(right). Both pictures showing the 5 m contour line (red line) derived from the optically derived bathymetry.

6.3 Updating the Chart Adequacy Process

6.3.1 Depth area layer

In the Depth layer, the bathymetry is segmented into depth ranges, which are inferred from the depth of channels and anchorage areas leading to ports in their vicinity. The depth information in the chart up to the extinction depth is considered historic in comparison to the satellite imagery collected in the last 10 to 15 years. For Nigeria study site, the depth ranges were segmented from 0 m to 5 m, 5 m to 30 m, 30 m to 40 m and greater than 40 m. However, the depth of extinction for optical-driven bathymetry was about 5.5 m. Thus, only the 5 m contour of the depth area layer was updated. Figure 6.9 shows the changes in the bathymetry for the Depth layer.

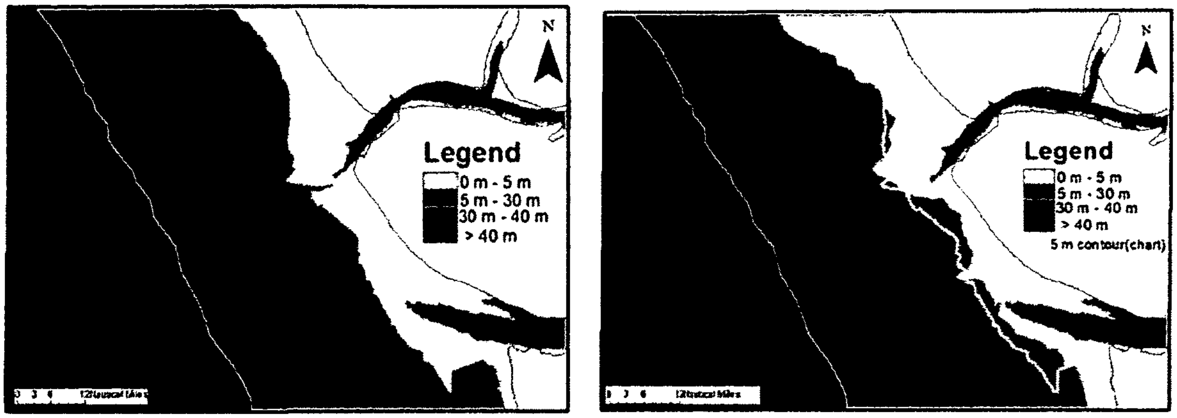


Figure 6.10 Depth area class derived from the chart (left) and the depth area updated using optical-derived bathymetry (right).

6.3.2 Chart adequacy classification

The updated Depth layer is introduced back into the chart adequacy classification procedure to provide updated chart adequacy areas for navigation. The new thematic map shows the areas of changes in the chart adequacy classification (Figure 6.10). These areas are located mainly in the northern parts of the Escravos area (yellow circle).

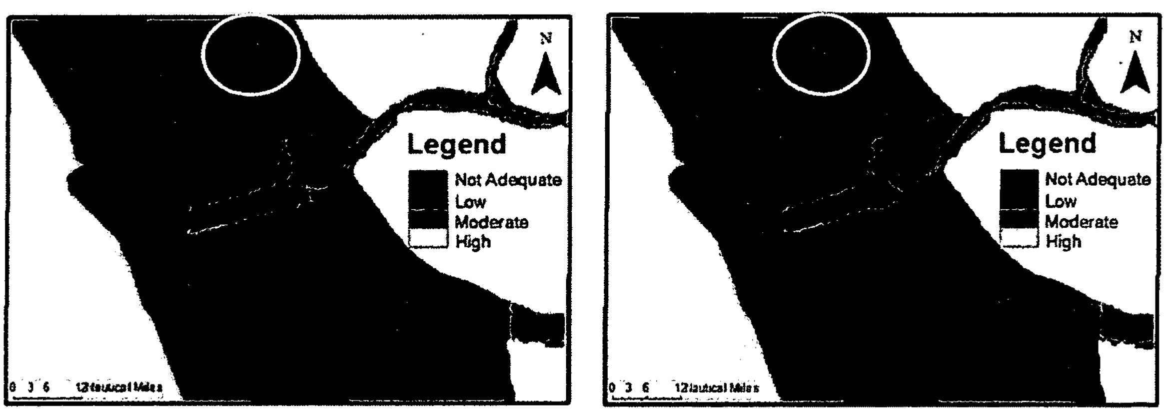


Figure 6.11 Chart adequacy classification derived from the chart(left) and the Chart adequacy classification updated using optical derived bathymetry (right).

6.3.3 Hydrographic priority maps

The updated chart adequacy class is then intersected with the maritime significant area class to produce an updated hydrographic priority map. The new priority map based on the information from the optically-derived bathymetry is presented along the original prioirity map (based only from the chart and sailing directions) in Figure 6.11. In spite of the updated depth information from the optically-derived bathymetry, very little change (blue circle) was observed in the updated survey priority map.

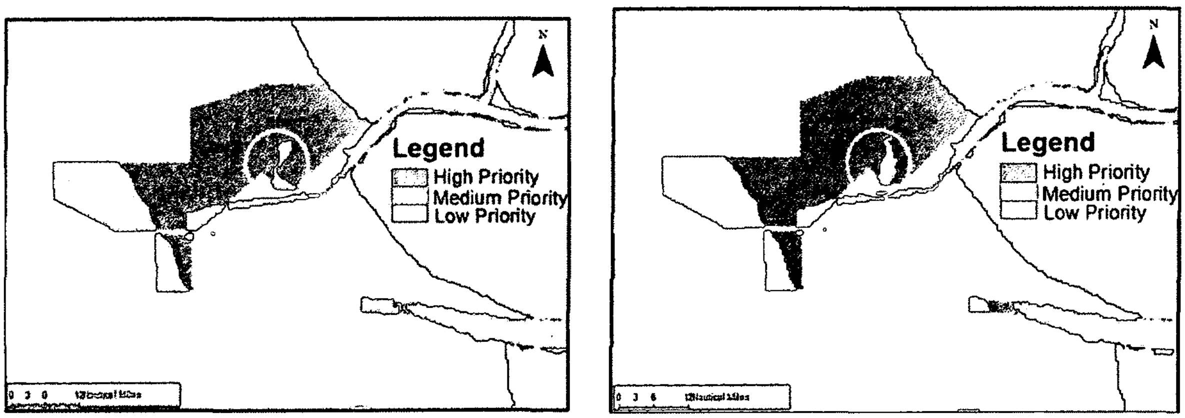


Figure 6.12 Hydrographic priority map derived from the chart (left) and Hydrographic priority map updated using optical derived bathymetry (right).

6.4 Belize Study Site

6.4.1 Geographic setting

The Belize study site is in the Big Creek area located in the southeast of Belize and bounded by the Caribbean Sea to the east and Guatemala to the south. The area covers a total coastline of about 148 km. The seafloor in the study area is characterized by mud, sand and an extensive coral reef system. The area is a wave dominated environment with a tidal range of about 0.5 m. Winds coming from the northeast produce waves of about 0.3 m in amplitude. These waves generate alongshore currents setting south (NGA, 2011). The magnitude of the current depends on the energy of the wind and angle of approaching waves. These currents transport sediments discharged from the South Stann Creek and Big Creek southwards forming long barrier islands. The waters in the area are considered very clear because of the coral reef that acts as a filter by consuming particulate matter suspended in water columns thereby enhancing the clarity of the water.

6.4.2 Landsat imagery

The Big creek study area study site is larger than the Nigerian study site and required 4 overlapping Landsat satellite images to cover the whole area. Recent images covering the area were downloaded from the USGS website. These images were collected at different times under various environmental conditions (Figure 6.12). Consequently, each image was processed separately. Like the satellite images in the Escravos area, these images are referenced to WGS 84 datum and have a positional uncertainty better than 50 m. Although the cloud coverage was similar in all images (< 10%), the cloud distribution was different in every image and did affect the merging of all the datasets together. The clouds were removed using the same process discussed above for the Nigeria study site.

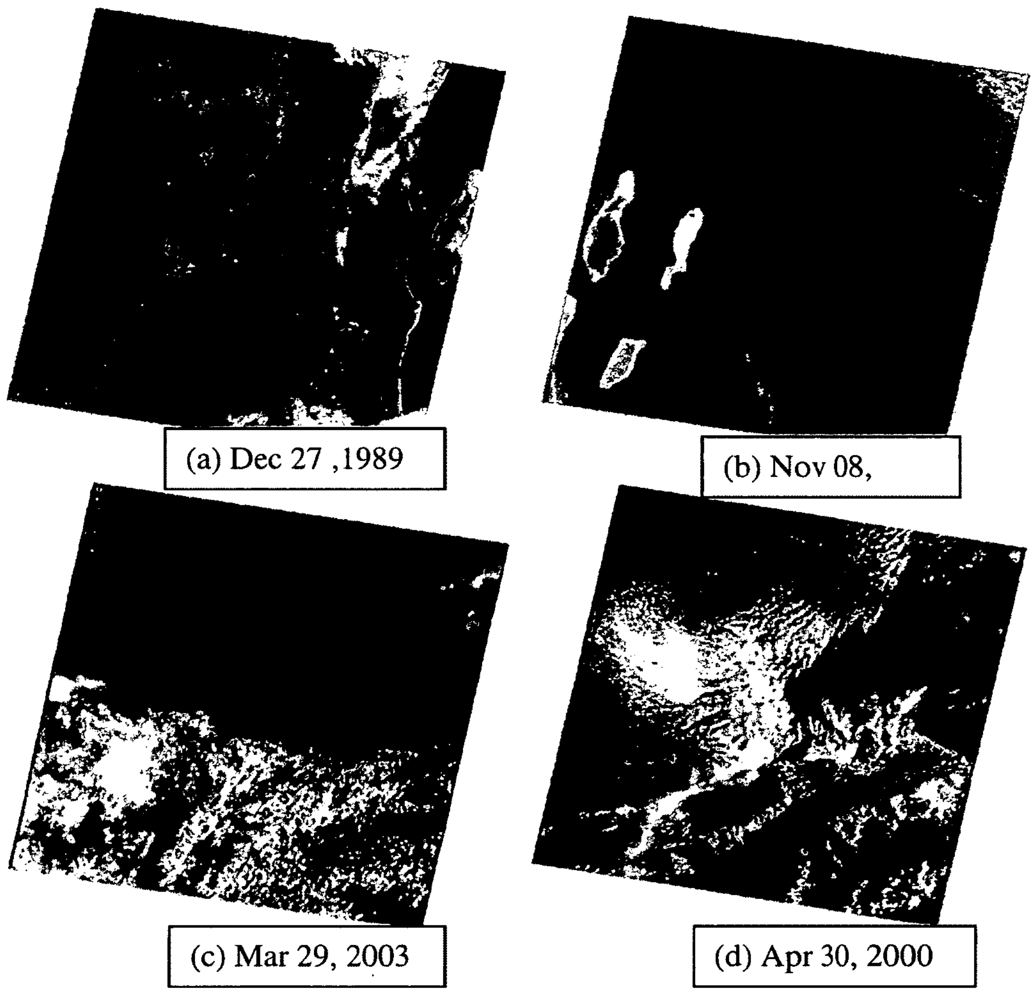


Figure 6.13 Landsat images covering the Big Creek area showing the times of image collection

6.4.3 Nautical chart

The Belize study area is covered by the Admiralty chart 1797 ('Monkey River to Colson point') (Figure 6.13). The chart was published in 1989 with a scale of 1:125,000. The horizontal datum is WGS 84 and a Mercator projection is used. The chart soundings are presented in meters and referenced to LAT. Survey periods in the chart range from 1834 to 1991. These surveys were carried out by the British Government Surveys, while the more recent surveys (1988-1991) are from commercial surveys.

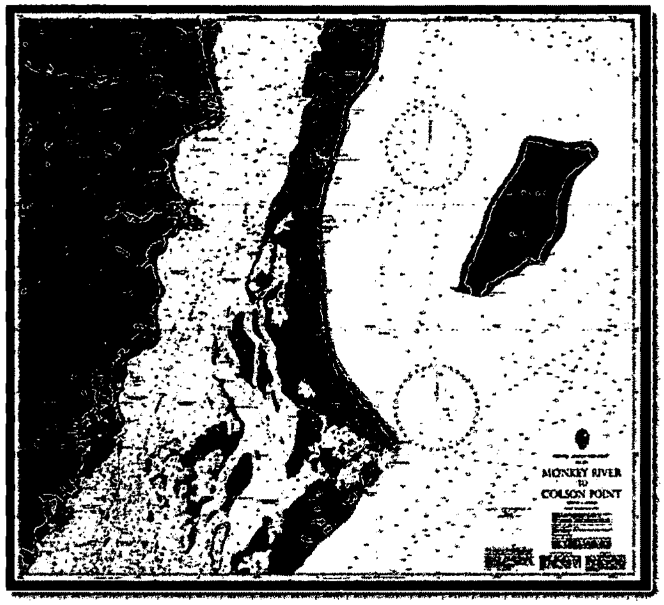


Figure 6.14 BA Charts 1797 (Scale: 1:125,000).

6.4.4 Optically-derived bathymetry procedure

The same procedure used in the Escravos area was used to derive the bathymetry in the Big Creek (Belize) area. Each of the satellite images that cover the Big Creek area was processed separately, where a different threshold was used for determining the water separation boundary for each image scene. Using the blue and green bands masked from cloud cover, a filtered Stumpf algorithm result model was generated (Figure 6.14).

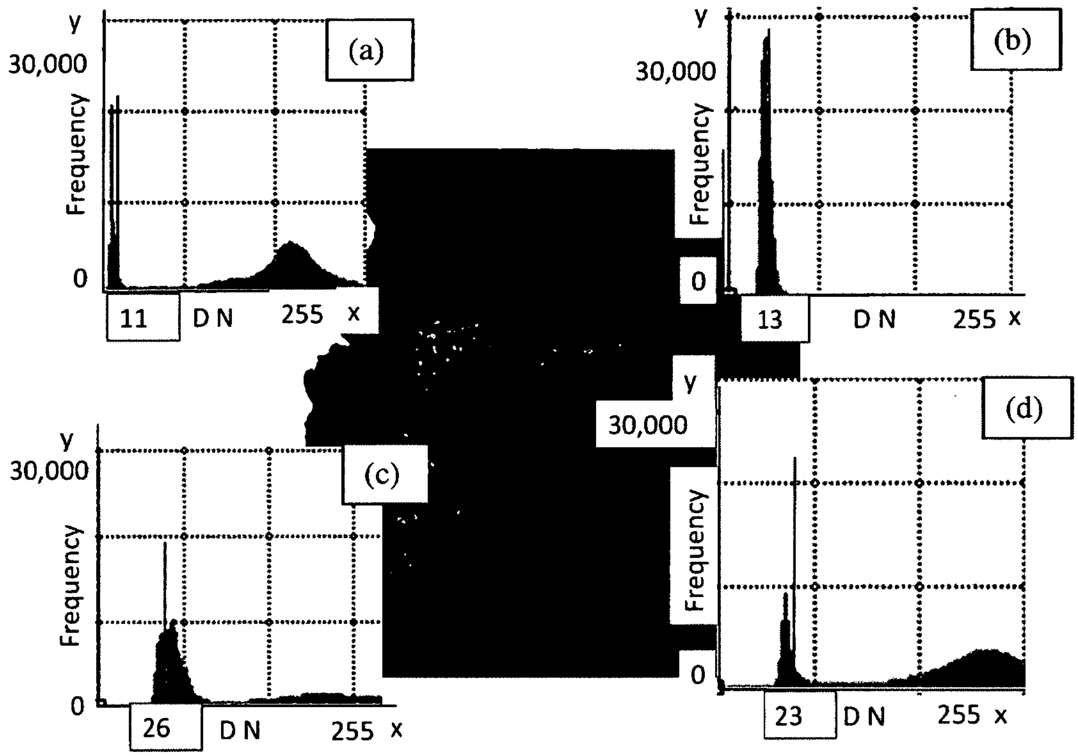


Figure 6.15 Near-infrared images of the Big Creek area. The NIR image histograms showing the Land/Cloud-Water threshold for each image.

The algorithm results were referenced to the LAT using chart soundings, and a linear regression applied. Due to many incomplete and unsurveyed areas on the chart, soundings were selected only from surveyed areas (I) and (IV) that have been stable (i.e., consistent with the optically-derived bathymetry models) over time (Figure 6.15). The correlation between the algorithm model and the chart soundings showed good linear results. A correlation coefficient of 0.85 was calculated for the Landsat image in Figure 6.12a and a correlation coefficient of 0.80 was calculated for the Landsat image in Figure 6.12c (Figure 6.16). The chart soundings were used to calculate a gain and offset for each bathymetric model, where equations 6.2a and 6.2c relate to Landsat images in Figure 6.12a and Figure 6.12c, respectively:

$$y = -131.33x + 163.39 \quad [6.2a]$$

$$y = -0.0018x + 1.0765 \quad [6.2c]$$

where y(a) is the optically derived bathymetric model referenced to LAT, x is the Stumpf algorithm result, and -131.33(a) and -0.0018(b) are the offset values and 163.39(a) and 1.0765(b) are the gain values.

The soundings in the areas covered by the Landsat images in Figure 6.12b and Figure 6.12d are considered unreliable due to incomplete and unsurveyed areas. The bathymetric surface generated from Landsat image in Figure 6.12a was used to reference the bathymetric surfaces generated from Landsat images in Figure 6.12b and Figure 6.12d selecting soundings from areas where both surfaces that overlap areas II and IV (Figure 6.15), respectively. This gave a good correlation of 0.73 (b) and 0.82 (d). The gain and offset were then calculated, and a bathymetric surface generated for (b) and (d) using the equations.

$$y = -0.0017\,x + 1.06 \quad [6.2b]$$

$$y = -255.27\,x + 269.5 \quad [6.2d]$$

Where y is the optically derived bathymetric model referenced to LAT, x is the local ratio result, -0.0017(b) and -255.27 (d) are offsets and 1.06(b) and 269.5(d) are gain values.

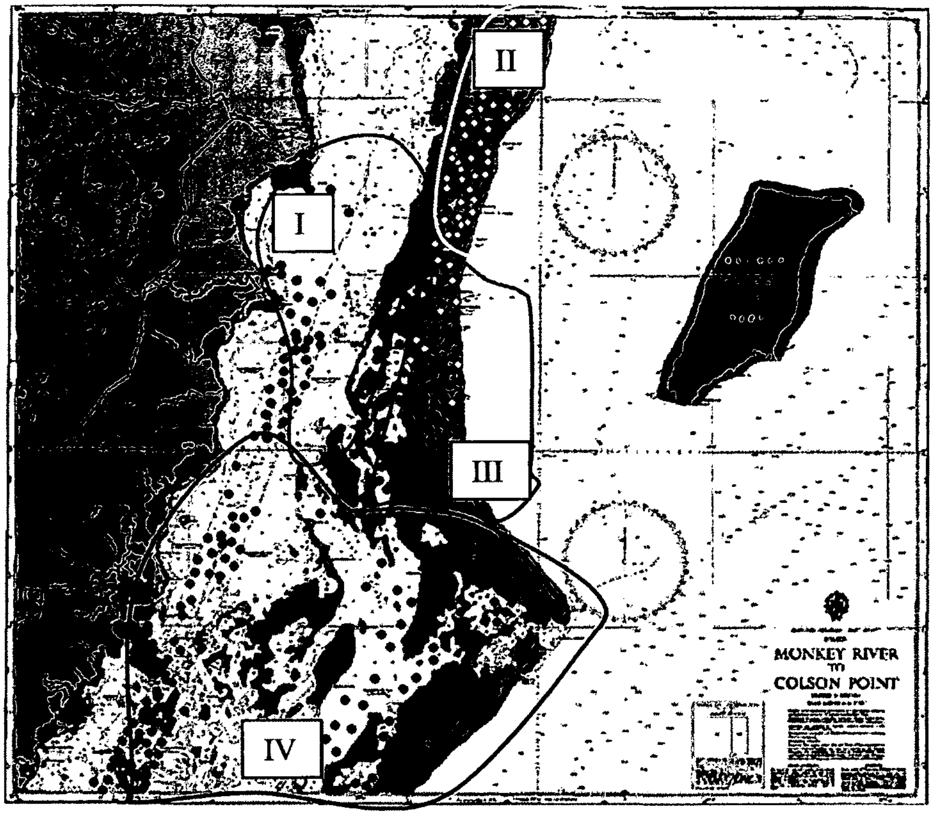
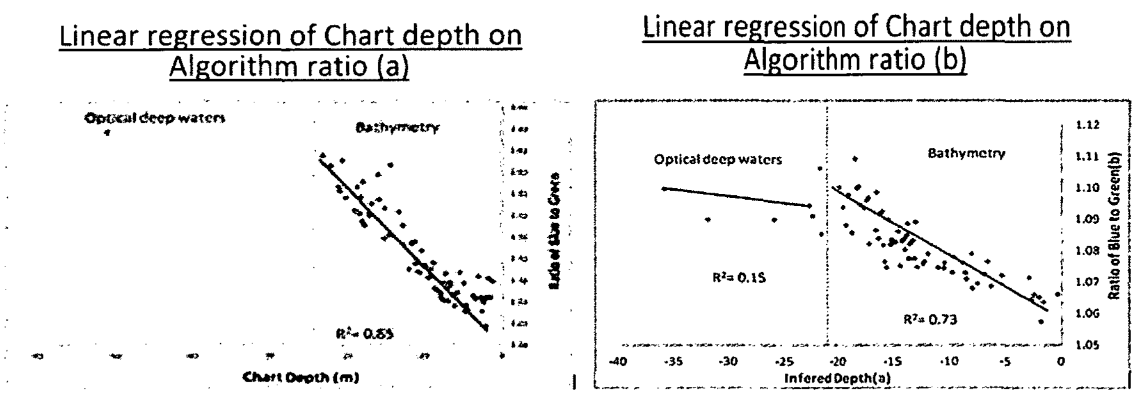


Figure 6.16 Chart 1797 showing where soundings were selected to generate a bathymetric surface for each of the Landsat images covering the chart.



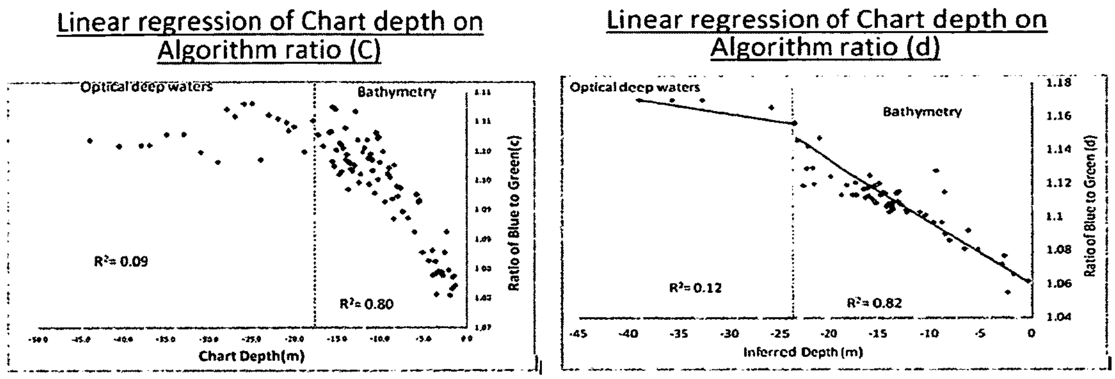


Figure 6.17 Correlation of the algorithm result to chart soundings for all the Landsat images: (a) correlation values for Landsat image Figure 6.12a, (b) correlation values for Landsat image Figure 6.12b, (c) correlation values for Landsat image Figure 6.12c, and (d) correlation values for Landsat image Figure 6.12d.

The depths of extinction that was calculated for Landsat images for the images Figure 6.12a, Figure 6.12b, Figure 6.12c and Figure 6.12d, were calculated to be 24 m, 21 m, 24 m and 17 m, respectively. All bathymetric models were merged together into one seamless surface (Figure 6.17). In places of surface overlap, the bathymetric surface with a higher R^2 value was given preference. Due to the limited accuracy of the gain and offset calculation from the chart soundings, a surface discontinuity occurred in some places as a result of different depths values that were calculated (typically, up to ± 2 m offset).

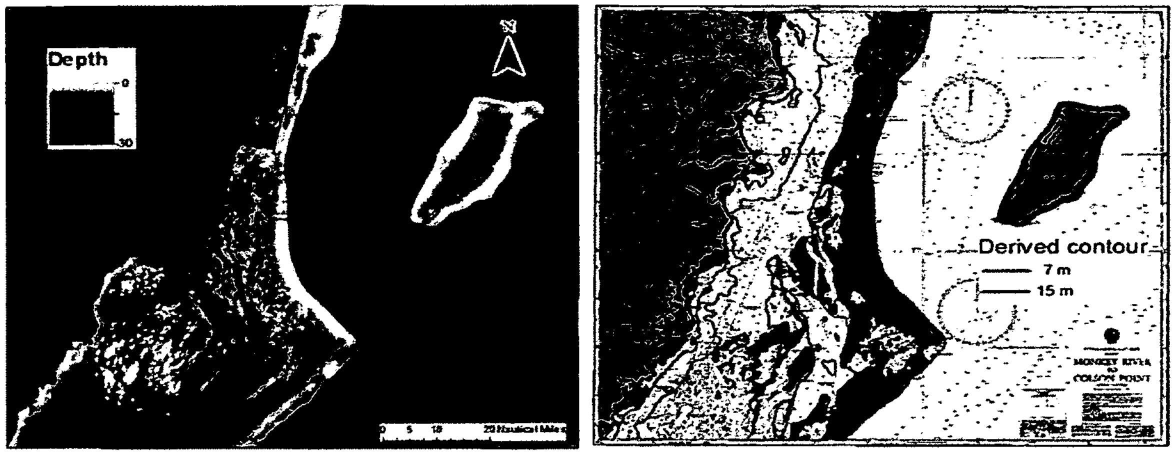


Figure 6.18 Merged bathymetric surface for Belize (left) and Chart 1797 showing the 7 m and 15 m contour line from the optically derived bathymetry.

6.5 Updating the Chart Adequacy Process

6.5.1 Depth area layer

The depth ranges based on the chart and the sailing directions for Belize were inferred from the depth of the Big Creek Channel and the Inner Channel. The depth ranges were 7 m, 15 m, and 40 m. Based on the extinction depths of the Landsat images that range between 17 m to 24 m below the LAT 0 m contour line. Consequently, only the 7 m and 15 m contours of the depth area layer were updated using the optically-derived bathymetry. Figure 6.18 shows the changes in the bathymetry for the Depth layer.

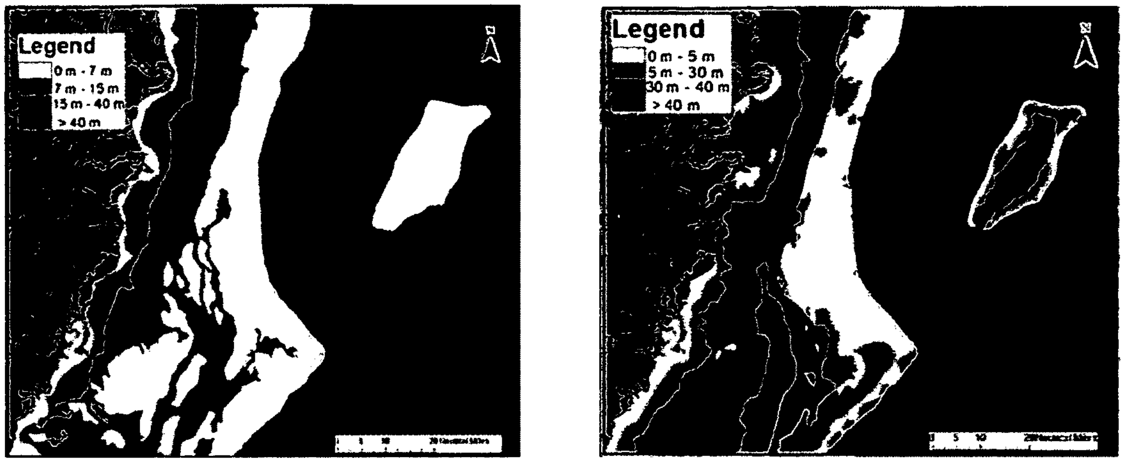


Figure 6.19 Depth area class derived from the chart (left) and the depth area updated using optical derived bathymetry (right).

6.5.2 Chart adequacy classification

The updated depth area layer is introduced into the chart adequacy classification process to provide updated chart adequacy areas for navigation based on the new depth information. The new thematic map shows changes (yellow circle) in the chart adequacy classification of areas in a yellow circle.

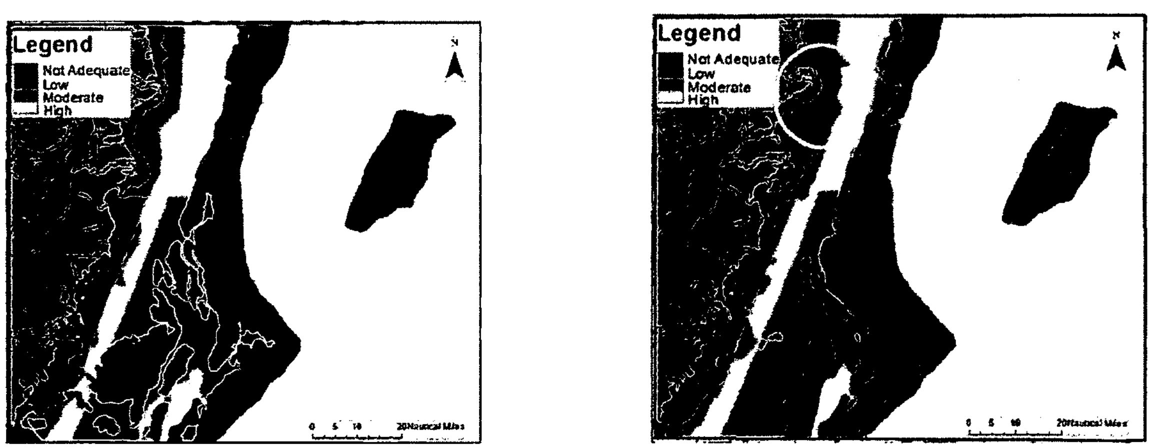


Figure 6.20 Chart adequacy classification derived from the chart (left) and the Chart adequacy classification updated using optical derived bathymetry (right).

6.5.3 Hydrographic priority maps

The updated chart adequacy class is intersected with the maritime significant area class to produce an updated hydrographic priority map based on the information from the optically-derived bathymetry (Figure 6.20). The Big creek area showed remarkable changes in priority along the Inner Channel. These changes are mainly in the northern part of the channels and around Big Creek.

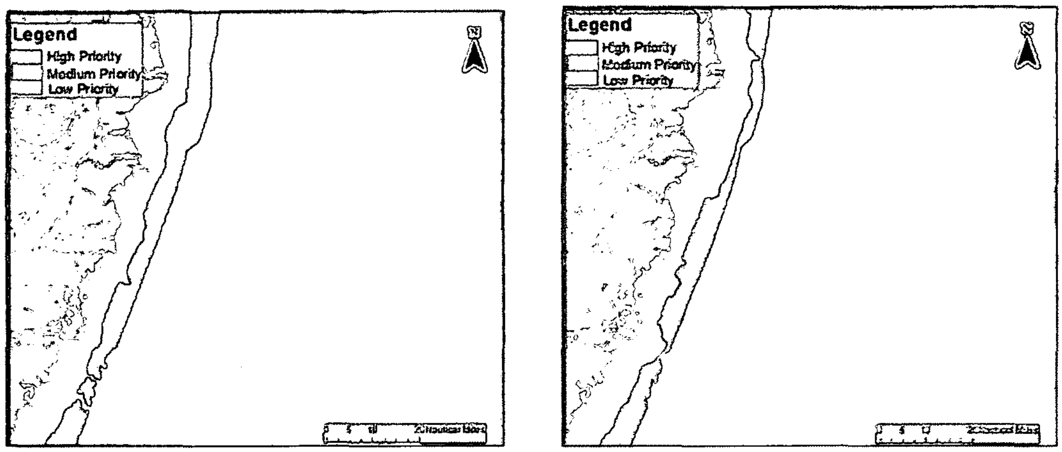


Figure 6.21 Hydrographic priority map derived from the chart (left) and Hydrographic priority map updated using optical derived bathymetry (right).

VII. DISCUSSION

7.1 Robustness

The study set out with the aim of assessing the adequacy of nautical chat for navigation with a view to prioritize areas for survey. The study involved a two-step process: 1) a chart adequacy evaluation using information from a nautical chart and 2) updating the adequacy evaluation using optically derived bathymetry. For the use of this process in other locations around the world, it is important to evaluate the robustness of the process and include the capabilities and limitations that have been learned through this study. In order to evaluate the robustness of the processes, each process will be investigated separately.

7.1.1 Chart adequacy evaluation

The chart adequacy evaluation using symbols, warning and soundings from nautical charts and sailing direction was successfully applied to delineate sea areas into hierarchical levels of chart adequacy for navigation. It was also able to prioritize areas for hydrographic survey. The effectiveness of the process does not depend on the availability of depth information as incomplete survey areas and unsurveyed areas can be assessed following the same procedure. The evaluation process is modular and allows the change of weight values to classes for the production of priority maps. Furthermore, additional layers to improve the adequacy assessment may be added to reflect availability of information or a particular country requirement, e.g. Automatic Identification System

(AIS) class as additional navigation layer. In general, the evaluation process can be applied to any chart covering any part of the world.

Despite the potential of the chart adequacy evaluation, the process cannot account for changes in the seafloor after a survey is conducted. This problem was partially solved using optically- derived bathymetry for optically shallow parts of the sea area. In addition, there are situations where two or more symbols and warnings are used to refer to the same information on the chart. Consequently, some symbols become redundant when evaluated for use in the chart adequacy process. An example is the evaluation of the chart quality class where the combined use of "slanting soundings" and "broken depth contours" refer to the same quality of data as "fine upright soundings." Accordingly, not all symbols and warnings that indicate the adequacy of an area for navigation were used for the process.

Furthermore, the applications of these chart symbols are very subjective and are left to the judgment of the cartographer. As a result, each chart may be slightly different from the other. Thus, it was difficult to define a specific set of rules to categorize symbols and warnings for each adequacy class. Typically, less than 2% of the soundings collected during a hydrographic survey are represented on the nautical chart. This reduces the information available for analysis when determining chart adequacy for navigation and prioritization of survey. Also, there is a possibility that significant features are lost in the data due to the reduction of soundings used to produce the chart. The use of smooth sheets, if available, may further improve the process as several soundings are not included in the final chart product.

7.1.2 Optically derived bathymetry

The updated process using optically derived-bathymetry improved the chart adequacy evaluation for shallow-water areas up to the extinction depth. The wide swaths of Landsat images ensure that very few satellite images are required to cover a nautical chart. The process serves as a reconnaissance tool for investigating sea areas before a high resolution hydrographic survey (e.g., MBES or ALB) is conducted. The Landsat geo-referenced imagery is provided with a 50 m horizontal uncertainty. This uncertainty is reasonable for goals of the study charting application. Also, as part of the procedure the optically-derived bathymetry is referenced to the vertical datum of the chart and does not require additional information beyond the satellite imagery and the chart. An additional benefit of the process is the use of multiple Landsat images with repeatable coverage from the USGS archives. The procedure can generate a time series that can be used to monitor seafloor changes in the coastal environment.

The main limiting factor for the performance of the optically-derived bathymetry is the environment. Water clarity is a key factor that determines the penetration of light in water. The depth of the seafloor can only be estimated to the extent of this penetration. Hence, the success of this process is very limited in murky waters as compared with clear waters. Another environmental factor is the presence of cloud cover in satellite images. This is particularly prevalent in tropical areas. Cloud cover prevents the extraction of relevant information from the image. Consequently, the process was unable to estimate bathymetry in areas below the clouds. Efforts are made to select only images with less than 10% cloud cover to reduce the impact on the process. Another factor is the presence of sun glint, which also limits the ability to infer bathymetry.

Another limiting factor is the selection of chart soundings for vertical referencing of the bathymetry. The selection of chart sounding for the linear transformation of algorithm surfaces to a reference datum poses a problem where there is no reliable sounding data on the chart. In such situations, it is recommended that the algorithm result be inspected to identify areas of seafloor stability. This is done by comparing contours on the chart to the seafloor in the algorithm result and identifying areas of similar geological features.

7.2 Marine Spatial Planning

In the chart adequacy procedure, the maritime significant areas were limited to only navigational significant areas. In addition to hydrographic offices, this procedure can be used by other groups for marine spatial planning application. Marine spatial planning is defined as the process of analyzing and allocating spatial and temporal distribution of human activities in the marine areas to achieve ecological, economic and social objectives that are usually specified through a political process (IOC, 2009). A couple of examples for the marine spatial planning that are a derivative of the current study are stability of the seafloor (Nigeria) and route planning (Belize).

7.2.1 Monitoring seafloor changes (Nigeria)

Seafloor changes over a time period were monitored using the optically-derived bathymetry process. This was possible due to the availability of archived Landsat images with repeatable coverage. A time series was generated over a 15 year period using three Landsat images that were collected in the same season (January 1986, December 1999, October 2001). The 5 m depth contours of these surfaces were then compared to show the changes in the seafloor at that depth over the 15-year period (Figure 7.1). The time series indicates gradual erosion that is occurring at the southern part of the Escravos area. Based on the local coastal conditions (i.e., along shore current and river output), it is possible that these sediments are transported to the northeast. This effect is seen as accretion of sediments along the bar (mole) protecting the Escravos channel and also at the mouth of the Benin River, where the sediments are trapped by oil rigs. From the study, the area around the mouth of the Benin River which is charted at a depth ranging from of 5 m to 7 m is observed to be shoaler in the optical-driven bathymetry at a depth of ~3 m. This poses a danger to navigation and may lead to grounding of vessels within the area. Thus, it is recommended that the area be surveyed with better resolution to ascertain the actual depth, and the information reflected on the relevant chart.

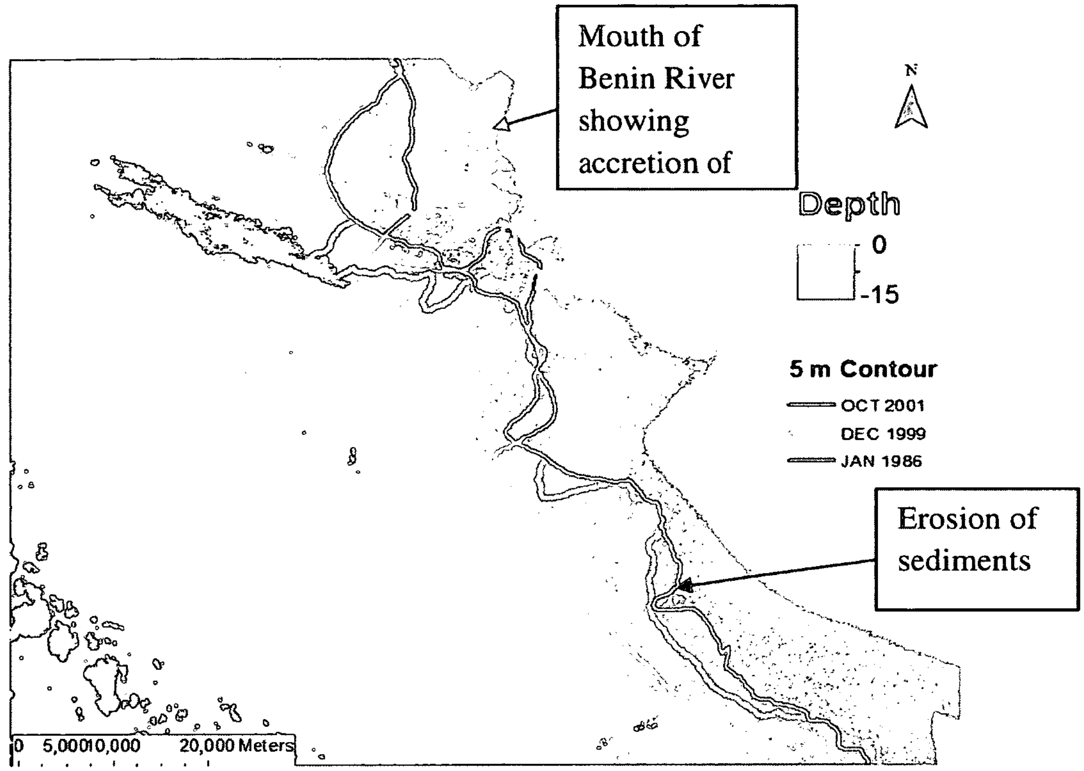


Figure 7.1 Optically derived bathymetry of the Escravos area showing the 5 m contour line over a 15-year period (Green - 1986, Yellow - 1999 and Red - 2001).

The reliability of this method of change analysis was evaluated by looking at the possible sources of uncertainty. These sources of uncertainty include uncertainty in measurements of the satellite sensor, geo-referencing, and model parameters. Other sources of uncertainty are those introduced during the chart production process either from the equipment used and/or the cartographic process. Some of these uncertainties can be readily quantified while others such as uncertainties from the cartographic process, are more difficult to estimate. However, for our purposes, a rough estimate of the uncertainty for the satellite derived contour displacement between two epochs was calculated using the formula:

$$\sigma_{\Delta x} = \left[\left(\frac{\partial x_1}{\partial z_1}\right)^2 \sigma_{z_1}^2 + \left(\frac{\partial x_2}{\partial z_2}\right)^2 \sigma_{z_2}^2\right]^{\frac{1}{2}}$$

$$= [(\cot\theta)^2\, \sigma_{z1}^2 + (\cot\theta)^2\, \sigma_{z2}^2]^{\frac{1}{2}}$$

Where Δx = contour displacement between two epochs, θ = seafloor slope, x_1 and x_2 are the positions of the 5m contour in Jan 1986 and Oct, 2001 respectively. If we take $\sigma_{z_1} = \sigma_{z_2}$ = 1.83 m (the value calculated empirically for Cape Ann), this gives an uncertainty of ± 2796 m. While this estimated uncertainty is quite large (nearly 3 km), due to the shallow seafloor slope in the project site, it is still relatively small compared to some of the contour displacements depicted in Figure 7.1, indicating that some areas may have experienced quite a bit of actual change.

It is important to note that the chart cannot be used in the time series as a reliable baseline, because the last survey around the Benin River was conducted in 1913. Although beyond the scope of this thesis, the analysis of uncertainty is recommended topic for continuing research. In particular, a rigorous assessment of the uncertainty in satellite-derived bathymetry should be performed.

7.2.2 Route planning (Belize)

Another marine spatial planning application is route planning. The wide coverage of the Landsat image provides a great opportunity for shipping and tourism route planning even in unsurveyed areas. This is application is ideal for clear water conditions such as investigated in Belize, where optical-driven bathymetry was generated up to a depth of 24 m in most areas. In Belize, the Inner channel passage through the reef system passes over comparatively-shallow waters in the northern section of the chart 1797. From the optical-driven bathymetry, it was noticed that the existence of a deeper channel system to the east of the northern section of the current "Inner Channel" location. This natural deep channel system provides the best natural transportation route through the reef system (Figure 7.2). As a result, deep draft vessels can safely navigate up north to Belize City and reduce the risk of grounding and potential damage to the reef system.

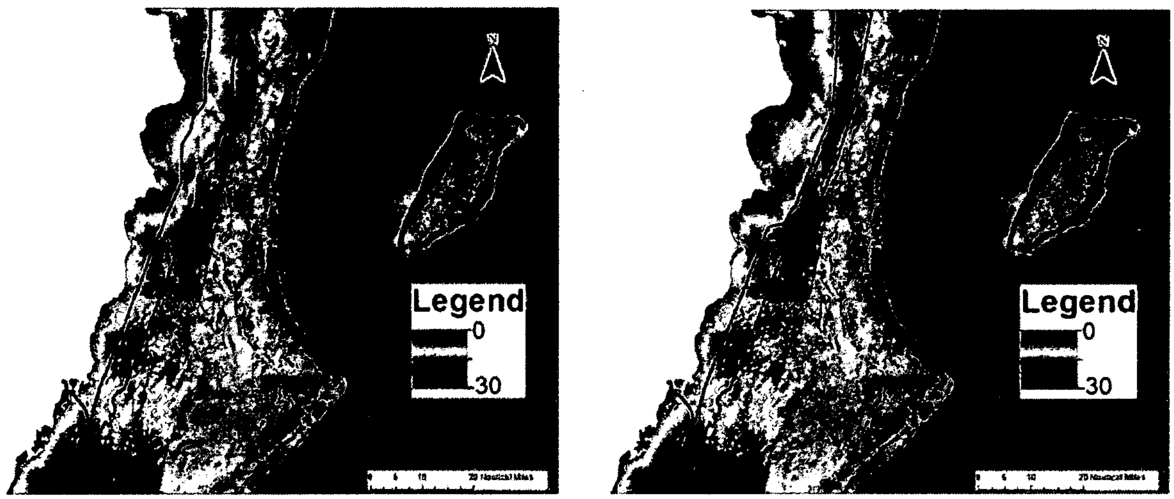


Figure 7.2 Optically-derived bathymetry of the Big Creek area showing the Inner Channel (left) and the recommended channel passage (right).

By updating the Navigation Significant Areas layer in the chart adequacy evaluation for chart 1797, the high-priority areas that require survey are reduced by about 50% (Figure 7.3). In addition to commerce the route planning can help fisheries and tourism, that may require additional routes to access an atoll (such as the Glover reef system). However, a systematic survey of these routes will be required before they can be put to service.

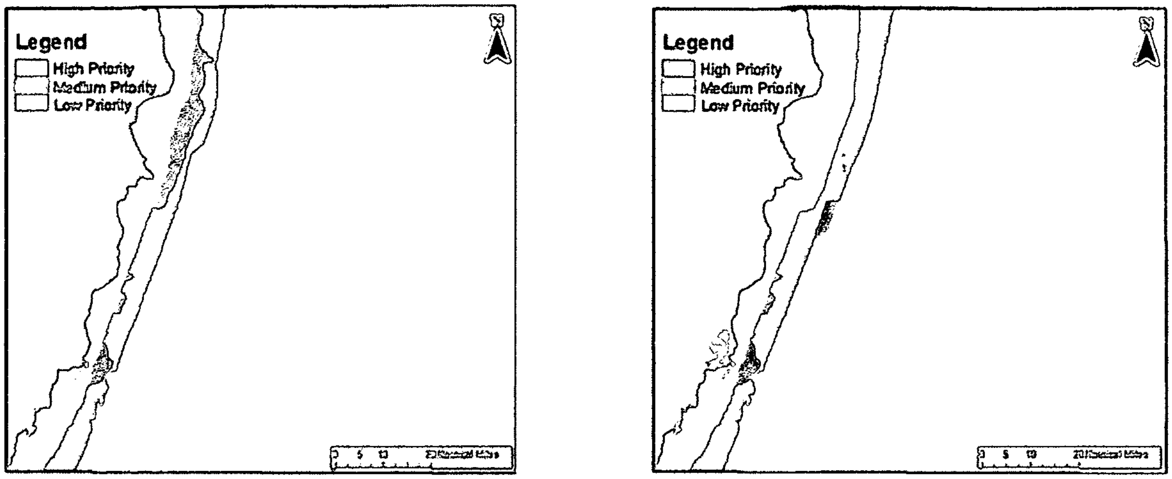


Figure 7.3 Hydrographic priority map showing the priority areas of the inner channel (left) and the priority areas if the inner channel is moved to the recommended route (right).

VIII. SUMMARY AND CONCLUSIONS

IHO Publication No. 55 (C-55) is issued by the IHO to show the extent of hydrographic surveying and nautical charting, worldwide. The aim of C-55 is to provide base data for governments as they consider the best ways of implementing the responsibilities set out in IHO SOLAS publication. C-55 is used by the IHO to identify and assist to prioritize requirements for progressing modern surveys and chart production. The IHO C-55 document indicates that many coastal states lack the capacity to plan and implement a prioritized survey program. The C-55 document states the extent of survey for each area in terms of percentage coverage. This is too vague to determine high-priority areas that are in need of hydrographic surveys and improved nautical charts. A major challenge in global data compilation is obtaining hydrographic, charting and maritime safety information from developing countries.

The motivation for this study is to provide tools for any hydrographic office to analyze a given chart and determine the priority area that are in need of hydrographic surveys and improved nautical charts. In this thesis, two processes were developed. The first process evaluates the adequacy of a given navigational chart and prioritizes sea areas for survey or resurvey. The focus of the process is on the chart adequacy information and maritime significant areas available on nautical charts and sailing directions. The process identifies and prioritizes areas that require survey within a chart. The nautical charts of the territorial waters of Belize and Nigeria were used to develop this process. From the C-55, both countries were identified as having gaps in their hydrographic data. Based on a standardized analysis and assessment methodology to evaluate the adequacy hydrographic surveying and nautical charting coverage, it was noticed that one of the limitations in this procedure is that the source layers for the procedure are sometimes out of date. The second process in the study addresses this issue by using optically-derived bathymetry from satellite imagery to update the Depth area layer in the chart adequacy evaluation with the most recent depth information and to monitor any morphological changes of the seafloor. From a practical perspective, the bathymetry should be accessible to the user with a resolution and accuracy sufficient to provide a bathymetric estimate in unsurveyed areas and to indicate any major discrepancies between the current bathymetry to the chart's soundings and the depth contours.

In the first process, chart adequacy and completeness information were evaluated by five main data classes: reliability diagrams (zone of confidence or source diagram), chart quality symbols/indicators, doubtful-danger markings, survey completeness and depths areas. The source diagram provides information on the origin, scale and spatial limits of the hydrographic data used to prepare the chart from which the quality of the survey data can be inferred. Chart completeness refers directly to the thoroughness of a hydrographic survey that was conducted. This is shown on the chart by the use of completeness warnings and cautionary notes. They can also be inferred from the distribution of soundings. Chart quality symbols/indicators are cartographic symbols on a chart that supplement depth information and are used to draw attention to the dangers inaccurate depth data portend (IHO, 2011). Chart quality symbols include depth contours, broken depth contours, coastlines and broken coastlines. Doubtful danger abbreviations are abbreviations used to indicate the positional or depth inaccuracies of features in a nautical chart. Depth areas are sea areas whose depth range is determined by the navigational considerations of vessels transiting though the area. The depth area ranges are inferred from the depths of dredged channels, ports and other sources of information that may give an idea of the type of vessels transiting through such areas. Maritime significant areas are areas that are delineated for their navigational importance such as ports, harbors, navigational channels, anchorages. Maritime significant areas also comprise areas of cultural and natural importance such as marine protected areas (MPA), military restricted areas, and areas for exploration and exploitation of natural resources. In the context of nautical charting and safety to navigation, the maritime significant area was evaluated by two classes; navigational significant areas and non-navigational significant areas. In this study, only navigation significant areas were considered for the priority scale. This is due to the relatively clear spatial definition of these areas in the chart and the sailing directions.

The Chart adequacy and completeness information was assessed based on five main data classes that are also considered as evaluation criteria. Each class was further sub-divided into various elements that can be used to assess the adequacy of the chart for navigation. A weighted percentage was allocated to each class based on its assessed importance in the navigation of a vessel. Each element was numerically rated by the degree of danger it poses to the safety of navigation, ranging from 1 to 5. A value of 1 indicates the least danger to the safety of navigation and a value of 5 is the most dangerous to the safety of navigation. The class layers were combined into one layer based on the rating factor using *ArcMap*. The resulting sea areas were ranked as "not adequate", "low", "moderate" and "high adequacy" based on a manual classification method derived from empirical observation of chart 1797 and 3321. The study results show that 21% (1277 km^2) of the total marine area (5933km^2) in BA Chart 1797 of Belize and 27% (571km^2) of the total marine area (2112 km^2) in BA Chart 3321 of Nigeria are rated as "not adequate". Maritime significant areas were evaluated based on two evaluation criteria: navigational significant and non-navigational significant areas. Each class was divided into elements according to the use of the area. The classes of the maritime significant areas were rated based on their importance to navigation on a Boolean logic. Areas that are important to navigation were rated as 1 (true) and all other areas were rated as 0 (false). The classes were summed together into a maritime significant area class layer. The study results show that 6% (352 km^2) of the total marine area (5933km^2) in BA Chart 1797 of Belize and 21% (441 km^2) of the total marine area (2112 km^2) in BA Chart 3321 of Nigeria are ranked as "navigational significant". The maritime significant areas were intersected (one layer was multiplied by the other) in order to prioritize areas within the chart for surveying. The results of the intersection yield priority areas with a score range from 0 to 5. Areas with the highest scores have higher priority for survey. Based on the numeric priority scores, three priority areas were generated: low priority, priority and high priority areas. The study results showed that 1% of the area in chart 1797 (Belize) and 6% in chart 3321 (Nigeria) are areas with high priority for survey.

In the second process, the study was conducted in two steps: 1) evaluate the different optically-derived bathymetry algorithms and 2) quantify the potential improvements that optically-derived bathymetry can add for the evaluation process to assess adequacy of hydrographic surveying and nautical charting coverage. Landsat satellite imagery from the USGS public web archives was used in the study. Four channels (Blue, Green, Red, and Near Infrared) from the satellite imagery were used in the study. The satellite imagery was loaded into a GIS environment (*ArcMap10*) and processed using the available functions in the software without the need to code any new tools.

Two bathymetry-extraction algorithms were evaluated using a LANDSAT image over a well-controlled study site, northern coast to Cape Ann, Massachusetts, U.S.A. The results from both algorithms were compared to a high resolution reference dataset generated from a USACE ALB survey and to the chart's soundings from a NOAA chart. The optically-driven bathymetry process included: 1) water separation, 2) spatial filtering, 3) applying the bathymetry algorithms and 4) referencing the bathymetry to the chart's datum. The procedure configuration was chosen base on the linear correlation values between the optic-driven bathymetry and the chart soundings, where the ALB reference dataset was used to validate the comparison results. The procedure configuration with the best correlation values was a low-pass Stumpf algorithm using the Blue/Green bands. The benefit of the Stumpf algorithm is that it is a band-ratio algorithm that utilizes two bands to reduce the number of parameters required to infer depth. The selected configuration for the optically-derived bathymetry was applied to Nigeria and Belize study site to update the depth area layer. The updated depth area layer was then re-introduced to the chart adequacy evaluation. This generated an improved chart adequacy classification and hydrographic survey priority maps.

The two processes seem to be robust for use in other study sites. The chart adequacy evaluation using symbols, warning and soundings from nautical charts and sailing direction was successfully applied to delineate sea areas into hierarchical levels of chart adequacy for navigation. It was also able to prioritize areas for hydrographic survey. The effectiveness of the process does not depend on the availability of depth information. The evaluation process is modular and allows the change of weight values to classes for the production of priority maps. Furthermore, additional layers to improve the adequacy assessment may be added to reflect availability of information or a particular country requirement. However, the process cannot account for changes in the seafloor after a survey is conducted. This problem was partially solved using optically- derived bathymetry for optically shallow parts of the sea area. Furthermore, it is difficult to define a specific set of rules to categorize symbols and warnings for each adequacy class as different symbols are used by different cartographers. The optically derived-bathymetry improved the chart adequacy evaluation for shallow-water areas up to the extinction depth. The wide swaths of Landsat images ensure that very few satellite images are required to cover a nautical chart. The process serves as a reconnaissance tool for investigating sea areas before a high resolution hydrographic. The main limiting factor for the performance of the optically-derived bathymetry is the environment (water clarity, cloud cover and sun glint) that limit the range of depth and the coverage. Another limiting factor is the selection of chart soundings for vertical referencing of the bathymetry. The procedure developed in this study is not limited only to chart adequacy evalution and can be used for other things, such as marine spatial planning. Two examples of marine spatial planning that are a derivative of the current study are stability of the seafloor (Nigeria) and route planning (Belize).

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