Thesis

Analysing the changes in bathymetry of Saldanha Bay between the years 1977 and 2021

by

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DECLARATION

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ABSTRACT

Possessing one of the finest natural harbours on the South African coast, along with its ideal location on a major international trading route, the Saldanha Bay Municipality has been identified as a key development zone in the blue economy, earmarked to lead major developments in the region. Saldanha Bay is strategically positioned to serve the envisaged oil-and-gas sector on the west coast of the African continent and is a critical area for development for South Africa's 'blue economy'.

Studies like Henrico & Bezuidenhout (2020) have proven that the changes made during the construction of the Port of Saldanha (PoS) have altered the shape and slope profile of Saldanha Bay (herein called the Bay, which refers to both Inner and Outer Bay, described in section 1.2) significantly, thus changing the hydrodynamics of the Bay.

The aim of this study is to compare and analyse the changes in bathymetry of Saldanha Bay between 1977 and 2021. The general tendency of gradual increase in depth from the coastline towards the mouth of the Bay, with sharp increases in depth off Elandspunt and Salamanderpunt, is the same for both 1977 and 2021. The Ordinary Kriging (OK) interpolation method, employed by means of a Geographic Information System (GIS), was selected for creating surface models of the bathymetry of Saldanha Bay, and for conducting the comparison between the two datasets. Said comparison will determine the change in bathymetry over the 44-year period. A slope analysis was also performed to determine the stability of the ocean floor of the Bay.

The results of this study indicate a general increase in depth since 1977, with most of the pixels in the graphical representation of the Bay (68.2%) indicating a depth increase between 0.395 - 3.203 m, and an average increase in depth within Big Bay of 1.799 m between 1977 - 2021. There were also two areas identified which experienced changes beyond the standard deviation and showed significant increases or decreases in depth. The general slope trend of Big Bay in 2021 remained fairly like that of 1977, with most of the Bay having a relatively low slope, between 0 - 1.3 degrees. However, in 2021 it can be seen that there is a slight increase in overall slope of Big Bay since 1977, with and average slope of 0.51 recorded in 2021, 0.2 degrees more than in 1977. Furthermore, in 2021 the majority of Big Bay had a slope of 1.3 degrees or less, 0.4 degrees more than in

1977. Finally, in 2021 Big Bay also showed an increase in the maximum slope recorded in the Bay, with a maximum slope of 14.8 degrees, more than twice the maximum slope recorded in 1977.

The findings of this study support the statements made by Flemming (1977) and Henrico & Bezuidenhout (2020) that the construction of the PoS changed the sedimentation processes within Saldanha Bay to some extent. However, the findings of this study are only relevant for a portion of Saldanha Bay, the inclusion zone in Big Bay as indicated in section 4.3. In this area however, there has been a total loss of 49 364 560.0 m^3 in volume. The exact nature and driving forces behind this loss in volume still requires further investigation to be fully understood.

OPSOMMING

Saldanhabaai Munisipaliteit, wat een van die beste natuurlike hawens aan die Suid-Afrikaanse kus huisves, en wat ideaal geleë is op ‘n internasionale handelsroete, is as ‘n sleutel-ontwikkelingssone in die Blou Ekonomie van Afrika, Suider Afrika en Suid-Afrika in besonder geïdentifiseer. Die betrokke munisipale area is geoormerk om toonaangewend te wees in grootskaalse ontwikkelings in die streek. Saldanhabaai is strategies uitstekend geposisioneer om die beoogde olie- en gassektore aan die weskus van Afrika as ‘n kritieke komponent van Suid-Afrika se Blou Ekonomie te bedien.

Studies soos die van Henrico & Bezuidenhout (2020) het bewys dat veranderinge aangebring tydens die oprigting van die Saldanhabaai Hawe die vorm en hellingprofiel van Saldanhabaai aansienlik verander het end us die hidrodinamieke (Die Baai wat verwys na beide Binne- en Buitebaai, beskryf in afdeling 1.2).

Die hoofdoel van hierdie studie was om die veranderinge in die diepte profiel van Saldanhabaai soos in 1977 bepaal met dié van 2021 te vergelyk en te analiseer. Die algemene tendens van geleidelike dieptetoename vanaf die kuslyn na die mond van die Baai, en skerp dieptetoename teenaan Elandspunt en Salamanderpunt, is onveranderd tussen 1977 en 2021. Die Gewone Kriging (GK) interpolasiemetode, toegepas deur middel van ‘n Geografiese Inligtingstelsel (GIS), is gekies om oppervlakmodelle van die diepte profiel van Saldanhabaai te skep, en om genoemde twee stelle data te vergelyk. Sodanige vergelyking sal die verandering in die diepte profiel in die Baai oor die 44-jaarperiode illustreer. ‘n Hellingontleding is ook gedoen om die stabiliteit van die seebodem van die Baai te bepaal.

Die resultate van hierdie studie dui op ‘n algemene toename in diepte sedert 1977, met die meeste van die beeldpunte in die grafiese voorstelling van die Baai (68.2%) wat op ‘n dieptetoename van tussen 0.395 en 3.203 m dui, en ‘n gemiddelde dieptetoename in Big Bay (Grootbaai) van 1.799 m vir die periode 1977 tot 2021. Twee sones is ook geïdentifiseer wat die statistiese standaardafwyking verander het. Hul afwykings was tweeledig; enersyds het albei beduidende dieptetoename getoon, andersyds, beduidente diepte-afname. Die algemene hellingtendens vir Big Bay (Grootbaai) in die 2021-meting het feitlik onveranderd van die van 1977 gebly, deurdat die grootste deel daarvan

gekenmerk is deur ‘n relatief lae helling, naamlik 0 tot 1.3 grade. Daar was egter in 2021 ‘n geringe toename in die totale helling van Big Bay (Grootbaai) 0.51 wat 0.2 grade meer is as in 1977. Boonop het die meerderheidsdeel van Big Bay teen 2021 ‘n heling van 1.3 grade of minder gehad, 0.4 grade meer as in 1977. Ten slotte, in 2021 het Big Bay (Grootbaai) ook ‘n toename in die maksimumhelling in die Baai getoon, met ‘n maksimumhelling van 14.8 grade, meer as dubbel die maksimumhelling aangeteken in 1977.

Die bevindinge van hierdie studie ondersteun die bevindinge van Flemming (1977) en Henrico & Bezuidenhout (2020), naamlik, dat die oprigting van die Saldanhabaai Hawe die sedimentasieprosesse binne Saldanhabaai tot ‘n sekere mate beïnvloed het. Die bevindinge van die huidige studie is direk toepasbaar slegs op ‘n deel van Saldanhabaai - die insluitingsone genaamd Big Bay (Grootbaai). In hierdie area was daar ‘n totale volumeverlies van 49 364 560 m^3. Die presiese aard van, en dryfkragte agter hierdie verlies vra vir verdere wetenskaplike ondersoek.

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LIST OF ABBREVIATIONS

Abbreviation	Description
CRP	Central Reference Point
CSIR	Council for Scientific and Industrial Research
DEM	Digital Elevation Model
GIC	General Instrument Corporation
GIS	Geographic Information Systems (Eng) Geografiese Inligtingstelsels (Afr)
GK	Gewone Kriging
GPS	Global Positioning System
GSD	Ground Sampling Distance
HI	Hydrographic Instruction
HSV	Hydrographic Survey Vessel
IDW	Inverse Distance Weighting
IDZ	Industrial Development Zone
LAT	Lowest Astronomical Tide
LiDAR	Light Detection and Ranging
MBES	Multi-Beam Echosounders
MIDAs	Maritime Industrial Development Areas
MRU	Motion Reference Unit
MSL	Mean Sea Level
OK	Ordinary Kriging
PoS	Port of Saldanha
RMSD	Root-Mean-Square Deviation
RMSE	Root-Mean-Square Error
SA	South Africa
SAN	South African Navy

SANHO	South African Navy Hydrographic Office
SAR	Synthetic Aperture Radar
SAS	South African Ship
SBES	Single-Beam Echosounders
SBH	Saldanha Bay Harbour
SBM	Saldanha Bay Municipality
SES	Socio-Ecological Systems
SIP	Strategic Integrated Projects
SMB	Survey Motorboats
SoNAR	Sound Navigation and Ranging
SV	Sound Velocity
SVP	Sound Velocity Profile
UTM	Universal Transverse Mercator
VBES	Vertical-Beam Echosounders
WWII	Word War II (Second World War)

CHAPTER 1: INTRODUCTION AND PROBLEM STATEMENT

1.1 Research background

The South African (SA) government recognises the economic potential of its ocean areas and continues to improve the effective economic management of SA ocean resources, the so-called blue economy[1] (Welman & Ferreira, 2014). The goal of the blue economy is to make better use of countries' water resources, specifically the oceans, to create jobs and alleviate poverty in respective countries, SA included (SA Government, 2012; Welman & Ferreira, 2016). Saldanha Bay is one of the finest natural harbours on the South African coast as it is ideally located on a major international trading route (Flemming, 1977). As a result, Saldanha Bay has been identified as a key development zone in the blue economy, which led to major developments in the Saldanha Bay Municipality (Wiese, 2013). Saldanha Bay is strategically positioned to serve the envisaged energy sector, the exploration, processing and transport of oil and natural gas, in particular on the West Coast of the African continent and is a critical economic hub for development of South Africa's blue economy (Jacka, 2015).

Saldanha Bay first became a potential zone for industrial development in the late 1960s and early 1970s when feasibility studies for a comprehensive iron ore export project was initiated in 1969 (Flemming, 2015). These studies led to the selection and consequent development of Saldanha Bay as an export harbour. Construction of the Port of Saldanha (PoS) started in May 1973, and the first iron ore was loaded in September 1976 (Henrico & Bezuidenhout, 2020). The success with iron ore export was followed by the construction of oil transfer and storage facilities in the late 1970s (Flemming, 1977; Zwemmer & Van 'T Hof, 1976). The development of Saldanha Bay rolled on into the 1980s, when further expansion of the harbour allowed for handling of other cargo, including lead, zinc, and copper exports (Welman & Ferreira, 2016).

In his PhD thesis on the sedimentation processes of Saldanha Bay and Langebaan Lagoon, Flemming (1977) stated that changes in bathymetry would result in changes to all the other hydrographical characteristics of Saldanha Bay, which should theoretically have changed

[1] The blue economy (ocean or maritime economy) is defined as "economic and trade activities that integrate the conservation and sustainable use and management of biodiversity, including maritime ecosystems and genetic resources" (United Nations Conference on Trade and Development (UNCTAD), 2014: 2).

the sedimentation processes in Saldanha Bay – leading to possible coastal erosion and siltation. In a more recent study conducted by Henrico and Bezuidenhout (2020), the authors described the radical change in the bathymetry of Saldanha Bay because of the construction of the harbour in 1976. Henrico & Bezuidenhout (2020) concluded their study by stating that a similar study should be conducted with current bathymetrical data to determine how the sedimentation processes within Saldanha Bay had changed since the construction of the PoS. The issues raised in respective research by Flemming (1977) and Henrico & Bezuidenhout (2020) are closely related to the research problem of the current study. Notably, the study areas are the same. Similar data collection methods were also employed. Consequently, these scientific products contributed significantly to establishing the research problem of the current study. Their research will be reviewed in more detail in Chapter 2 (see section 2.5).

It is clear from the research of Flemming (1977), and Henrico & Bezuidenhout (2020) that disturbances in the bathymetry of Saldanha Bay because of anthropogenic activities will to some extent change the sedimentary processes in the Bay and result in coastal erosion on some beaches in the Bay. This indicates a correlative relationship between human activities and natural processes in the Saldanha Bay area; changes in anthropogenic activities (e.g., harbour construction and continuous dredging operations) will influence the natural processes (viz. storm surges, seasonal and tide changes, coastal wave setup and sediment morphology). Said correlation becomes cyclical, as all factors continuously and mutually influence each other (McGinnis & Ostrom, 2014). The study of socio-ecological systems (SES), which is part of the complex systems theory, is aimed at emphasizing the integrated concept of the 'humans-in-nature' perspective (Petrosillo et al., 2015).

From an SES theory perspective, the Saldanha Bay area can be described as an interconnected, bidirectional system made up of human and environmental factors, constantly interacting with each other and exhibiting some form of effect on one another. Following the logic of SES theory, the hydrodynamic and sedimentary systems of Saldanha Bay Harbour (SBH) will stabilize over time and shape a new bathymetric profile of SBH (Petrosillo et al., 2015). The interest of this study is to determine the current bathymetric profile of Saldanha Bay Harbour and to investigate whether there had been any changes in the bathymetry of SBH since the construction of the Port of Saldanha in 1976. Consequently, this chapter will commence with a brief introduction of the regional setting of the study, followed by an overview of the problem statement and the motivation of this study from which the study aim is stated. Next, the research questions and objectives are highlighted that provide direction to the study and describe concisely what the research is trying to achieve. Also, the research design is described, and the chapter will conclude with a short chapter overview.

1.2 Study area

The town of Saldanha is located approximately 100 km north-north-west of Cape Town. It is home to the only natural harbour on the west coast of South Africa, called Saldanha Bay Harbour (SBH). The harbour area is regarded as a biodiversity hotspot with several areas in and around the Bay declared environmentally protected (Clark et al., 2020). Saldanha Bay is the study area of this research, indicated by the red quare in Figure 1.1

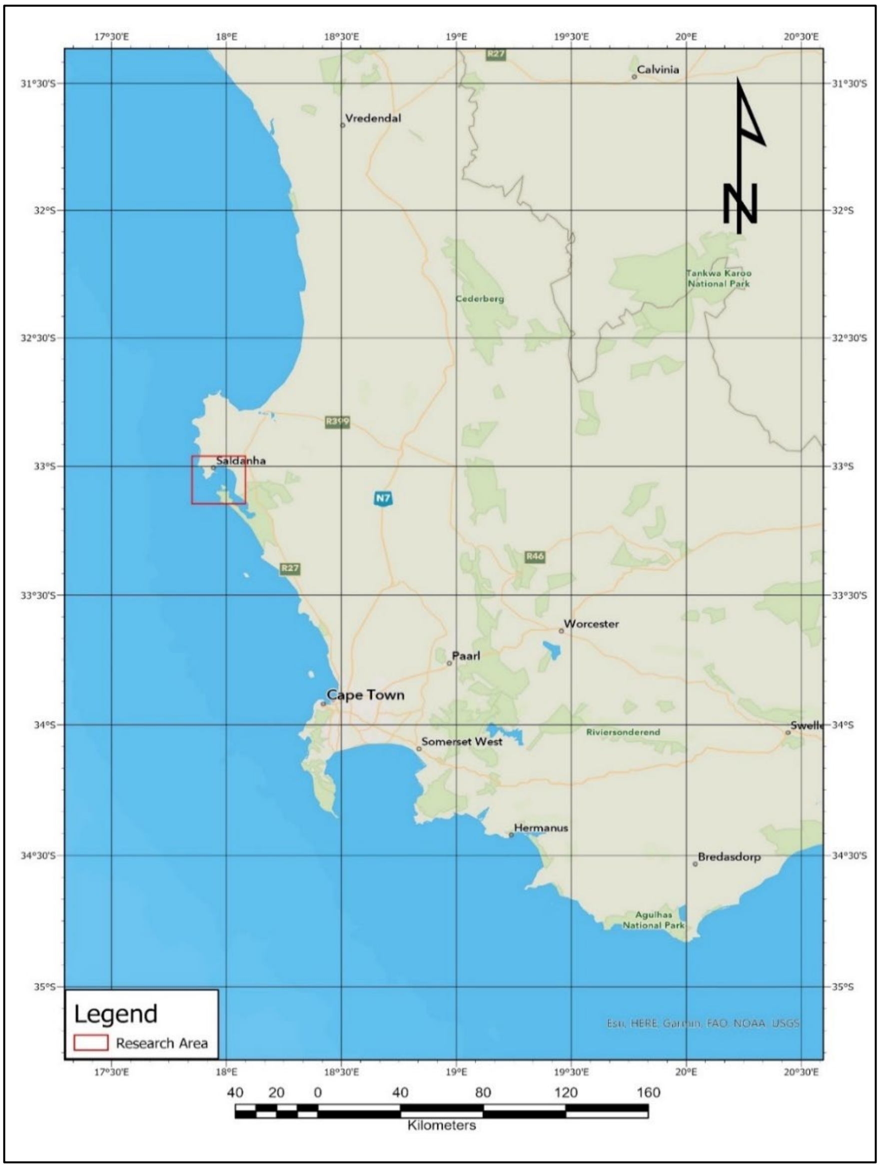

Figure 1.1: Map indicating the location of the study area

The Bay was the eventual product of granite intrusions which followed the breakup of the West Godwana continent approximately 500 - 550 million years ago (Flemming, 1977). This event eventually produced the modern physiography of the region, of which Saldanha Bay is one element. (Flemming, 1977). However, millions of years of continuous coastal erosion weathered the area down completely to the granite basement (Davies, 1973). Now, the local geology of Saldanha Bay is dominated by dome-like granite outcrops, defining the northern and southern headlands and controlling the deep-water entrance to the Bay (Du Plessis & De la Cruz, 1977).

One of the striking features of Saldanha Bay is the apparent symmetry of its shape, which seemingly fits two converging logarithmic spiral curves (Flemming, 1977). Silvester (1960) elaborates on the logarithmic spiral concept but does not address the phenomenon of converging logarithmic log-spirals describing the shape of pocket bays. This ‘log-spiral phenomenon’ has intrigued many researchers, with the main consensus being that this symmetrical shape is the result of wave refractions around the controlling headlands of the Bay (Davies, 1958; Silvester, 1960; Flemming, 1977). Another contributing factor to the Bay’s’ symmetry is its bathymetry. The Bay becomes gradually shallower towards the shoreline, resulting in an even dispersion of energy across the shoreline. In his thesis describing this phenomenon, Flemming stated that there is an intricate relationship between wave refraction, alongshore energy dispersion and the logarithmic spiral curves (Flemming, 1977, p. 52).

Within the Saldanha Bay area there are two specific areas of interest for this study, namely Port of Saldanha (PoS) and Saldanha Bay (herein called the Bay). The PoS is described as the collective anthropogenic features within the Bay (see Figure 1.2[A]). It consists of the stockpiling area (indicated by the dark-green fill colour), causeway (indicated by the light-green fill colour), iron ore jetty (dark-blue fill colour), and breakwater (indicated by the light green fill colour). The PoS was constructed in 1976. SBH includes both coastline and water body (see Figure 1.2[A]), divided into three smaller sections, namely Big Bay and Small Bay (Inner Bay), and Outer Bay. The Bay is connected to Langebaan Lagoon (indicated in Figure 1.2[A] and [B]) to the southeast and the Atlantic Ocean to the west (Smith & Pitcher, 2015). The town of Saldanha Bay is henceforth referred to as Saldanha; the bay central to this study, referred to either as Saldanha Bay or the Bay.

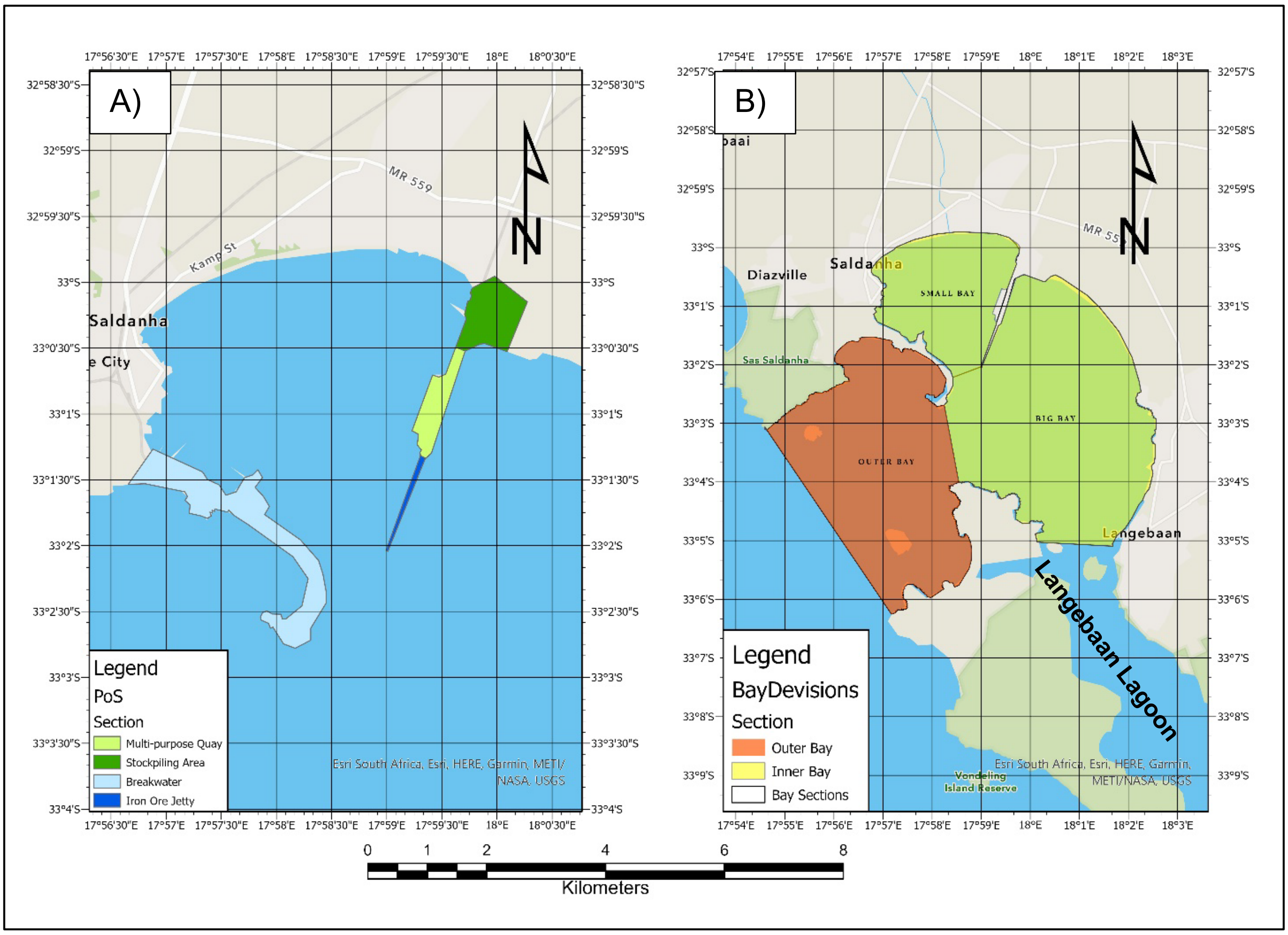

Figure 1.2: Illustrating (with annotated colours) the distinction between the Port of Saldanha (A) and Saldanha Bay (B)

Being largely dependent on weather patterns, the hydrodynamics of Saldanha Bay varies over the seasons (Wiese, 2013). During the months of summer (December to March), the Saldanha Bay area experiences stable and warm weather conditions with a persisting southeasterly wind that heats the surface water, while the deeper water mass remains cooler (Rothman et al., 2009; Wiese, 2013). As a result of this difference in temperature at various depths, the flow direction fluctuates in accordance with change in depth and associated water temperature. Surface water is controlled by wind direction, and deeper water is tidally driven, water mass thus rotates in a clockwise flow towards Langebaan Lagoon (Probyn et al., 2000). During the months of winter (May to August), the weather is less stable with fluctuating temperatures and wind strength and directions, resulting in a less pronounced temperature difference across changing depths (Probyn et al., 2000). Therefore, without a prevailing wind direction driving top water flow, water flow during winter is more uniform and generally follows the same pattern as the cooler deep water of summer (Flemming, 2015), i.e., flowing clockwise towards Langebaan Lagoon.

The reasons Saldanha Bay was selected as the physical study area to conduct this research are twofold: first, the strategic importance of Saldanha Bay to South Africa, as was highlighted in section 1.1; second, the author is a student at the South African Military Academy, in the Faculty of Military Science of Stellenbosch University, which is located in the town of Saldanha Bay. The Bay is worthy of scientific enquiry, and the researcher's proximity to the investigation site made measurements of the Bay logistically quite accessible, thus receptive to detailed investigation.

1.3 Research problem

Hydrodynamics is the study of fluids in motion (Wiese, 2013). The study is based on interaction between the physical laws of conservation of mass, and laws of momentum and energy in a body of water (Britannica, T. Editors of Encyclopaedia, 2020). Although energy can be changed from one form into another, the conservation of energy implies that energy can be neither created nor destroyed. In an isolated system, the sum of all forms of energy therefore remains constant, unless disturbed by an external force. As a result, when there is a change in energy resulting from an external disturbance in one part of this 'isolated system', the rest of the system will react to retain its stability (Britannica, T. Editors of Encyclopaedia, 2020).

In physical geography these laws are applied in the field of hydrography to describe and understand the physical features of a body of water, which includes bathymetry (submarine topography), the characteristics of tides, currents and waves, shape and features of the shoreline and the physical and chemical properties of the water (Luger et al., 1999). All these characteristics work together to form a hydrodynamic system, which is constantly working to abide by the physical laws of conservation of energy (Wiese, 2013). This means that changes in one part of the system (i.e., currents and waves), will result in changes in some, or all the system, in reaction to the original disturbance.

Saldanha Bay has no perennial rivers that enter the Bay (Welman & Ferreira, 2016). As a result, prior to the start of construction in 1973, the hydrodynamics of Saldanha Bay was only influenced by cyclic, natural tidal processes and wave action, resulting in a relatively stable bathymetric profile (Wiese, 2013; Flemming, 1977). However, the changes in the bathymetry of the Bay due to extensive dredging in certain areas during construction, radically changed the bathymetry and the shape and features of the shoreline of Saldanha

Bay (Henrico & Bezuidenhout, 2020). The construction of the causeway and the jetty divided Saldanha Bay into two sections, each with their own hydrodynamic conditions (see Figure 1.2[B]). Small Bay became protected from wave action, whereas Big Bay became locally more exposed more exposed to wave energy (Luger et al., 1999).

Studies such as Henrico & Bezuidenhout (2020) have proven that artificial (human-induced) changes made during the construction of the PoS have significantly altered the shape and slope profile of Saldanha Bay, thus changing the hydrodynamics of the Bay. These changes potentially catalysed the erosion and siltation processes which have been impacting some of the Langebaan beaches since then, as illustrated by the red hatched area in Henrico & Bezuidenhout (2020), Figure 1.3 below.

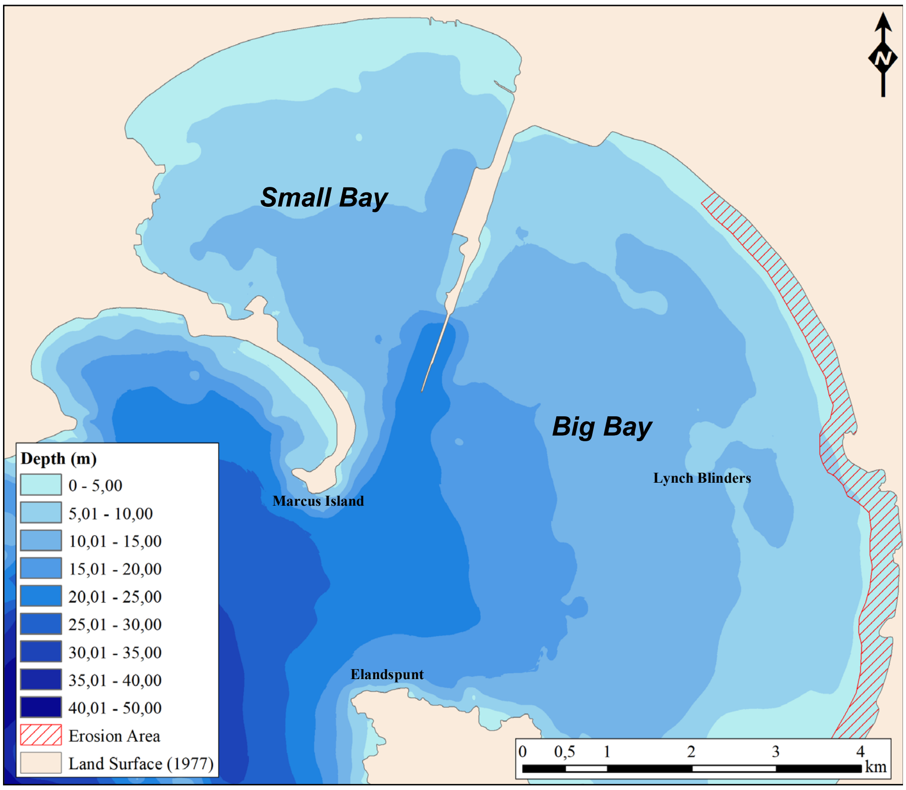

Figure 1.3: 1977 Bathymetry map of Saldanha Bay, illustration of the potential erosion area on Langebaan beaches

Source: Henrico & Bezuidenhout (2020)

Henrico & Bezuidenhout (2020) emphasized the importance of making a comparison between the 1977 bathymetry and the current bathymetry to determine how the Saldanha Bay sedimentation process changed after the construction of the PoS. Such a scientific comparison had not been done to date, thus leaving a void in research and literature, which prompted the research problem and associated research question for the current study.

Determining the current bathymetry of Saldanha Bay towards an improved understanding of the sedimentary processes causing erosion on some beaches in Langebaan is the research problem central to this research.

1.4 Significance and motivation for the study

As discussed in the previous section, the construction of the PoS changed the bathymetry of the Bay significantly, thereby ultimately causing erosion and siltation challenges. However, a complete survey of the Bay had not been conducted since 1977 (C Theunissen 2020, personal communication, 18 August), leaving a substantial time lapse in the analysis of the bathymetry of Saldanha Bay. Over the years, only selected surveys were conducted which mainly covered small areas outside the Outer Bay. Figure 1.4 shows the areas surveyed, the dates these areas were surveyed, as well as the scale at which datasets were created. It is visible from this figure that the entire Bay was surveyed between 1974 and 2004, but the only complete dataset available for the entire Bay was conducted in 1977, which is the legacy dataset described and highlighted throughout this thesis. Only small, selected areas within the Bay were surveyed after 1977.

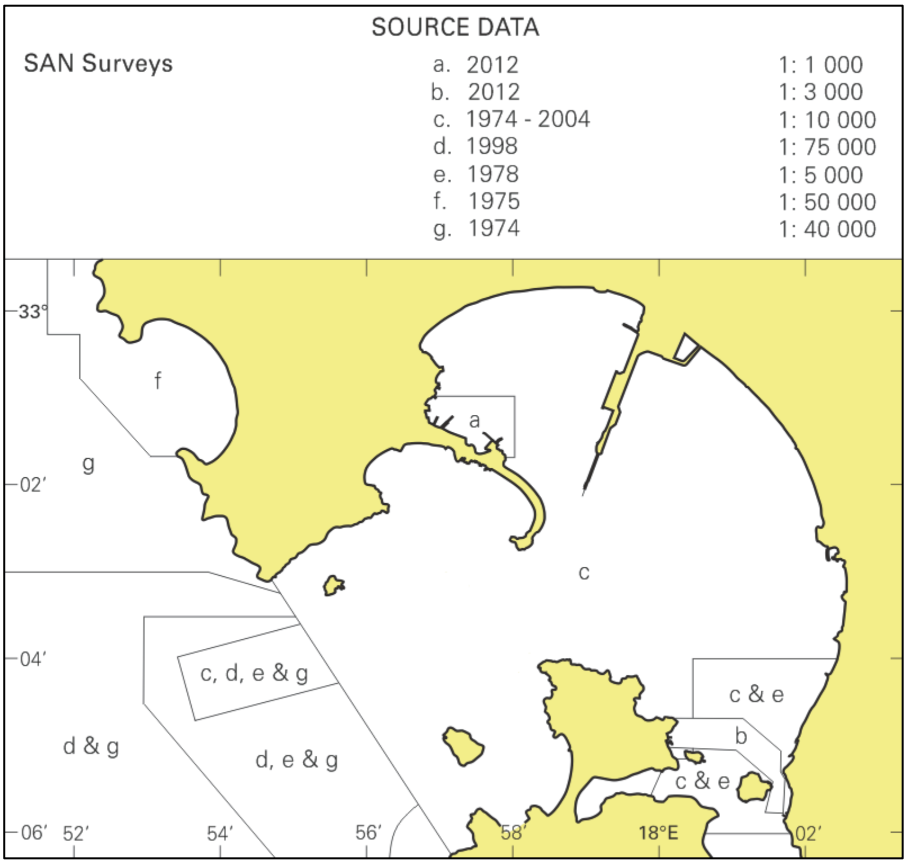

Figure 1.4: Data sources available to the South African Navy Hydrographic Office

To update their current nautical charts, the SA Navy (SAN) received a Hydrographic Instruction (HI)[2] to survey Saldanha Bay in the first half of 2021. The SAN has agreed to assist in this study by providing access to SAN equipment that was used for capturing the bathymetry data during this study (C Theunissen 2020, personal communication, 18 August).

In this study, the 2021 bathymetry of Saldanha Bay was compared with 1977 bathymetry data (44 years) to determine the extent of change in the bathymetry of the Bay, which can improve our understanding of the current sedimentation process in the Bay. More detail pertaining to these two datasets used to conduct this study is provided in Chapter 3 (see section 3.4). The results of this study will not only provide researchers with a current status of bathymetry of Saldanha Bay and introduce a methodological approach to conducting bathymetry analyses of Saldanha Bay using a Geographic Information System (GIS), but will also provide Saldanha Bay Municipality (SBM) and the Western Cape Government with valuable information regarding the environmental and related socio-economic impact of changes to the bathymetry of Saldanha Bay over the past four decades. Changes that influenced the sedimentary processes, construction of the coastline (coastal erosion) and siltation will help the relevant role players to make informed decisions regarding urban development, coastal erosion mitigation and flood risk reduction within the Saldanha Bay area.

This study may inspire similar studies in other regions which can add value to the decision-making processes regarding urban development through mitigation of coastal erosion and reduction of flood risks.

1.5 Aim, research questions and research objectives

1.5.1 Research aim

The aim of this study is to compare and analyse the changes in bathymetry of Saldanha Bay between the years 1977 and 2021.

[2] An order issued by the Hydrographic Office of the SA Navy to conduct a survey mission.

1.5.2 Research questions

From considering the research problem and significance of the research, the following research questions were investigated during this research:

a. Primary research question: To what extent did the bathymetry of Saldanha Bay change between the years 1977 and 2021?

b. Secondary research questions

   i. What where the bathymetries of Saldanha Bay in 1977 and 2021?

   ii. Did changes in bathymetry over the 44 year period occur, and if so, how did that affect sedimentary processes?

   iii. What is the impact of changes to the bathymetry of Saldanha Bay to the profile of the coastline? (This is only applicable if (ii) is answered in the affirmative).

   iv. What is the extent of beach erosion and siltation challenges that occurred over the research period decades due to changes to the bathymetry of Saldanha Bay? (This is only applicable if (ii) is answered in the affirmative).

1.5.3 Research objectives

To achieve the aim of this study, the following research objectives were identified:

a. Primary research objective: To determine the differences between the 1977 and 2021 bathymetries of Saldanha Bay by means of Geographic Information Systems (GIS).

b. Secondary research objectives

   i. To describe the bathymetry of Saldanha Bay for 1977 and 2021, respectively.

   ii. To compare the bathymetry of Saldanha Bay in 1977 with the bathymetry of Saldanha Bay in 2021.

   iii. To discuss the reasons for the observed bathymetric changes identified in (ii).

   iv. To highlight the impact of the changes to the bathymetry of Saldanha Bay over the past four decades on sedimentary processes, siltation, and the extent of beach erosion.

1.6 Research design

During this study, a Geographic Information System (GIS) with the capacity to employ specific interpolation methods was used to conduct a bathymetry analysis of Saldanha Bay. Bathymetric data was acquired from the South African Navy Hydrographic Office (SANHO) as vector point datasets. The point datasets, for both 1977 and 2021, consist of depth measurements, known as soundings. A comparative analysis was conducted through these two datasets to determine the changes in bathymetry of Saldanha Bay over the 44 year period. The results will be analysed and interpreted to provide insight in terms of the impact of the measured changes to the bathymetry of Saldanha Bay.

The following sections briefly highlight the research methodology (approaches, data collection, processing, and analyses) of this study. A more detailed description of the research methodology of this study is provided in Chapter 3.

1.6.1 Methodological approach

A suitable methodological approach was selected to normalize the two bathymetric datasets acquired from the South African Navy Hydrographic Office for GIS analysis. Acquired data were processed and sampled to ensure comparability in terms of projection information, distribution and density. Such a procedure is essential when conducting a comparative study of this nature. After pre-processing, analyses of the data were be conducted through a variety of specialised analytical tools of the ArcGIS Pro software, version 2.8.0.

1.6.2 Data collection methods

This study used two point datasets (one captured in 1977, the other in 2021) which consists of depth measurements (soundings) of Saldanha Bay. The 1977 dataset consists of 3 052 sounding points, thus covering the entire Bay as well as the entrance to the Bay. The Bay was surveyed by the Hydrographer of the SA Navy by means of a Single-Beam Echosounder (SBES) hydrographic instrument. For the second dataset, the author of the current study was directly involved in the bathymetric survey of the Bay to collect the most recent sounding dataset of Saldanha Bay. This survey was conducted by the Hydrographer of the SA Navy in the first half of 2021. This time, however, a Multi-Beam Echosounder (MBES) hydrographic instrument was used to collect 1 968 sounding points. However, some problems were experienced during the 2021 survey. As a result, it was not possible to survey the entire Bay. More detail about these problems, as well as a comprehensive description of data collection, data processing and data analysis is provided in Chapter 3.

1.6.3 Data Processing

Both datasets were received from the Hydrographer of the SA Navy as point shapefiles, georeferenced by using different projections (1977: Hartebeesthoek94; 2021: WGS84 UTM34s) and covering different spatial extents. Thereafter, both these datasets were processed to prepare them for analysis. The first step of data processing was to convert both datasets to the same projection and ensure all height values were converted to metres above Mean Sea Level (MSL). Secondly, both datasets were clipped to the same spatial extent, covering most of Big Bay (see Figures 1.2[B] and 1.3). This was mainly due to the data collection challenges that were experienced during the 2021 bathymetric survey, as mentioned in the previous section.

1.6.4 Data Analysis

All data analysis pertaining to the current study, as described in this section, entails the use of GIS functionalities and operations. Firstly, an interpolation test was conducted between IDW and OK to identify the interpolation method best suited for the datasets collected for this study. Secondly, interpolation-based change detection was done by using the raster calculator to identify the changes in the interpolated surface models of 1977 and 2021. Change detection is necessary when conducting a comparative study between two different time-series datasets, as exemplified by Henrico & Bezuidenhout (2020). Finally, a slope analysis was done for both the 1977 and 2021 surface models and compared to identify any changes in slope between 1977 and 2021. All results generated from the analyses were scrutinized in this research to gain a clearer understanding of the extent to with the bathymetry of Saldanha Bay had changed since the construction of the PoS in 1977.

1.7 Study overview

This study was conducted according to the research overview illustrated by Figure 1.5. The research overview serves as a flow diagram of the sequential steps followed throughout this study to answer the research question, to achieve the research objectives and ultimately towards achieving the aim of this study (see section 1.5).

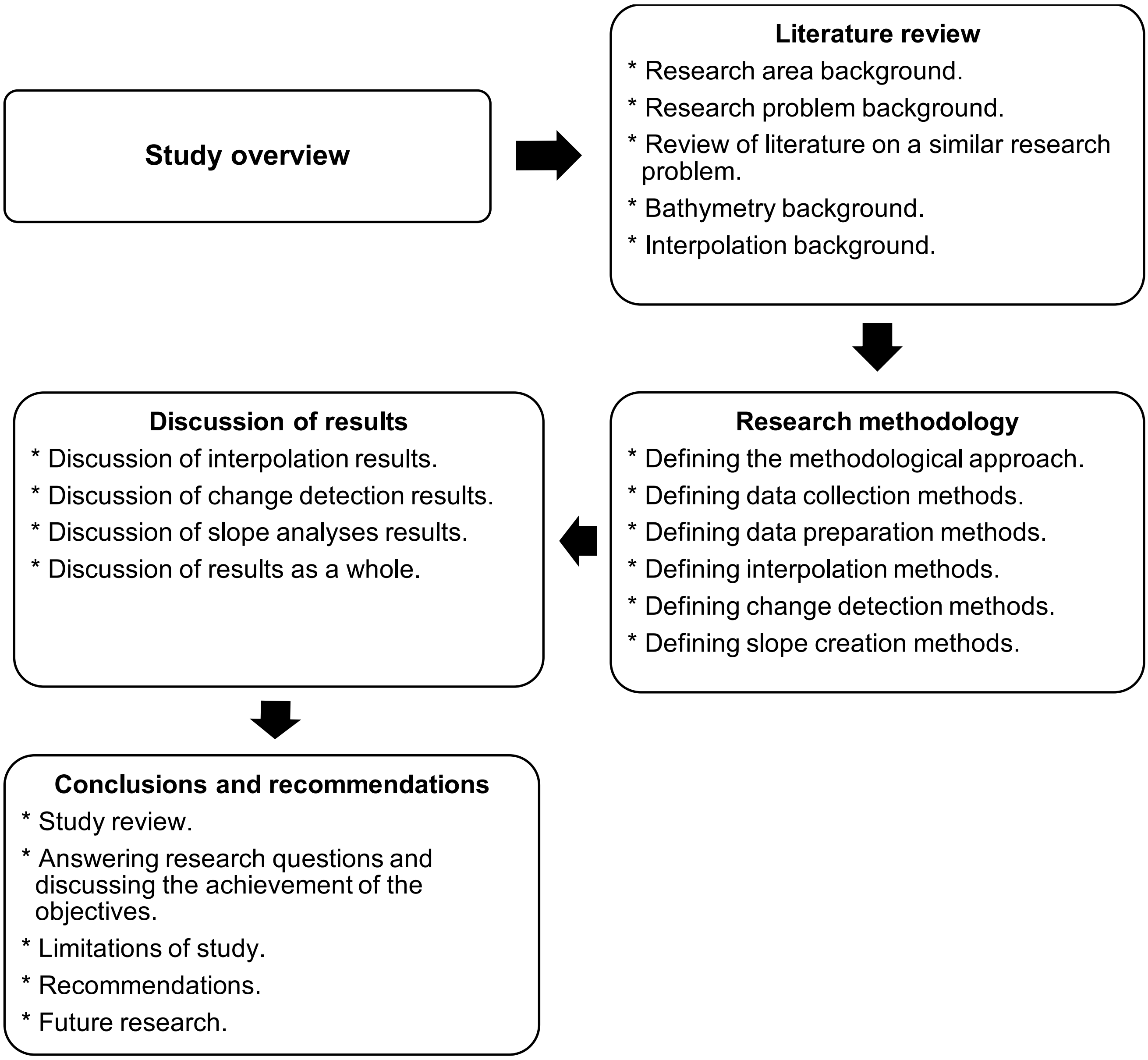

Figure 1.5: Study overview

In Chapter 2 a literature review is conducted to provide a detailed background to the development of Saldanha Bay, specifically the harbour, and how this relates to the research problem identified in this study. This is followed by an overview of nine studies with similar research problems and objectives, and how the research conducted in the current study may provide a unique view on the research problem central to this and related previous studies. The study of bathymetry, the instrumentation and techniques used to capture bathymetry data, and background to bathymetry analyses are also expanded in this chapter. Chapter 3 describes the study area, as well as the research methodology, in particular the methods used to collect, process, and analyse the bathymetric data to the current research. In Chapter 4, study results are presented and discussed. Chapter 5 highlights the findings of this study and states relevant limitations to the current study. This is followed by conclusions of the study, and the chapter ends with recommendations for future research.

1.8 Chapter summary

As a matter of contextualisation of the research and research topic, the first chapter introduced Saldanha Bay as the physical research area of this study. This was followed by a short discussion of anthropogenic interventions in the Bay, specifically the construction of the Port of Saldanha, as focal point of the research problem investigated by this study. Furthermore, the chapter gave an overview of the aim of the research, the research questions, and the research objectives of this study, as well as the research design that was be employed to respond to the research topic. The chapter concluded with a study overview outlining how all chapters contribute towards achieving the aim of this study.

The next chapter reviews the literature relevant to this study, with specific attention given to literature on the development of Saldanha Bay and the construction of the PoS. It also addresses aspects of capturing and analysing bathymetric data.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The previous chapter served as a study overview by providing an outline on how the study is structured to achieve the defined aim and related objectives. This chapter build on this structure by reviewing relevant literature, and by providing a detailed description of the development of Saldanha Bay, in particular the construction of the harbour, and hydrodynamics and sedimentation processes in the Bay. The focus then shifts to describing bathymetry in general, and methods to collect soundings as well as the interpolation methods used to predict and create surface models. Various studies relevant to the current research area are reviewed to provide insight into the significance of this study, i.e., to fill the gap of a comparative bathymetry analysis by using recently acquired sounding data of Saldanha Bay. The chapter concludes with an overview and a short prelude to the structure and information used during the research methodology phase of this study.

2.2 Development of Saldanha (1900-1973)

Up until the early to mid-20th century, Saldanha was mostly a small fishing village with limited harbour development, consisting mostly of small-scale fishing and military quays next to the town centre (Van der Waag, 2005). The rich population of fish, seals and birds in the Saldanha Bay area provided plentiful natural resources either as a source of income, or as a means of putting food on the table for the local community, or both (Visser et al., 2008). Saldanha Bay is also the only natural harbour on the west coast of South Africa which is situated on a very important and popular trading route connecting the Middle East with Europe (Welman & Ferreira, 2016).

The northern part of Saldanha Bay served as a perfect shelter (the most sheltered area in the Bay) for ships during storms, which ensured a steady stream of local and foreign vessels dropping anchor in the Bay (Welman & Ferreira, 2014), thus contributing to the local economy. This part of the Bay was an ideal docking location for loading vessels and fishing vessels which subsequently served the development of a fishing community in Saldanha Bay (Van der Waag, 2005). For the first part of the 20th century, however, Saldanha predominately remained a fishing village with very little development in infrastructure and diversified trade, mainly due to the lack of fresh water in the area (Smith & Pitcher, 2015).

Events during WWII brought Saldanha out of the shadows and into the spotlight, as it assumed great importance after being selected as a convoy staging point for the allied forces (Van der Waag, 2005). This newfound external attention led to a big injection of resources to develop the area as a military port (Welman & Ferreira, 2014). In 1942, coastal defence guns were set up on several of the protruding heads around the Bay. A naval training base, named South African Ship (SAS) Saldanha, was established in the area relatively soon hereafter. SAS Saldanha started operations in 1948 (Wiese, 2013; Van der Waag, 2005).

The construction of a 35 km freshwater pipeline from the Berg River was arguably the most important development during this time. It solved the freshwater challenges of the Saldanha community, a major step toward becoming a focal point for development in the area (Welman & Ferreira, 2014; Visser et al., 2008).

The population of Saldanha increased through stable, large scale public sector employment and its peripheral socio-economic spin-offs not least of all the demand for consumer resources such as food, and especially fish and other marine products as the local, natural food source (Probyn et al., 2000). This local increase in the demand for fish, along with increased national demand, resulted in the industrialization of fishing in the area, leading to the construction of bigger factories which provided more work opportunities (Welman & Ferreira, 2016). During the 1960s and 1970s, the town of Saldanha promised work, opportunities, and resources, outweighing the prospects of other towns in the rural areas surrounding Saldanha (Welman & Ferreira, 2014). This caused many people to move away from the surrounding towns to Saldanha, thus stimulating the socio-economic growth of the town (Smith & Pitcher, 2015).

In the late 1960s, Saldanha was identified as an Industrial Development Zone (IDZ), a pivotal moment that would ensure a large investment of government’s effort and money in the development of substantial industrial infrastructure (National Planning Commission, 2011; Welman & Ferreira, 2016). Due to its naturally sheltered condition and deep waters, the Bay was ideally suited for a port destined to deal with large ships capable of transporting massive loads of raw metals. The construction of an international port in Saldanha Bay was a logical consequence (Zwemmer & Van 'T Hof, 1976).

2.3 Construction of the PoS (1973-1976)

Major developments related to the construction of the PoS started in 1973 with the construction of a causeway, stretching from the mainland to Marcus Island, as indicated in Figure 2.1 (Zwemmer & Van 'T Hof, 1976).

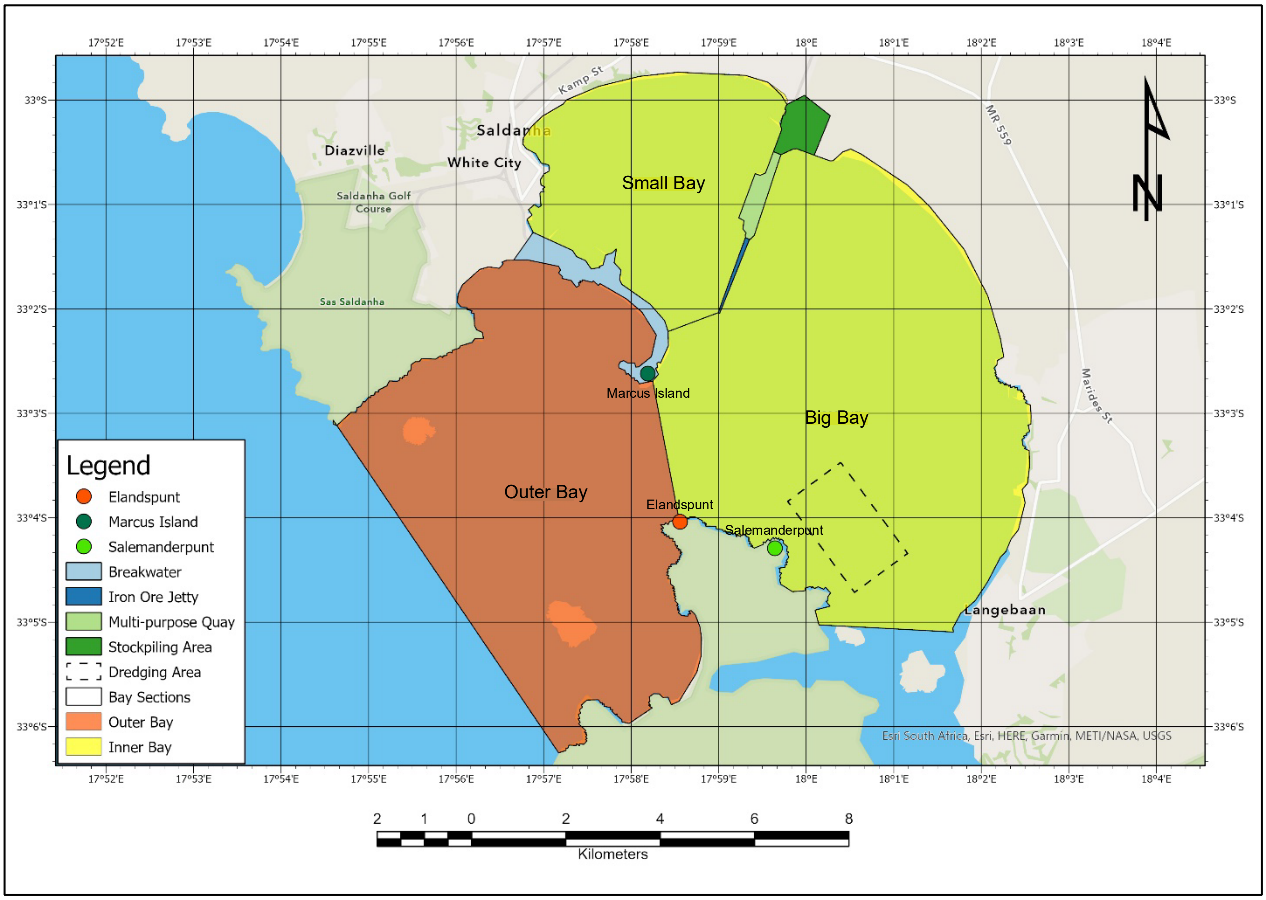

Figure 2.1: Orientation chart – map of Saldanha Bay, which indicates where the breakwater, causeway, stockpiling area, and iron ore jetty were built, as well as the dredging area.

In the original construction programme, the plan was to undertake the project in two phases. The first phase was to construct a breakwater to Marcus Island to create a shelter for the second phase of construction, namely to build the stockpile area, causeway and ore loading jetty. By extending the northern peninsula through a breakwater to Marcus Island, the existing sheltered area was enlarged considerably (Zwemmer & Van 'T Hof, 1976). The causeway was constructed by firstly dumping quarry stone on an underwater mound of sand, which was raised by hopper dredgers to a level of five metres below mean sea level (MSL) (Hudson, 2020). In the meantime, the caissons for the ore loading jetty were built up to a height of 16.5 m in a dry-dock before it was transported to the ore loading jetty for its final building stage. After being floated out of the dry-dock, the height of the caissons was extended from 16.5 m to 30 m (Zwemmer & Van 'T Hof, 1976). Illustrated by Figure 2.1, this development also included the construction of a 3.1 km long causeway (including a 900 m long iron and oil loading jetty), a 1.7 km breakwater, and a stockpile area (Hudson, 2020). A quay channel with a depth of 23 m and a turning basin of 580 m in diameter was also dredged. This gave the port the potential to accommodate vessels with a draft of up to 21.5 m (Hudson, 2020). A multipurpose harbour was also later constructed, and a second shipping channel with a depth of 12 m was dredged (Welman & Ferreira, 2014). The construction of a breakwater, causeway and stockpile area required a significant amount of sand-fill, most of which was obtained by hopper dredgers from a sand bank to the east of Elandspunt, indicated by the purple square in Figure 2.1 (Zwemmer & Van 'T Hof, 1976).

Construction took approximately three years, with the first iron ore being shipped out of the PoS in September of 1976 (Henrico & Bezuidenhout, 2020). The construction of the PoS altered the shape and bathymetry of Saldanha Bay considerably, as indicated by a recent study conducted by Henrico and Bezuidenhout (2020). More detail about this study is provided below in section 2.5.7. Post construction, Saldanha Bay consisted of an Inner Bay and Outer Bay region respectively, both of which were formed to a certain effect with the construction of the breakwater, as indicated in Figure 2.1 (Smith and Pitcher, 2015). The Inner Bay is further divided by the causeway into Small Bay on the west and Big Bay on the east and is separated by an imaginary boundary between the end of the jetty and Marcus Island (Smith and Pitcher, 2015).

The construction of the PoS represented a big investment in infrastructure, which not only laid the foundation for industrial development in the region, but also made the region dependent on a development path which would be largely industrial (Welman & Ferreira, 2016).

2.4 Development of Saldanha Bay since the construction of the PoS

Throughout history a strong link between ports and the economic dynamism of the cities around them existed, mainly since ports form nodes of employment, and commercial interaction with the global market (National Planning Commission, 2011; Welman & Ferreira, 2016). The transport and handling of goods through ports have a direct impact in the local economy. These activities create employment on both a local and regional level (Fujita & Mori, 1996). The construction of the PoS had the same effect. It served as catalyst of development in the area since its construction, as shown by Welman & Ferreira (2016) and indicated by Figure 2.2: an illustration of the expansion of the town of Saldanha since 1938.

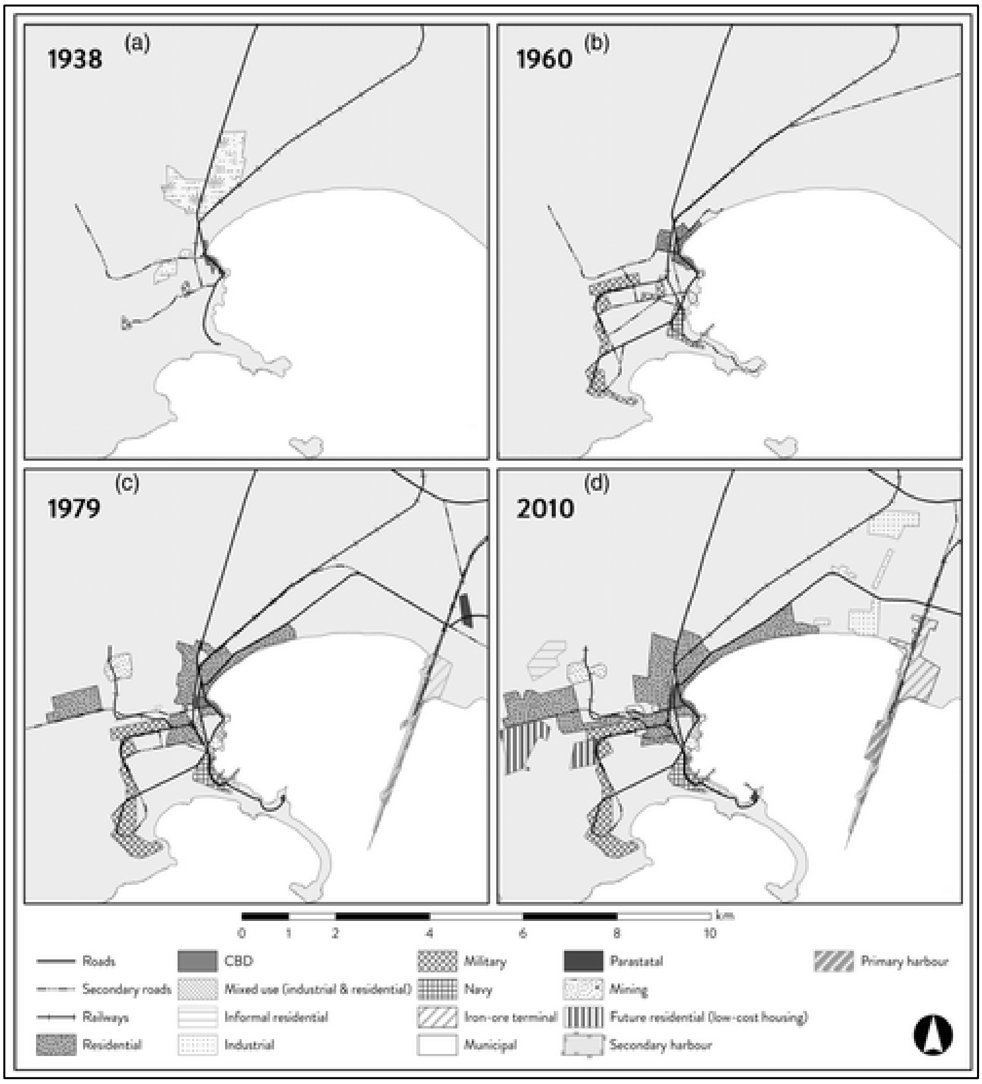

Figure 2.2: Figure illustrating the development of the town of Saldanha between 1938 and 2010

<u>Source</u>: Welman & Ferreira (2016)

From Figure 2.2 it is clear that little development occurred until the construction of the PoS 1973 - 1976. After completion of the PoS in 1976, exponential growth occurred (see Figure 2.2c) catalysed by many developments in the area (Welman & Ferreira, 2016).

During the 1970s, port-industrial complexes, consisting of fish factories at the time, were an essential feature in rapidly industrializing economies. These port-industrial complexes became known as Maritime Industrial Development Areas (MIDAs) as a product of an integration between the development of industries producing intermediate goods, such as steel and chemicals, and a restructuring of maritime transport and seaport systems (Nel & Rogerson, 2013). In the case of Saldanha Bay Municipality (SBM), state strategies supported development of economically disadvantaged areas which also played a part in developing the town as a MIDA (SA Government, 2011). As a result, since the construction of the harbour, the regional economy has been based on harbour-related industries such as steel manufacturing, fishing, and tourism. As illustrated in Figure 2.2(c), by 1979 the number of residential areas in and around the town of Saldanha had grown and the industrial infrastructure had been augmented with the addition of a general cargo quay, causeway, and floating oil jetties (Zwemmer & Van 'T Hof, 1976). In the 1980s, the PoS was upgraded by the addition of a multipurpose cargo terminal, which enabled the port to import oil and export high-value iron-ore, lead and copper (Hudson, 2020). However, there was little further industrial infrastructure development until after 2010 (Welman & Ferreira, 2014).

In 2011, as stated by the National Planning Commission (2011), the ‘blue economy’ initiative confirmed Saldanha Bay as one of the presidential priority development regions and was ultimately declared as an Industrial Development Zone (IDZ) (SA Government, 2012). In 2013, Saldanha Bay was selected by National Government to improve socio-economic development within the SBM. As an extension of this initiative, the departments of Trade and Industry, Economic Development, and Higher Education and Training were also instructed to promote skills development in the area to enhance the job creation capacity of Saldanha Bay as an IDZ (South African Government News Agency, 2013). Service Centres form part of new spatial interventions launched by the South African Government (Nel & Rogerson, 2013). Figure 2.3 indicates the proposed time frames of development in each IDZ.

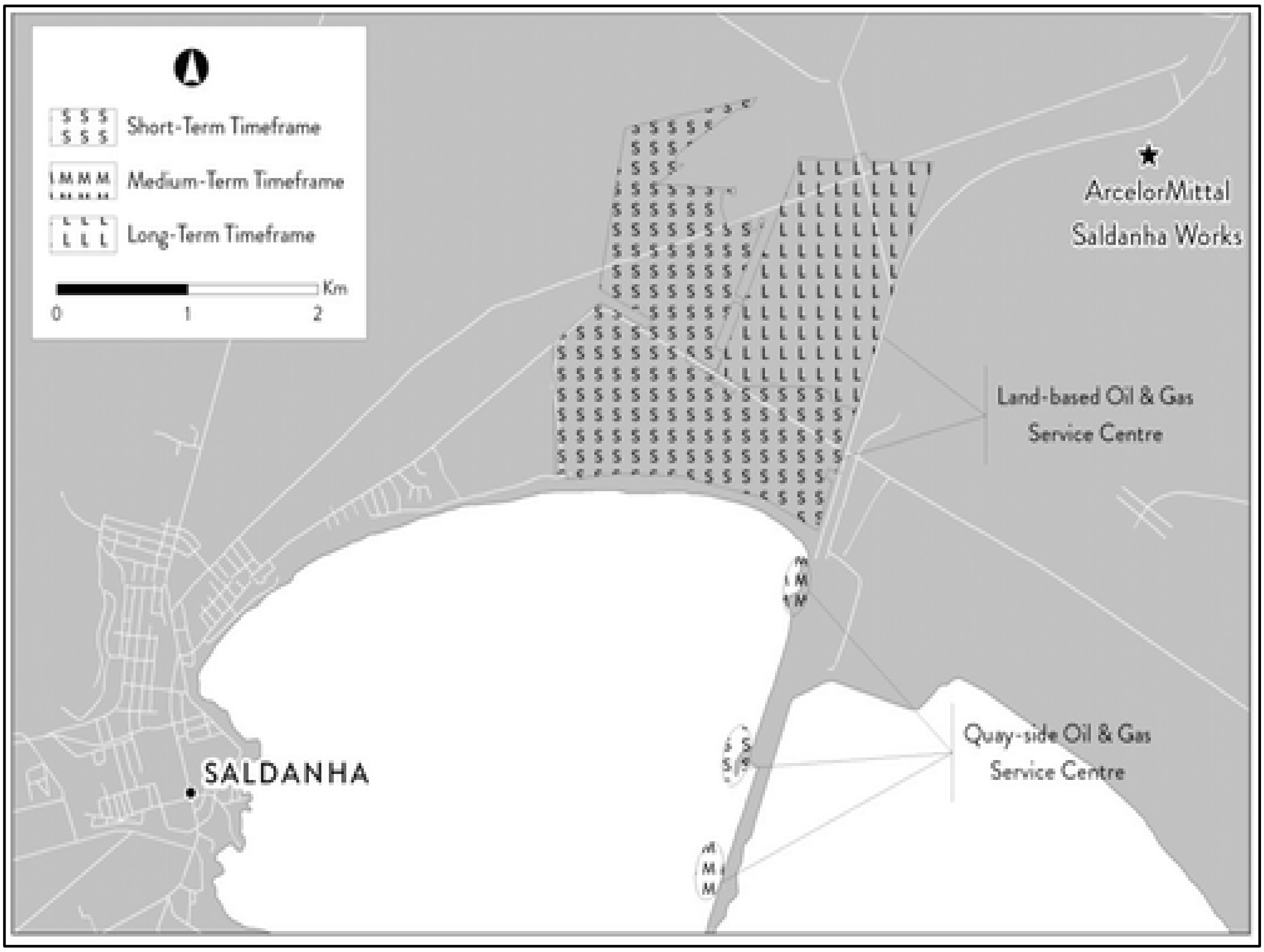

Figure 2.3: The proposed IDZ (short-, medium-, and long-term time frame) and Oil and Gas Service Centres of Saldanha Bay
Source: Welman & Ferreira (2014)

The degree of diversification in MIDAs can sometimes be limited due to largely mono-industrial tendencies, such as Saldanha being largely dependent on the export of crude materials. Being located on the southern tip of the continent, South Africa is ideally positioned to serve the East-West cargo traffic as well as the current booming African offshore oil and gas industry. As a result, the country’s major ports can be economically exploited to support regional development through similar industrial development interventions (Welman & Ferreira, 2016). The blue economy was earmarked to create jobs and alleviate poverty in the West Coast region of the country (Welman & Ferreira, 2016).

The development of the town of Saldanha has always been linked to the evolution of the port’s functions and capacity. The PoS has played an important role in the development of the area and is likely to continue to do so in the future. However, the impact of the PoS has not always been exclusively positive (Henrico & Bezuidenhout, 2020; Welman & Ferreira, 2016), as will be highlighted in the sections below.

2.5 Hydrodynamics and sedimentation processes in Saldanha Bay: a review of previous studies

An investigation into changes in bathymetry would require some understanding of the hydrodynamic and sedimentation processes active within the Bay, as they are the main natural drivers that may cause changes in bathymetry (Wiese, 2013; Flemming, 2015). Consequently, an overview of the available literature describing the hydrodynamic and sediment transportation processes within Saldanha Bay is provided next. It is important to note that the hydrodynamic and sediment transportation processes of Saldanha Bay and Langebaan Lagoon are linked, with changes in one likely to have an influence on the other (Flemming, 1977). For this section, nine studies on similar research problems and related research purposes to the current study on changes in the bathymetry of Saldanha Bay was described and evaluated with the aim and objectives of the current study in mind.

Over the years, numerous studies have been conducted on Saldanha Bay, most of which focussed on the sedimentation processes, ocean movements, water, and marine life. Some also investigated bathymetry mapping. In terms of the focus of the latter, as mentioned in Chapter 1 (see section 1.1), the studies conducted by Flemming (1977 and 2015) and Henrico & Bezuidenhout (2020) closely relate to the focus of this study. This section therefore provides a brief review of significant studies that were conducted to date on Saldanha Bay, specifically those relating to sedimentation and bathymetry, but a more in-depth review is conducted on the two studies mentioned above.

2.5.1 Shannon & Stander (1977): Hydrodynamics of Saldanha Bay

Shannon & Stander (1977) conducted a study in 1975 on Saldanha Bay before the construction of the causeway and jetty. In this study the authors investigated the hydrodynamics of Saldanha Bay. This study specifically investigated the natural forces which drove the currents within Saldanha Bay. From the data they collected, it was concluded that the direction and speed of flow of the top 5 m water column of the Bay is dependent on the speed and direction of the prevailing winds. The flow of the 5 m top water column ranged from 0.1 - 0.2 m/s, approximately 2.5% of the velocity of the prevailing winds (Shannon & Stander, 1977). The flow velocities at the entrance of Saldanha Bay were recorded as “small”, with the greatest velocities recorded at the entrance of the Langebaan Lagoon (see Chapter 1, Figure 1.2). However, the forces driving the flow at the entrance of the lagoon were attributed to tidal flow rather than wind force (Shannon & Stander, 1977). For the current study, it is important to understand the forces which drive the currents within the Bay, as well as the speed and direction of these currents, as they influence the energy distribution within the Bay directly and regulate where sediment is being transported and where it is being deposited. Shannon & Stander (1977) described the main forces which drive the circulation of currents within Saldanha Bay. However, a more detailed investigation of the dynamics of these currents is required in order to gain a clearer understanding of the currents which drive the current sediment transportation processes within Saldanha Bay.

2.5.2 Weeks, Boyd, Monteiro, and Brundrit (1991): Currents and circulation flow in Saldanha Bay

Weeks et al. (1991) conducted further investigation into the forces driving the circulation of currents within Saldanha Bay. Importantly, they used a different dataset for analysis. This dataset originated from the Sea Fisheries Research Institute (SFRI) marine pollution programme which investigated the changes to the circulation in Saldanha Bay before and after the construction of the iron-ore jetty of the PoS (Weeks et al., 1991). The drogue sampling stations captured data during the period 1976 to 1979. Although this study made use of a different dataset, the findings corroborate those of Shannon and Stander (1977) in two respects: firstly, the surface current velocities in Saldanha Bay were stated to be generally low (5-20 cm/s), mainly due to the low wind bias of all datasets used in their study (Weeks et al., 1991); secondly, besides the tidal driven channel that links Saldanha Bay to Langebaan Lagoon, the circulation within both Small Bay and Big Bay appears to be mainly wind-driven, specifically in the top 5 m of the water column (Weeks et al., 1991).

2.5.3 Flemming (1977): Hydrodynamics and sedimentation processes in Saldanha Bay

In the study conducted by Flemming (1977) for his doctoral thesis, the author investigated sedimentation in Saldanha Bay and Langebaan Lagoon. An transcript (updated version) to his doctoral study was compiled by Flemming 2015, however, only minor changes, corrections and small improvements were made. This extensive study performed a detailed investigation into the sediment transport processes within Saldanha Bay and the

Langebaan Lagoon, and covered data ranging from geomorphological history to particle size, particle composition, wave energy, and wave refraction patterns. However, most relevant for the current study is the fact that Flemming (1977) identified several distinct energy zones which are related to wave refraction patterns. The centrally exposed zone, and the semi-exposed and sheltered zones are all shown in Figure 2.4.

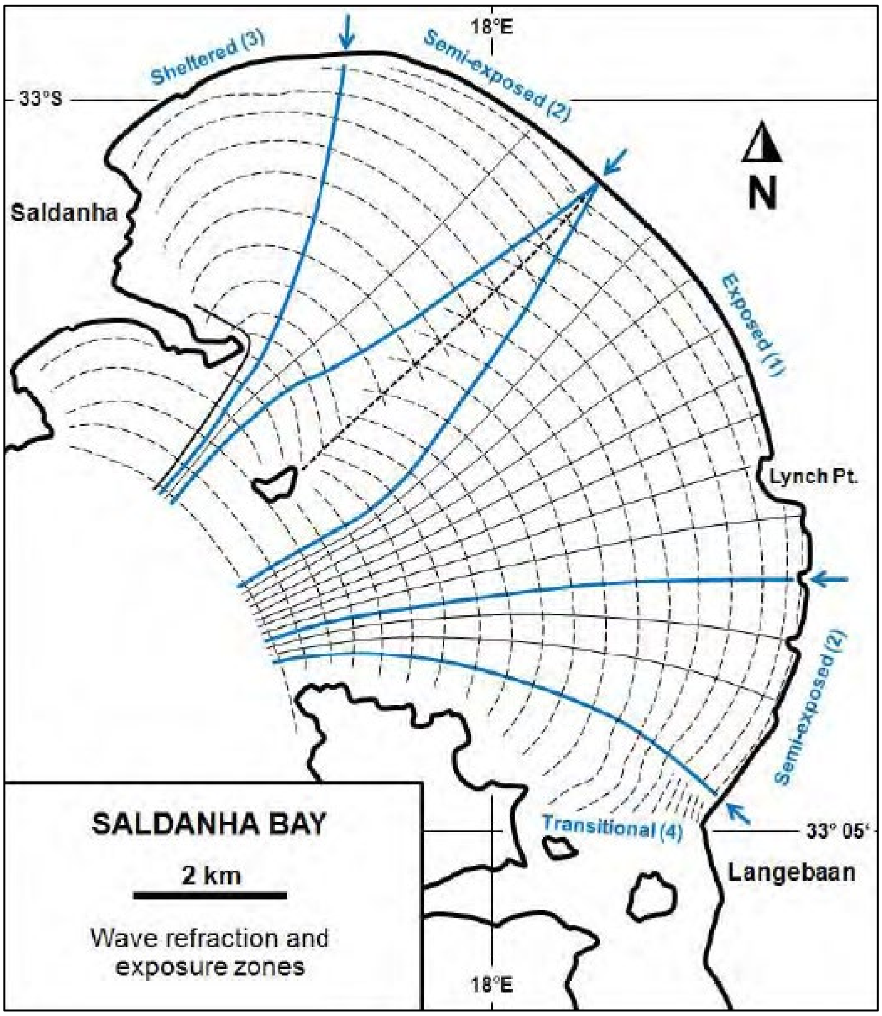

Figure 2.4: Wave refraction exposure zones

<u>Source</u>: Flemming (1977)

The transitional zone illustrated in Figure 2.4 is characterized by the interaction of ocean waves and tidal ebb currents leaving the lagoon system via the outflow channels that are situated in the southern, wave-sheltered part of Saldanha Bay. This shows that the majority of Big Bay is in an exposed wave energy area, which denotes that beach erosion and sediment transport are more likely to occur in these areas than in the areas indicated as Semi-exposed and Sheltered.

2.5.4 Zwemmer & Van 't Hof (1979): Construction of Saldanha Bay Port

The article by Zwemmer & Van 't Hof (1979) aimed to provide a clear understanding of the process followed during the construction of the PoS. As a point of departure, Zwemmer & Van 't Hof (1979) explained the reasons for selecting Saldanha Bay to be developed as an ore export terminal. These reasons included: Saldanha Bay's ideal location on a major global trading route; the wide entrance to the Bay and its proximity to deep water which would allow the PoS to handle the traffic of very large ships; and the natural shape of the Bay which required relatively few engineering works during construction. The main engineering works which needed to be conducted during construction of the PoS was the extension of the northern peninsula, Hoedjiespunt, to Marcus Island in the middle of Saldanha Bay by means of a breakwater (Zwemmer & Van 'T Hof, 1976). The construction of the breakwater enlarged the existing sheltered area within Saldanha Bay considerably. The location of the iron ore loading jetty was selected in such a way that a berthed ship would head on to the prevailing wind and significantly reduced swell through the remaining opening between Marcus Island and the southern peninsula, Elandspunt (see Figure 2.1) (Zwemmer & Van 'T Hof, 1976). There was also extensive dredging done by hopper dredgers to deepen the approach channel, as well as to harvest enough sand from the ocean floor to construct the breakwater. In total, 30 million m^3 of soil were displaced through dredging during the construction period (Zwemmer & Van 'T Hof, 1976). One condition of the original contract was that the PoS needed to be operational within three years of the contract being awarded. Construction duly started in 1973, and the first iron ore was loaded on 23 September 1979.

2.5.5 Luger & Van Ballegooyen (2000), CSIR (n.d.) and Monteiro & Brundrit (1990): Thermocline

In 2000, a three-dimensional model of Saldanha Bay was created by Luger & Van Ballegooyen. This model was able to distinguish surface currents from bottom currents. From this model, there were indications that there is a thermocline, i.e., different flow directions at various depths due to the change in temperature, during the summer months. The thermocline is well illustrated (see Figure 2.5) in a report drafted by the Council for Scientific and Industrial Research (CSIR) for the Harbour Master Port of Saldanha.

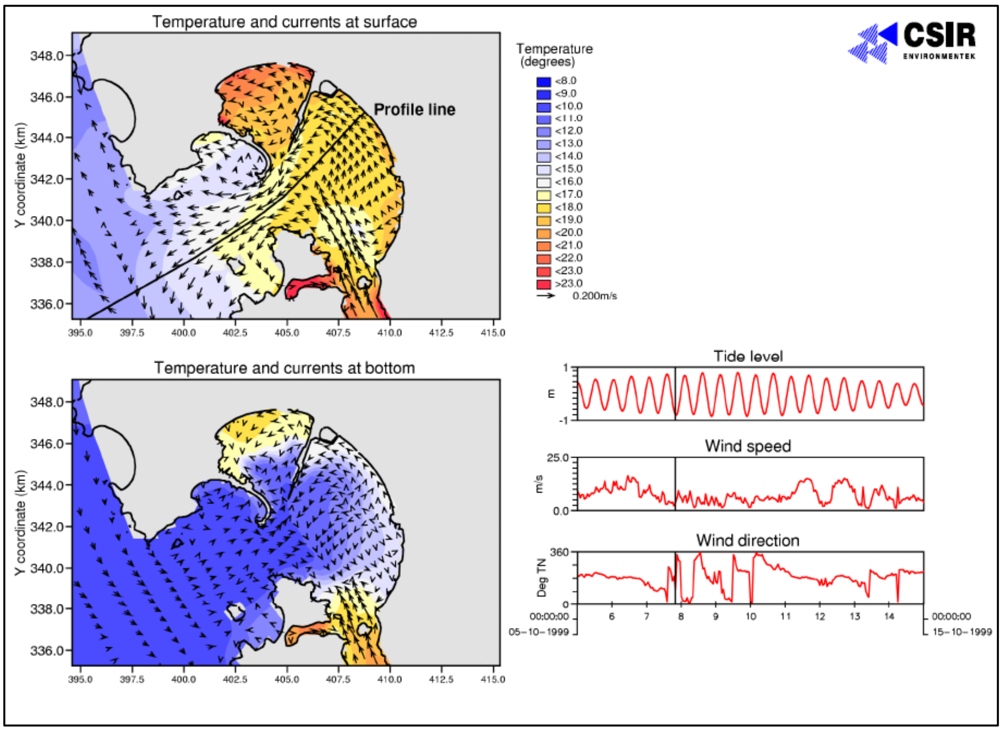

Figure 2.5: Three-dimensional (x, y, z) model illustrating thermocline (surface and sub-surface temperature distribution)
Source: CSIR (n.d.)

The presence of a thermocline was investigated in more detail by Monteiro and Brundrit in 1990 through their use of a time series dataset. From this data it was discovered that there exists a thermocline in the summer months at depths ranging from three to six metres. The top water column had an average temperature rising to between 18 ℃ to 20 ℃, with water temperatures in the depths ranging between 11 ℃ to 13 ℃ (Monteiro & Brundrit, 1990). They inferred that the presence of this thermocline could result in fluctuating flow directions between the colder and warmer water columns. However, the thermocline disappears in winter when a more isothermal water column exists in the Bay. Temperatures ranging between 13 ℃ and 14 ℃ leads to a more uniform flow during the winter months (Monteiro & Brundrit, 1990). The seasonal presence of the thermocline can be explained by the upwelling caused by southerly winds during summer the colder water of the Atlantic Ocean into the Bay and thereby pushes the warmer water to the surface, where the reigning temperature is maintained by high summer temperatures (Monteiro & Largier, 1999; Monteiro & Brundrit, 1990).

In terms of the impact of the construction of the PoS on flow patterns in the Bay, Monteiro & Brundrit (1990) concluded that the construction of the causeway and jetty had a significant impact on the hydrodynamics of Small Bay by reducing the effect of tidal force (the effect of the tide to drive currents in and out of Small Bay) on water circulation. This in turn affects the water circulation within Small Bay, which ultimately affects the stratification of the water and increases the time of water exchange in Small Bay (Wiese, 2013; Monteiro & Brundrit, 1990). Later studies also confirmed that the construction of the PoS isolated Small Bay from the usual circulation patterns within the Bay, thus leading to Small Bay having a separate circulation pattern than the rest of the Bay, especially during the passage of cold fronts in winter (Weeks et al., 1991; Van Ballegooyen et al., 2008).

2.5.6 Wiese (2013): Modelling the hydrodynamics and sedimentation processes in Saldanha Bay

In his thesis for a Master degree in Engineering (Civil), Wiese (2013) aimed to expand on the knowledge of oceanic currents in Saldanha Bay by creating a two-dimensional model to replicate them. Based on this model, Wiese (2013) supported Shannon & Stander (1977) by confirming that the circulation patterns in Small Bay are largely driven by the prevailing winds, while the circulation patterns in Big Bay are largely driven by tidal flow in and out of Langebaan Lagoon (Wiese, 2013). However, in 2013 Wiese, through a two-dimensional mathematical model, performed a specific investigation on the effect of the structures erected during the construction of the PoS on the hydrodynamics and sediment transport processes within Saldanha Bay. In his study, Wiese stated that the outdated bathymetrical information available at the time limited the reliability of the result of the model (Wiese, 2013). From his investigation it was found that there were no significant changes in the hydrodynamics and sedimentation transport processes in the Bay (Wiese, 2013). There were, however, changes in these processes during 1 in 100-year meteorological events, i.e., large scale weather conditions predicted to only happen once every 100 years. 1 in 100-year winds caused the greatest flow velocities prior to construction of the PoS, and 1 in 100-year storm surges created the greatest flow velocities after the construction of the PoS, a combination which resulted in most of the sediment transport occurring in the main channels of the mouth of Langebaan Lagoon (Wiese, 2013).

Wiese (2013) also made it clear that the construction of the PoS altered the flow patterns within the entire Saldanha Bay, a conclusion echoed by several other authors (Henrico & Bezuidenhout, 2020; Flemming, 2015; Wiese, 2013; Van Ballegooyen et al., 2008). From the findings of Wiese (2013), two were of significance for the current study. Firstly, the construction of the PoS altered the flow patterns and speeds of the currents within Saldanha Bay, which could influence bathymetry over an extended period. Secondly, Wiese (2013) mentioned that one of the limitations of his study was the fact that the bathymetry data were outdated, which influenced the reliability of his findings. This limitation supports the importance of conducting a more recent bathymetry survey of Saldanha Bay to gain a more accurate understanding of the sediment transport processes within the Bay.

2.5.7 Henrico and Bezuidenhout (2020): Determining the change in the bathymetry of Saldanha Bay due to the harbour construction in the seventies

Setting out to investigate the changes to the hydrodynamic sedimentation processes in Saldanha Bay because of the harbour constructions that took place in the early 1970s, Henrico and Bezuidenhout (2020) compared bathymetric data from Saldanha Bay before construction (1957) and after construction (1977) of the harbour. The data were analysed and compared in ArcGIS. The bathymetric data they used to analyse the depth profile of the Saldanha Bay consisted of two time series point datasets (1957 and 1977) that included 3 475 and 1 292 georeferenced elevation points respectively. These bathymetries point datasets were interpolated using the Ordinary Kriging (OK) interpolation method to produce two bathymetric digital elevation models (DEMs) with a ground sampling distance of 5 m (see Figure 2.6).

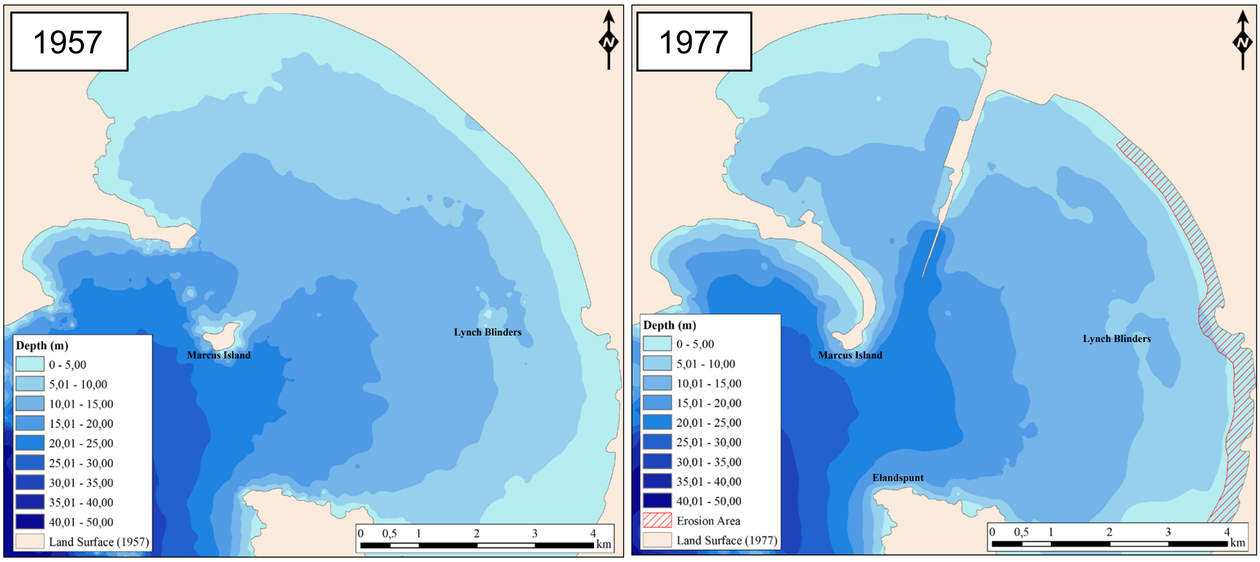

Figure 2.6: Bathymetry maps of Saldanha Bay before construction (1957) and after construction (1977) of the PoS

Source: Henrico & Bezuidenhout (2020)

The 'Difference' tool in the ArcGIS Image Analysis window was used to compute the change between the 1957 and the 1977 bathymetric maps. Their findings are illustrated in Figure 2.7 below.

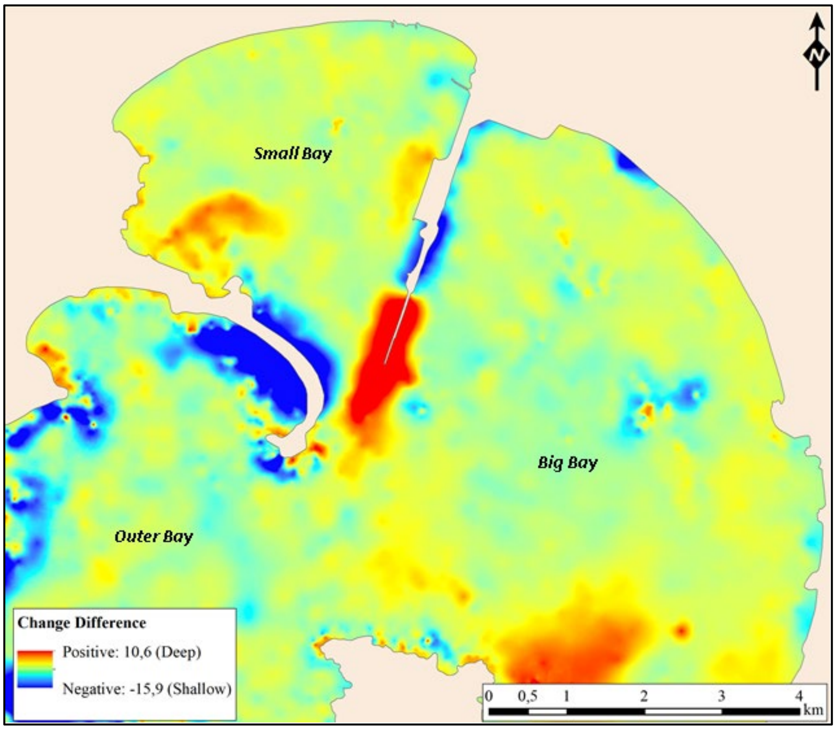

Figure 2.7: Bathymetric map of Saldanha Bay showing the difference before construction (1957) and after construction (1977) of the Saldanha Bay harbour
Source: Henrico & Bezuidenhout (2020)

The results from their study showed that the Bay became slightly deeper and that the slopes of the bottom profile in general became smoother and steeper, especially around the breakwater, causeway, and north-eastern shoreline. Henrico and Bezuidenhout (2020, p. 247) concluded that a "similar study should be repeated with more current bathymetric data to determine how the Saldanha Bay sedimentation process changed since harbour construction to the current sedimentation status to provide important information on current beach erosion and siltation challenges within Saldanha Bay". The findings of Henrico and Bezuidenhout (2020) played an important role in identifying and formulating the research problem of this study, which aims to serve as a follow up to their study, as recommended by the authors. The raw 1977-point dataset used by Henrico and Bezuidenhout (2020) to determine the 1977 bathymetry of Saldanha Bay is the same selected to perform the current study.

2.5.8 Reflection on the reviews of previous studies conducted on Saldanha Bay

From the various studies highlighted in the previous subsections (2.5.1 to 2.5.7) it is evident that anthropogenic influences over the years have impacted the bathymetry within the Bay, which led to changes in hydrodynamics and sediment transport processes. These changes are causing additional problems relating to erosion and sediment deposition within the Bay. It is also paramount to perform regular studies to provide those affected and those responsible for mitigating said changes, with continuous information – an informed picture – of the real, present impact of hydrographic changes on the coastline and marine life within the Bay. Lacking from the studies reviewed in this section is more recent bathymetry data which may indicate trends regarding sedimentation and possible negative impacts experienced within the Bay due to increased anthropogenic activities. Current expansion and development under way under IDZ objectives within Saldanha Bay are further cause for action research.

This study therefore fills a void in research by applying the most recent bathymetry survey (2021) of Saldanha Bay, the first since 1977. Even though regular depth measurements are conducted by the Port of Saldanha, it is mainly location specific and limited to small areas affecting the quay channel and turning basin in the port. It is important to note that the 2021 bathymetry survey conducted by the Hydrographer of the SA Navy does not cover the whole of Saldanha Bay (Inner and Outer Bay). Initially, a survey of both the Inner and Outer Bay was planned, but due to unforeseen circumstances (highlighted under the Limitations section in Chapter 5, see section 5.4) this did not materialize. However, a substantial area of Big Bay was surveyed. The researcher felt it was sufficient for conducting the current study because most of the anthropogenic activities conducted within Saldanha Bay has a direct influence on this part of Inner Bay. Consequently, the results of this study still provide valuable insights on the changes in bathymetry to parts of Saldanha Bay, specifically Big Bay, since the construction of the PoS; insights which may be projected onto other parts of the Bay.

2.6 Bathymetry background

Bathymetry is the foundation of the science of hydrography, which focuses on measuring and describing the physical features of bodies of water and the land areas adjacent to those bodies of water (NOAA, 2020). Beyond bathymetry, the field of hydrography also consists of the study of the shape and features of the shoreline, physical and chemical characteristics, currents and waves, the characteristics of tides, and properties of the water itself (NOAA, 2018). Bathymetric data is used in conjunction with representative data from some, or all the above-mentioned parameters to update nautical charts and develop hydrographic models, which is essential for safely navigating the oceans and waterways (NOAA, 2020).

By the 19th century, terrestrial geography such as the outline of continents, islands, mountain chains, and Great Plains, was well known and mapped. However, no technology was capable of measuring the depths of the sea accurately and swiftly at that time. As a result, the configuration of the seafloor was unknown by the start of the 19th century (Dierssen & Theberge, 2014). In the mid-19th century, scientific and commercial interests in the seafloor started to rise, leading to several new measuring technologies being developed (Kearns & Breman, 2010). One of these methods was the 'line-and-sinker' method which involved simply measuring the length of a weighted rope under water. With a weight resting on the seafloor the length of the rope underwater would represent the depth at that location. This method was used by Matthew Fontaine Maury to produce and publish the first bathymetric chart in 1853 (Dierssen & Theberge, 2014). However, the line-and-sinker method had several inherent inaccuracies caused by an angled line influenced by currents, mother vessel drifting, and difficulty to determine precisely when the sinker in fact reached the bottom (Van Der Wal & Pye, 2003).

Later developments, like the piano-wire sounding system aimed to mitigate the inaccuracies of the line-and-sinker method by using a thin wire which is less affected by surface and subsurface currents (Dierssen & Theberge, 2014). The piano-wire sounding system takes less time to observe soundings and provides a better indication of when the weight reaches the ocean floor than that of earlier methods (Dierssen & Theberge, 2020). In the early 20th century, bathymetric data collection technologies progressed from point sounding line-and-sinker methods to acoustic sounding methods, and before the end of the 20th century, catalysed by war, a wide array of bathymetric measuring tools had been developed (Dierssen & Theberge, 2020).

Currently, depth measuring techniques make use of a variety of measuring platforms, ranging from satellites orbiting high above Earth, suborbital aircraft, ships on the sea surface and remotely operated vehicles hovering above the seafloor or seabed (Kearns & Breman, 2010). Depending on which platform is used, and the objectives of the mission, measuring the depth of water mass may involve any one or combination of acoustics, optics, or radar altimetry to either direct measurement, or inferred bathymetry (Dierssen & Theberge, 2020). Each method provides different spatial resolutions and can probe depths ranging from shallow coastlines to the deepest oceanic trenches.

Determining what the underwater topography of a body of water looks like with a very high precision can be useful in a variety of applications. Bathymetric surveys are conducted for secure surface or underwater navigation, measurements of level of siltation, or underwater stockpiles, riverbed surveys, and many more (NOAA, 2018). Among these applications is modern hydrodynamic and sedimentary movement research, which was the application of bathymetric analyses in the current study. Hydrodynamics is a field of study concerned with the forces at play in a body of water in motion, with a broad scope of applications. By providing an understanding of the forces involved in a moving body of water, hydrodynamics may be used to provide more insight into certain hydrographical observations, such as changes in the bathymetric profile of a body of water. The opposite is also true; if the bathymetry of a body of water changes, then the hydrodynamics of that body of water will also change. Consequently, bathymetry can be used to inform hydrodynamic research, with applications varying from reasonably simple, where bathymetry is the only variable taken into consideration, to very complex, where bathymetry is used alongside many other variables (Wiese, 2013).

At the complex end of the spectrum, bathymetry is used in hydrodynamic modelling where bathymetric data is used to create models able of calculating variation in currents, tides, water temperature, and salinity in an area (NOAA, 2018). These models can also be used to predict natural threats like coastal flooding and rip tides. However, this type of hydrodynamic research is highly specialised and uses expensive and advanced modelling equipment and software (NOAA, 2021). Large companies such as Intertek developed such advanced hydrodynamic models to provide hydrodynamic modelling services to clients involved in a wide range of sectors around the world. These models may range in nature and scale from oceans, seas, coastal waters, ports and harbours to lochs, lakes, and rivers. Dubbed by Intertek as their Modelling Plus+ technology, advanced hydrodynamic models use hydrodynamic inputs to quantify and predict related processes such as sediment transport, and scour and water quality (e.g., physical, chemical, and biological) (Intertek, 2021). With bathymetry being the variable investigated in this study, it is important to understand the method and purpose of inquiry used in the field of bathymetric studies.

This section served as background to the field of bathymetry and served as the base for establishing the research methodology of this study. The following section provides more detail on the specific methods used during bathymetry surveys in recent times.

2.7 Methods used for bathymetry surveys

Specifically considering bathymetry, modern methods used to capture bathymetric data consists of processes which gather information about the physical characteristics of the seafloor by measuring its reflected and emitted radiation from a distance (Smith & Pitcher, 2015). The primary means of collecting data concerning the seafloor is single-beam and multi-beam SoNAR. These techniques determine ocean floor depth by measuring the time it takes for either a laser light or acoustic SoNAR pulse to travel through a column of water and back, taking into consideration factors such as speed of sound in water, time, sensor characteristics, and related variables (Kearns & Breman, 2010). More recently, advancements in light detection and ranging (LiDAR) and synthetic aperture radar (SAR) technologies (techniques) have made mapping bathymetry over broad areas more efficient and cost-effective (Dierssen & Theberge, 2014; Havens & Sharp, 2016). However, LiDAR and SAR have their inherent limitations, thus they were not considered as possible techniques to be used to capture the bathymetric datasets during this study.

The following section provides more detail on the process involved in collecting bathymetric data using underwater single-beam and multi-beam SoNAR, as they were the platforms used to collect the data during this study. This will be done by giving a brief overview on their operations, benefits and drawbacks.

2.7.1 Measuring bathymetry using underwater single-beam SoNAR

Single-beam echo sounding (SBES) is generally accepted by hydrographic scientists as the most common method for bathymetric data collection (Kearns & Breman, 2010; Li et al., 2007). Sound navigation and ranging (SoNAR), originally intended as a listening device, was developed for bathymetry in the 1930s, and since then has proven to be a versatile technology for bathymetry measurement.

The use of sound to measure ocean depths works on the same principle as LiDAR, yet it sends a single pulse of sound through a column of water and measures the elapsed time for the pulse to travel to the seafloor and be reflected to the sensor (Dierssen & Theberge, 2020). One half of the round-trip travel time multiplied by the velocity of sound in sea water equals the depth at a given point. The two-way travel-time of this pulse is important, because time is halved and multiplied by the mean sound velocity for the water mass of which the depth is being measured to yield water depth, as formulated by the following equation (1) (Lubbers & Graaff, 1998):

$$\textit{Depth} = \tfrac{1}{2}\,\mathrm{Vw}\ \mathrm{t} \qquad (1)$$

where:

(Vw) is the velocity of sound in sea water in m/s.

(t) is the two-way travel time in seconds.

Sound velocity in sea water can reach between 1 400 m/s and 1 600 m/s but averages 1 500 m/s. An acoustic signal is dependent on the characteristics of the water. It is affected by salinity, temperature, and pressure of the column of water (Le Bas & Huvenne, 2008). Additional processing of measurements considers factors such as the drift of the vessel, tides, instrument errors (Kearns & Breman, 2010), and the sea state.

SBES is used for measuring depths directly below the vessel, as soundings are only acquired directly underneath the transducer, mounted on the bow of the ship (NOAA, 2018). As a result, the line spacing between survey lines will influence the scale and resolution of the final product (NOAA, 2018) because the SBES instrument only highlights a narrow strip of the seabed with the depth between these lines being omitted. It does not provide continuous coverage of the seafloor (Dierssen & Theberge, 2020). The most common method for collecting SBES data is to run the survey lines perpendicular to the underwater slopes with a predetermined spacing between lines. Tie lines are also run as a means for providing cross validation and quality assurance. These tie lines run perpendicular to the survey lines at a wider spacing (Dierssen & Theberge, 2020).

The raw data recorded for SBES measurements consist of the time it takes for a sound pulse to travel to the seafloor and back (2-way travel time). By knowing the fixed velocity at which sound travels through seawater, the amount of time it takes for the sounding to travel to the ocean floor and back can be used to compute the observed depth (Kearns & Breman, 2010). However, unless seas are extremely calm, vessels move up and down over the waves and this movement needs to be mitigated to obtain an accurately observed depth. With changing tides and vessel draft also being taken into consideration, numerous corrections must be made to each measured depth to account either for variability in the ocean, or for movement of the vessel, or both, as shown in Figure 2.8.

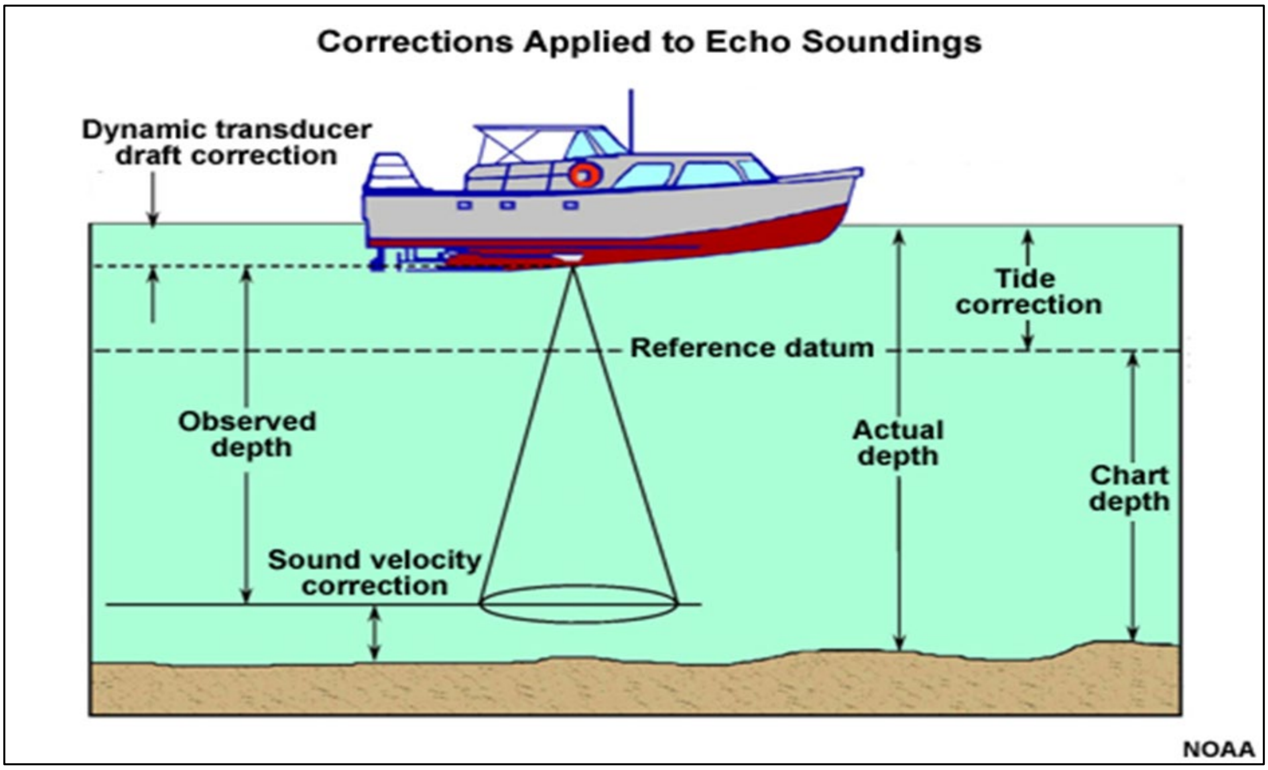

Figure 2.8: An illustration showing the corrections needed to process observed soundings in order to get a charted depth measurement
Source: NOAA (2018)

Because the speed of sound is not constant throughout a water column, a correction needs to be applied for each "observed depth". The "sound velocity profile" is measured with a sound velocimeter, which is lowered into the water column every day before starting a survey (Dierssen & Theberge, 2020).

When the vessel moves through the water, its draft changes, known as settlement and squat. Static draft, depth of the transducer when standing still, settlement, and squat are collectively called dynamic draft, which varies with the speed of the vessel through the water. Dynamic transducer draft correction must be made to account for the fact that the echo sounder transducer is below the water surface. Finally, a correction needs to be made to consider the rise and fall of the tide. Tide correction is made from an internationally accepted reference datum to provide a “charted depth” measurement. However, because SBES only takes point depths, SBES data will have to undergo some form of interpolation process to predict the depths of unmeasured areas to create a surface model (Costa et al., 2009).

2.7.2 Measuring bathymetry using underwater multi-beam SoNAR

The first multi-beam echosounder system (MBES) was developed and manufactured by General Instrument Corporation (GIC) in 1977 (Vilming, 1998). It used the same principles as SBES to capture millions of precise soundings that provide extremely accurate bathymetric data (Costa et al., 2009; Henrico & Bezuidenhout, 2020; Che Hasan et al., 2014). The MBES instruments were developed specifically to create a more accurate picture of the ocean floor. Since its introduction, the MBES instrument is the preferred method for measuring the depth and relief of the sea floor, especially when investigating changes in bathymetry, as these instruments can capture data at a much finer spatial resolution than SBES (NOAA, 2018).

The principle of operation of the MBES instrument is that it effectively blankets the seafloor with pulses of sound energy which provide an array of measured depths – practically covering the entire surface of the seafloor. These soundings can then be interpolated and analysed with GIS software to create very high-resolution bathymetric maps.

Today, high-resolution measurements of ocean depth and bottom reflectivity are produced by MBES platforms. Each ping of a MBES emits a single wide swath of sound (up to 153 degrees) that reflects off the seafloor. The echo is received by an array of transducers and then separated electronically into several individual beams for each of which a depth is calculated. The spatial resolution of this MBES data is dependent on four factors, namely characteristics of the sensor (swath width and acoustic frequency), water depth, and survey route design, which impacts the spacing between adjacent soundings. Very high resolution is attainable in shallow water, but the swath width is decreased. Conversely, the efficiency of ship operation is increased in deep water as the swath width expands geometrically but resolution is decreased (see Figure 2.9). Various sound frequencies (e.g., 12 – 400 kHz) are also employed for different depth ranges – the lower the frequency, the deeper the depth measurement possible, while higher frequency is associated with higher resolution, but shallower depth.

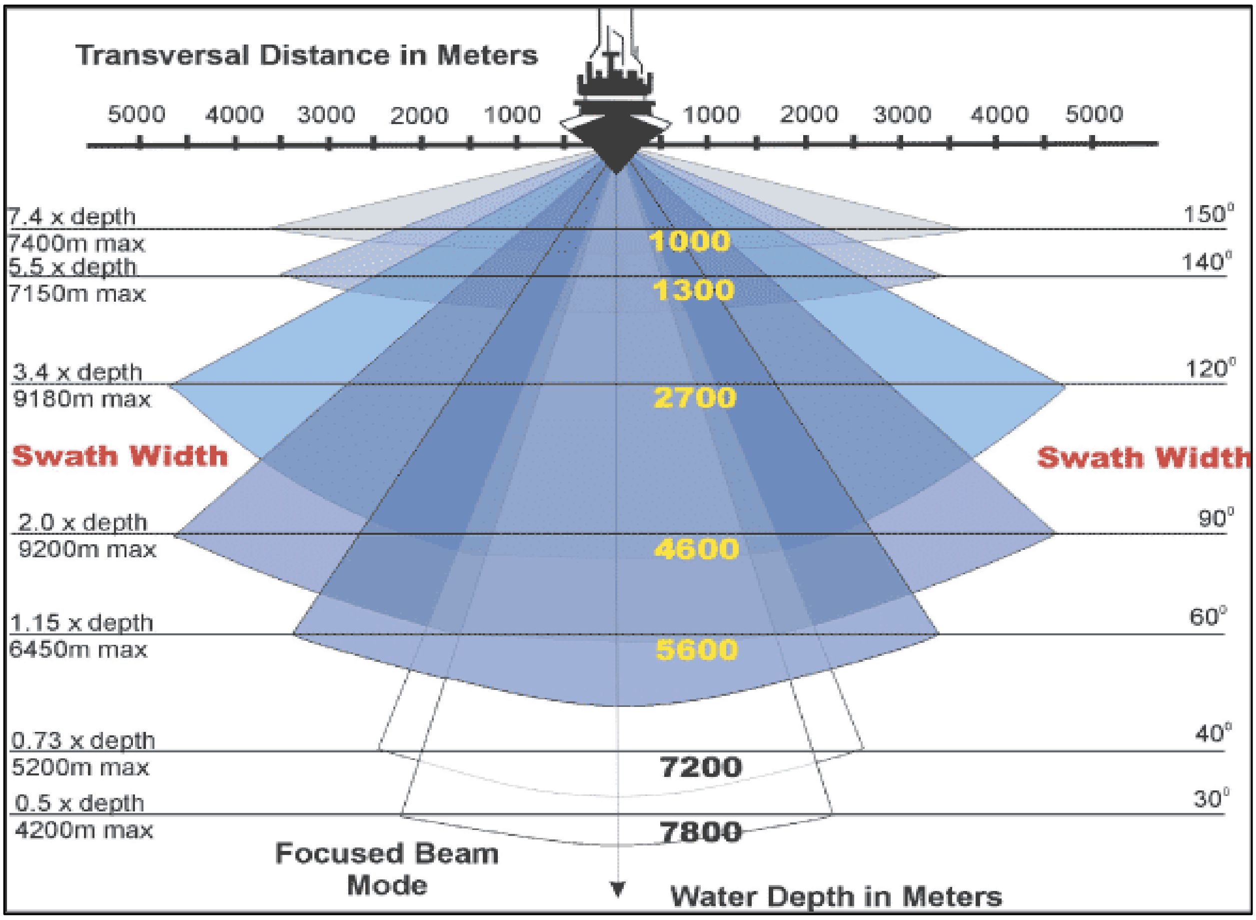

Figure 2.9: Relationship between water depth and swath width: 1180MBES system
Source: Sakellariou et al. (2018)

A swath of the seafloor is acoustically imaged with each pass of a survey ship as it follows a pattern like “mowing the lawn”. A series of overlapping swaths produce a bathymetric map of the area being surveyed. An overlap of at least 20 percent is usually planned to account for any degradation in data collected from the outer beams. The outer beams generally have a lower accuracy due to the more acute angle of pulses, with good quality data generally only coming from the centre 60 percent of the beams (Sakellariou et al., 2018). Consequently, an overlap is needed to ensure that there are no areas of low data quality in the dataset.

MBES also collects backscatter data, characterised by the strength of the returned signal, which may be used to provide information about the geology of the seafloor (Sakellariou et al., 2018). Softer surfaces (such as mud or sand) will absorb more energy and have weaker backscatter, whereas harder surfaces (such as rocks) will reflect more energy and produce stronger backscatter (Kearns & Breman, 2010).

According to Dierssen (2010, p. 3), two of the main disadvantages of acoustic measurements are “the time and cost associated with making measurements from a ship in deep waters or a small vessel in shallow waters. To build up coherent images at a high resolution, many survey lines with overlapping tracks must be run. Because the swath width decreases in shallow water, many more survey lines/tracks are required in coastal estuaries and bays with shallower water. Hence, detailed surveys in coastal regimes require considerable time and effort to cover relatively small portions of the seabed”. This timeous nature of collecting data using the MBES instruments was one of the limiting factors in this study, as mentioned in Chapter 5 (see section 5.4). In general, acoustic methods can be used throughout all oceanic depths, from shallow estuaries to the deepest trenches (Dierssen & Theberge, 2020).

2.8 Interpolating bathymetric datasets

Interpolation is the process of making inferences about an entire geographic area from an ‘incomplete’ dataset (Childs, 2004). It is nearly impossible to collect and illustrate a height value for every corner of an area. Therefore, almost all datasets will inevitably be incomplete (Ali, 2004). Consequently, the process of interpolation is required when representing terrains as a continuous surface (Aguilar et al., 2005).

There are numerous interpolation techniques for creating bathymetric surface models, such as Inverse Distance Weighted (IDW) interpolation, Spline, Kriging, and Topo to Raster interpolation, all of which assume that bathymetry is spatially autocorrelated (Amante & Eakins, 2016). The notion of spatial autocorrelation can be attributed to Tobler’s 1st Law of Geography – “everything is related to everything else, but near things are more related than distant things” (Tobler, 1970, p. 304). In terms of bathymetry, this means that depths at a specific location will be more similar than depths further away. However, different interpolation techniques employ different mathematical algorithms to produce surface models. As a result, the various interpolation techniques will produce divergent surface models, even if they are developed from the same point dataset (Aguilar et al., 2005; Ali, 2004; Erdogan, 2009). Interpolation techniques can be classified into two general groups, viz. geostatistical interpolation, which uses both mathematical and statistical functions to predict unknown values, and deterministic techniques, which only incorporates mathematical functions to predict unknown values (Henrico, 2021; Childs, 2004). Geostatistical methods include autocorrelation, which are described on the ESRI website[3] as "the statistical relationship among the measured points. Because of this, geostatistical techniques do not only have the capability of producing a prediction surface, but also provide some measure of the certainty or accuracy of the predictions" (ESRI, 2020). All Kriging methods are geostatistical methods of interpolation, whether Ordinary Kriging, Simple Kriging, Probability Kriging, Disjunctive Kriging, or Empirical Bayesian Kriging (ESRI, 2020).

Furthermore, interpolation techniques may be either local, using a subset of measurement to predict unknown values, or global, using all values to predict unknown locations (Childs, 2004). Interpolation techniques may also be exact, where the surface model has the same values at the measured locations, or inexact, where the surface model is not constrained by the measured values (Amante & Eakins, 2016). ESRI further describes[4] an exact interpolator as an "interpolation technique that predicts a value that is identical to the measured value at a sampled location" (ESRI, 2020). An inexact interpolator predicts a value that is different from the measured value and is used to avoid sharp peaks or troughs in the output surface (Longley et al., 2005). Interpolation techniques can be any combination of geostatistical or deterministic, local, or global, and exact or inexact (ESRI, 2020). The selected technique must be based on sample density, sample distribution, terrain characteristics and measurement uncertainty (Kalivas et al., 2013). Most importantly, however, each interpolation technique has mathematical constraints for predicting unknown values that need to be considered (Amante & Eakins, 2016).

Spatial interpolation has many applications for creating and analysing spatial features and therefore many of the over 40 interpolation methods which exist have been integrated into GIS software (Ferreira et al., 2017; Meng et al., 2013). The ArcGIS Pro 2.8.0 software that was used to conduct the analysis during the current study has a suite of interpolation methods available in its Geostatistical Analyst extension.

[3] An overview of the Interpolation toolset—ArcGIS Pro | Documentation
[4] Deterministic methods for spatial interpolation—ArcGIS Pro | Documentation

Even though there are many interpolation methods available, only a few are widely used to conduct spatial analyses (e.g., topo-to-raster, Kriging, radial basis function, nearest neighbour, IDW, local and global polynomials and spline), all of which are available in the Geostatistical Analyst (Henrico, 2021; Meng et al., 2013; Childs, 2004). From this portfolio of interpolation methods, there are two that are favoured among researchers for creating digital elevation models, such as to illustrate bathymetry, namely, IDW interpolation method and Kriging interpolation method, specifically Ordinary Kriging (OK) (Henrico, 2021; Ferreira et al., 2017; Kalivas et al., 2013). It is important to note that factors such as sounding density, distribution and accuracy may influence the accuracy of any given interpolation method and should be carefully considered when selecting an interpolation method for analysis (Amante & Eakins, 2016; Childs, 2004).

Both IDW and OK where considered as potential interpolation methods for creating surface models to represent Saldanha Bay's bathymetry. Even though IDW and OK are the preferred method for interpolating surfaces, they differ significantly in their approach towards calculating and predicting spatial correlation when creating interpolation surfaces (Henrico, 2021). For that reason, the following section provides an overview of IDW and OK interpolation methods is provided in the next section. Both methods were tested with the datasets used during this study (see Chapter 3, section 3.6.1). The OK method was found the best suited for creating the surface models to represent Saldanha Bay's bathymetry with the datasets available for this study.

2.8.1 Inverse Distance Weighted (IDW)

IDW is a deterministic interpolation method, and therefore uses a mathematic algorithm to make predictions (Childs, 2004). The algorithm used by IDW is simple. It predicts unknown values by considering their proximity to known values while ignoring the spatial distribution of the data (Henrico, 2021).

IDW follows a nearest neighbour approach which applies a weighted influence on data points based on their proximity to unknown points, and therefore abides by Tobler's 1st Law. IDW determines the value of unsampled locations by using a weighted linear combination of a set of known sampled values, where the weight is a function of the inverse distance between locations and can be raised to any mathematical exponent (Ferreira et al., 2017). This means that the weight decreases with increasing distance, while the decrease is rapid with a higher exponent. The optimal exponent value can be obtained by minimizing the root mean square deviation (RMSD) estimated through cross-validation (Ferreira et al., 2017). IDW is calculated by the following equation (2), as described by Wang et al. (2014, p. 3746):

$$Z = \sum_{i=1}^{n} \frac{1}{(d_i)^p} Z_i / \sum_{i=1}^{n} \frac{1}{(d_i)^p} \tag{2}$$

where:

Z is the estimated value of the predicted point.

Z_i is the value of sampled point i.

d_i is the distance between the predicted and sampled points.

p is the power parameter (weighted exponent) and must be a positive real number.

n is the number of sampled points.

De Souza et al. (2003) affirmed that the IDW algorithm is well suited for creating floor surfaces and digital elevation models (DEM). It is based on its ability to create smooth surfaces (De Souza et al., 2003). They also stated that one of the attractive characteristics of this method is that it allows for the alteration of the size of the search neighbourhood used, number of neighbours processed in calculations, and power parameter, allowing for a level of fine tuning of parameters to produce a more accurate interpolation surface. However, the first disadvantage of IDW is that it does not account for data trends. Furthermore, IDW has a disadvantage where a lack of sample points reduces accuracy and causes a “bulls-eye” effect – concentric circles appearing round known points (Setianto & Triadini, 2013).The value of the power parameter also affects the accuracy of the interpolation surfaces created by applying the IDW method. A lower parameter will create a smooth surface, while a high parameter will place more weight on nearby points, ultimately creating a less smooth surface (Pham et al., 2016). According to Pham et al. (2016), the best value for the power parameter is 2.

2.8.2 Ordinary Kriging (OK)

The Geostatistical Analyst extension in the ArcGIS Pro software used in the current study offers a variety of Kriging methods to choose from, including OK. Among the other Kriging methods available are simple Kriging, universal Kriging, indicator Kriging, probability Kriging, disjunctive Kriging, and empirical Bayesian Kriging, each with its own intrinsic ability to process different data types (ESRI, 2020). However, Ordinary Kriging (OK) is the most widely used interpolation method and is consequently the default interpolation method in the ArcGIS Pro software (ESRI, 2020; Henrico, 2021).

OK is a geostatistical interpolation method, which means it accounts for statistical trends within the data. Geostatistics assumes that the studied phenomenon is stationary (Vieira, 2000). There are three hypotheses underpinning geostatistical inferences, namely, first order stationarity, second order stationarity, and semivariogram, with the latter being the most used tool in geostatistics (Ferreira et al., 2017).

The semivariogram accounts for spatial autocorrelation between known values and incorporates a best-fit model that considers both distance and direction when determining the spatial relationship of the data. However, OK does not identify any overriding trends or directional drift. The semivariogram used in the OK interpolation method incorporates the following unbiased equation (3) to calculate spatial relationships (Olea, 1999):

$$y(h) = \frac{1}{2n(h)} \sum_{i=1}^{n(h)} [Z(x_i + h) - Z(x_i)]^2 \tag{3}$$

where:

$y(h)$ denotes the semivariograms.

h represents the distance/lag.

$n(h)$ represent the number of value pairs.

Z is the intrinsic random function.

n is the number of sample points.

x_i are date values at point i.

A critical component of generating any Kriging model, including OK, is the generation of the semivariogram (see Figure 2.10), a plot that shows the variance in the distance between all pairs of sampled locations (Scheeres, 2016).

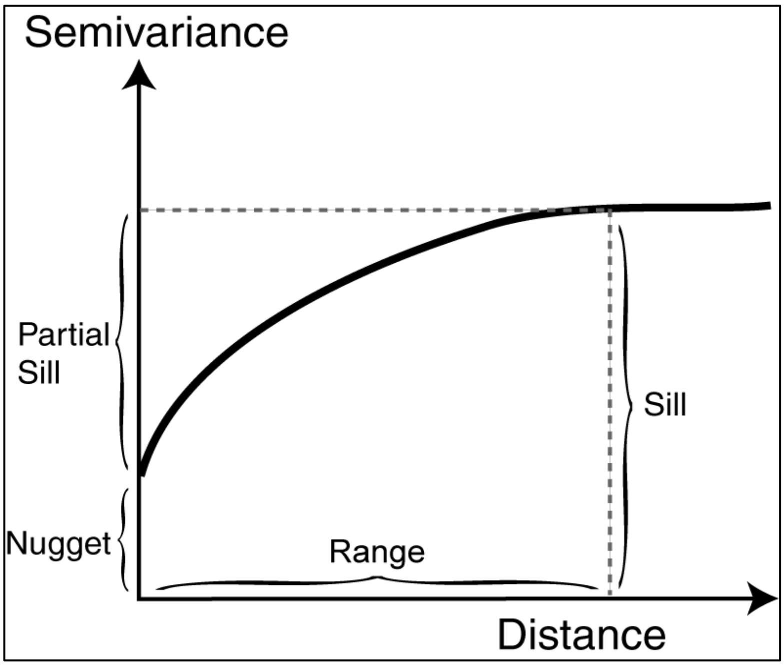

Figure 2.10: Graph illustrating a semivariogram plot generated by the Kriging model
Source: Scheeres (2016)

The range, indicated on the X-axis, represents the autocorrelation that exists among points based on distance, where the nugget, indicated on the Y-axis, is the error or random effect, and the sill, also indicated on the Y-axis, shows the distance at which points are no longer spatially autocorrelated (Henrico, 2021; Scheeres, 2016). In the model, points near one another are expected to be more similar than points that are farther apart (Scheeres, 2016).

The OK interpolation tool in ArcGIS allows the user to 'fine tune' the semivariogram model by offering a variety of functions (e.g., circular, spherical, exponential, Gaussian and linear). Each function influences the modelling of data in its own way, which means that the 'best' model is dependent on specific characteristics of the dataset being analysed (ESRI, 2020). The process to achieve the best-fit representation of the data normally entails trial-and-error to find the parameters that optimise the model (GIS Geography, 2017; Henrico, 2021). While Kriging may be more complex than other types of spatial interpolation, it does have the potential to generate more accurate, validated surfaces.

Ultimately, OK was selected as the preferred interpolation method for this study. A more detailed motivation regarding the reasoning behind the selection of OK for this study is provided in section 3.6.1.

2.9 Conclusion

Through an extensive review of relevant literature for this study, Chapter 2 provided the foundation of knowledge that was used to conduct the research methodology that is discussed in the following chapter. Chapter 2 highlighted the economic importance of Saldanha Bay by unpacking the history and development of Saldanha Bay before and after construction of the PoS. The importance of the PoS to the South African government as highlighted in this chapter contributes much to the significance of this study. The chapter continued by reviewing nine studies which focussed on similar research problems within Saldanha Bay as the current study. It also illustrated the void in literature which this study would fill. Finally, Chapter 2 concluded with an in-depth review of the data collection and data analyses methods used during this study.

The following chapter builds on the knowledge foundation provided in Chapter 2 by giving a detailed account of the research methodology used during this study.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

The previous chapter consisted of a comprehensive review of literature relevant to this study. In the current chapter, the methodological approach followed during this study is described. A research structure is provided to illustrate the steps that were followed to achieve the aim of this study. Specific attention is given to data collection, data processing, and data analysis. GIS software used to conduct this study is also introduced, specifically the process which entailed the creation of the bathymetry maps which forms the basis for the comparison between the sounding datasets of 1977 and 2021 respectively.

3.2 Methodological approach

3.2.1 Qualitative versus Quantitative research

The methodological approach used in a study governs how the study will be conducted, from the type of data to be collected and how the data is collected, to the methods and tactics used to analyse the data (Apuke, 2017). There are mainly two types of data that can be collected, namely quantitative data(statistics) expressed as numbers, and qualitative data (descriptive data) expressed as words (Kumar, 2014). Each of these data types have their own set of advantages and disadvantages (McCombes, 2019). The main distinction between these two types of data is determined by the underpinning restrictions imposed by the method of enquiry, freedom and flexibility in the structure, and the approach of the researcher when answering the research question (Brown, 2006). A quantitative research approach favours these restrictions, whereas a qualitative research approach advocates against the restrictions (Kumar, 2014). The following two paragraphs briefly explain the nature of inquiry in both the qualitative and quantitative research approaches.

The qualitative approach is described by Kumar (2014, pp 167 – 199) as an "understanding of thoughts, concepts, or experiences, and making use of interviews with open-ended questions, observations described in words, and literature reviews that explore concepts and theories" to collect data about a given topic. Furthermore, the qualitative research approach involves the collection of data in a non-numerical form, i.e., texts, pictures, videos, etc, with the purpose to understand and interpret social interactions (Kumar, 2014; Apuke, 2017; McCombes, 2019).

Quantitative research is used to establish generalized facts about a topic while testing and confirming theories and assumptions by the testing hypotheses, looking at cause and effect, and making predictions (Apuke, 2017). Quantitative research requires the reduction of a phenomenon to numerical values upon which the statistical analysis is carried out (Glatthorn & Joyner, 2005). Additionally, quantitative research makes use of experiments, observations recorded as numbers, and surveys with closed-ended questions to collect data about a given topic (Glatthorn & Joyner, 2005).

A clear definition of the methodological approach that will be followed when conducting any research study is key to the establishment of any sense of validity or reliability for the findings of that study (Kumar, 2014). To this end, Apuke (2017) created a set of criteria to determine the best methodological approach that should be incorporated for a specific study, shown in Table 3.1 below.

Table 3.1: Criteria for Qualitative versus Quantitative research (Apuke, 2017)

Criteria	**Qualitative Research**	**Quantitative Research**
Purpose	To understand & interpret social interactions.	To test hypotheses, look at cause and effect, and make predictions.
Variables	Study of the whole, not variables.	Specific variables studied.
Type of data collected	Words, images, objects.	Numbers and statistics.
Form of data collected	Qualitative data such as open-ended responses, interviews, participant observations, field notes, reflections.	Quantitative data based on precise measurements using structured and validated data-collection instruments.
Type of data analysis	Identify patterns, features, themes.	Identify statistical relationships.
Results	Particular or specialized findings that are less generalizable.	Generalizable findings that may be applied to other populations.
Final report	Narrative report with contextual description and direct quotations from research participants.	Statistical report with correlations, comparisons of means, and statistical significance of findings.

The following section states the research aim, research questions and research objectives within the context of criteria set out above to define the methodological approach to collecting and analysing the data in this study.

3.2.2 Defining the methodological approach in this study

The purpose of this study is to analyse the changes in bathymetry of Saldanha Bay between 1977 and 2021, thereby determining the effect of the construction of the PoS on the hydrodynamic and sediment transport processes within Saldanha Bay – a cause-and-effect related purpose generally associated with quantitative research:

Variables. The variable of the change in depth of Saldanha Bay between 1977 – 2021 is studied during this research, thus forming the criteria for quantitative research.

Data collected. Numerical data is collected during this study in the form of point depth measurements or sounding (measured in metres). The data used in this study is collected through SBES and MBES SoNAR equipment, the most common and accurate instruments for conducting bathymetric surveys, thus forming the quantitative criteria for the form of data collected.

Data analyses. The OK interpolation method, available in the geostatistical wizard extension in ArcGIS Pro software, is used to analyse the point datasets and create the bathymetric models used to determine the change in the bathymetry of Saldanha Bay between 1977 - 2021. OK accounts for statistical trends within the data by using a semivariogram that accounts for spatial autocorrelation between known values.

Results: The results of this study are specifically related to Saldanha Bay's bathymetry, hydrodynamic processes, and sedimentary transport processes, and cannot be generalized to other areas or 'populations', making the criteria for qualitative research.

Reporting. The final report of this study is in the form of a statistical report detailing the comparison between the 1977 and 2021 bathymetric models, making the criteria for a quantitative final report.

The aim of the study is to explain a phenomenon through gathering data in numerical form and analysing the data mathematically. When applying the criteria outlined in Table 3.1 to determine the best methodological approach to be followed during this study, it becomes clear that a quantitative approach is best suited to the achievement of the aim and objectives of this study.

3.3 Research structure

After establishing the methodological approach that would be followed during this study, a research structure was designed. Having a detailed research structure is an important part of reliable research, as it provides the researcher with a rational guideline that serves to keep him/her focussed on his/her research objectives (Kumar, 2014).

To this end, the following section gives an overview of the research structure adhered to during this study. This is done by explaining the sequential steps followed to collect and analyse the data to be used to detect the change in the bathymetry of Saldanha Bay between two time series data sets (1977 and 2021). The research structure of this study is shown in the flow chart below (see Figure 3.1).

RESEARCH STRUCTURE	
PHASE ONE: Data Collection	
1977 Dataset • Legacy dataset • Captured using SBES • Collected from SANHO • Point-depth shapefile • 300 m Spatial resolution	**2021 Dataset** • Captured dataset • Captured using MBES • Captured in conjunction with SANHO • Point-depth shapefile • 100 m Spatial resolution
PHASE TWO: Data Preparation	
1977 Dataset • Projected to UTM 34s • Depth geometry calculated in metres • Data clipped to the spatial extent of the research area (Big Bay)	**2021 Dataset** • Projected to UTM 34s • Depth geometry calculated in metres • Data clipped to the spatial extent of the research area (Big Bay)

PHASE THREE: Data Analysis

1977 Dataset

- Geostatistical Wizard used (ArcGIS Pro)
- Determine best interpolation method:
  - ✓ OK used with GSD of 2.7 m
  - ✓ Slope creation
  - ✓ Change detection

2021 Dataset

- Geostatistical Wizard used (ArcGIS Pro)
- Determine best interpolation method:
  - ✓ OK used with GSD of 2.7 m
  - ✓ Slope creation
  - ✓ Change detection

PHASE FOUR: Identifying Trends

- Determine trends and changes in bathymetry between 1977 and 2021
- Areas with significant changes in depth and slope are indicated

Figure 3.1: Flow chart illustration the research strategy employed during this study

As shown in Figure 3.1 above, this study was conducted through the completion of four sequential steps.

Phase One – Data Collection. As shown by Figure 3.1, the first step was to collect the data required to achieve the primary and secondary objectives for this study. The data collected for this study consisted of two sets of bathymetric data, one for 1977 and one for 2021. The 1977 dataset was collected by the SAN by means of SBES equipment and was availed by the Hydrographic Office of the SAN as charted point depths in a shapefile format. The 2021 data was collected in conjunction with the SAN by means of MBES during the first part of 2021. SANHO provided a quality controlled and depth verified point shapefile of the bathymetry of Saldanha Bay.

Phase Two – Data Preparation. The collected data was then processed and prepared for analyses using the ArcGIS Pro Software. To prepare the data, all measured depths were uniformly described in metres, georeferenced through UTM 34S projection, and clipped to the research area – the Big Bay section of Saldanha Bay. The 'projection' and 'clipping' tools that form part of the spatial analysis extension in the ArcGIS Pro 2.8.0 software were used to conduct data processing.

Phase Three – Data Analysis. Analysis started with selecting a suitable interpolation method for creating the surface models that would represent the 1977 and 2021 bathymetry through a statistical comparison between two interpolation methods, IDW and OK. The OK method was selected over the IDW interpolation method to create the bathymetric models. Secondly, slope models were created for both surface models to identify changes in the slope profile of the respective surface models. Surface models were subjected to change detection analyses, whereas slope models were compared to reveal statistical changes between the two time series datasets. The 'Geostatistical Wizard' that forms part of the spatial analysis extension in ArcGIS Pro 2.8.0 software was used to conduct interpolation during this study. The raster functions of 'slope' and tools of 'raster calculator: minus' that form part of the spatial analysis extension in ArcGIS Pro 2.8.0 software were used to conduct slope and change detection analyses during this study.

Phase Four – Identifying trends: In the fourth phase, the results produced by the various analyses in the third phase were scrutinized to determine any trends and changes in the bathymetry of Saldanha Bay between 1977 and 2021. This entailed identifying the location of areas which experienced a statistically significant change in depth between the 1977 and 2021 datasets, as well as identifying statistically significant changes in the slope of the Bay between these two datasets. Identifying trends in changes in depth and slope would provide the insights necessary to evaluate the effect of the construction of the PoS on the hydrodynamic and sediment transport processes within Saldanha Bay.

The rest of this chapter expands on the phases described above.

3.4 Data collection

The researcher was not directly involved in the collection and processing of the 1977 dataset. Said data was obtained as a georeferenced point shapefile. This legacy dataset consisted of 3 052 sounding points which were captured during a 1977 SAN survey of the Saldanha Bay area for the SAN to update their nautical charts (C Theunissen 2020, personal communication, 18 August). The legacy 1977 dataset was used during this study. After being clipped from its original extent to the extent of the research area of this study, it only consisted of 613 points (section 3.4.3 for more description). The Data Release Agreement to use this legacy dataset in the current study is attached as Appendix A.

Conversely, the researcher of this study was directly involved in the capture and processing of the 2021 dataset used in this study, which consisted of assisting the SAN with the capturing of soundings in the Bay using the survey vessel (see Table 3.2). The 2021 dataset consisted of 1 968 sounding points, all of which were utilised for in this study. Communication (via email) with the Hydrographic Office of the SAN to request the 2021 data used during this study is attached as Appendix B.

The 1977 dataset was georeferenced by means of the Hartebeesthoek 1994 projection, while the 2021 dataset was projected through WGS84 Universal Transverse Mercator (UTM) 34 South projection. However, for a quantitative comparison, the two datasets must have the same projection and expression of depth to accurately illustrate fluctuations and changes over time (Henrico & Bezuidenhout, 2020; Li et al., 2007). Variations in these parameters would influence how the surface models are created through the interpolation process, ultimately reducing the reliability of the results obtained from the analysis. Consequently, both datasets were converted to have the same projection (WGS 1984 UTM 34s). Additionally, the depth measurements for both datasets were converted to metres below Mean Sea Level (MSL).

The following sub-sections provides insight into the methods used to collect both bathymetry datasets used during this study, as well as the data processing methods that were required to prepare the data for analysis.

3.4.1 1977 data collection

The Hydrographic Office of the South African Navy has been utilising the South African Ship (SAS) Protea as a Hydrographic Survey Vessel (HSV) since 1972. It was the vessel used to conduct the survey that captured the 1977 dataset used in this study. The Protea is fitted with sensors capable of conducting ocean depth surveys from 50 m to 7 000 m and is also equipped with smaller Survey Motorboats (SMB) capable of conducting independent ocean depth surveys down to 2 m. The SMBs are utilised for survey operations where 'under keel clearance' is critical. They were therefore the preferred platform for collecting the bathymetric data of Saldanha Bay.

The 1977 survey utilized both the SAS Protea and her SMBs to capture bathymetric data (see Figure 3.2), as mentioned previously. This 1977 dataset was captured by means of the SBES instrument.

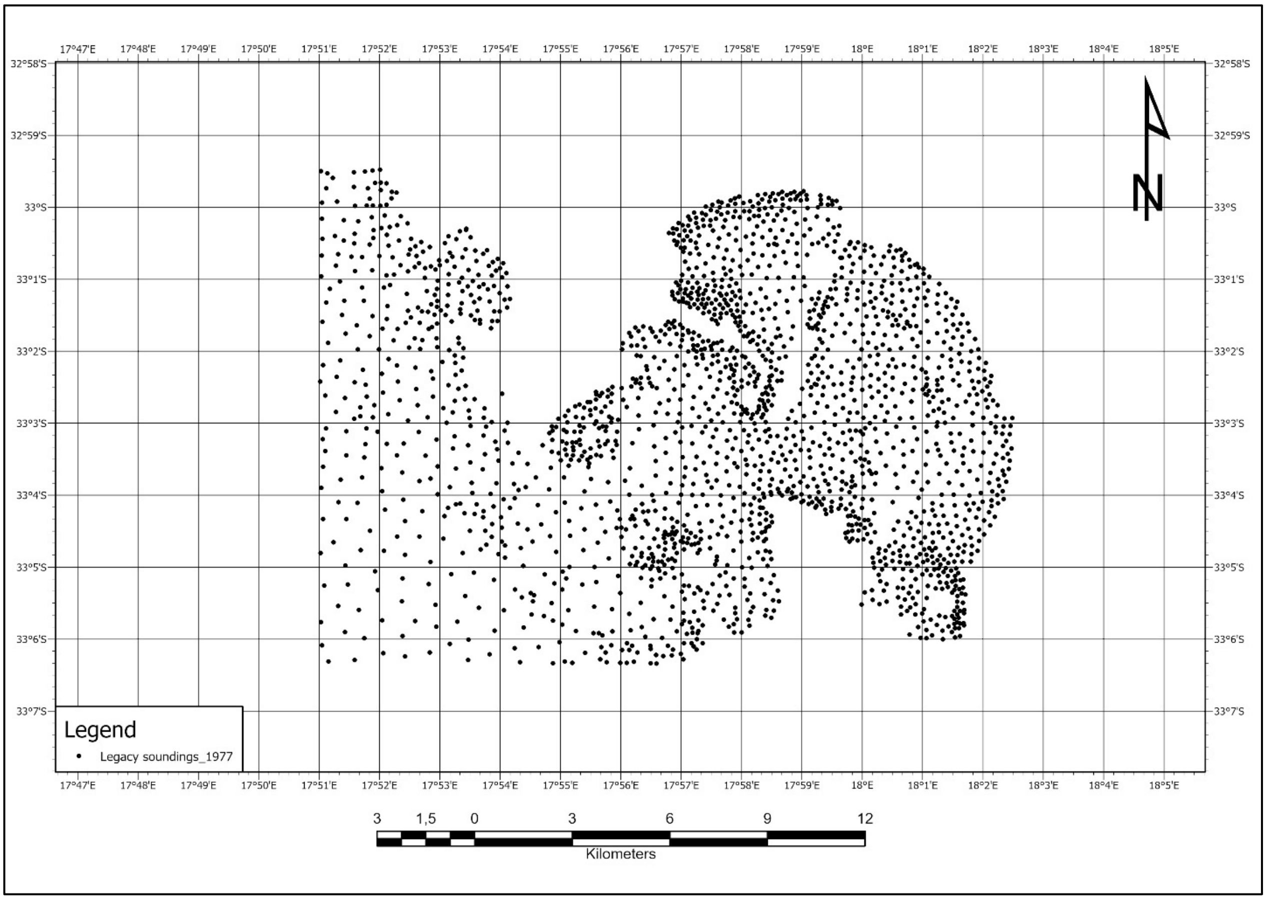

Figure 3.2: The 1977 legacy dataset, as received from the SANHO

3.4.2 2021 survey of Saldanha Bay bathymetry

In early 2020, a request was made to the Hydrographer of the SA Navy to survey Saldanha Bay since the last time the entire Bay was surveyed was in 1977 (see Appendix C). A new survey of the Bay was required for various reasons, not least of all the strategic importance of the Bay to the South African economy and the planned expansion and development of the region through IDZ initiatives, as highlighted in Chapter 2 (see section 2.4). The mission to survey the bathymetry of the Bay formed part of a larger surveying project embarked upon by the Hydrographic Office to update the nautical charts used by the SAN (C Theunissen 2020, personal communication, 18 August). The Hydrographer agreed to the request to conduct a new survey of the Bay, and formal approval was acquired from the Hydrographic Office for this study to form part of the surveying team to conduct the survey. Furthermore, official approval was also acquired through signing a data release agreement (Appendix A) for the surveyed bathymetric data to be made available for analyses during the current study. However, for this release agreement to adhere to SANHO data distribution policies, the data could only be released at a spatial resolution of 100 m, in the form of a georeferenced point depth shapefile subjected to WGS84 UTM34s projection.

There are several important factors to consider before the start of a survey to ensure that the research area is surveyed accurately, and time- and cost-effectively. This is routinely done by drawing up a survey plan which is governed by a Hydrographic Instruction (HI) issued by the Hydrographic Office. This document has a military security classification of "Restricted" and could therefore not be added as an appendix. However, the following section will give a brief overview of the survey structure provided by the HI.

Hydrographic Instruction. The purpose of the HI is to provide a clear instruction for the survey team to follow to achieve mission success. These instructions included the following for this study:

a. <u>Survey limits and special notes</u>: This consists of the coordinates defining the area to be surveyed as well as any specific areas or features needing special attention. For this survey the defined spatial limits were Big Bay, Small Bay, and Outer Bay. There were also several areas identified which needed special attention, which included several shoal investigations, quay depth investigations and a wreck investigation.
b. <u>Scale</u>: The survey had to be conducted on a scale of 1:5 000 and required a full seafloor search.
c. <u>System</u>: The survey should be carried out using QINSY software in conjunction with the multi-beam echosounders (MBES) sensors and HINAPS software in conjunction with the single-beam echosounders (SBES) sensors. QINSY and HINAPS are software packages designed to govern the capture, quality control, and processing of raw bathymetric data captured by the MBES and SBES sensors.
d. <u>Geodetic information</u>: The geodetic requirement for this survey governs how the captured bathymetric data should be georeferenced. It involved the following:
    i. *Spheroid*: WGS84.
    ii. *Tidal Datum*: Predicted height for Saldanha.
    iii. *Projection*: Universal Transverse Mercator (UTM) Zone 34 South.

e. Constraints: The constrains beyond which acceptable data can no longer be measured with confidence: wave height and period, wind speed, current conditions, and meteorological conditions, are to be determined by the Chief Surveyor daily.

f. Bathymetry: The primary method for bathymetric data acquisition for the survey area is MBES, however SBES check lines should also be conducted at regular intervals for MBES error estimation. These estimations are greatly influenced by the environmental sound velocity (SV). As a result, an SV measurement must be made each morning before the start of surveying, concurrent with regular SV checks throughout the day. Swath overlap, speed over the ground and the number of beams used are at the charge of the Chief Surveyor having considered data density requirements, as influenced by the following factors:

   i. *Along track beam footprints*: this refers to the width of the beam (swath width). Smaller width is more accurate but more time consuming, while a wider width is less accurate but less time consuming.
   ii. *Maximum ping rate must be used*: this refers to the number of soundings per second emitted by the MBES/SBES sensors.
   iii. *Roll, pitch, and yaw effects*: influences on the beam footprint.
   iv. *Bin size*: 0.30-0.50 m bin size recommended for acquisition, survey data to be rendered at a bin size of 1 m.
   v. Minimum detectable object size: must be 1 m^3.

Finally, some logistical preparations for data capturing need to be made to ensure that the data is captured and stored in a consistent manner for the duration of the survey mission. These preparations for data acquisition are outlined in the following section.

Data acquisition considerations. Evaluating the survey constraints and establishing the parameters for data acquisitions, as highlighted in the HI, are checks that must be done by the Chief Surveyor before the start of each day of surveying. The parameters for data acquisition differed slightly from day to day, as they had to be adjusted slightly based on the survey constraints on any given day. For the most part, constrains were within acceptable limits during the survey. The main constraint was the strong southeasterly winds – which actually blows in a S-SSW direction – causing wave surges which pushed the effect of pitch, roll, and yaw on the beam footprint beyond the limit for acceptable data. As documented by Flemming (1977), this local directional wind variant also existed during the last interglacial period (around 120 ka BP). Data acquisition parameters which need to be taken into consideration before the start of daily surveying include installation offset correction for the instrument, data logging parameters, SV, geodetic parameters, survey speed, line spacing, tides and data type (see Table 3.2).

Table 3.2: Data acquisition parameters and consequences

Data Acquisition Parameter	Parameter consequence
Installation Offset	There are two installation offsets. The first is the spatial relationship between all the sensors of the MBES system (transducer, motion reference unit, GPS). All these sensors have installation offsets. A Central Reference Point (CRP) needs to be defined upon each new installation of a MBES system, usually at the transducer. These corrections remain constant for the duration of the survey mission. Secondly, to ensure that the measured depth is the true depth, a correction needs to be made for vessel draft, as the transducer is below the waterline (see section 2.7).
Data logging	During the survey, a consistent format for data logging needs to be adhered to that links the metadata of the raw data format. The convention used for this study was (Nnnn_yyyymmdd_hhmmss_Vesselname_system): ✓ Nnnn: Survey line nr. ✓ yyyy: Year. ✓ mm: Month. ✓ dd: Day. ✓ Vessel name: Seemeeu. ✓ System: Multibeam Acoustic System - S7k.
Sound Velocity	An SVP measures the speed of sound at different vertical levels of the water column and is used to accurately estimate depth from raw data captured by the transducer. An SVP must be done every time an area is surveyed.
Geodetic Parameters	The geodetic parameters used for the bathymetric survey of the 2021 soundings used in this study were: ✓ Spheroid: WGS84. ✓ Tidal Datum: Daily water-level predictions. ✓ Projection: UTM 34 South. ✓ Central Meridian: 021°E.
Survey Speed	The speed at which the survey is conducted as a direct influence on the density of the sounding that reaches the seafloor and to some degree influences the resolution of the final raster dataset, as it has an impact on the distance between pings. The survey speed for this surveying mission was 5 – 6 knots (~9 – 11 km/h).

Tides	MBES data need to be corrected in real time for draft and tide variations, as well as attitude variations (roll, pitch, yaw and latency) captured by the Motion Reference Unit (MRU) of the vessel.

It is important to note that in the initial HI it was indicated that the entire Saldanha Bay would be surveyed during this project. However, due to several factors limiting the progress of the survey, only a portion of Saldanha Bay could be surveyed (see Figure 3.3). These limitations relate to mechanical problems experienced, the influence of extreme weather conditions, and financial constraints. More detail relating to these limitations are provided in Chapter 5 (see section 5.4).

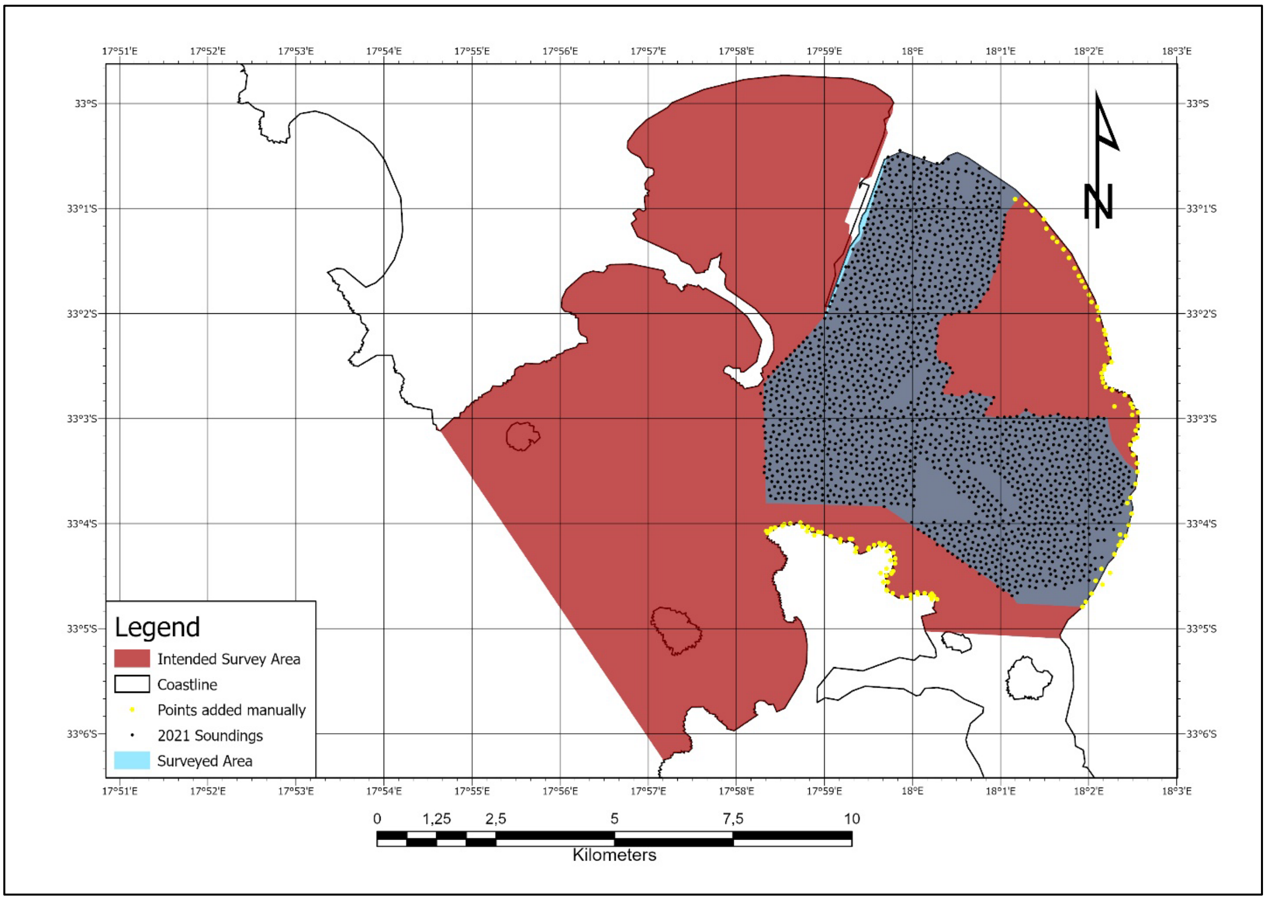

Figure 3.3: 2021 soundings dataset, as received from SANHO

3.4.3 *Data processing*

The purpose of data processing is to prepare and alter the point dataset received from SANHO for them to be suitable for analysis. To ensure that the changes in bathymetry detected through the analysis processes represent actual changes in bathymetry and are not the result of data distortion, it is extremely important that both datasets being compared are georeferenced by means of the same projection and depths are expressed in the same measuring unit. To this end, both the captured bathymetric datasets needed to undergo some processing to ensure that they were fit for the purpose of this study – creating surface models which represent the bathymetry of Saldanha Bay in 1977 and 2021 respectively, by using ArcGIS Pro 2.8.0 software.

The first step was to ensure that the measured points were georeferenced correctly, i.e., to make sure that they were placed at the correct/same location on the earth's surface. Common georeferencing ensures that the individual pixels of the raster surface models are spatially aligned. It was necessary for the pixels of the two raster surface models to align as it would enable the Raster Calculator 'Minus tool' to deduct the values of overlaying pixels during analysis of change. Due to the relatively small scale of the research area, Universal Transverse Mercator (UTM) projection was used with Latitude 34° South. This grid system is the preferred method for this study as it is most accurate for projecting data with a relatively small spatial distribution (i.e., not spanning across multiple latitudes), which is a characteristic of this study area (ESRI, 2020). The 2021 dataset received from SANHO was already georeferenced through a WGS84 UTM 34 South projection, while the 1977 dataset was georeferenced by means of the Hartebeesthoek 1994 projection. Consequently, only the 1977 dataset was projected using the 'project' tool under the Spatial Analyst extension of the ArcGIS Pro software. This tool allows the user to choose which projection method is most suitable when expressing the *x* and *y* coordinates of point datasets. The dialogue box used for selecting the appropriate projection of the 1977 data in this study is illustrated by Figure 3.4.

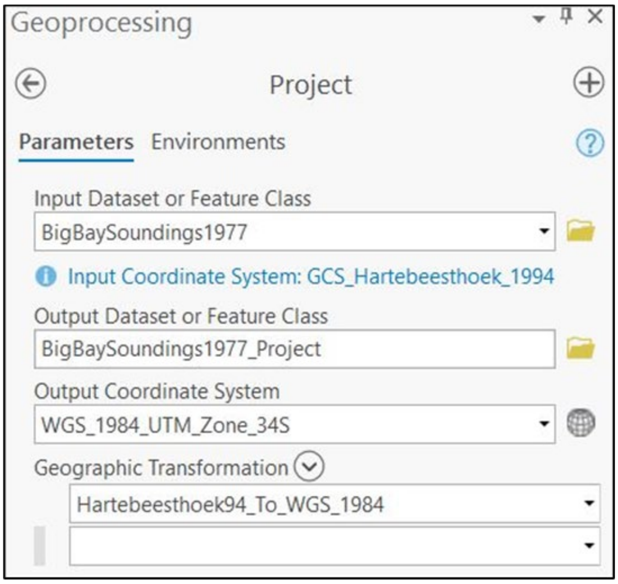

Figure 3.4: Project tool dialogue box

The workflow consisted of selecting the point 1977 dataset received from SANHO as the 'Input Dataset', defining the name of the output dataset, and defining the coordinate system used to project the output dataset. As shown in Figure 3.4, a geographic transformation of Hartebeesthoek 1994 to WGS84 UTM 34S was conducted.

Next, both datasets needed to be clipped to the same spatial extent. Clipping both datasets to the same extent is essential for creating comparable surface models through an interpolation analysis (Henrico & Bezuidenhout, 2020; ESRI, 2020). This is because a change detection analysis will be done through the raster calculator, which deducts the values of pixels at the same location in order to determine change. The clipping tool under the Raster Functions tab within the ArcGIS Pro 2.8.0 software was used to clip both datasets to the same spatial extent. The workflow of the clipping tool used for this processing step is shown below (Figure 3.5).

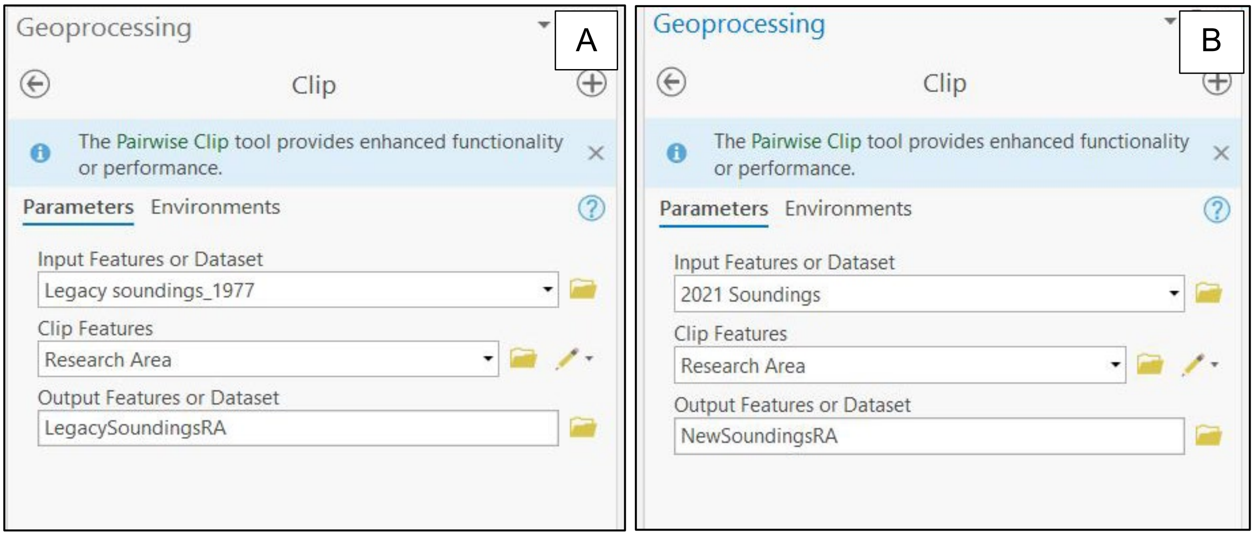

Figure 3.5: Dialogue boxes for clipping 1977 (A) and 2021 (B) point datasets

Figure 3.5 illustrates how the 1977 and 2021 point datasets were clipped to the spatial extent of Big Bay, the research area of this study. The output datasets generated from these clips are illustrated in Figures 3.6 and 3.7 below. These point datasets are the ones that were used for analysis.

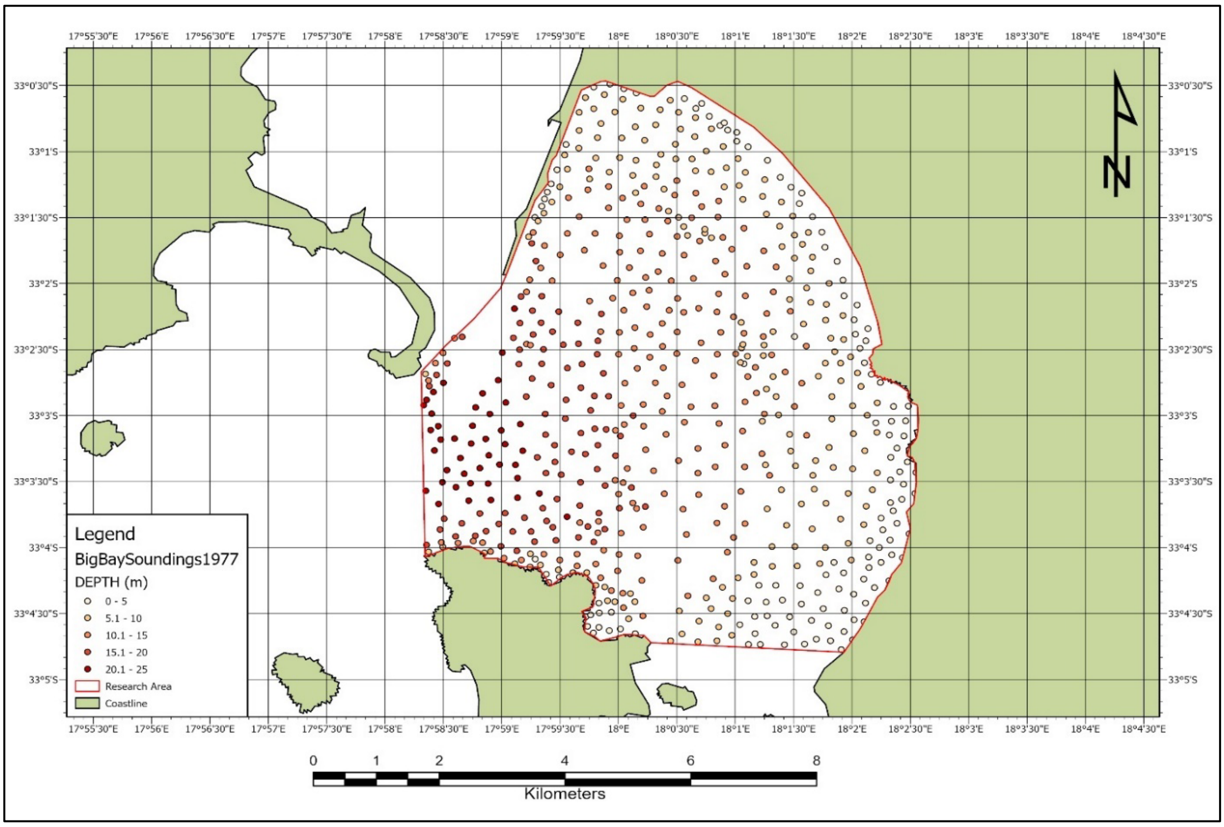

Figure 3.6: 1977-point dataset used for analyses

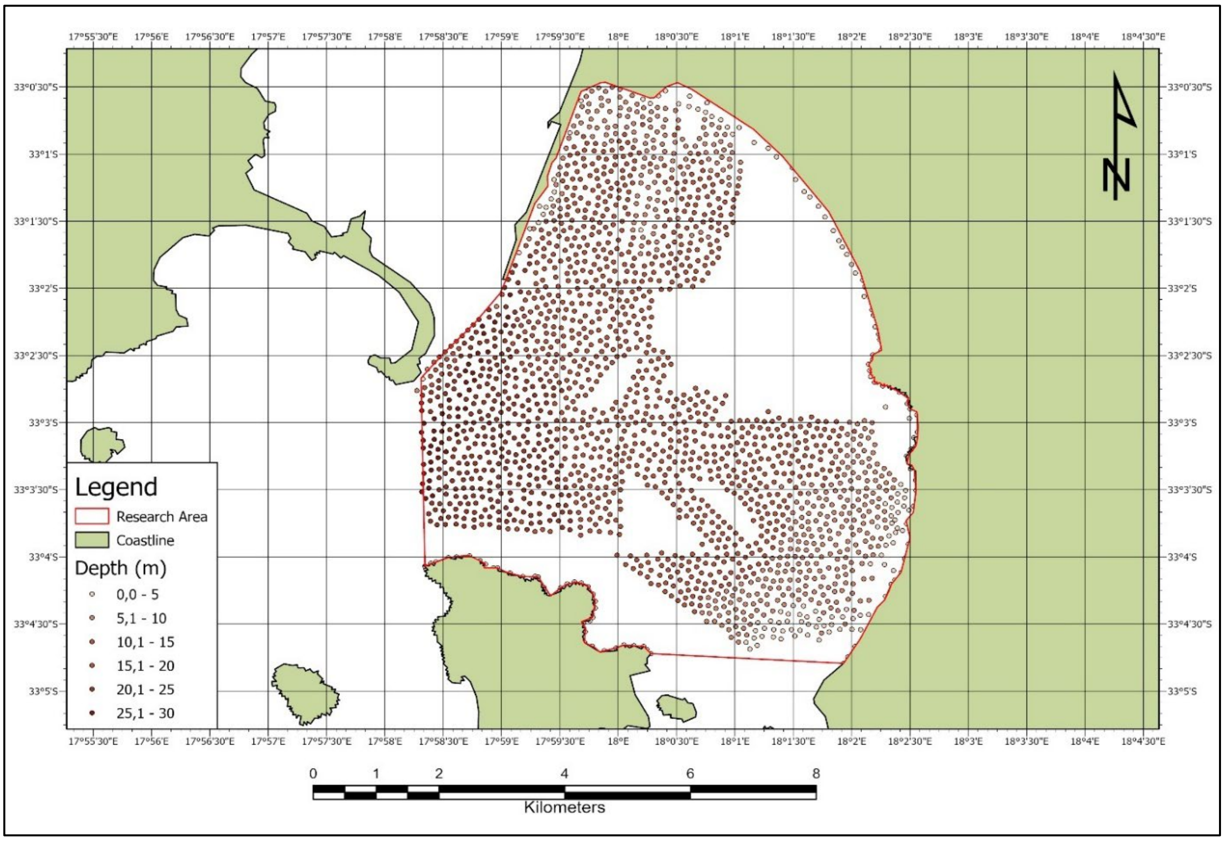

Figure 3.7: 2021-point dataset used for analysis

After processing, the 1977 dataset consisted of 613 data points, whereas the 2021 dataset remained at 1 968 data points. From the figures above, the 2021 dataset is revealed as more densely distributed than the 1977 dataset. The 2021 dataset has a spatial resolution of 100 m, whereas the 1977 dataset has a spatial resolution of 300 m. The 1977 dataset, however, is more evenly distributed across the research area, whereas the 2021 dataset incorporates large areas without measurements. These variations in distribution and spatial resolution ultimately influences the reliability and validity of the analyses and results of this study. It is discussed in more detail in section 5.4.

To validate the influence of the different datasets on the accuracy of the interpolation method used during this study, sample interpolation tests of both the 1977 and 2021 sounding points were conducted. Both these datasets were reduced to 247 points (see Figure 3.8[a]) to represent similar spatial distributions. In Figure 3.8(a), the red points represent the 1977 dataset and the blue points the 2021 dataset. The statistical results for both datasets are within acceptable ranges and correspond well with each other, which shows that the interpolation results are similar (see Figures 3.8[b] and [c]) when using an equal number of points that have comparable spatial distributions. From the 2021 points a root-mean-square error (RMSE) of 1.799 and a standardized mean error (SE_{mean}) of 0.049 were identified, whereas the RMSE of the 1977 points were 1.9, with an SE_{mean} of 0.046. A further description of these errors is provided in Chapter 4 (see section 4.2.1). These validation tests confirmed that, even though the spatial resolution is different for both datasets (100 m vs 300 m), the influence of the sounding points on the accuracy of the interpolation model is negligible.

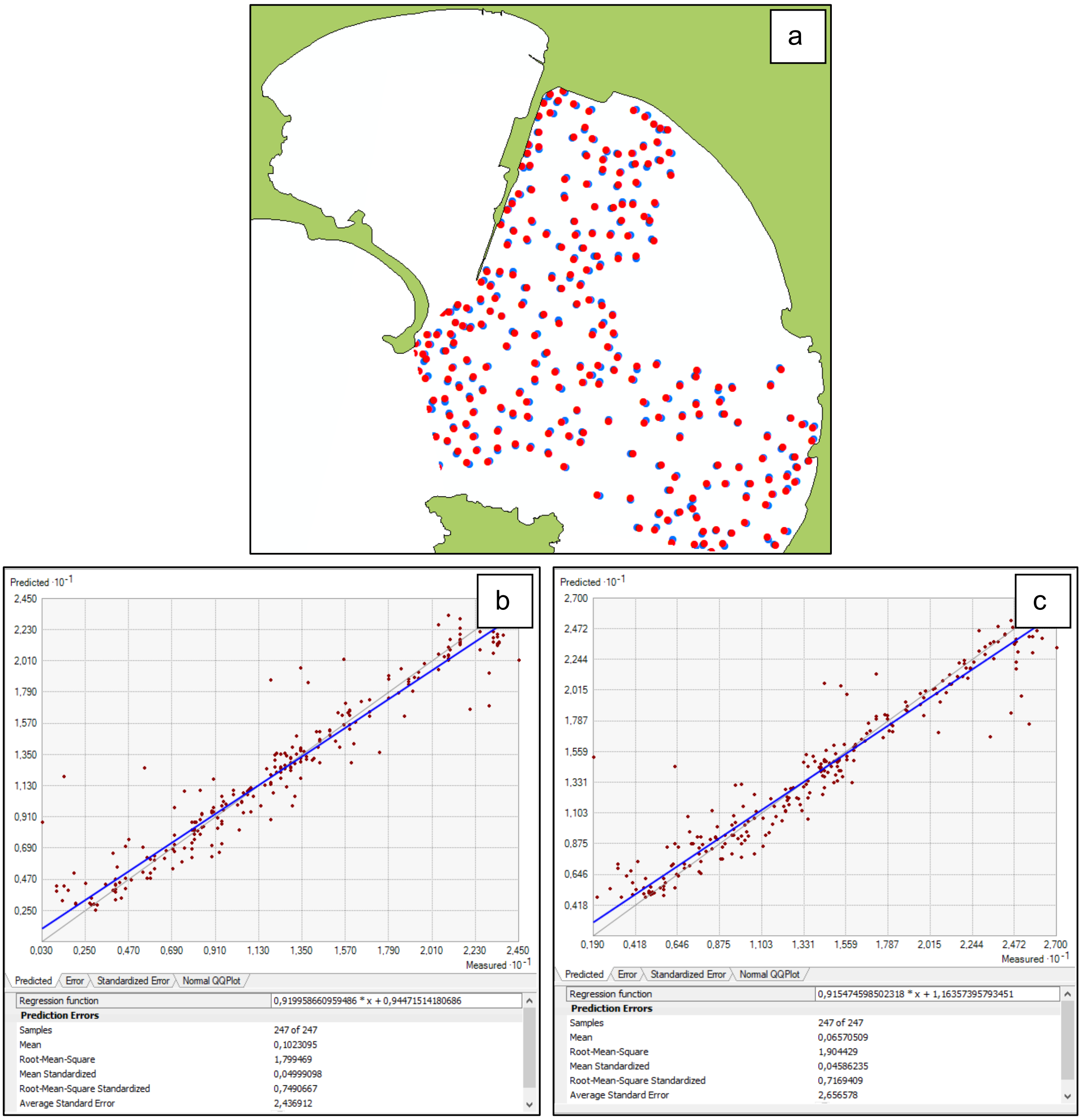

Figure 3.8: Validity tests – influence of sounding points on the accuracy of the interpolation models

3.5 Data analysis tool

Once both datasets were correctly georeferenced and clipped to the same spatial extent, they were ready for analysis by means of the Geostatistical Wizard extension of the ArcGIS Pro software.

ArcGIS Pro 2.8.0 software is the latest addition to the ESRI software. It is the selected GIS platform for data analysis in this study. ArcGIS Pro 2.8.0 is equipped with a suite of geostatistical and deterministic interpolation tools, which were used to create surface models of the 1977 and 2021 bathymetry of Saldanha Bay relevant to this study. These tools have built in quality controls that enable the user to produce accurate surface models. The software is also capable of analysing and comparing various surface models at the same time. It is consequently ideally suited for a comparison of the respective 1977 and 2021 bathymetric data. Finally, ArcGIS Pro 2.8.0 allows the user to create complete maps of the surface models after analysis which can be exported to various vector file formats (AIX, EMF, EPS, PDF, SVG, and SVGZ) and raster file formats (BMP, JPEG, PNG, TIFF, TGA, and GIF).

The Geostatistical Analyst tool, under the special analysis extension of ArcGIS Pro, has several available interpolation tools, each using a specific interpolation technique. As mentioned in the previous chapter (see section 2.8), there are two main groupings of interpolation methods, geostatistical and deterministic. However, each of these groupings have several interpolation techniques available under them. The following section discusses the interpolation tools in the Geostatistical Analyst application of the ArcGIS Pro software that were considered for analyses during this study.

3.6 Creating the 1977 and 2021 bathymetry surface models of Saldanha Bay

The 1977 and 2021 point datasets (soundings) have inherent gaps i.e., unmeasured locations between datapoints. As a result, these point datasets are not continuous representations of the bathymetry of Saldanha Bay for the respective years surveyed. To create continuous representations of the bathymetry of Saldanha Bay for 1977 and 2021, these point datasets must undergo a process called interpolation. Consequently, the first step in the analyses process was to create two surface models, one representing 1977 bathymetry, and one representing 2021 bathymetry, by interpolating the two collected point datasets.

The Geostatistical Wizard consists of a dynamic set of dialogue boxes called ‘Setup Pages’, which are designed to facilitate the process of building and evaluating the performance of an interpolation model. The pages are set up in a sequential manner where choices made on one page determines the options available on the following. The wizard provides guidance for the entire process of creating a surface model, from choosing a suitable interpolation method to providing a summary measure of the models' expected performance. The Geostatistical Wizard workflow used during this study consisted of three steps, which are described in more detail in the sub-sections below. These steps are:

1) selecting an interpolation method,
2) setting up of parameters, and
3) cross-validation.

3.6.1 Selecting an interpolation method

The first step of the wizard is to select a suitable interpolation technique to create an accurate surface model. However, as mentioned in Chapter 2 (see section 2.8), there is no single best interpolation method since all methods are conditioned on spatial and temporal components (Šiljeg et al., 2015; Childs, 2004; Erdogan, 2009; ESRI, 2020). This means that selecting a superior or preferred interpolation method is largely dependent on the phenomenon being measured as well as the methods used to collect the data. Any interpolation method is therefore largely site-specific and data-specific.

Even though there are many interpolation methods available, IDW and OK are the preferred methods for creating terrain models (Amante & Eakins, 2016; Henrico, 2021). As a result, OK and IDW where the main interpolation methods considered for this study. The functioning of these methods is explained in more detail in Chapter 2 (see section 2.8).

Based on the results obtained from the study by Henrico (2021), IDW was identified as the most suitable interpolation method to predict the bathymetry of Saldanha Bay. However, the author also mentioned that the preferred interpolation method is dependent on the uniqueness and characteristics of the sample points. Since this study is using a dataset that is different from the mentioned study by Henrico (2021), it just made sense to conduct such tests to determine the best interpolation method to use during this study. It is important to find the best interpolation method when creating bathymetry maps because these maps were to be used for comparative purposes to determine the changes in the bathymetry of Saldanha Bay between 1977 and 2021 – inaccurate maps would skew the results of this study.

3.7 Interpolation tests to find the most suitable method to use during this study

Both the 1977 and 2021 datasets were utilised using the ArcGIS Pro software to determine the most suitable interpolation method to use for this study. This was accomplished by creating two surface models for each dataset (one using IDW, the other OK). The two models for each dataset were compared by examining the cross-validation statistics and error plots, created by the Geostatistical Wizard, side by side to determine the best interpolation technique for this study. Johnston et al. (2003) states that "generally, the best model is the one that has a standardized mean nearest to zero, the smallest root-mean-square prediction error, the average standard error nearest to the root-mean-square prediction error, and the standardized root-mean-square prediction error nearest to one". However, cross-validation for IDW does not include the average standard error or standardized root-mean-square prediction error, consequently only the standardized mean and root-mean-square prediction error were used to compare the surface models.

For this test, the standard setup parameters (discussed in the following section) for both the IDW and OK interpolation methods were used for this comparison. The Geostatistical Wizard already optimizes some parameters, like the power parameter used in the IDW interpolation method or the semi-variogram model for the OK interpolation method. The search neighbourhood for both interpolation methods were the same, i.e., a maximum of 10 neighbours, a minimum of 2 neighbours, and a single search sector. It was found that both interpolations performed very well and produced acceptable accuracy results in creating bathymetry surface models of Saldanha Bay. It was, however, determined that OK performed slightly better than IDW. The differences in standardized mean error (SE_{mean}) and the root-mean-square error (RMSE) for each interpolation method are indicated in Table 3.3.

Table 3.3: Interpolation test results that indicate the preferred method to use during this study

Prediction Errors	**1977**		**2021**	
	OK	***IDW***	***OK***	***IDW***
RMSE	1.527	1.831	1.094	1.111
SE_{mean}	0.002	-0.239	0.001	0.030

Even though IDW proved to be a better interpolation method for the 1977 point dataset used by Henrico (2021), OK slightly outperformed IDW when interpolating the specific 1977 dataset of this study. It is important to mention that the spatial extent as well as the total number of data points of the dataset used for analyses in this study differed from that of Henrico (2021). On account of the test results, it was decided to henceforth apply the OK interpolation method for creating all bathymetry surface models and maps required to compare the respective 1977 and 2021 datasets.

3.7.1 Interpolation parameters

As part of the setup pages of the Geostatistical Wizard application, the parameters of the interpolation must first be established before the surface model can be created. These parameters allow for optimization of the accuracy of the surface model created. The setup pages of Geostatistical Wizard also include a cross-validation page which indicates the accuracy of the surface model created. The interpolation parameters used in this study were the same for both the 1977 and 2021 datasets, which ensured that the optimal settings were selected to minimise the root-mean-square error. This process is illustrated by Figure 3.9. The results of the test conducted are discussed in more detail in Chapter 4 (see section 4.2).

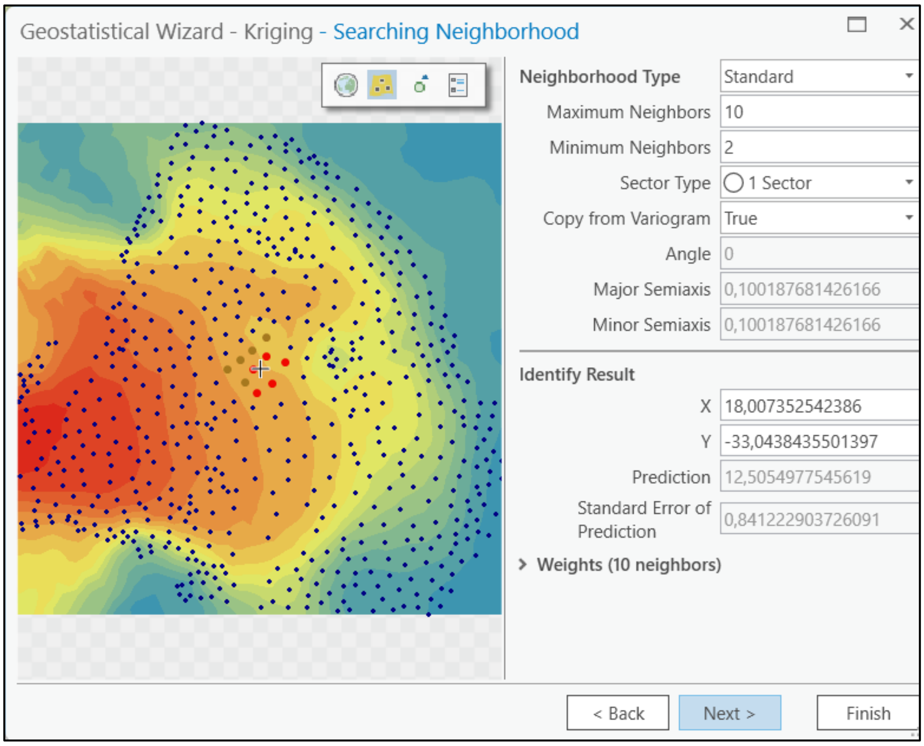

Figure 3.9: The second page of the Geostatistical Wizard, interpolation parameters used for the OK interpolation of the 1977 and 2021 datasets

3.8 Change detection and slope analyses

To analyse the changes in bathymetry of Saldanha Bay based on the respective 1977 and 2021 datasets, a change detection analysis was conducted. This change detection analysis proceeded in four steps:

a) Step 1: Converting interpolation model to raster format: The first step was to convert the surface models created through OK interpolation into a format that allows for the analyses that needs to be done for the purposes of this study. Therefore, both the 1977 and 2021 surface models were converted to raster files (.tiff) with the default spatial resolution of 2.7 m (Ground Sampling Distance – GSD). The GSD was selected during the conversion from the Geostatistical Layer to Raster.

b) Step 2: Clipping rasters to the extent of the research area: The second step was to clip both raster files to the spatial extent of the research area of this study, as the surface models created through the interpolation process offer predictions for the areas outside of the research area which are included in the surface model. These predictions have a very low accuracy due to their distance from any known values and are therefore disregarded for this study (see Chapter 4, section 4.3 and Figure 4.9).

c) Step 3: Creating slope analyses: The slope of the Bay drives the local acceleration of currents and may cause erosion as it moves sediments and creates bedforms (Dolan, 2012). The slope of ocean floors has geomorphological importance to benthic habitats and is linked to the process of sedimentation because sediments move downslope due to gravity. A slope analyses would therefore provide valuable insights into the degree to which the Bay had changed since 1977. The third step was therefore to create a slope model for both the 1977 and 2021 clipped raster models. The Slope tool in the Spatial Analyst extension of ArcGIS Pro software was used to create the slope products, and the Degree Output Measurement setting was selected to illustrate the slope incline in degrees.

d) Step 4: Determining the changes in area size through the raster calculator function in ArcGIS Pro software: Finally, a change detection analysis of both the slope and bathymetry models was done by means of the raster calculator. Raster Calculator is a tool available in the ArcGIS Pro software under the

Spatial Analyst extension. Raster Calculator computes the difference between two overlayed pixels at the same location. In this study, the minus ‘function’ of the raster calculator was used to estimate the change in bathymetry and slope of the respective sounding datasets by calculating the difference in values of pixel pares at the same location. From this a change in slope and bathymetry maps was created for closer analyses.

3.9 Chapter summary

This chapter outlined the step-by-step process that was followed to achieve the set objectives towards reaching the aim of the study. The purpose of this chapter was to provide a clear understanding for all the steps taken during the methodology phase of this study. The chapter discussed the methods and tactics used for data collection, data processing and data analysis, and aimed to provide transparency regarding research methods used. The next chapter presents the results of this study and analyse and describes the results.

CHAPTER 4: DISCUSSION OF RESULTS

4.1 Introduction

The previous chapter outlined the methods and tactics used during this study to achieve the research objectives of this study. This chapter builds on this by presenting the results produced by the process of analysis, and by discussing the insights gained from scrutinising these results. The focus of this chapter is to present the findings of this study clearly, and highlight insights gained through analysis of the results, which may improve our understanding of the anthropogenic impact of the PoS on the bathymetry of Saldanha Bay.

As a point of departure, the chapter introduces and describes the surface models representing the respective 1977 and 2021 bathymetry of Saldanha Bay, created through the interpolation process described in Chapter 3 (see section 3.6). This is followed by the unpacking of the results obtained from the change detection analysis, described in Chapter 3 (see section 3.7). The chapter concludes by discussing the possible causes and impacts of the identified change in bathymetry.

4.2 Interpolation Results

The first objective of this study (see Chapter 1, section 1.5.3) is to describe the bathymetry of the Bay for 1977 and 2021 respectively. Consequently, the first outputs generated from the analysis process were the surface models representing the 1977 and 2021 bathymetry, produced by interpolating the point datasets through OK interpolation, as discussed in Chapter 3 (see section 3.6). Additionally, the sections following thereafter unpack the results obtained from the interpolation process for the 1977 and 2021 datasets respectively. As a start, the raw geostatistical layers and their associated cross-validation results are discussed. Next, the rectified surface models, clipped to the research area of this study are introduced, and the characteristics of the bathymetry of Saldanha Bay are described.

4.2.1 1977 Surface Model

The geostatistical layer representing the 1977 bathymetry (see Figure 4.1) stores the source of the data from which it was created, and also stores the model parameters from the interpolation. The geostatistical layer consists of a standardized error map (see Figure 4.2), which indicates the areas where there is a low certainty of prediction.

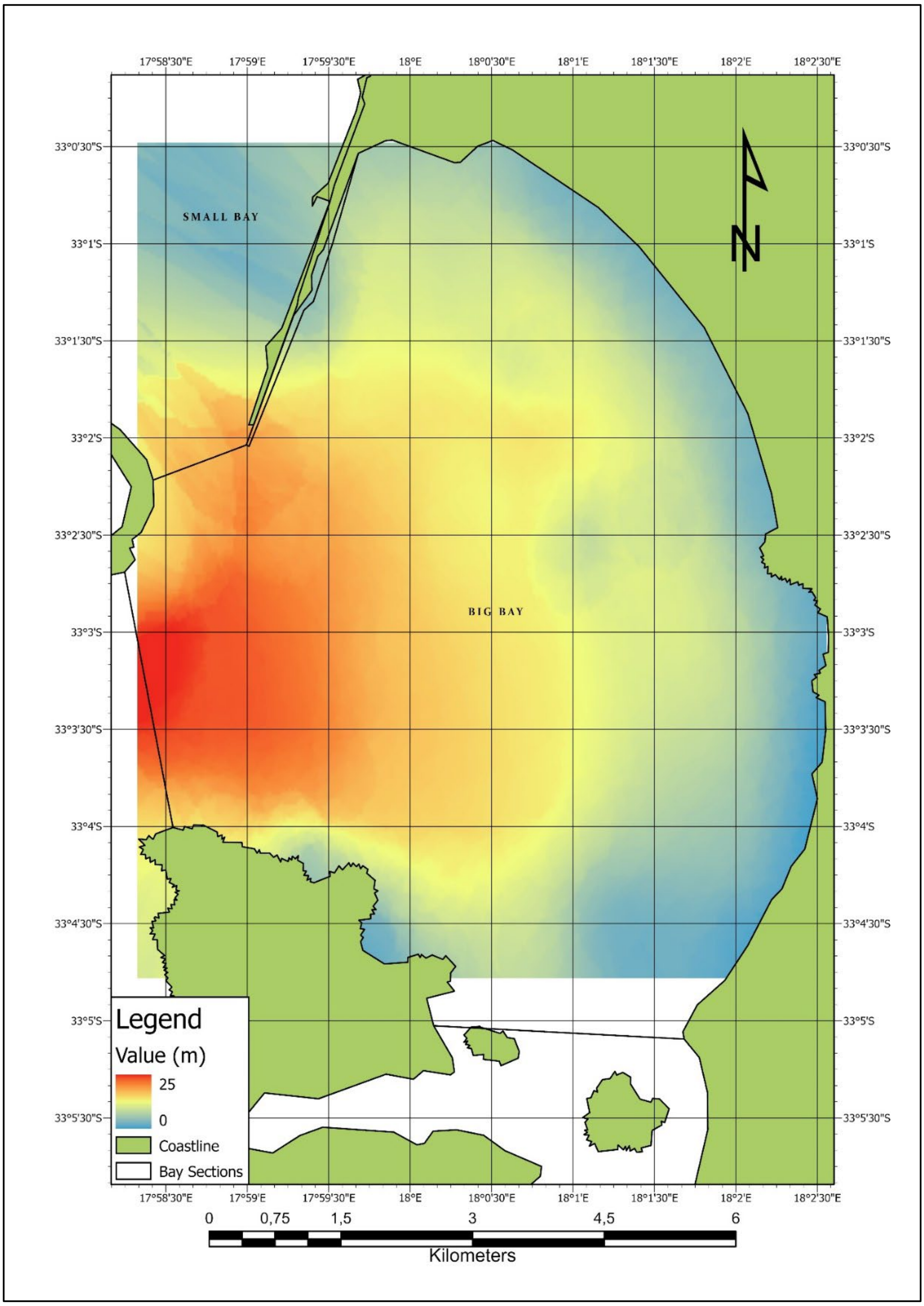

Figure 4.1: Geostatistical layer produced by the Geostatistical wizard for 1977 dataset

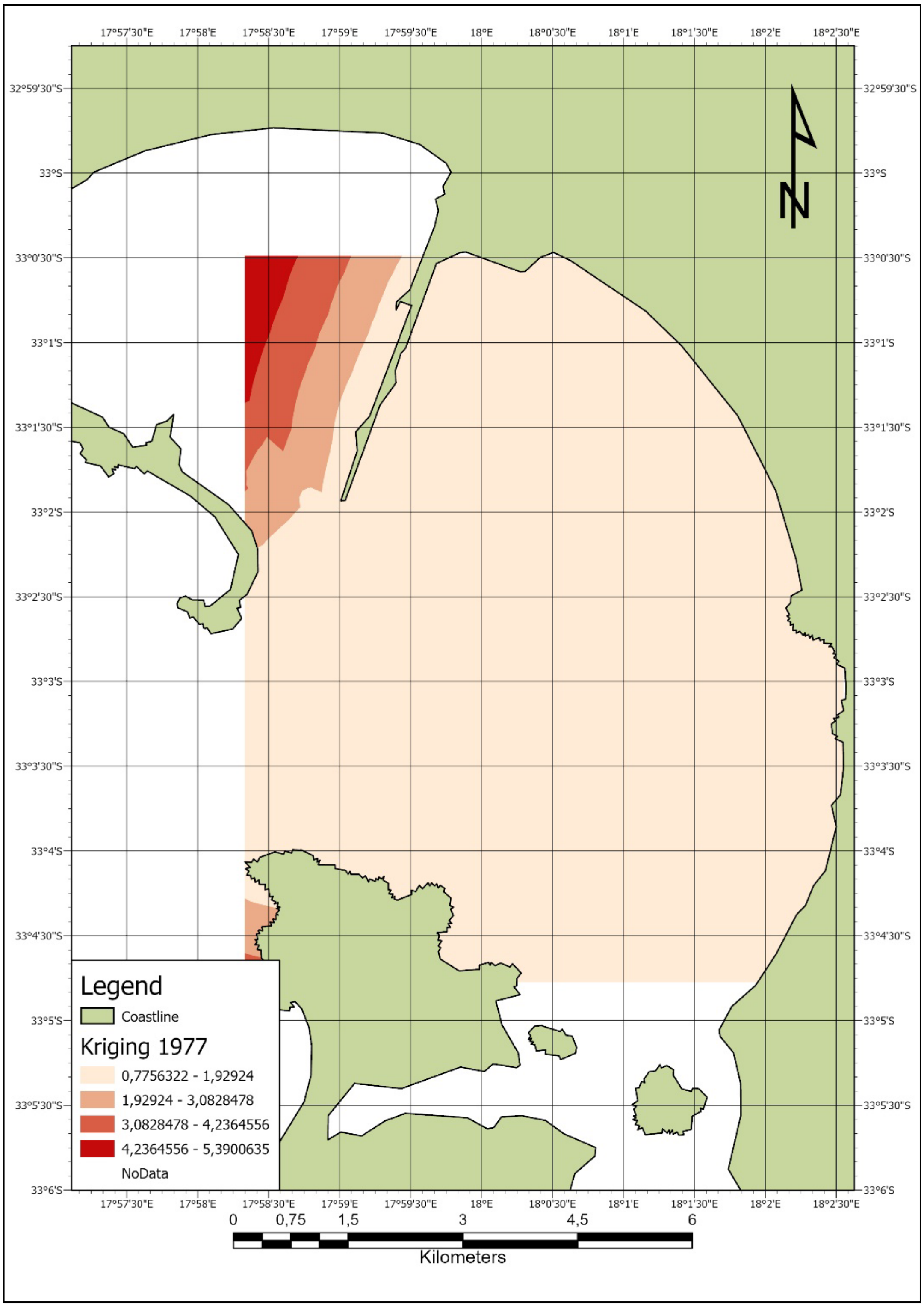

Figure 4.2: Map illustrating the standardized error distribution of the 1977 surface model

Part of the information stored in the geostatistical layer is the standardized error (SE_{mean}) of the predicted values (see Figure 4.2). Figure 4.2 shows that the entire research area has a low standardized error. As a result, all the data throughout the research area for the 1977 surface model may be used for analysis.

The ability to view and manipulate the results of selected parameters was helpful in selecting the optimal parameters for creating the surface models (see Chapter 3, section 3.6.2). The cross-validation results of the 1977 surface model can be seen in Figure 4.3 below.

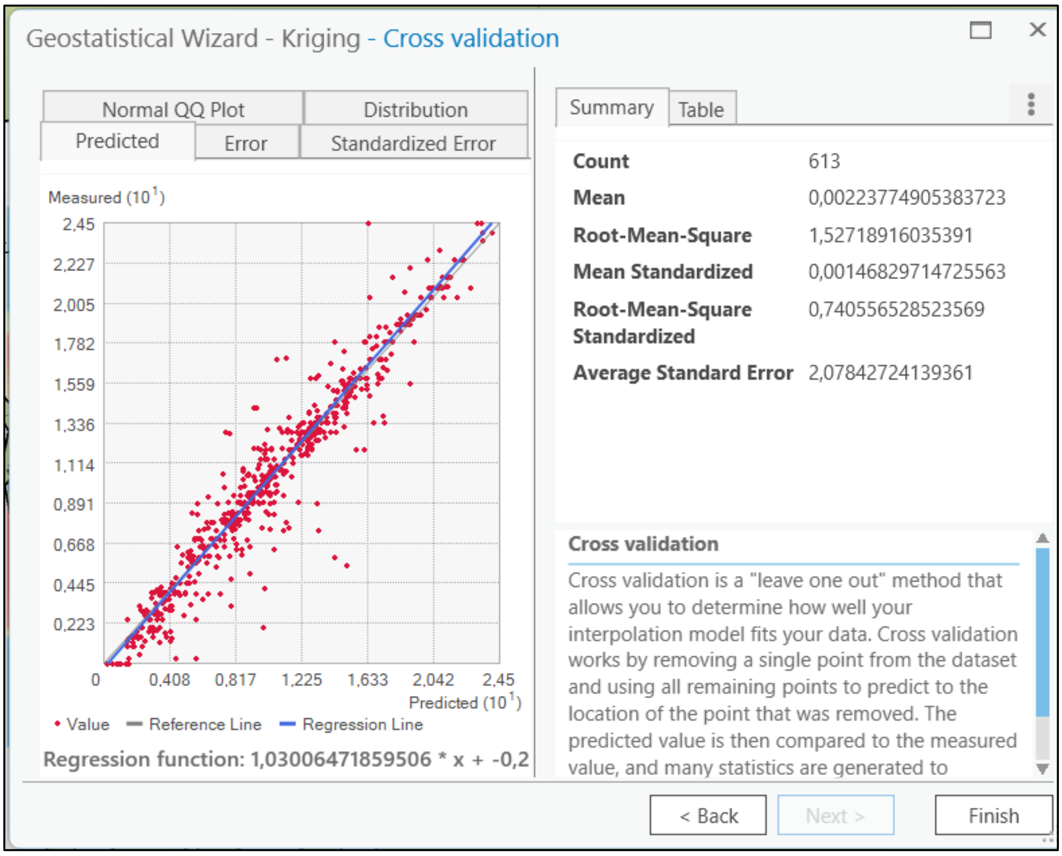

Figure 4.3: Cross-validation graph showing the accuracy of the 1977 surface model

As illustrated by Figure 4.3, a total of 613 datapoints were used to do the interpolation. The accuracy of the model is illustrated by two statistical indicators, the root-mean-square error (RMSE) and the Standardized Mean Error (SE_{mean}). A lower RMSE and a SE_{mean} close to zero indicates that the created surface model is accurate (Johnston et al., 2003). The surface model representing the 1977 bathymetry of Saldanha Bay had an RMS of 1.527 and SE_{mean} of 0.001, optimized by changing the search neighbourhood used, as indicated in Chapter 3 (see section 3.6.2). The regression graph illustrates how well the surface model fits the measured values, with the regression line (grey line in Figure 4.3) representing the idealized bathymetry, and the reference line (blue line in Figure 4.3) representing the fit of the created model. The closer these lines are together, the more accurate the surface model, with a perfect fit between these two lines illustrating an optimal model.

Ideally the Regression function of the Reference line would have the form Y = X i.e., the slope is 1 and the point where the regression cuts the Y-axis is 0. The values in the Regression function of the 1977 data reveals that the Regression Line of the 1977 data departs only marginally from the Reference Line defining a perfect fit (Y: 1.03 and X: -0.2). This speaks in favour of the approach adopted in this study.

Once the optimal surface model for representing the 1977 bathymetry was created, the surface model was converted from a geostatistical layer to a raster layer (tiff format) and clipped to the spatial extent of the research area of this study. For display purposes, the raster layer comprises 15 depth classes ranging from 1 - 24, and which are represented by shades of blue colour in Figure 4.4 (dark blue = deep; light blue = shallow) was used as symbology. This raster dataset was subsequently used to represent the 1977 bathymetry (see Figure 4.4).

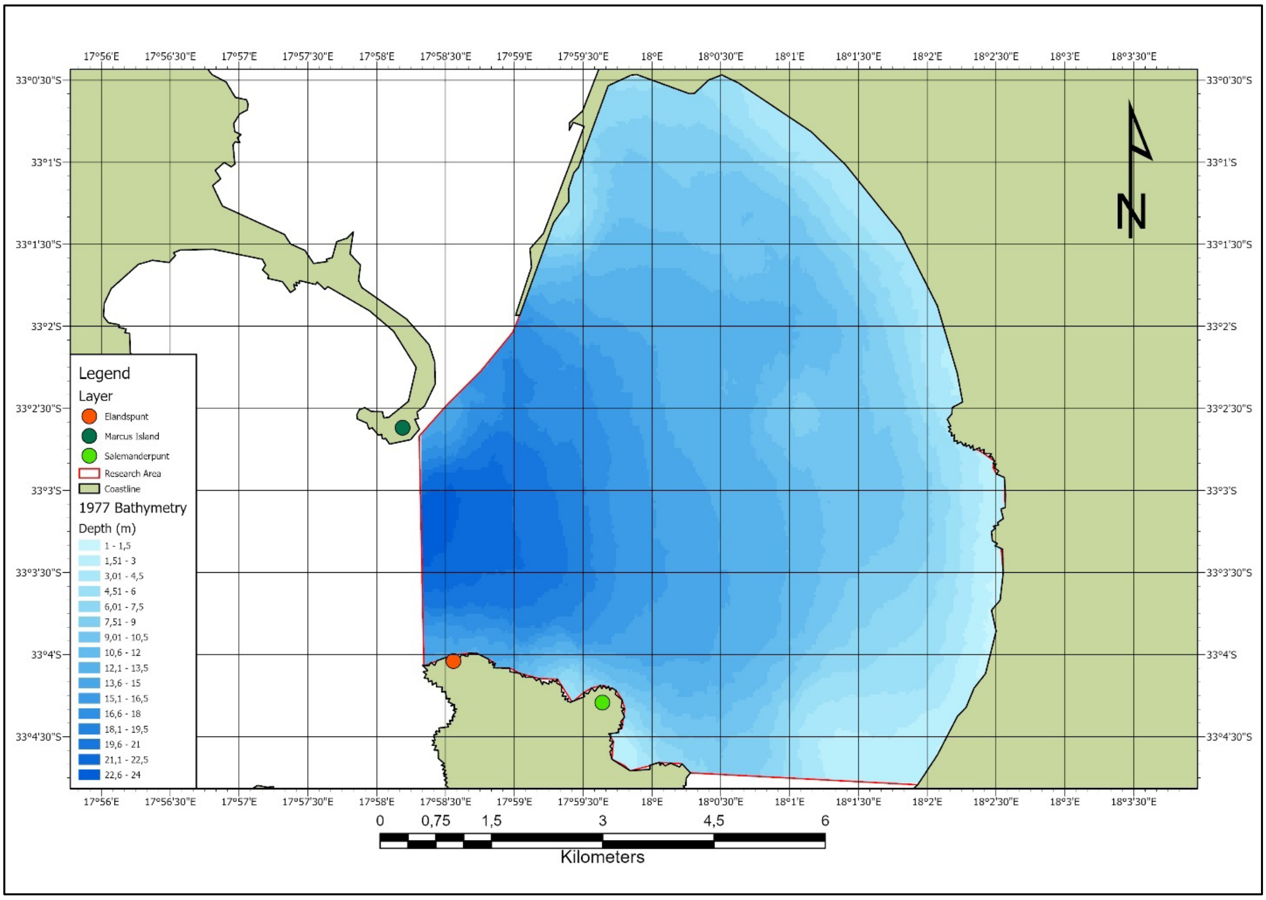

Figure 4.4: Map illustrating the surface model representing the 1977 bathymetry of Big Bay

As shown by Figure 4.4 and described by Flemming (1977), the bathymetry of Big Bay gradually increases in depth from the coastline towards the mouth of the Bay, with sharp increases in depth off Elandspunt (indicated by the orange dot on Figure 4.4) and Salamanderpunt (indicated by the green dot on Figure 4.4).

Figure 4.5 below illustrates the breakdown of Saldana Bay's bathymetry in 1977. The graph illustrates the number of pixels with the same depth values, with the X-axis depicting depth in metres and the Y-axis depicting count (number of pixels).

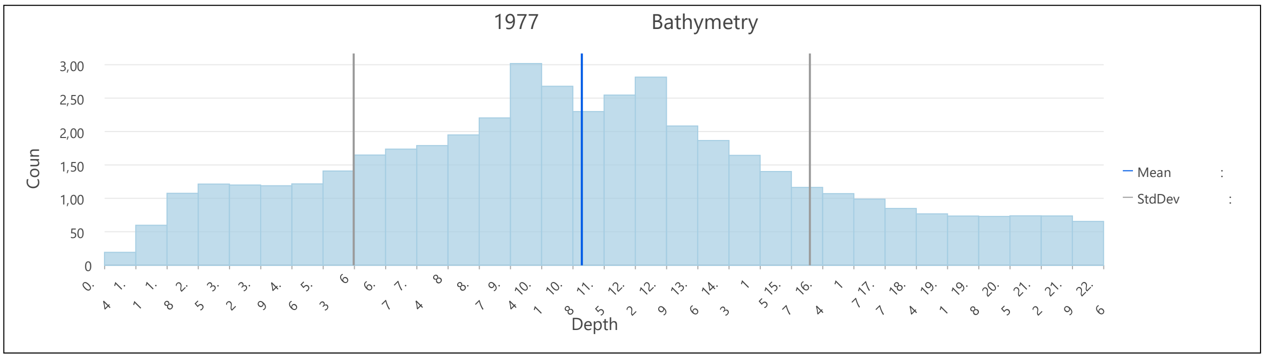

Figure 4.5: Graph illustrating the distribution of depth measurements for 1977 bathymetry

From Figure 4.5 it is evident that the data approaches a normal distribution, being only slightly skewed towards shallower depths with most depth measurements falling between 6 m and 16 m and with an average depth of 11.01 m. The maximum depth measured in 1977 is 22.6 m. A standard deviation of 5.05 may be described as large and may indicate that the data is, on average, relatively evenly distributed around the mean.

4.2.2 2021 Surface Model

As mentioned in section 4.2.1, the geostatistical layer representing the bathymetry stores the source of the data from which it was created and stores the model parameters gained from interpolation. The geostatistical layer and the standardized error maps for the 2021 data are illustrated below in Figures 4.6 and 4.7 respectively.

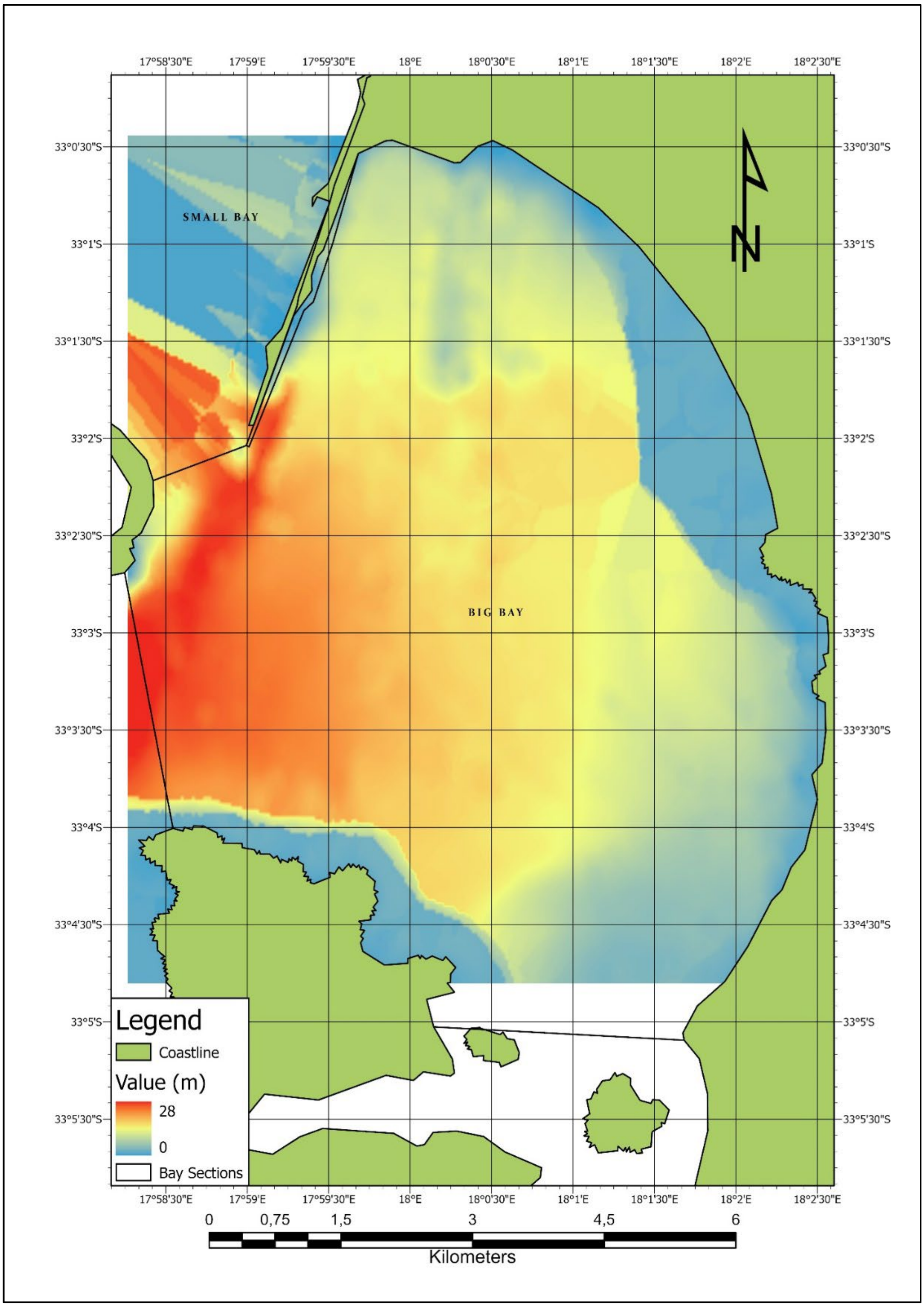

Figure 4.6: Geostatistical layer produced by the Geostatistical wizard for the 2021 dataset

Part of the information stored in the geostatistical layer is the SE_{mean} of the predicted values (see Figure 4.7). Figure 4.7 indicates that some areas within the research area contain a relatively high SE_{mean}, which indicates a low certainty of prediction. This is mainly due to large gaps of unmeasured datapoints in certain areas of the captured point dataset used to create the 2021 surface model. The areas of unmeasured points (see section 4.3,

Figure 4.11) correspond directly with the areas showing a high SE_{mean} value. As a result, only a portion of the 2021 surface model was used for conducting the change detection analysis, as not the entire surface model consists of reliable data. This is discussed in more detail in section 4.3.

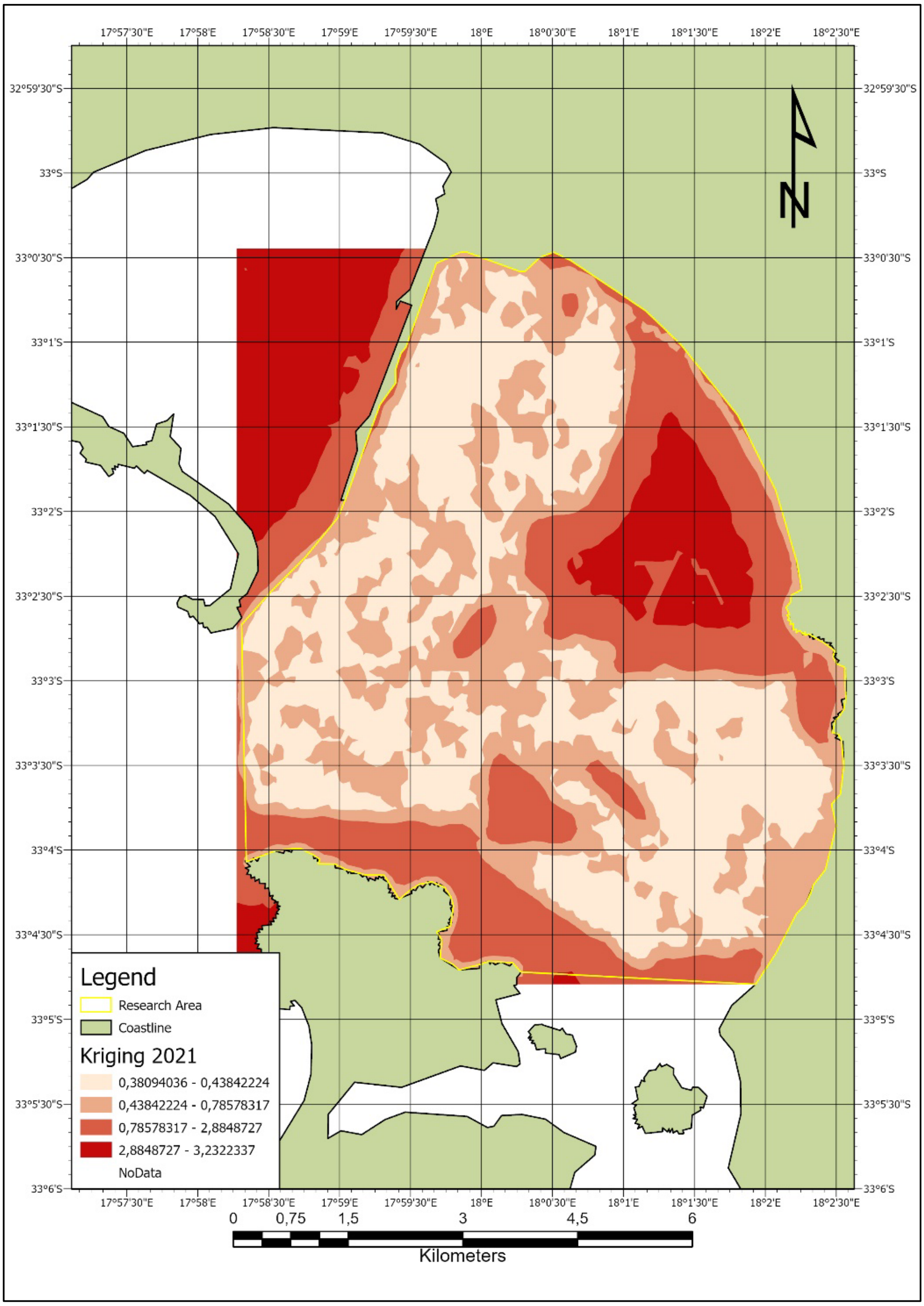

Figure 4.7: Map illustrating the standard error distribution of the 2021 surface model

As in the case of the 1977 dataset, the ability to view and manipulate the results of selected parameters was helpful in selecting the optimal parameters for creating the surface models for the 2021 dataset (see Chapter 3, section 3.6.2). The cross-validation results of the 2021 surface model may be seen in Figure 4.8 below.

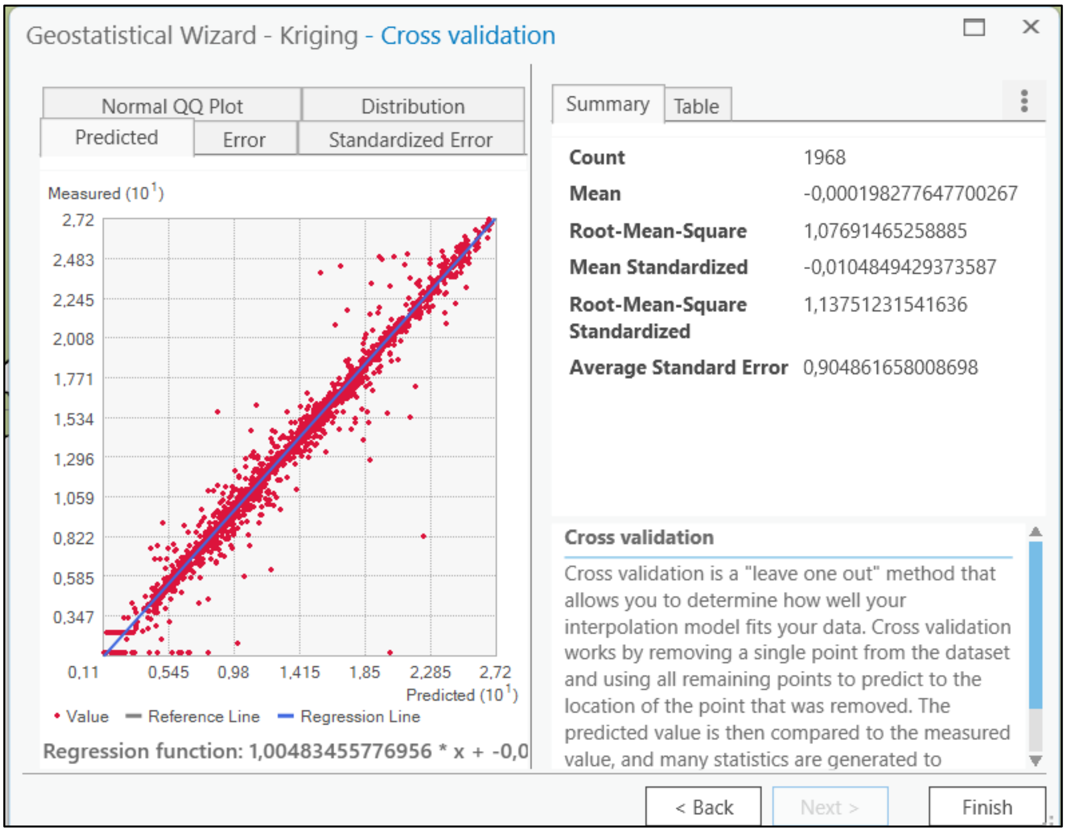

Figure 4.8: Cross validation graph showing the accuracy of the 2021 surface model

As illustrated by Figure 4.8, a total of 1 968 datapoints were used to do the interpolation for the 2021 dataset, more than three times that of the 1977 dataset. The surface model representing the 2021 bathymetry of Saldanha Bay had an RMSE of 1.076 and SE_{mean} of -0.010, which was optimized by changing the search neighbourhood used, as indicated in Chapter 3 (see section 3.6.2). These are more accurate values than those of the 1977 model, mainly due to the number of datapoints in the raw dataset. The slope of the Regression Line (1.004) and its origin at zero (Y=X=0) shows that the bathymetric data of the 2021 survey is even better correlated with the Reference Line than the 1977 data. The 2021 surface model is marginally more accurate than the 1977 surface model, but both interpolation models delivered a good fit and are therefore suitable for comparison purposes.

Once the optimal surface model for representing the 2021 bathymetry was created, the surface model was converted from a geostatistical layer to a raster layer and clipped to the spatial extent of the research area of this study. For display purposes, the raster layer in this case comprises 19 depth classes ranging from 0.5 m to 28.5 m, and which are represented by shades of blue colour in Figure 4.4 (dark blue = deep; light blue = shallow) was used for the symbology (see Figure 4.9).

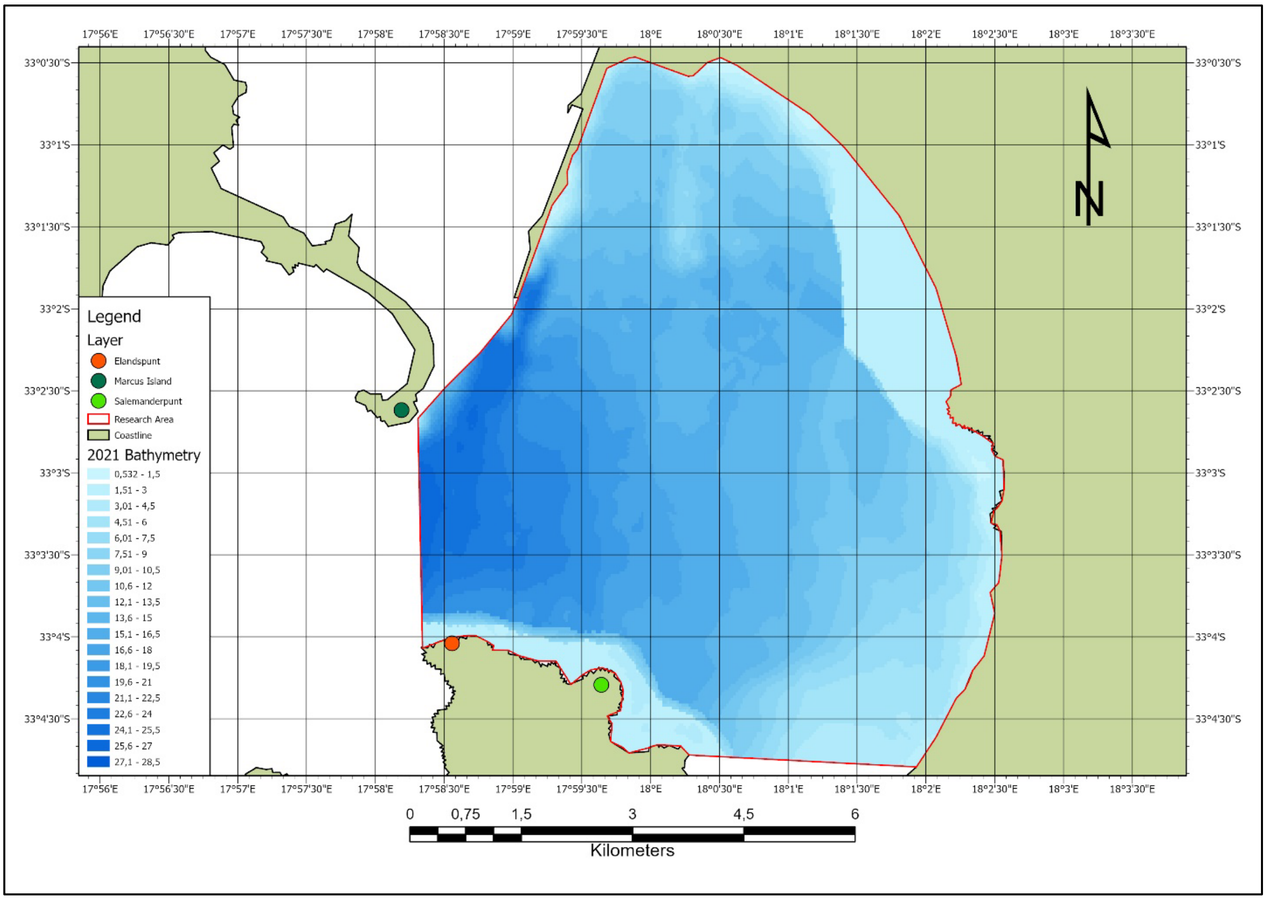

Figure 4.9: Map illustrating the surface model representing the 2021 bathymetry of Big Bay

Figure 4.9 depicts the 2021 bathymetry of Big Bay, with an overall tendency of gradual increases in depth from the coastline towards the mouth of the Bay. Sharp increases in depth are noticeable off Elandspunt (orange dot) and Salamanderpunt (light green dot). Although some differences are visible between the 1977 and 2021 surface models, the trends between the two datasets are largely similar (see Figure 4.4).

Figure 4.10 illustrated the breakdown of the bathymetry of Saldana Bay in 2021. The graph illustrates the number of pixels with the same depth values, with the X-axis depicting depth in metres and the Y-axis depicting pixel count (the number of pixels).

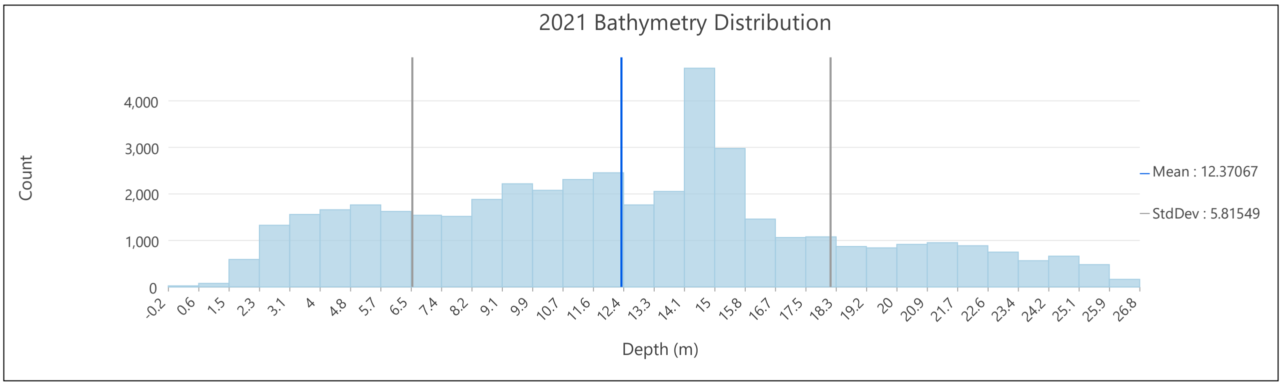

Figure 4.10: Graph illustrating the distribution of depth measurements for 2021 bathymetry

According to Figure 4.10, the data shows a pronounced skewness towards shallower depths with most of the depth measurements falling between 6.5 m and 18.1 m. The first order standard deviation of the 2021 dataset included depths of up to 18.1 m, 2.1 m more than in 1977, indicating an overall increase in depth across the Bay over 44 years. When considering the average depth of 12.3 m, then a substantial increase of 1.3 m is calculated which ultimately indicates that there was an overall increase in depth since 1977.

4.3 Change in bathymetry between 1977 - 2021

Once the surface models that represent the bathymetry of Saldanha Bay for the years 1977 and 2021 were created, a change detection analyses could be conducted.

The first consideration of the change detection analyses was to eliminate the areas of low predictive certainty from the analysis. Due to the spatial distribution of the 2021 soundings, there are some areas within the surface models with low levels of accuracy. Since the accuracy of the predicted depth values reduces with an increased distance from measured values, the areas with no measured values will have a low accuracy in predicting depth values. As a result, a certain zone within the produced surface models was excluded from change and slope analysis. This zone is indicated in Figure 4.11.

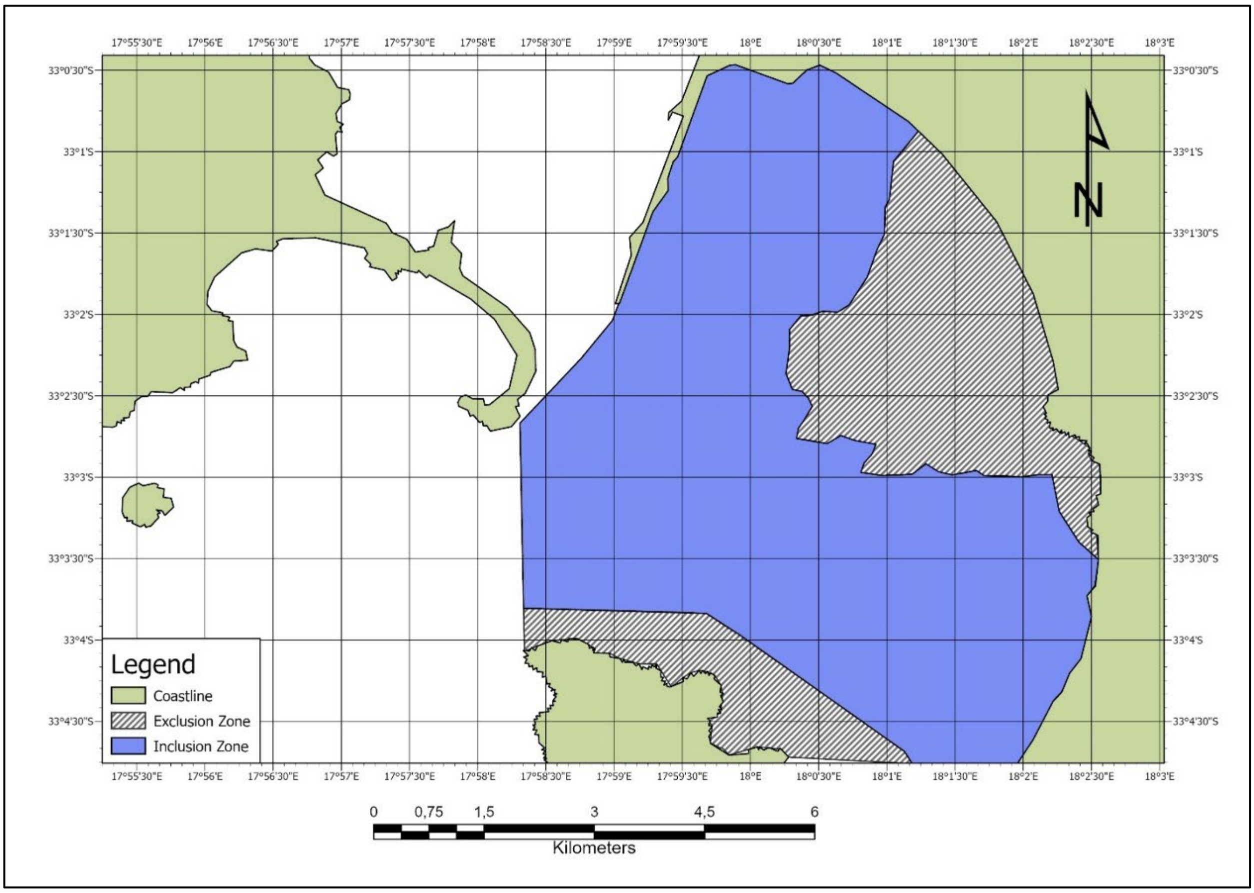

Figure 4.11: Map illustrating the inclusion and exclusion zones for the 1977 - 2021 change detection

Both the 1977 and 2021 surface models where clipped to the spatial extent of the ‘inclusion zone’ (see Figure 4.11). These ‘new’ surface models, clipped to the inclusion zone, went through the change detection analysis to create a change detection raster file, as discussed in Chapter 3 (see section 3.8).

The results of the change detection analysis are illustrated in Figure 4.12. Changes are indicated between the red and blue colour spectrum, with hues of yellow, orange, and red indicating sediment deposition (decreasing depth) and hues of yellow, green and blue indicating sediment removal (increasing depth). Red and blue areas indicate significant changes in depth (more than three metres) whereas orange and green indicate less significant changes (less than 3 metres).

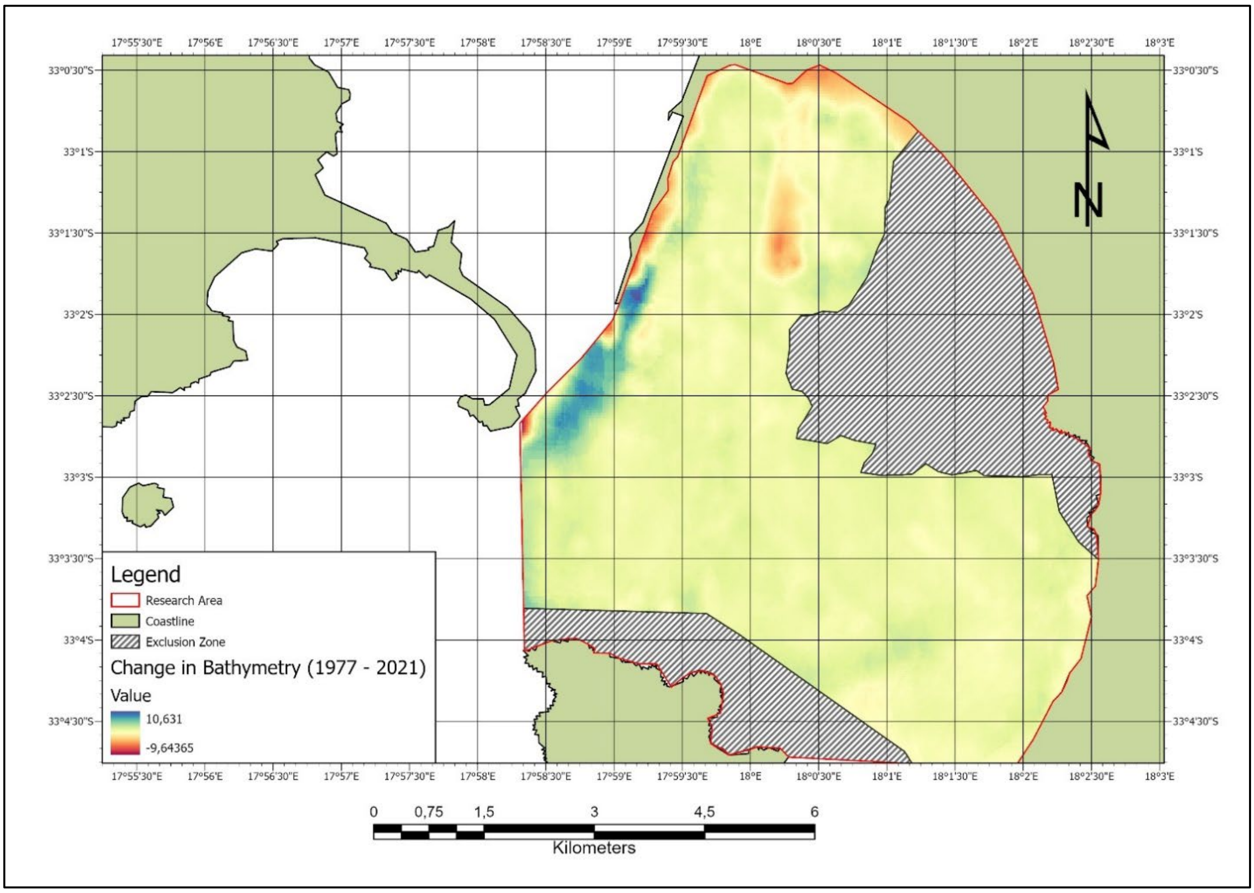

Figure 4.12: Map illustrating change in bathymetry between 1977 and 2021

From the change detection map, the majority of Big Bay experienced a slight increase in depth, as most of the Bay displays a green hue. It can also be seen that there are two areas which experienced significant change, one showing a significant increase in depth (indicated in blue on Figure 4.12), and one showing a significant decrease in depth (indicated in red on Figure 4.12).

To gain a more quantifiable understanding of the overall change in bathymetry between 1977 and 2021, the change detection raster file was explored from a statistical viewpoint. To this end, a histogram chart was compiled to illustrate the distribution of change in depth throughout the Bay (see Figure 4.13). This is done by grouping individual pixel depths together and estimating the number of pixels with the same change in depth values.

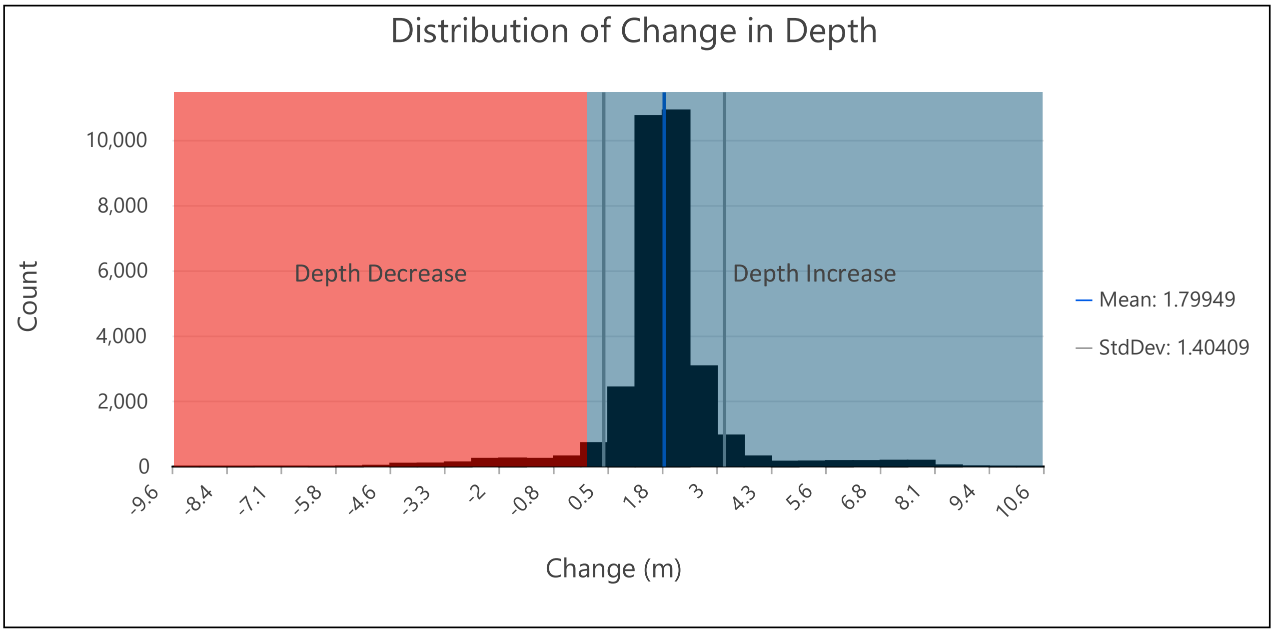

Figure 4.13: Graph illustrating the distribution of change in bathymetry between 1977 and 2021

The histogram graph above (see Figure 4.13) illustrates the distribution of change in depth between 1977 and 2021. The X-axis indicates, in metres, the amount of change in depth that occurred between 1977 and 2021 for a specific pixel. The Y-axis indicates the number of pixels which have experienced a certain amount of change in depth between 1977 and 2021. The respective mean and standard deviations are also indicated on the graph.

The mean value (blue line on Figure 4.13) indicates the average value of the change detection pixels. From the mean value there has been an average increase in depth across the entire research area of 1.799 m between 1977 and 2021. With an area of 27.44 km^2, this equates to a total loss of 49 364 560 m^3 in sediment volume. It is important to note that these calculations are only based on the 'inclusion zone', and not the entire Big Bay.

From Figure 4.13, it can also be seen that most of the research area experienced an increase in depth or sediment transport, as most of the pixels have positive values (on the blue side of the X-axis). The increase in depth is illustrated more clearly by the standard deviation line (grey lines on Figure 4.13). This is a first order standard deviation and therefore illustrates the limits within 68.2% of the data falls. In statistics, the standard deviation is a measure of the amount of variation or dispersion of a set of values. From Figure 4.13 the standard deviation of the change detection dataset is 1.404.

Consequently, 68.2% of the data falls between 0.395 m and 3.203 m. Furthermore, the standard deviation is relatively small, indicating a distribution of data close to the mean value. It should be noted that these values are still positive, and effectively means that approximately 70% of the research area experienced depth increase of up to 3.2 m.

However, there were areas that experienced change in depth that fall outside the standard deviation of the dataset, i.e., areas experiencing a depth decrease of any kind and areas experiencing a depth increase of more than 3.2 m. These areas are illustrated in Figure 4.14 below.

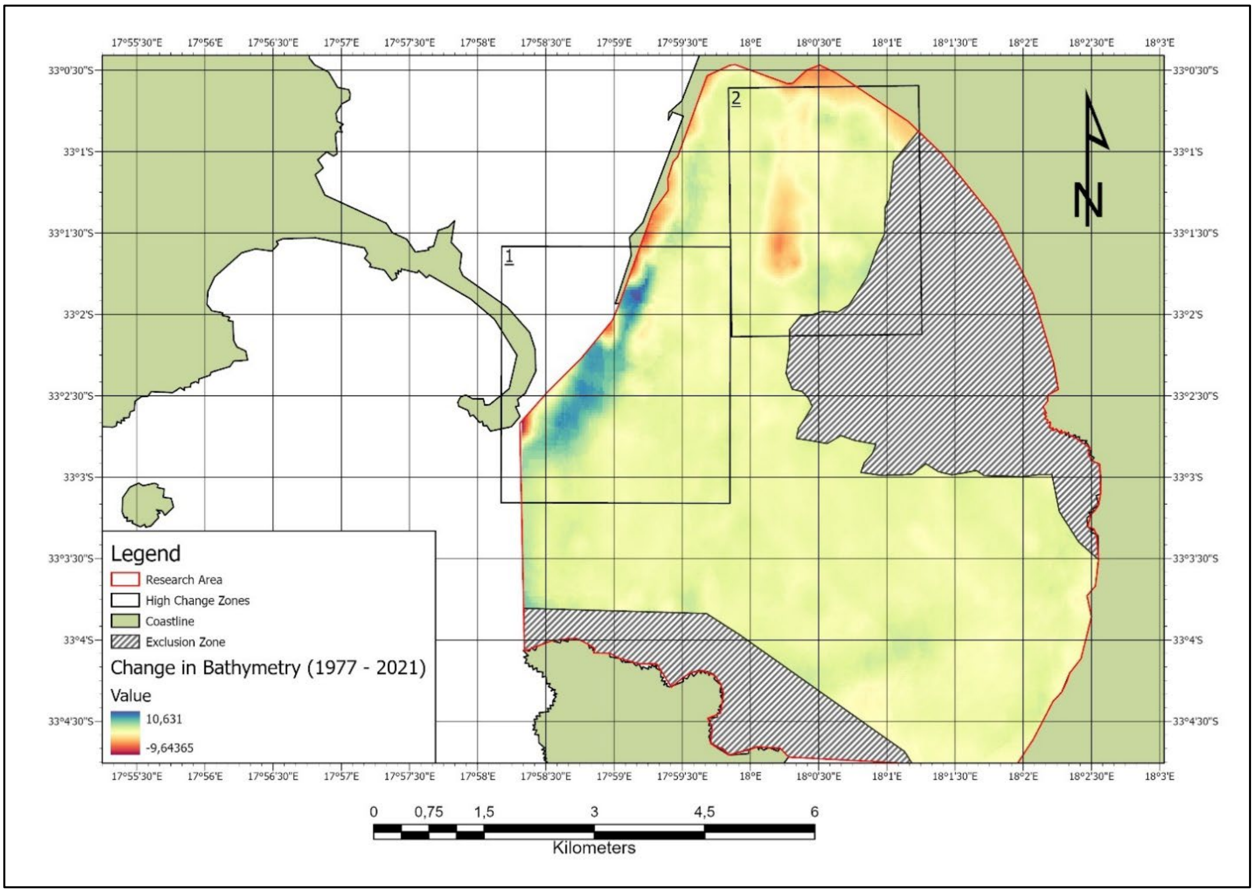

Figure 4.14: Map illustrating two zones which experienced significant change

The following two sections discuss the two areas of significant change in more detail. This is done by describing the extent of change in depth in these areas, as well as discussing the possible reasons for these extensive changes in depth.

4.3.1 Area of significant change: Zone 1

Zone 1 (see Figure 4.15) is the first area which experienced large changes between 1977 and 2021. This Zone is located between the tip of the iron ore jetty and Marcus Island, at the end of the breakwater. From Figure 4.15, this area (indicated by the red arrows) has experienced a significant increase in depth, with some areas showing up to 10.6 m of depth increase.

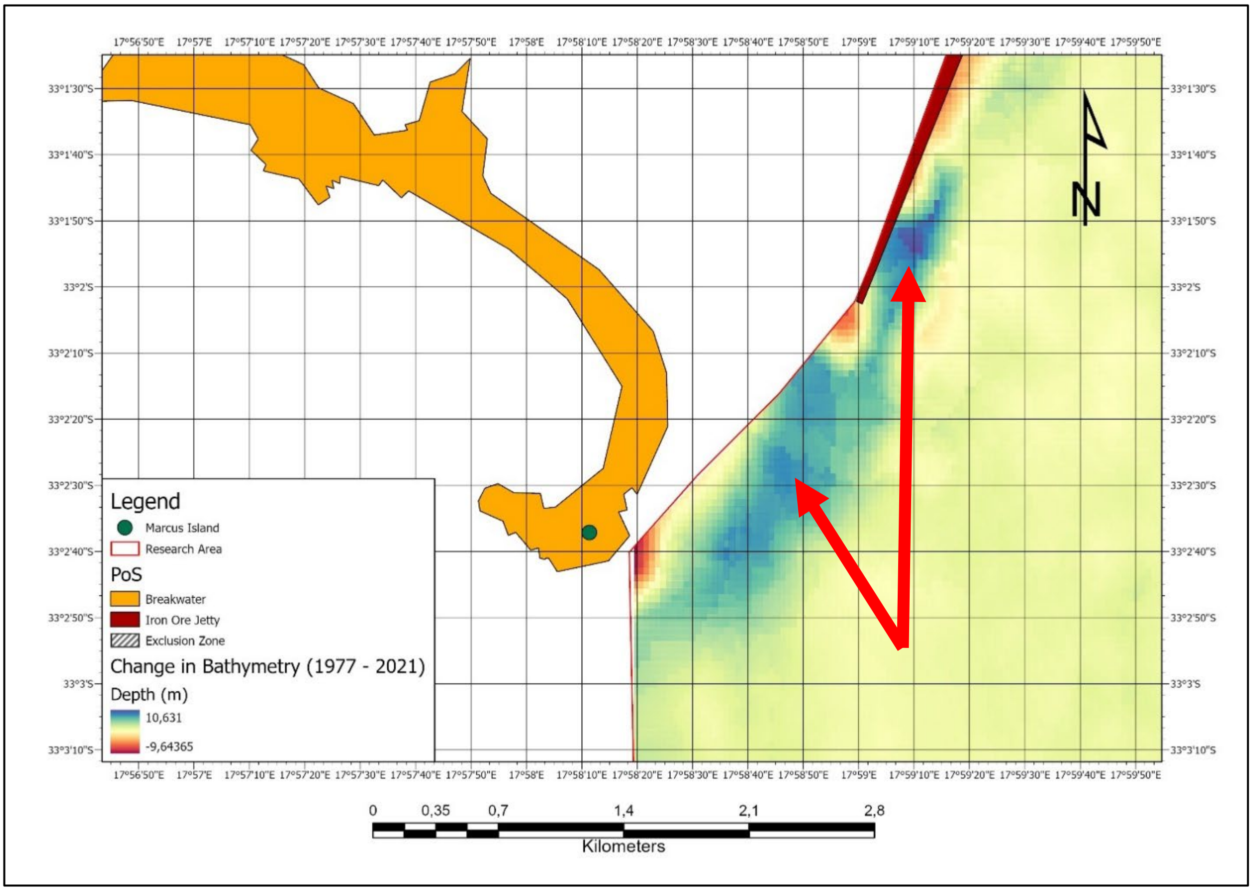

Figure 4.15: Map illustrating Zone 1 with high change in bathymetry

As mentioned in Chapter 2 (see section 2.4), as part of the Strategic Infrastructure Plan consisting of 18 Strategic Integrated Projects (SIPs), Transnet proposed a project which aimed to increase South Africa’s capacity to export more iron ore to world markets. As part of this project, the Sishen-Saldanha iron ore corridor was upgraded from 60 to 88 million tons per year (Welman & Ferreira, 2016).

The large increase in depth in Zone 1, illustrated in Figure 4.15, is the direct result of these upgrades, which included the deepening of the approach channel through dredging for ships with a draft of up to 20.5 m to enter the PoS. The channel is dredged to -23.7 m at the commencing of the channel and -23 m at the port entrance. The areas of significant decrease in depth (at the edge of the boundary shown in red) in Figure 4.15 is due to the extension of the iron ore jetty and the addition of a new multi-purpose quay.

As a result, it can be concluded that the changes in depth indicated in Figure 4.15 can be attributed to human intervention in the form of dredging within the Bay because of the construction of the PoS.

4.3.2 Area of significant change: Zone 2

Zone 2 (see Figure 4.14) is the second area which has experienced significant change. This zone is located on the eastern side of the iron ore jetty, close to the shore (indicated by the red arrows). What makes this zone unique is the fact that it is the only area within Big Bay that has experienced a significant amount of sediment deposition, resulting in a decrease in depth. In effect, some areas in zone two have experienced a depth decrease of almost 10 m.

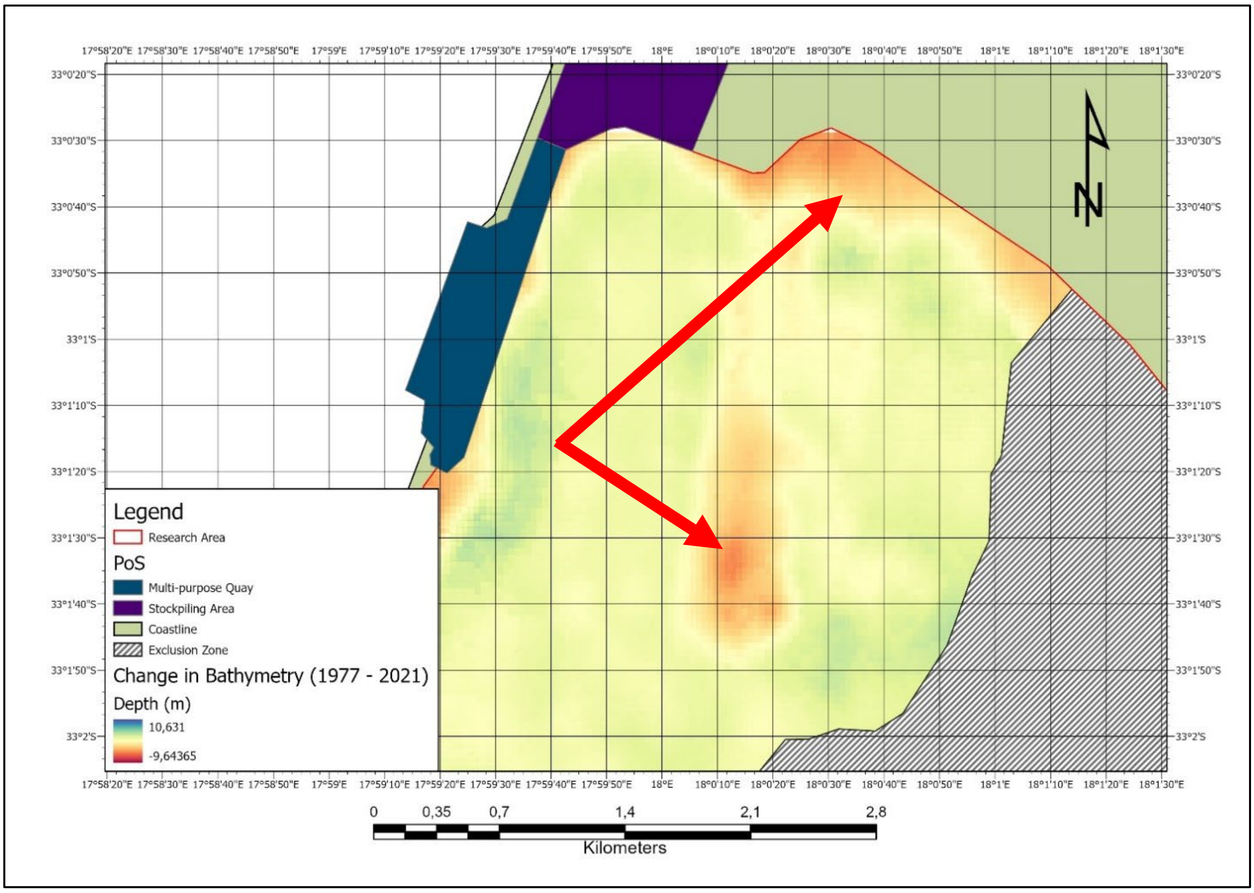

Figure 4.16: Map illustrating Zone 2 with high change in bathymetry

The factors driving the sediment transport in Zone 2 is a bit more complicated than that of Zone 1, as there are no clear, or documented, direct human interventions which could have caused these changes. As a result, the effect of the construction of the PoS on the flow patterns within Saldanha Bay were investigated to better understand the driving factors behind the decrease in depth illustrated in Figure 4.16. Consequently, the studies by CSIR (1982) and Wiese (2013) (see Chapter 2, sections 2.5.5 and 2.5.6) were revisited to gain a better understanding of the changes to the bathymetry of Saldanha Bay, as indicated in the preceding sections.

4.3.3 Tide effect

As mentioned previously (see Chapter 2, section 2.5.6), Wiese (2013) developed a two-dimensional model illustrating the effect of the construction of the PoS on current speeds within Saldanha Bay. Amongst other things, his results show that the largest change in current speed from before to after the construction of the PoS was observed when simulating the changes in current speed during a 1 in 50-year tide event (see Figure 4.17).

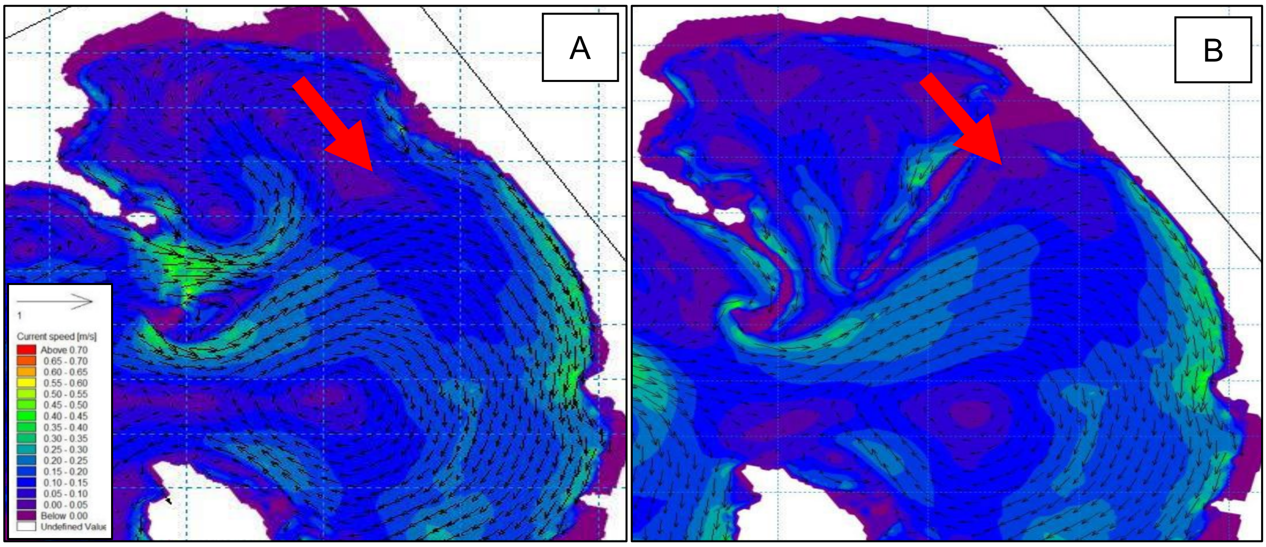

Figure 4.17: Two-dimensional model illustrating current speed during 1 in 50-year tide event, before construction (A) and after construction (B) of the PoS
<u>Source</u>: Adapted from Wiese (2013)

In these models, the purple areas represent the slowest flow speeds, whereas the hues ranging from yellow to green represent areas with the highest flow speeds. When comparing the current speeds from before the construction of the PoS (Figure 4.17A) with that of the current speeds from after the construction of the PoS (Figure 4.17B), then an increase in the amount of 'slow' current speeds is evident, i.e., a larger purple area, after the construction of the PoS. This reduction in current speed appears to be directly linked to the construction of the PoS which is obstructing the natural flow of the currents within the Bay, forcing the current to turn and slow down to flow around the PoS. This impacts the sediment transport processes within the Bay. Zone 2 (as described above in section 4.3.2 and indicated by the red arrows on Figure 4.17) is located at the point where the current must turn and slow down to go around the PoS, resulting in a loss of current speed and energy, which in turn encourages sediment deposition.

4.3.4 Wind effect

Related to the studies described in Chapter 2 (see section 2.5.5), the CSIR delivered a research report to the Harbour Master of Port of Saldanha inclusive of a three-dimensional (including depth) model of the flow patterns within Saldanha Bay, post construction of the PoS. In this report, the flow patterns of the Bay during prevailing NW winds (dominant during winter) and during prevailing SE winds (dominant during summer) are also described and illustrated. The bottom current simulations shown in the CSIR report are indicated by Figure 4.18.

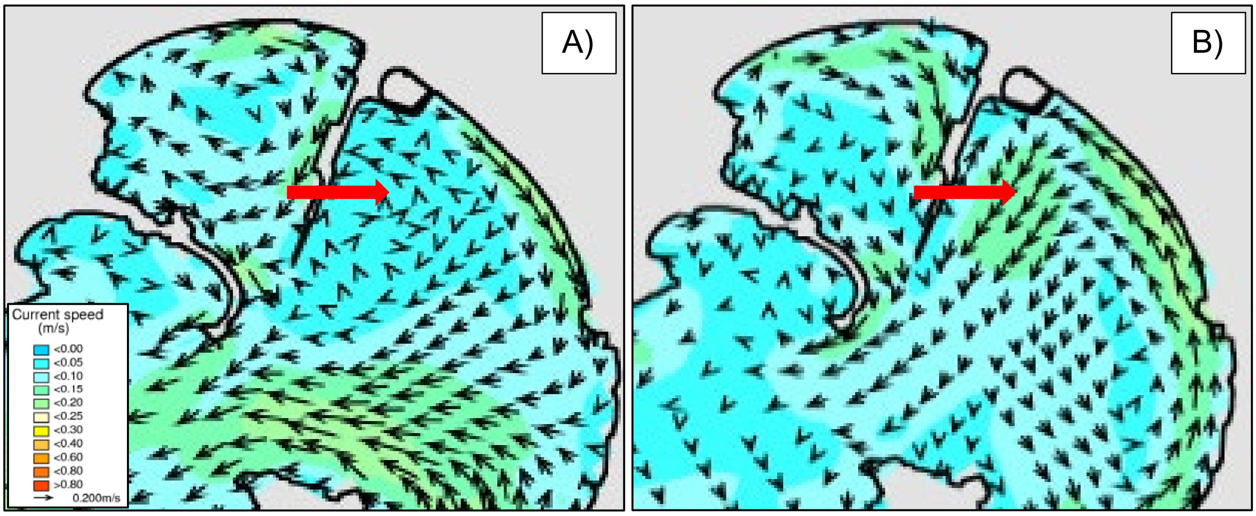

Figure 4.18: Charts Illustrating the current speeds in Saldanha Bay after the construction of the PoS during prevailing NW winter winds (A) and prevailing summer SE winds (B)
<u>Source</u>: Adapted from CSIR (n.d.).

From the results produced by the CSIR report, the flow speeds are close to zero in all scenarios. The most notable reduction in flow speeds is during winter when a NW wind prevails. The areas in the Bay where these low flow speeds occur correspond with the location of Zone 2 (as described above in section 4.3.2 and indicated by the red arrows in Figure 4.18).

Between the current speed results of Saldanha Bay, as illustrated by both Wiese (2013) and the CSIR report, the decrease in depth identified in Zone 2 may be attributed to the slow current speeds in this area, as the slow current speeds will result in loss of energy, ultimately leading to sediment deposition. However, to gain a complete understanding regarding the sediment deposition identified in Zone 2, further research may be required regarding the effect of the construction of the PoS on wave energy and circulation patterns within the Bay, a point discussed further in Chapter 5 (see section 5.4). Sediment deposition may also have resulted from the dumping of dredge spoil within the Bay, but this possibility has not been confirmed to date.

4.4 Slope analyses results

Once the change detection was done, the next step towards understanding the extent of change in bathymetry in Saldanha Bay between 1977 and 2021 was doing a slope analysis. The distribution of slope for Big Bay for both 1977 (see Figure 4.19) and 2021 (see Figure 4.20) is illustrated below.

As shown in Figure 4.19 there was a gentle slope across Big Bay in 1977, an average slope gradient of 0.37 degrees, with most of the Bay having a slope of less than 0.9 degrees. There were some areas in the 1977 representation of Big Bay which showed a higher slope, with the maximum recorded slope being 7.3 degrees, mainly coinciding with the sharp escarpment off Salemanderpunt, as mentioned in section 4.2. As indicated in Figure 4.19, a standard deviation of 0.49712 and a mean of 0.37381 were achieved for the slope analysis conducted with the 1977 dataset. This is an indication that most of the Bay had a relatively shallow gradient (below 0.5 degrees), pointing to a gentle change in depth across the Bay.

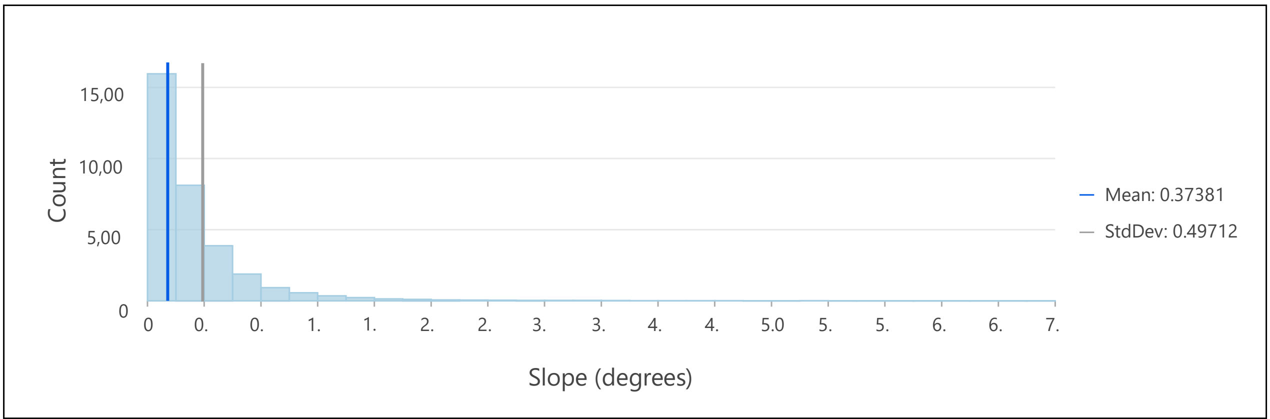

Figure 4.19: Graph illustrating the distribution of the slope of Big Bay in 1977

As shown in Figure 4.20, the general slope trend of Big Bay in 2021 remained fairly like that of 1977, with most of the Bay having a relatively shallow gradient, between 0 and 1.3 degrees. However, in 2021 there is a slight increase in the overall slope of Big Bay since

1977, with and average gradient of 0.51 degrees recorded in 2021, which is 0.2 degrees more than in 1977. Also, in 2021 the majority of Big Bay had a gradient of approximately 1.3 degrees, which is 0.4 degrees more than in 1977. Also, the standard deviation (0.77772) and the mean (0.51054) derived for the slope analysis that was conducted with the 2021 dataset, are respectively higher than that for the slope analysis with the 1977 dataset. This is an indication that there was a slight increase in the average slope within the Bay, pointing to a steeper decrease in depth throughout most of the Bay.

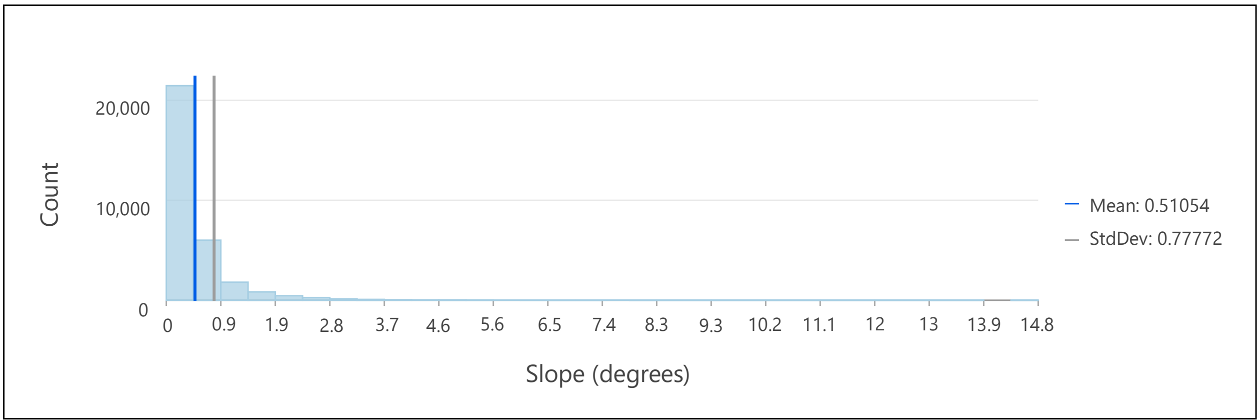

Figure 4.20: Graph illustrating the distribution of the slope of Big Bay in 2021

In 2021, Big Bay also showed an increase in the maximum slope recorded in the Bay, with a maximum gradient of 14.8 degrees, more than twice the maximum slope recorded in 1977, most likely because of the dredging which resulted in the change in depth, as identified in section 4.3.1.

4.5 Discussion of results

The first results produced in this section were that of the surface models which represented the bathymetry of Big Bay within Saldanha Bay for 1977 and 2021 respectively. These showed an increase in the average depth from 11.0 m to 12.3 m. This was confirmed during the change detection analysis process, with most of the Bay illustrating a slight increase in depth.

The change detection analysis also detected two zones which indicated changes in depth beyond the first order of standard deviation within the Bay. The first zone indicated a significant increase in depth, which could be attributed to the dredging activities during 2012 to deepen the approach channel by 12 m to accommodate vessels with a draft of up to 20.5 m. The second zone indicated a significant decrease in depth, pointing to sediment deposition in the area. This suggests that the construction of the PoS was the most likely cause of the changes in flow pattern caused by the construction of the PoS, resulting in a reduction of the flow within this zone. This does point to the construction of the PoS as a possible cause of the change in bathymetry identified within this area.

Finally, a slight increase in the overall slope of the Bay was also detected. The increase in slope was not large enough to reveal its impact on the sediment transport processes within the Bay. However, the increased slope may largely be attributed to dredging activities within the Bay. Other possible influences on the slope could include the deposition of sediment identified in Zone 2 and the slight increase in depth identified across the Bay.

From these results it can be concluded that the construction of the PoS, and the anthropogenic activities related to the maintenance of the Port, did result in significant changes to the bathymetry of Big Bay from 1977 to 2021. However, due to limitations regarding data collection, which is discussed in the next chapter (see section 5.4), only a portion of Saldanha Bay could be analysed. As a result, the full effect of the construction of the PoS on the bathymetry of Saldanha Bay still needs further investigation.

4.6 Chapter summary

This chapter provided an overview of the results gathered during this study. Results revealed that there were some changes to the overall bathymetry and slope of Big Bay over the forty-four years since 1977 until 2021. There are two main areas of change, one experiencing a rather significant increase in depth, and the other a significant decrease in depth. Regarding changes in slope, there was a slight increase in the average slope from 1977 to 2021. However, there was a marked increase in the maximum slope recorded from 1977 to 2021. From the results reported in this chapter, it can be construed that anthropogenic activities within Saldanha Bay had a pronounced impact on the bathymetry of the Bay. The possible causes and mitigation of these changes are discussed in more detail in the next chapter (Chapter 5).

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

As mentioned in Chapter 2 (see section 2.4), Saldanha Bay is a key area for economic growth in South Africa and has been identified as a priority industrial development zone in the country. As a result of this, Saldanha Bay has been the target of much government investment in infrastructure over the past 50 years and continues to be a focal area for future development.

The environmental impact of these developments cannot be overlooked, as it could have serious consequences for the economic productivity of the area, as mentioned in Chapter 1 (see section 1.3). To this end, this study aimed to establish the change in bathymetry of Saldanha Bay after the construction of the PoS (1977 – 2021). The change in bathymetry identified during this study may be used in conjunction with the body of research already done to identify the hydrodynamic impact of the construction of the PoS (see section 2.5), to gain a clearer understanding of the impact the PoS on sediment transport processes within Saldanha Bay.

Studies like Flemming (1977) and Henrico & Bezuidenhout (2020), among others, have investigated the effects of the anthropogenic activities within the Bay, and have proven that the changes made during the construction of the PoS have significantly altered the shape and slope profile of Saldanha Bay. These studies also agree that these changes would have some form of impact on sediment transport processes within Saldanha Bay. These findings are backed by several other studies, as mentioned in Chapter 2 (see section 2.5).

The changes made to the bathymetry of Saldanha Bay during the construction of the PoS potentially catalysed the erosion and siltation processes impacting most of the Langebaan beaches (Flemming, 2015; Henrico & Bezuidenhout, 2020). Henrico & Bezuidenhout (2020) emphasize the importance of making a comparison between the 1977 bathymetry and new and updated bathymetry to determine how the Saldanha Bay sedimentation process changed after the construction of the PoS in 1976. Hence, the researcher used the 1977 sounding points of the Bay and became directly involved in the latest bathymetry survey of the Bay (2021) by the Hydrographer of the SA Navy to acquire updated sounding points of the Bay – the first major survey of the Bay since 1977. See Chapter 1, Figure 1.4 for other, a really more confined, measurements conducted over the years.

The aim of this study was to analyse the changes in bathymetry of Saldanha Bay between the years 1977 and 2021. To achieve the aim of this study, research questions were developed that needed to be answered, and objectives were stated accordingly (see Chapter 1, section 1.5). Reflection on these research questions and objectives is presented in this chapter under section 5.3. But first, a summary of the literature review and findings is provided. This chapter also stipulates limitations to the current study that were identified while conducting the study. Recommendations and possible considerations for future studies are also provided.

5.2 Study review

5.2.1 Background

The theory to perform interpolation for bathymetry has been extensively tested and is well documented in the literature. The most widely used and most suitable interpolation methods, done through a GIS, are well known. Over the years, various studies about Saldanha Bay were conducted, including the impact of the construction of the PoS on the bathymetry of the Bay and the impact of sedimentation. There exists no new and updated bathymetric data on the Bay to accurately investigate the impact of the construction of the PoS on the bathymetry of the Bay and to determine what has changed over the past 44 years. Hence, a request was directed to the Hydrographer of the SA Navy for an updated survey of the Bay. The request was approved, and the latest survey commenced in February 2021. The survey lasted until May 2021, and even though various obstacles were encountered during this survey, which are highlighted as limitations in this chapter, almost the entire Big Bay area was surveyed. Big Bay was identified as the most important area to be studied because the construction of the PoS, specifically the construction of the breakwater, significantly impacted the hydrodynamics within this section of Saldanha Bay.

From the above paragraph it is evident that this study filled a void in scientific evidence by conducting an updated bathymetric survey on Saldanha Bay through soundings collected in 2021, and the resultant analysis of the nature and extent of change in the bathymetry of the Bay between 1977 and 2021.

5.2.2 Literature study

Chapter 2 consisted of a literature study, inclusive of a brief historical account of past and present developments of the town of Saldanha. The construction of the PoS was discussed, as well as its effect on the hydrodynamics and sedimentation processes in the Bay. Next, a background on bathymetry and methods to measure ocean depths were provided, specifically focussing on the SBE and MBE instruments. Various studies relating to Saldanha Bay were also reviewed. The latter part of Chapter 2 was devoted to the application of interpolation methods by using a GIS.

5.2.3 Empirical research - summary of findings

The empirical component of this study consisted of four phases, which included: data collection, data preparation, data analysis and change detection. Interpolation maps illustrating the bathymetry of Saldanha Bay for 1977 and 2021 were created. These maps were necessary for comparative purposes, i.e., to compare the extent of change of bathymetry within the Bay between the years 1977 and 2021.

Data collection. The 1977 dataset was collected through SBES equipment by the SAN and was provided by the Hydrographic office of the SAN as charted point depths in a shapefile format. The 2021 data were collected during a survey by the SAN from February to May of 2021, using MBES. The SANHO also provided the quality control and depth verification on the sounding points collected during this survey.

Data preparation. Both the 1977 and 2021 datasets were transformed to the same projection (UTM 34S); a requirement for comparative study purposes. All depth values were converted to metres. Data was clipped to the extent of the research area.

Data analysis. The data analysis was done through the ArcGIS Pro Geostatistical Wizard to create surface models which represent the respective 1977 and 2021 bathymetry. The OK interpolation method was employed. From these surface models, slope models were created for both datasets.

Change detection. Both surface and slope models underwent change detection analysis. The results of the various analyses where then scrutinized to determine any changes in the bathymetry of Saldanha Bay since 1977.

Results indicated that both datasets had an overall tendency of gradual increases in depth from the coastline towards the mouth of the Bay, with sharp increases in depth off Elandspunt and Salamanderpunt. The results further indicated that there was an average increase since 1977 in depth within the reliable dataset extent (inclusion zone in section 4.3) of 1.799 m. There were also two areas identified which experienced changes beyond the standard deviation. These areas showed significant increases or decreases in depth. The results of change indicated in these two areas were described in Chapter 4, sections 4.3.1 and 4.3.2. Relatively small changes in the slope profiles between 1977 and 2021 were also indicated in Chapter 4.

It was confirmed by this study that changes in the bathymetry of Saldanha Bay were experienced since 1977. It was mentioned by Flemming (1977) that changes in bathymetry of Saldanha Bay would result in changes to all other hydrographical characteristics of the Bay. This study confirms that changes in fact occurred. Even though these changes might not seem significant, the construction of the PoS did alter the wave refraction and direction, and tidal movement within the Bay. These changes therefore altered the sediment transport processes and hydrodynamics, which led, and still leads, to extensive coastal erosion along the Langebaan beaches. So much so that in recent years the Saldanha Bay Municipality was forced to construct a groyne embankment to increase natural deposits of beach sand to stabilise and rehabilitate the vanishing Langebaan beachfront, as shown by Figure 1.3 in Chapter 1 (Henrico & Bezuidenhout, 2020).

The findings of this study support the statements made by Flemming (1977) and Henrico & Bezuidenhout (2020) that the construction of the PoS would have changed the sedimentation processes within Saldanha Bay to some extent. However, the findings of this study are only relevant for a portion of Saldanha Bay, the inclusion zone in Big Bay, as indicated in Chapter 4 (see section 4.3). In this area there has been a total loss of 49 364 560 m^3 in sediment volume. The exact nature and driving forces behind this loss in volume still requires further investigation.

However, of the two zones of significant change which were identified in Chapter 4 (see section 4.3), only the changes in Zone 1 could be attributed to a specific driving force, as these changes were made through dredging during the expansion upgrades to the PoS in 2012 and 2013 (Welman & Ferreira, 2014). The second zone of significant change experienced sediment deposition, or a decrease in depth, most likely due to changes in the flow pattern and speed of currents caused by the construction of the PoS described in section 4.3.2. However, due to the limitations experienced during this research, mentioned in section 5.4 below, further research needs to be conducted to fully understand the change in sediment deposition in Zone 2.

This study has successfully described and visually illustrated the bathymetry of Big Bay for 1977 and 2021. Based on the findings gained from analysing the changes between these two bathymetric profiles, several different changes in terms of depth and slope were identified. These findings point towards both a direct anthropogenic impact within the Bay and changes because of variations in the hydrodynamics regime within the Bay. These findings contribute to our understanding regarding the impact of the PoS on the environment and serve as a point of departure for future studies investigating the interactions of human activities within Saldanha Bay, and its impact on the environment.

5.3 Answering research questions and achievement of objectives

To achieve the aim of this study, various research questions and related objectives were formulated (see Chapter 1, section 1.5). Answering these questions and achievement of the objectives (primary and secondary objectives) are presented below. For simplification, the primary research aim was attained by achieving all the secondary objectives, which are highlighted below. The secondary research objectives are therefore referred to as objectives 1 to 4. Ultimately, a statement is made that the study aim was achieved. The findings below were mainly derived from the empirical research conducted in this study, and the results and analysis derived from comparing the bathymetry of Saldanha Bay for 1977 and 2021, as described in Chapter 4.

a) Reflection on objectives 1 and 2: Objectives 1 and 2 are closely related, the one aiming to provide a description of the different datasets and the other to physically compare these two datasets. These objectives were achieved from the descriptions and interpolation tests conducted, including the surface and slope models, through the respective 1977 and 2021 datasets in Chapter 4, sections 4.2, 4.3 and 4.4. Consequently, the correspondent secondary research questions (i and ii, see Chapter 1, section 1.5.2) were answered.

b) Reflection on objectives 3 and 4: Objectives 3 and 4 relate to the bathymetric comparison between the 1977 and 2021 datasets and the possible reasons for the observations relating to the changes that occurred, as well as the impact of these changes on the sedimentary processes, siltation, and the extent of beach erosion. Although only the majority of Big Bay was surveyed and not the entire Saldanha Bay – as was initially planned (see description regarding this limitation below in section 5.4) – the author still feels that objectives 3 and 4 were successfully achieved by the discussion of the results in Chapter 4 (see section 4.5).

Since all secondary objectives were achieved (as indicated above), it can be stated that the primary objective of this study was successfully achieved and consequently, research question 1 is answered. By means of a comparative analysis, differences were indicated between the 1977 and 2021 bathymetry of Saldanha Bay. The results show both increases and decreases in ocean depth since the construction of the PoS, and two areas were identified that show significant changes (see Chapter 4, section 4.3). Additionally, slope analyses were conducted that indicated some changes. It is evident from the above discussions that all research questions were answered and that all research objectives were successfully achieved. Some in full, some in part, yet sufficiently answered to respond to the research aim by answering the main research question. Therefore, it is conclusive that the study aim was accomplished.

5.4 Limitations of this study

While conducting this research, various challenges were experienced, which impacted the research design and interpretation of findings. The following limitations are identified for this study.

a) As previously mentioned, the latest survey conducted by the Hydrographer of the SA Navy in 2021 experienced various obstacles which resulted in only the majority of Big Bay being surveyed. This negatively impacted this study, because only Big Bay could be surveyed and hence considered for determining the extent of the bathymetry changes that occurred within the greater Saldanha Bay from 1977 to 2021. Reasons for only surveying Big Bay related to mechanical problems experienced with the vessels used by the Hydrographer to survey the Bay. Another factor that influenced this survey was weather conditions, which over the three months of surveying restricted the time available to do the surveys. The West Coast is characterised by continuous and sometimes heavy winds with an average speed of 11 m/s, which often increase during the afternoons. These weather conditions influenced and forced the survey to only be conducted in the mornings and during days when the waves and swells within the Bay were relatively stable and small. This significantly reduced the time available to conduct the survey which is an arduous and time-consuming exercise. The financial implications of such a survey should not be underestimated. Lastly, the restraining effect of the aquaculture farms on surveying the Bay will in future have to be mitigated to survey the entire Bay.

b) Another limitation identified during this study was the limited data received, as mentioned in the section above. Because this dataset only covered a partial area of Big Bay, the large gaps in the dataset further decreased the research area of this study. As a result of this decreased research area, a large portion of Saldanha Bay remains unsurveyed in recent years, and consequently the change in bathymetry throughout the entire Saldanha Bay could not be determined. This is an important factor which inhibited this study in fully answering all research questions posed at the beginning of this study (see section 5.3). As a result, there is still further investigation necessary to fully determine the effect the construction of the PoS had on Saldanha Bay as a whole.

c) Finally, the spatial distribution of the two point datasets was another limiting factor identified during this research. The 1977 dataset had a spatial resolution of 300 m with sounding points that are evenly distributed, whereas the 2021 dataset had a spatial resolution of 100 m with sounding points clustered more densely in certain areas. The accuracy of any interpolation method is reliant on the spatial distribution patterns of the input dataset. As a result, there was a slight difference in the accuracy between the surface models created from the two time series datasets. Consequently, a small portion of the identified changes in bathymetry could be attributed to varying accuracies of the interpolation models. However, as shown by the interpolation test in Chapter 3 (see section 3.4.3), the influence of the spatial distribution on the accuracy of the interpolation models is not significant. However, it is recommended that future studies make use of datasets with the same spatial distribution when comparing interpolation models created from these datasets in order to ensure complete validity of the results.

5.5 Recommendations

Even though the research area of this study was limited to a particular section of Saldanha Bay, viz. Big Bay, due to the bathymetry survey constraints experienced during 2021, the study revealed that several changes to the physical characteristics of the bathymetry within Saldanha Bay had occurred. With the Saldanha Bay area being identified as an IDZ and earmarked for significant future development, it is extremely important for governing entities at national and regional levels to be well informed regarding the nature and extent of the impact these upgrades would have. Considering this, the following recommendations were formulated concerning the bathymetry of Saldanha Bay:

a) <u>Recommendation 1</u>: It is recommended that frequent bathymetric surveys, sediment movement tracking and bio-indicator monitoring be conducted to ensure that the PoS can operate as efficiently and as sustainably as possible, ensuring a maximum return on investment from the economic activities within the Bay.

b) <u>Recommendation 2</u>: It is recommended that a new request be forwarded to the Hydrographic Office of the SA Navy to survey the entire Saldanha Bay, including Inner Bay and Outer Bay, which were excluded during the 2021 survey. This will provide a complete picture of the extent of bathymetric change experienced in Saldanha Bay since the construction of the PoS.

c) <u>Recommendation 3</u>: It is recommended that the bathymetric changes identified in this study, along with any bathymetric changes identified in future, should be used in conjunction with sediment tracking studies in order to identify exactly from where sediment is being transported, and where sediment is being deposited. This will provide decision-makers with a clearer understanding of how to best manage the sediment transport processes within Saldanha Bay.

d) Recommendation 4: Future wave modelling and longshore currents should be included in similar studies to determine the sedimentation processes within the Bay and mitigate the coastal erosion challenges currently being experienced on beaches in Langebaan, with its associated impact on the human and physical environment.
e) Recommendation 5: The effect of the Langebaan Lagoon should be included in studies about the bathymetry profile of Saldanha Bay.

5.6 Future research

This study was limited to the geospatial context of the survey that was conducted in 2021. A survey of the entire Saldanha Bay is required to gain a full understanding of how the bathymetry of Saldanha Bay had changed since the construction of the PoS. It is important to conduct research which will improve our understanding, and the full width and depth of impact of both natural and anthropogenic changes to the bathymetry of Saldanha Bay.

Further studies should be conducted to track the movement of sediment within Saldanha Bay. Since the Saldanha Bay and Langebaan Lagoon systems are interconnected, the changes in one affecting the other, it is important for sediment transport studies to view these systems not in isolation.

During the data collection phase of this study, it was notable how many mussel and fish farms are scattered across Saldanha Bay. These farms are likely to influence the bathymetry and sediment transport processes within the Bay. There are currently no studies investigating the link between changes in bathymetry, coastal erosion and the location and activities of aquafarming. As aquafarming constitutes major current and future economic activities within Saldanha Bay, these activities could potentially influence the bathymetry of parts of Saldanha Bay. Comprehensive, bold impact studies would be required.

5.7 Chapter summary

The aim of this study was to analyse the changes in bathymetry of Saldanha Bay between 1977 and 2021 by achieving a set of related primary and secondary objectives. This chapter served as an overview of how these objectives were met to achieve the aim of this study. The chapter has outlined the findings in this study and highlighted the importance of these findings. There have been changes to the bathymetry of Saldanha Bay. However, there are still large gaps in our understanding of the exact nature of the relationship between the PoS and the hydrodynamic and sediment transport processes within Saldanha Bay, which also impacts Langebaan Lagoon. Due to the economic significance of the PoS, it is therefore important that an effort should be made to investigate the full scope of interactions the PoS has with its surrounding environment to ensure that the area is developed in a profitable, sustainable and environmentally accountable manner.

BIBLIOGRAPHY

Aguilar, F.J., Agüera, F., Aguilar, M.A. and Carvajal, F., 2005. Effects of terrain morphology, sampling density, and interpolation methods on grid DEM accuracy. Photogrammetric Engineering & Remote Sensing, 71(7), pp.805-816.

Ali, T.A., 2004, April. On the selection of an interpolation method for creating a terrain model (TM) from LIDAR data. In Proceedings of the American Congress on Surveying and Mapping (ACSM) Conference (pp.16-21).

Amante, C.J. and Eakins, B.W., 2016. Accuracy of interpolated bathymetry in digital elevation models. Journal of Coastal Research, (76 (10076)), pp.123-133.

Apuke, O.D., 2017. Quantitative research methods: A synopsis approach. Kuwait Chapter of Arabian Journal of Business and Management Review, 33(5471), pp.1-8.

Brown, R.B. and Brown, R., 2006. Doing your dissertation in business and management: the reality of researching and writing. Sage.

Childs, C., 2004. Interpolating surfaces in ArcGIS spatial analyst. ArcUser, July-September, 3235(569), pp.32-35.

Clark, B., Hutchings, K., Biccard, A., Brown, E., Dawson, J., Laird, M., Gihwala, K., Swart, C., Makhosonke, A., Sedick, S., Turpie, J. and Mostert, B., 2020. The state of Saldanha Bay and Langebaan Lagoon: *Technical Report, October 2020.* [Online]. Available at: https://anchorenvironmental.co.za/sites/default/files/2020-11/The%20State%20of%20Saldanha%20Bay%20and%20Langebaan%20Lagoon%202020_0.pdf. Accessed: 23 July 2021.

Costa, B.M., Battista, T.A. and Pittman, S.J., 2009. Comparative evaluation of airborne LiDAR and ship-based multibeam SoNAR bathymetry and intensity for mapping coral reef ecosystems. Remote Sensing of Environment, 113(5), pp.1082-1100.

Davies, J., 1958. Wave refraction and the evolution of shoreline curves. *Geophysical Studies,* volume 5, pp. 1-14.

Davies, O., 1973. Pleistocene shorelines in the Western Cape and South-West Africa. Annals of the Natal Museum, 21(3), pp.719-765.

De Souza, E.C.B., Krueger, C.P. and Sluter, C.R., 2003. Determinação das variações volumétricas no ISTMO da ilha do mel utilizando PDGPS. Boletim de Ciências Geodésicas, 9(1).

Dierssen, H.M., 2010. Perspectives on empirical approaches for ocean color remote sensing of chlorophyll in a changing climate. Proceedings of the National Academy of Sciences, 107(40), pp.17073-17078.

Dierssen, H.M., Theberge, A.E. and Wang, Y., 2014. Bathymetry: History of seafloor mapping. Encyclopedia of Natural Resources, 2, p.564.

Dierssen, H.M. and Theberge, A.E., 2020. Bathymetry: assessment. In Coastal and Marine Environments (pp. 175-184). CRC Press.

Du Plessis, A. and De la Cruz, M.A., 1977. Geophysical investigations in Saldanha Bay. Transactions of the Royal Society of South Africa, 42(3-4), pp.285-302.

Encyclopaedia Britannica, 2020. *Saldanha Bay.* [Online]. Available at: https://www.britannica.com/place/Saldanha-Bay

Erdogan, S., 2009. A comparision of interpolation methods for producing digital elevation models at the field scale. Earth surface processes and landforms, 34(3), pp.366-376.

ESRI, 2020. *About ArcGIS Pro.* [Online]. Available at: https://pro.arcgis.com/en/pro-app/get-started/get-started.htm
[Accessed 4 10 2020].

Ferreira, I.O., Rodrigues, D.D., Santos, G.R.D. and Rosa, L.M.F., 2017. In bathymetric surfaces: IDW or Kriging?. Boletim de Ciências Geodésicas, 23, pp.493-508.

Flemming, B.W., 1977. Distribution of recent sediments in Saldanha Bay and Langebaan Lagoon. Transactions of the Royal Society of South Africa, 42(3-4), pp.317-340.

Flemming, B.W., 2015. *Depositional Processes.* Stellenbosch, South Africa: National Researchly Institute for Oceanology.

Fujita, M. and Mori, T., 1996. The role of ports in the making of major cities: self-agglomeration and hub-effect. Journal of development Economics, 49(1), pp.93-120.

GIS Geography, 2017. *Kriging interpolation: The prediction is strong in this one.* [Online]. Available at: https://gisgeography.com/kriging-interpoltion-prediction. Accessed: 3 September 2021.

Glatthorn, A.A. and Joyner, R.L., 2005. Writing the winning thesis or dissertation: A step-by-step guide. Corwin Press.

Che Hasan, R., Lerodiaconou, D., Laurenson, L. and Schimel, A., 2014. Integrating multibeam backscatter angular response, mosaic and bathymetry data for benthic habitat mapping. Plos one, 9(5), p.e97339.

Havens, K.J. and Sharp, E. J., 2016. Remote Sensing. In: K.J. Havens and E.J. Sharp, eds. *hermal Imaging Techniques to Survey and Monitor Animals in the Wild.* Academic Press, pp. 35-62.

Henrico, I., 2021. Optimal interpolation method to predict the bathymetry of Saldanha Bay. Transactions in GIS, 25(4), pp.1991-2009.

Henrico, I. and Bezuidenhout, J., 2020. Determining the change in the bathymetry of Saldanha Bay due to the harbour construction in the seventies. South African Journal of Geomatics, 9(2), pp.236-249.

Hudson, T., 2020. *Africa Port & Ships: Port of Saldanha Bay.* [Online]. Available at: https://africaports.co.za/saldanha-bay. Accessed on: 15 January 2021.

Intertek, 2021. *Hydrodynamic Modelling.* [Online]. Available at: https://www.intertek.com/energy-water/hydrodynamic-modelling. Accessed on: 23 March 2021.

Jacka, C., 2015. *Port South African Handbook: Upstream Oil and Gas.* Johannesburg: Transnet National Port Authority. SAOGA. [Online]. Available at: https://www.saoga.org.za/web/sites/default/files/2019-11/saoga-port-handbook-2015-low-res_rev01.pdf.

Johnston, K., Ver Hoef, J., Krivoruchko, K. & Lucas, N., 2003. *ArcGIS 9: Using ArcGIS Geostatistical Analyst.* [Online]. Available at: https://dusk.geo.orst.edu/gis/geostat_analyst.pdf. Accessed on: 26 October 2021.

Kalivas, D.P., Kollias, V.J. and Apostolidis, E.H., 2013. Evaluation of three spatial interpolation methods to estimate forest volume in the municipal forest of the Greek island Skyros. Geo-Spatial Information Science, 16(2), pp.100-112.Kampfer, A., 2007. *South African Navy Tide Tables,* Cape Town: South African Navy Publications Unit.

Kearns, T.A. and Breman, J., 2010. Bathymetry-The art and science of seafloor modeling for modern applications. Ocean globe, 2010, pp.1-36.

Kumar, R., 2014. *Research methodology: A step-by-step guide for beginners.* London: SAGE Publications.

Le Bas, T.P. and Huvenne, V.A.I., 2009. Acquisition and processing of backscatter data for habitat mapping–comparison of multibeam and sidescan systems. Applied Acoustics, 70(10), pp.1248-1257.

Li, D., Xia, S., Sui, H. and Zhang, X., 2007. Change Detection Based On Spatial Data Mining. Wuhan University, white paper, pages-8.

Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W., 2005. New developments in geographical information systems; principles, techniques, management and applications. Geographical Information Systems: Principles, Techniques, Management and Applications, 2nd Edn. Abridged, eds P. Longley, M. Goodchild, D. Maguire and D. Rhind (New Jersey, United States: John Wiley & Sons Inc), 404.

Lubbers, J. and Graaff, R., 1998. A simple and accurate formula for the sound velocity in water. Ultrasound in medicine & biology, 24(7), pp.1065-1068.

Luger, S.A., Schoonees, J.S., Mocke, G.P. and Smit, F., 1999. Predicting and evaluating turbidity caused by dredging in the environmentally sensitive Saldanha Bay. In Coastal Engineering 1998 (pp. 3561-3574).

McCombes, S., 2019. *How to write a research methodology.* [Online]. Available at: https://www.scribbr.com/dissertation/methodology/. Accessed on: 15 August 2021.

McGinnis, M.D. and Ostrom, E., 2014. Social-ecological system framework: initial changes and continuing challenges. Ecology and society, 19(2).

Meng, Q., Liu, Z. and Borders, B.E., 2013. Assessment of regression kriging for spatial interpolation–comparisons of seven GIS interpolation methods. Cartography and geographic information science, 40(1), pp.28-39.

Monteiro, P.M.S. and Largier, J.L., 1999. Thermal stratification in Saldanha Bay (South Africa) and subtidal, density-driven exchange with the coastal waters of the Benguela upwelling system. Estuarine, Coastal and Shelf Science, 49(6), pp.877-890.

Monteiro, P.M.S. and Brundrit, G.B., 1990. Interannual chlorophyll variability in South Africa's Saldanha Bay system, 1974–1979. South African Journal of Marine Science, 9(1), pp.281-287.

National Planning Commission, 2011. *National Development Plan vision 2030.* Pretoria: National Planning Commission. [Online]. Available at: http://policyresearch.limpopo.gov.za/bitstream/handle/123456789/941/NDP%20Vision%202030.pdf?s.

Nel, E.L. and Rogerson, C.M., 2013, June. Special economic zones in South Africa: Reflections from international debates. In Urban Forum (Vol. 24, No. 2, pp. 205-217). Springer Netherlands.

NOAA, 2018. *What is bathymetry?* [Online]. Available at: https://oceanservice.noaa.gov/facts/bathymetry.html. Accessed on: 20 January 2021.

NOAA, 2020. *What is hydrography?* [Online]. Available at: https://oceanservice.noaa.gov/facts/hydrography.html. Accessed on: 20 January 2021.

Olea, R.A., 1999. Ordinary Kriging. In Geostatistics for Engineers and Earth Scientists (pp. 39-65). Springer, Boston, MA.

Petrosillo, I., Aretano, R. and Zurlini, G., 2015. Socioecological systems. Reference Module in Earth Systems and Environmental Sciences, pp.1-7.

Pham, T., Van Huynh, C., Tran, P. and Chau, T., 2016. *Impact of the power value in IDW interpolation on accuracy of the soil organic matter (SOM) mapping.* Hanoi, Vietnam.

Probyn, T.A., Pitcher, G.C., Monteiro, P.M.S., Boyd, A.J. and Nelson, G., 2000. Physical processes contributing to harmful algal blooms in Saldanha Bay, South Africa. South African Journal of Marine Science, 22(1), pp.285-297.

Rothman, M.D., Anderson, R.J., Boothroyd, C.J.T., Kemp, F.A. and Bolton, J.J., 2009. The gracilarioids in South Africa: long-term monitoring of a declining resource. Journal of applied phycology, 21(1), pp.47-53.

Sakellariou, D., Bailey, G.N., Momber, G., Meredith-Williams, M., Alsharekh, A., Rousakis, G., Panagiotopoulos, I., Morfis, I., Stavrakakis, S., Pampidis, I. and Renieris, P., 2015. Preliminary report on underwater survey in the Farasan Islands by the R/V Aegaeo, May–June 2013.

Scheeres, A., 2016. *Kriging: Spatial Interpolation in Desktop GIS.* [Online]. Available at: https://www.azavea.com/blog/2016/09/12/kriging-spatial-interpolation-desktop-gis/. Accessed on: 3 September 2021.

Setianto, A. and Triandini, T., 2013. Comparison of kriging and inverse distance weighted (IDW) interpolation methods in lineament extraction and analysis. Journal of Applied Geology, 5(1).

Shannon, L.V. and Stander, G.H., 1977. Physical and chemical characteristics of water in Saldanha Bay and Langebaan Lagoon. Transactions of the Royal Society of South Africa, 42(3-4), pp.441-459.

Šiljeg, A., Lozić, S. and Šiljeg, S., 2015. A comparison of interpolation methods on the basis of data obtained from a bathymetric survey of Lake Vrana, Croatia. Hydrology and earth system sciences, 19(8), pp.3653-3666.

Silvester, R., 1960. Stabilization of sedimentary coastlines. Nature, 188(4749), pp.467-469.

Smith, M.E. and Pitcher, G.C., 2015. Saldanha Bay, South Africa I: the use of ocean colour remote sensing to assess phytoplankton biomass. African journal of marine science, 37(4), pp.503-512.

South African Government News Agency, 2013. *Saldanha Bay IDZ to boost economic development.* [Online]. Available at: https://www.sanews.gov.za/south-africa/saldanha-bay-idz-boost-economic-development. Accessed on: 23 January 2021.

Tobler, W.R., 1970. A computer movie simulating urban growth in the Detroit region. Economic geography, 46(sup1), pp.234-240.

Van Ballegooyen, N., Steffani, N. and Pulfrich, A., 2008. *Environmental Impact Assesment: Proposed reverse osmosis plant, iron-ore handeling facility, Port of Saldanha - Marine impact assessment specialist study.* Joint CSIR/Pices Report.

Van der Waag, I., 2005. A brief military history of the Saldanha Bay. Military History Department, University of Stellenbosch. Area http://academic. sun. ac. za/mil/mil_history/saldanha. htm.

Van Der Wal, D. and Pye, K., 2003. The use of historical bathymetric charts in a GIS to assess morphological change in estuaries. Geographical Journal, 169(1), pp.21-31.

Vieira, S.R., 2000. Geoestatística em estudos de variabilidade espacial do solo. Tópicos em ciência do solo. Viçosa: Sociedade Brasileira de Ciência do Solo. In. Novaes, R.F., Alvarez, V.V.H., Schaefer, C.E.G.R. Tópicos em ciências do solo. *Revista Brasileira de Ciência do Solo, v*olume 1, pp. 1-53.

Vilming, S., 1998. The development of the multibeam echosounder: A historical account. The Journal of the Acoustical Society of America, 103(5), p.1637.

Visser, D., Jacobs, A. and Smit, H., 2008. Water for Saldanha: War as an agent of change. Historia, 53(1), pp.130-161.

Wang, S., Huang, G., Lin, Q., Li, Z., Zhang, H., & Fan, Y. (2014). Comparison of interpolation methods for estimating spatial distribution of precipitation in Ontario, Canada. International Journal of Climatology, 34(14), 3745–3751. https://doi.org/10.1002/joc.3941

Weeks, S.J., Boyd, A.J., Monteiro, P.M.S. and Brundrit, G.B., 1991. The currents and circulation in Saldanha Bay after 1975 deduced from historical measurements of drogues. South African Journal of Marine Science, 11(1), pp.525-535.

Weeks, S.J., Monteiro, P.M.S., Nelson, G. and Cooper, R.M., 1991. A note on wind-driven replacement flow of the bottom layer in Saldanha Bay, South Africa: implications for pollution. South African Journal of Marine Science, 11(1), pp.579-583.

Welman, L. and Ferreira, S.L., 2014. Regional development of Saldanha Bay region, South Africa: the role of Saldanha steel. Bulletin of Geography. Socio-economic Series, 26(26), pp.219-231.

Welman, L. and Ferreira, S.L., 2016. The co-evolution of Saldanha Bay (town and hinterland) and its Port. Local Economy, 31(1-2), pp.219-233.

Wiese, M.J.B., 2013. A two-dimensional mathematical model investigation of the hydrodynamics and sediment transport of Saldanha Bay and Langebaan Lagoon (Doctoral dissertation, Stellenbosch: Stellenbosch University).

Zwemmer, D. and Van't Hof, J., 1979. The construction of Saldanha Bay Harbour. Civil Engineer in South Africa, 21(10), pp.238-240.

APPENDICES

Appendix A: Data Release Agreement received from the Hydrographic Office to use the 1977 legacy dataset of Saldanha Bay

HYDROGRAPHIC OFFICE
REPUBLIC OF SOUTH AFRICA

Tel: (021) 787-2408
Fax: (021) 787-2233
Email: hydrosan@iafrica.com

Hydrographic Office
Private Bag X1
Tokai
7966

Our ref:

AGREEMENT FOR RELEASE OF

HYDROGRAPHIC INFORMATION

1. This agreement stipulates the conditions in terms of which hydrographic information listed below, over which the SA Navy holds copyright hereafter referred to as the information, is released.

2. Information supplied: **Depth contours and sounding extracted from ENC ZA500040 for study purposes.**

3. The information is released on the following conditions:

   a. The receiver of this information recognises the copyright on the information supplied by the SA Navy.

   b. The information may not be sold, released or supplied to a third party without the written approval of the National Hydrographer.

   c. The information supplied may only be used for bona vide non-profit research.

   d. The information supplied may not be used for navigational purposes or as part of an ECDIS.

   e. Due recognition must be given to the National Hydrographer as the supplier and copyright holder of the information.

4. The National Hydrographer reserves the right to withdraw the release of this information at any stage.

5. Neither the National Hydrographer, the SA Navy Hydrographic Office, the SA Navy nor a member or employee is liable to any person or to any dependant of such person, for any loss or damage resulting from any bodily injury, loss of life or loss of or damage to property caused by or arising out of or in any way connected with any data displayed after being modified from the original supplied format.

6. This agreement has been reached between the National Hydrographer and

NAME:.. COMPANY: ....

SIGNATURE: ....

DATE: ....

SOUTH AFRICAN NATIONAL HYDROGRAPHER: CAPTAIN (SA NAVY)

DATE: 13/11/20

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Appendix B: Approval received from the Hydrographer to use the bathymetry data collected during the 2021 survey of Saldanha Bay

From: Du Toit, LM, Mr
Sent: 19 July 2021 09:20
To: Hydrographic Office
Subject: Saldanha Bay Bathymetry

Good morning Cdr,

I hope you are doing well.

As discussed during our phone call last week, can you please send me the bathemetry of Saldanha Bay in shapfile format, for use in ArcGIS.

As I butchered my email over the phone I am not certain whether the correct adress came through.

If you could send the data through in response to this email it would be greatly appreciated.

Regards,

CO L.M. Du Toit | Bsc (NWU), Bsc Hons (NWU)
Academic Assistant
School of GeoSpatial Studies and Information Systems
Faculty Military Science, Stellenbosch University
:
: Private Bag x2,Military Academy, Frans Erasmus drive, Saldanha, 7395
Room A105

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Sent from Mail for Windows 10

From: Hydrographic Office
Sent: Thursday, 22 July 2021 14:57
To: Du Toit, LM, Mr
Subject: RE: Saldanha Bay Bathymetry

CAUTION: This email originated from outside the Stellenbosch University network. Do not click links or open attachments unless you recognize the sender and know the content is safe.

Good afternoon CO Du Toit,

Attached please find the dataset for Saldanha Bay as requested.

In the dataset, the area bounded by the geographical limits below is the 'raw data edit' and not the final data. In the area enclosed by these positions, there are inaccuracies in the data due to a tidal error.

1 33.02958°S and 18.00098°E

2 33.02958°S and 18.010106°E

3 33.013614°S and 18.010106°E

4 33.013614°S and 18.00098°E

Disclaimer: Please note that neither the National Hydrographer, the SA Navy Hydrographic Office, the SA Navy nor a member or employee is liable to any person or to any dependant of such person, for any loss or damage resulting from any bodily injury, loss of life or loss of or damage to property caused by or arising out of or in any way connected with any data displayed before and after being modified from the original supplied format.

Kind regards,

Superintendent Paper Chart Production
Registration No: GISc0862

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Appendix C: Request submitted to the Hydrographic Office to conduct a new survey of Saldanha Bay

Subject: FW: Saldanha Bay Survey

From: **Mark Blaine**
Date: Wed, 17 Jun 2020 at 13:10
Subject: Saldanha Bay Survey
To: Hydrographer, SA Navy
Cc: Bezuidenhout

Good morning Theo

Our telephone conversation on 15 June 2020 has reference.

I have cc'd both Prof Jacques Bezuidenhout and Dr Ivan Henrico on this email.

As discussed we, at the Faculty of Military Science of Stellenbosch University, are engaged in a project to investigate the bathymetric changes and sediment transport modelling of Saldanha Bay over the last four decades.

I have attached a support letter from the Western Cape Government as well as an article written by Prof Bezuidenhout and Dr Henrico on the above for your perusal.

Attached also find two chart extracts on the proposed areas to be surveys and where additional information would be required. The first extract shows the three areas of the Bay while the second extract shows the southern limit of the area referred to as Big Bay.

The Hydrographic Office is requested to assist with the surveying of the areas indicated by orange circles. The priority for the required information would be Big Bay, Small Bay and then Outer Bay.

We know that the Hydrographic Office is currently experiencing difficulties due to the restricted availability of SAS PROTEA and the survey launches as well as the work on Project HOTEL which also impacts your office. It would however be appreciated if the above information could be made available by June 2021.

If required, myself and prof Bzuidenhout could visit the Hydrographic Office to provide more insight into the project, its funding and objectives and the exact requirements for its successful completion.

Your assistance in the above would be greatly appreciated.