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

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Abstract

The construction of the Saldanha Port has been the reason for the major changes in the bathymetry and sediment dynamics observed in Saldanha Bay in the last decades. In this paper, newly acquired soundings from the National Hydrographer were used to analyse the changes between 1977 and 2021 - over a 44-year period - in the bathymetry of Saldanha Bay. The Ordinary Kriging (OK) interpolation method, available through the Geostatistical Wizard in ArcGIS Pro, was used for creating surface models to conduct comparisons with the bathymetry of Saldanha Bay. The results indicate a general increase in depth since 1977 of between 0.395 and 3.203 m, and an average increase in depth within the Big Bay of 1.799 m. Between 1977 and 2021, a total volume loss of 49 364 560.0 m^3 in sediment was calculated - an indication of how the sedimentation process in Saldanha Bay has changed subsequent to the construction of the harbour.

Keywords: *bathymetry, hydrodynamics, GIS techniques, interpolation, ordinary kriging, Saldanha Bay*

1. Introduction

The South African government has recognised the economic potential of its ocean areas and has made large strides towards improving the way in which its ocean resources are managed (Welman and Ferreira, 2014). The goal of this blue economy[1], as it was coined, is to make better use of the country's water resources, specifically the oceans, to create jobs and alleviate poverty in the country (South African Government News Agency, 2013; Welman and Ferreira, 2016). Saldanha Bay is one of the largest natural harbours on the South African coast and is located on a major international trading route (Flemming, 1977). As a result, Saldanha Bay has been identified as a key development zone in this blue economy, which has led to major development in the region (Wiese, 2013).

[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).

Saldanha Bay has no perennial rivers that enter the Bay (Monteiro and Largier, 1999; Welman and Ferreira, 2016). As a result, prior to the start of construction in 1973, the hydrodynamics of Saldanha Bay was influenced only by cyclic natural tidal processes and wave action, resulting in a relatively stable bathymetric profile (Flemming, 1977; Wiese, 2013). 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 were commenced in 1969 (Flemming, 2015; Welman and Ferreira, 2016). 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 and Bezuidenhout, 2020; Zwemmer and Van't Hof, 1979). This led to the development in the late seventies of facilities for the exportation of iron ore, the transfer of oil and for storage (Flemming, 1977; Zwemmer and Van't Hof, 1979). The development of Saldanha Bay rolled on into the 1980s, when further expansion of the harbour allowed for other types of cargo handling, including those for lead, zinc and copper exports (Welman and Ferreira, 2016).

However, on account of extensive dredging in certain areas during the construction of the harbour, the changes made in the bathymetry of Saldanha Bay radically changed the bathymetry and shape of the shoreline (Henrico and Bezuidenhout, 2020). The construction of the causeway and the jetty split the Inner Bay of Saldanha Bay into two sections, namely Small Bay and Big Bay, each with its own hydrodynamic conditions (see Figure 1). Small Bay is protected from wave action, while Big Bay is more exposed to wave energy (Luger et al., 1998).

As noted by Flemming (1977) and Henrico and Bezuidenhout (2020), changes made during the construction of the PoS have significantly altered the shape and slope profile of Saldanha Bay, both of which have in turn changed the hydrodynamics of the Bay. These changes have potentially catalysed the erosion and siltation processes that impacted on some of the Langebaan beaches (indicated by the red hatch fill in Figure 1). However, a complete survey of the Bay has not been conducted since 1977 (Cdr C. Theunissen, personal communication, 18 August 2020), leaving a substantial gap in the analysis of the bathymetry of Saldanha Bay – hence, the motivation for this study. 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 respect by providing access to SAN equipment that was used for capturing the bathymetry data during this study (Cdr Theunissen, C. 2020. Correspondence. 18 August, Cape Town).

The focus of this study was to determine the current bathymetric profile of Saldanha Bay Harbour (SBH) and to investigate whether there had been any changes in the bathymetry of SBH since the construction of the Port of Saldanha in 1976. To this end, the 2021 bathymetry of Saldanha Bay was compared with the legacy 1977 bathymetry data to determine the extent of

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

change in the bathymetry which could improve our understanding of the current sedimentation process in the Bay. While the research methodology and analytical approaches in this publication remain robust, it has been determined post-publication that the 2021 data utilised was preliminary and unverified by the Hydrographic Office. Subsequent review has led to the revocation of this dataset due to technical issues, including system drop-outs in positioning, malfunctioning of the sound velocity probe, and inaccuracies in tidal data inputs. These challenges have contributed to the vertical separation artefacts, which could negatively impact the reliability of the results presented here. Readers are advised to consider these data limitations when interpreting the findings of this study.

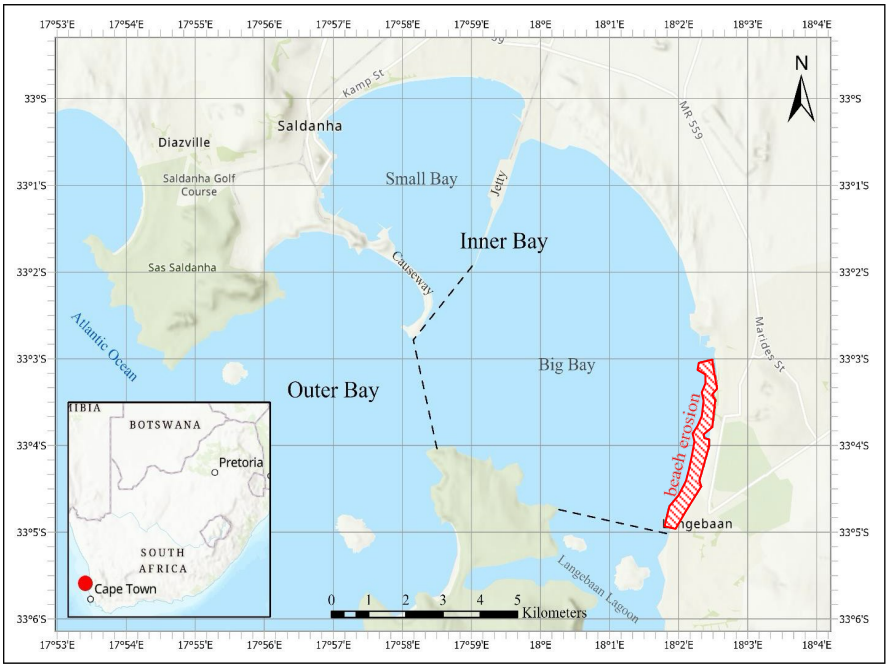

Figure 1. Saldanha Bay regions separated by imaginary boundary lines. The location of Saldanha Bay on the West Coast of South Africa is indicated by the red dot on the inset figure.

2. Input data

The two bathymetric datasets used during this study were both surveyed by and received from the National Hydrographer. The legacy 1977 dataset consisted of 3 052 sounding points, covering the entire Bay, as well as the entrance to the Bay, both of which were surveyed using the Single-Beam Echosounder (SBES) instrument. The 2021 dataset consisted of 1 968 sounding points

covering only the Big Bay area, which was surveyed with a Multi-beam Echosounder (MBES) instrument. Both datasets were received as point shapefiles, georeferenced using different projections (1977: Hartebeesthoek94; 2021: WGS84 UTM34s) and covering different spatial extents.

3. Pre-processing

Both bathymetric datasets were projected to the same projection (i.e., WGS84 UTM34s) and all height values were converted to metres (Mean Sea Level). Secondly, as illustrated by Figure 2, both datasets were clipped to the same spatial extent to cover most of Big Bay. During the 2021 survey campaign, and owing to mechanical problems experienced with the vessels, the influence of extreme weather conditions, and financial constraints, the entire Inner and Outer Bay could not be surveyed. These data collection challenges reduced the study area to Big Bay only, but since most of the harbour activities take place within the Big Bay area, this had no detrimental effect on the purpose of this study.

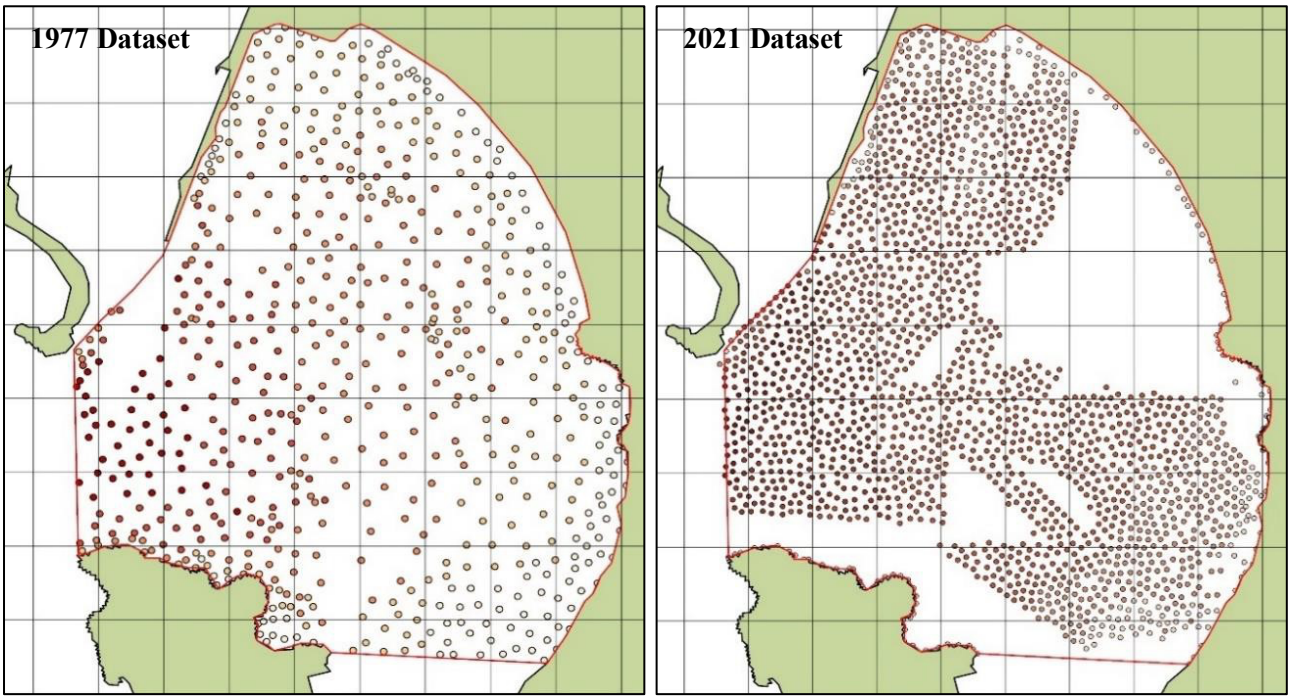

Figure 2. Map illustrating the processed 1977 and 2021 bathymetry soundings in Big Bay used for analyses

The legacy 1977 dataset used during this study was clipped from its original extent to the extent of the study area and only 613 sounding points remained. The 2021 dataset consisted of 1 968 sounding points and all points were used for conducting the 2021 bathymetry analyses. From Figure 2, it is evident that the 2021 points are more densely distributed than those on the 1977 dataset. The 2021 dataset has a spatial resolution of 100 m, while the 1977 dataset has a spatial resolution of 300 m. The 1977 dataset, however, shows a more even distribution across the study area, while, on the other hand, the 2021 dataset has large data gaps. Additionally, 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 generalised to 247 points to represent similar spatial distributions. The results of these sample tests confirmed that even though the spatial resolution is different for both datasets (100 m *vs* 300 m), the influence of the density of the sounding points on the accuracy of the interpolation models is negligible.

As meaningful interpolation of the survey points over these large data gaps was not possible, these areas were excluded from the analysis. The exclusion zones are indicated by the areas with the grey diagonal stripes in Figure 3.

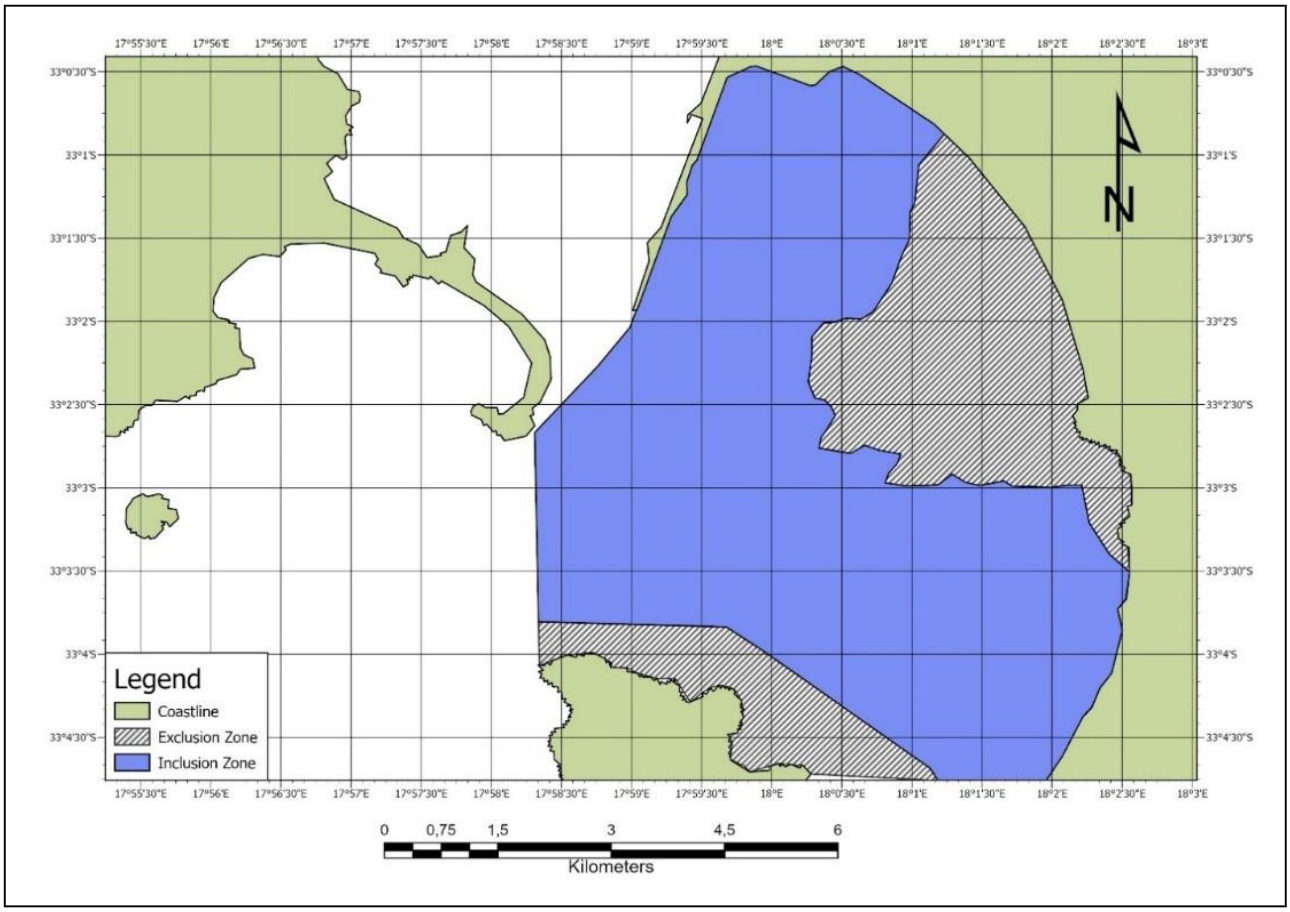

Figure 3. Map illustrating the inclusion and exclusion zones for this study

1. Surface model creation

The process of interpolation is used to create a continuous surface model from known points to estimate unknown values at unknown locations (Srivastava et al., 2019). There is no single best interpolation method since all methods are conditioned on spatial and temporal components. 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. Interpolation methods are therefore

largely site-specific and data-specific (Childs, 2004; Erdogan, 2009; ESRI SA, 2020; Šiljeg et al., 2015). Even though there are many interpolation methods available, the inverse distance weighting (IDW) and ordinary kriging (OK) are two well-known and commonly used interpolation methods to produce surface models (Amante and Eakins, 2016; Henrico, 2021). Subsequently, a test was conducted between IDW and OK to determine the best interpolation method to use for the specific datasets of this study. Since OK marginally outperformed IDW in terms of both the 1977 and 2021 datasets (see Table 1), it was the preferred method to use in this study.

Table 1. Accuracy test results of OK and IDW interpolation methods in estimating the bathymetry of Saldanha Bay

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

Consequently, two surface models were created from the point datasets using the OK interpolation method, one representing the 1977 bathymetry and one representing the 2021 bathymetry. These surface models were used for the comparative analyses through change detection and by comparing the slope profiles of both bathymetry products.

2. Change detection and slope analysis

The analysis of the changes in the bathymetry of Saldanha Bay between the years 1977 and 2021 consisted of three phases. Firstly, the surface models were created and analysed visually. The surface models were created through OK interpolation and were converted to raster files (.tiff), with a default spatial resolution of 2.7 m (ground sampling distance). Because the interpolation process gives nonsensical predictions outside of the area of interest, both raster files were clipped to the spatial extent of the study area. Secondly, a change detection analysis was conducted to determine the areas within the study area with significant changes in depth. The ArcGIS raster calculator was used to compute the difference between two overlayed pixels by subtracting the 1977 bathymetry from the 2021 bathymetry. Lastly, slope profiles of both datasets were created. The slope of the Bay drives the local acceleration of currents and can cause erosion as it moves sediments and creates bedforms (Dolan, 2012). The slope of the ocean floor is of geomorphological importance to benthic habitats and, because sediments move downslope in response to gravity, the slope of the ocean floor is linked to the process of sedimentation. A slope analysis would, therefore, provide valuable insights into the degree to which the Bay has changed since 1977. 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.

3. All the results generated were analysed to gain a clearer understanding of the extent to which the bathymetry of Saldanha Bay has changed since the construction of the PoS. Results

3.1. 1977 Surface model results

The 1977 surface model was classified into 16 classes of depth, ranging from 1 m to 24 m. The result is displayed in Figure 4, where dark blue indicates deep water and light blue, shallow water areas.

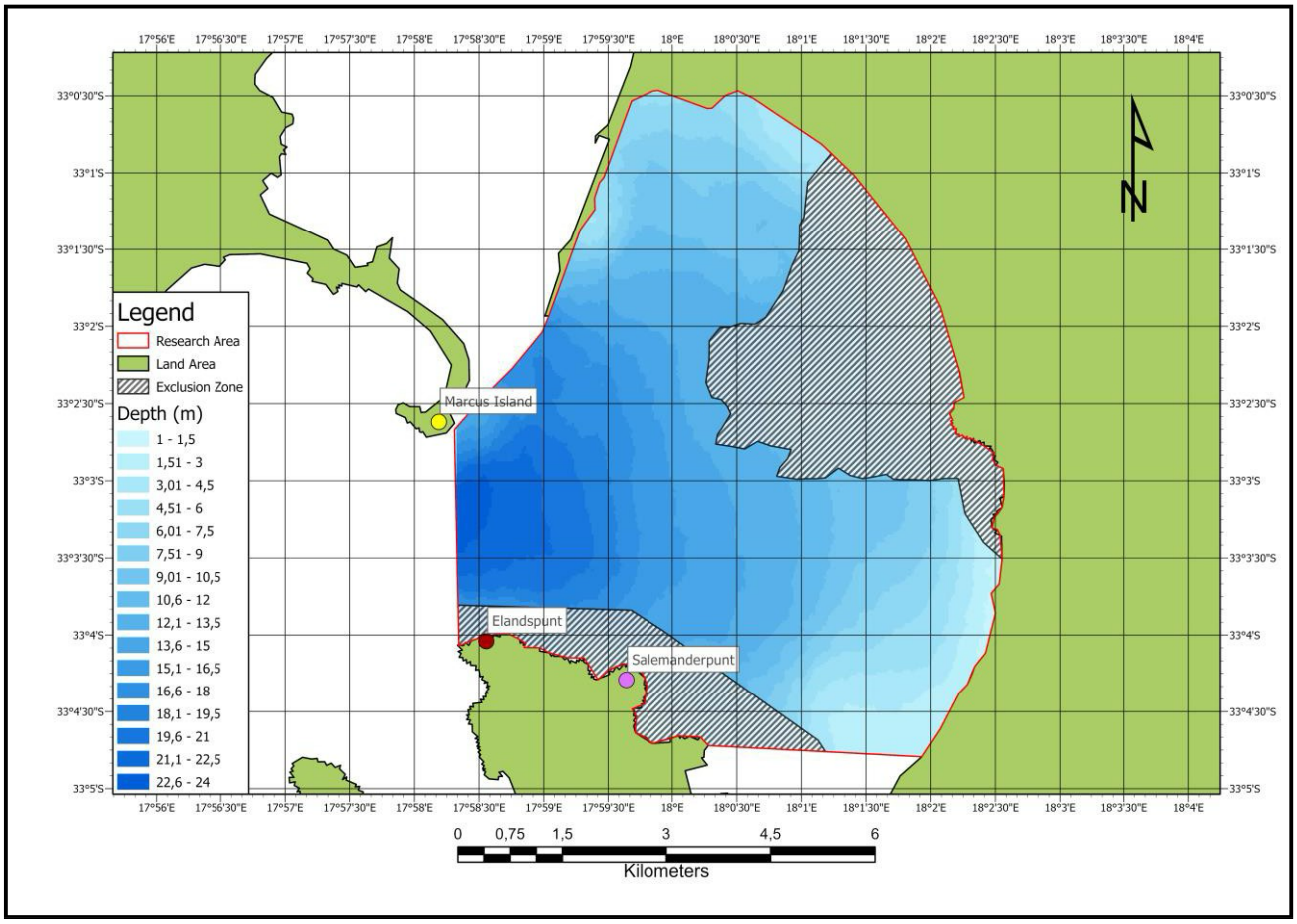

Figure 4. Surface model representing the 1977 bathymetry of Big Bay

The 1977 surface model result (Figure 4) shows that the bathymetry of Big Bay becomes gradually shallower towards the shoreline, resulting in the even dispersal of energy across the shoreline. A depth frequency breakdown of the Saldana Bay bathymetry in 1977 is illustrated in terms of the graph in Figure 5, with the X-axis depicting depth in metres and the Y-axis depicting count (number of pixels).

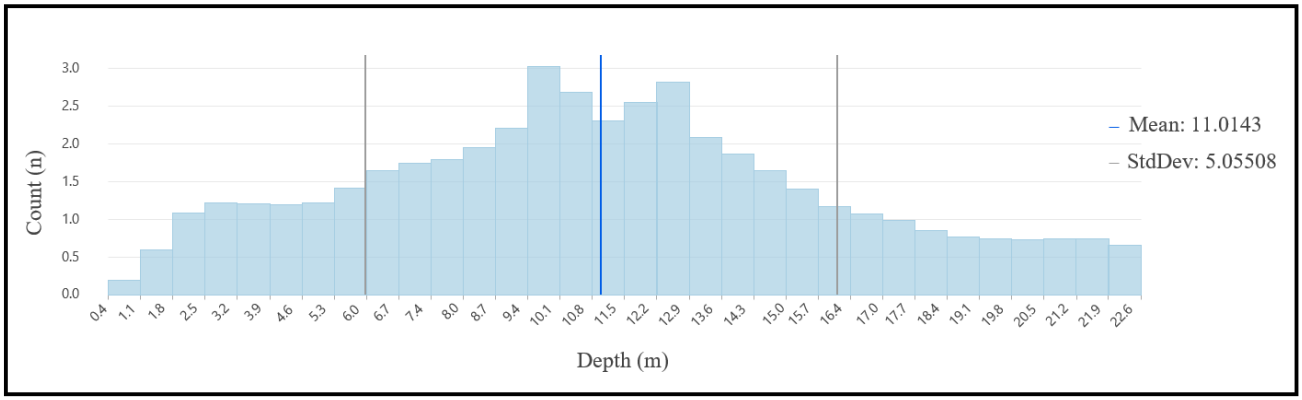

Figure 5. Distribution of depth measurements for 1977 bathymetry

Figure 5 shows 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 was 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.

3.2. 2021 Surface model results

For comparison purposes, the 2021 surface model was also classified into 16 classes of depth ranging from 0.532 m to 27 m. The result is displayed in Figure 6, where dark blue indicates deep water and light blue, shallow water areas.

The 2021 surface model result shows an overall tendency for the bathymetry of Big Bay to become gradually shallower towards the shoreline. Sharp increases in depth, indicated by the dark blue areas, are noticeable off Elandspunt and Salamanderpunt. Although some differences are visible between the 1977 and 2021 surface models, the trends between the two datasets are largely similar. The depth frequency breakdown of the Saldana Bay bathymetry in 2021 is illustrated by the graph in Figure 7.

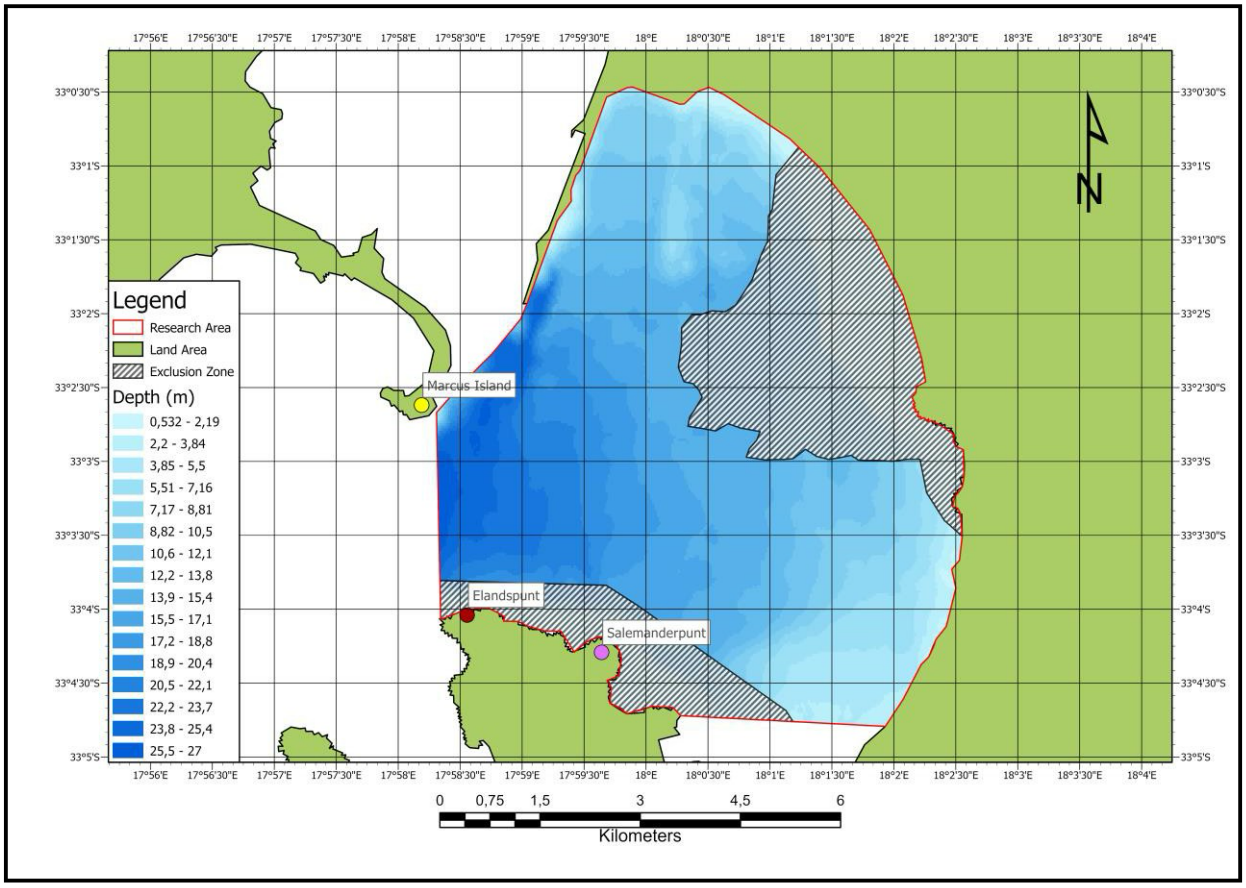

Figure 6. Surface model representing the 2021 bathymetry of Big Bay

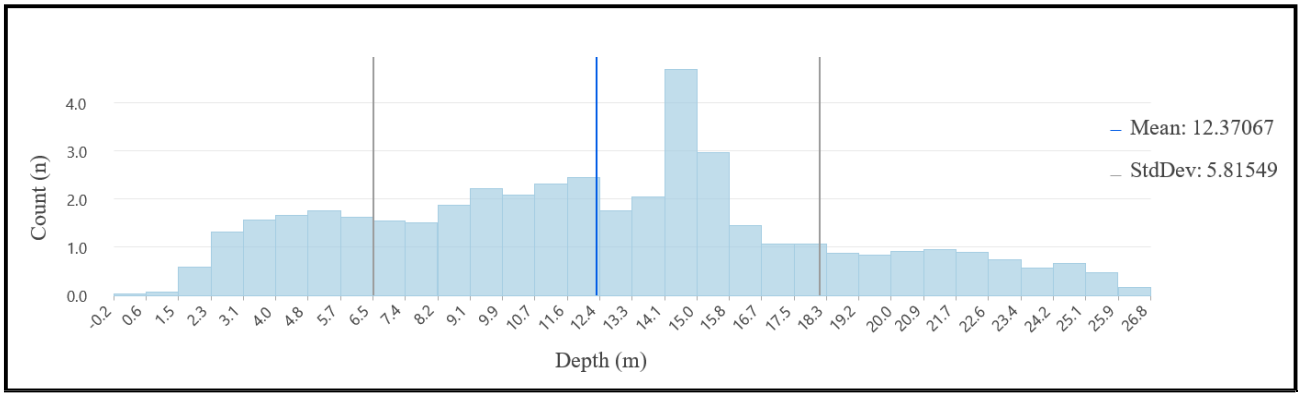

Figure 7. Distribution of depth measurements for 2021 bathymetry

Figure 7 illustrates pronounced skewness towards the 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 deeper than those measured in 1977, thus indicating an overall increase in depth across the Bay over 44 years. On considering the average depth of 12.3 m, a substantial increase of 1.3 m could then be calculated, the magnitude of which ultimately indicates that there has been an overall increase in depth in the Bay since 1977.

3.3. Change detection results

The results of the change detection analyses are illustrated in Figure 8 below. 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 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 three metres).

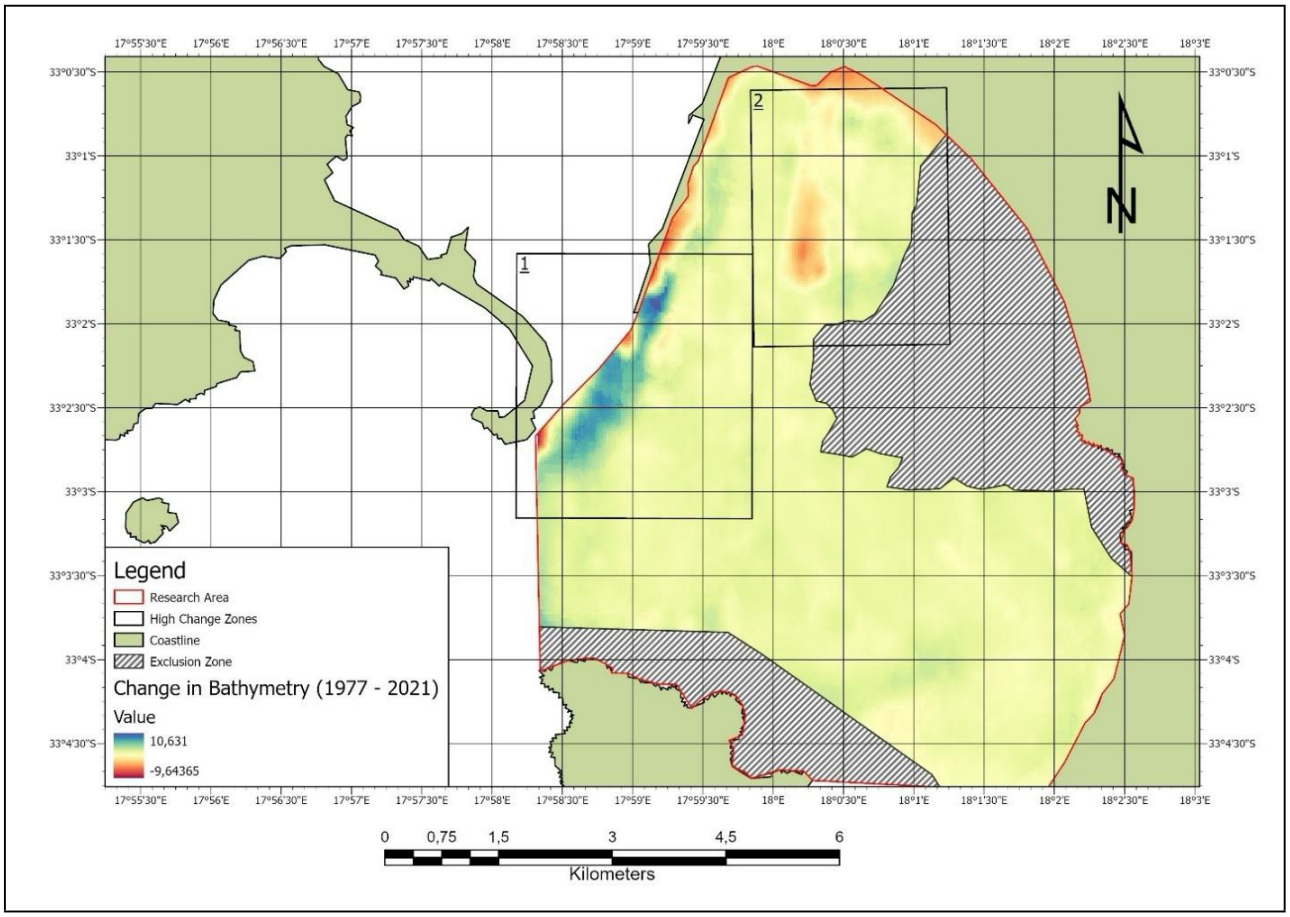

Figure 8. Map illustrating change in bathymetry between 1977 and 2021

From the change detection map, the majority of Big Bay experienced a slight increase in depth. However, there are two areas which experienced major change. Zone 1 is located between the tip of the iron ore jetty and Marcus Island, at the end of the breakwater, and shows an increase in depth (blue in Figure 8) of up to 10.6 m. Zone 2 is located on the eastern side of the iron ore jetty, close to the shore and is the only area within Big Bay that has experienced a significant amount of sediment deposition, resulting in a decrease in depth (red in Figure 8). Some areas in Zone 2 have experienced a depth decrease of almost 10 m.

To gain a more quantifiable understanding of the overall change in bathymetry of Saldanha Bay between 1977 and 2021, the change detection raster file was explored from a statistical viewpoint.

To this end, a histogram graph was compiled to illustrate the distribution of change in depth throughout the study area (see Figure 9). This was done by grouping individual pixel depths together and estimating the number of pixels with the same change in depth values.

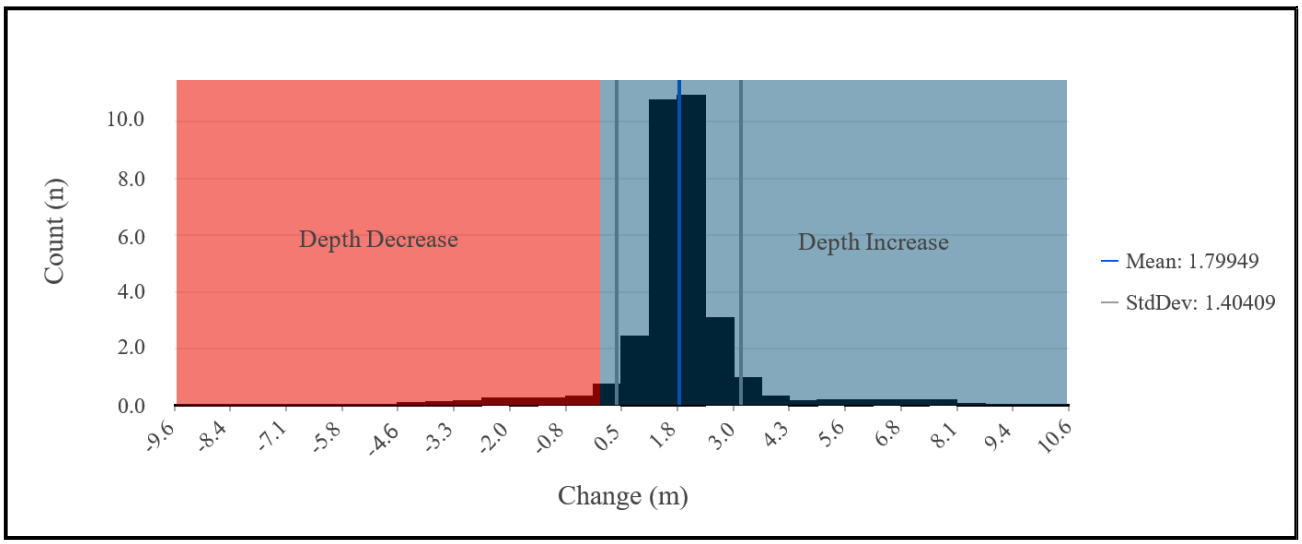

Figure 9. Histogram of the distribution of change in bathymetry between 1977 and 2021

The X-axis indicates the amount of change in depth (m) that occurred between 1977 and 2021 for a specific pixel, whereas the Y-axis indicates the number of pixels which experienced a certain amount of change in depth. The mean and standard deviation are also indicated on the graph.

The mean value (blue line on Figure 9) indicates an average increase in depth across the entire research area of 1.799 m. With an area of 27.44 km^2, this equates to a total volume loss of 49 364 560.0 m^3 in sediment. It is important to note that these calculations are based only on the 'inclusion zone', and not on the entire Big Bay area.

It is evident that most of the study area experienced an increase in depth, as most of the pixels have positive values (on the blue side of the X-axis). The standard deviation of the change detection dataset is 1.404 (grey lines on Figure 9). Consequently, 68.2% of the data fall between 0.395 and 3.203 m. Furthermore, the standard deviation is relatively small, indicating a distribution of data close to the mean value. Notice that these values are still positive, above zero, which effectively means that approximately 70% of the study area experienced a depth increase of up to 3.2 m.

However, there were areas that experienced a change in depth that fall outside the standard deviation of the dataset, i.e., areas experiencing a depth decrease of any kind and a depth increase of more than 3.2 m. These areas are located in Boxes 1 and 2 in Figure 8.

3.4. Slope analysis results

The distribution of gradients in slope for Big Bay for both 1977 and 2021 is illustrated below. As shown in Figure 10, the slope gradient across Big Bay in 1977 averaged at 0.37 degrees and was generally less than 0.9 degrees. There were some areas in the 1977 representation of Big Bay which showed a steeper slope, with the maximum recorded slope being 7.3 degrees, that mainly coincided with the sharp escarpment of the coast off Salamanderpunt. A standard deviation of 0.49712 and a mean of 0.37381 indicate that most of the study area in 1977 had a relatively shallow gradient (below 0.5 degrees), pointing to a gentle change in depth across the area.

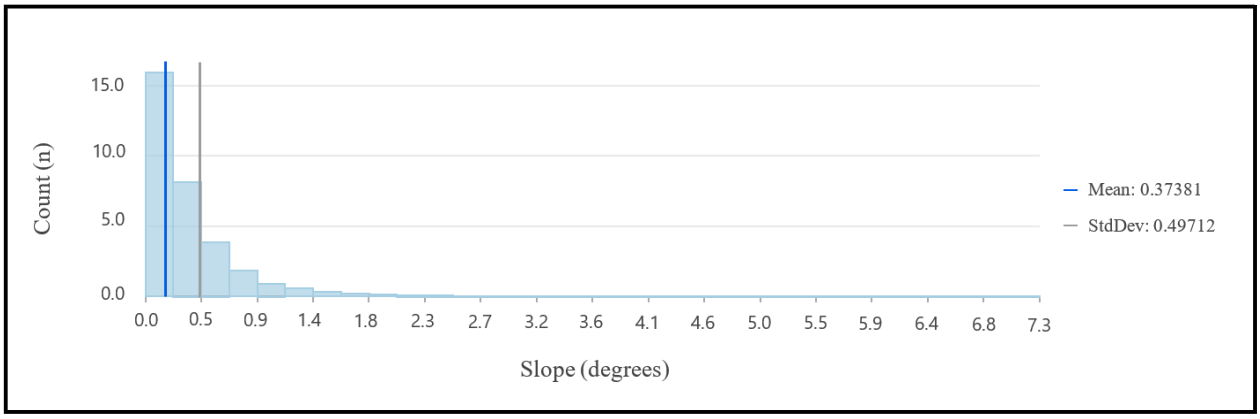

Figure 10. Graph illustrating the distribution of the slope of Big Bay in 1977

Figure 11 illustrates the general slope trend of Big Bay in 2021. It is fairly similar to that of 1977, except for an overall slight increase, with an average gradient of 0.51 degrees recorded in 2021, which is 0.2 degrees more than in 1977. Furthermore, in 2021, most of Big Bay had a gradient of approximately 1.3 degrees, which is 0.4 degrees more than in 1977. A standard deviation of 0.77772 and a mean value of 0.51054 were calculated for the 2021 dataset. Since these values are higher than those for the 1977 slope analysis, this is an indication that there has been a slight increase in depth since 1977 in the average slope gradient within the study area.

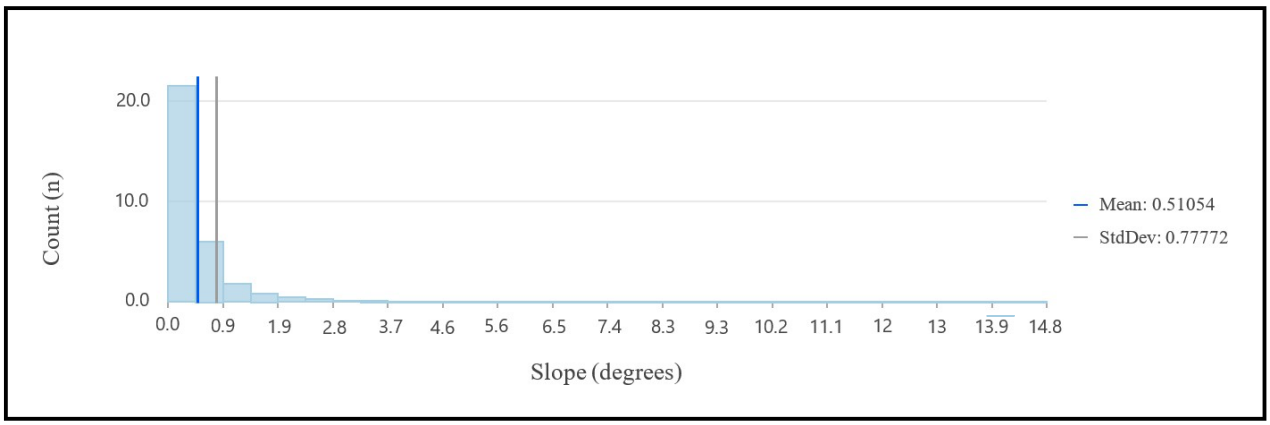

Figure 11. Graph illustrating the distribution of the slope of Big Bay in 2021

In 2021, Big Bay also showed an increase in the maximum slope (14.8 degrees) recorded in the Bay which is more than twice the maximum slope recorded in 1977, most likely because of the dredging activities, which resulted in major local depth changes.

4. Discussion of results

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

The change detection analysis also detected two areas or zones which indicated changes in depth beyond the first order of the standard deviation. Zone 1 (Box 1) 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. Zone 2 (Box 2) indicated a significant decrease in depth, pointing to sediment deposition. It is suggested that this deposition could be largely attributed to the changes in flow pattern caused by the construction of the PoS, resulting in a reduction in the flow within this zone. This does indeed point to the construction of the PoS as a possible cause of the change in the bathymetry identified within this area.

Finally, a slight increase in the overall slope of the study area was also detected. The increase in slope was not large enough to reveal its impact on the sediment transport processes within the study area. However, it can be stated that the increased slope could be largely attributed to essential dredging activities to deepen the approach channel to accommodate large vessels (Smith et al., 2019). Other possible influences on the slope could include the deposition of sediment from the dredging activities identified in Zone 2 (Figure 8).

From these results it is possible to state that the construction of the PoS, and the anthropogenic activities related to the upkeep of the Port did in fact result in changes to the bathymetry of Big Bay between 1977 and 2021. However, owing to limitations regarding data collection, only a portion of Saldanha Bay could be analysed. From a scientific perspective, larger time series before and subsequent to the port construction would be needed to gain better insights into the extent of natural sediment dynamics as a reason for the observed changes.

5. Conclusion and recommendations

Over the years, various studies on Saldanha Bay have been conducted. They include the impact of the construction of the PoS on the bathymetry of the Bay and the impact of sedimentation. However, post-1977, new and updated bathymetry data on Saldanha Bay has been lacking, thus

preventing accurate investigations into the impact of the construction of the PoS on the bathymetry of the Bay and determinations as to what has changed over the past 44 years.

It was confirmed by this study that changes in the bathymetry of Saldanha Bay have indeed taken place between 1977 and 2021. It was mentioned by Flemming (1977) that changes in the bathymetry of Saldanha Bay would result in changes in all the other hydrographical characteristics of the Bay. This study has shown that changes have indeed occurred, and it would be interesting to determine whether the changes made to the bathymetry of Saldanha Bay during the construction of the PoS potentially catalysed the erosion and siltation processes impacting on most of the Langebaan beaches. These morphological changes have in recent years caused the Saldanha Bay Municipality to construct a groyne embankment to increase the natural deposition of beach sand to stabilise and rehabilitate the vanishing Langebaan beachfront (Henrico and Bezuidenhout, 2020).

The findings of this study further verify the statements made by Flemming (1977) and Henrico and Bezuidenhout (2020) that the anthropogenic activities (construction of the PoS and dredging) have changed the sedimentation processes within Saldanha Bay. However, as indicated in Figure 3, the findings of this study are only relevant for a portion of Saldanha Bay, namely, the inclusion zone in Big Bay. In this area there has been a total volume loss of 49 364 560.0 m^3 in sediment. The exact nature and driving forces behind this loss in volume and where these sediments are being deposited still requires further investigation.

This study was limited to the extent of the survey that was conducted in 2021. A complete survey of Saldanha Bay is required to gain a full understanding of how the bathymetry of Saldanha Bay has changed since the construction of the PoS. From this, it is important to conduct research which will improve our understanding of these changes, and the extent to which they are due to direct anthropogenic intervention (i.e., dredging) and how much these changes relate to changes in the hydrodynamic and sediment transport processes within Saldanha Bay.

6. Acknowledgments

The National Hydrographer is thanked for kindly releasing the bathymetric and chart data of Saldanha Bay.

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