

Determining the change in the bathymetry of Saldanha Bay due to the harbour construction in the seventies

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Abstract

Bathymetry is the science to study and measure the depths of the ocean floor. The differences in water depth, underwater slope and ocean floor structure were investigated using a geographic information system (GIS). This article investigates changes to the hydrodynamic sedimentation processes in Saldanha Bay as a result of the harbour constructions that took place in the early 1970s. The construction of the harbour included the massive dredging operations and resultant relocation of 30 million m³ of soil. Bathymetric data from Saldanha Bay before (1957) and after (1977) the construction of the harbour in the early seventies were analysed and compared in ArcGIS. It was found that the overall depth of the inner part of Saldanha Bay increased with about 1.4 m and that the bottom and slopes were smoothed. The physical structure that was constructed for the harbour had a serious impact on the hydrodynamic sedimentation processes. It was found that these interventions altered the depth profile of the Bay and the article finally draws conclusions on coastal and beach formation, based on the change in the hydrodynamic sedimentation processes of Saldanha Bay.

Keywords: bathymetry, hydrodynamics, GIS techniques, Saldanha Bay.

1. Introduction

Linked to the Langebaan Lagoon, Saldanha Bay is a significant natural harbour approximately 100 km north-north-west of Cape Town, South Africa. Saldanha Bay was formed as a result of unique geological events dated at ~500 Ma (Bezuidenhout and Potgieter, 2018) and the current broken shoreline of the area consisting of various types of granites and ignimbrites is evident to this. Saldanha was, however never developed as a harbour by the European seafaring powers, notwithstanding the ideal anchorage and its setting on one of the major trade routes. The reason for this was mainly due to the lack of reliable sources of fresh water in the area. This changed during the Second World War when Saldanha Bay was selected and consequently fortified by the Allied forces as a naval convoy assembly point. A 35 km fresh water pipeline was also constructed from the Berg River and this had a fundamental impact on the potential of the Bay (Visser et al., 2008).

After WWII, various fishing enterprises and military units were established around the Bay and the local population grew steadily. The construction of an iron ore port commenced in May 1973 with

the first iron ore shipment leaving Saldanha Bay during September 1976. During this development, a 3.1 km long causeway that includes a 900 m long iron and oil loading jetty, a stockpile area and a 1.7 km breakwater (Figure 1) were constructed (Hudson, 2020). Figure 1 shows a historic chart of Saldanha Bay that was completed before the breakwater, iron ore jetty, causeway and stockpile area were built, these structures are artistically added to the figure.

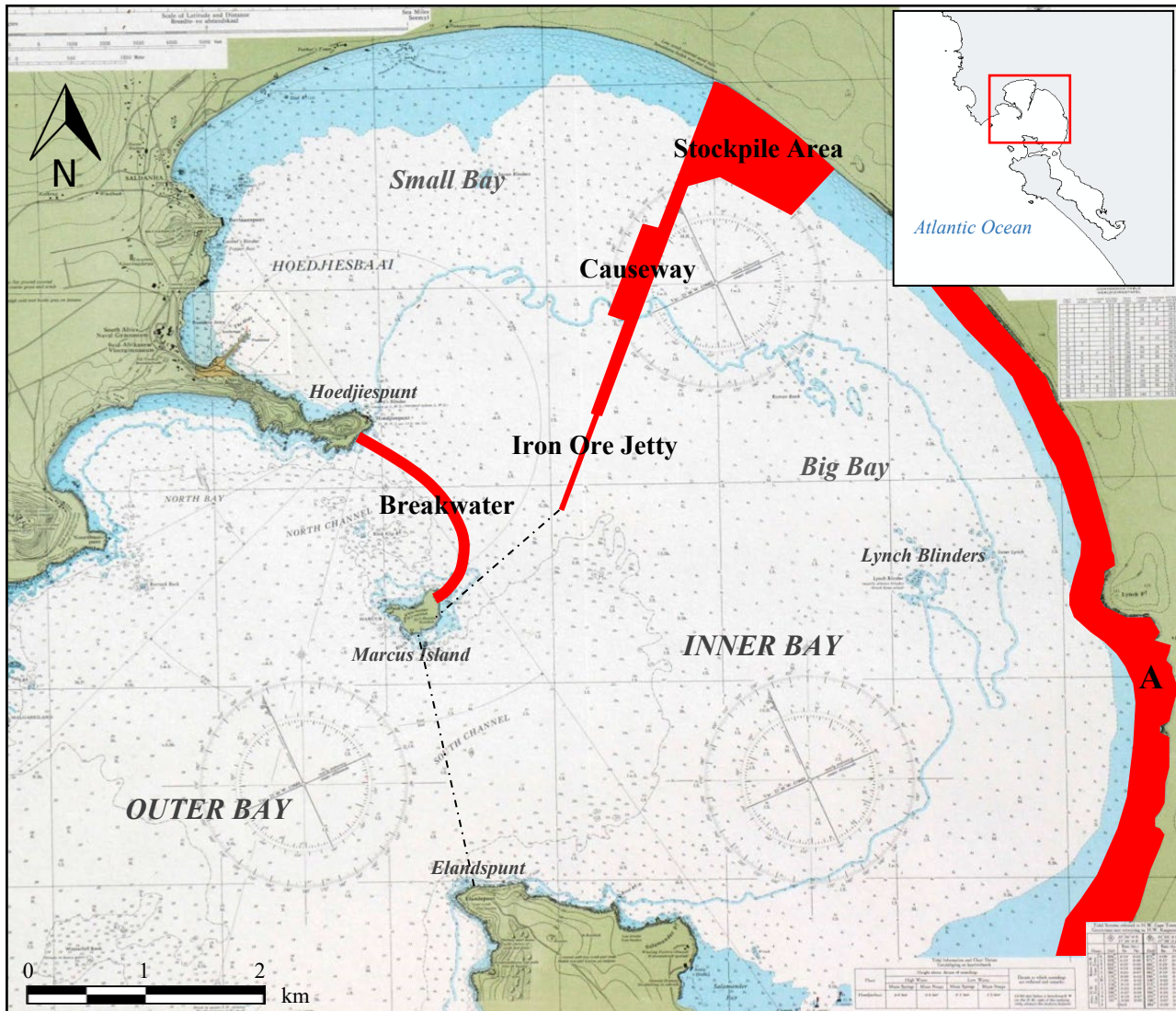


Figure 1: Orientation chart - a picture of a historic chart of Saldanha Bay, which indicate in red where the breakwater and iron ore jetty were built, as well as an area A where erosion took place (The Hydrographer of the South Africa Navy, August 1957).

During the harbour construction in the seventies, a quay channel with a depth of 23 m and a turning basin of 580 m in diameter was also dredged. This gives 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. The Port of Saldanha consists of an Inner Bay and Outer Bay region which were partially formed with the construction of the breakwater that connected Hoedjiespunt with Marcus Island (Smith and Pitcher, 2015). These regions which are separated by an imaginary boundary between Marcus Island and Elandspunt are indicated on Figure 1. The Inner Bay is further split by the causeway into Small Bay on the west and Big Bay on the east

which is separated by an imaginary boundary between the end of the jetty and Marcus Island (Smith and Pitcher, 2015). The Port of Saldanha is the largest on the African continent regarding the export of iron ore and currently handles approximately 60 million tons of cargo per year (Transnet, 2018). Part of Transnet's short and long term port development plans are the expansion of the Port of Saldanha Bay to include upgrades to the rail system and construction of additional berths, pipelines and quays. This would increase the handling of cargo volumes to approximately 90 million tons per year within the next 30 years (Transnet, 2017).

The post-war development significantly altered the hydrodynamics of the Saldanha Bay and the Langebaan Lagoon. As a result of this beach sand deposit patterns started to change, with several beaches showing signs of erosion. The area where noticeable erosion occurred is marked as A in Figure 1 and this include beaches like Paradise, Leentjiesklip and Calypso.

Lopez et al. (2017) states that coastal erosion is one of the main contributing factors that influence the natural characteristics of coastal water bodies. Coastal erosion is caused by anthropogenic factors, such as man-made construction of harbours, breakwaters and water channels, and through natural processes, such as storm surges, river runoff, coastal wave setup, extreme seasonal and tide changes and sediment morphology (Lopez et al., 2017; Woodworth et al., 2019). In terms of sediment morphology, Aragonés et al. (2016) states that changes to water depth influence sediment movement which inevitably influences the structure of coastal areas.

This study investigated the man-made interventions and consequences on the bathymetry of the Saldanha Bay. The results of this study suggest that the harbour construction in the seventies did have consequences on the coastal and beach formation that influenced the natural characteristics of the Bay. A follow-up study that investigates the degree of influence on the coastal and beach formation of the Bay, by comparing the results of this study with up-to-date bathymetry data of Saldanha Bay, is planned.

This study employed geographic information system (GIS) techniques to model and investigate the bathymetry of the Bay by studying charts before and after the major harbour construction took place. The changes to the hydrodynamic sedimentation processes are highlighted, which resulted in coastal erosion to occur and ultimately influenced the coastal and beach formation of the Bay. The following sections deal with the methods, analyses, results and conclusions of this study.

2. Methodology

Geographic information systems are widely used to study the effects that human actions and natural processes have on the bathymetry of coastal areas (Flemming, 1977; Weeks et al., 1991; Aragonés et al., 2016; Li et al., 2001; Van Der Wal and Pye, 2003). Most of these studies focus on a set of factors, such as sediment morphology, storm surges, wave actions, wind-forcing, channelling and port construction as the major contribution factors to coastal erosion. Some studies do not focus on the factors that cause coastal erosion, but evaluate the instrumentation accuracy (Sánchez-Carnero et al., 2012; Dierssen and Theberge, 2014) and bathymetry data interpolation techniques (Tranchant

and Vincent, 2000; Giordano et al., 2015) to state the most accurate means and methods to use when conducting bathymetry analysis. Studies regarding Saldanha Bay bathymetry that investigated the impact of dredging and the construction of the causeway and jetty at the Port of Saldanha Bay, found that these anthropogenic factors do affect the morphology and distribution of the sediments that impacts the environment, causing erosion of the Langebaan beaches (Luger et al., 1999; Wiese, 2013). However, these studies also found that the impact is within acceptable ecological limits and the influence on the natural characteristics of the Bay is insignificant.

Similarly, to the studies by Luger et al. (1999) and Wiese (2013), this study focus on the anthropogenic factors of dredging and the construction of the causeway and breakwater at the Port of Saldanha Bay. However, this study is unique because it compares two time series bathymetric data sources (before and after the harbour construction) of the Saldanha Bay area, acquired from The Hydrographer of the South African (SA) Navy and draw conclusions on the coastal and beach formation. It was found that the harbour construction in the seventies radically changed the hydrodynamic sedimentation processes of Saldanha Bay, causing coastal erosion.

2.1. Software

The ArcMap 10.5.1 GIS application was employed to process, analyse and present the data. The ArcGIS for Desktop platform is a GIS software with functionalities to work with geospatial data. Its many capabilities range from mapping and data manipulation and management to spatial analysis (ESRI, 2019). It is an ideal application for analysing water depths, because it includes statistical and surface modelling tools with various interpolative methods to analyse and map data trends.

2.2. Bathymetric data collection and pre-processing

The bathymetric data used to analyse the depth profile of the Saldanha Bay consisted of two time series datasets (1957 and 1977) that included 3 475 and 1 292 georeferenced elevation points, referred to as soundings (Figure 2). Sea floor topography (bathymetry) can be measured by various means – such as aircraft, satellites, drones and ships (Giordano et al., 2015), and instruments, such as lead lines (an early technique to drop a line from a ship to estimate sea floor depth), vertical beam echosounders (VBES), singlebeam echosounders (SBES), multibeam echosounders (MBES) and Light Detection and Ranging (LiDAR) instrumentation (Menza et al., 2012; Westington et al., 2018). Traditionally, ships are utilised to collect bathymetry data. The MBES is a Sound Navigation and Ranging (SoNAR) instrument, which is nowadays more commonly used to capture millions of precise soundings that measure the sea floor depth (Costa et al., 2009; Hasan et al., 2014). These instruments are mounted under or on the side of the ship and sends a beam of sound to the bottom of the sea floor that bounces of the sea floor and reflects back to the instrument. The speed of reflected signals informs the SoNAR of the distance to the sea floor that records these measurements, known as soundings (Menza et al., 2012; Dierssen and Theberge, 2014; Westington et al., 2018). These soundings can be interpolated to create very high resolution bathymetric maps.

Data mining consisted of applying pre-processing methods to capture, sort, convert and clip the acquired data for analysis (Nallan et al., 2014). The soundings of these two datasets (1957 and 1977) were pre-processed and the surface interpolation results were clipped to the area of interest boundary indicated by the extent of Figure 2.

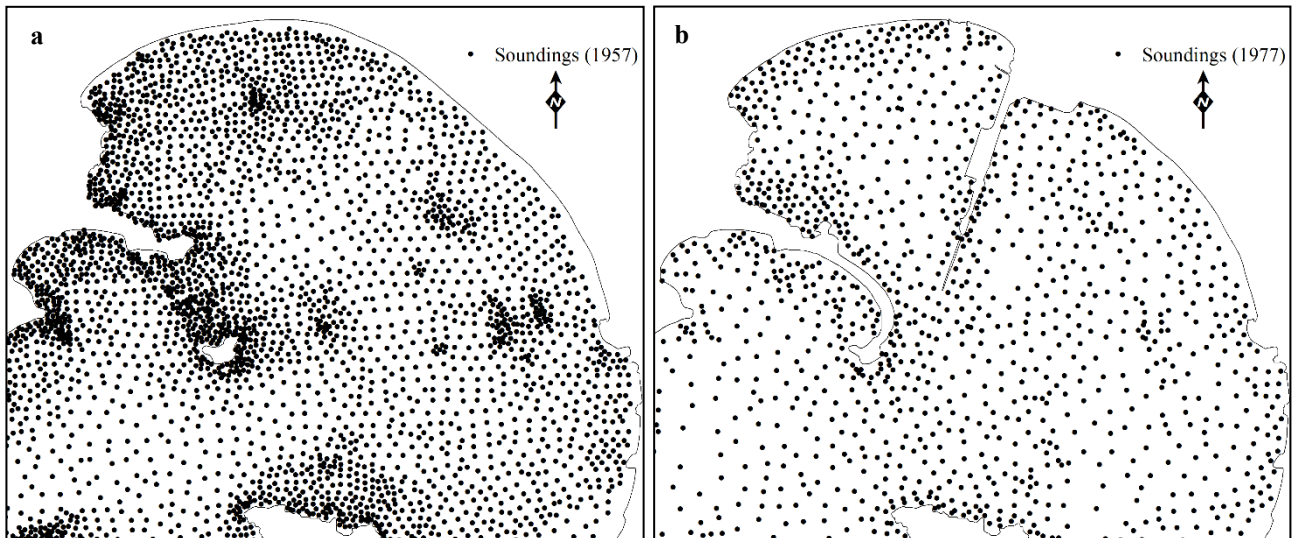


Figure 2: Bathymetric sounding layers used during analysis at a scale of 1:60 000: (a) first time series data (1957) with 3 475 soundings, and (b) second time series data (1977) with 1 292 soundings.

The first time series data were derived from the 1:14 400 scale Hoedjiesbaai chart published in 1957, by the SA Hydrographic Office. The chart was projected to the Transverse Mercator projection and the coordinate system was WGS 1984 UTM Zone 34S. This chart was used to capture by means of digitising the 3 475 soundings in Fathoms, which were converted to metres (Figure 2a). The second dataset consisted of 1 292 soundings which were surveyed in 1977 by The Hydrographer of the SA Navy. These soundings were received as a projected point dataset in meters (Figure 2b).

Both these datasets had the same projection and heights and were either converted or received to metres above Mean Sea Level. Datasets need to be similar to illustrate fluctuations and changes over time and conduct an accurate assessment of the results, which is a necessity when comparing two datasets (Li et al., 2007).

2.3. Interpolation technique and slope creation

After pre-processing, the bathymetry point datasets were interpolated to produce two bathymetric digital elevation models (DEMs) with a ground sampling distance of 5 m. The Spatial Analyst extension in ArcGIS consists of various interpolation tools that predict the values and locations of sample points. Interpolation measures the degree of association between objects and is based on the principle of spatial correlation (Childs, 2004). It considers similarities and interdependence to predict sample points through weighted averages. The Ordinary Kriging interpolation method with a spherical semivariogram model was used during this study. It is a geostatistical interpolation technique that uses a weighted linear combination of known sample points to estimate the values of

cells at locations that lack sampling points (Longley, 2005; GIS Resources, 2019). It is the default Kriging method in ArcGIS and assumes that there is no trend in the spatial relationship between features, unlike the Universal Kriging method that estimates trends between data. For display purposes, the bilinear interpolation resampling method (available through the raster layer properties on the Display tab of the ArcGIS software) was used to smooth out the pixel appearance of the interpolated DEM results. These results are described as bathymetric maps and are illustrated by Figures 3 and 4.

The next step was to create a slope analysis (Figure 5), because of its geomorphological importance to benthic habitats and link to sediment surfaces. The local acceleration of currents cause erosion, it moves sediments and creates bedforms (Dolan, 2012), for which slope is a good indicator. The Slope tool was used to create the slope products and the Degree Output Measurement setting was selected to illustrate the inclination of slopes in degrees.

2.4. Change detection

The last step of the data analysis involved change detection to illustrate the change in the depth profile of the Saldanha Bay from 1957 to 1977. To achieve co-registration between the two sounding point datasets, both these datasets were clipped to the same area of interest boundary. The geostatistical method of Ordinary Kriging that includes autocorrelation of measured points was used to create the interpolated surface maps with an output cell size of 5 m. The interpolation results therefore covered the same geographical extent which is essential for performing the change detection technique.

The 'Difference' tool in the ArcGIS Image Analysis window was used to compute the change between the 1957 and the 1977 bathymetric maps. This tool creates a pixel-over-pixel comparison in the form of a grey-scale temporary raster layer that can be exported as a raster dataset (Henrico et al., 2020). The symbology style of this analysis product was changed to display a red-to-blue colour ramp (Figure 7), where red hues represent negative changes that indicate deep water areas and blue hues represent positive changes that indicate shallow water areas.

3. Results and Discussion

Harbours that are constructed in bays regularly suffer from siltation of their basins. River mouths that deposit large amounts of alluvium into these bays are often the major cause of changes in its bathymetry (Van Schijndel and Kranenburg, 1998). Large amounts of fluvial sediment, such as gravel, sand, silt, and clay are commonly deposited in these bays, especially when rivers are in flood. The harbours consequently require continuous dredging in order to ensure safe shipping lanes. Saldanha Bay has no rivers that enter the bay, apart from a few perennial springs. The bathymetry of Saldanha Bay before the harbour construction of 1973 was therefore only influenced by cyclic natural tidal processes and wave action. This would have resulted in a relatively stable bathymetry that was

mainly guided by the resistant granitic shoreline of Outer and some part of Inner Saldanha Bay (Figure 1). The bathymetric map of 1957 demonstrates this with the Outer Bay becoming systematically shallower up to Marcus Island (Figure 3). The Inner Bay shows the same tendency except for the area around Lynch Blinders in the eastern part of the Bay.

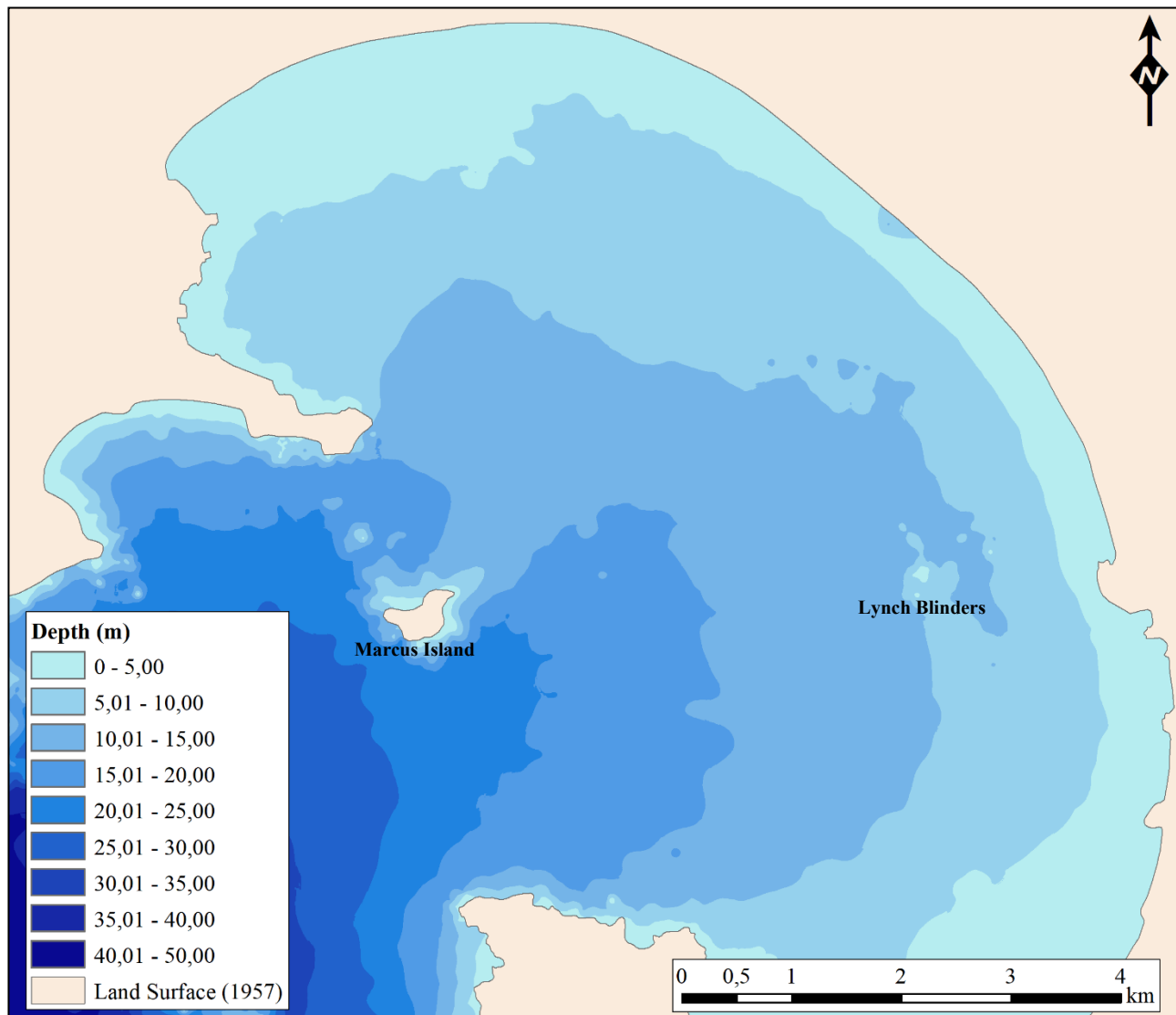


Figure 3: Surface interpolation result indicating the bathymetry map of Saldanha Bay before the harbour construction (1957).

The natural balance of this system was significantly disrupted by the harbour construction that commenced in the 1970s. The final construction of the causeway, the breakwater, the stockpile area and the jetty significantly changed the physical features and hydrodynamic sedimentation process of the Bay. The construction of the breakwater and the jetty effectively formed the two relatively isolated water bodies, known as Small Bay to the west and Big Bay to the east, which make up the Inner Bay area (Figure 1). Eight million m³ of sediment were dredged to create a shipping lane and turning basins adjacent to the jetty (Zwemmer and Van't Hof, 1979). The notable impact of the harbour construction on the coastal and beach formation is evident when comparing the red hatch fill area marked A in Figure 4 with the same area in Figure 3. The depth profile range of 0 – 5 m for 1977 indicates that the coastal area is steeper than in 1957, which is an indication of coastal erosion. When

comparing Figures 3 and 4, it is also noticeable that the Inner Bay is much more even after the construction when compared to before the harbour was built. The dredging had a noticeable effect on the sedimentation processes that smoothed the ocean floor of the Bay.

The West Coast experienced significant storms during May 2020 and afterwards, which severely eroded the beaches in the area marked A. This may have been as a result of the change in depth profile of that area. The Saldanha Bay authorities then took measures to stop the erosion on the affected beaches through the construction of a bolder beachfront wall that could act as a wave breaker. A groyne embankment was also erected to increase natural deposits of beach sand (Kaytech Engineering Fabrics, 2011) to stabilise and rehabilitate the vanishing Langebaan beachfront.

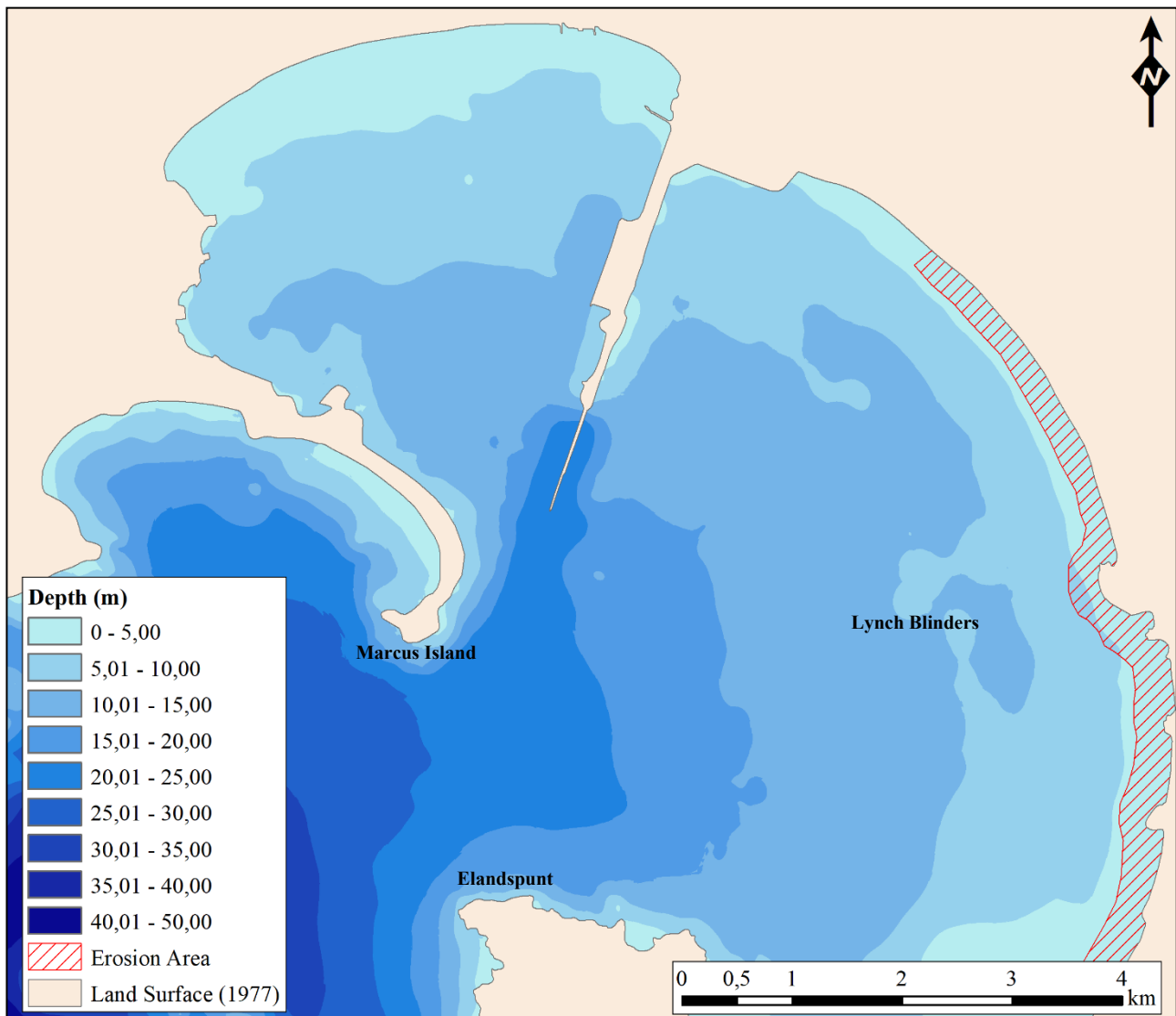


Figure 4: Surface interpolation result indicating the bathymetry map of Saldanha Bay after the harbour construction (1977). The area of beach erosion is indicated by the red hatch fill.

The harbour construction also had an influence on the slope profile of the bathymetry in the Bay. It is clear in Figure 5 that the slopes were more pronounced after construction occurred. This is specifically noticeable around Marcus Island where the breakwater was constructed. The steeper banks of the shipping channel are also visible around the jetty. During the construction dredged sand

was initially displaced by heavy sea and eventually stored in Small Bay at an area in the lee of Hoedjiespunt. This sand was used in the final stages of the causeway construction and the increased slopes in that area is also visible on Figure 5.

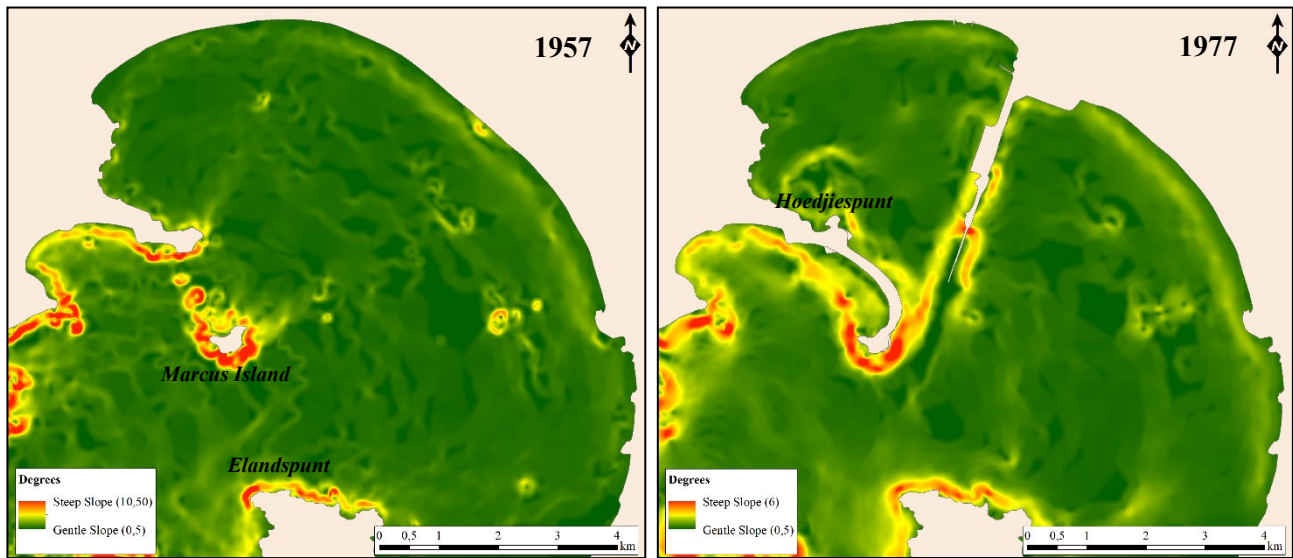


Figure 5: Bathymetric of Saldanha Bay that indicates the slope calculations in degrees before (1957) and after (1977) the harbour construction.

The harbour construction and dredging had a significant effect on the seafloor of Saldanha Bay that consequently impacted the bathymetry of the Bay. This is illustrated by bathymetric profiles measured at three prominent areas within the Saldanha Bay, which is indicated by lines A, B and C on the location inset (Figure 6). The 1977 depth profiles are smoother than the 1957 profiles and visible changes to the seafloor depth is noticeable which may be a result of the resettlement of finer sediment. The construction of the breakwater is easily visible by the variation in water depth for the 1977 (A to D) profile, indicated by the green circle. The effect of the harbour construction and dredging on the beach and coastal areas is visible when examining the bathymetric profiles. All three profiles show that the average depth of the Bay increased from 1957 to 1977, due to the dredging and harbour construction (Figure 6). The slope of the surf zone increased significantly, and this is most visible in profile C to D (red circles).

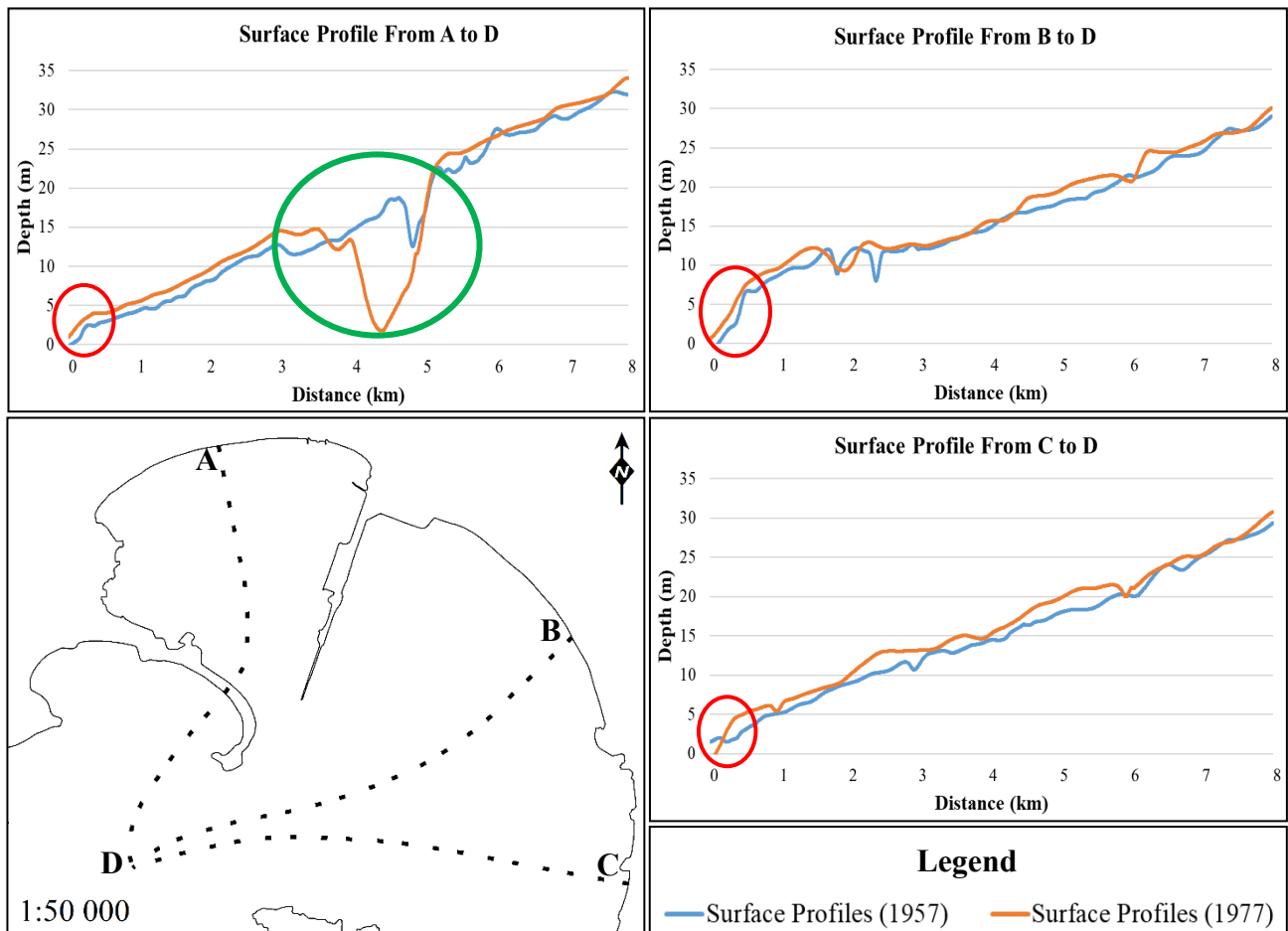


Figure 6: Bathymetric profiles of Saldanha Bay before (1957) and after (1977) the harbour construction. Adapted from Flemming (2015).

The construction of the causeway, the breakwater, the stockpile area and the jetty required about 30 million m³ of soil, which was mostly obtained by local dredging. This soil was dredged in both Small and Big Bay, which is illustrated by Figure 7. The high positive changes (10.6 m change difference) indicate deep areas (red hue) and the high negative changes (15.9 m change difference) indicate shallow areas (blue hue). Areas with small positive changes are indicated by the yellow colour and areas with small negative changes are indicated by the turquoise colour.

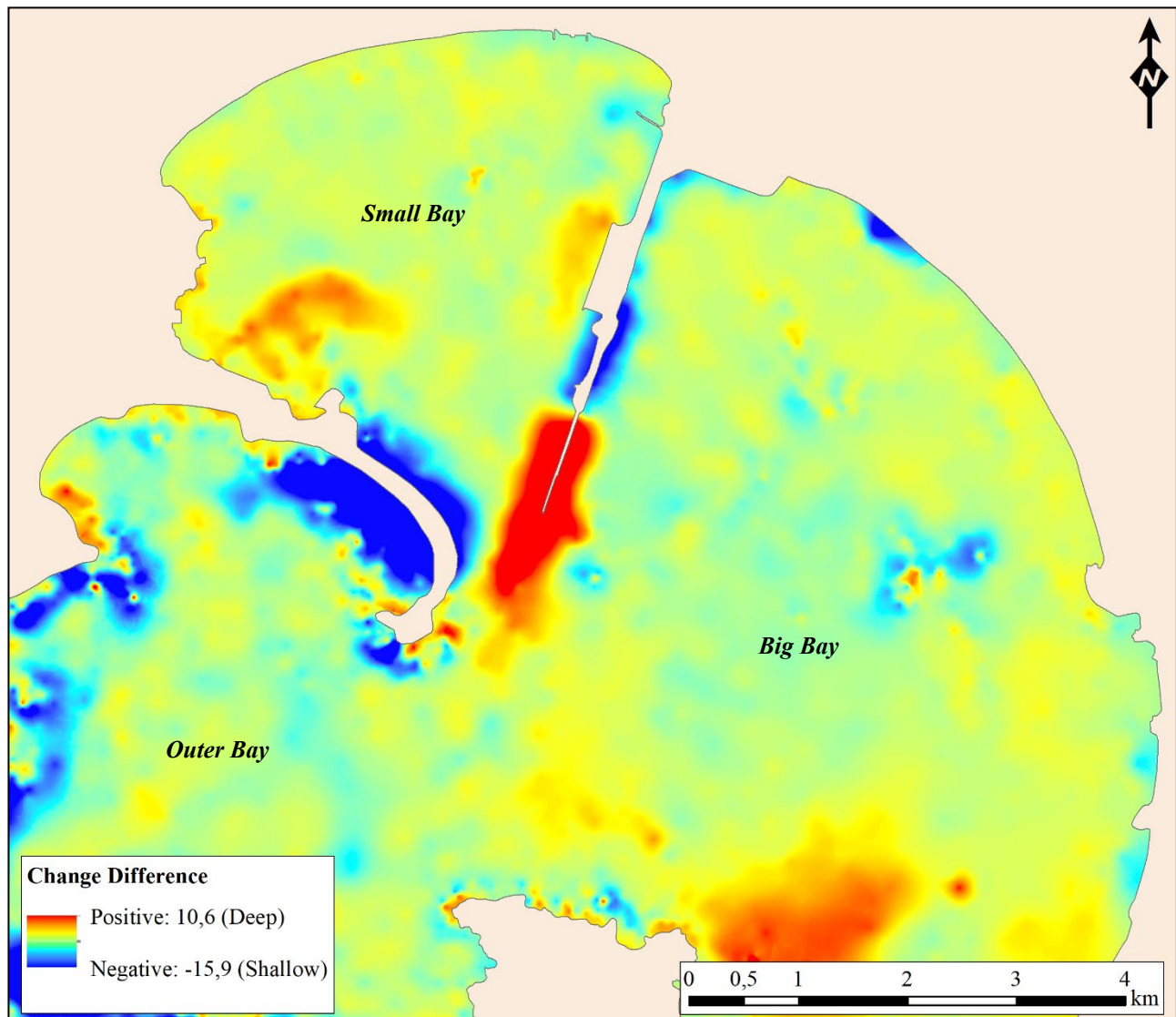


Figure 7: Bathymetric map of Saldanha Bay showing the difference before (1957) and after (1977) the harbour construction.

The dredging effectively increased the average depth of most of the Inner Bay (Small and Big Bay) by about 1.4 m, while the Outer Bay stayed relatively stable with a decrease in mean depth of approximately 0.6 m. The measurements of the Saldanha Bay soundings, collected in 1957 and 1977, for both the Inner and Outer Bays (see Figure 1) are indicated by Table 1.

Table 1: Bathymetry data indicating measurements of the Inner- and Outer Bay sections of Saldanha Bay for 1957 and 1977

Measurement of soundings at MSL				
Year	Bay section	Min. depth (m)	Max. depth (m)	Mean depth (m)
1957	Inner Bay	0.07	23.85	8.41
	Outer Bay	0.08	45.79	20.55
1977	Inner Bay	0.30	24.50	9.81
	Outer Bay	0.90	45.00	19.97

The culmination of the harbour construction is that Saldanha Bay became, on average, 0.8 m deeper, that the bottom of the Bay became more even and that current hydrological movement significantly changed with the addition of physical structures and the change in bathymetry. These changes had an obvious effect on the wave refraction and direction and tidal movement that altered the sediment deposition within the Bay, which made the north-north-eastern and eastern part of the coastal and beach formation more exposed and thus susceptible to erosion.

All of these changes will inevitably, over a prolonged period, have significant influences on the sandy parts of the coastline of the Bay. A follow-up study is therefore underway to investigate the degree of influence on the coastal and beach formation of the Bay, by comparing the results of this study and up-to-date bathymetry data of Saldanha Bay.

4. Conclusions

Saldanha Bay was naturally formed over an extended period of time. The harbour construction of the seventies radically changed the hydrodynamics of Saldanha Bay. In addition, it also changed the bathymetry of the Bay, due to extensive dredging in certain areas in the Bay in order to supply soil or building material to the harbour structure. This disrupted the normal sediment deposition and flow patterns, which resulted in erosion and siltation challenges in different parts of the Bay.

This 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. This study should be repeated with more current bathymetric data to determine how the Saldanha Bay sedimentation process changed after the harbour construction compared to the current situation. This will provide important information on current beach erosion and siltation challenges that exist within the Saldanha Bay.

5. Acknowledgement

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