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The influence of wave action on coastal erosion along Monwabisi Beach, Cape Town

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Abstract

The coastline to the east of the Monwabisi Beach tidal pool has been subject to substantial visible coastal erosion. Monwabisi is located near the City of Cape Town and is situated along the northern coastline of False Bay. The erosion that has occurred has raised concern as it is damaging local infrastructure. The coastline retreat to the east of Monwabisi was investigated through analysis of aerial photographs and wave data to establish whether there is a relationship between dynamic wave action that this bay is subjected to, and the observed erosion within the study area. The maximum lateral coastal erosion at the Monwabisi study area from 2003 until 2014 was approximately 30m in a landward direction. Based on the correlation of the results between the rate of coastline retreat and the wave data, the study has concluded that the extreme rates of coastline retreat experienced within the study area at Monwabisi is most likely a direct result of a combination of influences including the number and height of big wave events, waves coming from a more southerly direction, the underlying geological substrate of the study area, and the impact that the local infrastructure has had on the geological substrate. Three time periods of maximum monthly erosion rates occurred from June 2008 to November 2009, March 2010 to March 2011 and April 2011 to June 2012.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has reported and warned that global climate change and sea-level rise will seriously affect the natural environment and human society along coastal zones (IPCC, 2007). The average global temperature has increased during the past century (Hansen et al., 2006; IPCC, 2007; Rosenzweig *et al.*, 2008), and perhaps the most commonly recognised effect of this warming is the eustatic rise of sea level (Allen and Komar, 2006).

Coastline erosion is a global phenomenon aggravated by human activities with changes and modifications made to the coastal areas due to urbanisation (Unterner *et al*. 2011). The coastline of

South Africa is predominantly composed of soft sandy beaches with fewer rocky areas (Theron et al. 2010; Harris et al., 2011). High energy waves on this open coast result in favourable conditions for coastline erosion (Theron *et al.* 2010). A quantification of the risks associated with coastal erosion along the South African coast is essential when considering that over 40% of South Africans reside within 100km of the coastline and could be affected by future sea-level rise (SLR)-induced erosion (Unterner *et al.* 2011) and many of these areas are undergoing massive urban and population expansion (Theron *et al.* 2010). Waves, tides and SLR are the main contributors to coastal erosion and damage to local infrastructure in South Africa, especially when high intensity storms occur alongside high tides (Theron *et al.* 2010). One example of a high intensity storm event, that produced very large swells in conjunction with a high equinox tide, was the KwaZulu-Natal storm of 18-20 March 2007 (Smith *et al.* 2010). This event resulted in over R2 billion damages to infrastructure along the coast (Theron *et al.* 2010).

Here, we present a case study from Monwabisi Beach, False Bay, on the South African Cape Peninsula, where coastal retreat has been systematically measured to determine whether there is a direct relationship between wave action and coastline erosion. Prior research in this area undertaken by Hughes (1992) confirmed that False Bay is vulnerable to SLR induced erosion along most of its coastline and this is caused by storm surges. To date, however, little has been known about the impact of the high energy waves that these storms generate, and the influence they have on coastline retreat along the coast of False Bay. Monwabisi is one of the recreational areas that were developed along the northern coast of False Bay in 1987 (Theron & Schoonees, 2007) and has visible infrastructural damage along the coast which has occurred over the past three decades.

Figure 1. Aerial photograph of Monwabisi Beach which is located along the northern coastline of False Bay, Cape Town. The red rectangle marks the selected study area to the east of the tidal pool and recreational facilities.

Figure 2. Photograph showing the visible coastal erosion and damage to infrastructure at the Monwabisi study area.

2. Regional setting and coastal hydrodynamic regime

The South African west coast experiences a Mediterranean-type climate relying almost entirely on (winter) polar frontal, cyclonic weather systems for its rainfall. The coast is washed by the cold Benguela upwelling system, ultimately driven by the South Atlantic Anticyclone (SAA) which generates the southerly winds that induce upwelling (Cohen and Tyson 1995).

The northern coastline of False Bay, including Monwabisi Beach, is relatively straight and displays a combination of rocky and sandy areas (Theron & Schoonees, 2007). The outcrops of rocky shoreline found in this area are composed of aeolianite, which forms the base of the stratigraphy of the False Bay dune plume. The False Bay dune plume ranks among one of the largest along the southern west coast and extends inland for *ca.*15km with dune orientations concordant with the present-day summer winds (Roberts *et al.*, 2009). These unconsolidated, partly vegetated, dunes border the landward margin of Monwabisi Beach. The beaches along the northern section of False Bay, including Monwabisi, are exposed to inundation by southerly swells, as the mouth of the bay opens to the south (Theron & Schoonees, 2007). At Monwabisi Beach, the prevailing wave directions are from the south-west and the south, with winter months brining the largest swells (Theron & Schoonees, 2007). The tidal range of False Bay varies with neap tide at a low around 0.3m and spring tide reaching a high of about 1.9m (Giljam, 2002). False Bay also experiences a high astronomical tide with a maximum of about 1.25m above the mean sea level (Theron & Schoonees, 2007). Occasionally sections of the coastal road along the north of the bay are flooded due to the combination of the high spring tide, wave run-up and wave set up (Theron & Schoonees, 2007). The waves along the Monwabisi Beach surf zone create a longshore current that flows along the coast in an eastward direction (Theron & Schoonees, 2007). When strong south-easterly winds blow, the current changes direction, and flows in a westward direction parallel to the beach. A counter-clockwise eddy current is formed at the beach next to the tidal pool (Figure 1) as a result of the spur that was built next to the tidal pool (Theron & Schoonees, 2007).

3. Methods

3.1 Digitising long-term coastal changes using aerial photography

For the study it was decided to focus on the area east of the tidal pool at Monwabisi Beach (Figure 1). This area was selected because of the extensive erosion of the coastline and damage to the local infrastructure (road). Aerial photographs have been used to digitise long term changes and calculate the rate of coastline retreat over this period using ArcGIS software. These data were integrated with wave data for False Bay for the years 2000-2014 to identify trends. Georeferenced aerial photographs were obtained from the City of Cape Town for the years 2003, 2007, 2008, 2009, 2011, 2012 and 2013. For the years 2010 and 2014, georeferenced aerial photographs were supplied by the National Geo-spatial Information Centre in Cape Town. The selected years were based on availability of high-resolution aerial photography where coastline retreat could be quantified. Additionally, wave data was available from this period. These full colour and colour infrared aerial photographs were taken using calibrated large format photogrammetric sensors mounted to a fixed wing aircraft. On each georeferenced aerial photograph, the most landward evidence for erosion was digitised for consistency and to quantify the retreat of the coastline. The pattern of erosion was identified by eye and the erosion polylines were then carefully digitised across the study area. Next, all of the digitised landward erosion lines were superimposed on one image and thirteen transect lines were created across the study area to calculate a distance of retreat in metres along each transect line. The measurements are reflected as metres per month (m/month).

3.2 Wave data

Wave data obtained from the Council for Scientific and Industrial Research (CSIR) were studied and analysed for the identification of big wave events during these time periods. These data were collected with a directional Datawell Waverider buoy offshore of Slangkop, positioned at 34°12'14.40"S, 18°17'12.01"E in a depth of 70m water and is located about 5.4km offshore. The wave data are processed offshore on the buoy and broadcasted back to a shore station onshore every thirty minutes (CSIR, 2002). In this investigation, significant wave heights (Hmo), maximum wave heights (Hmax) and extreme wave heights (h1) were studied to correlate time periods experiencing significantly higher wave heights than the mean. Wave direction was analysed to establish if these time periods of increased coastline erosion were associated with a prevailing swell direction. The average wave height where the waves were greater than 8m were also calculated for each period and the standard deviation derived, as 8m represents a significant wave height associated with storm events causing visible changes in coastal erosion. The number of events with wave heights higher than 7, 8, 10, 12 and 14m were counted, as peaks contributing to erosional events. Scatter plots of wave height data were created and the directions were plotted as a histogram. According to the CSIR (2002) classification, Hmo is defined as the average wave height (peak to trough) of the top third of the waves (in m). h1 is the sum of highest peak and deepest trough (m). Hmax is the largest difference between a peak (crest) and its following trough (m).

4. Results

4.1 Long term changes from aerial photography

From the stacked aerial photographs and digitised polylines, it is clear that the 2003 polyline shows that the coastline is on the southern edge of the road and the road is still intact and usable (Figure 3A). The retreat of the coastline is clearly visible with each year's erosion polyline showing a noticeable retreat of the coastline (Figure 3). With the erosion polylines and thirteen vertical transect lines digitised on the aerial photographs (Figure 3A) the total distance of retreat for each transect line was calculated in m/month Figure 4(A). By 2014, the shoreline retreat amounted to 30m from its original position in 2003. It must be noted that there could be error associated with digitising along individual polylines, but aerial photographs were carefully selected to avoid shadows and obstructions and minimise error.

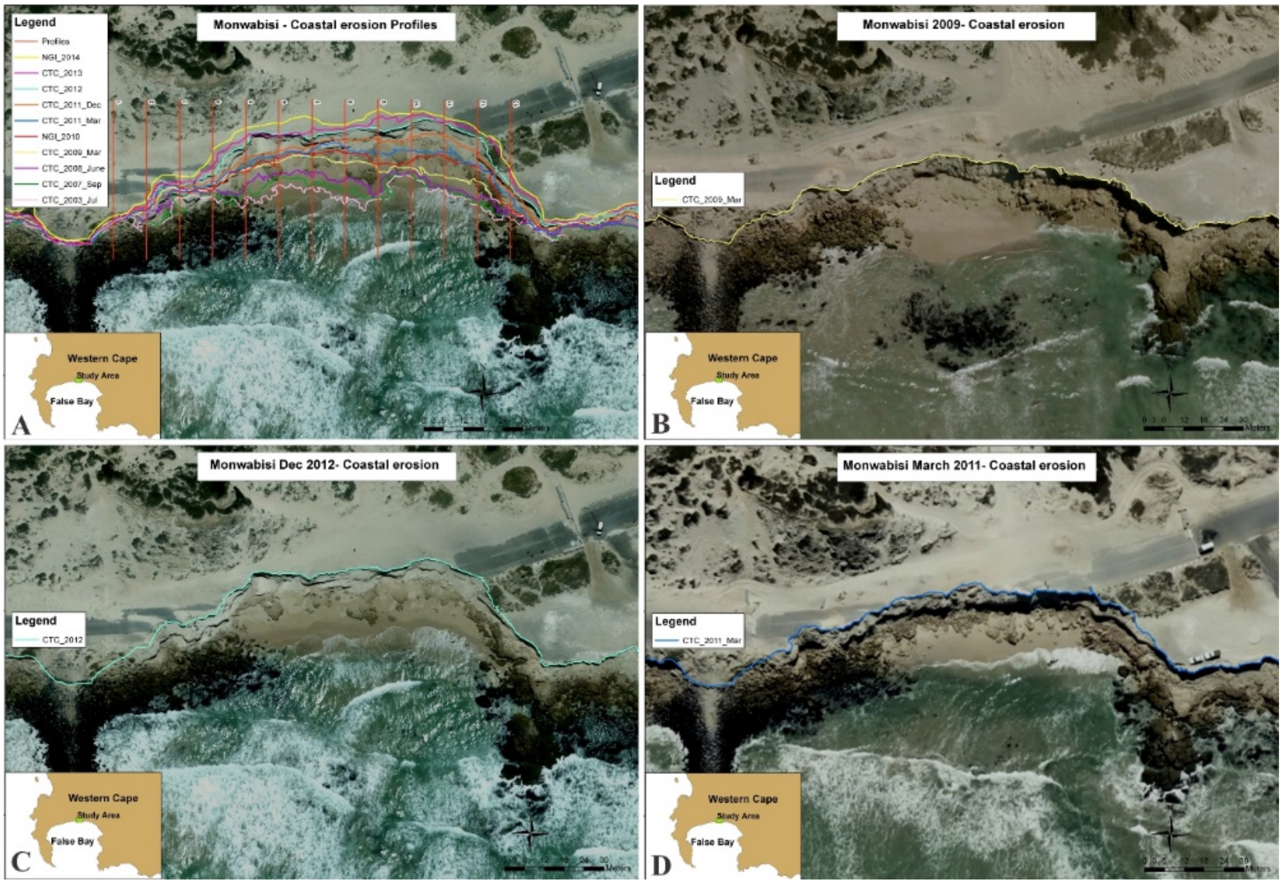


Figure 3. A series of aerial photographs taken by the City of Cape Town at Monwabisi Beach. This shows the study area east of the tidal pool and recreational facilities at Monwabisi Beach located along the northern coastline of False Bay. Photograph (A) is from 2012 and includes the composite erosion polylines for the year 2003 and years 2007-2014. It also includes thirteen vertical transect lines that were created across the study area to produce the profiles that were used to work out the rate of coastline retreat. Figures 3(B), (C) and (D) display the erosion polylines for the years of the three time periods with the greatest rates of change. Figure 3(A) demonstrates that the retreat of the

coastline is clearly visible with each year's erosion polyline showing a noticeable change of the coastline.

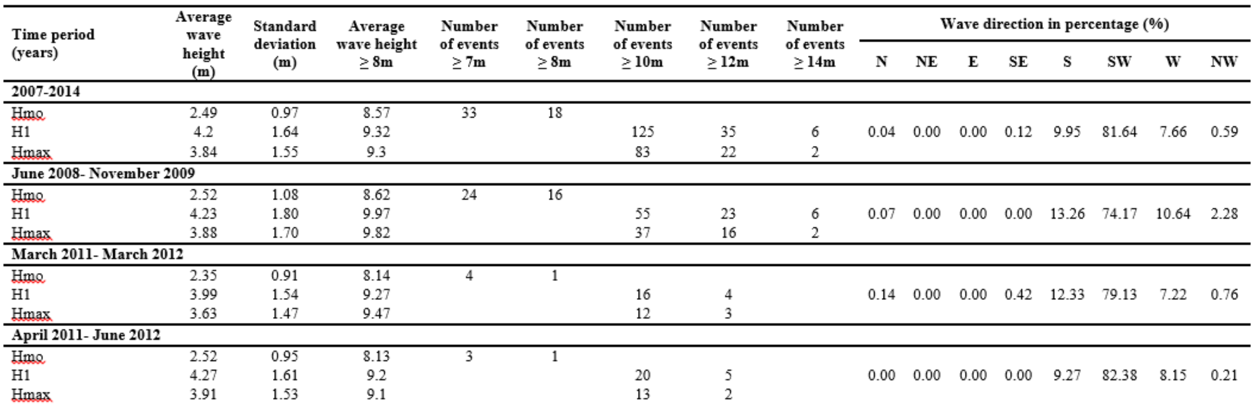
4.2 Identification of significant events

Three time periods of increased rates of change in metres/month of beach retreat are visible in Figure 4A. The first is from June 2008 to November 2009, the second is from March 2010 to March 2011 and the third from April 2011 to June 2012.

During these three time periods most of the transect lines show a dramatic increase in rate of change per month. The first time period has the biggest increase in rate of change per month with transect line 9 reaching a high of 0.75m/month in March 2009 (Figure 4A) and an average of 0.38m/month across all transect lines (Figure 4B). The third time period has the second largest rate of change per month with transect line 12 (Figure 4A) reaching a high of 0.66m/month in June 2012 and an average of 0.35m/month across all of the transect lines (Figure 4B). The second time period's rate of change per month is considerably less than the first and the third, but the increase in rate of change is still significant with transect line 13 reaching a high of 0.40m/month in March 2011 (Figure 4A) and an average of 0.17m/month across all of the transect lines (Figure 4B).

The same time periods were used to compare the wave data for the Hmo, h1, Hmax and wave direction. Similar results were found across all three time periods and the values for these datasets are shown in Table 1. Table 1 also provides the wave direction values as a percentage.

Table 1. Average wave heights, standard deviation, number of events and wave direction for the entire study period and the three significant time periods of interest. Wave direction as a percentage indicates the amount of swell coming from the listed directions within the stipulated time period.



Time period (years)	**Average wave height (m)**	**Standard deviation (m)**	**Average wave height ≥ 8m**	**Number of events ≥ 7m**	**Number of events ≥ 8m**	**Number of events ≥ 10m**	**Number of events ≥ 12m**	**Number of events ≥ 14m**	**Wave direction in percentage (%)**							
									N	**NE**	**E**	**SE**	**S**	**SW**	**W**	**NW**
2007-2014																
Hmo	2.49	0.97	8.57	33	18											
H1	4.2	1.64	9.32			125	35	6	0.04	0.00	0.00	0.12	9.95	81.64	7.66	0.59
Hmax	3.84	1.55	9.3			83	22	2								
June 2008- November 2009																
Hmo	2.52	1.08	8.62	24	16											
H1	4.23	1.80	9.97			55	23	6	0.07	0.00	0.00	0.00	13.26	74.17	10.64	2.28
Hmax	3.88	1.70	9.82			37	16	2								
March 2011- March 2012																
Hmo	2.35	0.91	8.14	4	1											
H1	3.99	1.54	9.27			16	4		0.14	0.00	0.00	0.42	12.33	79.13	7.22	0.76
Hmax	3.63	1.47	9.47			12	3									
April 2011- June 2012																
Hmo	2.52	0.95	8.13	3	1											
H1	4.27	1.61	9.2			20	5		0.00	0.00	0.00	0.00	9.27	82.38	8.15	0.21
Hmax	3.91	1.53	9.1			13	2									

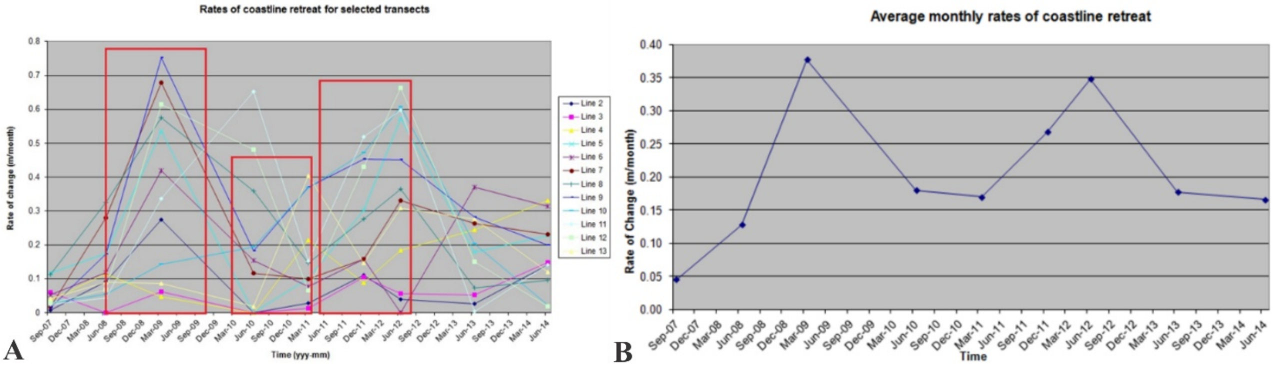


Figure 4. (A) Rates of coastline retreat in m/month for each transect line for the time period of 2003-2014. The three red rectangles mark the three time periods with the highest rate of change in m/month.(B) Average monthly rates of coastline retreat in m/month for the time period of 2003-2014.

4.3 Correlation of coastal and wave data

Wave data sets (Hmo, h1, Hmax and wave direction) were compared to the coastal retreat at the times of highest rates of retreat change at Monwabisi Beach. Figure 5A shows the Hmo for the time period from 2007 to2014. The average wave height for the time series was 2.49m with a standard deviation of 0.97m. For the first time period, average wave height was 2.52m, which is slightly higher than the average for the entire period. The average wave height for the second time period was 2.35m, which was lower than the average for the entire time period. The average for the third time period was again 2.52m. The averages for the first and the third time periods were higher than the average for the entire time period. This too is a reflection of the increased rate of coastline retreat experienced during these two periods. During this period there were thirty-three events where the wave height measured over 7m with eighteen of the events that had wave heights measuring over 8m. For the Hmo the three time periods of interest accounted for thirty one of the thirty three events experienced over the entire time series with wave heights measuring over 7m. The three time periods also included all of the eighteen events with wave heights measuring above 8m for the entire time period. The average height of waves greater than 8m was 8.57m. The predominant wave direction was from the south west accounting for 81.64% and the second highest was waves from the south accounting for 9.95%. A similar trend was observed for the h1 and Hmax data sets (Table 1).

<u>June 2008 to November 2009</u>

Figure 5B displays the Hmo for the first time period of interest from June 2008 to November 2009. In this time period the average wave height was 2.52m with a standard deviation of 1.08m. There were twenty four events where the wave height measured over 7m with sixteen of the events that had wave heights measuring over 8m. Three events were recorded in the time series with wave heights greater than 9m. The average value for waves higher than eight metres was 8.57m. The wave direction was from the south-west for 74.17% of the time, with the second peak direction from the south accounting for 13.26% of all the waves. A similar trend was observed for the h1 and Hmax data sets (Table 1).

March 2010 to March 2011

Figure 5C displays the Hmo for the second time period of interest from March 2010 to March 2011. In this time series the average wave height was 2.35m with a standard deviation of 0.91m. During this period there were four events where the wave height measured over 7m with one event that had wave heights measuring over 8m. The average value for waves higher than eight metres was 8.14m. The wave direction was from the south-west for 79.13% of the time, with the second peak direction being from the south and accounting for 12.33% of all the waves. A similar trend was observed for the h1 and Hmax data sets (Table 1).

April 2011 to June 2012

Figure 5D displays the Hmo for the third time period of interest April 2011 to June 2012. In this time series the average wave height was 2.52m with a standard deviation of 0.95m. There were three events where the wave height measured over 7m with one event that had wave heights measuring over 8m. The average value for waves higher than eight metres was 8.13m. The wave direction was mainly from the southwest (82.38%) and the second peak from the south accounts for 9.27% of all the waves. A similar trend was observed for the h1 and Hmax data sets (Table 1).

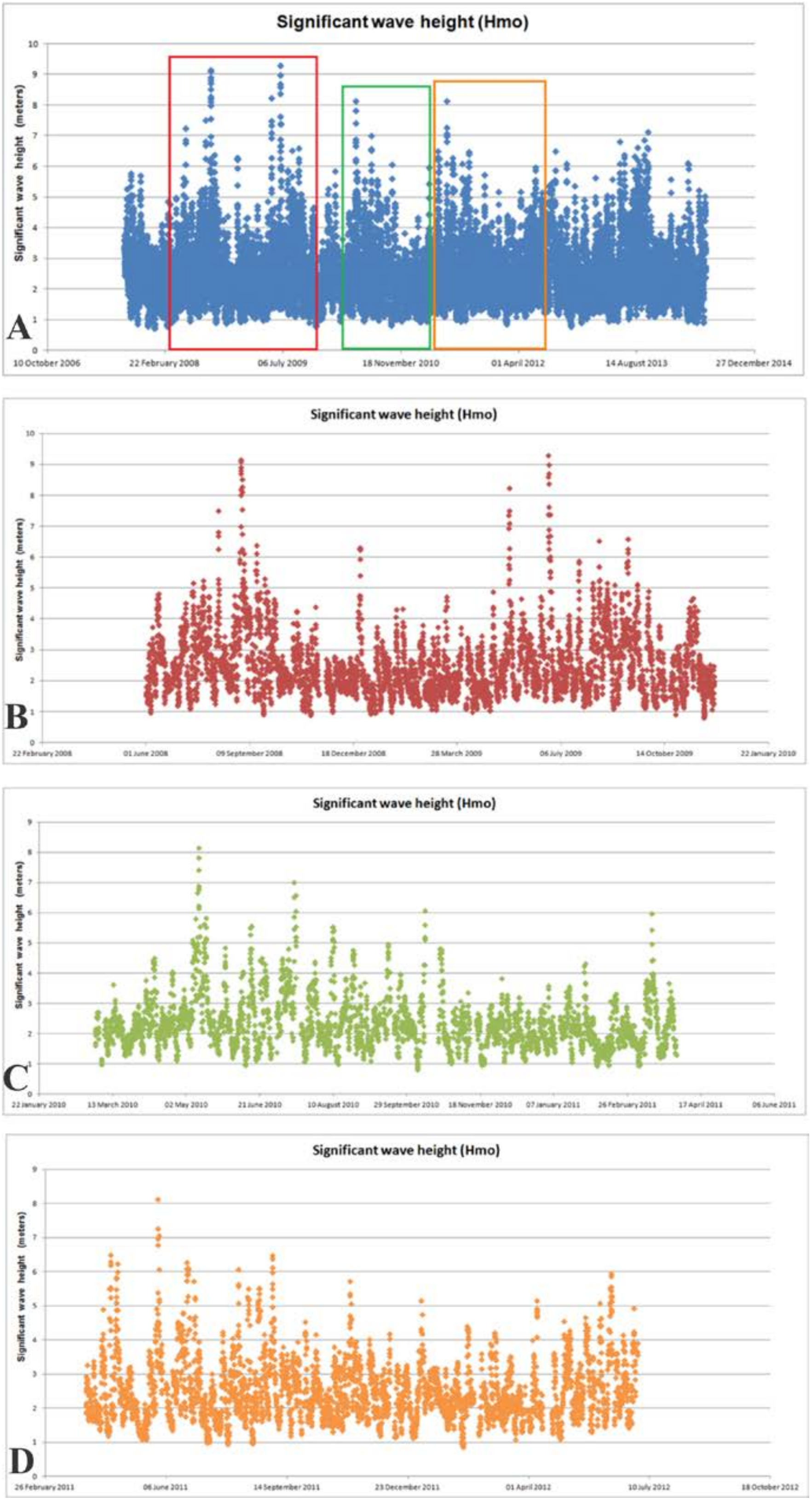


Figure 5. A. Scatter plot for the Hmo wave data of the entire study period (2003-2014) in blue. The colour rectangles show the three different time periods of increased rate of change identified in Figure 4B. The red rectangle is for the first time period June 2008 to November 2009 (B). The green rectangle represents the second time period March 2010 to March 2011 (C) and the orange rectangle represents the third time period April 2011 to June 2012 (D).

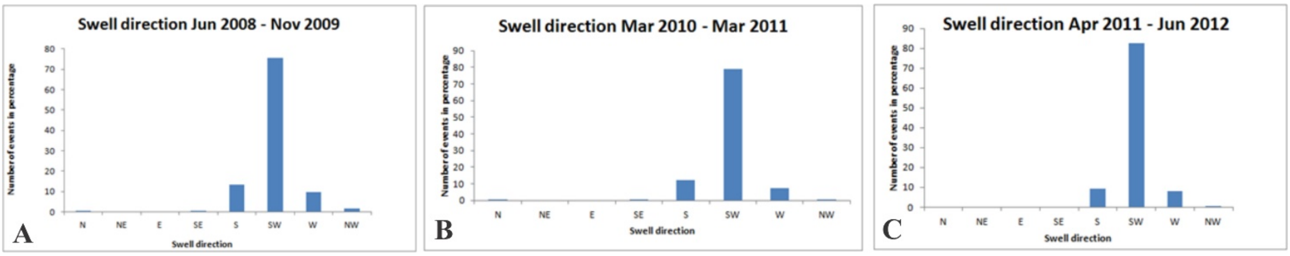


Figure 6. The histograms above display the wave direction aspercentages for the three time periods. In all three time periods it is observed that the dominant swell direction is from the south -west with another (less) dominant peak from the south.

5. Discussion

Through this research carried out at Monwabisi Beach, we aimed to identify a relationship between wave action (waves, storm waves and wave direction) and coastal erosion and shoreline retreat. The Monwabisi Beach study area is experiencing extreme rates of coastline erosion and has already experienced damage to some of the local infrastructure. The aerial photos identified the three time periods with the highest rates of change in coastline retreat and their sympathetic correlations with wave data. Based on the correlation of the two results it can be deduced that during times of high intensity storms, especially in winter, greater wave heights are experienced resulting in increased coastline retreat.

5.1 Wave direction

The entire time period investigated, as well as the three identified time periods of significant erosion, displayed mainly a south-westerly wave direction. The second most prominent wave direction during the considered time periods is from the south, in agreement with the results of Theron and Schoonees (2007). From 2003 until 2014, Monwabisi Beach has experienced a south-westerly wave direction for 81.64% of the time and a southerly wave direction for 9.95% of the time. The first significant time period of coastal erosion (June 2008 to November 2009) had a slightly lower percentage (74.17%) of waves from the south-west and a higher southerly wave direction, occupying 13.26% of the time.

This first period (June 2008 to November 2009), as noted in Figure 4A, had the highest rate of coastline retreat which is most likely a result of the more southerly wave direction experienced during this period. The combination of having the highest number of big wave events and the biggest percentage of southerly swell suggests that this is the reason for the first time period showing the most significant increase in coastline retreat. The beaches along the northern shores of False Bay, including Monwabisi Beach, are less protected against waves from a more general southerly direction. It is suggested here that the reason for this is the position of the mouth of the bay opening to the south and the waves move in an unhindered nature across the bay, finally breaking onto the northern shoreline (Theron & Schoonees, 2007). The second time period (March

2010 to March 2011) also experienced a significant southerly wave direction occupying 12.33% of the time, but in accordance with the data displayed in Figure 4A, failed to show a similar increase in rate of coastline retreat to the first and third time periods. These results suggest that a stronger southerly wave direction component, when combined with a higher number of big wave events, causes an increase in rate of coastline retreat.

5.2 Seasonality

Figures 5B, C and D demonstrate that the majority of big wave events with wave heights ranging from 7 to 14m occurred during the winter months. Figure 4A also shows the largest increase in rate of coastline retreat (with an average of approximately 0.25m per month) over the winter months. Winter is the rainy season for Cape Town (Cohen & Tyson, 1995) and in winter high intensity storms are experienced quite frequently, causing high energy waves of great heights around the Western Cape and False Bay coastline (Theron *et al.* 2010).

5.3 Erosion rates for the Monwabisi shoreline

During the three significant time periods for coastal retreat at Monwabisi Beach, most of the transect lines showed a dramatic increase in rate of change per month (June 2008 to November 2009; March 2010 to March 2011; April 2011 to June 2012). The first time period experienced the largest increase in rate of change per month with transect line 9 reaching a high of 0.75m/month in March 2009 (Figure 4A) and an average of 0.38m/month across all transect lines (Figure 4B). This time period experienced the most big wave events and had the highest percentage of waves from a southerly direction causing this time period to show the highest rate of coastline retreat. The third time period had the second biggest rate of change per month with transect line 12 reaching a high of 0.66m/month in June 2012 (Figure 4A) and an average of 0.35m/month across all of the transect lines (Figure 4B). This agrees with the previous findings as this period had the second highest number of big wave events. The rate of change per month for the second time period was considerably less than the first and the third, but the increase in rate of change was still significant with transect line 13 reaching a high of 0.40m/month in March 2011 (Figure 4A) and an average of 0.17m/month across all of the transect lines (Figure 4B). This coastline retreat rate was lower than the other two time periods as it experienced the least amount of big wave events.

The maximum lateral coastal erosion at the Monwabisi study area from July 2003 until June 2014 was approximately 30m. The minimum loss of coastline was approximately 3m in the study area. The middle of the embayment within the study area which is open to the south and southwest was subjected to the most significant coastal erosion. This middle section of the embayment is the least protected area with a predominantly sandy shore and less rocks to buffer the coastline from the erosive power of big wave events (Figure 3A). The geological substrate of aeolianite forms the base of the road within the middle of the study area and is composed of relatively erodible strata (Roberts et al., 2009). The standard erosion rates that unconsolidated coasts experience range between 0.3 and 1.0m/year (Smith *et al.* 2010). The undercutting along the study area by wave action has caused the road and surrounding area to collapse at a much greater rate than normally experienced by unconsolidated coasts. A tentative suggestion for this may be that the road platform further weakened the substrate and caused an increase in erosion rates along the study area as a result of the undercutting from wave action.

6. Conclusions

The aim of this study was to determine if there is a relationship between wave action and long term changes (coastline erosion) experienced in the coastline along the study area at Monwabisi Beach. Aerial photographs were used to digitise long term changes to calculate the rate of coastline retreat and compare these values to wave data. The aerial photography and wave data analysis demonstrate a clear correlation between dynamic wave action, in combination with a more southerly wave direction, and the extensive coastal erosion experienced at Monwabisi Beach. For purpose of this study, only wave data for the period 2003-2014 were used. This was to ensure a direct overlap with the period in which the aerial photographs were available. The wave data for this study included significant wave heights (Hmo), extreme wave heights (h1), maximum wave heights (Hmax) and wave direction data. Three time periods of increased rates of change in m per month were identified (Figure 4B), corresponding to autumn and winter months. The first time period of interest was from June 2008 to November 2009, the second time period of interest was from March 2010 to March 2011 and the third was from April 2011 to June 2012. It was evident that these time periods included wave events of greater heights than the rest of the time series (Figure 5B, C and D).

This study has concluded that the extreme rates of coastline retreat experienced within the study area at Monwabisi Beach is a direct result of the combination of influences including the number and height of big wave events; waves coming from a more southerly direction; the underlying geological substrate of the study area; and the impact that the local infrastructure has had on the geological substrate.

The findings of this study infer that the northern coastline of False Bay such as at Monwabisi Beach, which consist of mostly sandy and erodible beaches (Spargo, 1991), are vulnerable to wave action induced coastal erosion. The beaches along the northern shoreline are relatively unprotected from high energy waves driven by significant storm events especially during the autumn and winter months (Theron & Schoonees, 2007). The mouth of False Bay which lies open to the south offers little protection to its north coast. This allows big wave events from a south and south-westerly direction to reach the shores unhindered causing increased coastline retreat (Theron & Schoonees, 2007). More extreme rates of coastline erosion can be expected where local infrastructure such as coastal roads are constructed on coastal aeolianite. It is recommended that continuous monitoring of coastline retreat along the coasts of False Bay should be sustained as SLR is anticipated to drive increased coastal erosion.

7. Acknowledgements

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