Saw-tooth bars defined

a case study of the Ameland Inlet

Part 1

Werkdocument RIKZ/OS-99.114x
maart 1999

Lisa Gordeau

Universiteit Utrecht

Rijksinstituut voor Kust en Zee/*RIKZ*

Preface

The case study of the Ameland Inlet concerning saw-tooth bars was carried out from December 1st to March 15th. The research was executed at the National Institute for Coastal and Marine Management (RIKZ) in The Hague as an internship assignment. The internship was coordinated from the Utrecht University (Faculty of Physical Geography) as well.

The report includes two parts. Part one constitutes the textual report. Part two consists of the Appendices necessary for understanding the research.

I would like to thank Daan Dunsbergen, Aart Kroon and Cornelis Israel for their constructive ideas and comments. I would also like to thank Edwin Biegel for his practical help with the computer applications.

Table of contents

Abstract

Saw-tooth bar features occur on the downdrift side of the ebb-tidal delta of the Ameland Inlet as well as in front of the island of Ameland. The height difference between bar maximum and trough minimum can amount to 150 cm on the ebb-tidal delta and to about 25 cm in front of Ameland. Their lengths range between 500 m and 2 km. Their width generally ranges between 100 and 500 m. Saw-tooth bars and troughs migrate in a downdrift (eastern) direction with a mean rate of 100-200 m/yr.

The saw-tooth bars on the ebb-tidal delta gradually migrate into the ones lying in front of Ameland in 1989. A transition zone exists between these two types of bars in 1993 and 1996 where the downdrift migration of bars and troughs is disturbed. This transition zone migrates dowdrift and coincides with the outflow area of an inner lake. This inner lake originated in 1993 by the extension of a sandy spit along the north-west coast of Ameland. In 1989, this spit was absent. Bar and trough dimensions differ distinctly for both locations in 1993 and 1996.

1. Introduction

1.1 Framework

Within the framework of the program COAST*2000, research is carried out to study the interaction between tidal inlets and adjacent Dutch islands coasts. Attention is paid to the morphodynamic behaviour of tidal inlets and connecting barrier island coasts, with special emphasis on ebb-tidal deltas. Ebb-tidal deltas are situated at the seaward side of tidal inlets and are of prime importance to the sediment bypassing at the inlet to the adjacent downdrift barrier island coast. A series of swash bars are present on the Dutch ebb-tidal deltas. These swash bars and swash-bar complexes have a cyclic behaviour (FitzGerald, 1984, Sha, 1990, Oost, 1995). Swash bars and swash bar complexes are present on the downdrift side of ebb-tidal deltas in the Dutch Wadden Sea (see *fig. 1*) and migrate, under the influence of wave-action, toward the north-western coast of the downdrift barrier island.

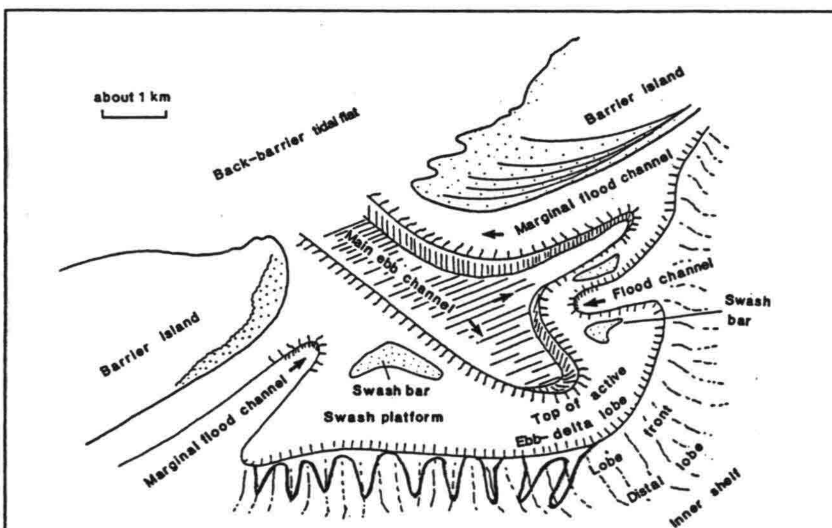

Figure 1: General morphology of an ebb-tidal delta, modified after Sha (1990).

At the downdrift side of the ebb-tidal delta front (see *fig. 1*) as well as on the northward side of barrier islands saw-tooth bars are present. Little is known about their genesis, morphometric characteristics and their morphodynamic behaviour. Saw-tooth bars migrate downdrift along the delta front. They are of importance to the sediment supply to the eroding north coast of the downdrift barrier islands.

1.2 General morphology and genesis of saw-tooth bars

Saw-tooth bars represent subtidal, longshore-current transverse sandbars, distinctly present at the downdrift side of an ebb-tidal delta. They originate at a waterdepth of about 5 m and are alternated by rip channels. Their shore-normal length ranges between 200 m and 1.5 km with an alongshore spacing of about 100 to 500 m (Antia, 1994). The development of saw-tooth bars is not fully understood. There are two hypotheses with regard to their formation. According to Flemming and Antia (1990) and Antia (1996), the rhythmic morphology owes its origin to the presence of rip currents in combination with a longshore-standing edge-wave oscillation. This edge-wave oscillation is generated when a progressive edge wave is effectively reflected at an ebb-tidal delta. Another possibility is that saw-tooth bars arise as a spontaneous instability of the coupled water-bottom system due to waves, tides and wind-driven longshore currents (De Swart, pers. comm.).

1.3 Ameland Inlet

The Ameland Inlet is situated between the barrier islands Terschelling and Ameland connecting the Dutch Wadden Sea and the North Sea (see *fig. 2*). The ebb-tidal delta of the Ameland Inlet is, together with the Terschelling and the Texel Inlet, among the largest of inlets between the Frisian islands. The ebb-tidal delta consists of one main ebb channel, which shows cyclic migration patterns (Sha, 1990). A distinction between ebb- and flood dominated channels exists. Sandwaves are present at the downdrift (eastward) side of the delta, together with intertidal shoals, which show cyclic migration directed downdrift. Sandwaves are wave-like bedforms with wave-lengths greater than 60 m and a trough to crest height of at least 2 m (Van Alphen and Damoiseaux, 1989).

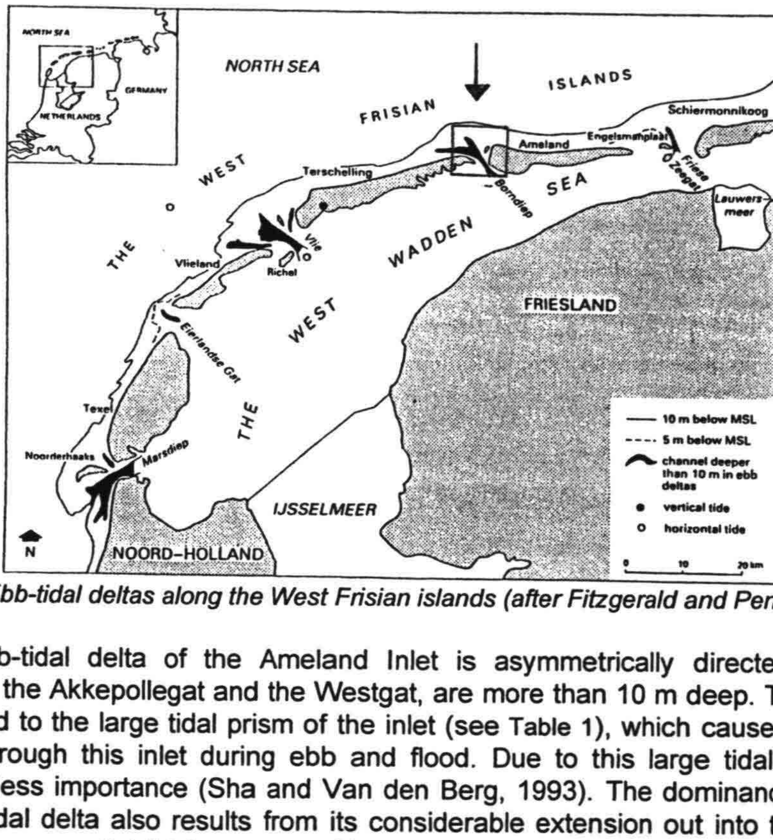

Figure 2: Ebb-tidal deltas along the West Frisian islands (after Fitzgerald and Penland, 1987).

The ebb-tidal delta of the Ameland Inlet is asymmetrically directed updrift. Both main channels, the Akkepollegat and the Westgat, are more than 10 m deep. This updrift asymmetry is ascribed to the large tidal prism of the inlet (see Table 1), which causes strong tidal currents flowing through this inlet during ebb and flood. Due to this large tidal prism, waves are of relatively less importance (Sha and Van den Berg, 1993). The dominance of tidal currents on the ebb-tidal delta also results from its considerable extension out into the sea. Interaction of marine shore-parallel tidal currents with onshore-offshore directed inlet tidal currents, which is enhanced by the ebb-tidal delta shoals, causes the large ebb-tidal delta of Ameland to be asymmetrical updrift.

Table 1: Hydraulic and geometric values.

Borndiep Inlet	
Mean tidal prism (10^6 m^3)	450
Mean tidal range (m)	2.30
Sign. wave-height Hs (m)	1.10
Max. Inlet depth (m)	28.5
Ebb delta seaward dist. (km)	6.0

From: Sha, 1989.

The Ameland tidal inlet is a downdrift-offset inlet, which means that the downdrift barrier island is situated more seaward than the updrift one. The downdrift offset is produced by wave refraction around the ebb-tidal delta and through the landward migration of swash bars from the ebb-tidal delta (Hayes and Kana, 1976, Hayes, 1979, Sha, 1989, Fitzgerald 1996). Wave refraction causes a longshore drift reversal at the downdrift part of the inlet and causes the downdrift located island to be a natural sand trap. The point of reversal is located in the bight between the ebb-tidal delta and the island of Ameland (see *Fig. 3*). Another mechanism which causes the downdrift offset, is the landward migration of swash bars from the ebb-tidal delta (FitzGerald, 1984). Ameland consequently exhibits a drumstick shape at its western end.

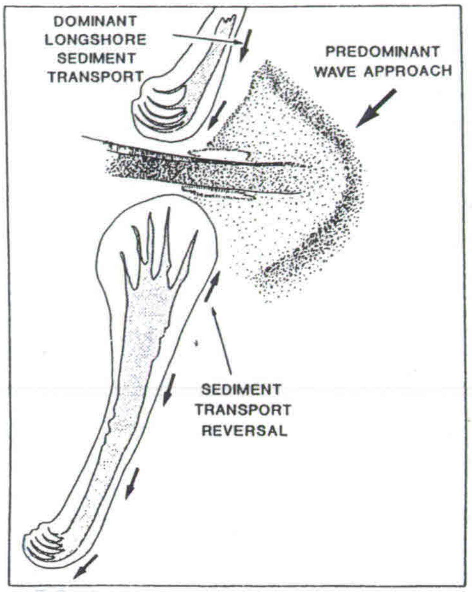

Figure 3: Downdrift offset of a barrier island after Hayes and Kana (1976). The accretionary updrift portion of the barrier is formed from the longshore transport of sand toward the inlet caused by a reversed longshore drift due to wave refraction and from the landward migration of swash bars from the ebb-tidal delta (FitzGerald et al., 1984)

The Bornrif bar is a sandy spit attached to the downdrift island of Ameland. This bar originates from the periodical coalescence (e.g. 1926 and 1986) of south-east migrating swash bars, present on the ebb-tidal delta, under the influence of wave-action. These swash bars join together to form a large swash-bar complex and periodically attach to the north-west coast of Ameland (Israel, 1998). After the most recent attachment (1986) of the Bornrif bar, the development of the sandy spit influences the coastline of northern Ameland. The sandy spit extends and curves toward the south-east. Due to this extension and the curving of the sandy spit, an inner lake is created in 1993, which is filled during flood and emptied during ebb. This in- and outflowing water partly erodes the north coast of Ameland.

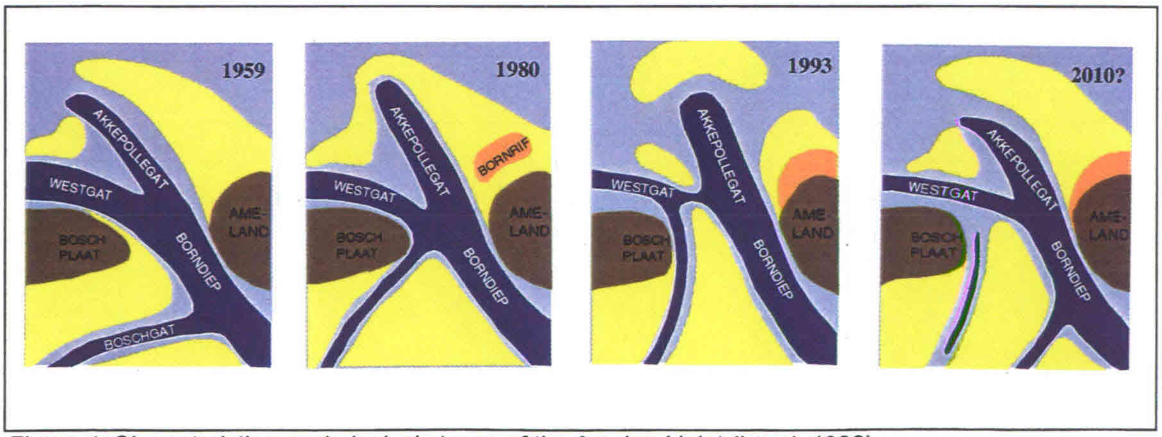

Figure 4: Characteristic morphological stages of the Ameland Inlet (Israel, 1998).

A cyclicity was detected in the morphodynamic behaviour of the Ameland Inlet and its tidal delta (Israel, 1998). Four morphological stages have been recognized within a period of 50-60 years (see *fig. 4*).

This paper is focused on the saw-tooth bars of the ebb-tidal delta of the Ameland Inlet. Saw-tooth bars can be recognized above the 10 m isobath on the downdrift side of the ebb-tidal delta. They radiate from the delta rim and tend to fade out in an easterly direction extending over a distance of about 15 km (De Swart, pers. comm.). Saw-tooth bars of the Wadden ebb-tidal deltas generally have lengths of about one kilometre and wavelengths of about 500 m and reach an approximate height of 2 m. The seaward ends of the crestlines are directed dowdrift with respect to their landward ends (Ehlers, 1988). Migration rates are in the order of 100 m/yr (Kroon, pers. comm.).

1.4 Objectives

The relationship between the saw-tooth bars lying on the ebb-tidal delta front and the ones lying in front of the barrier island are studied for the years of which data are available. This definition will be assessed by getting morphometric information of saw-tooth bars; dimensions, spatial patterns, sediment budgets and the spatial development of these characteristics in a downdrift direction (to the east). Finally, calculations to the dynamic behaviour of saw-tooth bars are carried out to establish their migrational characteristics.

Possibly, stages in ebb-delta morphology, as formulated by Israel (1998), are coupled to possible stages in saw-tooth bar characteristics.

1.5 Hypothesis

Saw-tooth bars are present on the downdrift ebb-tidal delta front and gradually transform c.q migrate into the ones present north of the Island of Ameland. The bars will finally decay, which means decrease in height and volume, at the central part at the island of Ameland. The direct relationship will be evident from the gradual course of the morphometric characteristics like bar heights, bar spacing and bar volumes in a downdrift direction.

2. Defining saw-tooth bars and troughs

2.1 Data overview

Two types of available data sets are used to identify saw-tooth bars, (i) Jarkus-measurements which are surveyed every year at the North Sea side of Ameland and (ii) so-called *Vaklodings-data* which are measured every four years and cover the North Sea side of the Ameland ebb-tidal delta. Both types of data constitute sea-bottom depths determined along shore-normal transects by sounding vessels of Rijkswaterstaat. Jarkus transects extend to about 2 km offshore, Vaklodings transects extend to about 4 km offshore (see *Fig. 5*). Bottom depths are measured with digital acoustic depth sounders. Jarkus data are available from 1965. *Vaklodingsdata* are available for the years 1989, 1993 and 1996. Accordingly, the years 1989, 1993 and 1996 were used in this study for comparison.

Bathymetric maps of the area north of Ameland were made from Jarkus cross-shore profiles. Data points along these profiles were interpolated by the program DIGIPOL. Output grids have grid-cell sizes of 15*15 m. Maps derived from Vaklodings-data combined with Jarkus-data were provided as interpolated maps which have grid-cell sizes of 20*20 m. As maps constructed from Jarkus-data only, possess larger grid-cell resolution due to a more accurate recording technique, these maps are more precise (see *Appendix 1b*). Therefore they are preferred over maps constructed from Vaklodings-data combined with Jarkus-data (see *Appendix 1a*) for the analysis. Consequently, maps derived from the Jarkus-data were used for saw-tooth bar analysis of the area north of Ameland, maps derived from Vaklodings-data were used for saw-tooth bar analysis in front of the ebb-tidal delta.

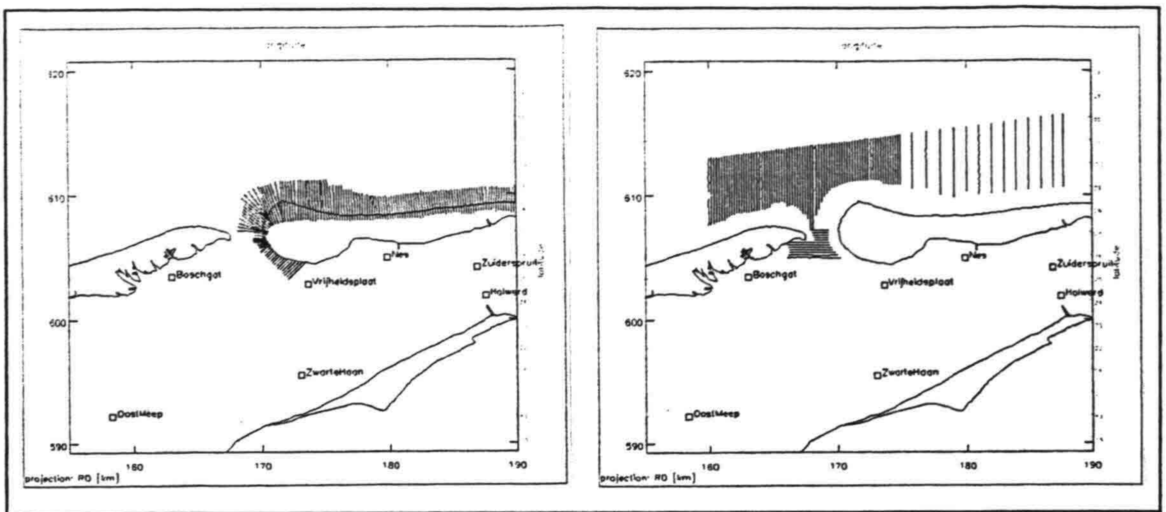

Figure 5: Jarkus transects along Ameland (left), Vaklodings-transects along the ebb-tidal delta (right)

2.2 Saw-tooth bar definition

The saw-tooth bar c.q. trough phenomenon is considered a disturbance of bars and troughs on a initial undisturbed sea-bottom. This consideration is used to describe saw-tooth bars morphometrically and implies no genesis mechanisms. The initial map represents the sea bottom in case no saw-tooth bars and troughs are present. The initial bathymetric map was produced in two different ways.

An initial sea-bottom-depth map was created by averaging all available bottom-depth maps of the studied area. As, in time, the saw-tooth bars migrate in a downdrift direction, bars and troughs will alternate on bathymetric maps of different years. Averaging over all available maps resulted in a mean bottom depth between bars and troughs by adding up the values of similar grid-cell of bathymetric maps available and dividing by the amount of maps used. In this way, all migrating irregularities that are smaller than saw-tooth bars, were ignored.

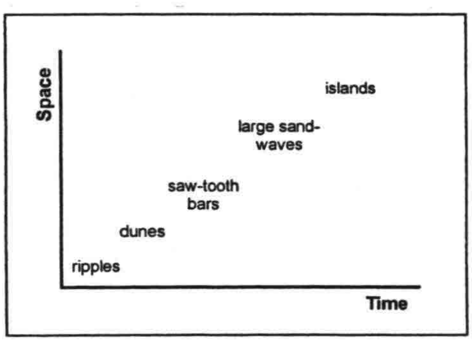

Figure 6: To highlight the saw-tooth bar phenomenon, smaller- and larger-scaled features have to be filtered of the initial map.

The resulting mean map was digitized along interpreted depth isolines in case no bars were present. This digitizing technique was necessary as irregularities remained after averaging, mainly induced by the limited amount of bathymetric charts. Larger-scaled features (see *fig. 6*) were ignored by the digitizing method as well; larger scaled features like steady sand bulges, originating from the morphology of the island like the sandy spit were filtered by digitizing along their depth contours and are therefore present on the initial sea-bottom depth map.

This first technique of creating an initial bathymetric map was applied on maps constructed out of Jarkus-data for the area north of Ameland first. Bathymetric maps were constructed for the years 1989 to 1997. A mean bathymetry of the sea-bottom for these years was produced by averaging these 9 maps within the ArcInfo module GRID. Remaining irregularities were filtered out by digitizing. Resulting initial bathymetric sea-bottom map showed no irregularities after displaying it with the ArcInfo-application Geokaart (see *Appendix 2*) and after plotting shore-normal profiles of which one is plotted in *Appendix 3*. Therefore, the constructed resulting map was accepted as being accurate and was used for further analysis.

With the second procedure, separate initial bathymetric maps for the years 1989,1993 and 1996 were created. These initial maps were created by digitizing interpreted depth contours in case no saw-tooth bars were present. This comprehends digitizing a mean depth contour between a saw-tooth bar protrusion and a saw-tooth trough indentation (see *Appendix 4*). Digitizing was carried out between depth contours -6 and –9 m for the Jarkus-maps, as landward of -6 m the shore-parallel breaker-bars are located and -9 m represents the seaward limit of the bathymetric maps. This is the area wherein saw-tooth bars and troughs generally exist. Initial bathymetric sea-bottom maps for each year were obtained (see *Appendix 5*). Larger-scaled sand-waves were taken into account by digitizing their contours. So they can not be reflected at the residual bathymetric map after subtraction.

The same procedure was repeated for the maps derived from *Vaklodingsdata* (see *Appendix 6*), resulting in initial bathymetric sea-bottom maps for the area along the ebb-tidal delta (see *Appendix 7*). Digitalization of the *Vaklodings*-map was carried out between depth contours -6 and –10 m. The saw-tooth bar phenomenon does not extend the –10 m depth contour. Landward of the –6 m isobath shore-parallel breaker-bars are situated and obscure the saw-tooth bar phenomenon.

All initial bathymetric maps were tested on irregularities by plotting shore-normal profiles of which some are presented in *Appendix 8a + b*. Classic concave shore profiles are absent as sandwaves are present within the initial bathymetric maps, also visible in these maps by large-scale undulating depth contours (see *Appendices 5 + 7*). Profiles plotted across the ebb-tidal delta naturally lack a classic concave curve as the shape of the ebb-tidal delta is reflected. As the initial bathymetric maps and the plotted profiles do not show any irregularities or other conspicuous features, all created initial bathymetric maps are approved and used for further analysis. The method of digitizing an interpreted surface where no bars are present was already used by Hicks and Hume (1996) to determine morphometric parameter values of ebb-tidal deltas in New Zealand.

2.3 Morphometric analysis

The created initial bathymetric maps were used for subtraction from the actual bathymetric maps of the studied years. In this way, residual bathymetric maps were obtained, reflecting (i) bars; represented by sandvolumes above zero-level, and (ii) troughs; represented by sandvolumes below zero-level of the residual map. With the residual bathymetric maps, heights, widths, lengths, spacing, volumes and direction of bars and troughs were determined, as well as the downdrift development of these characteristics. Parameter values were determined by plotting profiles with the ArcInfo application Geoprof. To ascertain bar heights and trough depths, profiles were plotted along their crests. Resultant heights were averaged over their length. The reason for this is that maximum height is no representative parameter for banks and troughs as they are too capriciously shaped (see *Appendix 9a + b*). Bar c.q. trough length was defined by where these plotted profiles cross the zero-level. Mean width is determined by plotting several profiles perpendicular to the length axis of the bars and troughs. The amount of plotted profiles was dependent on bar/trough shape. The more unambiguous their shape, the less profiles were plotted. Wave-length of the saw-tooth bar phenomenon was determined by plotting profiles over several bars and troughs. Volumes of bars and troughs were roughly assessed by multiplying their mean height, width and length (first-order approximation).

These morphometric parameters were determined for all three years i.e. 1989, 1993 and 1996 separately, to determine the downdrift relationship between the saw-tooth bars. Mean parameter values were compared between the successively studied years to determine and explain morphological changes, by means of morphological data of the entire ebb-tidal delta.

2.4 Morphodynamic analysis

Displacement of the saw-tooth bar phenomenon is visualized by creating sedimentation c.q. erosion maps. These maps were created by subtraction of original bathymatric maps of successive years. In the resulting map, sedimentation is reflected by positive grid-cell values, erosion by negative grid-cell values.

Migrational rates of saw-tooth bars were ascertained by plotting one shore-parallel profile over bathymetric maps of several years. Displacement of saw-tooth bar crests is determined by the translation along the distance axis of the plotted profile.

3. Morphometric parameters of saw-tooth bars and troughs

3.1 Data overview

Morphometric parameters of one saw-tooth bar were obtained from the Jarkus-map as well as from the *Vaklodings*-map and were compared. Application of different original data for the study is permitted, as no significant parameter differences were observed.

3.2 Residual bathymetric maps

3.2.1 Mean initial bathymetric map

Residual bathymetric maps, representing bars and troughs, were produced in two ways as two types of initial bathymetric maps were created. First, the mean initial sea-bottom map was subtracted from the original bathymetric maps of the years 1989, 1993 and 1996 (see *Appendix 10*). Utility of the mean initial map is based on the residual bathymetric maps. Two trends in sea-bottom bathymetry obscure the visualization of the morphometry of the saw-tooth bars.

(i) From the residual maps, it is apparent that a larger-scaled morphodynamic phenomenon exists besides the saw-tooth bars. This phenomenon is clearly visible at the residual maps of the years 1993 and 1996; groups of saw-tooth bars repeatedly appear to be of greater height than adjacent groups of saw-tooth bars. This can be explained by the assumption that larger migrating sand-waves exist beneath the saw-tooth bars. The saw-tooth bars appearing higher, lie on the top of these so-called sand-waves. Saw-tooth bars appearing lower, lie in the troughs of these larger-scaled sand-waves. This sand-wave phenomenon is also displayed by plotting shore-parallel profiles over the saw-tooth bars (see *Appendix 11*). An undulating trend is observed within these profiles, which was interpreted as the larger-scale sand-waves existing besides the saw-tooth bars.

The thought that these sand-waves migrate arises from the fact that the produced initial bathymetric map used for the subtraction lacked any sand-wave like features. Migration of these sand-waves causes these features to be filtered of the initial bathymetric map by the averaging method. After subtraction of the initial bathymetric map the sand-waves re-appeared in the residual bathymetric map.

(ii) Another trend in sea-bottom development is visible in the map illustrations in *Appendix 10* as well. As the legends of all maps are identical it can be seen that the coast in front of Ameland erodes from 1989 to 1993, as the sea bottom of 1989 lies entirely above the sea bottom of 1993 and 1996. This trend is also illustrated in the plotted profile in *Appendix 11*; the profile plotted over the residual map of 1989 lies above the profile lines of the other two years. So, in addition to the larger-scale sand-wave phenomena, the coast in front of Ameland is subjected to large-scale erosion (about 30 cm over four years along the plotted profile) as well.

Anomalies from the initial bathymetric map not only show saw-tooth bars and troughs, but larger-scaled features as well. The residual bathymetric maps consequently do not exclusively highlight the saw-tooth bar phenomenon. Therefore, this mode of creating an initial sea-bottom map was rejected.

3.2.2 Digitized initial bathymetric map

The second mode of creating a residual bathymetric map was used for the study. Residual bathymetric maps, representing saw-tooth bars and troughs, are created for each year separately by subtracting the created initial bathymetric map from the original map (see *Appendix 12a + b*). The residual maps show that digitizing maps for each year separately is successful as all saw-tooth bar heights and trough depths fall in the same legend-range. It is reasonable to assume that large-scale trends like sand-waves and possible coast-line erosion (or sedimentation) are filtered and the saw-tooth bar phenomenon is exclusively highlighted in the residual maps. With these residual bathymetric maps, parameter values of all saw-tooth bars and troughs were determined.

3.3 Saw-tooth bars and troughs in 1989

Bar and trough numbers are presented in *Appendix 13a*. Parameter-values mean height (Hm), length (Lm), width (Wm) and volume (V) are plotted against bar number in *Appendix 14a* The morphology of the entire ebb-tidal delta morphology in 1989 is represented in *Appendix 15a*.

3.3.1 Saw-tooth bar results

Calculated parameter values are presented in Table 2. Bars 1 to 10 lie on the ebb-tidal delta front, bars 11 to 25 lie seaward of the breaker-bars in front of Ameland.

Standard deviation (2nd column), which is always about half the calculated mean height, illustrates the non-regular shapes of saw-tooth bars. Therefore, mean bar heights were used instead of a single height value.

Table 2: Parameter-values of saw-tooth bars in 1989.

Bar nr.	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	11	8	35	1350	80	12.000
2	4	3	10	325	25	350
3	18	13	41	250	525	22.500
4	10	6	23	650	275	17.500
5	12	5	20	375	225	9.800
6	21	10	35	300	175	11.700
7	9	7	25	425	475	18.100
8	11	4	21	1150	375	46.600
9	16	5	25	825	350	45.000
10	16	5	27	1150	350	65.000
11	13	5	31	1050	350	46.000
12	7	3	14	800	250	14.000
13	6	3	13	700	250	10.000
14	8	4	18	1150	350	32.500
15	8	3	15	1075	275	24.200
16	7	4	15	1300	325	29.000
17	4	3	11	950	300	11.300
18	7	3	15	1200	425	35.300
19	4	3	12	1500	175	11.100
20	15	4	22	1050	550	85.800
21	10	6	28	975	425	41.200
22	16	6	31	950	400	63.000
23	8	5	21	1050	475	39.000
24	12	6	24	1050	450	56.000
25	20	9	37	1100	450	101.200

Bar heights beneath 10 cm are arbitrary, considering the recording accuracy, (see *Discussion*). Bar height, length, width and volume results will be discussed successively;

- Saw-tooth bar heights on the ebb-tidal delta range between about 5 and 20 cm, with a mean of 12 cm. Bars in front of Ameland have a mean height of 10 cm, with a minimum for bars 12 to 19. Downdrift from bar 19 mean heights start to increase to a maximum of 20 cm in the east. No significant mean height difference exists between the two bar areas and the height values in the transition zone show no abrupt changes.
- Bar lengths show minimum values in front of Ameland with a mean of 630 m. Bars in front of Ameland show a fairly constant length of 1065 m. So bars in front of Ameland are distinctly

longer than those in front of the ebb-tidal delta, with an abrupt decrease in the transition zone.

- Bar widths show a rather constant value with a mean of 330 m, although some scattered inexplicable deviant values occur (see *Appendix 14a*).
- Bar volumes on the ebb-tidal delta remain fairly small, with a mean of about 13.000 m^3 for the first 7 bars. The bar volumes in the bight are distinctly larger with a mean of about 51.000 m^3 (bars 8 to 11).Bar volumes in front of Ameland are larger than those on the ebb-tidal delta and increase towards the east. No extreme in- or decreases in bar volume occur.

3.3.2 Saw-tooth trough results

Calculated parameter values of saw-tooth troughs in 1989 are presented in Table 3. Hm for saw-tooth troughs represents mean trough depth.

Table 3: Parameter-values of saw-tooth troughs in 1989.

Trough	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	-51	18	-88	1225	225	147.500
2	-20	8	-34	900	175	32.400
3	-21	20	-58	450	375	34.800
4	-40	26	-80	425	375	62.200
5	-42	28	-92	225	350	32.800
6	-37	15	-50	100	375	14.200
7	-5	4	-13	250	175	2.350
8	-9	6	-23	600	250	13.500
9	-16	10	-39	650	250	27.500
10	-12	8	-30	750	225	20.000
11	-13	6	-23	550	325	24.000
12	-5	3	-11	700	275	9.400
13	-15	6	-29	1050	275	44.500
14	-12	7	-27	1275	375	58.400
15	-12	5	-22	1250	325	49.900
16	-13	4	-21	1200	400	64.000
17	-7	4	-18	950	350	22.900
18	-8	4	-17	650	250	12.500
19	-8	3	-16	1125	350	32.300
20	-6	5	-17	625	325	12.000
21	-9	5	-18	1075	375	36.000
22	-5	5	-20	1050	210	13.500
23	-3	2	-7	700	200	4.200
24	-5	3	-14	700	375	13.000

- Saw-tooth troughs in front of the ebb-tidal delta are distinctly deeper than those in front of Ameland. A sudden decrease in trough depth occurs between troughs 6 and 7, which are situated in the bight between the ebb-tidal delta and Ameland. The first six troughs show rather large depth values, with a mean of 35 cm. Troughs in front of Ameland show fairly constant depths with a mean value of about 10 cm.
- Troughs in front of the ebb-tidal delta show an inexplicable atypical trend of maximum lengths along the updrift and downdrift edges and minimum lengths in between (see *Appendix 14a*). Trough lengths in front of Ameland are larger with a gradual length transition between the two areas.
- Trough width shows a sudden decrease for trough number 7 after which a downdrift width increase is observed.
- Saw-tooth trough volumes show a decrease towards the downdrift ebb-tidal delta side with a minimum of 2.340 m^3 for trough 7. Trough size tends to increase downdrift until trough 16 after which a size decrease is observed. The volume value range (between maximum and minimum values) is relatively small, therefore, volume changes can be denoted as gradual.

3.3.3 Bar direction and wave-length measurements

Wave-lengths were determined by measurement parallel to the shore, results are presented in Table 4. Bars 1 and 2 were excluded as their directions differed from the remaining bars.

Table 4: Wave-length of saw-tooth bars.

Bar nr.	Wave-length (m)
3 to 6	650
7 to 9	875
9 to 12	650
12 to 16	650
14 to 18	625
17 to 21	625
20 to 23	650
22 to 25	625

Saw-tooth bar wave-lengths show a fairly constant value with a mean of about 630 m, except for the downdrift part of the ebb-tidal delta where wave-length is nearly 900 m.

Table 5: Saw-tooth bar directions.

Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)	Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)
1	100	10	**14**	75	70
2	95	10	**15**	70	70
3	45	80	**16**	70	65
4	30	60	**17**	60	55
5	50	80	**18**	65	60
6	60	90	**19**	65	60
7	45	90	**20**	95	85
8	45	80	**21**	80	70
9	45	70	**22**	75	70
10	55	70	**23**	70	60
11	55	65	**24**	75	70
12	70	75	**25**	60	50
13	70	75			

Bars on the ebb-tidal delta show directions ranging between 30 and 60° with respect to the geographical north, with the exception of shore-parallel bars 1 and 2 (see Table 5). For bars in front of Ameland this range lies between 55 and 95°. Both ranges are larger than in preceding years. As directions with respect to the shoreline are concerned, the range is smaller for bars in front of Ameland (20°). Direction range of bars in front of the ebb-tidal delta is again 30°. For bars in front of Ameland it can be stated that direction depends on shoreline position, as was observed in 1993, in contrast to bars in front of the ebb-tidal delta for which no dependence relationship can be established.

3.3.4 Morphological explanation

A direct relationship seems to exist between the bars and troughs lying on the ebb-tidal delta and those situated in front of Ameland. Especially saw-tooth bar parameter values show gradual changes in a downdrift direction. Most parameters even show no significant differences for the two saw-tooth bar areas. A transition zone is indistinct in 1989. The slightly smaller extend of bars and troughs in the bight might be caused by the longshore drift reversal (see *Fig. 3, Introduction*). Migration of saw-tooth bars may be undisturbed in a downdrift direction due to the morphology along the north-west coast of Ameland (see *Appendix 15a*). A sandy spit was not yet present in 1989. Only a small protrusion existed (see *Appendix 15a*). Longshore currents are therefore not interrupted by shore-normal currents flowing in and out the inner lake as is the case in 1993 and 1996. No eastward, downdrift decay of saw-tooth bars is observed.

3.4 Saw-tooth bars and troughs in 1993

Bar and trough numbers are presented in *Appendix 13b*. Parameters Hm, length, width and volume are plotted and presented in *Appendix 14b*. The entire ebb-tidal delta morphology of 1993 is represented in *Appendix 15b*.

3.4.1 Saw-tooth bar results

Bars 1 to 11 lie on the ebb-tidal delta front, bars 12 to 20 lie seaward of the breaker-bars in front of Ameland. Calculated parameter values are presented in Table 6.

Table 6: Parameter-values of saw-tooth bars in 1993.

Bar nr.	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	18	6	29	1650	150	43.000
2	22	8	38	400	75	7.500
3	28	14	51	250	150	10.500
4	19	10	39	600	150	16.300
5	25	9	37	1000	250	50.900
6	25	8	37	1650	250	103.800
7	32	15	64	1425	225	100.000
8	27	13	51	1150	250	74.500
9	16	9	38	900	150	22.800
10	25	14	60	575	250	37.500
11	18	8	35	450	275	21.000
12	8	5	20	1150	275	25.500
13	8	4	16	975	225	18.000
14	20	7	30	950	400	75.000
15	15	9	32	1525	475	106.000
16	7	4	16	1450	250	25.500
17	7	4	16	1475	325	34.000
18	11	7	30	1350	475	70.000
19	7	3	13	1250	450	39.500
20	5	3	10	875	400	18.000

No saw-tooth bars were observed in the transition zone between bars 11 and 12, which represents a shore-parallel extend of 1.5 km. Several small sand mounds, mainly parallel to the shore were observed. These were not described by parameter values. Between bars 17 and 18, a similar area was recognized where only small-scaled sand mounds appeared. This area has a shore-parallel extend of about 2.5 km (see *Appendix 13b*). As no bars are present in the transition zone the two types of saw-tooth bars and troughs are consequently described separately. The stated hypothesis that the saw-tooth bars on the ebb-tidal delta gradually migrate c.q. transform to the easterly ones, can be rejected without any further morphological bar parameter analysis in this Amelander Inlet case. Nevertheless, the values will be discussed as they are used for comparison with other studied years.

- Saw-tooth bars on the ebb-tidal delta show a relatively constant mean height of 24 cm. Only bar 11, the most downdrift one on the ebb-tidal delta, shows a distinctly smaller mean height of 16 cm. Mean bar height in front of Ameland is 12 cm, but shows more variation as bars 14 and 15 are distinctly higher than the other ones.
- The length of the saw-tooth bars on the ebb-tidal delta increases up to bar 6 to a length of 1660 m, and decreases further downdrift to a minimum of 450 m for bar 11. The same trend in increase and decrease of bar length is observed in front of Ameland, with a maximum of 1520 m. So no distinct length differences between these two types of bars are observed.
- Saw-tooth bar width shows a well-defined increasing trend in a downdrift direction, with a minimum of 85 m on the ebb-tidal delta to a maximum of 470 m in the east in front of Ameland.
- Saw-tooth bar volumes are largest along the ebb-tidal delta, with a maximum of 103.750 m^3. An increase in volume to the east on the ebb-tidal delta is observed, after which volume decreases to a minimum for the most downdrift bar on the ebb-tidal delta, bar 11. The volumes of the bars in front of Ameland are smaller. With the exception of bars 14, 15 and 18, mean volume is about 27.500 m^3. Although bars 14 and 15, as well as bars 16 and 17, show a revival of the saw-tooth bar features (see *Appendix 13b*), the most downdrift sand mounds, which were not parameterized imply an extinction of the saw-tooth bar feature to the east, in front of Ameland.

3.4.2 Saw-tooth trough results

Calculated parameter values of saw-tooth troughs in 1993 are presented in Table 7.

Table 7: Parameter-values of saw-tooth troughs in 1993.

Trough	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	-92	37	-153	2150	275	524.200
2	-80	50	-151	400	300	99.200
3	-105	34	-136	325	350	119.300
4	-112	71	-236	1050	450	540.000
5	-74	50	-199	1525	400	464.000
6	-54	24	-110	1850	575	567.500
7	-117	73	-234	1050	500	632.500
8	-121	78	-220	1100	525	712.000
9	-81	43	-125	525	375	160.000
10	-26	16	-48	250	250	16.500
11	-25	8	-33	175	200	8.600
12	-15	7	-28	1050	250	40.600
13	-13	6	-24	825	275	30.000
14	-9	5	-22	1550	325	45.000
15	-14	6	-30	1600	350	59.000
16	-12	6	-22	1350	350	59.000
17	-9	4	-20	1350	350	41.600
18	-10	5	-20	1050	450	48.800
19	-7	3	-12	1025	350	24.300

The calculated data concerning mean and maximum trough depths show that on the ebb-tidal delta, trough-depth values are considerably larger than the saw-tooth bar height values (see *fig. 7*). This trend was induced by the digitizing method. Instead of digitizing mean depth contours between bars and troughs on the ebb-tidal delta, a general depth contour, based on its position updrift of the ebb-tidal delta as well as its position downdrift in front of Ameland, was digitized. This method is valid when analyzing the 2D *Vaklodingsdata*-map in Appendix 8. Rather than protrusions from a depth contour, representing saw-tooth bars, indentations on this depth contour exist, representing saw-tooth troughs. In this respect, the saw-tooth bar phenomenon is better referred to as the saw-tooth trough phenomenon.

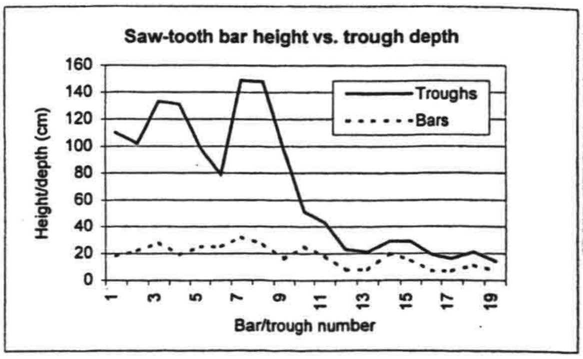

Figure 7: The saw-tooth bar phenomenon is rather referred to as the saw-tooth trough phenomenon as trough depths exceed bar heights considerably.

- Troughs 1 to 11 are located on the ebb-tidal delta. These troughs are distinctly deeper, with a mean of more than 90 cm, than those located in front of Ameland, which have a mean depth of 14 cm. Maximum trough depth values show a similar trend and constitute values of twice the mean depth.

- Trough lengths on the ebb-tidal delta as well as trough lengths in front of Ameland show a similar trend of increase and decrease in a downdrift direction. Mean length values are about 1 km for both types of troughs. Width values however do show distinct differences.
- Mean width of troughs on the ebb-tidal delta is 420 m and decrease to 310 m for troughs in front of Ameland. Width values show a parabolic trend of increase and decrease within the ebb-tidal delta part. Troughs in front of Ameland show an increase in width in a downdrift direction.
- Trough volumes of the ebb-tidal delta significantly differ from those in front of Ameland, with the exception of troughs 2, 3 and 9. Mean trough volume on the ebb-tidal delta amounts about 425.000 m^3, with a maximum of about 630.000 m^3. Mean trough volume in front of Ameland is about 40.000 m^3, with a maximum of 80.000 m^3.

3.4.3 Bar direction and wave-length measurements

Wave-lengths were determined by measurement parallel to the shore, results are presented in Table 8. Bars 1 and 2 were excluded as their directions differed from the remaining bars.

Table 8: Wave-length of saw-tooth bars.

Bar nr.	Wave-length (m)
3 to 6	525
5 to 8	925
7 to 10	650
9 to 11	500
12 to 16	550
14 to 17	500
18 to 19	525

Wave-lengths increase to a value of 925 m on the ebb-tidal delta, after which diminution of wave-length occurs to a minimum of 500 m on the delta. Wave-lengths in front of Ameland are fairly constant with a mean of 525 m.

Directions of saw-tooth bars were measured with respect to the geographical north and with respect to the shoreline for 1993 as well. Results are presented in Table 9.

Table 9: Saw-tooth bar directions.

Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)	Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)
1	5	5	**11**	35	110
2	0	20	**12**	50	60
3	45	75	**13**	50	55
4	45	75	**14**	45	40
5	30	50	**15**	50	45
6	10	35	**16**	50	45
7	30	55	**17**	60	45
8	45	80	**18**	65	50
9	40	70	**19**	65	55
10	35	75			

Angles measured with respect to the geographical north range from 30° to 45° on the ebb-tidal delta, with the exception of bars 1, 2 and 6, which all three have contrasting shapes and directions (see *Appendix 13b*). Bars in front of Ameland have directions ranging from 45° to 65° with respect to the geographical north. Angles measured with respect to the shoreline show more variation, as bars on the ebb-tidal delta are concerned. Bars in front of Ameland again show a constant range between 45 and 60°. Dependence of bar direction on geographical north seems to exist for bars situated on the ebb-tidal delta. This makes longshore current origin (wave either tide driven) less plausible. Bar directions in front of Ameland tend to depend on shoreline position and may consequently be formed by longshore currents, which does not coincide with observations in 1996.

3.4.4 Morphological explanation

Saw-tooth bar c.q. troughs do not migrate gradually downdrift in 1993, but quench toward the ebb-delta bight and start to form again downdrift of the bight, in front of Ameland. The transition zone is located between X-coordinates 174000 and 176000. This location is situated updrift from the transition zone location in 1996 (see next paragraph). This is attributed to the smaller extension of the sandy spit in 1993 (see *Appendix 15b*). The inner lake, created by the sandy spit could also disturb the downdrift continuous migration of saw-tooth bars. The observed shore-parallel bars in the ebb-delta bight could be induced by ebb- and flood currents flowing in and out the inner lake created by the sand spit present at this exact location in 1993. These shore-parallel bars then constitute flow-transverse bedforms. The significant difference in parameter values Hm, volume and wave-length subscribe the existence of two different types of saw-tooth bars. The saw-tooth bars on the ebb-tidal delta show a trend of origination in the west and vanishing toward the bight of the ebb-tidal delta, with a maximum size in between. Saw-tooth bars in front of Ameland show two revival areas with maximum saw-tooth bar sizes. The bars seem to vanish toward the east.

3.5 Saw-tooth bars and troughs in 1996

Bar and trough numbers are given in *Appendix 13c*. Parameter values Hm, length, width and volume are plotted and presented (see *Appendix 14c*). The entire ebb-tidal delta morphology is represented in *Appendix 15c*.

The residual map, constructed out of Jarkus-data, only extends to –8 m bottom depth, due to limited shore-normal depth soundings carried out in 1996. Since the saw-tooth bars in front of Ameland are not totally covered by the Jarkus-map, lengths of these bars were obtained from the *Vaklodings*-map where possible, if not, Jarkus lengths were determined. Mean bar heights were still obtained from the Jarkus-map as this map constitutes of more accurate data.

3.5.1 Saw-tooth bar results

Bars 1 to 8 lie on the ebb-tidal delta front, bars 9 to 11 lie in the bight between the ebb-tidal delta and Ameland, bars 12 to 21 lie seaward of the breaker-bars in front of Ameland. Calculated parameter values of saw-tooth bars in 1996 are presented in Table 10.

Table 10: Parameter-values of saw-tooth bars in 1996.

Bar nr.	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	21	13	48	1050	225	50.900
2	24	12	52	1550	275	107.500
3	22	11	46	1925	275	115.000
4	27	11	57	1650	400	175.000
5	20	10	40	1550	350	110.000
6	29	9	42	750	250	57.000
7	25	10	40	725	425	76.500
8	12	6	26	650	225	18.000
9	17	10	30	1150	200	40.000
10	8	5	20	750	200	12.000
11	5	3	10	750	225	8.500
12	3	2	7	550	125	2.000
13	6	4	14	850	350	20.000
14	7	4	16	1200	275	25.000
15	11	5	21	1175	275	40.000
16	7	4	19	1200	350	29.000
17	6	3	12	1175	275	20.000
18	9	6	21	550	325	16.000
19	3	2	8	600	250	4.500
20	5	3	10	600	250	7.100
21	9	3	13	625	275	16.000

- Bars lying on the ebb-tidal delta front are distinctly higher than those lying in front of Ameland. Mean bar height in front of the ebb-tidal delta is 23 cm (bars 1 to 8), mean bar height in front of Ameland is 8 cm (bars 12 to 21). Bars situated in the transition zone, represented by bars 9, 10 and 11 in this particular case, display a sudden decrease in mean bar height of 12 cm. Mean bar height reaches a minimum of 3 cm (which is an arbitrary height as recording accuracy is concerned, see *Discussion*) at the end of the transition zone, after which mean bar height increases again. Generally, maximum saw-tooth bar heights are twice the mean bar heights.

- Saw-tooth bar lengths show largest values in front of the ebb-tidal delta (see *Appendix 14c*). A sudden decrease in bar length is observed between bars 5 (1550 m) and 6 (750 m). Bar length reaches a minimum at bar 12 (550 m), after which the bars lengthen to a new maximum of about 1200 m, in front of Ameland. It can be stated that a transition zone where again a sudden change of bar length occurs exists for saw-tooth bar lengths as well. Although this transition zone covers a larger area of 7 bars.
- Mean saw-tooth bar widths show less variation, when compared to saw-tooth bar heights or lengths. Bars lying on the ebb-tidal delta have a mean width of about 320 m, bars in front of Ameland have a mean width of 300 m. A transition zone exists between bars 7 and 13 where bars display distinctly lower width values, with a mean of 200 m. Again, the edges of the transition zone displays abrupt bar width changes.
- Saw-tooth bar volumes have maximum values on the ebb-tidal delta. Bar 4 shows a maximum volume of nearly 200.000 m^3. Bars 5 to 12 show a decrease in volume with a minimum for bar 12 of about 2.000 m^3. Although less sudden changes in bar volumes exist, in comparison to changes in bar height or length, the downdrift reduction can still be denoted as rapid. The saw-tooth bars seem to quench until bar 12, after which they start to form c.q. grow again, to reach a new local maximum at bar 15 (20.000 m^3). Downdrift of bar 15, bar volumes decrease and quench until no bars are recognised downdrift of bar 19. Between bars 19 and 20, a large area with a length of about 4 km exists, without any recognizable saw-tooth bars. Several small sand mounds are present though. These were not taken into consideration in the parameter description.

3.5.2 Saw-tooth trough results

Calculated parameter values of saw-tooth troughs in 1996 are presented in Table 11.

Table 11: Parameter-values of saw-tooth troughs in 1996.

Trough	Hm (cm)	Sd (cm)	Hmax (cm)	Length (m)	Width (m)	Volume (m^3)
1	-50	30	-100	1225	325	205.000
2	-56	31	-101	1775	450	450.000
3	-40	18	-110	2350	525	500.000
4	-95	63	183	1200	550	640.000
5	-94	63	-189	1225	450	527.000
6	-119	25	-144	450	325	170.000
7	-40	20	-78	350	275	37.000
8	-16	10	-54	1350	300	26.500
9	-26	13	-54	1350	300	10.300
10	-14	8	-29	1300	325	60.000
11	-6	3	-10	725	250	11.000
12	-7	6	-25	950	350	22.500
13	-11	5	-22	1075	300	36.000
14	-13	6	-24	950	350	43.500
15	-9	3	-14	875	300	24.000
16	-13	5	-24	800	325	35.000
17	-11	4	-18	700	400	32.000
18	-20	10	-38	1050	350	74.200
19	-9	8	-24	850	325	26.000
20	-11	5	-19	825	325	28.000
21	-11	2	-15	575	325	20.500

The same digitizing method was used as discussed for 1993. Consequently, troughs dominate over bars in 1996 as well.

- Troughs situated on the ebb-tidal delta show distinctly larger mean depth values than those situated in front of Ameland. Mean trough depth on the delta is about 70 cm, mean trough depth in front of Ameland is about 10 cm. The boundary is drawn between bars 7 and 8. The transition is sudden, with a decrease in depth of more than one meter within two successive troughs.
- Saw-tooth trough lengths show a mean of 1.5 km on the ebb-tidal delta. A rapid decrease in length is observed from trough 4 to trough 7 (see *Appendix 14c*), after which the lengths increase and stabilise again to a mean of about 900 m.
- Trough widths are largest on the ebb-tidal delta as well, with a mean of 450 m (troughs 1 to 6) and a maximum of 560 m. Mean trough width in front of Ameland is 315 m (troughs 7 to 21).
- The difference between trough volumes situated on the ebb-tidal delta and those in front of Ameland is much larger than the difference in saw-tooth bar volume. This trend is due to earlier the explained trough bar domination. Troughs on the ebb-delta front have a mean of about 410.000 m^3 (troughs 1 to 6), with a maximum of 600.000 m^3 for trough 4. Troughs in front of Ameland have a mean volume of 35.000 m^3. The transition zone, represented by troughs 6, 7 and 8, shows a much more rapid volume change than the transition zone determined for the saw-tooth bars. While bars seemed to form again after their quenching in the transition zone, troughs remain relatively small after their quenching.

3.5.3 Bar direction and wave-length measurements

Wave-lengths were determined by measurement parallel to the shoreline. The downdrift development of wave-length is presented in Table 12.

Table 12: Wave-length of saw-tooth bars.

Bar nr.	Wave-length (m)
1 to 4	700
3 to 6	750
5 to 9	575
8 to 12	450
11 to 15	675
14 to 17	825
16 to 19	975
20 to 21	900

It is observed that wave-length decreases from the ebb-tidal delta (λ =700 m) to a minimum in the transition zone (λ = 450 m). Thereafter, wave-length increases from 675 m in the west to 900 m in the east, in front of Ameland.

Directions of saw-tooth bars, measured with respect to the geographical north as well as with respect to the shoreline, are presented in Table 13.

Table 13: Saw-tooth bar directions.

Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)	Bar number	Angle (w.r.t. north)	Angle (w.r.t shoreline)
1	30	60	**11**	45	55
2	60	55	**14**	55	50
3	20	50	**15**	50	45
4	40	45	**16**	45	30
5	45	60	**17**	45	30
6	35	60	**18**	45	30
7	35	65	**19**	45	30
8	30	75	**20**	45	40
9	45	90	**21**	45	40
10	45	60			

Bars 1 to 8, all situated on the ebb-tidal delta, have directions ranging between 45° and 65° with respect to the shoreline. In the transition zone, represented by bars 8 to 10 located in the bight between the ebb-tidal delta and Ameland, angles maximize to 90°, after which the angle decreases again to a constant range between 30° and 55° in front of Ameland. Generally bars lying on the ebb-tidal delta are directed more seaward with respect to the shoreline, than those lying in front of Ameland. Angles measured with respect to the geographical north range between 30° and 55° for all bars, apart from two exceptions on the western border of the delta. As this range is smaller than the previous one, it can be stated that direction is relatively independent on shoreline position. This stated fact might imply that saw-tooth bar direction is a function of wave-mechanisms or a combination of mechanisms rather than of merely current-mechanisms, as currents are generally directed parallel to the shoreline.

3.5.4. Morphological explanation

The observations of morphological saw-tooth bar and trough parameters in 1996 may be summarised as follows. All calculated parameter values of saw-tooth bars and troughs lying on the ebb-tidal delta significantly differ from those in front of Ameland, with all parameter values being largest on the ebb-tidal delta. In the transition zone, abrupt changes in parameter values occur. Saw-tooth bar height and volume data imply that the bars quench to a minimum in the transition zone, located between X-coordinate 176000 and 178000. The observations suggest that the saw-tooth bar morphology of Ameland in 1996 is not a continuous one, migrating from the ebb-tidal delta to the east. Bars do not totally fade out towards the east. This deduction is emphasised by wave-length observations which show a similar trend of diminution and increase within the transition zone. Saw tooth bars seem to fade out in the transition zone and are rebuilt downdrift of the transition zone. This transition zone corresponds to the outflow area of the inner lake created by the sandy spit present at this location in 1996 (see *Appendix 15c*). In and out flowing currents (ebb and flood) probably cause the interruption in downdrift saw-tooth bar migration. This transition zone is located downdrift from the transition zone in 1993 due to the downdrift extension of the sandy spit in 1996. Although in 1996, the entrance of the inner lake was smaller in extend when compared to 1993, which results in stronger currents, no flow-transverse bedforms were generated. These might be absent due to a more shore-parallel outflow of the inner lake in 1996 when compared to 1993.

Although saw-tooth bars quench towards the east, in front of Ameland, they also start to grow downdrift of this quenching. This trend is likely to be induced by wave- or combined wave-current mechanisms, as longshore currents are assumed to be constant. The analysed maps do not imply that the saw-tooth bars totally fade out towards the east.

3.6 Saw-tooth bar features of 1989, 1993 and 1996 compared

The entire ebb-delta morphologies of 1989, 1993 and 1996 are presented in *Appendix 15a-c*. These maps are used to clarify the differences in saw-tooth bar parameter values of different years. The ebb-tidal delta is subject to a cyclic development in which four characteristic stages are recognized (Israel, 1998). The schematic representation of the stages of ebb-tidal delta morphologies of 1989, 1993 and 1996 are also presented to explain the observed differences between the years (see *fig. 8*).

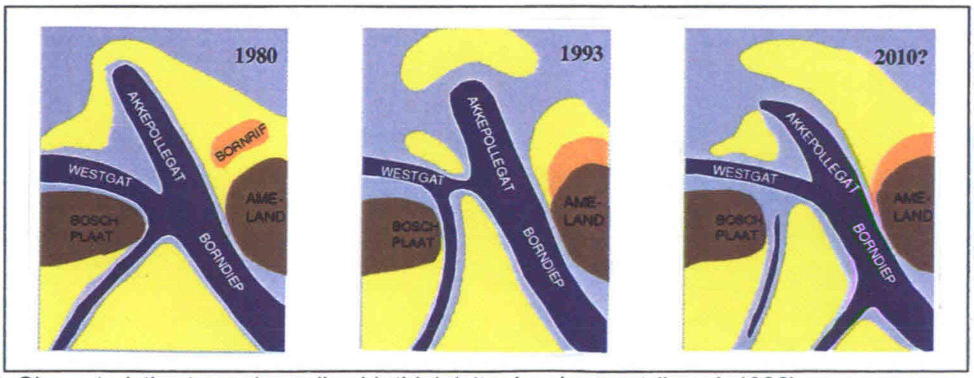

Figure 8: Characteristic stages in cyclic ebb-tidal delta development (Israel, 1998).

The studied area is divided into two parts; an ebb-tidal delta part and a north coast part of Ameland. Mean parameter values are calculated over these two areas and compared between two successive studied years. Additional information, which cannot be expressed by mean parameter values is also given (e.g. transition zone extend). The boundary between the two parts is chosen at X-coordinate 175000, on the basis of the general morphology of the entire ebb-tidal delta (see *Appendix 15a-c*). The given X-coordinate represents the boundary between saw-tooth bar locations on the front of the ebb-tidal delta and in front of Ameland. The eastward boundary is given by X-coordinate 186000 (see *Appendix 1*) and is used for total volume calculations. The two most westward nearly shore-parallel bars on the ebb-tidal delta are included in volume calculations as well as small sand mounds, often present in front of Ameland (see *Appendix 13*).

3.6.1 1989 versus 1993

For 1989, the boundary between the ebb-tidal delta and Ameland is situated between bars 9 and 10. For 1993, this boundary lies between bars 11 and 12. Calculations of mean parameter-values are presented in Table 14.

Table 14 : Mean-parameter comparison between 1989 and 1993.

	Saw-tooth bars			Saw-tooth troughs		
		1989	1993		1989	1993
Ebb-tidal delta	Hm (cm)	12	23	Hm (cm)	-26	-81
	Lm (m)	625	900	Lm (m)	550	950
	Wm (m)	275	200	Wm (m)	30	375
	Vm (m^3)	20400	45100	Vm (m^3)	40800	349500
	α_a (°)	57	29	α_a (°)	-	-
	α_r (°)	63	59	α_r (°)	-	-
	Vtot (m^3)	183700	525500	Vtot (m^3)	367000	3844300
	# bars	9	11	# troughs	9	11
Ameland	Hm (cm)	10	10	Hm (cm)	-9	-12
	Lm (m)	1075	1225	Lm (m)	915	925
	Wm (m)	350	375	Wm (m)	310	325
	Vm (m^3)	41500	45700	Vm (m^3)	27750	39350
	α_a (°)	70	54	α_a (°)	-	-
	α_r (°)	69	49	α_r (°)	-	-
	Vtot (m^3)	664500	475000	Vtot (m^3)	416500	511800
	# bars	14	9	# troughs	14	11

Legend:

Hm (cm)	mean height	α_a (°)	absolute angle (degrees)
Lm (m)	mean length	α_r (°)	relative angle (degrees)
Wm (m)	mean width	Vtot (m^3)	total volume
Vm (m^3)	mean volume	#	amount

Ebb-tidal delta. Comparing the 3D-presentations of the saw-tooth bars on the ebb-tidal delta in 1993 and 1989, saw-tooth bars in 1989 are almost absent (*Appendix 13*). Consequently, large differences in mean parameter values are observed in 1989 and 1993. Mean bar height in 1993 is twice the value of 1989. Mean bar volume and total bar volume values in 1993 are over twice the amount of 1989. Trough volumes even show a more spectacular increase. Mean wave-length is 775 m in 1989, which represents a decrease of about 100 m.

Ameland. Bars and troughs in front of Ameland show little difference in parameter values. Mean bar volume has increased with about 10 % in 1993, while total volume has decreased with about 30 % (200.000 m^3). Mean trough volume has increased with about 30 %, while total volume has increased with about 20 % (100.000 m^3). As initial bathymetric maps of the area in front of Ameland are quite similar, volume comparisons are highly valuable. The amount of bars and troughs has decreased in 1993. Correspondingly, mean wave-length has increased in 1993 with about 200 m.

Morphological explanation. Although volume comparisons are made, the value of the outcome is rather trivial as the difference between the initial bathymetric maps of the two compared years is large (see *Discussion*). On the ebb-tidal delta, the total volume of sand present in the saw-tooth bars and troughs decreased from 1989 to 1993, as trough volumes increased distinctly, while bar volume increased to a lesser extend. So although saw-tooth bars are more distinct, less sand is present in 1993. Analyzing characteristic stages represented in *fig. 8*, it is observed that the Bornrif bar has landed on the Ameland shore in 1993. In 1989, this shoal was still located on the ebb-tidal delta and could therefore act as a sand supplier to the ebb-tidal delta front. In 1993 and 1996, a lot of sand originating from the landed Bornrif bar is used for the expansion of the sandy spit and is therefore not used for saw-tooth bar formation. The presence of bars and troughs on the ebb-tidal delta front is probably related to the amount of sand present on the supratidal part of the ebb-tidal delta. When the extend of the supratidal shoal is large, the phenomenon is less pronounced (1989), in contrast to when this supratidal shoal extend is small (1993, 1996); then the phenomenon is distinctly present.

The saw-tooth bars in front of Ameland show less relation to the presence of the supratidal Bornrif bar shoal and its landing, as little changes occurred between 1989 and 1993. Nevertheless, the total net sand volume loss is about 700.000 m^3 as bar volume decreased and trough volume increased, which both result in a net loss of sand. So more sand is present in front of Ameland in 1989, probably caused by the undisturbed downdrift sand migration and the lack of sand trapping in a sandy spit. Due to the lack of a transition zone in 1989, bars are present along the entire coast, which results in a larger amount of bars and troughs. Bars are directed more parallel to the shore in 1993 when compared to 1989, possibly linked to the extra outflow from the inner lake which forces the bars towards the shore.

3.6.2 1993 versus 1996

For 1996, the boundary between the ebb-tidal delta and Ameland is situated between bars 8 and 9. For 1993, this boundary lies between bars 11 and 12. Calculations of mean parameter-values are presented in Table 15.

Table 15: Mean-parameter comparison between 1993 and 1996.

	Saw-tooth bars			Saw-tooth troughs		
		1993	1996		1993	1996
Ebb-tidal delta	Hm (cm)	23	22	Hm (cm)	-81	-57
	Lm (m)	900	1275	Lm (m)	950	1100
	Wm (m)	200	275	Wm (m)	375	350
	Vm (m^3)	45000	79800	Vm (m^3)	350000	262800
	α_a (°)	29	38	α_a (°)	-	-
	α_r (°)	59	62	α_r (°)	-	-
	Vtot (m^3)	525500	797500	Vtot (m^3)	3845000	2628000
	# bars	11	11	# troughs	11	11
Ameland	Hm (cm)	10	7	Hm (cm)	-11	-12
	Lm (m)	1225	900	Lm (m)	1225	925
	Wm (m)	365	250	Wm (m)	350	325
	Vm (m^3)	45700	18100	Vm (m^3)	46000	39400
	α_a (°)	54	47	α_a (°)	-	-
	α_r (°)	49	41	α_r (°)	-	-
	Vtot (m^3)	475000	227100	Vtot (m^3)	369000	511700
	# bars	9	13	# troughs	8	11

Legend:

Hm (cm)	mean height	α_a (°)	absolute angle (degrees)
Lm (m)	mean length	α_r (°)	relative angle (degrees)
Wm (m)	mean width	Vtot (m^3)	total volume
Vm (m^3)	mean volume	#	amount

Ebb-tidal delta. Significant differences exist for the following parameter values; mean length is about 360 m larger in 1996 than in 1993. Mean width is about 75 m larger in 1996. As initial bathymetric maps of both years are almost identical, volume changes are to show a lot of correspondence with actual volume changes. Mean bar volume as well as total volume increased with about 40 % (300.000 m^3) in 1996. Saw-tooth troughs in front of the ebb-tidal delta have shallowed with about 20 cm (30 %). Total trough volume has also significantly decreased with more than 30 % (1.000.000 m^3) in 1996 as well as mean volume (25 %). Mean absolute bar direction (α_a) in 1996 is ca 10° more shore-parallel than in 1993. In 1993, mean wave-length of saw-tooth bars on the ebb-tidal delta is about 650 m. In 1993, mean wave-length is 675 m. So no significant wave-length differences occur on the ebb-tidal delta.

Ameland. Largest differences occur in mean bar length. Probably, partly due to the fact that saw-tooth bars exceed the extend of the residual map in 1996. Although lengths were instead gathered from the *Vaklodings*-map, this was only feasible for a limited amount of bars. Since this complicates comparison as volume calculation are also affected. Bar width is almost 30 % smaller in 1996 than in 1993. The amount of bars has increased in 1996 with 25 %. Total bar volume decreased with 250.000 m^3. Troughs in front of Ameland show little changes over three years. Although mean trough volume has decreased, total volume has increased with almost 30 % (150.000 m^3), despite the length measurement limitations. This can be explained by the increase in amount of troughs in front of Ameland. This increase in trough amount (#) results in a wave-length decrease of 850 m in 1993 versus 550 m in 1996.

Morphological explanation. According to these observations, more sand was stored in the saw-tooth bars on the ebb-tidal delta in 1996 than in 1993. Trough volumes were less in 1996, which also signifies sand input. The total increase is about 1.5 million m^3. The schematic representations of the ebb-tidal delta (see *Fig. 7*) subscribes this observation as these indicate that more sand was present in the downdrift part of the subtidal ebb-tidal delta in 1996 when compared to 1993. This suggest a direct relationship between the supratidal ebb-tidal delta extend and the amount of sand in the saw-tooth bars in front of the ebb-tidal delta. In 1993, a larger part of the ebb-tidal delta is subtidal, which means less supratidal sand is present on the downdrift part of the ebb-tidal delta. Saw-tooth trough amount (#) has increased as well as total volume, which might be due to an increase in for instance current strength due to the extra passage over the ebb-tidal delta.

More sand was stored in the saw-tooth bars and troughs in front of Ameland in 1993 when compared to 1996. Volumes of troughs increased in 1996. This results in a net loss of sand of 400.000 m^3 in 1996 when compared to 1993. This could be caused by sand trapping of the bars of the ebb-tidal delta which show a reverse trend of increase of amount of sand. Larger bars on the ebb-tidal delta are possibly less mobile and therefore hardly migrate in a downdrift direction, which results in less sand in the bars in front of Ameland. Another cause could be sand trapping by the extending sandy spit.

Bars in front of Ameland fade out between X-coordinates 182000 and 184000 in 1993, after which they start to form again. For 1996, this occurs between X-coordinates 184000 and 186000. This difference cannot be explained by migrational characteristics (see *Migrational characteristics*). The transition zone, represented by decreasing parameter values (1996) or a total absence of bars (1993), differs in location as well. In 1993, the transition zone is located between X-coordinates 174000 and 176000, while in 1996, this is located between X-coordinates 176000 and 178000. The difference is explained by in- and outflowing currents of the inner lake present, created by the sandy spit, which expands downdrift throughout the years.

3.7 Migrational characteristics

Migration is assumed to be induced by longshore currents (tide- and wave-driven) as these are directed parallel to the coast in a generally easterly direction, which coincides with the direction of the bar migration.

3.7.1 Ameland

Migration of saw-tooth bars and troughs along the Ameland coast is reflected by maps presented in *Appendix 16a + b*. Two maps with original bathymetric data of successive years were subtracted here, resulting in a map with positive grid-cell values which represent sedimentation and negative grid-cell values which represent erosion within a year. Migration rates were calculated with profiles plotted along the bars and troughs. Migration rates were read from the X-axis. Examples of shore-parallel profiles are given in *Appendix 17*. Shore-parallel profile plotting assumes bars to migrate parallel to the shore. Results are presented in Table 16 where migrational characteristics of saw-tooth bars and troughs are divided in two areas; a western and an eastern part of the sea-bottom in front of Ameland (boundary at X-coordinate 184000) as for some years distinct differences exist between these two areas. For 1990 and 1995, bathymetric data were too limited for calculating migration rates.

Table 16 : Migration rates of saw-tooth bars in front of Ameland from 1989 to 1996.

Jarkus	Western part			Eastern part
	Migration rate (m/yr)	Maximum (m/yr)	Minimum (m/yr)	Migration rate (m/yr)
'89-'91	120	200 (center)	80 (rest)	140
'91-'92	270	600 (center)	120 (rest)	180
'92-'93	200	-	-	200
'93-'94	<100	180 (center)	0 (rest)	160
'94-'96	150	200 (E + W)	60 (center)	150

Migration rates show distinct differences throughout the years with a range of about 100 to 270 m/yr from 1989 to 1996. Especially for years 1991 to 1993 migration rates exceed the mean of about 160 m/yr. This period coincides with the period of formation of the sandy spit. The sandy spit creates a distinct bend between the ebb-tidal delta and Ameland, while in 1989 and 1996 the coastline shows a smooth transition between the ebb-tidal delta and Ameland. This curvature somehow seems to result in increased current-strength and increased migration rates of saw-tooth bars in front of Ameland. However, the observed differences could also be induced by prevailing weather conditions in these particular years.

A distinction was made between saw-tooth bar migration in a western and eastern part in front of Ameland due to the occurrence of distinct differences in *1992-1993* and *1993-1994*. These observed differences cannot be explained by the available bathymetric information. As the eastern part in front of Ameland showed more constant migration rate values, no distinction was made between minimum and maximum values. For the western part, most maximum migration rates are observed in the central part, which is situated downdrift from the bight between the ebb-tidal delta and Ameland. Hence, current strength is assumed to be strongest at this location, especially for *1991-1992*.

3.7.2 Ebb-tidal delta

Migration of saw-tooth bars and troughs along the ebb-tidal delta is reflected by maps presented in *Appendix 18a + b*. Migration rates on the ebb-delta were determined by plotting shore-parallel profiles on the original as well as on the residual maps, following the ebb-tidal deltas curvature. Data were only available with an interval of 3 or 4 years, so calculated migration rates are mean values over these years. Due to this large measurement interval, migration rate values are less reliable than those based on the Jarkus-data. Examples of plotted profiles over saw-tooth bars and troughs on the ebb-tidal delta are presented in *Appendix 19*. Results are shown in Table 17.

Table 17: Migration rates of saw-tooth bars on the ebb-tidal delta from 1989 to 1996.

Vaklodings-data	Migration rate (m/yr)
'89-'93	80
'93-'96	120

Migration rate measurements of 1989 to 1993 are uncertain as the bars in 1989 were very small. Therefore, the migration rate could only be based on three displacement measurements. The migration rate for 1993 to 1996 is more reliable in this respect. A stroboscopic effect, which could enter the migration rate measurements due to the large measurement interval, appears to be absent as the migration rate for 1993 to 1996 fairly well coincides with the mean migration rate of bars in front of Ameland (western part) for this period (see Table 16). A migration rate of 120 m/yr is somewhat lower than rate values observed in front of Ameland. This could be explained by the larger size of the saw-tooth bars and troughs on the ebb-tidal delta, which could result in a delay in displacement.

4. Discussion

4.1 Quantitative saw-tooth bar characterization

Several techniques, assumptions and conclusions discussed in the study need some marginal comment. Calculated parameter values are dependent on saw-tooth bar and trough definition, determined by the digitizing technique. The technique of creating a undisturbed initial bathymetric map of the sea bottom is to some extend arbitrary as the determination of initial depth contours was based on personal interpretation. However, no independent statistical procedure was available due to the natural curvature of the ebb-tidal delta. Deviances have consequently occurred while digitizing for each year separately.

Errors occur due to the recording technique of the acoustic depth sounders, which can have a systematic error of about 20 cm. A standard error of 5 cm is common as well. Observations and calculations concerning saw-tooth bars and troughs seem therefore rather trivial in some cases. Bars in front of Ameland, for instance, often show calculated mean heights between 3 and 10 cm. The saw-tooth bar phenomenon in front of the island however cannot be ignored, although these values might be inaccurate, as the alternating trend of bars and troughs is nevertheless apparent. The date of recording is another error inflicted by the recording technique. The exact date of recording differs for different years, although the bathymetric data are assigned to one year. Data of one bathymetric map can also consist of recordings carried out throughout a year, rather than a onetime recording of the entire area.

Volume calculations of saw-tooth bars and troughs are presented as solid figures although these should not be approached as the absolute volumes. Bars and troughs were assumed to be block-shaped, while in reality their shape is more oval as well as irregularly shaped. Saw-tooth bar and trough volumes are not equal in size within one year, which results in net sand surpluses or deficits. This illustrates the applied technique of defining saw-tooth bars and troughs. Depth contours were digitized representing general trendlines between saw-tooth bars and troughs. So no exact middle points between a saw-tooth bar crests and a saw-tooth troughs were digitized. This would result in a net sand amount of '0' m^3. Comparison between calculated volume differences of two years depend on the interpreted initial bathymetric maps. Initial bathymetric maps of 1989 and 1993 show distinct differences due to the fact that the entire ebb-tidal delta morphology has changed distinctly. Volume changes of saw-tooth bars and troughs are likely to be only a fraction of the volume changes occurring within the total ebb-tidal delta. Volume comparison between these to years are therefore less reliable than comparison between the years 1993 and 1996. For 1993 and 1996 initial bathymetric maps are almost similar.

Calculated saw-tooth bar migration rates appear plausible, however the lack of more frequent recorded data could lead to errors of judgement. Errors due to a so-called stroboscopic effect could have affected observations and therefore conclusions concerning migration rates, especially where the bars and troughs on the ebb-tidal delta are concerned.

4.2 Qualitative saw-tooth bar characterization

Only morphological information was used to identify the morphological characteristics, differences and migration rates of bars and troughs. External conditions like wave, wind and current conditions were left out of consideration. Information about these additional parameters could give new insights in remaining questions about genesis and evolution of the phenomenon and should therefore be studied in the future. These external conditions could also reject or alter previous interpretations. For instance, parameter values could differ throughout a year and show seasonal characteristics rather than yearly ones. Or, migrational characteristics may show large differences in rate and direction throughout a year, which cannot be deducted from the bathymetric observations.

4.3 Literature comparison

The saw-tooth bar phenomenon was assumed to have trough to crest heights of about 2 m, which is significantly lower for the Ameland Inlet saw-tooth bars. Assumed mean bar length and spacing fairly well coincides with observations at the Ameland Inlet. Actual migration rates are slightly larger than 100 m/y as was assumed earlier.

5. Conclusions

5.1 Downdrift saw-tooth bar relation

The hypothesis that saw-tooth bars and troughs situated on the ebb-tidal delta gradually migrate into the ones situated in front of Ameland, is valid for 1989, but has to be adjusted for 1993 and 1996.

A direct downdrift relationship of saw-tooth bars and troughs appears to exist in 1989. A transition zone where bars were present was much more indistinct. Parameter values neither differed for the saw-tooth bars on the ebb-tidal delta and in front of Ameland. The gradual downdrift migration is ascribed to the absence of a sandy spit in 1989, which results in a smooth, undisturbed coastline. Sand is transported downdrift by uninterrupted longshore currents without being trapped in a spit.

For the studied years 1993 and 1996, the downdrift migration is disturbed by the formation of a sandy spit generated in the bight between the ebb-tidal delta and Ameland. This sandy spit creates an inner lake which is filled and emptied by subsequently flood- and ebb-currents. Strong current action present at the lake entrance prevents the bars to cross the transition zone between the ebb-tidal delta front and Ameland. Bars and troughs are characterised as two different types, due to the distinct differences in parameter values. Bars form and fade out on the ebb-tidal delta after which they are being rebuild in front of Ameland. The saw-tooth bar features tend to decay totally in a downdrift direction in front of Ameland in 1993 solely.

5.2 Comparison of 1989, 1993 and 1996.

In 1989, the saw-tooth bar phenomenon was nearly absent. However, most sand was present on the ebb-tidal delta front in 1989, when compared to the other two studied years 1993 and 1996. When in 1993, the saw-tooth bar phenomenon was distinctly present, the amount of sand stored in bars and troughs decreased. Morphological changes of the entire ebb-tidal delta are denoted as the cause of the decrease. In 1989 no sandy spit was present and the supratidal shoal on the downdrift ebb-tidal delta was large in extend. In contrast to 1993 when the supratidal shoal extend was small and the sandy spit had extended downdrift, less sand was available for the saw-tooth bar phenomenon. For saw-tooth bars and troughs in front of Ameland, less dependence exists on ebb-tidal delta morphology. However, more sand was stored in the bars in 1989 due to the undisturbed downdrift sand migration.

In 1996, the sand storage in saw-tooth bars on the ebb-tidal delta and in front of Ameland showed a dissimilar trend. Sand storage increased for bars and troughs on the ebb-tidal delta due to the larger extend of the supratidal shoal on the ebb-tidal delta. A reversed trend of decrease of sand storage existed for bars and troughs in front of Ameland in 1996 attributed to sandtrapping by saw-tooth bar on the ebb-tidal delta as well as by the extended sandy spit.

5.3 Morphodynamic characteristics

Large differences in migration rates exist between different years as well as between different locations along the coast. Mean migration rate of saw-tooth bars in front of Ameland is about 160 m/y. Largest rates occur for *1991* to *1993* during the formation of the sandy spit. Migration rate of saw-tooth bars on the ebb-tidal delta is about 120 m/y. The slightly smaller rate is attributed to the larger extend of the saw-tooth bars and troughs here, which makes them less mobile.

6. Literature

Antia, E. E., 1994. Long-term and post-storm dynamic patterns of the subtidal rhythmic morphology along the East Frisian island coast, Germany. In: *Geologie en Mijnbouw*, **73**: 1-12.

Antia, E. E., 1996. On the significance of ebb-tidal deltas to the development of the subtidal longshore-rhythmic morphology (Sägezahnriffe) along the German North Sea coast. In: *Zeitschrift für Geomorphologie*, **40** (4): 477-485.

Ehlers, J., 1988. *Morphodynamics of the Wadden Sea*. A. A. Balkema, Rotterdam. 397p.

Flemming, B. W., Antia, E. E., 1990. Interaction between storm-induced resonance and nearshore morphodynamics along the Frisian barrier island coast, southern North Sea. 13th International Sediment. Congr., Nottingham, Abstr. Vol., p.171.

FitzGerald, D. M., 1984. Interactions between the ebb-tidal delta and the landward shoreline: Price Inlet, South Carolina. In: *Journal of Sedimentary Petrology*, **54**: 1303-1318.

FitzGerald, D. M., 1996. Geomorphic variability and morphologic and sedimentologic controls on tidal inlets. In: *Journal of Coastal Research*, **23**: 47-71.

FitzGerald, D. M., Penland, S., Nummedal, D., 1984. Control of barrier island shape by inlet sediment bypassing: East Frisian islands, West Germany. In: *Marine Geology*, **60**: 355-376.

FitzGerald, D. M., Penland, S., 1987. Backbarrier dynamics of the East Frisian Island. In: *Journal of Sedimentary Petrology*, **57**: 746-754.

Hayes, M. O., 1979. Barrier island morphology as a function of tidal and wave regime. In: S. P. Leatherman (Ed.), *Barrier islands: From the Gulf of St. Lawrence to the Gulf of Mexico*. Academic press, New York, N. Y., pp. 1-28.

Hayes, M. O., Kana, T. W., 1976. Terrigenous clastic depositional environments. Techn. Report 11, CRD, Dept. of Geology, University of South Carolina, Columbia, S. C., 364p.

Hicks, D. M., Hume, T. M, 1996. Morphology and size of ebb-tidal deltas at Natural Inlets on open-sea and bocket-bay coasts, North Island, New Zealand. In: *Journal of Coastal Research*, **12** (1): 47-63.

Israel, C. G., 1998. *Morfologische ontwikkeling Amelander Zeegat*. Werkdocument RIKZ/OS-98.147X. Rijksinstituut voor Kust en Zee/RIKZ, Den Haag.

Oost, A. P., 1995. *Dynamics and sedimentary developments of the Dutch Wadden Sea, with a special emphasis on the Frisian Inlet, a study of the barrier islands, ebb-tidal deltas, inlets and drainage basins*. Thesis, Utrecht.

Sha, L. P., 1989. Variation in Ebb-tidal delta morphologies along the West and East Frisian Islands, The Netherlands and Germany. In: *Marine Geology*, **89**: 11-28.

Sha, L. P., 1990. *Sedimentological studies of the ebb-tidal deltas along the West Frisian Islands, The netherlands*. Thesis, Utrecht, 160p.

Sha, L. P., Van den berg, J. H., 1993. Variation in ebb-tidal delta geometry along the coast of the Netherlands and the German Bight. In: *Journal of coastal research*, **9** (3): 730-746.

Van Alphen, J. S. L. J., Damoiseaux, M. A., 1989. Geomorphological map of the Dutch shoreface and adjacent part of the continental shelf. In: *Geologie en Mijnbouw* , **68** (4): 433-443.

Table of figures and tables

Figures

Tables