Rijkswaterstaat
Ministerie van Infrastructuur en Milieu

UNIVERSITY OF TWENTE.

Dune safety in Callantsoog

The Dune Safety Development due to sand nourishments, since 2000 in Callantsoog, the Netherlands

Final version

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Bachelor Thesis Civil Engineering
Thursday, June 21, 2018

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Picture front page: (Camping oude sluis, 2018)

Preface

At the moment you are looking at my bachelor thesis: 'Dune Safety in Callantsoog'. This thesis is written to complete my Bachelor Civil Engineering at the University of Twente. In this thesis the development of the dune safety in Callantsoog since the year 2000 is globally observed. This research is done on behalf of Rijkswaterstaat Water, Traffic and Living Environment (WVL, 'Water Verkeer en Leefomgeving'), in the department Flood Safety.

For 10 weeks I had the opportunity to be a part of the cluster Coast. The research is executed in the period of April until July 2018. Mostly, I was located at the office location Utrecht. But every Tuesday the department gathers in Lelystad, in which they have a coffee break to discuss the weekly findings. My colleagues made me feel welcome and they would always make time to answer the questions regarding my research, which I would like to thank them for. Here fore, I would also like to thank my supervisors at Rijkswaterstaat. Especially Rena Hoogland for her good care and the helpful feedback she gave me along the way. Rena Hoogland and I had weekly meetings in which we discussed the progress of the research. She also gave me the opportunity to visit the research area, where she enthusiastically explained about the area. Also Rinse Wilmink I would like to thank, for the input he gave me during the research.

At the university of Twente I would like to thank Joep van der Zanden, for the helpful feedback during the concept deadlines. Besides that, he also replied very fast on questions I asked through email.

Overall this was a very memorable time for me, in which I gained a lot of knew knowledge regarding multiple subjects!

Enjoy reading my thesis!

Evelien Hageman

Thursday, June 21, 2018

Abstract

In this thesis, the effect on the dune safety in the area of Callantsoog, due to the nourishment executed since the year 2000, are analyzed. The focus of dune safety is on the erosion volume and the erosion profile after a 1/3000-year storm.

Firstly, the volume increase and profile change of a number of coastal cross sections are analyzed. Since the year 2000, 8 nourishments are executed in the research area. Because of those nourishments, the dune and beach volume increased. Also because of the nourishments, changes occurred in the nearshore bathymetry data, which affects the wave energy reaching the dunes. The changes that the bathymetry underwent, caused less wave energy to reach the dune, so less erosion takes places during the surge storm. This change is confirmed by obtained post-storm dune foot of the past 18 years.

Two models are used to determine the dune safety. A distinction is made in an empirical dune erosion model, DUROS+, and a process-based model, XBeach 1D. At the moment the empirical model is the official model used by Rijkswaterstaat to assess the Dutch coastal primary barriers. It appears that the empirical model gives about double as much erosion volume compared to the process-based model. Before implementing the XBeach 1D model as official assessment tool of the Dutch coastal primary water barrier, it is suggested that some extra research has to executed.

The comparison in the models is made, since a pilot nourishment is executed at a depth of -10m NAP in the year 2017. This depth is not taken into account in the empirical model. But the question is, if this deep shoreface nourishment does have influence on the dune safety. However, it seems that a nourishment at this depth, and even significantly higher, does not have noteworthy changes on the erosion volume and erosion profile at this moment.

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Terminology

English	Dutch	Explanation
Actual coastline (MKL)	Momentane Kustlijn	Yearly determined actual coastline
Annual coastal transect data (JARKUS)	JAaRlijkst KUStmetingen	Depth measurements in different cross-sections of the Dutch coast
Assessing coastline (TKL)	Te Toetsen Kustlijn	Average location of the coastline at the 1 of January
Basic coastline (BKL)	Basis Kustlijn	Reference coastline
Beach nourishment	Strand suppletie	Relocation of sand from bigger depth to beach
Boundary profile	Grensprofiel	The least amount of 'dune' that should fit in the post-storm profile
Deeper bathymetry data	Vakloding	Those are the depth measurements that reach a depth of 20 meters
Dune foot	Duinvoet	Location where the slope of the dune become steeper in the landward direction
Dune reinforcement	Duinverzwaring	Reinforcement of the dune, in this thesis with sand
Erosion point	Afslagpunt	The new dune foot (point P, in DUROS+)
Erosion profile	Afslagprofiel	Eroded part of the dune, above storm surge level
Hydraulic conditions	Hydraulische randvoorwaarde	Flood event corresponding to safety norm (1: x years)
Hydraulic loads	Hydraulische belastingen	New term for Hydraulic conditions
Nourishments program	Suppletieprogramma	A program regarding the planned nourishments, that will be executed in a certain period of time
RSP	Rijksstrandpalenlijn	Reference line along the coast
Shoreface nourishment	Vooroever suppletie	Relocation of sand from bigger depth to the shoreface
Water Act	Water wet	Dutch law, regarding among other the dune safety
Weak links	Zwakke schakels	Locations along the Dutch Coast which in 2003 where weak spots in the Dutch primary water barrier

1. Introduction

In recent years, there has been an increasing interest in the dune safety of Callantsoog. In 2003 this location was classified as one of the 10 Weak Links in the Dutch coastal defense barriers. Different sand nourishments to increase the dune safety in Callantsoog are executed since. It seems that the dune safety has increased and Callantsoog would not be classified as a weak link at this moment, but the exact influence of those nourishments on the dune safety is unknown. The research question is:

> ***What are the effects of the executed nourishments since the year 2000 till now on the dune safety in Callantsoog?***

In this report the dune safety in Callantsoog in the period of 2000 till now, will be analyzed and tested with the help of two different testing models. Firstly, the DUROS+ model is used, followed by XBeach 1D. Eventually the results of the two different methods will be compared. The pilot deep shoreface nourishment of 2017 is analyzed more detailed.

The aim of the research is to develop an advice towards Rijkswaterstaat regarding the development of the dune safety, as a result of the executed nourishments. This advice will include information about the effects of the different nourishments on the dune safety of Callantsoog, from 2000 till now. In the advice also, the comparison of the two models will be taken into account.

The structure of this thesis is as follow, firstly the theoretical framework regarding the area of Callantsoog, the software package MorphAn and the research design, including the research questions are given in chapter 2. The methodology is written down in chapter 3. In the chapters 4, 5, 6 and 7 the results are presented and the sub questions are answered. Followed by the conclusion in chapter 8, in which the main research question will be answered. Eventually a discussion and recommendations are given in chapter 9 and 10.

2. Theoretical framework

In this chapter an area description of Callantsoog will be given. Followed by the research plan and research questions.

2.1. Area description

Callantsoog is a small village located in the province Noord-Holland in the Netherlands, it is located near the North Sea, see Figure 1. Callantsoog has a popular family beach. The village of Callantsoog is built directly behind the dunes and at walking distance to the beach, as visualized in the picture on the front page. That is why the dunes in Callantsoog have a high cultural, historical and scenic value. The dunes also function as coastal defense barrier of the Netherlands. To maintain the values and make sure that the function as coastal defense barrier is not endangered, the dunes and beaches are dynamically maintained with sand.

Figure 1 Map of the Netherlands (GoogleEarth, 2018)

In Figure 2 (bigger shown in: Appendix F on page 73), a soil map of the coast at Callantsoog of the year 2000 is given. In this soil map horizontal lines are drawn to create a wide frame around the research area, Callantsoog. The vertical line is given as a reference line, for the comparison in the different soil maps over the past 18 years (in Appendix F). In a soil map, the depth measurements are visualized with the use of colors. To give an idea what height refers to what function, the beach is at a height in-between -2m +NAP and 3,5m +NAP, so globally the yellow and orange parts in the map represent the beach.

Also, visible in this map is the sand bank located under water. Before the year 2000 there are no maintenance operations executed below the water, this bank is naturally formed by the waves. This bank was already present since the first depth measurements executed in 1965. Comparing the framed area of the map in Figure 2, to the other part of the map, it shows that the dune row at Callantsoog are relatively narrow. Which means that the dunes could be a fragile spot in the coastal defense barrier of the Netherlands.

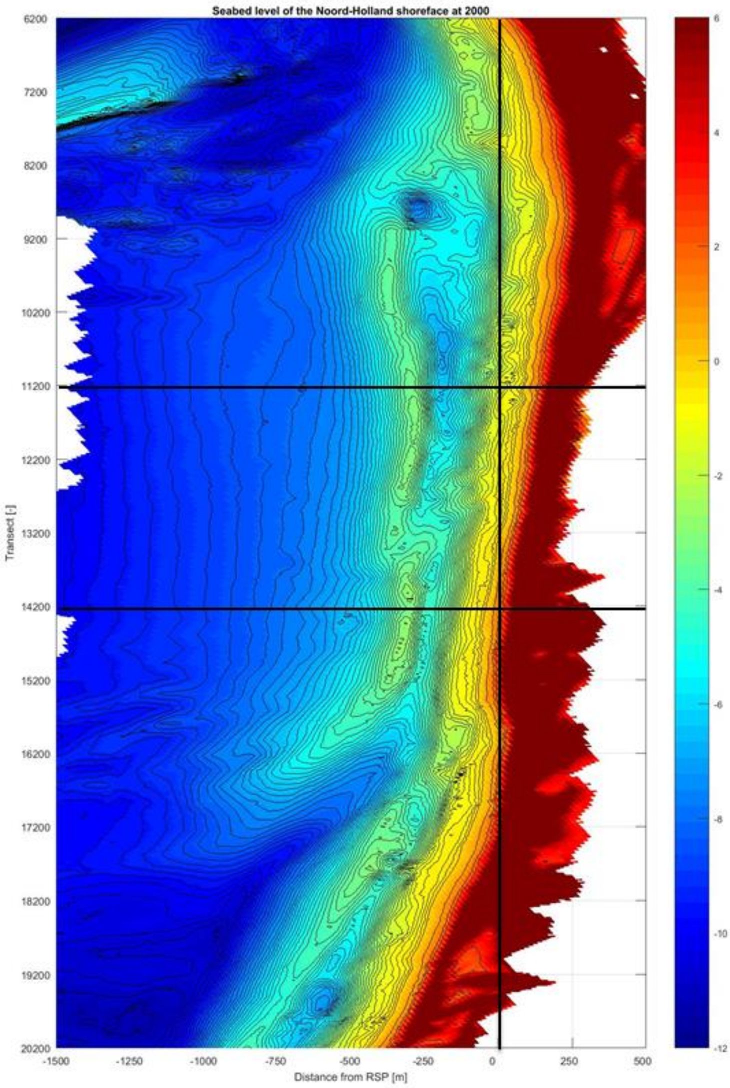

Figure 2 Soil map 2000 (bigger in Appendix F) (Rijkswaterstaat , 2018)

The relatively small dunes are also shown in Figure 3, this figure shows a map of Callantsoog extracted from GoogleEarth. The coastal area at Callantsoog can be divided into different cross sections. Those cross sections are called transects. The transects 1123 until and including 1381 cover the area of

Callantsoog. Those transects are visualized in Figure 3, again a frame is placed around the research area (white frame). For a selection of transects every year measurements are executed to analyze the Dutch coastline. Those bathymetry data are called JARKUS data (JAaRlijkst KUStmetingen). In Figure 3, the transects for which JARKUS data exist are shown. Is this map also, the relatively narrow beach and dune are visualized. Especially transects 1228 until and including 1288 (red frame) are narrow compared with for example transect 1381 (orange frame).

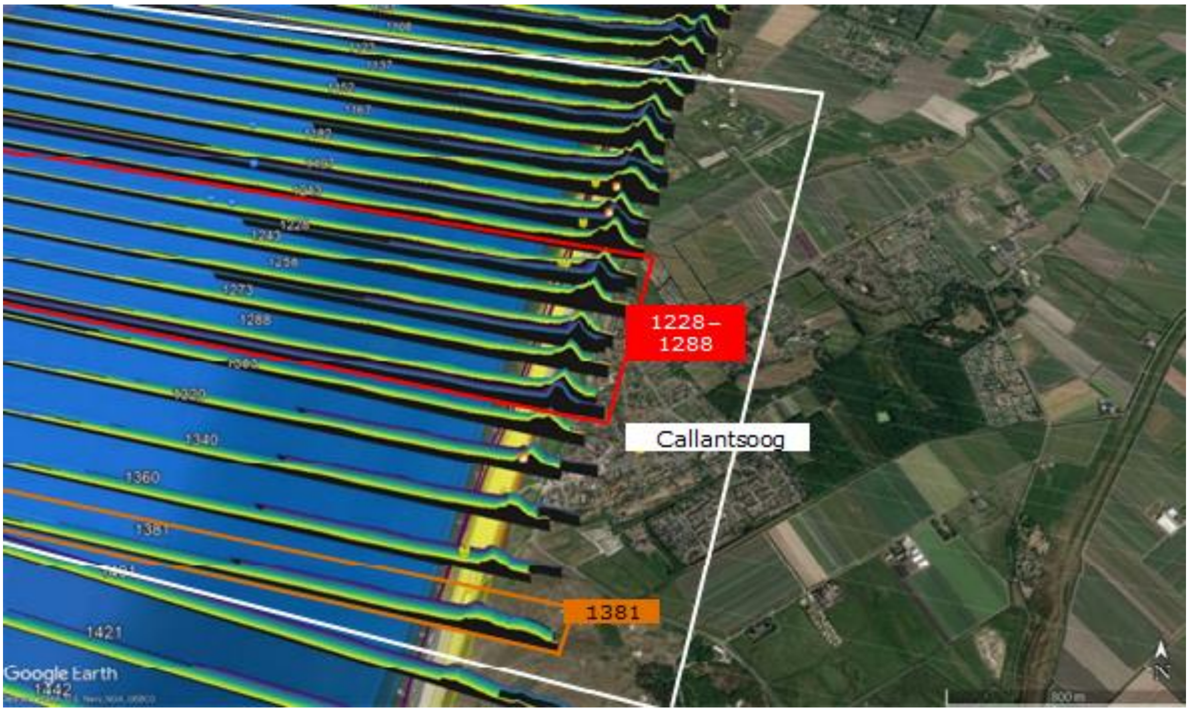

Figure 3 Top South View of Callantsoog (Image extracted from: GoogleEarth, kustviewer.kml loaded into GoogleEarth in order to visualize the JARKUS-data and BKL at the beach of Callantsoog) (GoogleEarth, 2018)

Maintenance

Rijkswaterstaat maintains the Dutch beaches and shoreface. The Waterboards are responsible for the maintenance of the dunes. In 2001 and 2006 all the coastal barriers have been tested and improved if required by the at that time new regulations. In 2003 new understandings were found regarding extreme weather conditions, as a result of climate change and sea-level rise. So, prior to 2003 the assumed storm strength, relating to water levels, wave heights and wave periods were underestimated. This meant that multiple locations along the Dutch coast were not able to cope with a so called 'Super Storm'. In 10 places along the Dutch coast the primary water barriers needed to be reinforced, those places are referred to as 'Weak Links'. Callantsoog was one of those 'Weak Links', in Callantsoog a superstorm was at that time defined as a storm which may occur once every 10.000 years. (Hoogheemraadschap Hollands Noorderkwartier; Arcadis; Rijkswaterstaat, 2013)

Because Callantsoog was classified as a 'Weak Link', extra maintenance had to be executed. Since the dunes are normally the responsibility of the Waterboards, this is a close partnership between the Waterboards and Rijkswaterstaat. The decision was made to increase the safety of the dune by nourishments executed by Rijkswaterstaat. A nourishment basically is the relocation of sand, from the intertidal zone (depth of at least -20m +NAP) to for example the beach or shoreface.

In Figure 4, cross sections of transect 1228 are given. In the left graph, the years 2016 and 2017 are shown and in the right graph 2002 and 2003. In the left graph a beach nourishment and a deep shoreface nourishment are visible. This deep shoreface nourishment is unusual and will be more elaborately explained in the next paragraph. In the right graph a shoreface nourishment is visible.

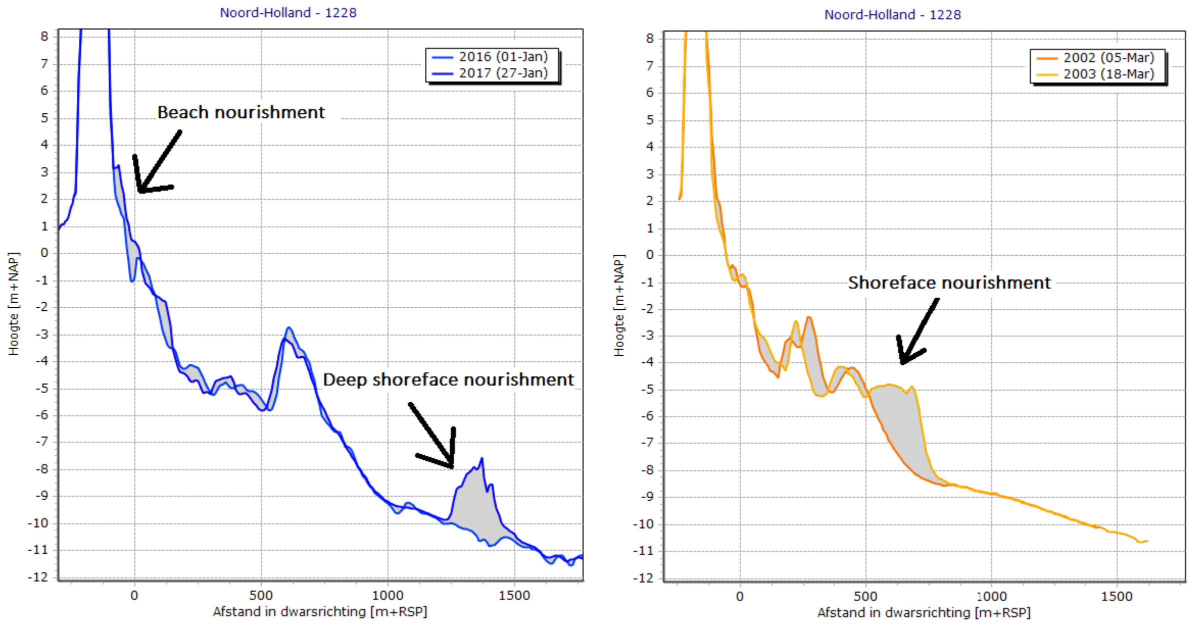

Figure 4 Cross section transect 1228, in 2016 and 2017 & 2002 and 2003 (Software package MorphAn, 2018)

In Callantsoog multiple nourishments are executed over the years. In Table 1 an overview of the nourishments is shown. As visible, since 1976, 15 nourishments with different lengths and volumes have been performed near or at the beach of Callantsoog.

Table 1 Nourishments in Callantsoog since 1976

	Start date	End date	Start transect	End transect	Length	Type	Volume $*10^3$ m^3
1	09-1976	09-1976	1298	1375	775	Dune reinforcement	342
2	01-1979	12-1979	1115	1280	1650	Dune reinforcement	470
3	08-1986	10-1986	1083	1373	2900	Beach nourishment	1242
4	08-1986	10-1986	1175	1205	300	Dune reinforcement	78
5	05-1991	06-1991	1100	1400	3000	Beach nourishment	538
6	05-1996	06-1996	1001	1410	4090	Beach nourishment	4590
7	05-1999	06-1999	1320	1400	800	Beach nourishment	144
8	06-2001	10-2001	1108	1401	2930	Shoreface nourishment	1500
9	02-2003	05-2003	1000	1600	6000	Shoreface nourishment	2315
10	06-2003	07-2003	1110	1375	2650	Beach nourishment	438
11	06-2004	07-2004	1110	1374	2640	Beach nourishment	264
12	03-2006	10-2006	1000	1520	5200	Shoreface nourishment	1652
13	04-2013	07-2013	1000	1421	4210	Shoreface nourishment	2000
14	02-2017	03-2017	1213	1421	2080	Beach nourishment	400
15	02-2017	12-2017	1213	1401	1880	Deep shoreface nourishment	1000

As was shown in Figure 4, in 2017 a deep shoreface nourishment at the coast near Callantsoog is executed. A deep shoreface nourishment is special, since this is not done before at this depth. This method is a pilot to come to a more efficient method of nourishments. Since it is performed at bigger depths, bigger boats can be used and there is no need for a pipe installation towards the beach. Also, the recreational value of the beach, during the execution of the nourishments can be remained. A disadvantage however is the amount of sand needed. In Figure 4 only a part of the deep shoreface nourishment is shown in a cross section of transect 1228. At the time of the measurements, the nourishment was not fully executed yet. Comparing this to a 'normal' shoreface nourishment, for example the one in 2003, also shown in Figure 4, you see the difference in depth. The deep shoreface nourishment starts at a depth of about -10m NAP, compared to the shoreface nourishment which ends at a depth of about -9m NAP.

Morphological development

The coastline in Callantsoog is observed for a long time, for some of the transects the first data is from 1965. In Figure 5, JARKUS data of about every 5 years is given for transect 1320. In 1965 (red line), you see the sandbank that was already mentioned in paragraph 2.1. So, because of a certain wave energy along the coast such a bank was formed. Since 1965 the sandbank moved seaward (different green lines). And from 2005 (blue line), the shoreface nourishments of 2001 and 2003 are visible. Those nourishments are placed on the seaside of the bank. It seems that the nourishments push the existing bank forward/landward. Naturally this bank was moving more seaward, as shown in Figure 5. The sandbank in 1965 (red line), slowly moves more seaward in 1990 (green line). But from 2009 (blue line), the bank movement has turned landward.

What also is pointed out in Figure 5, is the dune reinforcement of 1976.

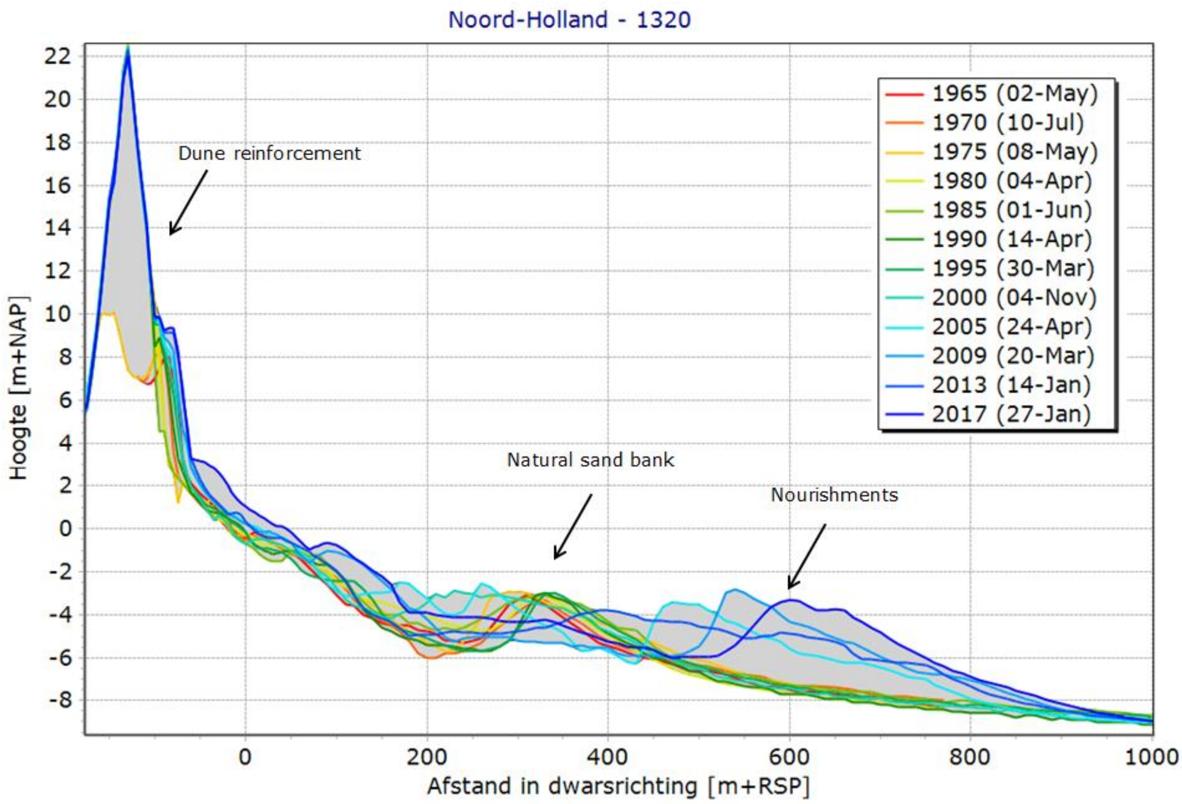

Figure 5 JARKUS 1320: 65, 70, 75, 80, 85, 90, 95, 00, 05, 09, 13 and 17 (Software package MorphAn,

When zooming in over time, Figure 6 shows the JARKUS data of the same transect 1320, of the years 2000 till 2017. While taking a close look at this data, you see the nourishments over time being placed further seaward. Which seems to happen parallel to the erosion directly on landside of the moving sandbank. So, the area between 500m +RSP and 800m +RSP becomes less deep because of the nourishments. But the area in between 200m +RSP till 500m +RSP seems to become deeper over the past 18 years. Also, some sedimentation on the beach and dunes occurred.

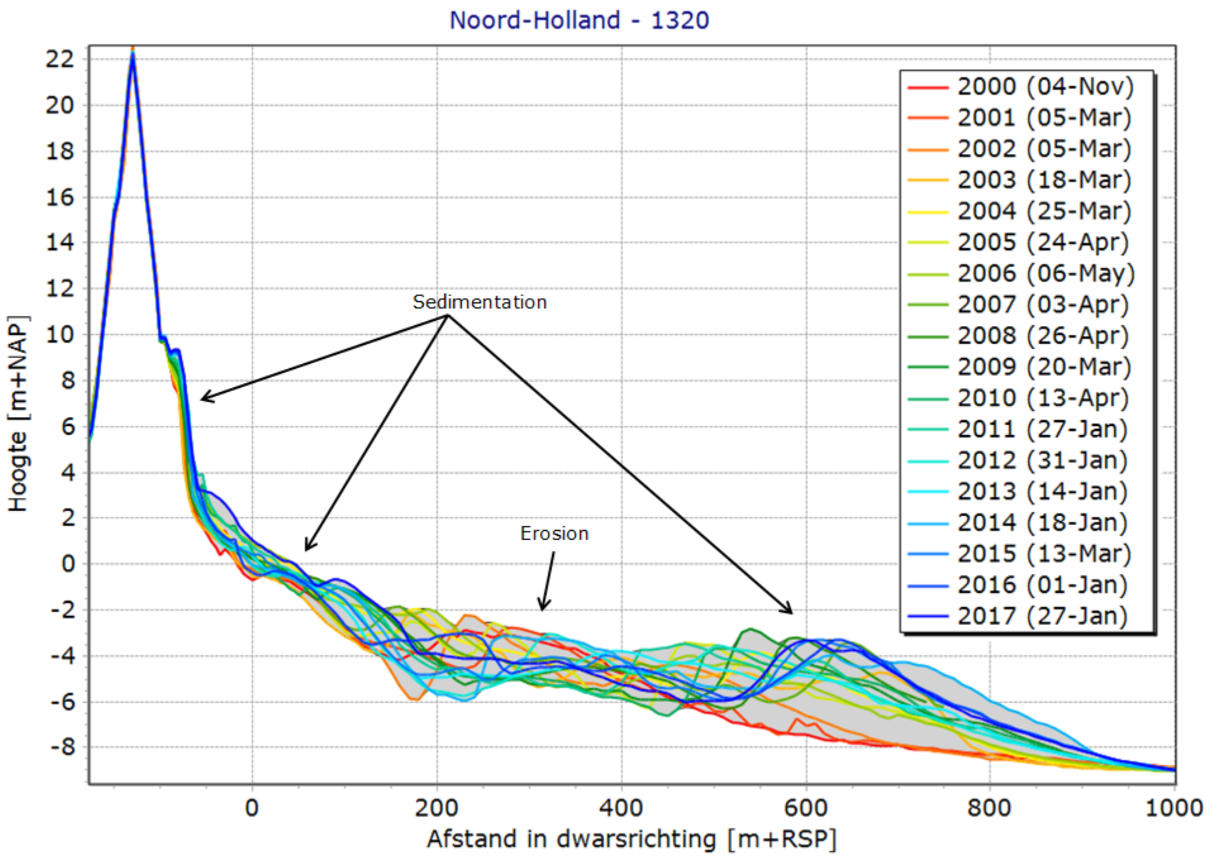

Figure 6 JARKUS 1320- 00-17 (Software package MorphAn, 2018)

In Figure 7, on page 18, you can see the changes that the coastline at transect 1320 encountered. This graph is regarding the period 1965 till 2017. Herein, the actual coastline measured each year (MKL-positions) are plotted against the cross-shore distance to the RSP (Rijksstrandpalenlijn). The RSP is a references line, used for coastal related perpendicular distance. So, the y-axis represents the distance to the reference line RSP. In this case the higher the number, the more seaward the position. In this figure also the reference coastline (Basis Kustlijn, BKL) and the different executed nourishments are shown. What is less clear in the graphs, is the beach nourishment executed in 2017. It is hidden behind the deep shoreface nourishment.

What can be extracted from Figure 7 is the development of the coastline over the years, for transect 1320. From the year 1965, the coastline developed more and more landward. In 1976 a dune reinforcement was executed, after this you see the MKL-position slowly moving more seaward (frame 1). This dune reinforcement, was also mention in 2.1 and visualized in Figure 5. After all the beach nourishments (except in 2004) the MKL-position rapidly moved more seaward, but this effect seems less stable since the MKL-positions move landward again in about 2 years after the nourishment (see frame 2, 3, 4, 5 and 6). The effects of the shoreface and deep shoreface nourishments are more difficult to determine based on this figure, since most of the time more nourishments are executed around those. After 2008 the coastline started to develop more landward again (see frame 7), this may be explained since in between 2006 and 2013 no nourishments are executed. Generally, there may be concluded that the development of the coastline in Callantsoog became more seaward since 1965.

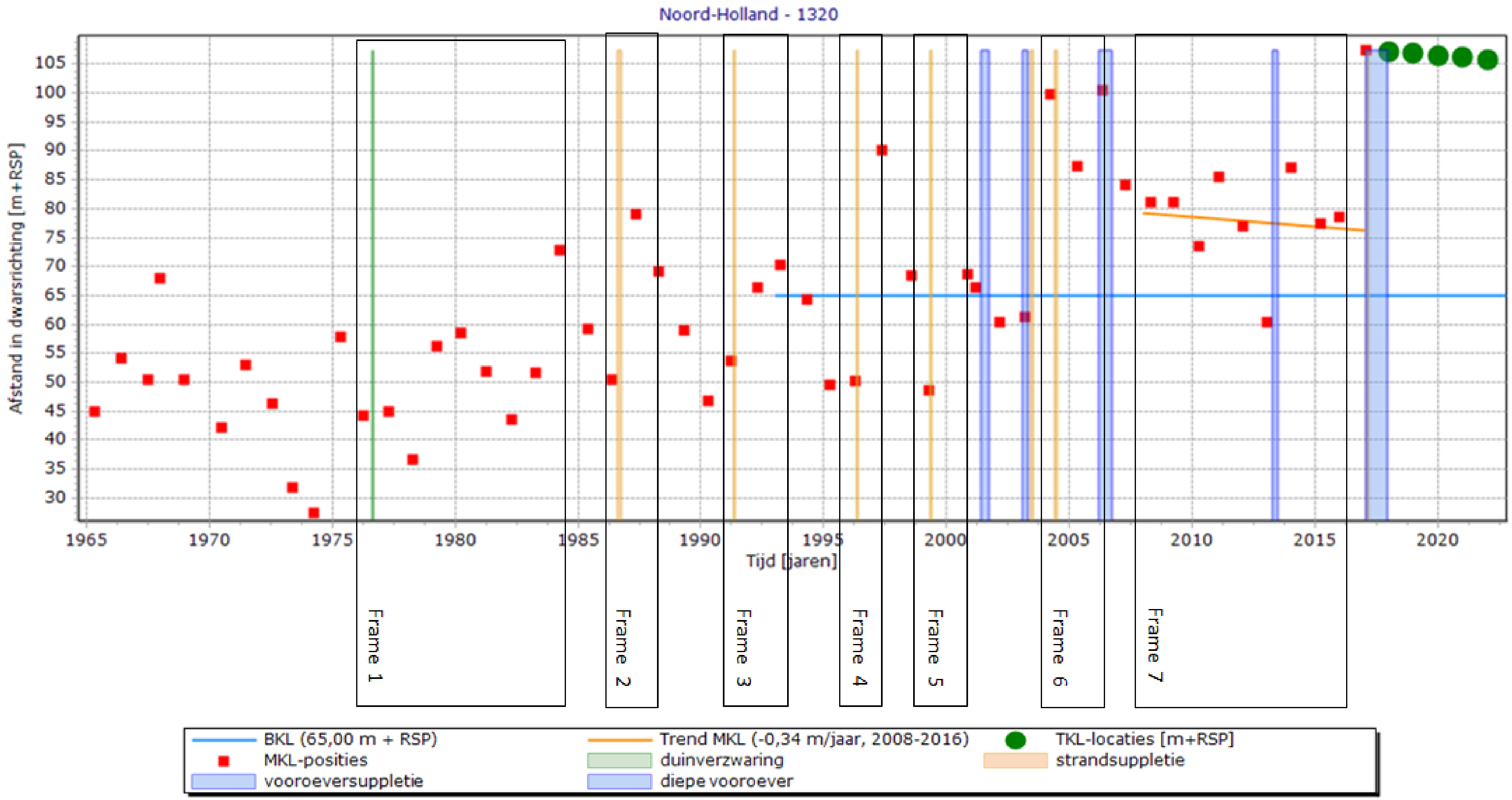

Figure 7 Coastline development since 1965, transect 1320 (Software package MorphAn, 2018)

Since in 1990 the decision was made to maintain the coastline in a dynamic way, to avoid structural erosion. During this time the BKL was set as reference coastline. The from 1993 established BKL is clearly visible in Figure 7, and the nourishments executed to meet the requirements of the BKL are also visible.

In certain locations the BKL is relocated in order to fulfill the needed sand volume, to ensure the safety of the hinterland. This was also the case for Callantsoog, there is a relatively small frontal dune with a big wind and sea load. Since 2012 Hoogheemraadschap Hollands Noorderkwartier, Provincie Noord-Holland and Rijkswaterstaat decided that the BKL will be relocated seaward and this had to be formal in 2017. The relocated BKL will be further referred to as HBKL. The relocation differs from 2 to 37 meters as compared to Rijksstrandpalenlijn. Even though the HBKL was not formalized jet, since 2012 the maintenance of the coast is geared towards the new reference line. (Rijkswaterstaat, 2017)

2.2. Research design

In this paragraph the research design is structured. Firstly, the main research question is presented with its corresponding sub question.

Research question

In order to meet the objective of the research, the following questions will be answered. In first instance, the main research question is established:

What are the effects of the executed nourishments since the year 2000 till now on the dune safety in Callantsoog?

With 'dune safety' in this question is referend to the dune development and the effects of a 1/3000-year storm on the erosion profile and erosion volume.

Sub questions

To frame the research question and specify the research, 4 sub questions are formed. Those sub questions also limit the research, so the amount of work fits the research time of 10 weeks. Shortly below each question, a description of why this question is important to answer the research question and a short hypothesis is given.

1) ***How did the total volume and the volume of the shoreface, beach and dune change over the past 18 years and what were the influences of the performed nourishments on those volumes?***

In order to determine the effect of the nourishments on the dune safety, it is important to create a wider view of the development of the different volumes. The change in volume in the dunes will suggest how the dune became weaker and/or stronger. By also calculating the total, shoreface and beach volume, the movement of the sediments over the shoreface towards the dune might be visible. This could give inside information of the influence of the nourishments on the development of the dune.

Hypothesis: Since 8 nourishments are executed over the past 18 years, the expectation is that all the defined volumes have grown. After a beach nourishment a rapid increase on the beach volume is caused, eventually this probably develops sedimentation on the dune and shoreface. Expected is, that after shoreface nourishments, over time the sedimentation on the beach and dune increased.

Therefore, expected is that the beach and dune volume enlarged more compared to the shoreface volume.

2) How did the erosion point develop over the past 18 years according to the DUROS+ model?

The erosion point, or the post-storm dune foot is directly associated with dune safety. The erosion point can be compared over the years. Assuming that the landside of the dune did not encounter significant changes, a more seaward developing erosion point means that the dune positively developed regarding dune safety and the dune is able to cope with a stronger storm.

Hypothesis: As visible in the JARKUS comparison in Figure 6, the dune foot developed more seaward over the past 18 years. This would mean that with the same erosion volume the erosion point would be located more seaward. Also, in the JARKUS profiles, the sedimentation on the shoreface increased. Since more sedimentation causes a decrease in the wave acceleration, expected is that the erosion point will be located further seaward. For both reasons expected is that the erosion point has developed seaward.

3) How did the modeled erosion profile and erosion volume change over the past 18 years and what are the differences in outcome of the DUROS+ and XBeach 1D model?

The reason why a comparison between two models will be made, is because Rijkswaterstaat is currently considering a transition to a new model, potentially the XBeach 1D model. Also is expected that the lower shoreface is of importance in the dune erosion. The lower shoreface is not taken into account in the DUROS+ model. Only is the erosion point not included in the output of XBeach 1D, therefore the erosion volume and erosion profile are used for the comparison. With the use of a calculation tool, the erosion volume of XBeach 1D is calculated and a comparison with DUROS+ is made.

Hypothesis: Based on the literature expected is that the erosion volume of DUROS+ will be bigger compared to XBeach 1D. Generally, it seemed that the erosion profile of DUROS+ is wider, the relocation of the sand takes further away from the dune foot. This makes the slope of the DUROS+ profile less steep compared to the XBeach 1D erosion profile.

4) What is the influence of the deep shoreface nourishment on the erosion volume and erosion profile, and how does the location of this nourishment affect the erosion volume according to the XBeach 1D model?

The aim of this question is to specifically focus on the deep shoreface nourishment of 2017. This nourishment is particularly interesting, since this is a pilot nourishment and the effect on the dune safety is therefore unknown. This nourishment has not developed over the shoreface yet and not even the whole nourishment is visible in the most recent JARSKUS-dataset. That is why this nourishment will be drawn into MorphAn and scenarios will be developed. Those scenarios are based on different locations of the deep shoreface nourishment along the cross-shore profile. In this way, the possible effects on the erosion volume and erosion profile of those scenarios can be analyzed and evaluated.

Hypothesis: Expected is that the erosion volume will decrease when the deep shoreface nourishment is located. The wave energy is expected to decrease near the deep shoreface nourishment. So, less wave energy will reach the dune and less erosion will occur. The closer the deep shoreface nourishment is located more landwards, the more decrease in wave energy is expected.

DUROS+ is not designed to encounter the lower shoreface in the calculation of the erosion volume and erosion profile. Therefore DUROS+ will not give different solutions when the deep shoreface nourishment is located.

3. Methodology

In order for the reader to understand all the aspects of the main and sub question, the methodology is shared. Firstly, the used software will be explained. Followed by a 'step-by-step-plan' that is executed during the research. For each step a detailed method is written down below the step.

3.1. Software package MorphAn

The software used by Rijkswaterstaat to test the dunes is MorphAn, a software package to analyze and assess a sandy coastline. The visually orientated design of MorphAn helps to analyze and visualize the collected data, but also to make adjustments if necessary or wished for. In general, MorphAn can be used to analyze the coastal morphological development over the years. The software is developed on behalf of Rijkswaterstaat by Deltares with contribution of STOWA. (Deltares, 2018)

In MorphAn a module named DUROS+ is integrated, also called the Dune Safety Model. With this module calculations regarding safety can preformed. DUROS+ calculates the dune erosion, the erosion profile and the boundary profile. This model is a fully probabilistic approach consisting of three components. Namely the hydraulic conditions, a probabilistic method and a dune erosion model. Currently DUROS+ is the official model used by Rijkswaterstaat to test the dune safety. In Appendix B a detailed explanation of DUROS+ is given.

However, dune erosion is a dynamic process of cross-shore sediment transport. This transport takes place from the dunes toward the beach and the upper shoreface of the cross-shore. In this process the erosion is formed because of the surge and severe wave attacks. And during such events the profiles changes the whole time. (Den Heijer, 2013)

Therefore, a new model is designed, and tested at the moment. This model is the XBeach 1D model, also integrated in MorphAn. XBeach 1D is a potential new model for Rijkswaterstaat. Since XBeach 1D is not an official tool yet and it is a rather complex model, it is discussed in less detail. In Appendix C more information regarding XBeach 1D is given.

Comparison DUROS+ and XBeach 1D

Both models are 1D models, the 1D dune erosion approach is used as a well-supported way to monitor the state of the sea defense along the coastline. But XBeach 1D encounters the alongshore sediment transport during a storm. The dune erosion models estimate the response of the dunes to a normative hydraulic loading condition. (Den Heijer, 2013)

According to van Santen et al (2012) the 1D approach for the area of Callantsoog is applicable. This is based on the complexity of the bathymetry and the absence of coastal structures.

Both models estimate a post-storm bathymetry profile based on maximum storm conditions; the pre-storm bathymetry; and the representative grain size. From previous research on D++ (another model to determine dune safety), XBeach and DUROS+, is concluded that presently applied method DUROS+ over-estimates the dune erosion. (den Heijer, et al., 2011)

The DUROS+ model is a relatively simple model, an empirical volume-based model. The model is built to recreate a surge storm with at least a maximum surge storm level minus 1 for 4 till 6 hours. But different types of storms could have different influences on the dune erosion. DUROS + does not encounter the wave climate during a storm. Van Gent et al (2008) found out that the wave climate does have a significant influence on the dune erosion and therefore the dune safety. Some studies have shown that a higher wave period could cause the erosion volume to increase significantly. A 50% increase of the wave period, from T_p=12s to T_p= 18s, results in 24% more dune erosion (van Gent, et al., 2008) (Den Heijer, 2013). It is suggested that this probably has to do with the increase of wave energy near the dune face. During this longer wave period, an increase of 10 to 15% is observed. It is adequate that essential processes which could lead to dune failure are taken into account when the safety of the dune is assessed. The overtopping and inundation also have to be taken into account, that is another reason why XBeach is designed.However, XBeach 1D is a processed based model, which does encounter the wave height at each location and time, the water velocity, the sediment concentration. XBeach 1D does not encounter each single wave, since this is a very calculation intense process. XBeach creates an envelope of waves and uses it as one (von Gronau, 2017). But on the other hand, the DUROS+ model is based on experiments on a scale model of the narrowest dune along the Dutch coast (location: Terheide). Therefore, it suits the Dutch conditions and practice. XBeach is based on theories but the question is if this is representative for the Dutch coast.

3.2. Step-by-step research execution

The following steps are executed to gain the needed results. In this step by step plan, also the selections and presumptions are given and explained.

I. Creating a workspace in MorphAn

The input needed to create a MorphAn workspace are given. Firstly, the boundary profile is imported in which the reference coastline is defined (BKL). The other needed input is:

JARKUS

The most recent bathymetry information, JARKUS-data from 2000-2017, is loaded into MorphAn and a selection of transects is made. In this selection the transects between 1123 and 1381 with annual data availability are included. (As a JRK-file.)

The JARKUS data are not always of a sufficient length to execute the needed calculations. So, data is added. This can be done on the seaward side of the JARKUS with the deeper bathymetry data (vakloding), which Rijkswaterstaat collects regularly. On the landside of the JARKUS this is done with the AHN (Actueel Hoogtebestand Nederland, Dutch actual height document).

Failure norm

The failure norm is defined for tracks, for the track of Callantsoog this norm is 1/ 3000 (Ministerie van Infrastructuur en Milieu, 2016).

HB2017

The measured hydraulic conditions along the coast need to be converted to hydraulic loads corresponding to a storm strength at the defined failure norm. Those loads are the HB (hydraulische belastingen). Since 2017 the HB are newly defined. How the HB is defined and how the failure norm per cross section is determined is explained in Appendix A.

The hydraulic loading model uses statistical methods and time series of measurement data to derive probability distributions of waves and surge. Using probability distributions, this can be converted to boundary conditions for each individual storm event (Den Heijer, 2013).

Those calculations are executed in the software package ‘Ringtoest’. The input is:

- Track number and failure norm (for Callantsoog: 13-3, 1/3.000)
- Database of measured hydraulic conditions of the area (WBI2017_Duinen_13-3)

Each specific cross section is linked to the corresponding hydraulic loads at a certain failure probability requirement. Those hydraulic loads are statistically determined based on measurements along the coast. The hydraulic loads consist of the following parameters:

- Surge storm level - Rp [m+NAP]
- Wave height - Hs [m]
- Wave period – Tp [s]
- 50%-fractile of grain diameter - D50 [m]

This information is loaded into MorphAn. (As a BND-file) In Appendix A the HR2017 are further explained.
Also is the HB2017 for the used transects given in the appendix, they can be found in section HB2017 of Appendix H, Appendix I, Appendix J and Appendix K.

Nourishment data

The most recent nourishments dataset, is imported into the workspace. This data is abstracted from an existing file of Rijkswaterstaat. Only a selection is made of the necessary nourishments (Rijkswaterstaat, 2018). (As a CSV-file.)

II. With the use of MorphAn the total volumes are determined, also the volume of the shoreface, beach and dune. This is done over a period of 18 years, starting in 2000. In this way the volume development can be analyzed.

To determine the volume, firstly the definition of each volume has to be set. The total area can be defined by different boundaries: the seaward boundary, landward boundary, upper boundary and lower boundary. The upper boundary is needed as input for MorphAn, in order to execute the calculations. The boundaries are visualized in Figure 8. The outer seaward boundary is usually set around 700m +RSP for the whole of the Dutch coast. But looking at this specific selection of transects, the decision is made to set the outer seaward boundary at 1700m +RSP. In this way a bigger part of the morphological development can be taken into account, including the deep shoreface nourishment. The deep shoreface nourishment is located around 1400m +RSP at a depth of -10,00m + NAP, this is also visible in the graphs of Figure 8.

The landward boundary is set at -300m RSP, further landward than usually. In this way the biggest part of the dunes is taken into account, this will give a wider view of the dune development over the years.

The upper boundary and the lower boundary for the total volume are defined in order to include all of the dune and all of the shoreface where significant changes occur for all the transects. The upper boundary is 30,00m NAP and the lower boundary is -12,00m NAP. For the shoreface, beach and dune volume, parts of the total volume are taken, so the sum of those is the total volume. For the shoreface volume, the boundaries are set at -12,00m NAP and -2,00m NAP. For the beach volume the boundaries are -2,00m NAP and 3,50m NAP. The value 3,50m NAP is set to make sure the beach nourishments do not directly influence the dune volume. The remaining part is the dune volume, from 3,50m NAP till 30,00m NAP. An overview of the values is written down below and visualized in Figure 8.

➔ Total volume	Lower boundary: -12,00m NAP	Upper boundary: 30,00m NAP
➔ Shoreface volume	Lower boundary: -12,00m NAP	Upper boundary: -2,00m NAP
➔ Beach Volume	Lower boundary: -2,00m NAP	Upper boundary: 3,50 m NAP
➔ Dune volume	Lower boundary: 3,50m NAP	Upper boundary: 30,00m NAP

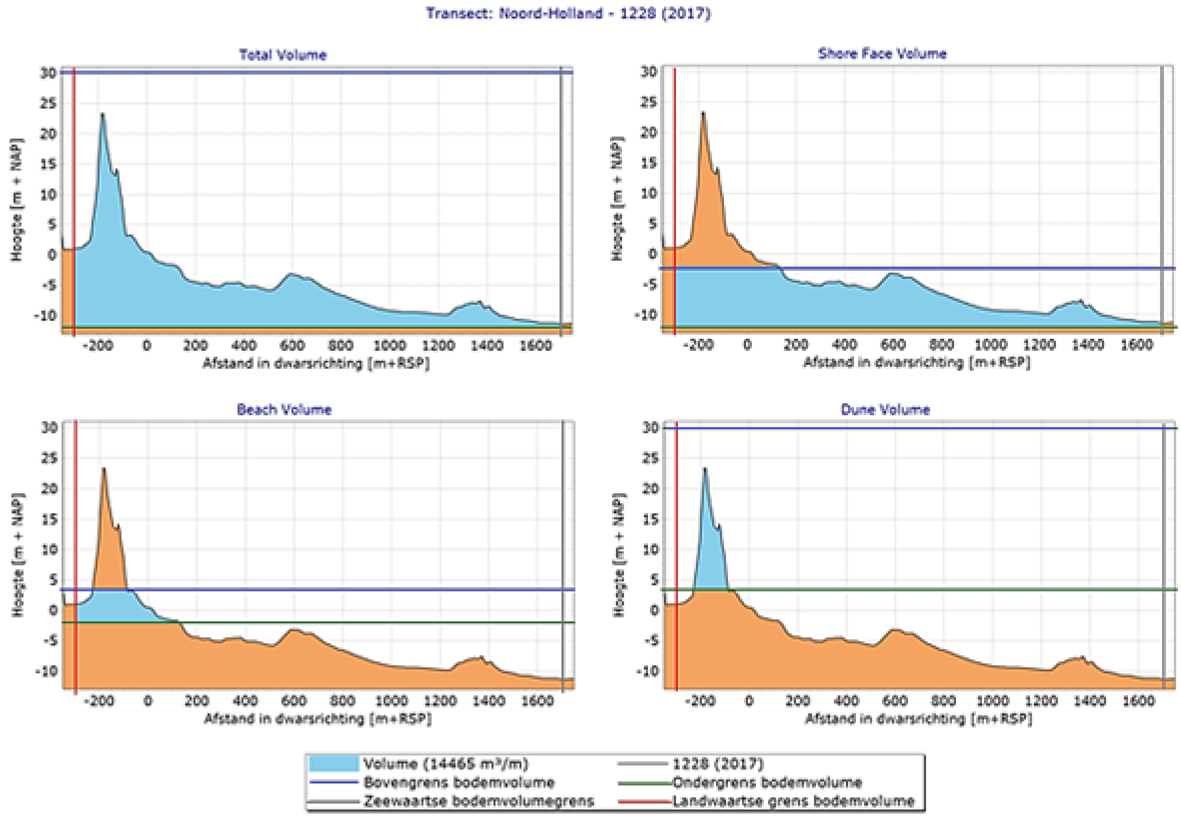

Figure 8 Overview of volumes in transect 1228- 2017 (Software package MorphAn, 2018)

III. Determining the development of the erosion profile over the past 18 years in DUROS+

In MorphAn the Dune Safety Model (DUROS+) can be added, in which firstly a selection of the transects and years is made before the calculations can be performed. In this case the same selection of transects for the years 2000-2017 is needed, so 1123 till 1381. DUROS+ calculates the erosion profile, boundary profile and combines those two to give a R-t diagram, in this diagram the erosion points are plotted over time. This R-t model, gives a clear view of the development of the erosion point. This shows clearly the development of the dune safety, which is useful in the selection of transects. But, for the comparison of XBeach 1D and DUROS+ the erosion profile and the erosion volume are needed. The calculation method used in DUROS+ uses are given in Appendix B.

IV. Selection of 4 transects

Transect 1123 until and including 1381 cover the area of Callantsoog. Since the time scope of the research is insufficient to analyze all the 17 transects, a selection of 4 transects is made. The 3 main criteria for the selection are based on the impact of dune failure, the deep shoreface nourishment of 2017 and the dune safety. An overview of the criteria is shown in Appendix D.

- The village of Callantsoog is closely located behind the dunes, which significantly increase the impact of a dune failure. That is why this is one of the criteria of the transect selection. In the table it is given whether at the location of the transects, the buildings are built directly behind the dune.
- The fourth sub question of this research is regarding the deep shoreface nourishment of 2017. In the second criterion, the transects at which the deep shoreface nourishment is executed are shown. Also, an overview is given of where this nourishment is already visible in the JARKUS of 2017.

- With the use of MorphAn and the Dune Safety model, the dune safety of the past 18 years is tested. The hydraulic conditions HR2006 and HB2017 are used for this. Firstly, it is shown in which of the transects the boundary profile fits in the dune since 2000. Afterwards, is tested if the determinative erosion point crosses the landward boundary (this only considered the transects for which the boundary profile did fit inside the dune, otherwise MorphAn cannot determine a landward boundary).

The selection consists of a diverse combination of transects. The following combination of transects is selected: 1182, 1228, 1258 and 1320. The transects are shortly discussed in Appendix D.

V. Making a calculation tool to compare the XBeach 1D output, with the DUROS+ output.

The erosion profile of XBeach 1D, is given in the form of a table, just as the JARKUS data. The area above the surge storm level, in between the erosion profile and the JARKUS profile, is the erosion volume (see the yellow area in Figure 9). This volume can be calculated by subtracting the post-storm dune volume above surge storm level (blue area) from the pre-storm volume above surge storm level (yellow and blue area).

In formulas:

$$A = (if\ x > storm\ surge\ level \rightarrow calculate\ \Delta y * \Delta x, else\ 0)$$
$$volume = \sum A$$
$$erosion\ volume = pre\ volume - post\ volume$$

This is how the erosion volume of the XBeach model is calculated. Also, the DUROS+ erosion profile is added in this calculation tool, to be able to give a clear overview of the different erosion profiles and volumes.

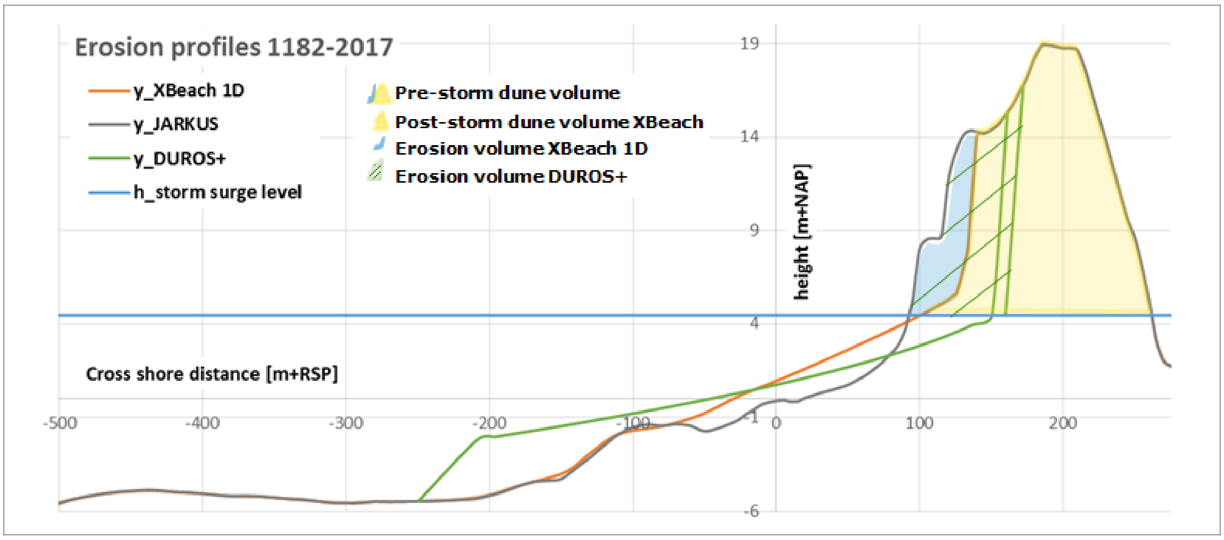

Figure 9 Overview volume labels

VI. Selection of years

After the construction of the calculation tool, a selection of years is made. Since from the year 2003 a more active method of maintenance is carried out, this is the first year of the selection. Also, the last year, 2017 is selected. And in between, 2008 and 2013 are selected, since in between those years no nourishments are executed. So, eventually for the years 2003, 2008, 2013 and 2017 the erosion profiles will be compared. And the trend in development will be compared.

VII. Determining the erosion profile and erosion volume for the selected transects for the selected years in XBeach 1D

From the DUROS+ model in MorphAn, a XBeach model can be created. This means that exactly the same input for both models is used, in the form of the JARKUS data and Hydraulic Loads. In Appendix C, the XBeach 1D model is further explained.

VIII. The deep shoreface nourishment (DSN) firstly will be drawn into the transects 1228, 1258 and 1320 (in 1182, this nourishment will not take place)

Firstly, the JARKUS of 2017 are adapted, to make sure the DSN is not already visible in the reference year. This is done by copying the coordinates of -1200 to -1800m +RSP from the year 2016 to 2017. With the use of the adaption possibility in MorphAn.

Afterwards the DSN is drawn into the JARKUS, also the erosion profile and erosion volume are determined.

IX. Establish scenarios for the development of the deep shoreface nourishment in transect 1320 and implementing this in MorphAn

The scenarios are also drawn into the JARKUS of the reference profile, with the help of MorphAn. The scenarios are drawn into MorphAn with the following input, see Table 2. In this table the location is specified in the form of a starting and end point. Also, is the total volume, and the eventual thickness of the nourishments given. Since a nourishment is not placed as an exact rectangle shaped from on the bottom, angle is added to convert the shape of the noursishment

Input	Relative to	location min x	location max x	volume	thickness	angle
Scenarios		[m+RSP]	[m+RSP]	[m^2]	[m]	[m]
DSN	Reference	1300	1530	518	3,29	100
DSN1	Reference	1070	1300	518	3,29	100
DSN2	Reference	840	1070	518	3,29	100
DSN3	Reference	610	840	518	3,29	100
DSN3a	DSN3	510	610	-250	3,93	50

Table 2 Scenarios DSN

Table 2 shows that the nourishment design does not change in volume, thickness and angle. But the location of the nourishment is variable. As an extra research, the erosion that occurs landward of a nourishment is imitated in DSN3, this scenario is called DSN3a.

In Figure 10 the design of the DSN scenarios are visualized. Further explanation and motivation of the scenarios can be found in Appendix E.

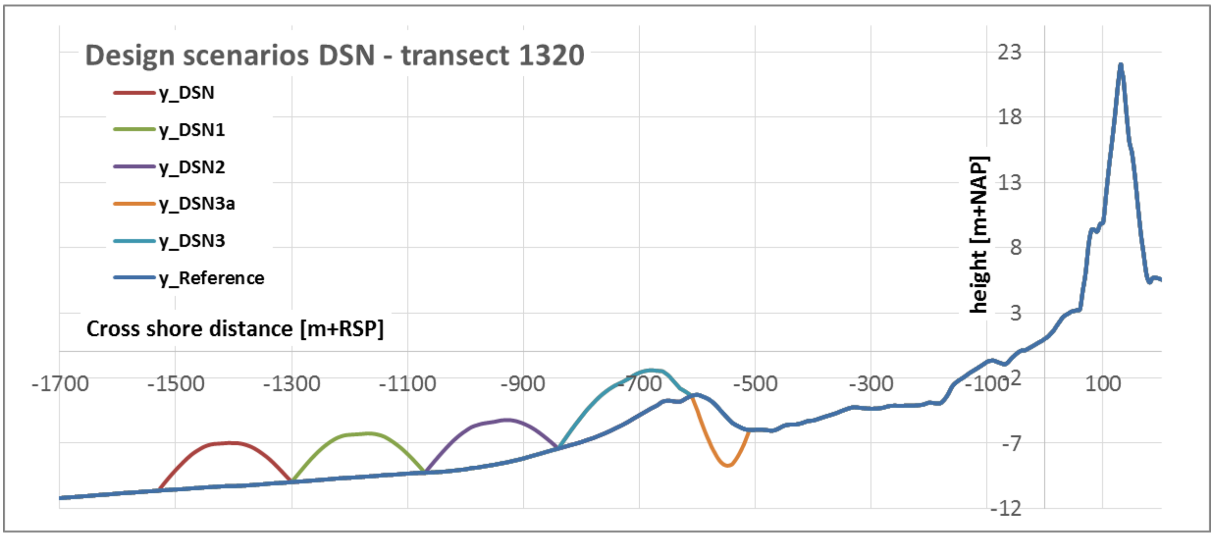

Figure 10 Design DSN scenarios

X. Determining the erosion volume and profile of the DSN scenarios

With the new input for the XBeach 1D model, the calculations are executed. The calculation tool is used to transform the output of XBeach 1D to the erosion volume and erosion profile.

4. Volume development

The first sub question will be answered in this paragraph. The sub question is:

How did the total volume and the volume of the shoreface, beach and dune change over the past 18 years and what were the influences of the performed nourishments on those volumes?

All the volumes of each transect, year and different sections are given in Appendix G. Throughout this chapter only the volume development of the transects 1182, 1228, 1258 and 1320 are discussed globally and an in-depth analysis is given for transect 1182. This transect functions as an example. For the other transects only an overview of the results are given. The rest of the results are presented in Appendix I, Appendix J and Appendix K.

Firstly, a general view of the volume development will be sketched based on the soil maps of the past 18 years. Afterwards a more in-depth analysis will be given on transect 1182. In this more in-depth analysis, the erosion and sedimentation are pointed out in the cross sections. Afterwards, diagrams where the volume is plotted against time will be discussed. And finally, the exact volumes for each year are given and the development of the dune volume will be more elaborately discussed.

In the volume development of the transects, factors as storms are not taken into account. But in the conclusion, this will be mentioned as parameter that also has influence on the volume development of the transects.

4.1. General volume development

In the soil maps in Appendix F, the combined bathymetry data of the past 18 years are visualized. In Figure 11, a part of the soil maps of the years 2000, 2003, 2004, 2013, 2014 and 2017 are presented.

There are some nourishments clearly visible in those maps. When discussing the depths of -4m+NAP and 2m+NAP especially the beach nourishments of 2003 and 2004 are shown. A green area has formed seaward of the existing yellow area.

Also, the shoreface nourishments are visible. Presented is that those nourishments are generally placed seaward of the existing sandbank in the profile (see in comparison of 2013 and 2014). The nourishments also seem to have significant influence on the volumes. But based on those maps, that is difficult to determine.

Also, a comparison in the years 2000 and 2017, as shown in Figure 11. The sandbank moved more seaward and the area in between the sandbank and the beach is about the same depth. With the exception of the area immediately on the landward of the sandbank, a small canal seems to have formed there. Generally looking at the year 2000 and 2017, it seems that the volume increased.

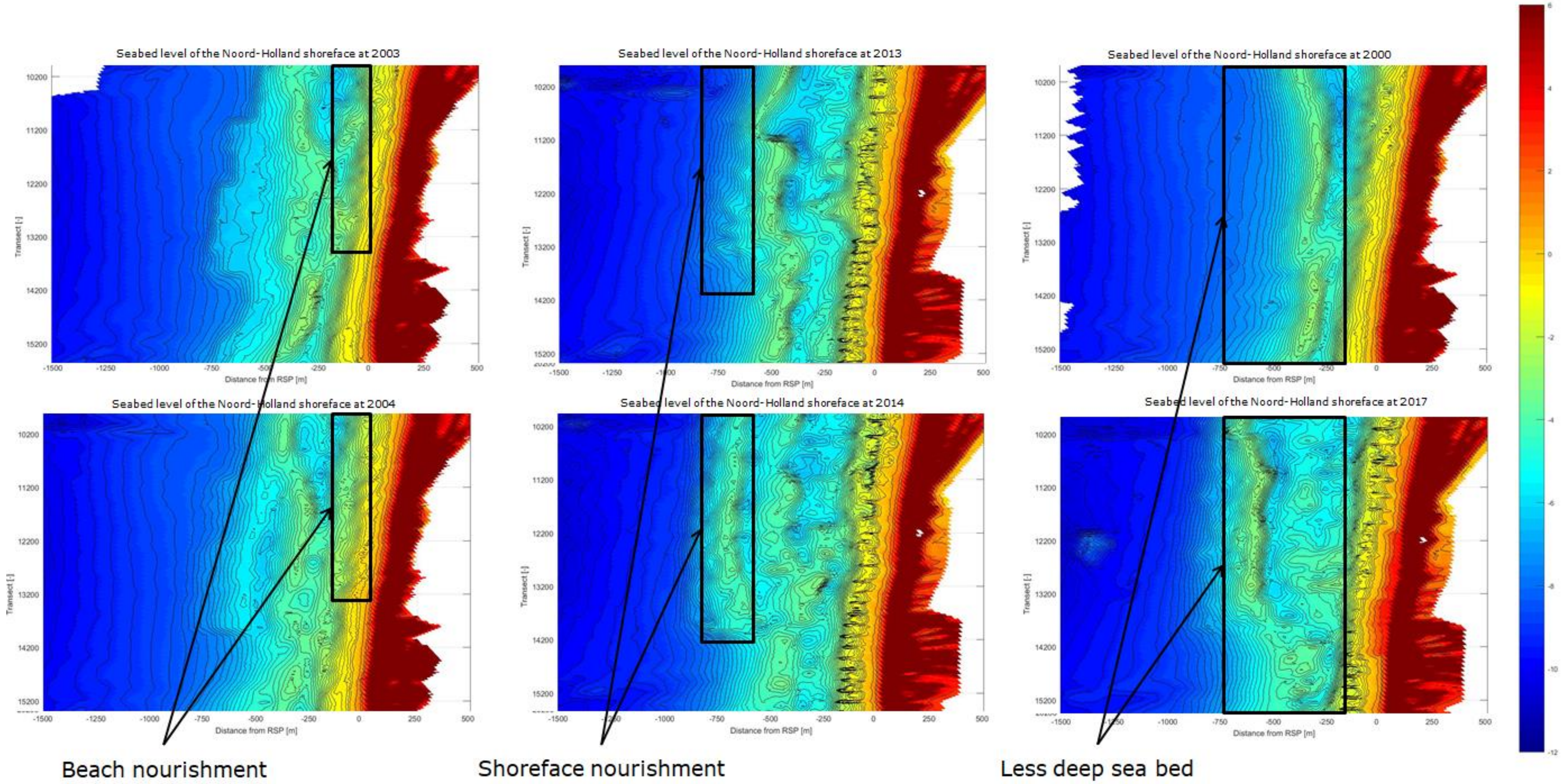

Figure 11 Soil map: From up to down, left to right 2003, 2004, 2013, 2014, 2000 and 2017 (full size and of all years can be found in Appendix F) (Rijkswaterstaat , 2018)

4.2. In-depth analysis of transect 1182

Since 2000 in transect 1182 are multiple nourishments executed, as shown in Table 1. In total 4 shoreface nourishments are executed, the executions started in 2001, 2003, 2006 and 2013. In Table 1 the nourishments received the following numbers: 8, 9, 12 and 13. Also, more information regarding the nourishment is given in Table 1. In transect 1182, also 2 beach nourishments are executed which started in 2003 and 2004, numbered 10 and 11. In Figure 12 a cross section of transect 1182 is given for the years 2001, 2002, 2004, 2007, and 2013. In this figure the executed nourishments are pointed out. Clearly visible is the seaward moving location of the shoreface nourishments over the years, the nourishments are located seaward of the existing bank. In this way the existing bank is pushed more landward, with the idea that the sand will transport further towards the beach and dunes and structural erosion is counteracted. The sedimentation of the dunes is also shown in Figure 12, comparing the red line to the blue line above 4m+NAP, it shows that the dune became wider over the years. So, based on this figure the dune volume increased over the years. Also, the beach volume (in between -2m+NAP and 3,5m+NAP) increased in between the year 2001 and 2014.

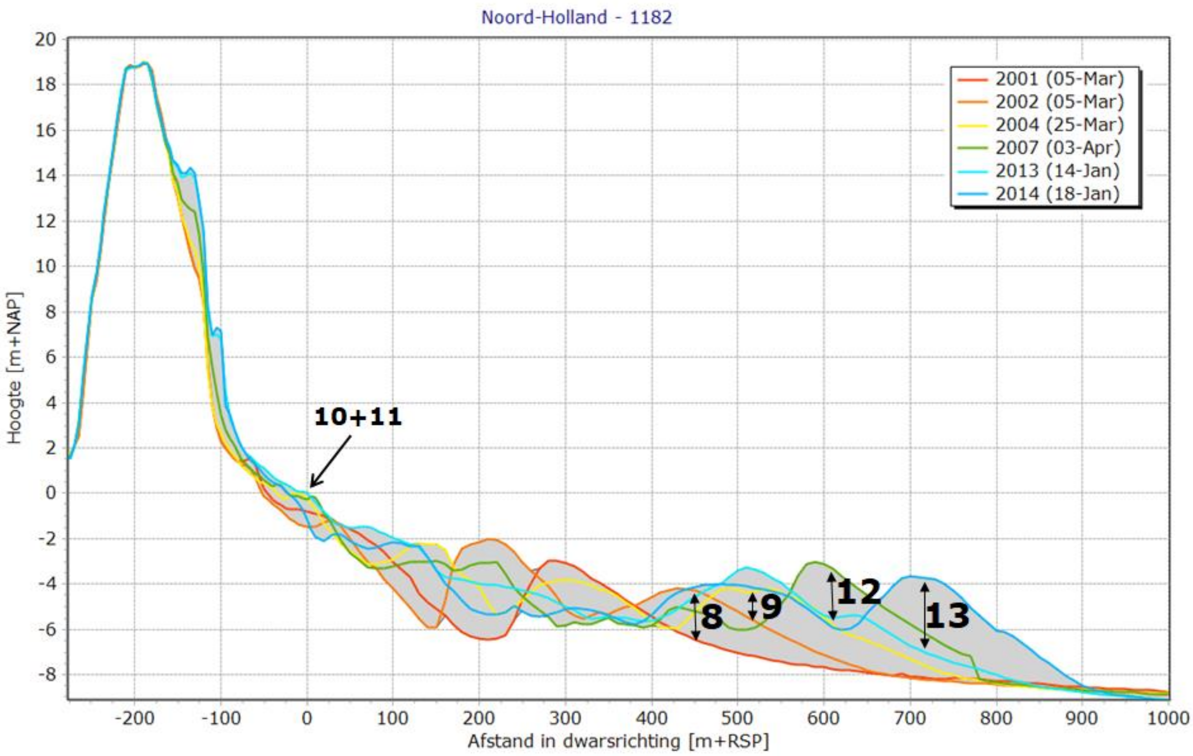

Figure 12 Overview nourishments transect 1282 (Software package MorphAn, 2018)

In Figure 13 all the JARKUS data of the past 18 years are visualized. As suggested in the previous paragraph, the beach volume did increase, comparing 2000 and 2017. But the dark blue line of 2017, is not the highest line. Which means that the beach volume increased first and decreased a little again afterwards. In Figure 25, the relocation of the bank is clearer and the erosion on the landward side of the bank as well. The exact shape and size of this erosion is not in the scope of this research. However, this is of influence on the shoreface volume. What also has influence on the shoreface volume is the erosion on the seaward side of the sand bank. Even though a lot of volume is added to the system, it is not clear from these images if the shoreface volume increased significantly.

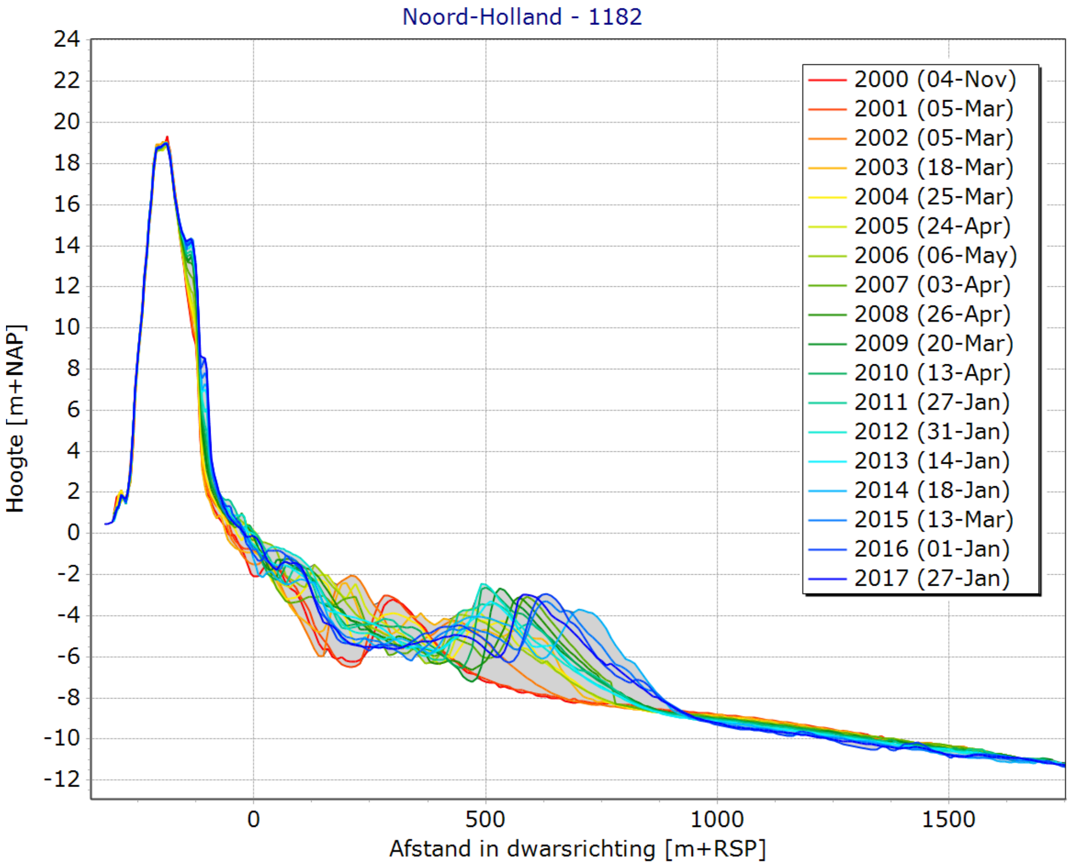

Figure 13 JARKUS comparison 2000-2017, transect 1182 (Software package MorphAn, 2018)

In Figure 14 the volumes of the total, shoreface, beach and dune are plotted against the time. The y-axis might give a distorted view, but the decision was made to use the same axis settings per volume for the different transects. On the right bottom corner of each graph the trend of the period 2003-2017 is given.

In the figure, generally, it becomes clear that the volume development from 2000 till 2003 and from 2003 till 2017 are rather different. For example, in the total volume development from 2000 till 2003, the increase in volume is bigger, compared to 2003 till 2017. Even though, this last period is about 5 times as long. This can be explained because of the consisted under water maintenance that has been executed since 2003. To give an idea of the volume increasements of volume, in Table 3 an overview of the volumes of transect 1182 in the years 2000, 2003 and 2017 are given. Also, the volume differences from 2000-2003, 2003-2017 and 2000-2017 are given. Those values support the suggestion that in the period from 2000 till 2003 the total and shoreface volume significantly increased. The beach and dune volume increased more during the period of 2003-2017, this can be explained because the shoreface nourishments probably needed some years to develop towards the dunes.

Table 3 Volumes 2000, 2003 and 2017 Transect 1182

Years	Total volume [m^2/m]	Shoreface volume [m^2/m]	Beach volume [m^2/m]	Dune volume [m^2/m]
2000	12876	10118	1256	1501
2003	13748	10963	1266	1520
2017	14172	11015	1441	1716
2003-2000	872	845	10	19
2017-2003	424	52	175	196
2017-2000	1296	897	185	215

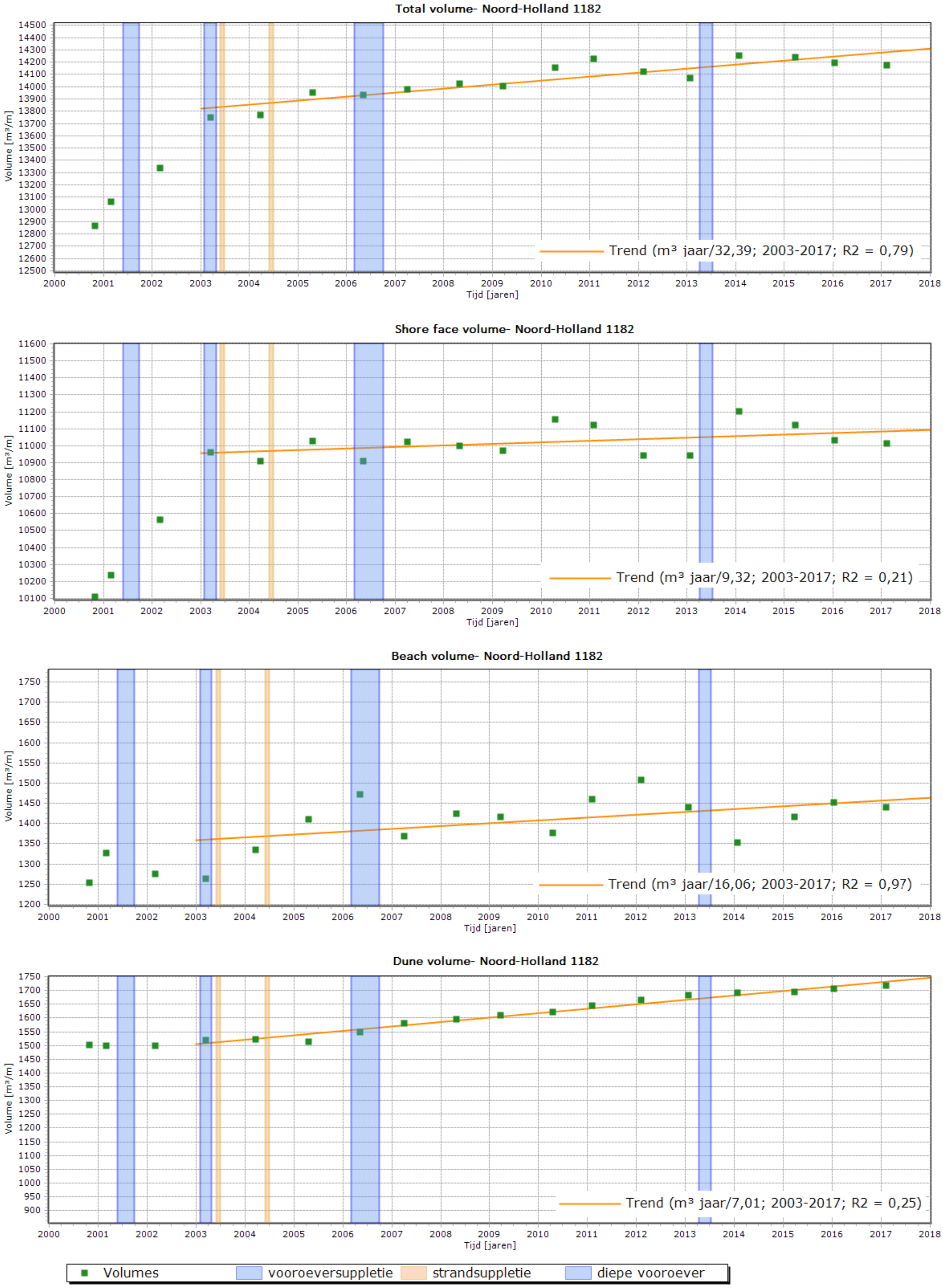

Figure 14 Visualization of volume development over time of transect 1182 (Software package MorphAn, 2018)

For all transects the volumes increased, visualized in Figure 15.

All nourishments were executed over all transects, only the nourishments of 2017 (beach and a small part of the deep shoreface nourishment) are not executed in transect 1182. But the volume of transect 1228 increased significantly more than 1320. This might be explained by the alongshore sediment transport.

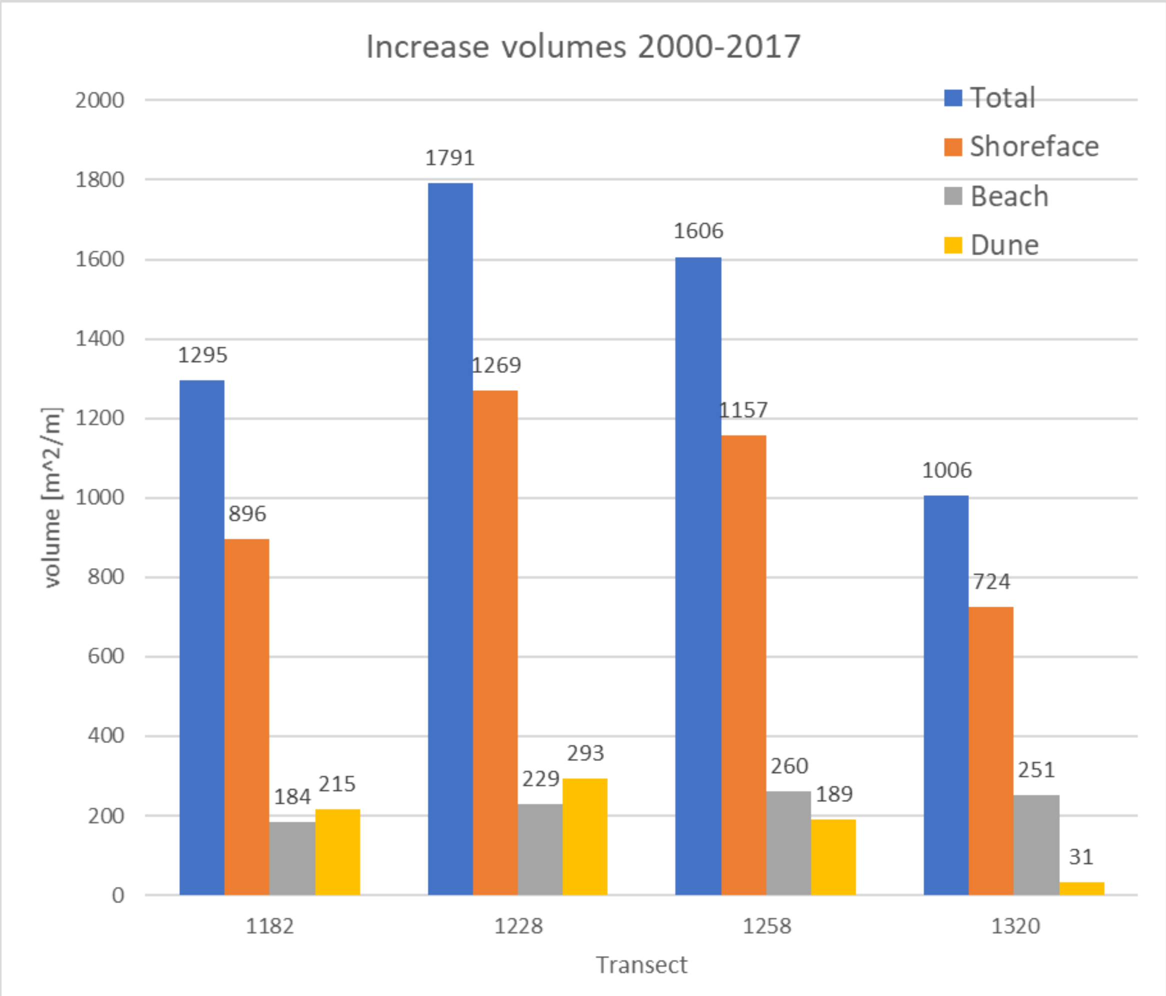

Figure 15 Volume increase 2000-2017

5. Erosion point

The second sub question will be answered in this paragraph. The sub question is:

> ***How did the erosion point develop over the past 18 years according to the DUROS+ model?***

This is a relatively straight forward question, but for the development of the dune safety very meaningful. The erosion point or the new dune foot, point P in DUROS+ moved over the years over the length of the cross shore of the transects. Point P is visualized in Figure 24 of the methodology (also in Figure 17). The height of the erosion point remained on the storm surge level. As given in Appendix H, Appendix I, Appendix J and Appendix K, for transect 1182 the storm surge level is at 4,48m+ NAP, for 1228 and 1258 4,49m+NAP and for 1320 4,50m+NAP. Logically, if the situation on the landside of the dune did not change and the erosion point moved seaward, the safety of the dune increased.

Based on the shoreface bathymetry, the DUROS+ model fits the erosion profile and the post-storm dune foot is set. Since the bathymetry over the years encountered multiple changes, the erosion points also changed position.

The DUROS+ model does not take the whole cross shore into account, generally just the width until X_{max} and Y_{max} fit in the transect and the erosion is equal to the sedimentation. In Figure 16 the cross-shore distance of point P is plotted over time. For the transects 1182, 1228 and 1258, it seems that the development in the erosion point is kind of similar with a couple exceptions. Transect 1320 undergoes some striking changes, for example in 2012. This cannot be explained by the volume development of the dune, since this different is noteworthy. But probably the upper profile of the bathymetry was of big importance in those changes.

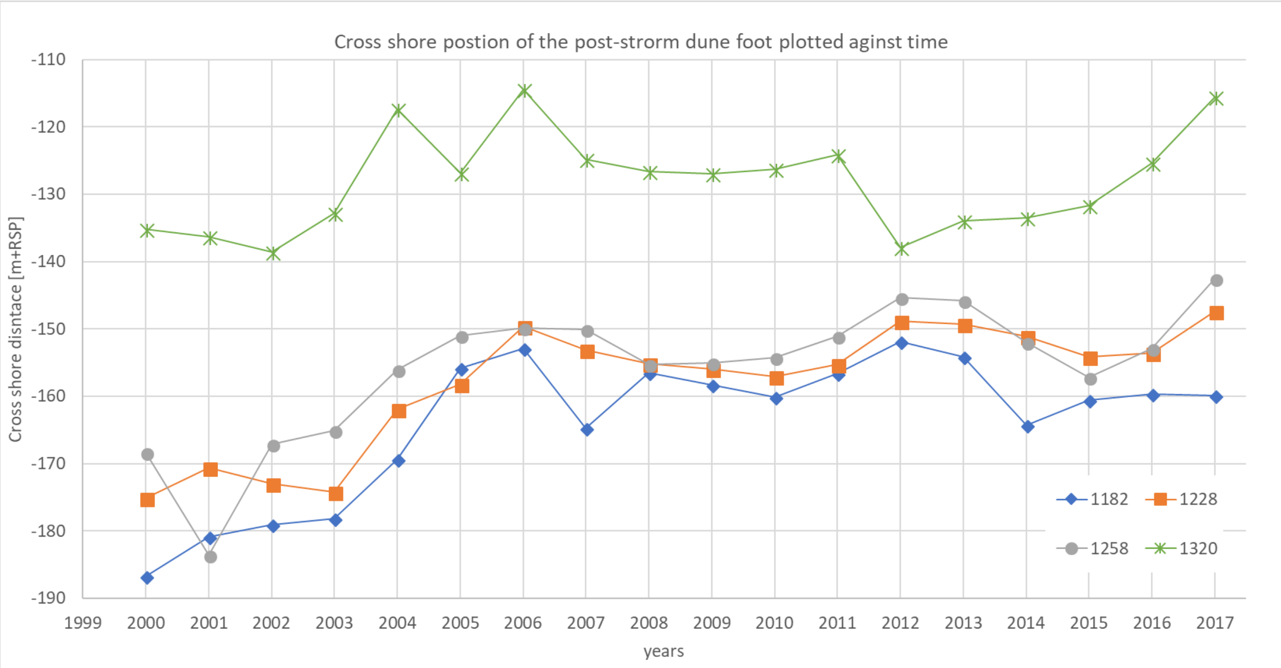

Figure 16 Cross shore position of new dune foot

To support this assumption, the JAKRUS and erosion profile of 2012 and 2017 are plotted. In the development of transect 1320 in Figure 16, the difference in the year 2012 and 2017 seem extraordinary big. With the use of Figure 17 this can be explained.

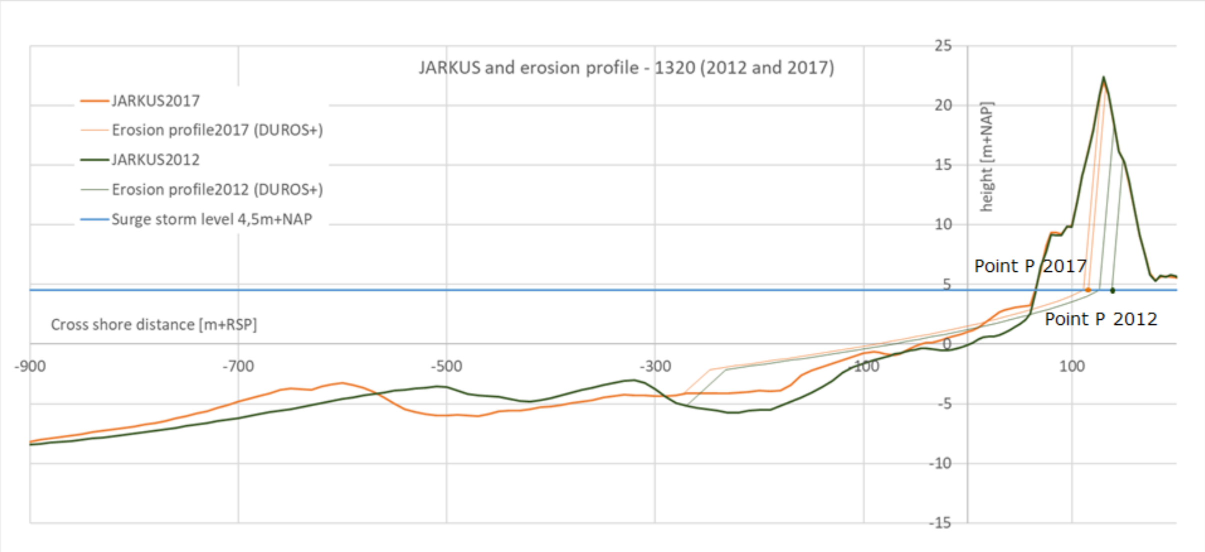

Figure 17 JARKUS and erosion profile 1320 (2012 and 2017)

The width of x_{max} and y_{max} in the DUROS+ erosion profile are similar for both years. But in the green JARKUS(2012), the bathymetry in between -300m+RSP and -100m+RSP is significantly deeper than the orange line (2017). This is why the erosion profile has to be located more landward to equalize the erosion and sedimentation.

After the fitting of the erosion profile, a margin of 25% is added to the erosion volume. This margin compensates for the storm duration and other uncertainties. Since the erosion volume of 2012 already is bigger, this 25% is also bigger. This volume need to fit in the dune, behind the other erosion profile. So in this case, this 25% of 2012 erosion volumes, has to be located on a lower part of the dune, so the eventual erosion point is again moving more landward than 2017.

So, the upper bathymetry data are a reason why the difference in the erosion point over the years may differ so much.

6. Erosion profile and erosion volume

The third sub question will be answered in this chapter. The sub question is:

> ***How did the modeled erosion profile and erosion volume change over the past 18 years and what are the differences in outcome of the DUROS+ and XBeach 1D model?***

In this chapter an elaborated analysis of the erosion profiles and erosion volume for transect 1182 are given. For the other transect just the eventual results are shown. The erosion profiles of those transects are given in the appendix under the subsections 'Erosion profile' and 'Erosion volume', for transect 1228 in 0, transect 1258 in Appendix J and for transect 1320 in Appendix K.

6.1. Erosion profiles transect 1182

In Figure 18, the DUROS+ and XBeach 1D erosion profile of transect 1182 are plotted including the surge level and JARKUS profile, for the years 2003, 2008, 2013 and 2017. The grey line is the JARKUS data, the blue line is the storm surge level, in this case 4,48m+NAP, the orange line is the erosion profile after the XBeach simulation and the green line the DUROS+ erosion profile. As visible in the graph, the DUROS+ green line above the surge storm level, has a double line. This corresponds with the area A and area T, as described in Appendix B. Area A is the erosion profile with the corresponding erosion volume and the line T volume is located in a way that volume T is 25% of A. Volume T in to compensate for insecurities and the storm duration which is not taken into account in volume A. The erosion volume of DUROS+ is equal to the sum of volume A and T.

DUROS+

The erosion profile of DUROS+ is rather straightforward to explain. In the methodology the shape of the erosion profile of DUROS+ is explained. In the comparison of the erosion profiles over the years, the only variable for each transect is the bathymetry data, since the hydraulic conditions are similar for the selected years. So, the outcome of the x_{max} and y_{max} DUROS+ are constant. Only the location of the profile differs because it is fitted to equalize the sedimentation and erosion.

Based on the DUROS+ approach of calculating the dune erosion, a gentle slope in the upper shoreface would mean that the erosion profile has to be located less landward to equalize the sedimentation and erosion. Which means that the erosion point would be located further seaward and the dune safety is increased. So, expected is that after all the nourishment that are executed on the shoreface, the slope has become less steep and the dune safety increased. Also, because of the nourishments, sedimentation took place on the dunes. Therefore for the same slope with a dune reaching further seaward, the erosion point would be located further seaward as well.

When taking a look at transect 1182, for the years 2003, 2008, 2013 and 2017 (Figure 18). A couple of things in the DUROS+ erosion profile stand out. In 2003 the parabolic line is intersected by the sand bank and there does not reach the point of y_{max}. This could mean that in reality more erosion would happen, since this sandbank can be eroded as well. The erosion profile in 2008 and 2013 are rather comparable, the bathymetry data of 2013 seems to be a little more stabilized, in 2008 the seas bed seem to be less smooth. However, it does not seem to have noticeable changes in the erosion profiles. This will be checked again in the erosion volumes.

The bathymetry data of 2017, approached from the dune side, seems to reach the -5m NAP closer landward compared to 2008 and 2013. In 2003 this depth is also reached more landward, but then again, the profile is intersected with the sandbank.

So, expected is that the erosion volumes of 2003 and 2017 are bigger compared to the other years.

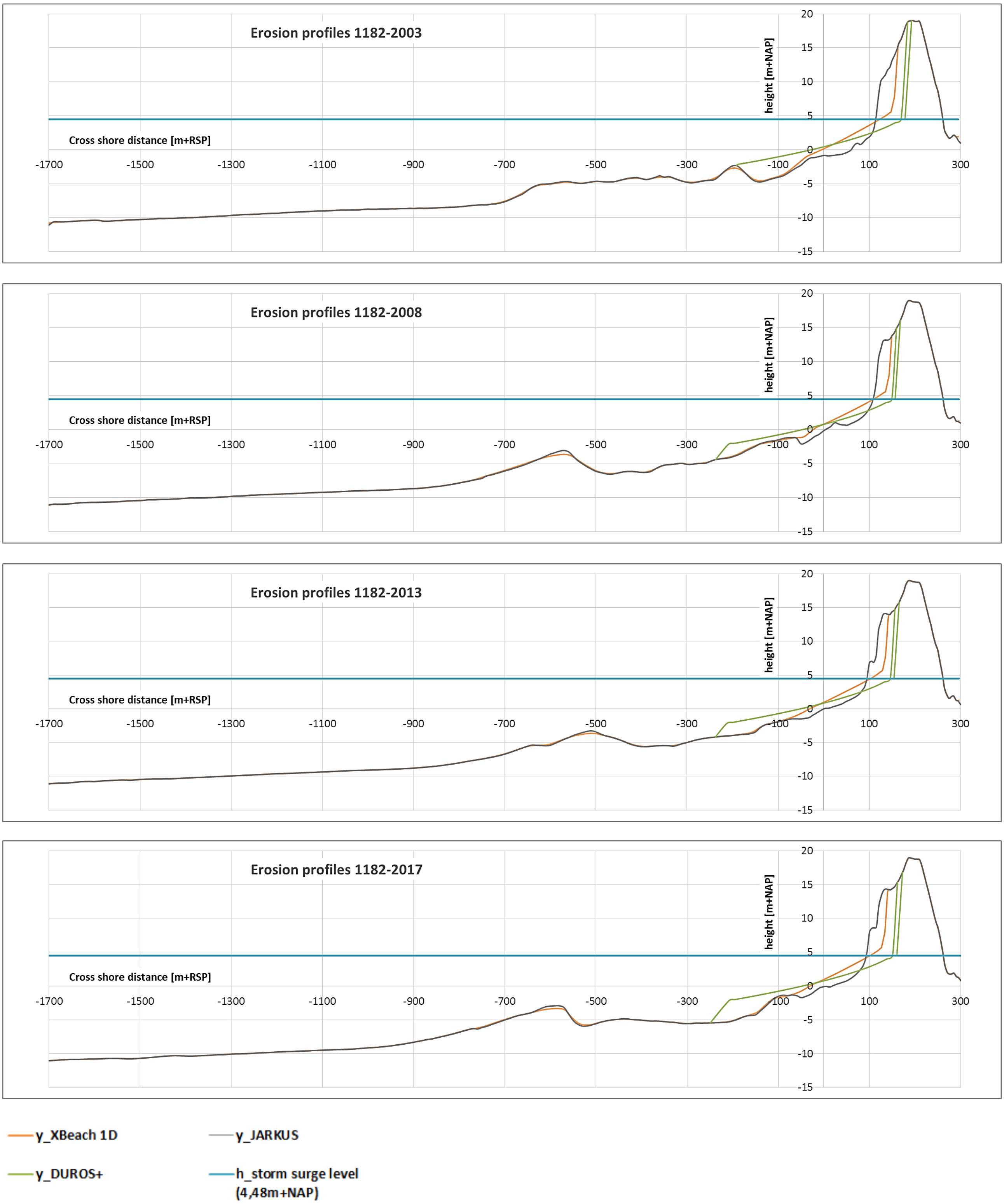

Figure 18 Erosion profiles XBeach and DUROS+ of transect 1182 (2003, 2008, 2013, 2017)

XBeach

Just as for the DUROS+ model, the bathymetry data is determinant for the erosion profile of XBeach 1D. The bathymetry data has significant influence on the wave propagation, dissipation and consequently wave driven currents. So, the wave energy that reaches dune and causes the erosion is very much depending on the bathymetry.

Comparing the years in Figure 18, the XBeach 1D erosion profiles seem more or less the same. What stands out is the interception of the post-storm and pre-storm profile, this is at the surge storm level.

Comparison

When comparing the erosion profiles as given in Figure 18, clearly shown is that in the erosion profile of DUROS+ is located further landward, which means that the erosion volume is also bigger. The new dune foot is located further landward, but also lower in the profile. The new dune foot of DUROS+ is always located on the storm surge level. The dune foot of XBeach on the other hand, in researched cases, is always higher than the storm surge level. This can be explained because XBeach 1D also takes the wave height and run-up into account. Therefore, the water reaches a higher point on the dune and the erosion also takes place at a higher point in the profile.

Also, the slope in which the sand is relocated, is significantly steeper for XBeach compared to DUROS+. In DUROS+ this slope is formed parabolic seaward. Until y_{max} is reached, then the slope is 1:25, this is elaborately explained in the methodology. In the year 2003 this point is not reached; all the sand can be relocated before y_{max} is reached. In XBeach 1D, time step by time step the relocation of the sand is determined based on theoretical formulas. Also explained in Appendix B.

6.2. Erosion volume transect 1182

The erosion volumes of transect 1182 are displayed in Table 4. Like explained before, the erosion volumes of DUROS+ are calculated in the MorphAn software and the XBeach erosion volumes are calculated with the designed calculation tool. Both volumes are defined as the eroded dune volume above the storm surge level. For DUROS+ this corresponds with the volume above the dune foot. For XBeach 1D this is not the case, as explained in the above paragraph the dune foot in the XBeach 1D profile is located higher. But for the comparison between the two, the volumes above the storm surge level is used.

Table 4 Erosion volumes Transect 1182

	Erosion volume [m³/m]		Comparison	
Year	XBeach 1D	DUROS+	DUROS+ – XBeach [m^3/m]	XBeach / DUROS+ [%]
2003	295	617	322	48
2008	211	398	186	53
2013	242	444	202	55
2017	255	547	292	47

In Table 4, also the XBeach 1D volume is subtracted from the total DUROS+. And the XBeach 1D volume is expressed as a percentage of the DUROS+ total volume. In which stands out that the XBeach erosion volume is overall about 50% of the DUROS+ erosion profile. How such big differences are possible is difficult to determine.

The size of both volumes, increase and decrease during the same years. The highest erosion volumes are in the year 2003. The erosion volume of XBeach 1D is formed among other by the wave energy, therefore in Figure 19 the average wave height, based on the wave energy, is plotted in combination with the JARKUS profile. In the figure the years 2003 and 2017 are plotted.

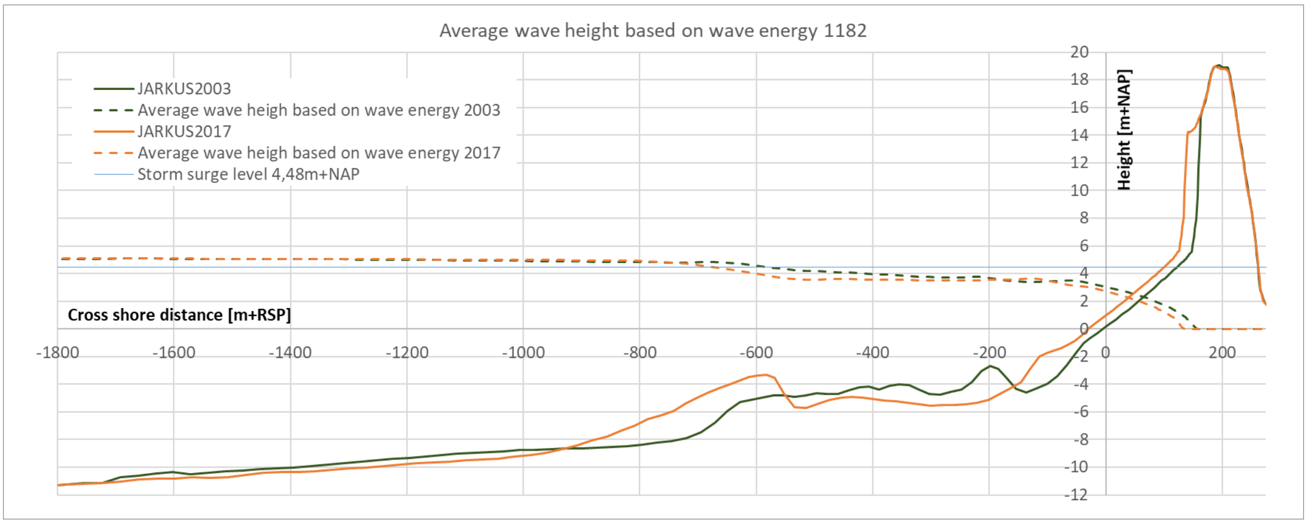

Figure 19 Average wave height base on wave energy 1182

In Figure 19 you see that starting on the left side of the graph (seaside), the average wave height does not show big differences. The difference in the dissipation of the energy becomes visible at -700m+RSP, as a reaction on the sandbank in JARKUS2017.

At about -175m+RSP the sandbank in JARKUS2003 causes the average wave height to decrease even below the average wave height of 2017 for just a short location. This might be because the sandbank in JARKUS2003 is a little higher than the sandbank of JARKUS2017. Probably the location of the sandbank also has influence on the energy dissipation. Eventually the wave energy of 2017 is lower when reaching the dune. This corresponds with the lower erosion volume of 2017.

7. Deep shoreface nourishment

The fourth sub question will be answered in this chapter. The sub question is:

> ***What is the influence of the deep shoreface nourishment on the erosion volume and erosion profile, and how does the location of this nourishment affect the erosion volume according to the XBeach 1D model?***

This question will be answered based on transect 1320. For transect 1320 the deep shoreface nourishment (DSN) is drawn into the bathymetry data. Also, three scenarios are drawn into the data, the location of the deep shoreface nourishment is the variable in those scenarios. As explained in the hypothesis, expected is that the erosion volume will significantly decrease when the deep shoreface nourishment is placed.

The calculations are executed with the model XBeach 1D, since for the DUROS+ model the outcomes will not change with or without the deep shoreface nourishment. For DUROS+ only the upper part of the cross shore is taken into account. Neither of the scenarios locations are high enough.

7.1. Erosion profile DSN

In Figure 20 on the next page, two graphs are given. In the upper graph, the DSN is visible in the input JARKUS profile at the depth of -10m +NAP and starting at -1300m +RSP. The erosion profile of the data with and without the DSN are plotted in both graphs, but difficult to detect. In the lower graph the erosion profile with DSN (orange line) is plotted almost directly on top of the reference erosion profile (purple line). This makes the line look like one red line, however it are different erosion profiles.

Apparently, the designed and executed deep shoreface nourishment does not have a direct significant influence on the erosion profile. This is also the case for transect 1228 and 1258, see Appendix I and Appendix J.

7.2. Erosion volume DSN

Taking a look at the erosion profiles it does not show any significant changes. The erosion volumes of the reference profile and the profile with the DSN are given in Table 5. The erosion volume of the bathymetry with the DSN did decrease compared to the reference, but not a significant amount.

Table 5 Erosion volumes DSN 1320

1320 Erosion volumes	XBEACH [m^3/m]	DUROS+ [m^3/m]
Reference	197	385
DSN	189	385

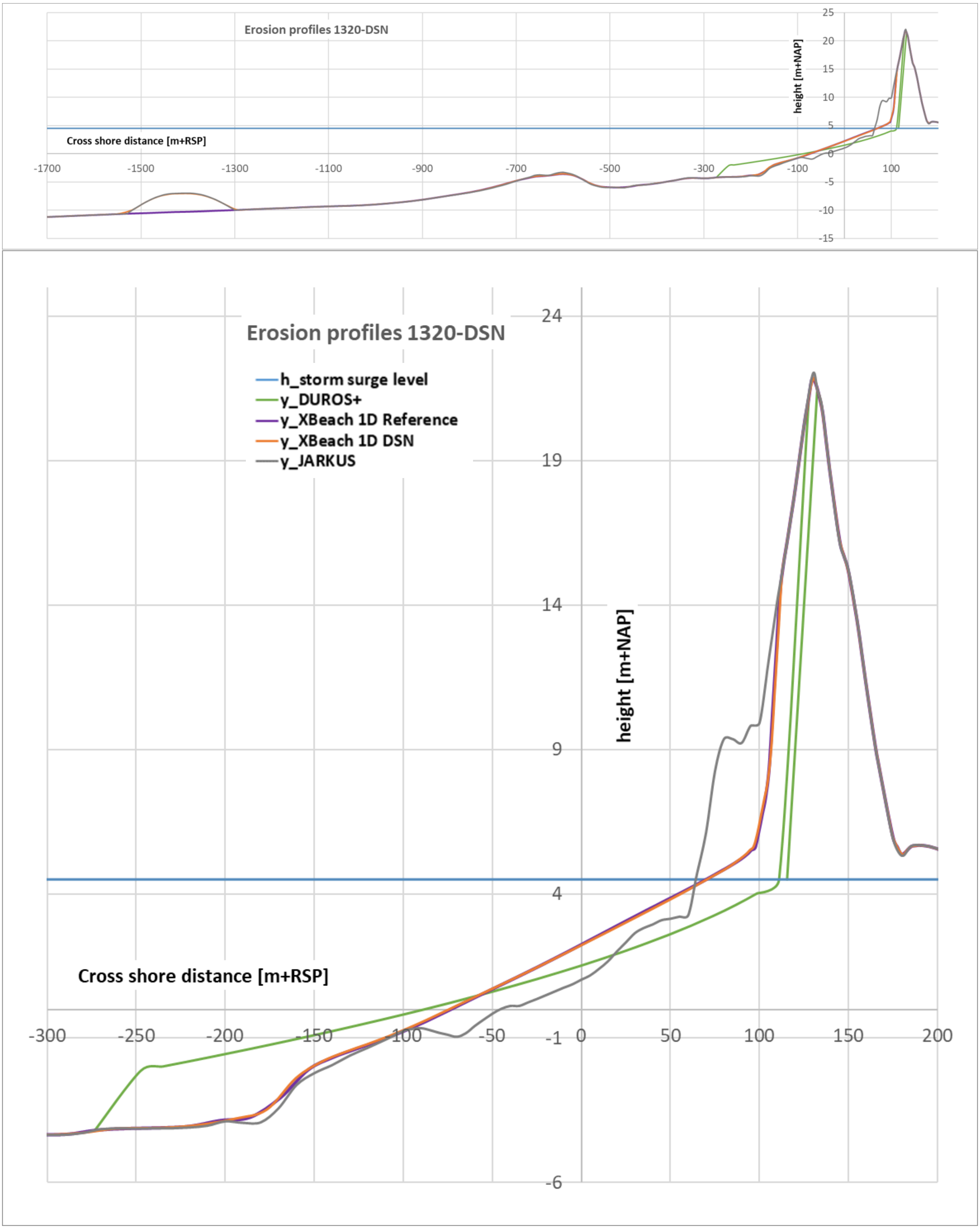

Figure 20 Erosion profile and zoom-in 1320-DSN

Average wave energy DSN

To explain the ‘changes’ in the erosion profile and volume, the energy dissipation is rather important. In the graph below, Figure 21, the average wave height based on the wave energy is plotted with the JASRKUS. This is extracted from XBeach 1D with and without the deep shoreface nourishment. The orange lines correspond to the DSN and the dark green line to the reference without DSN.

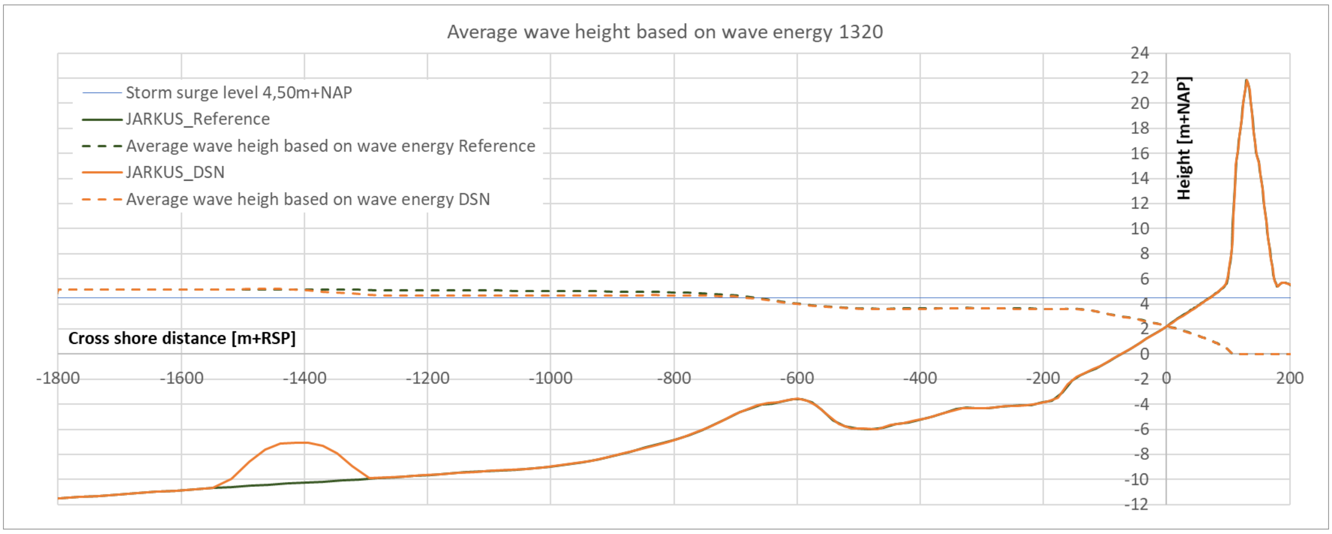

Figure 21 Average wave height based on wave energy 1320 Reference and DSN

As expected, the wave height based on the wave energy decreases at the DSN. It is remarkable that eventually the average wave height based on the wave energy are equal, again for both scenarios. This causes the erosion volumes not to differ significantly.

7.3. DSN scenarios 1320

The scenarios of the DSN are given in the methodology and Appendix E. The scenarios consist of the relocation of the deep shoreface nourishment in the direction towards the dune. In Figure 10 the scenarios are drawn.

Contradicting to the expectations is the influence of the DSN scenarios nihil on the erosion profiles of transect 1320. The graphs are very comparable to Figure 20 and presented in Appendix K Erosion Profile DSN 1, 2, 3 and 3a.

Since barely any difference can be spotted in the erosion profiles, the focus will immediately be on the erosion volumes.

Erosion volumes

In Table 6, the erosion volumes for the different scenarios are given. The DUROS+ erosion volume did not change, since this model does not encounter the lower shoreface.

Table 6 Erosion volumes DSN scenarios

	Erosion volume [m³/m]		Comparison	
Name	**XBeach 1D**	**DUROS+**	**DUROS+ – XBeach [m^3/m]**	**XBeach / DUROS+**
Reference	197	385	188	51%
DSN	189	385	196	49%
DSN1	181	385	204	47%
DSN2	188	385	197	49%
DSN3	185	385	200	48%
DSN3a	175	385	210	46%

Interesting is that the erosion volume did not just decrease when the location became less deep. Firstly, the volume did decrease, for DSN and DSN1. But for DSN2 the volume increased.

The difference in DSN3 and DSN3a is very interesting. Scenario 3a is an estimated guess of what could happen after scenario 3. However, are no specific numbers used for this guess, just the location of erosion is intimated. Based on the graph, the differences which occur at the erosion are behind the sand bank. At that point the average wave height, based on the wave energy of scenario DSN3a, is a little lower. In this eroded area, the wave has another 'obstacle' which could cause the decrease in energy.

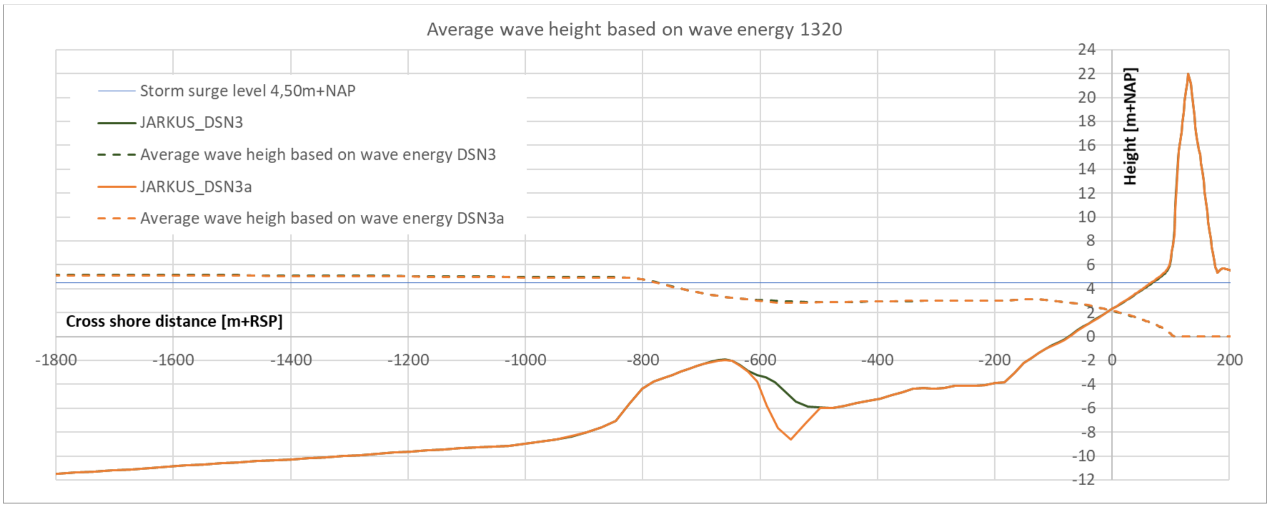

Figure 22 Average wave height based on wave energy DSN3 and DSN3a

8. Conclusion

Based on the executed research the following conclusion can be drawn.

Dune safety

The executed nourishments increased the volumes of researched transects. In this development the weather conditions which could lead to sedimentation and erosion are not taken into account. The volume increase took among other place at the dunes. Also, the upper part of the cross shore profiles underwent significant changes due to the nourishments. The upper bathymetry became less steep, which in the case of DUROS+ caused the erosion point to develop seaward. Also, in XBeach 1D the erosion volume decreased while the bathymetry became less steep. In XBeach 1D this is because of the wave energy that reached the dunes, during a storm simulation. The dissipation of energy increased on the upper shoreface, so less wave energy reaches the dun and less erosion takes place.

Even though both models have a different approach, DUROS+ is an empirical model and XBeach 1D a process-based model. Out of both models may be concluded that the dune safety, based on the erosion volume, increased over the past 18 years.

Deep shoreface nourishment

It seems that the deep shoreface nourishment does not have a significant influence on the dune safety at the moment. It is located too deep to perform noticeable changes on the wave energy that reaches the dune and therefore on the dune erosion. Even when the nourishment is located higher on the profile, its effects on the erosion profile, at the moment, are unremarkable. In the erosion volume, some small changes are visible, but those does not seem to be of high importance.

Upper profile

From those results, may be concluded that the upper profile is of major importance for the dune erosion volume under extreme conditions. While the lower profile only has marginal influence. Even with DSN3, the dune erosion does not significantly change.

XBeach 1D and DUROS+

Even though different articles suggest that the sandy coast at Callantsoog is assessable with the empirical model DUROS+, the difference compared to XBeach 1D are big. The XBeach 1D erosion volumes are about half of the DUROS+ erosion volumes, in the tested circumstances. Which one is more accurate is undiscovered in this research.

9. Discussion

Since this is a small research, some assumptions are made which have to be taken into account during the interpretation of the results. Below the most important assumptions and its possible influence on the results will be discussed.

Volumes development

In the volume development, the only variable that was encountered where the executed nourishments. However, storms could also play an important role in the change of volumes over the years. Just as the longshore sediment transport, which was not taken into account during the analyses of the volume development.

HB2017

The HB2017, which are used as input for the erosion models, are interpolated statistical based values. Such storms are not measured before, so the reliability of those values is questionable. However, the same input is used for both models. If the hydraulic conditions would not be realistic, still the comparison in the results can be made.

Erosion models

The most important part of the discussion is the reliability of the used models. The DUROS+ model is an empirical model, based on experiments executed on a small imitation of the weakest spot in the Dutch coast. So, it does not come as a surprise that the erosion volumes of the DUROS+ model is bigger compared to XBeach 1D, a process-based model. It is suggested that the Noord-Holland coast is not a very complex coast because of the absence of coastal structures. Therefore, the DUROS+ model is sufficient to assess multiple areas along the coast of Noord-Holland (including Callantsoog). However, the differences are very big, which makes the reliability of either model questionable. What should be mentioned is that the increase and decrease of the erosion volume happen simultaneously in both models. So, even though the approach is very different, the models agree in the positive or negative development of the coast in the tested cases.

Since DUROS+ is designed for the Dutch coast, it would seem that its reliability is high. But XBeach 1D is based on the theory behind the process, which should be reliable as well.

Design deep shoreface nourishment

The design of the deep shoreface nourishment is based on the actual executed nourishment. However, the nourishments eventually may be located a little wider, or shorter. This is not expected to be of importance, since the influence of the nourishment are barely noticeable anyway.

Influence deep shoreface nourishment

In the conclusion the suggestion is given that the deep shoreface nourishment is without influence on the coastal safety at the moment. However, the development of the nourishment is unknown, which means that the influences are still in development. Probably in about 5 till 10 years more can be suggested about the effect of this nourishment.

10. Recommendations

After this research some recommendations for further research are established. The focus of this research is dune safety of Callantsoog and the influences of nourishments. Recommendations regarding the further maintenance, deep shoreface nourishment, DUROS+ and XBeach 1D are formed.

Further maintenance

Based on the executed nourishments and developments over the past 18 years, the desired results in the dune safety are gained. Recommended is to remain the same maintenance policy, actively maintaining the coast with sand. It is important to keep active in the maintenance since the erosion on the coast occurs continuously. Along with that further research can be executed regarding more efficient types of nourishments. Testing the efficiency of deep shoreface nourishments might be a good start for this.

Maybe if another nourishment is placed behind the deep shoreface nourishment, the sand will transfer (more/faster) towards the upper profile. This is how the natural sandbank located on the shore of Callantsoog moved more seaward since 2000 as well, however the sediment transport is at shallower areas very different compared to the depth of -10m+NAP. Recommended is to first further investigate the expected behavior and analyze the options.

Deep shoreface nourishment

At the moment the deep shoreface nourishment does not seem to have influences on the dune safety. However, the deep shoreface nourishment has not developed over the seabed yet. It is recommended to closely monitor the nourishment and analyze the sediment transport. When the sand will transfer towards the beach the effects on dune safety have to be tested again. However, based on the tested scenarios, the sand has to move to the very upper part of the profile in order to significantly positively affect the dune safety.

Usability XBeach and DUROS+

Before implementing the XBeach 1D model as official assessment tool of the Dutch coastal primary water barrier, suggested is that some extra research has to be executed.

Recommended is, to further investigate the model XBeach 1D in combination with practical tests. Some practical test might give more insight information of the usability of XBeach in the assessment of the Dutch coast. XBeach is a complex model and important is to remain the link with the reality.

In multiple articles is suggested that the Noord-Holland coast is not a very complex coast and therefore the DUROS+ model is sufficient to asses multiple areas along the coast of Noord-Holland (including Callantsoog). But the differences in the outcomes of both models are therefore even more remarkable. More research has to be executed in this area, also the practical test might give useful information in this topic.

Practical recommendations XBeach

Since XBeach 1D is in the development phase at the moment, some practical recommendations are given. A practical recommendation regarding XBeach would be, the implementation of the average wave energy and the erosion volume. At the moment those are not jet an option in the MorphAn software. The erosion profile is given and the erosion volume can be calculated in anther program (for example Excel or MATLAB), but this is missing in the integrated XBeach 1D model in MorphAn. At the moment the average wave height based on the wave energy is given, but the average wave energy per location is missing.

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Appendix A. Hydraulic Loads 2017

The safety of the Dutch primary water barriers are defined as a failure norm. This norm represents a storm strength, which is predicted to occur only every x years. According to the Water Law, the dunes at Callantsoog should be able to cope with a storm strength which occurs every 3.000 years (Ministerie van Infrastructuur en Milieu, 2016).

This value corresponds to a track among the Noord Hollandse coastline. For every cross section/ transect this norm is converted to a failure probability requirement. This failure probability is divided over different causes, for dunes this is a relatively simple division. Expected is that the failure of dunes is for 70% related to dune erosion and for the other 30% to is related generally unknown factors. Also, the length effect factor is needed to convert the failure norm per track to a failure probability requirement per cross section. This factor is based on the variability per track, for Callantsoog this is 2. (Rijkswaterstaat, 2016)

Eventually the following formula is used to convert the requirement per track to a requirement per cross section:

$$P_{eis;dsn} = \frac{\omega P_{eis}}{N_{dsn}}$$

With;
$P_{eis;dsn}$ - failure probability requirement per cross section [1/year]
P_{eis} – failure norm per track [1/year]
ω – failure probability factor [-]
N_{dsn} – length effect factor per cross section [-]

So the failure probability requirement for each cross section at Callantsoog is once every 8571 years.

$$P_{eis;dsn} = \frac{0{,}7 * \frac{1}{3000}}{2} = \frac{1}{8571}$$

This calculation is executed in the software package ‘Ringtoets’. Also, the hydraulic loads are calculated in this software. The input is:

- Track number and failure norm (for Callantsoog: 13-3, 1/3.000)
- Measured hydraulic conditions of the area

Each specific cross section is linked to the corresponding hydraulic loads at a certain failure probability requirement. Those hydraulic loads are statistically determined based on measurements along the coast. The hydraulic loads consist of the following parameters:

- Surge storm level - Rp [m+NAP]
- Wave height - Hs [m]
- Wave period – Tp [s]
- 50%-fractile of grain diameter - D50 [m]

Appendix B. Details DUROS+

The DUROS (DUin eROSie) model is based on the expected shape of the erosion profile. DUROS+ is the same as DUROS but including the effect of the peak period of the energy density spectrum.

DUROS+ can be seen as a calculation model, the expected dune erosion during a storm surge is specified. This can be combined with the consideration of the safety of the dune. DUROS+ estimates a post-storm profile based on maximum storm conditions (water level, wave height, wave period) and the pre-storm bathymetry together with a representative grain size. With a maximum intensity during a storm length of 5 hours (den Heijer, et al., 2011).

Guided principles DUROS+

In the testing method of DUROS+ there are some guided principles that should be taken into account. Those guided principles are written down below:

- During a storm surge, the dune erosion takes place around the surge storm level. The area just below the surge storm level is transformed into an erosion profile. The storm surge level is the maximum water level reached during the storm. At a depth of -20m NAP in the water, the changes during a surge storm are assumed to have limited impact and the impact on the coastline of those changes are negligible.
- The shape of this erosion profile depends on the significant wave height, the peak period (both at the depth of circa NAP -20) and the fall velocity of the of the eroded sediments in stagnant water at 5 degrees Celsius.
- The shape of the erosion profile is independent of the storm surge level.
- The shape of the erosion profile is independent of the coastal profile before the storm.
- The shape of the erosion profile is independent of the wave direction.
- The shape of the erosion profile is independent of the possible debris in the erosion profile.
- The eroded sand will only be carried seaward.
- The dune erosion processes during a storm surge will be interpreted in a 1-dimensional process.
- The amount of erosion depends on the time in which the water level is at its maximum, but in this model, this is not taken into account
- The shape of the erosion profile and the vertical position depends on the maximum wave height (h_{max}), significant wave height at -20m NAP(H_{0s}) and the wave period at a depth of -20m NAP (T_p). The maximum values of those parameters during a storm surge will be reached at the same time, when h_{max} is reached.
- In Figure 23 the points P and R* are shown. P is the original dune at the height of the storm surge level. And R* at the surface of dune, this point is mainly very important after the surge storm for the coastal management. Generally, there will be referent to R* if the extent of dune erosion is meant.

Shape of erosion profile and volume A

As shown in Figure 23 the dune slope (duintalud) of the eroded area is 1:1. The foot of the dune is at point P, where the slope transforms from a steep to a gentler slope.

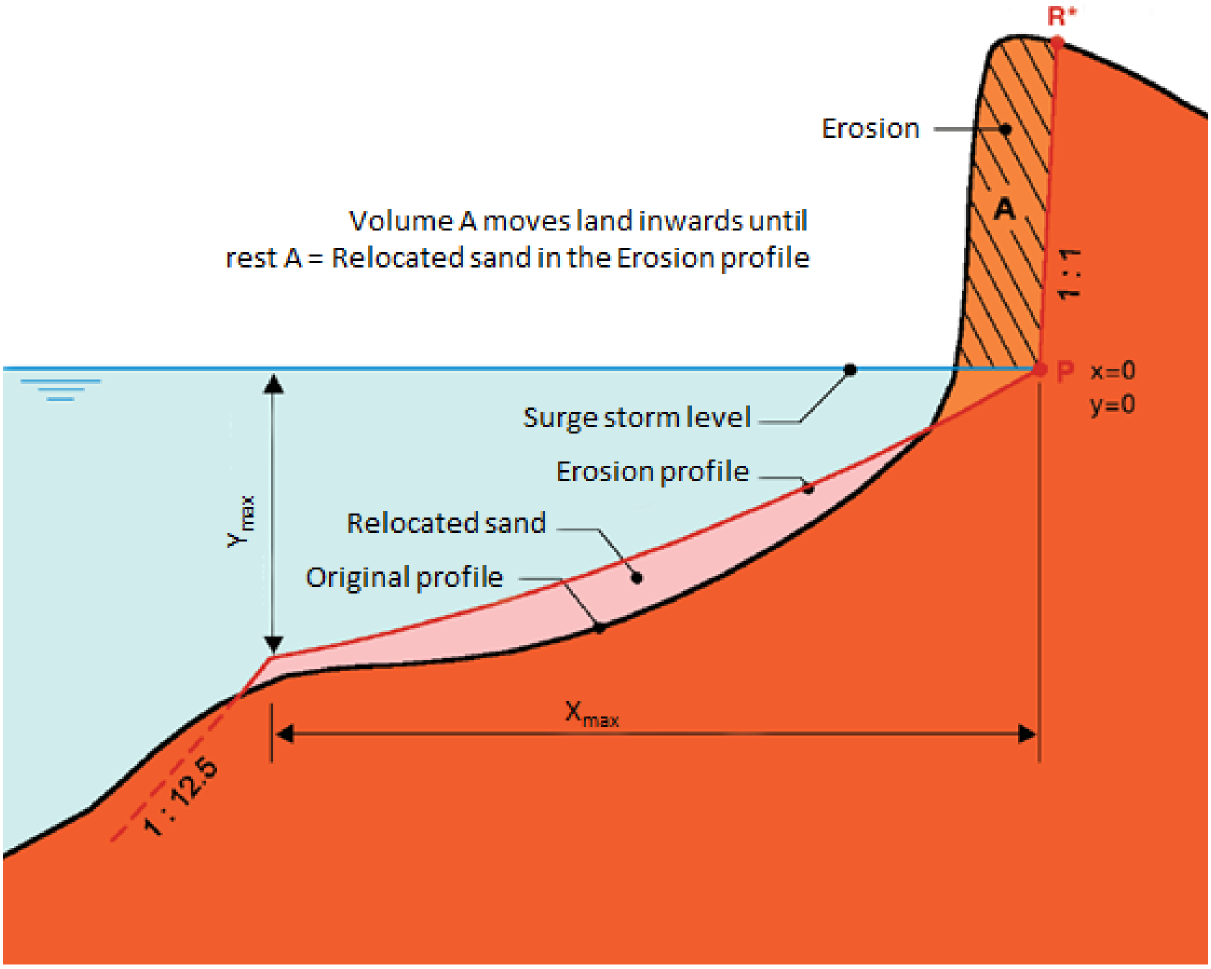


Figure 23 DUROS+ model (WL | Delft Hydraulics, Alkyon en TU Delft, 2007)

From the point P (x=0, y=0) the erosion profile is based on a parabolic seaward, perpendicular to the coast according to the following formula:

$$\left(\frac{7.6}{H_{0s}}\right) y = 0.4714 \left[\left(\frac{7.6}{H_{0s}}\right)^{1.28} \left(\frac{12}{T_p}\right)^{0.45} \left(\frac{w}{0.0268}\right)^{0.56} x + 18\right]^{0.5} - 2.0$$

Until:

$$x_{max} = 250 \left(\frac{H_{0s}}{7.6}\right)^{1.28} \left(\frac{0.0268}{w}\right)^{0.56}$$

So,

$$y_{max} = \left[0.4714 \left\{250 \left(\frac{12}{T_p}\right)^{0.45} + 18\right\}^{0.5} - 2.0\right] \left(\frac{H_{0s}}{7.6}\right)$$

Seaward on, starting at the point (y_{max}, x_{max}), the slope is set at 1:12.5 until this line intersects the original cross section (see in Figure 23).

With;
H_{0s} – significant wave height in deep water [m]
T_p – wave period at the peak of the energy density [s]

w – fall velocity of the dune sand in seawater with a temperature of 5 degrees Celsius [m/s]
x – distance from the new dune foot [m]
y – depth below the surge storm level [m]
The formulas are valid when $12\ s < T_p < 20\ s$. If $T_p < 12\ s$, the value $T_p = 12\ s$ is used. When $T_p > 20\ s,\ T_p < 20\ s$ is used.

The eventual area volume A is defined by point P, R* and the erosion profile. Point R is the erosion point of the erosion profile. As shown in Figure 23, Volume A is being shaped inside the boundaries of the dune, line P- R* and the erosion profile. Since point P is again depending on Y_{max} and X_{max}, volume A depends on among others the fall velocity, wave period at peak of the energy density and wave height.

For every cross section the amount of dune erosion is calculated, above the storm surge level. This is volume A in Figure 23 and Figure 24. The shift of R* to R is calculated in a way that that delta R has a dune volume T of 0.25A, this is where point R is located. This 0.25A is equal to the 'extra' volume T. As illustrated in Figure 24. This extra volume is necessary to add and not just a safety measure. It is necessary since the calculated erosion volume is normally not equal to the amount of erosion that in reality accords during the calculated storm. So, a compensation has to be made for the accuracy of the DUROS+ model.

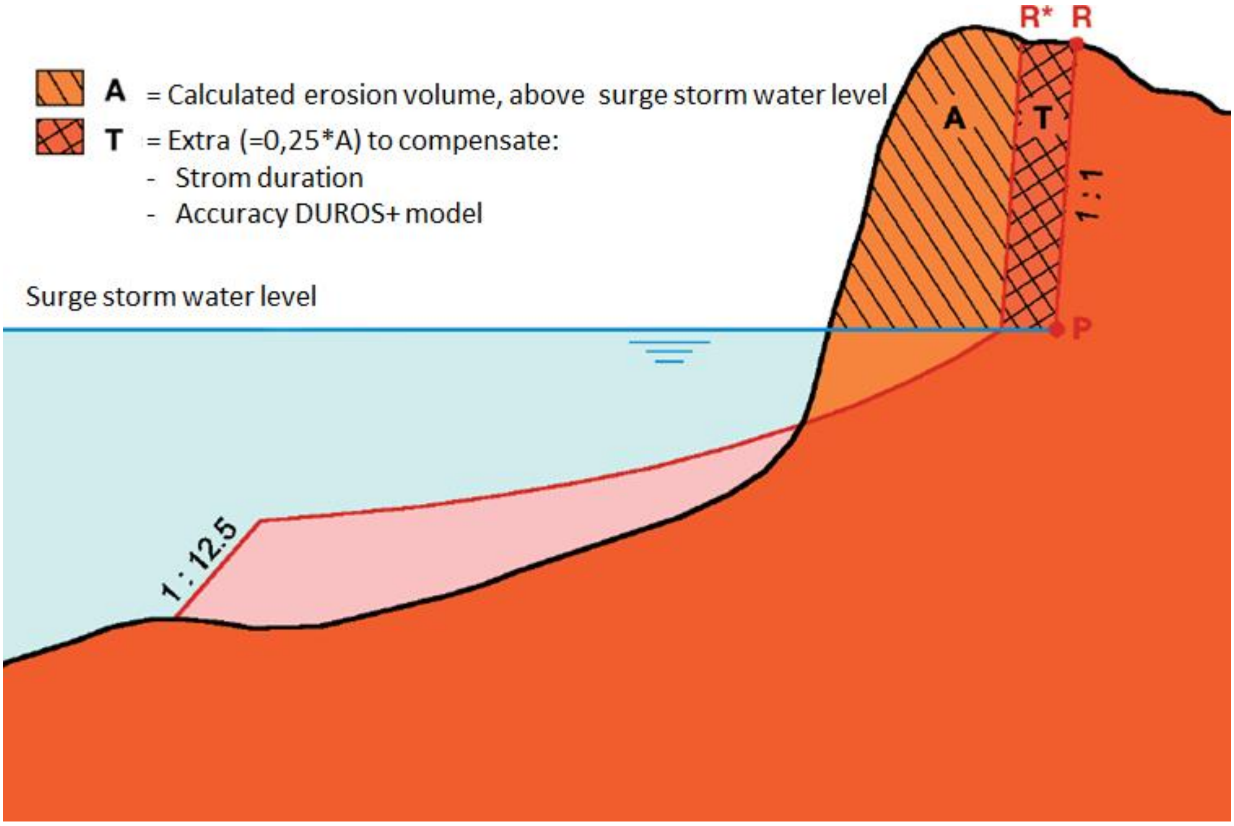


Figure 24 DUROS+ model with extra volume T (WL |Delft Hydraulics, Alkyon en TU Delft, 2007)

DUROS+ safety test of a cross section of the dune

To determine whether a cross section of dune is considered 'safe', a relatively easy testing method is applied. A certain erosion profile corresponding with storm X is already calculated (see the above section). This profile can be compared with the profile boundary of a dune, when this boundary profile is crossed, the dune fails. So, point P of the erosion profile may not cross Boundary profile base position. In MorphAn, such a boundary profile can be visualized in the cross section of the dune, see Figure 25. The boundary profile is shown as a yellow trapezium in the cross- section, on the corner of this boundary profile the Boundary profile base position is also shown.

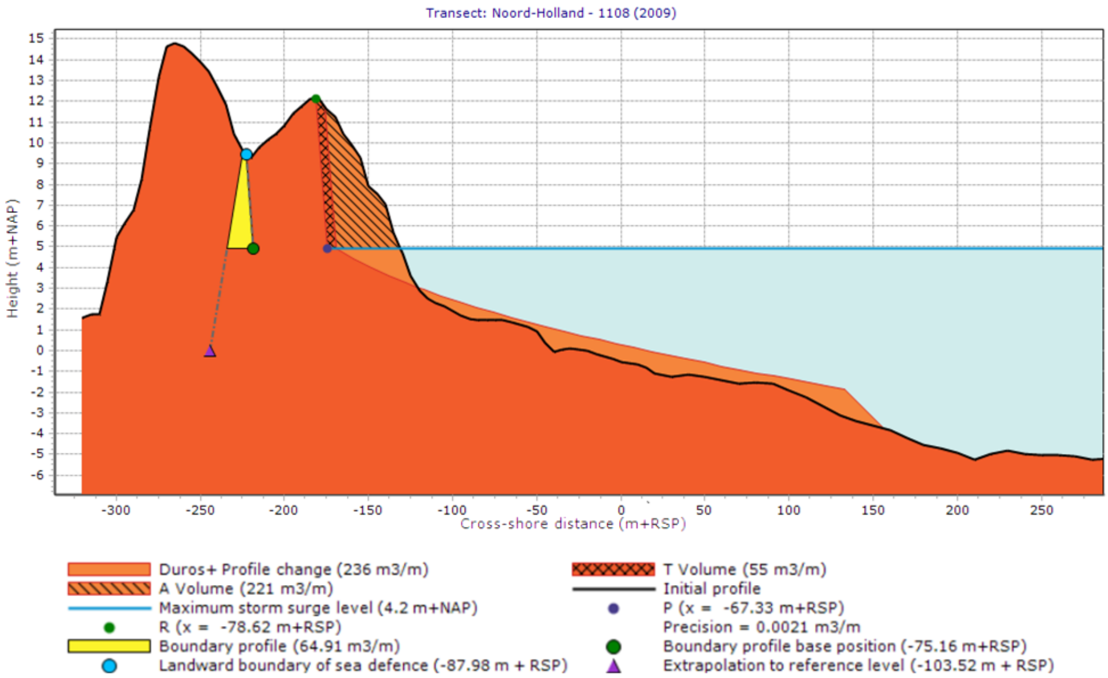


Figure 25 Cross section of transect 1108 (2009) (Extracted from: MorphAn)

Appendix C. Details XBeach 1D

Since XBeach is not an official calculation tool for Rijkswaterstaat yet, there is less information available about XBeach compared with DUROS+. In this report only, the calculation modules build into XBeach will be shortly discussed. Those will not be discussed elaborately for the following reasons; the formulas are very complex and fully understanding them would be too time consuming for the scope of this research; also, for the outcome of the research the exact calculation performed by XBeach are less important. The continuity on the other hand is significantly more important.

XBeach, (eXtreme Beach behavior) is also a module designed to determine the dune safety. The biggest difference in XBeach compared with other models, is that XBeach takes into account the variation in the wave height and strength over time. Those resolve the long-wave motion, this is mainly the responsibility for the swash waves that actually hit the dune front or overtop it. XBeach is process-based model, at each time step, the calculations are repeated and implemented in the profile.

As described in Roelvink et al (2009): *'With this innovation the XBeach model is better able to model the development of the dune erosion profile, to predict when a dune or barrier island will start over washing and reaching and to model the developments throughout these phases.'*

XBeach is not yet an official software to determine the dune safety for Rijkswaterstaat, but it has a lot of potential and therefore this module will also be used in the research. Also, the a deep shoreface nourishment will not have an influence on the DUROS+ model. In this model the cross-shore profile does not have influence on the erosion volume.

Qualitative description

Dune erosion is a dynamic process of different sediment transports, the profile during storm condition changes rapidly. The dune sand is transported to the beach and shoreface over the cross shore, but also over the long shore. The wave height determines the wave energy, the breaking of the waves causes dissipation of wave energy (Den Heijer, 2013).

The different modules that are calculated every time step in XBeach are the wave, flow, morphology and sediment modules. The link between those modules are visualized in Figure 26.

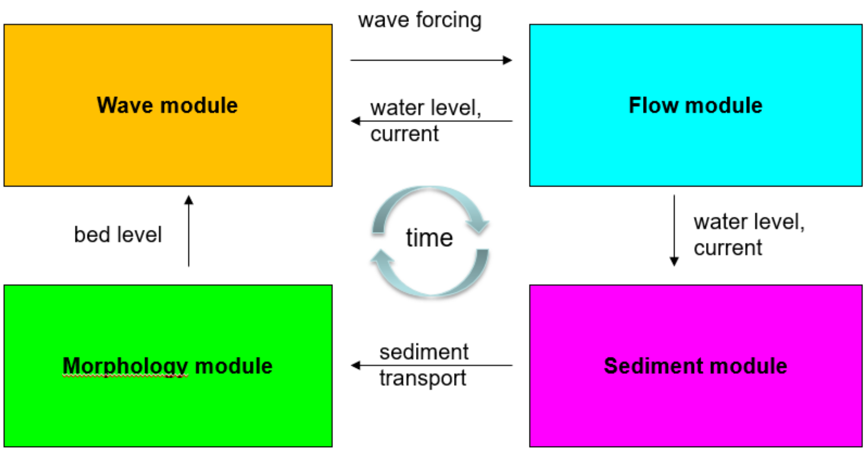


Figure 26 Modules in XBeach (Deltares, 2017)

When you for example start at the wave module, the version of XBeach implemented into MorphAn, uses a so-called wave envelope. The short waves and the long waves are combined into this envelope, in this way a significant amount of time is spared during the calculations. The wave envelope is schematized in Figure 27. In the wave module calculation, the refraction, wave breaking, wave friction and wave dissipation in time are calculated and form the input for the flow module.

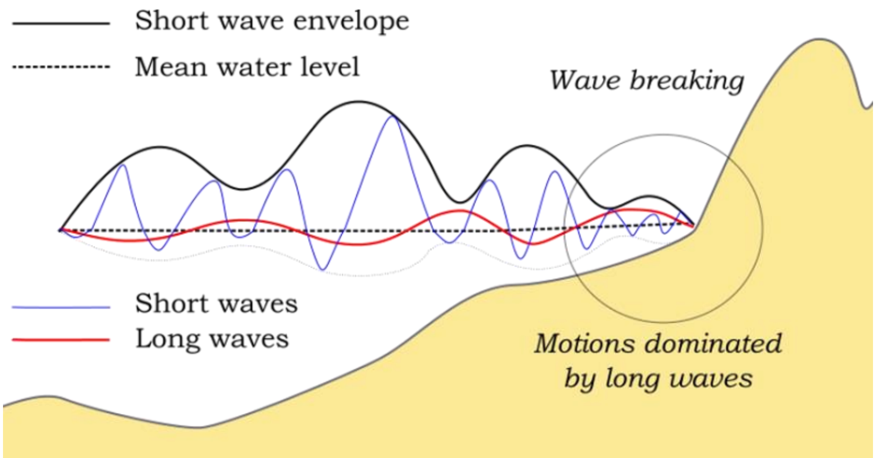


Figure 27 Schematization wave envelope (Deltares, 2017)

In the flow module, the water level gradient, viscosity, bed friction, wave forcing, advection and acceleration for the longshore and cross-shore direction are taken into account.

In the sediment module, the concentration, pick up, transport and diffusion of sediment are taken into account. Not only the cross-shore sediment transport is taken into account, but also the alongshore transport. Since the alongshore current is crucial, which could lead to significantly more dune erosion (Den Heijer, 2013).

The last module, the morphology module the bathymetry change is calculated and again used in the wave module.

In the research the storm simulated in XBeach takes 18000 seconds (5 hours). This is to achieve a fair comparison with DUROS+. The DUROS+ model is based on stationary condition during 5 hours, with maximum intensity. Also, are the hydraulic conditions and grain size are kept at an equal value for the same reason. This means that the tide is also not included and the same force from a depth of -20m NAP is executed on the profile.

In Figure 28 the process in XBeach is described in a flow diagram.

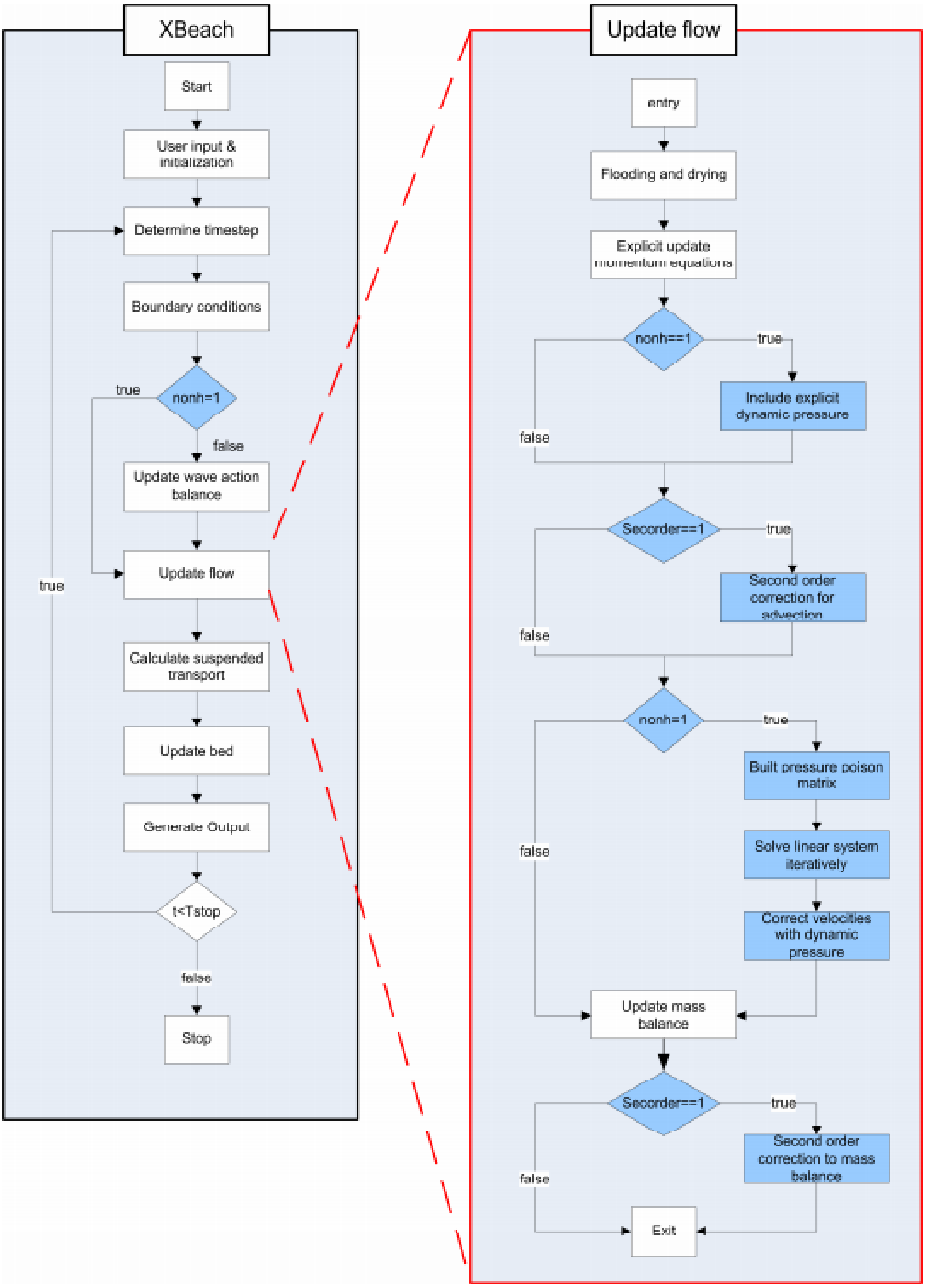


Figure 28 Flow diagram XBeach
(Delft University of Technology and Deltares, 2009)

Input

XBeach needs a more extended input than DUROS+. XBeach needs the following input (Deltares, 2017):

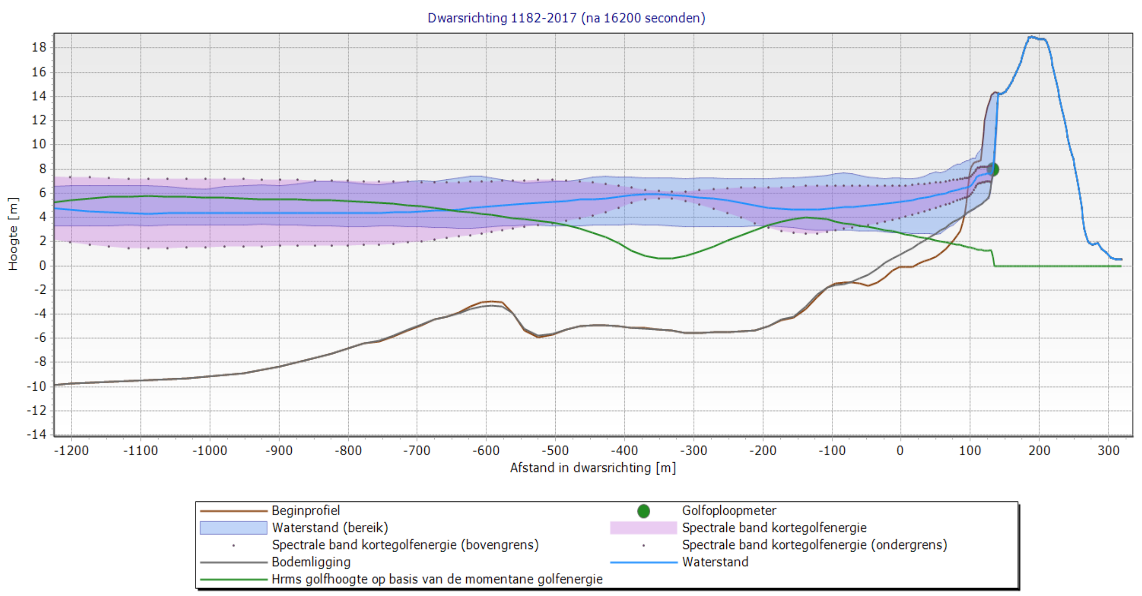
- Profile – Profile definition
- Waves – Wave period condition
- Vertical tide – The specification of the water height over time (also possible to import those data)
- Parameters – Information about the total period of calculations and the grain size
- Output specifications – Possibility to choose the output data

The input of XBeach 1D is very important in the comparison with DUROS+. The DUROS+ model is based on a 5 hours storm with continue intensity of the storm. Therefore, the storm duration in XBeach 1D will be 18000 seconds, 5 hours. The tide changes will not be taken into account and assumed is that the grainsize does not change over time. The wave timeseries is specified based on a spectrum shape (Den Heijer, 2013). The input for the selected transects can be found in Appendix H, Appendix I, Appendix J and Appendix K.

Output

After running the model, the following output is given (Deltares, 2017):

- Cross-shore – Presents the output variables in a cross-shore view (see next page)
- Time series – presents the development of output variables in time at a specified cross-shore position
- Runup – presents a time series of the wave run-up evaluation
- Run report – summarizes the messages created during the model run



Appendix D. Selection of transects

The description of the criteria is explained in paragraph 3 in task IV. In the tables below, for each transects is shown if it meets the criteria. Based on those criteria, a selection of a diverse combination of transect is given. Namely, transect 1182, 1228, 1258 and 1320. The transects a spread over the total area of Callantsoog. Behind the transect of 1228 and 1258 there are no direct buildings located, in contrast with 1258 and 1320. In one of the transects, 1182 the deep shore nourishment is not executed, but only in 1228 this nourishment is visible in the JAKRUS of 2017. Regarding the safety it seems that transect 1182 was already considered save with the HR2006, 1320 and 1228 is not considered safe in either HR.

Criteria		Impact	Deep shoreface nourishment		Dune safety			
Transect					HR2006		HR2017	
	Selected	Village directly behind the dunes	Executed at	Visibile in the JARKUS 2017	Boundary profile fits in the dune since	Determative erosion point crosses the landward boundary	Boundary profile fits in the dune since	Determative erosion point crosses the landward boundary
1123					2003	-	2000	
1137					2004	-	2000	
1152					2002	-	2000	
1167					2000		2000	
1182	x				2000		2000	
1197					2002	-	2000	
1213			x	x	2000	x	2000	x
1228	x		x	x	2000		2000	x
1243		x	x	x	2004	-	2000	
1258	x	x	x		2004	-	2002	-
1273		x	x		2003	-	2000	x
1288		x	x		2000	x	2000	x
1303		x	x		2001	-	2000	
1320	x	x	x		2015	-	2000	x
1340		x	x		2017	-	2000	x
1360			x		2016	-	2000	x
1381			x		2000	x	2000	x

Appendix E. Design scenarios deep shoreface nourishment

In this appendix the implementation of the deep shoreface nourishment will be explained. Also, the motivation for the scenarios will be given.

Implementation DSN in MorphAn

In the MorphAn software, changes can be made to bathymetry data. In this case the DSN will be drawn into the transects 1228, 1258 and 1320. For transect 1228 the designed volume is 495,0 m^3/m, for the transect 1258 and 1320 517,5 m^3/m.

In first instance, for the three transects the DSN is drawn into the bathymetry. This is visualized in Figure 29 for transect 1228. The yellowish line of the bathymetry is the dry measurement (27-01-2017), blue the wet measurement (25-03-2017) and the red part connecting those two is the interpolated value.

It is noticeable that the blue line is intersected with a green line, the green line is the adapted value to from 2016. This is done to create a reference for the changes. Than at last the purple part of the graph, this is the created DSN. In the upper part of the figure the input data is visible, but those are also written down in Table 7. Figure 29 Shows clearly what how the DSN is implemented in the transect.

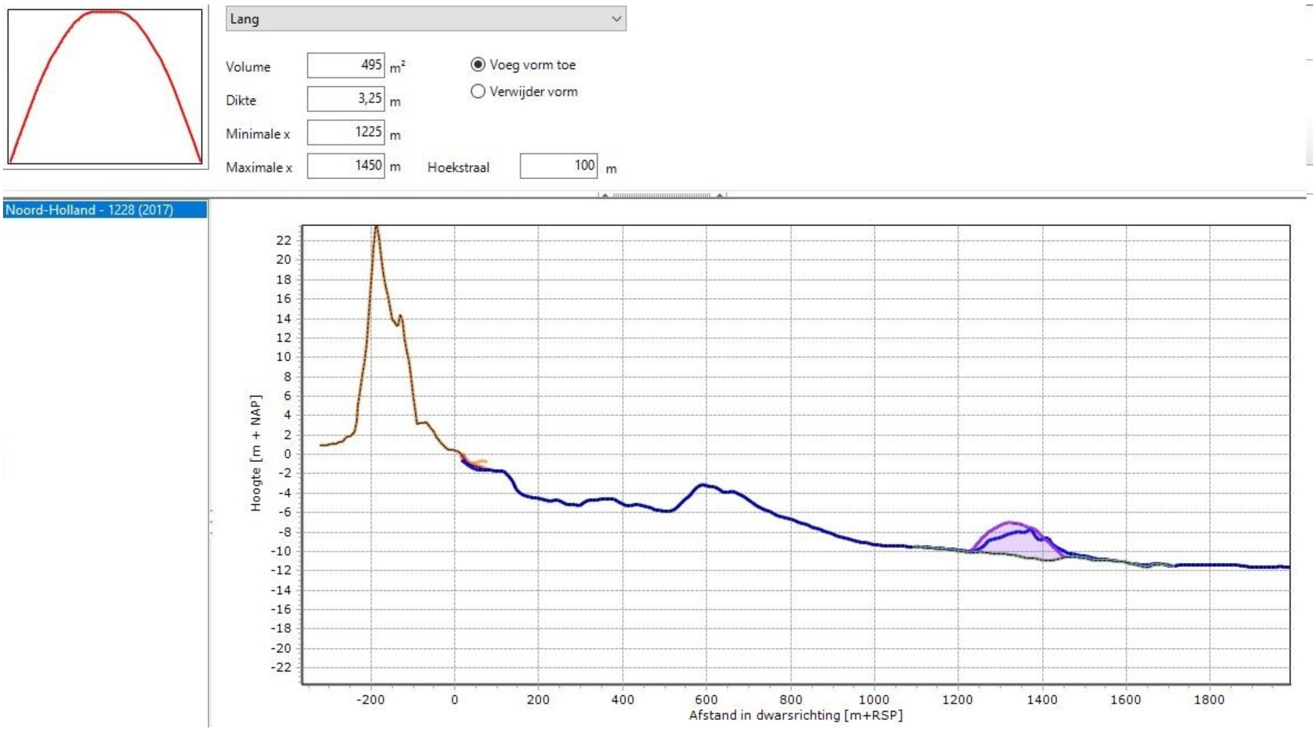


Figure 29 DSN 1228 (Print screen MorphAn)

Table 7 Design of the DSN and scenarios

Transect	Relative to	Location min x [m+RSP]	Location max x [m+RSP]	Volume [m^2]	Thickness [m]	Angle [m]
1228	Reference 1228	1225	1450	495	3,25	100
1258	Reference 1258	1275	1500	518	3.25	100
1320	Reference 1320	1300	1530	518	3,29	100

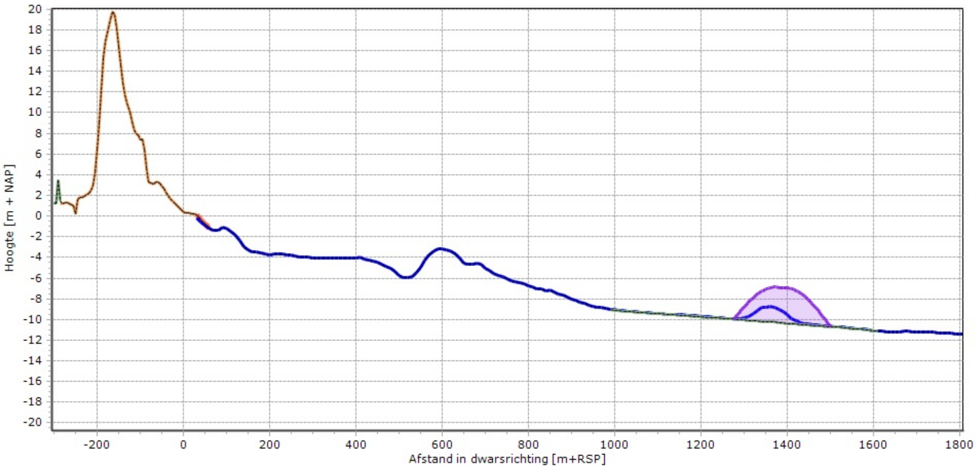


Figure 30 DSN 1258 (Print screen MorphAn)

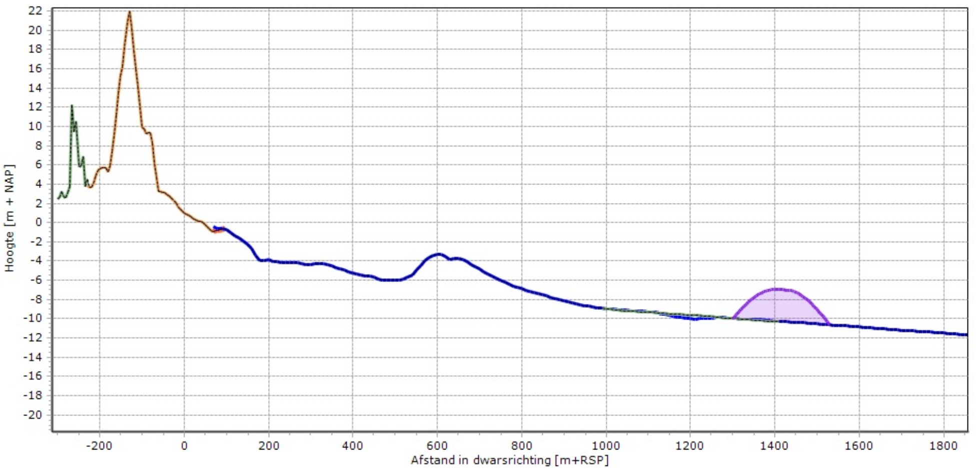
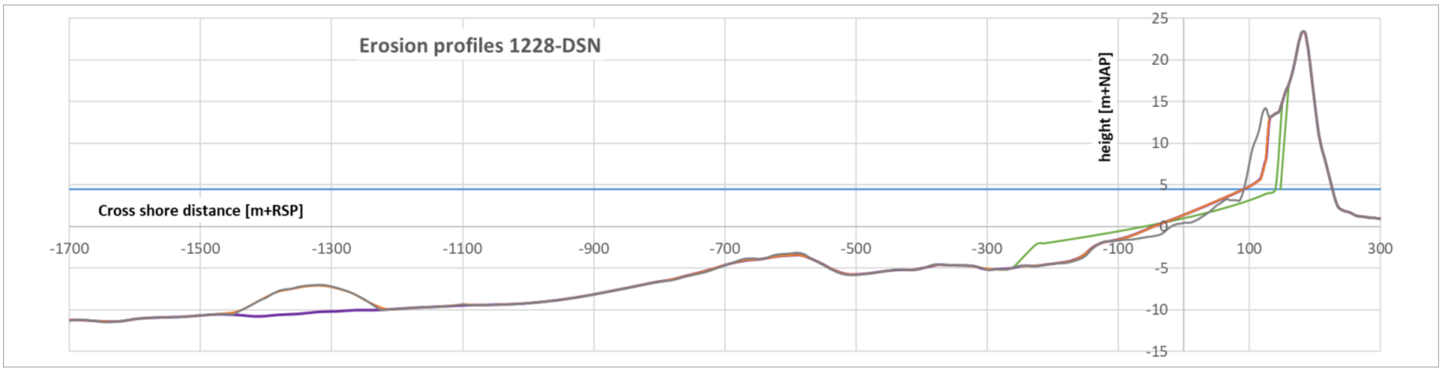
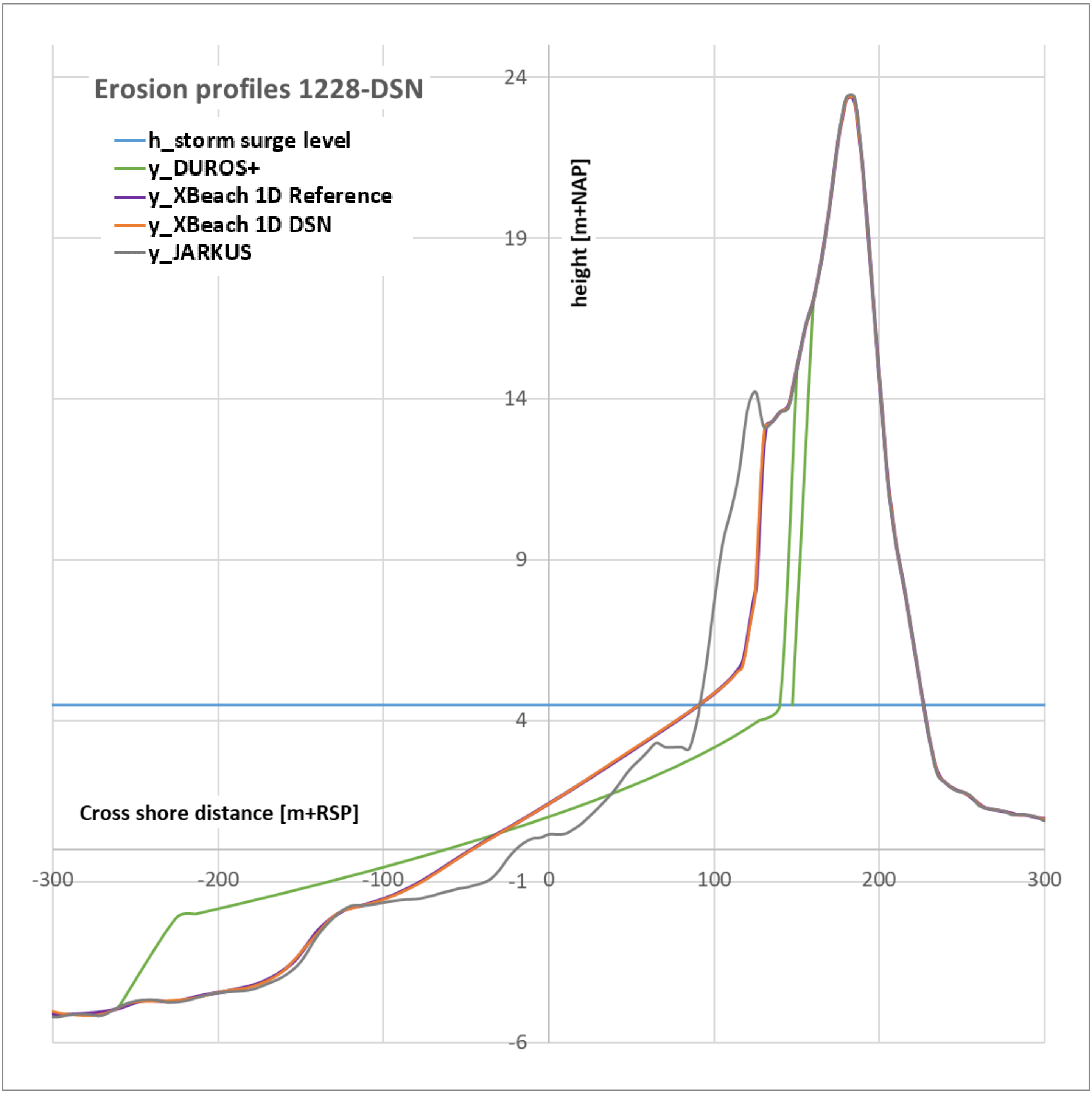


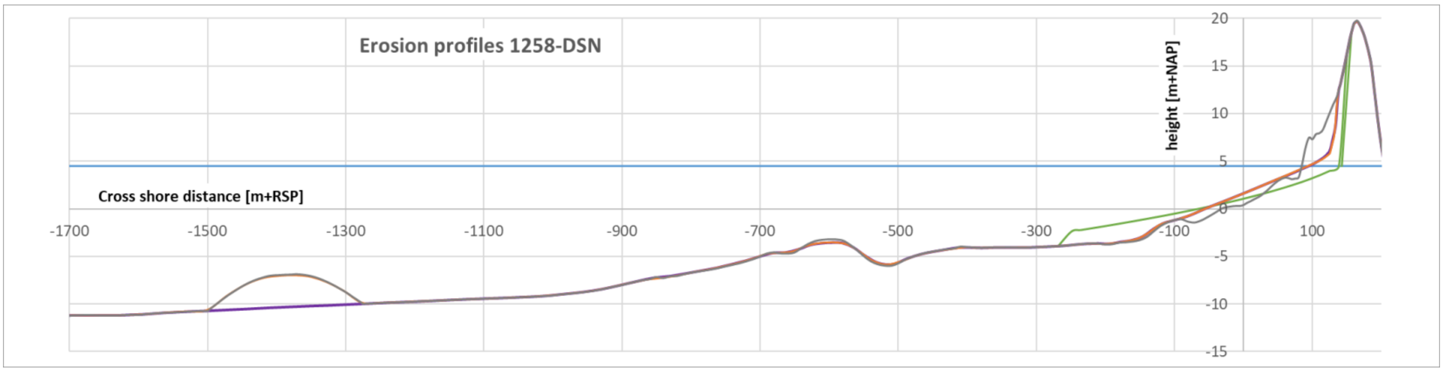
Figure 31 DSN 1320 (Print screen MorphAn)

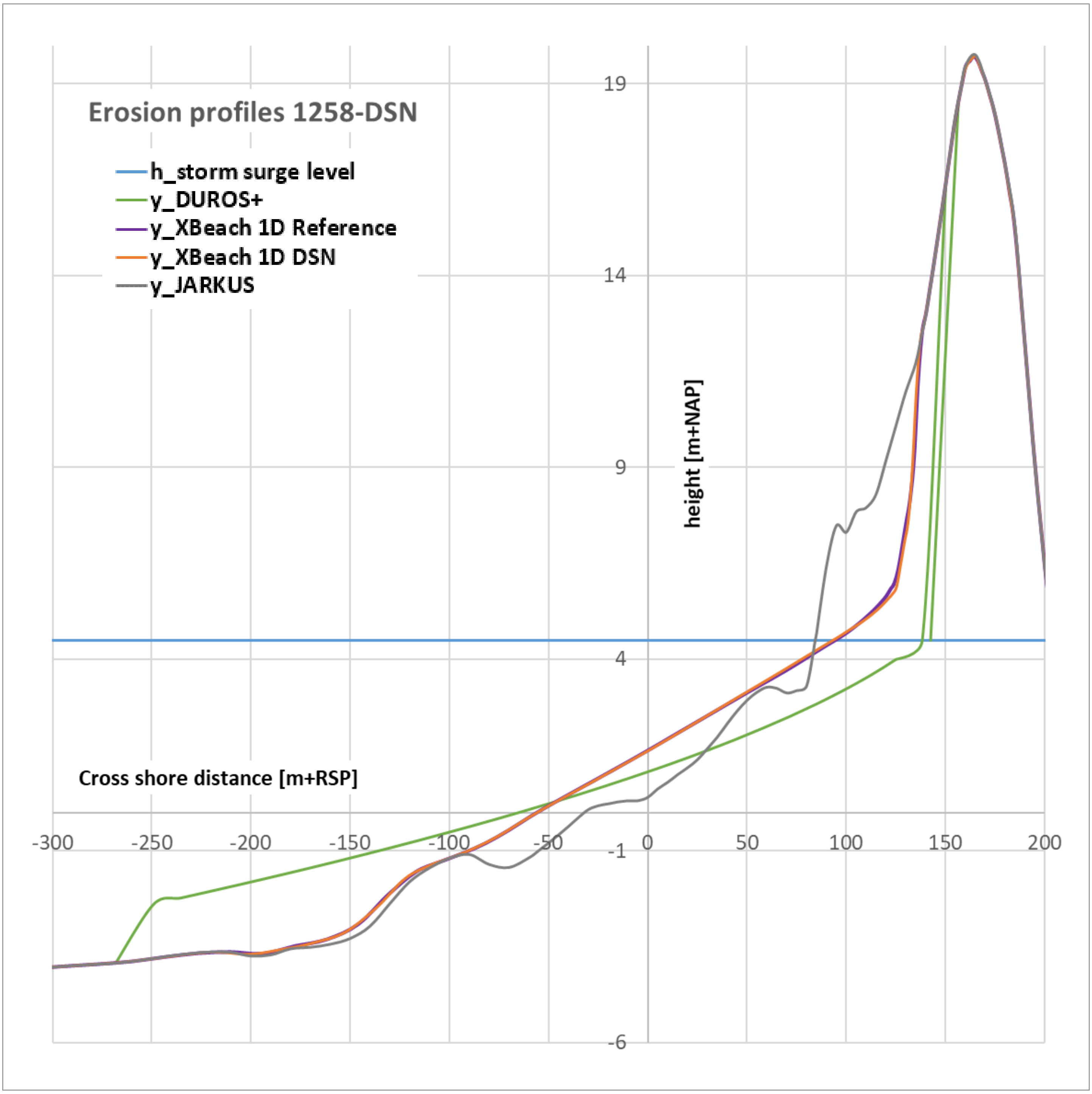
Erosion Profile DSN 1228



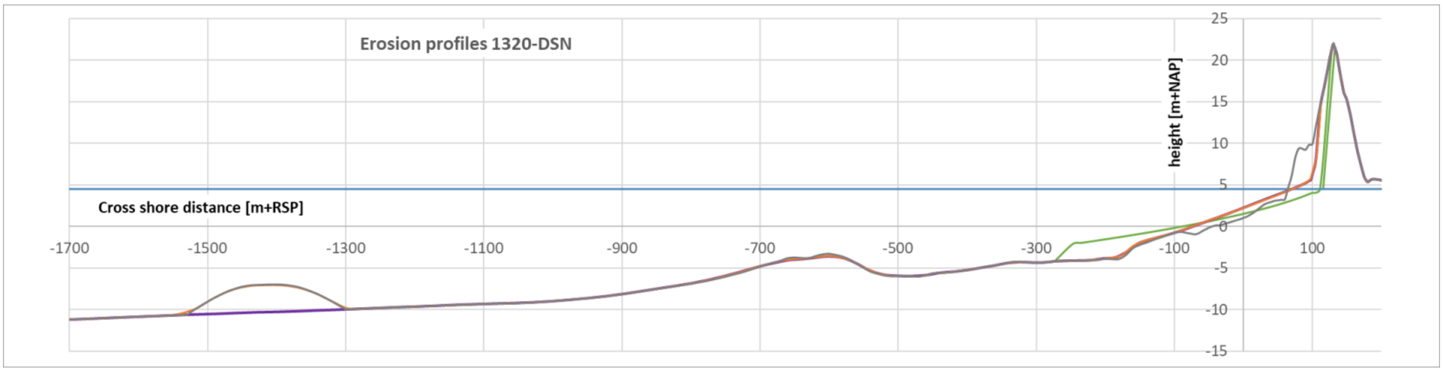


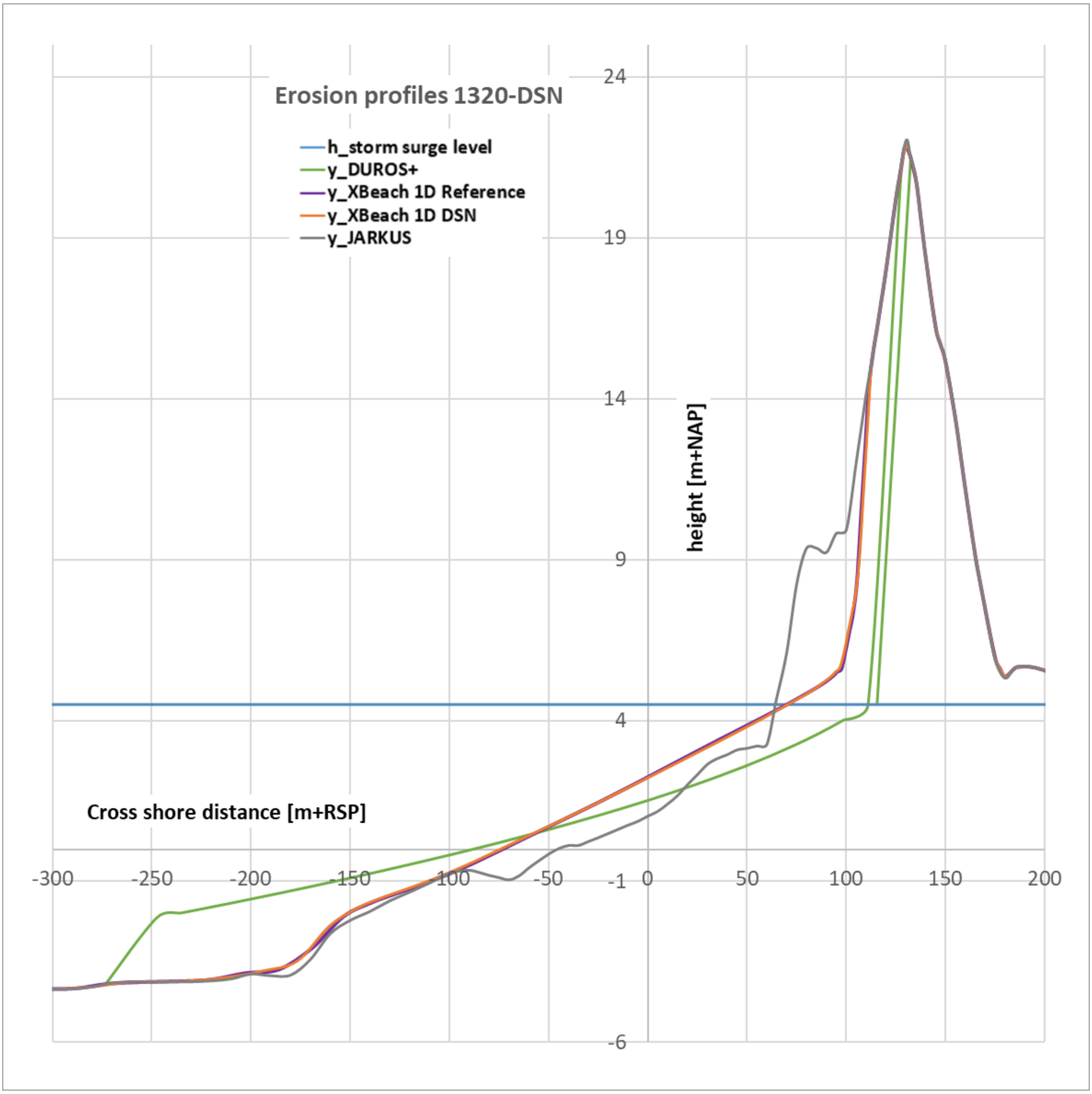
Erosion Profiles DSN 1258





Erosion profiles DSN 1320





DSN Extreme and Test

The results of the DSN compared to the reference are above. It seems that the DSN does not have significant influence on the erosion profiles. Therefore, two rather extreme scenarios are designed to test the influence of the model. The scenarios are called Test and Extreme. Both for transect 1320, in Table 8 the input for those scenarios are shown and visualized in Figure 32.

Table 8 Input MorphAn scenarios Extreme and Test

Scenario	Relative to	Location min x [m+RSP]	Location max x [m+RSP]	Volume [m^2]	Thickness [m]	Angle [m]
Test	Reference 1320	500	700	700	5,5	100
Extreme	Reference 1320	1300	1530	1500	9,53	100

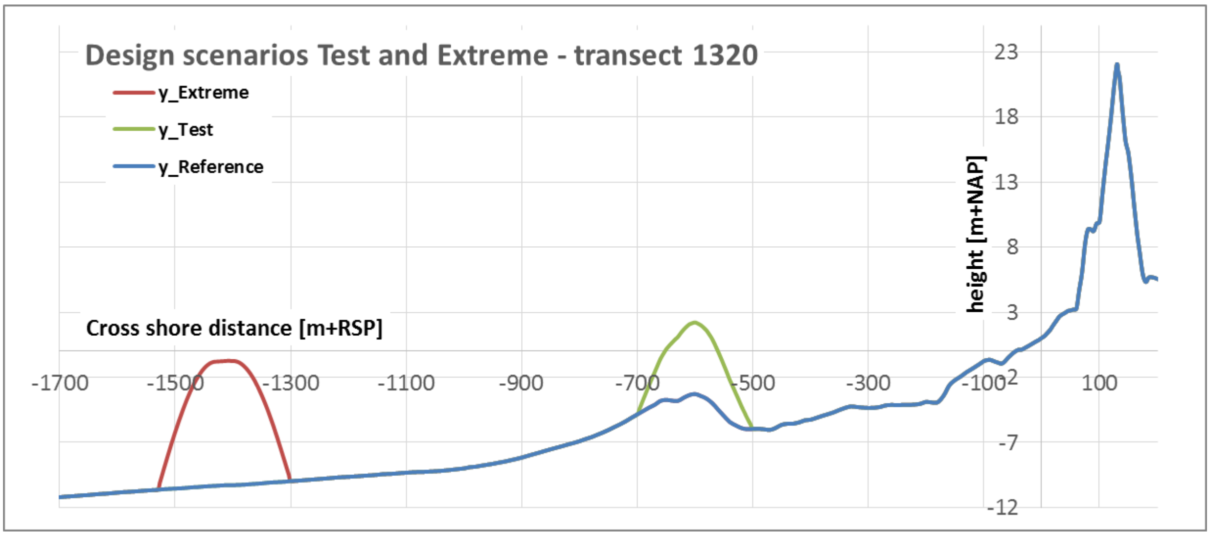
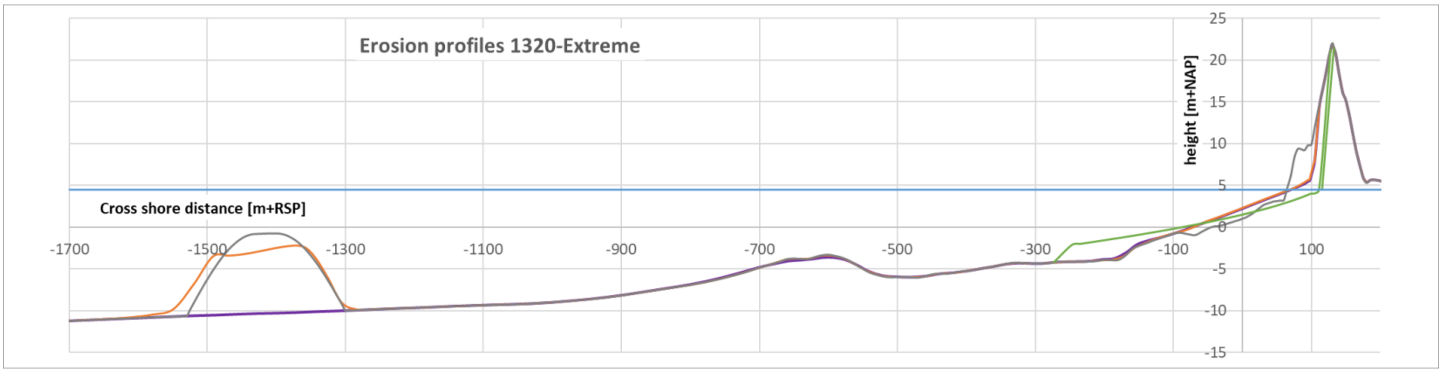
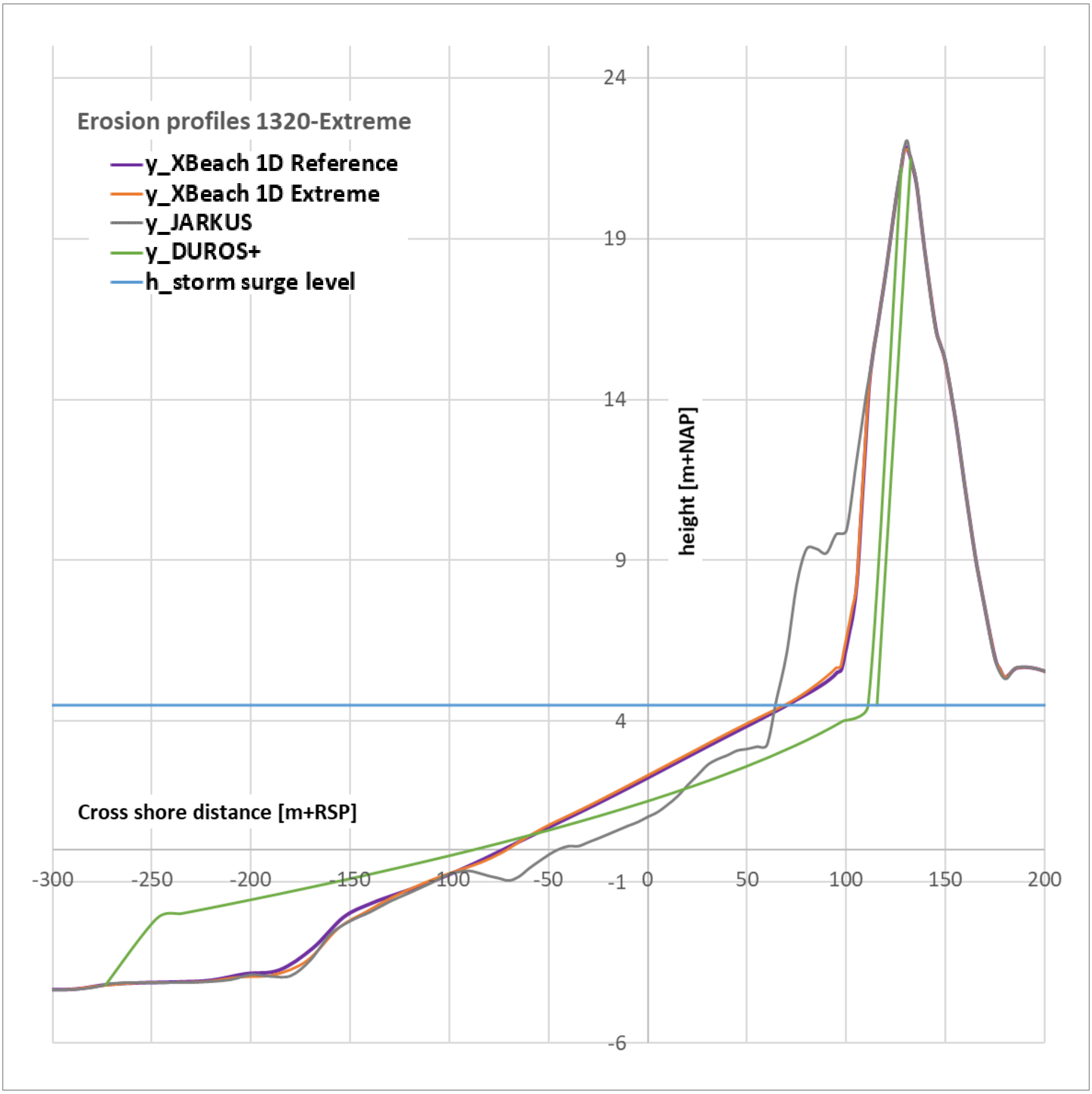


Figure 32 Visualization Test and Extreme

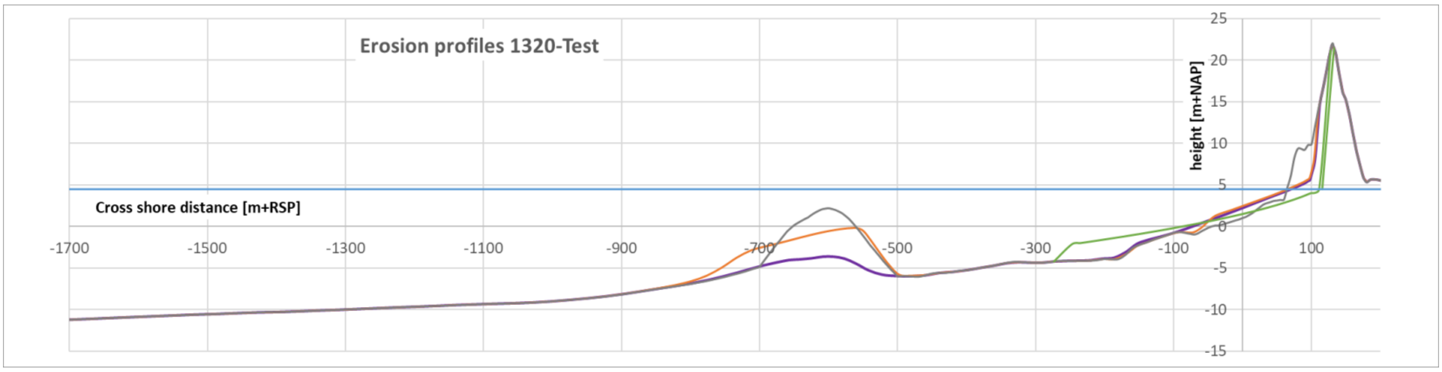
The results of those Test and Extreme are shown below. Again, shown is that those scenarios do not have significant influences. However, in the scenario Test, where the nourishment is located more landward, the erosion volume decreased a little.

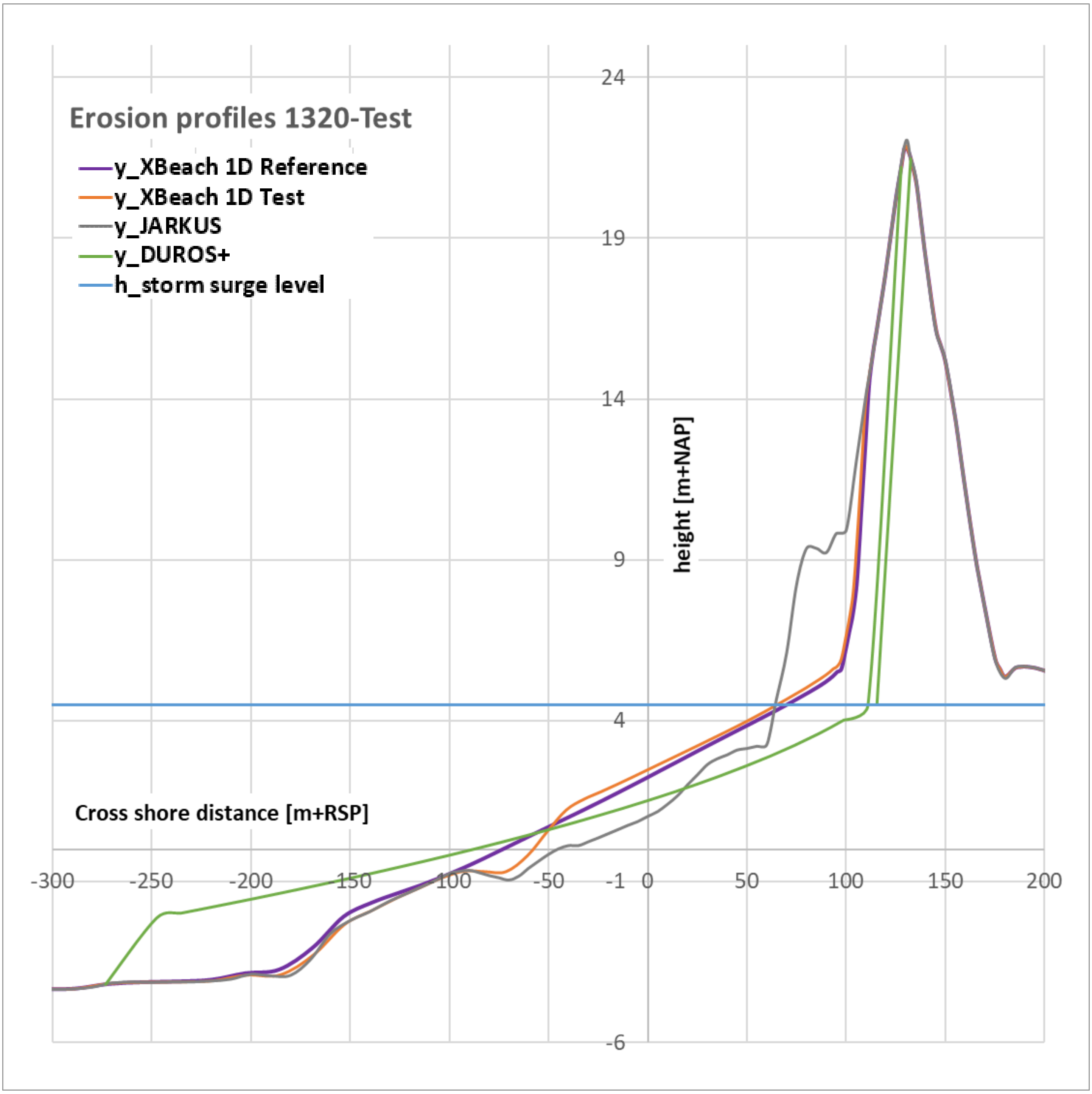
Erosion profile Extreme





Erosion profile Test





DSN Scenarios

So the size of the nourishment seems to have less influence than the location of the nourishment, based on the scenarios Test and Extreme. Therefore the decision is made to further evaluate the location of the nourishment. The nourishment is located more landward to test the influence on the dune erosion. See Figure 33 and Table 9. For the scenarios DSN3a, the erosion that seems to occur behind a nourishment imitated to determine what effects that might have. Because of the time, this is only done for scenario 3.

Table 9 MorphAn input DSN scenarios

Scenario	Relative to	Location min x [m+RSP]	Location max x [m+RSP]	Volume [m^2]	Thickness [m]	Angle [m]
DSN1	Reference 1320	1070	1300	518	3,29	100
DSN2	Reference 1320	840	1070	518	3,29	100
DSN3	Reference 1320	610	840	518	3,29	100
DSN3a	DSN3	510	610	-250	3,93	50

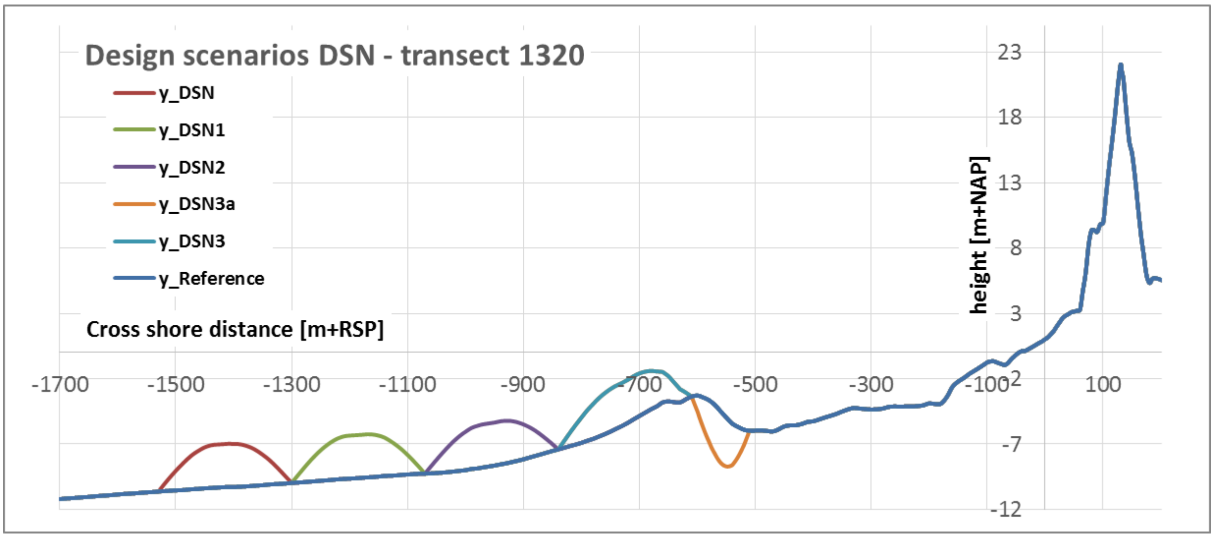
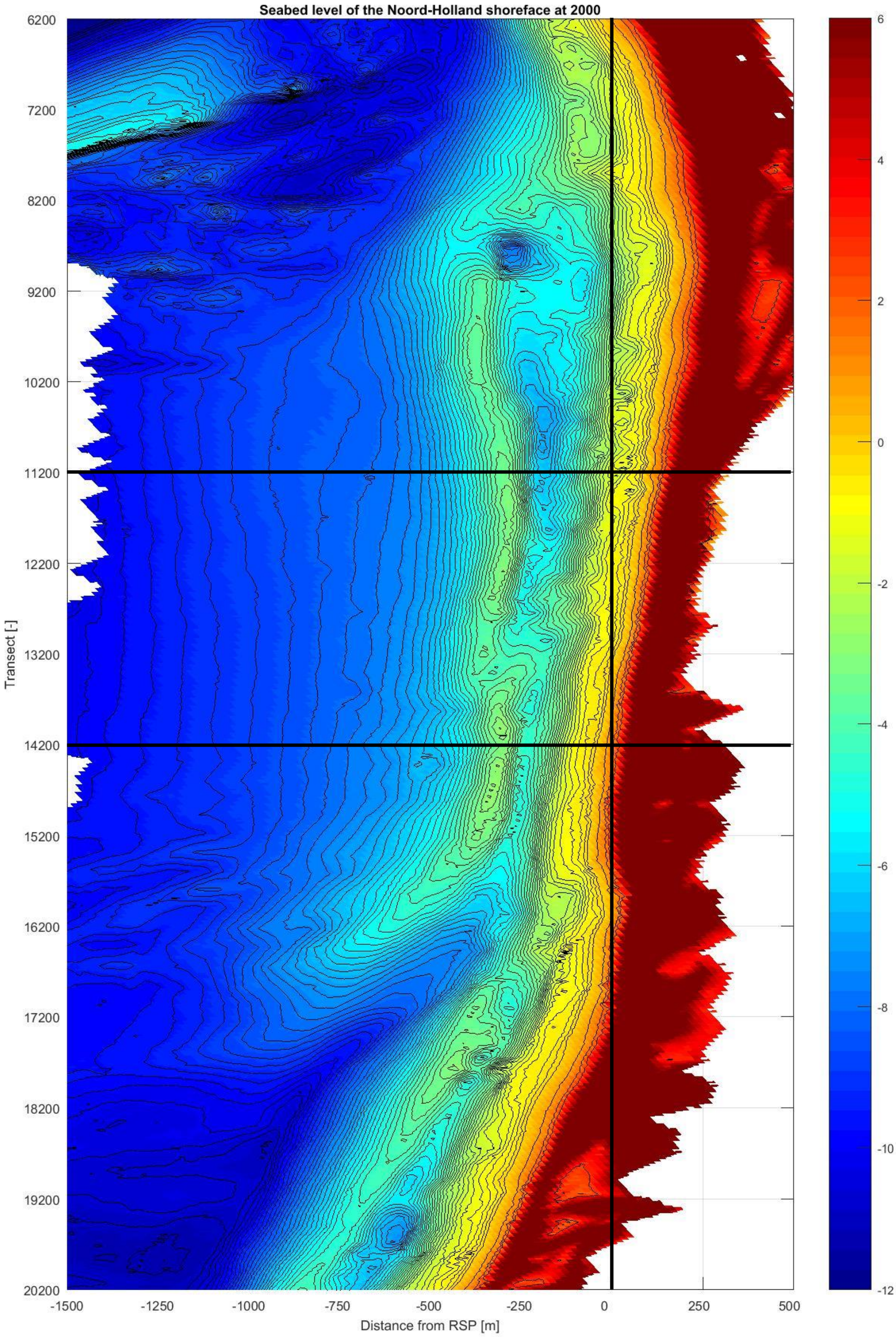
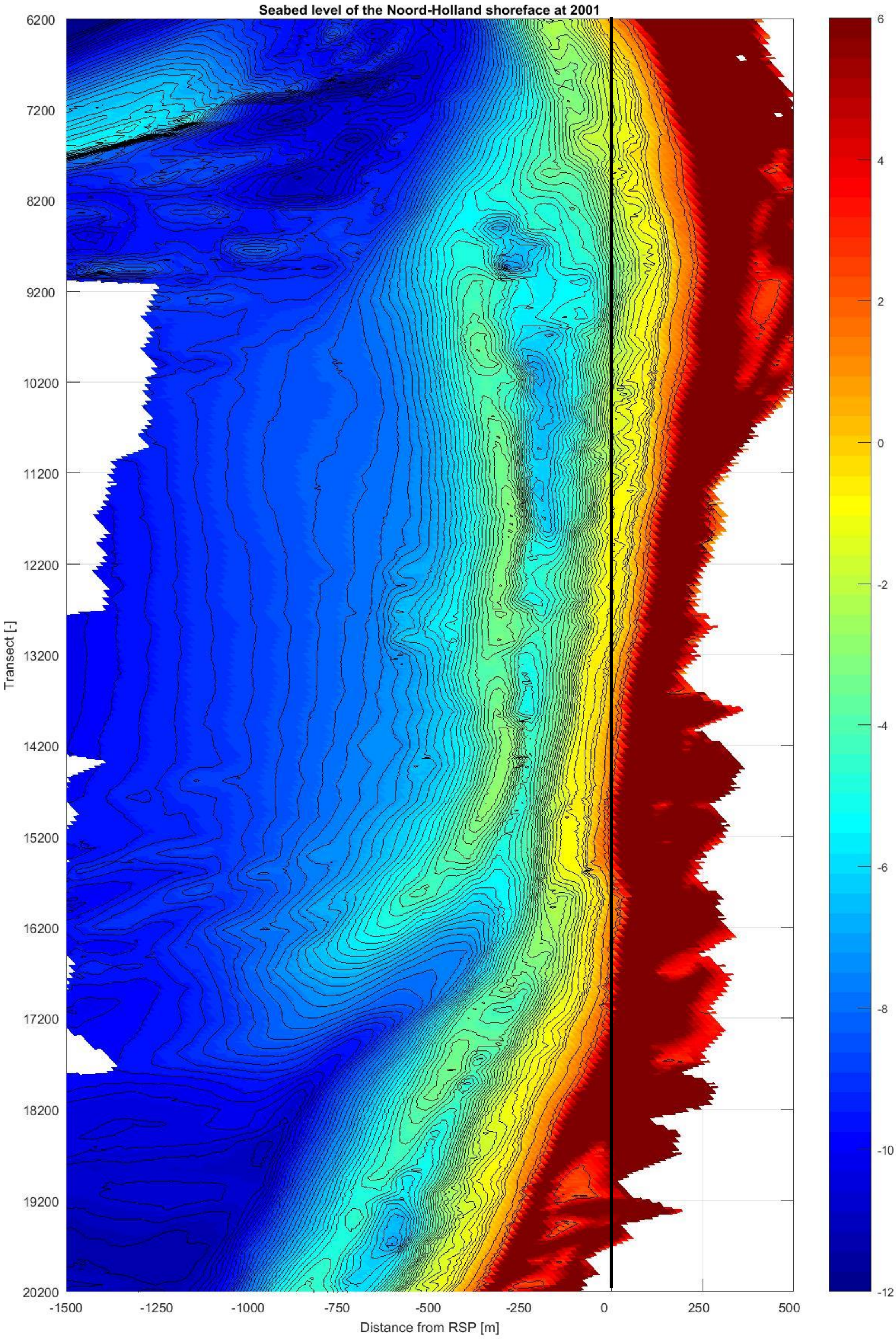
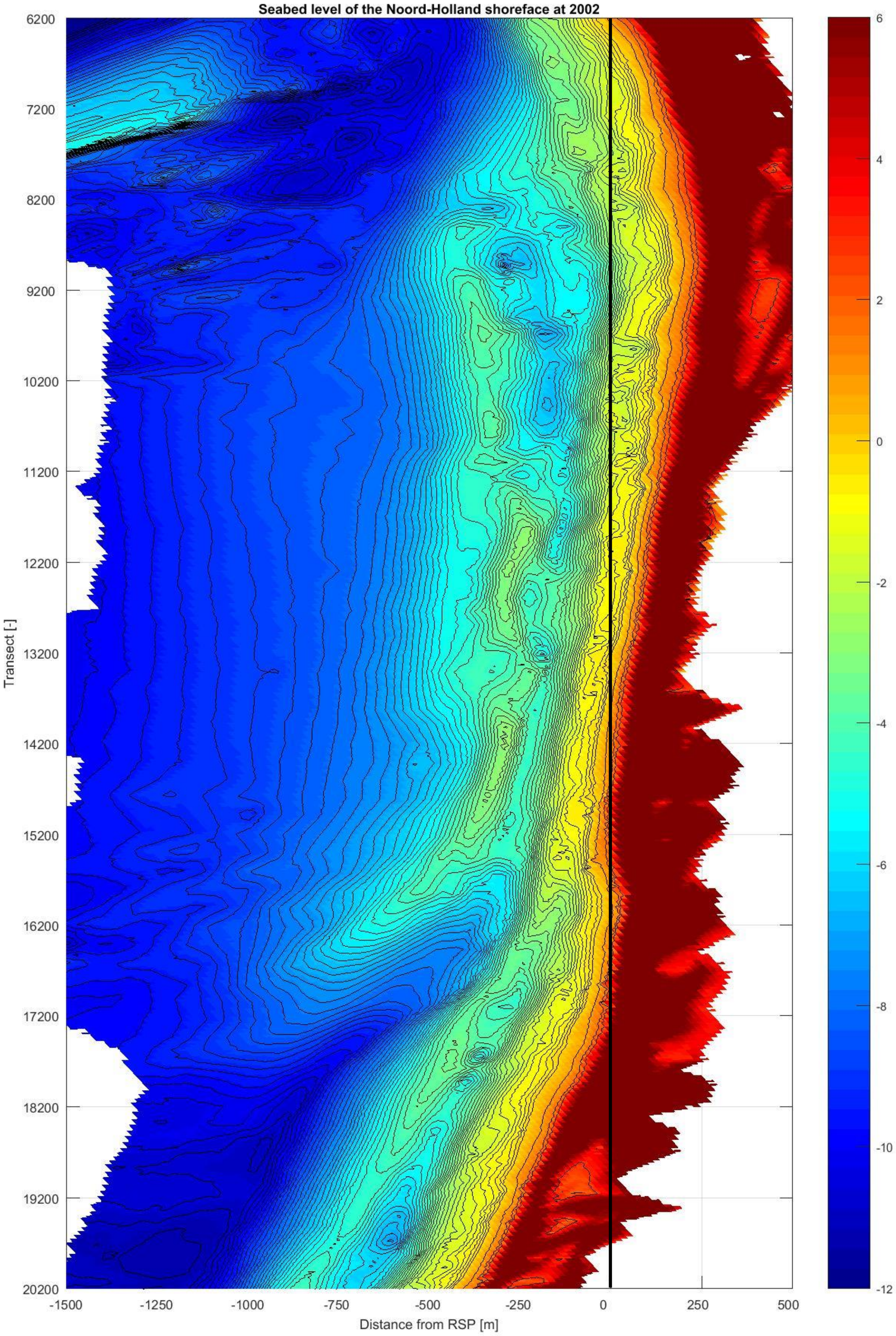


Figure 33 Visualization scenarios DSN

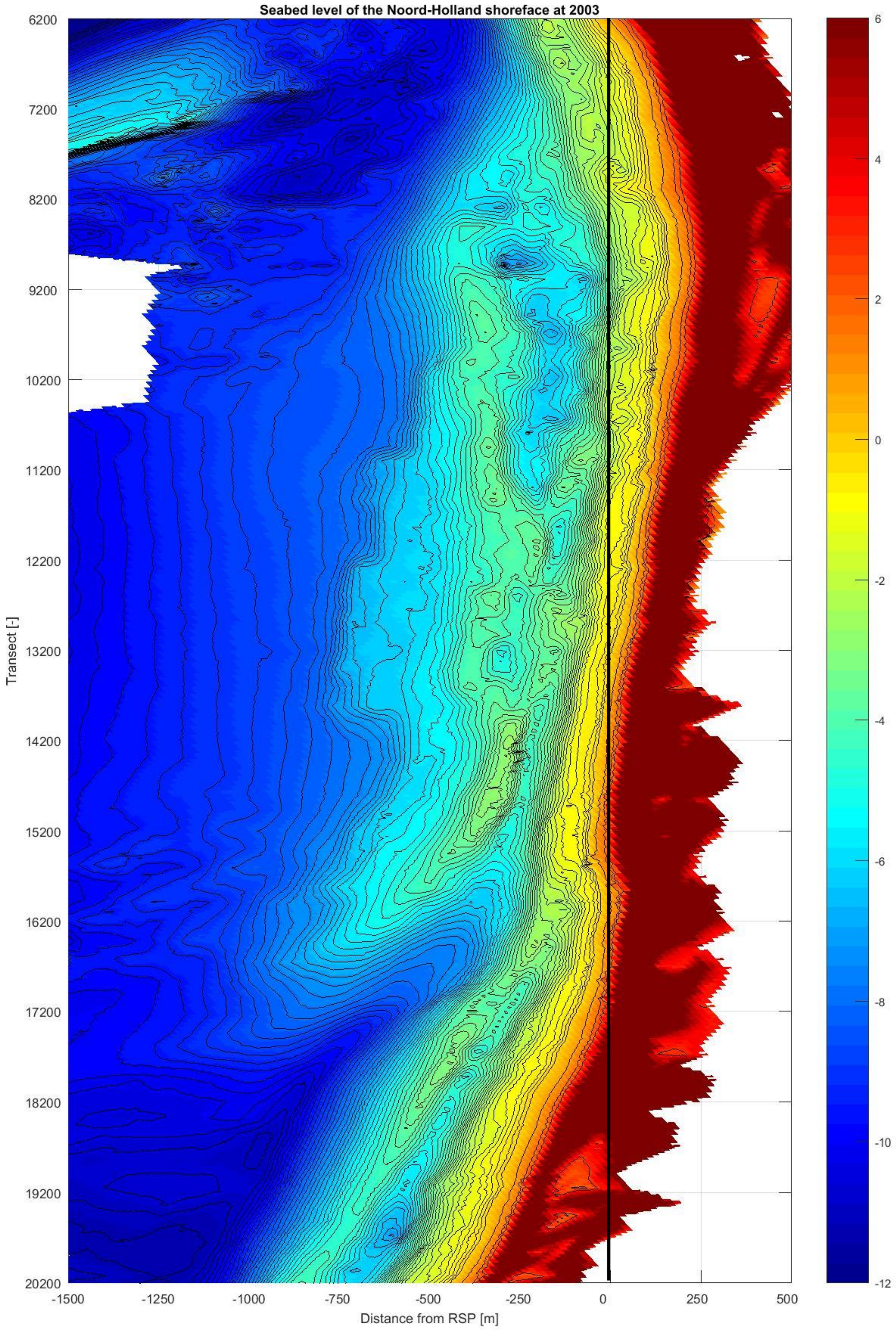
Appendix F. Soil maps 2000-2017

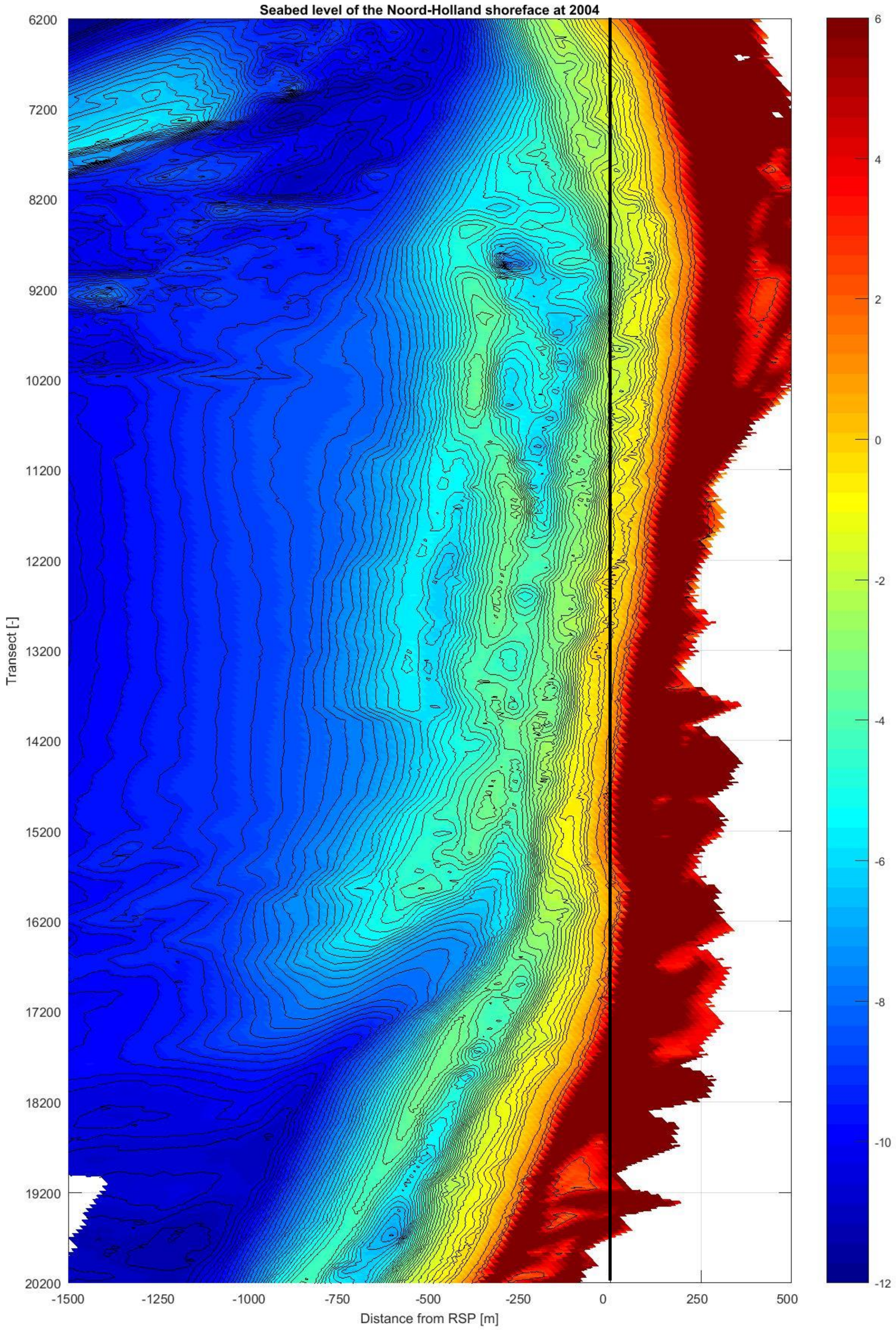



Seabed level of the Noord-Holland shoreface at 2001
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

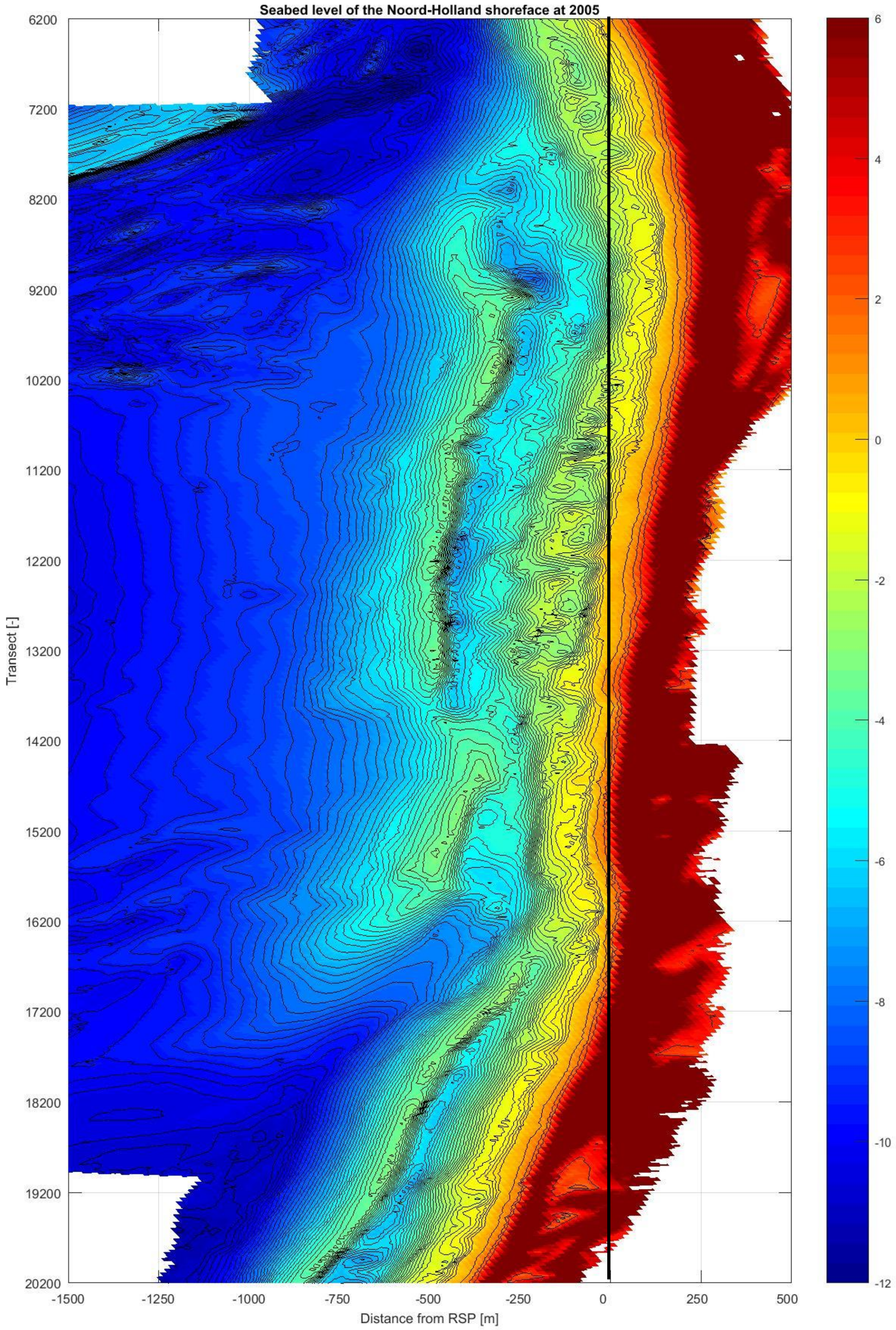


Seabed level of the Noord-Holland shoreface at 2002
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
Transect [-]
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12

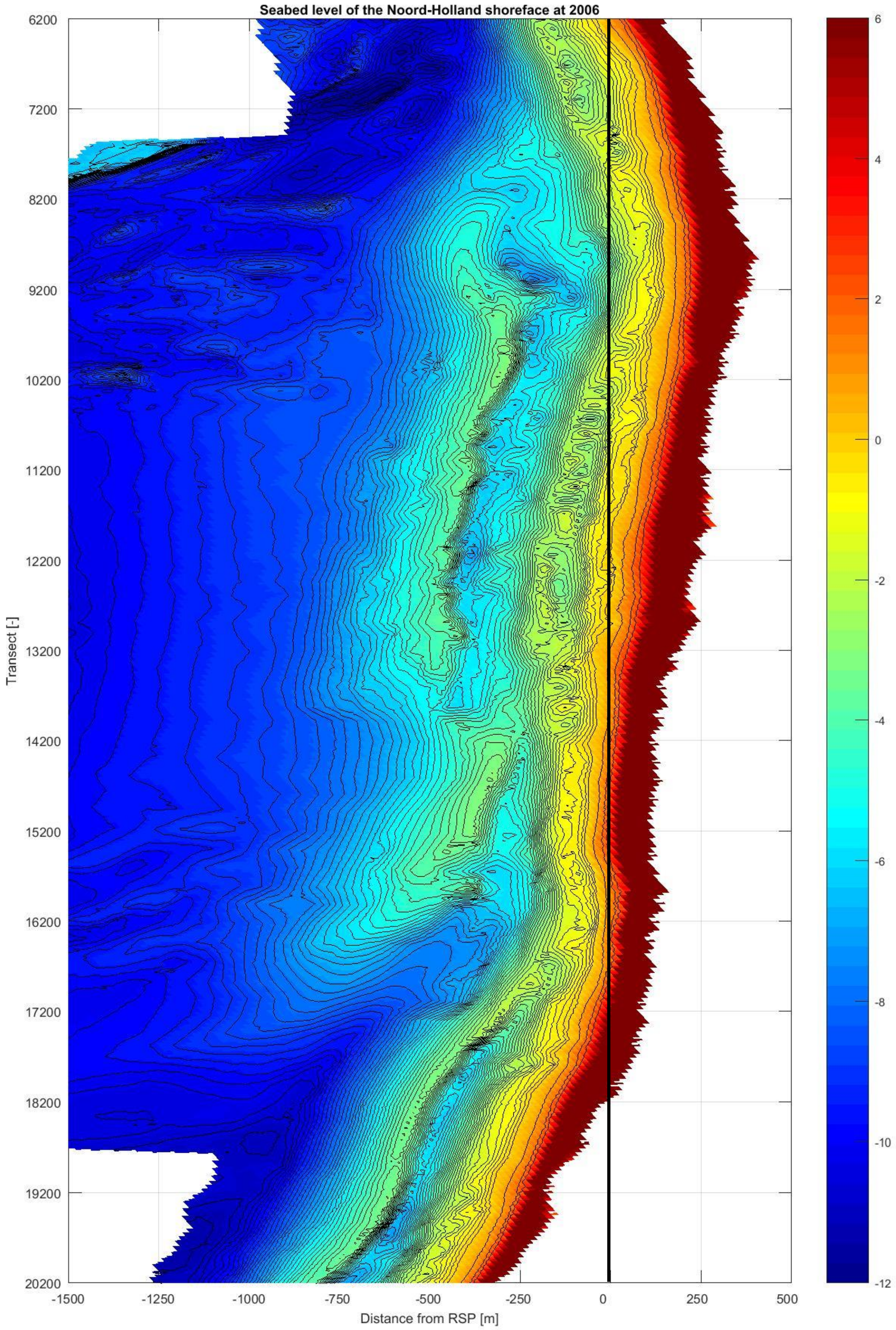

Seabed level of the Noord-Holland shoreface at 2003
Transect [-]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12



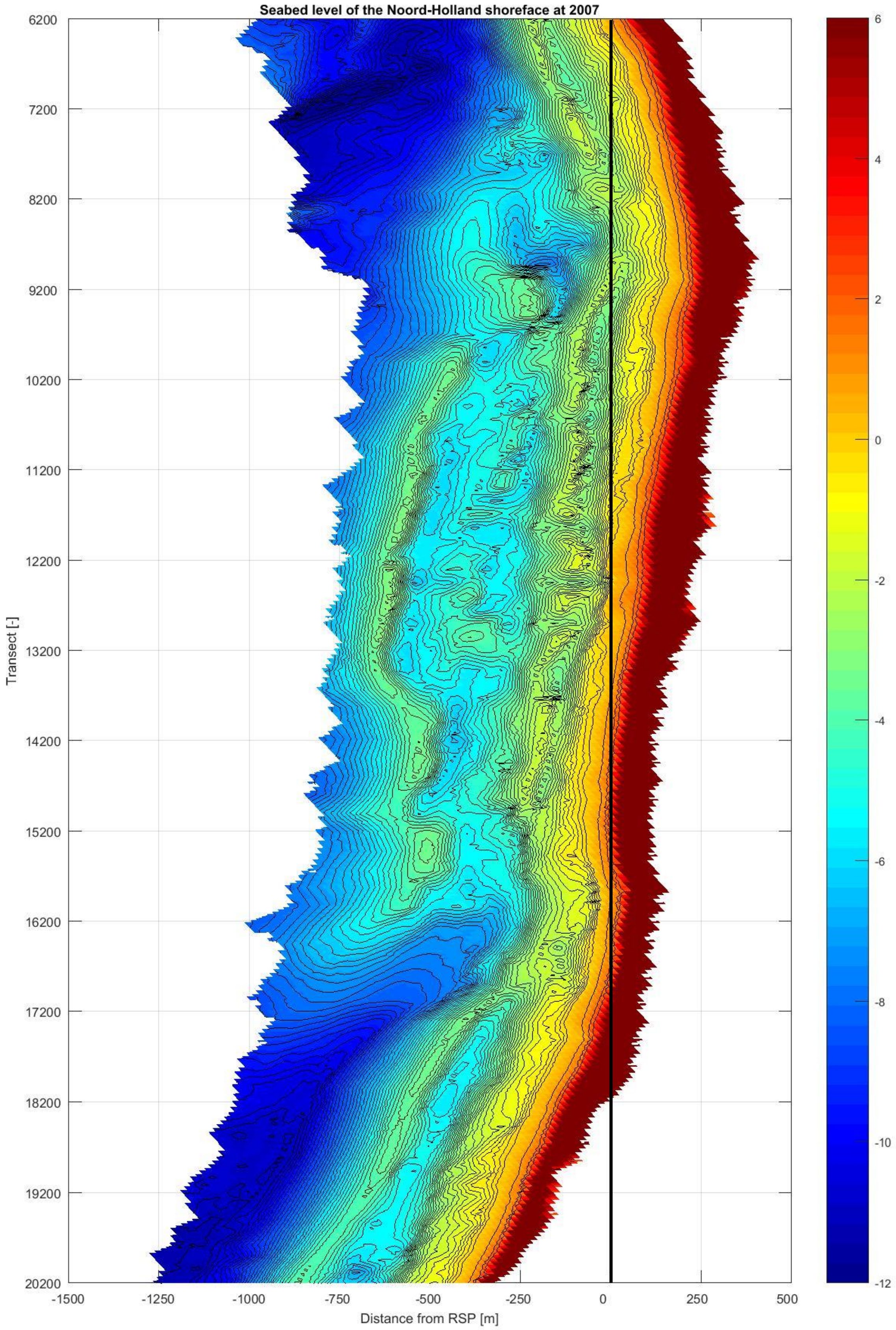
Seabed level of the Noord-Holland shoreface at 2004
Transect [-]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12

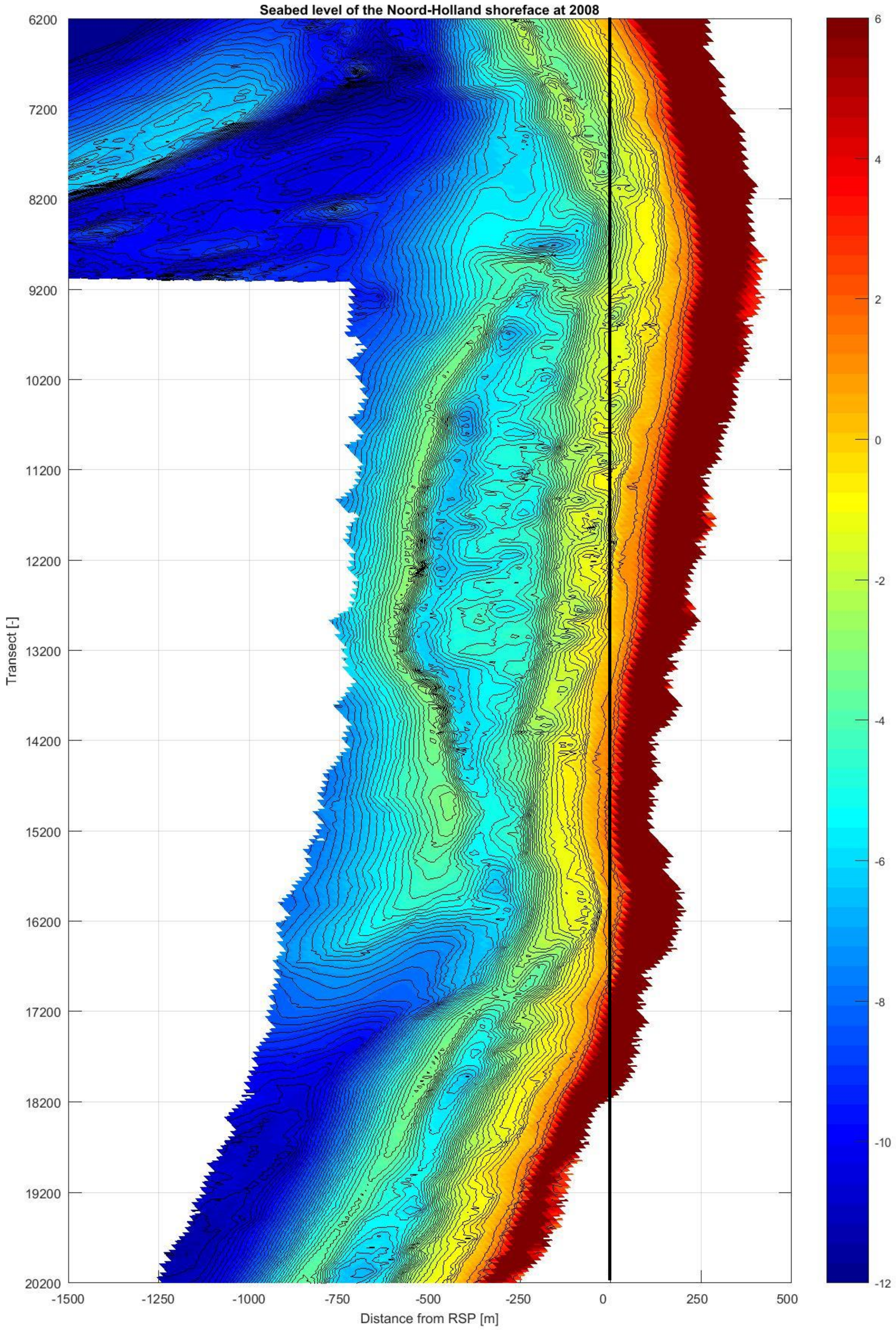


Seabed level of the Noord-Holland shoreface at 2005
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

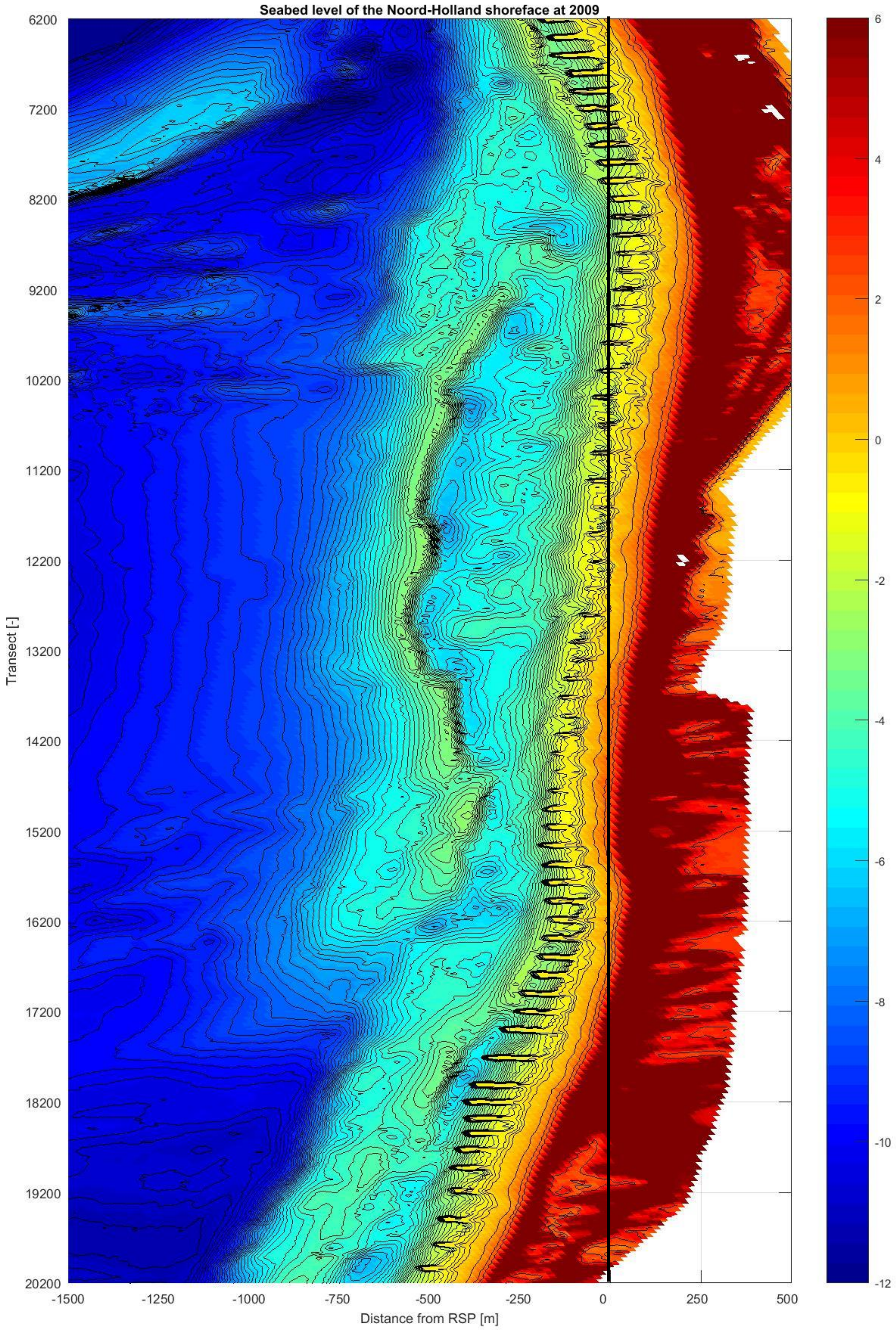


Seabed level of the Noord-Holland shoreface at 2006
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

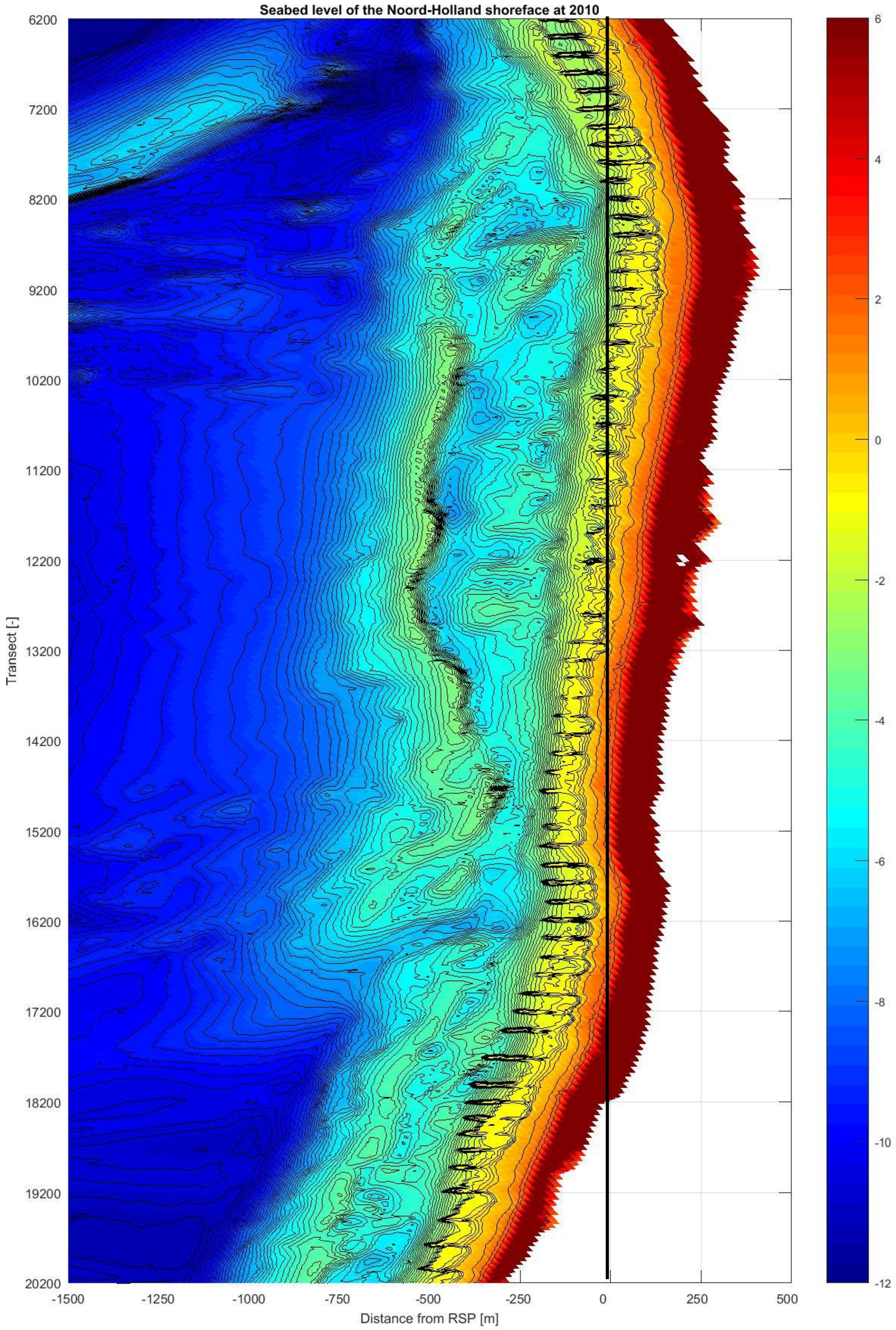

Seabed level of the Noord-Holland shoreface at 2007
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
Transect [-]
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12



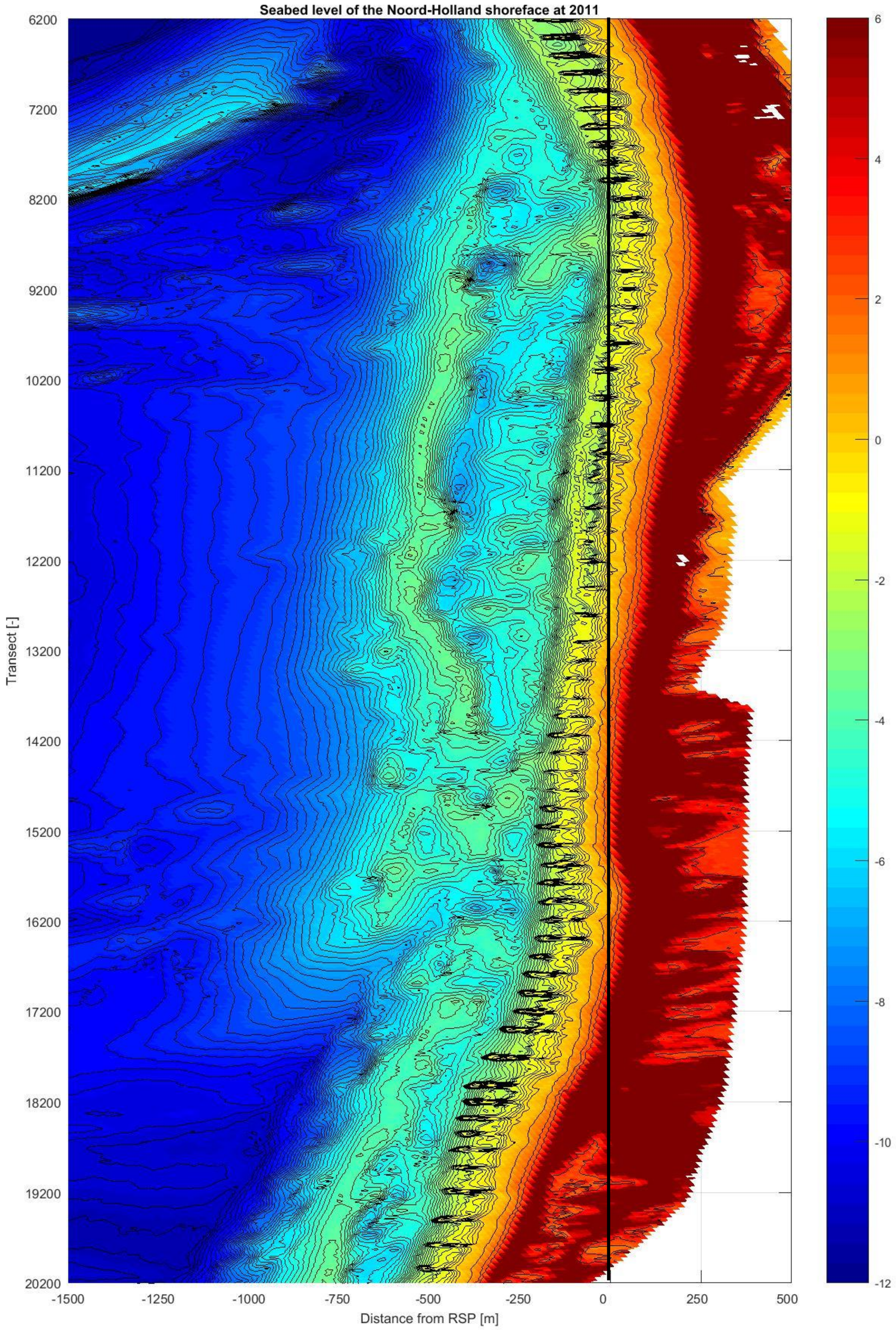
Seabed level of the Noord-Holland shoreface at 2008
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
Transect [-]
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12


Seabed level of the Noord-Holland shoreface at 2009
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

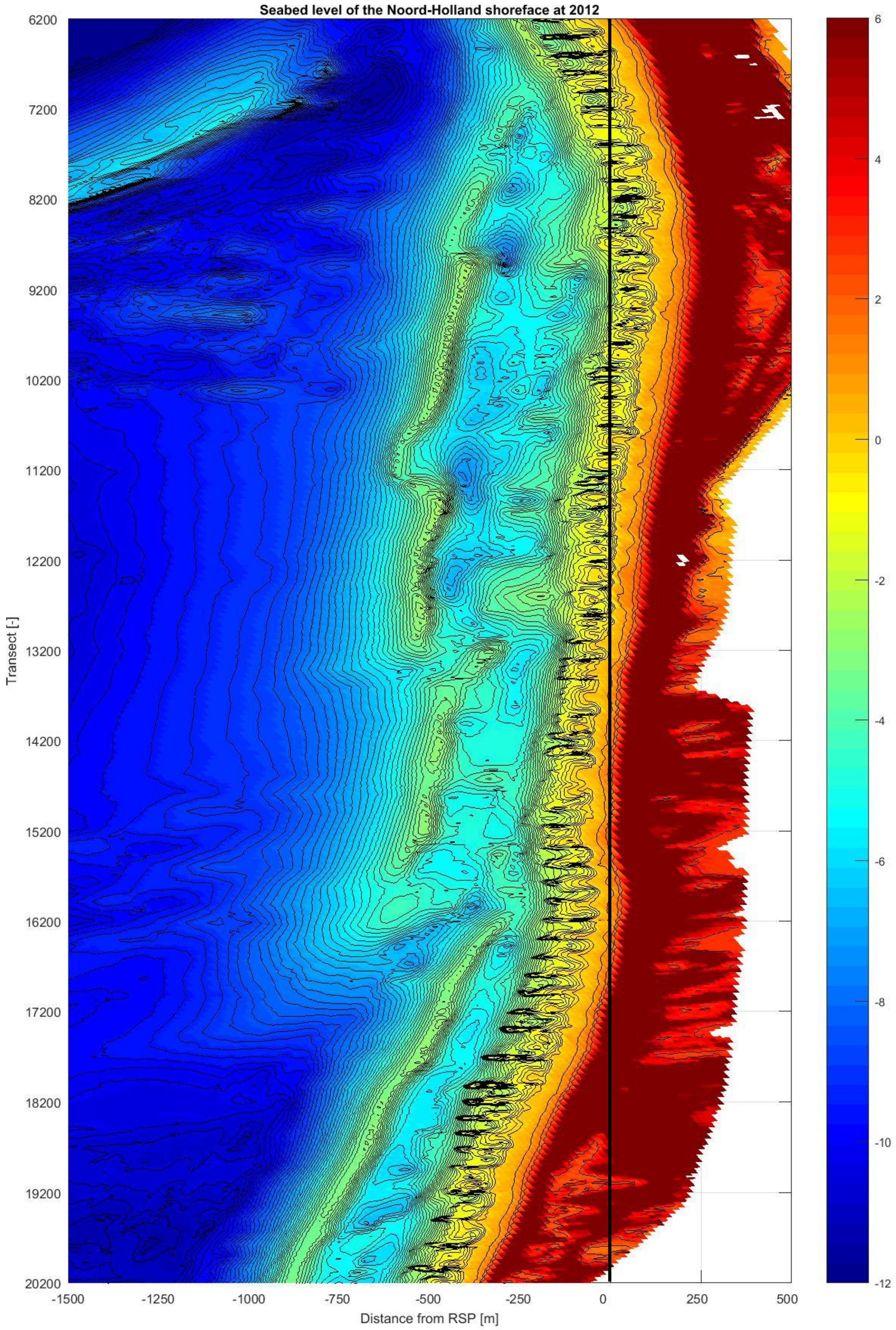
vv



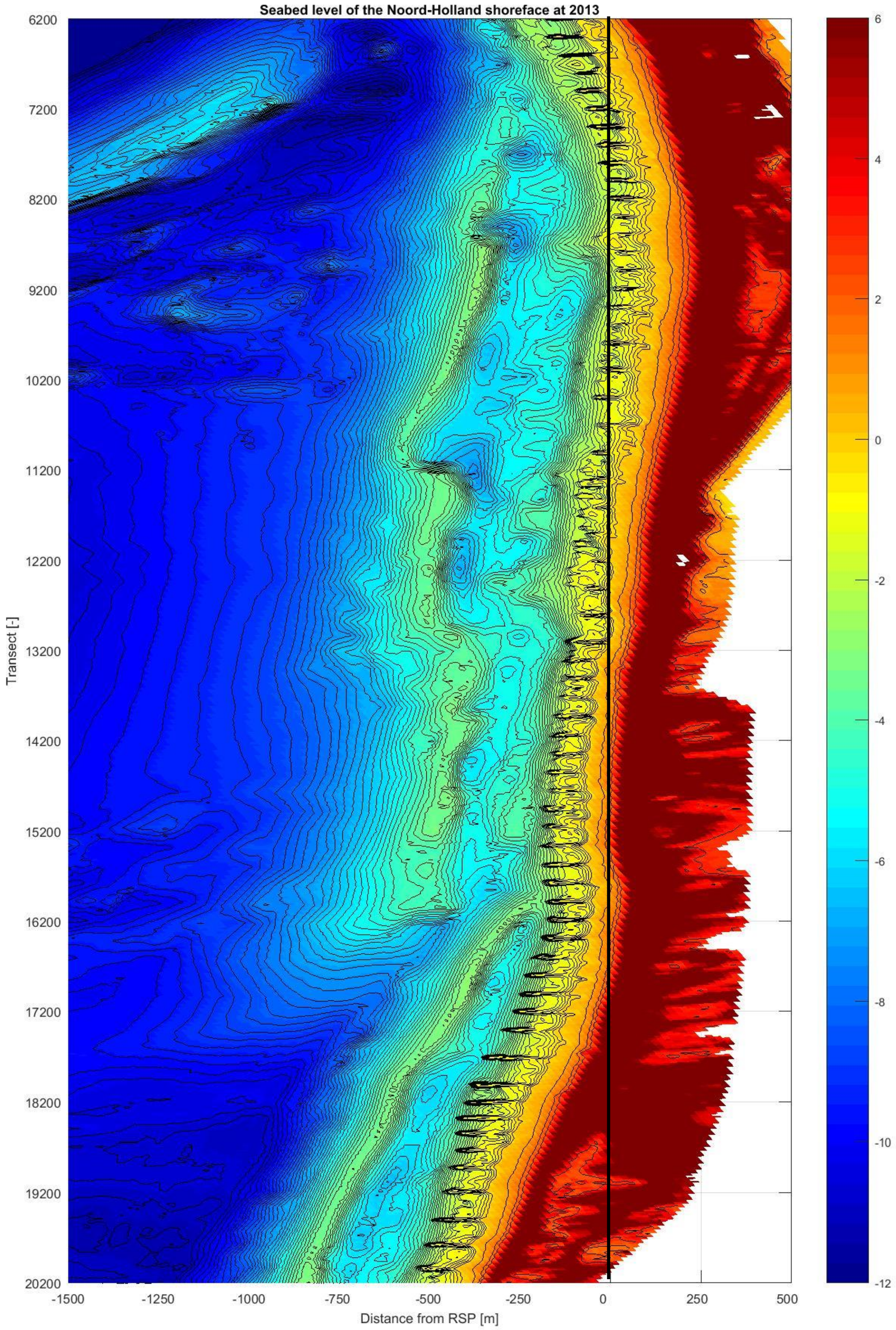
Seabed level of the Noord-Holland shoreface at 2010
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

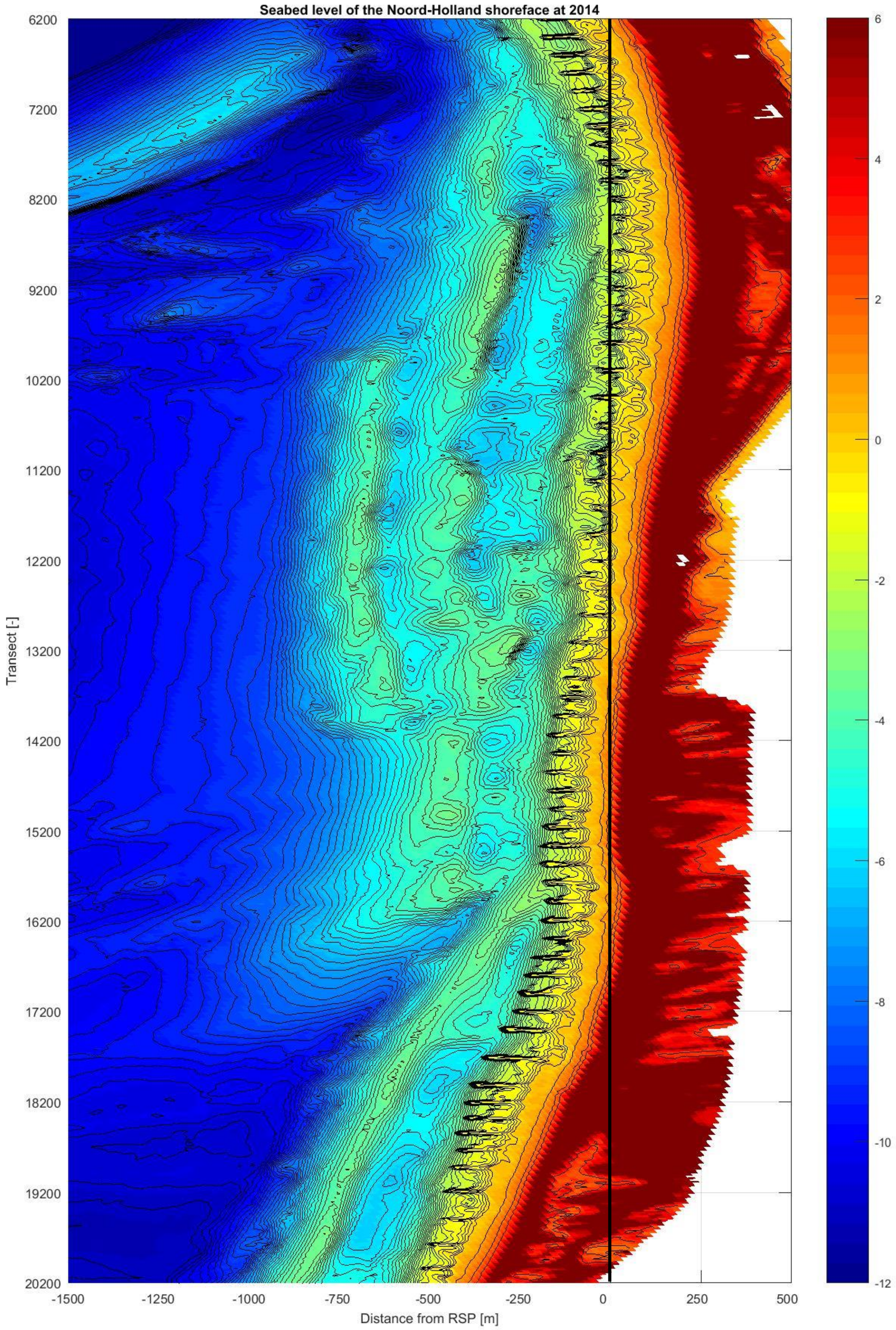


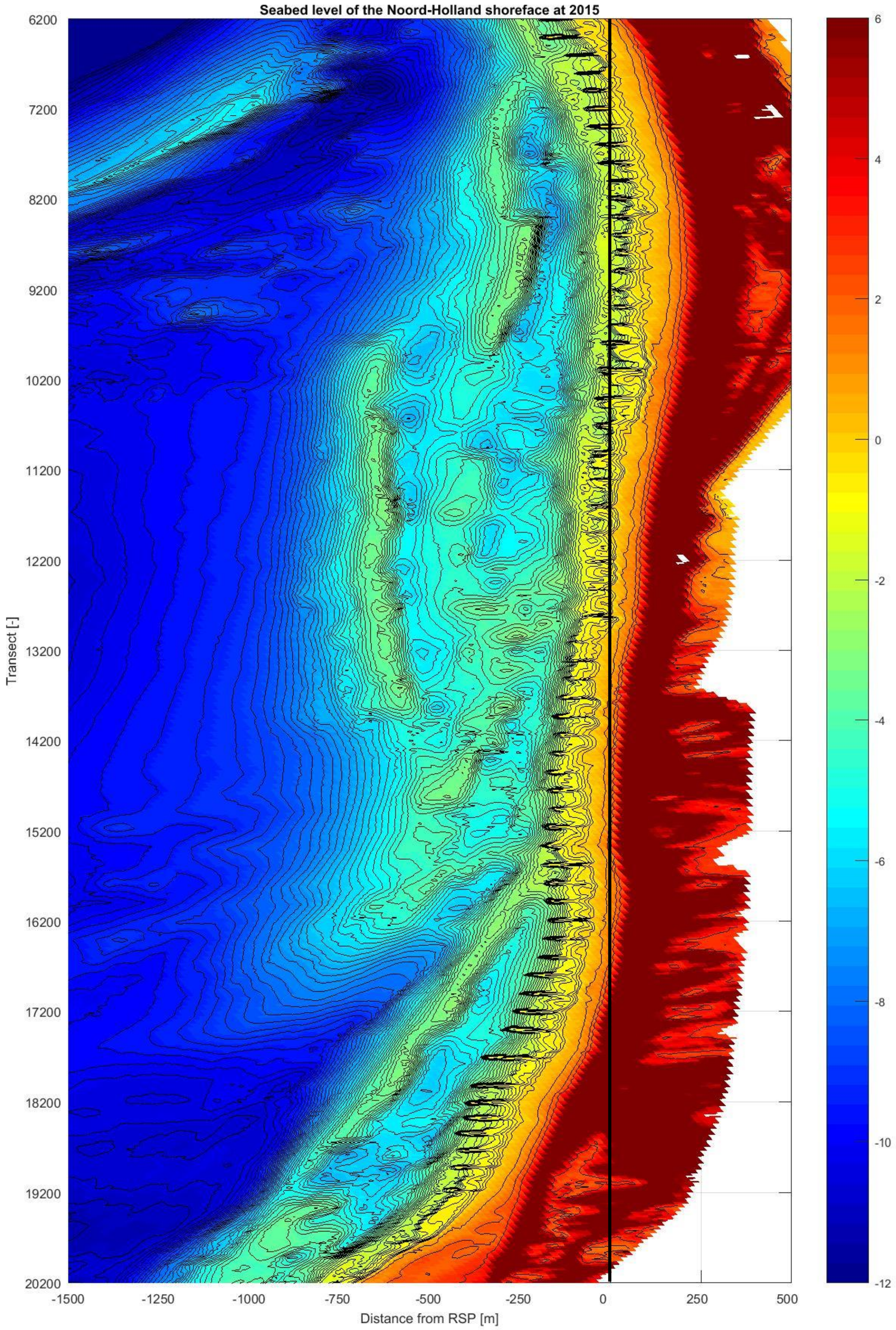
Seabed level of the Noord-Holland shoreface at 2011
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12



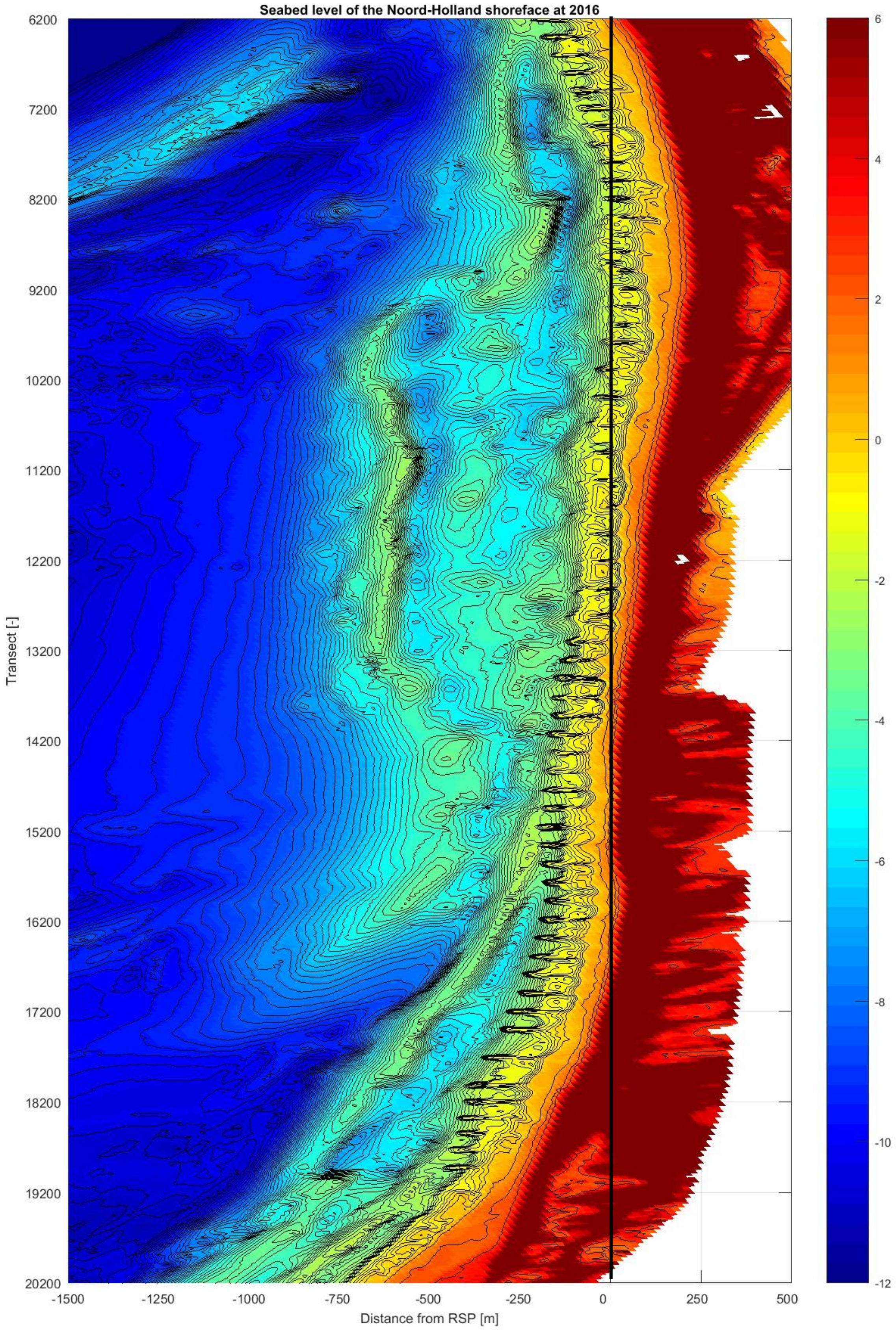
Seabed level of the Noord-Holland shoreface at 2012
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12


Seabed level of the Noord-Holland shoreface at 2013
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
Transect [-]
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12

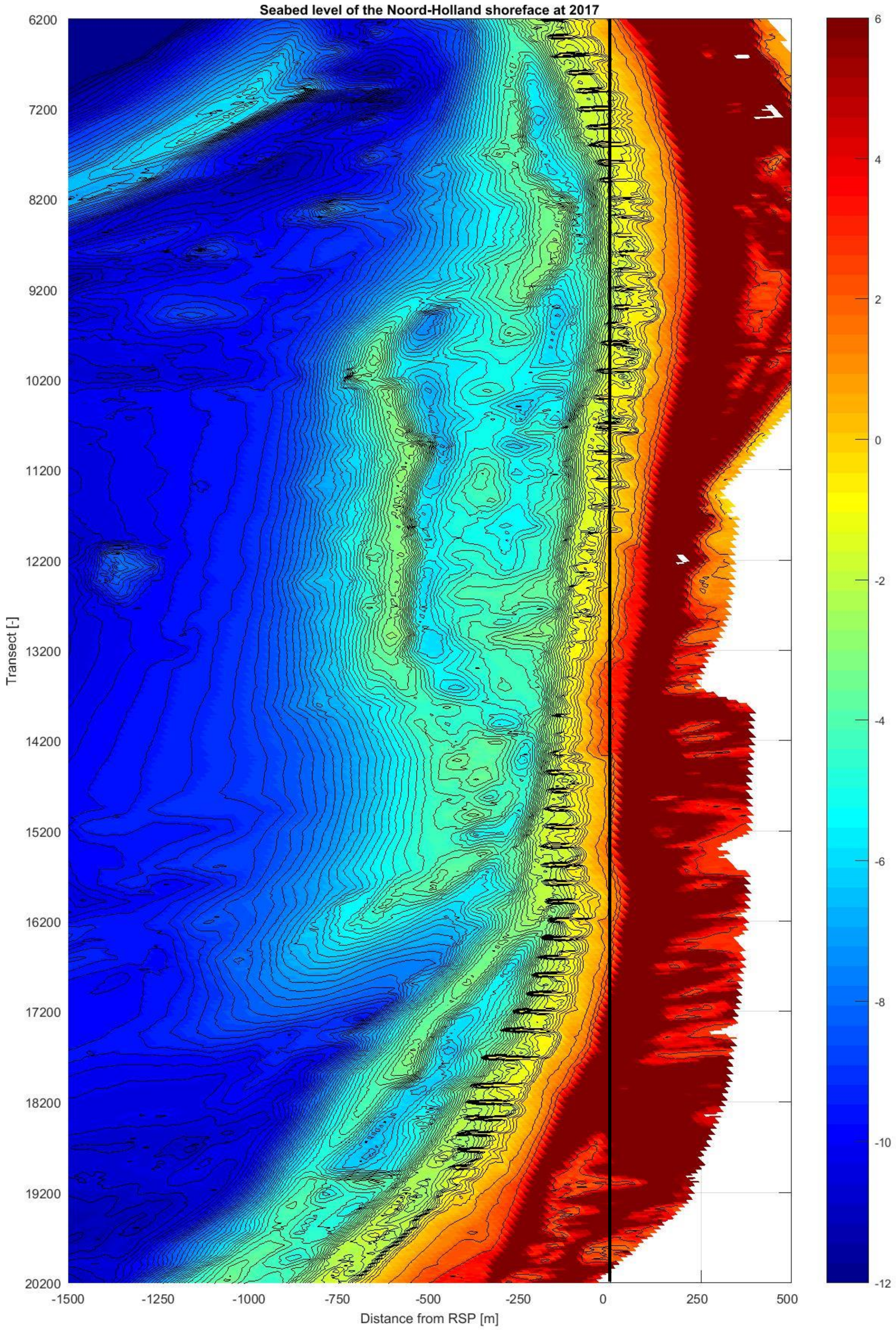

Seabed level of the Noord-Holland shoreface at 2014
Transect [-]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12



Seabed level of the Noord-Holland shoreface at 2015
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12



Seabed level of the Noord-Holland shoreface at 2016
Transect [-]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
Distance from RSP [m]
6
4
2
0
-2
-4
-6
-8
-10
-12



Seabed level of the Noord-Holland shoreface at 2017
Transect [-]
Distance from RSP [m]
6200
7200
8200
9200
10200
11200
12200
13200
14200
15200
16200
17200
18200
19200
20200
-1500
-1250
-1000
-750
-500
-250
0
250
500
6
4
2
0
-2
-4
-6
-8
-10
-12

Appendix G. Volume development

In this appendix all volumes of all the transects from 2000- 2017 are given.

Volume development [m³/m]

Transect	Date	TOTAL	SHOREFACE	BEACH	DUNE
1123	nov-00	12229	10178	1171	881
	mrt-01	12219	10243	1109	867
	mrt-02	12485	10449	1169	867
	mrt-03	13056	10998	1159	899
	mrt-04	13125	10997	1238	890
	apr-05	13295	11095	1304	896
	mei-06	13160	10907	1318	935
	apr-07	13383	11109	1299	976
	apr-08	13280	10916	1372	992
	mrt-09	13290	10965	1314	1010
	apr-10	13239	10837	1363	1039
	jan-11	13121	10694	1365	1063
	jan-12	13009	10639	1282	1089
	jan-13	13243	10762	1374	1107
	jan-14	13729	11228	1370	1131
	mrt-15	13575	11069	1361	1145
	jan-16	13627	11072	1393	1162
	jan-17	13567	10970	1418	1179
1137	nov-00	12244	10185	1069	990
	mrt-01	12220	10183	1069	968
	mrt-02	12619	10590	1060	968
	mrt-03	13065	10985	1080	1001
	mrt-04	13232	11083	1165	985
	apr-05	13117	10907	1229	980
	mei-06	13186	10909	1265	1012
	apr-07	13481	11125	1301	1055
	apr-08	13401	10993	1333	1075
	mrt-09	13317	10927	1295	1095
	apr-10	13247	10835	1296	1116
	jan-11	13116	10681	1291	1145
	jan-12	13236	10833	1239	1165
	jan-13	13283	10797	1296	1191
	jan-14	13803	11281	1313	1209
	mrt-15	13609	11031	1346	1231
	jan-16	13695	11151	1290	1254
	jan-17	13634	11069	1303	1262
1152	nov-00	12513	10156	1138	1220
	mrt-01	12533	10195	1131	1206
	mrt-02	12913	10623	1084	1206
	mrt-03	13448	11136	1087	1225
	mrt-04	13433	10990	1226	1217

	apr-05	13396	10938	1244	1215
	mei-06	13329	10833	1262	1234
	apr-07	13604	11077	1259	1268
	apr-08	13471	10931	1249	1291
	mrt-09	13531	10879	1343	1309
	apr-10	13401	10799	1290	1313
	jan-11	13410	10765	1310	1335
	jan-12	13522	10797	1370	1356
	jan-13	13527	10807	1338	1381
	jan-14	14056	11335	1336	1385
	mrt-15	13899	11198	1300	1402
	jan-16	13963	11204	1331	1428
	jan-17	13897	11144	1306	1448
1167	nov-00	12538	10133	1171	1234
	mrt-01	12589	10125	1234	1229
	mrt-02	13094	10633	1232	1229
	mrt-03	13451	10967	1237	1248
	mrt-04	13536	10975	1312	1249
	apr-05	13574	11016	1314	1244
	mei-06	13565	10918	1385	1262
	apr-07	13894	11209	1383	1302
	apr-08	13742	11031	1386	1325
	mrt-09	13613	10901	1367	1345
	apr-10	13780	10993	1426	1361
	jan-11	13665	10898	1387	1380
	jan-12	13759	11013	1333	1413
	jan-13	13787	10993	1363	1431
	jan-14	14049	11256	1347	1446
	mrt-15	14072	11238	1380	1455
	jan-16	13946	11112	1367	1467
	jan-17	13883	11027	1388	1467
1182	nov-00	12876	10118	1256	1501
	mrt-01	13072	10245	1329	1498
	mrt-02	13343	10567	1278	1498
	mrt-03	13748	10963	1266	1520
	mrt-04	13769	10910	1339	1521
	apr-05	13954	11028	1412	1514
	mei-06	13938	10909	1481	1549
	apr-07	13982	11025	1379	1579
	apr-08	14027	10998	1434	1595
	mrt-09	13999	10973	1417	1609
	apr-10	14163	11155	1387	1620
	jan-11	14225	11121	1462	1643
	jan-12	14117	10944	1509	1664
	jan-13	14068	10945	1443	1681
	jan-14	14247	11203	1355	1690

	mrt-15	14233	11121	1419	1694
	jan-16	14193	11033	1454	1705
	jan-17	14172	11015	1441	1716
1197	nov-00	12397	10164	1196	1037
	mrt-01	12439	10209	1198	1032
	mrt-02	12894	10654	1208	1032
	mrt-03	13145	10892	1205	1047
	mrt-04	13266	10965	1242	1059
	apr-05	13250	10861	1329	1061
	mei-06	13362	10859	1411	1092
	apr-07	13535	11076	1326	1132
	apr-08	13556	11098	1297	1162
	mrt-09	13654	11056	1404	1194
	apr-10	13557	10956	1382	1219
	jan-11	13642	11012	1387	1242
	jan-12	13397	10837	1291	1268
	jan-13	13381	10765	1334	1283
	jan-14	13873	11229	1343	1301
	mrt-15	13788	11109	1370	1309
	jan-16	13743	11110	1292	1340
	jan-17	13849	11102	1393	1354
1213	nov-00	13116	10245	1276	1595
	mrt-01	13234	10318	1324	1591
	mrt-02	13512	10624	1297	1591
	mrt-03	13918	11005	1300	1613
	mrt-04	13984	11024	1348	1611
	apr-05	14200	11048	1540	1613
	mei-06	14130	11007	1477	1647
	apr-07	14156	11026	1457	1674
	apr-08	14217	11065	1451	1700
	mrt-09	14386	11170	1486	1730
	apr-10	14186	11015	1424	1747
	jan-11	14295	11092	1431	1771
	jan-12	13889	10658	1431	1799
	jan-13	13989	10721	1449	1819
	jan-14	14602	11357	1407	1838
	mrt-15	14463	11167	1447	1849
	jan-16	14254	10977	1415	1862
	jan-17	14901	11465	1564	1872
1228	nov-00	12674	10287	1269	1119
	mrt-01	12881	10528	1256	1098
	mrt-02	13035	10698	1239	1098
	mrt-03	13417	11105	1198	1114
	mrt-04	13556	11124	1302	1130
	apr-05	13521	10978	1402	1141
	mei-06	13600	10967	1456	1177

	apr-07	13852	11221	1423	1208
	apr-08	13676	11027	1417	1232
	mrt-09	13777	11138	1392	1247
	apr-10	13712	11053	1391	1268
	jan-11	13737	11046	1397	1294
	jan-12	13695	10914	1458	1324
	jan-13	13585	10817	1419	1349
	jan-14	14091	11307	1416	1368
	mrt-15	13983	11210	1392	1380
	jan-16	13924	11131	1391	1402
	jan-17	14465	11556	1498	1411
1243	nov-00	12534	10302	1285	946
	mrt-01	12680	10473	1276	931
	mrt-02	12854	10661	1262	931
	mrt-03	13306	11110	1255	940
	mrt-04	13517	11174	1385	958
	apr-05	13485	11056	1467	962
	mei-06	13393	10995	1407	991
	apr-07	13415	11074	1327	1014
	apr-08	13552	11128	1400	1024
	mrt-09	13574	11128	1409	1037
	apr-10	13375	10890	1438	1047
	jan-11	13437	10960	1410	1067
	jan-12	13575	11025	1461	1089
	jan-13	13524	10984	1439	1101
	jan-14	13838	11333	1397	1109
	mrt-15	13828	11323	1398	1108
	jan-16	13829	11354	1356	1119
	jan-17	14207	11637	1478	1092
1258	nov-00	12510	10399	1265	846
	mrt-01	12644	10496	1253	895
	mrt-02	12883	10736	1251	895
	mrt-03	13389	11241	1241	907
	mrt-04	13394	11112	1357	925
	apr-05	13273	10989	1367	916
	mei-06	13327	10986	1395	947
	apr-07	13657	11286	1406	964
	apr-08	13435	11095	1369	972
	mrt-09	13373	10992	1410	972
	apr-10	13474	11098	1397	979
	jan-11	13413	10984	1430	999
	jan-12	13663	11223	1429	1011
	jan-13	13551	11096	1432	1023
	jan-14	13948	11510	1416	1023
	mrt-15	13676	11305	1360	1011
	jan-16	13726	11372	1329	1024

	jan-17	14116	11557	1524	1035
1273	nov-00	12708	10292	1387	1030
	mrt-01	13130	10683	1425	1022
	mrt-02	13180	10763	1394	1022
	mrt-03	13616	11209	1357	1050
	mrt-04	13533	11034	1447	1051
	apr-05	13602	11034	1511	1056
	mei-06	13680	11050	1558	1072
	apr-07	13826	11239	1500	1087
	apr-08	13704	11162	1453	1089
	mrt-09	13645	11065	1481	1099
	apr-10	13868	11259	1504	1104
	jan-11	13782	11141	1521	1120
	jan-12	13925	11342	1444	1139
	jan-13	13613	10957	1516	1141
	jan-14	13982	11368	1475	1139
	mrt-15	14121	11477	1514	1129
	jan-16	13902	11265	1497	1140
	jan-17	14077	11325	1617	1134
1288	nov-00	13215	10261	1373	1580
	mrt-01	13685	10764	1396	1524
	mrt-02	13641	10697	1419	1524
	mrt-03	14171	11272	1396	1503
	mrt-04	14336	11255	1512	1569
	apr-05	14279	11163	1562	1554
	mei-06	14358	11250	1522	1586
	apr-07	14389	11325	1463	1601
	apr-08	14403	11240	1565	1598
	mrt-09	14314	11203	1558	1553
	apr-10	14251	11055	1583	1613
	jan-11	14219	11086	1551	1581
	jan-12	14326	11184	1551	1590
	jan-13	14118	11013	1513	1593
	jan-14	14500	11431	1481	1589
	mrt-15	14499	11418	1500	1581
	jan-16	14568	11468	1512	1588
	jan-17	14752	11429	1685	1637
1303	nov-00	12620	10188	1332	1099
	mrt-01	13274	10781	1400	1093
	mrt-02	13111	10647	1371	1093
	mrt-03	13707	11296	1346	1065
	mrt-04	13717	11116	1487	1115
	apr-05	13614	11034	1491	1090
	mei-06	13880	11193	1543	1143
	apr-07	14035	11399	1498	1138
	apr-08	13710	11134	1439	1137

	mrt-09	13784	11175	1505	1104
	apr-10	13769	11098	1538	1133
	jan-11	13682	11064	1498	1120
	jan-12	13547	10943	1480	1124
	jan-13	13606	10987	1458	1160
	jan-14	14098	11498	1456	1143
	mrt-15	14201	11529	1522	1150
	jan-16	13912	11278	1494	1140
	jan-17	14295	11567	1601	1127
1320	nov-00	13344	10589	1526	1229
	mrt-01	13389	10601	1563	1225
	mrt-02	13459	10675	1559	1225
	mrt-03	13922	11196	1518	1207
	mrt-04	14204	11275	1665	1264
	apr-05	13923	11090	1606	1227
	mei-06	14154	11162	1700	1292
	apr-07	14187	11318	1590	1279
	apr-08	14134	11223	1646	1265
	mrt-09	13986	11109	1645	1231
	apr-10	13961	11021	1666	1273
	jan-11	14104	11141	1706	1257
	jan-12	14016	11145	1610	1260
	jan-13	13978	11085	1627	1266
	jan-14	14408	11514	1629	1265
	mrt-15	14183	11285	1643	1255
	jan-16	14210	11356	1600	1254
	jan-17	14350	11313	1776	1260
1340	nov-00	13567	10529	1637	1400
	mrt-01	13503	10450	1644	1409
	mrt-02	13812	10792	1611	1409
	mrt-03	14137	11220	1585	1333
	mrt-04	14300	11226	1665	1409
	apr-05	14434	11270	1748	1416
	mei-06	14306	11076	1789	1441
	apr-07	14274	11207	1645	1422
	apr-08	14217	11122	1672	1423
	mrt-09	14300	11103	1755	1442
	apr-10	14440	11242	1774	1424
	jan-11	14426	11274	1764	1388
	jan-12	14164	11018	1746	1400
	jan-13	14235	11045	1734	1457
	jan-14	14710	11558	1701	1451
	mrt-15	14509	11367	1691	1450
	jan-16	14542	11458	1626	1457
	jan-17	14494	11480	1868	1146
1360	nov-00	12951	10485	1459	1006

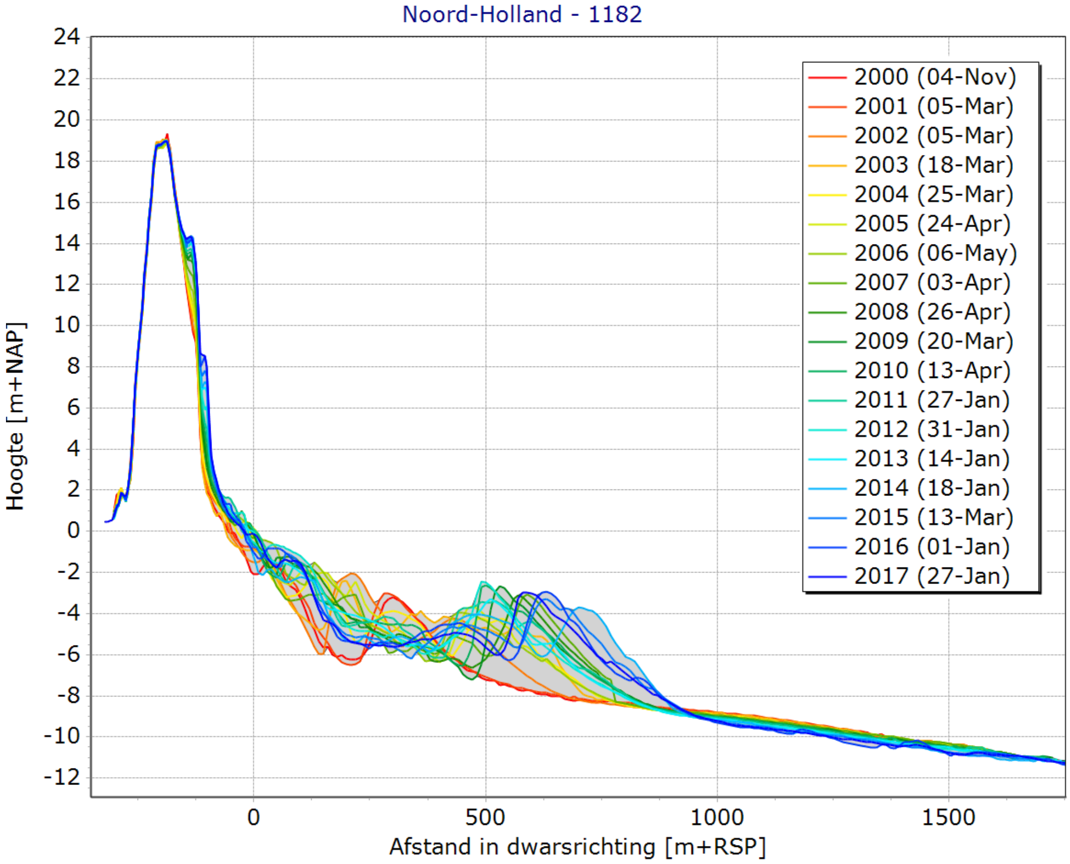
	mrt-01	12883	10420	1472	991
	mrt-02	13279	10834	1454	991
	mrt-03	13695	11272	1437	986
	mrt-04	13717	11242	1481	994
	apr-05	13698	11094	1625	980
	mei-06	13529	11006	1518	1005
	apr-07	13740	11259	1472	1008
	apr-08	13672	11168	1514	990
	mrt-09	13773	11201	1568	1003
	apr-10	13758	11140	1614	1004
	jan-11	13733	11142	1573	1019
	jan-12	13641	11064	1542	1035
	jan-13	13626	11047	1544	1034
	jan-14	14111	11565	1510	1037
	mrt-15	13879	11340	1504	1035
	jan-16	14041	11512	1486	1043
	jan-17	14039	11283	1716	1040
1381	nov-00	14819	10446	1671	2702
	mrt-01	14854	10438	1702	2714
	mrt-02	15251	10862	1675	2714
	mrt-03	15649	11304	1656	2689
	mrt-04	15616	11247	1675	2695
	apr-05	15268	10967	1618	2682
	mei-06	15417	10949	1752	2715
	apr-07	15764	11315	1725	2724
	apr-08	15644	11138	1790	2715
	mrt-09	15720	11127	1846	2747
	apr-10	15641	11047	1836	2758
	jan-11	15668	11100	1791	2778
	jan-12	15542	11031	1734	2777
	jan-13	15426	10924	1722	2780
	jan-14	16026	11505	1730	2791
	mrt-15	15980	11459	1738	2783
	jan-16	15841	11377	1673	2791
	jan-17	15995	11273	1929	2792

Appendix H. Results transect 1182

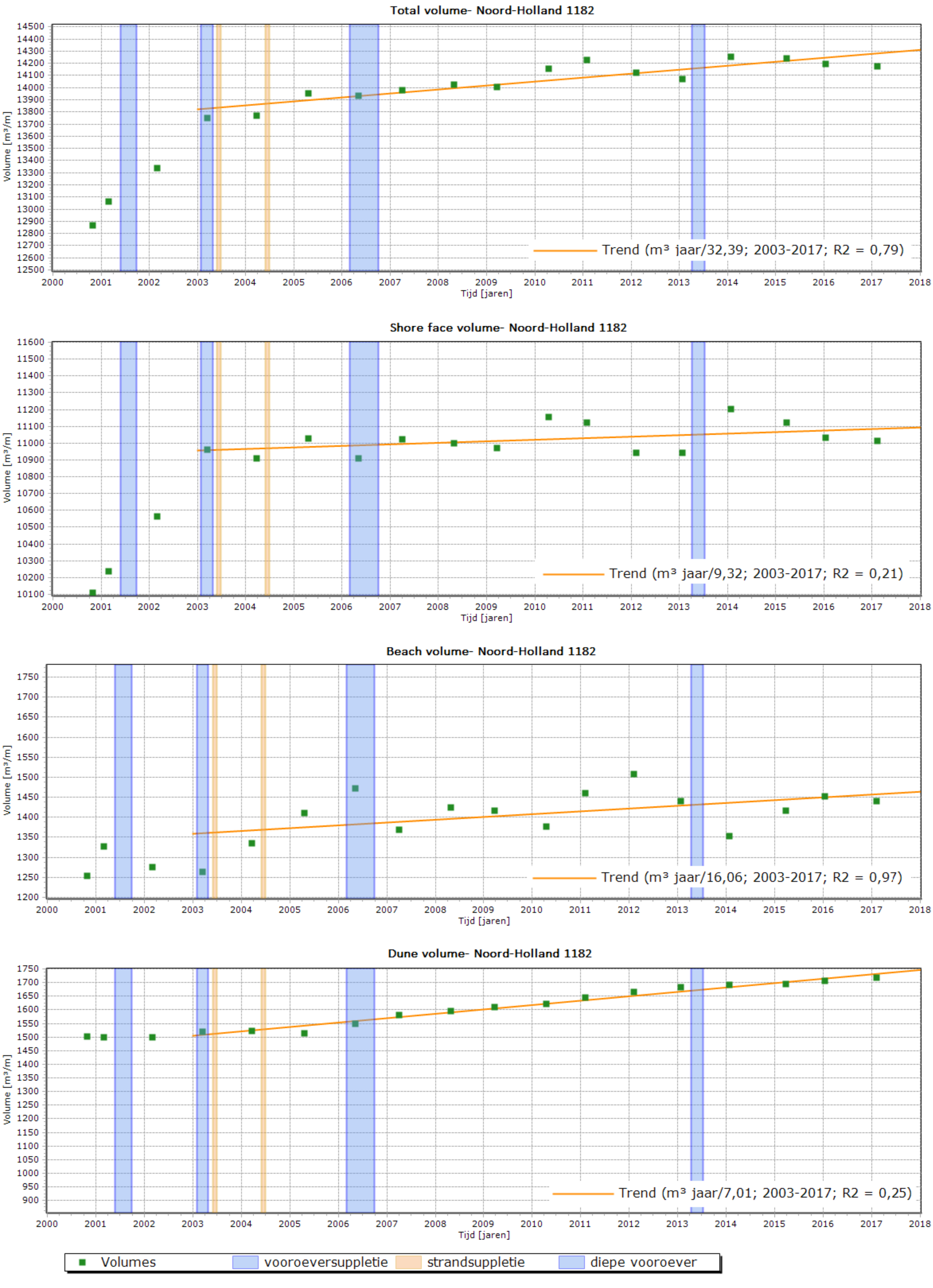
1182 – HB2017

wave height	wave period	surge storm level	50%-Fractiel of grain diameter
H_s [m]	T_p [s]	R_p [m+NAP]	D50 [mirco m]
9,97	16,51	4,48	223

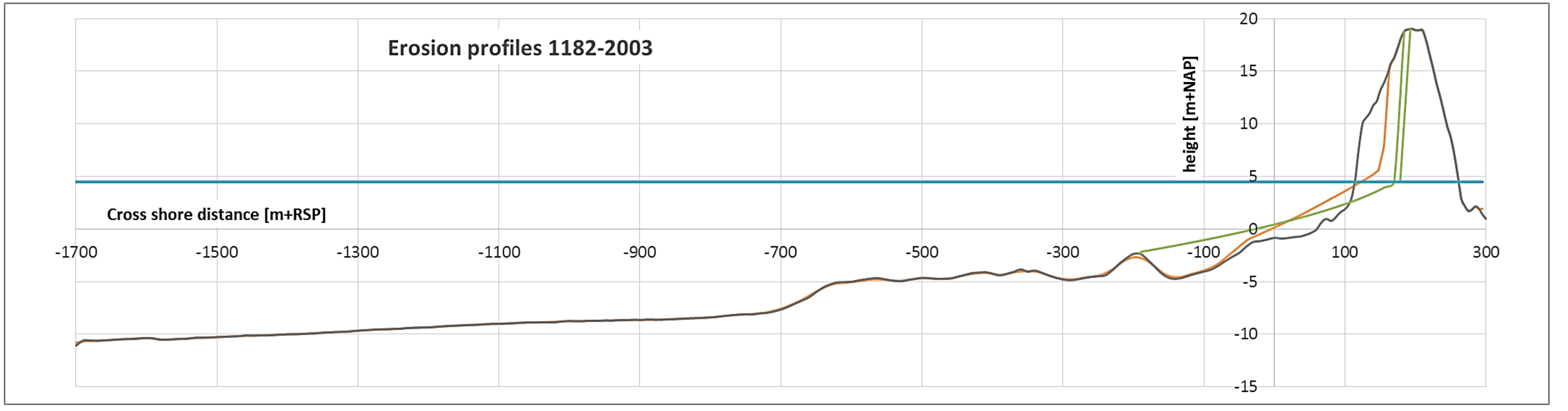
1182 - Volume development

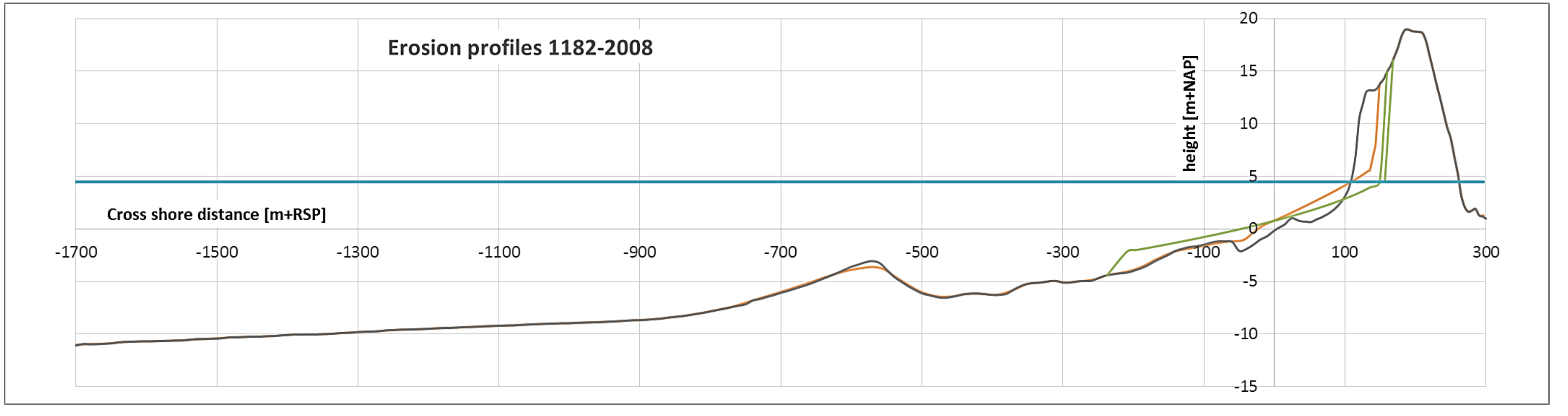


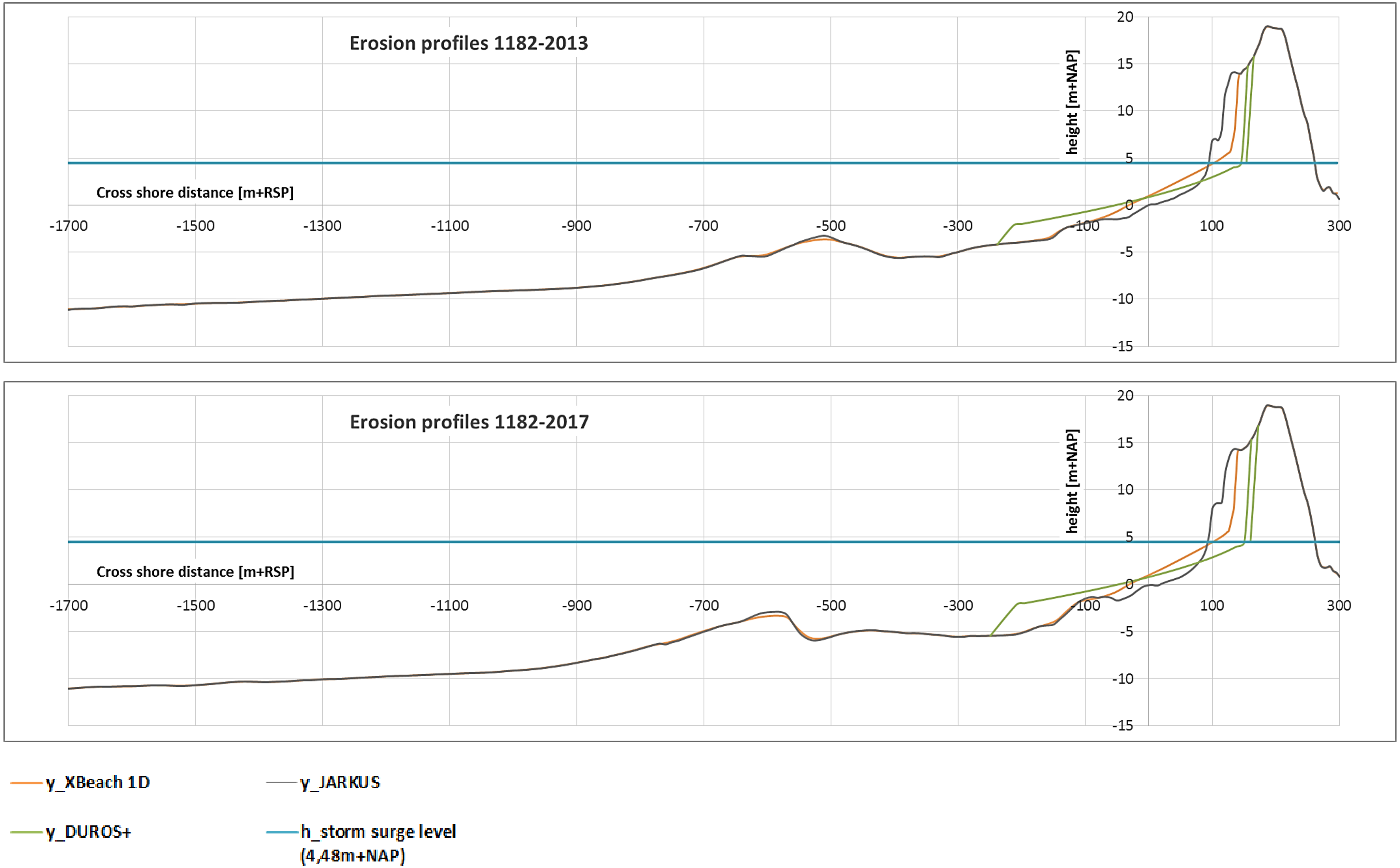
Years	Total volume [m²/m]	Shoreface volume [m²/m]	Beach volume [m²/m]	Dune volume [m²/m]
2000	12876	10118	1256	1501
2003	13748	10963	1266	1520
2017	14172	11015	1441	1716
2003-2000	872	845	10	19
2017-2003	424	52	175	196
2017-2000	1296	897	185	215


Total volume- Noord-Holland 1182
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/32,39; 2003-2017; R2 = 0,79)
Shore face volume- Noord-Holland 1182
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/9,32; 2003-2017; R2 = 0,21)
Beach volume- Noord-Holland 1182
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/16,06; 2003-2017; R2 = 0,97)
Dune volume- Noord-Holland 1182
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/7,01; 2003-2017; R2 = 0,25)
Volumes
vooroeversuppletie
strandsuppletie
diepe vooroever

1182 - Erosion profiles







Erosion profiles 1182-2013
height [m+NAP]
Cross shore distance [m+RSP]
20
15
10
5
0
-5
-10
-15
-1700
-1500
-1300
-1100
-900
-700
-500
-300
-100
100
300
Erosion profiles 1182-2017
height [m+NAP]
Cross shore distance [m+RSP]
20
15
10
5
0
-5
-10
-15
-1700
-1500
-1300
-1100
-900
-700
-500
-300
-100
100
300
y_XBeach 1D
y_JARKUS
y_DUROS+
h_storm surge level (4,48m+NAP)

1182 - Erosion volumes

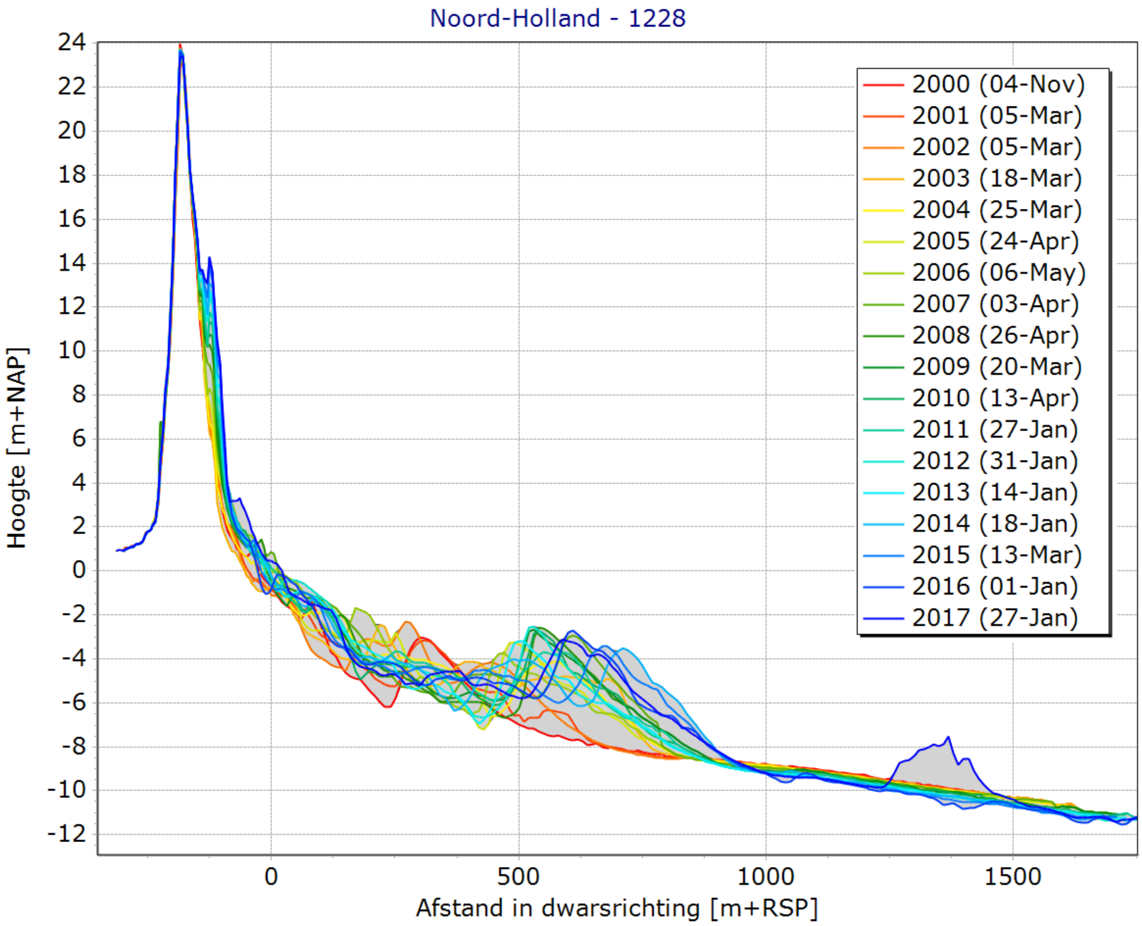
	Erosion volume [m³/m]		Comparison	
Name	**XBeach 1D**	**DUROS+**	**DUROS+ – XBeach**	**XBeach / DUROS+**
2003	295	616	321	48%
2008	211	398	187	53%
2013	242	444	202	55%
2017	255	548	293	47%

Appendix I. Results transect 1228

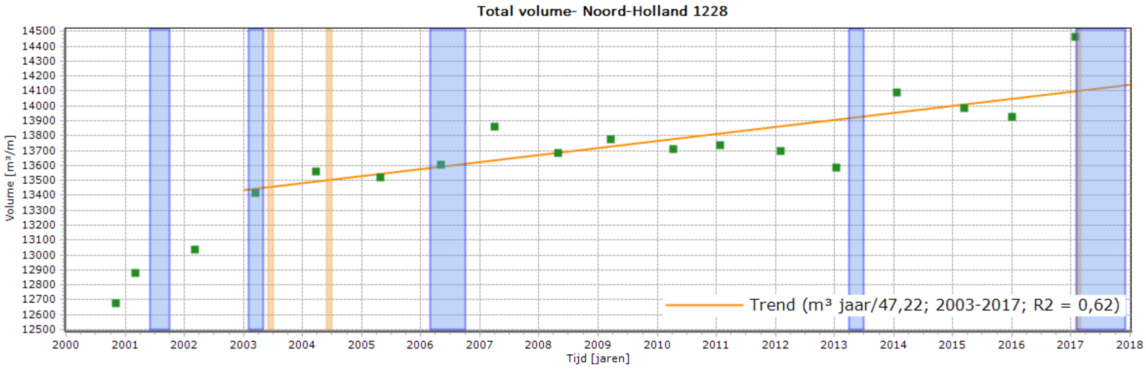
1128- HR2017

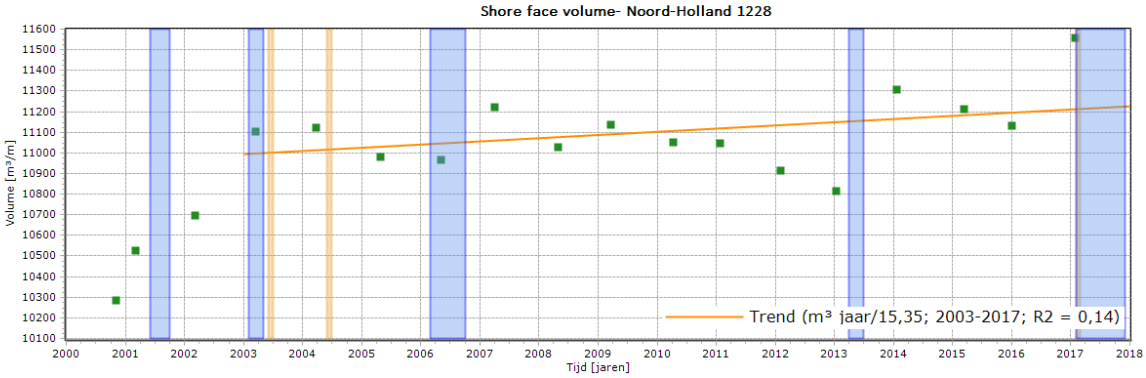
wave height	wave period	surge storm level	50%-Fractiel of grain diameter
H_s [m]	T_p [s]	R_p [m+NAP]	D50 [mirco m]
9,66	16,5	4,49	217

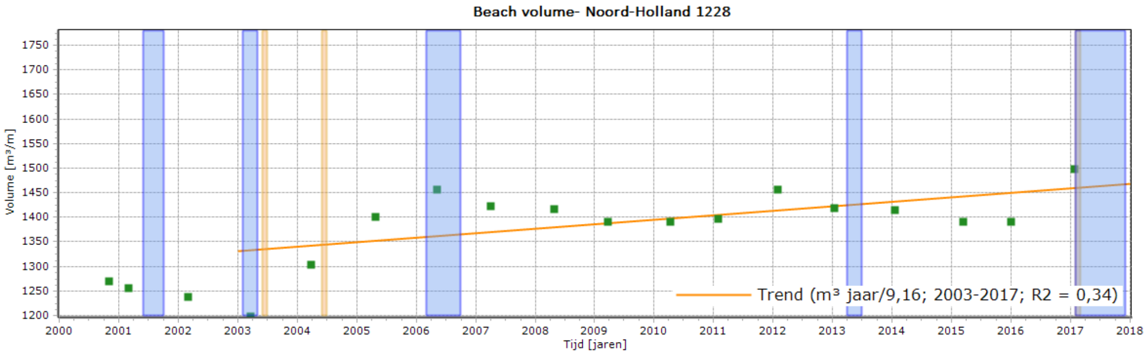
1228 - Volume development

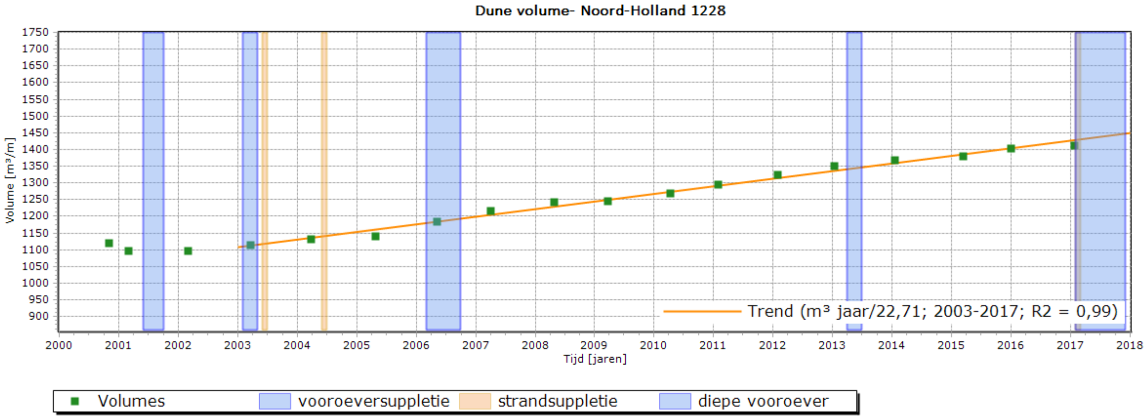


Years	**Total volume [m²/m]**	**Shoreface volume [m²/m]**	**Beach volume [m²/m]**	**Dune volume [m²/m]**
2000	12674	10287	1269	1119
2003	13417	11105	1198	1114
2017	14465	11556	1498	1411
2003-2000	743	819	-70	-5
2017-2003	1047	451	299	298
2017-2000	1791	1269	229	293

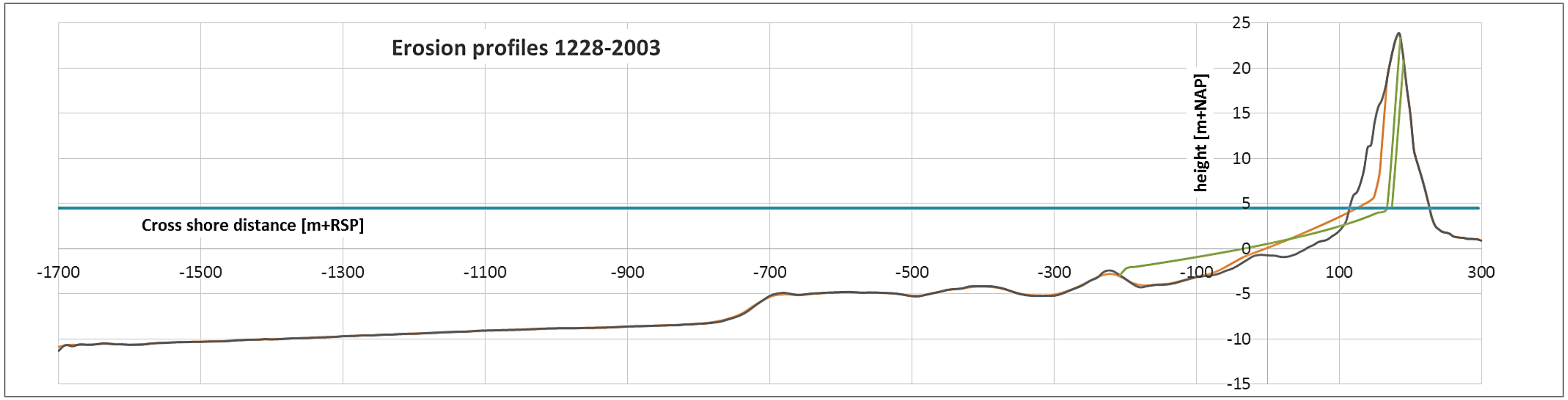

Total volume- Noord-Holland 1228
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/47,22; 2003-2017; R2 = 0,62)

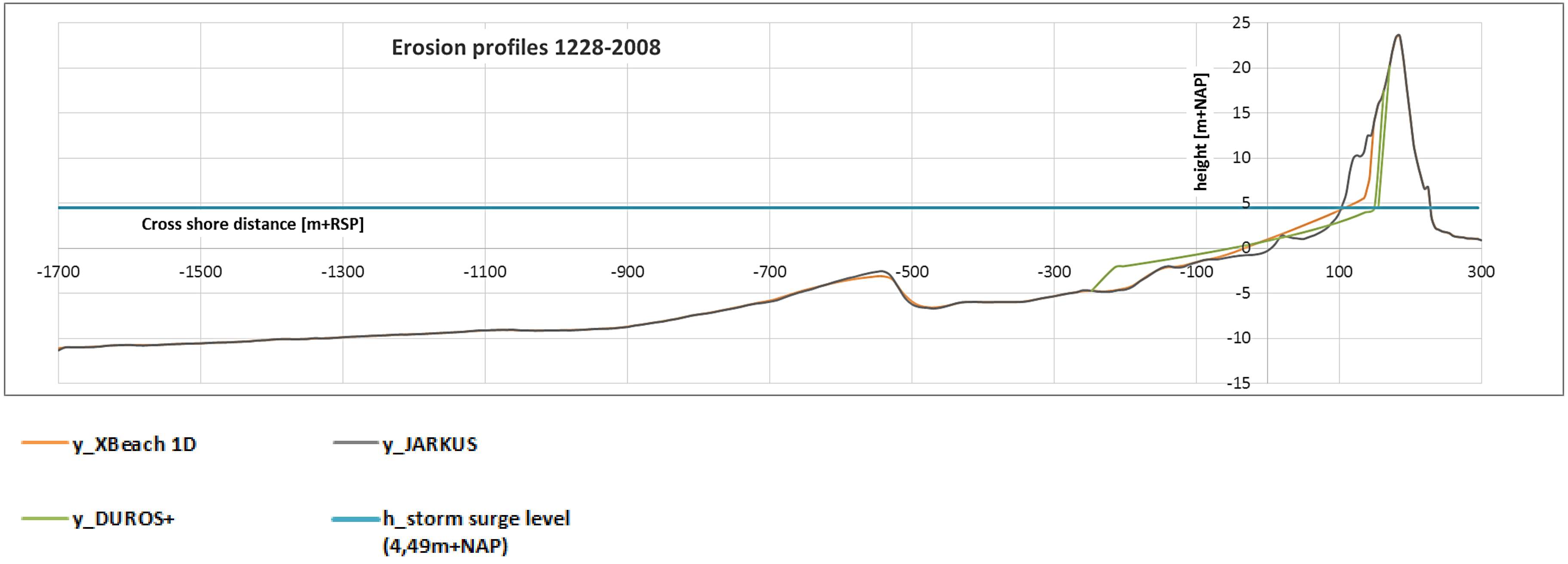

Shore face volume- Noord-Holland 1228
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/15,35; 2003-2017; R2 = 0,14)

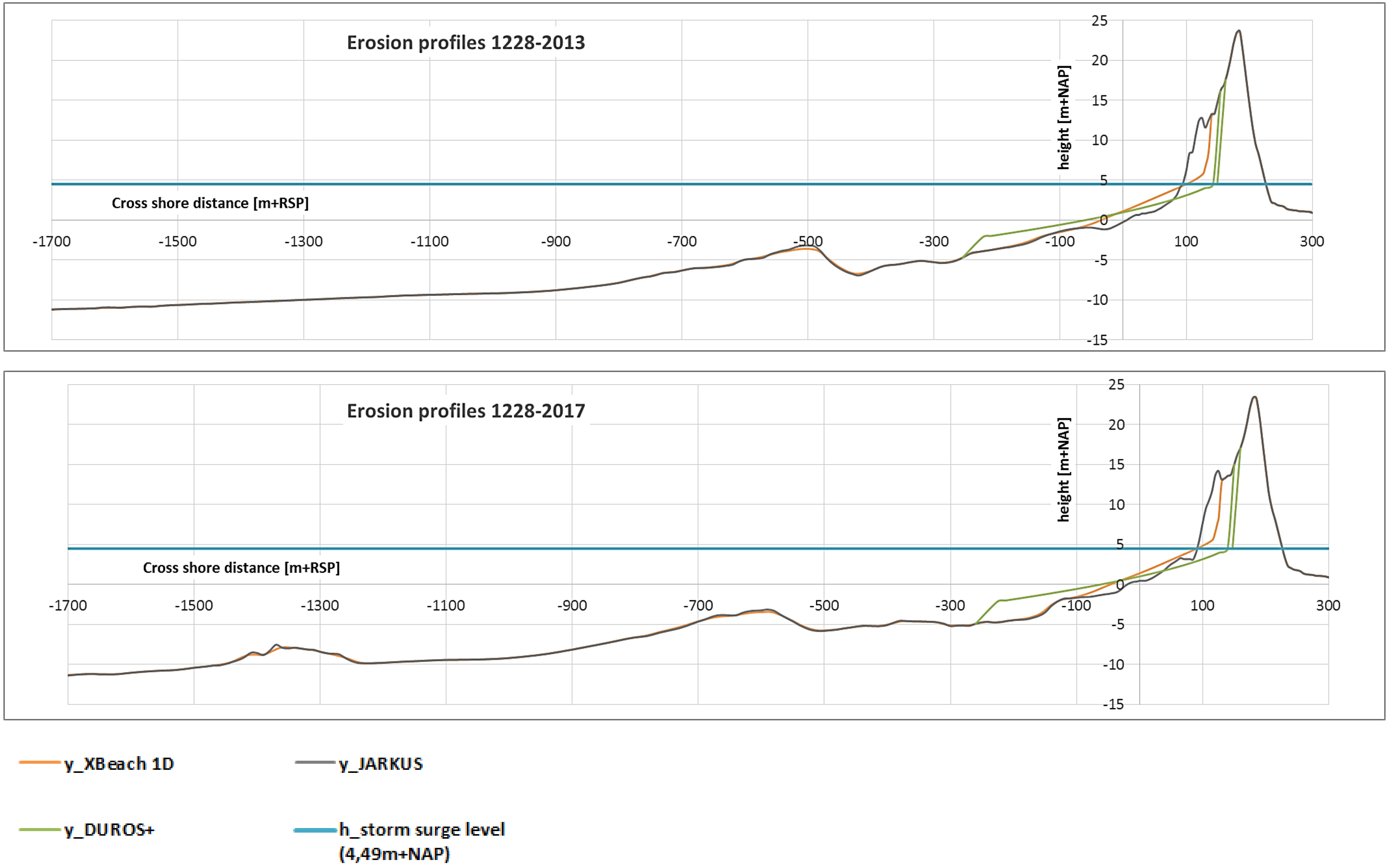

Beach volume- Noord-Holland 1228
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/9,16; 2003-2017; R2 = 0,34)


Dune volume- Noord-Holland 1228
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/22,71; 2003-2017; R2 = 0,99)
Volumes
vooroeversuppletie
strandsuppletie
diepe vooroever

1228 - Erosion profiles







Erosion profiles 1228-2013
Cross shore distance [m+RSP]
height [m+NAP]
-1700
-1500
-1300
-1100
-900
-700
-500
-300
-100
100
300
25
20
15
10
5
0
-5
-10
-15
Erosion profiles 1228-2017
Cross shore distance [m+RSP]
height [m+NAP]
y_XBeach 1D
y_JARKUS
y_DUROS+
h_storm surge level (4,49m+NAP)

1228 - Erosion volumes

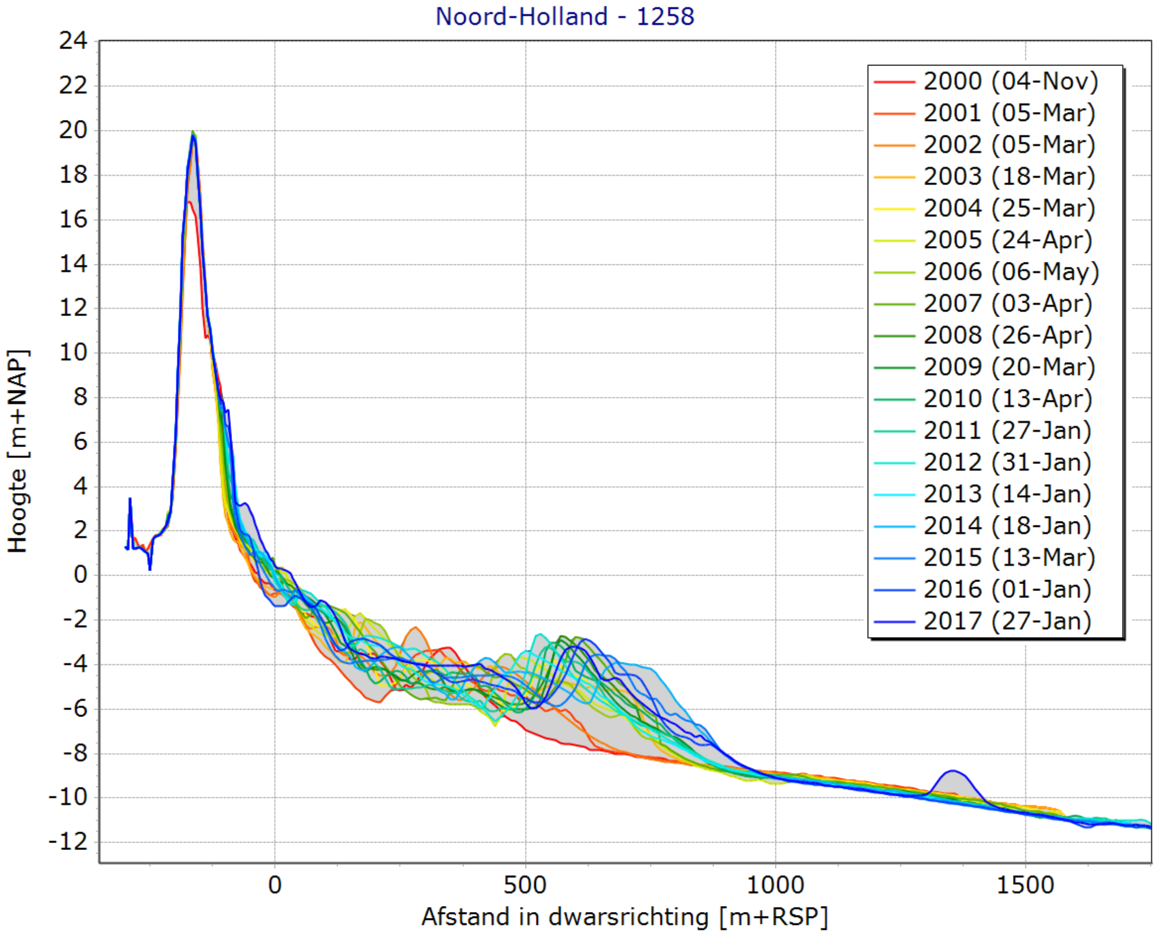
	Erosion volume [m³/m]		Comparison	
Name	**XBeach 1D**	**DUROS+**	**DUROS+ – XBeach**	**XBeach / DUROS+**
2003	284	624	340	46%
2008	202	390	188	52%
2013	237	410	173	58%
2017	177	449	272	39%
Reference	177	449	272	39%
DSN	167	449	282	37%

Appendix J. Results transect 1258

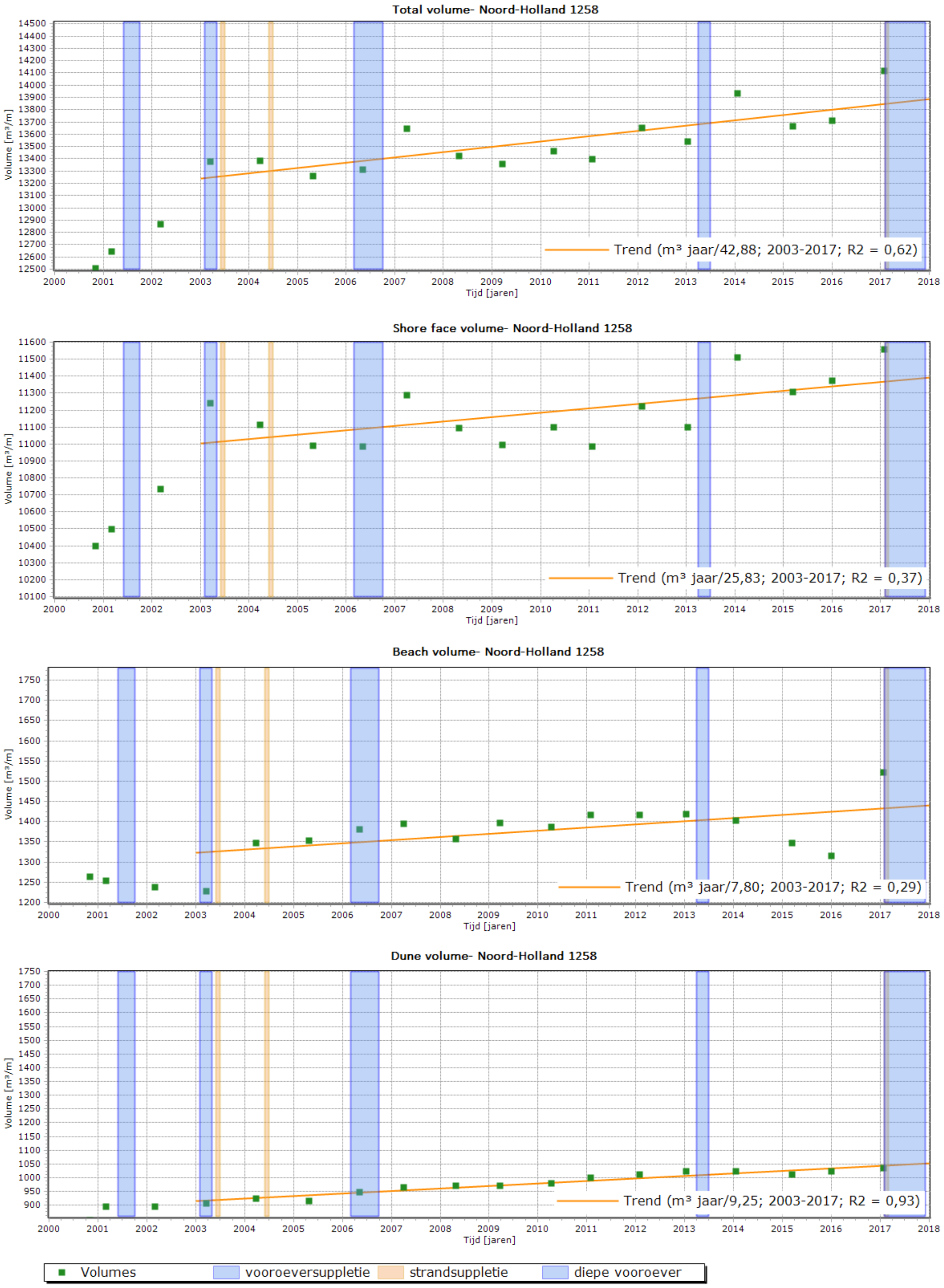
1258 - HB2017

wave height	wave period	surge storm level	50%-Fractiel of grain diameter
H_s [m]	T_p [s]	R_p [m+NAP]	D50 [mirco m]
10	16,5	4,49	213

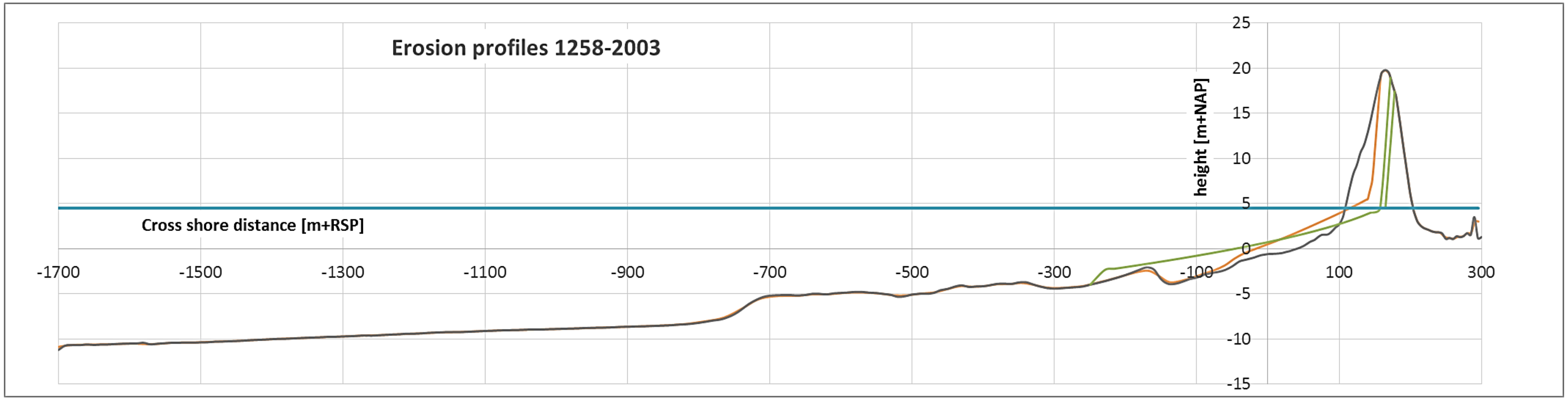
1258 - Volume development

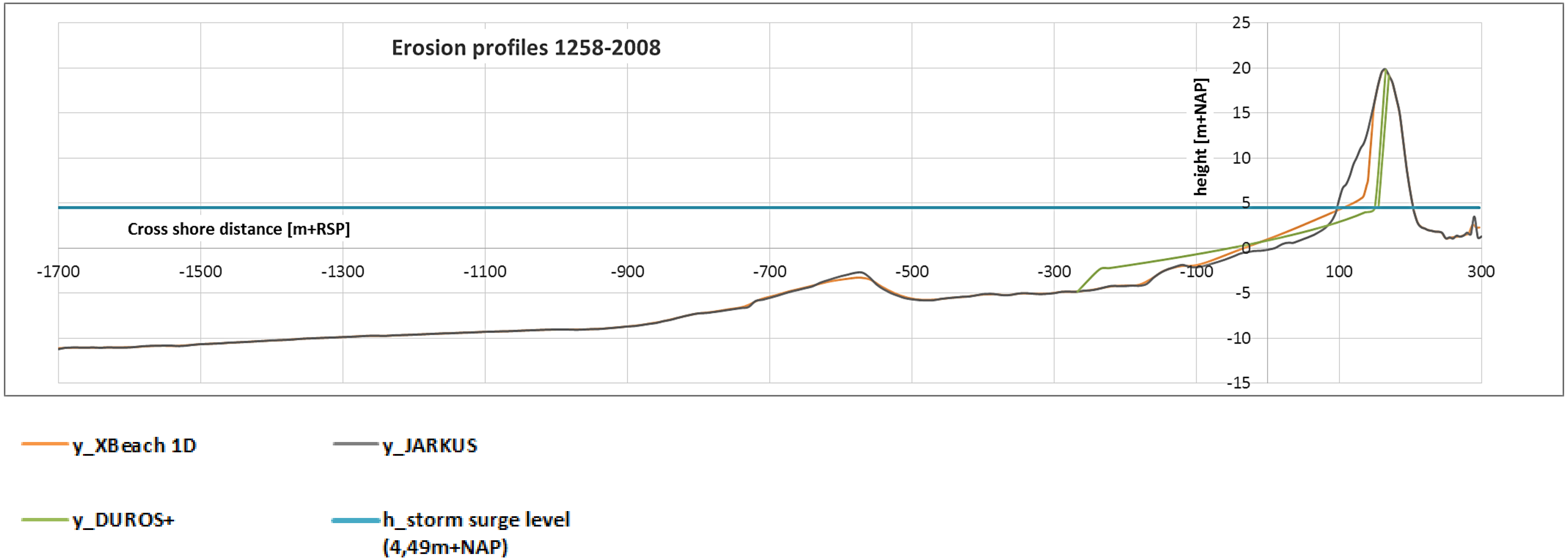


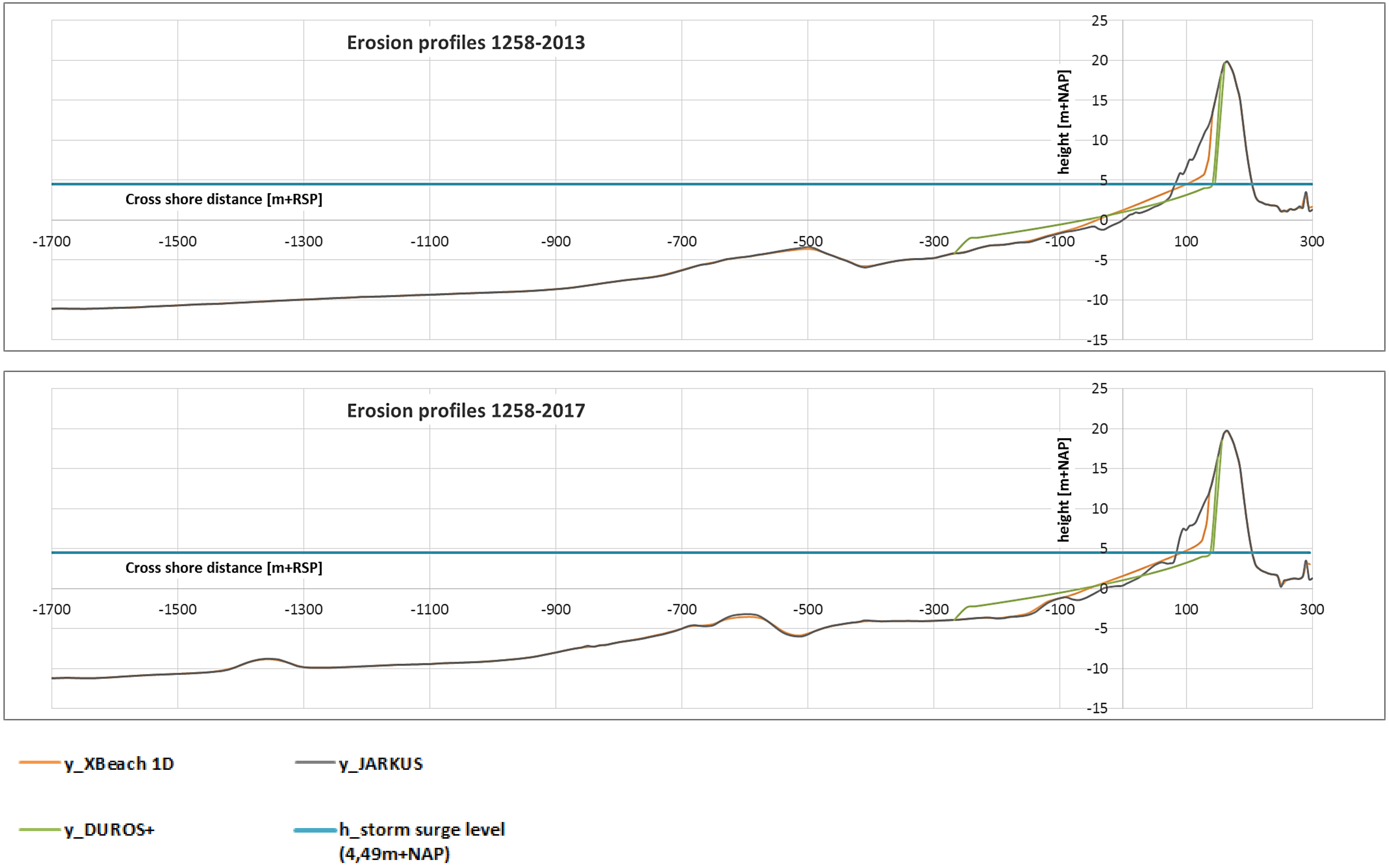
Years	Total volume [m²/m]	Shoreface volume [m²/m]	Beach volume [m²/m]	Dune volume [m²/m]
2000	12510	10399	1265	846
2003	13389	11241	1241	907
2017	14116	11557	1524	1035
2003-2000	880	842	-23	62
2017-2003	727	316	283	128
2017-2000	1606	1157	260	189


Total volume- Noord-Holland 1258
Volume [m³/m]
Trend (m³ jaar/42,88; 2003-2017; R2 = 0,62)
Tijd [jaren]
Shore face volume- Noord-Holland 1258
Volume [m³/m]
Trend (m³ jaar/25,83; 2003-2017; R2 = 0,37)
Tijd [jaren]
Beach volume- Noord-Holland 1258
Volume [m³/m]
Trend (m³ jaar/7,80; 2003-2017; R2 = 0,29)
Tijd [jaren]
Dune volume- Noord-Holland 1258
Volume [m³/m]
Trend (m³ jaar/9,25; 2003-2017; R2 = 0,93)
Tijd [jaren]
Volumes
vooroeversuppletie
strandsuppletie
diepe vooroever

1258 - Erosion profile






Erosion profiles 1258-2013
height [m+NAP]
Cross shore distance [m+RSP]
Erosion profiles 1258-2017
height [m+NAP]
Cross shore distance [m+RSP]
y_XBeach 1D
y_JARKUS
y_DUROS+
h_storm surge level (4,49m+NAP)

1258 - Erosion Volumes

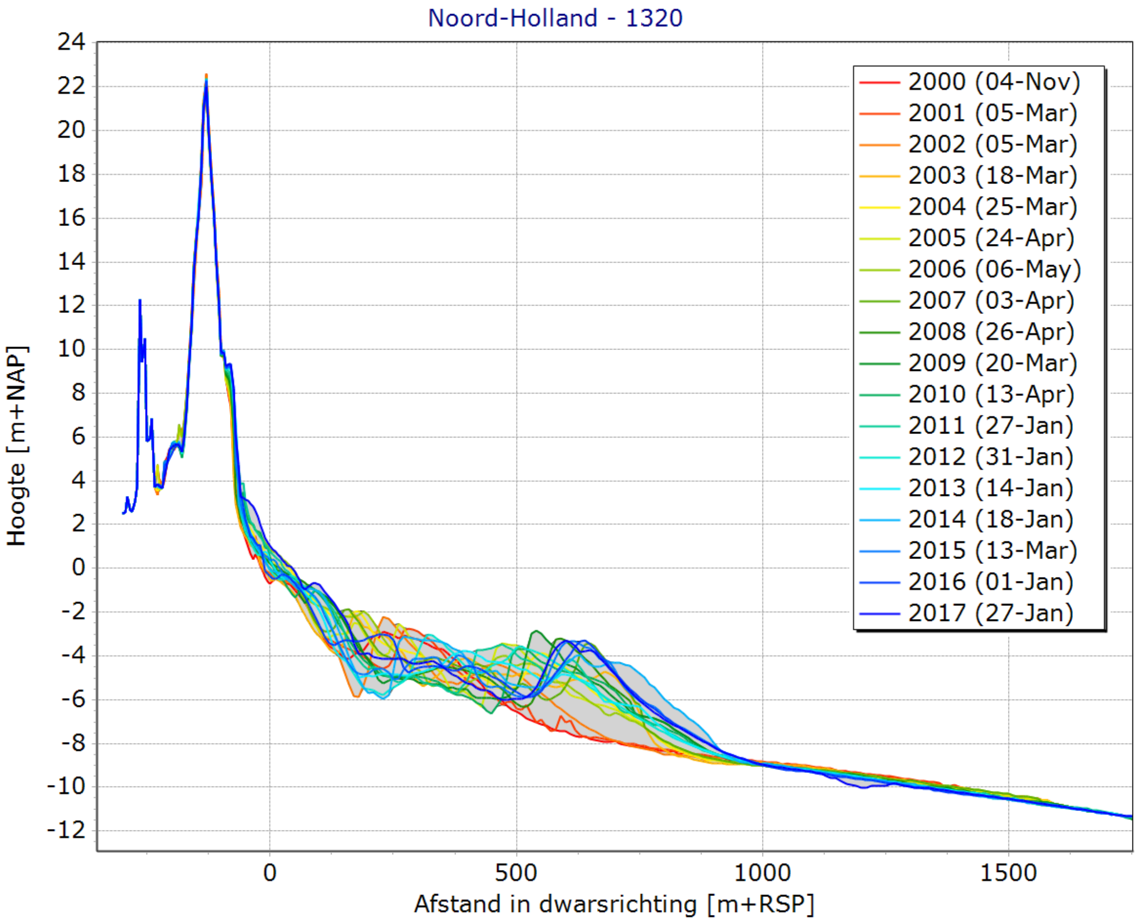
	Erosion volume [m³/m]		Comparison	
Name	**XBeach 1D**	**DUROS+**	**DUROS+ – XBeach**	**XBeach / DUROS+**
2003	265	558	293	48%
2008	232	468	236	50%
2013	249	354	105	70%
2017	183	321	138	57%
Reference	194	321	127	60%
DSN	186	321	135	58%

Appendix K. Results transect 1320

1320 - HB2017

wave height	wave period	surge storm level	50%-Fractiel of grain diameter
H_s [m]	T_p [s]	R_p [m+NAP]	D50 [mirco m]
9,64	16,48	4,5	222

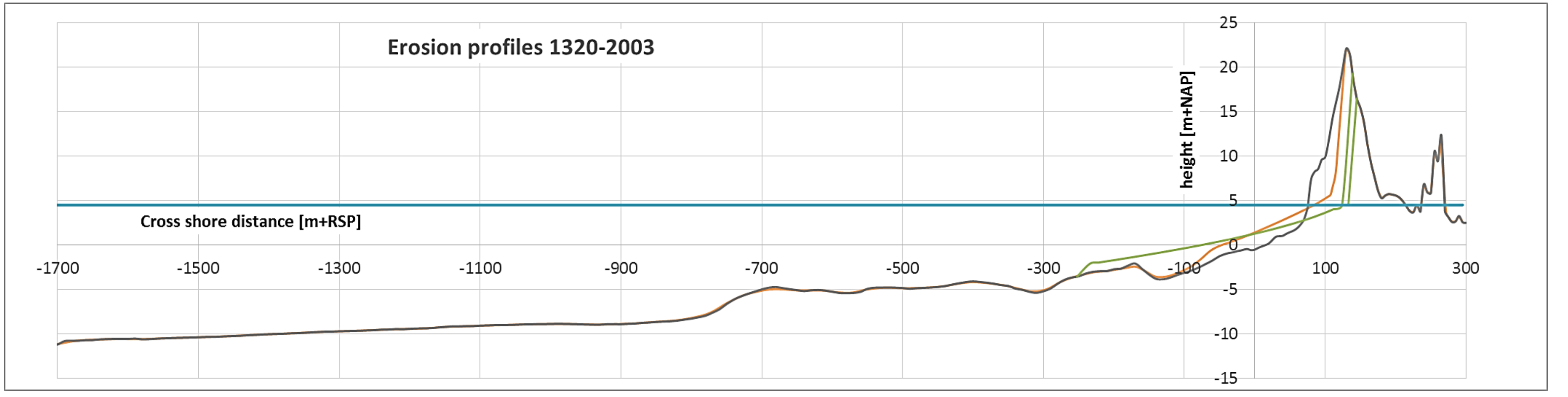
1320 - Volume development

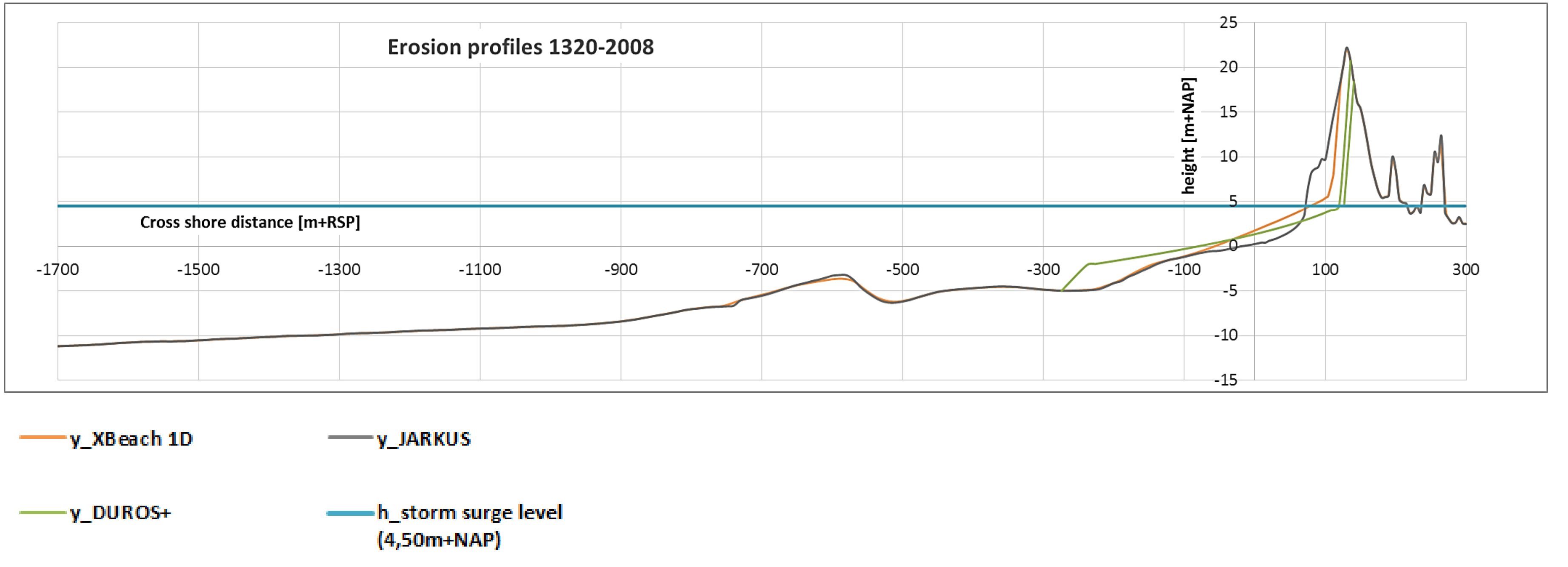


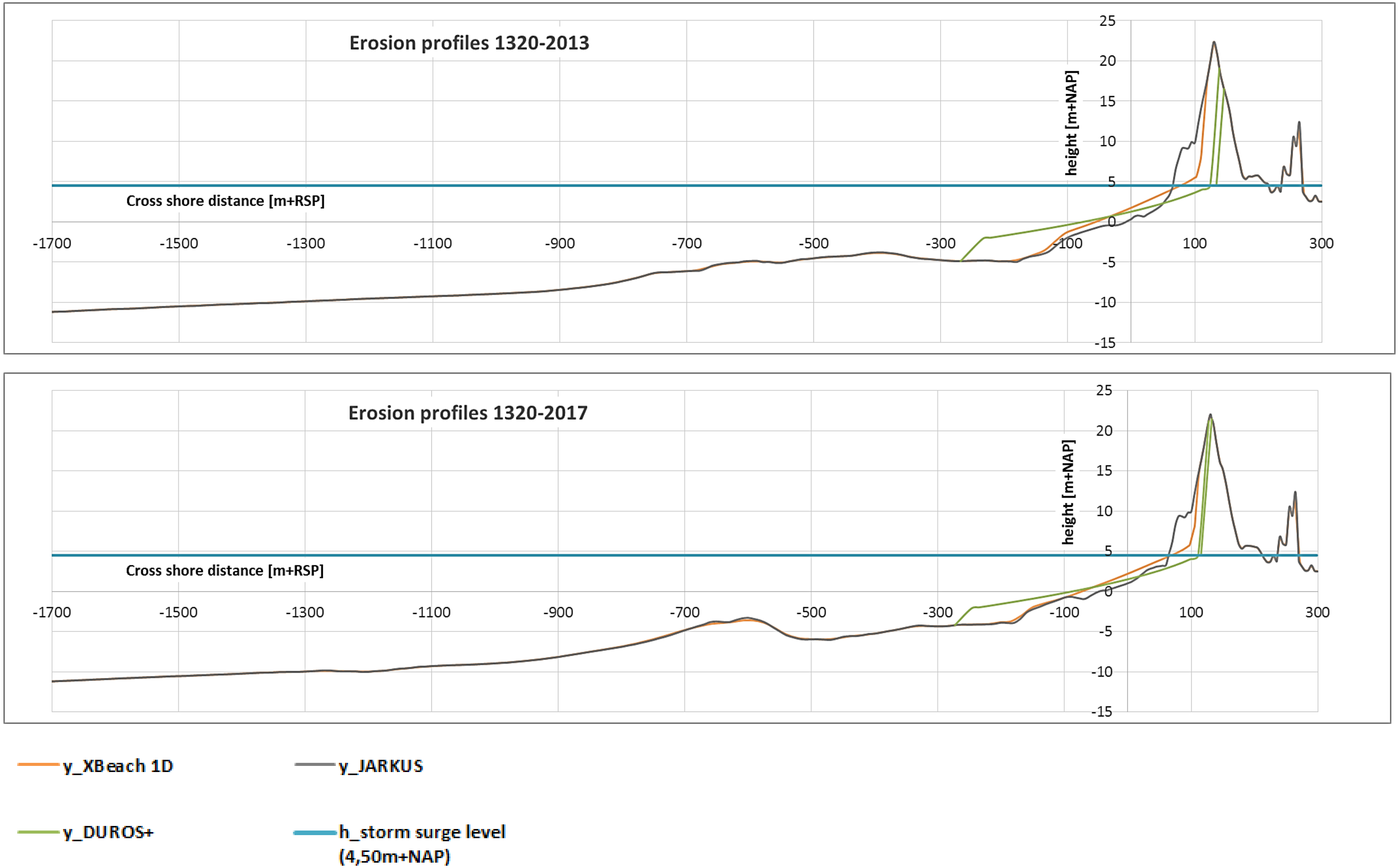
Years	Total volume [m²/m]	Shoreface volume [m²/m]	Beach volume [m²/m]	Dune volume [m²/m]
2000	13344	10589	1526	1229
2003	13922	11196	1518	1207
2017	14350	11313	1776	1260
2003-2000	578	607	-8	-22
2017-2003	428	117	258	53
2017-2000	1006	724	251	31


Total volume- Noord-Holland 1320
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/18,73; 2003-2017; R2 = 0,30)
Shore face volume- Noord-Holland 1320
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/10,34; 2003-2017; R2 = 0,12)
Beach volume- Noord-Holland 1320
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/5,25; 2003-2017; R2 = 0,15)
Dune volume- Noord-Holland 1320
Volume [m³/m]
Tijd [jaren]
Trend (m³ jaar/3,14; 2003-2017; R2 = 0,62)
Volumes
vooroeversuppletie
strandsuppletie
diepe vooroever

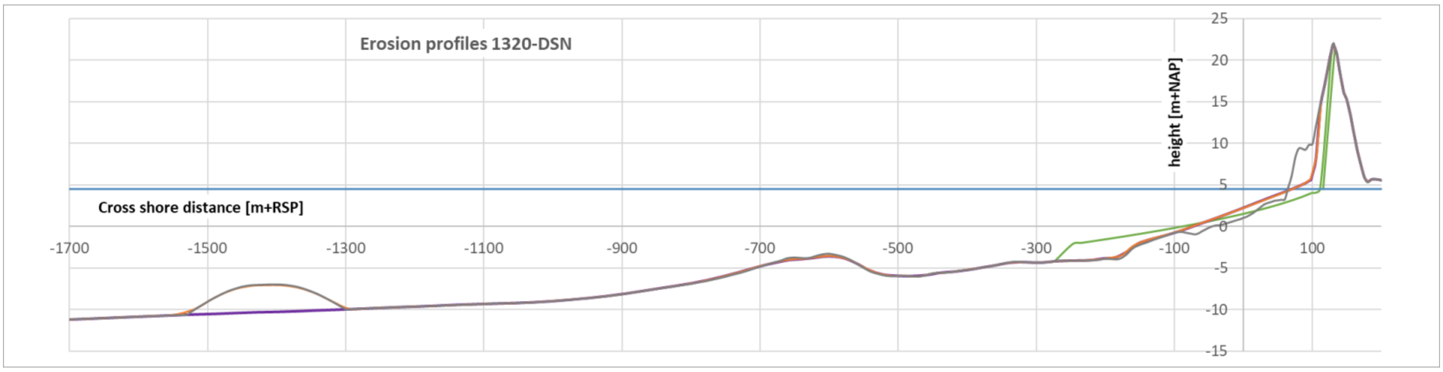
1320 - Erosion profile

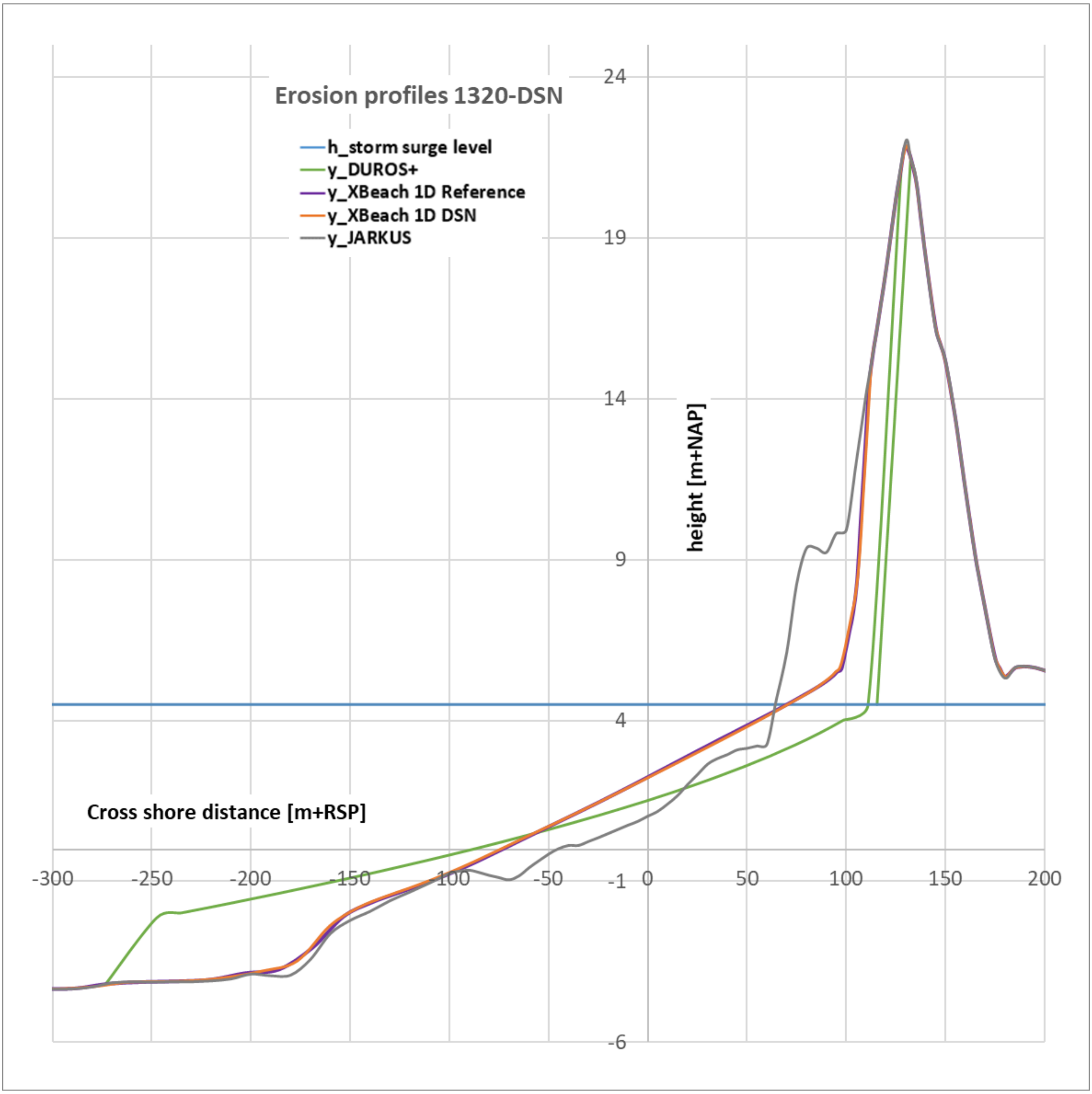




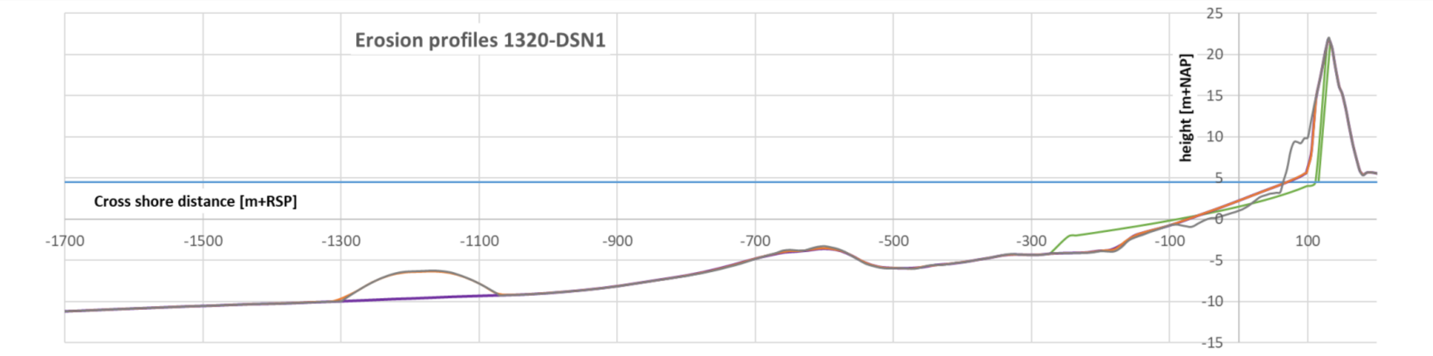

Erosion profiles 1320-2013
height [m+NAP]
Cross shore distance [m+RSP]
25
20
15
10
5
0
-5
-10
-15
-1700
-1500
-1300
-1100
-900
-700
-500
-300
-100
100
300
Erosion profiles 1320-2017
height [m+NAP]
Cross shore distance [m+RSP]
y_XBeach 1D
y_JARKUS
y_DUROS+
h_storm surge level (4,50m+NAP)

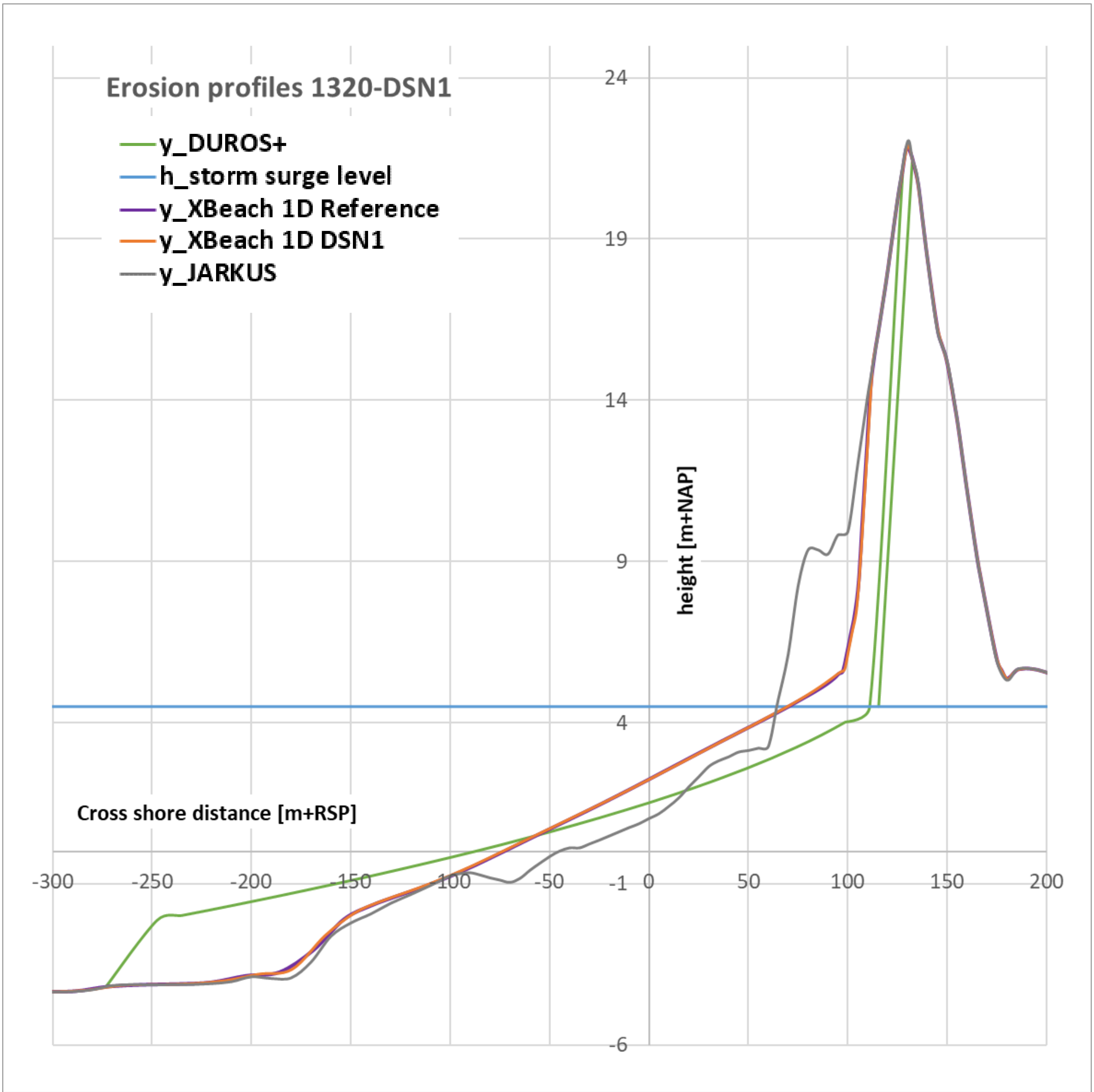
1320 - Erosion profiles DSN



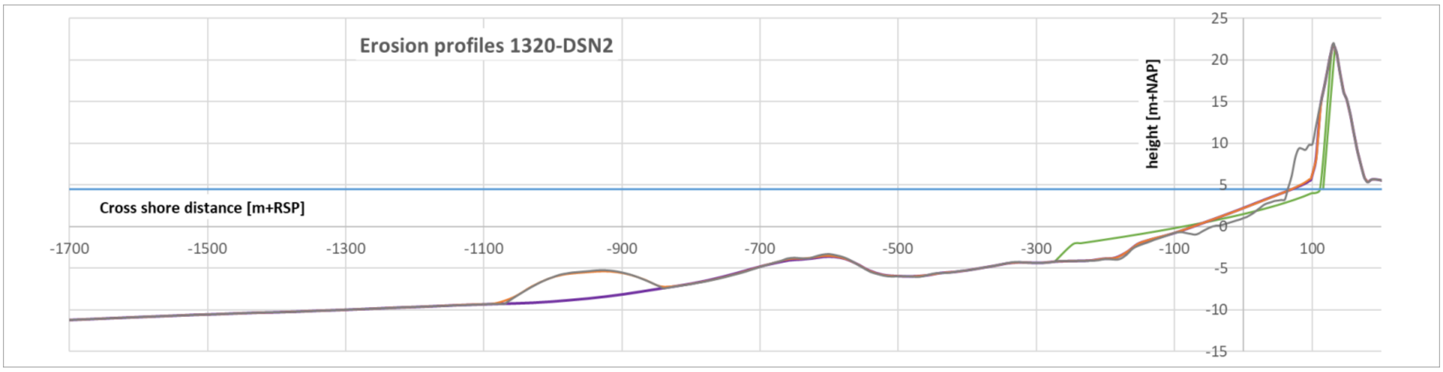


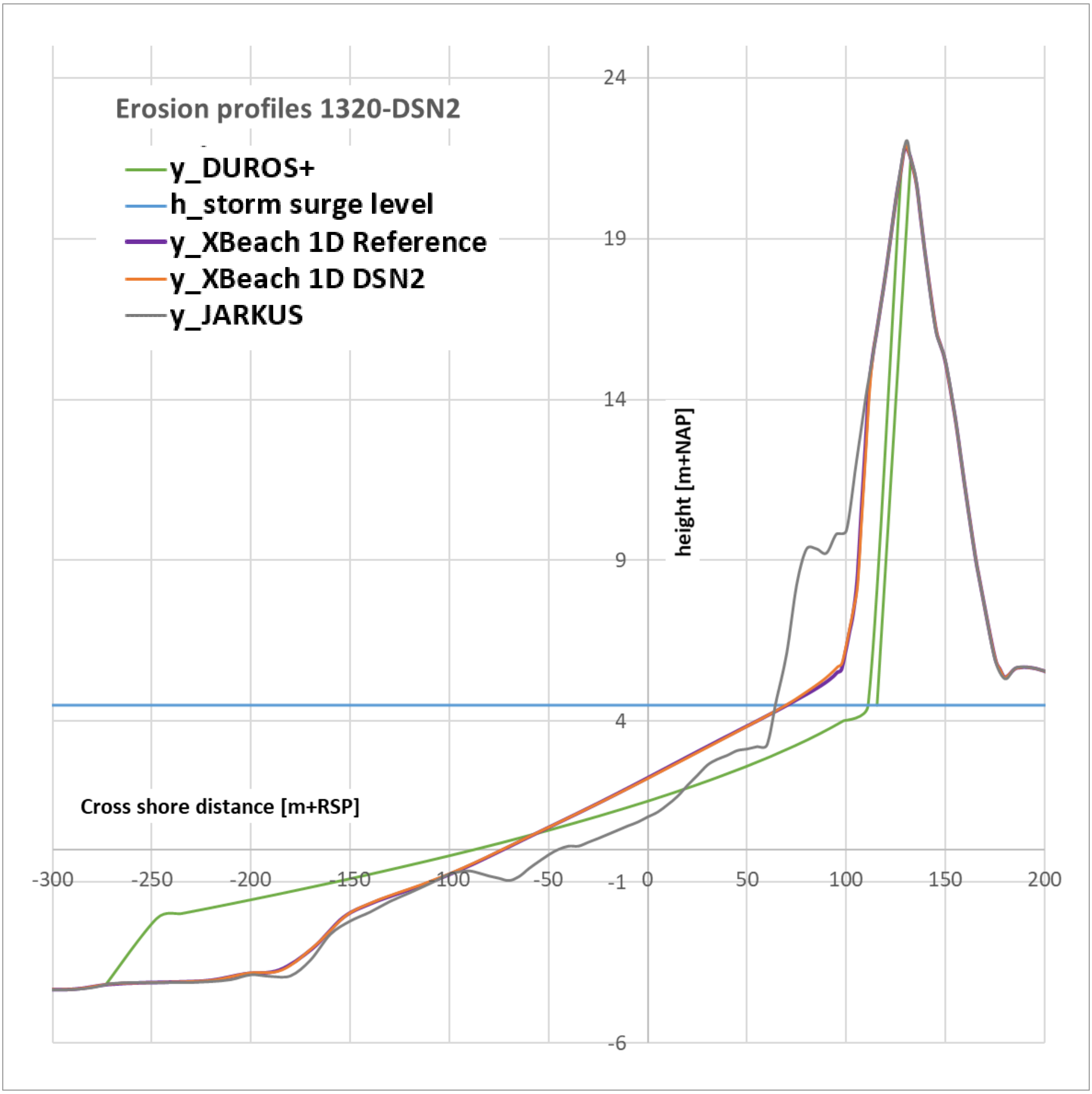
1320 - Erosion profiles DSN 1



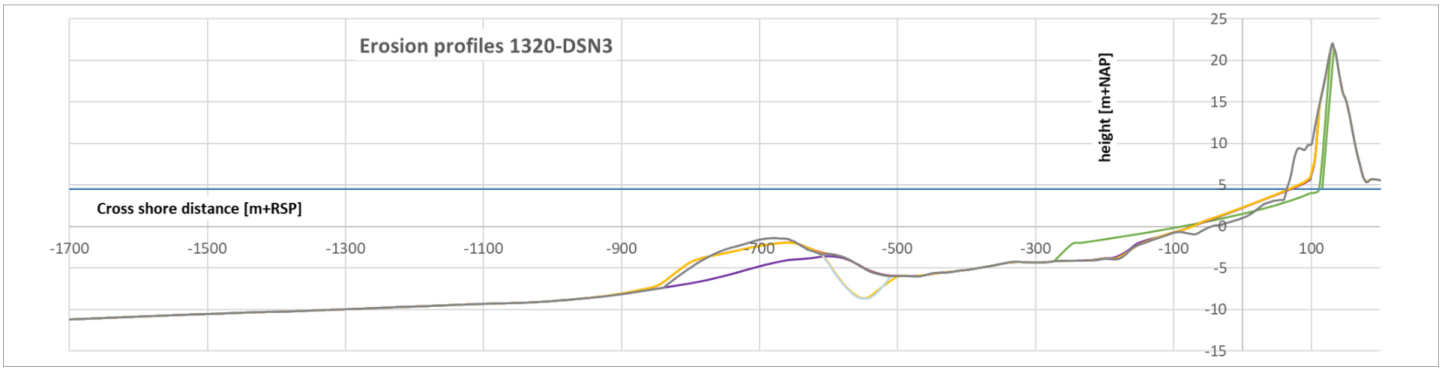


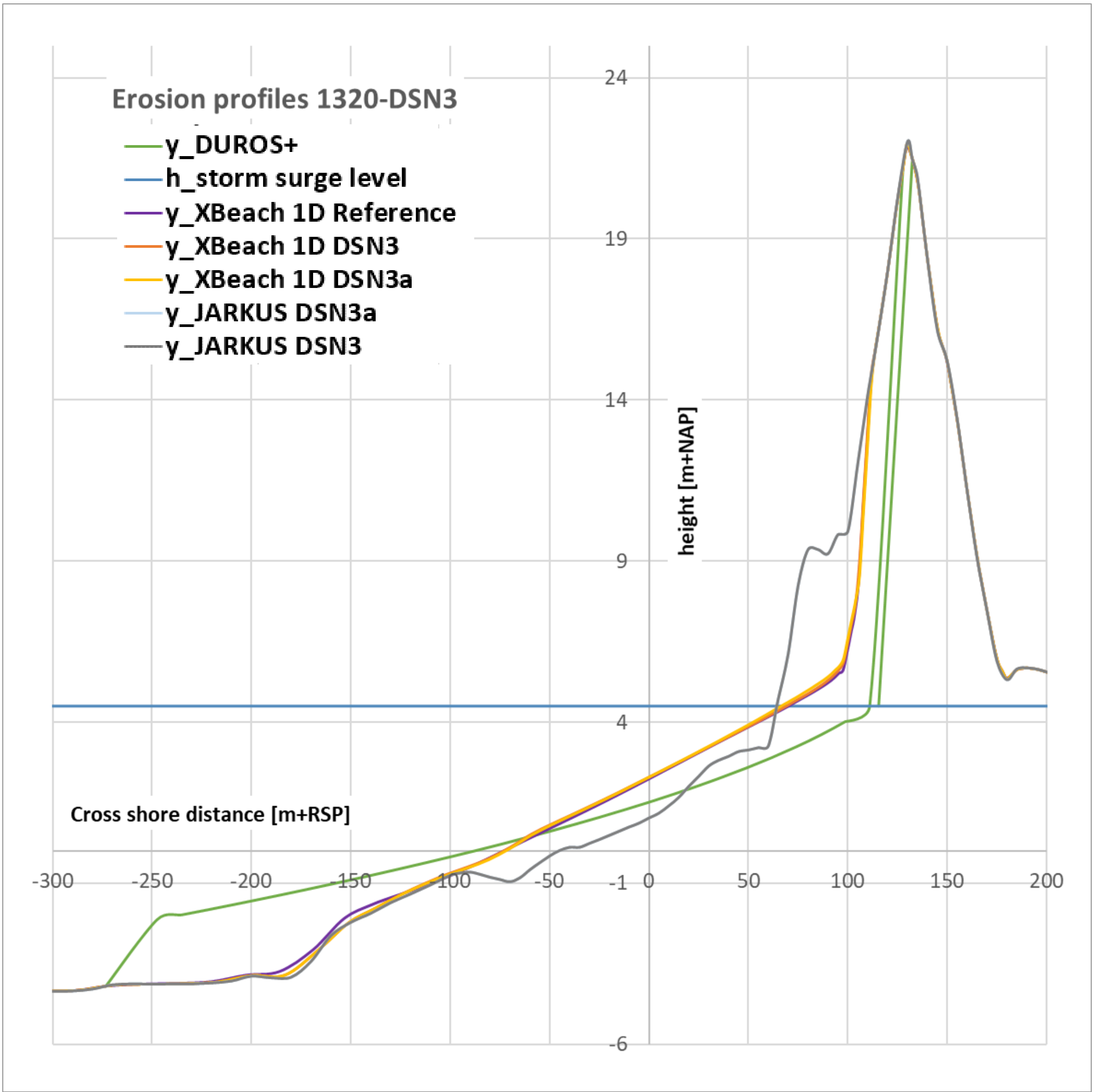
1320 - Erosion profiles DSN 2





1320 - Erosion profiles DSN 3 and 3a





1320 - Erosion volumes

	Erosion volume [m^3/m]		Comparison	
Name	**XBeach 1D**	**DUROS+**	**DUROS+ – XBeach**	**XBeach / DUROS+**
2003	285	588	303	48%
2008	248	523	274	47%
2013	278	650	372	43%
2017	187	385	198	49%
Reference	197	385	188	51%
DSN	189	385	196	49%
Extreme	181	385	204	47%
Test	163	385	222	42%
DSN1	181	385	204	47%
DSN2	188	385	197	49%
DSN3	185	385	200	48%
DSN3a	175	385	210	46%