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Ministerie van Infrastructuur en Waterstaat

RWS INFORMATIE

Update Erosion Eastern Scheldt

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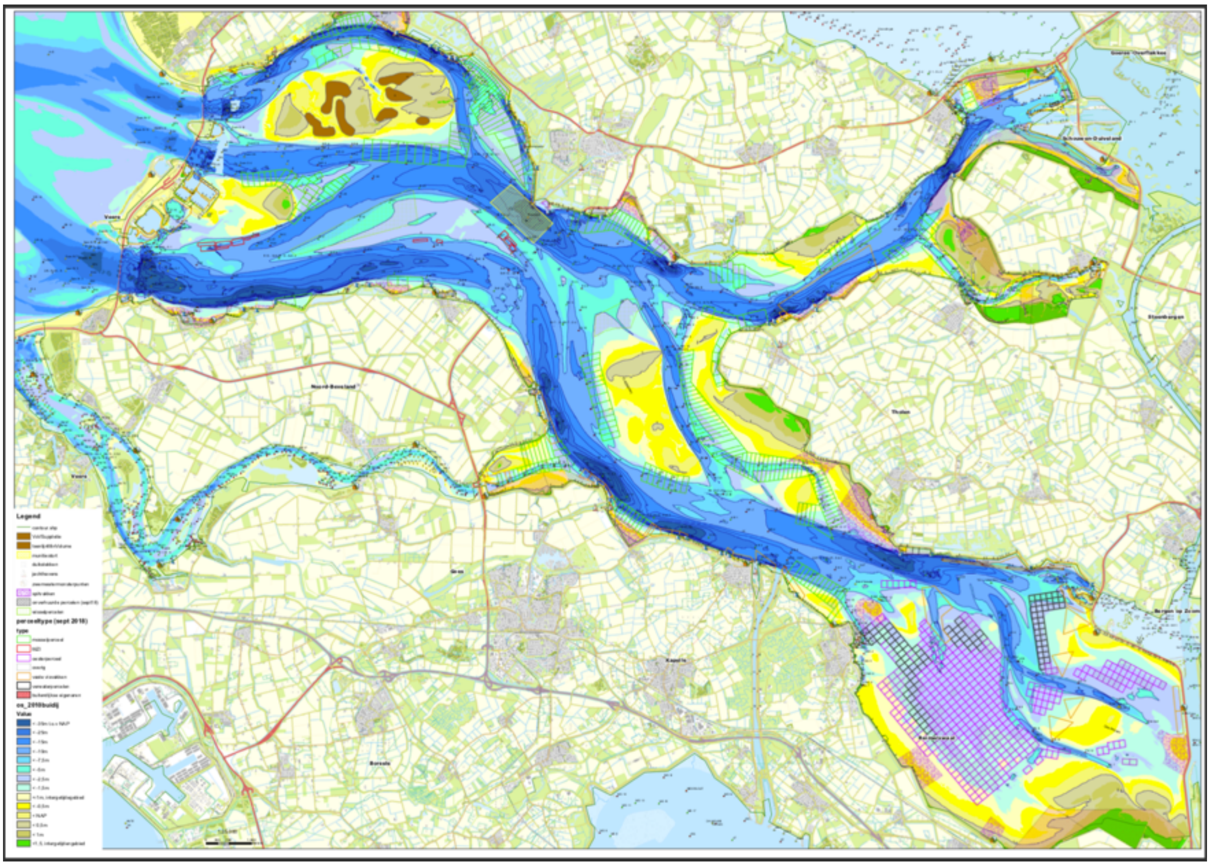

Colophon

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Preface

One day I had a guest lecture about the subject morphology. During this lecture I got motivated to continue with this subject. I decided my thesis subject had to contain the topic morphology.
At the HZ University of Applied Sciences, I found this topic. There was a request of Rijkswaterstaat Zee and Delta to provide an update of the rate of erosion in the Eastern Scheldt.

At the HZ University of Applied Sciences, I met Wietse van de Lageweg and at Rijkswaterstaat I met Eric van Zanten. Together they supported me during this study, and I would like to thank them both for their excellent guidance and advices. They have shown me a lot of different views of morphology and motivated me to continue in this subject.

Furthermore, I also would like to thank Lodewijk de Vet of Deltares for supporting me with feedback and advices during the study.

L.J.O. Beiboer

Abstract

In 2012 two reports were published about the sand deficit of the Eastern Scheldt by Deltares. These two reports "Volume analysis on RTK profiles of the Eastern Scheldt" and "Prediction of the Eastern Scheldt morphological evolution based on erosion trend" were used to visualise the sand deficit of the Eastern Scheldt and to make predictions of the height and emersion time of the intertidal flats. During the last few years, researchers noticed a potential change of the erosion rate on the intertidal flats. Because of this a new study was needed.
Furthermore, the manager of the Eastern Scheldt, Rijkswaterstaat, is designing and planning to execute new nourishments in the Eastern Scheldt.

This study aims to provide an update of the erosion rate of the intertidal flats and its subareas in the Eastern Scheldt to generate new predictions for designing and planning sand nourishment on the intertidal flats. Because of the suggestions of a changed rate of erosion in the Eastern Scheldt, the following hypothesis was formulated:

The erosion rate of the tidal flats in the Easter Scheldt has decreased since 2010.

To investigate this hypothesis a research question was formulated. The main research question is:

Has the erosion trend of the tidal flats in the Eastern Scheldt in the period 2010 until 2019 changed compared to the erosion trend in the period 1987 - 2010, as described in the reports by Deltares.

The sub-questions supporting the above main question are:

- *Is the erosion trend as observed in this study for the 2010-2019 period compared with the trend established by Deltares on every tidal flat the same? Or are there some erosion spatial variations in the period 2010 – 2019 in comparison to the period 1990 – 2010?*
- *Can the spatial and temporal variations in tidal flats erosion be related to hydrodynamical (wave, tides) and morphological (sediment, elevation) processes in the Eastern Scheldt?*
- *What does the update of the erosion rates of the intertidal flats mean for their emersion time in the context of sea-level rise projections up to the year 2100?*

The available data for this study were the RTK profiles, Vaklodingen, satellite images and wind data. The RTK profiles and Vaklodingen were used to determine the rate of erosion and to redesign the subareas on the flats. Determination of these subareas was based on the satellite image of 2019. The wind data was providing information about the most common wind directions.

The available data was analysed to meet different data quality requirements. The height of the profiles, which have passed the different conditions, was converted to the average height per year and a regression line was fitted. This regression line

reflects the average rate of erosion. With the rate of erosion for the different profiles and years, the following sub-question could be answered.

Is the erosion trend as observed in this study for the 2010-2019 period compared with the trend established by Deltares on every tidal flat the same? Or are there some erosion spatial variations in the period 2010 – 2019 in comparison to the period 1990 – 2010?

A key finding of this study is that the rate of erosion is lower in the period 2010 – 2019 compared to the period 1987 - 2010. This result was observed on all the intertidal flats in the Eastern Scheldt. However, at some of the intertidal flats, the rate of erosion has changed more than on others. This change is also noticeable after analysing the results of the erosion versus the height of the profiles on the flats, i.e. a comparison of the erosion for different parts within the tidal flats. The results are showing more regression lines with a negative slope. This indicates a higher erosion rate at the higher areas of the flat and a lower erosion rate on the lower areas of the flat.

Another indication of a decrease of the erosion rate is the difference between the height as predicted in the previous Deltares reports and the present height of the flats. The present height of the flats is higher than predicted. This observation indicates that the erosion rate has been less than what was predicted in 2012.

Analysing the change in the rate of erosion a hydrodynamical reason for this morphological development could not be detected, because the received frequentation of the profiles was different from the received frequentation of the hydrodynamical data. As a consequence, the following sub-question could not be answered completely:

Can the spatial and temporal variations in tidal flats erosion be related to hydrodynamical (wave, tides) and morphological (sediment, elevation) processes in the Eastern Scheldt?

The spatial and temporal variations in tidal flat erosion are related to morphological processes because the surrounding of an intertidal flat is not completely the same in all areas. At some parts of the intertidal flat, a large fetch is located in front of the flat. This large fetch will influence the waves and morphological processes. This results in spatial variations on the intertidal flat.

Later in this study, the profiles of the intertidal flats have been compared with each other. This comparison delivered reliable data to design subareas on the intertidal flats. Within these subareas, the rate of erosion was estimated. This rate of erosion was used for predicting the height and emersion time of the intertidal flats in the Eastern Scheldt for the years 2030, 2040, 2050, 2060, 2070 and 2080. The update of these predictions answered the last sub-question of this study:

What does the update of the erosion rates of the intertidal flats mean for their emersion time in the context of sea-level rise projections up to the year 2100?

Updating the erosion rate will help to visualise the latest morphological development in the Eastern Scheldt. Furthermore, it illustrates also the emersion time of the intertidal flats. The update of the erosion rate of the Eastern Scheldt shows the emersion time is increasing between 0 and 40% in hectares of the intertidal flats, while the hectares of the areas with a higher emersion time are decreasing.

Nevertheless, at some intertidal flats there is sedimentation, and this means the areas will increase in height as well as in the emersion time.

Apart from the rate of erosion the sea-level rise can also be added for determining the emersion time of the intertidal flats into the future. In this context the emersion time will decrease faster than only with the rate of erosion. Furthermore, the emersion time of the areas showing sedimentation is also decreasing if sea-level rise is applied. Taking this into account adding the sea-level rise will show a more realistic illustration of the emersion time.

As a result of this study, the erosion trend of the intertidal flats showed the erosion trend is changed in the period 2010 - 2019 relative to the period 1987 - 2010. The erosion trend has decreased by 30%. This change in the erosion trend is also visible in the analysis of erosion versus height. The analysis showed there are more regression lines with a negative slope in the period 2010 - 2019 than in the period 1987 - 2010. This indicated that higher areas are eroding faster than the lower areas on the intertidal flats.

As a conclusion, a decrease of the erosion rate of the intertidal flats in the Eastern Scheldt leads to a change in the definition of the subareas on the intertidal flats, because these have also changed.

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Definitions

ArcGIS
ArcGIS is an application for visualising data and calculating data based on x-, y- and z-coordinates.

Emersion time (ET)
The emersion time is the time an intertidal flat will rise above the sea-level

RD Coordinates
The RD coordinates (Rijks-Driehoek) system is the coordinate system used by the Dutch geographical service. The RD coordinates consist of x- and y-coordinates. The y axis is from North to South and the x axis is from West to East. Before 1987, Amersfoort was used as point zero, but this has been changed. Now, the Netherlands is in the positive area of the graph. Figure 1 is an illustration of the RD coordinates. In this illustration point zero is in Amersfoort.

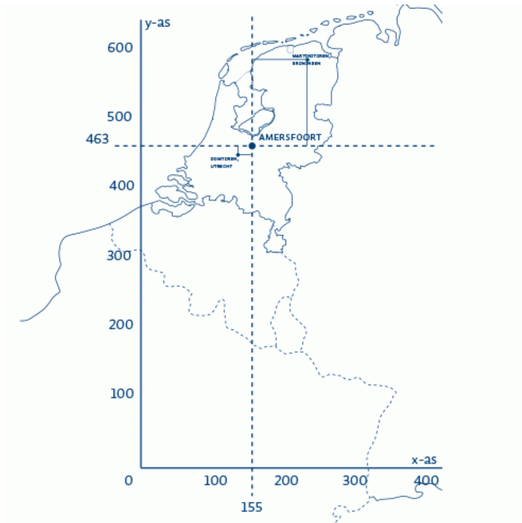


Figure 1. RD Coordinates system overlayed on The Netherlands.

RTK profile
An RTK profile is a straight line on which height data are determined with a GPS pole. RTK stands for real-time kinematic positioning. The RTK profile record elevation data from intertidal flats and are collected by walking. These RTK profiles are measured almost every year, starting from the 80's, depending on the specific profile.

Vakloding
A Vakloding is a way of collecting height or depth data of a certain area by an airplane. These data consist of x-, y- and z-coordinates and can be shown as a layer in ArcGIS.

1 Introduction

This chapter will describe the background and study area.

1.1 Background and Motivation

After the storm flood in 1953, the Dutch government decided to close all the open connections to the sea in Zeeland with dams. Due to protests against closing the Eastern Scheldt with a dam, the Dutch government decided to build a storm surge barrier to protect the hinterland. The storm surge barrier was built in the mouth of the Eastern Scheldt in 1986, at the west side of the Eastern Scheldt. Furthermore, the rivers flowing into the Eastern Scheldt were disconnected by a dam to protect the hinterland, creating a tide flow of 3 meters and a stable water level between Rotterdam and Antwerp. One of the reasons to build a storm surge barrier instead of a dam was the expected decline of the ecosystem functioning inside the Eastern Scheldt. Besides the protection of the hinterland by the storm surge barrier, experts also mentioned a negative effect on the erosion and sedimentation process on the intertidal flats in the Eastern Scheldt (Louters, Berg, Jan H. van den, & Jan, 1998). The balance between the erosion and sedimentation would be disturbed because the erosion would be increased, but there was not enough information available to inform society about the magnitude of this effect. Figure 2 is an illustration of the situation the Eastern Scheldt before the storm surge barrier was built. Figure 3 is an illustration of the situation in the Eastern Scheldt after the dykes and the storm surge barrier was built.

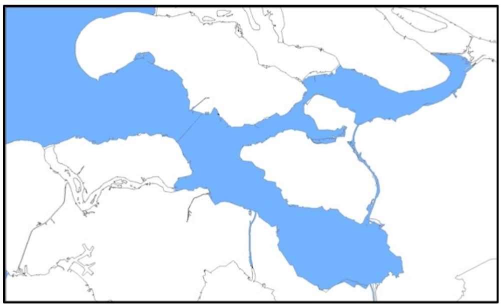


Figure 2. Eastern Scheldt before the storm surge barrier and dams.

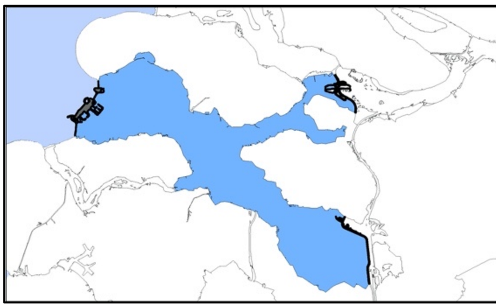


Figure 3. Eastern Scheldt after the storm surge barrier with the dams.

Nowadays, the effect of this disturbed balance between the erosion and sedimentation is visible in the Eastern Scheldt. Due to the storm surge barrier, the sedimentation transport of sediment from the tidal channels to the shoals on the intertidal flats has become less or is disappeared, but the erosion force of waves on the flats is still present. This imbalance between erosion and deposition means that the intertidal flats in the Eastern Scheldt will slowly disappear. A prior study estimated that with an average rate of 1 cm per year all the tidal flats will have disappeared in the second half of the 21th century (E. van Zanten & L.A. Adriaanse, 2008). This disappearing process is called the sand deficit of the Eastern Scheldt because the eroded sand will not return in a natural way to the intertidal flats and there is a lot of sand needed to re-establish the height of the flats.

One of the effects of the sand deficit of the Eastern Scheldt is the declining ecosystem functioning. Moreover, this effect also endangers the safety of dykes. The effects on nature are visible in the emersion time of the intertidal flats. The emersion time is the time an intertidal flat will rise above sea-level. Over the years, the emersion time has become less due to erosion of the flats as well as sea-level rise. This means animals who used the flats as a food resource get less time to eat (E. van Zanten & L.A. Adriaanse, 2008). Figure 4 is an illustration of the emersion time.

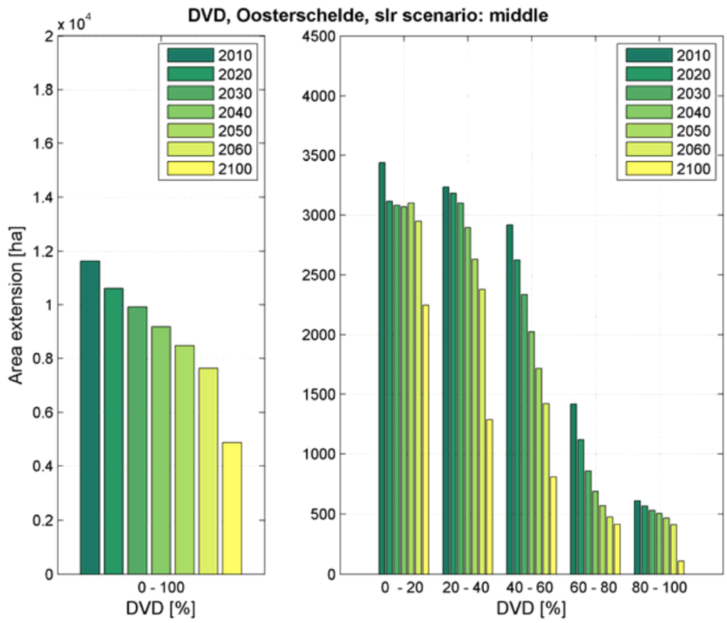


Figure 4. Emersion time chart created by Deltares 2012.

To restore the emersion time of the intertidal flats the manager of the Eastern Scheldt, Rijkswaterstaat, has executed various sand nourishments, such as the nourishment on the intertidal flat Roggenplaat in 2019 and on the intertidal flat Galgeplaat in 2012. In 2025, a new nourishment is planned. The nourishments are expected to have a life span of 25 years, so for the design of the nourishments, it is important to work with up to date figures of the rate of erosion. Because last estimates are already 10 years old and a recent study suggests that the rate of erosion may be slowing down (de Vet, P. L. M., van Prooijen, & Wang, 2017). This means that it is decided to update the predictions using the latest elevation information of the marshes and flats in the Eastern Scheldt.

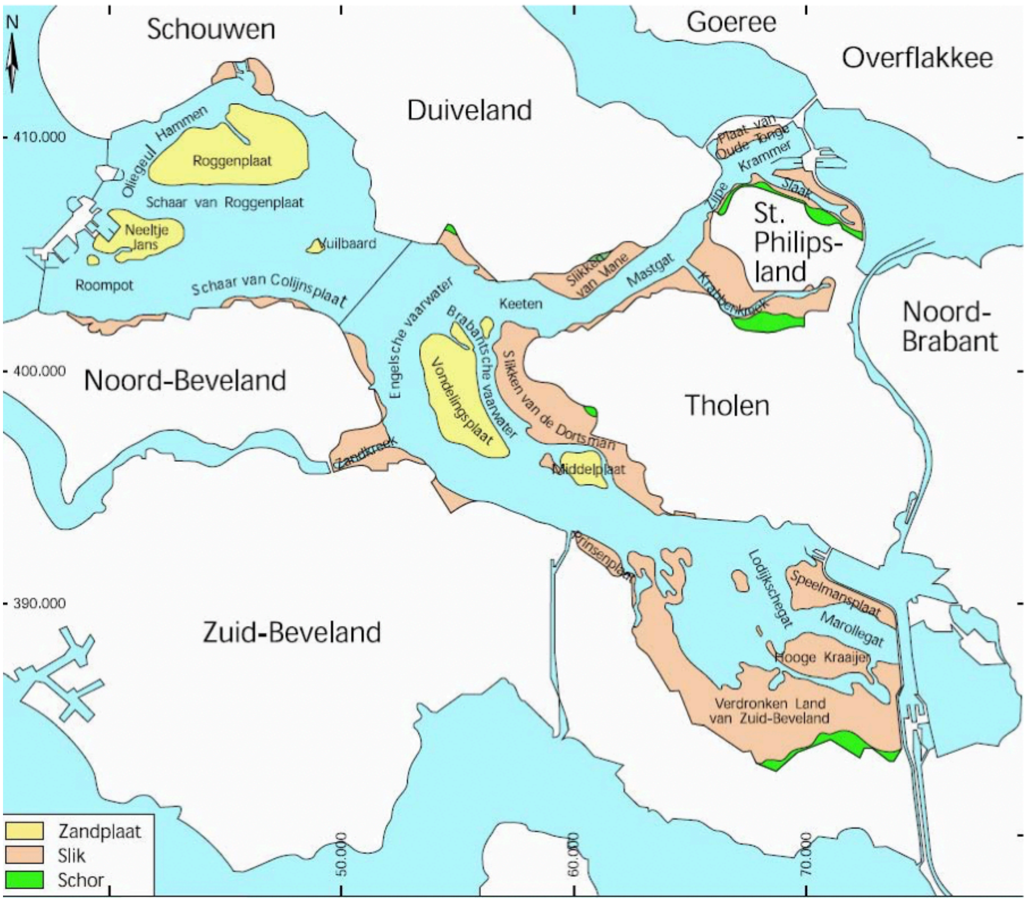


Figure 5. The Eastern Scheldt with the intertidal flats. The Eastern Scheldt is located at the southwest of the Netherlands. The yellow and brown areas are the intertidal flats.

1.2 Research Area

The Eastern Scheldt is located in the southwest of the Netherlands and has a substantial number of intertidal flats. This research applies to the intertidal flats in the Eastern Scheldt. Figure 5 is an illustration of the Eastern Scheldt with the location of the intertidal flats. On the west side of the Eastern Scheldt is the storm surge barrier located. The storm surge barrier is connected to the intertidal flat Neeltje Jans. This research will provide an update to the reports "Volume analysis on RTK profiles of the Eastern Scheldt" and "Predictions of the Eastern Scheldt morphological evolution based on erosion trend", both published in 2012 by Deltares.

In this research, the erosion rate in the period 2010 until 2019 will be analysed, using the same methodology as applied by Deltares. Based on the results of this analysis new predictions will be made to forecast the height and emersion time of the intertidal flats in the Eastern Scheldt. Figure 4 is an illustration of emersion time of the intertidal flat in the Eastern Scheldt.

1.3 Thesis outline

The layout of this thesis follows the order of the research approach. Figure 6 is an illustration of the thesis outline in steps.

In chapter two, the research objective and research question will be established based on previous relevant work and available data.

Chapter three will introduce the data of the selected intertidal flats. The data will be checked before visualising ('data quality assessment'). In addition to the data from the intertidal flats, wind data will be introduced at the end of chapter three.

The data from chapter three will be filtered in chapter four based on three conditions. The first condition is about boundaries and where all the profiles will overlay each other. The second condition is a check if 75% of all the measured points of the profile are inside the boundaries. The last condition is about the years which will be used for the analysis.

The data which have met the conditions will be used for calculating the rate of erosion per profile on the selected intertidal flats. The last paragraph will proceed with the wind data.

Chapter five will execute a correlation between the profiles on the intertidal flats.

In chapter six the results of chapter five will be used to determine the subareas on intertidal flats. The subareas will help to predict the height and emersion time for the years 2030, 2040, 2050, 2060, 2070 and 2080. These forecasts will be visualised in chapter seven.

In chapter eight a comparison will be made between the height of the intertidal flat in 2019 and the predicted height in 2020 estimated by Deltares in 2012.

In chapter nine the conclusions of this research will be formulated.

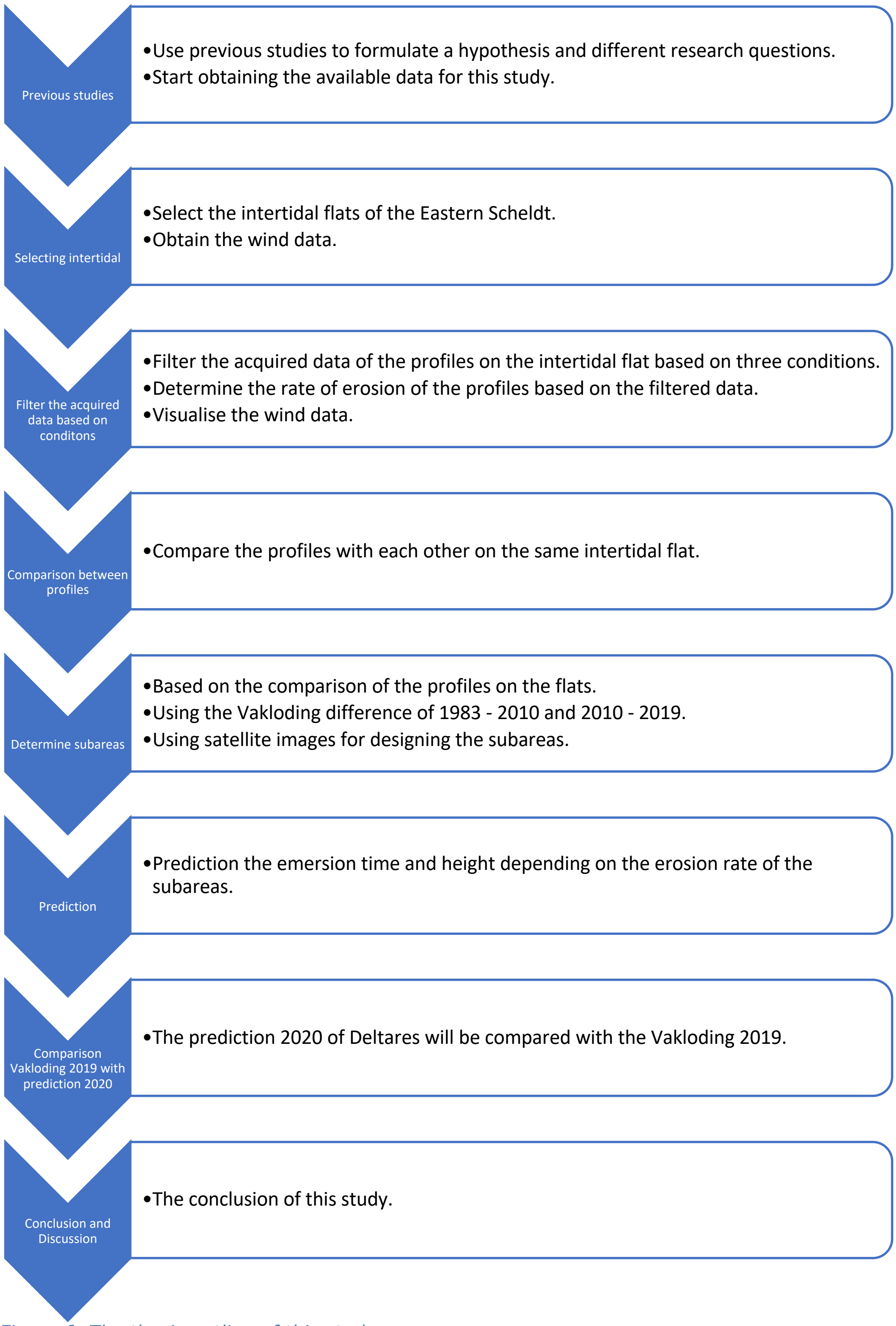


Figure 6. The thesis outline of this study.

2 From literature to hypotheses

In this chapter the aim, hypothesis and research question will be established based on previous relevant work and the available data.

2.1 Available data

In this study, a lot of data is available from the Eastern Scheldt like Vaklodingen, RTK profiles and satellite images. A Vakloding is a way of collecting height or depth data of a certain area by a plane or a boat. These data consist of x-, y- and z-coordinates and can be shown as a layer in ArcGIS. ArcGIS is an application for visualising data and calculating data based on x-, y- and z-coordinates. Vaklodingen have been acquired in 1983, 1990, 2001, 2007, 2010, 2013, 2016 and 2019. These Vaklodingen were used to visualise a spatial image of the height in the Eastern Scheldt. However, the accuracy of these Vaklodingen are approximately between 5 and 10 cm.

RTK profiles are straight lines on which height data are determined with a GPS pole. An RTK profile records elevation data from intertidal flats and these data are collected by walking across the tidal flats. Along these lines, the accuracy of the data is higher than the Vaklodingen. The accuracy of the RTK profiles is approximately 1 cm and show a spatial image of the Eastern Scheldt. These profiles are measured almost every year, starting from 1980, with the exact starting date varying with the specific RTK profiles. Figure 7 is an illustration of an RTK profile.

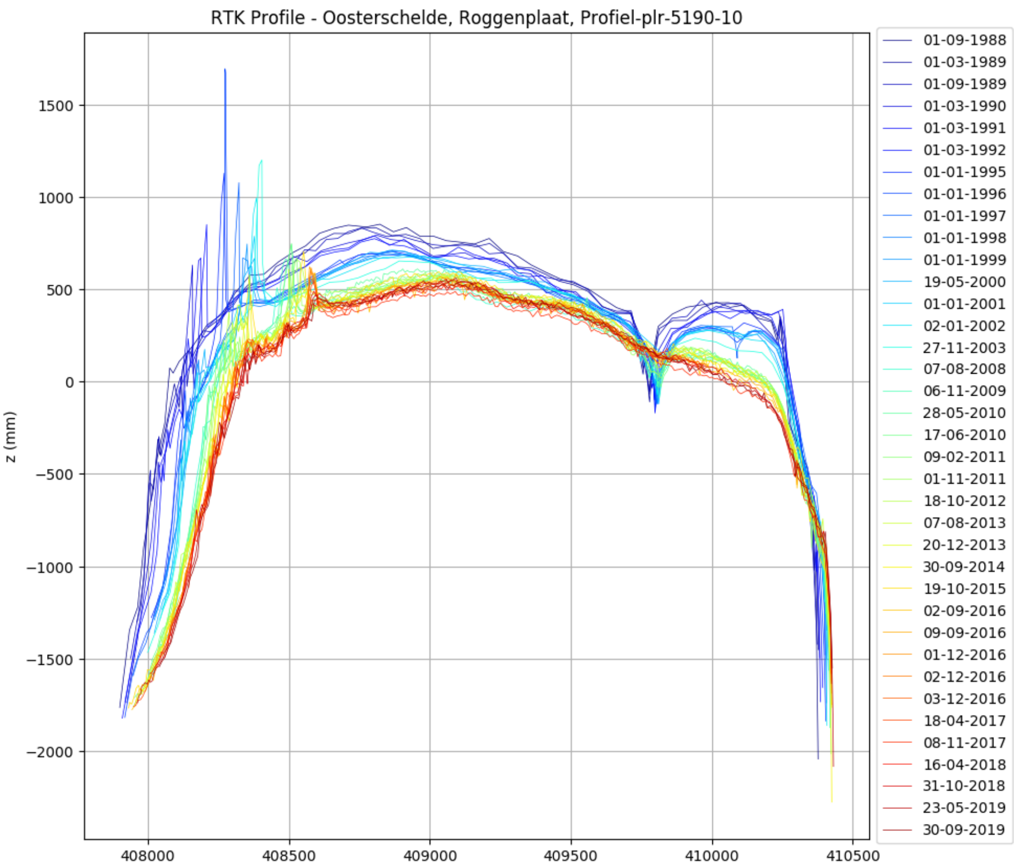


Figure 7. An illustration of the RTK profile. RTK profile Profiel_plr_5190_10 on the intertidal flat Roggenplaat, Figure 8.

Furthermore, the RTK profiles are positioned in such a way the height of the RTK profile can be compared with other profiles on the same intertidal flat. Figure 8 is an illustration of the Vakloding and RTK profiles. The RTK profiles are the lines on the intertidal flat. The Vakloding are the coloured areas on the flat. These colours are based on height.

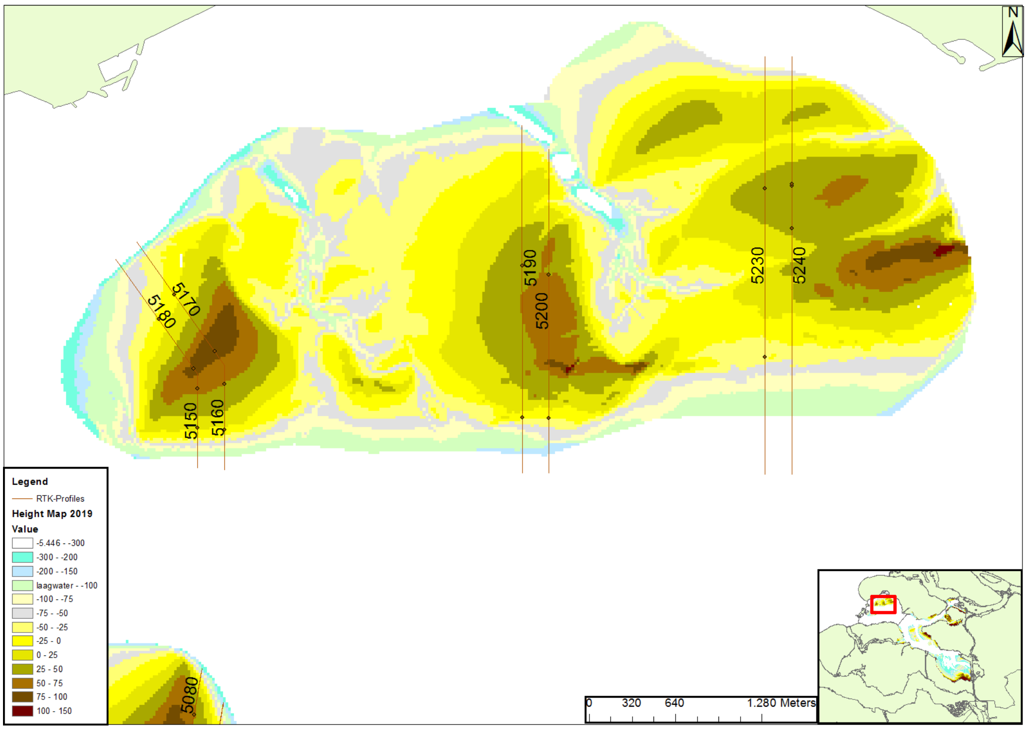


Figure 8. The RTK profiles on the intertidal flat Roggenplaat and the coloured areas are the Vakloding data of the year 2019.

2.2 Previous relevant work

2.2.1 Erosion study of the Eastern Scheldt

To evaluate the magnitude of the sand deficit of the Eastern Scheldt, two papers were published in 2012 by Deltares. Those papers are “Volume analysis on RTK profiles of the Eastern Scheldt” (Santinelli & de Ronde, 2012) and “Prediction of the Eastern Scheldt morphological evolution based on erosion trend” (Santinelli & De Ronde, 2012). In the first paper, an analysis was done on the intertidal flats in the Eastern Scheldt using RTK profiles. The analysis visualised the amount of erosion in mm per year on the intertidal flats in the Eastern Scheldt in the period 1987 until 2010. The erosion rate of the Eastern Scheldt in this period was on average 9 mm per year.

This rate of erosion is mainly controlled by exposure to the dominant wind from the South West and storms, so the erosion rate varies between and within intertidal flats depending on local circumstances. Figure 9 is an illustration of the erosion difference on an intertidal flat.

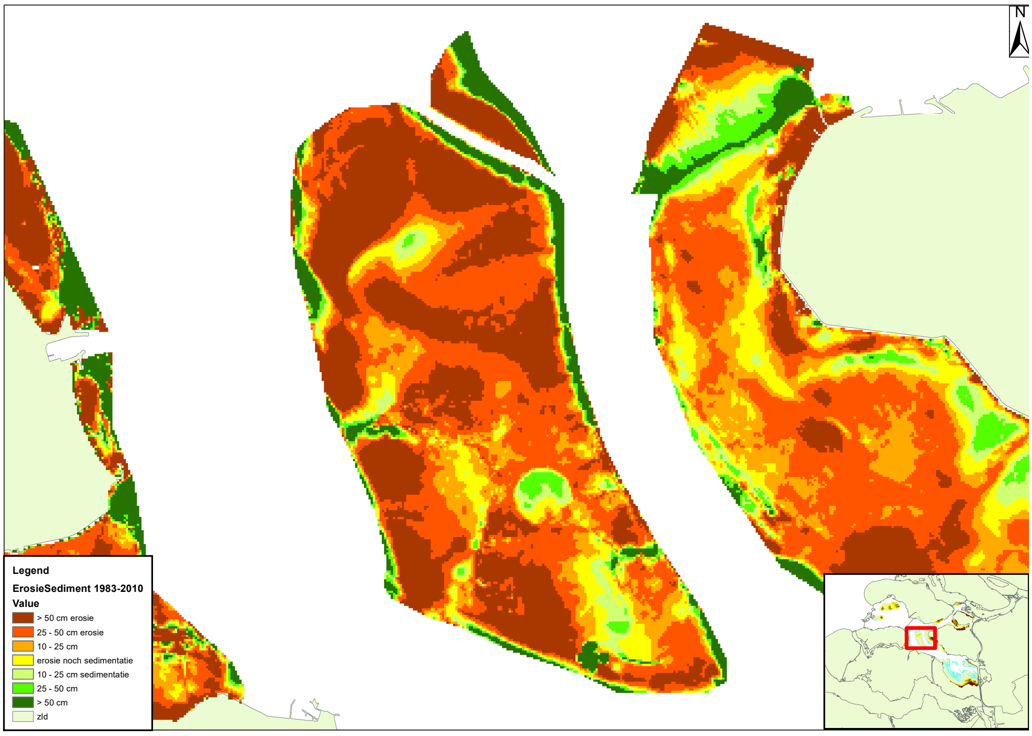


Figure 9. Vakloding difference 1983 – 2010 of the tntertidal flat Galgeplaat. The red areas in the north and west are eroding faster than in the eastern areas.

Figure 10 is an illustration of a wind rose of the period 1987 – 2010. The most dominant wind from the South West.
The results of the first report were used in the second report to design homogeneous areas on the intertidal flats. These areas are also called subareas. The behaviour at these homogeneous areas will be considered as one morphological development.

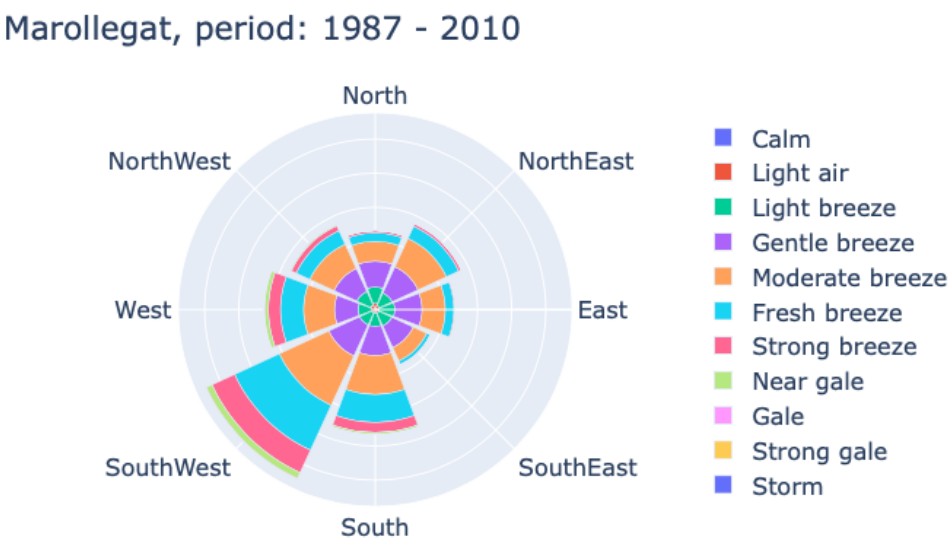


Figure 10. Wind rose of the location Marollegat of the period 1987 - 2010.

Besides the erosion rate of report one, Vakloding of the Eastern Scheldt was also used to determine these subareas. The Vakloding used are 1990, 2001, 2007 and 2010. With these subareas on the intertidal flats, it was possible to make predictions based on the erosion rate of the subareas. The predictions were made to forecast the height and the emersion time of the intertidal flats. Predictions were made for the years 2020, 2030, 2040, 2050, 2060 and 2100.

2.2.2 *Consequences for nature*

These predictions of the emersion time show a decrease of the emersion time. The emersion time is important for animals foraging on the intertidal flats. When the emersion time is decreasing animals, like seals and water birds, have less time to look for food resources and places to rest.

An estimation of the number of oystercatchers showed a decrease with eighty percent around 2045. Moreover, this will also occur to the other water bird animals using the intertidal flats in the Eastern Scheldt (van Zanten & Adriaanse, 2008).

2.2.3 *Close-up study of the intertidal flat Galgeplaat*

Another study about the sand deficit of the Eastern Scheldt is a case study "De morfologische ontwikkeling van de Galgeplaat" (van der Hoeven, M. L. E. B, 2006) This report is a close-up study on the intertidal flat Galgeplaat to determine which hydrodynamical and aerodynamical processes influence the erosion and sedimentation on the Galgeplaat. Hydrodynamical processes are waves, current and tide. The aerodynamical process is the wind.

One of the results of this report indicated the rate of erosion in the period from 1994 until 2001 is less extreme than the rates observed before 1994. As a result of the declining rate of erosion, the Galgeplaat is expected to erode less. Furthermore, in the period 1994 until 2001 also fewer extreme storms were observed, making the trends for the Galgeplaat uncertain and further study with new data will be required to obtain an up to date understanding of its morphological development.

A second result of this report showed the wind blew 44% from a characteristic South West direction during the period 1987 – 1993. This also explained the decline of the height of the intertidal flat Galgeplaat. This means there is a relation between hydrodynamical and aerodynamical processes and rate of erosion.

2.2.4 *Indication of a changed erosion trend*

In 2017 the paper "The differences in morphological development between the intertidal flats of the Eastern and Western Scheldt" (de Vet, P. L. M., van Prooijen, & Wang, 2017) was published. This paper mentioned there could have been a decrease in the erosion rate on the intertidal flats in the Eastern Scheldt around 2007. A decrease of the rate of erosion could have occurred because of the steepness of the tidal flats. The change of the erosion rate suggests there could be a new equilibrium between the erosion and sedimentation on the intertidal flats. Because of this possibility of a new equilibrium the erosion rate needed to be analysed again to test for this suggestion.

2.3 Research Objectives

2.3.1 *Aim of the study*

In 2012 a study was carried out by Deltares about the sand deficit of the Eastern Scheldt. A basin-wide analysis was made of the height measurement and morphological development of tidal flats. This study has provided important insights into the erosion rate of the flats and the difference in the degree of erosion between the areas in the Eastern Scheldt up to the year 2010.

Furthermore, the paper “The differences in morphological development between the intertidal flats of the Eastern and Western Scheldt” suggests the rate of erosion is decreased. This suggestion points out a new analysis is required.

This research aims to provide an update of the predictions of the future elevation of the tidal flats of the Eastern Scheldt employing data from 2010 until 2019, using the methodology as applied by Deltares. Because of the sand nourishments on the intertidal flats in the future.

2.3.2 *Hypothesis*

The paper “The difference in morphological development between the intertidal flats of the Eastern and Western Scheldt” and the case study “De morfologische ontwikkeling van de Galgeplaat” both mention a potential declining rate of erosion in the Eastern Scheldt. In such a manner, the erosion trend established in 2012 need a revision to receive a more decent prediction of the emersion time and height.

The hypothesis of this research is:

- The erosion rate of the tidal flats in the Easter Scheldt has decreased since 2010.

2.4 Research questions

After determining the research objectives, it is possible to produce one main question and three sub-questions.
The main question for this research is:

- *Has the erosion trend of the tidal flats in the Eastern Scheldt in the time period 2010 until 2019 changed compared to the erosion trend in the period 1987 – 2010, as described in the report of Deltares?*

The sub-questions supporting the main question are:

- *Is the trend established by Deltares on every tidal flat the same or are there some erosion spatial variations in the period 2010 – 2019 in comparison to the time period 1990 – 2010?*
- *Can the spatial and temporal variations in tidal flat erosion be related to hydrodynamical (wave, tides) and morphological (sediment, elevation) processes in the Eastern Scheldt?*
- *What does the update of the erosion rates of the intertidal flats mean for their emersion time in the context of current sea-level rising to 2100?*

3 From measured data to illustration

For this study RTK profiles and Vaklodingen were used to analyse the rate of erosion in the Eastern Scheldt. The measured data from the RTK profiles and Vaklodingen were provided by Rijkswaterstaat.
In this chapter the RTK profiles and Vaklodingen will be introduced with illustrations. These illustrations will provide a detailed picture and quantitative understanding of the data. After the introduction of the RTK profiles and Vaklodingen the aerodynamical data will also be introduced and illustrated. This aerodynamical data are provided by Rijkswaterstaat.

Important notes:

1. *All the illustrations in this chapter are also visible in appendix 1 and 2*
2. The colour range of the illustrations in this chapter is based on the age of the measured line. The older lines are blue, and the younger lines are red. With this colour range it is possible to see the pattern of erosion and deposition and the resultant morphological development.

3.1 RTK profiles

3.1.1 Introduction of the data

The provided data from Rijkswaterstaat Zee and Delta exist of RTK profiles and Vaklodingen. RTK profiles are straight lines on which height is determined with a GPS pole. Each point of the RTK profiles consists of an x-, y- and z-coordinate. The x- and y-coordinate will give the position of the measurement based on RD coordinates. The z-coordinate is the height and is converted to a NAP height.

The RTK profiles are on the intertidal flats and the values are obtained by walking across the flat. These profiles are measured almost every year, starting from the 1980s, with the exact starting date depending on the specific RTK profile. Points along the profile are not equidistant on the horizontal axis, and the number of them differs per measurement campaign.

Because the data are obtained by walking the measurement error of the height on the RTK profiles is 1 cm. Compared to the Vakloding data the measurement error of the Vakloding data is between 10 and 15 cm. A lower deviation will result in a more accurate result.

3.1.2 Database

All the RTK profiles on the intertidal flats in the Eastern Scheldt are stored in an RTK database, an interface-based database of Microsoft Office Access. Figure 7 is an illustration of the data of an RTK profile (2.1). The database is called RWS_Profielen and was provided by Rijkswaterstaat. The data in the database for this study are from 1987 to 2019, this means there are 32 years of data. Figure 11 shows the locations of all the profiles in the Eastern Scheldt.

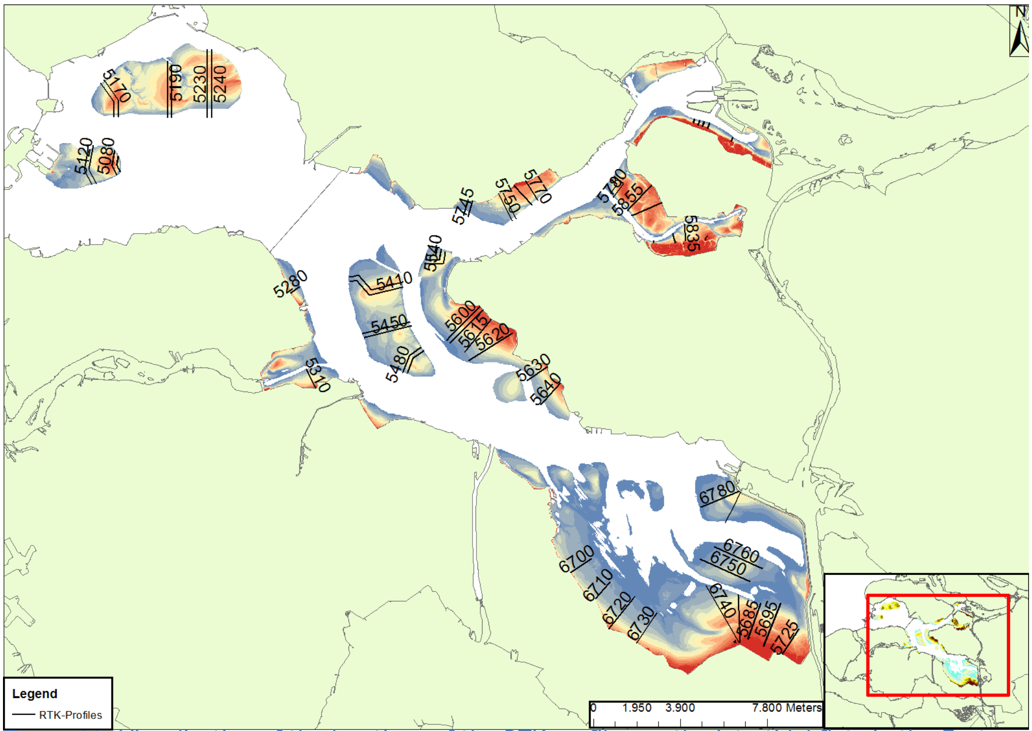


Figure 11. Visualisation of the locations of the RTK profiles on the intertidal flats in the Eastern Scheldt.

3.1.3 *Selecting intertidal flats*

The intertidal flats are sandy bars and salt marshes and are located in the Eastern Scheldt. For this study only selected intertidal flats will be used. The selection is based on the available RTK profiles which have also been used for the paper “Volume analysis on RTK profiles of the Eastern Scheldt” published in 2012 by Deltares. Because of this it will be possible to compare the results of this study with the results of the study of Deltares. Figure 12 shows the selected intertidal flats in the Eastern Scheldt for this study.

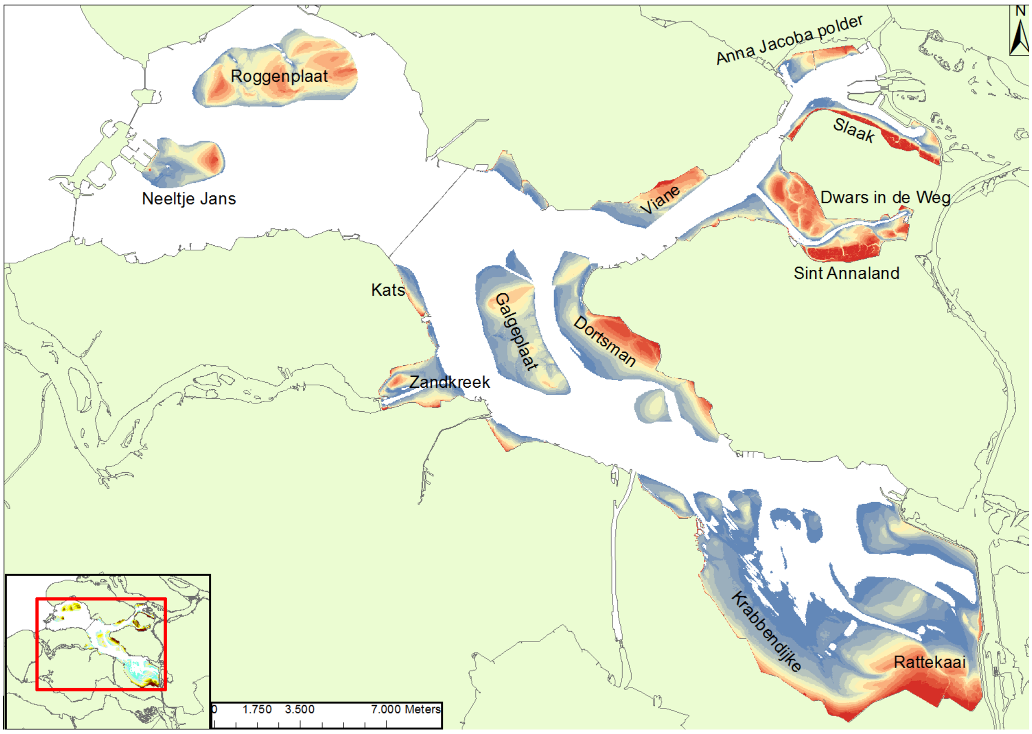


Figure 12. The selected intertidal flats in the Eastern Scheldt for this study.

3.1.4 *Check of the measured data*

When data are collected from the database they need to be checked. The data were checked to estimate if the measured lines per year have been carried out along the same lines, the profile lines. In order to check this, the x- and y-coordinates of each measured line per year were drawn in one graph with the x-coordinates on the x axis and the y-coordinates on the y axis. All the measured lines per year should overlap each other.

Between these lines there is a regression line to check if the lines are straight. The regression line is the best fitting straight line based on the measured coordinates. This regression line is visualised as a dotted line. Figure 13 is an illustration of this check. This checking method is repeated for every RTK profile on the selected intertidal flats.

When all measured lines per year of one profile are straight and overlapping each other, the data of the measured lines are used in further analysis. When a measured year of a profile is not a straight line, compared to the lines of the other years of the same profile, that year will be removed from the profile analysis.

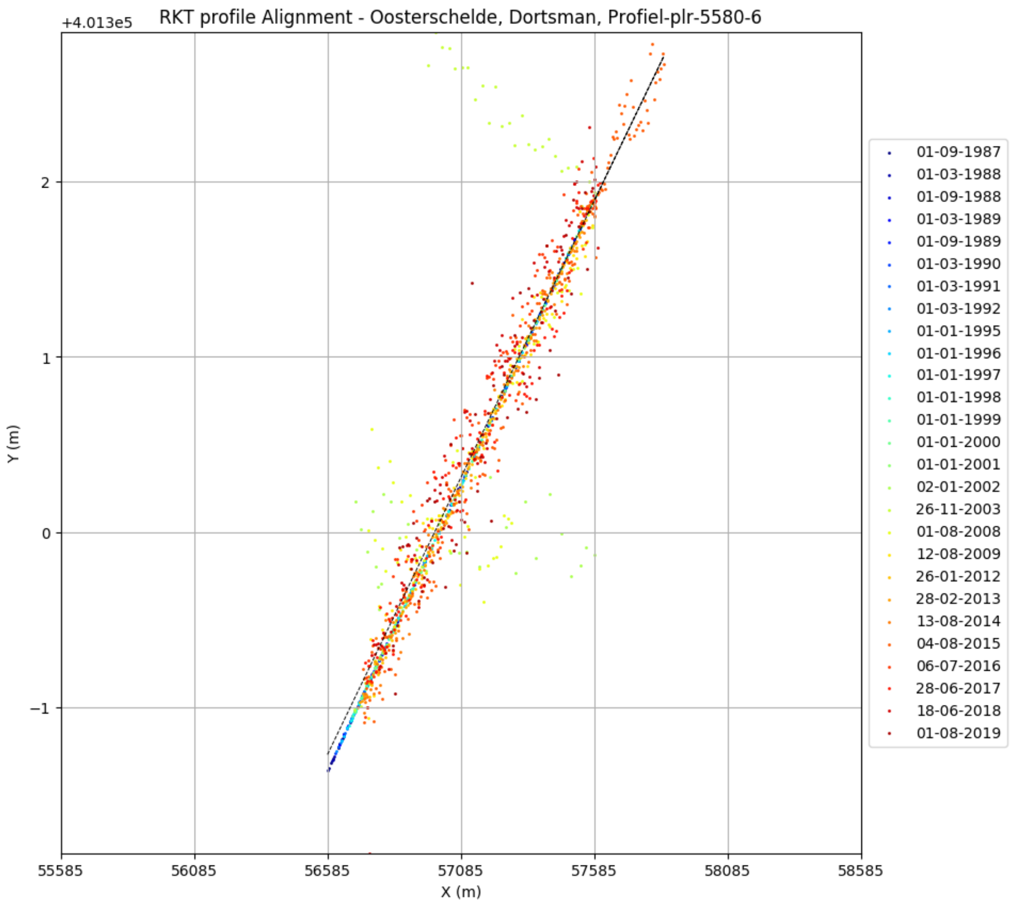


Figure 13. Check if each year of the Dortsman Profiel-plr-5580-6 is straight by plotting the x- and y-coordinates.

3.1.5 *Visualisation height*

When the RTK profiles are checked, the heights per year of the RTK profile can be visualised. In this way it is possible to see the heights from different years in one graph. Figure 14 is an illustration of an RTK profile. The z-coordinate is shown on the y axis, and on the x axis the distance from the starting point of the profile.

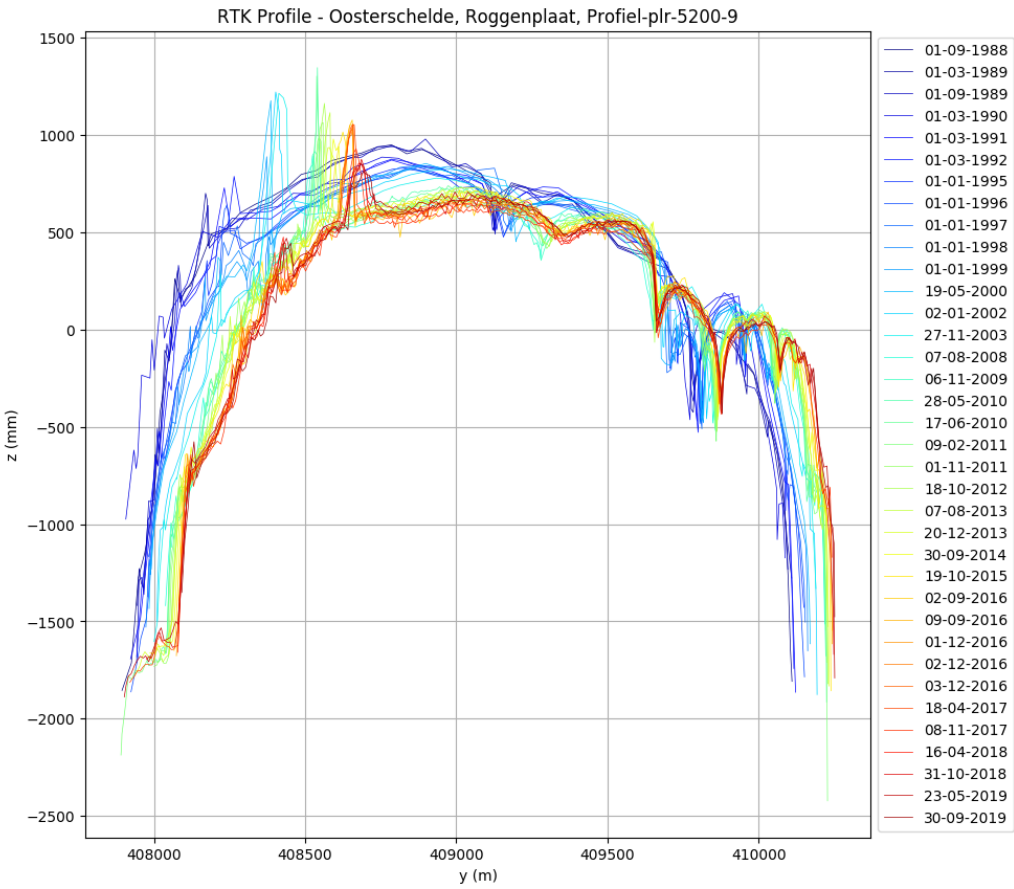


Figure 14. All the heights per year from the RTK-profile, Roggenplaat Profiel-plr-5200-9. Height in millimeters relative to ordnance level NAP. The tidal range at this location is between -1300 to +1300 millimeters.

3.2 Vakloding

3.2.1 Introduction of the data

Besides the RTK profiles, there are also other data on heights available. This data is called Vaklodingen and they are stored in ArcGIS. The Vakloding dataset has a horizontal resolution of 20m x 20m. This is less precise than the horizontal resolution of the RTK profiles, which spans from a few decimetres to several metres. Therefore, profiles based on Vaklodingen measurement will be smoother and more uncertain in terms of height values.

Because of this horizontal resolution, the measurement error of the Vaklodingen is 10-15 centimetres. This means the Vakloding data are not accurate measurements. But the Vakloding can provide a spatial visualisation of the Eastern Scheldt and the Vakloding can be used as a check for the RTK profiles. Because of the spatial visualisation, the Vaklodingen can also be used to design the subareas.

Figure 15 is an illustration of a difference between the Vakloding 1983 and Vakloding 2010.

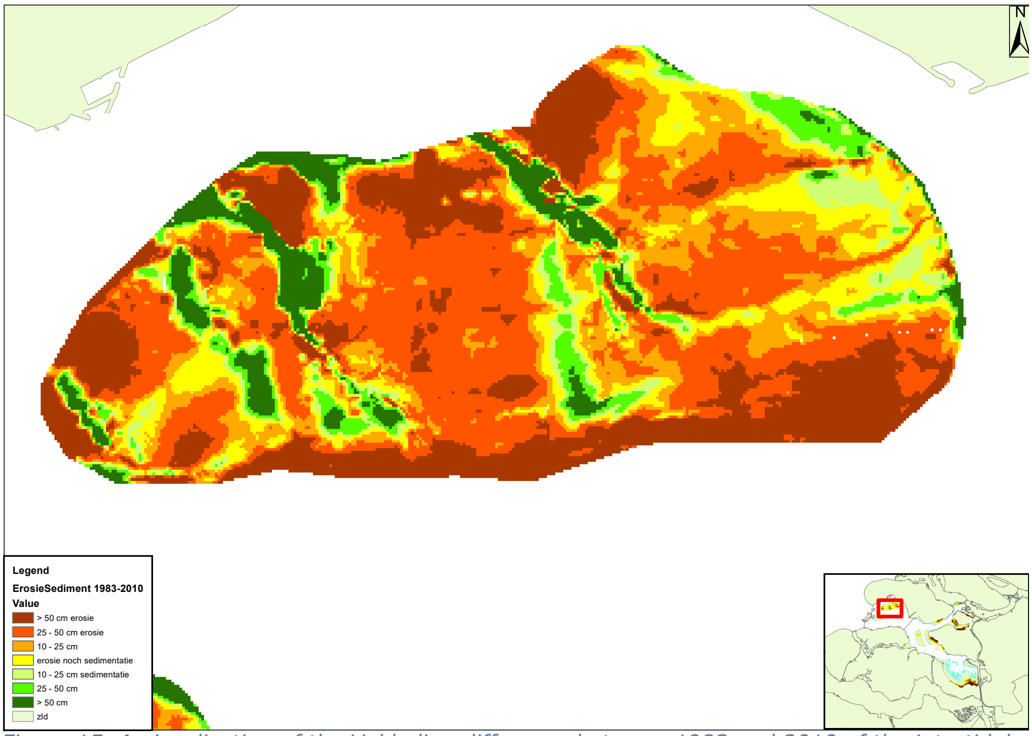


Figure 15. A visualisation of the Vakloding difference between 1983 and 2010 of the intertidal flat Roggenplaat. The red colour is erosion and the green colour sedimentation.

The Vakloding data have been collected with a boat sailing on the Eastern Scheldt or with an airplane flying over the area. The collected data are uploaded into ArcGIS as a raster. This raster contains all the heights of the entire Eastern Scheldt, including the depths of the channels.

The Vakloding database consists of the datasets of 1990, 2001, 2007, 2010, 2013, 2016 and 2019.

3.2.2 *Visualisation of the height*

The height of the Vakloding can be shown as spatial visualisation. Figure 16 is an illustration of spatial visualisation of an intertidal flat together with the lines of the RTK profiles

Furthermore, the height per year of the profile can be visualised. The heights of different years were plotted in one graph. Figure 17 is an illustration of a Vakloding profile. On the y-axis the height is shown and on the x-axis the y-coordinate.

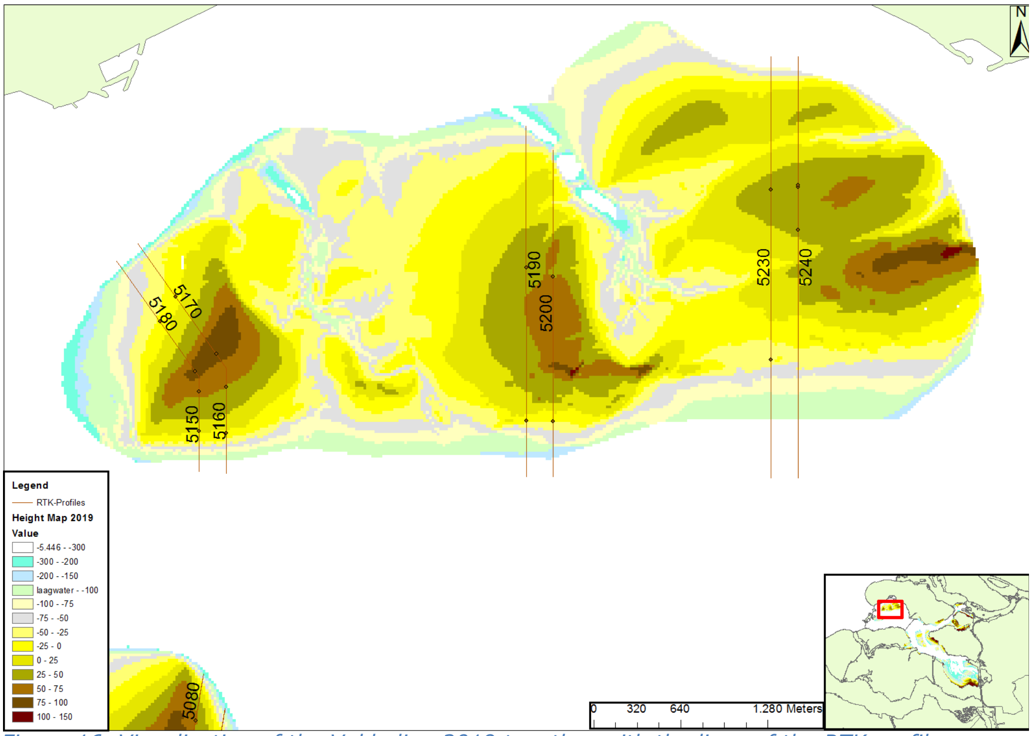


Figure 16. Visualisation of the Vakloding 2019 together with the lines of the RTK profiles.

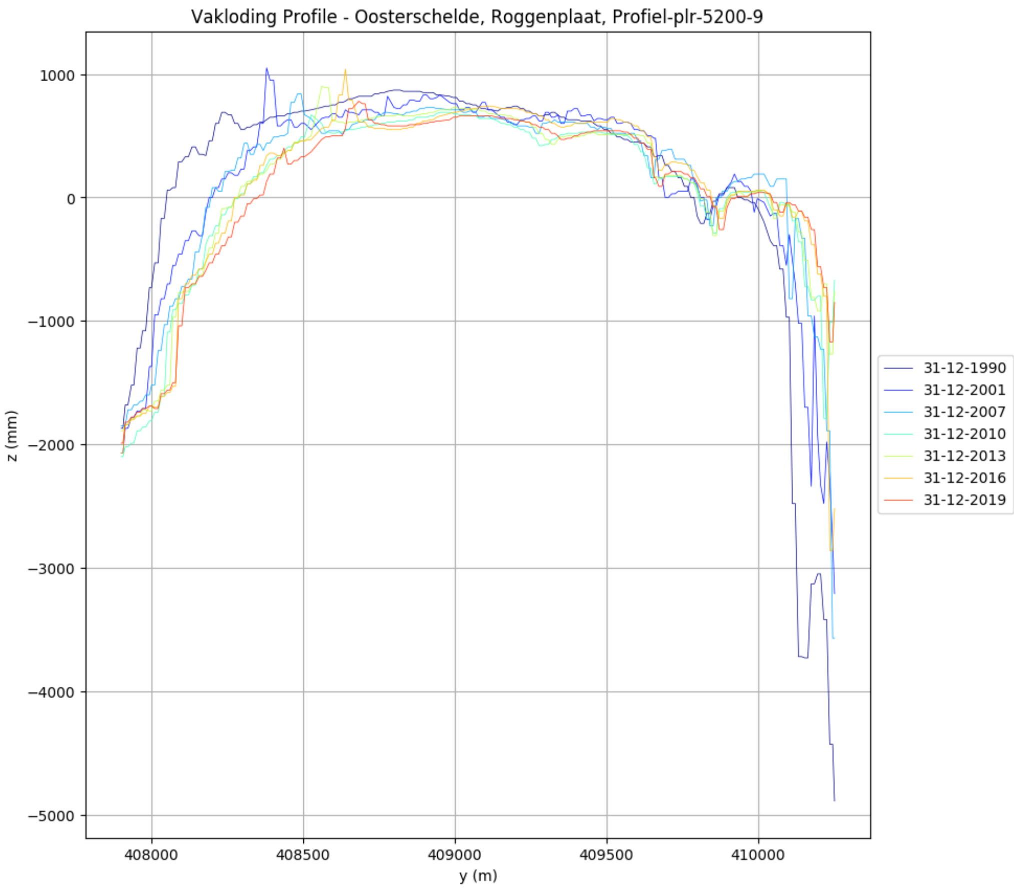


Figure 17. All the heights per year from the Vakloding profile, profile Roggenplaat Profiel-plr-5900-9.

3.3 Visualisation RTK- and Vakloding profile

Comparing Figure 18 and Figure 19 shows erosion in both images. The channel in the RTK profile between 409500 and 410000 has moved to the right and the original channel has been filled up. This is also visible in the Vakloding where the green colour shows a sedimentation below the RTK profile 5200. Figure 18 is the Vakloding difference of 1983 – 2010 together with the lines of the RTK profiles. Figure 19 is the RTK profile Profiel-plr-5190-10.

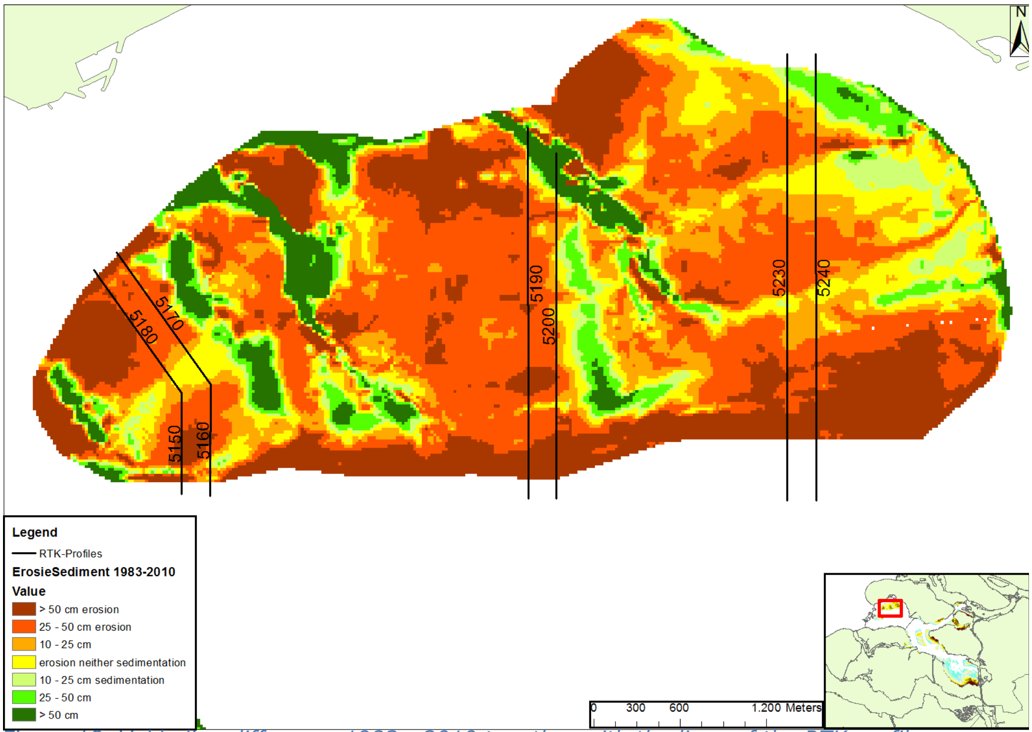


Figure 18. Vakloding difference 1983 - 2010 together with the lines of the RTK profile. Intertidal flat Roggenplaat.

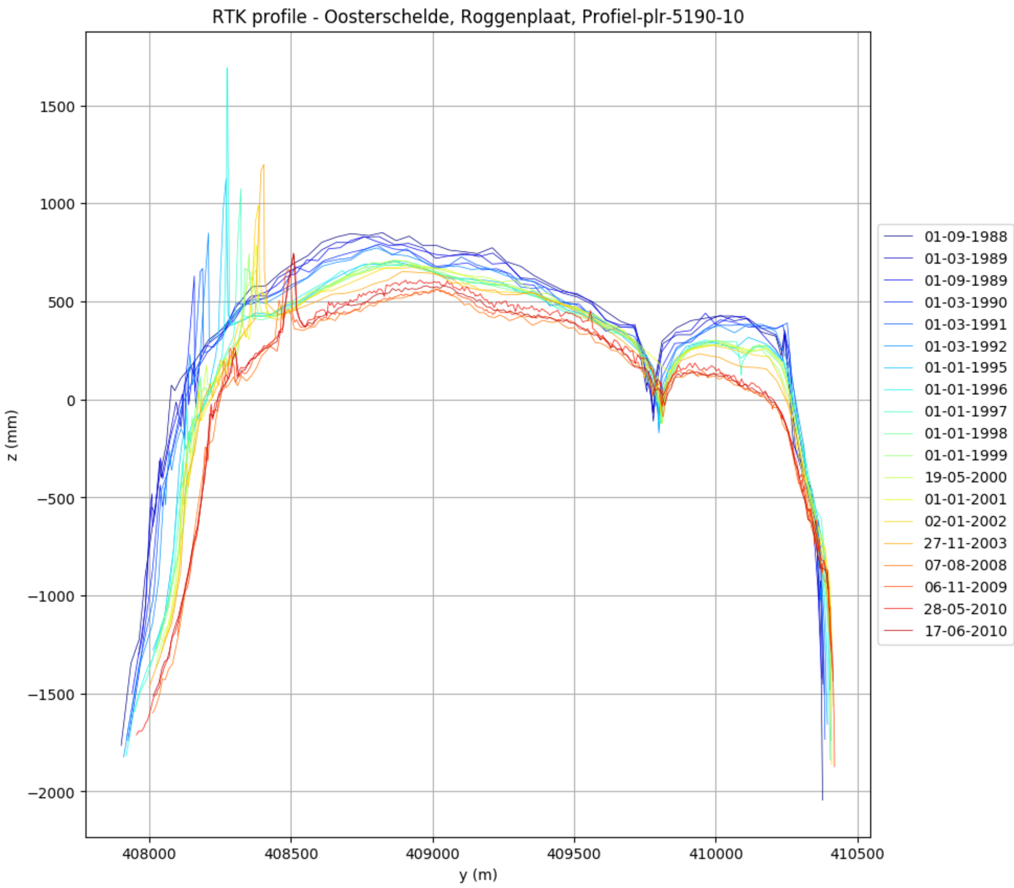


Figure 19. RTK profile Profiel-plr-5190-10, Roggenplaat in the period 1987 - 2010.

The RTK profiles and Vakloding profiles can be put together in order to get a more detailed image of the height of one profile. Figure 20 is an illustration of an RTK profile and Vakloding profile together. The years of the Vakloding profile are shown as dotted lines. When the checks and visualisations were done, the data of the RTK profiles and Vakloding profiles were used in chapter four.

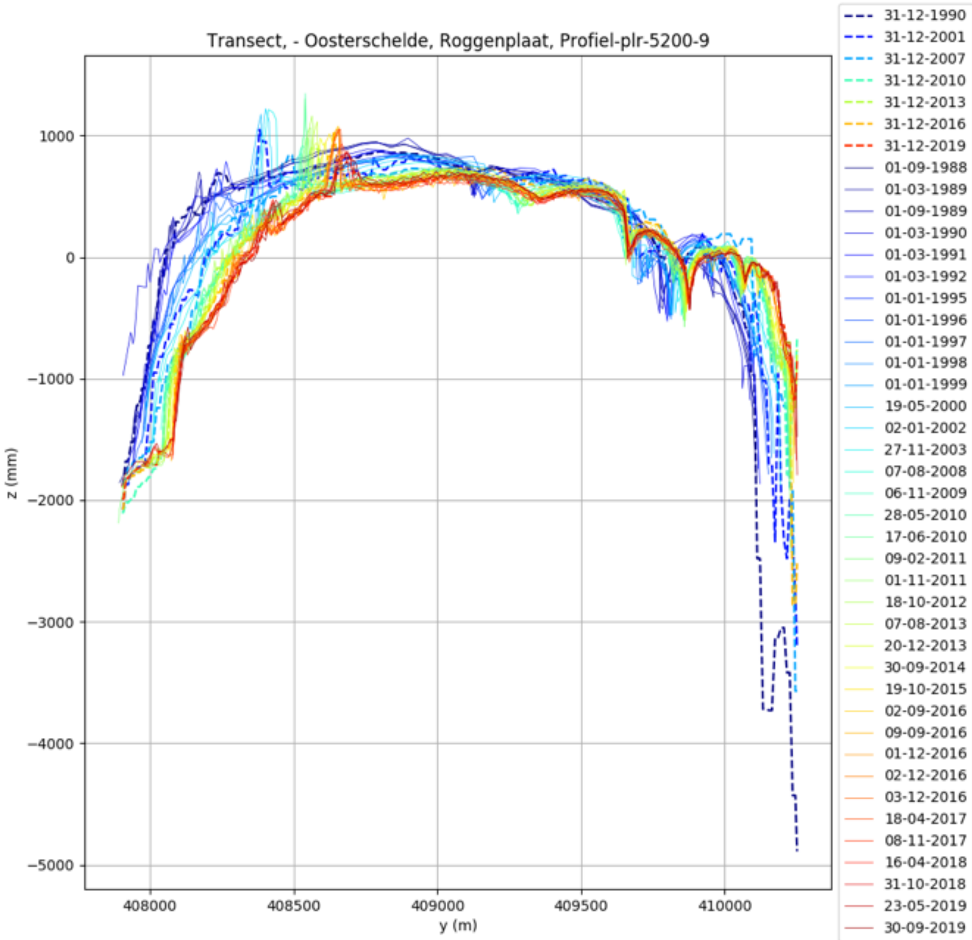


Figure 20. Vakloding profiles (dotted lines) together with the RTK-profile, Roggenplaat Profiel-plr-5200-9.

Analysing the RTK profiles and Vakloding profiles there are some differences. The RTK profiles have a higher measurement frequentation than the Vakloding profiles. The measurement frequentation of the RTK profiles is once a year.
After 2010 some profiles were not measured anymore because of financial reasons. This means the Vakloding profiles are necessary to provide enough data for the period 2010 - 2019.

Another difference is the accuracy of the data. The RTK profiles have a deviation of 1 cm while the Vakloding profiles have a deviation of 10-15 cm.

In this study, the RTK and Vakloding profiles are used together to have enough data to analyse the erosion trend in the period 2010 - 2019. To minimise the measurement error, the average height will be calculated for determining the erosion trend.

3.4 Aerodynamical data

3.4.1 Introduction

Apart from the RTK profiles and Vakloding profiles, so called morphological data, also aerodynamical data were available for analysis. In this study, only the wind data will be used. The wind data will be used to visualise the most common blowing direction.

Based on this direction, the morphological development of the intertidal flats can be interpreted because the wind is influencing the waves depending on the length of the fetch in front of the tidal flats.

3.4.2 *Wind*

The wind data were obtained at two locations in the Eastern Scheldt, these locations area Marollegat and Stavenisse. These locations provided wind data for 30 years. Figure 21 is an illustration of the Eastern Scheldt with measurement stations. The measure station Marollegat is located on the eastern side of the Eastern Scheldt and the station name is MRG. MRG is an abbreviation of Marollegat. The measure station Stavenisse is located close to the intertidal flat Viane and is located in the central northern part of the Eastern Scheldt. The name of the station is STAV, this is an abbreviation of Stavenisse.

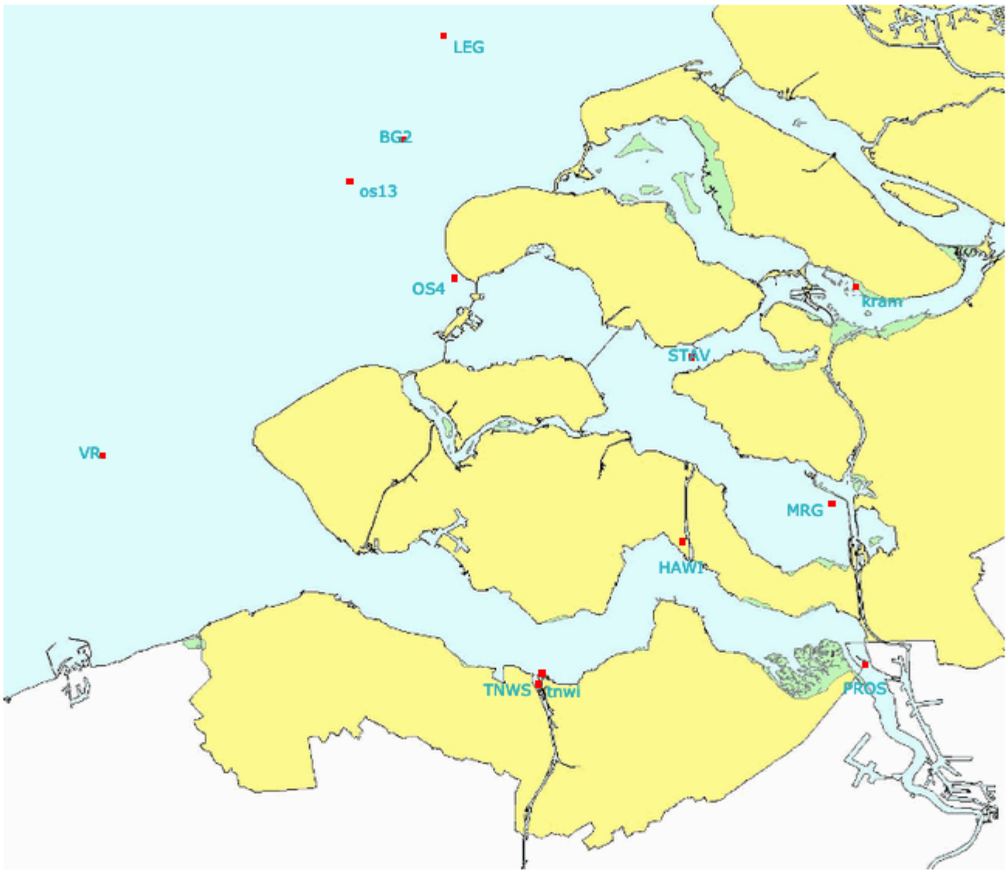


Figure 21. Locations of the measured wind data in 1990.

Before using the wind data, the data need to be analysed for inconsistencies. The measurement frequency is every 10 minutes. The consistency will be determined by counting the missing data and express the missing data as a percentage of the total observations. The years with 20 per cent at the measure location Stavenisse area: 1990, 2014 and 2018. At the measure location Marollegat, these are 1997 and 2018.

As a result, Marollegat has less data gaps than Stavenisse. Furthermore, obtained data at the location Marollegat can be extended to 1987. This means there are 32 years of wind data to analyse.

However, the distance between the intertidal flats on the western side of the Eastern Scheldt and the measuring location Marollegat is larger than the distance between the intertidal flats on the western side and the measuring location Stavenisse. Also, the measuring location Stavenisse is more located in the centre of the Eastern Scheldt.

Therefore, the measuring location Marollegat will only be used for the intertidal flats located on the eastern side of the Eastern Scheldt. The measuring location Stavenisse will be used for the intertidal flats on the west and north side of the Eastern Scheldt.

4 Visualisation to regression lines

Chapter three gave an impression of the amount of data and the structure of the data. In chapter four the visualised data from chapter three will be analysed. Before analysing three conditions have to be met. These conditions are necessary to get comparable results. The analysis results will be compared between different intertidal flats and also with the different profiles on the same intertidal flats. Comparing the results of this data will happen in chapter five.

Important note:

1. *All the illustrations in this chapter are also published in appendix 3, 5, 6 and 7.*

4.1 Trend analysis

4.1.1 Introduction

With the trend analysis, the datasets of the RTK profiles and Vakloding profiles will be used from chapter three. The elevation data profiles, shown in Figure 20, will be calculated to an average height per year based on three conditions. These conditions will be explained in the subparagraph conditions.

Calculating the rate of erosion, the average height will be used, because the average height is estimated on the surface between two measured points of a measured year. Later in this paragraph, the estimated average height per year per profile will be illustrated and a regression line will be added to estimate the rate of erosion.

4.1.2 Conditions

To determine the rate of erosion of the profile three conditions need to be passed. With these conditions, the results will be more reliable, and the profiles can be compared with each other.

The first condition is about boundaries and where all the profiles will overlay each other. Between these boundaries, the average height per year can be determined and the results per year can be compared with the other years on the same profile. The boundaries are on both ends of the overlaid area. Establishing these boundaries per profile will be done by looking for the shortest overlay of the measured length of the years.

In mathematical terms, a group with only the maximum distance values per year is created and a group with the minimum distance values per year. Then from the maximum value group, the minimum value is taken, because this is the lowest maximum value. In the same way with the minimum value group here the maximum value is taken because this is the highest minimum value. These two values will be the boundaries of the area. Inside these boundaries, all the years will overlay each other

The second condition is a check if 75% of all the measured points of the profile are inside the boundaries. This second condition will help to create a reliable dataset for the trend analysis because in this way the amount of data which will be used for comparison is more equal to the other datasets per year per profile. The percentage is determined at 75% because with a higher percentage a lot of the profiles cannot meet this condition.

When a profile cannot meet the second condition some of the years will be removed to reach 75 percent. By removing years, the boundaries will be going further away from each other because the years with the smallest amount of data will be removed. Increasing the distance between the boundaries causes more of the measured points to be available for analysis. The removing process will be repeated until the condition of 75% has been met. The removed years of the profiles are published in appendix 4.

It is important to note that not every profile can pass the second condition. Figure 22 illustrates the removed profiles on the intertidal flats. The removed profiles are the red lines and these profiles were not be used further in the study.

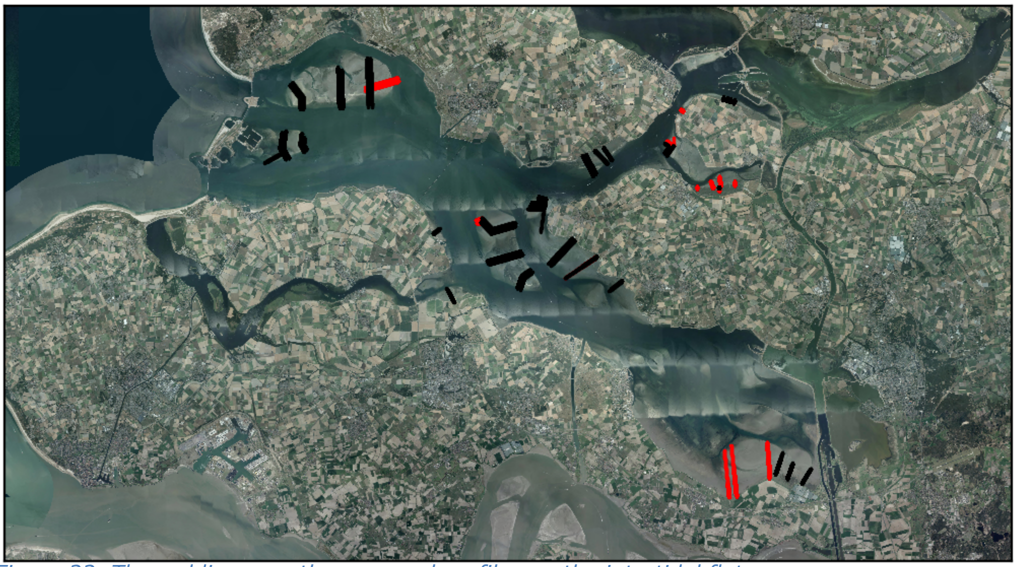


Figure 22. The red lines are the removed profiles on the intertidal flats.

The third and last condition is about which years will be used for the analysis. The dataset for the analysis starts with the year 1987, because of the construction of the storm surge barrier in that year. When the storm surge barrier was built, the sand deficit of the Eastern Scheldt started to affect the morphological development of the intertidal flats in the Eastern Scheldt.

The dataset for the analysis ends with the year 2019 because this is the latest provided dataset. In this way, 32 years of data will be used for this trend analysis

4.1.3 *Summary of the conditions*

In summary, the conditions used in this study to determine the boundaries of the analysed profiles are:

1. *All the years have to overlay each other.*
2. *75% or more of all the measure points has to be inside the boundaries established in condition one.*
3. *The datasets starts with the year 1987 and ends with 2019, so in total 32 years of data.*

Figure 23 is an illustration of these conditions. The black vertical lines are the boundaries.

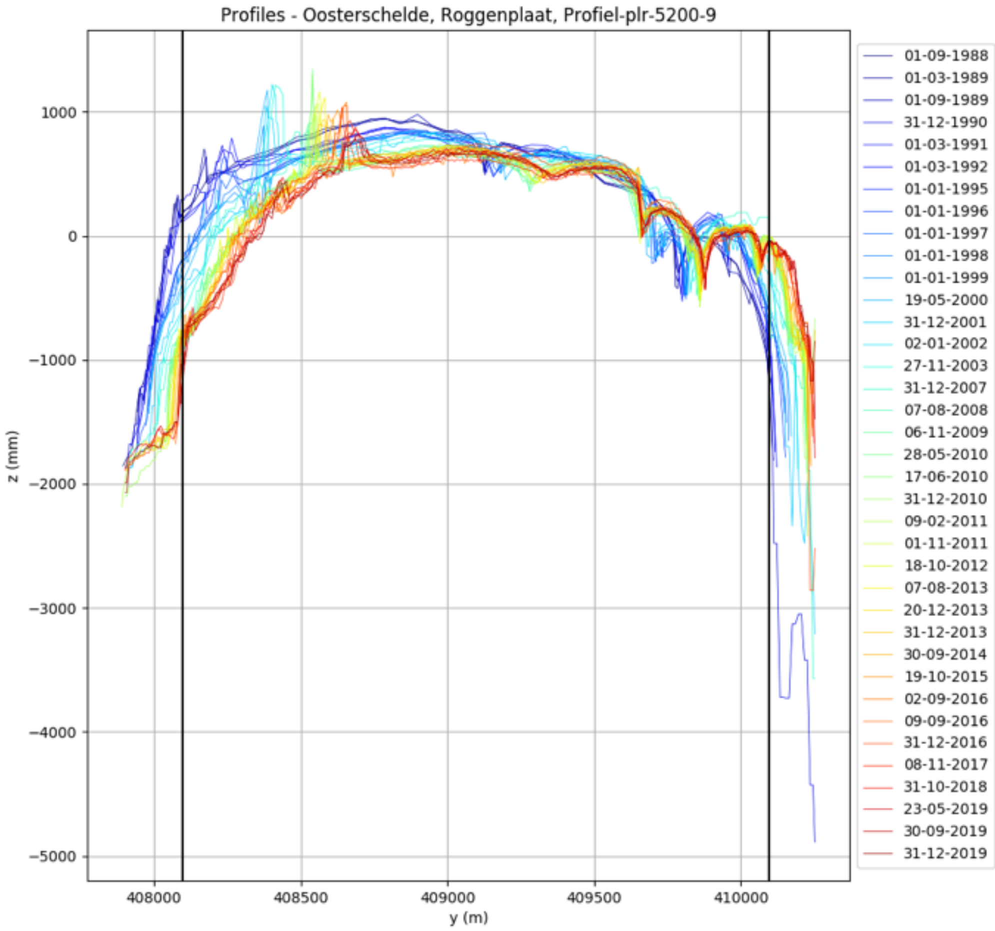


Figure 23. Visualisation of the conditions applied on a profile. Roggenplaat Profiel-plr-5200-9.

4.1.4 *Regression line*

After determining the boundaries, the average height and the rate of erosion per profile can be determined. The average height is determined by dividing the surface below the graph by the length between the boundaries, the two vertical lines in Figure 23. The average height is calculated for each year and all the years together, from 1987 until 2019.

Figure 24, Figure 25 and Figure 26 are illustrations of the average height per year of three profiles. The blue line is the average height per year and the red line is a regression line. The decline of the regression line is an estimate of the rate of erosion in the period 1987 – 2019.

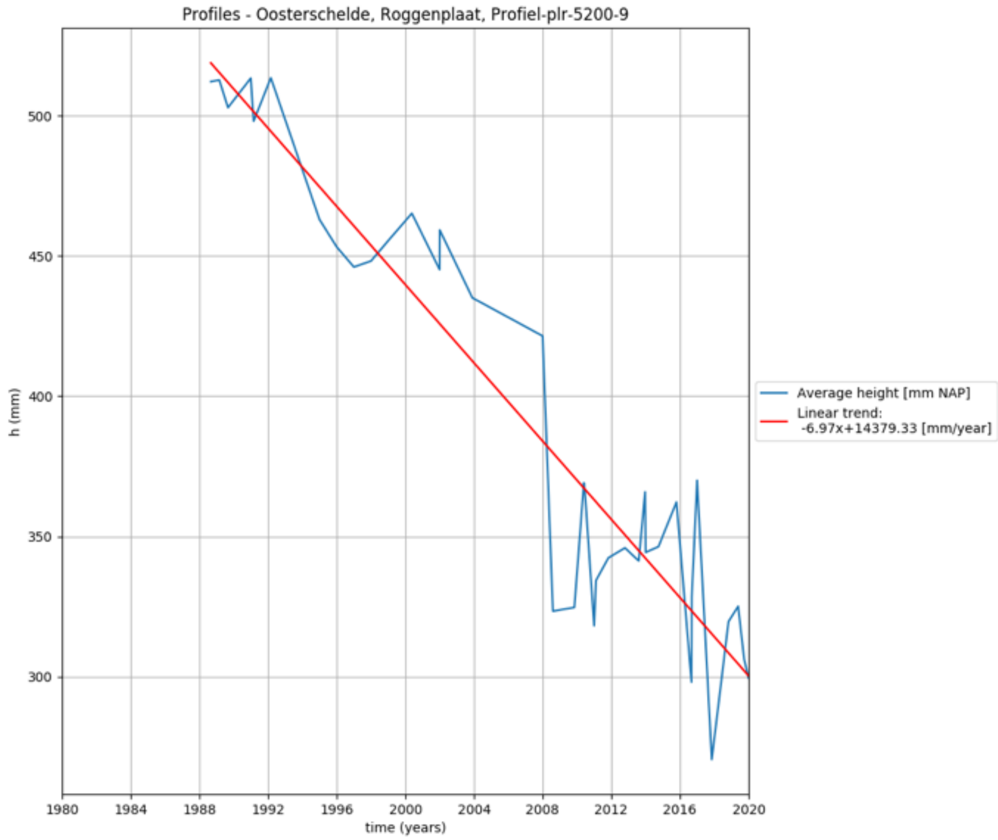


Figure 24. The average height per year together with a regression line. Profiel-plr-5200-9 on the Roggenplaat. The elevation is in millimeter respect to NAP. The regression line shows the average annual erosion of 32 years, in this image -6,9 mm/year.

4.1.4.1 Analysis regression line 1987 - 2019

Analysing the blue lines of Figure 24, Figure 25 and Figure 26 shows that the blue line between 1987 and 2010 is smoother than between 2010 and 2019. The reason for this difference is because of the use of Vakloding profiles. After 2010 the amount of data of the RTK profiles have been decreased. Because of this shrinkage of this dataset, the Vakloding are added besides the RTK profiles to determine the average per year. The other profiles are published in appendix 5.

Using the Vakloding profile data results also in an increase of the measurement error because the measurement error of a Vakloding profile is 10-15 centimetre while the measurement error of an RTK profile is 1 centimetre.

Apart from adding data of the Vakloding profiles data of some years of measured profiles were removed to pass the condition “75 percent or more of all the measure points have to be inside the boundaries”. Nevertheless, some profiles could not pass this condition and were removed from the list and excluded from further analysis.

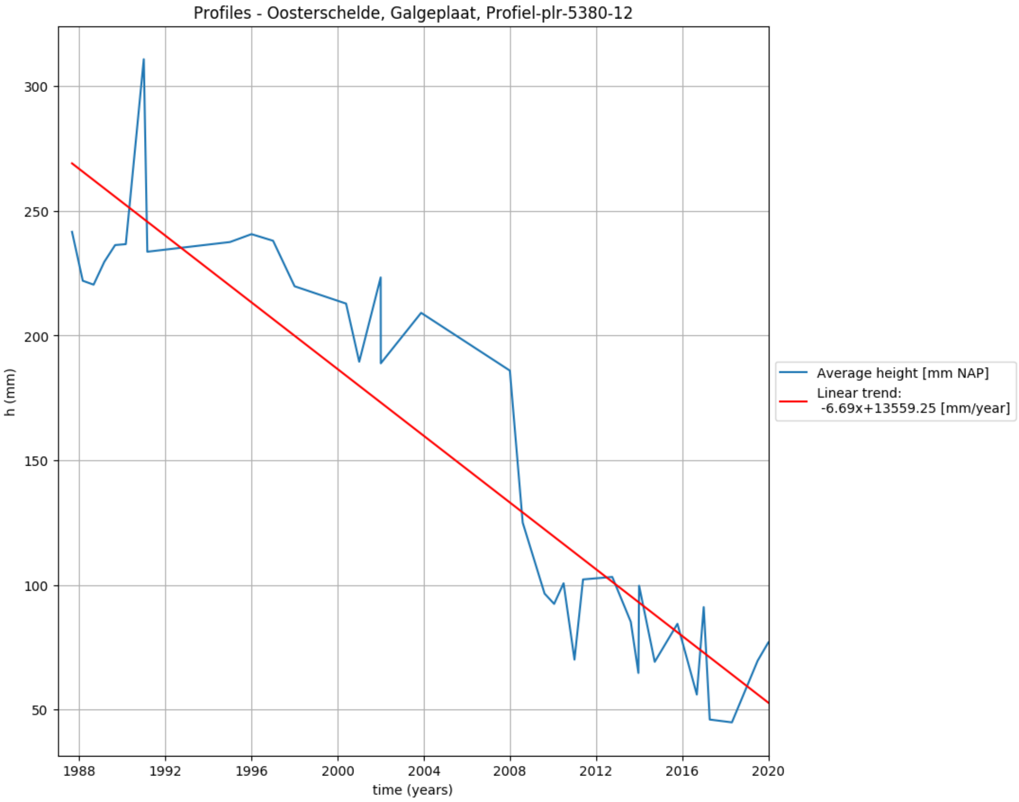


Figure 25. The average height per year together with a regression line. Profiel-plr-5380-12 on Galgeplaat. The elevation is in millimeter respectively to NAP. The regression line shows the average annual erosion of 32 years, in this image -6,7 mm/year.

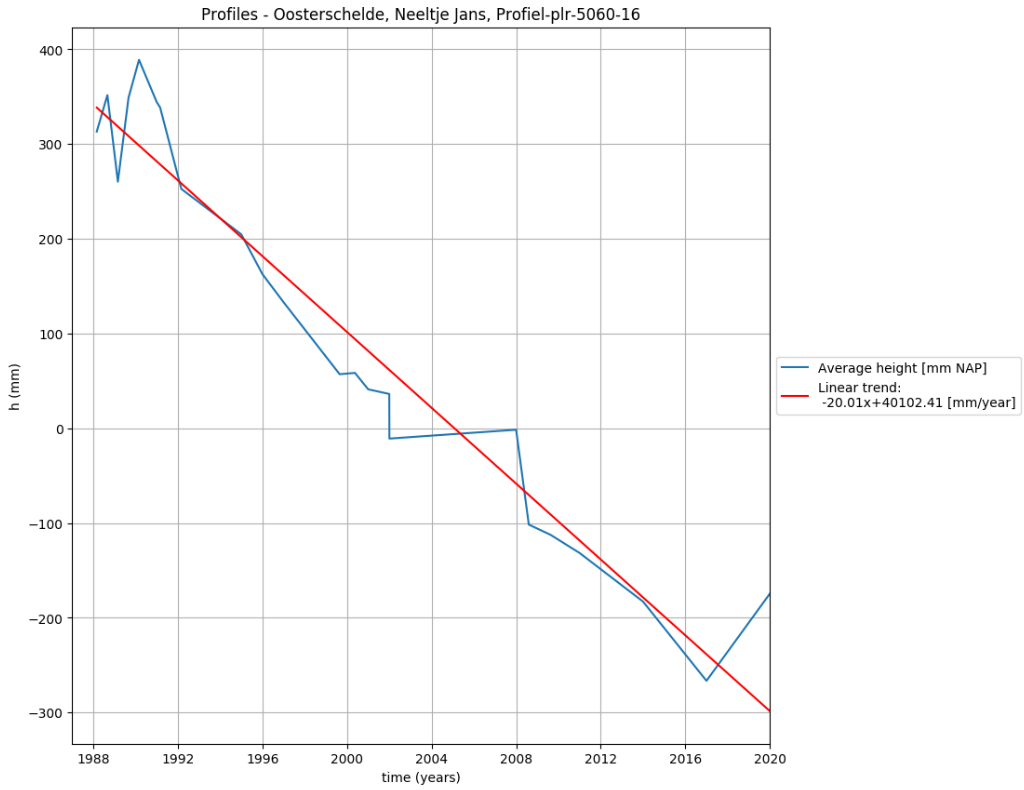


Figure 26. The average height per year together with a regression line. Profiel-plr-5060-16 on Neeltje Jans. The elevation is in millimeter respectively to NAP. The regression line shows the average annual erosion of 32 years, in this image -20 mm/year.

Using one regression line estimates the average erosion rate between all the average heights per year. But this regression line is just a straight line and does not show any changes in the period 1987 – 2019. To visualise the changes in the period the regression line has to be split into multiple regression lines.

4.1.4.2 Analysis regression line 1987 – 2010 and 2010 – 2019

Comparing the regression lines between 1987 - 2010 and 2010 - 2019 shows a decrease in the rate of erosion. This change of the erosion rate is also visible on the other profiles. These profiles are published in appendix 6

Figure 27, Figure 28 and Figure 29 are illustrations of three profiles of three intertidal flats. These illustrations have a breakpoint in 2010. The first regression line, the red line, is 1987 – 2010 and the second line is 2010 – 2019.

Using two breakpoints gives a better result of the erosion rate. However, the breakpoint in 2010 is a chosen breakpoint. To determine a natural breakpoint a statistical analysis is required.

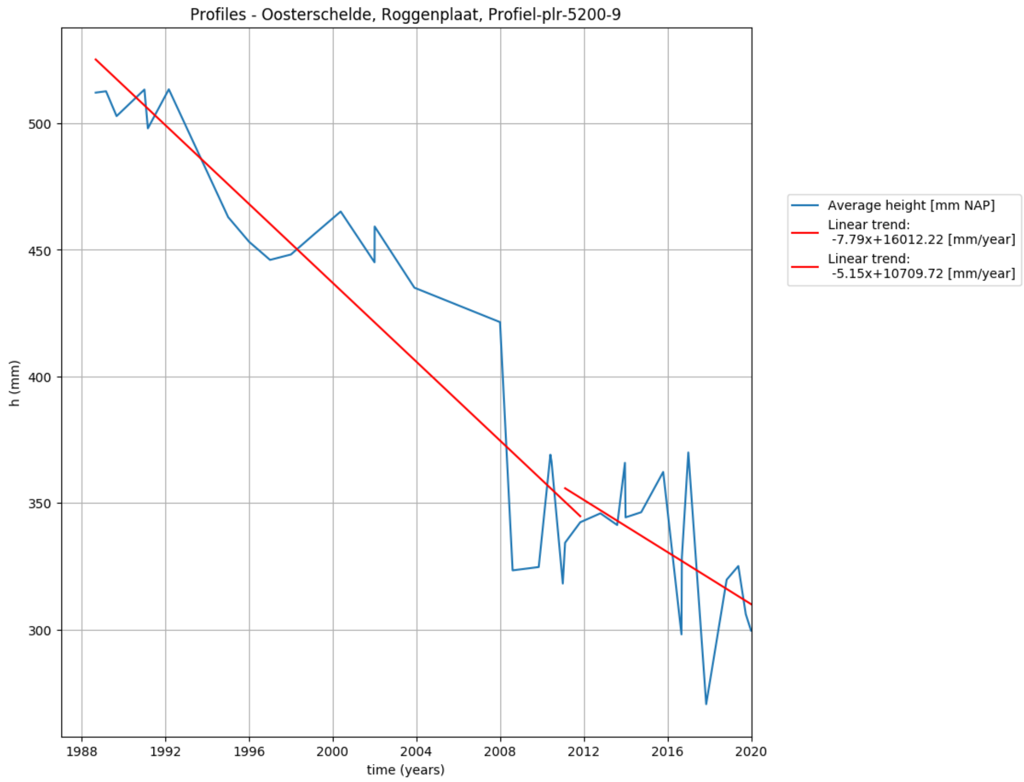


Figure 27. The average height per year together with a regression line. Profiel-plr-5200-9 on the Roggenplaat. The elevation is in millimeter respectively to NAP. The regression line shows the average annual erosion of 32 years, in this image -7,8 mm/year in 1987 – 2010 and 5,2 mm/year in 2010 – 2019.

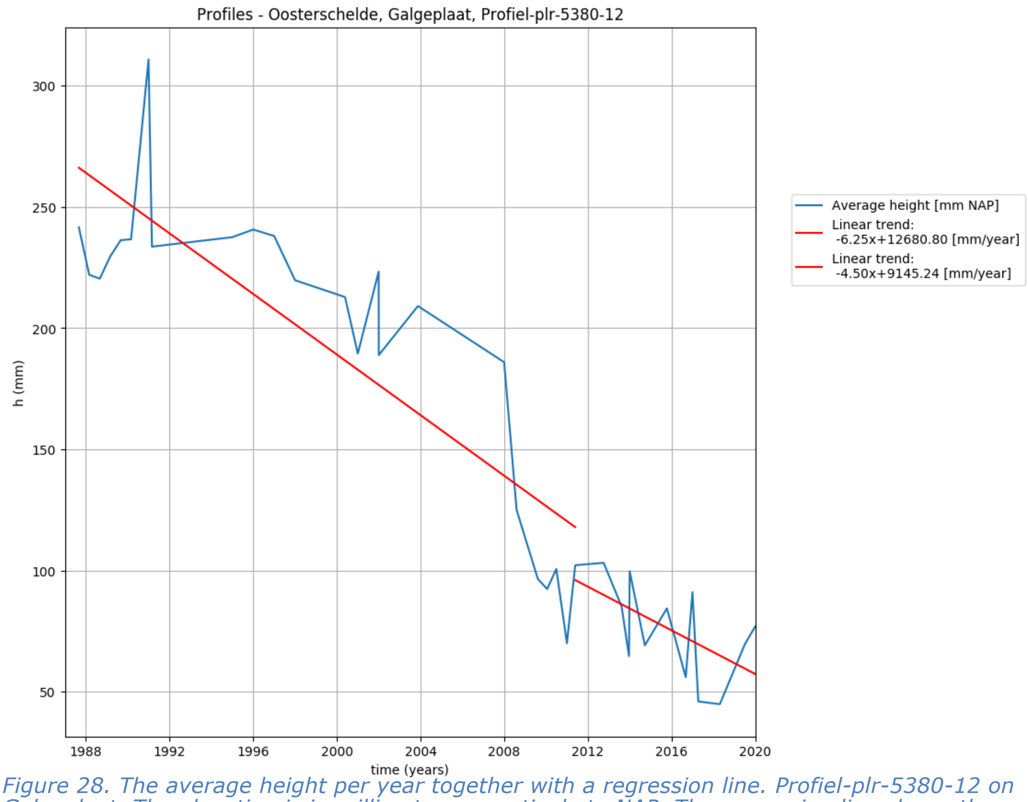


Figure 28. The average height per year together with a regression line. Profiel-plr-5380-12 on Galgeplaat. The elevation is in millimeter respectively to NAP. The regression line shows the average annual erosion of 32 years, in this image -6,3 mm/year in 1987 – 2010 and 4,5 mm/year in 2010 – 2019.

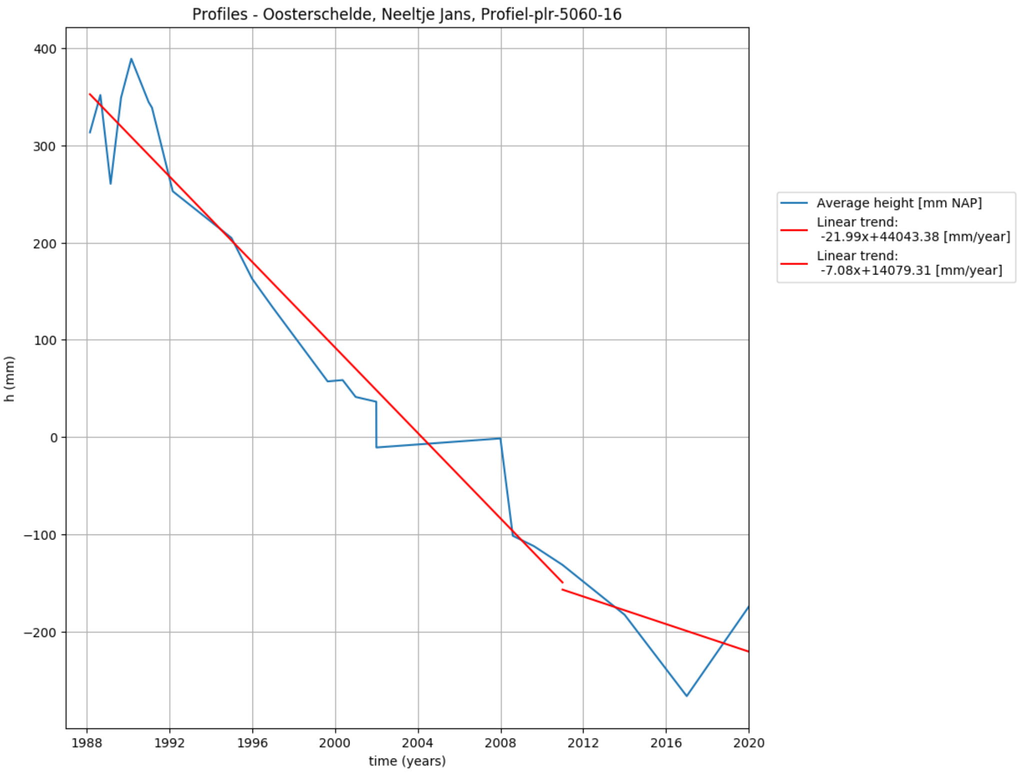


Figure 29. The average height per year together with a regression line. Profiel-plr-5060-16 on Neeltje Jans. The elevation is in millimeter respectively to NAP. The regression line shows the average annual erosion of 32 years, in this image -22 mm/year in 1987 – 2010 and -7 mm/year in 2010 – 2019.

4.1.4.3 Result of the regression lines

The results of the rate of erosion from all available profiles on the intertidal flats (paragraph 3.1.3) can be put together to determine the rate of erosion per intertidal flat and for the entire Eastern Scheldt. Determining the rates of erosion of the intertidal flats are based on a weighted average erosion rate. This weighted average per intertidal flat is calculated with the formula:

$$weighted\ erosion\ rate = \frac{\sum(erosion\ rate * distance)}{\sum Distance}$$

In Table 1 the results of the formula are published. Determining the rate of erosion of the Eastern Scheldt is calculated with the same formula, but now the total sum of the distances of all the profiles in the Eastern Scheldt are used.

Looking into Table 1 shows a missing value of the intertidal flat Sint Annaland. This value was not provided by Deltares in 2012.

Table 1. Erosion rates of the intertidal flats and the Eastern Scheldt in the period 1987 - 2019.

Intertidal flat	Erosion rate 1987 – 2010 [mm/year]	Erosion rate 2010 – 2019 [mm/year]	Erosion rate 1987 – 2019 [mm/year]
Dortsman	-13	-9,42	-10,92

Dwars in de Weg	-29	-26,44	-27,26
Galgeplaat	-6	-1,01	-4,98
Kats	-21	-4,53	-14,09
Neeltje Jans	-10	-6,65	-8,00
Rattekaai	0	3,49	2,77
Roggenplaat	-9	-8,44	-9,37
Sint Annaland	-	-4,96	-2,46
Slaak	-12	-2,57	-4,20
Viane	-9	-8,89	-9,30
Zandkreek	-5	-0,24	-4,41
Eastern Scheldt	-9	-6,27	-8,09

4.1.5 Conclusion

Comparing the erosion rates of the period 1987 - 2010 and the period 2010 - 2019 shows a decrease in the rate of erosion. However, the decrease of the erosion rate was not the same on all the intertidal flats. Some were eroding faster than others.

The erosion rate of the intertidal flats located in the south and eastern side of the Eastern Scheldt has changed more than on the intertidal flats located at the western side of the Eastern Scheldt. Furthermore, the intertidal flat Rattekaai is sedimenting. This means the erosion is decreasing faster at the eastern end of the Eastern Scheldt.

Analysing the results of the column erosion rate 1987 - 2019 shows the values are often in between the erosion rate of the period 1987 - 2010 and 2010 - 2019. The reason for the deviation is because of using the Vakloding dataset. The results of the column erosion rate of 1987 - 2010 are determined by Deltares and only RTK profiles were used.

Apart from this deviation, the results of the column erosion rate 1987 - 2019 show an acceleration of the decreasing in the erosion rate. If the value is closer to the column erosion rate 2010 - 2019 the acceleration of the decreasing in the erosion rate is going faster than when the value is closer to the column erosion rate 1987 - 2010.

4.2 Natural breakpoint analysis

4.2.1 Introduction

In addition to the Trend analysis with one regression line for the entire period from 1987 to 2019, it is also possible to have multiple regression lines. To visualise the multiple regression lines this paragraph is divided into four parts.

The first part is an introduction to the statistic package used to determine the multiple regression lines. The second part will calculate the number of breakpoints of the dataset.

In the third part, the results of the second part will be applied to the dataset to illustrate the multiple regression lines. The last part is a conclusion about the use of multiple regression lines.

4.2.2 F-static in R

A single regression line determines the average erosion rate between all the average heights per year, but this regression line is just a straight line and does not show any changes in the period 1987 – 2019. To visualise the changes in the period the regression line has to be split into multiple regression lines.

A new regression line needs to start at the place where a change did occur. This place is called a breakpoint. To figure out where the changes are located and to estimate every change is reliable it needs to be checked with statistics. This statistical process will be done with the function F-static in the program language R.

The first step is to add the average height per profile into the function. The function will check if there are any changes over the years. Figure 30 is an illustration of the results of the function. The dotted line shows a year of a certain breakpoint.

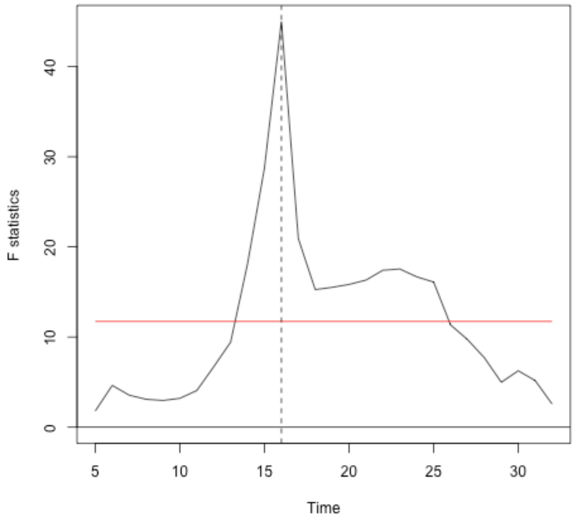


Figure 30. F statistics of the profile Profiel-plr-5200-9.

4.2.3 *BIC – RSS Graph*

Figure 30 is an illustration for determining the breakpoints. To estimate the number of reliable breakpoints a BIC – RSS graph will be used. BIC is the abbreviation of Bayesian Information Criterion, a criterion for model selection among a finite set of

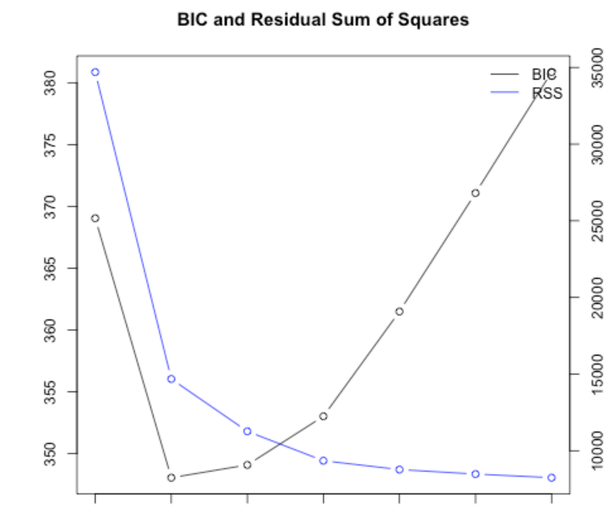


Figure 31. The number of breakpoint for profile Profiel-plr-5200-9.

models where the model with the lowest BIC is preferred. This results into the number of breakpoints. The RSS is the abbreviation of Residual Sum of Squares, a method to estimate the reliability of the calculation. Figure 31 is an illustration of the BIC – RSS graph.

4.2.4 *Visualisation of multiple regression lines*

The F-statics function calculates some possibilities of the number of breakpoints. With the BIC – RSS graph the number of breakpoints will be determined. When the number of breakpoints is determined it can be converted to the years where the breakpoints are.

Figure 32 is an illustration of the results of the BIC – RSS graph. The red lines are the erosion rates during two periods of time. The breakpoint can be found at the place where one red line ends and another red line starts. The green dotted line is the average erosion over the period 1987 – 2019.

4.2.5 *Conclusion*

In the trend analysis paragraph, the average height per year of the profile was determined and was plotted in a graph together with a regression line. This regression line does not show any changes in the period.

In this paragraph, the average height dataset was checked for breakpoints by using statistical methods. After the statistical analysis, most of the profiles could be described using multiple regression lines. Table 2 is an illustration of a weighted average on the numbers of breakpoints per intertidal flat in the Eastern Scheldt.

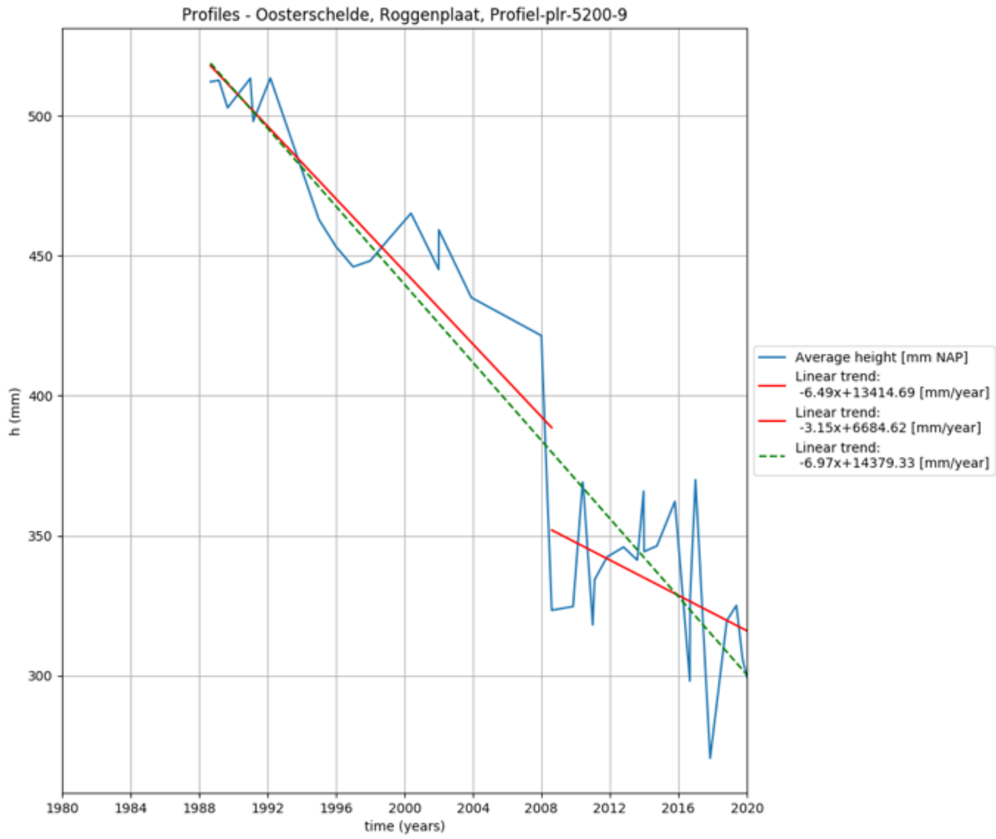


Figure 32. Multiple regressions of the profile Profiel-plr-5200-9, Roggenplaat.

Table 2. The number of breakpoints on the intertidal flats and the Eastern Scheldt.

Intertidal flat	Number of breakpoints
Dortsman	2
Dwars in the Weg	0
Galgeplaat	2
Kats	2
Neeltje Jans	2
Rattekaai	1
Roggenplaat	2
Sint Annaland	0
Slaak	1
Viane	2
Zandkreek	3
Eastern Scheldt	2

Analysing Table 2 shows there are breakpoints in the period 1987 - 2019. The average number of breakpoints in the Eastern Scheldt is two. This means in the period 1987 - 2019 the erosion rate is been changed twice in the Eastern Scheldt. As a deduction, this could indicate that the morphological evolution of the intertidal flats in the Eastern Scheldt is decreased in the period 1987 until 2019.

However, this result is a weighted average so the number of breakpoints on the intertidal flats is different. Also, the year of the breakpoints is not the same on all the intertidal flats.

4.3 Erosion versus Height

4.3.1 Introduction

After determining the erosion rate per profile in the first paragraph, the erosion rate could also be related to the height of the profile. With this correlation, it is possible to show if higher areas are eroding faster or slower compared to the lower areas.

This section is divided into three parts. The first part is an illustration of the data to be used. In the second part, the correlation will be calculated and illustrated in an erosion versus height graph. In this graph, a regression line will be added. The last part is a conclusion of the results of this paragraph.

4.3.2 Visualisation of a profile

For determining the erosion versus height, the RTK profiles and Vakloding profiles will be used. Before the relation between the erosion versus height can be estimated, the dataset including the boundaries needs to be divided into subsections. Each subsection has a maximum length of 200 meters and all the subsections are equally divided.

Figure 33 is an illustration of a profile divided into equal subsections. The black vertical lines are the boundaries and the grey vertical lines are the boundaries of the subsections.

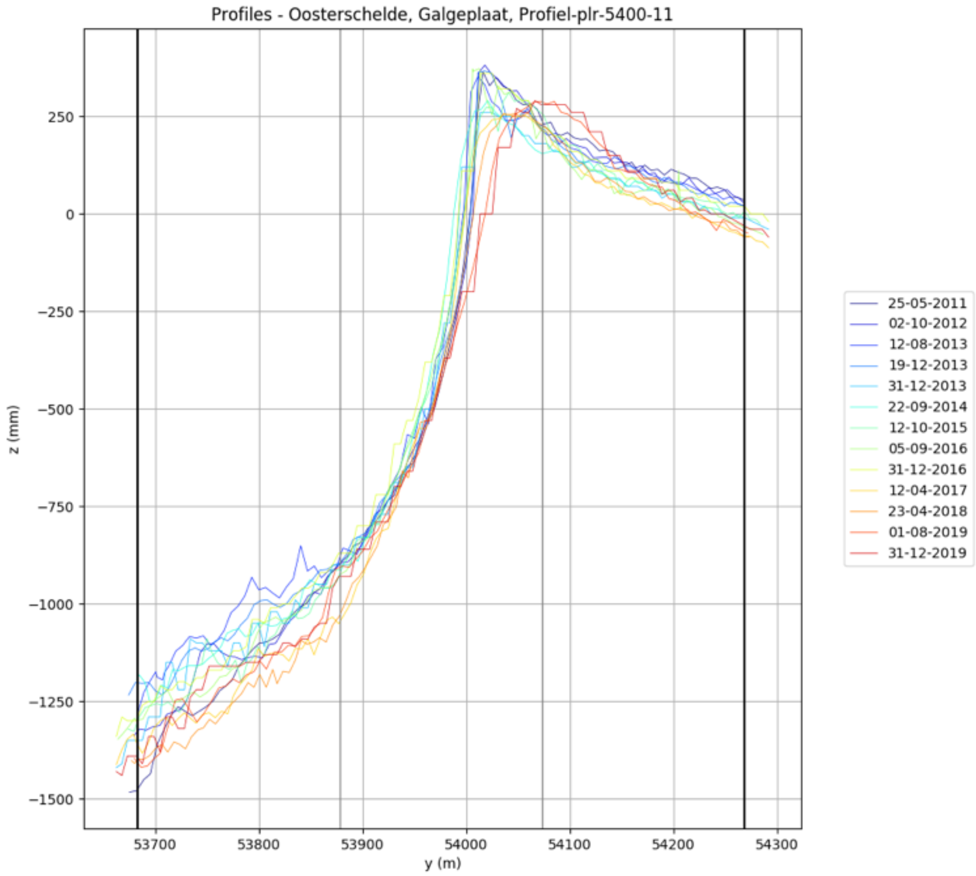


Figure 33. Illustration of a profile divided in equally sized subsections.

4.3.3 *Calculation of erosion versus height*

To determine the rate of erosion, the dataset of the whole area between the two black boundaries will be used. To calculate the erosion rate depending on the height, the rate of erosion will be calculated in each subsection.

Besides calculating the rate of erosion, the heights of the subsection will also be collected in one group. This group is ordered, and the median of this group is calculated. The median of this group is the median height. This process will be repeated for each subsection per profile per intertidal flat.

Figure 34 is an illustration of the results after calculating the rate of erosion and the height of one intertidal flat. In this illustration, a regression line has been drawn to visualise if higher parts or lower parts are eroding faster. The blue area around the red line is a 95% confidence range of the regression line. This illustration suggests only a small correlation between the rate of erosion and the height of the intertidal flat because the R-square value is 0.03. This means the rate of erosion is not related to the height of the intertidal flat.

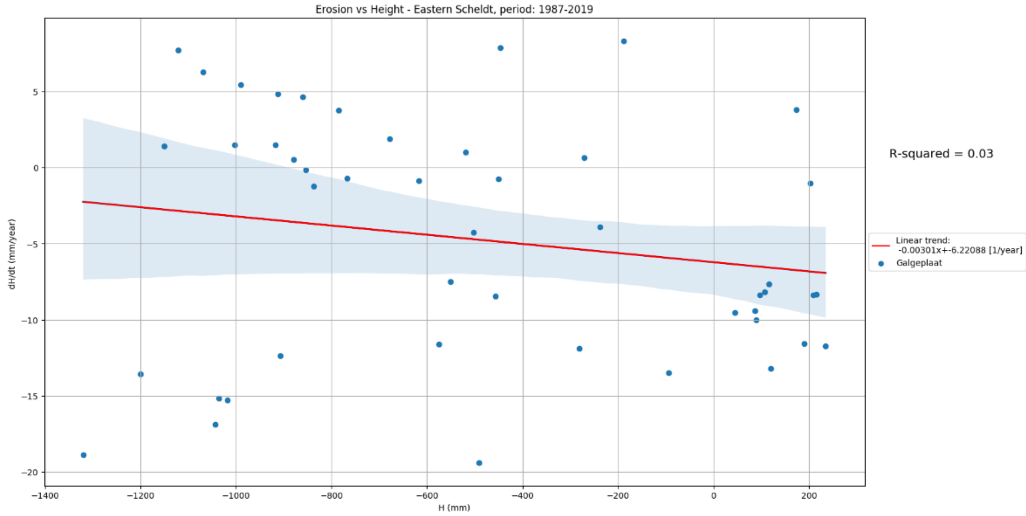


Figure 34. An illustration of the erosion versus height of one intertidal flat.

4.3.4 *Conclusion*

Determining the erosion versus height will help to visualise if higher areas on the intertidal flat are eroding faster than the lower areas on the flat. When this occurs, the intertidal flat is getting flatter. This means the emersion time will also be decreasing.

When the lower areas are eroding faster than the higher areas the intertidal flat is getting smaller. This means the amount of hectares the animals, such as seals and water birds, can use is decreasing. Figure 35 is an illustration of all the intertidal flats of the Eastern Scheldt together in one graph.

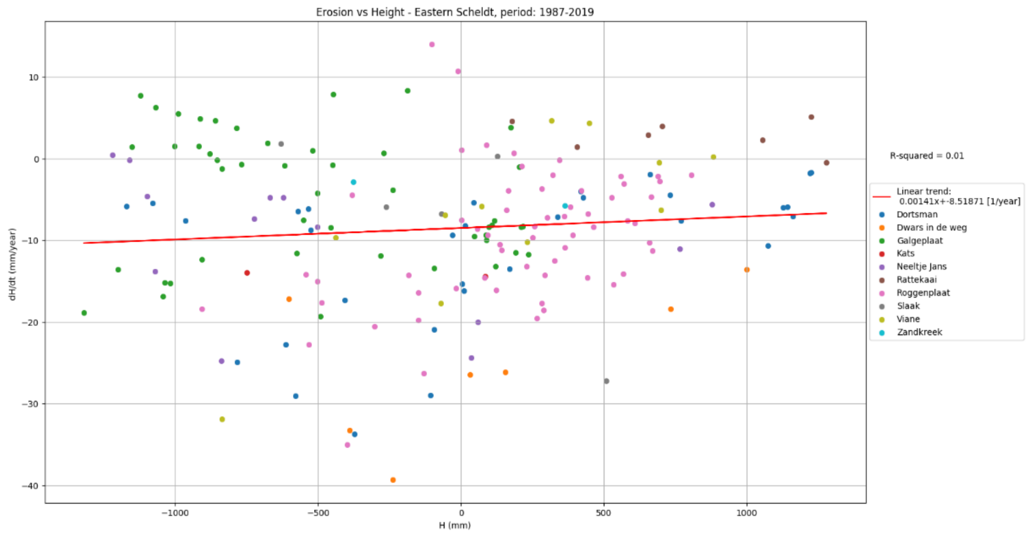


Figure 35. Erosion versus Height of all the intertidal flats together.

Besides this illustration, two time periods can also be compared with each other. These periods are from 1987 until 2010 and 2010 until 2019. Comparing these periods will give a change in the regression line.

Table 3 provides the regression lines of the chart erosion versus the height of the profile. The table shows the results of all the intertidal flats (paragraph 3.1.3)

Table 3. Slopes of the regression lines per year of the Erosion versus Height in the time period 1987 - 2019.

Intertidal flat	Slopes of regression lines 1987 - 2010	Slopes of regression lines 2010 - 2019
Dortsman	0.00588	0.00703
Dwars in de Weg	0.01170	0.00913
Galgeplaat	0.00045	-0.00445
Kats	-0.00007	-0.01398
Neeltje Jans	-0.00097	-0.00814
Rattekaai	-0.00087	-0.00303
Roggenplaat	0.00156	0.00691
Sint Annaland	-	-
Slaak	-0.03040	0.01710
Viane	0.01664	0.01314
Zandkreek	-0.00512	-0.01171
Eastern Scheldt	0.00163	0.00062

Determining the R-square value of Figure 35 shows a R-square value of 0.01. This means the rate of erosion is not related to the height of the intertidal flat. Because of this reason, the results cannot be used in this study.

4.4 Wind Data

The provided wind data from the locations Marollegat and Stavenisse will be illustrated in a wind rose. This wind rose shows the most common wind direction and also the most common wind speed of all the directions.

Figure 36 is an illustration of the wind data from the measuring location Marollegat in the period 1987 - 2019. Figure 37 is an illustration of the wind data from the measuring location Stavenisse in the period 1990 – 2019. The most common direction in both illustrations is South West. The measured wind speed will be divided into 12 areas. These areas are related to the Beaufort scale (KNMI). Table 4 is the Beaufort scale.

Table 4. Beaufort Scale.

Force	*Name*	*Speed [m/s]*
0	Calm	0 - 0.2
1	Light air	0.3 - 1.5
2	Light breeze	1.6 - 3.3
3	Gentle breeze	3.4 - 5.4
4	Moderate breeze	5.5 - 7.9
5	Fresh breeze	8.0 - 10.7
6	Strong breeze	10.8 - 13.8
7	Near gale	13.9 - 17.1

8	Gale	17.2 - 20.7
9	Strong gale	20.8 - 24.4
10	Storm	24.5 - 28.5
11	Violent storm	28.5 - 32.6
12	Hurricane	> 32.6

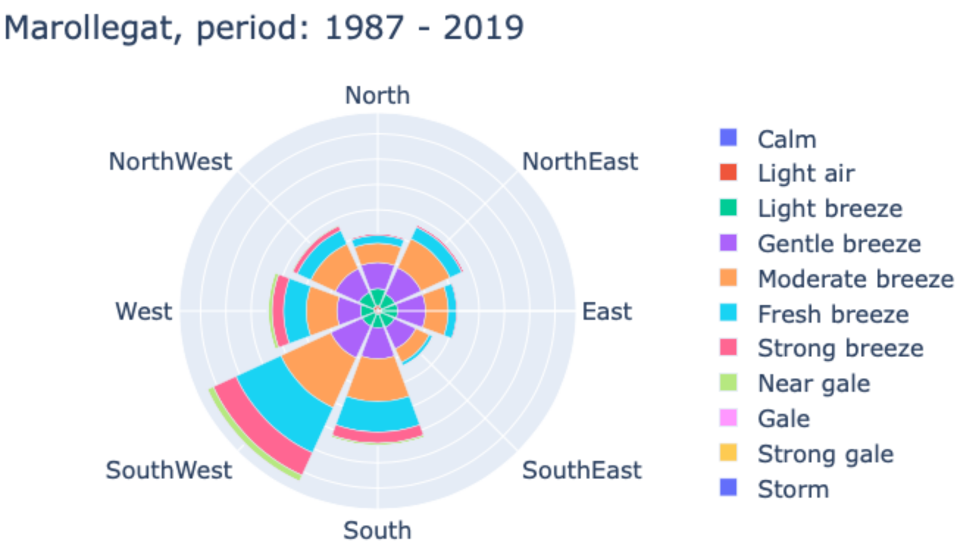


Figure 36. Windrose Marollegat 1987 – 2019.

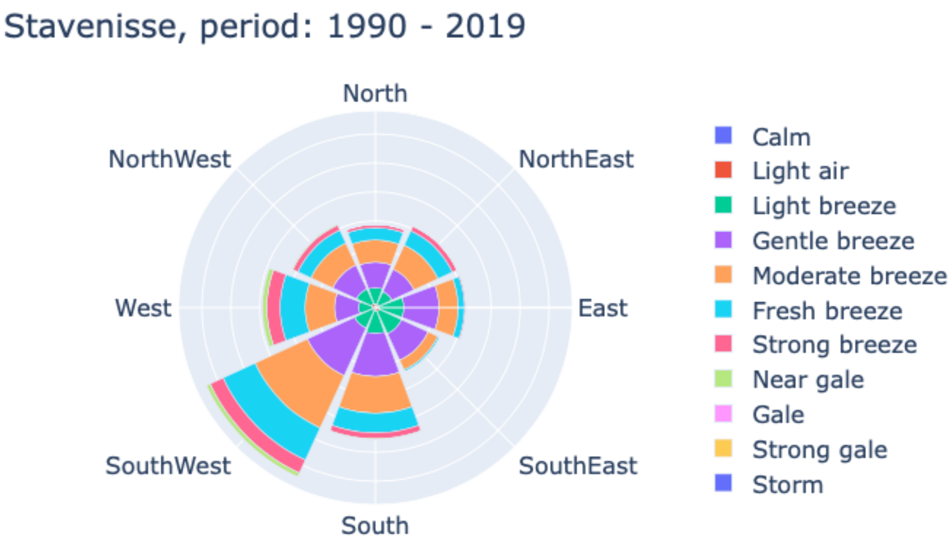


Figure 37. Windrose Stavenisse 1987 - 2019.

5 Comparing profiles

In chapter three and four a data framework was set up. The results of this data framework made it easier to work with the data and it was also more reliable to compare different profiles with each other. Comparing the results will be done in this chapter.

Important notes:

1. *All the illustrations in this chapter are also published in appendix 8 and 9.*
2. *For all illustrations with two graphs the left graph will be a visualisation of the profile based on the height and the x- or y-coordinate. The right graph will be the average height per year of the profile and the regression line is the rate of erosion.*
3. *The colour range in the left graph of the illustrations with two graphs is based on the age of the measured line. The older lines are blue, and the younger lines are red.*
    a. *With this colour range it is possible to see the pattern of erosion and deposition and the ultimate morphological development.*
    b. *When the red line is above the blue line there is sedimentation and when the blue line is above the red line there is erosion.*

5.1 Compare profiles of the intertidal flat

In this paragraph, the profiles from selected intertidal flats will be compared with each other from the same intertidal flat. This comparison will help to determine the subarea later in this study, in chapter six. This comparison will be made because every profile on the intertidal flat is behaving differently. Some parts of the intertidal flat are eroding faster than other parts on the flat.

The selection of the intertidal flats is based on the number of profiles on the intertidal flat. These profiles on the flats give the possibility to create multiple subareas. Determining these subareas will be done in chapter six.
The selected intertidal flat for this comparison are:

- *Dortsman*
- *Dwars in de Weg*
- *Galgeplaat*
- *Neeltje Jans*
- *Rattekaai*
- *Roggenplaat*
- *Viane*

5.1.1 Dortsman

5.1.1.1 Introduction

The intertidal flat Dortsman, Figure 38 and Figure 39, is located above the intertidal flat Galgeplaat and is connected to the island Tholen. The flat Dortsman has profiles on the sand plate and profile on the salt marshes. For this analysis the following profiles will be used:

- *Profiel-plr-5530-1*

- *Profiel-plr-5540-2*
- *Profiel-plr-5550-3*
- *Profiel-plr-5560-4*
- *Profiel-plr-5570-5*
- *Profiel-plr-5580-6*
- *Profiel-plr-5600-7*
- *Profiel-plr-5610-8*
- *Profiel-ssl-5620-2*
- *Profiel-ssl-5630-3*

The profiles with “ssl” in the name are salt marshes, the other are sand based profiles.

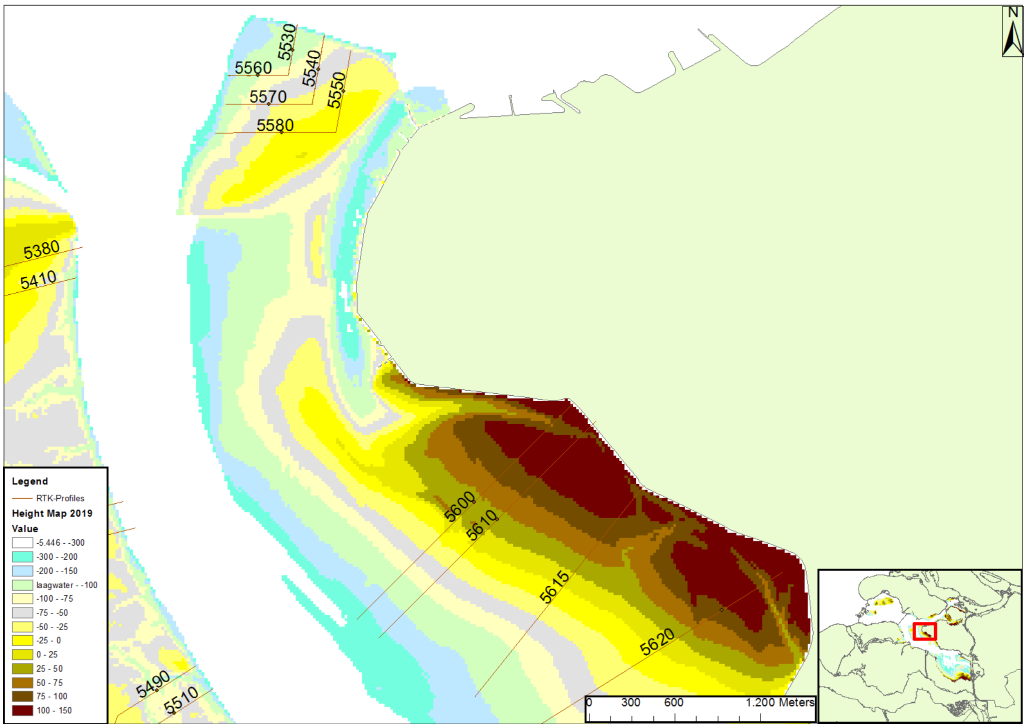


Figure 38. Intertidal flat Dortsman, North Part

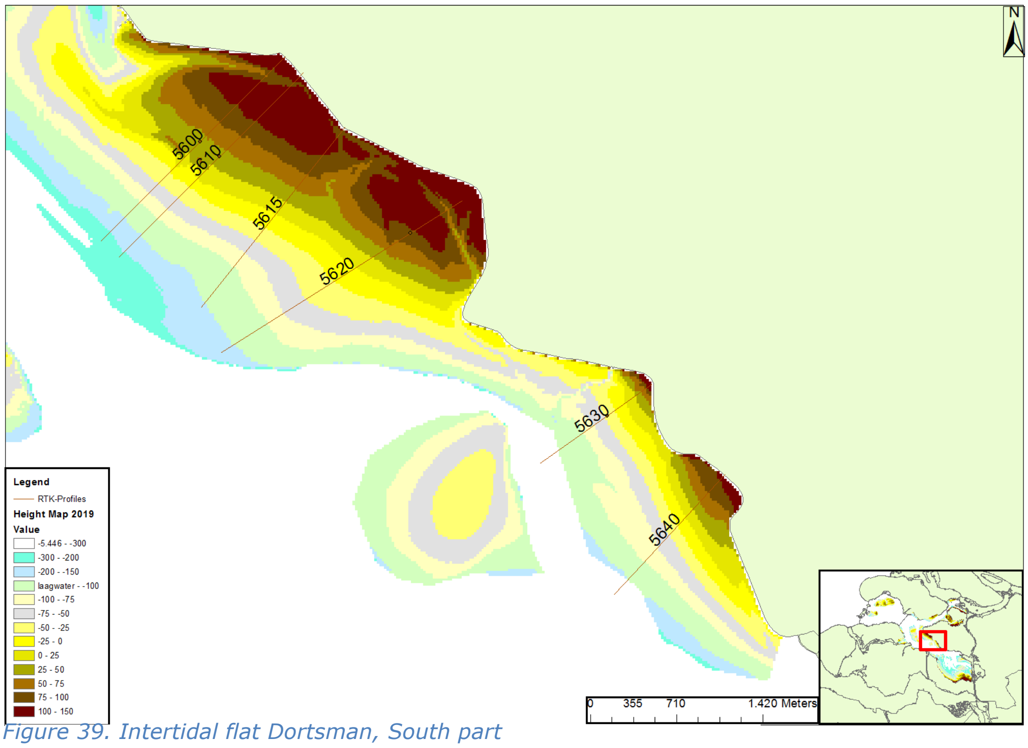


Figure 39. Intertidal flat Dortsman, South part

5.1.1.2 Analysis

Comparing these profiles shows there is some erosion on every profile. Figure 40 is an illustration of the erosion on one of the profiles. Analysing the first four profiles shows a difference in erosion rate based on the height of the profile.

One of the reasons for a higher rate of erosion on the sand-based profiles is the fetch in front of the profiles. The salt marshes profiles do not have the same fetch in front of the profiles.

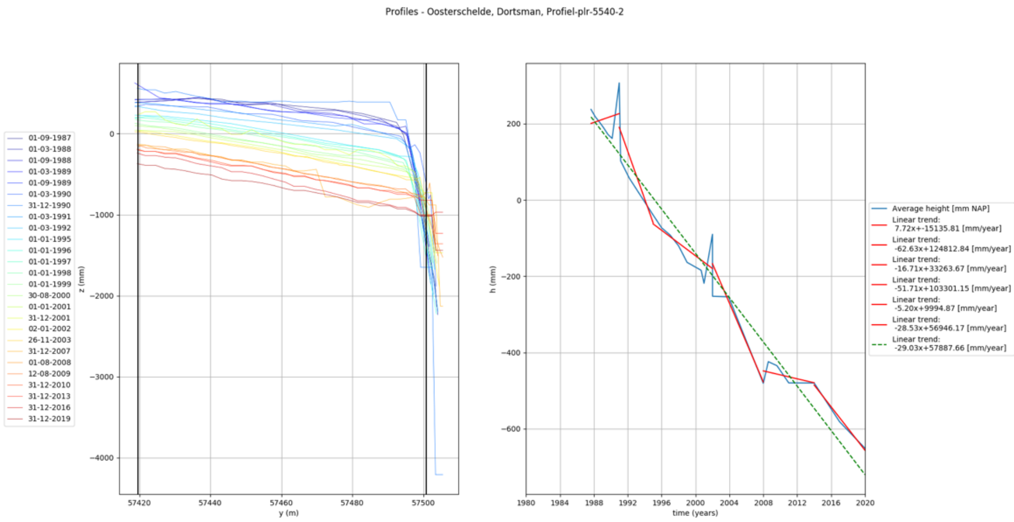


Figure 40. Dortsman Profiel-plr-5540-2, left side the profile and right side the average height per year of the profile.

5.1.1.3 Conclusion

Because of the fetch on the sand plate, the intertidal flat can be divided into different areas. The first area is located in the North/Northwest and is not connected to the shore. The other area is connected to the shore and this area is also a salt marsh.

5.1.2 Dwars in de Weg

5.1.2.1 Introduction

The intertidal flat Dwars in de Weg, Figure 41, is located in the North East of the Eastern Scheldt and is connected to the island Sint Philipsland. This connection to the shore means the intertidal flat is a salt marsh.

For this comparison, only three profiles will be used. These profiles are:

- *Profiel-plr-5780-4*
- *Profiel-plr-5785-5*
- *Profiel-plr-5790-6*

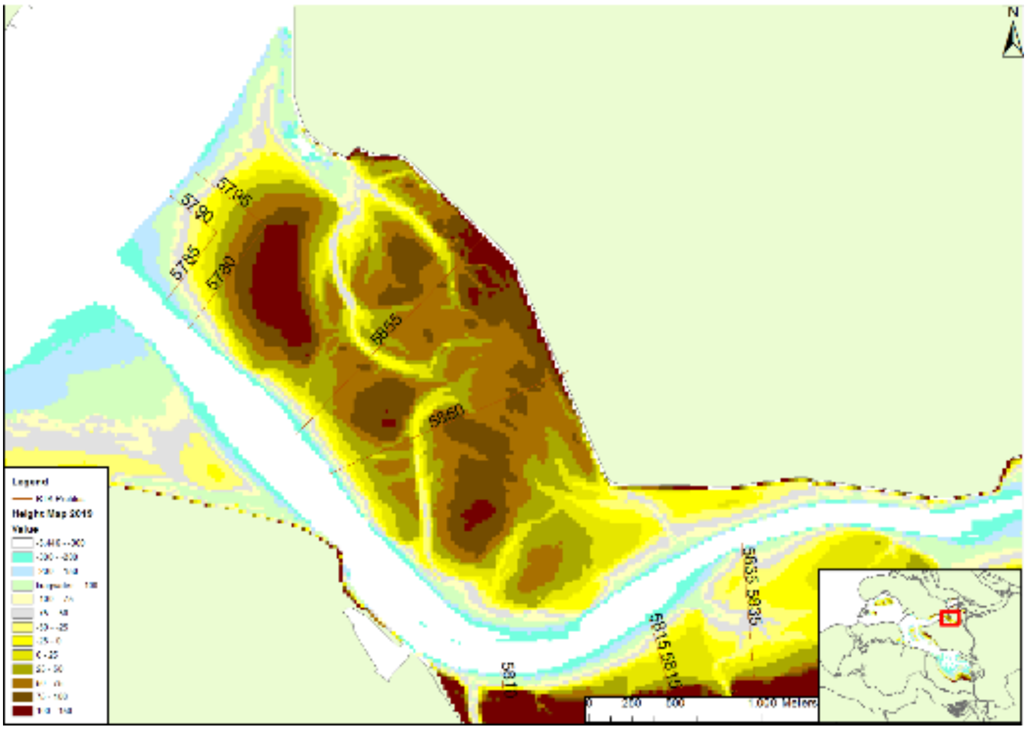


Figure 41. Intertidal flat Dwars in the Weg.

5.1.2.2 Analysis

These three profiles are related to each other because all the profiles show a similar morphological development. This means the profile will be in the same subarea. Figure is an illustration of one of the three profiles.

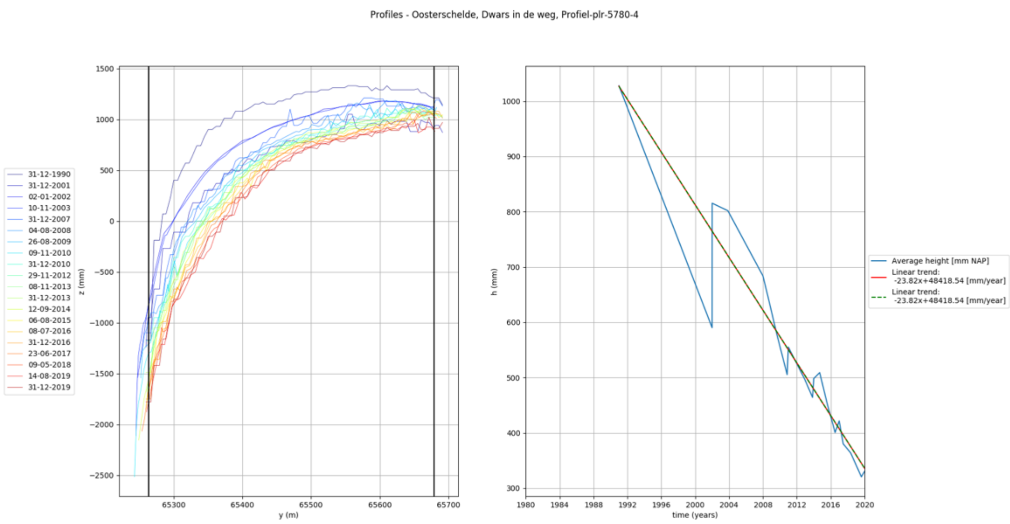


Figure 42. Dwars in de Weg Profiel-plr-5780-4, with the profile on the left side and the average height per year of the profile on the right side.

5.1.2.3 Conclusion

Because of the similarity of the morphological development, the profiles will be used in the same subarea.

5.1.3 Galgeplaat

5.1.3.1 Introduction

The intertidal flat Galgeplaat, Figure 43, is located on the east side of the Zeeland Bridge and the flat is an island. The northern part of the Galgeplaat is highly exposed to waves because the wind is predominantly coming from the West, Figure 44. The wind measuring location Marollegat is used for the intertidal flat Galgeplaat.

Furthermore, the wind the wind generates substantial waves for the Eastern Scheldt because there is a large fetch in front of the flat. The fetch is from the flat till the Zealand Bridge. The profiles of the intertidal flat Galgeplaat which will be used for this analysis are:

- *Profiel-plr-5370-10*
- *Profiel-plr-5380-12*
- *Profiel-plr-5400-11*
- *Profiel-plr-5410-13*
- *Profiel-plr-5420-3 (figure 43)*
- *Profiel-plr-5500-6 (figure 44)*
- *Profiel-plr-5510-8 (figure 45)*

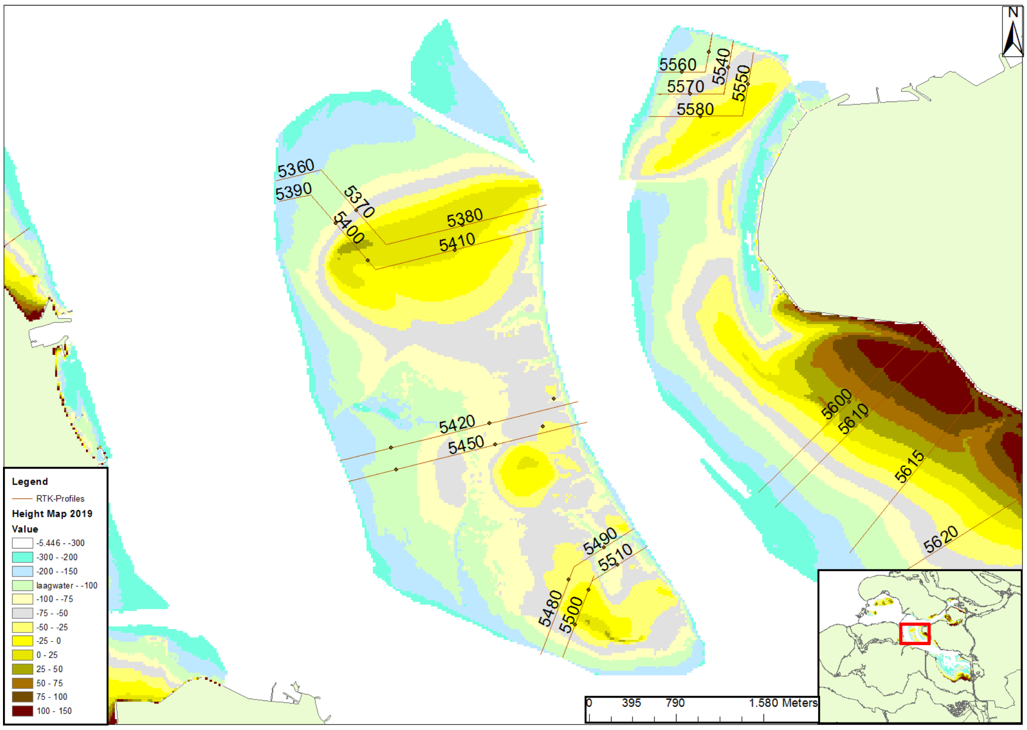


Figure 43. Intertidal flat Galgeplaat.

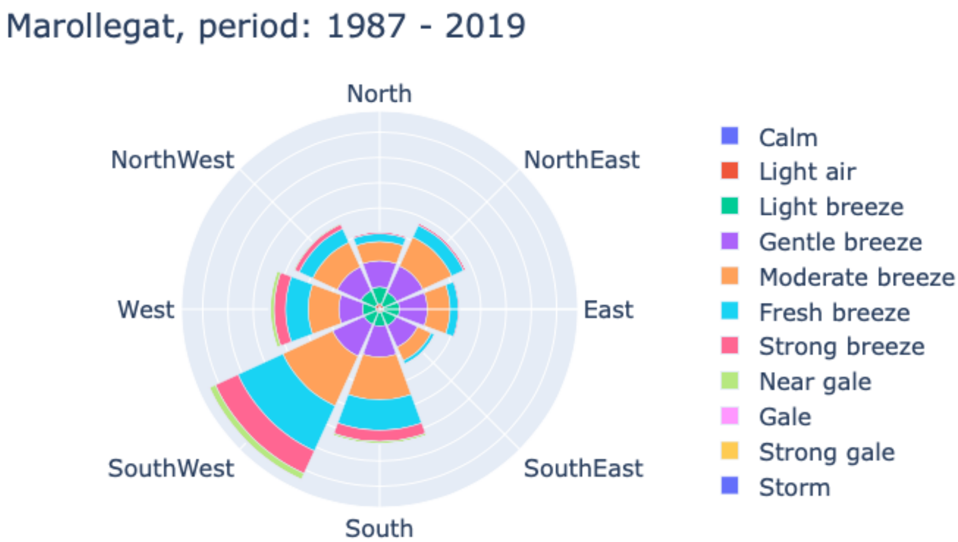


Figure 44. Windrose of the location Marollegat. Time period 1990 - 2019.

5.1.3.2 Analysis

A comparison of the profiles shows a difference in the morphological development within the Galgeplaat. The profiles in the north part have a higher rate of erosion while the middle section of the flat is accreting. The profiles in the South part are also eroding, but with a lower rate of erosion than the profiles in the North part.

Figure 45 is an illustration of one of the profiles in the North part. Figure 46 is an illustration of one of the profiles in the middle section and Figure 47 from the South part.

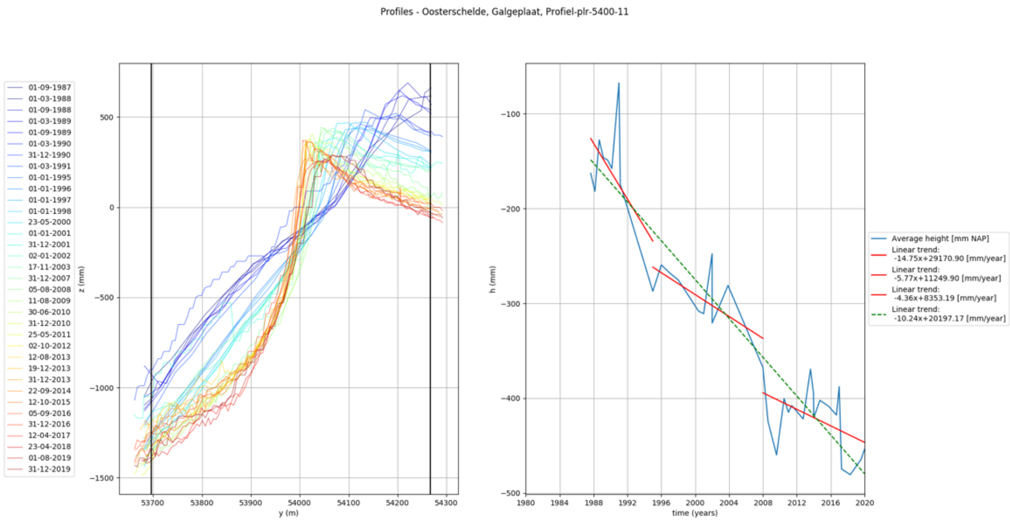


Figure 45. Galgeplaat Profiel-plr-5400-11, with the profile on the left side and the average height per year of the profile on the right side. The profile direction is from north west to south east.

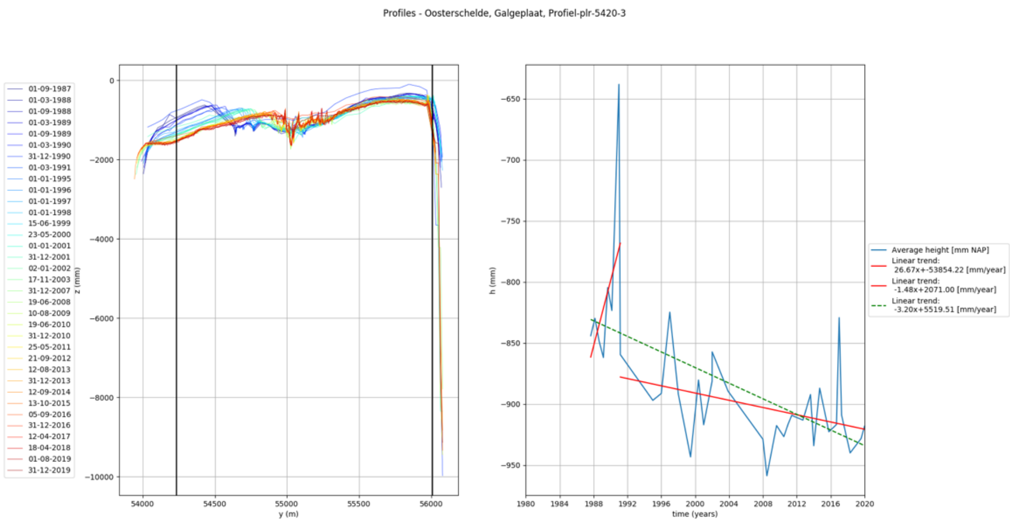


Figure 46. Galgeplaat Profiel-plr-5420-3, with the profile on the left side and the average height per year of the profile on the right side. The profile direction is from west to east.

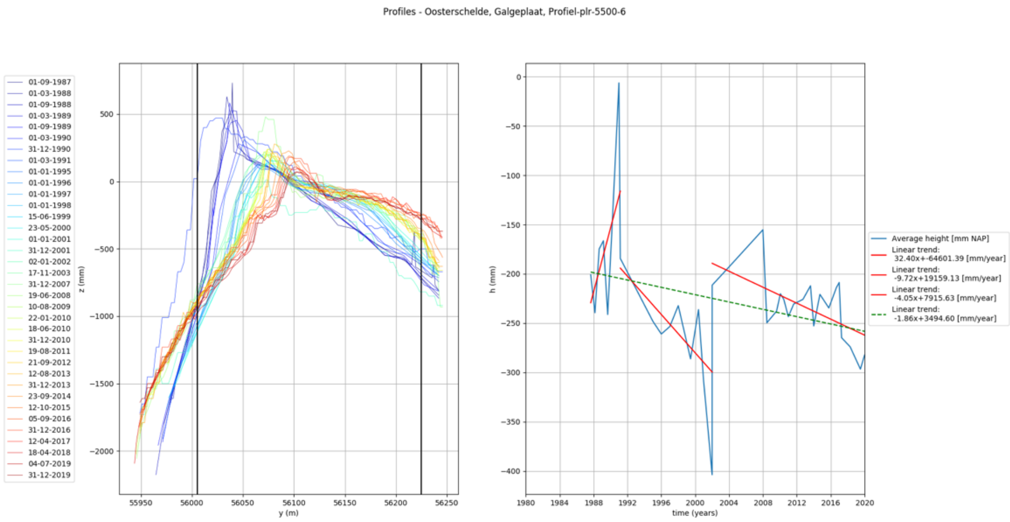


Figure 47. Galgeplaat Profiel-plr-5500-6, with the profile on the left side and the average height per year of the profile on the right side.The profile direction is from south to north.

5.1.3.3 Conclusion

Because of the different morphological development of the profiles, the intertidal flat can be divided into different subareas.

5.1.4 Neeltje Jans

5.1.4.1 Introduction

Neeltje Jans, Figure 48, is the intertidal flat connected to the storm surge barrier of the Eastern Scheldt and is located at the West side of the Eastern Scheldt. Neeltje Jans is located on the South West side of the intertidal flat Roggenplaat. Neeltje Jans was a construction island where some parts of the storm surge barrier were built.
The profiles for this analysis are:

- *Profiel-plr-5050-15*
- *Profiel-plr-5060-16*
- *Profiel-plr-5070-17*
- *Profiel-plr-5080-21*
- *Profiel-plr-5090-21*
- *Profiel-plr-5100-19*

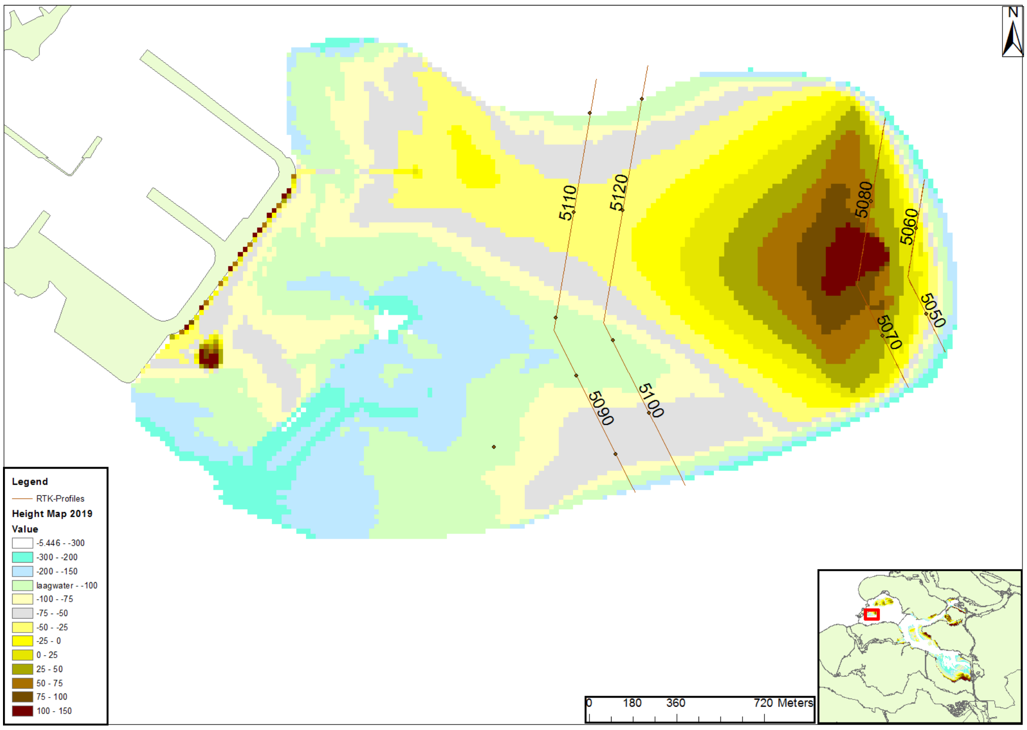


Figure 48. Intertidal flat Neeltje Jans.

5.1.4.2 Analysis

Analysing these profiles show a common pattern to all of the profiles. On every profile, the low areas are increasing in height and the high areas are decreasing in height. Figure 49 is an illustration of this morphological development. Because of this, the elevation of the intertidal flat Neeltje Jans is getting more equally distributed (i.e. flattening).

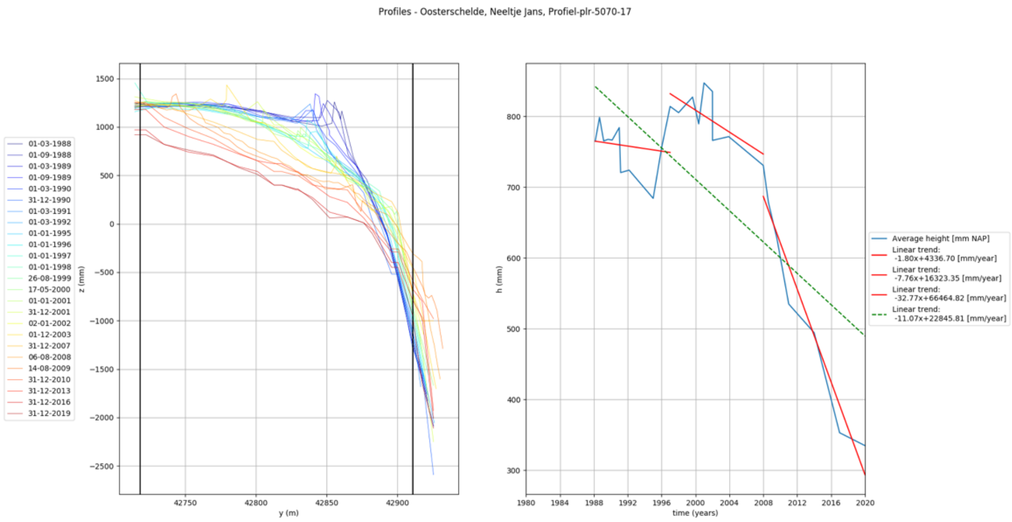


Figure 49. Neeltje Jans Profiel-plr-5070-17, left the profile and right the average height per year of the profile. The direction of the profile is from north to south.

However, the two profiles on the northern side of flat Neeltje Jans are showing a different morphological development compared to the other profiles. The profiles on the northern side are eroding on the waterside and the top of the profile, while the other profiles are accreting on the waterside. Figure 50 is an illustration of one of the profiles on the northern side of the flat.

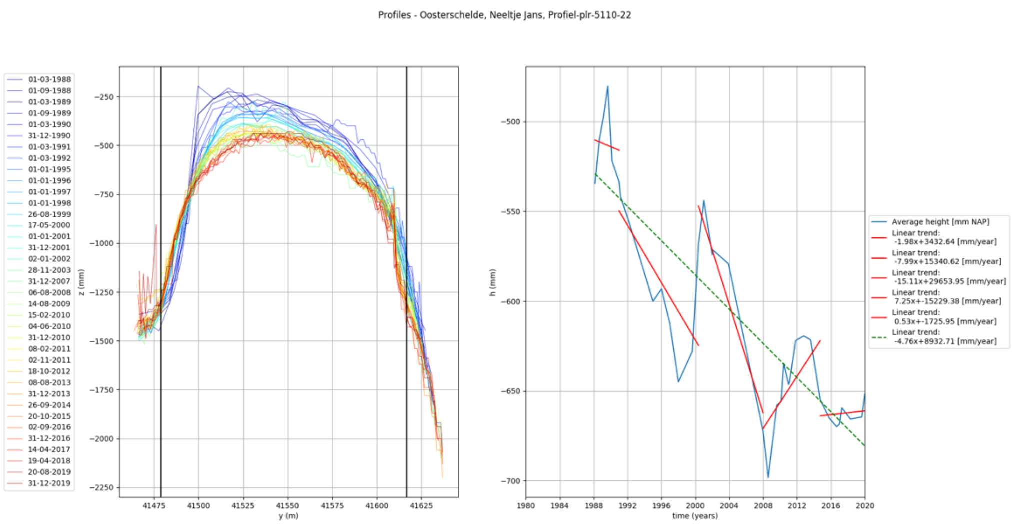


Figure 50. Neeltje Jans Profiel-plr-5110-22, left the profile and right the average height per year of the profile. The direction of the profile is from south to north.

5.1.4.3 Conclusion

Altogether, the intertidal flat Neeltje Jans can be divided into two parts. A part with a lot of erosion on the Northsides and a part where the high areas of Neeltje Jans are eroding faster than the surrounding area.

5.1.5 Rattekaai

5.1.5.1 Introduction

The intertidal flat Rattekaai is a salt marsh located in the South East of the Eastern Scheldt and also at the end of the Eastern Scheldt, Figure 51. Rattekaai is connected to the shore Zuid Beveland.

At the salt marsh, there is besides a vertical erosion or sedimentation also a horizontal erosion or sedimentation, because the end of the profile is much higher and is connected to the shore. For the analysis of the Rattekaai there are three profiles for comparison. These profiles are:

- *Profiel-ssl-5685-2*
- *Profiel-ssl-5695-3*
- *Profiel-ssl-5725-4*

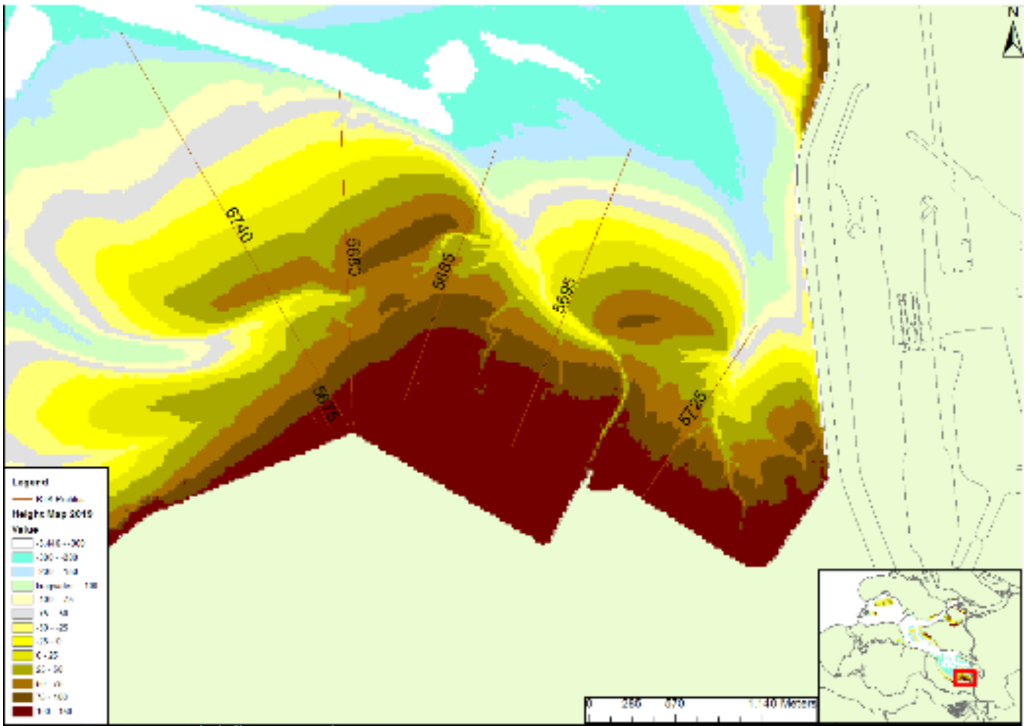


Figure 51. Intertidal flat Rattekaai.

5.1.5.2 Analysis

Analysing these three profiles showed a similarity of the morphological development. The morphological development is sedimentation

Figure 52 is an illustration of one of the profiles of the intertidal flat Rattekaai. In this illustration, the graph on the right side shows the average height per year and it is rising together with the regression line. A rising regression line corresponds to sedimentation.

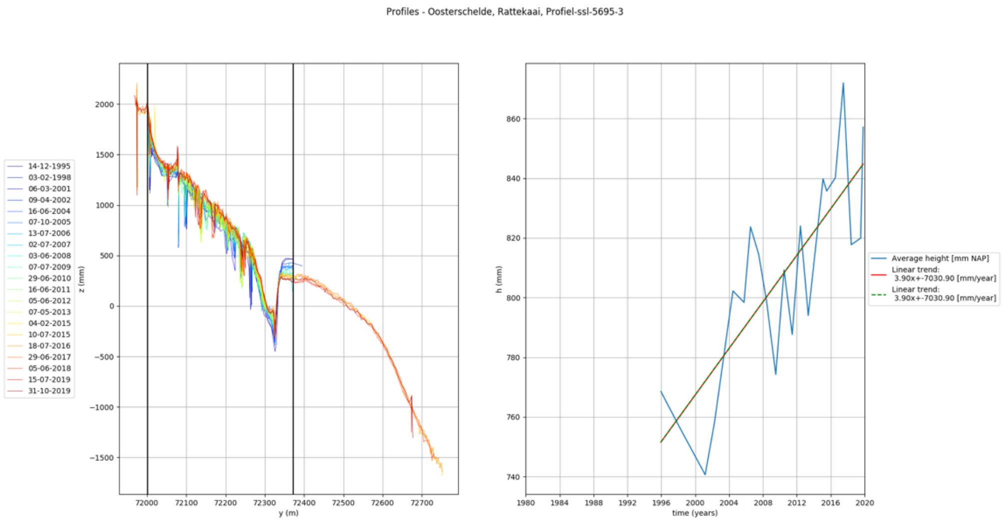


Figure 52. Rattekaai Profiel-ssl-5695-3, left the profile and right the average height per year of the profile. The direction of the profile is from south west to north east.

5.1.5.3 Conclusion

Because of the similarity of the morphological development the profiles, it is not necessary to divide the intertidal flat Rattekaai into subareas.

5.1.6 Roggenplaat

5.1.6.1 Introduction

The Roggenplaat, Figure 53, is the largest intertidal flat in the Eastern Scheldt and is located on the West side of the Eastern Scheldt close to the island Schouwen-Duiveland and the storm surge barrier.

The Roggenplaat is surrounded by water of the Eastern Scheldt and it also has a large fetch potentially generating substantial waves. The fetch is largest on the South East side of the Roggenplaat. The part in the South West of the Roggenplaat does not have a large fetch, because of the intertidal flat Neeltje Jans.

As such, the intertidal flat Neeltje Jans restricts the waves influenced by the wind when the wind is blowing from a South-West direction, because the intertidal flat Neetlje Jans is clearing away the large fetch in front of the intertidal flat Roggenplaat.

The profiles to compare on the intertidal flat Roggenplaat are:

- *Profiel-plr-5150-12*
- *Profiel-plr-5160-11*
- *Profiel-plr-5170-13*
- *Profiel-plr-5180-14*
- *Profiel-plr-5190-10*
- *Profiel-plr-5200-9*
- *Profiel-plr-5230-8*
- *Profiel-plr-5240-7*

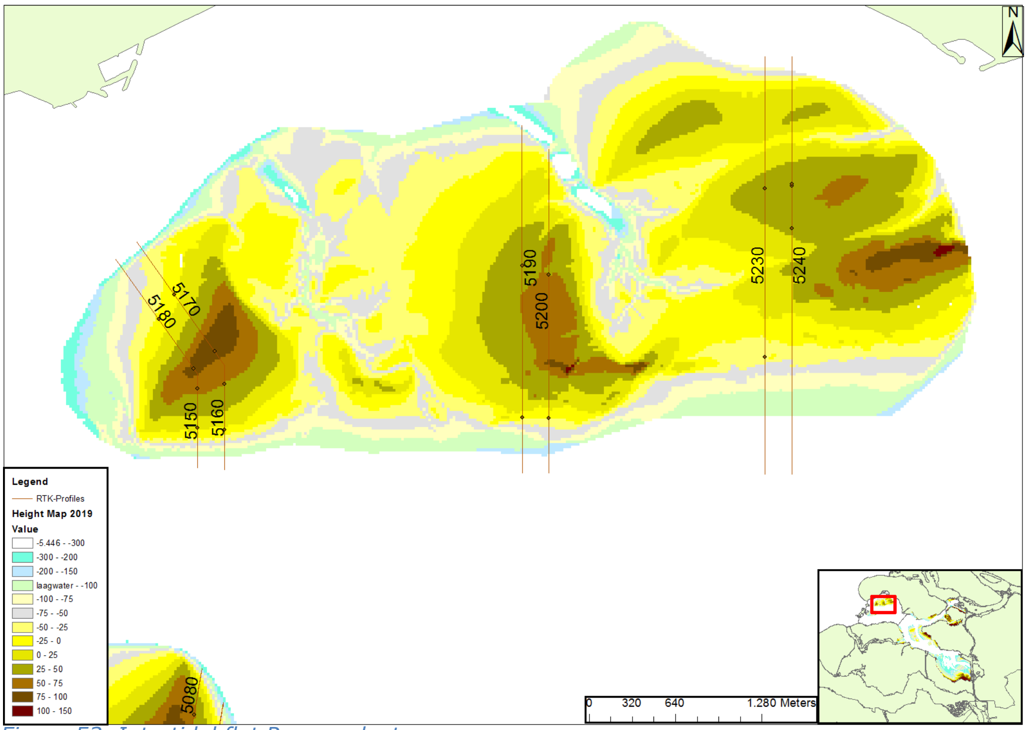


Figure 53. Intertidal flat Roggenplaat.

5.1.6.2 Analysis

Comparing the profiles of the intertidal flat Roggenplaat, the profiles show a similar morphological development. The profiles are eroding, but the Southside of the flat is eroding faster than the middle part and the northside of the flat.

Furthermore, the height of the flat on the Southside is also lower than the other parts of the flat, because of the large fetch in front of the Southside of the flat. The wind is blowing often from the directions South West and South. This means the wind has a large area to influence the waves in this fetch. The length of the fetch is from the South part of the flat until the island North-Beverland.

Figure 54 is an illustration of one of the profiles with a lot of erosion on the Southside and less erosion on the top and northside. The Southside is on the left side of the graph of the profile and the northside is on the right side of the same graph.

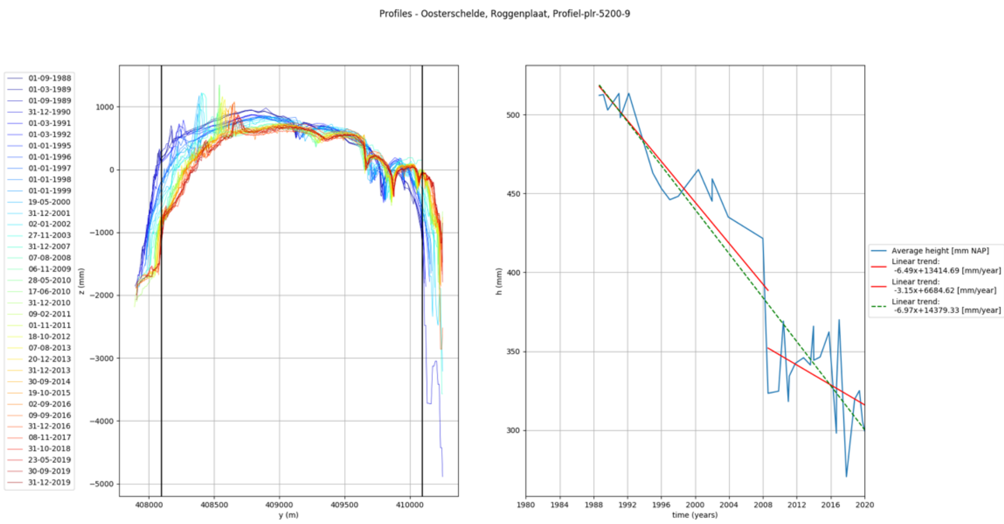


Figure 54. Roggenplaat Profiel-plr-5200-9, left the profile and right the average height per year of the profile. The direction of the profile is from south to north.

5.1.6.3 Conclusion

Analysis of the intertidal flat Roggenplaat shows that the flat can be divided into different subareas because of the different rates of erosion. These different rates of erosion occur by the influence of the wind and waves. Some areas are more exposed to the wind and waves than others. These areas are eroding faster than the other areas.

5.1.7 Viane

5.1.7.1 Introduction

The intertidal flat Viane is a salt marsh and is located on the North East side of the Eastern Scheldt, Figure. Viane is connected to the island Schouwen-Duiveland. In front of the Southside, there is a large fetch where the wind can influence the waves.

Moreover, the wind is blowing often from the South and South-West direction. This means the South part of the flat is exposed to a lot of wind and waves. The profiles for this analysis are:

- *Profiel-plr-5750-2*
- *Profiel-plr-5755-1*
- *Profiel-ssl-5765-1*
- *Profiel-ssl-5770-2*

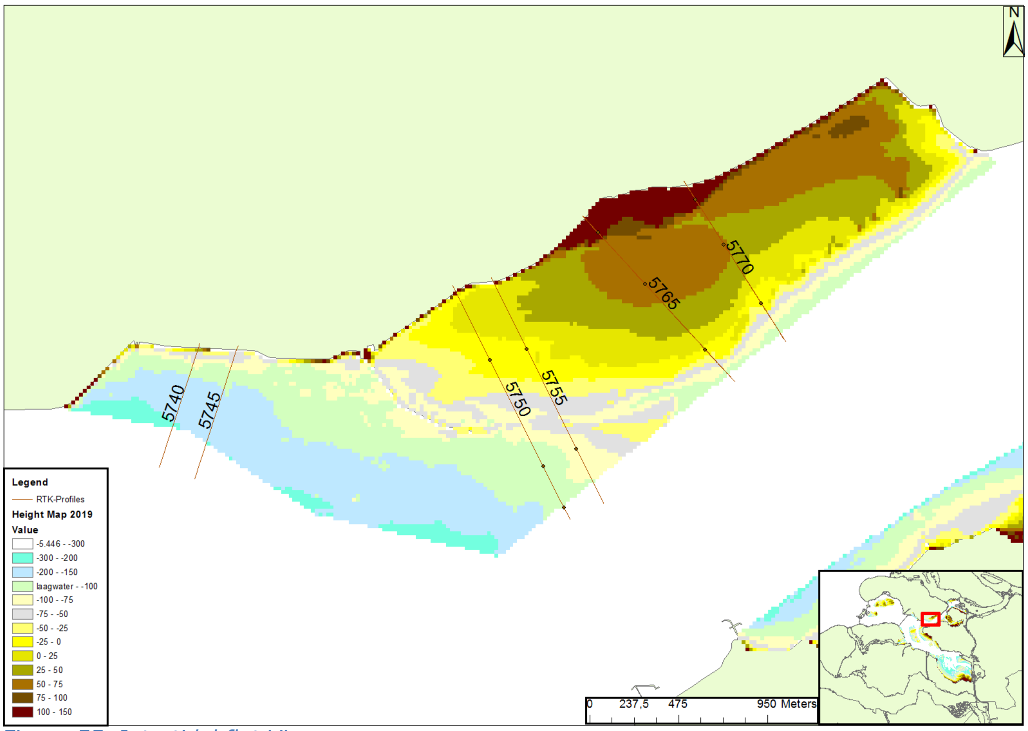


Figure 55. Intertidal flat Viane.

5.1.7.2 Analysis

The intertidal flat consists of salt marsh profiles and sand plates profiles. This means there is vertical and horizontal sedimentation or erosion because the end of the profile is much higher and is connected to the shore.

For this analysis, only the vertical erosion and sedimentation will be used. Comparing the profiles shows that there are differences between the profiles. The profiles in the middle and north part of the flat are accreting, while the profiles on the South part are eroding.

Figure 56 is an illustration of one of the profiles in the North part of the flat. Figure 57 is an illustration of one of the profiles in the South part of the flat.

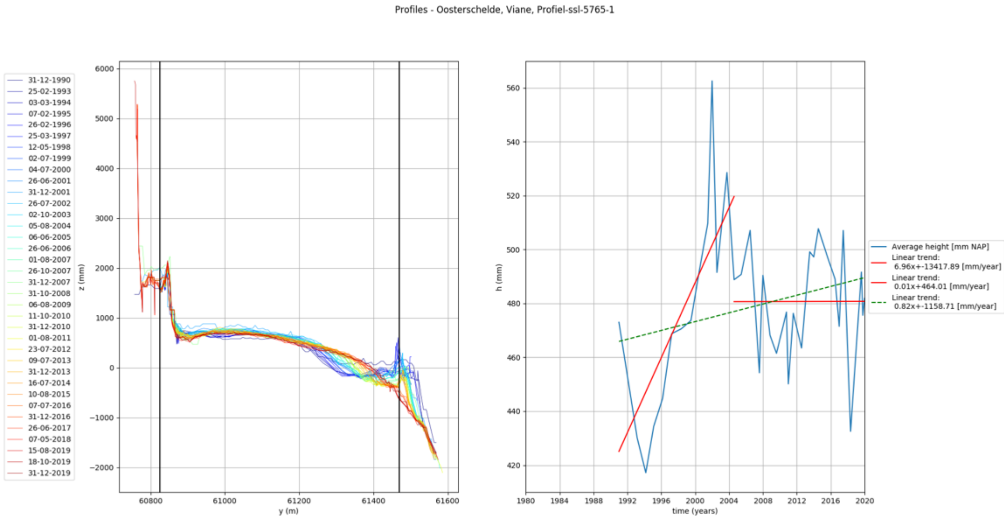


Figure 56. Viane Profiel-plr-5755-1, left the profile and right the average height per year of the profile. The direction of the profile is from north west to south east.

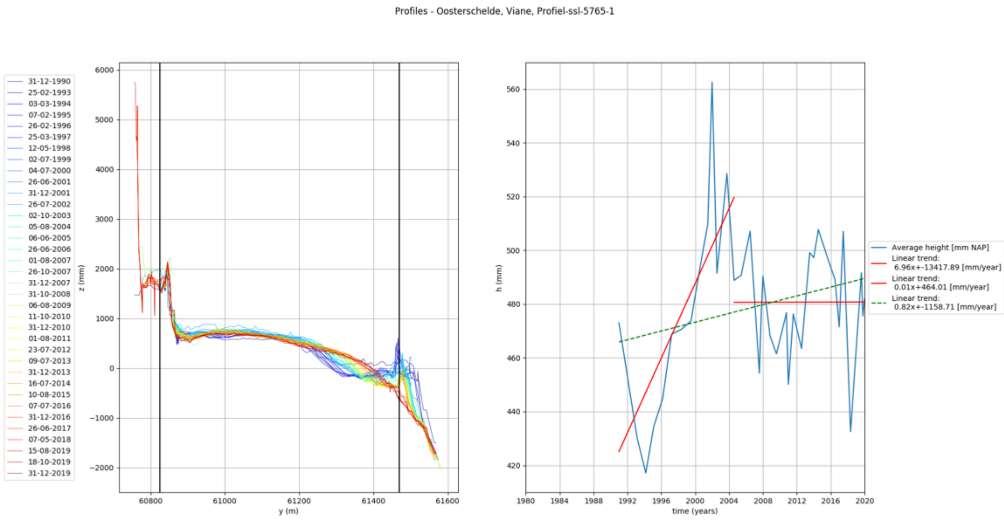


Figure 57. Viane Profiel-ssl-5765-1, left the profile and right the average height per year of the profile. The direction of the profile is from north west to south east.

Analysing the rate of erosion based on the height, Figure 58 shows especially the lower parts are eroding. This means the difference in height is expanding.

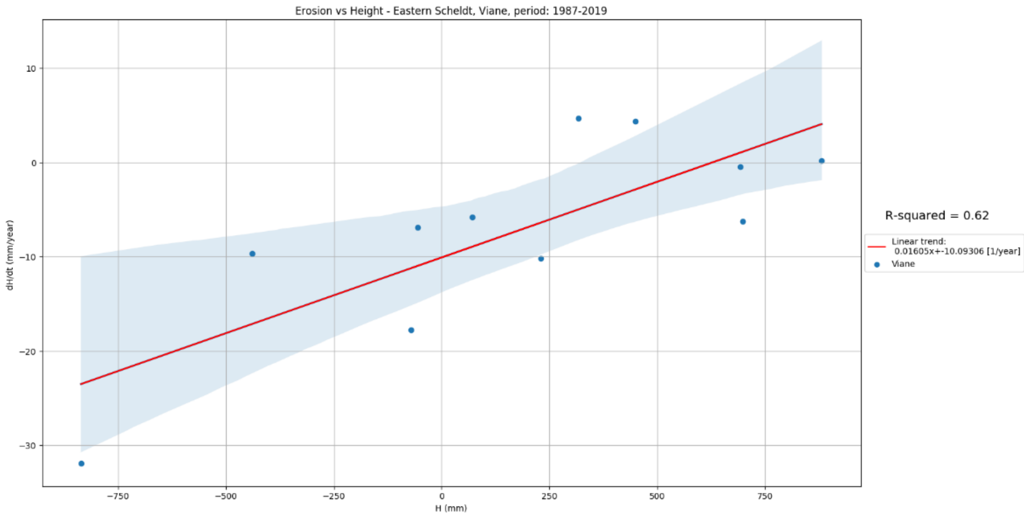


Figure 58. Erosion versus Height of the profiles on the intertidal flat Viane.

5.1.7.3 Conclusion

The profiles in the North part have a different morphological development than the profiles in the South part. This means the intertidal flat Viane can be divided into subareas.

5.2 Conclusion

5.2.1 Introduction

In this chapter, the profiles, which have met the conditions in chapters three and four, were compared with each other. The purpose of this comparison was to figure out if the profiles on the same flat have the same morphological development. Below, the three main morphological developments observed in this study are described.

The results of this analysis in this chapter will be used in chapter six. In chapter six the subareas will be determined based on the profile morphological developments

5.2.2 Large fetch

The analysis of the profiles was based on the erosion patterns and the erosion versus the height analysis. Areas on the flats with a large fetch in front are eroding faster than other profiles is the most occurring development.

These areas are on the northern side of the intertidal flat Galgeplaat and the Southside of the intertidal flats Roggenplaat and Viane. These areas are eroding faster because the wind is blowing often from the directions South, South West and West. With a large fetch in front of the flat, the wind can generate waves leading to more erosion.

5.2.3 Salt marshes versus tidal flat

Another morphological development was the difference between the salt marshes profiles and tidal flats profiles. The tidal flat profiles are eroding, while the salt marshes profiles are accreting. A possible reason for this difference is the height. The salt marshes are located higher and will be flooded only during storms in combination with high tide, which gives sedimentation the tidal flats are flooded during high tide which gives erosion.

6 Subareas intertidal flat

Comparing the profiles per intertidal flat will visualise the morphological developments of the profile. The profiles could be similar or different from each other. These similar and different morphological developments can be used to create groups, also called subareas.

These subareas will help to understand how an area of the intertidal flat will behave. The behaviour of a subarea will be considered as a homogeneous area. From every homogenous area, the weighted average erosion rate will be determined. This rate of erosion will be used to establish the height of the flat in the future and also to determine the emersion time of the flat in the future. Predicting the height and emersion time will be explained in chapter seven.

Important note

1. *All the illustrations in this chapter are also published in the appendix 10, 11, 12 and 13*

6.1 Introduction

For determining the subareas, a lot of data is needed to establish the subareas. The available data will provide six different maps per intertidal flat in the Eastern Scheldt. These six different maps are:

- *Profiles located on the intertidal flats*
- *Erosion and sedimentation difference between the Vakloding 1983 and 2010*
- *Erosion and sedimentation difference between the Vakloding 2010 and 2019*
- *Contours of the height from the Vakloding 2019*
- *Satellite image of 2019*
- *Subareas from Deltares.*

The profiles of the intertidal flats are used to visualise the intertidal flat and give an impression on the erosion rate of the intertidal flat. The visualisation of the profiles are the graphs on the left side in the figures and the erosion rate is the graphs on the right side.

6.2 Method for determining subareas

Determining the subareas was done on sketch paper first. Later these drawings on sketch paper were digitalised. The sketch paper was used to draw new and old subareas. The sketch paper made it easier to overlay the maps and to establish the new subareas.

paper. These subareas from Deltares were drawn with a dotted line. The subareas were checked with the map "erosion and sedimentation difference between the Vakloding 1983 and 2010". This map helped to visualise the choices from Deltares.

The second step was to draw the new subareas. This will be done to compare the maps "erosion and sedimentation difference between the Vakloding 1983 – 2010" and "erosion and sedimentation difference between the Vakloding 2010 – 2019". A difference between the two maps can be considered as a new subarea or a subarea needs to be changed.

Determining the borders of these new subareas was done with the satellite image of 2019 and contours of the height from the Vakloding 2019. The satellite image of 2019 shows how the landscape looks like. The image of the landscape can visualise patterns of sediment transport because the clarity of the water is cloudy. The satellite image of 2019 and the contours of the height from the Vakloding 2019 are both giving an indication where the environment on the intertidal flat is changing. As an example, a small channel can be used as a border of a subarea.

6.3 Subareas per intertidal flat

6.3.1 Introduction

In this paragraph, each intertidal flat of the Eastern Scheldt was analysed for the difference between the period 1987 - 2010 and the period 2010 - 2019.

Furthermore, some intertidal flats were combined, because these combinations were made by Deltares. To get a reliable result these combined intertidal flats will be kept the same in this study.

6.3.2 Dortsman

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in the changing of three subareas. The subareas in the centre of the intertidal flat have been combined because there was no difference in erosion between the two subareas.

Furthermore, the salt marshes have been removed, because the salt marshes will not behave the same as the sand areas and these salt marshes will not be used for this study. Moreover, the border of the green and yellow is moved more south-east compared to the determined subareas from Deltares.

Figure 59 shows the old subareas created by Deltares. Figure 60 shows the new subareas.

Figure 59. Intertidal flat Dortsman, subareas Deltares.

Figure 60. Intertidal flat Dortsman, new subareas.

6.3.3 Dwars in de Weg and Sint Annaland

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted basically in no change of the subareas of Deltares.

However, the channel between the intertidal flat is cut out of the subareas. This means the subareas are divided into multiple areas to visualise the channel between the intertidal flat.

Furthermore, the salt marsh on the intertidal flat Sint Annaland is also removed, because the salt marshes profiles are behaving differently than the sand plates profiles.

Figure 61 shows the old subareas created by Deltares. Figure 62 shows the new subareas.

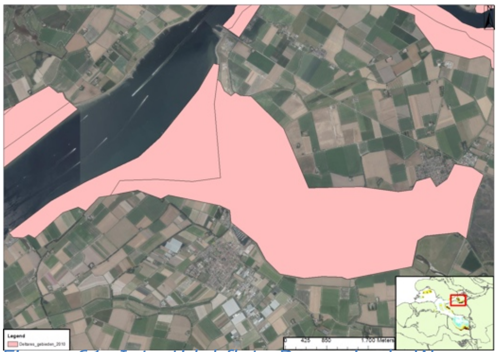


Figure 61. Intertidal flats Dwars in de Weg and Sint Annaland, subareas Deltares.

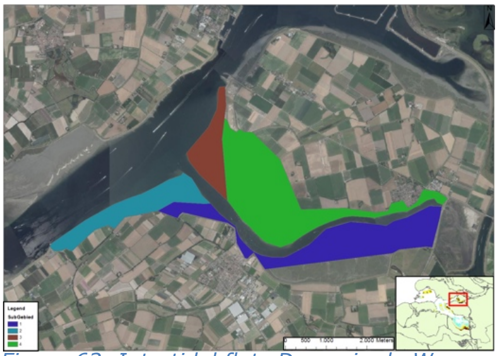


Figure 62. Intertidal flats Dwars in de Weg and Sint Annaland, new subareas.

6.3.4 *Galgeplaat*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of difference between these maps. All the subareas needed to be changed, except for the subarea in the North. This subarea is also not connected to the Galgeplaat, because there is a small channel between this flat and the Galgeplaat.

The subareas on the Galgeplaat have been changed because of the erosion difference. These changes where necessary, because the morphological developments of the subareas were changed.

Furthermore, the left side of the intertidal flat has been moved more to the right side, because the profiles did show erosion on the left side of the intertidal flat and in the middle part sedimentation.

The border for the new subareas has been chosen based on small changes in the environment, for example, the small rivers on the flat and also the underground differences based on satellite images.

Figure 63 shows the old subareas created by Deltares. Figure 64 shows the new subareas.

Figure 63. Intertidal flat Galgeplaat, subareas Deltares.

Figure 64. Intertidal flat Galgeplaat, new subareas.

6.3.5 *Krabbendijke and Rattekaai*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of similarities. However, two subareas have been combined and one subarea has been divided into two subareas. Nevertheless, the border of Deltares of the subareas against the shore is the same.

In this study, only tidal flat profiles will be used and for this reason, the salt marsh subareas have been removed.

Apart from these changes, some subareas are not connected to the other subareas. Each subarea created is based on the surface rising above the seawater level. Creating the subareas based on the surfaces above the waterline will help to create better predictions for subareas.

Figure 65 shows the old subareas created by Deltares. Figure 66 shows the new subareas.

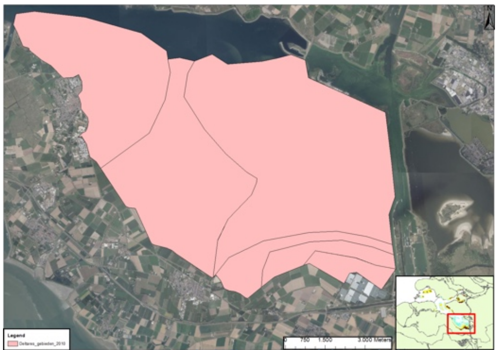


Figure 65. Intertidal flats Krabbendijke and Rattekaai, subareas Deltares.

Figure 66. Intertidal flats Krabbendijke and Rattekaai, new subareas.

6.3.6 *Neeltje Jans*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of different morphological developments. The subareas on the intertidal flat needed to be redesigned.

The new subarea in the East of the flat is shorter than created by Deltares. Furthermore, a subarea located in the South West has the format of the small lake inside the intertidal flat Neeltje Jans.

Figure 67 shows the old subareas created by Deltares. Figure 68 shows the new subareas.

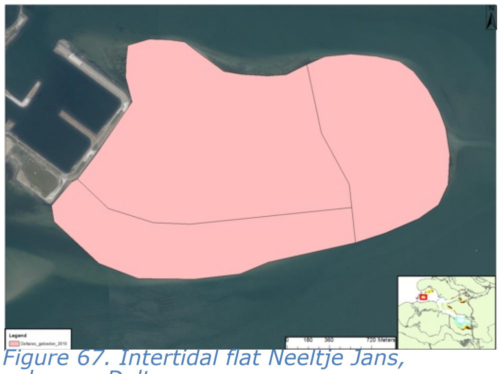


Figure 67. Intertidal flat Neeltje Jans, subareas Deltares.

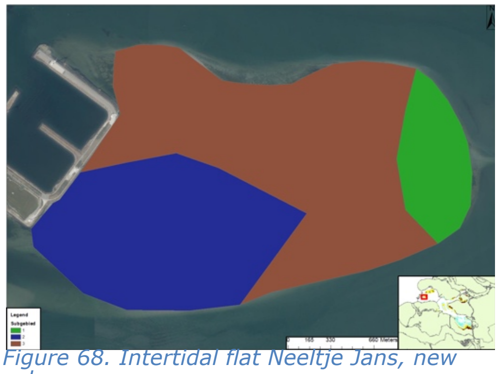


Figure 68. Intertidal flat Neeltje Jans, new subareas.

6.3.7 *Roggenplaat*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of similar morphological developments. However, there were a few changes.

The first change was the combination of two subareas. The subarea in the North of the flat has been merged with the subarea in the middle.

Another subarea on the Southside of the intertidal flat has been increased in size. The border on the northside of this subarea is moved more up north. This movement of the subareas was already predicted by Deltares.

Besides the move on the northside of this subarea, the border on the left side of this subarea has also been moved to the left

.

Figure 69 shows the old subareas created by Deltares. Figure 70 shows the new subareas.

Figure 69. Intertidal flat Roggenplaat, subareas Deltares.

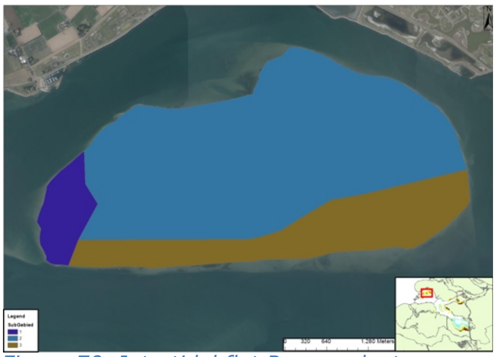


Figure 70. Intertidal flat Roggenplaat, new subareas.

6.3.8 *Slaak and Anna Jacoba polder*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of similar morphological developments. The subareas on the intertidal flats do not need to change. The salt marshes on the subareas are removed because the salt marshes are behaving differently than the sand plates
.

Figure 71 shows the old subareas created by Deltares. Figure 72 shows the new subareas.

Figure 71. Intertidal flats Slaak and Anna Jacoba polder, subareas Deltares.

Figure 72. Intertidal flats Slaak and Anna Jacoba polder, new subareas.

6.3.9 *Val*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in a lot of similar morphological developments. The intertidal flat Val was not divided into multiple subareas. Also, the salt marshes have been removed.

Figure 73 shows the old subareas created by Deltares. Figure 74 shows the new subareas.

Figure 73. Intertidal flat Val, subarea Deltares.

Figure 74. Intertidal flat Val, new subarea.

6.3.10 *Viane*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in different morphological developments. This means there were some changes needed to the subareas.

The subarea along the channel is divided into two subareas. On the Southside of the flat, the rate of erosion is higher than on the Southeast side. Furthermore, salt marshes have been removed.

Figure 75 shows the old subareas created by Deltares. Figure 76 shows the new subareas.

Figure 75. Intertidal flat Viane, subareas Deltares

Figure 76. Intertidal flat Viane, new subareas.

6.3.11 *Zandkreek, Kats and Goeschesas*

Comparing the two maps of the Vakloding difference of the period 1987 - 2010 and 2010 - 2019 resulted in similar morphological developments. These intertidal flats consist of three subareas. These subareas are the flats. The subareas on the intertidal flat Kats and Goeschesas do not have to be divided.

On the other hand, the intertidal flat Zandkreek was divided into two subareas, because there was more erosion in a specific area than in the surrounding area.

Figure 77 shows the old subareas created by Deltares. Figure 78Figure 76 shows the new subareas.

Figure 77. Intertidal flats Kats, Zandkreek and Goeschesas, subareas Deltares.

Figure 78. Intertidal flats Kats, Zandkreek and Goeschesas, new subareas.

6.4 Conclusion

In this chapter, the subareas from Deltares were checked for their steadiness the morphological development. When there were deviations the subareas needed to be redesigned.

As a result of this analysis, most of the large subareas on the intertidal flat have been split into multiple subareas. This dividing process was needed because those subareas were not behaving as a homogeneous area anymore.

Apart from the dividing process, some subareas have been merged and at some subareas, the border was just being moved. For example, the subarea located on the southside of the intertidal flat Roggenplaat. The border on the northside of this subarea was moved up more north. This movement was predicted by Deltares.

On the other hand, some parts of the subareas have been removed because these parts where salt marshes and these will not be used in this study.

7 Emersion time

In chapter six the subareas per intertidal flat were established. Each subarea is now considered as a homogeneous area. In this chapter, the average erosion rate of these subareas will be determined.
When the rate of erosion of the subareas are determined, the rate of erosion can be used for predicting the height and the emersion time in the future. The emersion time will be provided with the emersion time graph and with the hypsometric curve.

Important note:

1. *The emersion time illustrations in this chapter are also published in the appendix 14 and 16.*
2. *The hypsometric curve illustrations in this chapter are also published in the appendix 15.*

7.1 Introduction

The emersion time is important to be known because it is the time an intertidal flat will be rise above the sea-level. The emersion time will be expressed as a percentage of time.

In this study, the height and emersion time will be predicted for the years 2020, 2030, 2040, 2050, 2060, 2070 and 2080. The prediction will be based on the rate of erosion of the subareas. The erosion rate will be calculated from the period 2010 - 2019. For the prediction, the rate of erosion is a linear trend. The period 2010 - 2019 has been chosen because this is the most recent and therefore most reliable dataset.

Apart from the erosion rate, sea-level rise will also be taken into account for prediction the emersion time and height.

7.2 Comparison of ArcGIS versus Profiles

7.2.1 Introduction

The comparison between the erosion rate of the Vaklodingen and the profiles is required to check if the designed subareas are chosen correctly. For this check, the map "erosion and sedimentation differences between the Vakloding 2010 and 2019" is used as Vakloding.

At the designed subareas the two average erosion rates will be determined of the period 2010 - 2019. These two average erosion rates are the RTK profiles and Vakloding map "erosion and sedimentation differences between the Vakloding 2010 and 2019".

The average erosion rate of the Vakloding is established in ArcGIS and the average erosion rate of the RTK profiles is calculated with a formula.
The formula for calculating the average rate of erosion is:

$$Average\ rate = \frac{\sum(rate * distance)}{\sum distance}$$

A negative value of the average erosion rate indicates erosion and a positive value indicates sedimentation.

7.2.2 *Comparison*

Comparing the results of the average erosion rate higher of the profiles and the average erosion rate of the Vaklodingen showed a lot of difference. These differences are based on the accuracy, drawing the subareas and the dataset.
The erosion of the Vaklodingen is less accurate than the RTK profiles because the Vakloding data are obtained by a plane and a boat. The RTK profiles are obtained by walking on the intertidal flats.

In addition to the accuracy of the RTK profiles, the RTK profiles also contain more data of different years. This extra data makes the RTK profiles more accurate and reliable than the Vakloding data. Yet, the Vakloding data can help to visualize the erosion and sedimentation but cannot be used for calculations.

Besides the accuracy, the subareas itself are not perfect as well. The subareas are human-made and subjective. This means the borders of the subareas are not accurate. Moreover, determining the exact borders of a subarea is difficult because of the nature of the terrain.

7.2.2.1 Example of comparison with the intertidal flat Roggenplaat

As an example of this comparison, the subareas on the intertidal flat Roggenplaat will be used. The flat is divided into three subareas. Table 5 is an illustration of the result of the subareas on the intertidal flat Roggenplaat. Figure 79 is an illustration of the calculated erosion rate of the subareas on the intertidal flat Roggenplaat.

Table 5. Results of the rate of erosion from the Vaklodingen in ArcGIS and RTK profiles of the subareas on the intertidal flat Roggenplaat.

Sub Area	ArcGIS	RTK profiles
1	-14,76 mm/year	-3,56 mm/year
2	4,31 mm/year	-13,95 mm/year
3	-11,78 mm/year	- 18,7 mm/year

The results from ArcGIS show there is erosion in the West subarea and in the South subareas. The largest subarea experiences a sedimentation of 4 mm/year.

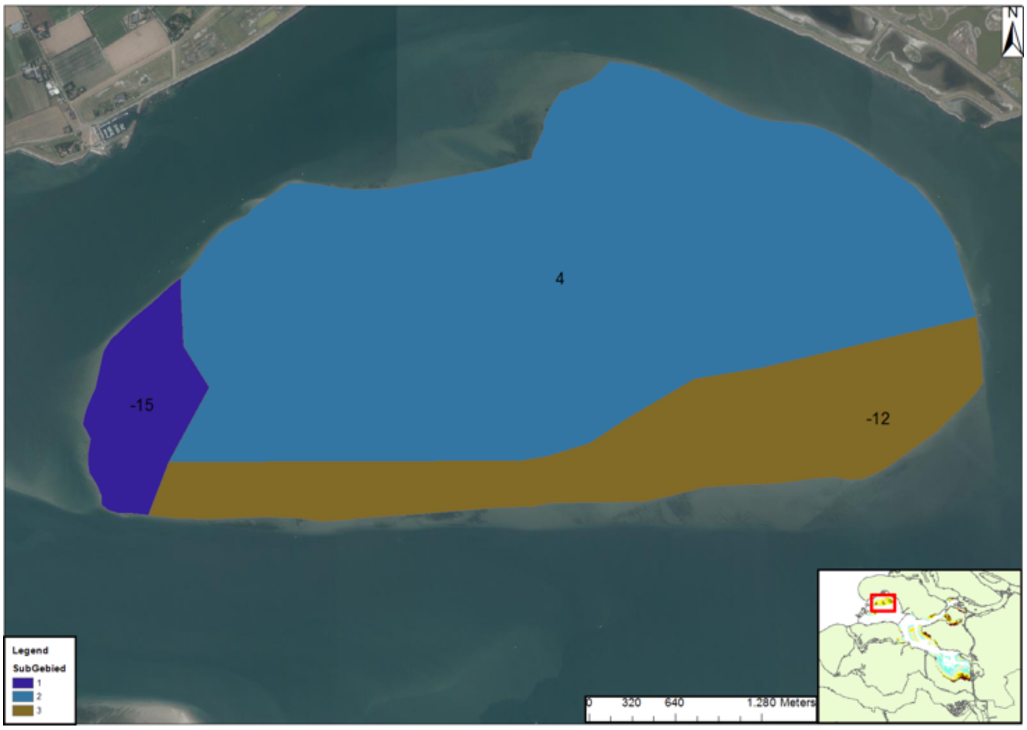


Figure 79. Erosion rates of the subareas based on the Vakloding in ArcGIS (Table 6), intertidal flat Roggenplaat.

7.2.3 *Rate of erosion subareas*

For this study, the average erosion rate from the RTK profiles will be used, because of the accuracy. The rate of erosion is a linear regression line. This linear line will be used to make predictions.

Table 6 shows the average erosion rate of all the subareas on the intertidal flats in the Eastern Scheldt. A negative value means erosion and positive value sedimentation.

Table 6. Weighted average erosion rate subareas.

Intertidal flat	Sub Area				
	1	2	3	4	5
Dortsman	-14,65	-1,53	-8,50	-4,41	4,22
Dwars in de Weg and Sint Annaland	-1,34	-23,49	-7,68	1,58	-
Galgeplaat	-7,56	1,93	8,52	7,85	-
Krabbendijke and Rattekaai	-6,67	-1,36	3,28	0,61	1,09
Neeltje Jans	-19,29	-3,56	-6,15	-	-
Roggenplaat	-3,56	-13,95	-18,7	-	-
Slaak and Anna Jacoba polder	-2,49	-2,38	-	-	-
Val	-6,22	-	-	-	-
Viane	-9,44	0,28	-8,27	25,91	-
Zandkreek, Kats and Goeschesas	-5,97	-7,05	-0,82	4,18	-

7.3 Prediction

7.3.1 Introduction

In this paragraph, the prediction of height and emersion time of the intertidal flat will be established based on the average erosion rate, a linear regression, of the profiles in the subareas and the sea-level. This prediction will display how much of the intertidal flat will rise above the water level during low tide.

The emersion time quantifies the time birds will have time available on the intertidal flats to look for food and to rest. This emersion time will be determined for the years 2030, 2040, 2050, 2060, 2070 and 2080.

7.3.2 Climate change

Climate change is an important aspect to take into account when the predictions will be made. Because of climate change, sea-level is rising. This means even without erosion of the intertidal flat, the emersion time of the intertidal areas will become shorter. If the rate of erosion is added, the emersion time will decrease faster than without the rate of erosion.

7.3.2.1 KNMI

The sea-level rise which will be used for making the predictions is provided by the Royal Dutch Meteorologic Institute (KNMI). In 2015, the KNMI published the paper climate scenarios 2014 (Klein Tank, Beersma, Bessembinder, Hurk, & Lenderink, 2014). The KNMI has defined four main scenarios. These scenarios are based on combinations between the worldwide temperature rise (Moderated and Hot) and the difference in airflow pattern (Low value, High value). The character G means moderated, and the character W means hot. The four scenarios are referred to as Glow, Ghigh, Wlow and Whigh. In this analysis, only the sea-level rise will be used. Table 7 shows the definitions of the words Glow, Ghigh, Wlow and Whigh.

Table 7. KNMI Scenarios.

Glow	Moderated worldwide temperature rises and Low air flow pattern
Ghigh	Moderated worldwide temperature rises and High air flow pattern
Wlow	Hot worldwide temperature rises and Low air flow pattern
Whigh	Hot worldwide temperature rises and High air flow pattern

7.3.2.2 Sea-level rise

The sea-level rise will be applied to the sea-level at low tide in the Eastern Scheldt. The average astronomic low water tide is -150 cm NAP and the average astronomic high tide is 150 cm NAP in the Eastern Scheldt. The sea-level rise is established in the four scenarios by the KNMI. Table 8 shows the sea-level rise of these four scenarios in the period 2036 - 2065. Table 9 shows the sea-level rise of these four scenarios in the period 2071 - 2100.

Table 8. KNMI scenarios in the period 2036 - 2065.

	Glow	Ghigh	Wlow	Whigh
Absolute level	+15 till +30 cm	+15 till +30 cm	+20 till +40 cm	+20 till +40 cm
Changing speed	+1 till +5,5 mm/year	+1 till +5,5 mm/year	+3,5 till +7,5 mm/year	+3,5 till +7,5 mm/year

Table 9. KNMI scenarios in the period 2071 – 2100.

	Glow	Ghigh	Wlow	Whigh
Absolute level	+25 till +60 cm	+25 till +60 cm	+45 till +80 cm	+45 till +80 cm
Changing speed	+1 till +7,5 mm/year	+1 till +7,5 mm/year	+4 till +10,5 mm/year	+4 till +10,5 mm/year

In both tables, the Glow and Ghigh do not show any difference. This is also happening with the scenarios Wlow and Whigh. To have a more reliable prediction these scenarios will be divided into more useful numbers. For this study three scenarios will be used. Table 10 shows the sea-level rise according to the KNMI in the period 2040 – 2060 and Table 11 shows the sea-level rise in the period 2070 – 2100.

Table 10. Created scenarios based on scenarios KNMI 2040 - 2060.

Period 2040 - 2060			
	Low	Average	High
Changing speed	+1 mm/year	+5,5 mm/year	+7,5 mm/year

Table 11. Created scenarios based on scenarios KNMI 2070 - 2100.

Period 2070 - 2100			
	Low	Average	High
Changing speed	+1 mm/year	+7,5 mm/year	+10,5 mm/year

7.3.3 Emersion time forecast

The emersion time will be determined based on the rate of erosion of the subareas in the Eastern Scheldt and sea-level rise. The starting point for these calculations is the map of the Vakloding in 2019, but this year will be assumed as 2020. At the end of the year 2019, the Vakloding map has been updated because of the nourishment on the intertidal flat Roggenplaat. These nourishments will also be taken into account for calculating the predicted height and emersion time.

The results of the emersion time will be visible in a map in ArcGIS. The values of the emersion time are expressed as a percentage of time. This map will display the areas which will rise above the sea-level at low tide in the Eastern Scheldt.

7.3.3.1 Formula predicted height

Before the predicted emersion time can be estimated, the predicted height needs to be determined. This height will also be calculated with the rate of erosion of the subareas on the intertidal flats. The results of this calculation are visible in ArcGIS and are published in appendix 17. The formula for calculating the predicted height is:

$$H_{yyyy} = H_{2020} - erosion\ rate * (yyyy - 2020)/10$$

Where H is the height in cm and erosion rate in mm/year.

The formula has a minus before the erosion rate because the rate of erosion is a positive value in ArcGIS. The H2020 is the Vakloding 2019 including the nourishment on the intertidal flat Roggenplaat.

This formula will help to determine the predicted height, although the sea-level rise is not taken into account. Figure 80 is an illustration of the predicted height of the intertidal flat Roggenplaat in 2030.

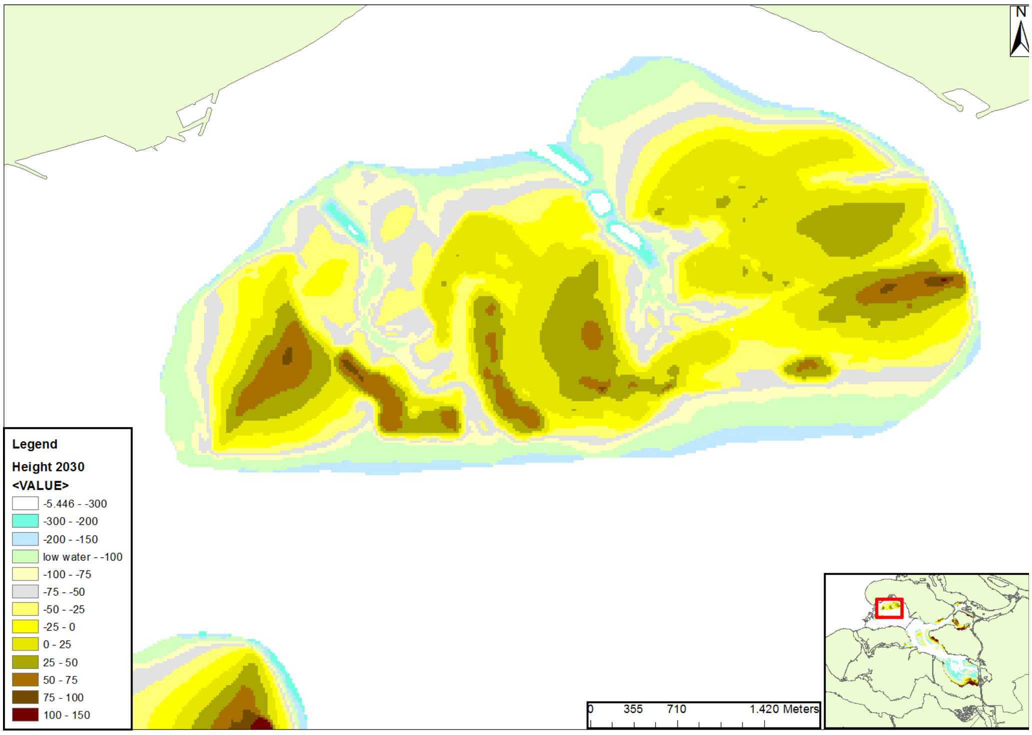


Figure 80. Predicted height of the intertidal flat Roggenplaat in 2030.

7.3.3.2 Formula of the predicted emersion time

After determining the predicted height, the emersion time can be estimated. Estimating the predicted emersion time of the intertidal flats will be done with the formula of Deltares. The difference between the predicted height and the height of 2020 is divided by three, because of the tide difference. The tide difference is 3 meters because the low tide is -150 centimetres and high tide 150 centimetres.

The formula from Deltares is:

$ET\_yyyy = (H\_yyyy - H\_2020)/3 + ET\_2020$ [H in cm]

In this formula, the sea-level rise is not taken into account. The new formula with the sea-level rise included is:

$ET\_yyyy = (H\_yyyy - H\_2020 - 〖SWL〗\_(rise - yyyy))/3 + ET\_2020$ [H in cm]

$SWL_{rise\ -\ yyyy}$ is the sea-level rise in a specific year expressed in cm. Figure 81 is an illustration of the emersion time on the intertidal flat Roggenplaat in 2030.

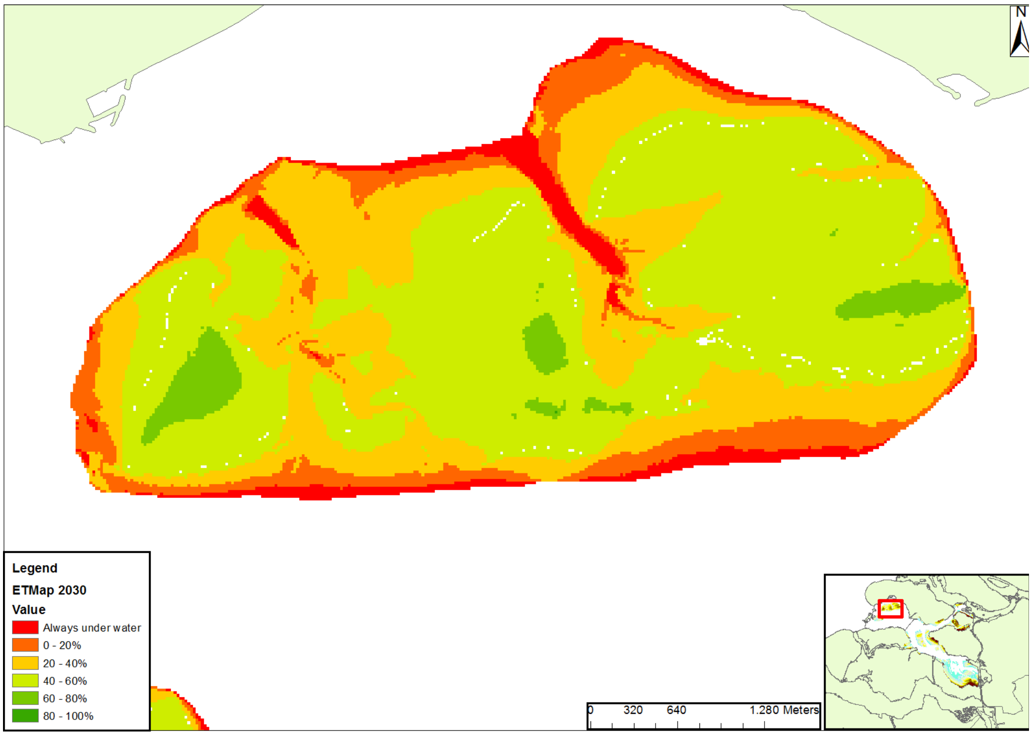
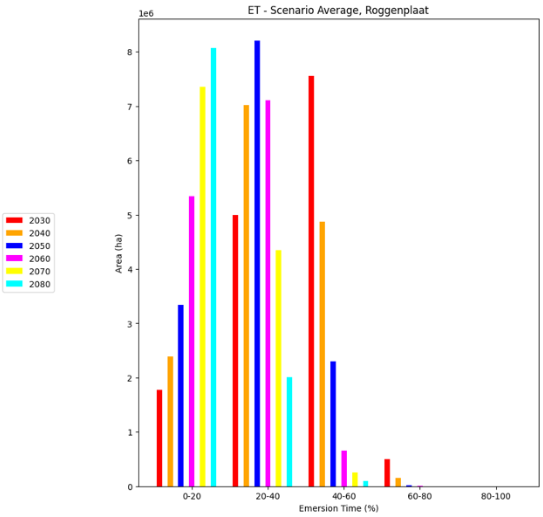


Figure 81. Emersion time of the intertidal flat Roggenplaat in 2030.

7.3.4 *Visualising emersion time and height*

After determining the predicted height and emersion time, the results can be illustrated in maps but also in two charts. The two charts are the emersion time chart and the hypsometric curve.

The emersion time chart is a bar chart and illustrates the size of the dry areas in the years 2030, 2040, 2050, 2060, 2070 and 2080 per class of emersion time stratified in 0-20%, 20-40%, 40-60%, 60-80% and 80-100% of the time. Each group visualises the number of dry hectares of the flat. When the bars of the groups one and two are higher than the bars with the same colour in the other groups, the time an area is rising above the sea-level is decreasing. Figure 82 is an illustration of the emersion time chart. The illustration shows left the emersion time chart and the right the total amount of hectare per group per year.



	0-20%	20-40%	40-60%	60-80%	80-100%
2030	1775200	4999600	7550800	499600	800
2040	2394000	7019600	4877600	158800	400
2050	3343200	8200400	2295200	23200	0
2060	5338000	7107600	654800	5600	0
2070	7360400	4346800	256400	400	0
2080	8075200	2012400	101600	0	0

Figure 82. The emersion time graph of the intertidal flat Roggenplaat, Scenario Average.

In addition to the emersion time chart, the emersion time can also be estimated from the hypsometric curve. The hypsometric curve visualises the height of the flat and the number of dry hectares. With these values, the emersion time can be estimated. An advantage of this chart is the explicit visualisation of the height of the intertidal flat. Furthermore, the curve also indicates the rate of erosion based on the slope of the line. Figure 83 is an illustration of the hypsometric curve for the Roggeplaat.

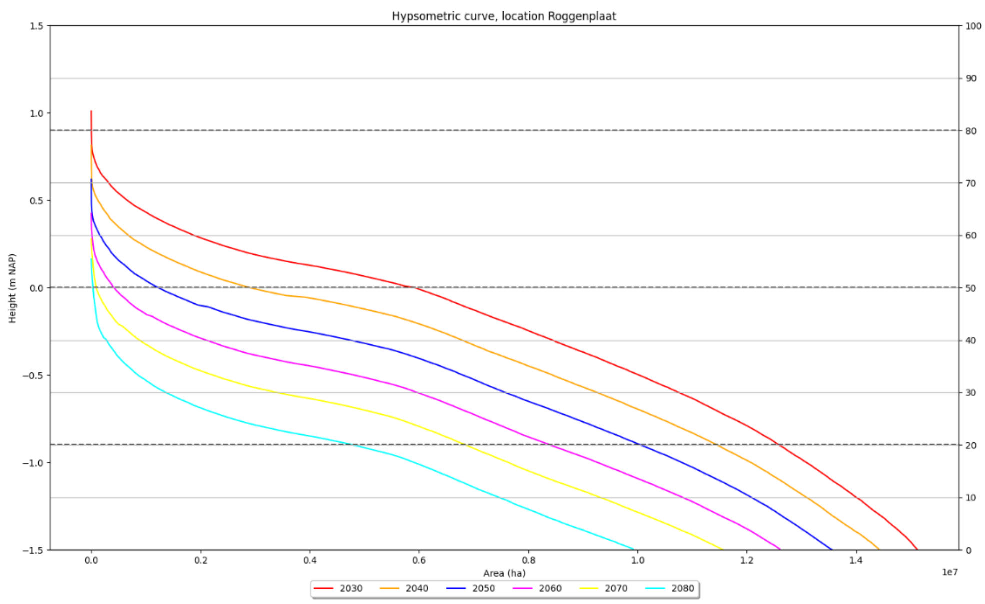


Figure 83. Hypsometric Curve of the intertidal flat Roggenplaat.

Analysing the two charts, Figure 82 and Figure 83, shows the categories 0-20% and 20-40% are increasing at the emersion time chart, while the other groups are decreasing. The reason for this increasing height of these two groups is because the intertidal flat will be lower due to the erosion. So, it will take more time for an area to rise above the sea level. This results in a shorter emersion time.

7.4 Conclusion

This chapter was devoted to the predicted emersion time and height. The predictions the predictions of the emersion times and heights were made for the years 2030, 2040, 2050, 2060, 2070 and 2080 based on the weighted average erosion rate of the profiles inside the subareas of the intertidal flats. The determination of the emersion time and height is because of the nature. When the emersion time and height are less, the animals have less time to relax and search for resources on the intertidal flats.
The sea level rise is included in the results of the estimated emersion time and height.

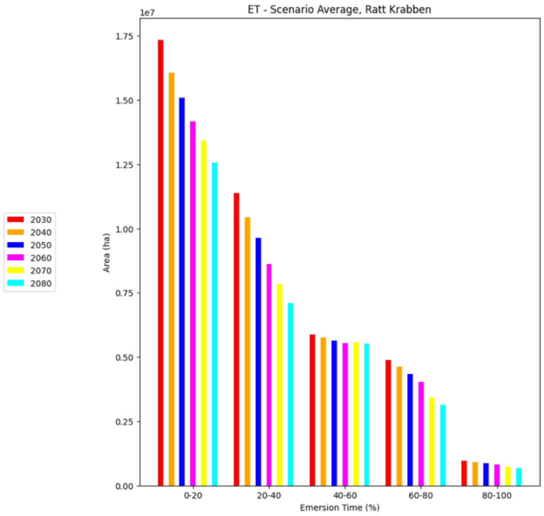
7.4.1 Emersion time

7.4.1.1 Intertidal flats

Analysing the results of the predicted emersion time chart of the intertidal flats shows the flats are decreasing because of the erosion of the flats. As a consequence of the erosion, the intertidal flats will become flatter. This is also visible in the groups 0-20% and 20-40% of the emersion time bar chart because these groups are increasing while the other groups are decreasing. However, when the predicted period will be expanded these two groups will also be decreasing in height.

Apart from these results, there were some intertidal flats which behaved differently. These intertidal flats are Dwars in de Weg, Sint Annaland, Rattekaai, Krabbendijke and Viane.
At the intertidal flats, Dwars in de Weg and Sint Annaland the groups 40-60% are growing instead of the other groups, because the largest subareas on the flats are showing sedimentation instead of erosion.

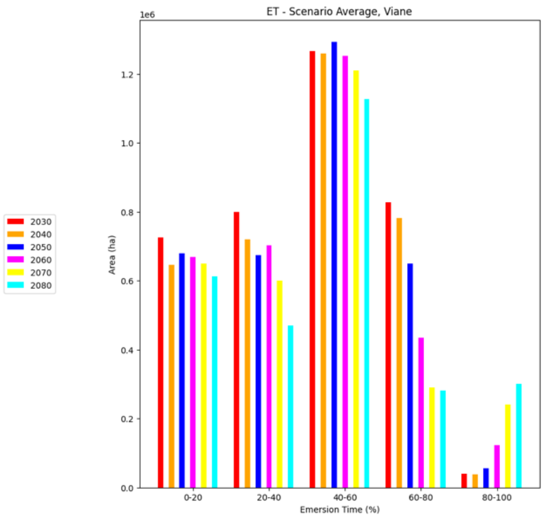
Furthermore, the emersion time chart of the intertidal flats Rattekaai and Krabbendijke is also different, as illustrated in Figure 84. It shows a decrease in every group, but the groups 0-20% and 20-40% are decreasing faster than the others. This difference does occur because of the erosion and sedimentation rate. In the higher areas there is sedimentation, while the lower areas are eroding. While the higher areas are sedimenting a decrease of the number of hectares in the groups 40-60%, 60-80% and 80-100% does occur because of the sea level rising.



	0-20%	20-40%	40-60%	60-80%	80-100%
2030	17328800	11389600	5871600	4894400	961600
2040	16064800	10436000	5753600	4635200	908400
2050	15097200	9636800	5642400	4329600	862400
2060	14164800	8629600	5538800	4025200	812800
2070	13411600	7829600	5580400	3428800	721200
2080	12564800	7098800	5533200	3124800	672000

Figure 84. The emersion time graph of the intertidal flat Rattekaai and Krabbendijke, Scenario Average.

In the emersion time chart of the intertidal flat Viane the largest group is 40-60%, because this flat is higher than the other flats in the Eastern Scheldt. Moreover, a large part of the intertidal flat Viane is sedimenting. This is also visible in the last two years in the group 80-100%. Figure 85 is an illustration of the emersion time in an average scenario of the intertidal flat Viane.

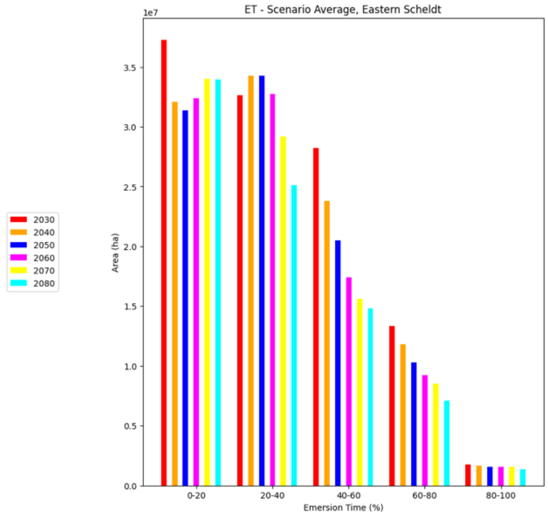


	0-20%	20-40%	40-60%	60-80%	80-100%
2030	724800	799200	1266800	827600	40800
2040	646400	720000	1259200	781200	38800
2050	679200	674000	1292400	649600	55200
2060	668800	702400	1252400	434400	123200
2070	649200	600800	1210000	290000	241200
2080	612800	469600	1127200	282000	301200

Figure 85. The emersion time graph of the intertidal flat Viane, Scenario Average.

7.4.1.2 Scenarios

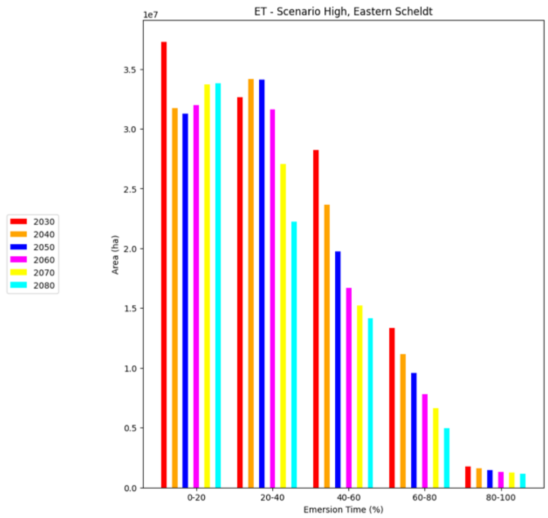
The predictions of the emersion times are estimated with a linear erosion trend and a linear sea-level rise. Because of the sea-level rise, table 6 and table 7, the predictions of the emersion time are divided into three scenarios. These scenarios are Average, High and Low. Figure 86 is an illustration of the emersion time of the Eastern Scheldt scenario Average.



	0-20%	20-40%	40-60%	60-80%	80-100%
2030	37244000	32638800	28220800	13334400	1749200
2040	32079200	34286800	23813600	11812000	1670800
2050	31368400	34256800	20496400	10289200	1561600
2060	32411200	32766000	17399600	9228800	1536800
2070	34017600	29187600	15604400	8529600	1538400
2080	33986800	25120800	14791200	7107200	1336000

Figure 86. The emersion time graph of the Eastern Scheldt, Scenario Average.

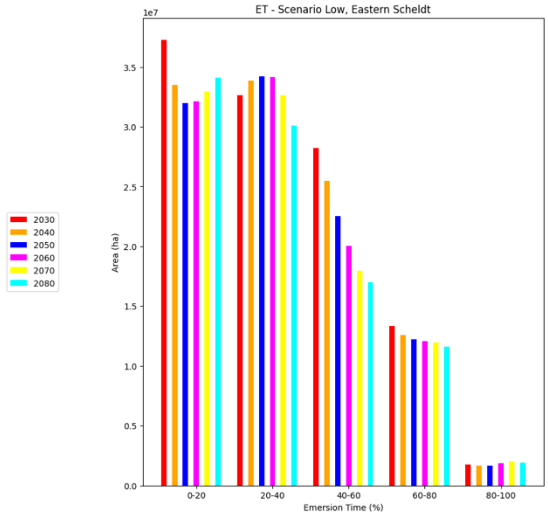
The emersion time charts of the scenarios Average and High have a similar bar chart. However, the number of hectares is decreasing faster at the scenario High than at scenario Average. Figure 87 is an illustration of the emersion time of the Eastern Scheldt scenario High.



	0-20%	20-40%	40-60%	60-80%	80-100%
2030	37244000	32638800	28220800	13334400	1749200
2040	31710800	34174400	23668400	11149600	1633200
2050	31286800	34090400	19743600	9570800	1461200
2060	31975600	31651200	16695600	7814000	1322800
2070	33721200	27077600	15218000	6632400	1240000
2080	33806000	22226000	14155600	4966800	1135200

Figure 87. The emersion time graph of the Eastern Scheldt, Scenario High.

The emersion time chart of the scenario Low is more related to the rate of erosion of the intertidal flats than to the sea-level rise. Figure 88 is an illustration of the emersion time of the Eastern Scheldt scenario Low.



	0-20%	20-40%	40-60%	60-80%	80-100%
2030	37244000	32638800	28220800	13334400	1749200
2040	33500400	33883200	25456800	12598000	1664800
2050	31977600	34241600	22528400	12232400	1675200
2060	32149600	34166800	20038400	12073600	1879600
2070	32948400	32660800	17971600	11986400	2010000
2080	34121200	30094800	17004400	11623200	1906400

Figure 88. The emersion time graph of the Eastern Scheldt, Scenario Low.

7.4.2 *Hypsometric curve*

Analysing the hypsometric curve showed some similarities with the emersion time chart. Instead of calculating the emersion time now the height of the intertidal flat will be used. The advantage of using the hypsometric curve is a direct illustration of the height of the intertidal flats and also the number of hectares at a certain height. A similarity between both charts is the decrease in the emersion time for most intertidal flats and marshes.

In addition to the decreasing emersion time, the hectares in the groups 0-20% and 20-40% are growing and visible, because the surface below the line is growing. This is visible by the slope of the lines between 0% and 20%.
Comparing the other hypsometric curves of the intertidal flat with the emersion time charts from the same intertidal flats shows the same result. Nevertheless, obtaining the values of the hypsometric curve is more difficult than the emersion time graph. Furthermore, the emersion time chart is also more illustrative than the hypsometric curve.

8 Emersion time comparison Deltares

In 2012 Deltares published two reports about the erosion rate in the Eastern Scheldt. These papers are: "Prediction of the Eastern Scheldt morphological evolution based on the erosion trend" and "Volume analysis on RTK profiles of the Eastern Scheldt". In the first paper, the same predictions have been made of the intertidal flats as in chapter seven of this research. The predicted years of Deltares were 2020, 2030, 2040, 2050, 2060 and 2100.

At the moment of writing this study, the year 2020, so there is more data available to make better predictions for the future evolution of the intertidal flats. This means the predicted height of 2020 from Deltares can be checked against the present situation. This check will be done in this chapter.

Important note:

1. *All the illustration in this chapter are also published in the appendix 16.*

8.1 Comparison with 2012 prediction by Deltares

8.1.1 Introduction

For this comparison, the predicted height in 2020 by Deltares (prediction made in 2012) and the Vakloding 2019 will be used. The reason for this comparison is to gain insight into the rate of erosion in the Eastern Scheldt. In addition to the rate of erosion, the landscape changes of the intertidal flats will also be visualised.

A Vakloding will be used because this dataset covered the whole Eastern Scheldt. Along with the Vakloding 2019, there is a Vakloding 2019 including the nourishment on the intertidal flat Roggenplaat. These two Vaklodingen will be used for this comparison.

8.1.2 Method

Determining the difference between the maps will be done in ArcGIS. The Vakloding map will be used as the starting point. Figure 89 is an illustration of the difference between the Vakloding 2019 and the predicted height in 2020. Figure 90 is the difference between the Vakloding 2019 including the nourishment and the predicted height in 2020. A positive value, the green colour, means the height of the Vakloding 2019 is higher than the predicted height. A negative value, the red colour, means the height of the Vakloding 2019 is lower than the predicted height. The yellow colour will visualise a small difference of -5 till 5 cm between the two maps.

The Vakloding without the nourishment was used for the analysis because the nourishment was logically not predicted in the map of Deltares and this nourishment will give an unrealistic visualisation of the situation

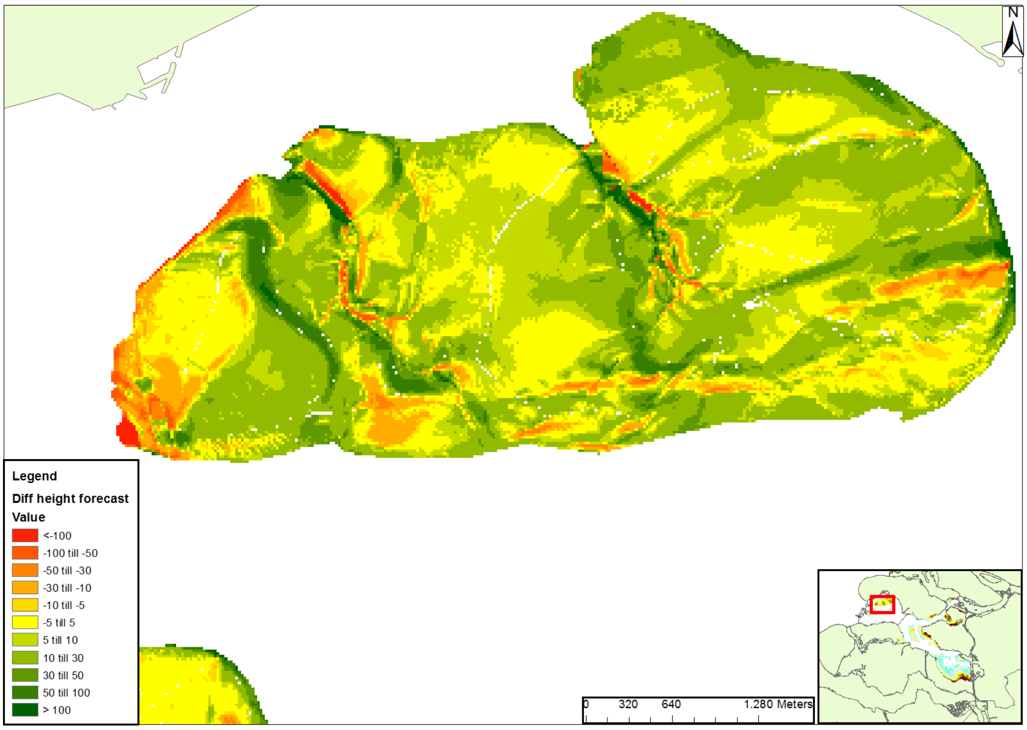


Figure 89. Difference between Vakloding 2019 without the nourishment on the intertidal flat Roggenplaat and prediction 2020 of Deltares.

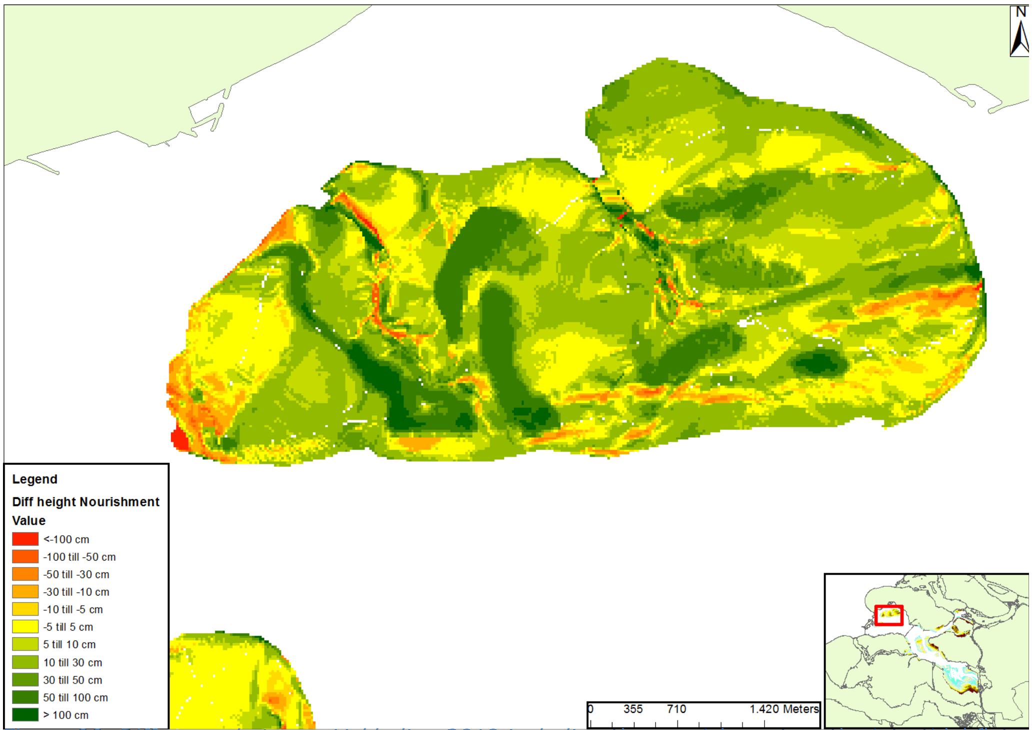


Figure 90. Difference between Vakloding 2019 including the nourishment on the intertidal flat Roggenplaat and prediction 2020 of Deltares.

8.2 Conclusion

In this chapter, a comparison is executed between the predicted height of 2020 and the present height of the Vakloding 2019. The Vakloding was chosen because it is the latest measured dataset of the whole Eastern Scheldt.

The Vakloding 2019 existed of two Vaklodingen. A Vakloding with nourishment on the intertidal flat Roggenplaat and a Vakloding without this nourishment. The Vakloding without the nourishment was used for the analysis because the nourishment was not predicted in the map of Deltares and this nourishment will give an unrealistic visualisation of the situation.

Analysing the difference between the two maps, prediction height of 2020 and Vakloding 2019 without nourishment, gave as result a more green and yellow coloured map. Figure 91 is an illustration of this result. Although there are also some red coloured areas where the erosion rate was higher than predicted. The red colour is visible on the intertidal flats Roggenplaat, Dwars in de Weg and Sint Annaland.

At the areas with a green colour the erosion is less and on the yellow areas the erosion is the same as predicted. A plausible reason for the differences could be the accuracy of the Vakloding data. Moreover, the prediction of Deltares is based on weighted averages and a linear erosion trend. In this way, the small channels on the flat are not taken into account.

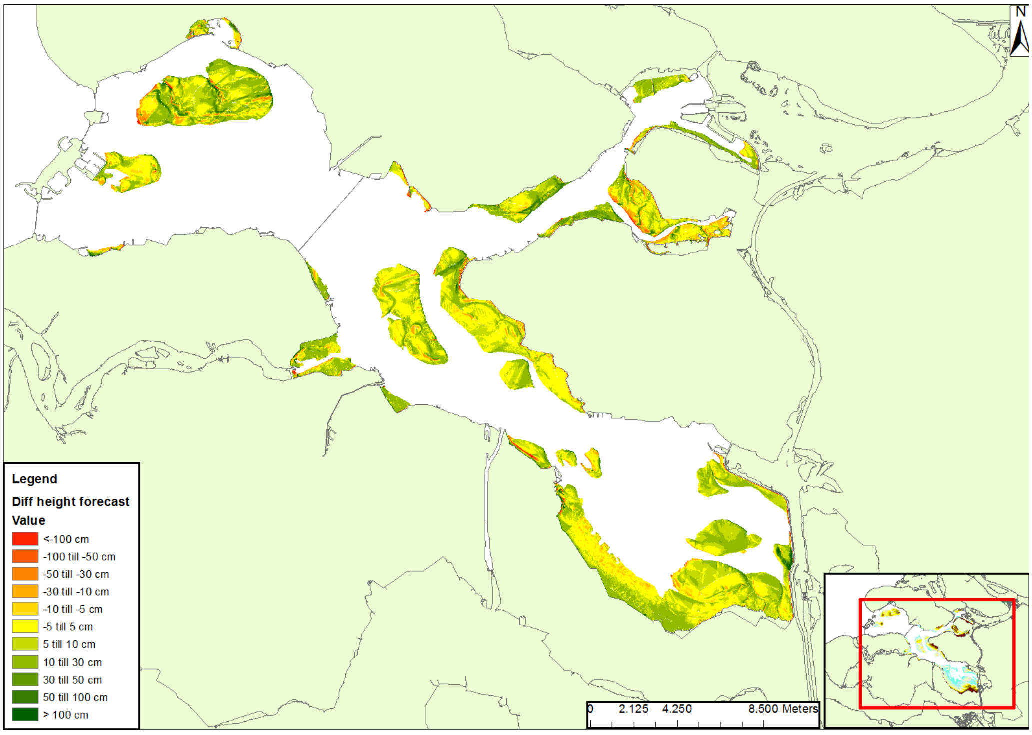


Figure 91. The result of the difference between Vakloding 2019 and prediction 2020 of Deltares in the whole Eastern Scheldt.

Besides the accuracy of data collection, the yellow and especially the green colour is an indication of a change of the rate of erosion on the intertidal flats. Furthermore, the red areas could indicate the determined subareas are not selected correctly. This means the designed subareas needed to be revised after a period of 10 years.

Apart from this reason, the Eastern Scheldt does change every year. This means the erosion rate established in 2012 is not a perfect match with the rate of erosion in 2019 due to the hydrodynamic variables in the Eastern Scheldt.

As a conclusion, the tidal flats and salt marshes in the Eastern Scheldt have eroded less since 2010 than predicted by Deltares in 2012.

9 Conclusion and Discussion

9.1 Discussion

9.1.1 *Ascertain the rate of erosion*

In chapter seven the established erosion rate is being used to determine the height and the emersion time of the intertidal flats for the years 2030, 2040, 2050, 2060, 2070 and 2080. This erosion rate is an average rate established in the period 2010 - 2019. Furthermore, this linear erosion trend is extended until 2080 to determine the height and the emersion time of the intertidal flats.

However, this research proved that the erosion rate is decreasing, as a consequence the predictions until 2080 are not completely reliable. Also, the sea-level rise is crucial for determining the emersion time and due to the uncertainty of today it also changes a lot. This will result in a revision every 10 - 20 years to furnish a reliable prediction of the height and emersion time of the intertidal flat.

Another way to spawn a more reliable rate of erosion for these predictions is a rate of erosion based on statistics. In chapter four the first steps have been made into a statistical analysis to determine the rate of erosion. As a result, the erosion rate in the Eastern Scheldt could be divided into three regression lines because of the two breakpoints in the period 1987 - 2019. Nonetheless, the number of breakpoints is a weighted average of all the intertidal flats in the Eastern Scheldt.

9.1.2 *Determine average height*

The rate of erosion is calculated based on the average height per year. To ascertain the average height per year calculation is done with RTK profiles and Vakloding profiles. The RTK profiles have a measurement error of 1 cm and the Vakloding profiles have a measurement error of 10 - 15 cm. To minimize the measurement error the average height was calculated. However, calculating the median height could also be a possibility to minimize the measurement error. The median will help to attain a more central value

Comparing the calculation method of the average height with the paper "The difference in morphological development between the intertidal flats of the Eastern and Western Scheldt" (de Vet, P. L. M. et al., 2017) a different method was used. In this paper, the RTK profile data was interpolated to 1 meter, because the distance between the measurement points were not the same. Interpolating the data will help to get a more reliable dataset to compare with other profiles. Instead of interpolating the data, the data were obliged to meet with three conditions to acquire a reliable dataset.

9.1.3 *Subareas*

In chapter six of this report, the borders of the subareas were selected based on human interpretation of different kind of data. These were the Vakloding difference of 1983 - 2010, Vakloding difference 2010 - 2019, profile analysis, satellite images of 2019 and the old subareas designed by Deltares in 2012.

These elected subareas are considered as homogeneous areas with the same morphological development. The homogeneous areas are simplified models of the morphological development on the intertidal flats. These models are used to predict the height and emersion time of the intertidal flats until 2080. Furthermore, these models are not taken horizontal morphological development into account. For example, the movement of the small channels on the intertidal flats.

In addition to the models, these models are based on a linear erosion trend while the morphological development in the Eastern Scheldt is changing every year. This means the predictions are becoming less reliable over the years. Also, nourishment is not included in the models. For example, the nourishment on the intertidal flat Roggenplaat was not predicted by Deltares in 2012.

Another example is the difference between the Vakloding 2019 and the prediction of Deltares in 2012. As a result, the height of the intertidal flats is decreasing less than predicted because of a decrease of the erosion rate. Moreover, this result can also be used for designing the subareas on the intertidal flats besides the other used maps in chapter six, because this comparison shows if the designed subareas are determined correctly.

9.2 Conclusion

In 2012 two reports were published about the sand deficit of the Eastern Scheldt by Deltares. These two reports “Volume analysis on RTK profiles of the Eastern Scheldt” and “Prediction of the Eastern Scheldt morphological evolution based on erosion trend” were used to visualise the sand deficit of the Eastern Scheldt and to make predictions of the height and emersion time of the intertidal flats. During the last few years, researchers noticed a potential change of the erosion rate on the intertidal flats. Because of this a new study was needed.
Furthermore, the manager of the Eastern Scheldt, Rijkswaterstaat, is designing and planning to execute new nourishments in the Eastern Scheldt.

This study aims to provide an update of the erosion rate of the intertidal flats and its subareas in the Eastern Scheldt to generate new predictions for designing and planning sand nourishment on the intertidal flats. Because of the suggestions of a changed rate of erosion in the Eastern Scheldt, the following hypothesis was formulated:

The erosion rate of the tidal flats in the Easter Scheldt has decreased since 2010.

To investigate this hypothesis a research question was formulated. The main research question is:

Has the erosion trend of the tidal flats in the Eastern Scheldt in the period 2010 until 2019 changed compared to the erosion trend in the period 1987 - 2010, as described in the reports by Deltares.

The sub-questions supporting the above main question are:

- *Is the erosion trend as observed in this study for the 2010-2019 period compared with the trend established by Deltares on every tidal flat the same? Or are there some erosion spatial variations in the period 2010 – 2019 in comparison to the period 1990 – 2010?*
- *Can the spatial and temporal variations in tidal flats erosion be related to hydrodynamical (wave, tides) and morphological (sediment, elevation) processes in the Eastern Scheldt?*

- *What does the update of the erosion rates of the intertidal flats mean for their emersion time in the context of sea-level rise projections up to the year 2100?*

The available data for this study were the RTK profiles, Vaklodingen, satellite images and wind data. The RTK profiles and Vaklodingen were used to determine the rate of erosion and to redesign the subareas on the flats. Determination of these subareas was based on the satellite image of 2019. The wind data was providing information about the most common wind directions.

The available data was analysed to meet several data quality requirements. The height of the profiles, which have passed these conditions, was converted to the average height per year and a regression line was fitted. This regression line reflects the average rate of erosion. With the rate of erosion for the different profiles and years, the following sub-question could be answered.

Is the erosion trend as observed in this study for the 2010-2019 period compared with the trend established by Deltares on every tidal flat the same? Or are there some erosion spatial variations in the period 2010 – 2019 in comparison to the period 1990 – 2010?

A key finding of this study is that the rate of erosion is lower in the period 2010 – 2019 compared to the period 1987 - 2010. This result was observed on all the intertidal flats in the Eastern Scheldt. However, at some of the intertidal flats, the rate of erosion has changed more than on others. This change is also noticeable after analysing the results of the erosion versus the height of the profiles on the flats, i.e. a comparison of the erosion for different parts within the tidal flats. The results are showing more regression lines with a negative slope. This indicates a higher erosion rate at the higher areas of the flat and a lower erosion rate on the lower areas of the flat.

Another indication of a decrease of the erosion rate is the difference between the height as predicted in the previous Deltares reports and de present height of the flats. The present height of the flats is higher than predicted. This observation indicates that the erosion rate has been less than what was predicted in 2012.

However, a decreasing erosion trend is not directly an indication of a lower emersion time because of the sea-level rise.

Despite the change of the rate of erosion a hydrodynamical reason for this morphological development could not be detected, because the measurement frequency of the profiles is different from the measurement frequency of the hydrodynamical data. As a consequence, the following sub-question could not be answered completely:

Can the spatial and temporal variations in tidal flats erosion be related to hydrodynamical (wave, tides) and morphological (sediment, elevation) processes in the Eastern Scheldt?

The spatial and temporal variations in tidal flat erosion are related to morphological processes because the surrounding of an intertidal flat is not completely the same in all areas. At some parts of the intertidal flat, a large fetch is located in front of the flat. This large fetch will influence the waves and morphological processes. This results in spatial variations on the intertidal flat.

The profiles of the intertidal flats were compared with each other. This comparison delivered reliable data to design subareas on the intertidal flats. Within these subareas, the rate of erosion was estimated. This rate of erosion was used for predicting the height and emersion time of the intertidal flats in the Eastern Scheldt for the years 2030, 2040, 2050, 2060, 2070 and 2080. The update of these predictions answered the last sub-question of this study:

What does the update of the erosion rates of the intertidal flats mean for their emersion time in the context of sea-level rise projections up to the year 2100?

Updating the erosion rate will help to visualise the latest morphological development in the Eastern Scheldt. Furthermore, it illustrates also the emersion time of the intertidal flats. The update of the erosion rate of the Eastern Scheldt shows the emersion time is increasing between 0 and 40% in hectares of the intertidal flats, while the hectares of the areas with a higher emersion time are decreasing. Nevertheless, at some intertidal flats there is sedimentation, and this means the areas will increase in height as well as in the emersion time.

Apart from the rate of erosion the sea-level rise can also be added for determining the emersion time of the intertidal flats into the future. In this context the emersion time will decrease faster than only with the rate of erosion. Furthermore, the emersion time of the areas showing sedimentation is also decreasing if sea-level rise is applied. Taking this into account adding the sea-level rise will show a more realistic illustration of the emersion time.

The erosion trend has changed in the period 2010 - 2019 relative to the period 1987 - 2010. This change in the erosion trend is also visible in the analysis of erosion versus height. The result of this analysis: there are more regression line with a negative slope in the period 2010 - 2019 than in the period 1987 - 2010. This also indicated that higher areas are eroding faster than the lower areas on the intertidal flats.

As a conclusion, a decrease of the erosion rate of the intertidal flats in the Eastern Scheldt leads to a change in the definition of the subareas on the intertidal flats, because these have also changed.

10 Reference

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11 Appendix

In this study a lot of pictures are made. These pictures were also visible in this report. Furthermore, these pictures are also visualised in the appendix documents. Each number is a link to the appendix. The appendixes are:

1. *Profiles alignment*
2. *Profiles visualisation*
3. *Profiles with boundaries*
4. *Removed years*
5. *Trend analysis 1987 – 2019*
6. *Trend analysis breakpoint 2010*
7. *Erosion versus Height*
8. *Visualisation profiles and rate of erosion*
9. *Profiles on the intertidal flats*
10. *Vakloding 1987 – 2010*
11. *Vakloding 2010 – 2019*
12. *Satellite Images 2019*
13. *New Subareas*
14. *Emersion time charts*
15. *Hypsometric curve*
16. *Vakloding 2019 versus height Deltares 2020*
17. *Predicted Height maps*
18. *Predicted Emersion time maps*