# Final thesis report

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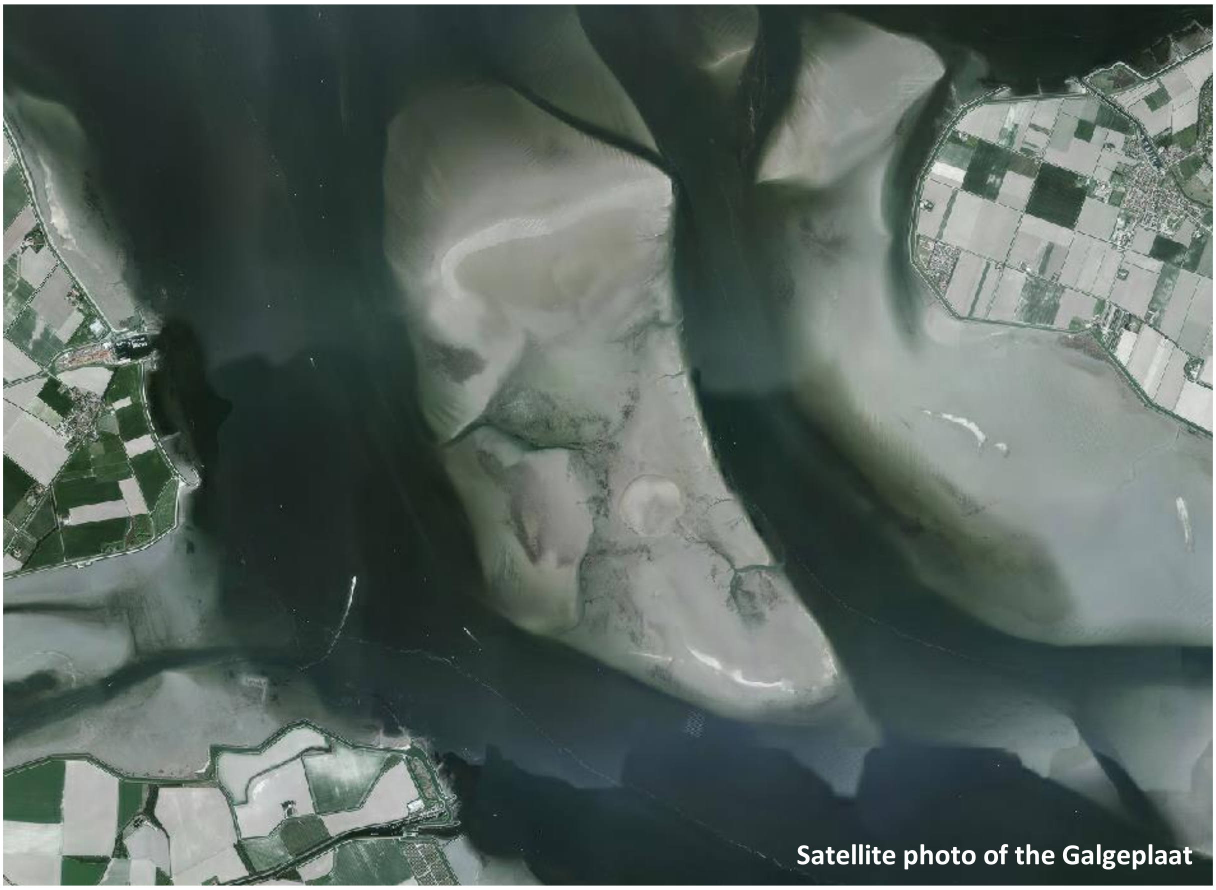

Satellite photo of the Galgeplaat

# Galgeplaat tidal flat and its future

INVESTIGATION ON THE MORPHODYNAMICS OF THE GALGEPLAAT AND A FIRST EXPLORATION TO A SAND NOURISHMENT ON THE GALGEPLAAT TIDAL FLAT

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## Preface

Dear reader,

As an international student of civil engineering, I met a lot of different nationalities. This allowed me to talk about different countries and their civil engineering speciality. When discussing this I realised how extremely unique the Dutch coastal defence system is. The Netherlands monitors the dikes and beaches quite well. During my final thesis, I explored a tiny piece of this typical and unique Dutch coastal engineering. The coast of the Netherlands is unique and special but also vulnerable. The erosion and sea-level rise are a serious threat to valuable natural habitats. Currently, some 12 million $m^3$ of sand is replenished annually. And this amount is still increasing. Therefore, it is needed that measures are taken to prevent the loss of the unique and valuable Dutch coastal system. This final thesis has explored the consequence of erosion at the Galgeplaat tidal flat in the Netherlands.

My final thesis has been written to fulfil the graduation requirements of the Civil Engineering Program at HZ University. I would thank my supervisors for their excellent guidance during this process.

I hope you enjoy your reading.

Tom van Koeveringe

‘s-Gravenhage, November 30th, 2021

## Summary

The tidal area in the Eastern Scheldt is decreasing because of sand erosion and sea-level rise. Therefore, Rijkswaterstaat has investigated the possibilities to mitigate the consequences of erosion to maintain the intertidal areas. The height of the Galgeplaat tidal flat, the second-largest tidal flat in the Eastern Scheldt, has decreased substantially. This final thesis, commissioned by Rijkswaterstaat, describes the detailed changes of the Galgeplaat tidal flat.

Rijkswaterstaat provided three different types of data of the Galgeplaat tidal flat. Therefore, three different types of bed level height analyses are performed in this document. First, the satellite images of the Galgeplaat tidal flat are provided and the changes over time are described. Secondly, the data provided by 'Vaklodingen' has been analysed. These visualised interpolated maps gave a clearer indication of the morphological processes and trends at the centre of the Eastern Scheldt. And last, the profile analysis, which uses the most accurate and detailed data and provides a proper indication for the trend height of the Galgeplaat tidal flat.

To get a better understanding of the morphodynamic processes the hydraulic data has been analysed. Based on the literature review, wind and wave data are important parameters that influence sediment transport. The wind and wave data provided a better understanding of the trends, which were highlighted during the bed level height analysis.

The best solution for the Galgeplaat tidal flat erosion is sand nourishment. The trends are used to calculate the volume of the nourishment. The knowledge of the local hydraulic locations is used to obtain the best deposit location to design nourishment which a lifetime of 25 years.

## Glossary

| | |
|---|---|
| **Emersion time** | During this period the sea bed is not covered with water |
| **Hydrodynamics** | The branch of science that focuses on the dynamics of fluids in motion |
| **(Inter)tidal flat** | Essential horizontal and usually marshy or muddy land that is covered and uncovered by the change of tides |
| **Morphodynamics** | The process by which morphology affects hydrodynamics in such a way as to influence the further evolution of the morphology itself |
| **Tidal amplitude** | The elevation of tidal high water above mean sea level |
| **Tidal prism** | The volume of water in an estuary or inlet between mean high tide and mean low tide, or the volume of water leaving an estuary at low tide |
| **Vakloding** | Measurements of the height of the seabed by Rijkswaterstaat in sections of 20 m x 20 m |
| ***Zandhonger*** | Loss of sand along the coast and on tidal flats due to erosion |

*Table 1 Glossary table: Provides definitions of unusual words*

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# 1 Introduction

The Eastern Scheldt storm surge barrier has been an extraordinary project to protect the hinterland which is below sea level. The Dutch government decided to build a storm surge barrier, instead of a closed barrier due to natural and fishery purposes. By constructing the barrier, the intertidal behaviour was maintained and the hinterland was protected against flooding. The Eastern Scheldt is a preservation area because the intertidal area is a basis for rich ecosystems (*Natura 2000 Deltawateren*, 2016). Since the existence of the intertidal flats is threatened in the future, Rijkswaterstaat, the executive agency of the Dutch government, takes measures to prevent those intertidal areas from flooding.

This final thesis focuses on the intertidal area named Galgeplaat, the second-largest tidal flat in the Eastern Scheldt. Rijkswaterstaat is planning a sand nourishment to restore and maintain the ecological value of the Galgeplaat. Therefore, this study focuses on the erosion and sedimentation processes and aims to obtain a better understanding of the local changes in morphology. With the provided knowledge, from the detailed analysis, the first setup of the sand nourishment will be designed.

## 1.1 Area of interest

### 1.1.1 The Eastern Scheldt

The Eastern Scheldt is located in the south of the Netherlands This estuary has a large intertidal area, almost 35%. Eastern Scheldt is an elongated tidal basin of approximately 50 km in length and with a surface area of 310 km$^2$ (Rijkswaterstaat, 1990). The Eastern Scheldt is considered an engineered estuary because of the human interventions taken, such as the storm surge barrier (Wang et al., 2015).

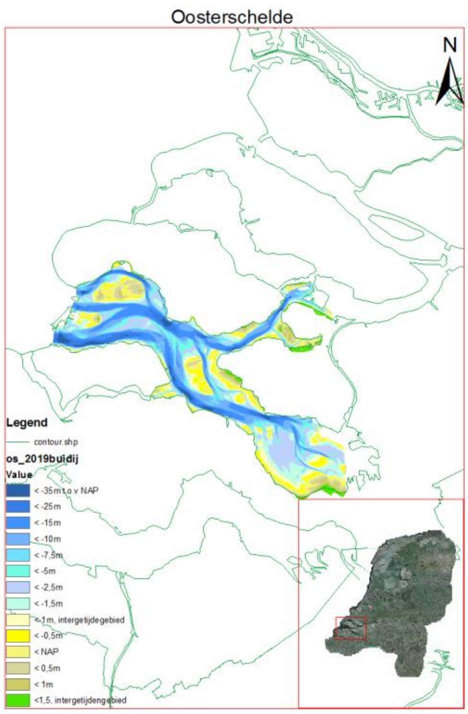


*Figure 1.1.1 The location of the Eastern Scheldt in the southwest of the Netherlands. (The highlighted area is the Eastern Scheldt)*

### 1.1.2 Galgeplaat

The Galgeplaat tidal flat is located in the middle of the Eastern Scheldt and this sandbar is the second-largest tidal flat of the Eastern Scheldt with an area of 950 hectares. Due to erosion, the area of the sandbar has decreased from 1.00 to 0,96 km$^2$ between 1985 and 2001, and the average bed level has reduced from NAP[1] -0.32 m to NAP -0,65 m. Around the Galgeplaat are three channels or waterways. On the east and west side, the slopes are quite steep. While at the southern and northern parts the slopes are less steep (van Zanten & Adriaanse, 2008).

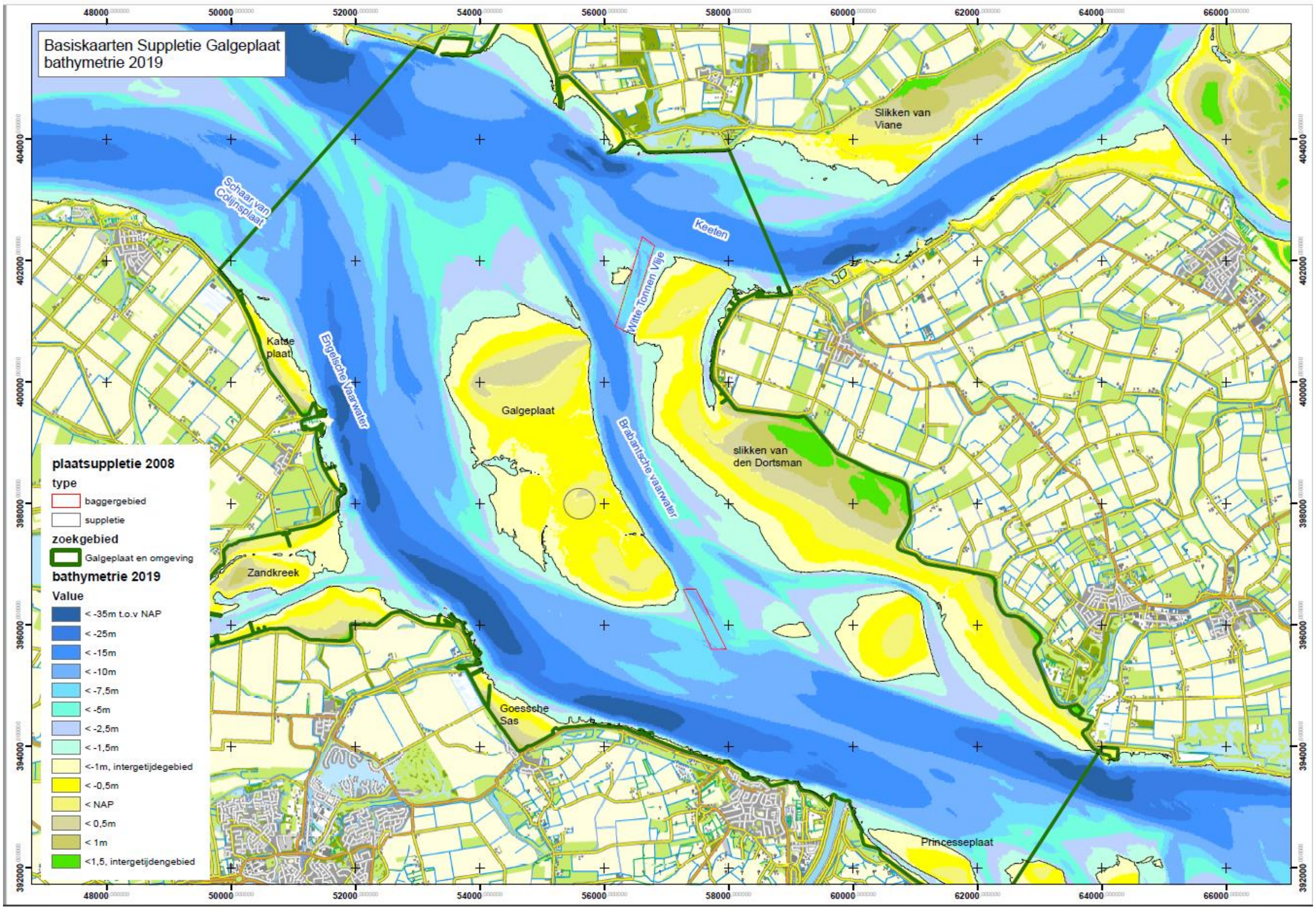


*Figure 1.1.2 Detailed map of the Galgeplaat tidal flat (Rijkswaterstaat)*

## 1.2 Introduction to 'zandhonger'

After the construction of the Eastern Scheldt storm surge barrier in 1986, the morphological balance was heavily disrupted (Figure 1.2.1)(indicated with placement barrier piers). The tidal amplitude in 1969 was comparable with the tidal amplitude in 1987 (Eelkema, 2013). A tidal prism is the volume of water in an estuary between mean high tide and mean low tide. The tidal range is the magnitude of the difference in elevation between low and high tide at a particular point in a body of water. As a result of the barrier and dams, there has been a decrease in the tidal prism of 30%, a decrease in tidal

[1] Amsterdam Ordnance Datum, Dutch reference water level

volume and a decrease in average flow velocities. (J. van der Werf, Reinders, van Rooijen, Holzhauer, & Ysebaert, 2015a).

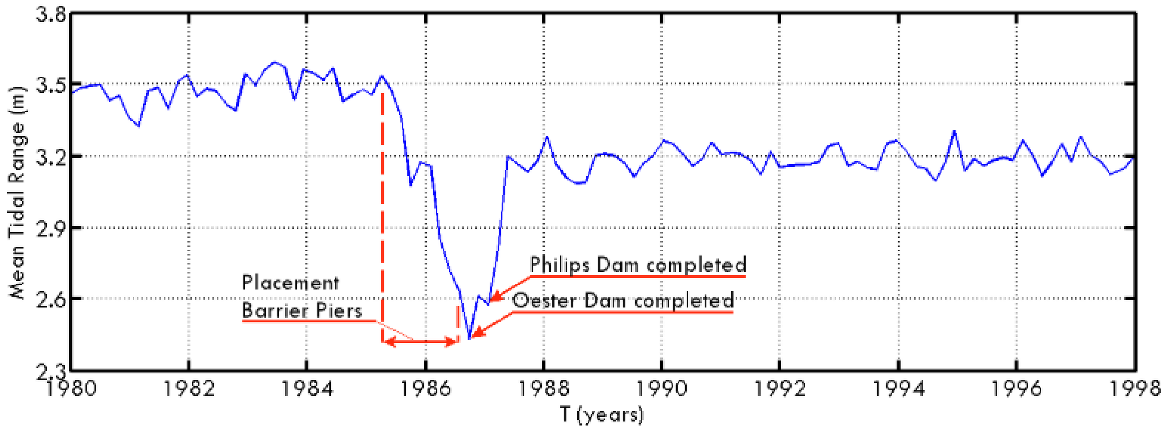


*Figure 1.2.1 Changes in the mean tidal range of the Eastern Scheldt from 1980 to 1998 due to the Delta Project (Mulder, 1994)*

Erosion is not causing problems as long as it is in balance with sedimentation. However, since the construction of the storm surge barrier, the sedimentation in the Eastern Scheldt has decreased and erosion increased on tidal flats. As a result, the tidal currents are not strong enough to cause sedimentation on the tidal flats but can still cause erosion in combination with wave action as shown in Figure 1.2.2. This concept is called the 'Zandhonger' (van Zanten & Adriaanse, 2008). The tidal prism was decreased following the construction of the barrier (Figure 1.2.2). This means that the channels are relatively large for the amount of water that passes through. If the capacity of the channels is too high, they will tend to become smaller. This system of water aims to get into a new balance. The channels are 'hungry'. This results in erosion at the intertidal areas located in the Eastern Scheldt (Hoeven, 2006).

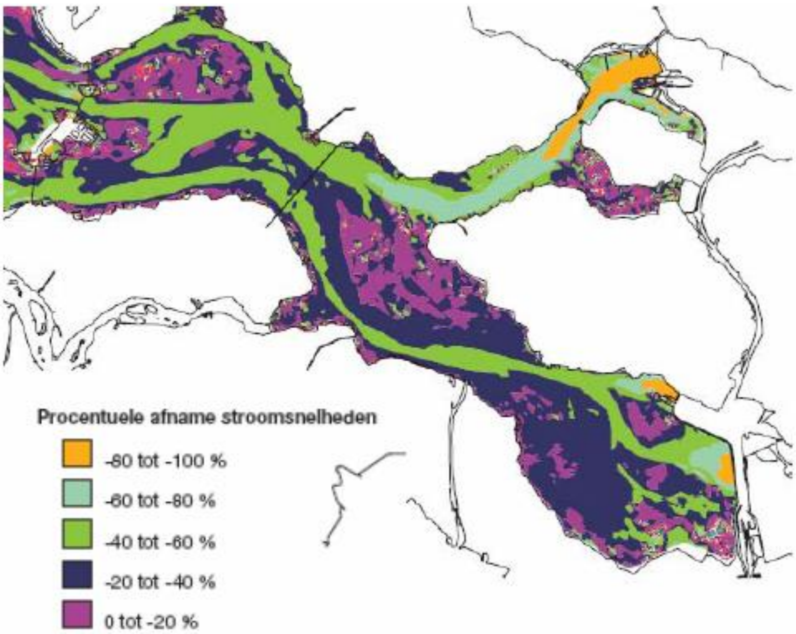


*Figure 1.2.2 Decrease in flow velocities in the Eastern Scheldt after the construction of the storm surge barrier* (Hoeven, 2006)

In the Eastern Scheldt, 50 hectares of the intertidal area will disappear underwater in the coming 50 years. The sand is transported from the intertidal zones to the channels (Borsje et al., 2011). If no measures are taken, research shows that the sand erosion and the relative sea-level rise will lead to further drowning of the intertidal areas around and before the storm surge barrier. Consequently, wave-attack on the barriers will increase, and their stability may therefore decrease. As such, tidal flats are of major importance for flood defence.

Furthermore, the intertidal areas are important foraging grounds for birds and therefore it is important to mitigate the negative effects of erosion (J. van der Werf et al., 2015a). Tidal flats are valuable habitats for animals. The flats of the Eastern Scheldt are of international importance for many wader species. Intertidal habitats are highly productive and provide essential ecosystem functions. The area of tidal flats worldwide is decreasing (J Van Der Werf, Reinders, Van Rooijen, Holzhauer, & Ysebaert, 2015). Globally, the main cause for this decline is sea-level rise. Other causes can be a coastal squeeze, subsidence by gas extraction, and erosion initiated by man-made constructions (Borsje et al., 2011). In the Eastern Scheldt, the erosion initiated by man-made constructions is the main reason of disappearance of tidal flats and shoals.

Rijkswaterstaat, the executive agency of the Ministry of Infrastructure and Water Management, takes measurements to compensate for further erosion. This pilot showed that sand nourishment is a suitable solution for the Galgeplaat (J. van der Werf et al., 2015a). In line with this programme, Rijkswaterstaat is going to design and implement nourishment at the Galgeplaat in the upcoming years (Witteveen+Bos, 2011).

In the past, data on the morphology of tidal flats have been gathered in the Eastern Scheldt. Rijkswaterstaat provides a long-term measurement of the water levels, waves, and wind. Furthermore, they investigated the morphological behaviour of the Galgeplaat (Hoeven, 2006).

## 1.3 Problem statement

Despite a wealth of data and research, there is still no full understanding of the processes governing the morphological behaviour of the Galgeplaat tidal flat. Based on research (Beiboer, 2020) the erosion rate is decreasing in the Eastern Scheldt, although the parameters which cause this decrease of erosion are still unknown. In the past research was done about the processes (Hoeven, 2006), yet new data may provide a more complete understanding of the current evolution of the Galgeplaat tidal flat (Deltares, 2012). Since the sand nourishment of the Galgeplaat is going to be designed, the processes of sediment transport at the Galgeplaat need to be understood in detail.


*Figure 1.3.1 Values shown are the coefficients of the linear trend of average heights [mm/year]* (Deltares, 2012)

## 1.4 Goals and objectives

### 1.4.1 Aim of the study

Rijkswaterstaat is going to design nourishment at the Galgeplaat tidal flat which needs to last for at least 25 years. To obtain the best design, a proper understanding of the processes at the Galgeplaat is needed. The data of the past can provide insights into the future of the Galgeplaat tidal flat. The data provided by Rijkswaterstaat can help to analyse the erosion and sedimentation processes in the centre of the Eastern Scheldt. In particular, the erosion processes are complex.

Therefore, this research aims to provide a more thorough understanding of the behaviour of erosion at the Galgeplaat to inform the design of the upcoming nourishment. Also, the ecosystems at intertidal zones are ecologically valuable and threatened in their existence. Therefore, these systems should be managed with care and represent a key factor in the design of the nourishment. A lot of investigations have been executed in the Eastern Scheldt. This document provides an overview of the relevant research for the Galgeplaat tidal flat.

### 1.4.2 Research questions

The main research question is:

***How can a nourishment be designed for the Galgeplaat taking into account the morphological trend that is revealed by the erosion data that are available for the period 1987-2020?***

To obtain a thorough understanding the following sub-questions will have to be answered.

1. What was the morphological trend of the Galgeplaat in the period 1987-2020?
2. How have waves affected the morphological changes in the Galgeplaat in the period 1987-2020?
3. How will the Galgeplaat morphologically evolve up to the year 2050 in the context of climate change?
4. How can a nourishment best be designed for the Galgeplaat considering the morphological trend of the past (1987-2020) and the expectations for the future (2021-2050)?

# 2 Theoretical framework

## 2.1 Lessons learned for previous studies

### 2.1.1 De ‘Zandhonger’ van de Oosterschelde

A study by van der Hoeven in 2006 aimed to describe the morphological trend of the Galgeplaat. The study performed an analysis based on data from 1983 until 2001: windspeed, wind direction, wave height and water levels. First, the profiles of the Galgeplaat tidal flat were analysed. After this, the wind data from a nearby observation station were collected and analysed. The water levels were analysed during storm events. The wave data was considered to be insufficient for analysis. The data was divided into three subperiods: 1984-1986, 1987-1993, 1994-2001.

The study of van der Hoeven (2006) aims to determine the hydrodynamical and aerodynamical processes which influence the erosion and sedimentation on the Galgeplaat. The results of this study are that erosion has decreased after 1994. This can be because from 1994 until 2001 fewer extreme storms occurred.  One of the parameters which had a strong correlation with the erosion rate was wind velocity. To obtain are stronger connection only the wind velocity above 5 m/s was considered. As a conclusion is given that the wind coming from the southwest is causing the most erosion.

An explanation can be given by looking at the slopes of the Galgeplaat tidal flat. The steep slope at the west part of the Galgeplaat will take all the energy of the wind waves. 44% of the time wind is coming from the south-west, based on the data from the period of 1987-1993. The fetch length of the wind of also at its maximum when coming from the south. Wind coming from the northern direction correlates with sediment transport, which tends to sedimentation. This is because of the gentle slope at the northern side of the Galgeplaat. Van der Hoeven stated that understanding the processes caused by wind are important to design a nourishment. The most important part is dividing the Galgeplaat into the right sub-areas. There is a strong correlation between the characteristic wind direction and the weather conditions (Hoeven, 2006).

### 2.1.2 The pilot nourishment

In 2008 a pilot nourishment at the Galgeplaat tidal flat was realized by Rijkswaterstaat. The pilot showed that nourishments are an effective way to counteract the negative ecological consequences of erosion (J. J. van der Werf et al., 2019). In the period of July-September 2008, a nourishment on the Galgeplaat was constructed. About 130,000 $m^3$ of sand was nourished at the Galgeplaat. This resulted in an average nourishment height of 65 cm, so the height of the area enclosed by the dike-ring was increased by 65 cm (J. van der Werf et al., 2015a). Four years after the nourishment in 2012 about 10% of the sand was transported. This indicates an erosion of 1.5-2.0 cm/year which is higher than the rest of de Galgeplaat, which was 0.5 cm/year across the same period. However, most of the transported sand ends up only 50 m from its initial location. It will take 40 years for the nourishment to be gone (Holzhauer & van der Werf, 2008). After the nourishment, the average height has risen from -0.8, -0.5 m NAP to -0.6, +0.4 m NAP. In Figure 2.1.1 is shown that the sand particles seem to move in the northern direction by 10 m/year (J. van der Werf, Reinders, van Rooijen, Holzhauer, & Ysebaert, 2015).

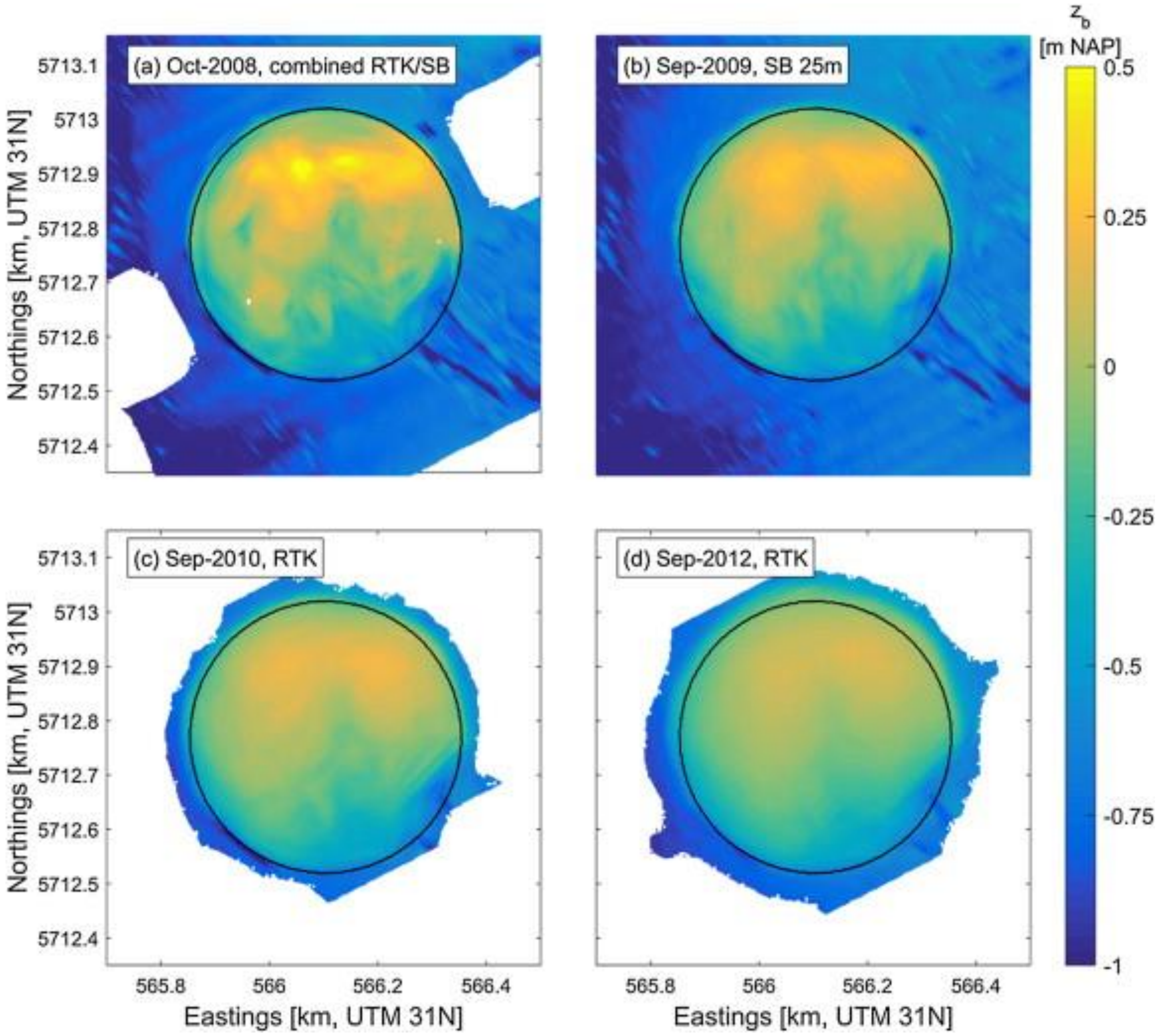


*Figure 2.1.1 The changes in the bed level over four years after the pilot nourishment on the Galgeplaat (J. van der Werf et al., 2015).*

This pilot has shown that nourishments can help to mitigate the negative effect of tidal flat erosion. So, sand nourishments are an effective way to counteract the negative consequences of tidal flat erosion in the Eastern Scheldt. The nourishment was relatively stable, because of the lifetime of 40 years, which provides sufficient time for the recovery of the benthic habitats. Yet, this pilot nourishment was not sufficient to provide enough foraging time for the wader birds since only 2% of the Galgeplaat was nourished (de Vet, van der Werf, & Stronkhorst, 2016).

### 2.1.3 The solutions to ‘zandhonger’

Rijkswaterstaat investigated solutions to sea-level rise and climate change. Because of the sea-level rise, the Eastern Scheldt storm surge barrier would not provide sufficient safety in 2100 with a sea-level rise of 60 cm. In 2050 a decision is expected about the future of the storm surge barrier. The concept of ‘Zandhonger’ will strongly influence the final decision. Based on current observations and understanding it is expected that it takes 100 years to stop the erosion in the Eastern Scheldt (van Zanten & Adriaanse, 2008).

The study of the 'zandhonger' considered all the possible solutions to mitigate the negative effects of erosion. The sand nourishment is considered to be the most suitable solution.

| Solution | Conclusion |
|---|---|
| **Removal of the storm surge barrier** | No option because of the high costs and uncertainty of effects. |
| **Increase the flow capacity of the storm surge barrier** | Unknown effect on 'Zandhonger' |
| **Connecting Volkerak to Eastern Scheldt** | Will result in an increase of volume of the Eastern Scheldt, but a decrease in the tidal prism |
| **Filing the channels in Eastern Scheldt so 'zandhonger' stops** | 400-600 $m^3$ of sand needed.<br>Too expensive and effectiveness is uncertain. |
| **Creating intertidal areas somewhere else** | Unrealistic |
| **Nourishing the intertidal areas** | Effective if done once in 20-30 years |
| **Oyster reefs** | The Japanese oyster seems to prevent erosion only if located at the edges of intertidal areas. However unlimited use of oyster beds will influence the commercial fishery in the Eastern Scheldt. And they cannot be placed in recreational areas. |

*Table 2 The solutions and conclusions of the zandhonger investigations* (Witteveen+Bos, 2011)

### 2.1.4 Final thesis Beiboer

In his final thesis, Beiboer (2020) investigated the erosion rate of the tidal flats in the Eastern Scheldt. During his research, he analysed elevation data of the tidal flats in the Eastern Scheldt and evaluated the erosion rate over space and time. The 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 outcome was observed on all the intertidal flats in the Eastern Scheldt. Beiboer found out that the erosion rate decreases in the Eastern Scheldt, however, his work does not include an explanation for this decrease.

Analysing the change in the rate of erosion a hydrodynamical reason for the morphological development could not be detected, because the received frequentation of the profiles was different from the received frequentation of the hydrodynamical data. The spatial and temporal variations in tidal flat erosion are related to morphological processes because the surroundings are dependent on the location of the tidal flat.

Later, Beiboer researched the profiles of the intertidal flats and compared the profiles provided by Rijkswaterstaat. In conclusion, Beiboer proved that the erosion rate has decreased by 30%. While Beiboer focussed on a statistical analysis of the Eastern Scheldt, this thesis will focus on the spatial variations in the centre of the Eastern Scheldt. The statistical analysis can be used to understand the behaviour of the different morphological features located in the centre of the Eastern Scheldt (Deltares, 2012) & Beiboer, 2020).

### 2.1.5 Intertidal flats in engineered estuaries

Sediment relocations can affect the eco-morphology of intertidal flats, even if the sediments are dropped at flow channels. However, the complex mitigating and delayed responses of intertidal flats to sediment relocation works emphasize the necessity of adaptive management strategies in estuaries such as the Eastern Scheldt. Due to the large importance of wind, the net sediment transport on intertidal flats is largely controlled by the wind. Sediment nourishments are interventions that may be utilized to compensate for intertidal flat erosion (de Vet, 2019)

### 2.1.6 Eastern Scheldt inlet morpho dynamics

This study aims to describe the effects of the storm surge barrier on the Eastern Scheldt on the Galgeplaat. Both short- and long-term effects. Tidal inlet morphology is characterized by complex interactions between currents, waves and sediment on varying spatial and temporal scales. This behaviour can be influenced by human interventions. Due to the storm surge barrier, the sedimentation has decreased and the erosive process due to wind waves is still acting. The morphological activity declined, and sediment volume has decreased, however, it is still unclear where the eroded sediment is transported to (Eelkema, 2013).

### 2.1.7 Summary of the previous research

Due to the storm surge barrier and closure of the upstream branches, the net effect of the sediment transport is erosion. In 2008 research was done about the typical erosion rate and 0,01m/year was estimated. When extrapolated, this means that in 2100 half of the original intertidal flats in the Eastern Scheldt will have been eroded below NAP (van Zanten & Adriaanse, 2008).

A large number of studies about morphology, erosion and the Eastern Scheldt are available. This thesis will distinguish itself in applying the previous research in the current situation at the centre of the Eastern Scheldt. For the design of the nourishment, the morphology of the Galgeplaat tidal flat needs to be analysed. The different morphological features located on the Galgeplaat will have to be described and their behaviour must be understood. The knowledge of the previous studies will be used in the analysis of bed level changes and the analysis of the hydrological data.

## 2.2 Morphological processes in estuaries

Hydrodynamics and morphodynamics together form morphological development (Figure 2.2.1). The hydrodynamics consist of waves, velocity, tidal prism, sea-level rise. The morpho dynamics contains sediment transport, bathymetry and sediment composition. The study of the morphology and evolution of tidal flats is particularly well suited in the context of morpho dynamics. A more complex overview is given by Figure 2.2.2 based on the book Coastal Dynamics.

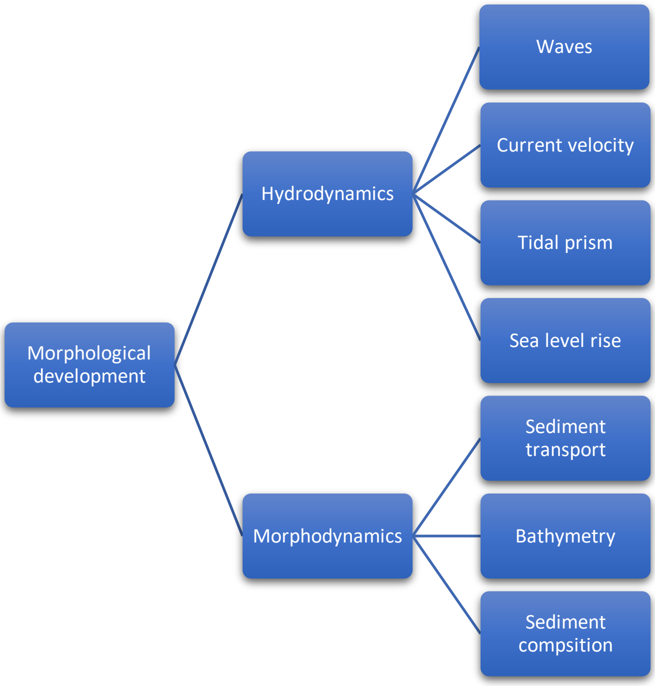


*Figure 2.2.1 The different parts of hydrodynamics and morpho dynamics*

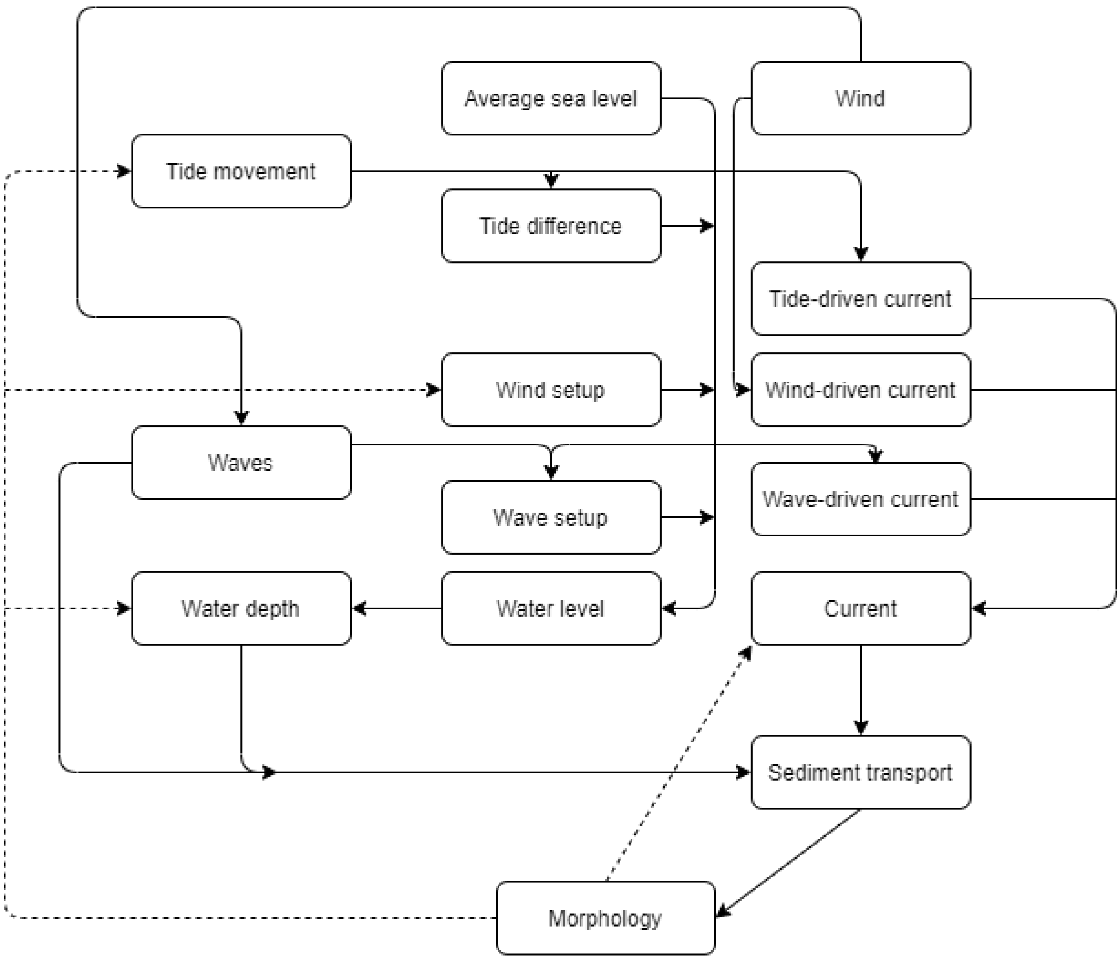


*Figure 2.2.2 The connections between morphology and hydrodynamics* ("Origin of the Dutch coastal landscape: Long-term landscape evolution of the ... - Peter Vos - Google Books," n.d.)

In Figure 2.2.3 a more basic approach for the process of bed level changes is provided. The bed level updates are caused by changes in hydrodynamics. Since the changes in hydrodynamics can result in sediment transport.

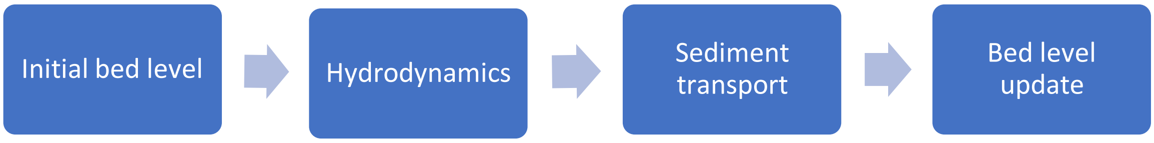


*Figure 2.2.3 A simple approach for changes in bed level*

## 2.3 Hydrodynamic changes

After the construction of the storm surge barrier, the hydrodynamic characteristics of the Eastern Scheldt changed. The characteristics which can influence the erosion rate are the average tidal range, average current velocity and tidal volume. All three parameters decreased after the construction of the storm surge barrier. In Table 3 the changes are shown.

| | Pre-barrier | Post-barrier | Change in % |
|---|---|---|---|
| **Total surface area ($km^2$)** | 452 | 351 | -22 |
| **Intertidal surface area** | 183 | 118 | -36 |
| **Tidal volume ($10^6$ $m^3$)** | 1283 | 915 | -29 |
| **Average current velocity (m/s)** | 1.2 | 0.8 | -33 |
| **Residence time water (days)** | 50 | 100 | +100 |
| **Fresh water input ($m^3$/s)** | 70 | 25 | -63 |
| **Salinity (‰)** | >25 | >30 | +15 |
| **Average tidal range (m)** | 3.7 | 3.25 | -12 |
| **Average concentration suspended matter (mg/l)** | 25 | 15 | -40 |

*Table 3 Changes in hydrodynamic characteristics of Eastern Scheldt (Brinke et al., 1994)*

## 2.4 The importance of tidal flats

Salt marshes are valuable because it enhances biodiversity, and dampen the waves (de Vet, 2019). The Eastern Scheldt with a huge variety of flora and fauna also forms a habitat for the birds of passage. So, the Eastern Scheldt has an international function for protected species. That is the reason why the Eastern Scheldt is a European Nature 2000 area and a national park. Especially the wader birds are threatened with extinction. These birds can only survive if there is enough food in the intertidal areas. The 'Zandhonger' decreases not only the total area of the intertidal zone but also the foraging time (Ministerie MenI, 2013). Therefore in the long term, these rare populations of intertidal flora and fauna may disappear if current trends continue (Witteveen+Bos, 2011).

## 2.5 Erosion of tidal flats

'Zandhonger' results in erosion of the intertidal areas. To obtain a new balance, in total 400-600 million $m^3$ of sand is needed (van Zanten & Adriaanse, 2008). In comparison, to maintain the sandy coastline of the Netherlands 10 million $m^3$ of sand is nourished annually. For the Eastern Scheldt, the sand is no longer naturally available due to the storm surge barrier, specifically because during the construction of the barrier very deep pits were created (Hoeven, 2006).

Tidal velocity is the main reason in an estuary why sediment transport takes place together with waves. The datum of the sea adjusts itself to balance between the wetted parameter of the channel and the flow velocities. This balance is mainly dominated by tidal waves. At the edges, more sedimentation takes place compared to the middle of a tidal flat. This is because the flow velocities are higher at the edges. At the location where the flow velocities are the highest, the erosion is also higher. The flow velocity is important for the transport capacity of the water. During spring tide, the flow velocities increase by 50% compared to the neap tide. This explains why the sediment transport can be up to 20 times higher during spring tide (Hoeven, 2006).

Another parameter, often used in intertidal areas, is the emersion time or '*droogvalduur*' of a certain body of water. The emersion time is defined as the time in which the location or element is not covered by water. The amount of emersion time is important for wader species to feed themselves. One goal of the nourishment is to increase the emersion time of the Galgeplaat tidal flat to increase the time for wader species (Holzhauer & van der Werf, 2008).

## 2.6 Erosion due to waves

In deep water, waves do not cause much erosion because the horizontal and vertical velocities are almost zero. Since the Eastern Scheldt is shallow water, we consider shallow-water waves. Waves are the most important reason for the vertical transportation of sand. Especially when the waves start to break, they can cause vertical sediment transport. In the intertidal zone the location where the waves break changes when time progresses due to high and low tide. Likewise, in an estuary, a big area is coping with breaking waves, which causes erosion (De Vet, Van Prooijen, & Wang, 2017).

Tidal currents or wave-driven currents cause horizontal sediment transport. So, waves can cause vertical transport and wave-driven currents vertical transport. Together those two parameters can cause erosion.

The waves cause a lifting force which results in vertical transport. The tide causes horizontal transport of the sediment. The erosion processes cause changes in bathymetry, the change in bathymetry can cause changes in the hydrodynamics processes.

## 2.7 Sand nourishments

Artificial nourishments can be applied for various reasons: to create new land, to compensate for losses due to erosion or to increase the safety at the hinterland. For designing nourishment, different aspects are considered.

The first one is the origin of sand. The required volumes of sand can be up to millions of $m^3$ per nourishment. The area from which the sand is coming is called the borrow area. The used for the nourishment can be land-based or a marine source. The marine sand is gathered by a dredger. The dredged sand from the borrow-pits is transported by pipeline or the dredger. Dredging means also disturbance of the biologically active surface layer, which will influence the ecosystem. If a nourishment project is foreseen in the vicinity of Natura 2000 areas, an assessment has to be made whether negative effects are to be expected.

The quality of sand is the second important aspect. If the supplied sand is located at an eroding tidal flat the new sand will tend to form a crust or blanket over the existing coastal formations. This means that the sand will dominate the morphology in the same way as the existing sand. Therefore, one of the basic rules for nourishment is to use relatively similar materials with similar grain sizes.

The third aspect is the location of the nourishment also named the deposit area. The deposit area needs to be selected based on the erosion rate, recreational purposes etc. The selections parameters differ a lot since they are based on local circumstances.

The last two aspects that should be considered when designing sand nourishment are the lifetime and volume of the nourishment. Those two are closely related to each other. The lifetime of nourishment is determined by the erosion rate at the deposit area and the volume of the nourishment (Bosboom & Stive, n.d.).

Since a few nourishments are placed in the Eastern Scheldt knowledge is gathered of doing large nourishments in intertidal areas (J. J. van der Werf et al., 2019) & (de Vet et al., 2016). Based on data and models the suppletion variants were selected. The variants were tested based on criteria that resulted in the nourishment design.

## 2.8 Climate change

Climate change will cause sea-level rise and more extreme weather conditions. Sea level rise causes an additional decrease of the intertidal area in the Eastern Scheldt. The sea level in the Netherlands has increased by 24 cm from 1890 through 2018. In the North Sea, an increase of 2 mm/year is measured by satellites. The global average is estimated at 3 mm/year. Rijkswaterstaat considers a sea-level rise for the upcoming 30 years of 2 mm/year (=60 mm in total). KNMI has three different scenarios: LOW, MIDDLE, HIGH to estimate the sea-level rise in the period of 1990-2100.

| Scenario | Total rise (cm) | Rise in periods(mm/year) |
|---|---|---|
| LOW | 35 | 2.5 (1990-2050)<br>4 (2050-2100) |
| MIDDLE | 60 | 4.2 (1990-2050)<br>7 (2050-2100) |
| HIGH | 85 | 5.8 (1990-2050)<br>10 (2050-2100) |

*Table 4 Sea-level rise prediction scenarios (KNMI, 2020)*

Likewise, sea-level rise decreases the emersion time of the tidal flats in the Eastern Scheldt. When the low water line increases in height the total tidal area decreases.

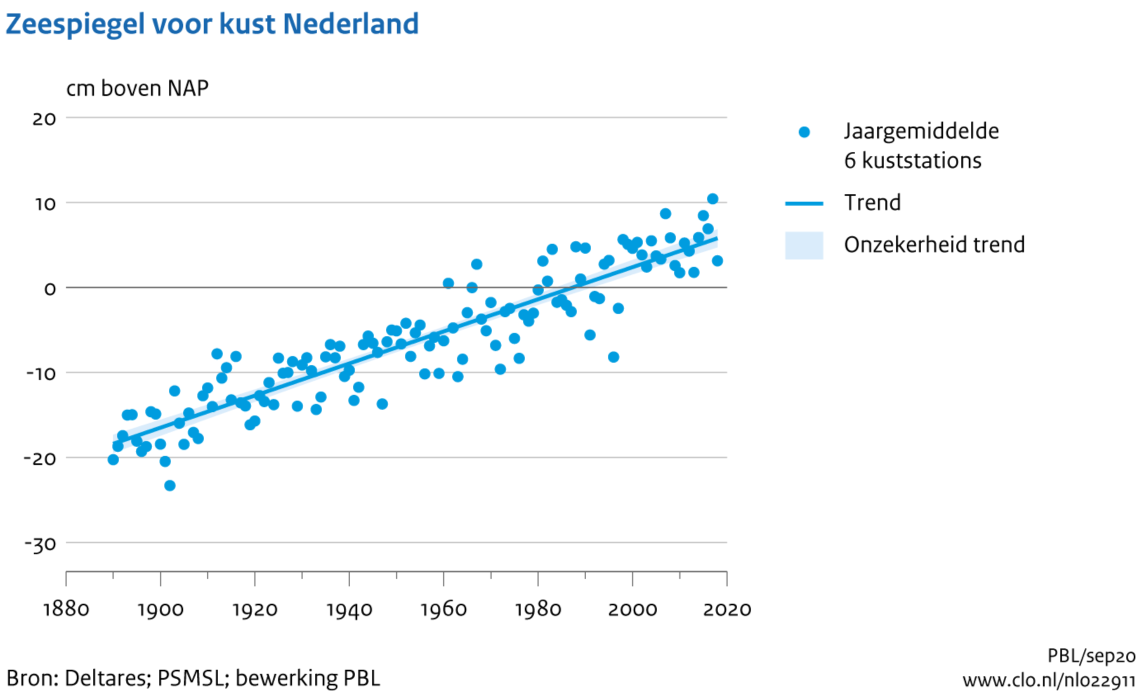


*Figure 2.8.1 Sea level rise in the Netherlands from 1980-2020*

# 3 Method

## 3.1 Step by step approach

**1. What was the morphological trend of the Galgeplaat in the period 1987-2020?**

The first research question can be answered by analysing the data collected by Rijkswaterstaat both RKT profiles and Vaklodingen. Also, the trend analysis results of the research of Beiboer will be compared with the profile. Beiboer concluded that the average erosion rate in the Eastern Scheldt decreased after 2010. However, bathymetry at the Galgeplaat can be different the erosion is expected to be inhomogeneous based on previous research and studies. The profiles will give accurate data for the height and the Vaklodingen will give a more overall view of the changes in bed level. The erosion can vary at different profiles, therefore breakpoints in the erosion trend can be seen.

**2. How have waves affected morphological changes in the Galgeplaat in the period 1987-2020?**

To answer this sub-question the knowledge of the analysis of the RKT-profiles and the vaklodingen, and the knowledge of the previous studies the wave data will be used. As shown in the theoretical framework the waves can affect the morphological changes in intertidal areas. The waves during storm events have the largest impact. Therefore, a study of waves and correlation with storm events with erosion rates will be made. Tidal currents can also impact the morphological changes however due to time limitations only the wave data will be analysed.

**3. How will the Galgeplaat morphologically evolve up to the year 2050 in the context of climate change?**

The goal is to predict the emersion time of the intertidal flat concerning the sea-level rise and erosion or sedimentation. The emersion time is the time that an area is above sea level. The emersion time quantifies the time wader species have available. To obtain the time of which the Galgeplaat is above sea level, likewise, the sea level rise will be taken into account. With the analysis of the first two subquestions, the new subareas will be chosen. The emersion time will be determined for every decade up to 2050.

**4. How can a nourishment best be designed for the Galgeplaat considering the morphological trend of the past (1987-2020) and the expectations for the future (2021-2050)?**

To obtain recommendations for the nourishment design a detailed study at the Roggeplaat nourishment (2019) is needed. Also, the knowledge of the pilot nourishment can be used to make predictions of the erosion rate in the future. Combined with the knowledge of the data analysis of the previous research questions the nourishment can be designed. The design aspects of nourishment are described in the theoretical framework.

| RESEARCH QUESTION | ACTIVITY | PRODUCT |
|---|---|---|
| **WHAT WAS THE MORPHOLOGICAL TREND OF THE GALGEPLAAT IN THE PERIOD 1987-2020?** | Analysing the profiles, vaklodingen and satellite photos | Chapters: 4.1 Satellite pictures, 4.2 Vaklodingen, 4.3 RTK-Profiles. |
| **HOW HAVE WAVES AFFECTED MORPHOLOGICAL CHANGES IN THE GALGEPLAAT IN THE PERIOD 1987-2020?** | Analysing the wind and wave data | Chapter: 4.4 Hydraulic data analysis |
| **HOW WILL THE GALGEPLAAT MORPHOLOGICALLY EVOLVE UP TO THE YEAR 2050 IN THE CONTEXT OF CLIMATE CHANGE?** | Estimating the emersion time considering the climate change and results from previous chapters | Chapter: 4.5 Morphological development Galgeplaat |
| **HOW CAN A NOURISHMENT BEST BE DESIGNED FOR THE GALGEPLAAT CONSIDERING THE MORPHOLOGICAL TREND OF THE PAST (1987-2020) AND THE EXPECTATIONS FOR THE FUTURE (2021-2050)?** | Define design recommendations based on the results from previous chapters | Chapter: 4.6 Design of the nourishment |

*Table 5 Research strategies: The activities taken, products delivered to answer the research questions*

## 3.2 Available data

1. **RTK Profiles**

RTK profiles are lines on which the height of the bed level is determined by a GPS pole. Each measurement consists of an x-, y- and z-coordinate. This is done by physically walking over a line at the area which needs to be measured. The measurements are taken every year and are collected in a database. Unfortunately, there is a gap between 2003 till 2008. The RTK profiles have been used to estimate the erosion rate for sub-questions one.

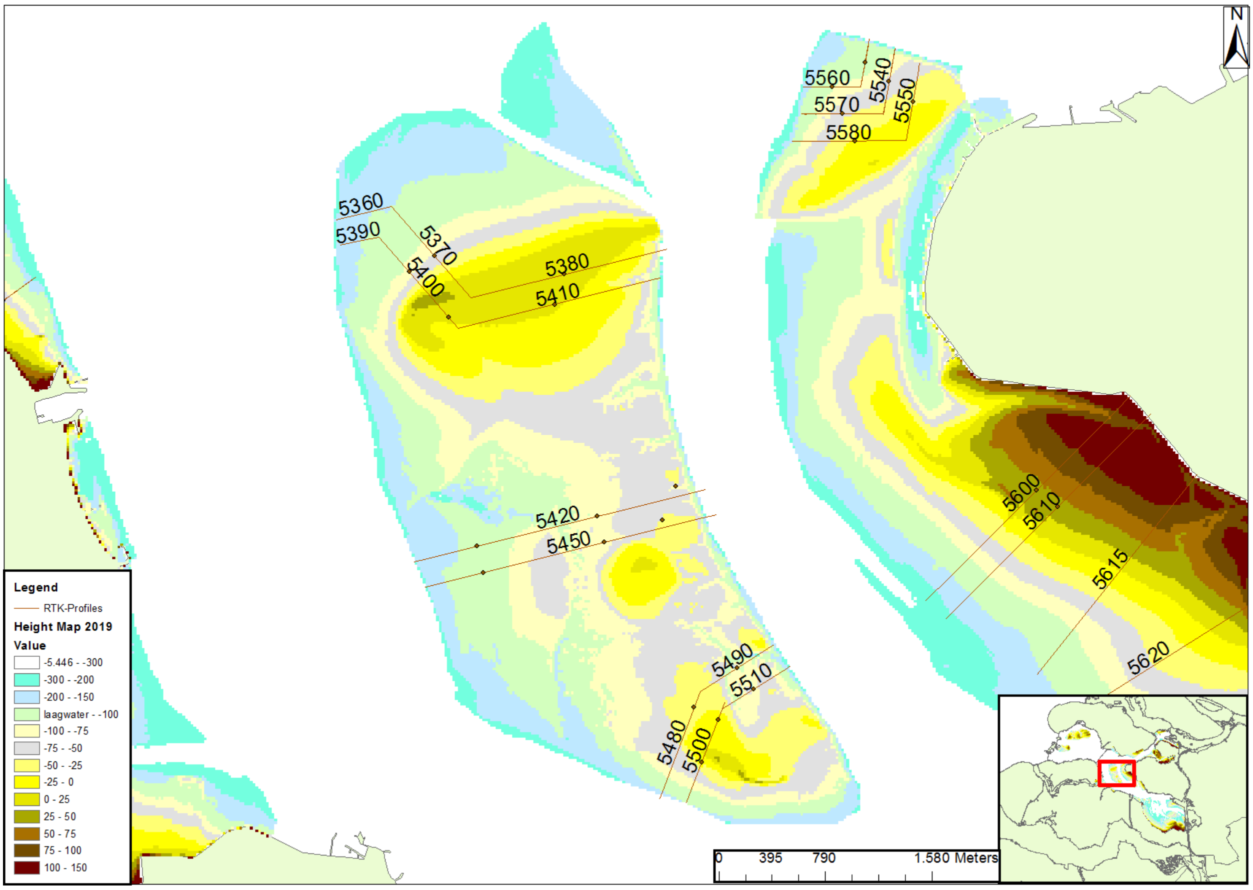


*Figure 3.2.0.1 An overview of the locations of the RTK-profiles*

## 2. Vaklodingen

The other dataset is called vaklodingen, which will be used to answer sub-question one and three. The dataset consists of x, y and z coordinates with a resolution of 20m * 20m. This data is gathered by an aeroplane and boat. The database consists of the sets of the years 1990, 2001, 2007, 2010, 2013, 2016 and 2019. From 2001 on the method of collecting the data became more accurate, due to laser altimetry. This data is stored in ArcGIS. The data is less accurate compared to the RTK Profiles with an error in the measurements of 10-15 centimetres, however, the RTK profiles only provide one straight line of measurement. In this thesis, the data is used to obtain a clear understanding of the bed level updates during the years, which is needed to estimate the emersion time. In Figure 3.2.0.2 an example of a map created by vaklodingen is shown.

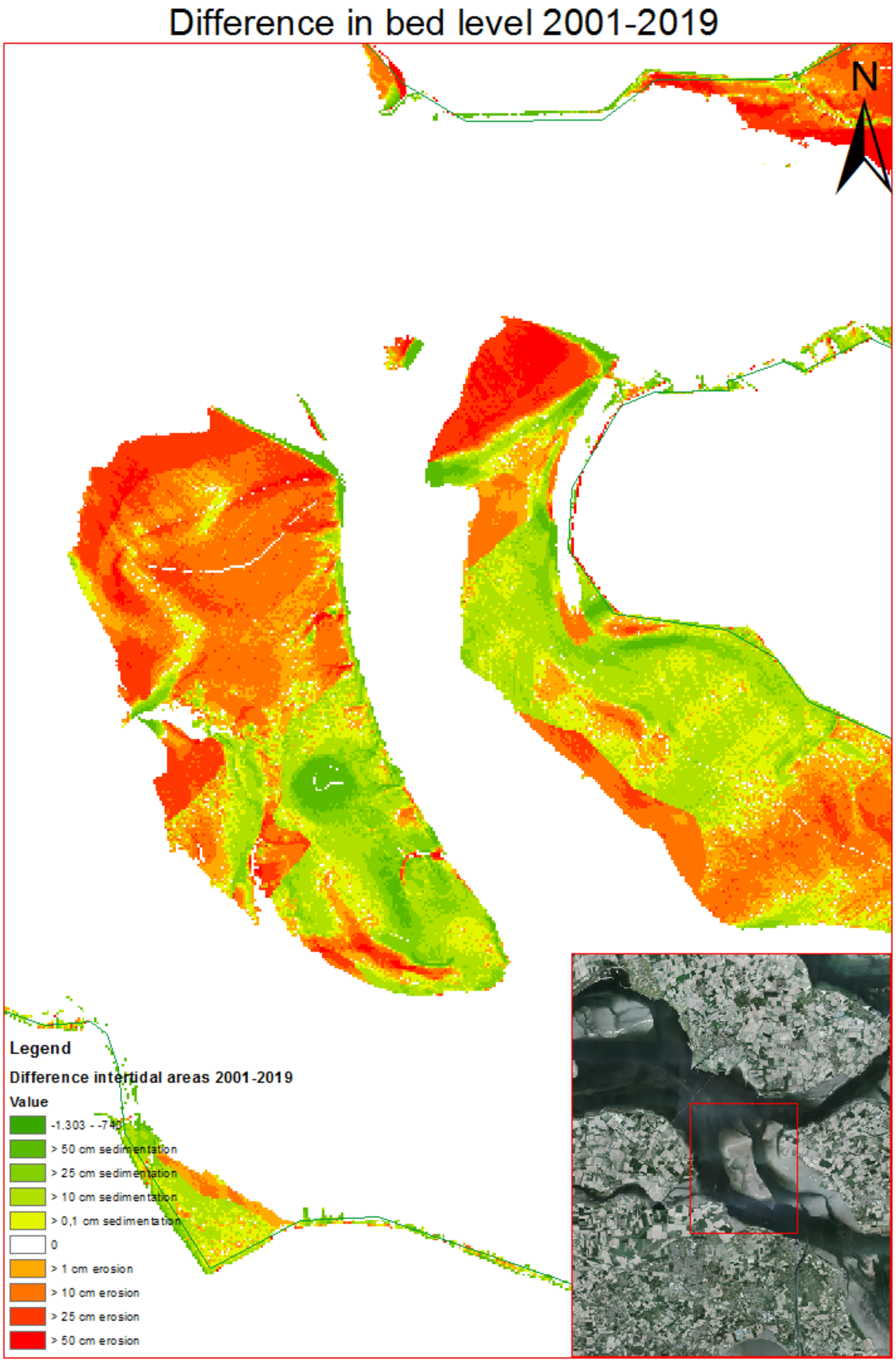


*Figure 3.2.0.2 An example of the 'vaklodingen'. The map shows the difference in bed level height from 2013 until 2019. The green colour indicates an increase and the red colour decrease in bed level height.*

### 3. Wind data

The wind data is used in the answer to sub-question two. The wind data is collected at several points in the Eastern Scheldt. The locations which are most relevant for the centre of the Eastern Scheldt is MRG and STV, which stands for Marollegat and Stavenisse.


*Figure 3.2.0.3 The locations of the wind stations located in the Dutch province of Zeeland.*

# 4 Results

In this chapter, the available data will be analysed. The chapter is divided into different steps which are explained in the chapter.

The satellite images are studied first the get an overview of the area of interest. Next, the vaklodingen will be used to obtain an impression of the erosion and sedimentation processes at the centre of the Eastern Scheldt. The vaklodingen give a good spatial overview of the change in bathymetry at the Galgeplaat tidal flat. The RTK-profile analysis, which is the next chapter, will provide a more detailed study of the changes in bed level height.

The first three chapters: satellite images, vaklodingen and RTK-profile analysis are focused mainly on obtaining the answer to the main research question. Chapter Hydraulic data, the last sub-chapter of the chapter aims to obtain the answers for research question two. The hydrodynamics processes are analysed by using the wind and wave data at a different location in the Eastern Scheldt. With the results of the data analysis, the Galgeplaat nourishment will be designed.

## 4.1 Satellite pictures

### 4.1.1 Introduction

The satellite pictures provide a clearer understanding of the so-called morphodynamic features, such as channels, located in the centre of the Eastern Scheldt. The pictures are selected based on the quality of the picture, the data of the picture (low tide, year). The most suitable pictures are taken at low tide, so the Galgeplaat tidal flat is visible the selected years are 2005, 2007, 2009, 2011. The maps can be found in Appendix A: Satellite images of the Galgeplaat tidal flat.

### 4.1.2 Morphodynamic features

The following objects are selected to be described (Figure 4.1.1). The analysis is made by taking the satellite photo from 2005 as a reference. The more recent images are used to analyse whether the different objects change in time and location or they are in a stable condition. The analysis is made with the use of ArcGIS.

Satellite picture 2005

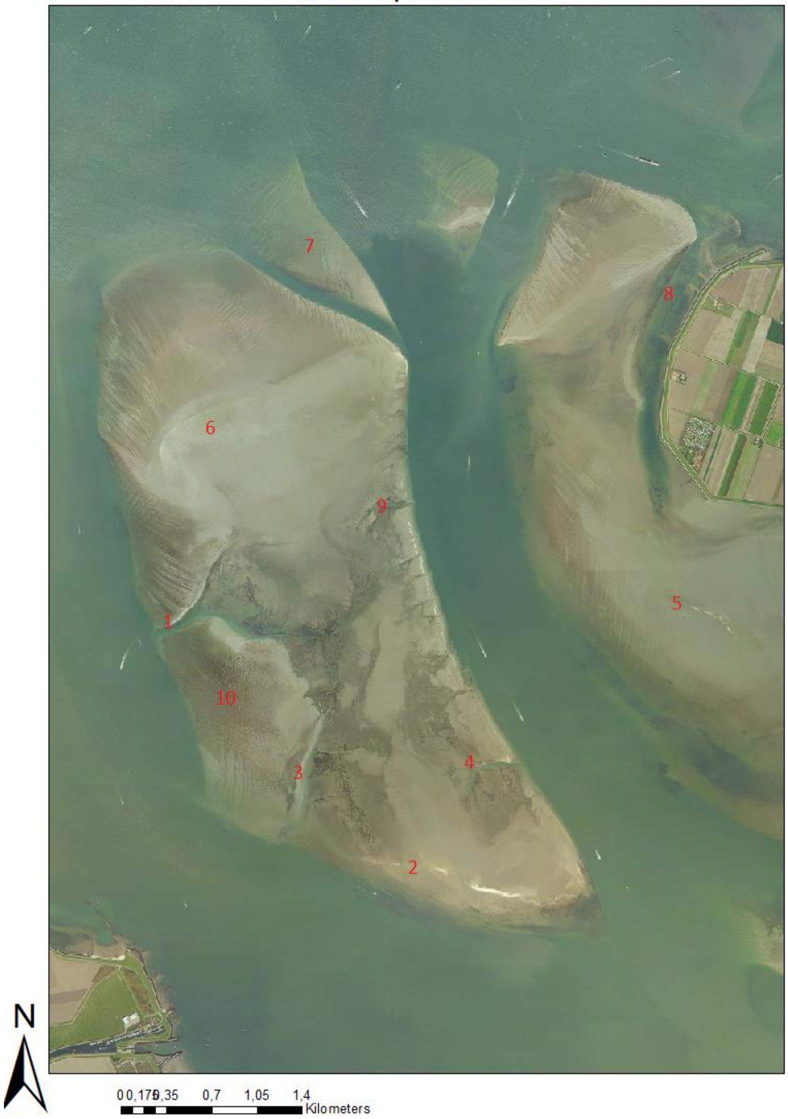


*Figure 4.1.1 The satellite picture 2005, with the numbers as indicated objects. Indicated objects are explained in the table on the right.*

| | Morphodynamic feature |
|---|---|
| *1.* | The western channel located on the Galgeplaat. |
| *2.* | The shell reef or crag located in the south of the Galgeplaat |
| *3.* | The southern channel located on the Galgeplaat |
| *4.* | The channel located at the south east of the Galgeplaat |
| *5.* | The shell reef or crab located on the Dortsman |
| *6.* | Shell reef in the northern part of the Galgeplaat |
| *7.* | The northern tidal flat above the Galgeplaat |
| *8.* | The channel located on the Dortsman |
| *9.* | The eastern channels of the Galgeplaat |
| *10.* | Oyster reefs on the Galgeplaat |

*Table 6 Morphodynamic features list*

#### 4.1.2.1 Morphodynamic feature 1: The western channel is located on the Galgeplaat tidal flat.

In the picture of 2005 (Appendix A: Satellite images of the Galgeplaat tidal flat, Figure 6.2.1) the channel was split up into two parts 200 m inwards. In the picture of 2007 can be seen that one part of the channel has been gone (Figure 6.2.2). The profile analyses have shown that the middle part of the Galgeplaat has increased in the last decade.

#### 4.1.2.2 Morphodynamic feature 2: The crag of shells

The dead shells located at the Eastern Scheldt can end up at the tidal areas and from a reef. This object has changed over time. The crag has increased in shape during the last 20 years. It also moved towards the middle of the Galgeplaat.

#### 4.1.2.3 Morphodynamic feature 3: The southern channel located on the Galgeplaat tidal flat

In 2005 the channels almost were a straight line. The shape of the channels has changed during the years to a more curved channel in 2011 (Appendix A: Satellite images of the Galgeplaat tidal flat, Figure 6.2.4). The oyster reefs located on the east of this channel has shrunken. The channel has increased in length during the years, this means that the channel now almost reaches object 1.

#### 4.1.2.4 Morphodynamic feature 4: The channel located at the south-east of the Galgeplaat tidal flat

The size of the channel has increased over the years. The length of the channel has increased towards the middle of the Galgeplaat and reached the area of pilot nourishment. The area of the oyster reef close to this channel has increased.

#### 4.1.2.5 Morphodynamic feature 5: The shell reef or crag located on the Dortsman

The pictures indicated a large increase in the number of shells located on the Dortsman. The location of the crag did not change in time. The increase in the number of shells visible on the satellite picture can be caused by erosion if it was covered with sand.

#### 4.1.2.6 Morphodynamic feature 6: The shell reef of a crag located on the Northern part of the Galgeplaat

The shell reef became more and more visible on the satellite pictures. The shape and location of this crag did not change in time.

#### 4.1.2.7 Morphodynamic feature 7: The northern part of the Galgeplaat tidal flat

The object indicated with a 7 is eroding substantially. By looking at the satellite photos it can be concluded that the shape of this object does not change horizontally. The only difference is that the channels between this object and the Galgeplaat tidal flat have shrunken.

#### 4.1.2.8 Morphodynamic feature 8: The channel located on the Dortsman

As stated in the previous chapter the higher area of the Dortsman in front of the channel is moving towards the dike. The channel however did not change in location. The shape of the channel is almost similar during the years. The channel is increasing in width and length.

#### 4.1.2.9 Morphodynamic feature 9: The Eastern channels of the Galgeplaat

The eastern part of the Galgeplaat has several channels in 2005. During the years not only the number of small channels increased but also the length of the channels increased. The increase in the length of channels is larger compared to the western part of the Galgeplaat tidal flat.

#### 4.1.2.10 Morphodynamic feature 10: Oyster reefs on the Galgeplaat

The total area of oyster reefs on the Galgeplaat in general increased. As time progresses the growth of the oyster reefs is visible in the satellite pictures. This is a positive effect for protecting the Galgeplaat against erosion, however oysters reef and wader species compete with each other in terms of food.

## 4.2 Vaklodingen

### 4.2.1 Introduction

The data consist of the sets of 1996, 2001, 2007, 2010, 2013, 2016 and 2019. In this chapter, a detailed look at the behaviour of the Galgeplaat will be performed. The 'vaklodingen' are less accurate (error of 0.10-0.15 m) compared to the RKT profiles in chapter 1, still, it can be valuable to perform an analysis based on vaklodingen because of the spatial visualisation of the differences in height in a certain period. The vaklodingen can also be used to determine the subareas.

### 4.2.2 Results

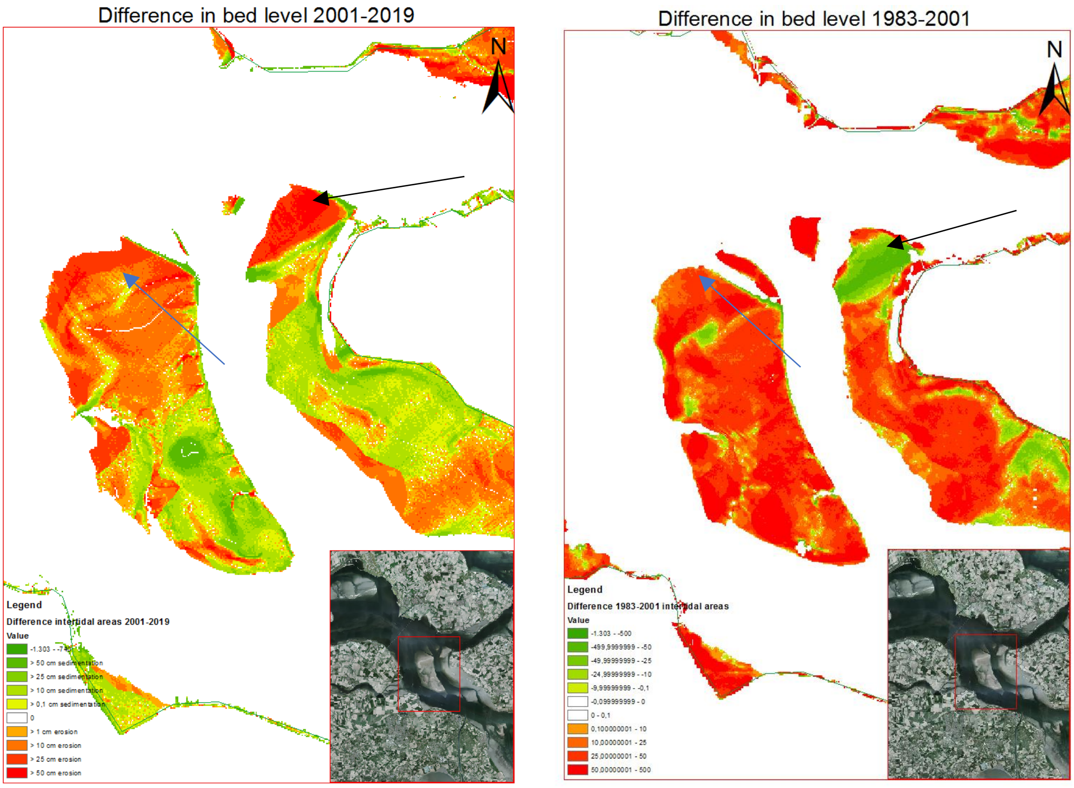


*Figure 4.2.1 Difference in height on the Galgeplaat of 1983-2001 and 2001-2019 (Red colour is erosion and green colour is sedimentation)*

In Figure 4.2.1 both the differences in bed level between 2001 until 2019 and the period from 1983 until 2001 are shown. The left map shows that the erosion in the northern parts is substantial. The green circle in the middle of the Galgeplaat tidal flat is the pilot nourishment executed in 2008. The southern part of the Galgeplaat has less eroded in this period. Also, the northern part of the Dortsman is eroding, while the southern parts are more or less stable. In conclusion, the Galgeplaat is eroding, especially in the northern parts, however, the rest of the Galgeplaat is facing erosion as well. It should be noted that the southern part of the Dortsman (indicated with the blue arrows) was substantially eroding in the period between 1983 until 2001, however in the next period from 2001 until 1983, the erosion rate decreased.

The northern part of the Galgeplaat (indicated with the black arrows) changed differently comparing the two periods. This points out that the location where the sand is moving changes in time, which expresses the non-homogenous behaviour of erosion and sedimentation. The left part of Figure 4.2.1 shows the difference in height between 2001 and 2019. The red parts are mostly located in the northern parts of the Eastern Scheldt. The green coloured areas did increase from 2001 until 2019. The northern areas of the Galgeplaat and Dortsman area decreased in bed level height.

#### *4.2.2.1 Maps of the variations in bed level*

For the different periods of the vaklodingen, variation maps have been made. The maps show the differences in bed level height of the Galgeplaat tidal flat and the Dortsman intertidal area. The maps are made in ArcGIS and visualised in Appendix B: Maps of erosion at Galgeplaat tidal flat. Each map shows us the difference between the two measurements. The following maps are provided: 2007-2010, 2010-2013, 2013-2016, 2016-2019.

The maps show us that erosion nor sedimentation is not constant in time and is non-homogenous. In Figure 6.2.1 the variations in bed level height are substantially different compared to the differences shown in Figure 6.2.2. The differences in bed level height do not correlate with the hydraulic data.

The last map (Appendix A: Satellite images of the Galgeplaat tidal flat, Figure 6.2.4) has a relatively large orange area, which means 0.1 – 10 cm of decrease in bed level height. This indicates an increase in the erosion rate between the period of 2013-2016 and 2016-2019.

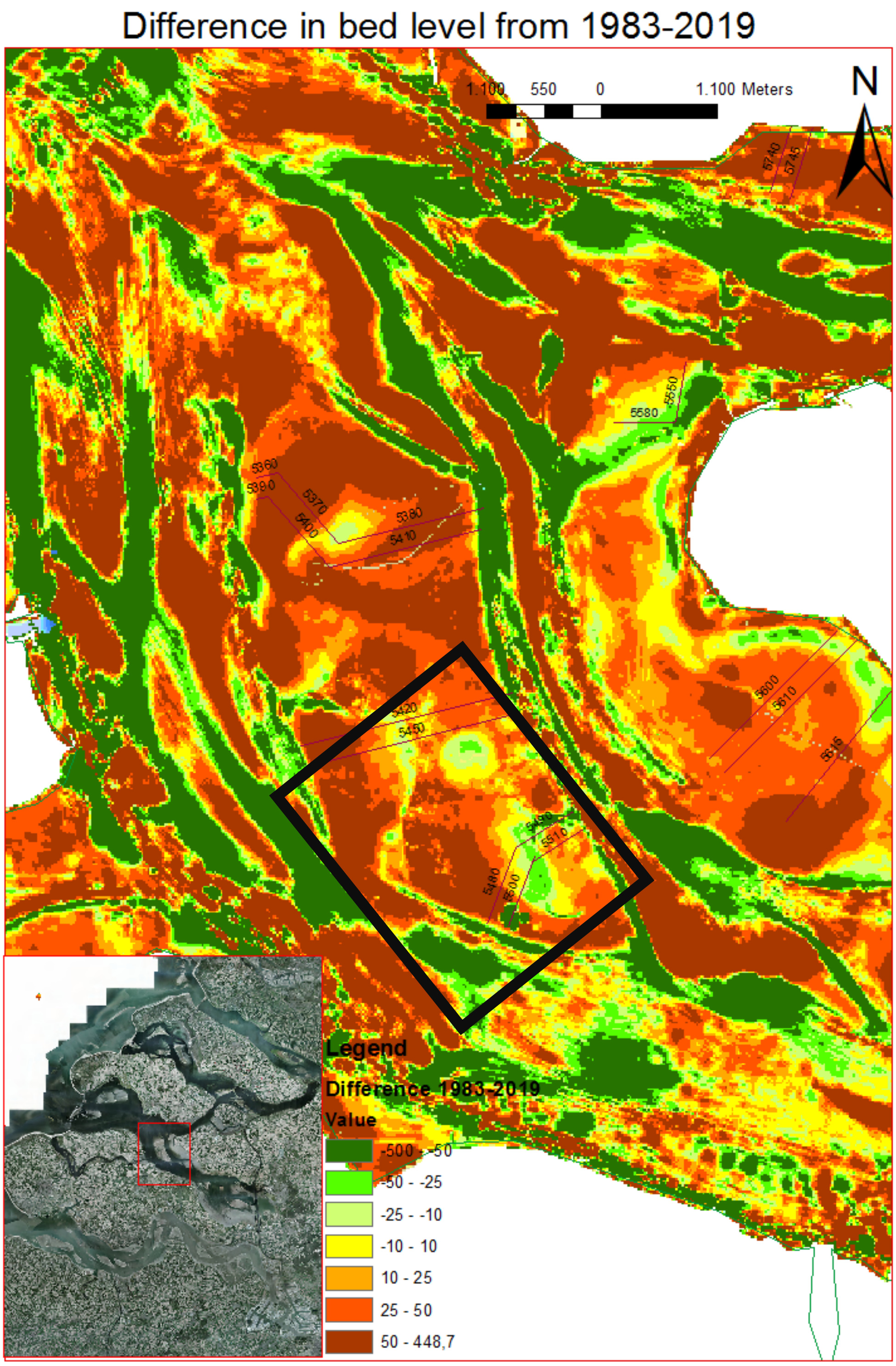


*Figure 4.2.2 Difference in cm in height on the Galgeplaat from 1983-2019 (Red colour is erosion and green colour is sedimentation)*

The map shown in Figure 4.2.2 is the difference in bed level over 36 years. The results are extraordinary: The sediment on the Galgeplaat tidal flat has been transported to the channels. The channels however are changed to different locations. The height of the bed level in the black box is eroding except for the green parts. The satellite photo shows us that the oyster reefs are located in the green parts inside the square. The oyster reef causes the prevention of erosion and even increase the height of the tidal area. An interesting change is an erosion of the circle of nourishment in 2008. The western part of the circle is eroding.

### 4.2.3 Conclusion

The analysis of the vaklodingen resulted in a clearer understanding of the process of sediment transport. The sand is transported from the intertidal areas to the lower parts of the Eastern Scheldt and channels. The erosion rate is not constant in time and changes in location. The areas where oyster reefs are located decrease in height significantly less, in some locations even sedimentation occurred. The edges of the Galgeplaat and the northern part of the Dortsman have eroded double.

### 4.2.4 Channels located in the centre of the Eastern Scheldt

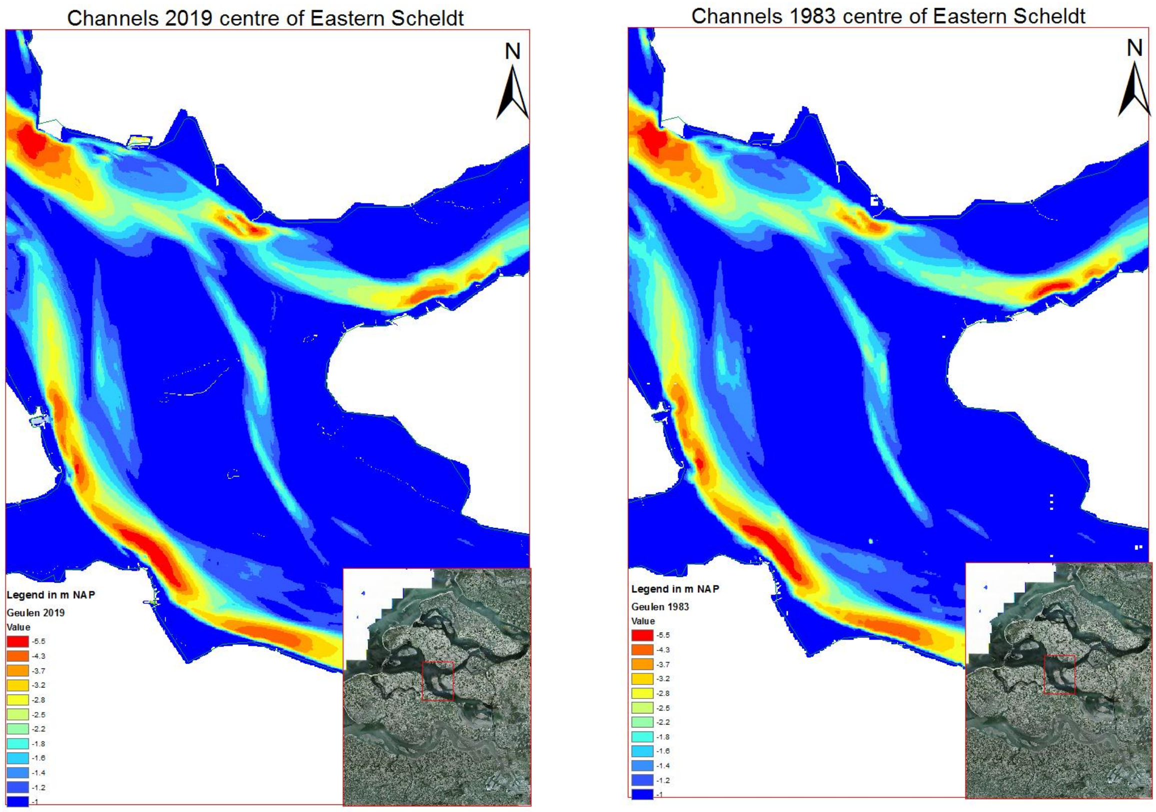


*Figure 4.2.3 The differences in height of the areas lower than -10 NAP*

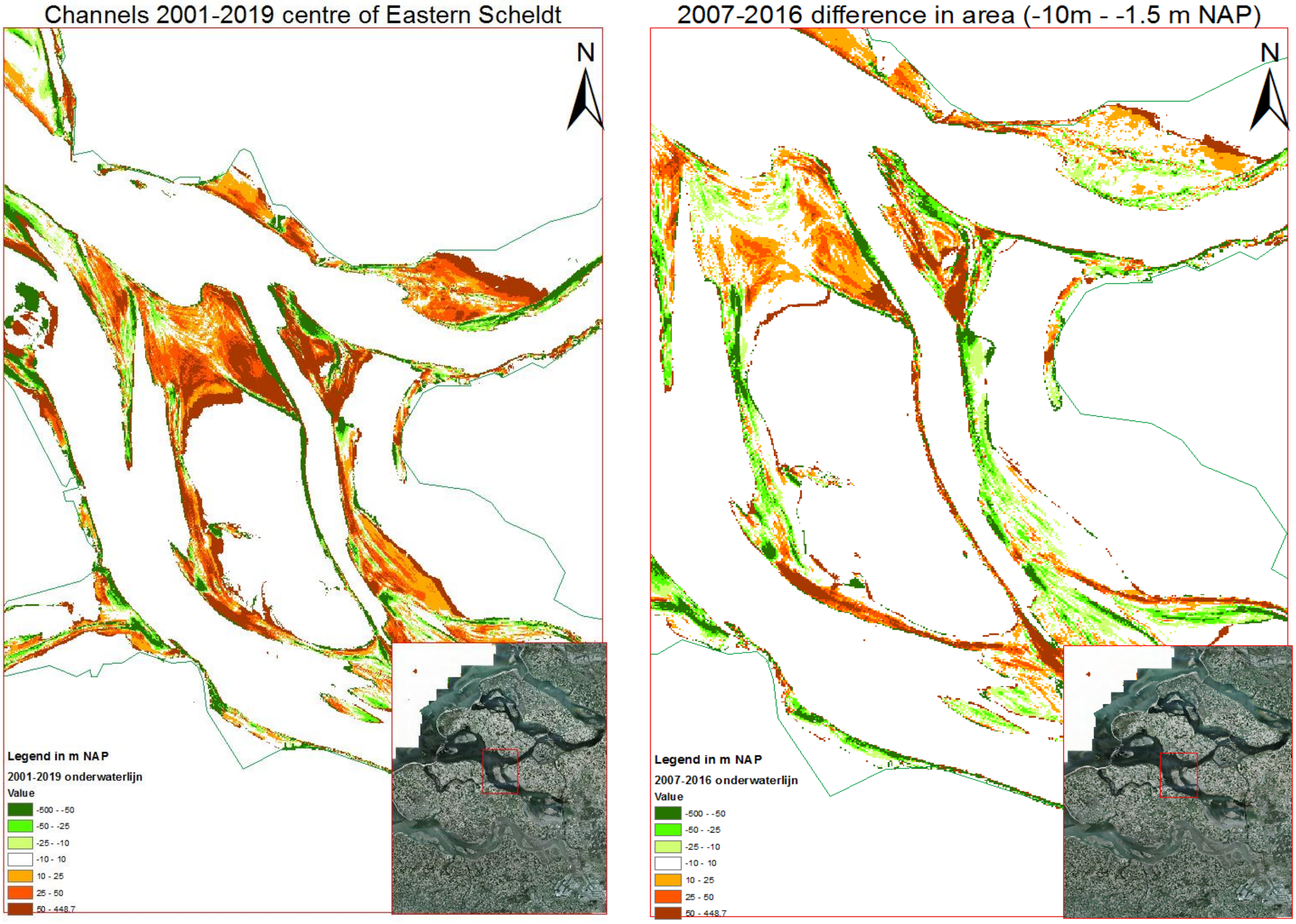


*Figure 4.2.4 The difference in height between the periods of 2001-2019 and 2007-2016, red part is decrease in height and green increase in height. The selection is from -10m NAP until -1,5m NAP*

The left part of Figure 4.2.4 shows us the difference in bed level height of the foreshores of the centre of the Eastern Scheldt. The right part is the same area but in a different period. As shown the western and northern parts are red from 2001 to 2019. The erosion in 2001 and 2019 is quite substantial. In the right part of Figure 4.2.4 can be seen that the area is greener coloured compared to the left part. The means that the behaviour of decrease or increase in bed level height has changed and is not constant in time and not constant in location. For example, the western part of the Galgeplaat is red in the left graph and green in the right part. The erosion of the Galgeplaat is not mainly focused on the intertidal area. The areas located at -10m NAP until -1.5 m NAP are facing erosion as well.

## 4.3 RTK-Profiles

A comparison of the profiles shows a difference in the southern and northern profiles. The northern part of the Galgeplaat is eroding faster compared to the southern parts. And the middle part of the Galgeplaat is accreting. Since there is a large number of profiles a selection of the most relevant profiles has been made. Therefore, various profiles located on all parts of the Galgeplaat and Dortsman have been selected Some profiles are located close to each other and therefore comparable with one just next to it.

The following profiles will be described:

| |
|---|
| 5420 |
| 5390 |
| 5400 |
| 5410 |
| 5490 |
| 5480 |
| 5600 |
| 5615 |
| 5580 |
| 5550 |

*Table 7. List of profiles which are located at the Galgeplaat and Dortsman tidal area*

#### 4.3.1.1 Profiles of the Galgeplaat

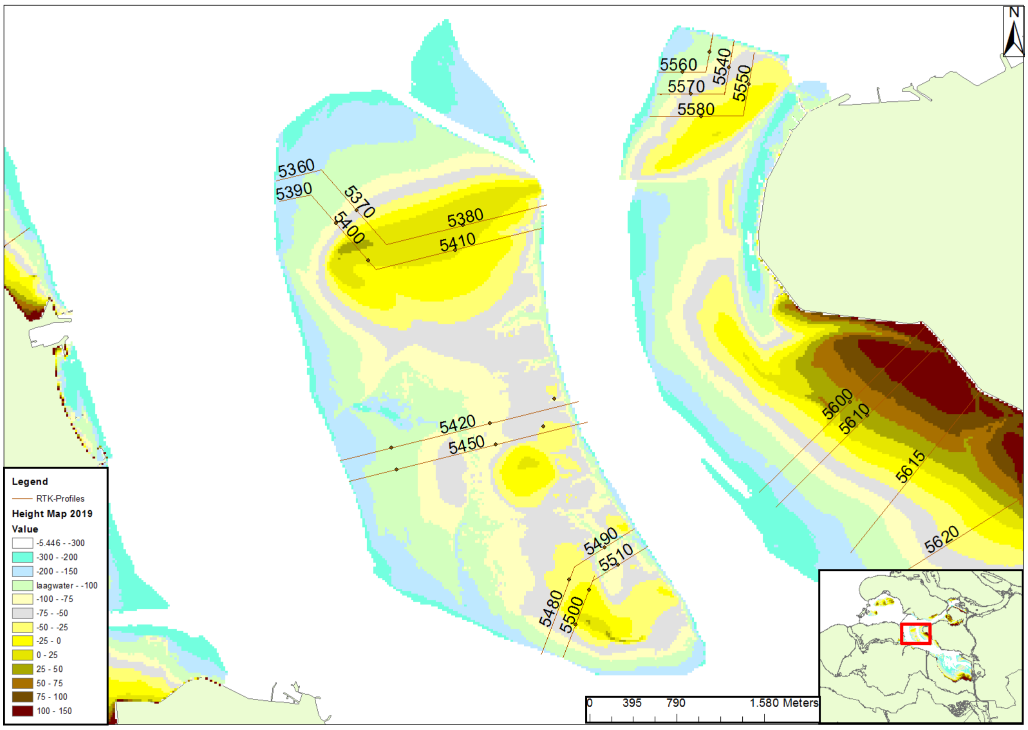


*Figure 4.3.1 Overview of the profiles on the Galgeplaat from ArcGIS*

This map shows all the profiles of which the data is gathered every year by Rijkswaterstaat.

### 4.3.1.2 Profile 5420

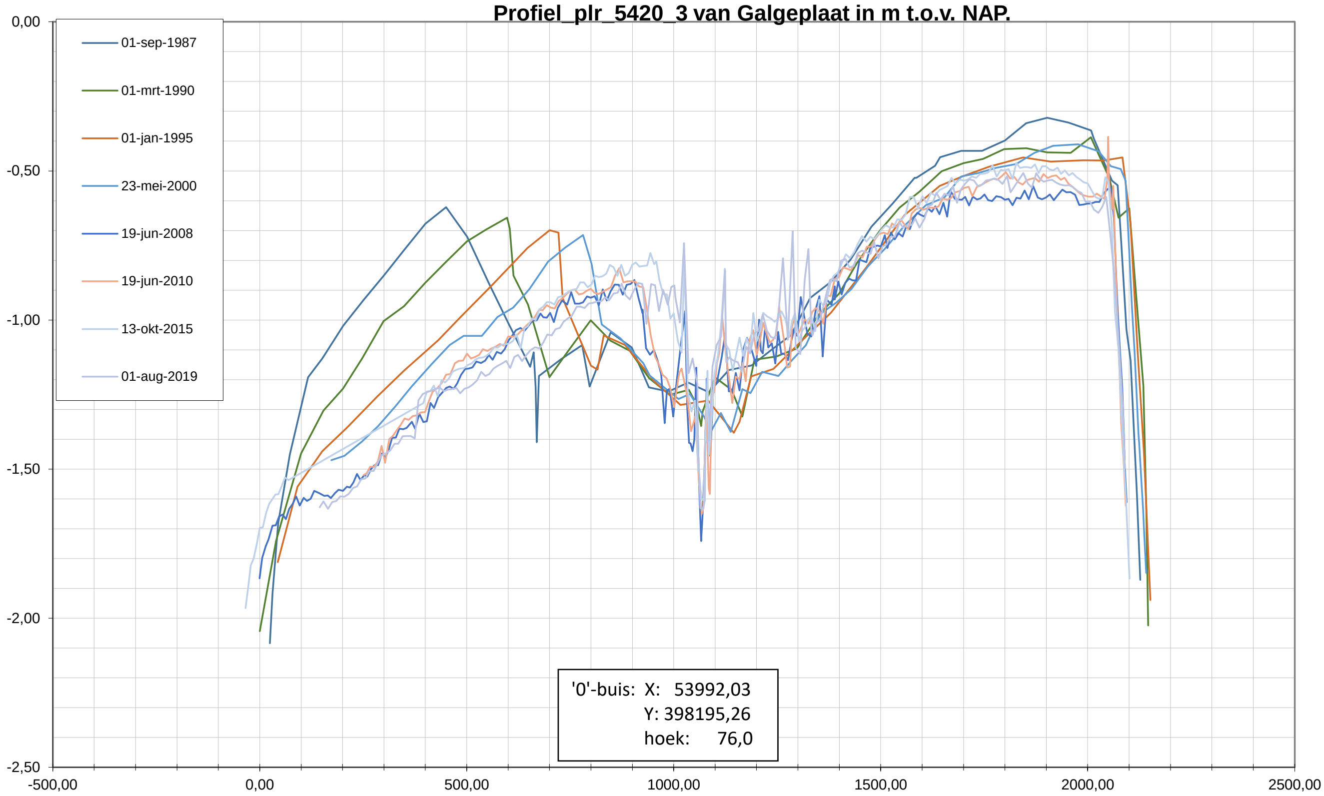


*Figure 4.3.2 Profile 5420 of the Galgeplaat with filtered measurements*

As shown in the overview map figure 4.2 this profile is located in the middle of the Galgeplaat and therefore a cross-section of the tidal flat. At the western part, of the Galgeplaat tidal flat the figure shows us that the height decreased in the past with a maximum of 0.5 m. The eastern part of the Galgeplaat has eroded in the past, however, in the last decade, the height does not decrease as fast as in the period 1987-2000. The height has decreased by 0.1-0.2 m NAP. In the middle of this profile is shown the height has increased in the last 15 years. So, the sediment is transported from the edge to the middle of the tidal flat. In 1986 this small channel was located at 600 m and in 2019 the channel was located at 1000 m this means in 33 years the channel is shifted to 400 m, which is 12 m/year. In the last 5 years, the location is quite stable.

Another interesting behaviour can be seen by looking at the period in which the erosion takes place. The graph shows us in the left part from 0-500 m that in the first few years the erosion was not that high. After that, the height decreased faster in time, and thereafter slower. This will partly be the result of the gap in the database since the period of 2003-2008 is missing. In the last decade, the height is almost constant. In short, the erosion in the left part is periodically more aggressive. So, from 1987-1991 can be seen as a period of erosion. And from 2014-2019.

In the middle of the graph (from 400 m up to 1000 m), large variations can be seen in bed level height. The explanation for this behaviour can be found in the satellite picture taken from the Galgeplaat. This shows us that in the middle of the Galgeplaat oysters are located, the number of oysters can result in variations in the bed level height.

Figure 4.3.3 shows us the erosion rate of the profile. The average height of the Galgeplaat is decreasing, however, the erosion rate is decreasing as well. As seen in profile 5420 the sediment can also be transported to a different location on the Galgeplaat. In Figure 4.3.2 the displacement of the different elements is shown. The higher part at the right was in the part located on the edge of the Galgeplaat, nowadays this higher part has been shifted both horizontally and vertically. The top was located in 1986 at 500 m while in 2019 is it located at 900 m horizontally. Vertically, the top in 1986 was at -0.6 m NAP, and in 2019 at -0.9 m NAP. This means a vertical displacement of about 0.1 m/year downwards. At the right higher part of this profile, the vertical displacement is also 0.1m/year, however, there is no clear horizontal transport visible.

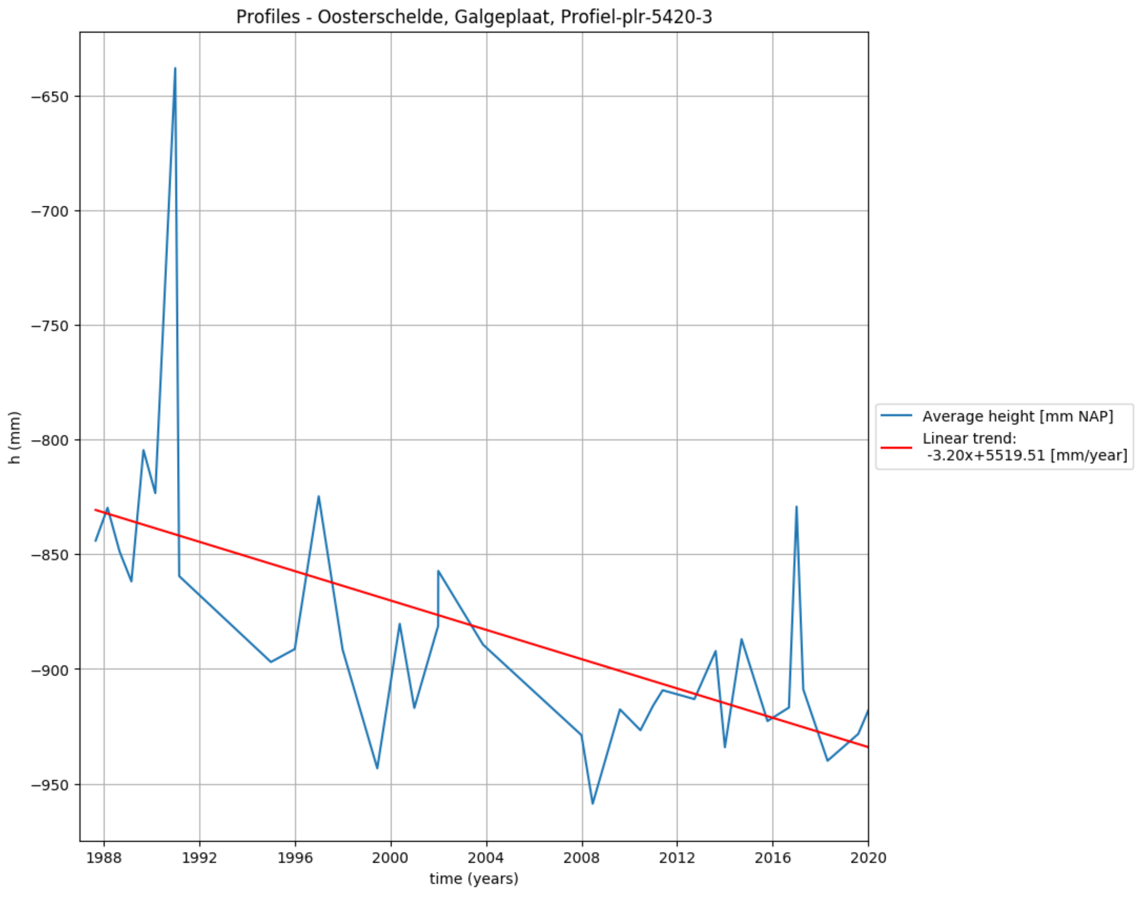


*Figure 4.3.3 Profile 5420 and the trendline of the height (Rijkswaterstaat) without breakpoint*

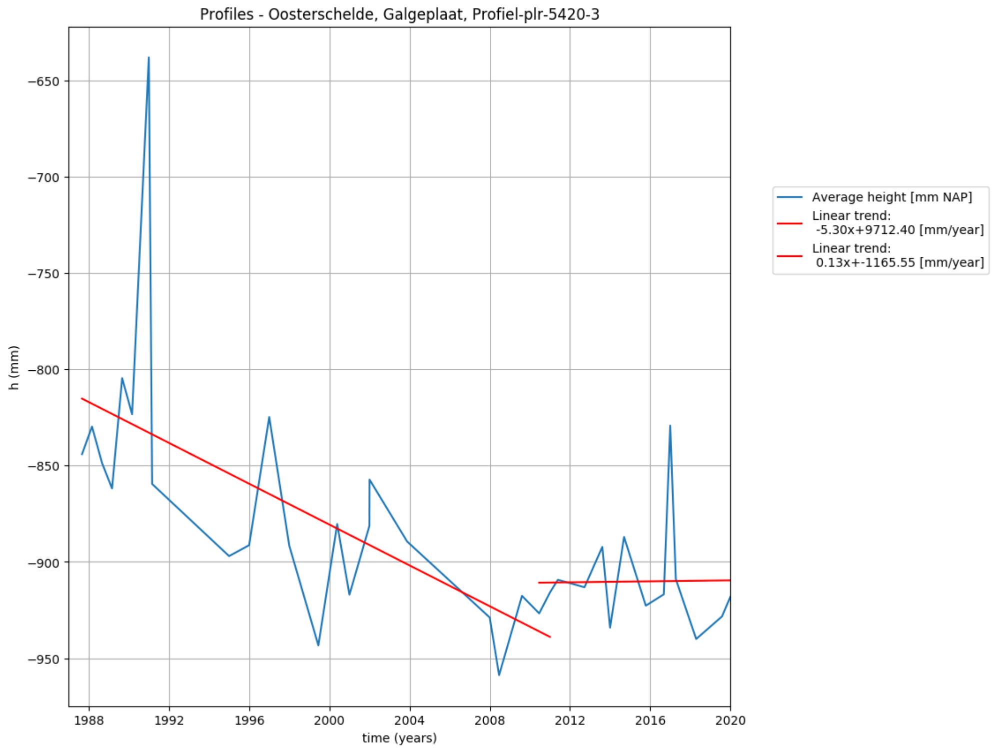


*Figure 4.3.4 Profile 5420 and the trendline of the height (Rijkswaterstaat) with a breakpoint*

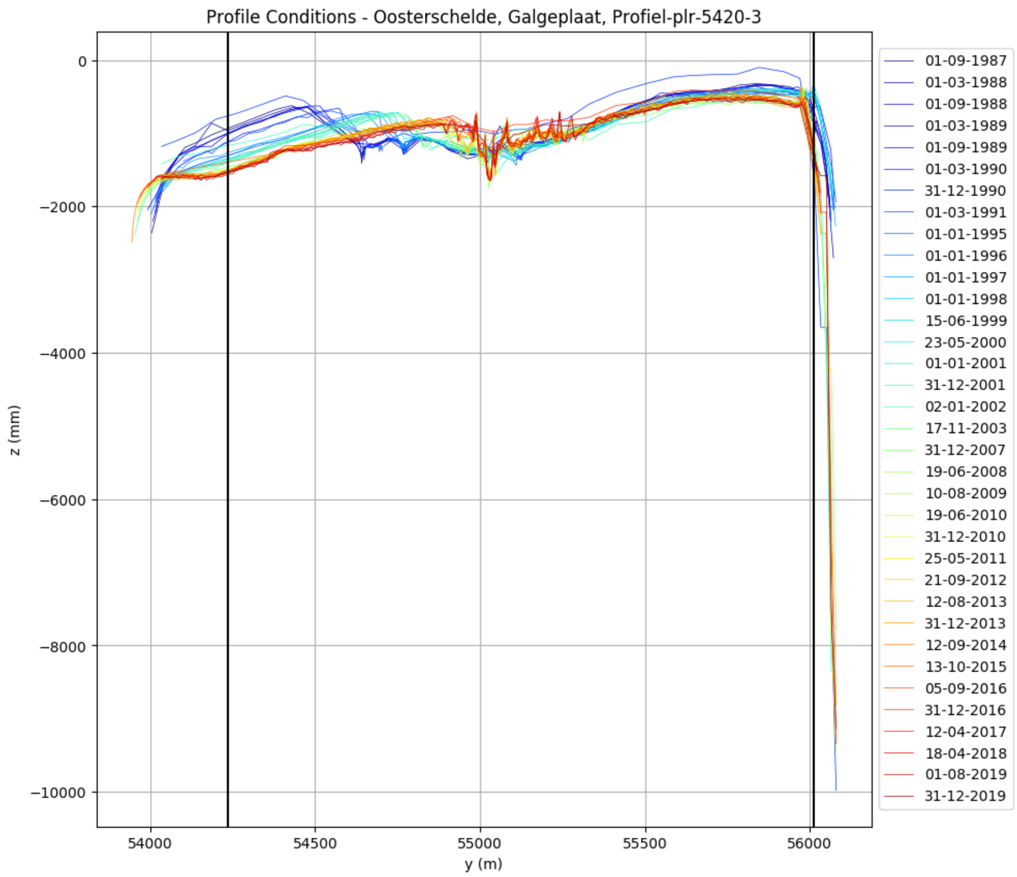


*Figure 4.3.5 Profile 5420 with boundaries based on height (Beiboer, 2020)*

### 4.3.1.3 Profile 5390

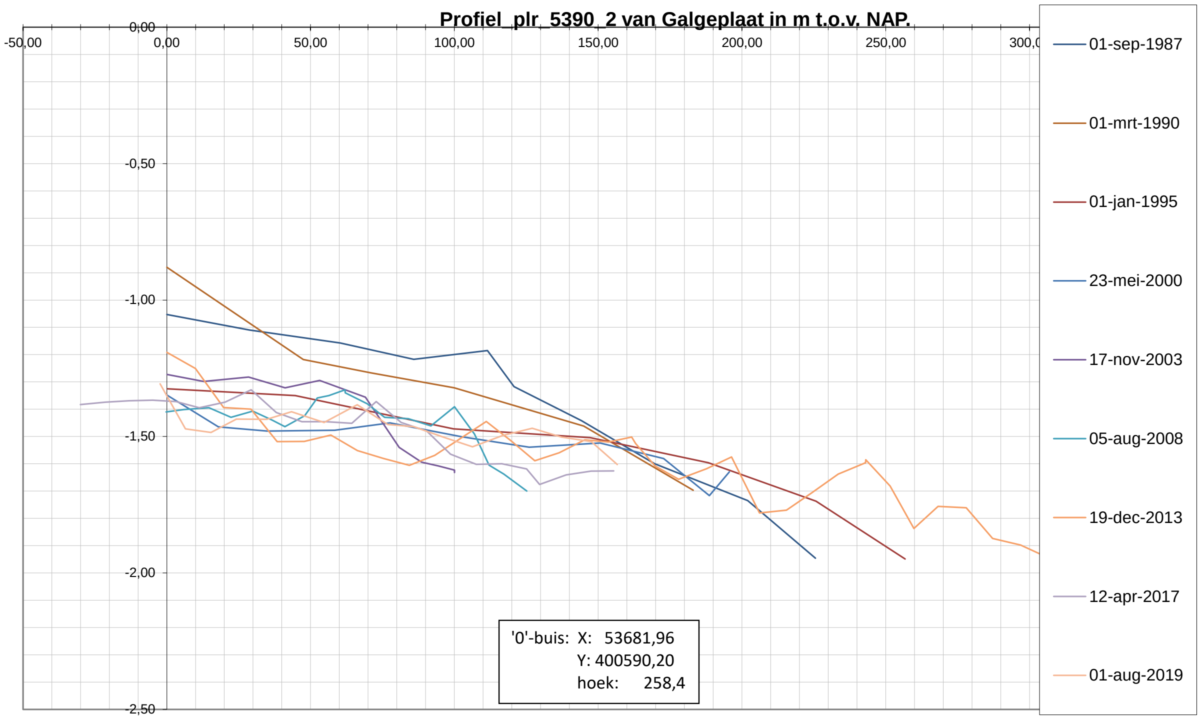


*Figure 4.3.6 Profile 5390 of the Galgeplaat.*

Profile 5390 is a measurement of about 250 m located at the most western part of the Galgeplaat tidal flat. The graph shows us that the differences in height are large compared with other profiles located on the Galgeplaat. The satellite picture shows us that at the location of profile 5390 several small channels are located which are covered by oysters. The straight lines are the first measurements. Still, the bed level has decreased by 0.4 m and is now located at -1.4 m NAP.

### 4.3.1.4 Profile 5400

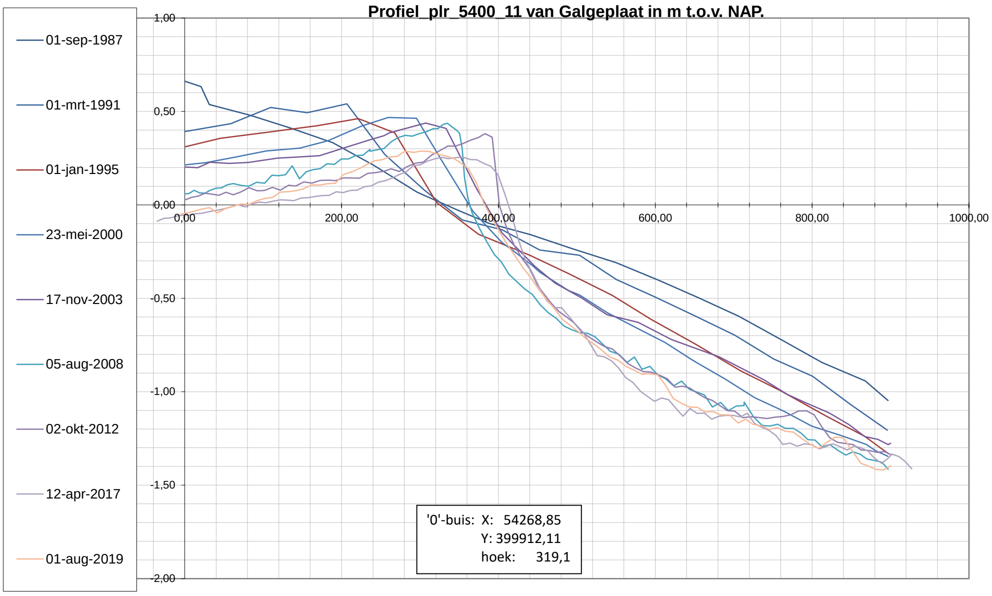


*Figure 4.3.7 Profile 5400 which is located in the northern part of the Galgeplaat*

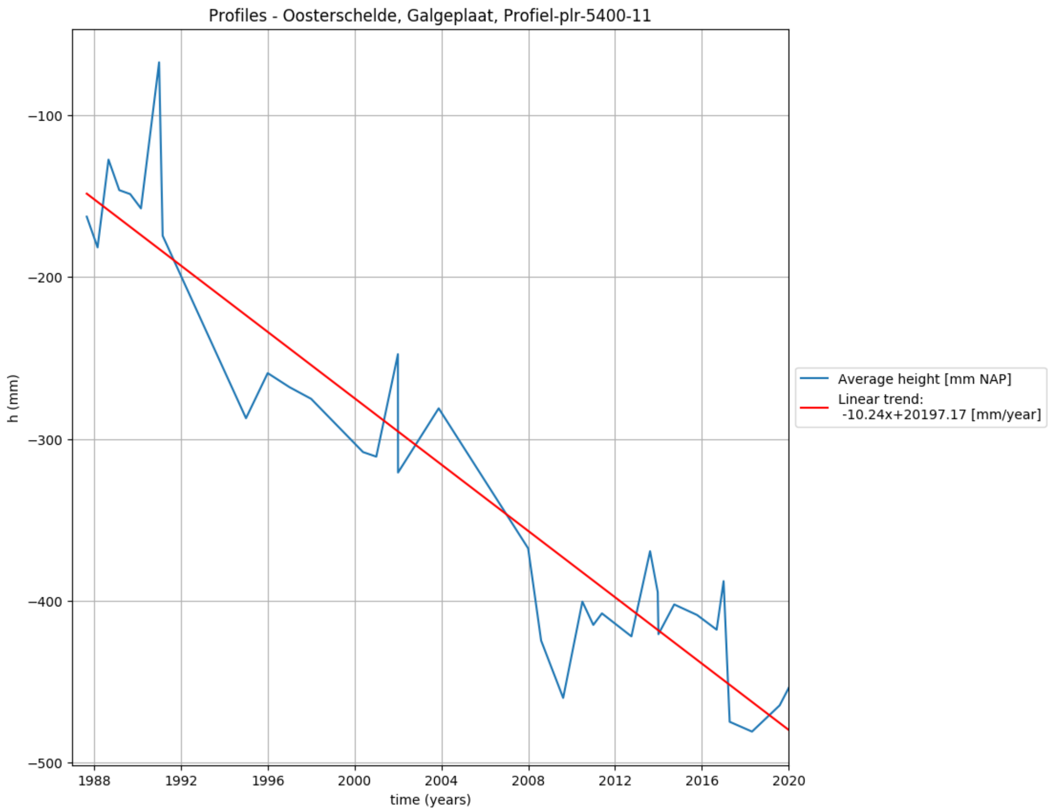


*Figure 4.3.8 Profile 5400 compared with the height trend (Rijkswaterstaat) without breakpoint*

As seen on the overview map this profile is connected to both profiles 5390 and 5410. The right part of this graph could be connected to the left part of profile 5390. The average height of the profile has decreased. Although in the graph is shown that the middle part of the profile has faced accretion. In the past, the profile was an almost straight line. As time progresses, we can see the left the erosion rate was quite high and from 420 m to 800 m. Last decade the profile in the middle formed an arrow-like shape. The sand has been transported from the area between 220 m and 400 m. However, the total amount of sand has decreased.

The average height of the profile is reduced by 12 mm/year till 2010 and from 2010 till 2020 by 8,7 mm/year.

### 4.3.1.5 Profile 5410

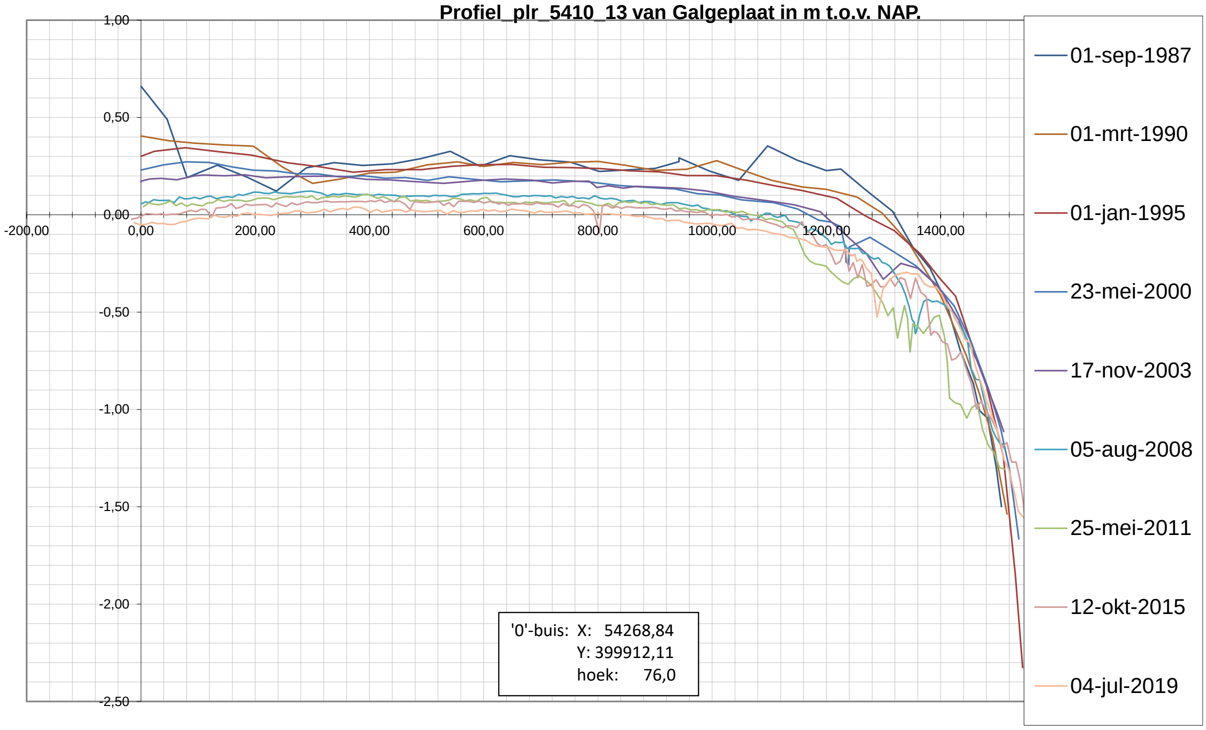


*Figure 4.3.9 Profile 5410 compared with the height trend (Rijkswaterstaat)*

The next profile is located next to profile 5400. In this profile shown in Figure 4.3.9, quite some interesting behaviour can be seen when we connect this profile to the erosion rate. First of all, there is erosion with 10 mm/year calculated from the period of 1987-2010. In the next period from 2010-2020, the erosion rate is almost equal the 0 mm/year. This can be seen in the graph as well. Furthermore, the erosion is quite equally spread, which means that the shape is maintained as time progresses. In the last measurement, we can see, in the right part of the graph, that the height is varying a lot. By looking at the pictures taken above can be seen that there is a small channel at the end of this profile. The shape of this channel is changing as time progresses.

### 4.3.1.6 Profile 5490

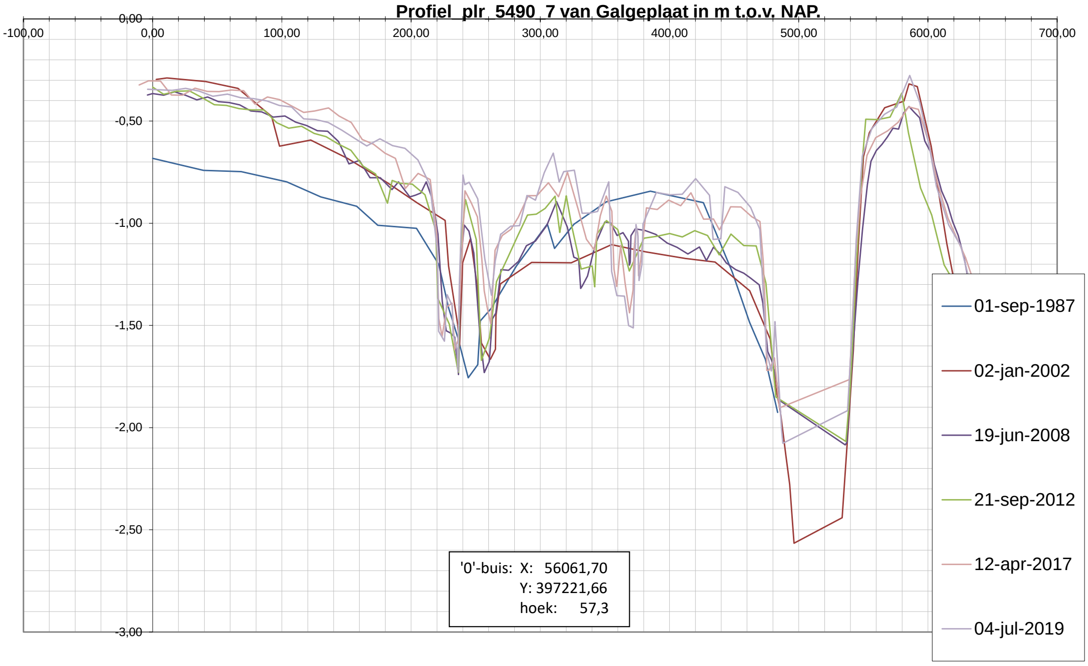


*Figure 4.3.10 Profile 5490 compared with the trend of the height (Rijkswaterstaat)*

The shape of this profile is extraordinary. At 0 m horizontally the graph shows us an increase in bed level height of about 0.4 m. And from 240 until 260 the bed level height increased by almost 1 m between 1987 and 2002. Between the two small channels, the bed level height decreased between the measurements of 1987 and 2002 and increased again afterwards.

The variation in bed level height is up to 2.3 m. To understand this shape, looking at the picture is needed. Therefore, a part of the satellite picture is added which is Figure 4.3.11. In this picture can be seen that the profile is crossing a channel twice, which declare the lower parts in the graph. We can also see that the location of the channels is stable. The locations do not change in time. In the first channel, an island has occurred as shown in Figure 4.3.10. Also, the Oyster reefs can be seen (The black material). This profile is measured less than most of the other profiles. The gaps last from 1987 till

2002 and from 2003 till 2009. Still, the profile shows that the bed level height in 1987 was 0.3 m lower than the last measurements. This indicates sedimentation instead of erosion.


*Figure 4.3.11 The line of profile 5490 plotted in the satellite photo of 2011 (Rijkswaterstaat)*

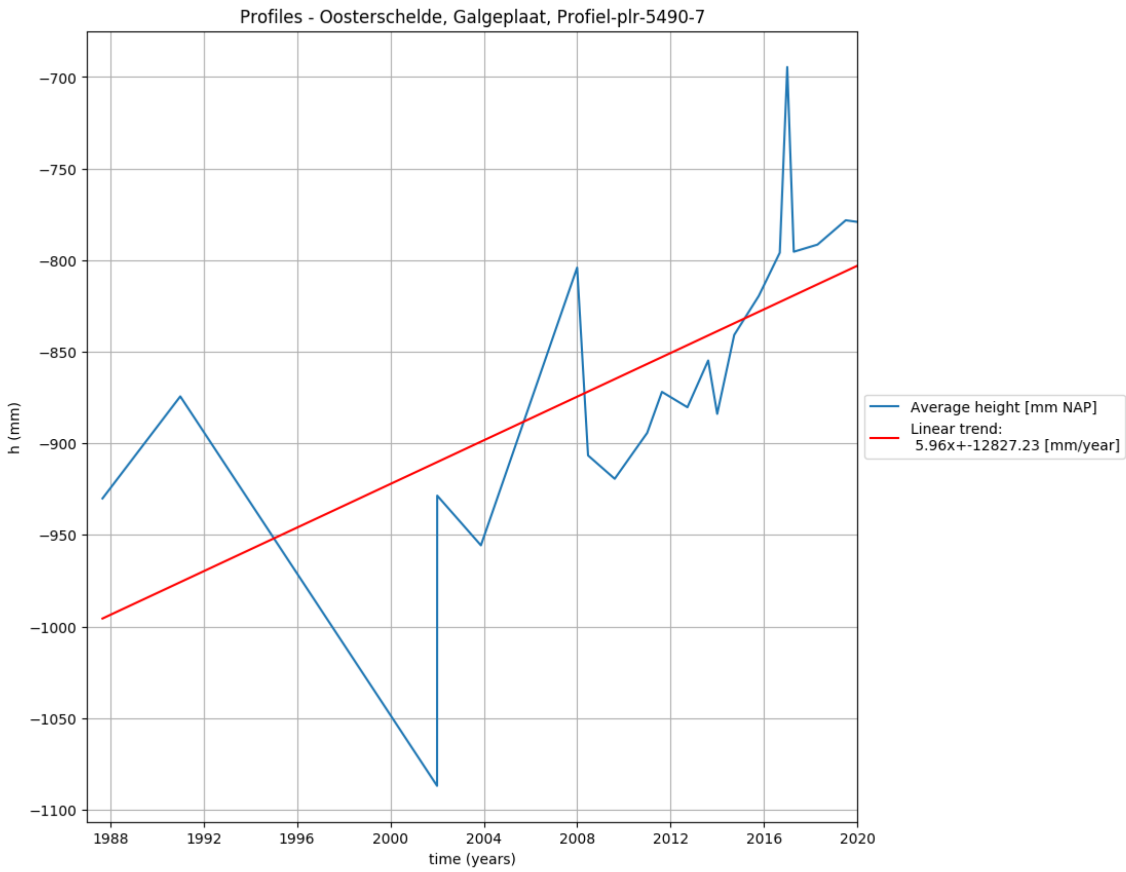


*Figure 4.3.12 The profile 5490 with the trend height. The linear trend is positive.*

The trend of the height shown in Figure 4.3.12 emphasizes this indication. (The linear trend is 15.68 mm/year).

If we plot the data and analyse the erosion rate the conclusion can be made that the height is increasing in the last decade. This means that the amount of sand has increased. This can be caused by the pilot nourishment executed on the Galgeplaat tidal flat in 2008. After 2008 an increase in the height is shown in Figure 4.3.12

### 4.3.1.7 Profile 5480

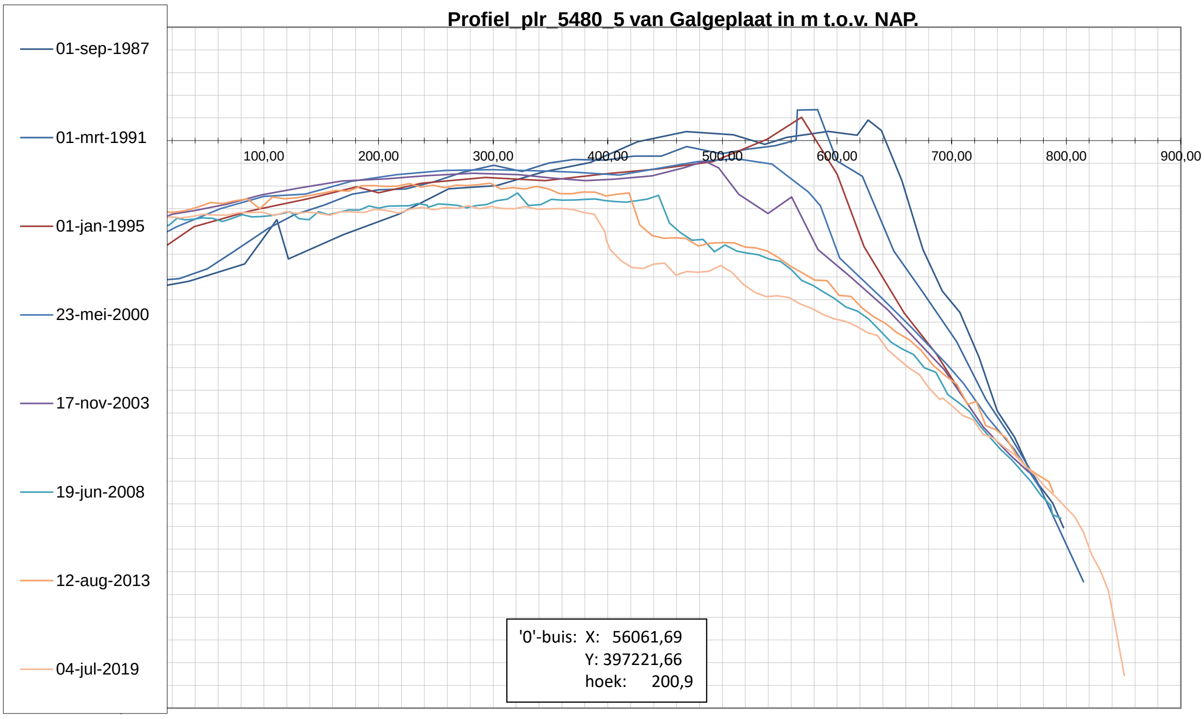


*Figure 4.3.13 Profile 5480 shows the bed level height located at the Galgeplaat. Profile 5480 is located at the edge of the tidal flat.*

The data of the profiles are measured at the edge of the southern part of the Galgeplaat. At the right part of this profile, a substantial decrease in the bed level height can be seen: maximum 1 m vertical at 610- 630 m. The higher part is flattening out and almost completely eroded. At the more recent measurement and shift in height can be seen between 400-500 m. At the left part of profile 5480 is accreting visible about 0.3 m. The results in an average decrease in bed level height of 0.1 m/year for the profile, with a local maximum of 0.3 m/year.

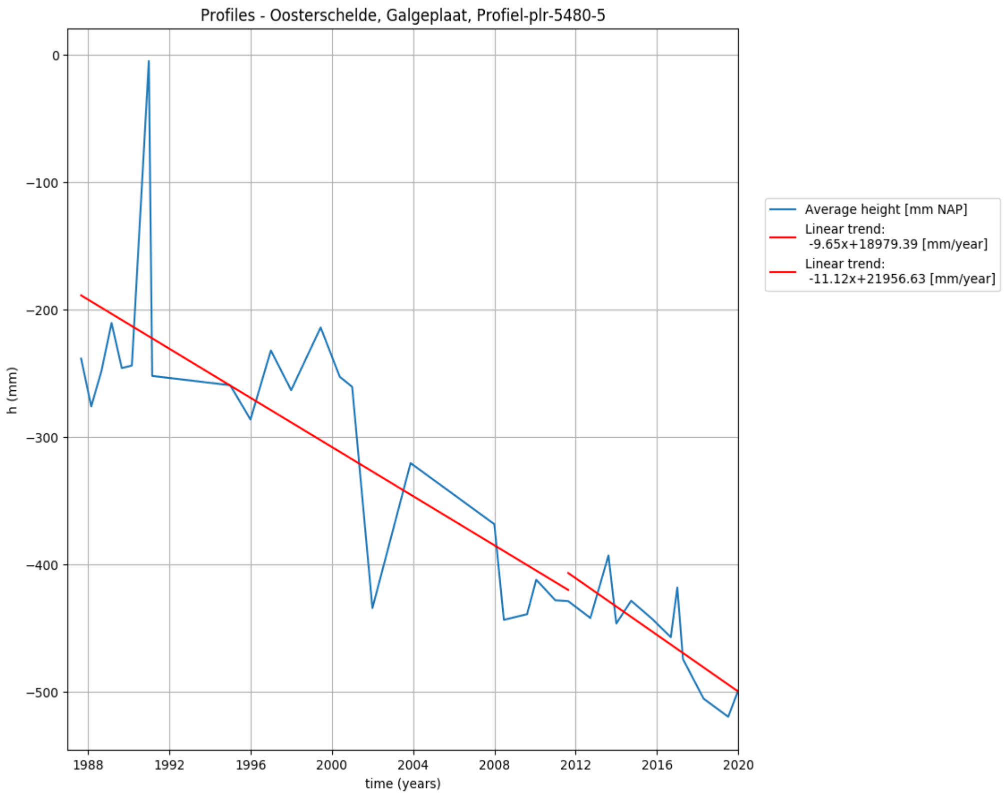


*Figure 4.3.14 The trend of the bed-level height of profile 5480 (Rijkswaterstaat)*

### 4.3.1.8 Profile 5450

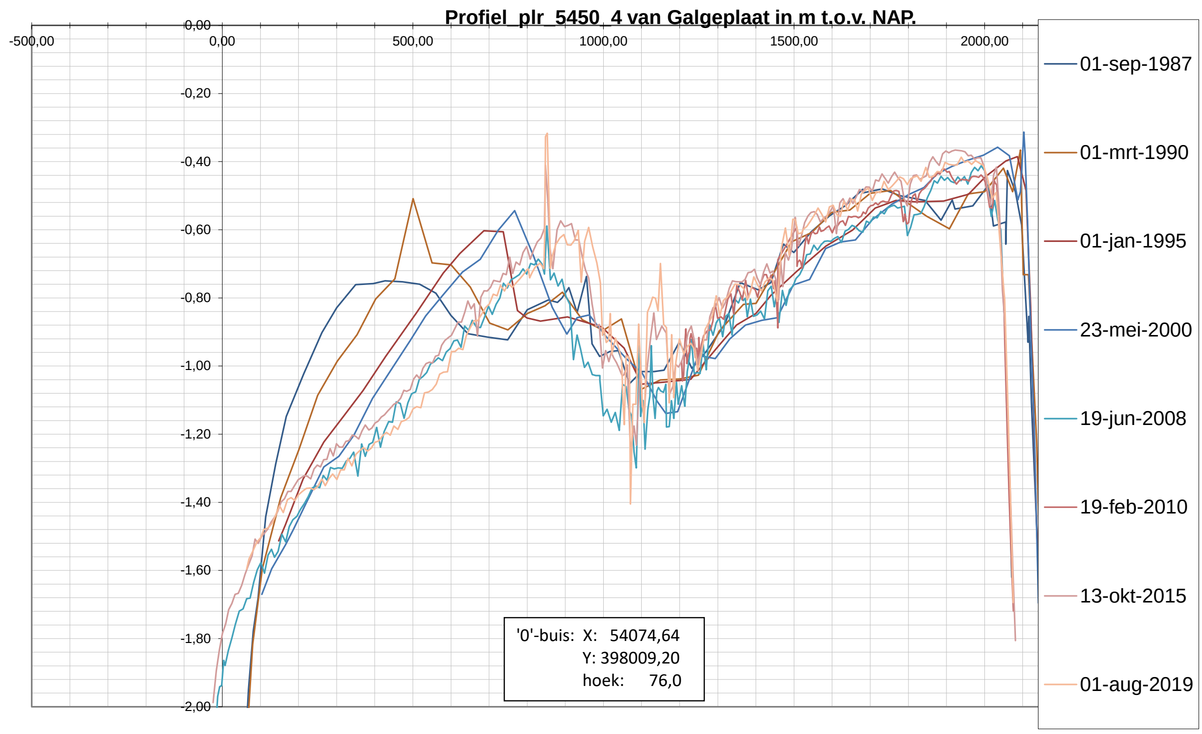


*Figure 4.3.15 Profile 5450 showing the bed level height in NAP (Rijkswaterstaat)*

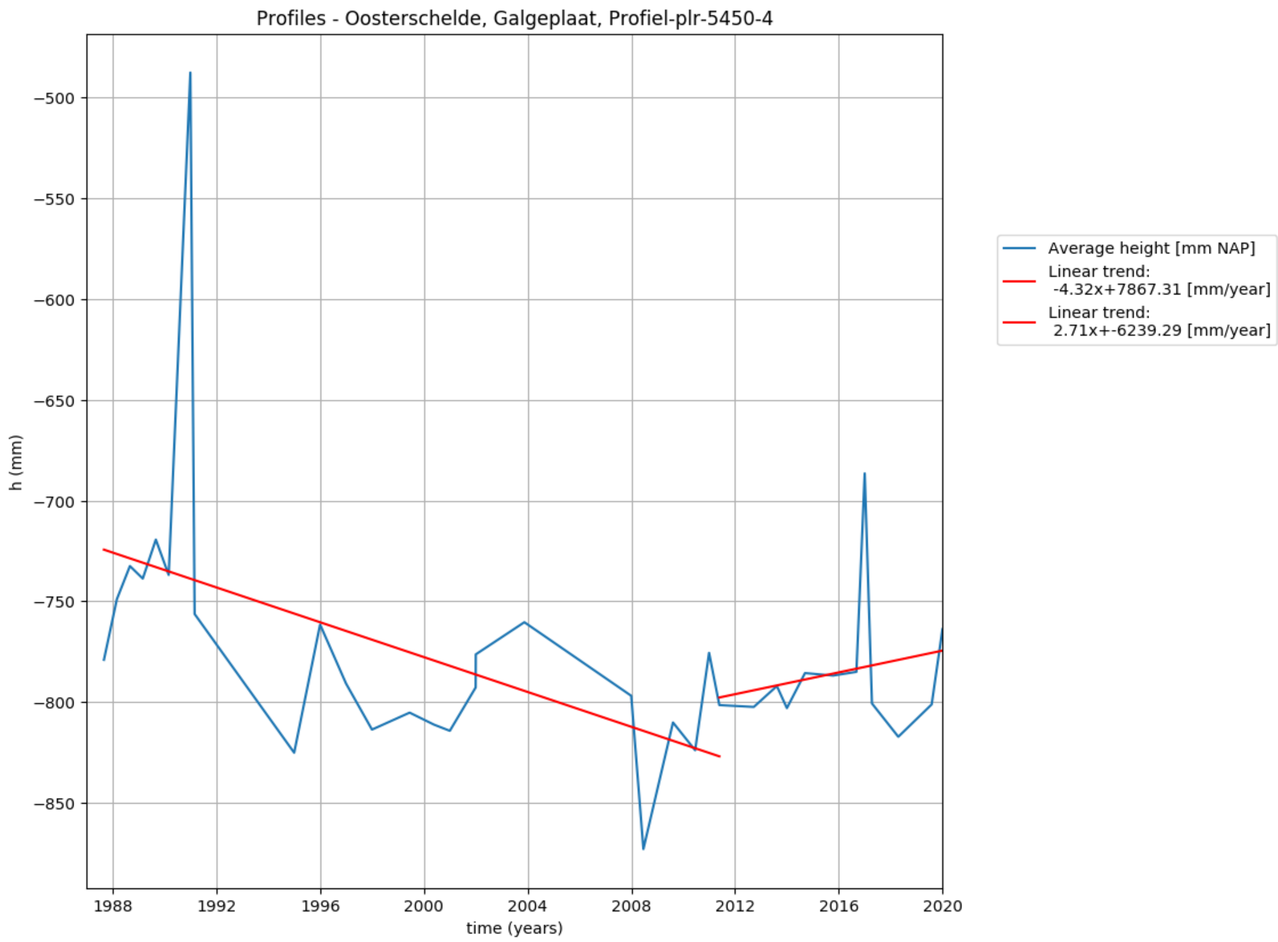


*Figure 4.3.16 The profile 5450 and trend analysis (Rijkswaterstaat)*

This profile is also located in the middle of the Galgeplaat tidal flat. This profile shows us that the erosion at the southwest of the Galgeplaat is the highest. We can also conclude that the height of the right part of the profile which is located northeast does not decrease or increase. However, the location of the Galgeplaat has been shifted to the left. The trend analysis shows us that the average height of this profile was decreasing before 2010 and increasing after 2010

### 4.3.1.9 Profile 5600

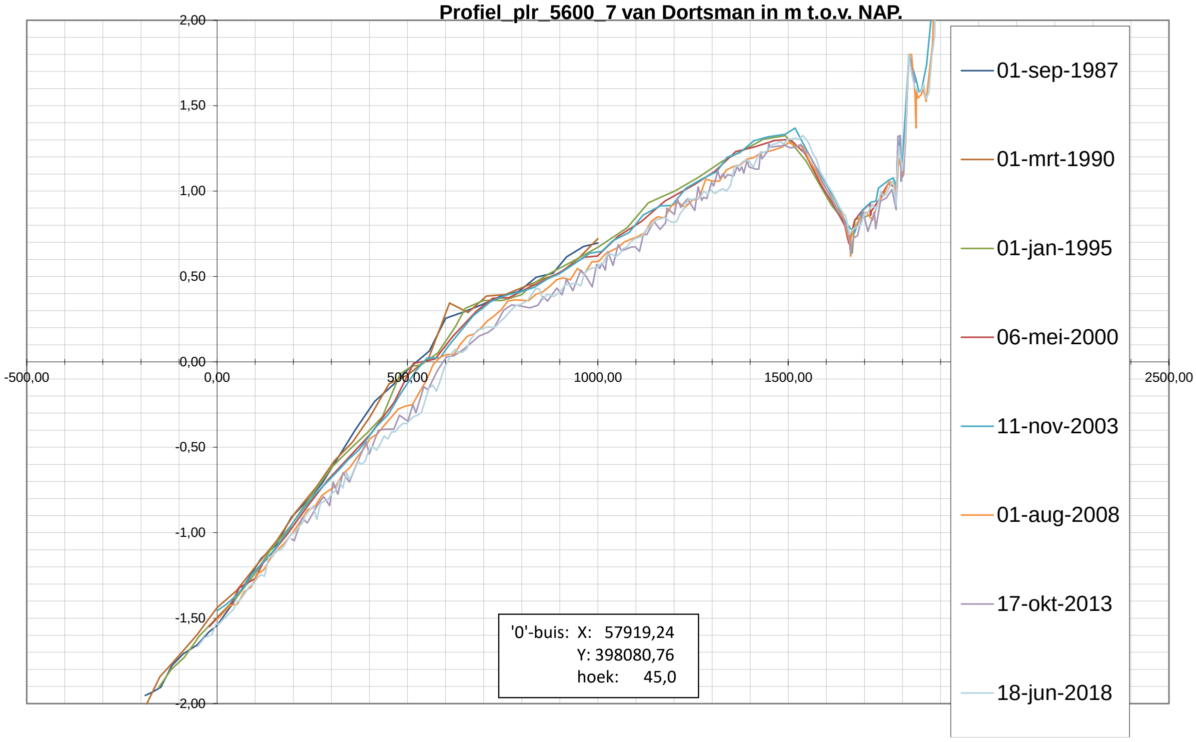


*Figure 4.3.17 Profile 5600 located at the Dortsman tidal area (Rijkswaterstaat)*

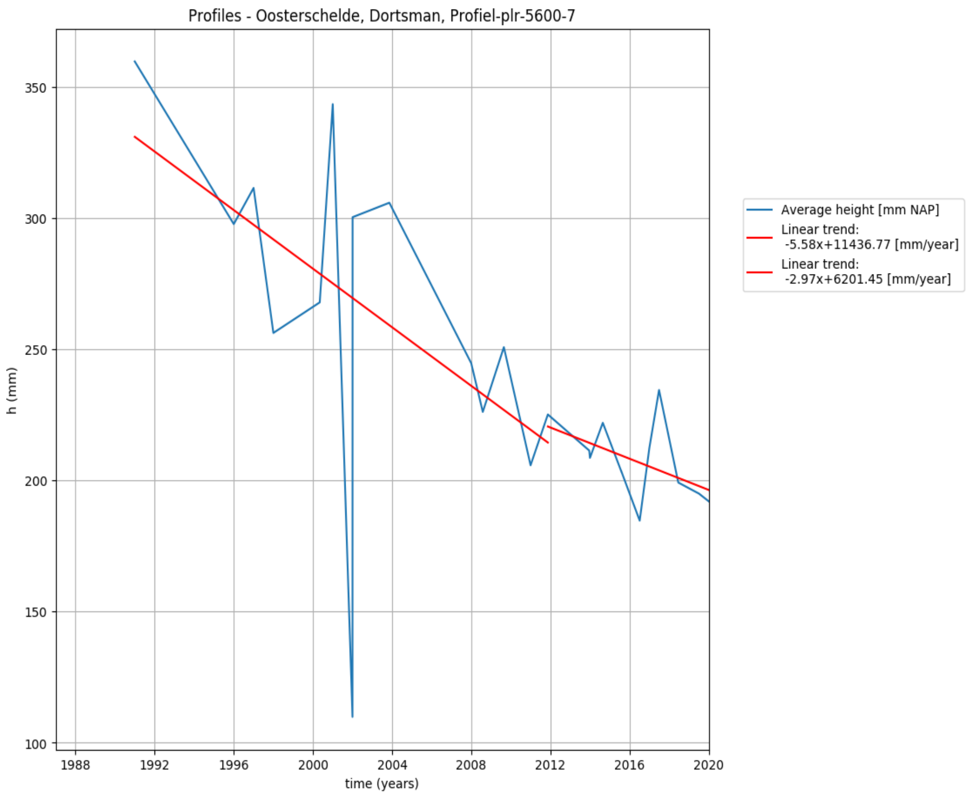


*Figure 4.3.18 The profile 5600 of the Dortsman and the trend analysis next on the right. (Rijkswaterstaat)*

Profile 5600 shows us the foreshore located close to the Galgeplaat. This foreshore seems to form quite stable behaviour compared to the graphs of the Galgeplaat. The only part that is facing erosion is the bed level from -0,5 m NAP – 0,5 m NAP.

The graph, Figure 4.3.20, is made from the data of profile 5600 and shows the linear trend. The erosion rate is divided into two parts. The first one is the period from 1989-2012 and the second one is from 2012 until 2020. The average erosion rate in the first period is -5,58 mm/year and in the second period -2,97 mm/year which means that the erosion rate decreased by 47%.

### 4.3.1.10 Profile 5615

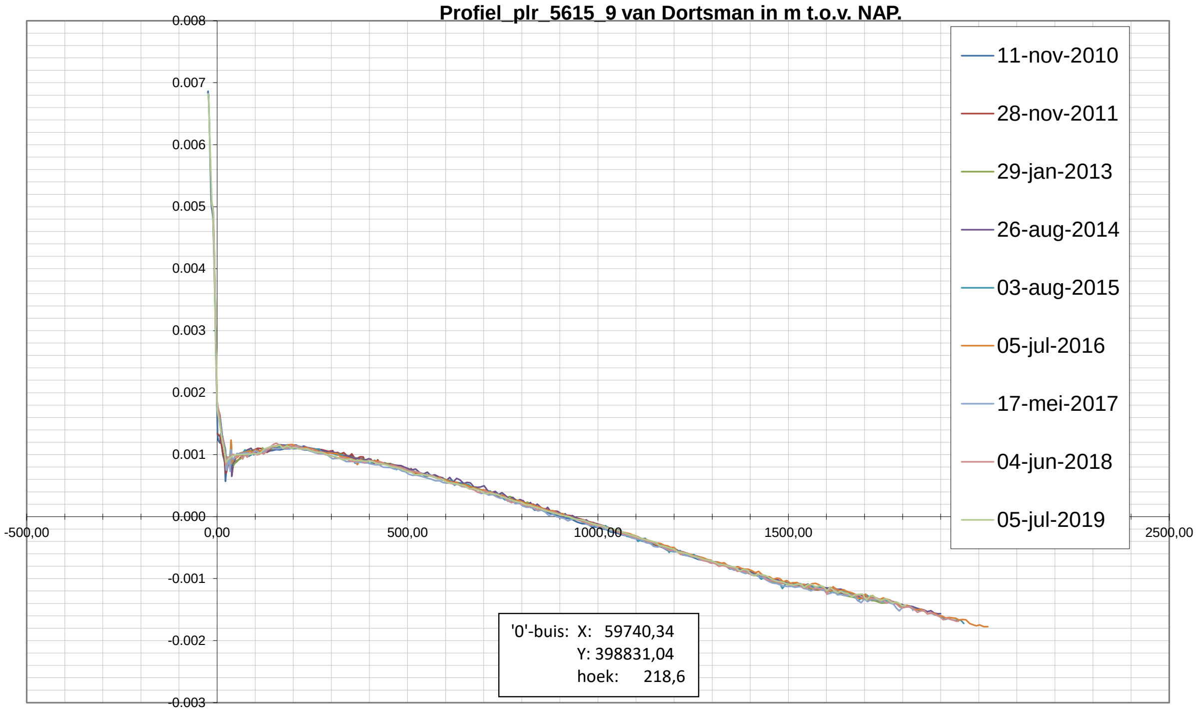


*Figure 4.3.19 Profile 5615 located at the Dortsman tidal area (Rijkswaterstaat)*

These measurements are coming from the Dortsman tidal area, which is located north of the Galgeplaat tidal flats. This profile is a foreshore of the dike. The height difference is very small compared to the profiles coming from the Galgeplaat. So, in this area, there is erosion nor sedimentation.

### 4.3.1.11 Profile 5580

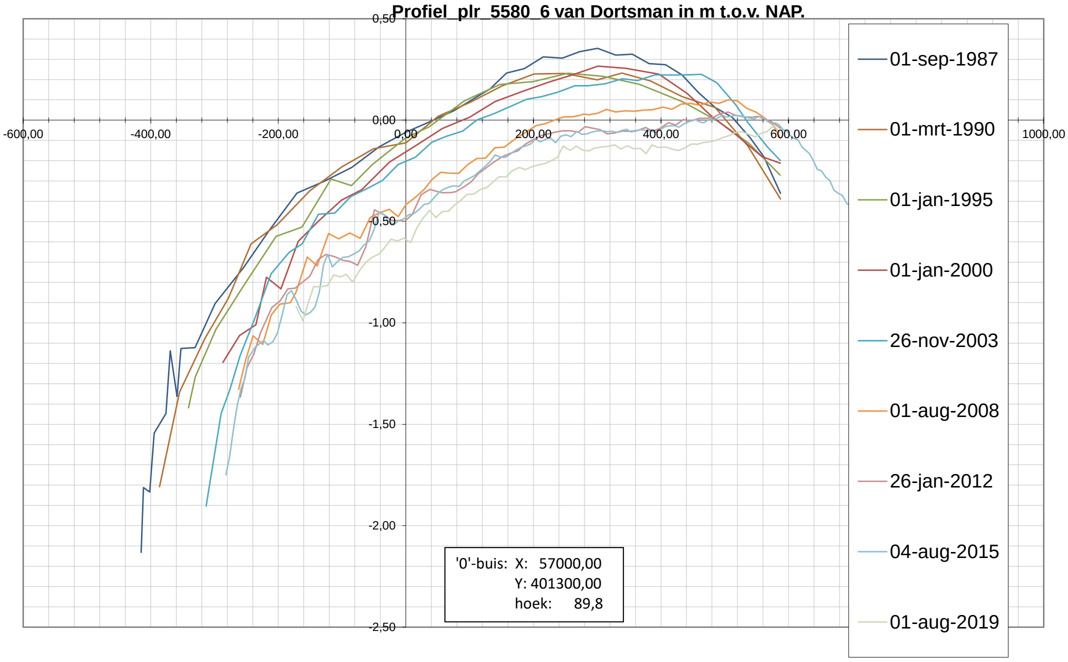


*Figure 4.3.20 Profile 5580 located on the Dortsman tidal area. (Rijkswaterstaat)*

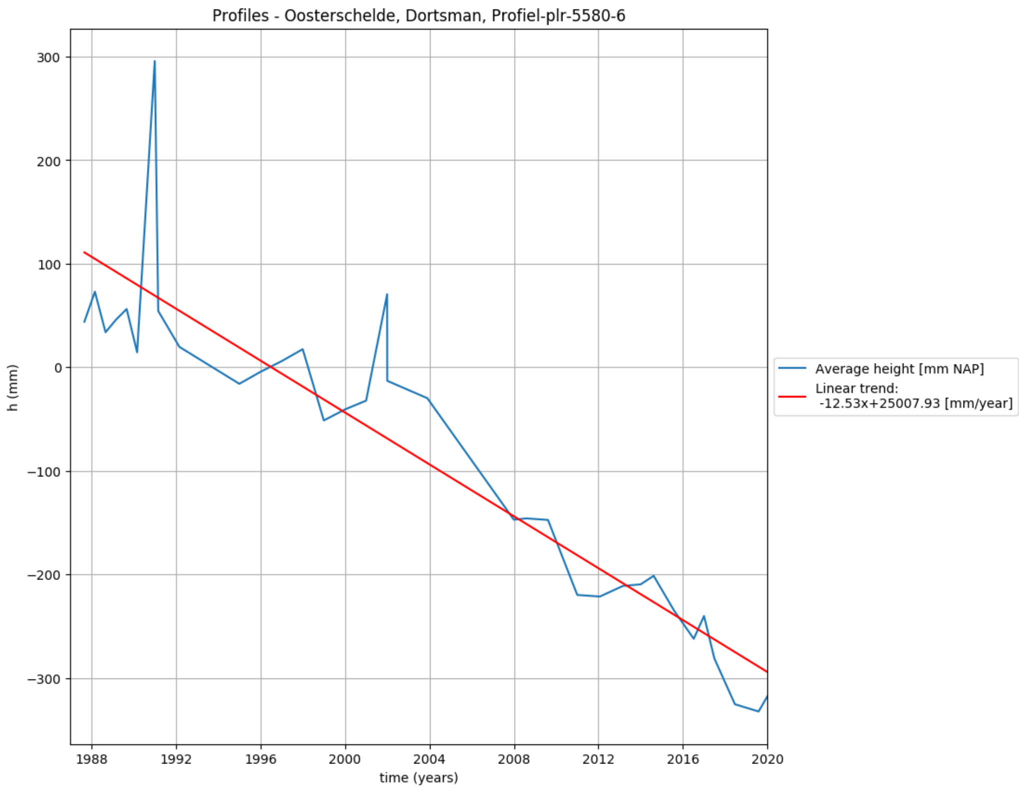


*Figure 4.3.21 The trend analysis of profile 5580 located on the Dortsman tidal area (Rijkswaterstaat)*

This profile is located in the most western part of the Dortsman tidal area. The graph shows the average height of this profile which decreased in both periods. Moreover, in the period from 2010 until 2020, the erosion increased compared to the period from 1983 until 2010. Profile 5580 shows us that the bed level is eroding quite equally in time which means that the shape of the profile remains. Although it seems like there is a gap, this can be related to the gap in the data from 2003 until 2008. It shows us also peeks; this is most likely related to the oyster reefs. In the rightest part of the profile (500-600m), an increase in height can be seen. The higher area is moving towards the dike.

#### 4.3.1.12 Profile 5550

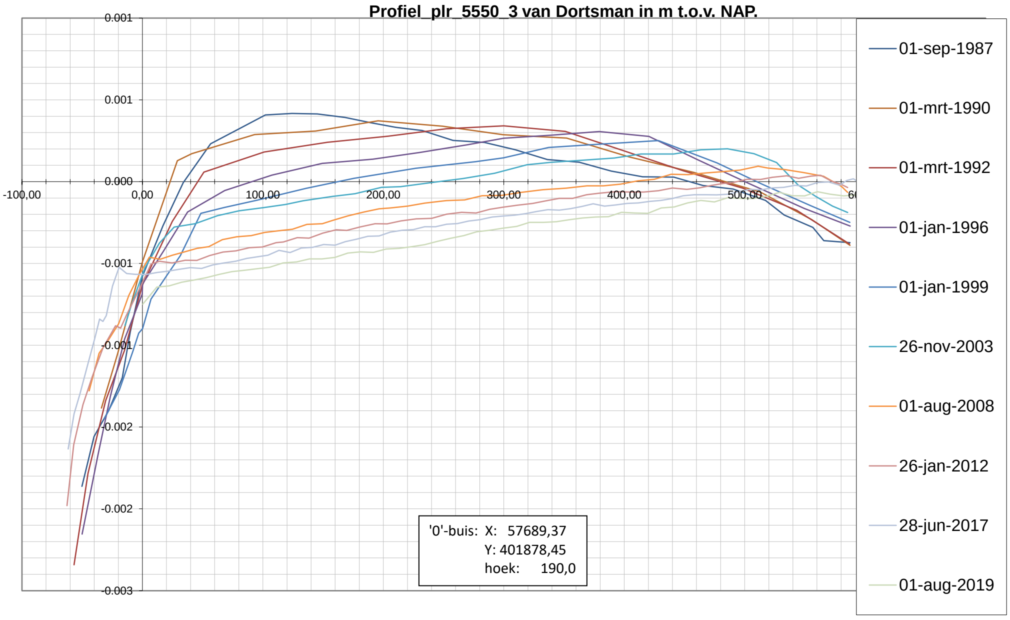


*Figure 4.3.22 Profile 5550 located at the Dortsman tidal area (Rijkswaterstaat)*

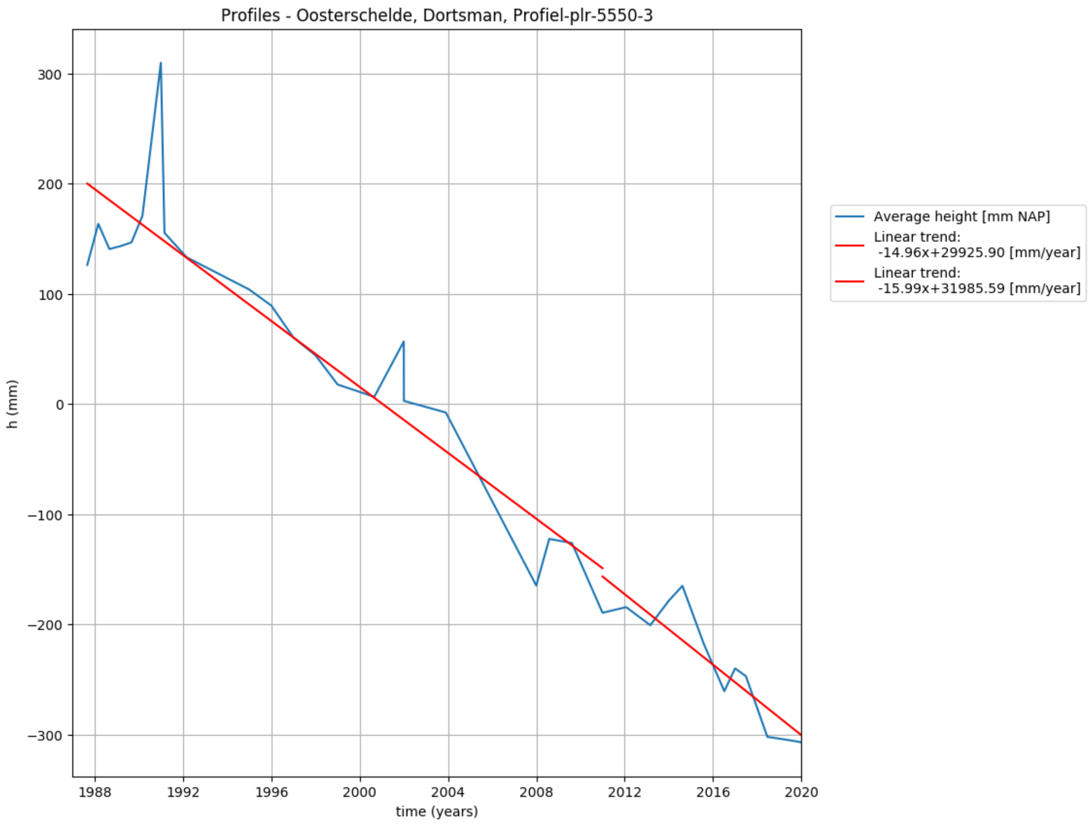


*Figure 4.3.23 Profile 5500 located on the Dortsman, compared with the trend of the height(Rijkswaterstaat)*

This profile shows us the behaviour of profile 5550 which is located at the Dortsman tidal area. The area is eroding substantially and continually. So, the erosion rate is stable.

### 4.3.2 Conclusion of profile analysis

| ***Profile*** | **Location** | **Height trend 1986-2010[mm/year]** | **Height trend 2010-2020[mm/year]** |
|---|---|---|---|
| *5420* | Galgeplaat | -5.3 | 0.13 |
| *5390* | Galgeplaat | - | - |
| *5400* | Galgeplaat | -12.35 | -8.68 |
| *5410* | Galgeplaat | -10.03 | -0.24 |
| *5490* | Galgeplaat | 1.12 | 15.68 |
| *5480* | Galgeplaat | -9.65 | -11.12 |
| *5450* | Galgeplaat | -4.32 | 2.71 |
| *5600* | Dortsman | -5.58 | -2.97 |
| *5580* | Dortsman | -10.42 | -14.44 |
| *5550* | Dortsman | -14.96 | -15.99 |

*Table 8 The height trend of the profiles located on the Galgeplaat and the Dortsman*

The behaviour of the profiles located on the Galgeplaat compared which each other is substantially different. The profiles located on the Dortsman tidal area are eroding almost equally as time progresses, which results in a constant decrease in bed level height. The outer parts of the Galgeplaat tidal flat are eroding faster than the middle parts of this sandbar. The middle of the flat is even accreting. The results show us also that the northern part of the Galgeplaat tidal flat is eroding faster than the southern part.

Part of the explanation can be found by looking at the maximum fetch length of the wind, which results in a wave attack on the Galgeplaat. The fetch length of the wind can be the length of the Galgeplaat until the Zealand Bridge, which is larger compared to other fetch lengths of the wind directions. Therefore, the wind, coming from South, South West and West, could generate substantial waves for the Eastern Scheldt and thus cause sediment transport dependent on the tidal influence. Although the profile 5480, which is located at the southern part of the Galgeplaat, has decreased the most (average decrease in bed level height in the period of 1986-2010) compared to the other profiles of the Galgeplaat.

In conclusion, the analysis of the profiles shows us the behaviour of the bed level height. The behaviour is non-homogeneous and the erosion is not constant in time. The profiles located in the northern outer parts are facing the largest erosion rate. And profile 5480, which is located on the southwest of the Galgeplaat, has eroded substantially in the last decade. The areas where the oyster reefs are located are less eroding or even accreting. So, from a morphological point of view, the oysters' reefs are a good solution for preventing erosion. However, the oyster's reef can form a thread for wader species that are on the same trophic level.

The western part of the Galgeplaat is still eroding while a constant erosion rate. And the eastern part of the Galgeplaat tidal flat is eroding much less.

The profiles located on the Dortsman are substantially more stable compared to the profiles located on the Galgeplaat. Except for the northern area of the Dortsman which is still eroding.

### 4.3.3 Conclusion of RTK analysis, vaklodingen and satellite pictures

#### *4.3.3.1 Galgeplaat*

The behaviour of the bathymetry of the Galgeplaat changed in the past. Comparing the two periods one from 1983-2001 and the other from 2001-2019 we can conclude that the erosion rate in the first period was substantially higher. The decrease in bed level height is especially visible in the northern part of the Galgeplaat. From 1983 until 2001 the whole Galgeplaat decreased in bed level, while in the second period the south eastern parts did not decrease in bed level height, moreover these parts increased.

The analysis of the objects showed, that the number of oysters located on the Galgeplaat increased during the period from 1986-2019 almost constant and equally. The areas where the oysters are located do not erode. Another interesting behaviour can be found by analysing the small channels of the Galgeplaat.

The average decrease of all profiles at the Galgeplaat is:

| Decrease in bed level height (mm/year) based on last 36 years of data. | Decrease in bed level height (mm/year) based on last 9 years of data. |
|---|---|
| -4.268 | -0.821 |

*Table 9 The estimated decrease in bed-level height due to erosion*

#### *4.3.3.2 Dortsman*

The Dortsman tidal area is more stable compared to the Galgeplaat. The northern part is eroding with a constant erosion rate. And the rest of this tidal area does not change in bed level height. However, the profile analysis shows the higher area of the northern part of the Dortsman did move towards the dike until 2008, after that the higher part started to erode. An explanation for the erosion at the northern part of the Dortsman tidal area could be the large fetch length of the wind coming from north to west. This could generate wave attacks and due to the tidal velocity sand erosion.

## 4.4 Hydraulic data analysis

### 4.4.1 Introduction

The hydraulic data is separated into wind data and wave data. The wind and wave data are coming from Rijkswaterstaat. The data is collected from several locations. The wind data is coming from the measurement station located in Stavenisse, which is close to the Galgeplaat tidal flat. This will provide a good indication of the wind at the Galgeplaat. The wind data has two different parameters: wind velocity and wind direction. These two parameters can be connected by plotting the wind data in a wind rose.

The wave coming from the Keetenboei, located north of the Galgeplaat, is used from the analysis of the wave data. The wave data consist of wave height and wave direction. Those two parameters can be visualised in a so-called wave rose.

### 4.4.2 Wind data

The wind data is gathered every ten minutes. The data is divided into direction and wind speed. During the analyses of the wind data, the relevant wind direction has been determined. The wind data from different measure stations have been analysed.

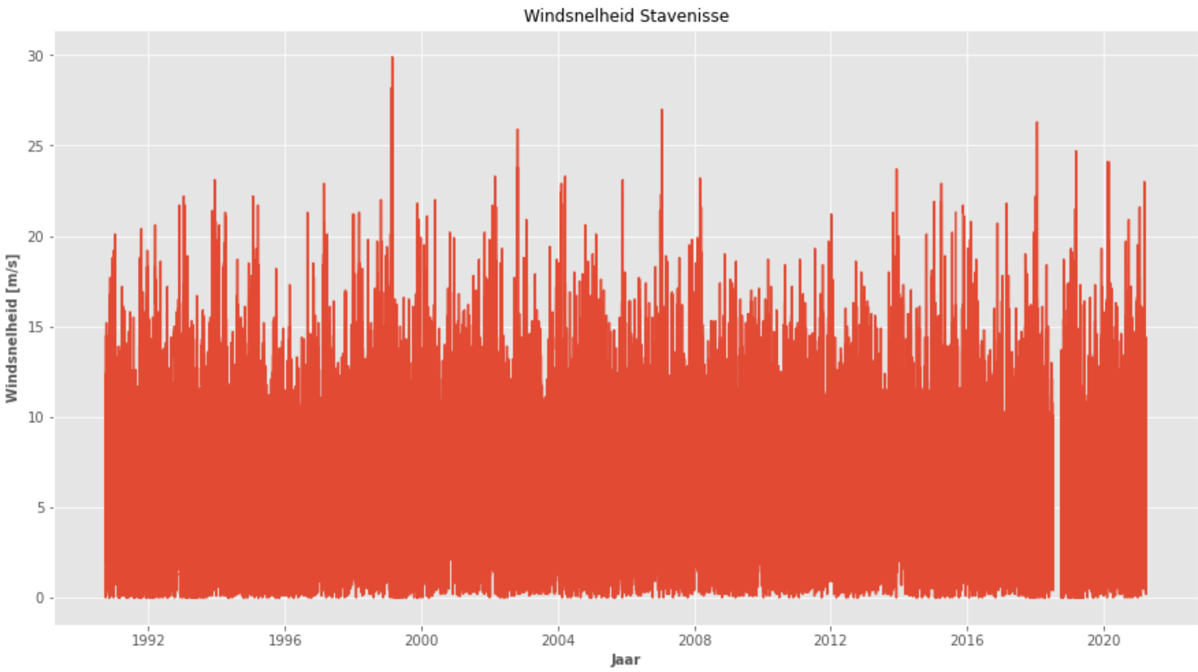


*Figure 4.4.1 Wind velocity at Stavenisse from 1991 until 2019*

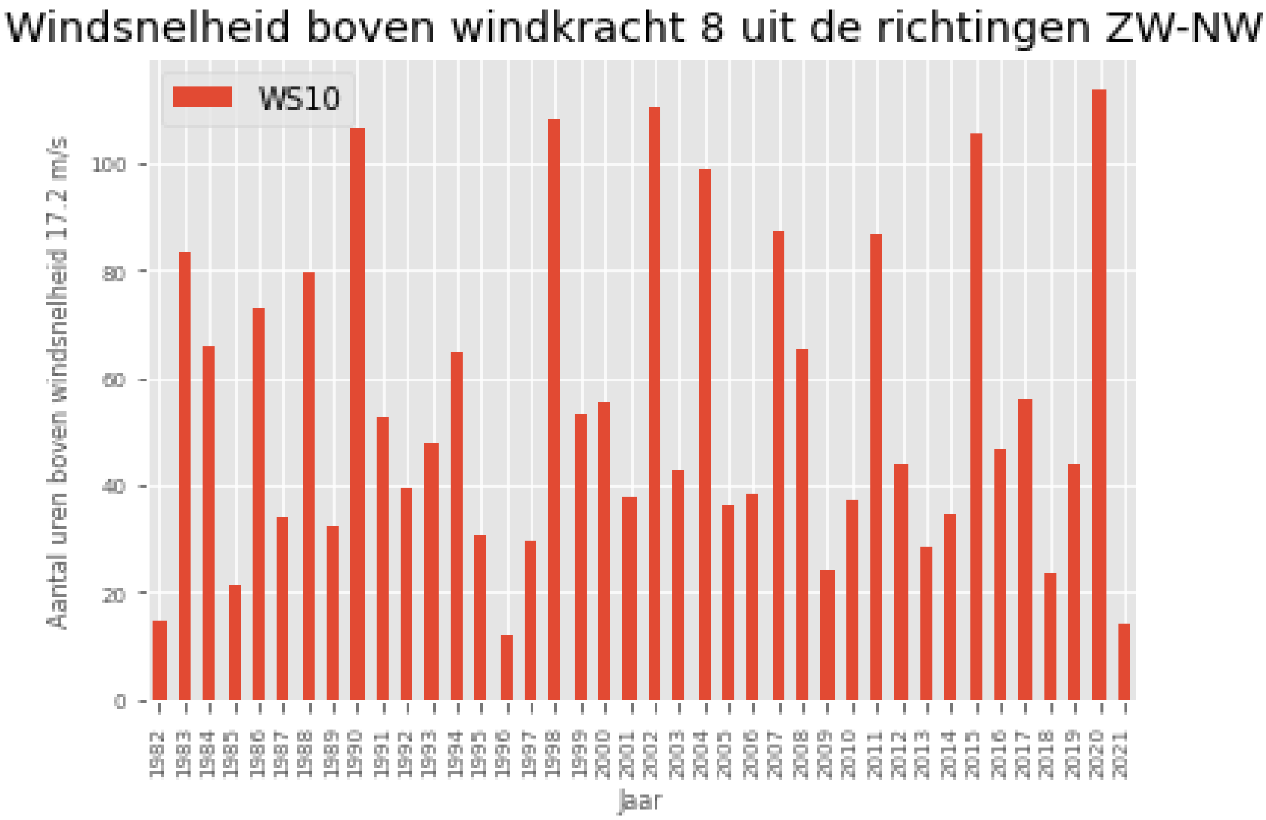


*Figure 4.4.2 Hours of wind above wind force 8 from the south-west to north-west direction at Stavenisse*

In Figure 4.4.2 a bar graph of the wind is shown. From the wind data, the periods in which the wind velocity is above wind force 8 have been selected. The years above 100 hours of wind above 17.2 m/s (wind force 8) are 1990, 1998, 2002, 2015, 2020. The years with less than 40 hours of wind from Southwest to Northwest direction are 1982, 1985, 1989, 1992, 1995, 1996, 1997, 2001, 2005, 2006, 2009, 2010, 2013, 2014, 2018, (2021). Especially the years 1995 - 1997 are pointing out.

What points out from the profile analysis is the peak at most of the profiles in 1990 with a strong decrease in height afterwards.

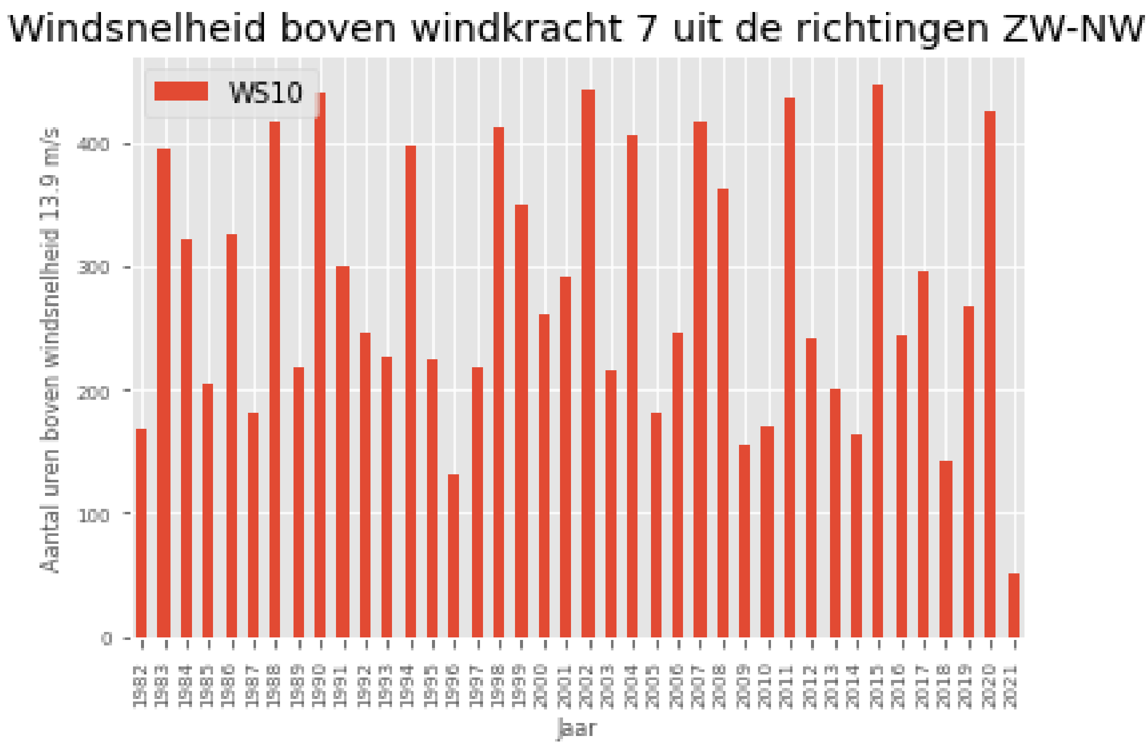


*Figure 4.4.3 Hours of wind above wind force 7 from the south-west to north-west direction at Stavenisse*

Comparing Figure 4.4.2 and Figure 4.4.3 shows that decreasing the wind force provides a bar graph in which the differences between the years become smaller.

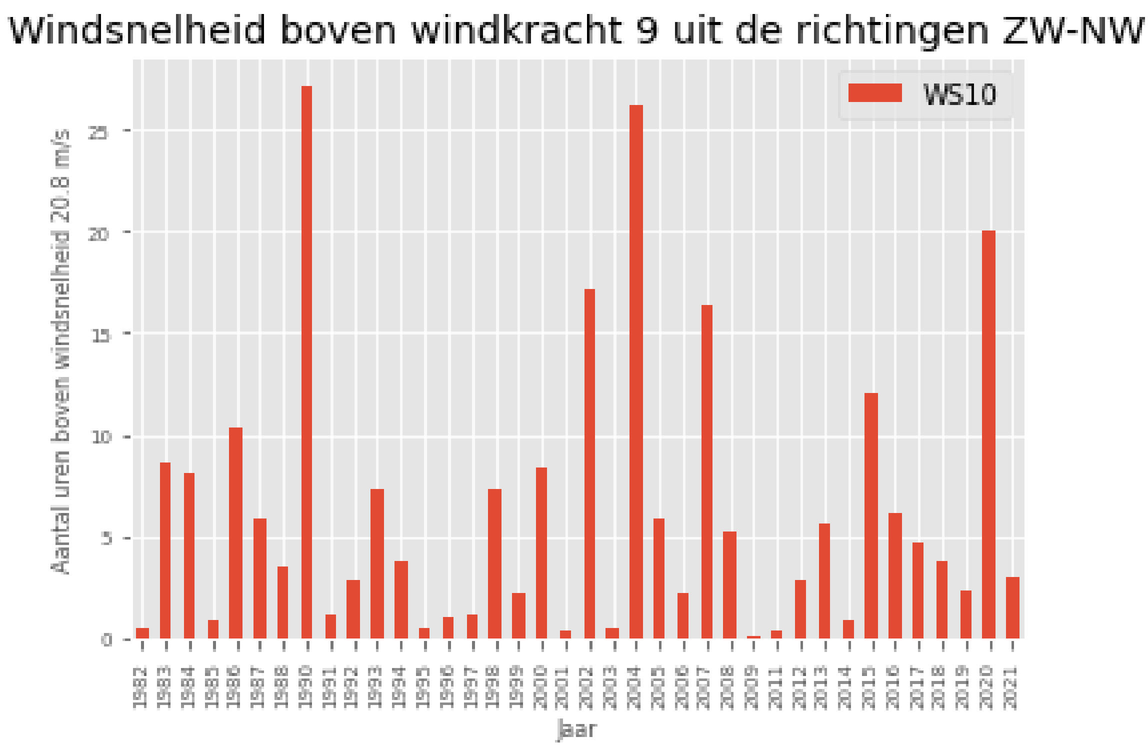


*Figure 4.4.4 Hours of wind above wind force 9 from the south-west to north-west direction at Stavenisse*

In Figure 4.4.4 the hours of wind above wind force 9 at Stavenisse is plotted. Chapter RTK-Profiles expresses that the years 1990, 2002 and 2004 were the years in which the bed level height shows us interesting behaviour in almost every profile at the Galgeplaat tidal flat and the Dortsman which is visualised in Figure 6.1.1. There is a strong correlation between the profiles and the years with the highest wind velocity from the relevant wind direction.

The height of profile 5420 does have decreases in height in the years 1990, 1998, 2002. However, in the three years with a smaller number of hours above wind force 8 from direction south-west to north-west the height does also decrease.

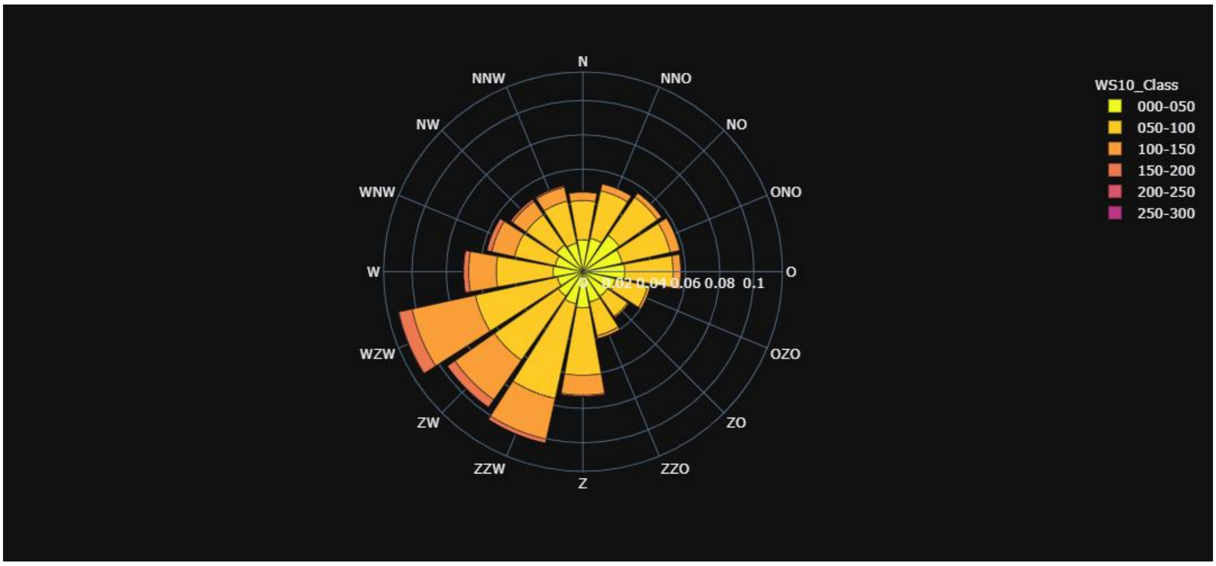


*Figure 4.4.5 Windrose based on the wind data from 1982-2019 at Stavenisse*

In Figure 4.4.5 the wind direction and velocity are plotted. This provides a clear understanding of the dominant wind direction. The largest wind velocity is coming from the southwest direction and is therefore chosen as relevant wind direction.

### 4.4.3 Wave data

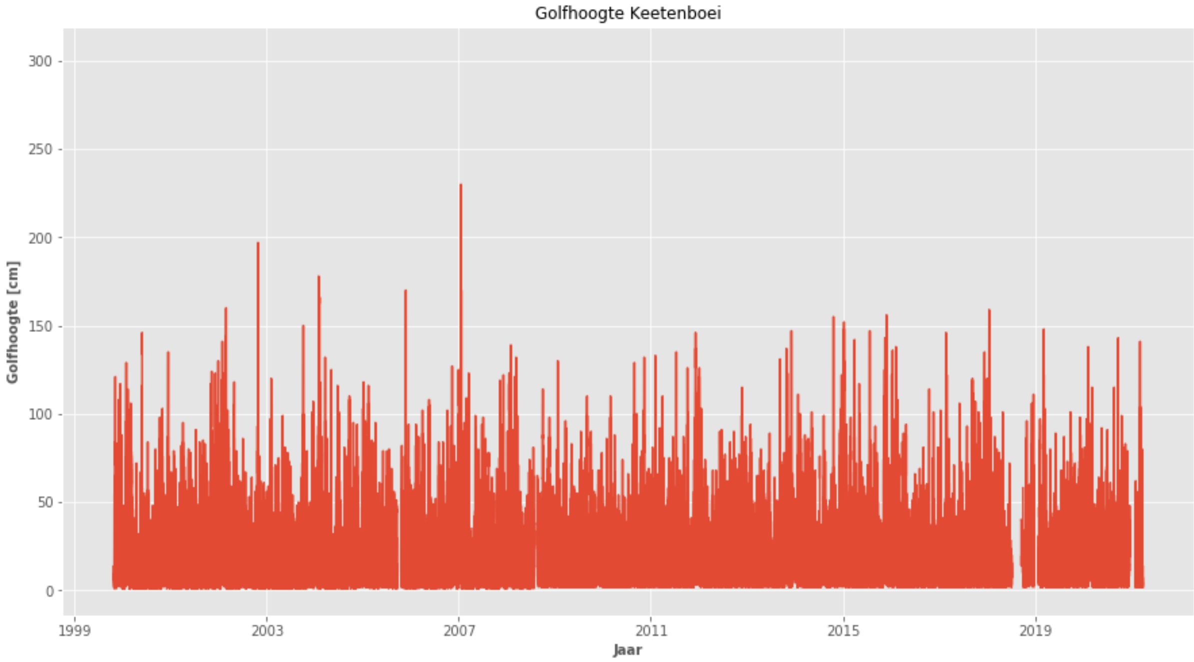


*Figure 4.4.6 The wave height of the Galgeplaat measured at the Keetenboei which is located north of the Galgeplaat tidal flat.*

In Figure 4.4.6 the wave height is plotted. The most relevant points in this graph are the largest peaks because they cause the largest impact at the erosion rate as van der Hoeven proved. The peaks in wave height above 1.5 m are has occurred 9 times in 20 years, which is one every 2 years on average. The wave height above 1.75 m has only occurred before 2007. Wave height above 1.5 m only occurs 8 times in 20 years.

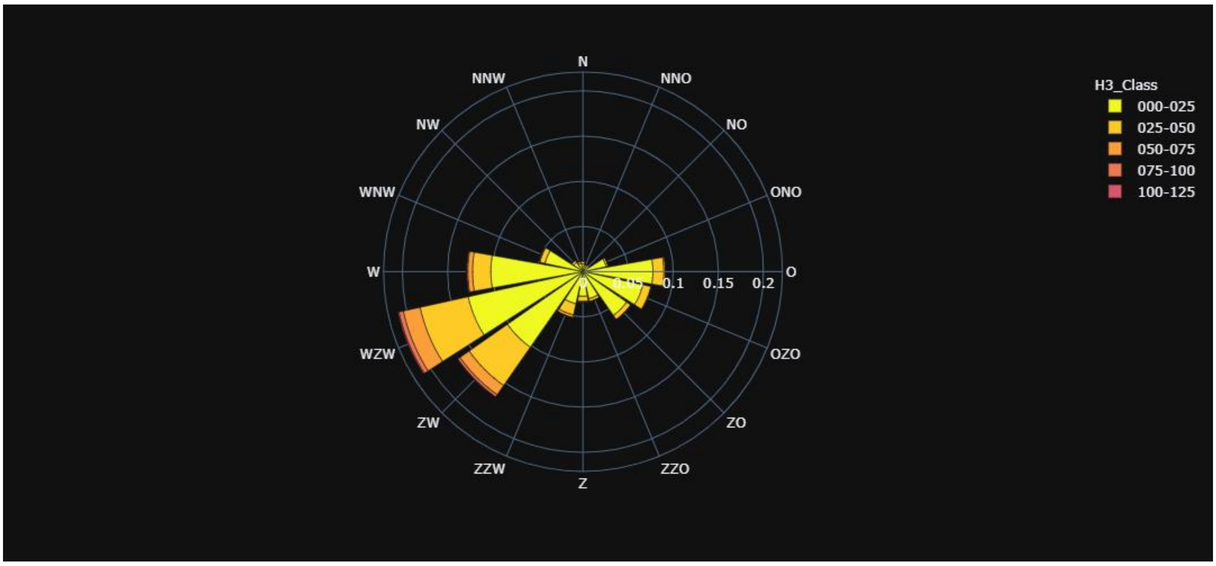


*Figure 4.4.7 Wave rose based on wave direction and wave height at the Roggenplaat. data from 2015-2019*

The wave data is plotted in Figure 4.4.7. The direction in which the largest waves are coming is West-South West. When comparing Figure 4.4.7 to Figure 4.4.5. It can be stated that the dominant wind direction is related to the dominant wave direction. And since there is no wave direction data at the Galgeplaat tidal flat the dominant wind direction will be further analysed.

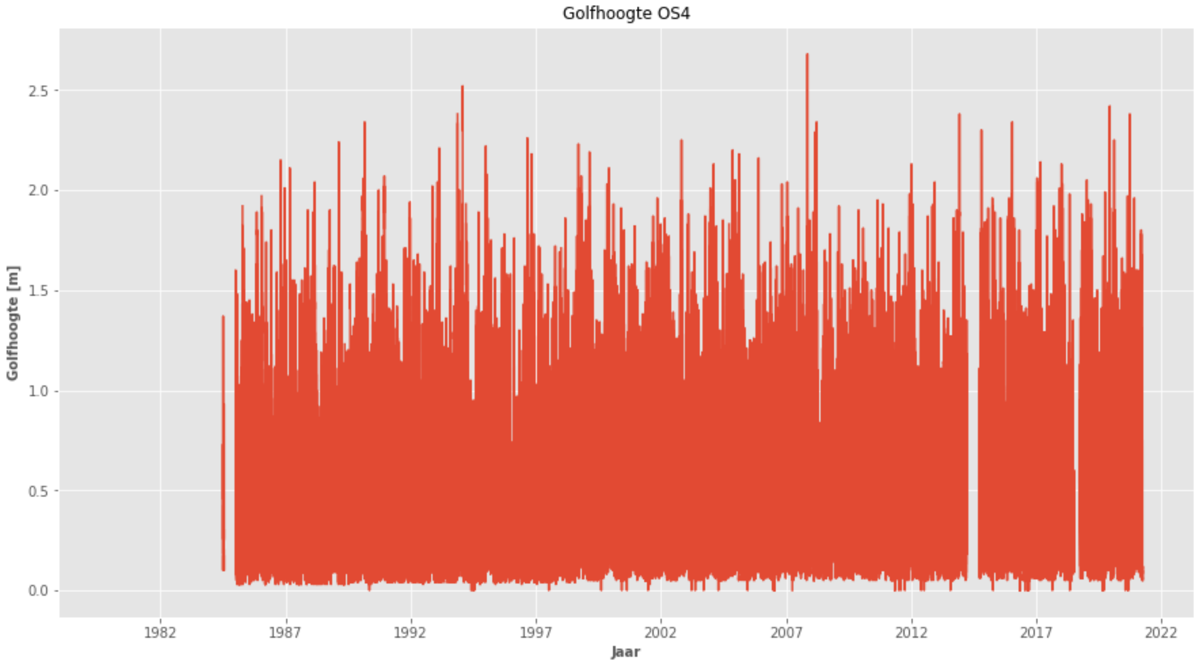


*Figure 4.4.8 Wave height based on the data coming from OS4*

Figure 4.4.8 is the wave height plotted over time. The average wave height at OS4 is 0.44 m. Since the dominant wave direction in ZW-NW, because these directions cause the largest wave and most likely those waves lose their energy on the tidal areas. Therefore, these directions are interesting for the analysis.

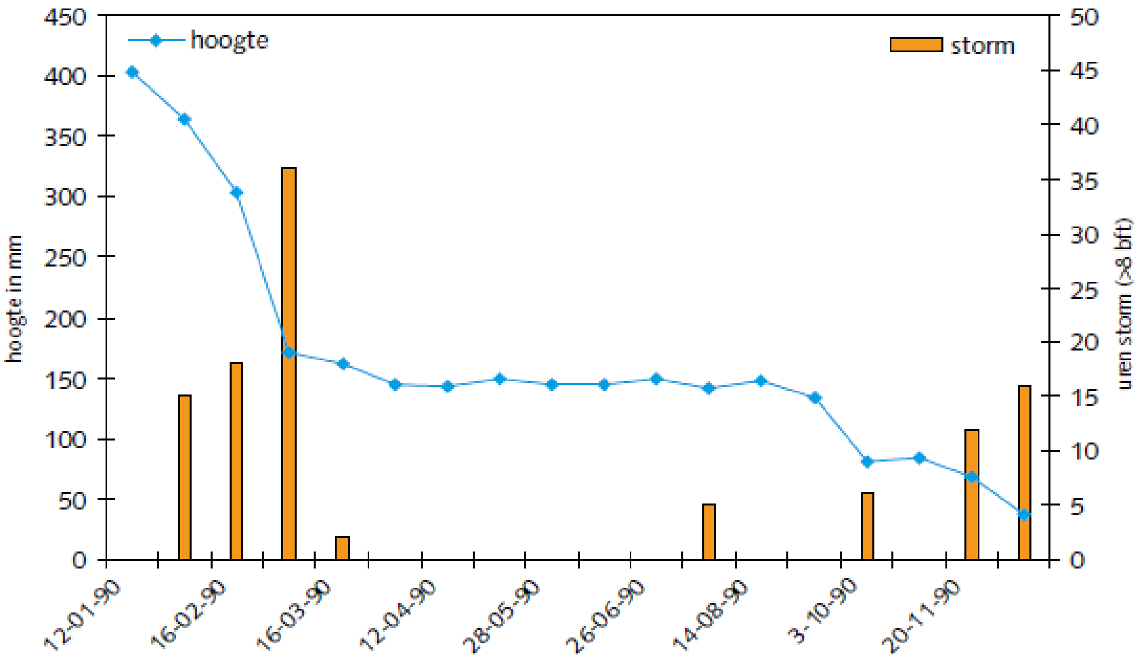


*Figure 4.4.9 The connection between the time of the storm and erosion in 1990.*(van Zanten & Adriaanse, 2008)

The connection between the time of the storm and the decrease in bed level height can be seen. The storm is defined as wind velocity above 8 Beaufort. The largest difference in height shows up after a storm event.

For this research, an update of the connection between the time of storm and erosion has been made. The correlation between storm and erosion is visualised in Figure 4.4.10.

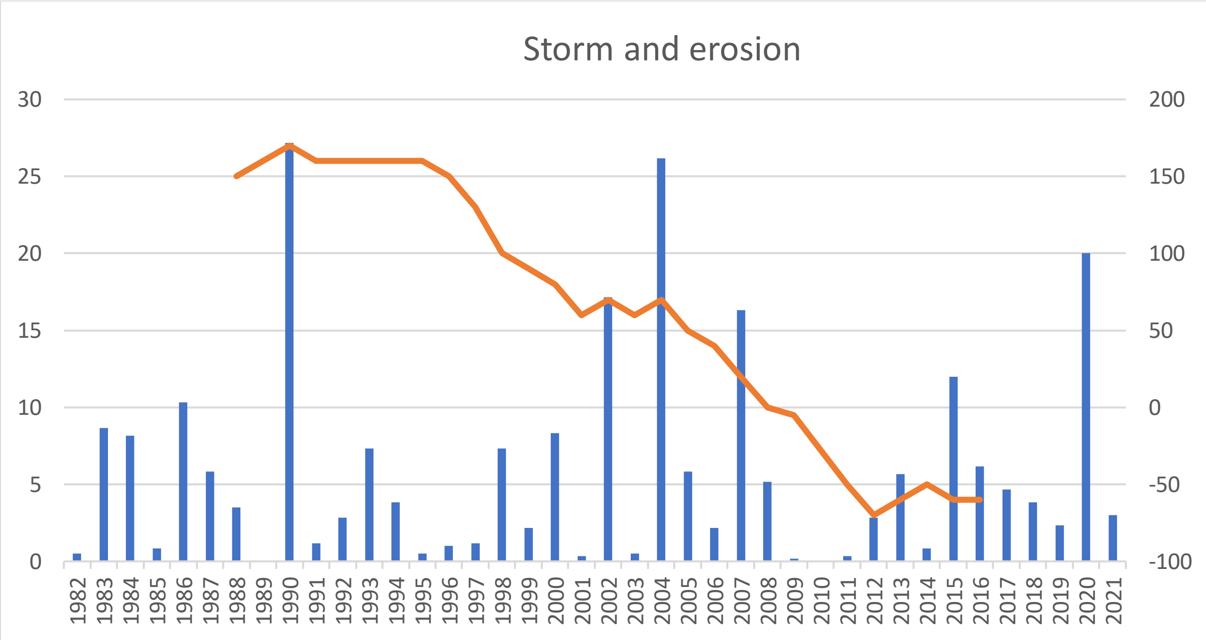


*Figure 4.4.10 The relation between storms and changes in bed level height. The orange line indicates the orange line. The bars are the number of hours in which the wind velocity is above wind force 9*

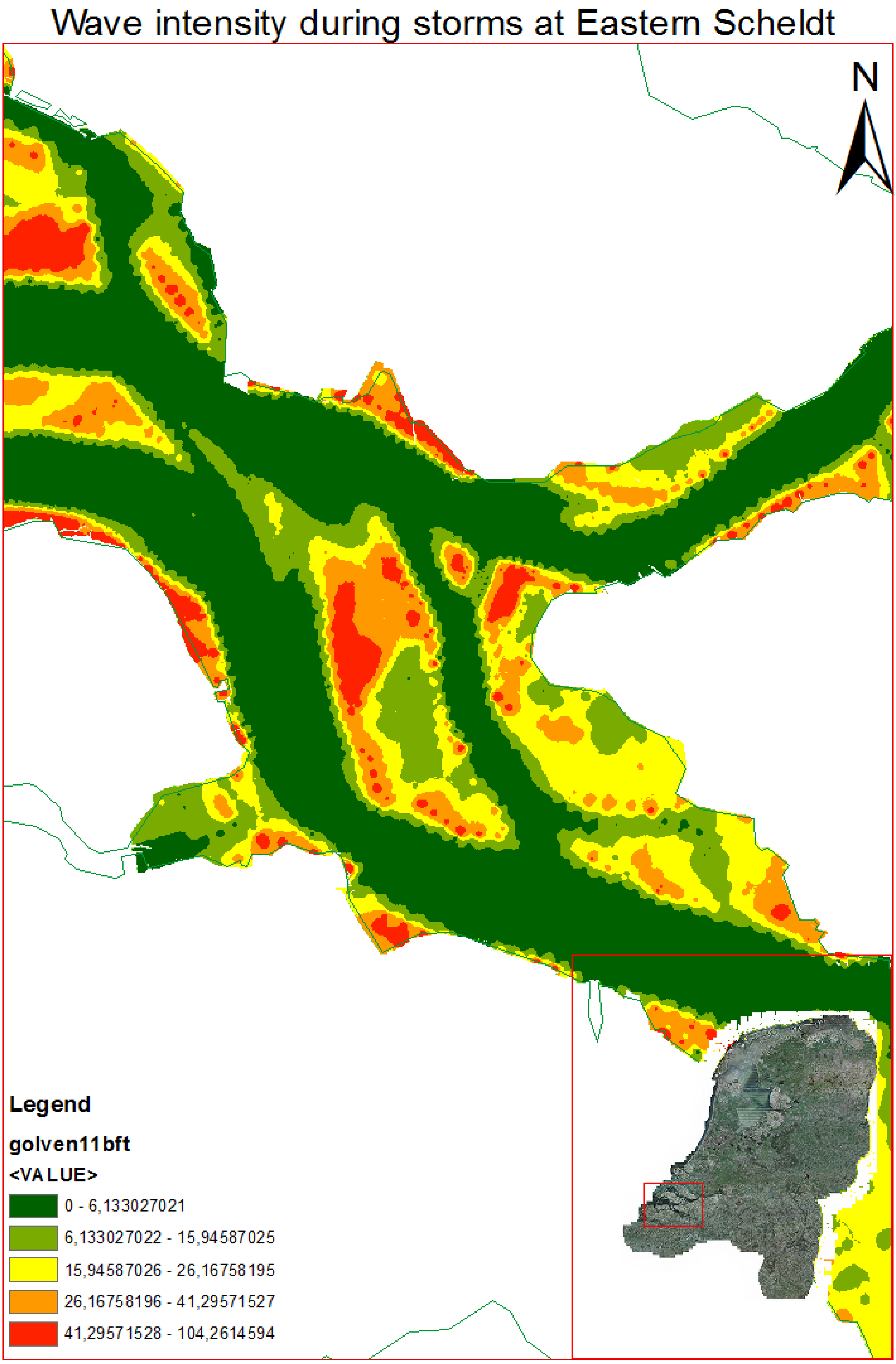


*Figure 4.4.11 The wave intensity at the centre of the Eastern Scheldt*

Figure 4.4.11 is shown that the domination wind direction which is west-south-west is also the direction in which the wave intensity is large compared to the rest of the Galgeplaat tidal flat. This map gives a good overview of where the waves act in the centre of the Eastern Scheldt.

## 4.5 Morphological development Galgeplaat

### 4.5.1 Emersion time

The emersion time is an important parameter for describing an intertidal area. Considering the decrease in bed level height calculated in the chapter: Conclusion of RTK analysis, vaklodingen and satellite pictures and the climate change scenario LOW from KNMI explained in the chapter: Climate change a calculation in ArcGIS has been made. As a result of the calculation, a map is made of the emersion time of the centre of the Eastern Scheldt.

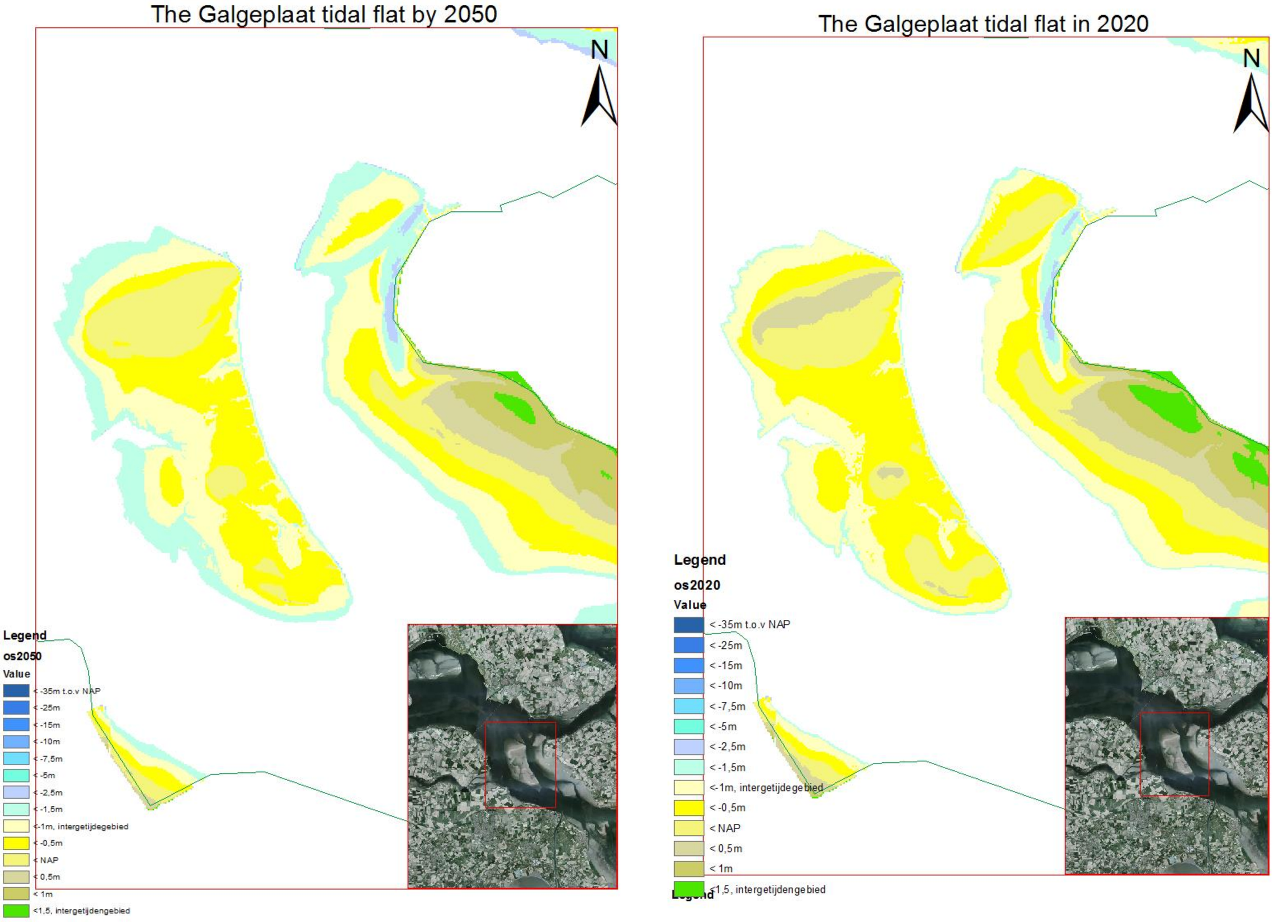


*Figure 4.5.1 Comparison between The Galgeplaat tidal flat in 2020 and by 2050*

As shown in Figure 4.5.1 area of the Galgeplaat which is over the low-water line will be reduced in the upcoming years. The area which will be emersed during low tide is substantially smaller in 2050 compared to 2020. This confirms the need for nourishment.

### 4.5.2 The future of the Galgeplaat

The Galgeplaat is still facing erosion. Together with the increased sea-level rise (IPCC, 2021), the Galgeplaat will reduce in its size. This means that the natural habitat will become smaller. Since the

Galgeplaat is part of the Natura 2000 (*Natura 2000 Deltawateren*, 2016) and its ecological importance it would be a great loss for the ecology. Therefore, Rijkswaterstaat is going the plan nourishment in the nearby future to prevent the Galgeplaat from flooding.

## 4.6 Design of the nourishment

### 4.6.1 Requirements

- The lifetime of the nourishment is given by Rijkswaterstaat and they have determined that the nourishment should last for 25 years.
- The nourishments must restore at least 40% of the area which is emersed. So that the habitat is restored
- The maximum height of the suppletion must be 80% of the area which is above the emersion time.
- The origin of sand must be defined by Rijkswaterstaat.
- The properties of the sand must be as close to the current properties of sand at the Galgeplaat.
- After nourishment, the tidal flat should have shallow slopes.
- The mussel beds cannot be nourished. Increased turbidity during or after the construction of the nourishment must be avoided because of the commercial fishery.
- The nourishment must be restoring the ecological habitat.
    - The nourishment must increase the emersion time of the Galgeplaat tidal flat for wader species.

#### *4.6.1.1 The lifetime of the nourishment*

Rijkswaterstaat decided that all the nourishment which they execute most have a minimum lifetime of 25 years. Since the ecological system needs time to recover after nourishment and the volume of the nourishment must be feasible a lifetime of 25 years is advised (Rijkswaterstaat, 2020).

#### *4.6.1.2 Maximum height of the suppletion*

To create a level of effectiveness of the nourishment Rijkswaterstaat uses the rule that the suppletion must be 80% of the time emerged. This includes that the height of the suppletion must be between 0.9-2.4 m NAP (Rijkswaterstaat, 2021).

#### *4.6.1.3 Origin of sand*

The borrow area will be determined by Rijkswaterstaat, based on the availability of sand. The is dependent on other projects.

#### *4.6.1.4 Quality*

The sand at the Roggenplaat, which is close to the Galgeplaat has the following properties:

| | Coarse (%) | Medium (%) | Fines (%) | Very Fines (%) | Silt (%) | D50 (µm) |
|---|---|---|---|---|---|---|
| Gemiddelde | 0,45 | 31,4 | 57,4 | 6,6 | 4,1 | 210 |
| Min | 0 | 3,4 | 33,0 | 0,1 | 0 | 99 |
| Max | 3,5 | 60,9 | 74,0 | 31,2 | 32,6 | 282 |

The borrow area Roompot has a $D_{50}$ of 180-250 μm, which is used for the suppletion of the Roggenplaat.

The particle properties at the Galgeplaat are similar to the Roggeplaat. From an ecological point of view and with the same properties is advised. This will help the ecosystem to recover faster. Also, grain size is an important factor for sediment transport. Therefore the sand parameters of the nourished material are advised to be similar to the current sand parameters (Jebbe Van der Werf et al., 2016).

##### *4.6.1.5 The slopes of the nourishment*

Steep slopes must be avoided since the wave energy dissipates at steep slopes, which will cause the nourishment to erode faster. Therefore shallow slopes are advised (Jebbe Van der Werf et al., 2016).

##### *4.6.1.6 Ecosystem preservation and restoration*

The Galgeplaat is part of the Natura 2000 area (*Natura 2000 Deltawateren*, 2016). The human impact on this ecosystem must be respected while executing and designing the nourishment. Yet, the nourishment will restore the habitat for wader species.

## 4.7 Design parameters

The design of the nourishment includes the determination of the most important and complicated design parameters:

1. The required volume of sand
2. Deposit areas

### 4.7.1 The required volume of sand

From the trend height of the RTK-profiles, the average decrease in bed level height can be calculated. The average decrease of all profiles at the Galgeplaat is:

| Decrease in bed level height (mm/year) based on last 36 years of data. | Decrease in bed level height (mm/year) based on last 9 years of data. |
|---|---|
| -4.268 | -0.821 |

The differences in the average decrease in bed level height in the two periods are because of the decrease in erosion rate. Between 1986-2020 the average erosion rate at the Galgeplaat tidal flat was almost 5 times larger compared to the erosion rate based on the RTK-profiles of 2010-2020. In this calculation, the required volume of sand is calculated for both periods. So, the positive scenario is based on the smaller erosion rate and the negative scenario is based on the larger erosion rate.

The required volume of sand is calculated by the different erosion rates. When considering the erosion rate from 1987-2020 volume of sand which will erode in the upcoming 25 years is 1.01 million $m^3$. Calculating the estimated sand which will erode by considering the erosion rate of the last 9 years 0.19 million $m^3$ will erode in the coming 25 years.

| The volume needed based on 1987-2020 of erosion (million $m^3$) | The volume needed based on the last 9 years of erosion (million $m^3$) |
|---|---|

| | |
|---|---|
| 1.01 | 0.19 |

The nourishment of the Galgeplaat tidal flat will also restore the volume of sand which has been eroded in the past. Based on the data given by the RKT-profile an estimation of the eroded sand is made. The sand which is eroded in the past 35 years is estimated at 1.33 million $m^3$.

| The volume of sand which is eroded (million $m^3$) |
|---|
| 1.33 |

This amount of sand has to be added to both the positive and negative scenario, which results in the volumes of:

| Negative scenario: volume of sand (million $m^3$) | Positive scenario: volume of sand (million $m^3$) |
|---|---|
| 2.34 | 1.52 |

The sea-level rise must also be taken into account. As stated Rijkswaterstaat considers a sea-level rise of 2.5 mm/year, similar to scenario LOW from KNMI. The emersion time of the Galgeplaat will be influenced by the increased sea level rise. Therefore, the volume of the nourishment must be sufficient for both 25 years of erosion and relative sea-level rise.

The total volume of sand:

| Negative scenario: volume (million $m^3$) | Positive scenario: volume (million $m^3$) |
|---|---|
| 3.2 | 2.4 |

### 4.7.2 Deposit areas

The Galgeplaat tidal flat has several possible locations for nourishment. The first option is located north on the Galgeplaat tidal flat. This can be a good location for nourishment since the northern part of the Galgeplaat is eroding quite stable. This part of the Galgeplaat does not have a steep slope, and the location is not close to the main channels. The second option is located left from option one. In this area, a shell reef is located. The area is eroding with an almost stable erosion rate. The third option is the area between the two smaller channels located west on the Galgeplaat tidal flat. From the data analysis is concluded that this area is quite stable. The fourth and last suitable location for bringing in the sand is located at the most southern part of the Galgeplaat. In this area, a shell reef is located. The southern part of the Galgeplaat is facing fewer wave attacks compared to the northern parts, which might influence the lifespan of the nourishment.


*Figure 4.7.1 The proposed locations for the nourishment*

In Figure 4.7.1 the selected locations are visualised.

#### *4.7.2.1 Score reasoning*

The possible deposit areas of the nourishment are selected based on:

The Galgeplaat is a vulnerable tidal area. Therefore, the nourishment can better be divided into phases at different locations. Between the nourished locations and the fishery areas and distance of 500 m is respected to prevent a highly increased turbidity. As discussed in *Morphodynamic feature 10: Oyster reefs on the* Galgeplaat the oyster reefs can have a positive influence on the erosion and sedimentation processes. Therefore, the oyster reefs have to be maintained during the execution of the nourishment and the **distance to oyster reefs** is an important criterion for the analysis.

The Galgeplaat has also channels, which will have influence the effectiveness of the nourishment. The sediment close to a channel can be transported due to the higher velocity of the water. Thus, the **distance to the channels** is taken into account. This criterion is taken to increase the stability of the nourishment and increase the lifetime. When nourishing the areas close to the channels due to the high flow velocities the nourishment could be eroded. To keep the sand at its original proposed location it is advised to stay away from the channels (Jebbe Van der Werf et al., 2016).

Since the stability of the deposit area will influence the lifetime and effectiveness of the nourishment the deposit areas should have a low **erosion rate** (Holzhauer & van der Werf, 2008).

Since the Eastern Scheldt is used for commercial fishery the locations of the mussel beds must be respected. Therefore, the **distance to those mussel beds** is also taken as a criterion for the MCA.

| Criteria (weight) | Option 1 | Option 2 | Option 3 | Option 4 |
|---|---|---|---|---|
| Distance oyster reefs (1) | 5 | 5 | 0 | 3 |
| Erosion rate (1) | 4 | 2 | 3 | 5 |
| Distance to mussel beds (2) | 4 | 5 | 4 | 5 |
| Distance to channels (2) | 3 | 5 | 1 | 3 |
| Total score | 23 | 37 | 13 | 22 |

*Table 10 The multi-criteria analysis with a 1-5 score*

The variant with the highest score is option 2. Options 1 and 4 both scored 16 points. The amount of sand that is needed is divided into those 3 options with the highest score. The nourishment will be +1.17 m NAP, which can be a real increase (Jebbe Van der Werf et al., 2016).

From the MCA is concluded that the northern part of the Galgeplaat tidal flat is a suitable location for nourishment. Since option three has scored the lowest this area is considered to be less suitable. The fourth option, which is close to the pilot nourishment, is still a realistic location for the nourishment. Therefore, different suitable locations have been further modified to obtain the best recommendations for the deposit areas of the nourishment.

The final locations of the 3 winning variants are visualised in Figure 4.7.2.

*Figure 4.7.2 New variants based on the MCA*

The total area of the proposed locations is 2404444 m$^2$. This results in an increase of 0.9 m NAP, which is a realistic increase for sand nourishment at tidal areas. In Figure 4.7.2 the options 1 and 2 are changed to increase the total deposit area.

# 5 Conclusion

In this research, an answer to the following question was investigated:

**'How can a nourishment be designed for the Galgeplaat taking into account the morphological trend that is revealed by the erosion data that are available for the period 1987-2020?'**

To answer this question, literature research was combined with location-specific wind and wave data.

The following sub-questions have been answered to obtain the nourishment design for the Galgeplaat tidal flat.

**1. What was the morphological trend of the Galgeplaat in the period 1987-2020?**

From the profile and vaklodingen can be concluded that the erosion is spatially in-homogeneous at the centre of the Eastern Scheldt. The sediment transport is not constant in time and location. At the northern part of the Dortsman tidal area, the erosion is more spatially homogeneous compared to the southern area. The erosion rate is substantially higher in the northern area. From the chapter, Vaklodingen can be concluded that the erosion is not consistent both over time and location. The trend of the bed level height of the Galgeplaat tidal flat, calculated in the Conclusion of profile analysis, has been -4.22 mm/year in the last 35 years which is provided in the chapter: Conclusion of RTK analysis, vaklodingen and satellite pictures. This means that the 'zandhonger' is continuing at the Galgeplaat tidal flat.

The erosion rate has decreased since 1986, by analysing the rate of erosion is found that the erosion rate has been smaller from 2010 to 2020 compared to 1987- 2010. The number of erosion rate variations have not decreased in time. Yet, the erosion rate has decreased over the years. So, the changes in erosion rate became smaller. To conclude the erosion rate is not stable over time. However, since the average erosion rate has decreased, the amplitudes of the erosion rate changes decreased.

**2. How have waves affected morphological changes in the Galgeplaat in the period 1987-2020?**

The waves affect the morphological changes of the Galgeplaat. The dominant wave direction which provides the largest waves is also the dominant wind direction. This is the west-south-west direction. The data analysis of the wind and wave data showed that the wind and wave parameters do not change in time. The average wave height is stable during the years.

In Figure 4.7.1 is shown that the west-south-west area of the Galgeplaat tidal flat is threatened by erosion. This proofs that waves can cause erosion. The decrease in erosion rate however is not a result of the decrease in wave height. Since the wave height trend is stable.

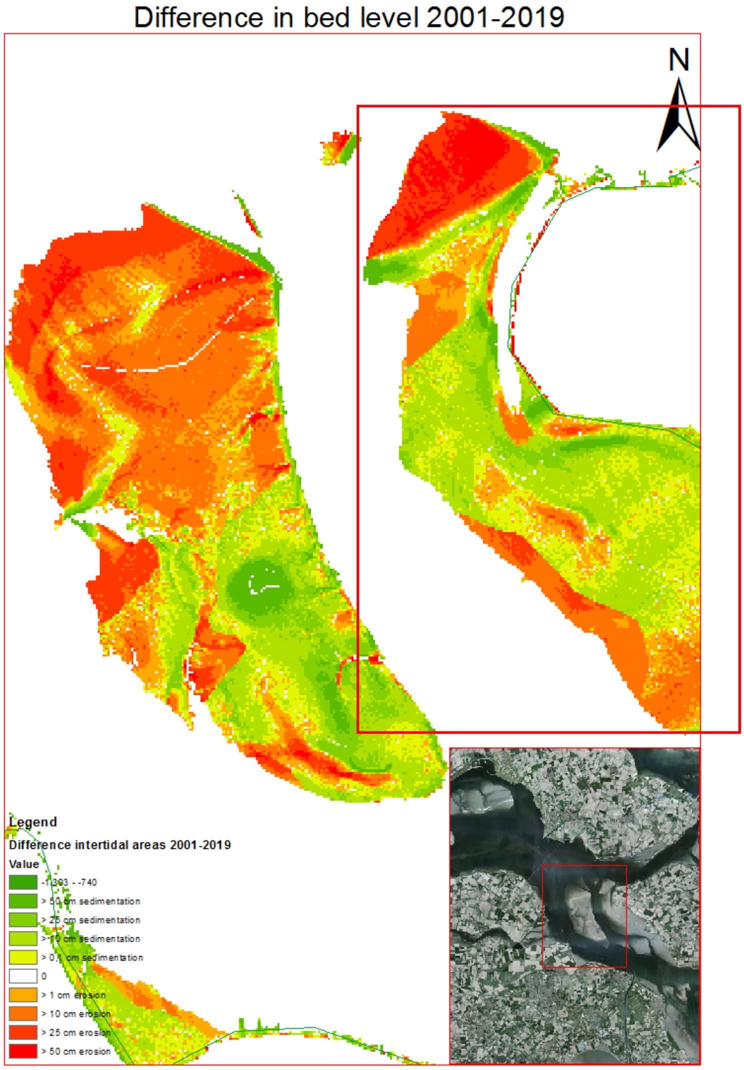


*Figure 4.7.1 The Galgeplaat tidal flat. Green is sedimentation and red is erosion.*

The area of the Dortsman, which is the red box, erodes in the northern parts. The rest of the intertidal area Dortsman is protected from waves by the Galgeplaat.

**3. How will the Galgeplaat morphologically evolve up to the year 2050 in the context of climate change**?

Considering the sea level rise the emersion time of the tidal flats in the Eastern Scheldt will be reducing. The sea-level rise is expected to be 13-41 cm by 2050. This means that the emersion time of the Galgeplaat tidal flat will be reduced substantially by sea-level rise. Therefore, the nourishment design respects the sea level rise. The process of erosion will continue in the upcoming years. The erosion rate will reduce even more most likely. Together with sea-level rise parts of the Galgeplaat tidal flat will drown.

**4. How can a nourishment best be designed for the Galgeplaat considering the morphological trend of the past (1987-2020) and the expectations for the future (2021-2050)?**

The nourishment volume calculated based on the bed level decrease of the last 33 years (1987-2010) is 2.34 million $m^3$. With the decreased erosion rate after 2010, the volume is calculated to be 1.52 million $m^3$. The difference occurs because of the change in the erosion rate. The best deposit areas are located in parts of the Galgeplaat with a small erosion rate, with enough distance to channels, and without removing the oyster reefs.

Nourishment can degrade other beach habitats and reduce the densities of invertebrate prey for wader species, surf fishes and crabs. Still, the large amount of research has a lot to so little progress towards understanding and predicting ecological impacts. Dredging displaces the natural balance and marine life.

# 6 Discussion and recommendations

## 6.1 Discussion

In chapter Results, the vaklodingen provided a spatially strong overview of the erosion and sedimentation in the area. However, due to the relatively large error in the measurements of 10-15 centimetres the data is not used to calculate the erosion rate. The differences in bed level height showed us differences in the same order as the error. Therefore, the profile, which is way more accurate is used for the bed level height analysis.

During the analysis of the RKT-profiles, a peek at 1990 and 2004 pointed out by most of the trend heights, which is visualised in Figure 6.1.1. The peaks occur also in years with a large number of wind hours which can be seen in Figure 6.1.2. A large number of hours of strong wind can result in sediment transport. Waves are providing the energy for the transport of sand and thus change the morphology.

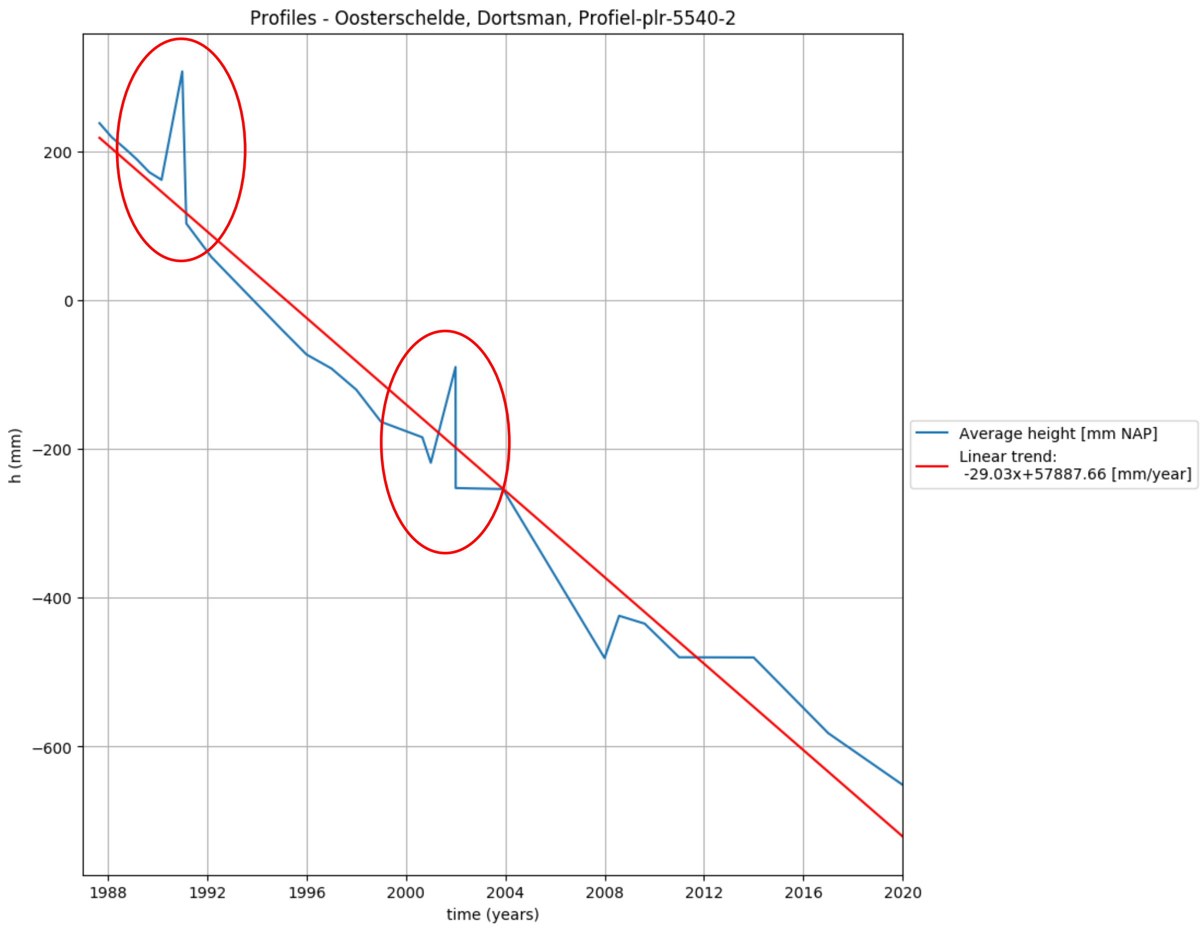


*Figure 6.1.1 Visualisation of the peaks in the years 1990 and 2002 of profile 5540 at the Dortsman (Rijkswaterstaat)*

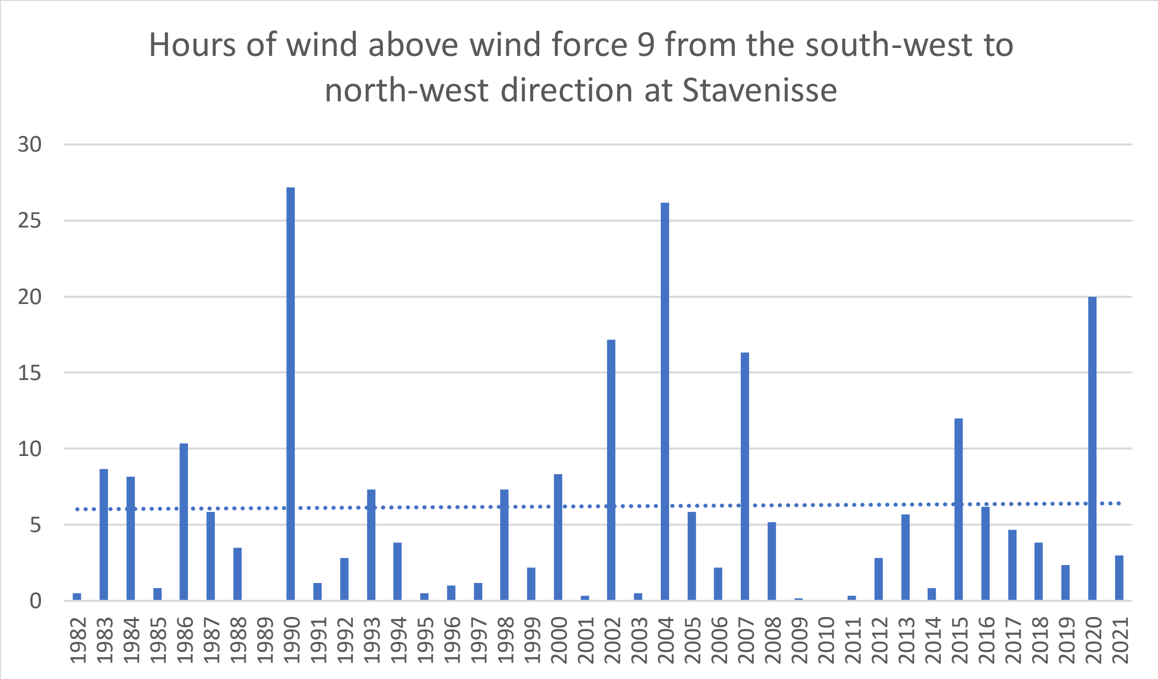


*Figure 6.1.2 Bar plot of the number of hours of wind above wind force 9 from south-west to north-west direction at Stavenisse (OS4)*

The effectiveness of the design of the nourishment is dependent on the sea level rise and further morphological changes in the Eastern Scheldt.

The erosion rate is calculated based on the average height per year. The RTK profiles have an error of 1 cm in the data. This means that the average erosion rate was calculated.

The calculations of the sand nourishment are based on the RTK-profiles which are points in a line at the Galgeplaat. This means that the local conditions and thus the erosion rate can be different than the estimated value based on those profiles. Still, the RTK-profiles are more accurate compared to the vaklodingen, therefore they are used to estimate the needed volume of sand.

As stated in the sub-chapter Hydrodynamic changes tidal currents are an important parameter for sediment transport. Due to the time limitations, this research paper did not analyse changes in tidal currents concerning the sediment transport at the Galgeplaat tidal flat. However, the wind-driven waves provided a strong correlation with the erosion at the Galgeplaat tidal flat.

The research done by Beiboer in 2020 provided an update of the erosion rate in the Eastern Scheldt. While Beiboer focussed on analysing all the intertidal areas of the Eastern Scheldt numerically, this report does provide a more detailed update of the morphological development in the centre of the Eastern Scheldt. The report is made to explore the possibility of executing a nourishment at the Galgeplaat tidal flat to mitigate the negative effects of beach erosion. In addition, this research investigated the correlation between the wind directions and wave directions and also wave height during storm events and erosion rate.

Beiboer also investigated the decrease in erosion rate in the Eastern Scheldt. In this paper, the decrease in erosion rate at the Galgeplaat is further investigated. The erosion rate last decade was 1/5 compared to the erosion rate just after the construction of the storm surge barrier. Yet, the pilot nourishment has a positive influence on the erosion rate, which explains the large decrease in erosion rate.

## 6.2 Recommendations

The tidal currents are influencing the sediment transport at the Galgeplaat tidal flat. The data of tidal currents can provide a better understanding of the relation between hydrodynamics and morphodynamics. In addition to this research, data about currents should be analysed. Despite the amplitude of data, the causes of erosion decrease/increase are not fully understood So, further research on the parameters with cause erosion increase/decrease with numerical modelling is needed.

The design of the nourishment should consider the sea level rise (IPCC, 2021). With the increased sea-level rise the volume must be larger to maintain the proposed emersion time. The height of the nourishment should be calculated, respecting the aim of the 80% emersion time. Also, the slopes need to be calculated. This will provide the final volume and area of the nourishment.

From an ecological point of view the following recommendations are made:

- The satellite images provided a more thorough understanding of the local circumstances. By further designing the nourishment of the Galgeplaat tidal flat the local circumstances must be respected to reduce the impact on the natural habitat.
- The oyster reefs resulted to have a positive effect on sand erosion. They prevent about 70 % to 100 % of erosion at the Galgeplaat tidal flat. Which could, from a building with a nature perspective, be part of the solution to reduce the erosion at the Galgeplaat tidal flat. The use of Oyster reefs in reducing erosion of tidal flats should be further researched.
- The nourishment of the Galgeplaat is advised to be spread over different locations. This will reduce the ecological impact and increase the emersion time of the Galgeplaat tidal flat. Since the erosion rate is high at the slopes of the Galgeplaat tidal flat the slopes of the nourishment are advised to be small with a maximum of 1:20.
- From an ecological perspective, the sand of the nourishment should have the same properties as the current sand about 100- 300 µm.

Further research on the pilot nourishment could provide more detailed information about the development of the nourished sand. This will improve the understanding of the local circumstances which the nourishment is facing.

After the construction of the nourishment monitoring, the impact on the ecological habitat and development of the nourishment is needed.

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# 1 Appendix A: Satellite images of the Galgeplaat tidal flat

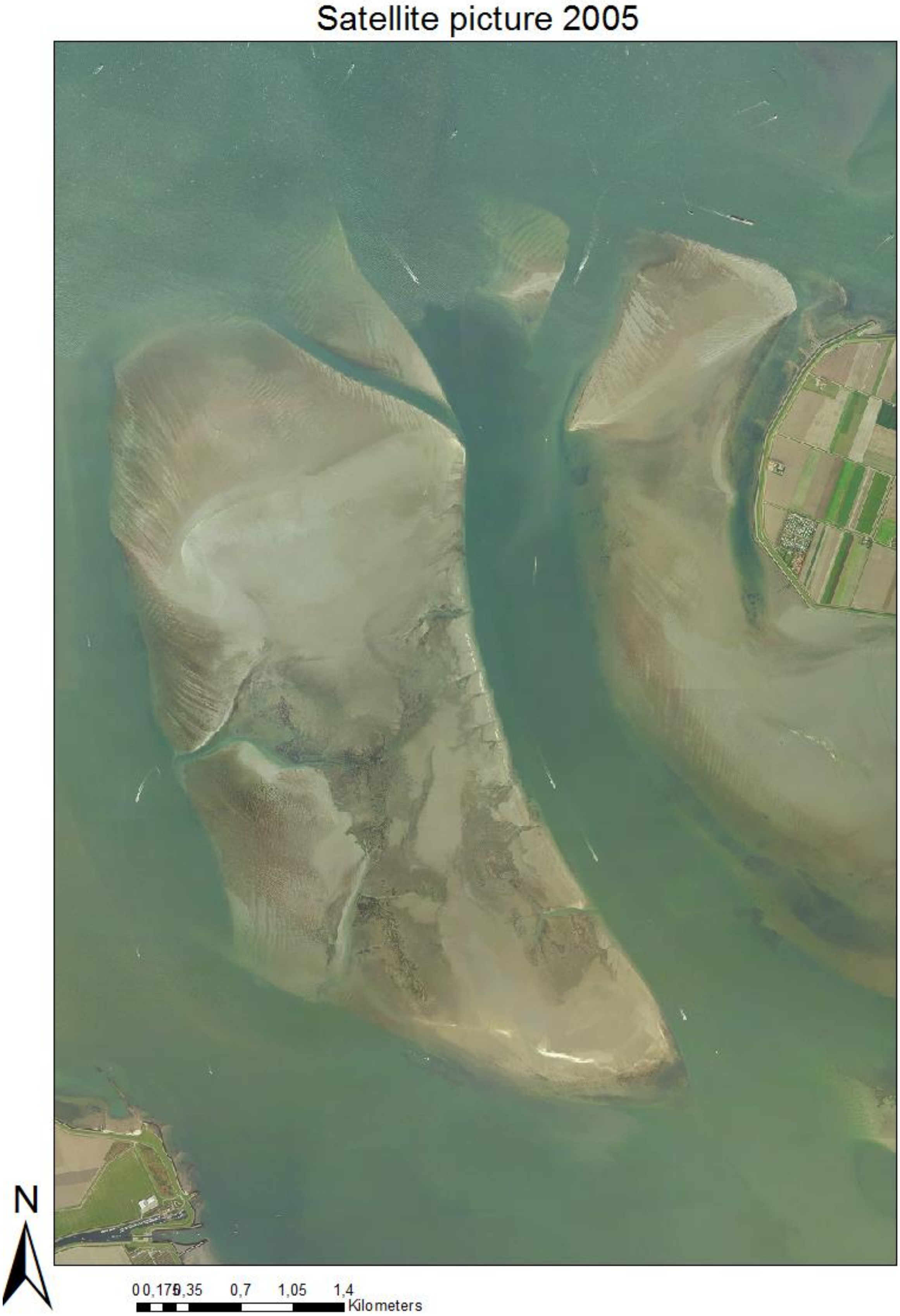


*Figure 6.2.1 Satellite photo of the Galgeplaat tidal flat of 2005.*

# Satellite picture 2007


*Figure 6.2.2 Satellite photo of 2007 of the Galgeplaat tidal flat*

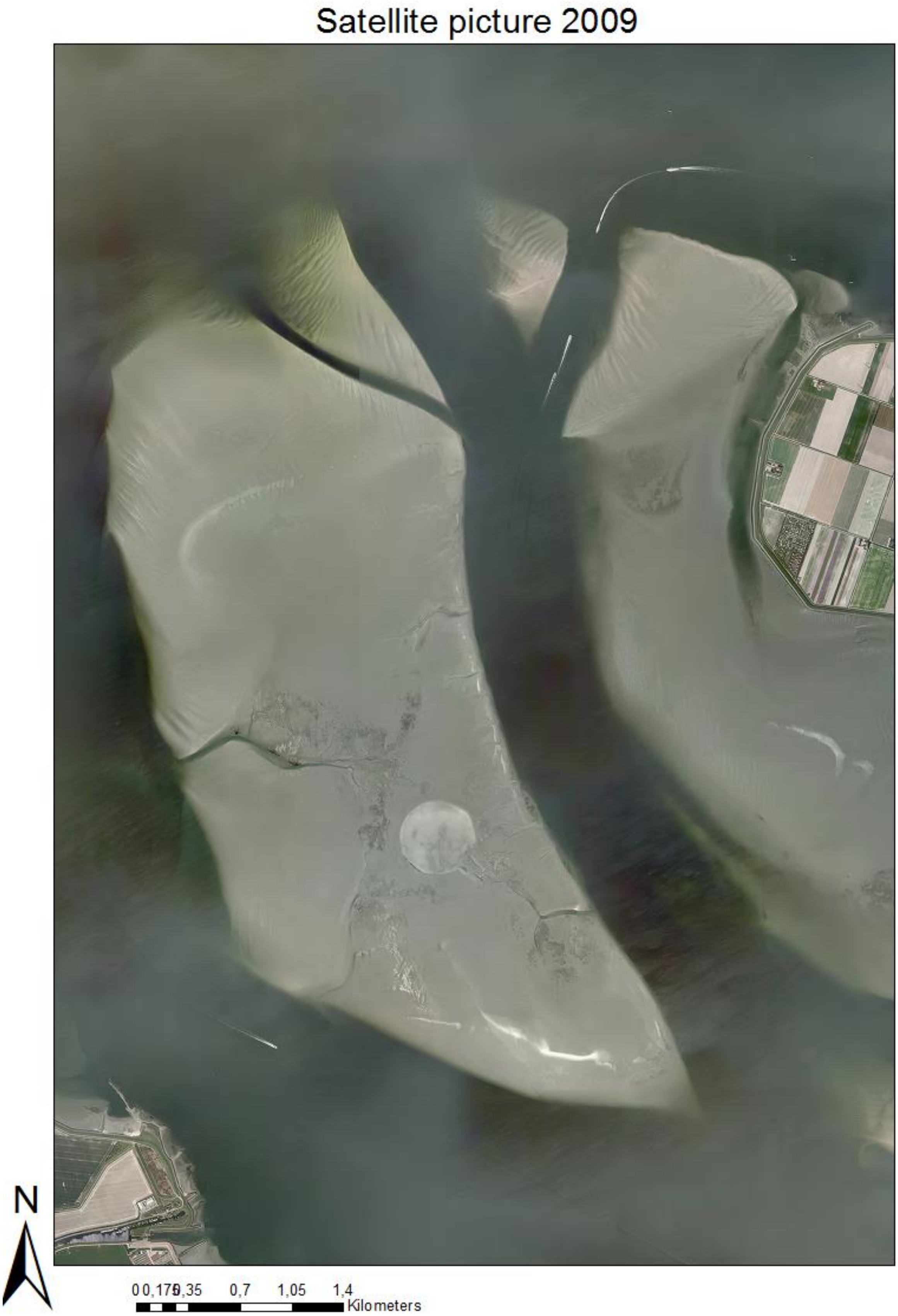


*Figure 6.2.3 Satellite photo of the Galgeplaat tidal flat in 2009*

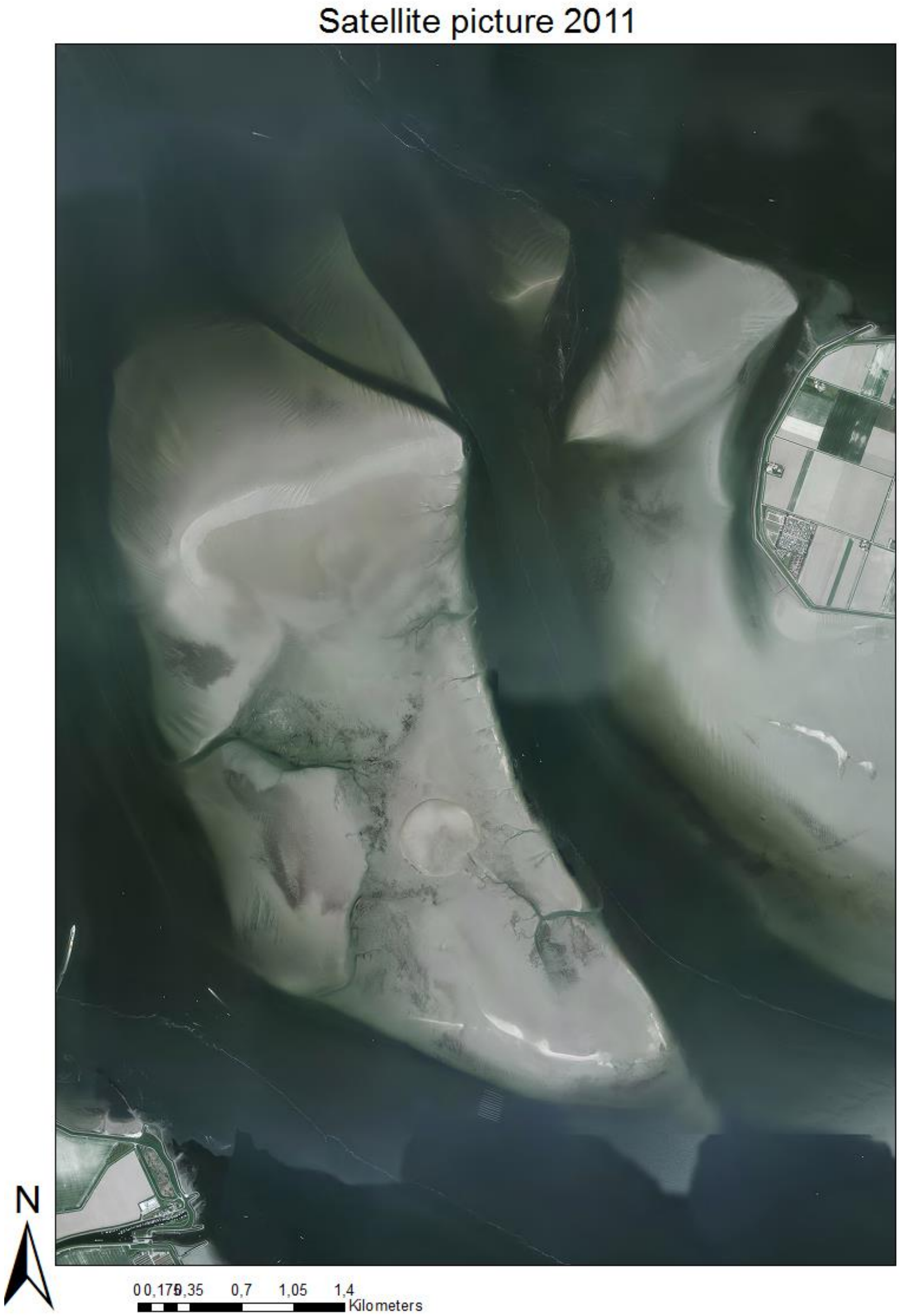


*Figure 6.2.4 Satellite photo of the Galgeplaat tidal flat in 2011*

# 2 Appendix B: Maps of erosion at Galgeplaat tidal flat

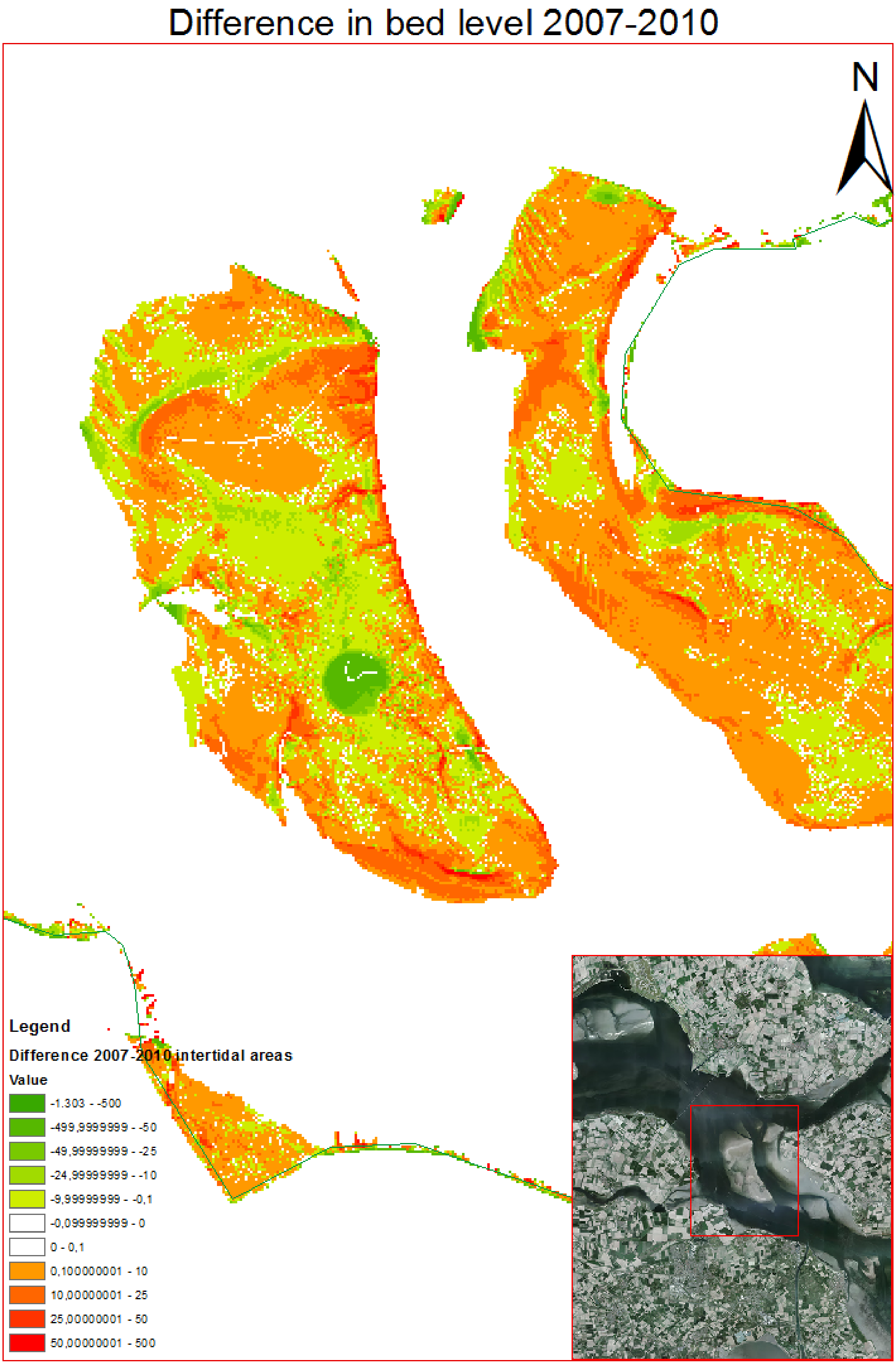


*Figure 6.2.1 Difference in bed level height from 2007 -2010 based on the vaklodingen*

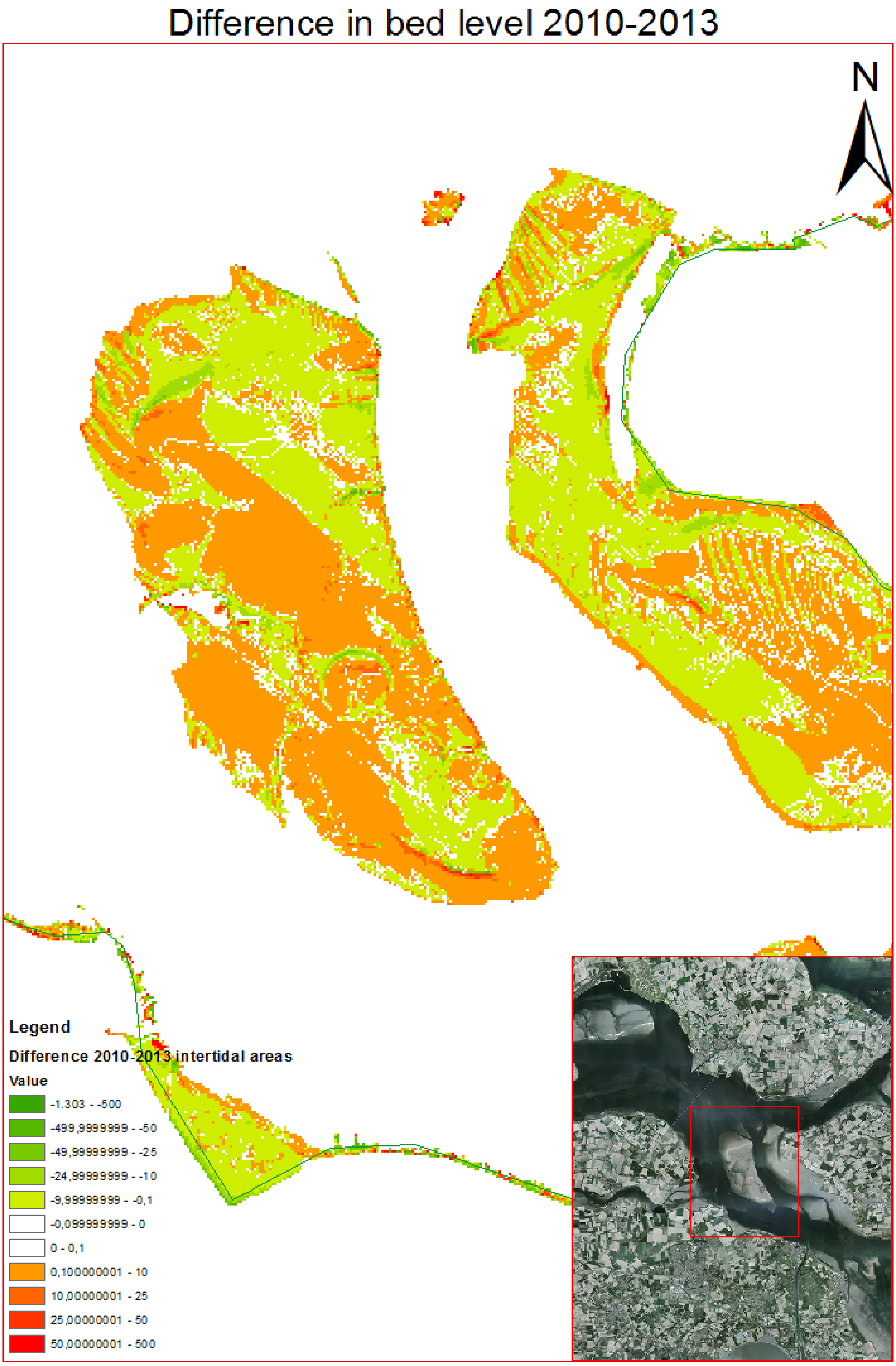


*Figure 6.2.2 Difference in bed level height from 2010-2013 based on the vaklodingen*

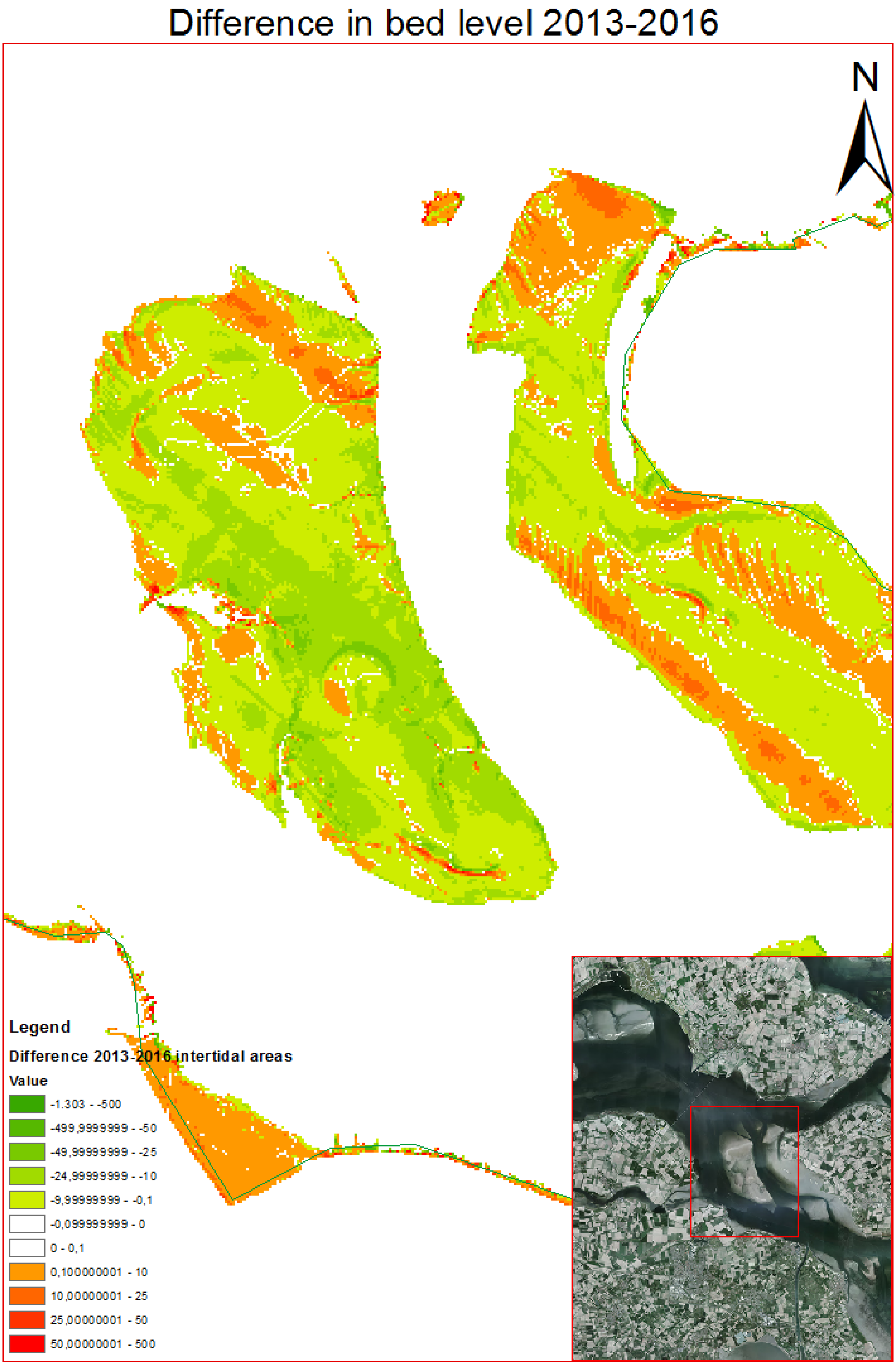


*Figure 6.2.3 Difference in bed level height from 2013-2016 based on the vaklodingen*

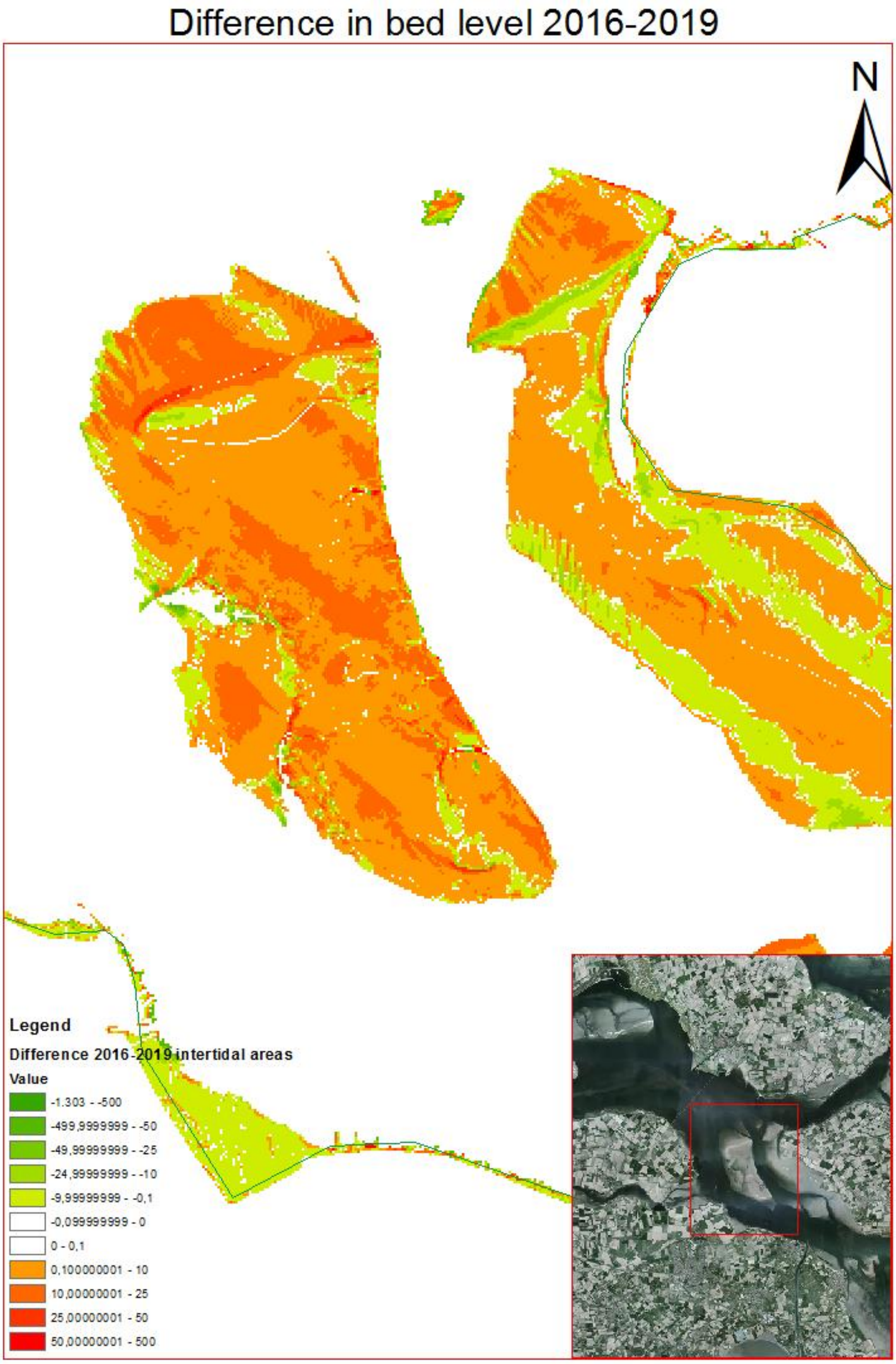


*Figure 6.2.4  Difference in bed level height from 2016-2019 based on the vaklodingen*