# Numerical Modeling of Constructed Foredune Blowouts in the Dutch Dunes

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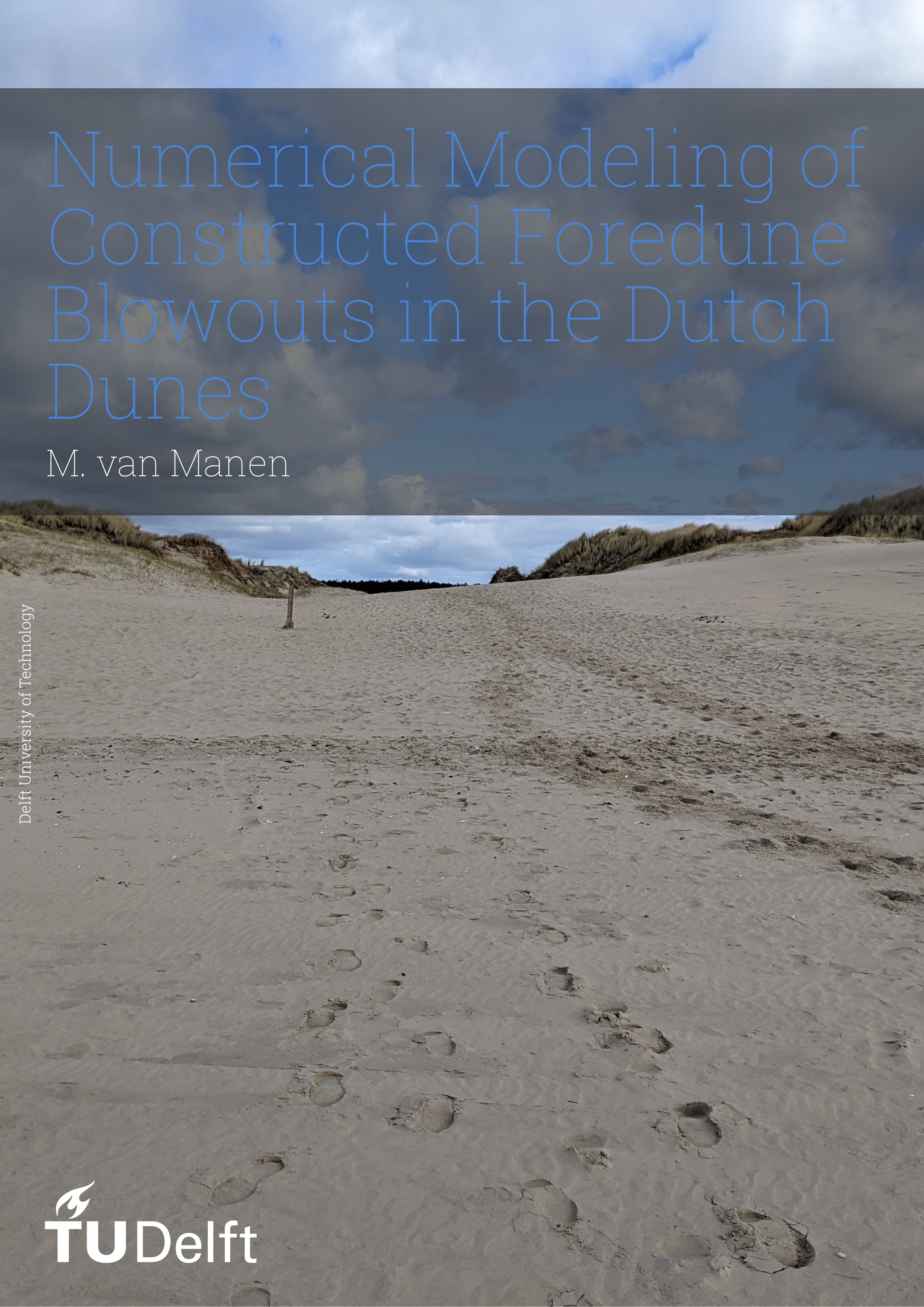

Delft University of Technology

TU Delft

# Numerical Modeling of Constructed Foredune Blowouts in the Dutch Dunes

by

M. van Manen

In partial fulfillment of the requirement for the degree of Master of Science in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences at Delft University of Technology to be defended publicly on July the 12th 2023

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Cover: View of ”de Kerf” in Schoorl, Photo by M. van Manen

# Preface

This thesis has been written as the final part of the Master of Science program in hydraulic engineering of the Civil Engineering Master at Delft University of Technology. This research was undertaken to understand the 'stikstof crisis' in general and the specific issues caused by excess nitrogen deposition in dunes from a civil engineering perspective.

I would like to express my sincere gratitude to all the members of my graduation committee: Sierd de Vries, Peter Herman, and Caroline Hallin. Their supervision, feedback, and guidance were invaluable. I extend a special thanks to Sierd for our weekly meetings, which provided insightful discussions and kept me on track during challenging times. Peter, your critical attitude and ecological insights greatly enriched my thesis. Caroline, thank you for your constructive feedback during progress meetings and for assisting me in setting up AeoLiS, as well as being available for questions.

I am grateful to Harrie van der Hagen, Bas Arens, and Stéphanie IJff for generously sharing their time and knowledge, answering my inquiries regarding foredune blowouts and nitrogen in the dunes.

I would be remiss if I didn't acknowledge my fellow graduate students for their interest, shared struggles, and much-needed distractions, which made the entire process more bearable and even enjoyable. Finally, I extend my heartfelt appreciation to my friends and family for their unwavering support, both emotional and otherwise, throughout the past ten years and these last ten months. This has been a long journey, and I couldn't have accomplished it without you.

*M. van Manen*
*Delft, July 2023*

# Summary


## Introduction

The Netherlands is a country with a history of human activity along the coast to ensure water safety. In the 1990's a new approach to coastal management was adopted that allowed for more experimentation in the Dutch dunes. Since then a slew of different types of projects have been undertaken, one of which is the construction of foredune blowouts. Foredune blowouts are gaps or indentations in the dunes from which bare sand can erode due to the wind. The motivation for the creation of constructed foredune blowouts can range from wanting to reintroduce gradients back into the landscape to ecological restoration, or water safety. Over the years different construction methods and designs have been created, however the evaluation of these projects has been difficult in the past due to broadly defined goals and limited monitoring data. The aim of this research is to investigate the potential of constructed foredune blowouts have in achieving water safety and preserving natural values in the Netherlands by modeling constructed foredune blowouts and evaluating the effect of various design aspects.

## Method

Insight into the effects of different designs of foredune blowouts is gained through the use of a modeling study that is set up in AeoLiS, a supply-limited aeolian sediment transport model. Different combinations of width, orientation and number of foredune blowouts are simulated in a stretched profile of a section of the Dutch Coast, leading to thirty two simulations. Additionally three alternate methods of implementing foredune blowouts as well as a scenario without a foredune blowout are simulated.

## Results

Model results show a pattern of erosion in the intertidal range and deposition along the dunefoot with limited sediment traveling from the beach through the foredune blowout. There is a clear pattern of erosion and deposition along the erosional walls of the foredune blowout and a limited development of a depositional lobe behind the blowout. Simulation of a foredune blowout induced through the removal of top soil and vegetation exhibits similarities with observations in the field.

## Conclusion

Constructed foredune blowouts offer a method of creating areas of bare sand which can create space for ecological succession in the vicinity of the blowout. The sand that is removed may also be used to reinforce weaker areas of the dune row. They can offer a diverse looking landscape if that is desirable. However model results do not indicate that constructed foredune blowouts facilitate additional growth of the dunes. The changes in bed level in the model are primarily a redistribution of sediment already situated within the primary dune row.

# Contents

# Nomenclature

## Symbols

| Symbol | Definition | Unit |
|---|---|---|
| $c$ | sediment concentration | $[kg/m^2]$ |
| $c_{sat}$ | saturated sediment concentration | $[kg/m^2]$ |
| $C$ | grain size distribution parameter | $[-]$ |
| $d_n$ | nominal grain size | $[m]$ |
| $D$ | deposition | $[kg/m^2/s]$ |
| $D_n$ | reference grain size | $[m]$ |
| $E$ | erosion | $[kg/m^2/s]$ |
| $g$ | gravitational constant | $[m/s^2]$ |
| $h_{veg}$ | vegetation height | $[m]$ |
| $H_{veg}$ | maximum vegetation height | $[m]$ |
| $m_a$ | available sediment mass | $[kg/m^2]$ |
| $q$ | sediment transport rate | $[kg/m/s]$ |
| $q_{sat}$ | equilibrium sediment transport rate | $[kg/m/s]$ |
| $t$ | time | $[s]$ |
| $T$ | adaption time scale | $[s]$ |
| $u_{th}$ | threshold velocity | $[m/s]$ |
| $u_z$ | wind velocity at height $z$ | $[m/s]$ |
| $u_*$ | near bed shear velocity | $[m/s]$ |
| $V_{ver}$ | vertical growth rate of vegetation | $[m/yr]$ |
| $x$ | distance | $[m]$ |
| $z$ | height | $[m]$ |
| $z_0$ | roughness length | $[m]$ |
| $\alpha$ | conversion constant | $[-]$ |
| $\gamma$ | sediment burial constant | $[-]$ |
| $\Gamma$ | roughness factor for the shear stress reduction by vegetation | $[-]$ |
| $\delta_{zb\ opt}$ | optimal burial rate for vegetation | $[m/yr]$ |
| $\delta_{zb\ veg}$ | bed level change | $[m/yr]$ |
| $\Delta_{hveg}$ | vegetation growth | $[m/yr]$ |
| $\kappa$ | von Kármán constant | $[-]$ |
| $\rho_a$ | Density of air | $[kg/m^3]$ |
| $\rho_{veg}$ | vegetation cover | $[-]$ |

# 1
# Introduction

The Netherlands is a small coastal nation located along the North Sea with a coastline of approximately 350 kilometers long, 250 kilometers of which consist of dunes (van Heuvel & Hillen, 1995). The formation of the oldest dunes found in the Netherlands can be dated back to a period of rapid sea level rise some five thousand years ago. The development of the ”young dunes” starts during the middle-ages when old westward lying beach ridges begin to erode. The sand that was trapped in these beach ridges starts being transported towards the current coastline and forms smaller and steeper new dunes.

Larger scale human activity in the dunes has been present since at least the 17th century. During this period, the dunes were used for agricultural activities such as grazing of cattle and small scale logging for firewood which led to destabilization and drift sands. This eventually led to the planting of Marram grass and pine trees in an effort to stabilize the drifting dunes in the 19th century (duinbehoud stichting, n.d.; Kust, 1986).

Starting in 20th century there was a focus on foredune fixation as a means of maintaining the foredune as a natural sea dike. This reduced the amount of sand that could be transported from the beach to the inner dunes further increasing the stabilization of the inner dunes (duinbehoud stichting, n.d.).

A different approach to coastal safety was adopted in the late twentieth century which allowed for more variation in the dune landscape. The Dutch dunes to this day still play an important role in ensuring the water safety for millions of people, contain important nature areas and are a popular tourist destination.

## 1.1. (Constructed) Foredune Blowouts

Blowouts are gaps or indentations within the dunes from which bare sand can erode due to the wind. They are defined by Hesp among others as ”a saucer-, cup- or trough-shaped depression or hollow formed by wind erosion on a preexisting sand deposit. The adjoining accumulation of sand, the depositional lobe, derived from the depression, and possibly other sources, is normally considered part of the blowout” (Hesp, 2002). Blowouts come in varying shapes and sizes but can generally be classified as either trough- or saucer- shaped (Hesp, 2002).

Blowouts can generally be described as consisting of three areas, the depositional lobe where sediment is deposited, the erosional walls which are the walls of the blowout and the deflation basin which sits between those walls (Hesp, 2002). Figure 1.2 illustrates both the trough- and saucer- shaped blowouts as well as the depositional lobe, the deflation basin and the erosional walls.

Foredune blowouts are blowouts located in coastal dune systems that extend on their seaward side to the beach, thereby connecting the blowout to a potential additional source of sediment. Constructed foredune blowouts are then foredune blowouts that have been created by people and not by nature.

### Examples of Constructed Foredune Blowouts

Various different designs of foredune blowouts have been created over the years. The first pilot project from 1997 was located in Schoorl and consisted of a single foredune breach (Meerkerk et al., 2007), this can be seen in Figure 1.3.

**Figure 1.1:** Photo of "de kerf" in Schoorl, Photo taken by M. van Manen

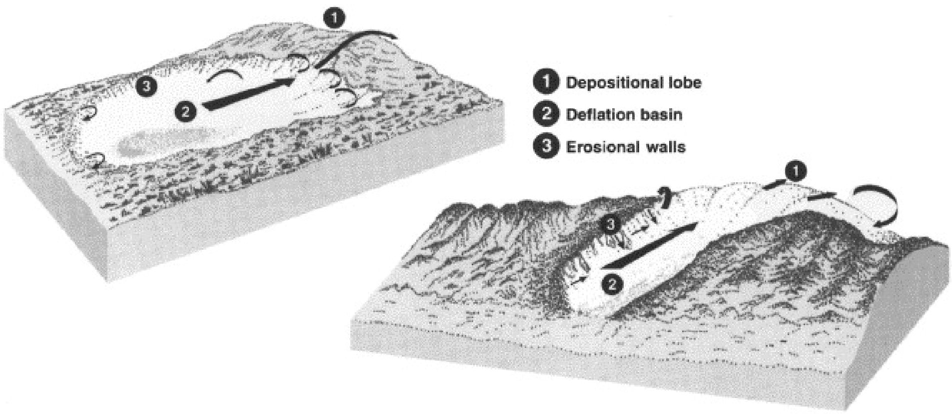



**Figure 1.2:** Schematic diagram of a saucer (left) and a trough (right) blowout with typical wind flow patterns indicated, source: (Hesp, 2002)

A project in Ameland created 8 foredune blowouts ranging from 20 to 90 meters in width, measured at the dune crest (Riksen et al., 2016). Two of these foredune blowouts can be seen in Figure 1.4. At the National Park Zuid-Kennemerland (NPZK), south of IJmuiden, 5 foredune blowouts ranging from 50 to 100 meters wide at the dune crest were created as part of the "Noordwest Natuurkern" project (Ruessink et al., 2018), as shown in Figure 1.5.

In Meijendel, 5 foredune blowouts were created by removing 1 to 2 meters of the topsoil (B. Arens, 2022), as illustrated in Figure 1.6. This method of construction differs from the previous examples where foredune blowouts are created through excavation of soil. Reason for the choice of this construction method was financial restraints.

The examples shown in Figures 1.3, 1.4, 1.5 and 1.6 highlight the lack of standardization in the designs of constructed foredune blowouts over the years. It is clear that the width, orientation, the number of blowouts and even the construction method can vary from project to project.

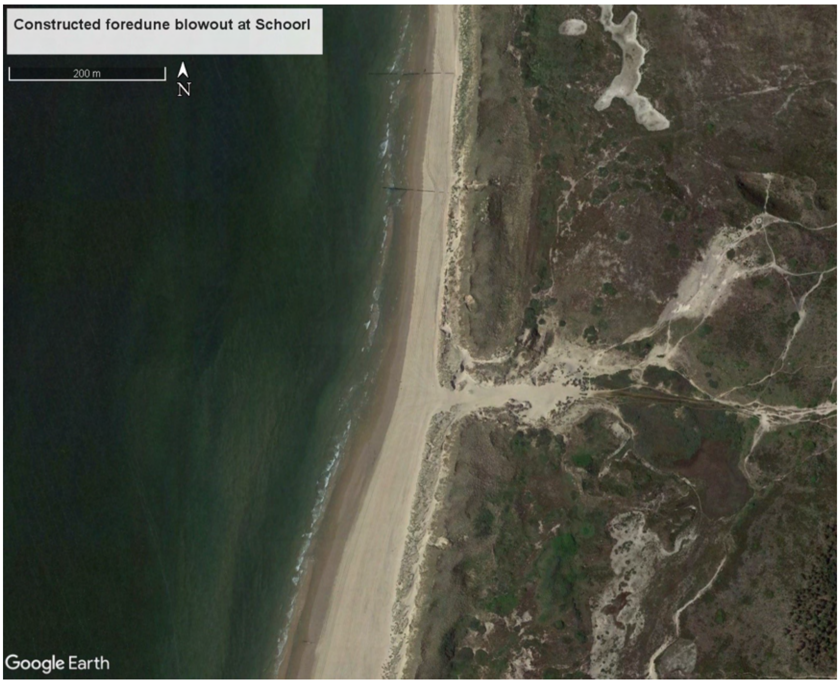



**Figure 1.3:** Image of the foredune blowout "de kerf" in Schoorl, constructed in 1997. Taken from Google Earth


**Figure 1.4:** Image of the foredune blowouts created on the eastern side of Ameland, constructed in 2011. Taken from Google Earth

Constructed foredune blowouts can be found in all coastal provinces, within the jurisdiction of 6 different water boards and in at least 10 of the 18 coastal dune Natura 2000 areas. Figure 1.7a illustrates Natura 2000 areas that contain a foredune blowout as well as some examples of locations where foredune blowouts have been constructed. This gives an indication of how widespread the creation of foredune blowouts has been over the years. According to B. Arens et al. (2023) there are 57 constructed foredune blowouts in the Netherlands as of 2023, superseding the number of autonomous foredune blowouts that can be found in the Netherlands. To understand the extensive construction of foredune blowouts in the past twenty-five years some context is needed.


**Figure 1.5:** Image of the foredune blowouts created near IJmuiden, constructed in 2012. Taken from Google Earth

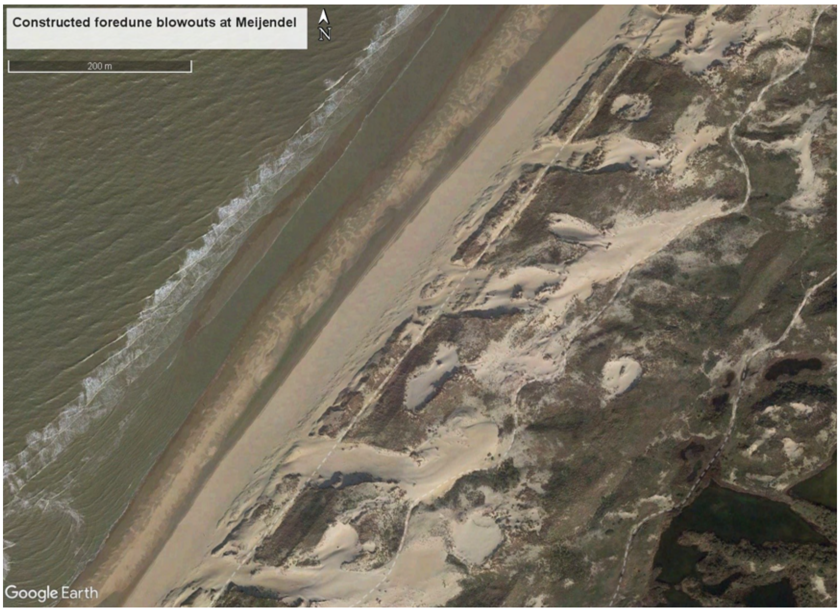
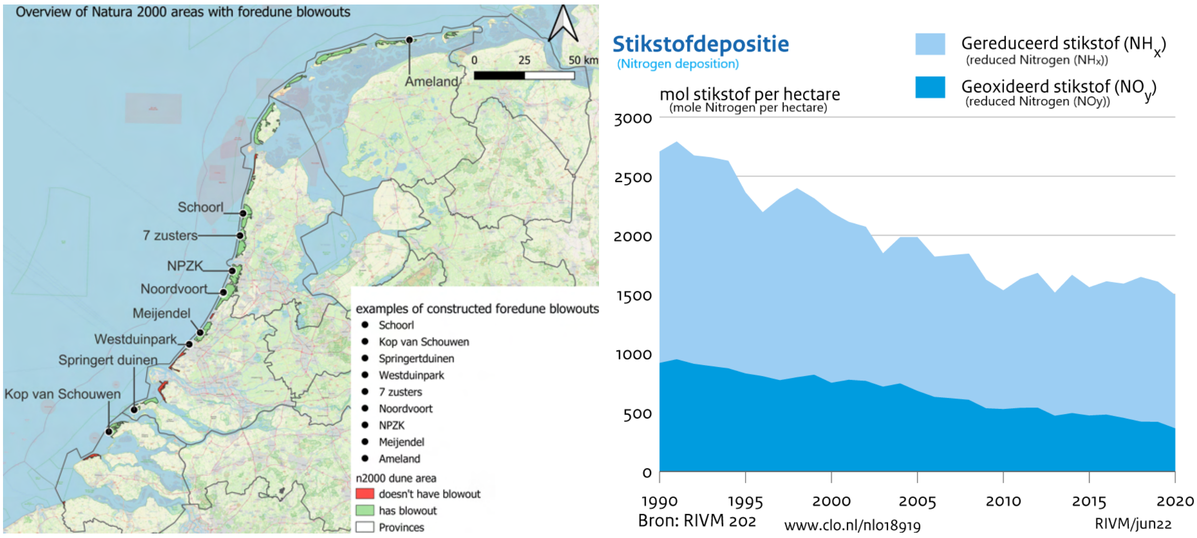



**Figure 1.6:** Image of the foredune blowouts created at Meijendel, constructed in 2014. Taken from Google Earth

## 1.2. Context & Rationale for the Creation of Foredune Blowouts

In the 1990s a new approach to coastal safety was adopted in the Netherlands, namely that of dynamic coastal management (Anonymus, 2000). This entails maintaining the coastal profile at the position it had in 1990, also known as the "basiskustlijn" ("base coastline"). This is done through the use of nourishments. Initially beach nourishments were used while nowadays shore face nourishments are more prevalent. Shore face nourishments are generally considered cheaper, less intrusive and more effectively imitate the naturally occurring grain size distribution.

This new approach also offered the possibility to develop and restore dynamic natural processes in the foredune as the foredune no longer needs to be maintained as stringently in its function as primary dike or embankment (VenW, 1996). This has to led multiple projects in which foredune blowouts were created such as at Schoorl and Meijendel.




**(a)** Natura 2000 areas characterized as dune landscapes within the Netherlands, the color indicates whether a foredune blowout has been constructed within each area

**(b)** Nitrogen deposition in the Netherlands since 1990. Source: (CBS et al., 2022)

**Figure 1.7:** Dune N2000 areas and examples of constructed foredune blowouts (a), and trend of the nitrogen deposition since 1990 (b)

## Natura 2000 & Nitrogen Emissions

Natura 2000 (also known as N2000) is a network of protected areas that was created by the European Union. It consists of areas protected by the Birds Directive of 1979 and the Habitat Directive of 1992. Its aim according the European Commission is "to ensure the long-term survival of Europe's most valuable and threatened species and habitats, listed under both the Birds Directive and the Habitats Directive" (Environment, 2008). There are three main obligations with regard to Natura 2000 areas that follow from the Habitat Directive (Remkes, 2022):

- Protected Habitats must sustainably and robustly be maintained in Natura 2000 areas, this is called a "favorable state of conservation". The requirements that must be achieved are specified within the conservation objectives of each area.
- Measures must be taken to prevent the loss of quality of protected nature within Natura 2000 areas.
- Plans and projects that might have an effect on protected nature may only gain a permit if it can be guaranteed there won't be any negative effects on the protected nature.

The Netherlands has 162 Natura 2000 areas, 18 of which are characterized as dune areas. As can be seen in Figure 1.7a these Natura 2000 areas overlap in large parts with the Dutch coast. These dune areas consist of various different habitat types, some of which are considered more or less important based on their relative abundance within the Netherlands compared to Europe or due to the unique species they support (LNV, 2006).

Habitat types that are of relatively large importance within the Dutch dune system are among others the grey dunes (H2130) and humid dune slacks (H2190). Additionally embryonic shifting dunes (H2110) and white dunes (H2120) are considered important as they play a role in the sustainable conservation of the grey dunes (LNV, 2006).

The dynamic nature of the dunes, caused by drifting sands and dune formations, has mostly been lost. The stabilization of the coast, the loss of historic use and an increase in nitrogen deposition are considered the chief causes of this loss (LNV, 2006).

Nitrogen emissions in the Netherlands have increased since the start of the 20th century in part due to the industrialization and modernization of agriculture and the advent of the car (Kooijman et al., 2012). This led to an estimated increase of emissions from 15 kg/ha/yr in 1950 to 40 kg/ha/yr in 1990. Nitrogen emissions have been decreasing since the 1990s though this reduction has stagnated since 2010 as can be seen in figure 1.7b.

Different plants and habitats that are protected under the Natura 2000 legislation are sensitive to excessive nitrogen emissions. For example both grey dunes and humid dune slacks are considered to be sensitive to nitrogen deposition (Bobbink et al., 2022). Nitrogen is an essential building block for both plants and animals, however different plants thrive under different concentrations of nitrogen. Grey dunes and humid dune slacks are habitat types in which plants grow under generally harsh environments. Additional nitrogen deposition in these environments leads to native species being out competed by vegetation more accustomed to these higher levels, leading to a decrease in biodiversity.

The fact that many Natura 2000 habitats in the Netherlands are sensitive to nitrogen deposition and that there is a legal obligation to only issue permits to projects that can be guaranteed not to have negative impacts, led to lawsuits by nature organizations (van Economische Zaken & en Milieu, 2017). This spurred the creation of the 'Programma Aanpak Stikstof' ("Integrated Approach to Nitrogen" or the PAS in Dutch).

The "Programma Aanpak Stikstof" is a legal framework with the goal to create a coherent approach that ensures that the conservation objectives of nitrogen sensitive habitats in the Natura 2000 areas can be realized while also offering insight into developments that might have an effect on these areas (Breedveld M.J., n.d.). This framework allowed permits to be issued for projects that emitted nitrogen by balancing the negative effects of said projects with protective and restoration measures in the area.

Within the PAS framework, various restorative and protective strategies have been described for all the different habitat types. Restoring the dynamic nature of the dunes is considered to be a proven restorative measure for grey dunes (Smits & Kooijman, 2012a, 2012b), white dunes (Smits et al., n.d.) and embryonic dunes (smits et al., 2012). The construction of foredune blowouts is seen as a method of restoring the dynamic nature of the dunes (S. Arens & Mulder, 2008; Ruessink et al., 2018). As such the creation of constructed foredune blowouts in the past decade can in part be attributed to the PAS program.

## 1.3. Goals of Constructed Foredune Blowouts & Stakeholders in the Dutch Dunes

Different goals have been cited for the creation of constructed foredune blowouts in the past. More recently a manual was created on the dynamization of the foredunes which cites 9 different goals for the construction of foredune blowouts (Bos-Staatsbosbeheer et al., 2022). These goals can generally be categorized as:

- Ecological goals
- Water safety / dune growing goals
- Aesthetic goals
- Other goals

### Ecological Goals

One reason for the creation of foredune blowouts in the past is that restoration of dynamic nature of the dunes was considered to be a proven restoration measure for white dunes (H2120) (Smits et al., n.d.), calcium rich grey dunes (H2130A) (Smits & Kooijman, 2012a) and calcium poor grey dunes (H2130B) (Smits & Kooijman, 2012b) within the PAS framework. The argument being that constructed foredune blowouts restore the dynamic nature of the dunes which then restores these habitat types.

Resetting the ecological succession and combating the effects of excess nitrogen deposition are also cited as goals for constructed foredune blowouts. Resetting the ecological succession can be done at different scales. Large scale transport can create swathes of bare sand either through erosion of soil or burial of vegetation. This bare sand offers space for the development of embryonic dunes which is a starting point of ecological succession within the dunes (Bos-Staatsbosbeheer et al., 2022). Small scale overpowdering can offer calcium rich sediment to the hinterdunes which would help reset the succession. The latter coincides with the goal to combat the effects of nitrogen deposition. The thought being that introduction of calcium rich sediment can aid in the binding of phosphate and counteract acidifcation (Bos-Staatsbosbeheer et al., 2022; Kooijman et al., 2012).

### Water Safety/Dune Growing Goals

Alternatively foredune blowouts have been created for water safety purposes. It is thought that foredune blowouts positively influence the rate at which sand can travel from the beach past the foredunes and into the hinterdunes, facilitating the growth of the dune massif in both width and height. This then would help counteract the effects of sea level rise and insure the water safety (S. Arens & Mulder, 2008; Delta, 2020). Additionally the soil that is removed for the construction of a foredune blowout could be used to reinforce the primary dune row at a different location.

### Aesthetic Goals

The aesthetical goals relate in part to the reintroduction of gradients, diversity and a more dynamic nature on different scales. This is often combined with ecological goals in that a dynamic and varied dune landscape would allow for more ecological variation and help combat the effects of excess nitrogen deposition and is seen as nicer to look at. These aesthetical goals aren't considered any further when looking at the effects of foredune blowouts as these are difficult to quantify and at times subjective.

### Other Goals

Other goals consist of increasing the volume of potable water within the dune massif, concentrating recreational areas to segregate vulnerable nature from human interaction, and to increase knowledge of the effects foredune blowouts. Just as the aesthetic goals these aren't taken further into account.

### Objectives of Constructed Foredune Blowouts

It should be clear that the objective of constructed foredune blowouts is to affect the transport of sand. Therefore understanding the erosion and sedimentation, essentially the change in sediment volume balance, that occurs in the dunes due to the introduction of constructed foredune blowouts, can aid in reaching the stated goals of constructed foredune blowouts.

### Stakeholders

A small overview of the different stakeholders that can be of importance when discussing the Dutch coast and dunes is given in Table 1.1 The fact that large parts of the Dutch coast are Natura 2000 areas complicates matters further. Natura 2000 areas are designated by the minister of Agriculture, Nature and Food Quality, after which a management plan is created in collaboration with the provincial government, the Ministry of Infrastructure and Water Management, Ministry of Defense and/or the Ministry of Agriculture, Nature and Food Quality (Rijksoverheid, n.d.).

**Table 1.1:** Overview of some of the different stakeholders for areas of the Dutch dunes

| Stakeholder(s) | Goal(s) |
|---|---|
| Rijkswaterstaat | Maintaining the "coastal foundation" |
| Water boards | Maintaining the level of water safety |
| Drinking water utility companies | Production of drinking water & management of nature areas [1] |
| Provincial government | Issuing of permits |
| Nature organizations | Protection of nature |
| Local municipality | Ensuring access to maintain economic activities |

### Evaluation

The evaluation process and criteria can vary from project to project, from organization to organization and even vary from person to person within organizations. This is in part due to the fact that in the past the goals for constructed foredune blowouts were often broadly defined (Nijenhuis, 2022). Funding for monitoring is often not readily available and has among other factors led to difficulties when comparing monitoring data between projects (Nijenhuis, 2022). This has led to a situation in which it is difficult to say with any certainty whether a constructed foredune blowout was a success and importantly which design aspects played a role in that success.

[1] Four Dutch drinking water utility companies use the dunes as a natural source and filter for water, as such they are mandated to protect and manage these areas under the Dutch 'drinkwaterwet' §2.

## 1.4. Research Aim

The goal of this research is to better understand the potential of constructed foredune blowouts, to gain insight into their role in ensuring water safety as well as their ability to safeguard natural values in the Netherlands and to answer the question:
How can constructed foredune blowouts affect the dutch dune system?

To answer this, the following sub questions have been formulated:

1. How do erosion and sedimentation patterns of constructed foredune blowouts impact dune transport rates?
2. How do different construction methods affect the sediment volume balance?
3. How can quantitative design aspects of constructed foredune blowouts be altered to better fulfill desired design goals?
4. To what extent can a program of requirements be established for the design of a constructed foredune blowout?

# 2

# Background & Case Studies

Some further background information on the PAS and previous (case) studies from the Netherlands is given here.

## 2.1. Further Developments of the PAS

In 2019 the Supreme Court of the Netherlands passed the judgment that the PAS wasn't allowed to be used to issue permits for projects where extra nitrogen is emitted, this led to the so called ”stikstof crisis” (nitrogen crisis). One of the arguments the court held, based on a ruling of the court of justice of the European union, is as quoted:

> The appropriate assessment of the implications of a plan or project for the sites concerned is not to take into account the future benefits of such ‘measures’ if those benefits are uncertain, inter alia because the procedures needed to accomplish them have not yet been carried out or because the level of scientific knowledge does not allow them to be identified or quantified with certainty. In the light of the foregoing, (...) the Habitats Directive must be interpreted as meaning that an ‘appropriate assessment’ within the meaning of that provision may not take into account the existence of ‘conservation measures’ within the meaning of paragraph 1 of that article, ‘preventive measures’ within the meaning of paragraph 2 of that article, measures specifically adopted for a program such as that at issue in the main proceedings or ‘autonomous’ measures, in so far as those measures are not part of that program, if the expected benefits of those measures are not certain at the time of that assessment (ECJ, 2018).

In other words, any preventive or restorative measure taken in or near Natura 2000 areas in relation to a project that might emit extra nitrogen can not be taken into account as part of the assessment of said project unless the benefits are certain at the time of the assessment.

### Nitrogen Deposition in the Dunes

Some controversy exists surrounding both the measured and modeled nitrogen deposition values found along the Dutch coast. The measured values have been consistently higher than predicted based on the AERIUS model created by the RIVM (Rijks Institute voor Volksgezondheid en Milieu or the National Institute for Public Health and the Environment). Initially this difference was corrected by adding an additional source to the model offshore, which was then aptly named ”stikstof uit zee” i.e. nitrogen from the sea. The reasoning in 2014 was that ammonium was entering the Dutch river system due to agricultural activities and flowing downstream towards the coast before evaporating near shore. The validity of this idea has come under scrutiny and as of 2021 the RIVM has announced that a new study is to be conducted regarding the discrepancy between the model and measurements. The results of this study have as of the time of writing not yet been published. (Kooijman et al., 2012; Noordijk et al., 2014; RIVM, 2021)

It should be noted that even if the actual nitrogen deposition values are lower than the measured values due to any type of error, the general consensus is still that the quality of the dunes is degrading

(E.E.A., n.d.). As there is still a legal obligation to protect the dunes, taking measures such as reducing emissions is still important.

## 2.2. Case Studies of Constructed Foredune Blowouts in the Netherlands

Some case studies of constructed foredune blowouts and the findings that have been reported on these case studies are briefly highlighted. Do note that some of the material referenced consists of grey literature.

### The Kop van Schouwen

An example of a project where constructed foredune blowouts were created is at the Kop van Schouwen. Here a pilot project called ”slim omgaan met zand” (smart approach to sand) was initiated under the PAS (Schouwen, 2019). The aim of the project is to create added value for tourism, nature and the local economy by better matching supply and demand of sediment and by approaching coastal nourishments differently.

The Kop van Schouwen is a Natura 2000 area which has negatively been impacted by excess nitrogen deposition. This has led to a decrease in biodiversity and a shift in its landscape. To combat this, a slew of different measures has been taken such as the removal of vegetation and nutrient-rich top soil as well as restoring the dynamic nature of dunes by stimulating sediment transport. This last measure is done by creating two foredune blowouts.

This has led to a large scale monitoring program at the Kop van Schouwen to maintain the legally mandated safety norms for flooding and potable water mining. As such there is a large amount of elevation data of the area containing the constructed foredune blowouts, both prior to construction and up to three years post implementation (Schouwen, 2019). Figure 2.1 shows the evolution of the landscape over a period of three years in which two foredune blowouts were created and top soil and vegetation were removed.

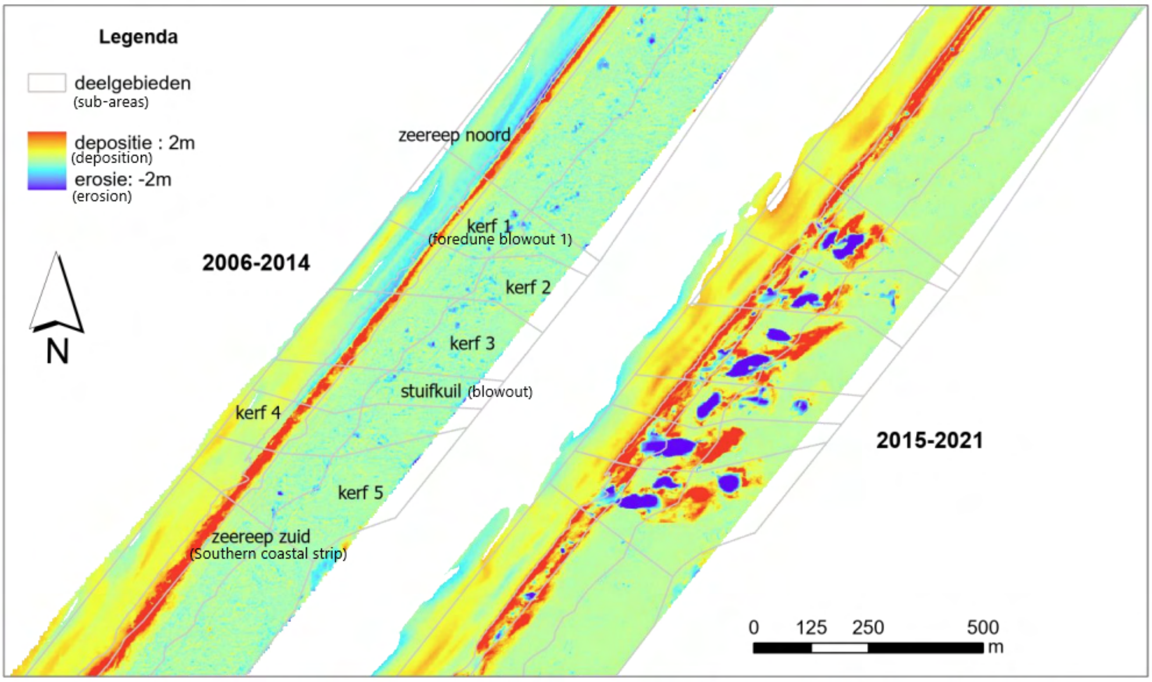

(a) (b)

**Figure 2.1:** Landscape of the Kop van Schouwen in 2015 (a) and 2018 (b), taken from Google Earth

### Meijendel

An example of a project is the development of foredune blowouts at Meijendel. The project was financed by the province of South Holland and executed within the PAS framework by the administrator Dunea with the goal of restoring and developing the grey dunes (B. Arens, 2022). While the goal of the project is restoring and developing the grey dunes, the evaluation of the project only considers the geomorphological developments (B. Arens, 2022).

The project consisted of the creation of blowout like features and the removal of vegetation. In total 5 foredune blowouts were created. This was done through the removal of 1 to 2 meters of topsoil due to financial restraints. Monitoring of the bed level changes was done through the use of laser altimetry and drone photography over a period of 6 years from 2015 to 2021. An example of a result from the monitoring campaign is shown in Figure 2.2.




*Figuur 3.2. Verschilkaarten strand/duin, 2006-2014 en 2015-2021 op basis van Jarkus-gegevens. Maxima 2006-2014: -4,67 en +5,90m, 2015-2021: -8,50 en 5,57m.*

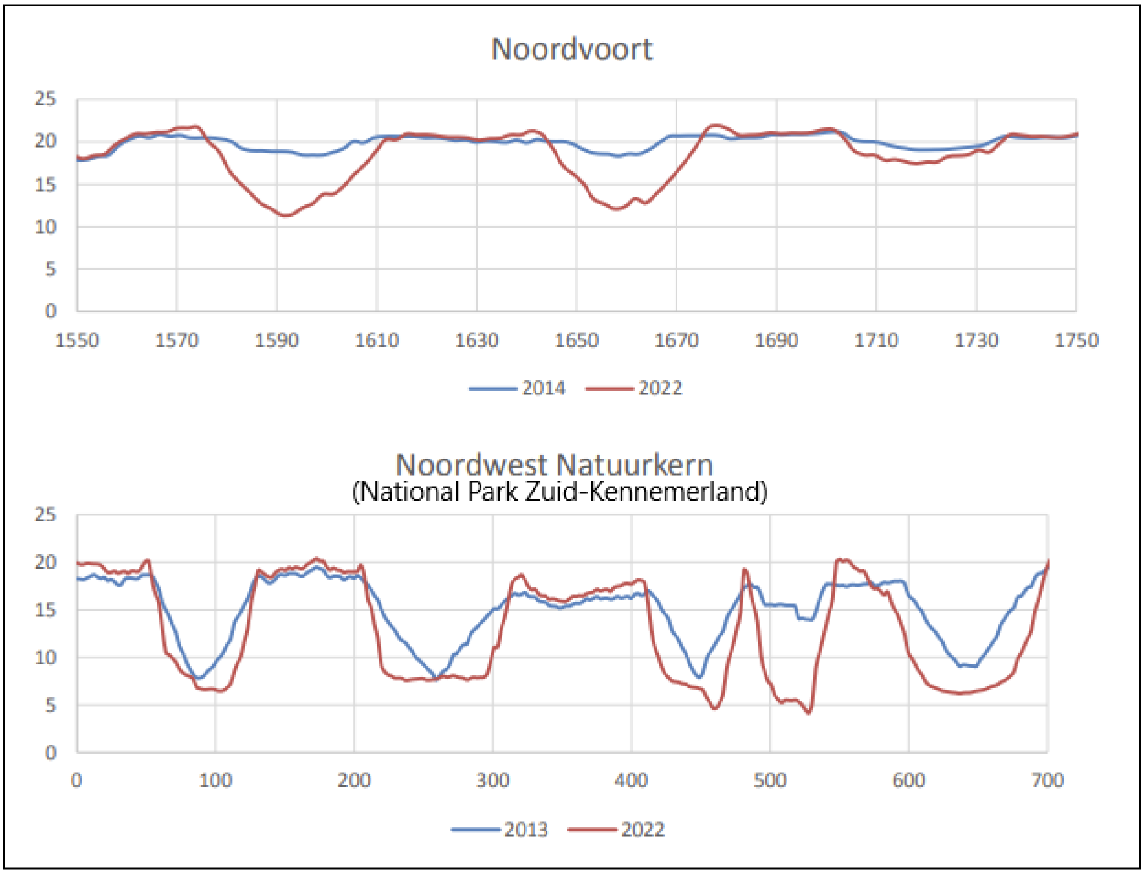
(Figure 3.2. Bedlevel difference map of the beach/dune, 2006-20014 and 2015-2021, based on JARKUS data. Maxima 2006-2014: -4,67 & 5,90m, 2015-2021: -8,50 & 5,57m)

**Figure 2.2:** Bed level changes that occrured in Meijendel prior to the introduction of foredune blowouts (2006-2014) and post construction of foredune blowouts (2015-2021). Source: (B. Arens, 2022) (internal report)

Based on the results of the monitoring campaign, volume balances for the period of 2006 to 2014 and for the period of 2015 to 2021 were created. According to B. Arens (2022) there was an increase in the net volume balance from $6.9\ [m^3/m.yr]$ over the period of 2006 to 2014 to $12.8\ [m^3/m.yr]$ over the period of 2015 to 2021. It should be noted that the bed level changes of the beach up to the dune foot were not taken into account for the creation of the volume balances (B. Arens, 2022).

## National Park Zuid-Kennemerland

Another project in which foredune blowouts was created is the 'Noordwest Natuurkern' project which took place within the National Park Zuid-Kennemerland just south of IJmuiden, shown in Figure 1.5. 5 foredune blowouts were created ranging from 50 to more than 100 meters wide as part of the Dutch Dune Revival project (PWN, n.d.). Figure 2.3 show the evolution of the cross sections of the foredune blowouts that were created at the National Park Zuid-Kennemerland as well as for a project in Noordvoort where foredune blowouts were created similarly to the project in Meijendel, through the removal of top soil (S. Arens, 2010).




*Figuur 49. Verschil in uitgraafdiepte bij Noordvoort en de Noordwest Natuurkern. 2013/2014 direct na de ingreep, 2022 huidige situatie. Y-as: hoogte in m NAP, X-as: afstand t.o.v. referentiepunt in m.*

(Difference in excavation depth at Noordvoort and the Noordwest Natuurkern. 2013/2014 directly after the operation, 2022 current situation. Y axis: height in m NAP, X axis: distance relative to reference point in m.)

**Figure 2.3:** Cross sections of existing foredune blowouts at the National Park Zuid-Kennemerland (Noordwest Natuurkern) and Noordvoort, created in different manners. Source: (Bos-Staatsbosbeheer et al., 2022)

# 3 Methodology

Aeolian modeling can be dated back to at least 1936 to the work of Ralph Bagnold, who did experiments in the Libyan desert. The Bagnold formula, named after its creator, relates the mass transport of sand, $q[kg/m/s]$, to the local wind speed, $u_z[m/s]$, see Equation 3.3.

This relation forms the basis of many other sediment transport formulas and is generally considered valid for desert conditions but overestimates transport rates for wet or supply-limited conditions making it sub-optimal for modeling coastal areas (De Vries et al., 2014). Supply-limited conditions refer to the case where the available amount of sediment of less than the calculated sediment transport.

AeoLiS is a process based aeolian sediment transport model developed for supply limited conditions making it a suitable model to simulate processes that occur along the Dutch coast. Strides have been made to simulate different typical dune forms such as barchans, parabolic dunes as well as foredune blowouts. It has been shown that foredune blowouts can be simulated reasonably well using AeoLiS (Meijer, 2020). Therefore to gain insight into how foredune blowouts can affect the Dutch dune system, a modeling study is set up in AeoLiS (using version 2.0.0.dev4).

## 3.1. Model Description of AeoLiS

The general model description is based on the work done by Hoonhout and de Vries (2019), Meijer (2020) and de Vries et al. (2023).

In AeoLiS, the sediment transport is discretized using a one dimensional advection scheme and is represented by:

$$\frac{\delta c}{\delta t} + u_z \frac{\delta c}{\delta x} = E - D \tag{3.1}$$

In which $c[kg/m^2]$ is the sediment concentration, $t[s]$ is the time, $x[m]$ the distance and $u_z[m/s]$ the speed with which the sediment concentration travels through the system. $E[kg/m^2/s]$ and $D[kg/m^2/s]$ represent the erosion and deposition of sediment.

The difference between the erosion and deposition, $E - D$, represents the sediment that is *'flowing'* also known as the net entrainment. This is determined by the amount of available sediment in the bed, $m_a[kg/m^2]$, the equilibrium concentration, $c_{sat}[kg/m^2]$, and the instantaneous concentration $c[kg/m^2]$.

$$E - D = min(\frac{\delta m_a}{\delta t}; \frac{c_{sat} - c}{T}) \tag{3.2}$$

$T[s]$ represents an adaption time scale that is assumed to be equal for both the erosion and deposition.

The saturated (equilibrium) sediment concentration, $c_{sat}$ is calculated using Bagnold's sediment transport relation:

$$q_{sat} = \alpha C \frac{\rho_a}{g} \sqrt{\frac{d_n}{D_n}} (u_z - u_{th})^3 \tag{3.3}$$

$q_{sat}[kg/m/s]$ is the equilibrium sediment transport rate, $u_z$ and $u_{th}$ are the wind velocity in $[m/s]$ at a height $z[m]$ and the threshold velocity respectively. $d_n[m]$ and $D_n[m]$ are the nominal grain size and reference grain size. $\rho_a[kg/m^3]$ is the density of air and $g[m/s^2]$ is the gravitational constant. $C[-]$ is a parameter related to the grain size distribution and $\alpha[-]$ is a constant related to the conversion of measured wind velocity to the near-bed shear velocity according to von Kármán's logarithmic law of the wall. von Kármán's logarithmic law of the wall relates the wind velocity $u_z[m/s]$ at any height $z[m]$ with the near bed shear velocity $u_*[m/s]$ as followed:

$$u_z = \frac{u_*}{\kappa} ln \frac{z}{z_0} \tag{3.4}$$

Where $\kappa[-] = 0.41$ is the von Kármán constant and $z_0[m]$ is the roughness length (Meijer, 2020).

The equilibrium concentration is calculated by dividing the transport rate $q$ with the wind velocity $u_z$.

$$c_{sat} = max(0; \alpha C \frac{\rho_a}{g} \sqrt{\frac{d_n}{D_n}} \frac{(u_z - u_{th})^3}{u_z}) \tag{3.5}$$

## Shear Velocity Threshold

The shear velocity threshold $u_{th}$ represents the effect of the bed on transport. Different processes can effect both the shear velocity as well as the shear velocity threshold locally such as the moisture level or roughness elements such as shells, vegetation, or fences and other types objects. In this study the effect of vegetation on the local shear velocity is taken into account however most other effects, such as armoring and soil moisture, have been neglected.

## Vegetation

Vegetation can be introduced to the model as a mask which can then vary both spatially and temporally and interacts with the bed shear velocity locally. Vegetation is implemented as a density (vegetation cover) $\rho_{veg}[-]$, which is defined as:

$$\rho_{veg} = (\frac{h_{veg}}{H_{veg}})^2 \tag{3.6}$$

$h_{veg}[m]$ represents the height of the vegetation locally at that time step and $H_{veg}[m]$ is the maximum height of the vegetation which is a constant that can be defined by the user and by default is equal to 1 meter.

## Vertical Growth

The vegetation growth in the vertical direction is determined by the following relation:

$$\Delta_{h\ veg} = V_{ver} * (1 - \frac{h_{veg}}{H_{veg}}) - ((|\delta_{zb\ veg} - \delta_{zb\ opt}|) * \gamma_{veg}) \tag{3.7}$$

$V_{ver}[m/yr]$ is the vertical growth rate as defined by the user in meters per year, $\delta_{zb\ veg}[m/yr]$ is the bed level change and $\delta_{zb\ opt}[m/yr]$ is the optimal burial rate in meters per year which can be defined by the user. $\gamma_{veg}[-]$ is a constant which determines the influence of sediment burial, by default this is equal to 1.

This relation states that the change in height of the vegetation, $\Delta_{h\ veg}$ is determined by its yearly growth rate times a factor that becomes smaller the closer the vegetation is to its maximum height and is reduced by any mismatch between the optimal burial rate and actual bed level change. The vegetation height is then updated accordingly:

$$h_{veg} = Max(Min((h_{veg} + \Delta_{h\ veg}), H_{veg}), 0) \tag{3.8}$$

## Horizontal Growth

Two different mechanisms exists through which vegetation is able to spread through the domain of the model, namely through lateral growth and germination. Germination in this case approximates the spreading of seeds over longer distances, which can naturally occur due to various different processes, with a given probability of germination per year and a Poisson distribution. Lateral growth is the process whereby vegetation is limited to spreading to neighboring cells in the four cardinal directions, with the odds of spreading determined once again with a user defined probability of spreading per year and a Poisson distribution.

Once a ”seedling” is established through lateral growth or germination, a positive value for the vertical growth, $\Delta_{hveg}$, is required or the ”seedling” is removed. This somewhat replicates the effect of the vegetation dying.

### Wind Shear Velocity Reduction

The effect the vegetation has on the local wind shear velocity in the model, is based on the work done by Raupach (Raupach et al., 1993). The local wind shear $u_*$ is reduced by a vegetation factor.

$$vegfac = \frac{1}{\sqrt{1 + \Gamma * \rho_{veg}}} \tag{3.9}$$

$\Gamma[-]$ is a roughness factor which by default is equal to 16 and $\rho_{veg}$ is the vegetation cover. A Gaussian distribution is applied as a filter to smoothen the difference in wind shear between cells to increase the stability of the simulation.

$u_*$ is then updated as followed: $u_* = u_* \times vegfac$.

## 3.2. Setup of the Modeling Study

In order to gain insight into the physical parameters of foredune blowouts which chiefly affect the location and amount of sediment flux, a modeling study is set up. First a base case is set up to calibrate the parameters for the sediment transport rate and vegetation growth rates and mechanics. A general overview of parameters and settings that are used in further simulations, based on findings from the base case, can be found in appendix A in Table A.1.

### Base Case

The base case consists of a JARKUS [1] profile from Noordwijk that is interpolated from a grid size of 5 meters to 1 meter. The profile is extended by 200 meter at the landward edge to distance the area of interest from the onshore boundary condition. This cross shore profile forms the basis of the elevation input and its length defines the size of the computational grid in cross shore direction. The two dimensional profile is stretched in the alongshore direction to create a three dimensional profile.

The length of the grid in alongshore direction is chosen to be dependent on the three design parameters of foredune blowouts that are varied in this study; the width, the orientation relative to the dune front and the number of foredune blowouts. This is done to limit the size of the computational grid and reduce simulation time.

A foredune blowout is introduced by locally replacing the elevation profile. A constant slope is introduced starting at the dune foot (+3m NAP[2]) and ending at the lee side of the primary dune row, as can been in Figure 3.1.

Vegetation is introduced into the model in a similar fashion. A vegetation cover, $\rho_{veg}[-]$, with a value equal to $0.30[-]$ is introduced everywhere from the dunefoot onwards in the landward direction except for where the foredune blowout is introduced.

Hourly wind data is taken from the IJmuiden KNMI (The Royal Netherlands Meteorological Institute) weather station for the period of 01/06/2021 to 01/06/2022. The Offshore wind velocities of the data set are reduced to zero to improve simulation time and prevent negative sediment concentrations at the boundary conditions. Both the original data set as well as the altered set that was used, can be seen in Figure 3.2.

### Roughness Parameter K

One of the more important variables is the bed roughness $k[m]$. Roughness affects how wel force is transmitted from the wind to the particles, lower values of $k$ mean that for an identical wind regime there is less transport. In this case a value of $k = 0.00001[m]$ or $k = 1e^{-5}[m]$ is chosen. This is based three factors:

1. The value used by Lisa Meijer for the Meijendel case study (Meijer, 2020);
2. The gross transport rate being between $10m^3$ and $40m^3$ per year for this value, considered as the typical range of transport rates along the Dutch coast (De Vries et al., 2012);

[1] JARKUS is a Dutch government program that measures the Dutch coast along certain profiles on a yearly basis.
[2] NAP is the Amsterdam Ordnance Datum.

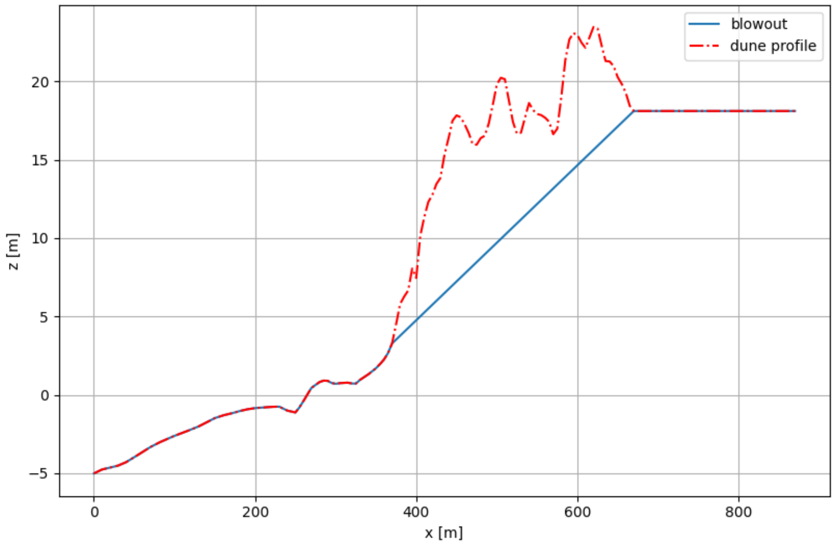
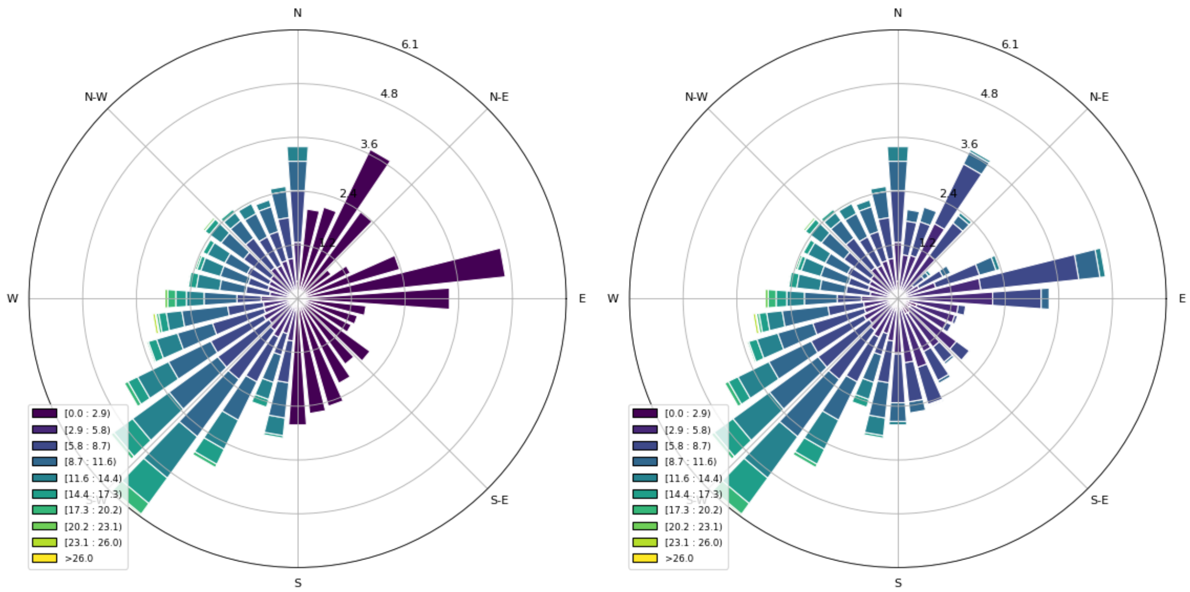



**Figure 3.1:** Illustration of the interpolated JARKUS profile as the dashed line, which runs from $x = 0[m]$ to $x = 671[m]$. The imposed foredune blowout is shown as the solid line from $x = 371[m]$ to $x = 671[m]$. The Landward extension is the horizontal plateau which can be seen from $x = 671[m]$ onwards.




**(a)** **(b)**

**Figure 3.2:** (a) is the windrose of the used data set in which the offshore wind speeds are reduced to zero, (b) is the windrose of the original data set. Both illustrate the wind speed in [m/s]

3. The definition of Nikuradse which states that $k = D_s/30$, given a grain size of $D_s = 300\mu m$ or $D_s = 0.3mm$ this also gives $k = 1e^{-5}[m]$.

## Chosen Vegetation Parameters

AeoLiS offers two different methods through which vegetation can spread, either through germination, a process by which vegetation can emerge randomly in any cell based on a probability that is given per year, or through lateral growth. Lateral growth limits growth to proximity with existing vegetation. Through an iterative process the design choice fell upon lateral growth with a probability of growth per year equal to 0.99.

The maximum vegetation height, $H_{veg}$, is chosen to be equal to 1.2 meters. This is based on general descriptions of Marram grass as well as a report from the state of California (Apteker, 2008).

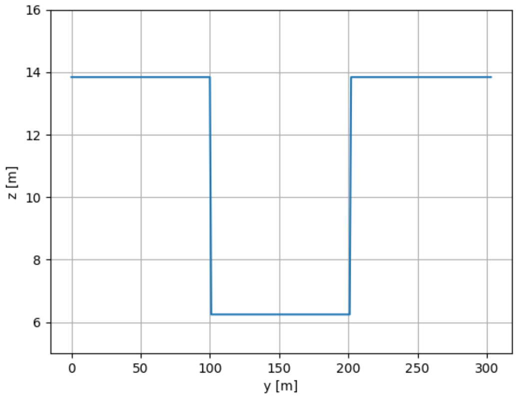
The value for the optimal burial rate, $\delta_{zb\ opt}$, is based on a study of Marram grass at the sand engine (Nolet et al., 2018) . This found an optimal sand burial rate for Marram grass is 0.30 meters per growing season with maxima measured up to 0.70 meters per year. A value of 0.30 meters per year is therefore chosen.

## 3.3. Variation of Different Design Aspects

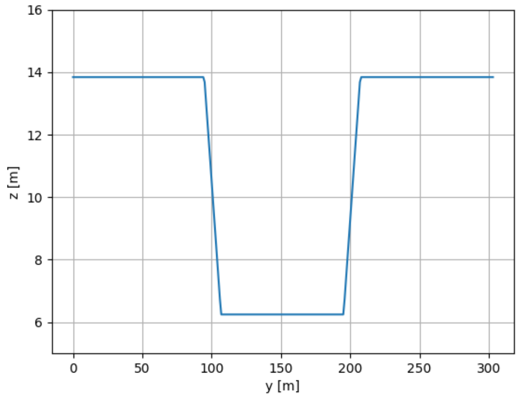
As mentioned in Bos-Staatsbosbeheer et al. (2022) much is still uncertain with regards to the optimal form of (constructed) foredune blowouts. Generally the orientation in relation to the prevalent wind direction, topside shape, width and internal wall angle are considered some of the important physical design parameters.

Foredune blowouts are often created in clusters within a limited project area. This limits the amount of space available, making the combination of width, number and spacing between foredune blowouts an active design choice. Additionally the effect of foredune blowouts have on each other is poorly understood.

As such different configurations are set up based on the width, orientation and the number of constructed foredune blowouts. For ease of implementation the imposed foredune blowout consists of a rectangle rather than a trapezoid. The internal wall angle is set to 90°, which while not representative of reality does not cause issues as the AeoLiS model can impose an internal angle of 33°, as is illustrated in Figure 3.3. This process is known as avalanching within the model.




(a)




(b)

**Figure 3.3:** Avalanching effect on the internal wall angle, (a) is an example of a longshore profile pre avalanching process, (b) is post avalanching

The width is chosen to be varied from 20 meters to 200 meters. This is based in part on existing constructed foredune blowouts that can be found in the Netherlands. As mentioned previously a project on Ameland consisted in part of constructed foredune blowouts with widths of approximately 20 meters (Riksen et al., 2016). Additionally multiple projects have had foredune blowouts in the range of 100 meters (Ruessink et al., 2018).

The orientation of the foredune blowout relative to the primary dune row is varied from 0°(shore-normal or westward facing) to 45°(facing South-West). The latter approximately aligns with the prevailing wind direction found in the Netherlands, this can also be noted in Figure 3.2.

The number of foredune blowouts within the area of interest is varied from a single foredune blowout, reminiscent of the first pilot in Schoorl, to two blowouts parallel to each other, similar to more recent projects such as at Meijendel. The spacing between two foredune blowouts, the distance between them, is kept equal to the width of the foredune blowout.

Table 3.1 shows the 32 different combinations that follow from the variations in the 3 design parameters as well as a short ID based on the specific parameters used. Two examples of the initial bed levels of two different simulations are shown in Figure 3.4.

**Table 3.1:** The different combinations of the variables leading to 32 different simulations, an ID based on the used width (W), orientation(O) and number of blowouts (N) is given as well

| Run | Width [m] | Orientation [°] | Number [-] | ID |
|---|---|---|---|---|
| Run 1 | 20 | 0 | 1 | W02O00N1 |
| Run 2 | 50 | 0 | 1 | W05O00N1 |
| Run 3 | 100 | 0 | 1 | W10O00N1 |
| Run 4 | 200 | 0 | 1 | W20O00N1 |
| Run 5 | 20 | 15 | 1 | W02O15N1 |
| Run 6 | 50 | 15 | 1 | W05O15N1 |
| Run 7 | 100 | 15 | 1 | W10O15N1 |
| Run 8 | 200 | 15 | 1 | W20O15N1 |
| Run 9 | 20 | 30 | 1 | W02O30N1 |
| Run 10 | 50 | 30 | 1 | W05O30N1 |
| Run 11 | 100 | 30 | 1 | W10O30N1 |
| Run 12 | 200 | 30 | 1 | W20O30N1 |
| Run 13 | 20 | 45 | 1 | W02O45N1 |
| Run 14 | 50 | 45 | 1 | W05O45N1 |
| Run 15 | 100 | 45 | 1 | W10O45N1 |
| Run 16 | 200 | 45 | 1 | W20O45N1 |
| Run 17 | 20 | 0 | 2 | W02O00N2 |
| Run 18 | 50 | 0 | 2 | W05O00N2 |
| Run 19 | 100 | 0 | 2 | W10O00N2 |
| Run 20 | 200 | 0 | 2 | W20O00N2 |
| Run 21 | 20 | 15 | 2 | W02O15N2 |
| Run 22 | 50 | 15 | 2 | W05O15N2 |
| Run 23 | 100 | 15 | 2 | W10O15N2 |
| Run 24 | 200 | 15 | 2 | W20O15N2 |
| Run 25 | 20 | 30 | 2 | W02O30N2 |
| Run 26 | 50 | 30 | 2 | W05O30N2 |
| Run 27 | 100 | 30 | 2 | W10O30N2 |
| Run 28 | 200 | 30 | 2 | W20O30N2 |
| Run 29 | 20 | 45 | 2 | W02O45N2 |
| Run 30 | 50 | 45 | 2 | W05O45N2 |
| Run 31 | 100 | 45 | 2 | W10O45N2 |
| Run 32 | 200 | 45 | 2 | W20O45N2 |

### Model Duration and Output Times

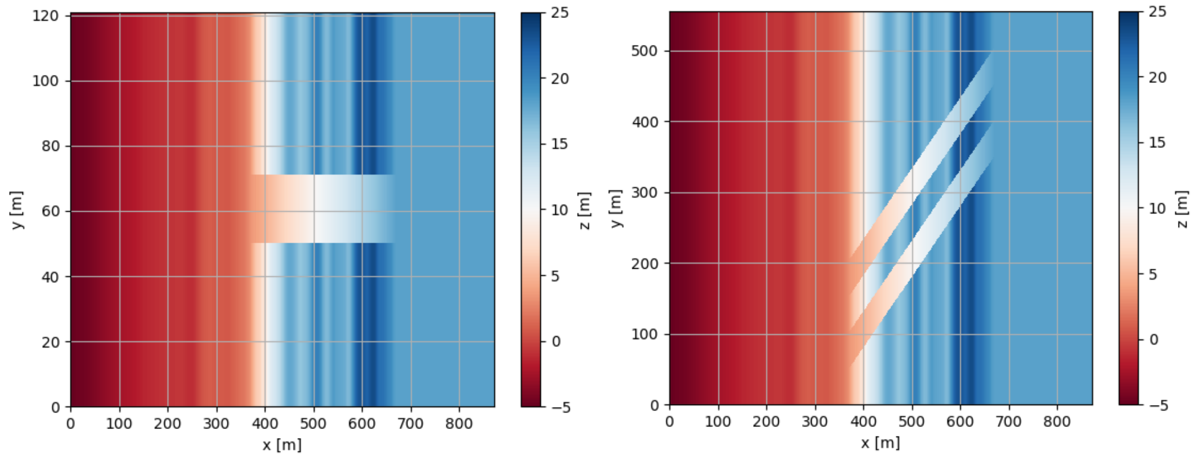
The model simulates aeolian transport for a period of three years. The model updates in time steps of 3600 seconds or hourly and outputs every 86400 seconds or daily. As the input wind data is shorter than the simulation period, the model automatically loops the wind input.

## 3.4. Simulated Construction Methods

In addition to the 32 simulations in which a foredune blowout is introduced through the removal of a section of the dune profile, four extra simulations have been run. Three of these simulations more closely resemble current construction methods:

1. Simulation with a trough shaped foredune blowout;
2. Simulation where the sediment that is removed is placed behind the foredune blowout as a mound of loose soil;
3. Simulation where a blowout is introduced through the consistent removal of vegetation;
4. Simulation of the dune profile without a constructed foredune blowout.

Figures A.2 and A.3 in the appendix show an impression of these methods.




**(a)** Run 1: Width = 20 m, Orientation = 0°, Number = 1[-]

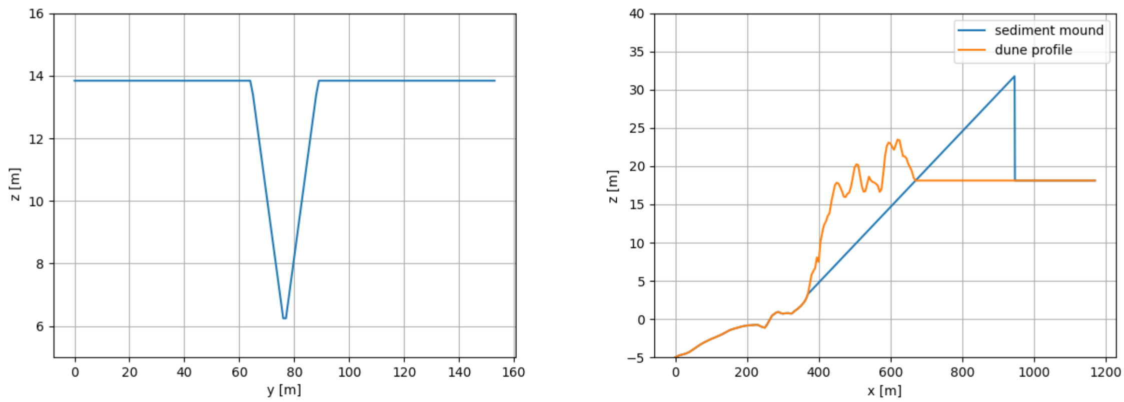
**(b)** Run 30: Width = 50 m, Orientation = 45°, Number = 2[-]

**Figure 3.4:** Two examples of different runs, the color map profile is given in meters

The trough shaped foredune blowout is created in a similar fashion to the rectangular blowouts. However, in this case, rather than creating vertical walls that run down to a constant slope of a certain width, a constant angle of 33 °is imposed from the central slope outwards back to the original profile in the longshore direction, as shown in Figure 3.5a.

The mound behind the foredune blowout is created by calculating the removed sediment mass and adding a wedge along the same slope with an equal volume. This can be seen in Figure 3.5b. As the wedge extends towards the landward boundary, the domain in the cross shore direction is extended as well.

The vegetation limited blowout is created by removing the ability of the vegetation mask to spread, by changing the probability of lateral growth to $0[-]$, and by removing a strip of vegetation across the dune profile. The fourth simulation consists solely of the interpolated profile and vegetation, without a foredune blowout or further restrictions on vegetation growth. Essentially this represents the undisturbed system.




**(a)**

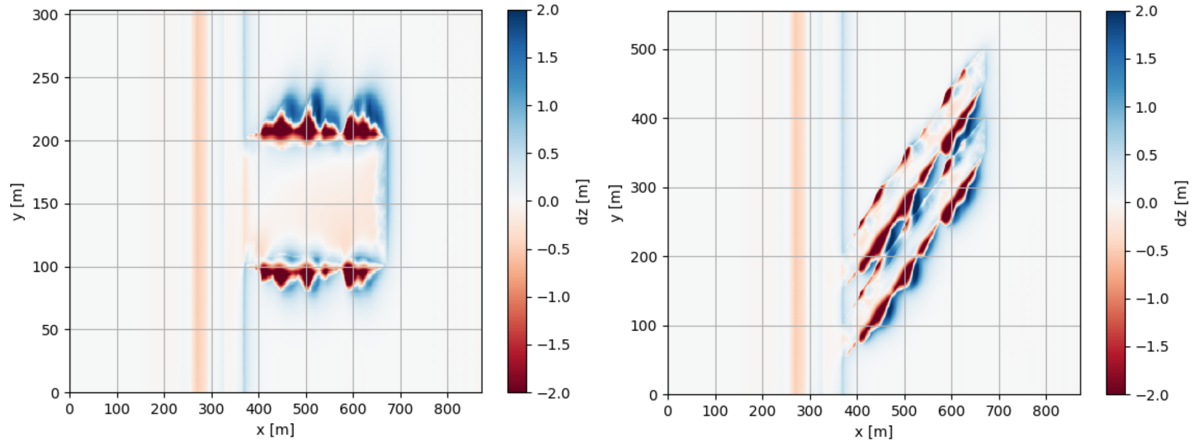
**(b)**

**Figure 3.5:** Cross section of the trough shaped blowout (a) and profile of the mass conservative blowout (b)

## 3.5. Normalization of the Simulation Data

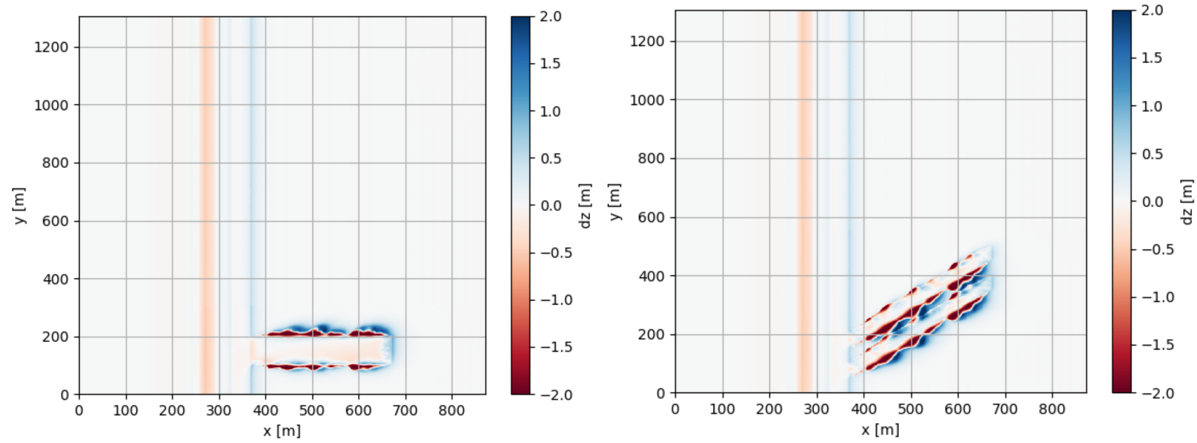
Figure 3.4 shows two examples of the simulations that were run. The length of the $y$ axis differs between these two simulations. This is because the size of the domain of the simulation is dependent on the variables as a way of limiting simulation time. The difference in size between the various simulations does make comparisons between them more difficult.

Figure 3.6 shows the bed level difference of the same two example simulations and it becomes clear that if one were to compare the erosion that takes place that the difference in width would skew the results. To counter this the data is normalized after the fact. This is done by adding sections of the simulation without a foredune blowout to the different simulations such that every single simulation is of equal width. Figure 3.7 shows the same simulations post normalization with equal width.




(a) (b)

**Figure 3.6:** Bed level difference of run 3 (W10O00N1) (a) and run 30 (W05O45N2) (b) with different domain widths




(a) (b)

**Figure 3.7:** Bed level difference of run 3 (W10O00N1) (a) and run 30 (W05O45N2) (b) post normalization with equal domain widths

## Characteristic Bed Level Change

The model outputs a bed level for every grid cell for the duration of the simulation, based on the specified output time. This makes it possible to calculate the difference in bed levels between any output time step. When talking about bed level changes generally the bed levels of the first and last time step are considered, as these highlight the long-term transport.

To gauge the bed level changes that occur and to make comparisons between different setups easier, a characteristic value can be expressed with the summation shown below. This sums the absolute value of the bed level difference, $|\delta Z|[m]$, over the domain of the simulation, with $x[m]$ and $y[m]$ being the length and width of the model domain, and divides this value by the width.

If the model is mass conservative, IE the modeled erosion and deposition are equal in size meaning no sediment is being created or is leaving the model at the landward boundary condition, then the sum of the absolute value of the bed level difference is further divided in half. This leads to the following equation:

$$\Delta Z = \frac{\sum_{x=0}^{x=x} \sum_{y=0}^{y=y} |\delta Z| dydx}{y} * \frac{1}{2} \tag{3.10}$$

## Comparison Between One and Two Foredune Blowouts

As the number of foredune blowouts is considered as one of the design parameters, a method of making comparisons between a single foredune blowout and two foredune blowouts is needed. This can be done by making a comparison between the erosion,$\delta Z_{neg}$, that takes place for two blowouts and the erosion that occurs for a single blowout and expressing this as a ratio.

$$ratio = \frac{\sum_{x=300}^{x=800} \sum_{y=0}^{y=y} \delta Z_{neg_2} dydx}{\sum_{x=300}^{x=800} \sum_{y=0}^{y=y} \delta Z_{neg_1} dydx} \tag{3.11}$$

# 4
# Results

The model results of the simulations based on the set up described in the previous chapter are shown in this chapter with the important details of the results highlighted.

## 4.1. Systematic Simulations

Table 3.1 illustrates the different runs with their exact dimensions. Figure 4.1 illustrates an example of the final bed levels and vegetation cover that the model outputs. In Figure 3.4a the imposed rectangular shape is clearly visible while in Figure 4.1a a more funnel like shape can be seen with the entrance of the constructed foredune blowout becoming wider. A wave like pattern is also visible along the edge of the foredune blowout. The entrance of the foredune blowout is starting to be closed off by vegetation in Figure 4.1b and there is a clear outline of where vegetation has died off and where it has survived.

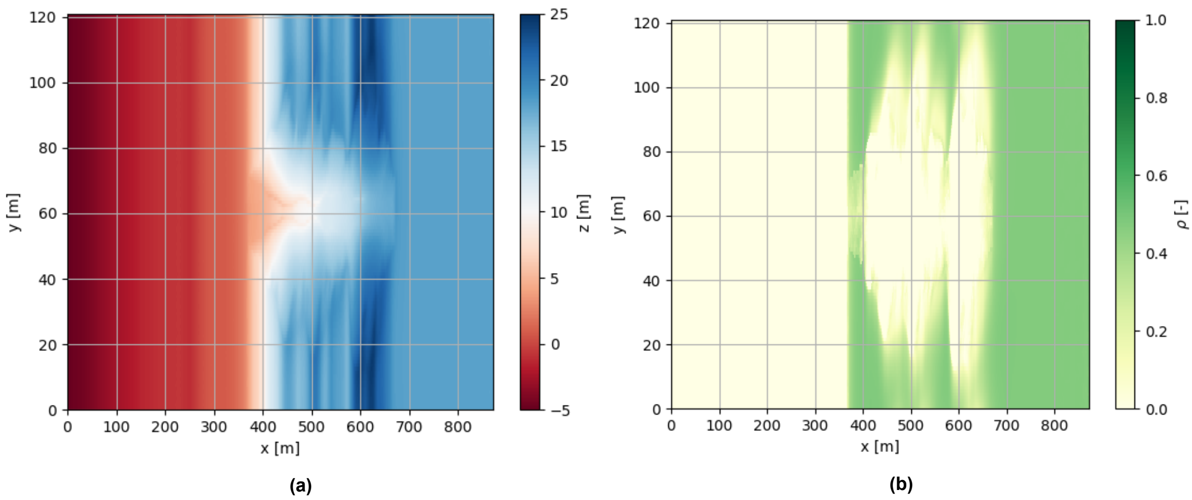
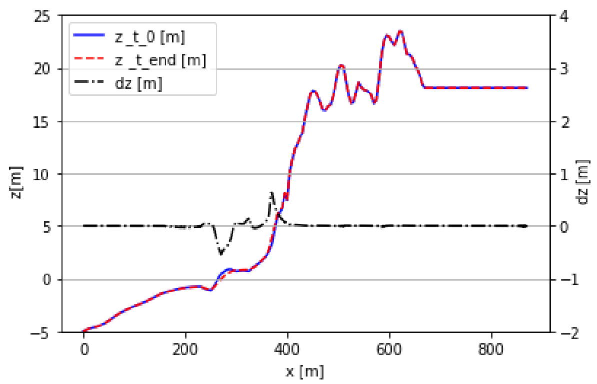



**Figure 4.1:** The final bed levels (a) and final vegetation cover (b) of a single foredune blowout with a width of 20m and an orientation of 0 °(W02O00N1)

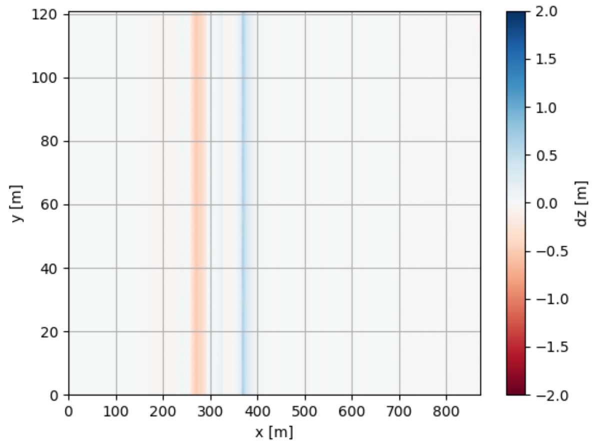
### Simulation without a Foredune Blowout

To compare the volume changes between different configurations of foredune blowouts as well as to better illustrate the "background" fluxes, a simulation without a foredune blowout is run. Figure 4.2a shows the initial and final bed level along a single transect as well as the bed level changes in relation to the profile. Figure 4.2b shows the bed level changes plotted as a color map over the entire domain.

Figure 4.2a highlights that there is an area of erosion from $x = 200[m]$ to $x = 300[m]$ where the bed level varies in the range of -1 to +1 meter and an area of deposition from $x = 350[m]$ to $x = 400[m]$ along the dune foot, where the bed level is around +3 meters. Beyond the range of $x = 400[m]$ hardly any changes in the bed level are seen. Figure 4.2b shows that this pattern of erosion and deposition is uniform in the along shore direction. This pattern of erosion and deposition up to the dune foot is also visible in all other simulations as will be shown later.




**(a)** The initial (blue) and final (dashed red) bed levels and the bed level difference (dash dot in black)




**(b)** Bed level change over the entire domain

**Figure 4.2:** Bed levels and bed level difference along a transect (a) and bed level changes over the entire domain (b)

## 4.2. Volume Balance & Characteristic Bed Level Changes

To better understand what effects constructed foredune blowouts have on the adjacent dunes, a closer inspection of the volume balances within the system is carried out.

An initial check to verify that the simulations are mass conservative, i.e. the erosion and sedimentation are equal to each other, is performed. Figure 4.3a shows the sum of the erosion and deposition of run 2 (W05O00N1) along the $x[m]$ axis on both a linear scale and a logarithmic scale. The Figure shows that the volume balance does not return to zero and even decreases from $x = 800[m]$ onwards. This latter phenomenon coincides with wiggles that develop in the bed level. Figure 4.3b plots the bed level changes of run 2 along the central transect on a logarithmic scale and illustrates the development of said wiggles from $x = 800[m]$ to the landward boundary.

When considering the the volume balances and changes of the various simulations the domain from $x = 800[m]$ onward is disregarded. While the volume balance up to $x = 800[m]$ is also not equal to zero, it is assumed that this discrepancy is due to rounding errors. For example, the volume balance of run 2 up to $x = 800[m]$ is equal to:

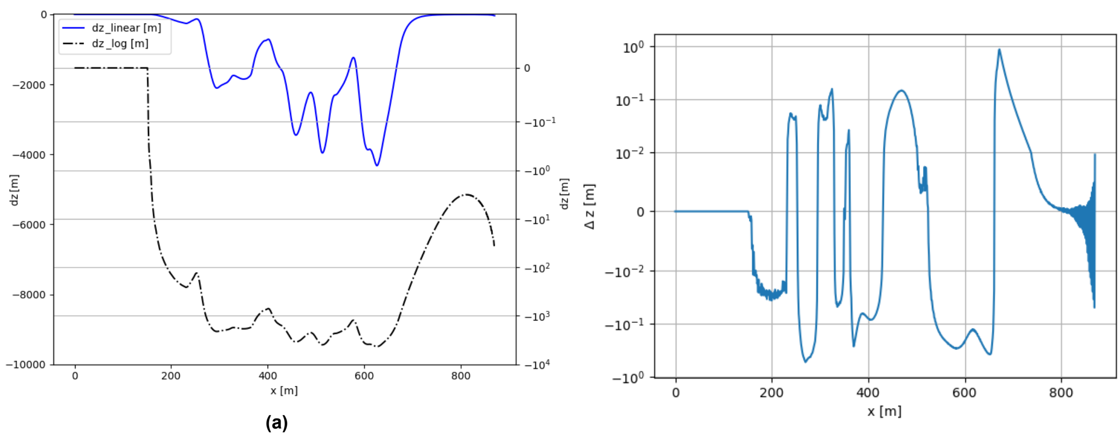
$$\sum_{x=0}^{x=800} \sum_{y=0}^{y=y} \delta Z dydx = -3.41[m^3] \tag{4.1}$$

Dividing this value over the size of the domain of the simulation prior to the normalization of the data, in this case that is $154[m]*800[m] = 123,200[m^2]$, gives $\frac{-3.41[m^3]}{123,200[m^2]} = -2.77E{-}5[m^3/m^2], or \frac{31}{1120000}[m^3/m^2]$. This holds true for all 32 runs as shown in Table A.3 in the appendix.

Using the summation method described in Equation 3.10, a characteristic value for the bed level changes for the 32 different simulations is created. This is done post normalization and up to $x = 800[m]$ so as to be considered mass conservative. The results are plotted in a bar chart shown in Figure 4.4. The values are grouped by orientation and color-coded by width.

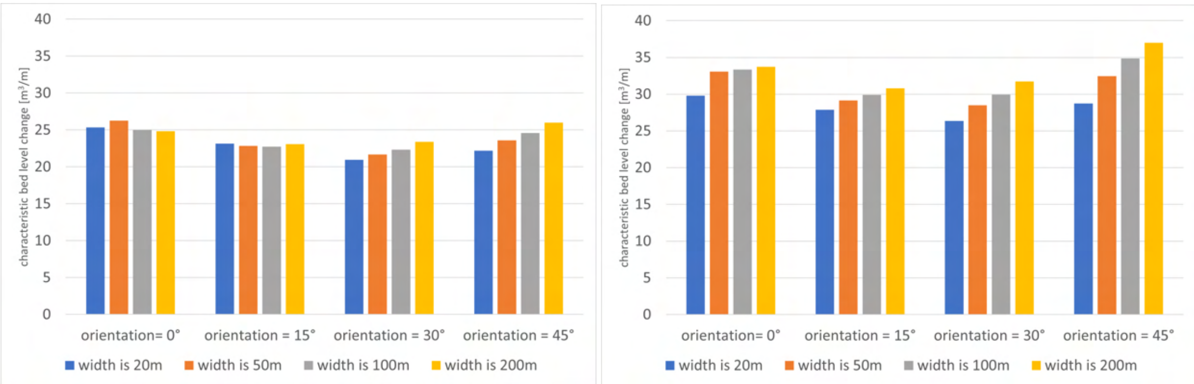
There is a pattern of decrease and then increase in the characteristic bed level change when comparing constructed foredune blowouts of equal width at different orientations. For example, the characteristic bed level change for a constructed foredune blowout with a width of 100 meters is equal to $25[m^3/m]$ for an orientation of 0°, this decreases to $22.5[m^3/m]$ for an orientation of 15°and $22[m^3/m]$ for on orientation of 30°, before increasing to a value of $24.5[m^3/m]$ for an orientation of 45°.

When comparing foredune blowouts of different widths at the same orientation, there is a clear trend in the increase of the characteristic bed level change for a larger width for orientations of 30°and 45°while this is less true for orientations of 0°and 15°.




(a) (b)

**Figure 4.3:** Volume balance of run 2 (W05O00N1) as a running sum on a linear scale (blue solid line) and on a logarithmic scale (black dash dot line) (a) and the bed level changes along the center of the y axis of run 2 (W05O00N1) on a logarithmic scale (b), note the wiggles from $x = 800[m]$ onward.




(a) (b)

**Figure 4.4:** Characteristic bed level change for single foredune blowout (a) and two foredune blowouts (b), grouped by orientation and color-coded by width

## 4.3. Wind Fields

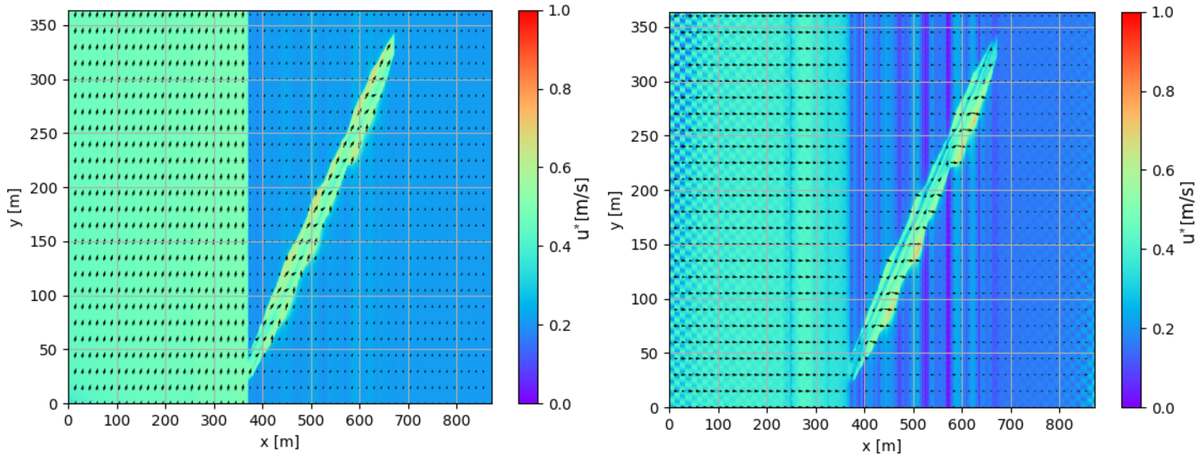
The driving force behind the sediment transport is the local wind shear as shown in Bagnold's transport relation (Equation 3.3). Two examples of what the model calculates are shown in Figure 4.5. Both the color bar and quiver represent the shear velocity $u_*[m/s]$, with the quiver also denoting the direction of the local wind shear.

There is a clear difference in the calculated wind shear velocities based on location. There is a rather uniform wind field on the beach from $x = 0[m]$ to $x = 370[m]$ and behind the dune row from $x = 670[m]$ to $x = 870[m]$. From $x = 370[m]$ to $x = 670[m]$ more variation in calculated wind shear is visible.

## 4.4. Erosion & Sedimentation Patterns

To understand how erosion and sedimentation caused by foredune blowouts affect the dune system, initial and final bed levels are considered as well as the difference between them. To illustrate, the model results of a single simulation are highlighted. An oversight of the different simulations can be found in Table 3.1.

In Figures 3.4a and 4.1a the initial and final state of the bed level can be seen while Figure 4.6a shows the difference between the initial and final bed levels for the domain. There is erosion visible along the walls of the foredune blowout and deposition in the basin and outside the constructed foredune blowout. The aforementioned erosion in the intertidal range, from $x = 200[m]$ to $x = 300[m]$, is also




**(a)** Southern wind of 16 m/s

**(b)** Westerly wind of 13 m/s

**Figure 4.5:** Example of calculated wind shear for two different wind velocities and directions

clearly visible.

The erosion and sedimentation patterns are examined over shorter time periods in addition to the initial and final state of the system. Figures 4.6b, 4.6c & 4.6d shows the calculated bed level changes on an annual basis. It illustrates that the erosion and sedimentation shift in space and reduce in scope over time.

## 4.5. Simulated Construction Methods

In addition to the 32 simulations run in which a foredune blowout is introduced through the removal of a section of the dune profile, three simulations have been run that more closely resemble current construction methods:

1. A simulation with a trough shaped foredune blowout;
2. A simulation where the mass of the foredune blowout is deposited behind it;
3. A simulation where a blowout is introduced through the consistent removal of vegetation.

To gauge the effect of these construction methods have on sediment transport, the same summation to create a characteristic transport value is applied for the three different construction methods and the situation without a foredune blowout, resulting in Figure 4.7. The calculated values for the trough shaped foredune blowout and the vegetation limited blowout are lower than the values found for the singular rectangular foredune blowouts, see Figure 4.4a, while the value for the mass maintained blowout higher. The value for the simulation without a foredune blowout is the lowest.

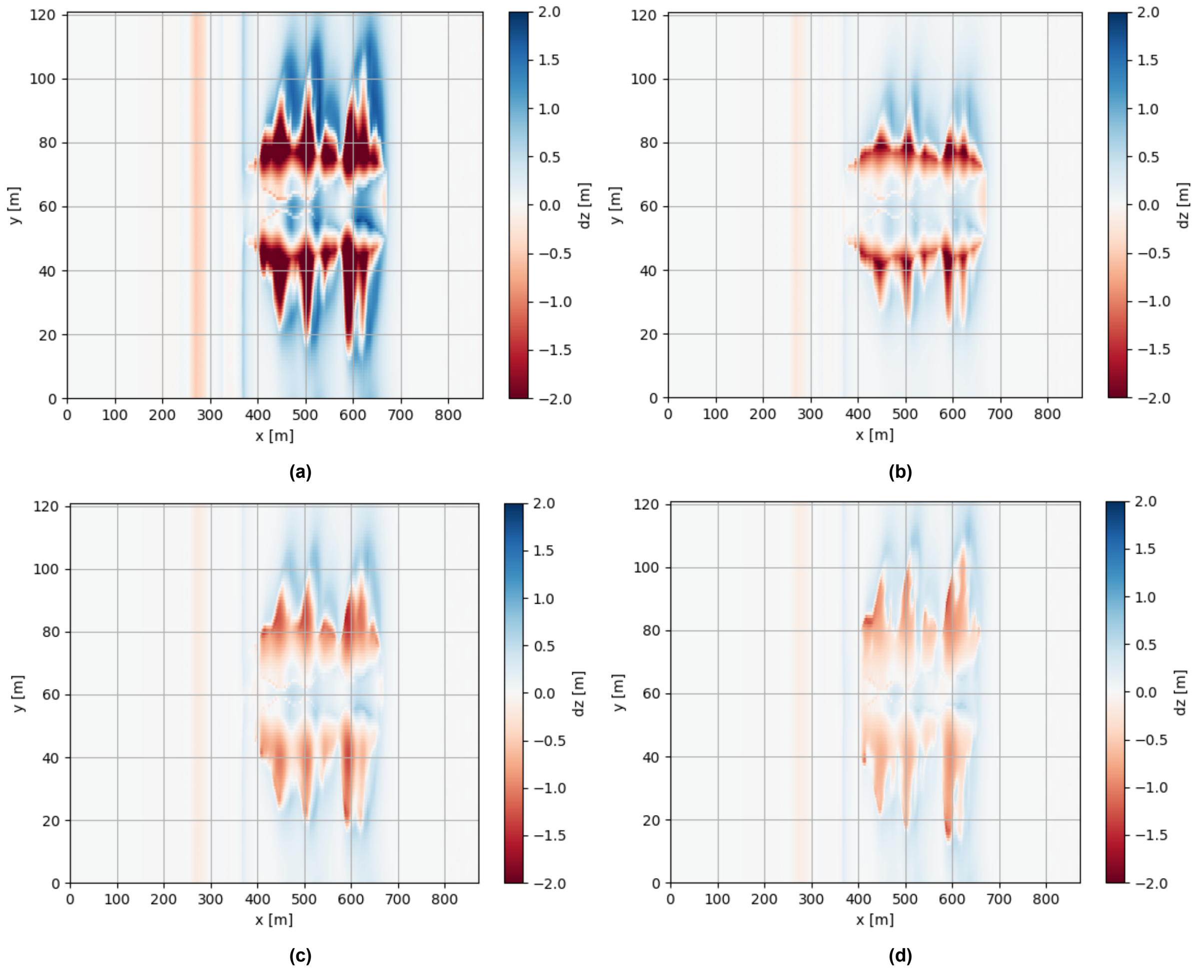



**Figure 4.6:** The total bed level change (a) as well as the bed level change per year for year one (b), year two (c) and year three (d) of run 1 (W02O00N1)

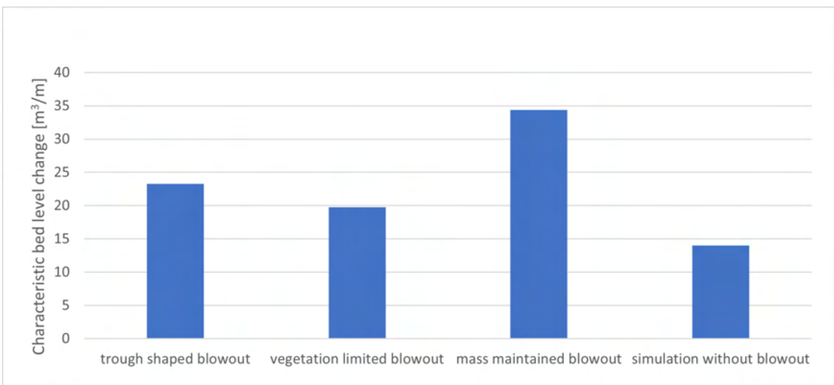



**Figure 4.7:** Characteristic bed level changes for the different construction methods and the simulation without a constructed foredune blowout

### Trough Shaped Blowout

Figure 4.8 shows the initial and final profile of the dune as well as the volume changes and vegetation cover. The initial trough shape is still clearly visible in Figure 4.8a whilst a more rectangular shape seems visible in Figure 4.8b. This rectangular shape is also visible in the erosion shown in Figure 4.8c.

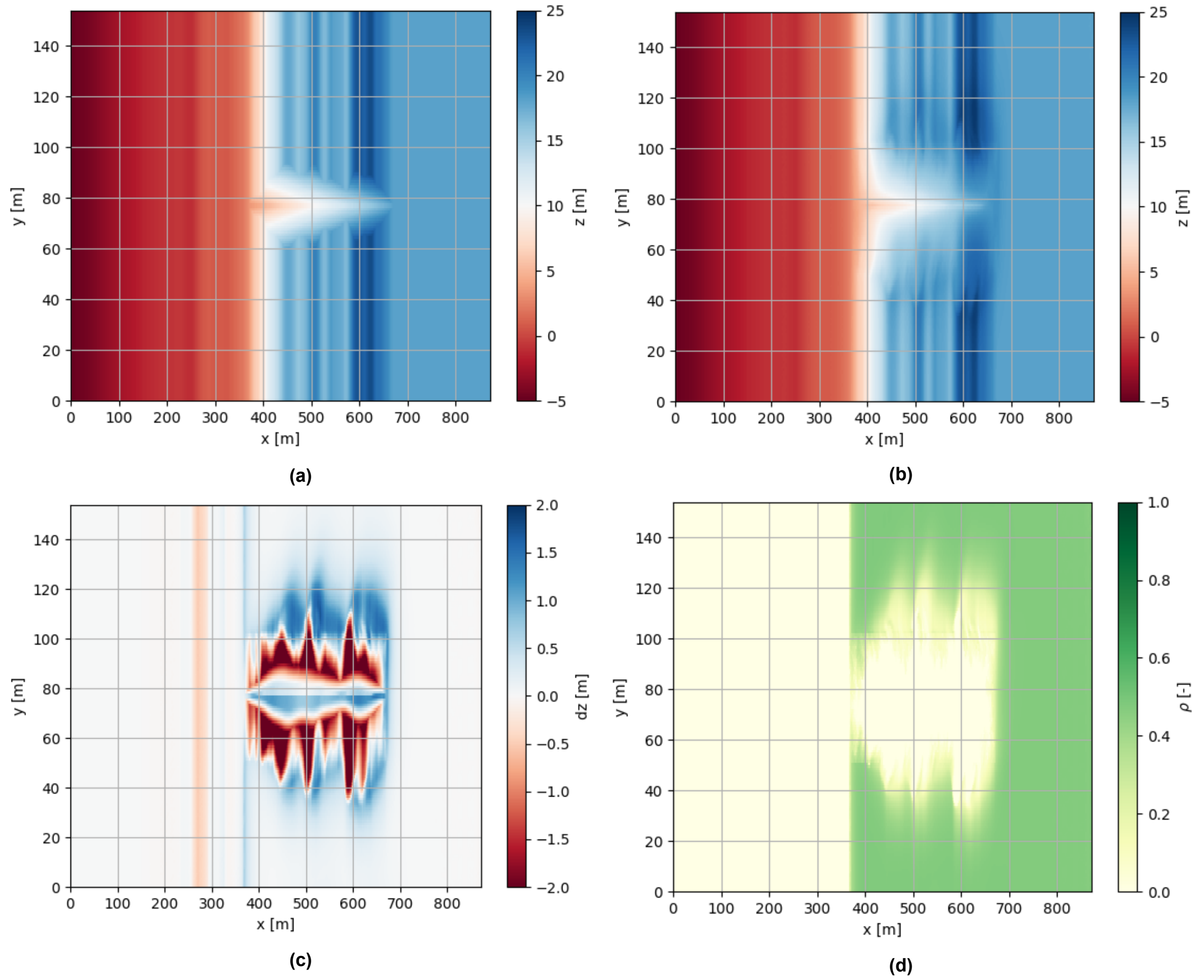



**Figure 4.8:** Initial (a) and final (b) bed levels, bed level difference (c) and final vegetation cover (d) of a trough shaped foredune blowout

### Mass Maintained Blowout

In this case the foredune blowout is still created through the removal of sediment along a rectangular profile, however rather than simply removing this sediment from the domain it is added as mound behind the ”exit” of the foredune blowout and with a similar slope, see Figure 4.9 . Note that the color bar is on a different scale compared to Figure 4.8 among others.

The initial sediment mound shown in Figure 3.5b is still clear in Figure 4.9a. Both the foredune blowout and the mound behind the blowout have a more conical shape in Figure 4.9b leading to somewhat of a hourglass shape, this is also visible in the outline of the vegetation cover in Figure 4.9d.

### Removal of Vegetation

For this simulation, rather than removing sediment, vegetation is removed at the location of the foredune blowout and horizontal growth is prohibited. This creates an area of bare sand that can more easily be eroded than the surrounding profile. This is akin to the method used at Meijendel where approximately 1 meter of top soil was removed. Figure 4.10 illustrates the initial and final bed levels and the difference between them as well as the final state of the vegetation cover. The outline of the area of bare sand is visible in Figures 4.10b, 4.10c, and 4.10d.

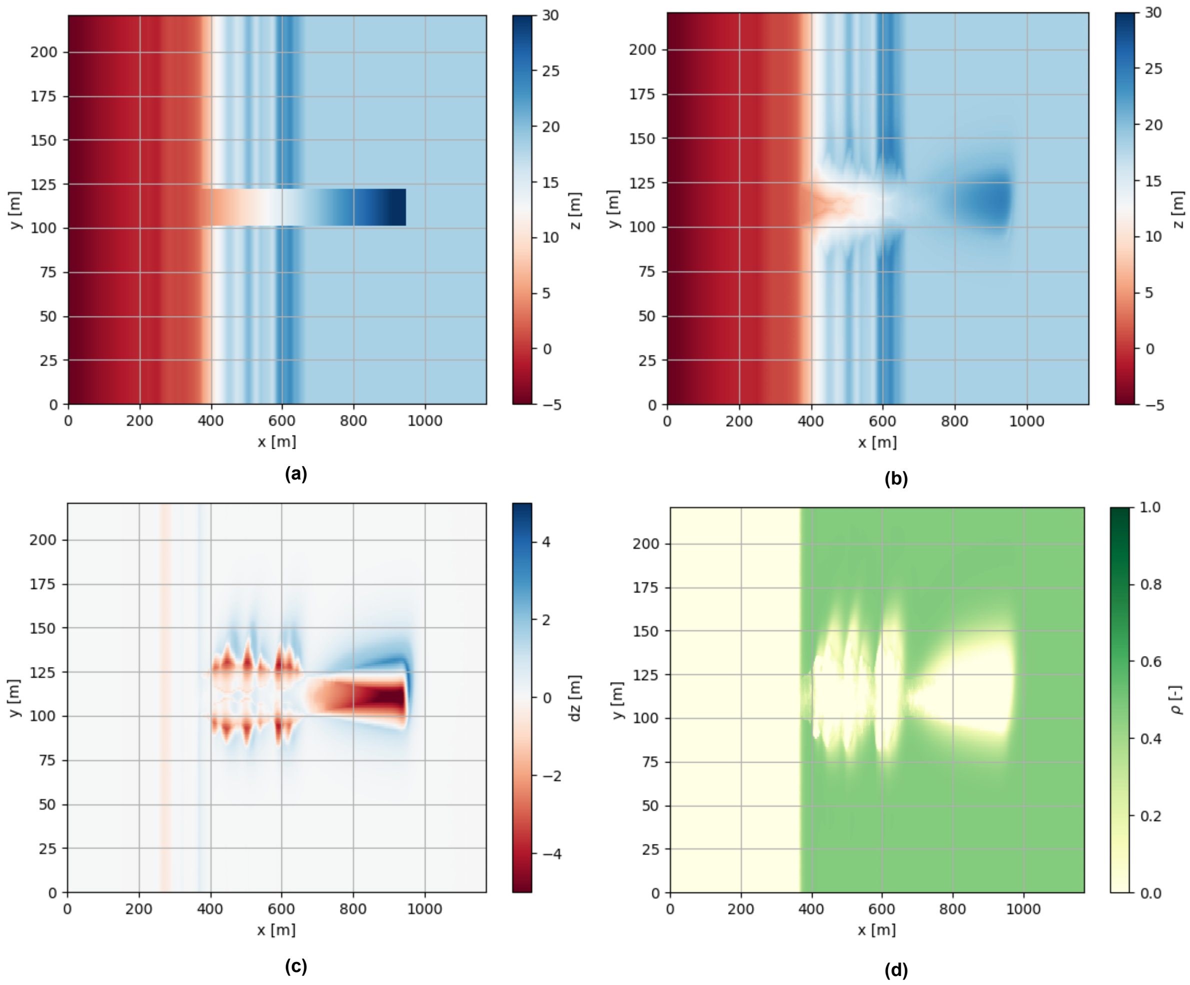



**Figure 4.9:** Initial (a) and final (b) bed levels, bed level difference (c) and final vegetation cover (d) of a mass conserved foredune blowout.

## 4.6. Quantitative Design Aspects

In addition to the summation of the transport that occurs for the different combinations already shown in Figure 4.4, a comparison of the transport that occurs for one and two foredune blowouts can be made using the ratio shown in Equation 3.11.

In this case the ratio is calculated as the erosion that occurs from $x = 300[m]$ to $x = 800[m]$ for two foredune blowouts divided by the erosion that occurs for a single foredune blowout with the same orientation and width over the same range, as shown in Equation 4.2. The choice of calculating the ratio from $x = 300[m]$ is made so as to exclude the erosion that occurs in the intertidal range from $x = 0[m]$ to $x = 300[m]$.

$$ratio = \frac{\sum_{x=300}^{x=800} \sum_{y=0}^{y=y} \delta Z_{neg_2} dydx}{\sum_{x=300}^{x=800} \sum_{y=0}^{y=y} \delta Z_{neg_1} dydx} \tag{4.2}$$

Figure 4.11 illustrates the calculated ratio grouped by width and orientation. The ratio increases towards a value of 2 both when comparing foredune blowouts of equal width at different orientations as well as when comparing foredune blowouts of differing widths orientated the same.

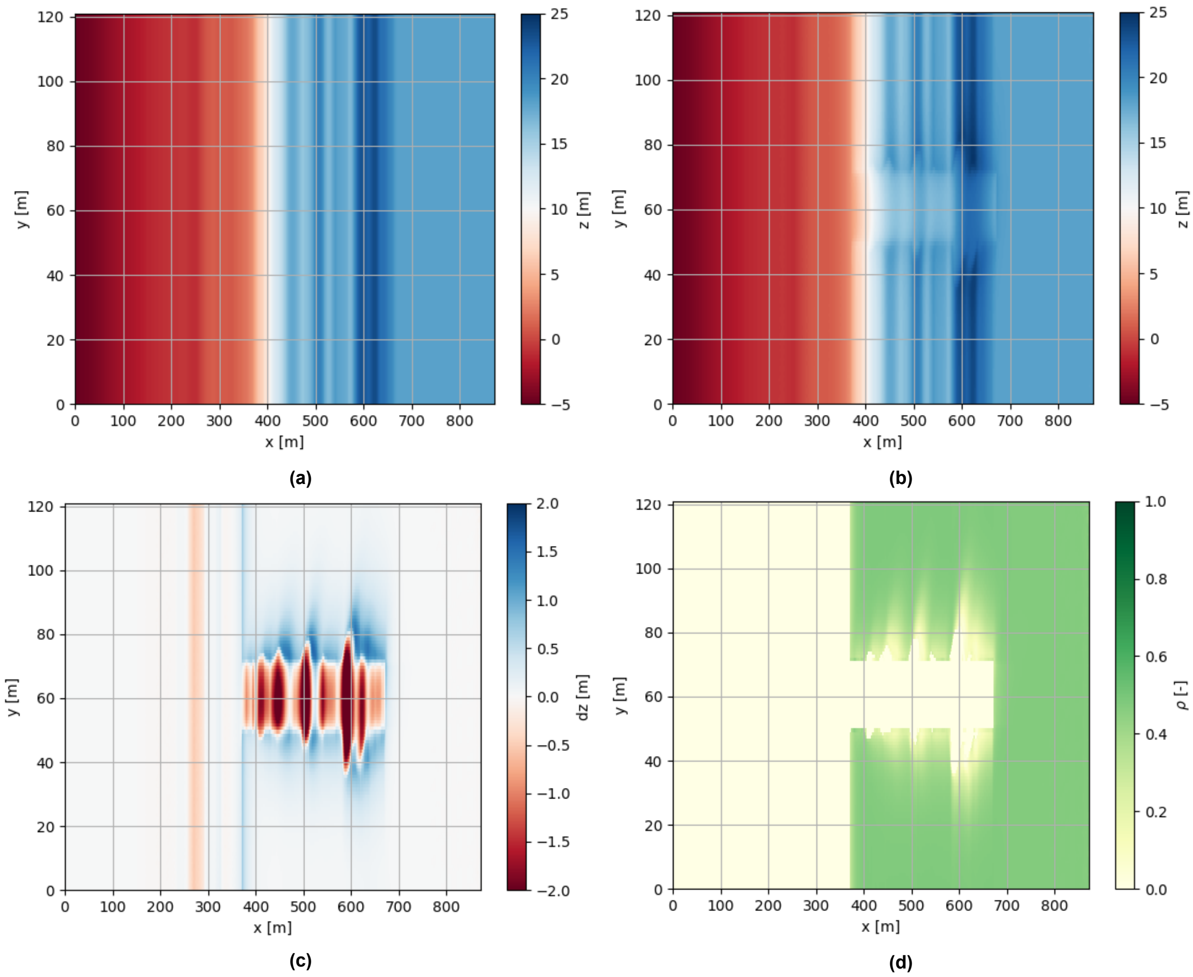



**Figure 4.10:** Initial (a) and final (b) bed levels, bed level difference (c) and final vegetation cover (d) of a foredune blowout with limted vegetation

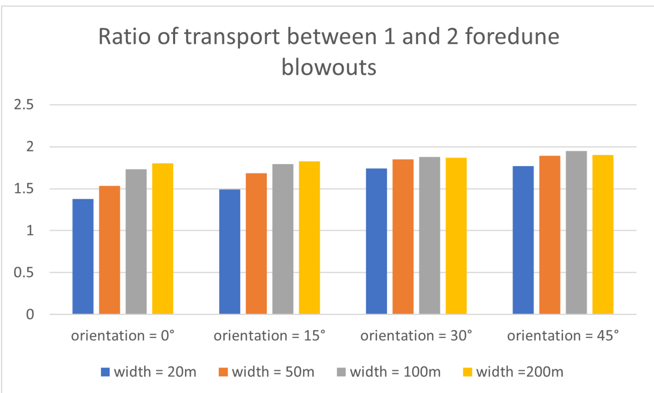



**Figure 4.11:** Ratio of transport that occurs between 1 and 2 foredune blowouts

# 5 Discussion

In this chapter, the model results are discussed in detail. First the general erosion and sedimentation patterns are considered, followed by a discussion of the simulations of various construction methods, the quantitative design aspects and a program of requirements. Then some model uncertainties are considered and lastly some examples of differences and simmilarities between field data and model results are discussed.

## 5.1. Erosion & Sedimentation Patterns

To understand the effect a foredune blowout has on the dunes, different subsections of the domain are considered. First the erosion and deposition up to the introduction of the foredune blowout are discussed, whereafter the erosion and sedimentation in the foredune blowout are examined.

### Erosion in the Intertidal Range

There is no discernible net increase in the erosion that takes place in the inter-tidal range when comparing any of the simulations or the situation without a constructed foredune blowout, see table A.4 in appendix. On closer inspection this result becomes clear. Erosion takes place when the concentration of sediment in the air column is less than its equilibrium concentration, which is dependent on the available sediment and the wind velocity. The wind climate for all simulations is limited in direction as can be seen in Figure 3.2, the foredune blowout is therefore always situated downstream or parallel to the inter tidal range. This limits any type of mechanism either increasing the local wind speed or limiting available sediment in the upstream direction.

### Deposition up to the Dune Foot

While the erosion that takes places prior to the constructed foredune blowout remains the same, this does not necessarily hold true for the deposition. It is possible that sediment that would normally be trapped at the foot of the dune in the situation without a foredune blowout is now transported to the hinterdunes through the created foredune blowout.

Table 5.1 shows the calculated deposition (dep.) up to $x = 400[m]$ for every single combination of width and orientation and number of blowouts as well as the difference between the deposition that occurs with and without a foredune blowout, abbreviated to $\Delta d[m^3]$. The comparison is done up to a range of $x = 400[m]$ as 90% of the deposition that occurs for a simulation without a foredune blowout occurs within this range, additionally the effect of the foredune blowout on the deposition is not yet as developed.

The deposition that occurs up to $x = 400[m]$ for a simulation without a foredune blowout is equal to $16726\ m^3$. Table 5.1 also shows $\Delta d$ divided by the width (W) of the foredune blowout and $\Delta d$ as a percentage of the total deposition (total dep).

The difference in deposition between a situation with and without a foredune blowout, $\Delta d$, varies per simulation. It does not however scale linearly with the width of the foredune blowout. Additionally for narrow blowouts it appear that more sediment is deposited than occurs without a blowout.

**Table 5.1:** Deposition up to the foot of the dune, deposition of simulation without a foredune blowout is equal to $16726[m^3]$, W02 = width of 20m etc., O = orientation & N = number of foredune blowouts

| run | ID | dep.$[m^3]$ | $\Delta d[m^3]$ | $\Delta d[m^3]/W[m]$ | $\Delta d$ /total dep.[%] | total dep. $[m^3]$ |
|---|---|---|---|---|---|---|
| run 1 | W02O00N1 | 16727 | -1 | -0.0 | -0.0 | 33042 |
| run 2 | W05O00N1 | 16467 | 260 | 5.2 | 0.8 | 34250 |
| run 3 | W10O00N1 | 16007 | 720 | 7.2 | 2.2 | 32607 |
| run 4 | W20O00N1 | 15069 | 1657 | 8.3 | 5.1 | 32398 |
| run 5 | W02O15N1 | 16740 | -13 | -0.7 | -0.0 | 30176 |
| run 6 | W05O15N1 | 16519 | 207 | 4.1 | 0.7 | 29772 |
| run 7 | W10O15N1 | 16008 | 718 | 7.2 | 2.4 | 29649 |
| run 8 | W20O15N1 | 15059 | 1667 | 8.3 | 5.5 | 30138 |
| run 9 | W02O30N1 | 16820 | -94 | -4.7 | -0.3 | 27302 |
| run 10 | W05O30N1 | 16577 | 149 | 3.0 | 0.5 | 28275 |
| run 11 | W10O30N1 | 16066 | 660 | 6.6 | 2.3 | 29152 |
| run 12 | W20O30N1 | 15054 | 1672 | 8.4 | 5.5 | 30506 |
| run 13 | W02O45N1 | 16873 | -147 | -7.4 | -0.5 | 28945 |
| run 14 | W05O45N1 | 16659 | 67 | 1.3 | 0.2 | 30800 |
| run 15 | W10O45N1 | 16164 | 563 | 5.6 | 1.8 | 32069 |
| run 16 | W20O45N1 | 15117 | 1609 | 8.0 | 4.7 | 33909 |
| run 17 | W02O00N2 | 16635 | 91 | 2.3 | 0.2 | 38833 |
| run 18 | W05O00N2 | 16210 | 516 | 5.2 | 1.2 | 43168 |
| run 19 | W10O00N2 | 15217 | 1509 | 7.5 | 3.5 | 43529 |
| run 20 | W20O00N2 | 13243 | 3483 | 8.7 | 7.9 | 44052 |
| run 21 | W02O15N2 | 16704 | 22 | 0.6 | 0.1 | 36341 |
| run 22 | W05O15N2 | 16223 | 504 | 5.0 | 1.3 | 38046 |
| run 23 | W10O15N2 | 15222 | 1505 | 7.5 | 3.9 | 39053 |
| run 24 | W20O15N2 | 13131 | 3595 | 9.0 | 8.9 | 40204 |
| run 25 | W02O30N2 | 16769 | -42 | -1.1 | -0.1 | 34394 |
| run 26 | W05O30N2 | 16290 | 436 | 4.4 | 1.2 | 37178 |
| run 27 | W10O30N2 | 15270 | 1456 | 7.3 | 3.7 | 39082 |
| run 28 | W20O30N2 | 13158 | 3569 | 8.9 | 8.6 | 41437 |
| run 29 | W02O45N2 | 16807 | -81 | -2.0 | -0.2 | 37480 |
| run 30 | W05O45N2 | 16388 | 338 | 3.4 | 0.8 | 42361 |
| run 31 | W10O45N2 | 15413 | 1313 | 6.6 | 2.9 | 45502 |
| run 32 | W20O45N2 | 13316 | 3410 | 8.5 | 7.1 | 48321 |

Smaller foredune blowouts can be closed off by vegetation more quickly than larger foredune blowouts, as can be seen in Figure 4.1b. This vegetation can trap more sediment as there is a feedback loop between vegetation height and reduction in local shear stress, leading to more deposition at the front of the foredune blowout. This explains the higher deposition values for smaller foredune blowouts than for wider blowouts though does not explain higher deposition levels than the run without a foredune blowout.

In general it seems there is no clear indication that there is any substantial ”suction effect” within the model. At best there is a slight mismatch in the erosion and deposition in front of the foredune blowout, however this is in the order of millimeters to a centimeter over a period of three years. This becomes clear when looking at Figure 5.1. This plots the difference between a simulation with and without a foredune blowout on a logarithmic scale.

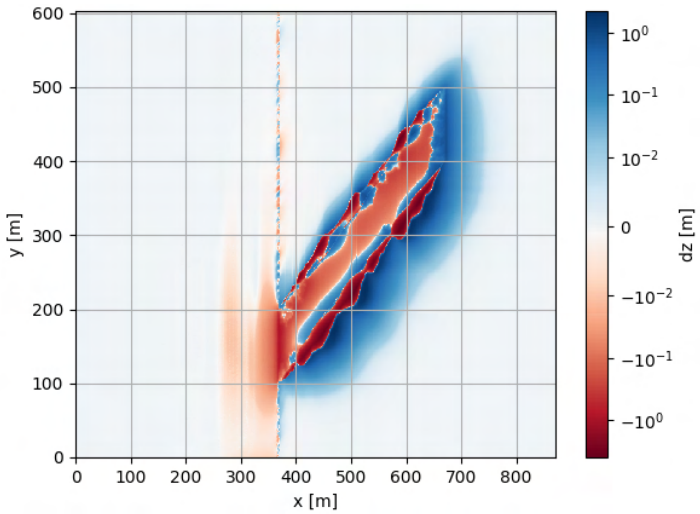
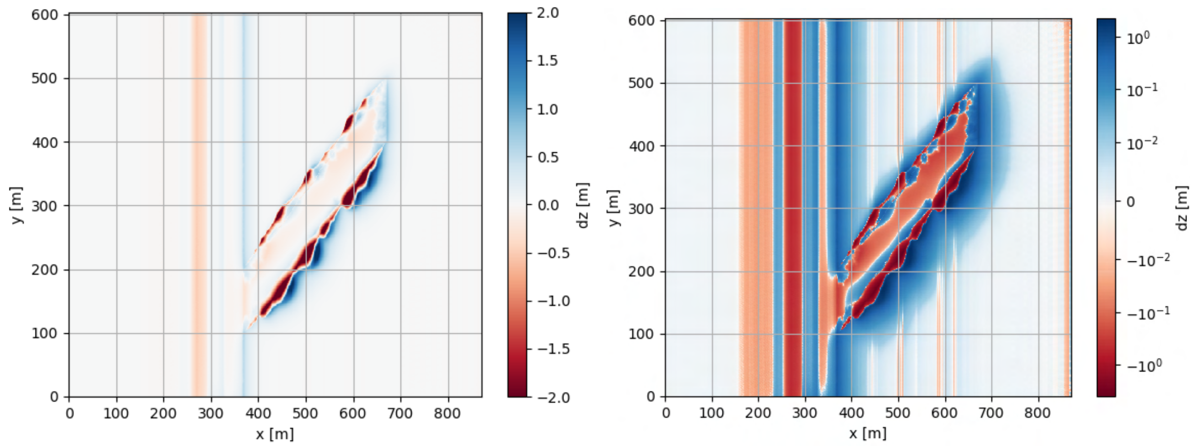



**Figure 5.1:** Plot of the difference in bed level change between a simulation with and without a constructed foredune blowout. Additional erosion is visible in front of the constructed foredune blowout on the scale of millimeters

## Bed Level Changes from the Foredune Blowout Onwards

Figure 5.2a reveals the erosion and sedimentation patterns that appear due to the introduction of a foredune blowout. It shows that there are generally three regions where deposition occurs and three regions where erosion occurs. Deposition occurs along the foot of the dune, along the erosional walls and at the ”exit” of the blowout. Erosion occurs in the intertidal range, along the erosional walls and in the deflation basin.




**(a)** **(b)**

**Figure 5.2:** Bed level changes of run 15 (W100O45N1) on a linear (a) and logarithmic (b) scale

It is clear that the largest bed level changes occur along the erosional wall whilst the behavior up to the dune foot is largely independent of the introduction of a foredune blowout as has already been discussed.

The erosion and deposition that occurs along the erosional walls can be attributed to local accelerations in the wind field. This can be seen in Figure 4.5, it should be noted that this is a different sized foredune blowout than shown in Figure 5.2.

Figure 4.5 shows the shear velocity at two different time steps with wind coming from different directions, it highlights the reason for large amounts of erosion and deposition along the erosional walls. For both situations there is a clear acceleration up the erosional walls along scarp like features out of the blowout followed by a deceleration.

This behavior in the model is based on the Venturi effect. The Venturi effect maintains that a fluid's velocity will increase as the area it is flowing through decreases due to the conservation of mass. In this case there is a constriction as wind flows up these scarps leading to local acceleration of wind shear velocity. These changes in wind shear velocity lead to the transport of sediment. The increase in wind shear leads to a higher saturated sediment concentration leading to erosion, followed by reduction of wind shear leading to a decrease in the saturated sediment concentration and deposition.

In general the erosion and the sedimentation patterns caused by the introduction of foredune blowouts have limited effect on the larger scale dune transport rates. There is no increase in erosion upstream of the foredune blowouts and there is an limited decrease in deposition up to the dune foot.

The predominant increase in sedimentation and erosion that takes place in the model, when compared to the simulation without a foredune blowout, is the redistribution of the foredune blowout and not transport of sediment from the beach through the foredune blowout. This idea is reinforced by Figure 5.3.

Figure 5.3 shows the running sum of the erosion and sedimentation as a function of the length of the cross shore profile for every combination of a single foredune blowout, run 1 (W02O00N1) through run 16 (W20O45N1). Up to the start of the foredune blowout the erosion and sedimentation is essentially identical, further reinforcing the notion that the behavior of the model upstream of the foredune blowout remains unchanged. The erosion and sedimentation patterns start to diverge past the start of the foredune blowout, though a clear pattern is visible, with a grouping based on the width of the foredune blowout.

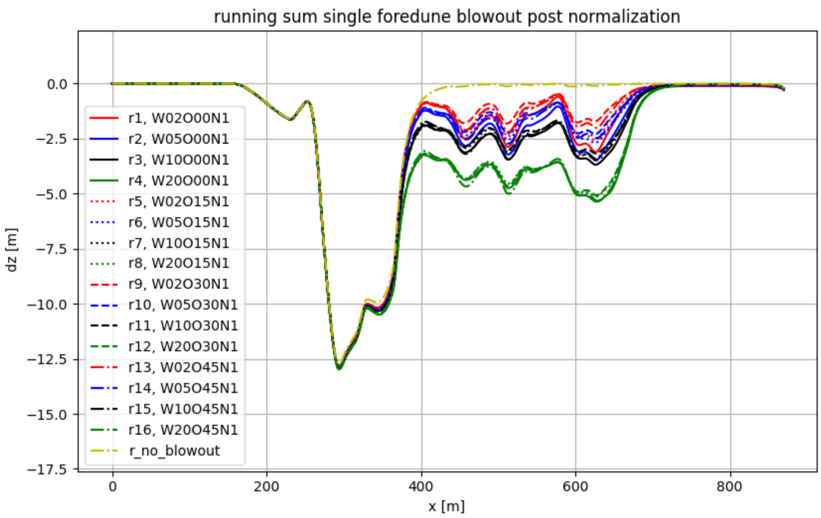


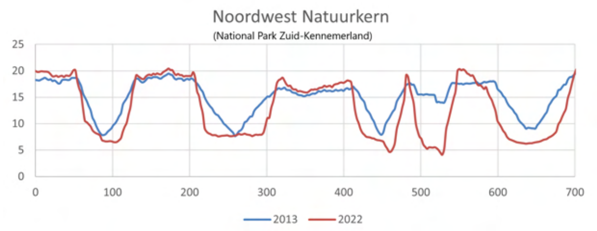

**Figure 5.3:** Running sum of erosion and sedimentation for every single foredune blowout configuration. Constructed foredune blowouts of equal width are plotted in the same color, foredune blowouts of equal orientation are plotted using the same linestyle.

### Range of Influence

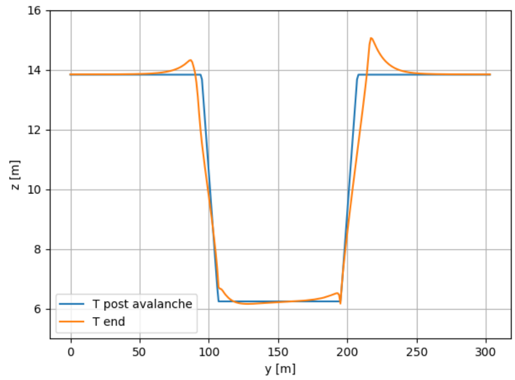
Inspection of the AeoLiS results reveals that for the chosen grain size the range of influence on sediment transport is limited. Figure 5.2 shows the bed level changes on a linear scale and on a logarithmic scale, it shows that in general the volume changes are dominated by the avalanching and further redistribution of the erosional walls. The logarithmic scale further enforces this and shows that at best the sphere of influence of a constructed foredune blowout is approximately 100 meters after which the same erosion and deposition patterns that occur without a foredune blowout return.

## 5.2. Simulation of Construction Methods

Comparing the initial and final profiles of the model results with profiles of the foredune blowouts in the National Park Zuid-Kennemerland shows similarities. Both the final profiles in Figure 5.4a (shown in red) as well as the final profile in Figure 5.4b (shown in orange) are generally cup-shaped however the initial profiles differ. In Figure 5.4a the foredune blowouts were constructed by excavating a trough- or V- shaped blowout which over time eroded into a more cup-shaped profile while the difference between the initial and final profile in the mode shown in Figure 5.4b is less distinct. It should be noted that the simulation period is 3 years while Figure 5.4b illustrates the change in profile over a period of 9 years.




**(a)** Cross section of existing constructed foredune blowouts at the National Park Zuid-kennemerland. Source: (Bos-Staatsbosbeheer et al., 2022)




**(b)** Example of initial and final cross section of Run 3 (W10O00N1)

**Figure 5.4:** Difference in cross section between model and existing foredune blowouts

## Trough Shaped Blowout

Comparing the bed level changes for a trough shaped blowout with the rectangular simulations shows similar behavior. The characteristic value for the bed level changes for the trough shaped blowout is equal to $23.29[m^3/m]$ which is less than the values for simulations with a similar width, orientation and number such as run 1 (W02O00N1) and run 2 (W05O00N1) shown in Figure 4.4. Figure 5.5 shows a longshore transect of the initial and final state of both the trough shaped blowout and of run 1 (W02O00N1). The Figure illustrates that the final profile of the erosional walls for both simulations appear similar.

There is no clear development of a deflation basin in the model results of a trough shaped foredune blowout, shown in Figure 5.5b, when compared to Figure 5.4a, with the deflation basin being the central area between the erosional walls, however this can be attributed to a difference in time scale. Figure 5.4a shows the evolution of the bed level over a period of 9 years while the simulations are over a period of 3 years.

This lack of a deflation basin likely contributes to the reduction in transport compared to a blowout with an initial width of 20 meters as the deflation basin does offer some sediment as can be seen for example in Figure 5.2.

## Mass Maintained Blowout

As the sediment, that in other simulations is removed, is in this case placed behind the dune as an extra mound, there is additional sediment available for transport and avalanching than in other cases. This is also reflected in the total transport which is equal to $34.36[m^3/m]$. The width of the foredune blowout in this case is equal to 20 meters. Comparing the value for the characteristic bed level change for this simulation with that of run 1 (W02O00N1) which also has a width of 20 meters reveals that the value is 1.35 times higher.

In the field foredune blowouts are often created by physically pushing sediment from the dune foot onwards, creating a blowout and a mound behind it. The perception that foredune blowouts create large depositional lobes is likely affected by this practice as differentiating between sediment that was placed by the construction method and sediment that was transported there through other means is difficult. The range of influence remains approximately 100 meters, however just by virtue of having a mound of bare soil further into the hinterdunes allows for sediment to reach further as well.

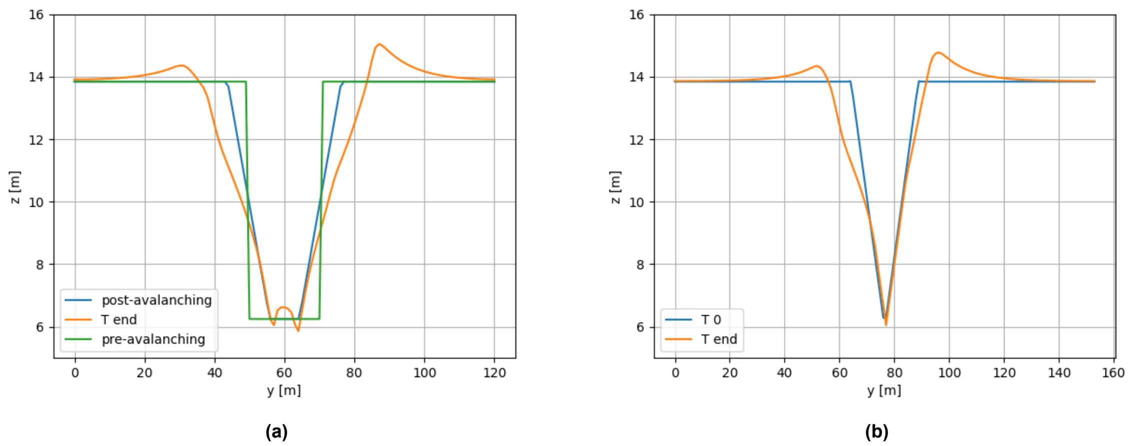



**Figure 5.5:** The initial and final cross shore profile of run 1 (W02O00N1)(a) and the trough shaped blowout (b)

### Removal of Vegetation

In the case of a vegetation limited blowout, less transport takes place than when a rectangular profile is introduced. This is to be expected as there is no initial avalanching and the erosional walls and deflation basin have merged into a single horizontal plane, limiting the surface area where interaction between sediment and wind can take place. Furthermore there are no initial scarp like features where local wind accelerations could take place.

At the project at Meijendel a similar approach of solely removing the topsoil was deployed due to a lack of funding. The model results show similar behavior in that by removing vegetation, transport of sand can be stimulated. The thickness of the removed layers at Meijendel however was on average 1.5 to 2 meters, which is different from the implementation in the model (B. Arens, 2022).

An advantage of this method is that it could be less intrusive and costly than moving large volumes of earth with heavy machinery. If uncovered roots start to reconstitute and require maintenance and removal, as was the case in parts of the project of Meijendel, then this advantage may be limited (B. Arens, 2022).

## 5.3. Quantitative Design Aspects

Some trends that stand out based on the normalized transport are discussed for the three chosen design variables.

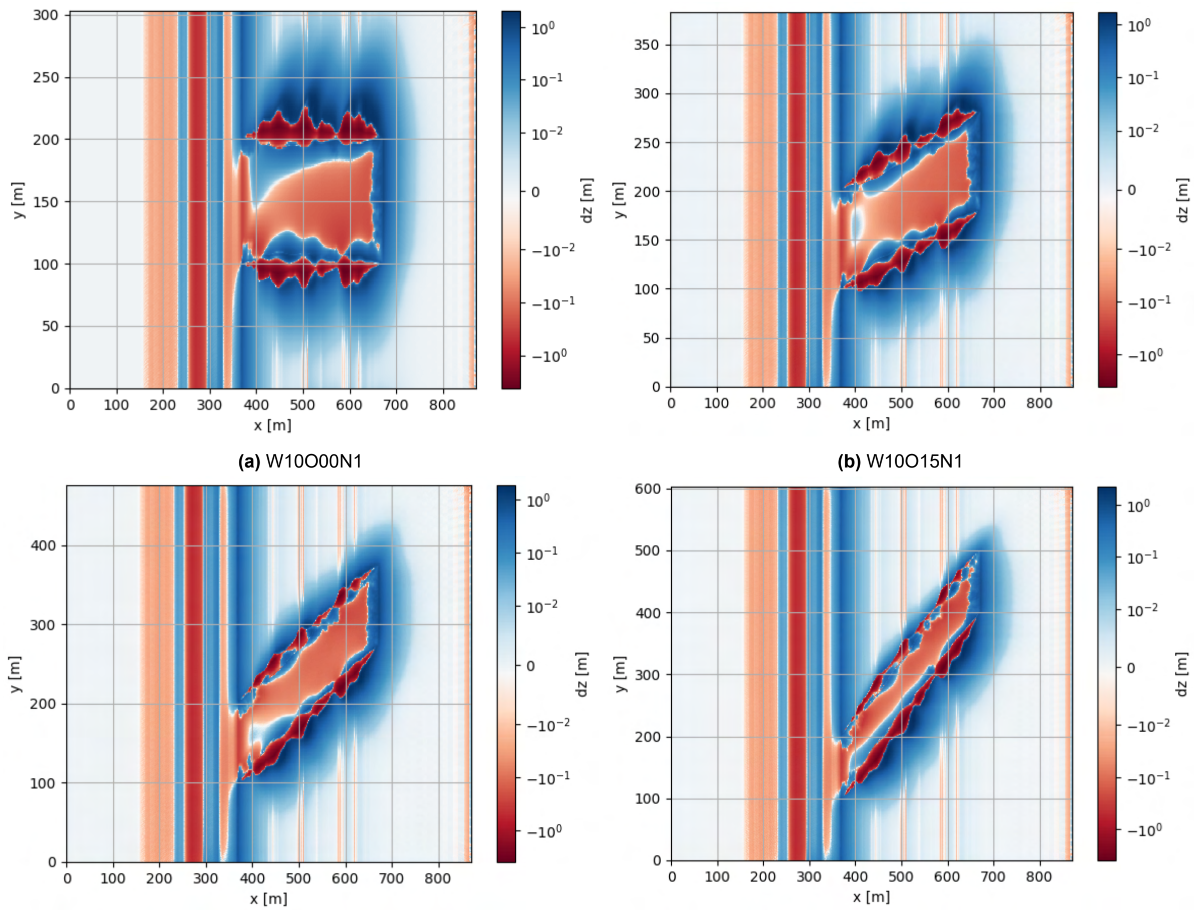
### Orientation of the Constructed Foredune Blowout

Transport rates are higher for foredune blowouts of equal width that are at an orientation of 0°or 45°than for foredune blowouts at an orientation of 15°or 30°, see Figure 4.4. This is likely caused by foredune blowouts rotating towards the dominant wind direction. This is based on the comparison of erosion and sedimentation patterns of foredune blowouts of equal width at different orientations plotted on a logarithmic scale.

Comparing the erosion and sedimentation patterns at the entrance of the foredune blowout of Figure 5.6a to the patterns in the other images found in Figure 5.6 shows this rotating effect. Though this is less clear for a foredune blowout at an orientation of 45°. A closer inspection of the wind is therefore required. Figures A.5 & A.6 in the appendix shows the same images post normalization and larger.

The potential transport for each wind direction can be calculated and plotted in a similar fashion to a wind rose, sometimes called a sand rose. This is done by calculating the potential transport for each time-step in the hourly wind data and summing these values per direction.

Figure 5.7a shows the sand rose for the given wind climate. The largest potential transport flux occurs at an angle of 50 °, however there is also a relatively large transport potential around 0°. This offers an explanation for why there is more transport for foredune blowouts that ostensibly are oriented in the direction of the direction of the significant wind direction.




**(a)** W10O00N1 **(b)** W10O15N1

**(c)** W10O30N1 **(d)** W10O45N1

**Figure 5.6:** Bed level change of four blowouts of same width, different orientation, on a logarithmic scale

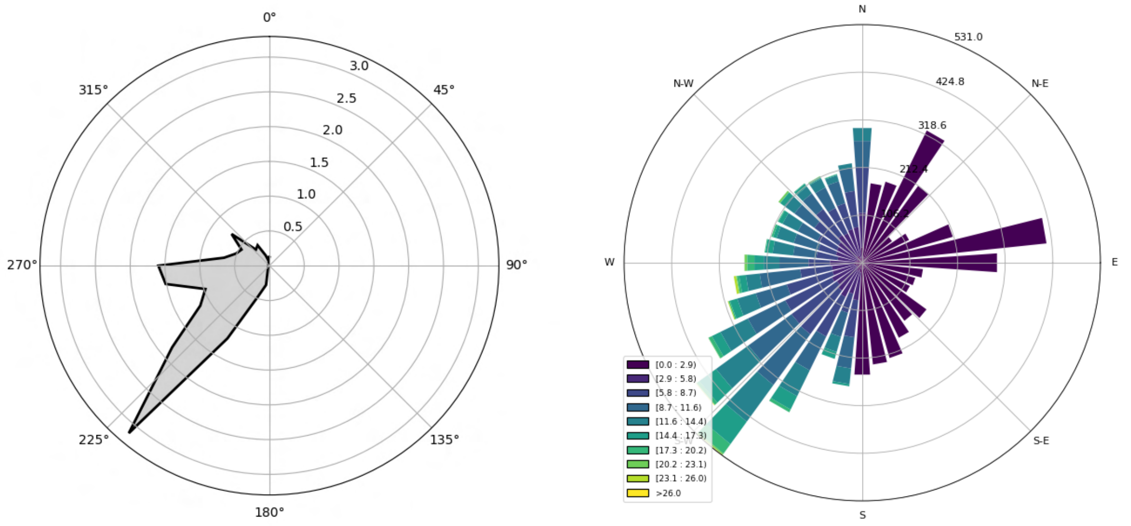
It could be argued that transport is large when foredune blowouts are aligned with the wind, this however does not explain the rotational pattern visible in the entrance of the modeled blowout. Inspection of the calculated wind shear further disproves this notion. Figure 5.8 shows the wind shear for two different orientations of the foredune blowout, for wind from two different directions. See Figures A.7 & A.8 in the Appendix for larger images.

Figure 5.8 illustrates that for a foredune blowout with an orientation of 0°, that the local wind shear is higher when the wind is coming from the south west compared to when the wind is coming from the west. The reverse holds true for a blowout orientated at 45°. This would run counter to the idea that constructed foredune blowouts should be oriented in the dominant wind direction.

Furthermore, this coincides with the downward trend of the yearly erosion and deposition rates, which is visible in Figure 4.6. If transport is dominated by reorientation of the foredune blowout along the erosional walls, as the data suggests, then a reduction in transport as the blowout rotates towards a 'dynamic equilibrium' orientation is to be expected. Simulations of longer time frames would likely offer data to either support or disprove this notion. Additionally simulations with a larger set of orientations would offer insight into the limits of this effect.

### Width of the Constructed Foredune Blowout

There is also a trend that the transport increases with the width of the foredune blowout, this can be explained when looking at Figure 5.2. The transport is dominated by the erosional walls, however the deflation basin does offer some sediment. As the deflation basin is larger for wider foredune blowouts, it is to be expected that more sediment transport takes place for larger foredune blowouts than smaller ones.




(a) (b)

**Figure 5.7:** The calculated potential sediment transport plotted as a sand rose (a) and the windrose of the used wind climate (b)

### Interaction Between Foredune Blowouts

In the field studies that have briefly been highlighted there is large variation in the number of foredune blowouts that are created and the spacing that is between them. To see whether foredune blowouts interfere with one-other, a comparison in the erosion that occurs can be made. Figure 4.11 shows the ratio of the transport that occurs for two foredune blowouts and one foredune blowout using the method described previously. As the distance between two foredune blowouts is kept equal to the width of the blowout, it becomes clear that for larger distances and for more acute orientations this ratio tends to a value of $2[-]$. The further the distance between the blowouts, the more sediment needs to be moved before the erosional walls start to interfere with one other. Figure 5.9 also shows the calculated local wind shear, it shows that the wind pattern are essentially identical within the foredune blowouts from $x = 370[m]$ to $x = 670[m]$.

### Ratio of Removed Soil to Transport

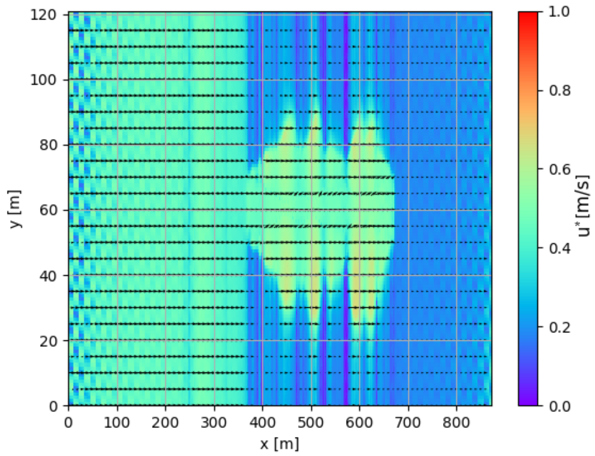
Based on the width and number of the constructed foredune blowouts. the volume of sediment that has been removed can be calculated. The calculated volumes are shown in Table A.2 in the Appendix.

Comparing the volume of the sediment that is removed for the construction of the foredune blowouts to their respective volume changes reveals that the transport never exceeds the volume of removed soil as is portrayed in Figure 5.10.

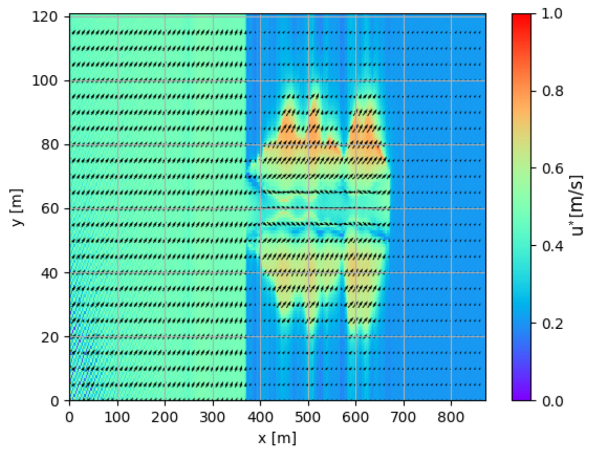
In general the model suggests that smaller foredune blowouts transport more sediment per unit width and for construction require less removal or displacement of sediment than wider foredune blowouts. This does not take vegetation into account as smaller foredune blowouts may be closed off more quickly than larger foredune blowouts.

### Closing Off of Foredune Blowouts

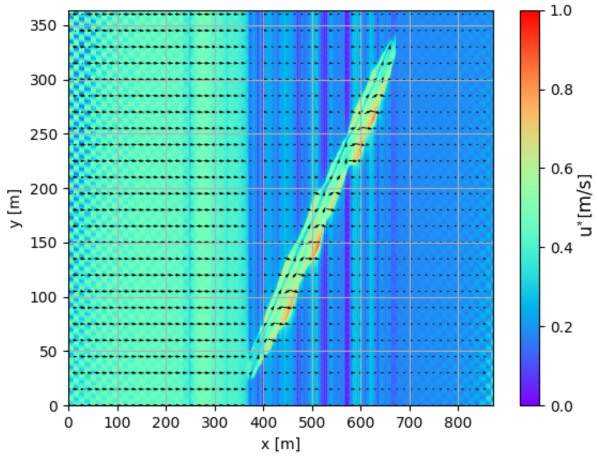
One potential issue of foredune blowouts is the possibility of embryonic dunes returning to the entrance of the foredune blowout effectively closing the blowout, this can be seen in Figure **??** where this phenomenon occurred in the model. If most transport that occurs originates from the redistribution of the foredune blowout, then the effect of closing off the mouth of the foredune blowout may not be as impactful on the total transport as might be expected. Additionally if the wind field in the foredune blowout isn't impacted by this newly created embryonic dune then the closing off of foredune blowouts is even less of an issue.



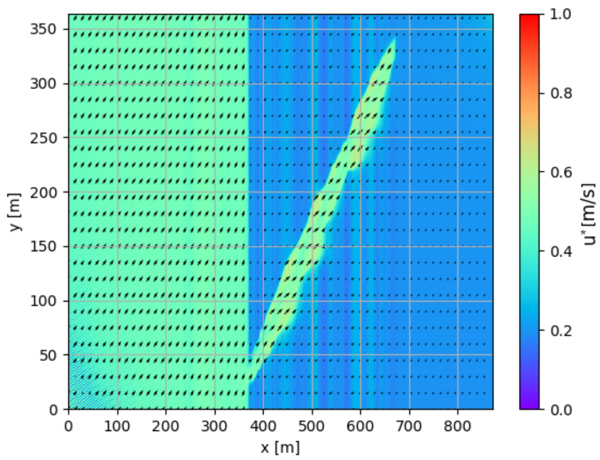

**(a)** Orientation 0°, wind direction -10 °, $u_w = 15[m/s]$




**(b)** Orientation 0°, wind direction 50 °, $u_w = 16[m/s]$




**(c)** Orientation 45°, wind direction -10 °, $u_w = 15[m/s]$




**(d)** Orientation 45°, wind direction 50 °, $u_w = 16[m/s]$

**Figure 5.8:** Local wind shear for different wind conditions and orientations of a foredune blowout

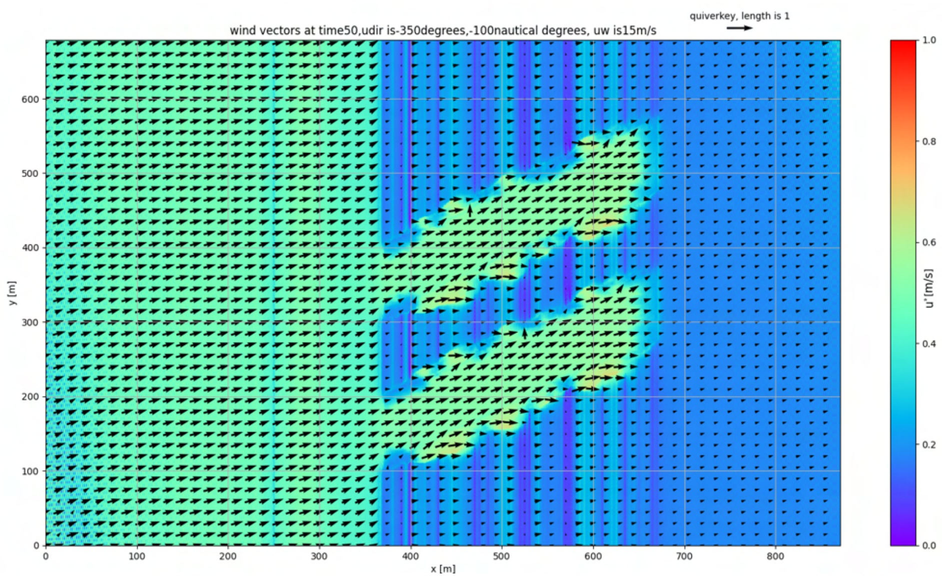
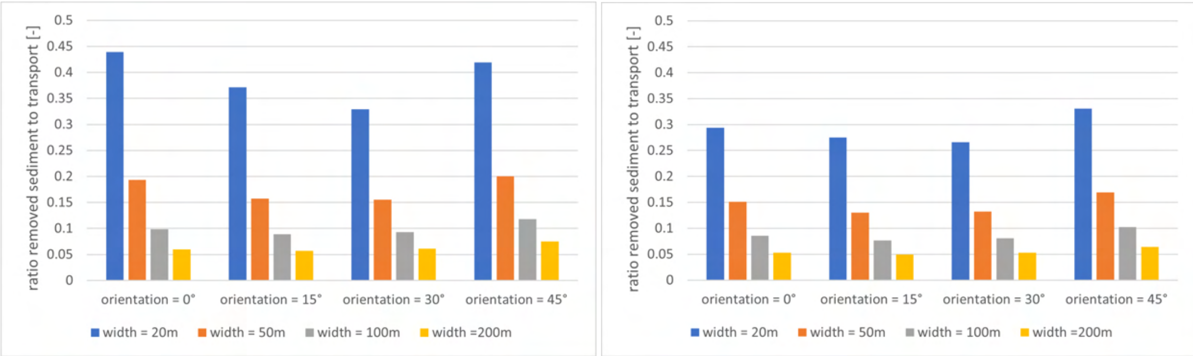


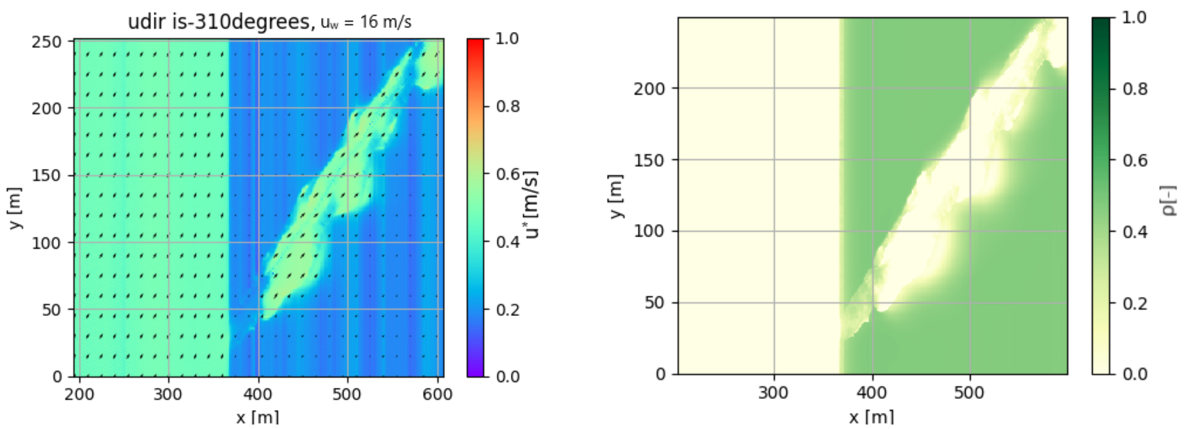

**Figure 5.9:** Example of the calculated wind field for two foredune blowouts (W10O30N2)




(a) (b)

**Figure 5.10:** Ratio of removed volume to erosion sorted by orientation and width for a single foredune blowout (a) and for two foredune blowouts (b)

The wind fields in the model remain largely unaffected by these forming embryonic dunes. Figure 5.11 shows the wind shear velocity for a section of run 13 (W02O45N1) on a certain time step as well as the vegetation cover at that time step. There is a reduction in the wind shear in the mouth(from $x = 370[m]\ to\ x = 400[m]\ and\ y = 20[m]\ to\ y = 70[m]$) of the foredune blowout which is being closed off by the vegetation, further downwind however the wind shear velocity increases again. The full images can be seen in Figure A.4 in the appendix.




(a) (b)

**Figure 5.11:** Calculated wind shear (a) through the mouth of the foredune blowout and the vegetation mask (b) for that same area on the same time step

## Design Goals

Generally design goals can be divided into three categories:

- Ecological goals
- Water safety / dune growing goals
- Aesthetical goals

Based on these different design goals, a few different effects could be desired from the introduction of a foredune blowout which can be summed up as follows:

- Creation of bare sand to reset ecological succession
- Influx of calcium rich sediment to aid in phosphate binding
- Increase of the local bed level to reinforce lower laying areas

- Reinforcement of the primary dune row using sediment that has been removed for the creation of a foredune blowout

Wider foredune blowouts create comparatively larger areas of bare sand by virtue of being larger, though the model results suggest that the range of transport beyond the blowout is limited regardless of width and orientation. The chosen grain size and the underlying formulas on which AeoLiS is based any correlation between the variations of different design choices and the influx of calcium rich sediment difficult, for reasons that will be discussed later. The model results show large increases in the bed level directly along the erosional walls and to a lesser extent at the exit of foredune blowout, though this declines rather quickly and within a range of 100 meters. Again the maximum range of transport within the model seems independent of the chosen variables. The volume of sediment that can be used to reinforce other areas of the primary dune row is larger for a wider foredune blowout, assuming the excavation depth is kept equal.

## 5.4. Program of Requirements

To create a program of requirements to standardize the creation of constructed foredune blowouts requires an understanding of the effect design choices have on the system as well as quantifiable objectives to couple the desired outcome(s) with the choices that are made.

Goals in the past have often been described broadly, making clear quantifiable objectives hard to define. This has led to different interpretations of success, sometimes even within organizations. Work has been done to streamline and standardize goals by the ”Programma naar een Rijke Waddenzee (PRW or the Programme towards a Rich Wadden Sea) ” program, by issuing a manual to help guide administrators with decision making (Bos-Staatsbosbeheer et al., 2022).

The model results of this study offer some insight into the behavior of foredune blowouts though this is limited by the assumptions that have been made, such as the effect of grain size and moisture on the transport. There are gaps in the current understanding of foredune blowouts that the need to be filled in before any kind of standard program of requirements can be set up.

## 5.5. Uncertainties due to Assumptions

Some of the uncertainties and assumptions made within the model that add to the difficulty of setting up any type of standard program of requirements are discussed here.

### Grain Size Distribution and Transport

In this study a single grain size was used, rather than a grain size distribution, which could alter the results of the simulations. Generally speaking there is a distribution of sediment in the cross shore direction along a beach, with larger sediments being deposited closer to the shoreline and finer grains being transported further onto the beach. These finer particles may then also be transported by aeolian processes under less windy conditions than larger particles due to a difference in mass. This could alter the spatial distribution of the erosion. Shifting initial erosion closer towards the dunefoot and increasing the range of deposition, as initiation of motion occurs at lower wind speeds, allowing for transport to occur more frequently.

One of the motivations for the introduction of foredune blowouts is increasing the transport of calcium rich sediment from the beach to the hinterdunes , where additional calcium aids in binding phosphate by counteracting acidification. This calcium rich sediment is often comprised of platelet shaped seashell debris (Bos-Staatsbosbeheer et al., 2022). Bagnold’s transport relation is however based on experiments done with quartz sand of a diameter of $240\mu$ meter and does not take grain shape into consideration (Bagnold, 1937). Some studies have been done on the effect of grain shape on transport rate such as (Deal et al., 2023) however the model does not take this into account. The manual issued by the Programme for a Rich Wadden sea (PRW) (Bos-Staatsbosbeheer et al., 2022) references an unpublished study which concludes that smaller more elongated particles travel further than larger more spherical grains based on a field study done at the National Park Zuid-Kennemerland. This would imply that the model underestimates the distance of transport.

### Saltation

Bagnold's transport relation is one of the underlying principles of the model, and is used to calculate the concentration of sediment within the air column. However this is a bulk transport relation that is based on a single mode of transport, namely saltation. This method of transportation entails particles "jumping", essentially being blown upwards and forwards by the wind before falling back down and bouncing and rolling onwards. In this manner there is a constant interaction between the sediment in the air and sediment in the bed.

Bagnold's transport relation is therefore not necessarily well equipped to describe small amounts of finer sediment particles traveling large distances higher up in the air column, sometimes referred to as suspended transport or overpowdering. An extreme example of this would be when Sahara sand is blown across the Mediterranean towards Europe. The same study cited by Bos-Staatsbosbeheer et al. (2022) measured fluxes of up to $63\ [grams/yr]$, based on the limited data shown in Bos-Staatsbosbeheer et al. (2022), with a weight percentage of carbonate content up to $9WT$%. The PRW manual Bos-Staatsbosbeheer et al. (2022) attributes these fluxes to suspended transport. Whether a flux of up to approximately $6\ [grams/yr]$ of calcium is enough to counteract the effects of acidification in vulnerable dune landscapes remains unclear.

### Surface & Soil Moisture

The soil moisture has not been taken into account in the model settings used to create the results. This may affect the calculated bed level changes and sediment transport. Soil moisture increases the shear velocity threshold due to the sand clumping together due to the water between the grains. This effect can easily be spotted when looking at the creation of sand castles, attempting to create a sandcastle from dry sand is a much more arduous labor than using wet sand.

In the case of the model, different effects such as waves, run up and even the tide could increase the local soil moisture level, thus increasing the local wind shear threshold and limiting the amount of available sand. This could subsequently shift the initial location of erosion towards the dunefoot locally increasing the amount of erosion.

### Cross Shore Profile Shape

The profile used in all the simulations consists of a dune and a horizontal extension at the landward boundary as can be seen in Figure 3.1. In reality dunes usually slope back downwards beyond the dune top rather than continuing on along a flat plane. This may affect the erosion and sedimentation as a flat plane will have a different effect than an undulating surface on the local wind shear, which is the driving force of the transport. This among other factors may contribute to the lack of clear depositional lobe in the simulations.

## 5.6. Case Studies

Some comparisons between the model results and results of existing field studies can be made to put model results into a larger perspective.

### The Kop van Schouwen

As part of the Kop van Schouwen "slim omgaan met zand" project a monitoring program was set up that measured the local bed levels from 2015 up until 2020(Schouwen, 2019). Different measures were taken as part of this project. Vegetation was removed starting in January of 2017 and work began on constructing foredune blowouts as well as removing the nutrient rich top soil in late September of 2017.

Figure 5.12 shows the difference in bed level between August 2017 and September 2020 projected onto a google satellite image of the area from 2018. The removal of vegetation and trees can be seen inland. There is a clear pattern of erosion along the dune foot and deposition in the constructed foredune blowouts.

There is a landward shift of the dunefoot according to the monitoring report Schouwen (2019) which would explain the pattern of erosion along the coast. Figure 5.13 shows the bed level from august 2017 in red, from October 2018 in blue, from September 2020 in green and the difference between 2020 and 2017 in black along the transect shown in Figure 5.12. The deposition that can be seen in the blowout in Figure 5.12 and along the black transect in Figure 5.13 appears to be due to the landward shift of the dunefoot and foredune blowout filling an area where the local bed level was lower.

The model does not include a landward shift of the dune foot which can explain the difference in behavior along the dune foot. The foredune blowout in the model ends with a flat area which differs from what Figure 5.13 shows where there is a drop in bed level behind the foredune blowout initially, which can explain why the pattern of deposition seen in the field study differs from the model results.

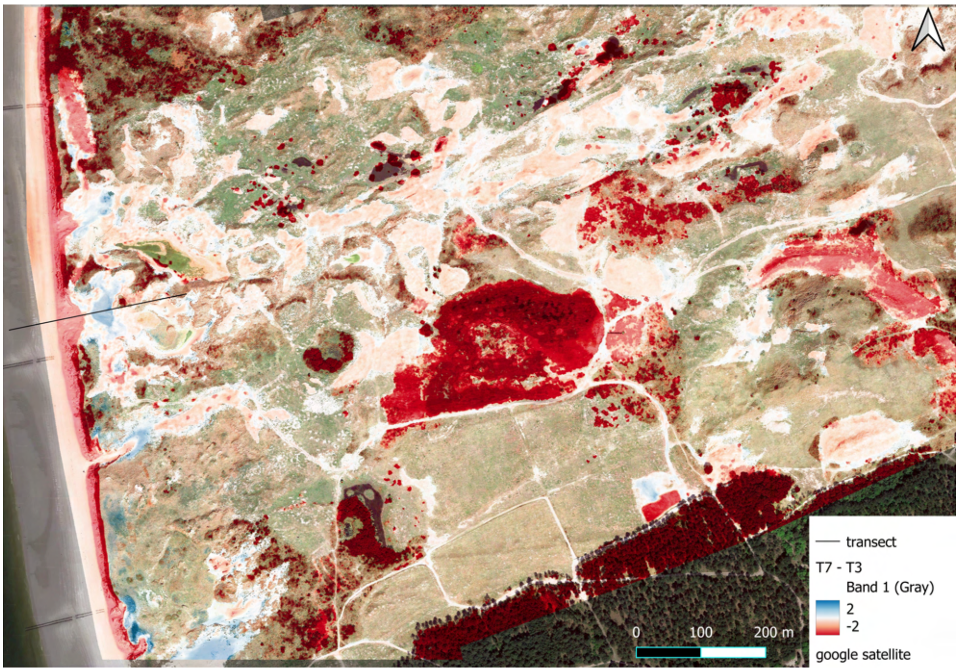



**Figure 5.12:** Bed level changes from 2017 to 2020 at the Kop van Schouwen, plotted from -2 meters to +2 meters, transect along which elevation data is plotted is shown in black

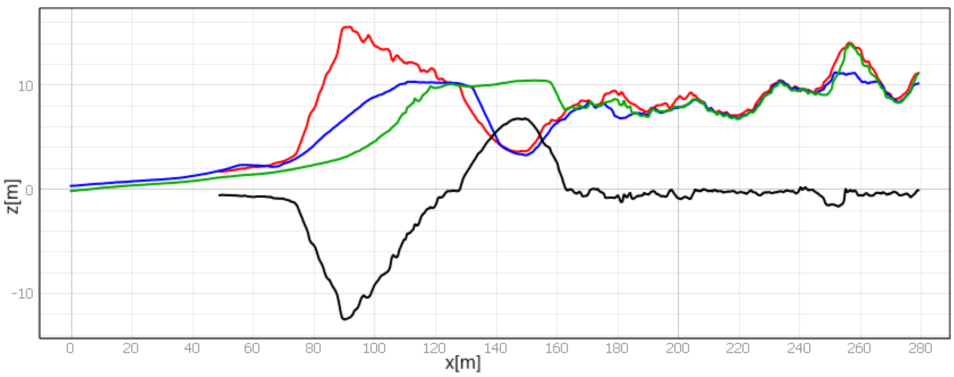
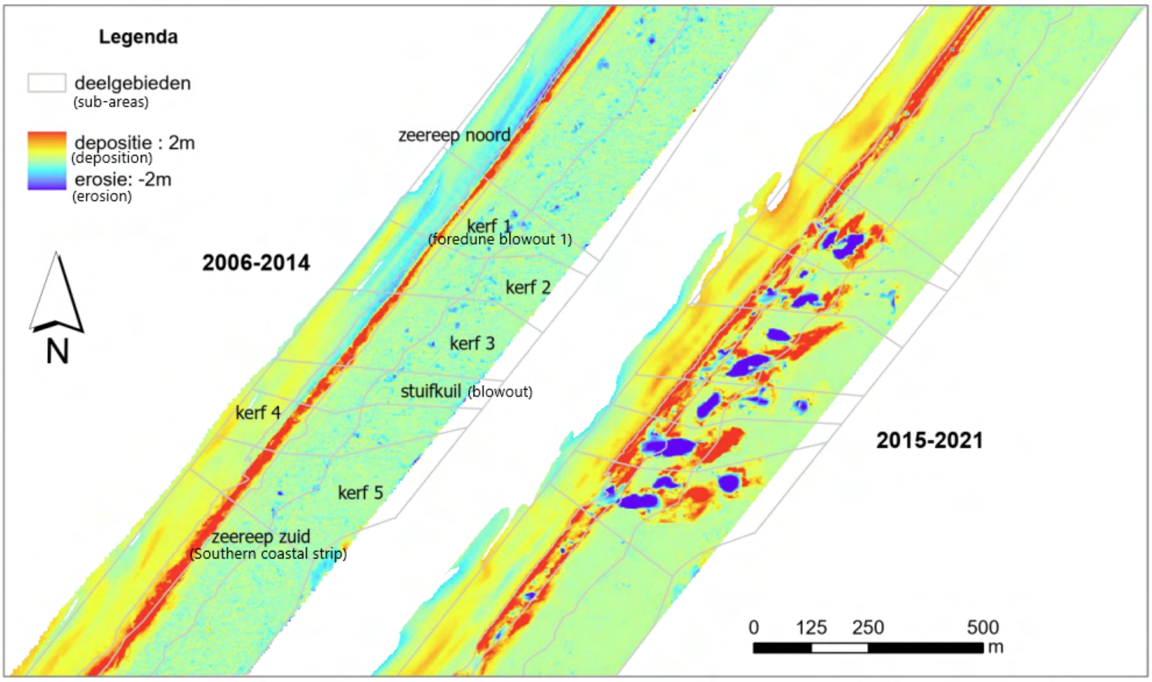



**Figure 5.13:** Bed level along the transect through the foredune blowout, data from august 2017 in red, October 2018 in blue, September 2020 in green and the difference between 2020 and 2017 in black

## Meijendel

At the project in Meijendel likewise a monitoring program was set up in which bed levels were measured. 5.14 shows the bed level changes over a period of 8 years prior to the project as well as the bed level changes over a period of 6 years post the removal of the top soil, taken from (B. Arens, 2022). The bed level changes between 2006 and 2014 share some similarities with the model result for a simulation without a foredune blowout in that there is deposition along the dune foot but very little activity beyond that. The bed level changes behind the primary dune row that are visible in the field study are attributed to the removal of local vegetation (B. Arens, 2022).

The model results do show different behavior when compared to the period from 2015 to 2021. While there is still deposition along the dunefoot in both cases, the beach volume also appears to grow in the field study which is not the case for the model results. The spread of the deposition in the model is much more limited then the field study data. Comparing the erosion that occurs for the vegetation limited simulation with the erosion that was measured in the different foredune blowouts does show some similarity. At Meijendel the measured erosion varied from approximately $6000[m^3]$ to $19000[m^3]$ over a period of six years while the total erosion for the vegetation limited simulation was in the order of $9000[m^3]$ over three years which is about equal to the upper limit of the measured erosion.




*Figuur 3.2. Verschilkaarten strand/duin, 2006-2014 en 2015-2021 op basis van Jarkus-gegevens. Maxima 2006-2014: -4,67 en +5,90m, 2015-2021: -8,50 en 5,57m.*

(Figure 3.2. Bedlevel difference map of the beach/dune, 2006-20014 and 2015-2021, based on JARKUS data. Maxima 2006-2014: -4,67 & 5,90m, 2015-2021: -8,50 & 5,57m)

**Figure 5.14:** Bed level changes that occurred in Meijendel prior to the introduction of foredune blowouts and post foredune blowouts source: (B. Arens, 2022) (internal report). Same as Figure 2.2

# 6 Conclusion

The aim of this thesis was to gain a better understanding of the role that constructed foredune blowouts can and may have to play in the Netherlands and to answer the question:
"*How can constructed foredune blowouts affect the Dutch dune system?*"
This is done by answering the four stated sub questions.

### How do erosion and sedimentation patterns of constructed foredune blowouts impact dune transport rates?

Based on the model results, the introduction of a foredune blowout does not increase the erosion that takes place along the beach and inter tidal area. The deposition that occurs along the dune foot remains the same outside of the direct bounds of the entrance of the foredune blowout. This means that the sediment that would deposit on the dune foot at the location of the foredune blowout is transported further inland, however there is no indication that sand deposited elsewhere along the dune foot also travels to the hinterdunes.

The erosion and sedimentation visible in and around the modeled constructed foredune blowout can be attributed to processes occurring within the foredune blowout. The erosion is the result of local accelerations caused by changes in the bed level along the erosional walls. This sediment is then deposited further downwind up to a range of 100 meters. Beyond this range the model behaves identical to a situation without a foredune blowout.

In summary, based on the model simulations run and the underlying assumptions that were made, foredune blowouts redistribute sediment that was already located within the dune massif further inland. Sediment that would otherwise be deposited where the blowout has been constructed travels further inland as well, though this does not hold true for sediment outside the direct bounds of the blowout.

### How do different construction methods affect the sediment volume balance?

Implementation of a trough shaped foredune blowout in the model is possible though not inherently necessary. The avalanching process within the model adjusts the rectangular profiles that are used, leading to similar erosion and sedimentation patterns.

By placing a large mound of sediment behind the foredune blowout rather than removing it or placing it in a depot, the sediment becomes available for transport. This offers more sediment though the range of transport does not increase within the model.

It is possible to induce a blowout like feature by removing and limiting the growth of vegetation within the model. This results in less bed level changes than for rectangular foredune blowouts. In the field a similar approach has been utilized at Meijendel where 1 to 2 meters of top soil was removed for the construction of foredune blowouts. This method may offer a less intrusive manner of inducing a local redistribution of sediment.

### How can quantitative design aspects of constructed foredune blowouts be altered to better fulfill desired design goals?

For ecological goals the restoration of the dynamic nature of the dunes as well as the reintroduction of calcium rich sediment into the hinterdunes is seen as essential. Model results suggest that orienting the erosional walls parallel to the prevalent wind direction induces smaller fluxes than when the wind flows over the erosional walls. More transport would align with the goal of resetting ecological succession, as both large scale erosion and sedimentation create areas of bare sand in which embryonic dunes could develop. Creation of wider foredune blowouts offer the larger areas of bare sand simply by virtue of being bigger, which again would align with the goal of resetting succession. In terms of range of transport, no distinct difference is observed between the different design combinations for chosen grain size. Creating multiple foredune blowouts induces more bed level changes, though proximity adversely effects this. To aid in resetting succession, model results suggest constructing blowouts further apart than their individual range of influence which in this case would be 100 meters. The effects of different design aspects on overpowdering can not be quantified using the model results produced, as neither the type of transport nor the grain size is implemented.

For water safety goals, two distinct mechanics are considered. Reinforcing a different location with removed soil of a foredune blowout and localized bed level increases. The orientation of the foredune blowout does not influence the volume of the removed soil in the model. It should be self evident that the volume of the removed soil is dependent on the width and depth of the foredune blowout and that the creation of wider foredune blowouts offer more sediment to use to reinforce the primary dune row elsewhere than smaller foredune blowouts for the same profile. It should be noted that removing more soil than is needed to reinforce does not further add to the water safety.

In terms of aiding the dune growing potential, the increase in bed level remains local and the sediment predominantly originates from within the blowout itself. Larger foredune blowouts do allow for more transport of sediment from the beach to the hinterdunes though this does not scale linearly and is relatively small portion of overall transport. Sediment that is transported, would otherwise have been deposited on the beach or along the dune foot. For local increases in water safety this may be sufficient though the model results do not show any evidence this would work for the systematic growth of the dunes across the entirety of the Dutch coastline.

### To what extent can a program of requirements be established for the design of a constructed foredune blowout?

Goals for foredune blowouts were often defined broadly in the past, leading to disagreements between parties and sometimes within organizations on whether any particular project was a success. The creation of a manual by the ”Programme for a Rich Wadden sea” does aim to remedy this by suggesting 9 standard goals for the creation of foredune blowouts. However there is still much uncertain with regards to blowouts before any kind of standardized program of requirements can be set up. Based on the model results, construction of larger foredune blowouts might be preferable as this would offer larger areas of bare sand and more removed sediment to reinforce other areas of the dunes.

## How can constructed foredune blowouts affect the Dutch dune system?

Constructed foredune blowouts offer a method of creating areas of bare sand which can create space for ecological succession in the vicinity of the blowout. The sand that is removed may also be used to reinforce weaker areas of the dune row. They can offer a diverse looking landscape if that is desirable. However model results do not indicate that constructed foredune blowouts facilitate additional growth of the dunes. The changes in bed level in the model are primarily a redistribution of sediment already situated within the primary dune row.

# 7 Recommendations

There are some general model recommendations that would aid in further improving model results. Additionally some thoughts are given as to what steps can be taken with regard to constructed foredune blowouts

## Length of the Simulation

The simulations run, offer insights into the behavior of (constructed) foredune blowouts over the period that they are simulated, in this case that is a period of 3 years. However gaining more insight into the long term developments of the system is of importance and also not within the scope of this thesis. Both geomorphological as well as ecological processes can take place on the scale of decades to millennia and further understanding the effects of decisions made today on the future will be of importance to ensure both safety and quality of life to the Dutch people and nature.

## Grain Size and Distribution

As mentioned in the discussion, a single grain size is used for every single simulation. This of course is an over simplification of reality and it would be useful to study the effect of different grain sizes and their distribution on the inner workings of foredune blowouts and whether this fundamentally alters model results.

## Soil Moisture

The model setup used doesn't simulate the effect of any soil moisture on the transport of sediment, which could limit availability of sediment in the intertidal range. AeoLiS does offer the ability to incorporate the effects of soil moisture so it would be interesting further study the effect of soil moisture on the workings of foredune blowouts.

## Large Scale Effects

The model setup and results look at the effect of foredune blowouts on a relatively local scale. It would be interesting to see what the effect of larger scale processes, such as long shore transport, would have on local sediment transport. Approaching the system on a larger scale allow for more accurate long term predictions and offer insights into different management approaches of Dutch dunes.

## Implementation of Vegetation

AeoLiS offers the ability to implement a vegetation mask that can locally affect the wind shear. The vegetation parameters that are available in the model are applied globally to every cell with vegetation with the exception of vegetation height. In reality embryonic dunes might have different growth rates, optimal burial rates and affect the wind shear differently than say grey dunes. It would be interesting to see whether a vegetation mask with different parameters behind the dunes than in front would alter model results.

## Grey Literature

While a large number of foredune blowouts have been created in the Netherlands over the years, information on these projects is often relegated to grey literature and is written in Dutch. This limitation can hinder access to data and field studies on a subject matter that is actively being researched. One possible solution is to encourage responsible parties to publicly share technical reports on constructed foredune blowouts through platforms such as STOWA (Stichting Toegepast Onderzoek Water or Foundation for Applied Water Research), which could greatly facilitate the provision of information.

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# A

# Extra Figures

**Table A.1:** Different variables and their values used for simulations

| variable | value | unit |
|---|---|---|
| timestep | 3600 | [s] |
| grainsize | 0.0003 | [m] |
| layer thickness | 10 | [m] |
| amount of layers | 3 | [-] |
| roughness k | 0.00001 | [m] |
| vertical vegetation growth rate | 1 | [m/year] |
| optimal burial rate | 0.3 | [m/year] |
| maximum vegetation height | 1.2 | [m] |
| lateral growth probability | 0.99 | [-] |

**Table A.2:** Volume of removed soil for different widths and number of blowouts

| width of blowout $[m]$ | number of blowouts [-] | removed volume $[m^3]$ |
|---|---|---|
| 20 | 1 | 37700 |
| 50 | 1 | 94200 |
| 100 | 1 | 188300 |
| 200 | 1 | 376600 |
| 20 | 2 | 75300 |
| 50 | 2 | 188300 |
| 100 | 2 | 376600 |
| 200 | 2 | 753300 |

**Table A.3:** sum of bed level changes up to $x = 800$ and the sum of the bed level changes divided by the size of the model domain

| run | ID | sum dzb(:800) | sum/domain |
|---|---|---|---|
| run 1 | W02O00N1 | -2.595 | -2.68079E-05 |
| run 2 | W05O00N1 | -3.41 | -2.76786E-05 |
| run 3 | W10O00N1 | -5.7488 | -2.36382E-05 |
| run 4 | W20O00N1 | -10.55 | -2.18336E-05 |
| run 5 | W02O15N1 | -2.73 | -2.36979E-05 |
| run 6 | W05O15N1 | -4.15 | -2.21688E-05 |
| run 7 | W10O15N1 | -6.53 | -2.12565E-05 |
| run 8 | W20O15N1 | -11.35 | -2.0742E-05 |
| run 9 | W02O30N1 | -3.7 | -1.95148E-05 |
| run 10 | W05O30N1 | -5.13 | -1.96101E-05 |
| run 11 | W10O30N1 | -7.61 | -1.99423E-05 |
| run 12 | W20O30N1 | -12.26 | -1.97233E-05 |
| run 13 | W02O45N1 | -5.26 | -1.80632E-05 |
| run 14 | W05O45N1 | -6.67 | -1.83645E-05 |
| run 15 | W10O45N1 | -9.03 | -1.86879E-05 |
| run 16 | W20O45N1 | -13.65 | -1.88744E-05 |
| run 17 | W02O00N2 | -3.03 | -3.57311E-05 |
| run 18 | W05O00N2 | -5.42 | -2.64648E-05 |
| run 19 | W10O00N2 | -9.67 | -2.38883E-05 |
| run 20 | W20O00N2 | -17.93 | -2.22788E-05 |
| run 21 | W02O15N2 | -3.75 | -2.52016E-05 |
| run 22 | W05O15N2 | -6.19 | -2.30283E-05 |
| run 23 | W10O15N2 | -10.49 | -2.23763E-05 |
| run 24 | W20O15N2 | -18.67 | -2.14894E-05 |
| run 25 | W02O30N2 | -4.75 | -2.12814E-05 |
| run 26 | W05O30N2 | -7.15 | -2.08333E-05 |
| run 27 | W10O30N2 | -11.31 | -2.08211E-05 |
| run 28 | W20O30N2 | -19.07 | -2.02184E-05 |
| run 29 | W02O45N2 | -6.32 | -1.94581E-05 |
| run 30 | W05O45N2 | -8.81 | -1.98067E-05 |
| run 31 | W10O45N2 | -12.85 | -1.99287E-05 |
| run 32 | W20O45N2 | -20.17 | -1.93051E-05 |

**Table A.4:** erosion up to x = 300, width equal to 1306[m]

| run | ID | erosion up to 300$[m^3]$ | erosion no blowout $[m^3]$ | difference $[m^3]$ | difference over width $[m^3/m]$ |
|---|---|---|---|---|---|
| run 1 | W02O00N1 | -17832 | -17680 | -152 | -0.12 |
| run 2 | W05O00N1 | -17861 | -17680 | -181 | -0.14 |
| run 3 | W10O00N1 | -17942 | -17680 | -263 | -0.20 |
| run 4 | W20O00N1 | -18021 | -17680 | -341 | -0.26 |
| run 5 | W02O15N1 | -17847 | -17680 | -167 | -0.13 |
| run 6 | W05O15N1 | -17899 | -17680 | -219 | -0.17 |
| run 7 | W10O15N1 | -17956 | -17680 | -276 | -0.21 |
| run 8 | W20O15N1 | -18015 | -17680 | -335 | -0.26 |
| run 9 | W02O30N1 | -17889 | -17680 | -209 | -0.16 |
| run 10 | W05O30N1 | -17922 | -17680 | -242 | -0.19 |
| run 11 | W10O30N1 | -17961 | -17680 | -282 | -0.22 |
| run 12* | W20O30N1 | -18001 | -17680 | -321 | -0.25 |
| run 13 | W02O45N1 | -17913 | -17680 | -234 | -0.18 |
| run 14 | W05O45N1 | -17932 | -17680 | -253 | -0.19 |
| run 15 | W10O45N1 | -17956 | -17680 | -276 | -0.21 |
| run 16 | W20O45N1 | -17973 | -17680 | -293 | -0.22 |
| run 17 | W02O00N2 | -17823 | -17680 | -143 | -0.11 |
| run 18 | W05O00N2 | -17926 | -17680 | -246 | -0.19 |
| run 19 | W10O00N2 | -18017 | -17680 | -337 | -0.26 |
| run 20 | W20O00N2 | -18081 | -17680 | -402 | -0.31 |
| run 21 | W02O15N2 | -17875 | -17680 | -195 | -0.15 |
| run 22 | W05O15N2 | -17946 | -17680 | -266 | -0.20 |
| run 23 | W10O15N2 | -18016 | -17680 | -336 | -0.26 |
| run 24* | W20O15N2 | -18058 | -17680 | -378 | -0.29 |
| run 25 | W02O30N2 | -17908 | -17680 | -228 | -0.17 |
| run 26 | W05O30N2 | -17957 | -17680 | -278 | -0.21 |
| run 27* | W10O30N2 | -18010 | -17680 | -330 | -0.25 |
| run 28 | W20O30N2 | -18028 | -17680 | -348 | -0.27 |
| run 29 | W02O45N2 | -17926 | -17680 | -246 | -0.19 |
| run 30 | W05O45N2 | -17958 | -17680 | -278 | -0.21 |
| run 31 | W10O45N2 | -17991 | -17680 | -311 | -0.24 |
| run 32 | W20O45N2 | -17977 | -17680 | -297 | -0.23 |

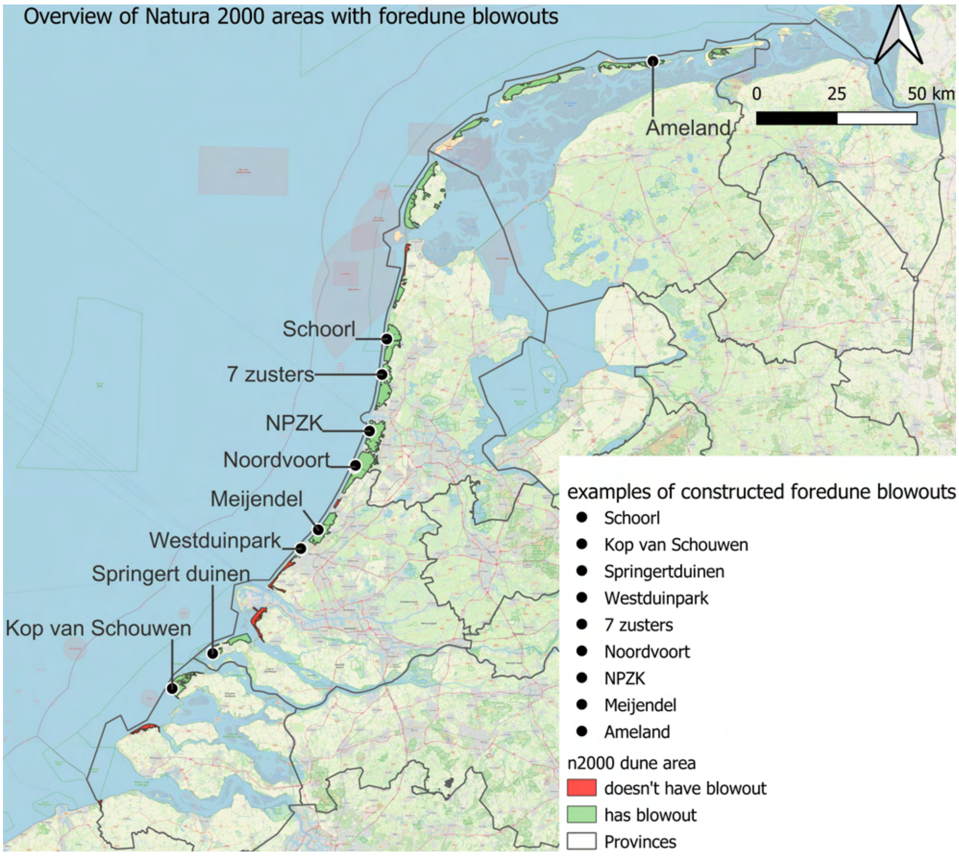



**Figure A.1:** Overview of N2000 areas that contain foredune blowouts with some examples given

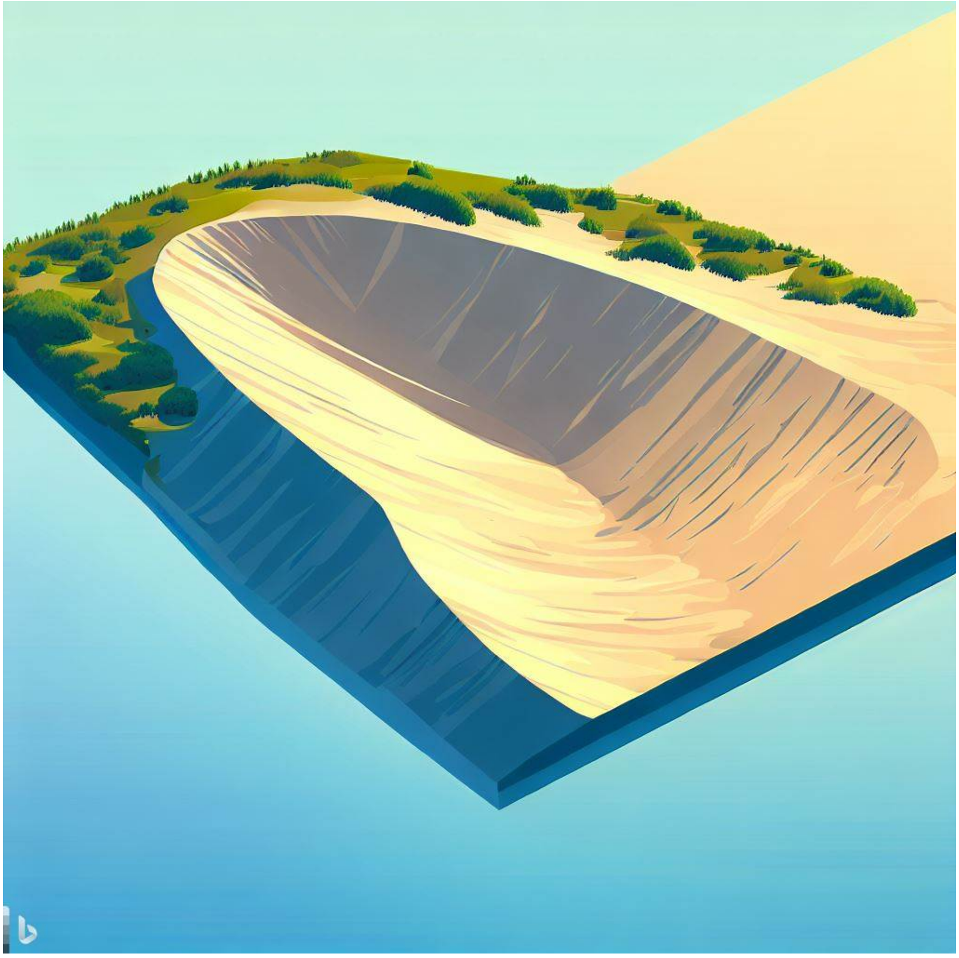
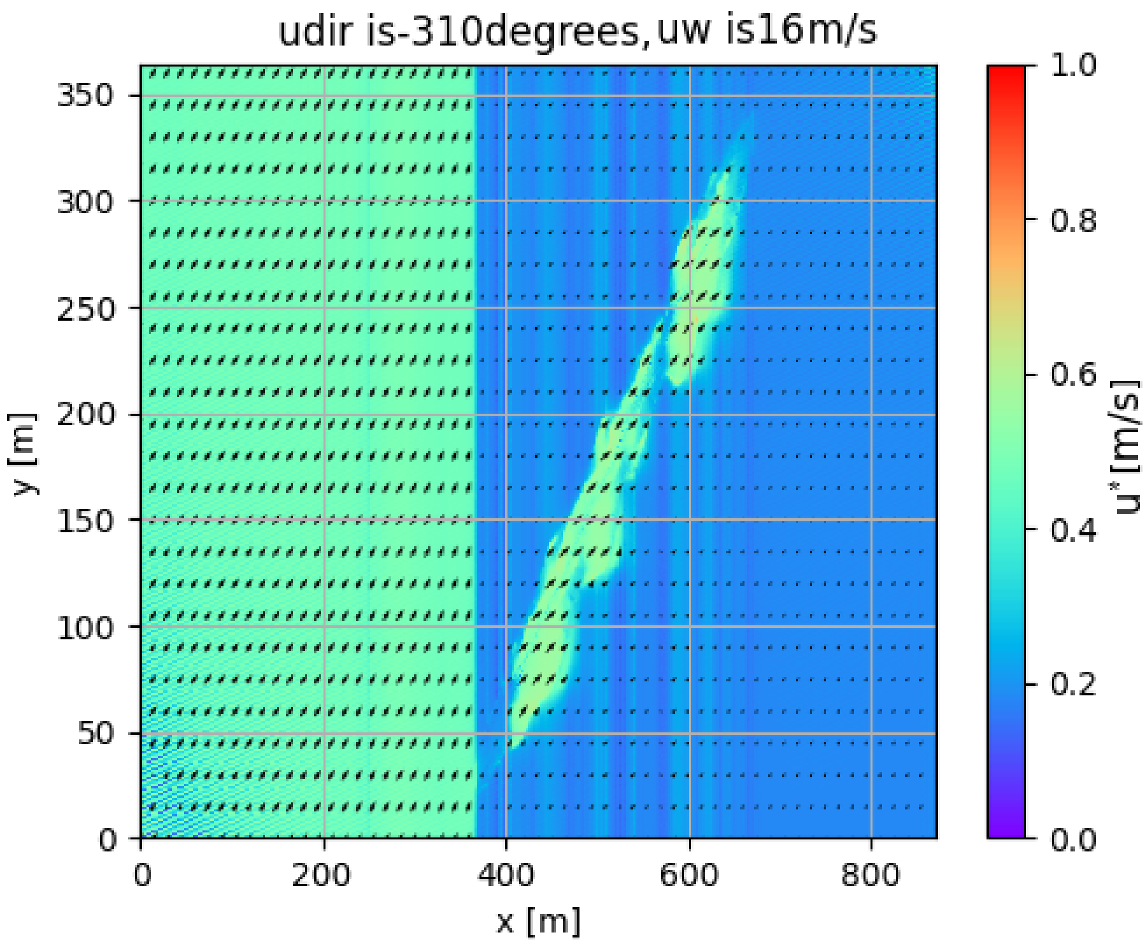
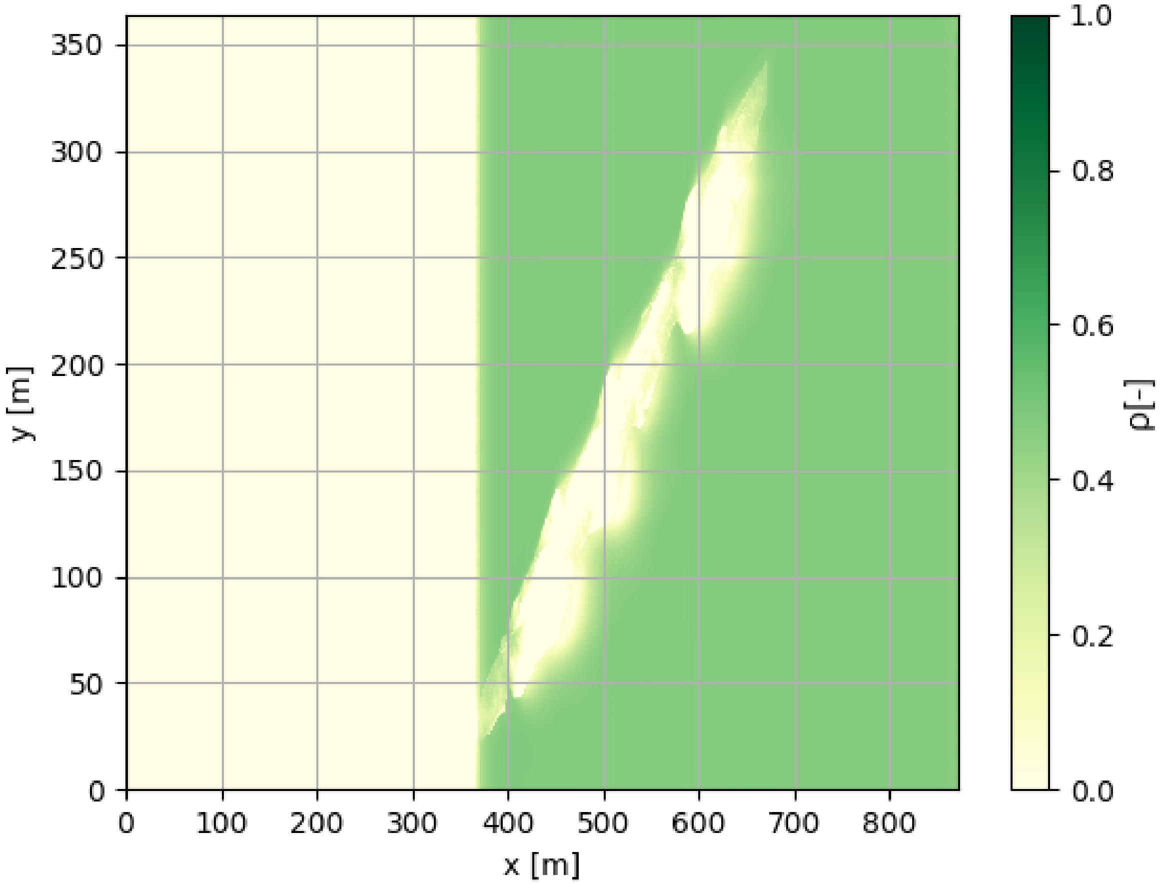


**Figure A.2:** impression of trough shaped blowout using ai image generator


**Figure A.3:** removal of vegetation creating blowouts at meijenedel

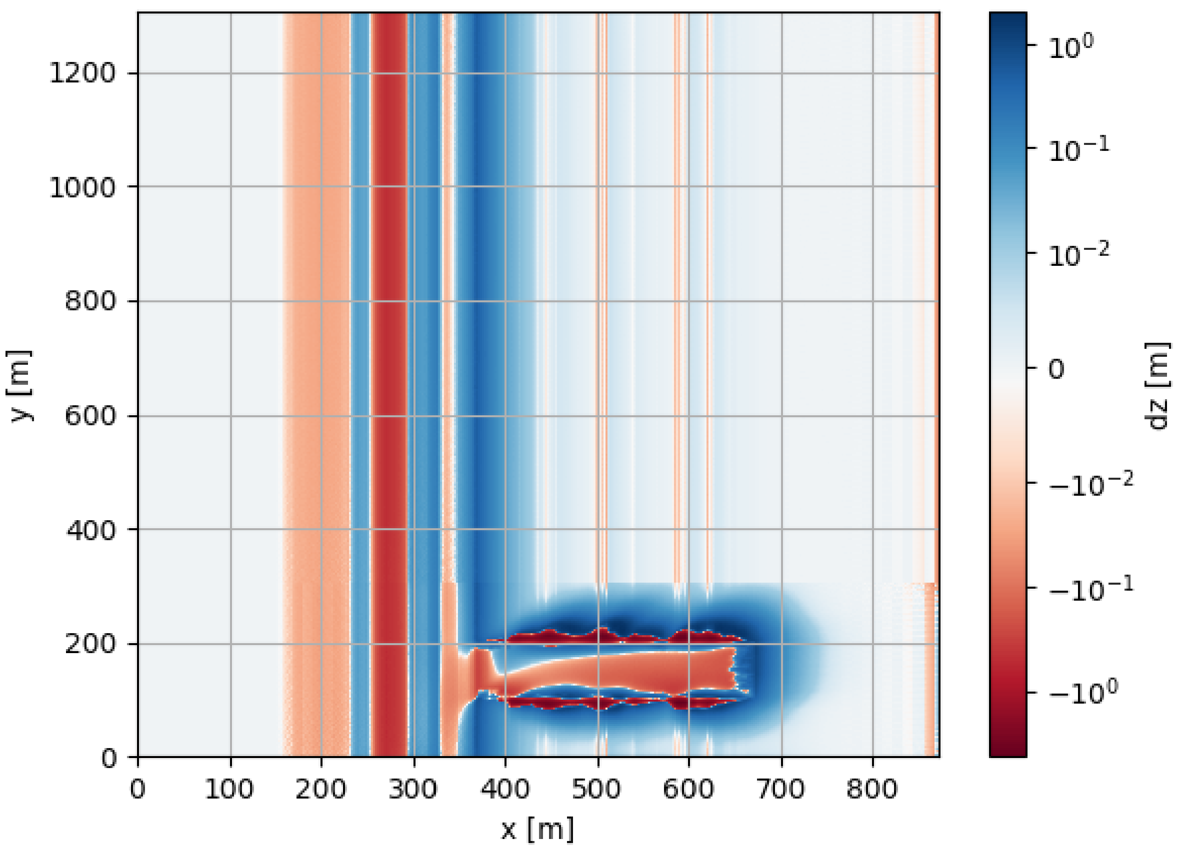



(a)

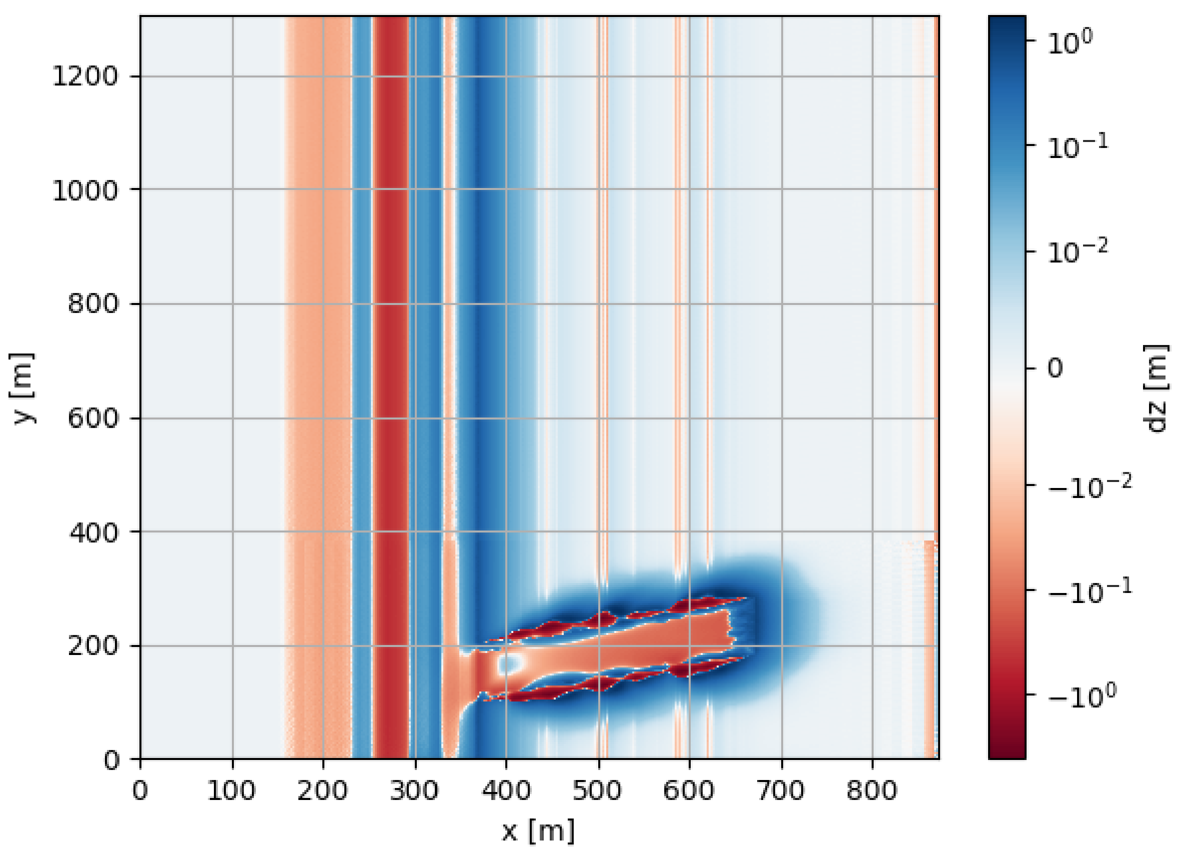



(b)

**Figure A.4:** example of the vegetation cover and the calculated wind shear for the same time step

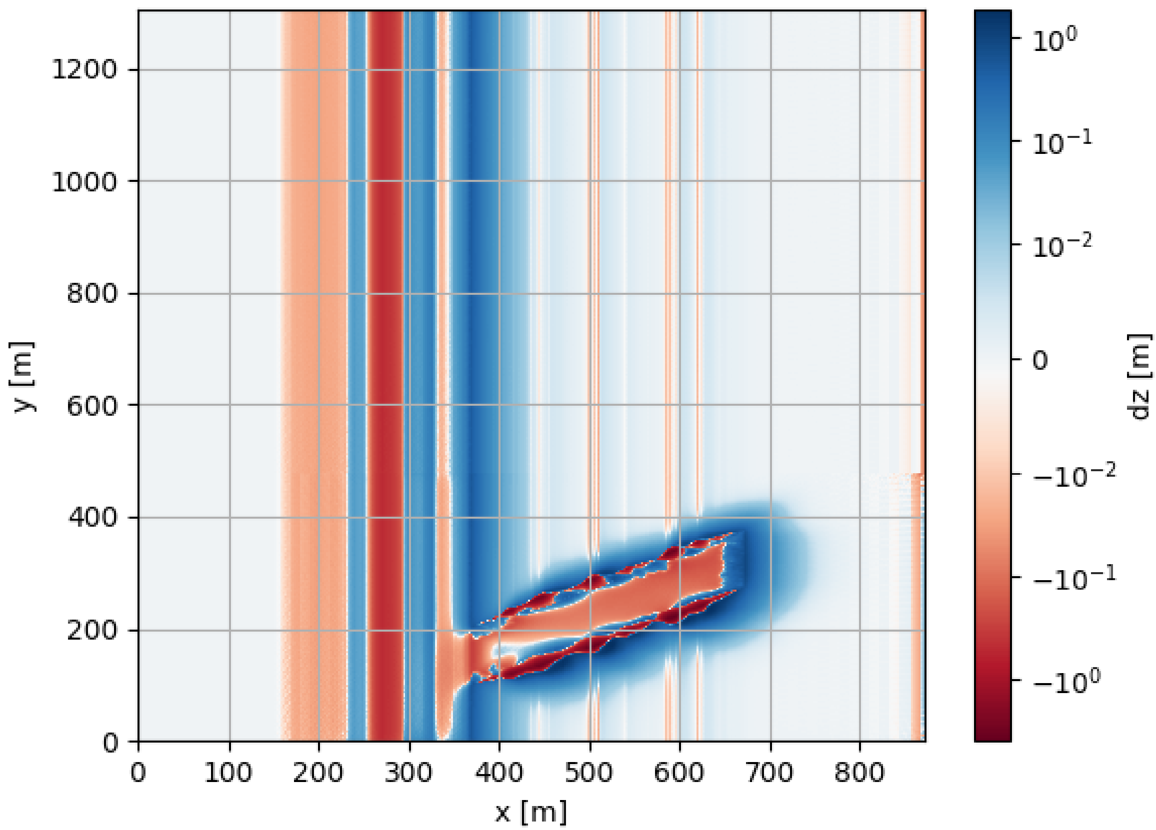



**(a)** W10O00N1

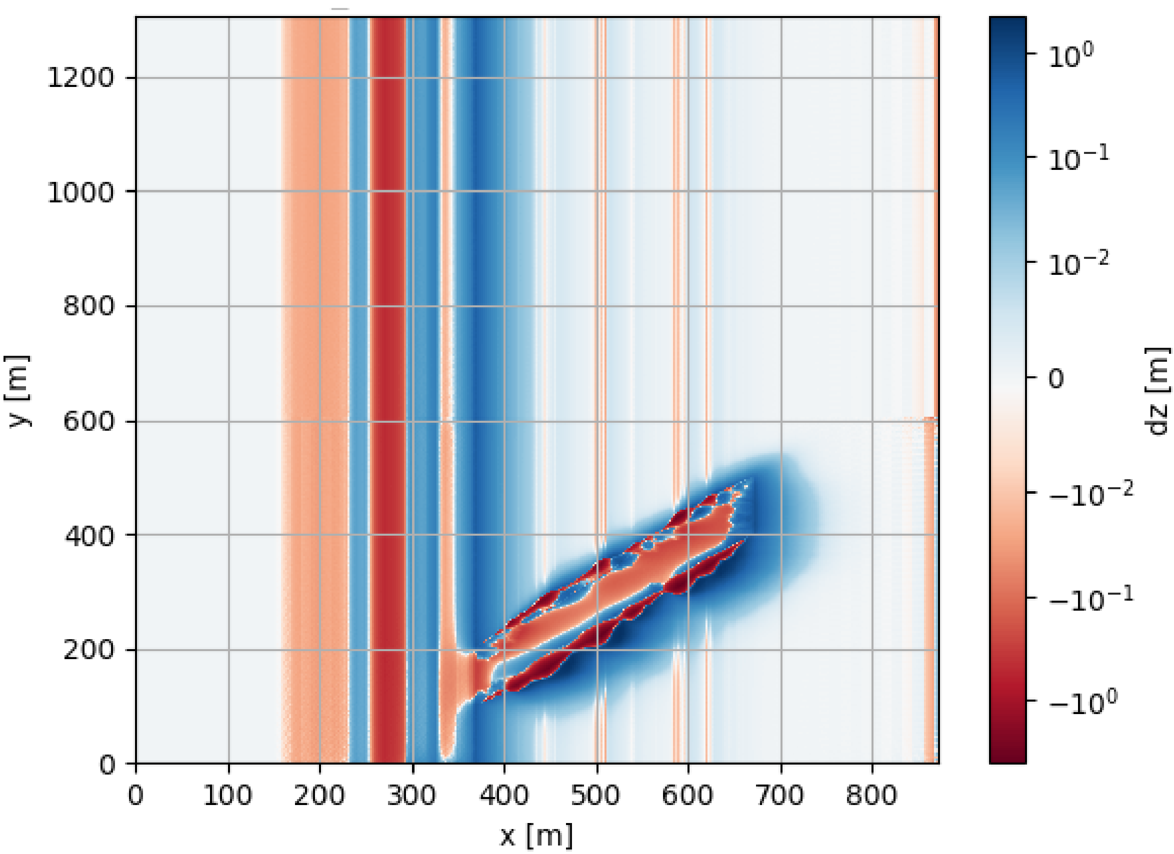



**(b)** W10O15N1

**Figure A.5:** Bed level change of four blowouts of same width, different orientation, on a logarithmic scale

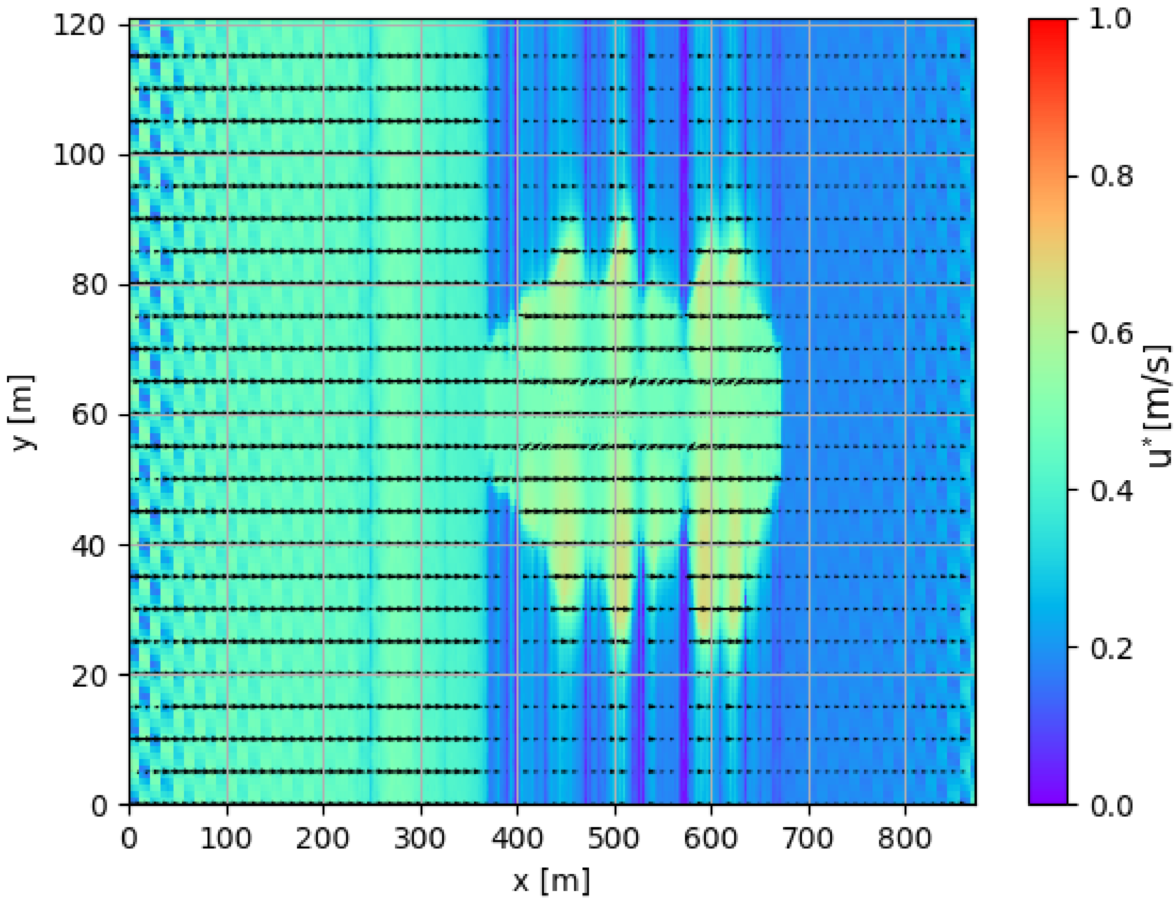



**(a)** W10O30N1

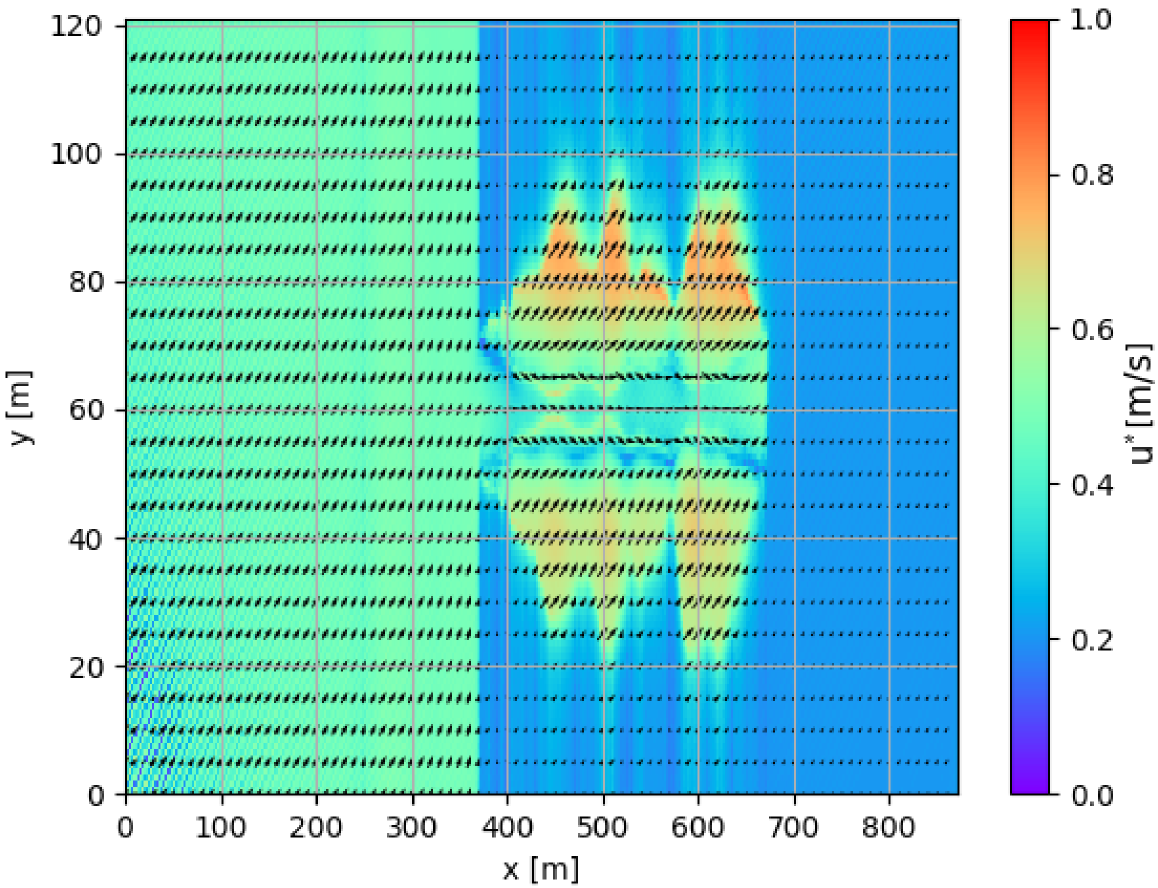



**(b)** W10O45N1

**Figure A.6:** Bed level change of four blowouts of same width, different orientation, on a logarithmic scale

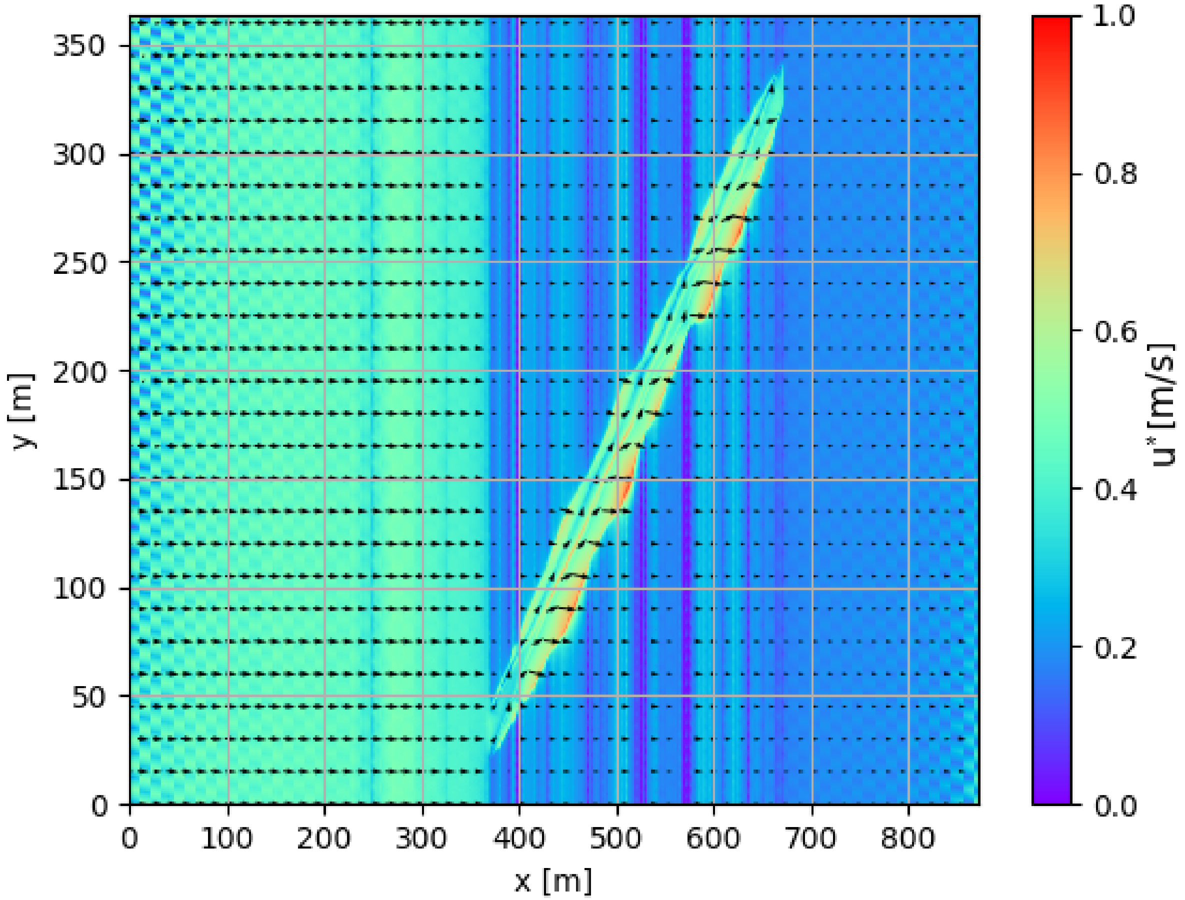



**(a)** Orientation 0°, wind direction -10 °

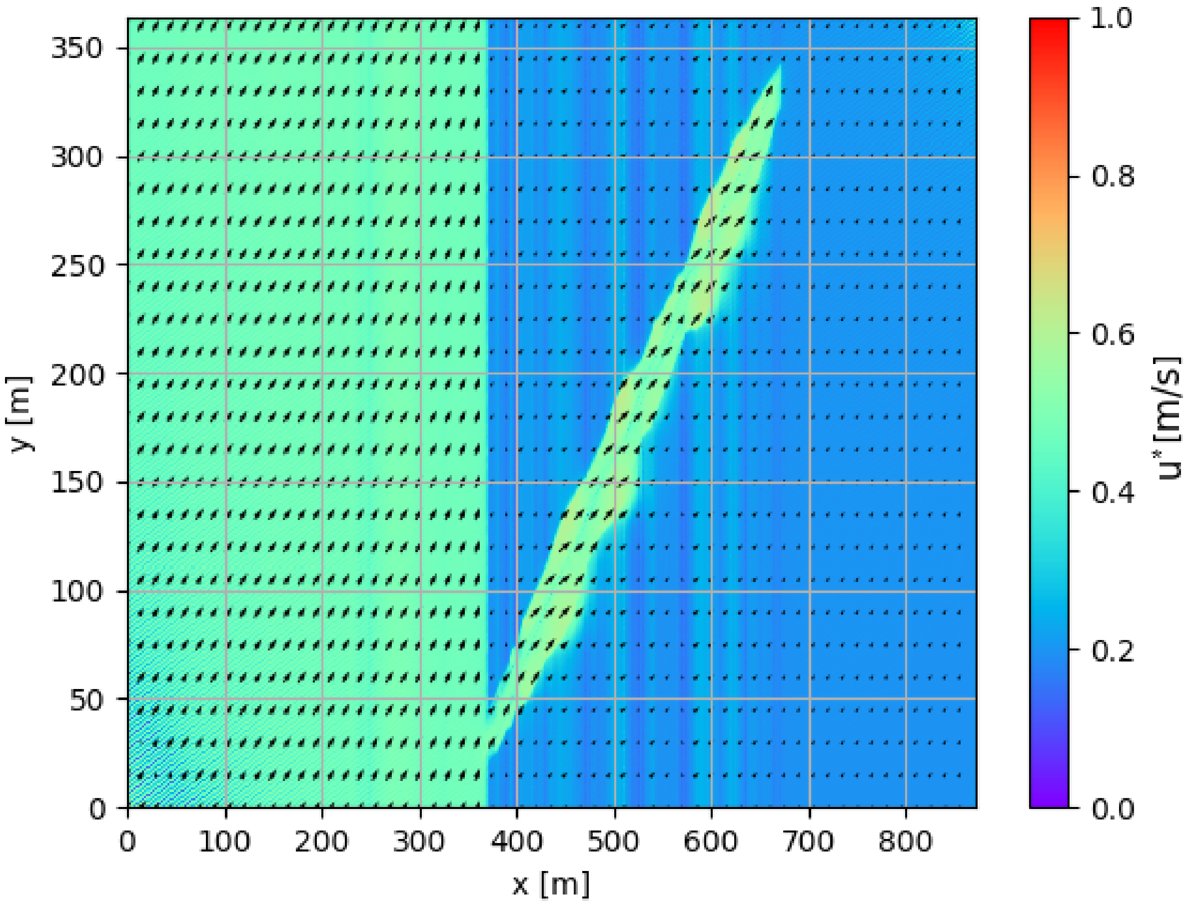



**(b)** Orientation 0°, wind direction 50 °

**Figure A.7:** Local wind shear for different wind conditions and orientations of foredune blowout




**(a)** Orientation 45°, wind direction -10 °




**(b)** Orientation 45°, wind direction 50 °

**Figure A.8:** Local wind shear for different wind conditions and orientations of foredune blowout