Linking habitat development to sedimentation dynamics after fore-dune notching

Matching habitat distribution with Aeolis model-output in Meijendel

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Matching habitat distribution with Aeolis model-output in Meijendel

MSc Thesis

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Abstract

Coastal dune systems provide many ecosystem services. With current management shifting its focus from mainly coastal protection to also include biodiversity, the need arises for tools to help aid this shift in management. One of the measures that can be taken to improve biodiversity is the creation of notches in fore dunes, which help to reintroduce sediment dynamics. Sediment dynamics havebeen linked to the development of habitat and affect the successional stages of the vegetation. These sediment dynamics can be modelled with the Aeolis model, which predicts the spatial patterns in sedimentation and erosion. However, Aeolis is not able to predict the impact of sediment dynamics on the biodiversity. Although models predicting habitat exist, no models yet exist to do so based on sedimentation dynamics for dune systems. The aim of this study is to test if the Aeolis model outcome can be used to predict habitat development. Using a case study focused on the coastal area of Meijendel, an Aeolis run was performed for one of the created notches, which outcomes were further processes using a geographical information system (GIS). The outcomes of Aeolis, in form of the sediment levels, were translated to habitat types using specified levels in sediment. Results show Aeolis is able to generally predict correct sedimentation and erosion patterns but is off with its prediction of the sedimentation levels. The combined sediment habitat model shows similar patterns to the official habitat map, which is to be expected as habitat would change not given the predicted sedimentation levels. The results may be influenced by the low predicted sedimentation by Aeolis, as the actual levels may locally be much higher than predicted. Also, the Aeolis model output is not yet fully compatible for processing in GIS software, making it impossible to use georeferencing and thus performing a numerical validation. Improvements can be made by conducting field visits before modelling, to gather a minimum of 3 but preferably 5 control points to enable georeferencing. The model should be further developed into a self-running model working of the Aeolis output for ease of use, and it would be advised to add the relative abundance of habitat as a probability factor to enhance model accuracy. However, this study showed that it is possible to model habitat development based on sedimentation dynamics modelling.

1. Introduction

Coastal dunes are highly dynamic ecosystems which provide valuable ecosystem services. Not only do they play a vital role in coastal protection, they also provide many socio-economic benefits (Ruessink et al., 2018). Especially in the Netherlands, coastal protection is ever more important due to climate change and rising seawater levels. Management has long focused on keeping dunes fit for the service of coastal protection (Everard et al., 2010), consisting of building and stabilizing dunes by planting vegetation and placing screens (De Jong et al., 2011). The stabilizing of especially the foredunes has the desired effect of reducing the risk of flooding of the land behind the dunes. This does, however, have its effect on other properties of the dunes, for instance the development of vegetation and dunes aesthetics (Ruessink et al., 2018). By stabilizing the dunes, sedimentation dynamics are reduced, which has a negative effect on the dune's biodiversity (Arens et al., 2022; Tonkens, 2022). New findings have led to a shift in focus of management, now also aiming towards an increase in dune biodiversity (Arens et al., 2022). The stabilized fore dunes mainly consisted of with *Ammophila arenaria* (European marram grass) stabilized white fore-dunes and grey dunes (Assendorp, 2010; Provoost et al., 2009; Van der Valk et al., 2013). New management practices aim to create a row of dynamic white dunes, which have more sediment exchange with the hinterland, resulting in a more natural gradient in the vegetation succession land inward (Arens et al., 2022; De Jong et al., 2011).

Currently, this new focus on more biodiverse dune systems has led to the introduction of foredune notching, which increases sediment dynamics in coastal dune systems (Riksen et al., 2016; Ruessink et al., 2018). Notching is the creation of baren sand strips in the dune. Often these are made relatively perpendicular to the coastline. The notches are created by removing vegetation and sediment from the dunes. This allows the wind to blow through the notch, picking up sand and dispersing it in the surrounding areas (Arens et al., 2022; De Jong et al., 2011). The inflow of sedimentation can affect the vegetation in the areas surrounding the notch (Riksen et al., 2016). The increase in sediment dynamics in turn affects the successional stage of the vegetation present in the area adjacent to the notch. The vegetation, especially behind the fore-dunes, is often in later successional stages, consisting of small shrubs and 'later' successional pioneer species (Tonkens, 2022). These later successional species often cope less with the increased dynamics, causing these species to disappear in the areas surrounding the notch (Arens et al., 2022; Kooijman et al., 2014). This process causes a shift in successional stages, effectively setting back succession to an earlier stage of pioneer species (Arens et al., 2022; Arens et al., 2009). The species taking over are, in the Netherlands, predominantly dune grasses, like the *Ammophila arenaria* species (European marram grass), which can cope with the increased sedimentation (Anwar Maun, 2009; Arens et al., 2022). When sedimentation levels more land inward drop to less than roughly 1 cm/year, the dunes change to grey dunes, where more plant species start growing and biodiversity increases (Riksen et al., 2016; Tonkens, 2022).

A relationship exists between the amount of sedimentation and the development of the habitat in dune systems (McGuirk et al., 2022; Tonkens, 2022). Research on the biodiversity in Dutch dunes shows how certain habitats develop under different sedimentation rates (Tonkens, 2022). His results (figure 1) show how the relative abundance of habitat types may change over increasing sedimentation levels. Under low sedimentation levels, up to around 0.8 cm/year, mostly grey dunes develop. When the sedimentation level increases, the relative abundance of grey dunes lowers, making place for white dunes, grass encroached areas and bare sand. The vertical bars are set as borders between sedimentation rates, ranging, from left to right, low, medium, and high (Tonkens, 2022).

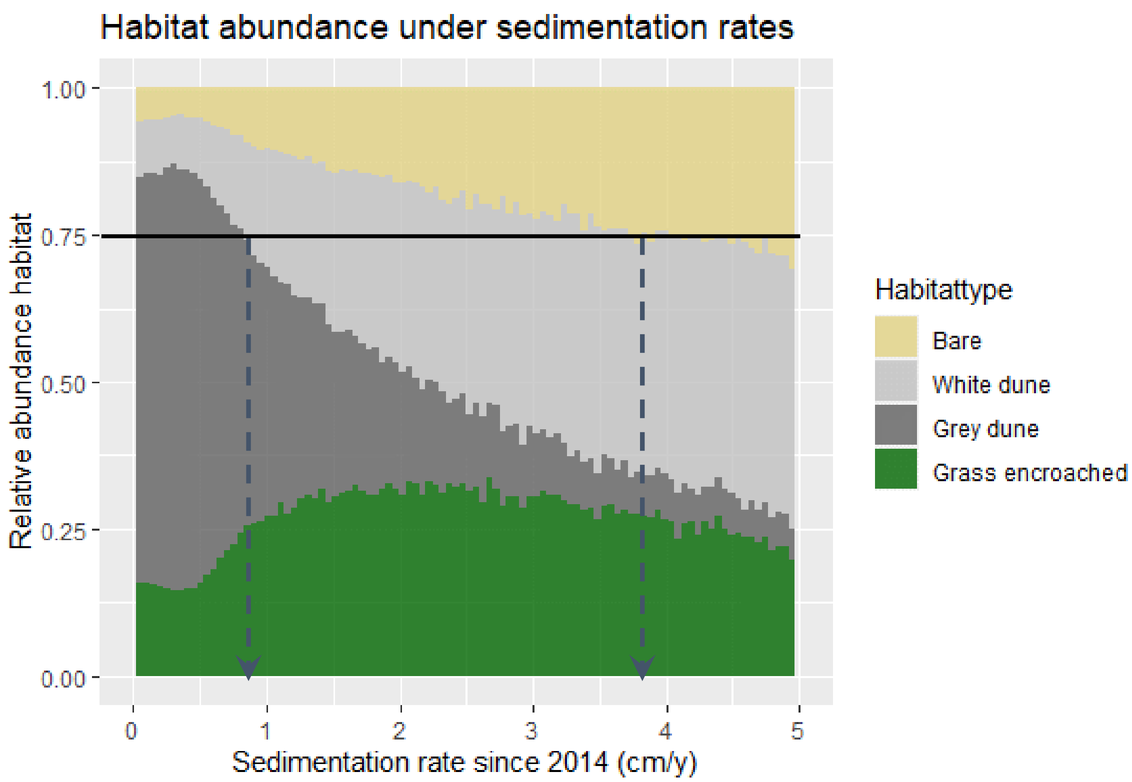

Figure 1: Graph showing the relative abundances of different habitat types under different sedimentation rates. The arrows indicate the boundaries which are set as points for low, medium, and high sedimentation (Tonkens, 2022).

Currently, the dynamics of the sedimentation and the aeolian processes at play can be modelled using the Aeolis model, created by Hoornhout et al. (2015). Using various input parameters, like weather conditions, running time, and vegetation development, the model can make predictions on the erosion and sedimentation levels in dune systems (De Vries & Van Manen, 2023; Meijer, 2020). Also, a number of models predicting the development of vegetation exist. One example is Nucom, which can model vegetation development in heathland and tundra areas. Nucom models the development of vegetation, taking the nutrient cycling and nutrient competition into account (Heijmans & Berendse, 2009). There are also more globally oriented models available, called Dynamic Global Vegetation Models (DGVM), which aim at modelling vegetation based on biotic and/or abiotic factors (Argles et al., 2022). However, literature does not yet show the use of models for predicting habitat based on sedimentation dynamics. When searching the literature, the main findings on linking habitat with sedimentation are found in the aquatic ecosystems, like research carried out by Milhous (1998), who linked the inflow of sediment to the formation of habitat, and Pisaturo et al. (2021) who modelled the habitat of fish species under influence of sediment flushes. However, for coastal dune systems, not much can yet be found on modelling habitat or vegetation. An example of a model linking aeolian processes to habitat was found in a review paper by Barrows (1996), where he looked at a model which was used to determine management actions to preserve the habitat of an endangered lizard species. However, no model was found with the aim to predict habitat development based on aeolian processes in coastal dune areas.

This research therefore aims to link the sedimentation outcomes of the Aeolis model to habitat development. The main objective is to predict habitat development in fore dune systems based on the predictions made by the Aeolis model. To do so, three subobjectives were set to break down the research into three steps, with 1) model the expected sedimentation dynamics after notching in fore dunes. This outcome could then be 2) translated into a format which can be used for integration in a geographical information system (GIS) to 3) model habitat development based on the spatial sedimentation pattern and what is known on the relationship between the sediment and habitat development.

To reach the objective, a case study setup is used. The chosen area for the case study is the coastal area of Meijendel, The Netherlands. This area was chosen as it is an area where notches in the fore-dunes had been made. Although the notches are not typically found in the Dutch coastal dunes, the area does show representative traits of the Dutch coast. Furthermore, a lot of data on this area was available, both in the form of field data as well as model input for Aeolis. Using this model input, an Aeolis run was performed for the study area. The outcomes were loaded into the ArcGIS Pro software where the modelling of habitat development was performed.

2. Methods

2.1 Study area: Meijendel

The area selected is part of the Meijendel natural area, a coastal area which stretches between the municipalities of Wassenaar and The Hague (figure 2), the Netherlands. Meijendel forms the largest continuous dune area, around 6km across, of the province of South Holland (The Hague, 2023; Van der Hagen et al., 2017). It is part of the Natura 2000 network, with aim at habitat conservation (Ministerie van Landbouw, n.d.). The selected area lays in the fore dunes of Meijendel, where a total of five notches have been created in 2015 (figure 2) (Van der Hagen et al., 2017). Although notches are not typically found along the Dutch coast, the area does show representation of the Dutch sand dune coast lines, with large sandy beaches and the typical open sand dunes (The Hague, 2023; Van der Hagen et al., 2017).

Figure 2: Arial photo of the notches created in the fore dunes of Meijendel (ESRI, 2023). The red box shows the study area.

Research regarding the biodiversity of the Dutch dunes forms the basis of this study, as this study continues upon findings of the study by Tonkens (2022). Available data for this area includes habitat maps from 2014, 2016 and 2022, based on the Natura 2000 habitat types. Elevation data is available from 2017 and 2019 in the form of aerial photos (Tonkens, 2023), as well as data from the AHN2 and the AHN3 which contain the official elevation data of the Netherlands (Actueel Hoogtebestand Nederland, 2022). In the case study, the model was run for one of the notches (figure 2), for which Aeolis model input was available (Meijer, 2020).

2.2 Approach

The main objective of this research was to link habitat development to sedimentation modelling in the case-study area of Meijendel. This was divided into three steps, each covering part of the research (figure 3). 1) The Aeolis model was applied to predict the sedimentation dynamics for the study area. 2) The outcome of Aeolis, defined as the differences in elevation between start and end, was transformed into a format interpretable for a GIS, where 3) the final modelling was done to create habitat development predictions.

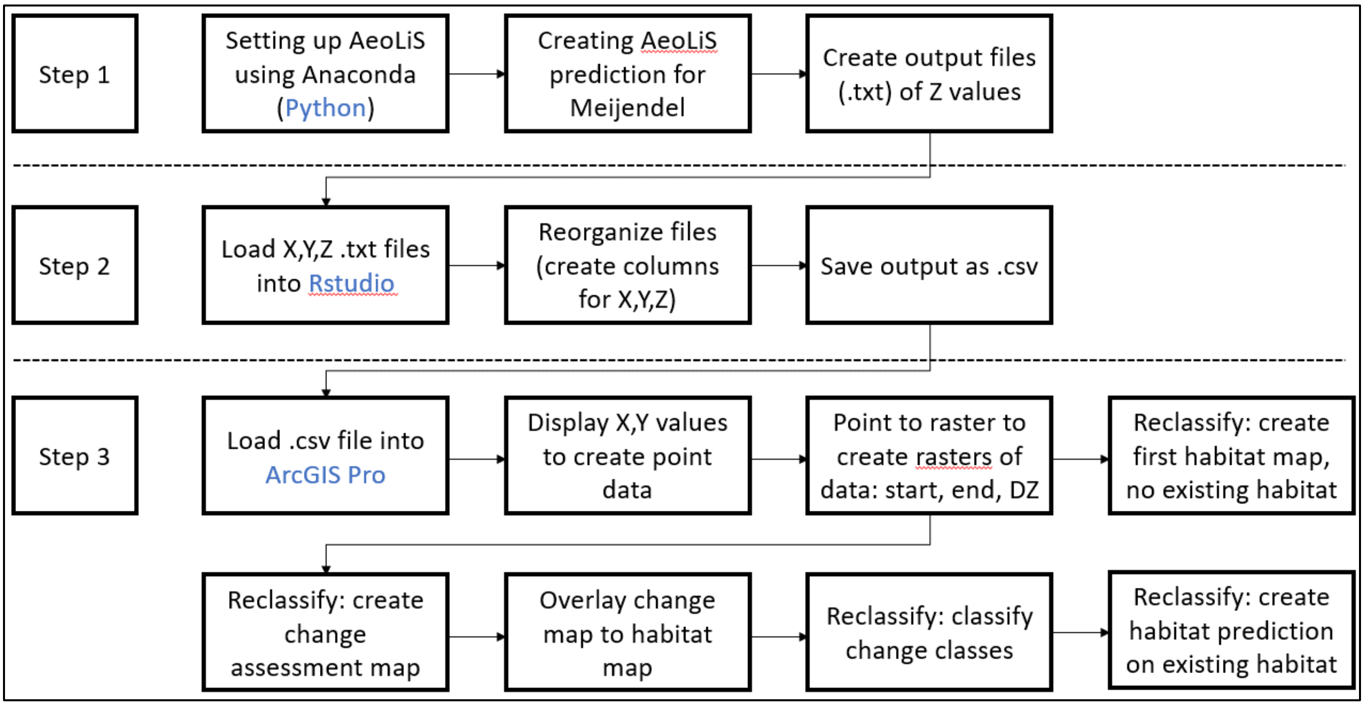

Figure 3: Overview of the workflow followed during the study. The workflow is divided into three parts, corresponding to the objectives.

2.2.1 Step 1: Model the expected sedimentation dynamics after notching in the fore dunes

The first objective was to create a sedimentation prediction for the selected study area (figure 2). Aeolis is a Python based model (Hoornhout et al., 2015), which was setup using the Anaconda software package (Anaconda Software Distribution, 2016; Python Software Foundation, 2023). The input consists of several input files, containing data on the location X and Y values, and the initial elevation as Z values, each formatted in a grid. Furthermore, files containing data on weather, tides, vegetation, and ground water are loaded in, as well as the model program file (appendix I). The input is based on research on the modelling of aeolian processes in dune systems. The data is based on the situation of 2015, when the notches in Meijendel were first created (Meijer, 2020). The main output is an updated grid with Z values, generated in the Network Common Data Form (NetCDF) format. Using Python coding, the data was extracted from the NetCDF file, and stored in separate text (.txt) files for the X, Y and Z values of the new grid. The three text files contained in grids the values, which needed to be transformed to work in a GIS environment. Therefore, it was chosen to save the data in a .csv file format, for further data processing.

2.2.2 Step 2: Translating the model outcome to a format which can be interpreted by GIS software

The data had to be edited to a format readable by the GIS, thus transforming the data from grid data to column data. The output files for the Aeolis model consisted of grids, one for the X, Y and Z values. To be readable in ArcGIS, the data had to be in a column format, with one column for each of the values (X, Y, Z, and ΔZ). All data transformations were done using the R programming language, through the Rstudio (version 4.3.1) user interface (R Core Team, 2023), with the tidyverse (Wickham et al., 2019) and tydir (Wickham et al., 2023) packages. The outcome datasets were stored in the .csv file format for further processing through ArcGIS Pro.

2.2.3 Step 3: Creating modelled habitat predictions

The main part of the analysis was done using ArcGIS Pro (version 3.2.0) (ESRI, 2022). First, the Aeolis outcome was loaded into the GIS. Using the 'display X,Y features' tool the tables were loaded as point feature in the GIS (see appendix II for GIS parameters). Using the 'point to raster' tool, the points were converted to raster data, using the mean interpolating function (see appendix III, figures 10, 11, 12 for visualisation of the Aeolis model input and output bed levels). By subtracting the final elevation values from the initial elevation values, a map showing the difference in elevation (ΔZ) could be made, showing sedimentation and erosion in cm/year. Using the 'reclassify' tool this ΔZ map could be converted to a first habitat map, displaying a habitat which would develop if no habitat were to be present at the starting point (t=0) of the model.

To take into account the presence of habitat at the start time of the model, a reclassification of the ΔZ map was made defining the continuous data in classes. This map had been classified to give sedimentation levels corresponding to the classes seen in figure 1, with the addition of a net change of 0 cm/year class and a class for areas with a negative net change per year (erosion). In Adobe Illustrator software (Adobe, 2023), the assessment map was overlaid on the current habitat map to create a visual evaluation of where the habitat might change. This evaluation was based on the findings by Tonkens (2022), which showed the response of the habitat to changing sedimentation levels. It was checked what level of sedimentation was predicted where, and how this would affect the habitat which was currently present at this site. Hereafter, the reclassify tool was used to create a map predicting the habitat development, creating a new classification on the ΔZ map which showed the predicted habitat types.

2.3 Validation

To assess the quality of the results found, two steps were taken. First, the quality of the model outcome of Aeolis was checked by comparing the ΔZ map to the differences in elevation of the AHN2 and AHN3 data, it was checked how well Aeolis predicted the sedimentation and erosion patterns. The AHN2 is an older version (collected between 2007-2012), with the newer AHN3 (collected between 2014-2019). Both datasets cover the Netherlands, divided into a number of tiles (Actueel Hoogtebestand Nederland, 2022). For the validation , from both the AHN2 and AHN3 dataset the same tiles were downloaded and loaded into a new map in ArcGIS Pro. Using the subtract raster tool, the data was subtracted to create a map showing the difference in elevation between the AHN2 and AHN3. As the time span between the creation of the AHN2 and AHN3 is 5 years, the subtracted AHN was divided by 5, so it would show an equal time frame compared to the Aeolis model run . By visual inspection, the outcome was compared to the ΔZ map produced by the Aeolis model outcome, to see if the spatial patterns overlapped.

The second assessment was focused on the habitat prediction made using the GIS model. This was done by comparing the predicted habitat with the existing habitat map, to visually inspect if the modelled habitat map showed similar spatial patterns as the official habitat of 2022. This was both done by visual inspection to the maps side by side, as well as by overlaying the maps in Adobe Illustrator.

3. Results

3.1 Results of the Aeolis model

3.1.1 The Aeolis output

With a simulation period of one year the Aeolis model predicts a maximal net sedimentation of 1.1 cm/year (figure 4a in blue), with most sedimentation occurring around the erosion zones (figure 4a in red). In those zones, the maximal net erosion levels are 2.6 cm/year. The location of the deposition predicted by the Aeolis model seems to generally match the sandy areas as can be seen in the aerial photo (figure 4b) (Google Earth Pro, 2016).

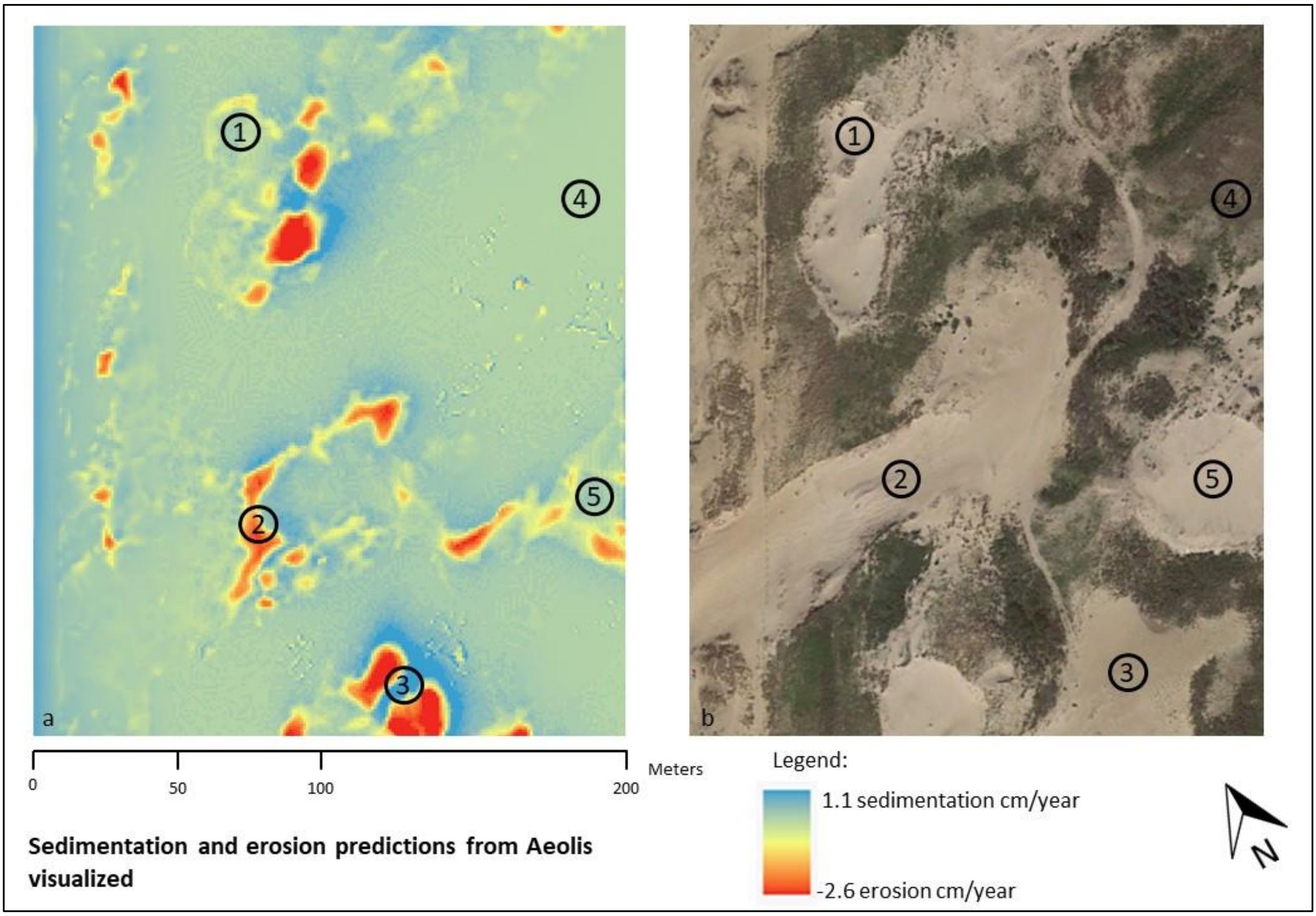

Figure 4: A visual representation of the outcome of the Aeolis model. This map is calculated by subtracting the calculated Z values at the end of the model from the initial Z values used as input. The numbers in the map show corresponding locations (Google Earth Pro, 2016).

3.1.2 Aeolis validation

When comparing the Aeolis output to actual elevation change seen by comparing the AHN2 and AHN3 datasets, it can be seen the Aeolis model shows similarity in the sedimentation and erosion patterns (figure 5). Most erosion is seen in areas 1 and 2 (figure 5a and 5b), with sedimentation predicted in both maps around the erosion area. Aeolis does, however, show an underestimation of the absolute values. The net sedimentation of 1.1 cm/year predicted is, according to the AHN data, 5 cm/year locally. The net erosion is even further apart, with net erosion of 2.6 cm/year predicted compared to 21 cm/year given by the AHN. The largest difference is found in the notch itself (area 1), where Aeolis predicts low sedimentation, and the AHN shows high erosion.

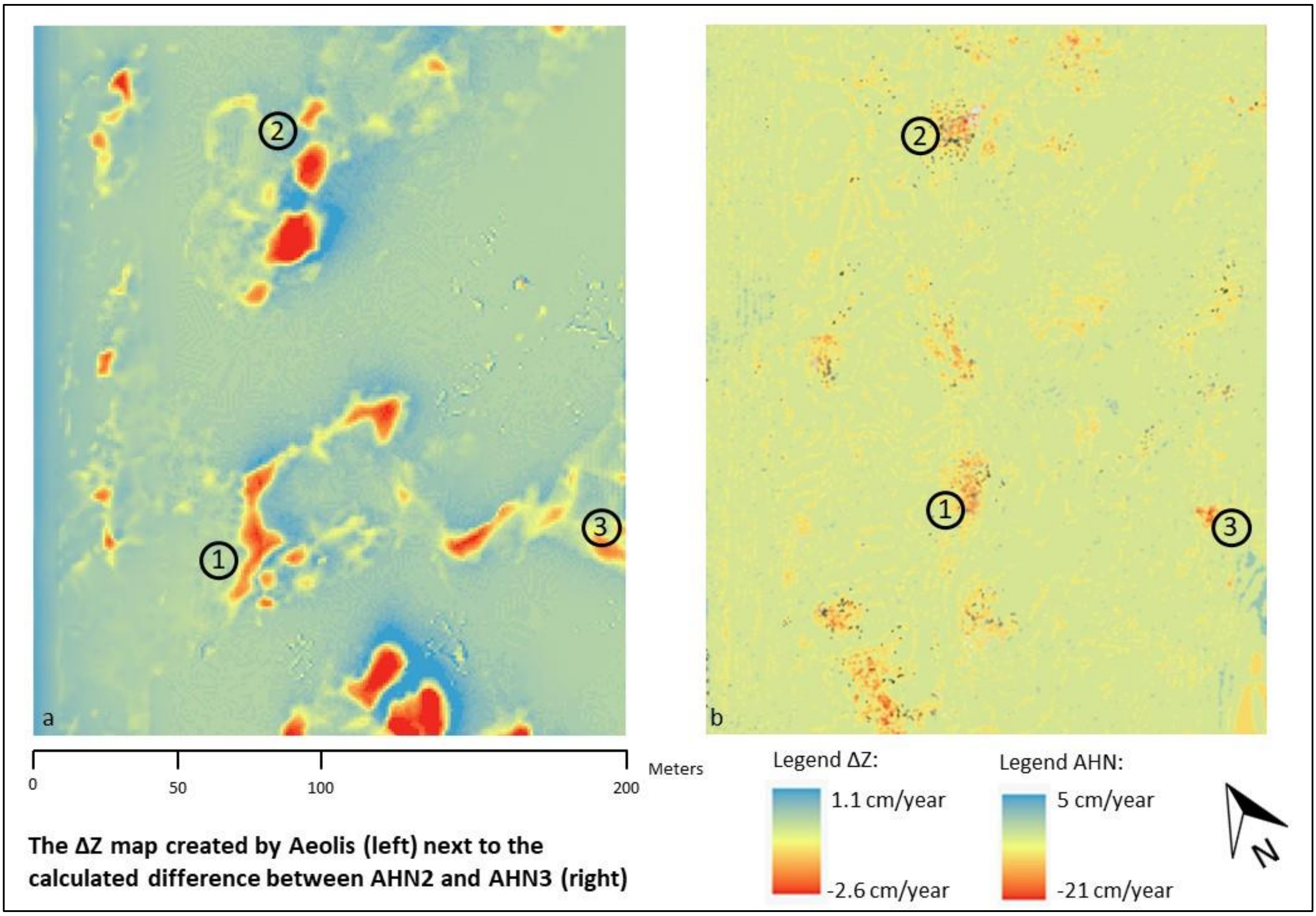

Figure 5: The output of the Aeolis model presented next to the differences calculated between the AHN2 and the AHN3. The AHN data has been divided so levels are within the same time span as the Aeolis model (Actueel Hoogtebestand Nederland, 2022).

3.2 Results of the GIS model

3.2.1 Exploring the possibility of linking habitat to sedimentation dynamics modelling

To explore the possibility of linking the Aeolis model to habitat development, a simple model was built to translate the net sedimentation to habitat types. Here, a comparison was made between the ΔZ given by Aeolis and the research outcomes created by Tonkens (2022). The model assumes no habitat to be present at the runtime of t=0, and simply takes the sedimentation and habitat development into account. The result shows mainly large areas of white dunes (figure 6a in green) and bare sand (figure 6a in yellow). Smaller patches of grey dunes form in the areas with low (less than 0.8 cm/year) net sedimentation (figure 6a in blue). The sandy areas appear in similar patterns to what is found in the aerial image (figure 6b). However, under predicted sedimentation, the model estimates larger parts of the sandy areas will overgrow to a white dune habitat.

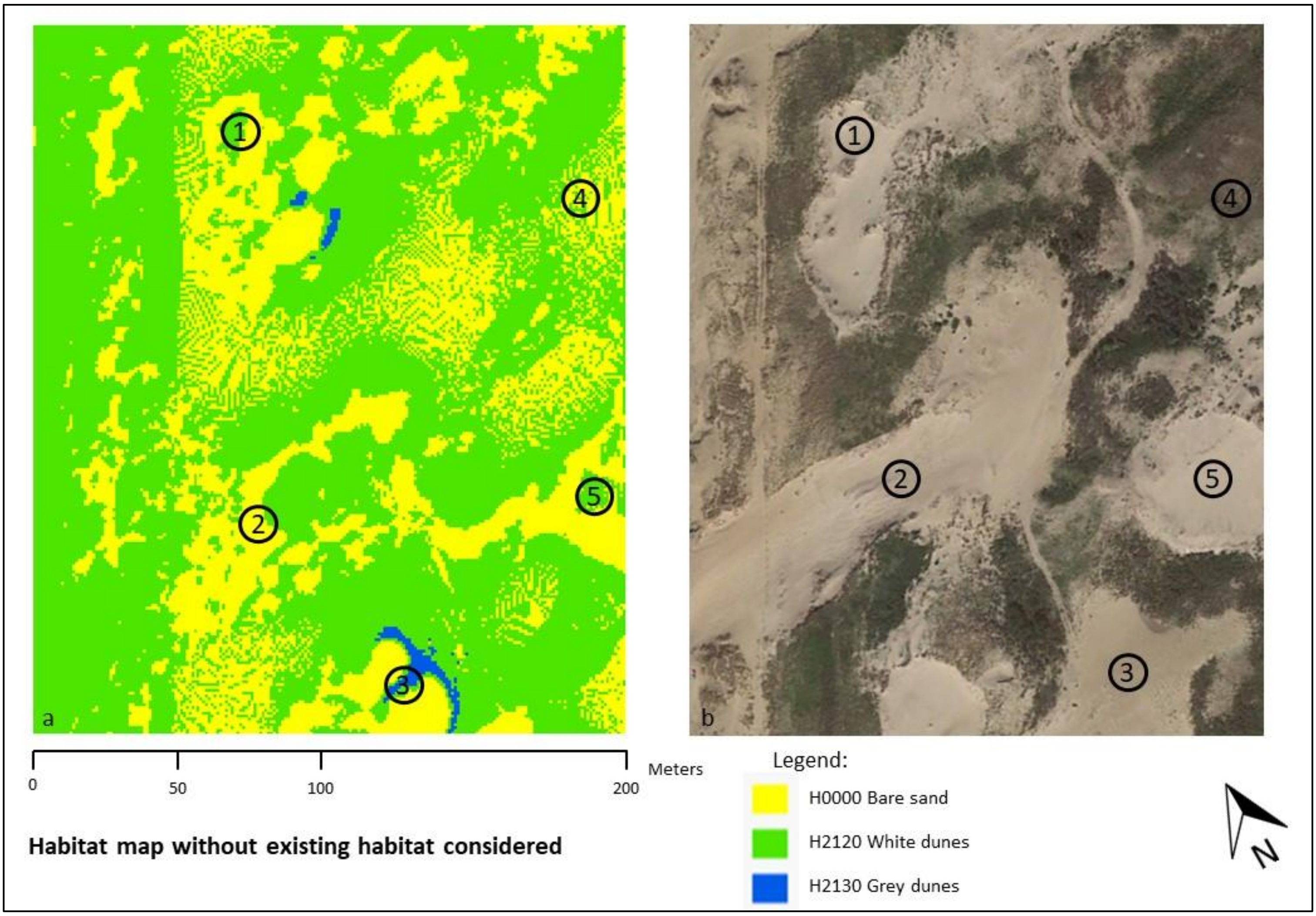

Figure 6: The calculated habitat, assuming no habitat would be present when the model runs. The model then predicts mainly white dune s to be formed, with larger patches of bare sand and some small formation of grey dunes. To the right is the aerial photo for location reference purposes (Google Earth Pro, 2016).

3.2.2 Modelling habitat development based on sedimentation dynamics modelling

To model the effect of the predicted sedimentation on existing habitat, an assessment was made to find locations of possible habitat change (figure 7a). The largest parts of the map show areas with mild sedimentation (figure 7a in light blue) and areas where the net bed level change is 0 (figure 7a in green). This can be found in areas 1, 4 and 5 (figure 7b). The remainder part (figure 7a in yellow) shows areas where the model predicted erosion, which indicates these areas are likely to remain sandy.

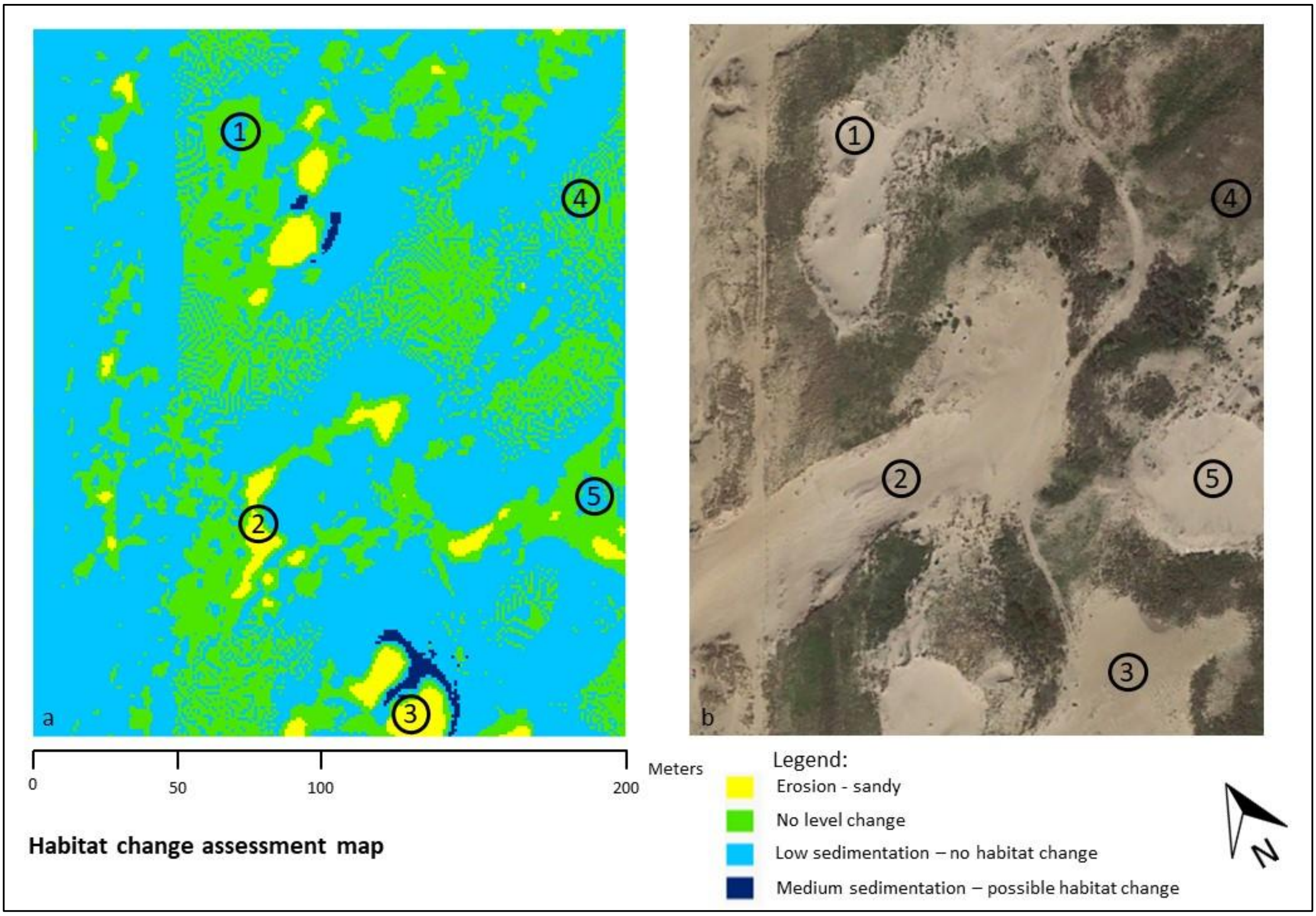

Figure 7: The map used to assess the possibility if habitat would change. This map was compared to the actual habitat map, and an assessment was made on where the habitat might change and where not, compared to the locations on the aerial photo (Google Earth Pro, 2016).

For modelling of the habitat, the map indicating possible habitat change (figure 7a) was laid over the official habitat map, to perform a visual assessment on where the habitat might change (see figure 14 in appendix III). By comparing the research by Tonkens (2022) with the created map (figure 14 in appendix III), an assessment could be made on whether the habitat would change or not. It was found that little changes would happen to the habitat based on the predicted sedimentation levels (figure 8a). The map mainly shows areas of white dunes (figure 8a in green) with larger patches of baren sand (figure 8a in yellow). Smaller patches of grey dunes are formed (figure 8a in blue), with even smaller patches of dunes with *Hippophaë rhamnoides* (H2160) (figure 8a in purple). The largest area of habitat H2160 is found around number 3 (figure 8a and 8b), which is at the location where this habitat occurs on the official habitat map (see figure 13 in appendix III).

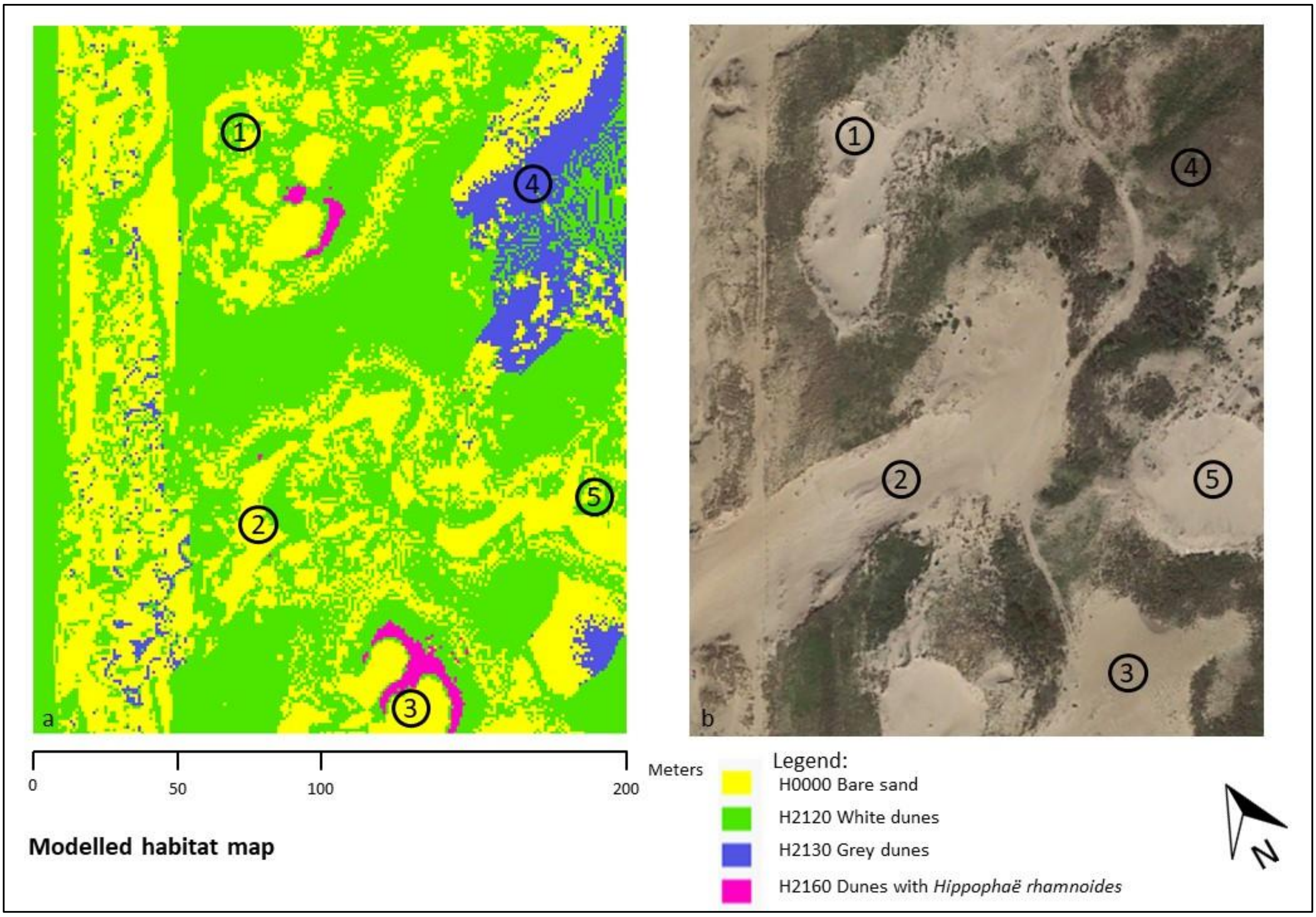

Figure 8: The predicted habitat taking the existing habitat into account. Mainly white dunes and bare sand are expected, with a small patch of grey dunes more land inward. Small patches of Dunes with Hippophaë rhamnoides may remain in the areas with lowest sedimentation. For comparison it is put next to the aerial photo (Google Earth Pro, 2016).

3.2.3 GIS model validation

Comparing the modelled habitat map with the official habitat map (figure 9), shows that the model is able to roughly predict the habitat patterns, with larger areas of habitat overlapping the official habitat map. However, it does show points of error, which can be seen in the red circles. The red circle close to area 1, the model predicts dunes with *Hippophaë rhamnoides* are formed (figure 9a), where the official habitat map shows bare sand (figure 9b). Around area 4, the model predicts mainly grey dunes with small areas of white dunes, where the official habitat map shows grey dunes and dunes with *Hippophaë rhamnoides*. At the right bottom, between areas 3 and 5 the model predicts bare sand, compared to the dunes with *Hippophaë rhamnoides* found in the official map. The largest difference can be seen in the notch itself, around area 2 where the model predicts (figure 9a) that the notch will overgrow with patches of white dunes, and small patches of even grey dunes. The official habitat map (figure 9b) shows the entire notch is bare sand.

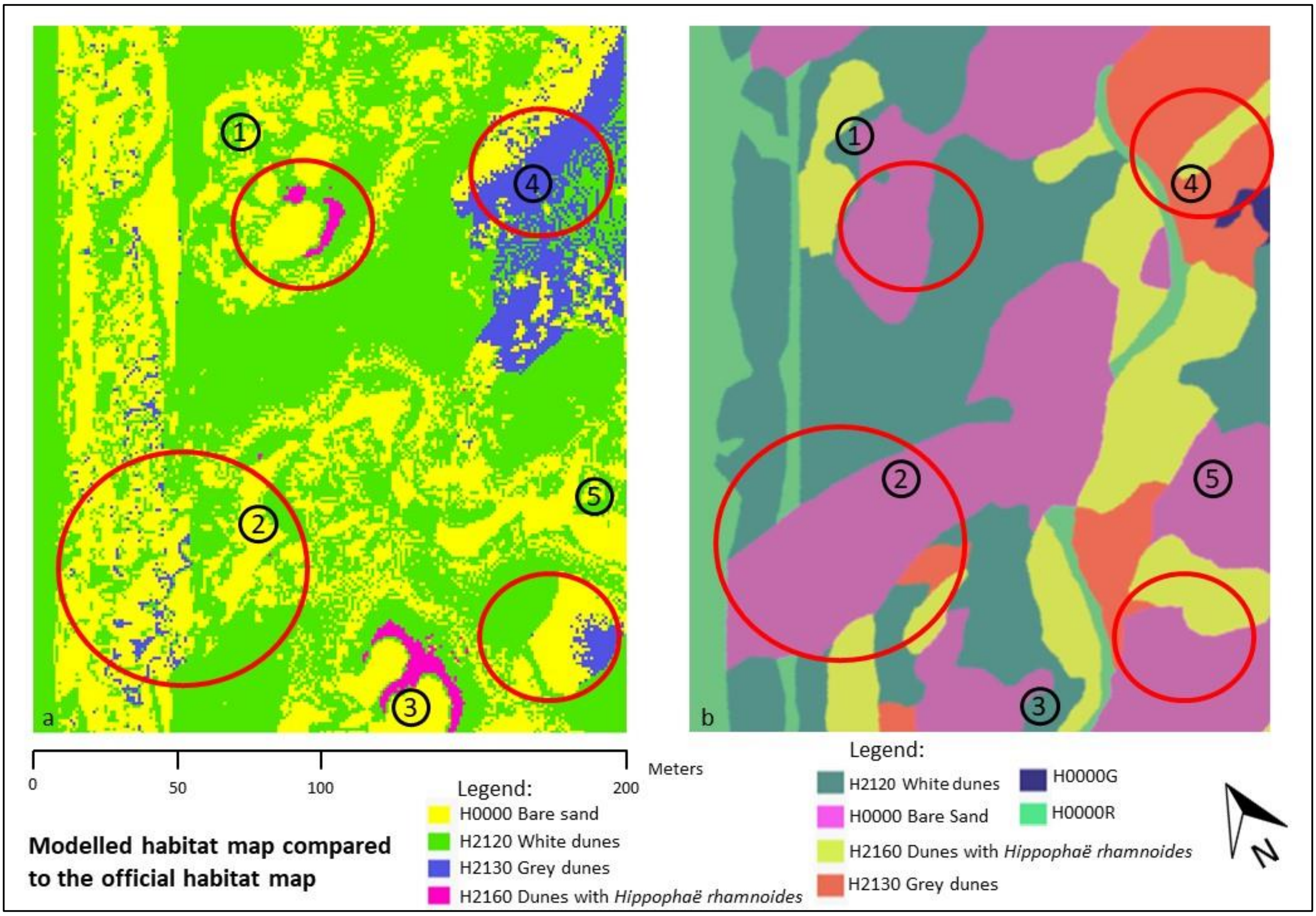

Figure 9: The modelled habitat map (a) compared to the official Natura 2000 habitat map (b). Red circles indicate the places where the modelled map and official habitat map differ.

4. Discussion

The objective of this study was to explore the possibility of using geomorphological modelling to predict habitat development in coastal dune areas. The results showed that predicting habitat development based on sedimentation is possible in very general terms only. It has been found possible to predict the general direction of changes in sedimentation and erosion. However, the results are still off in terms of effect size, making the step towards habitat development less accurate. Furthermore, the Aeolis output is not yet fully compatible with GIS, making it difficult to further process its output. Multiple steps could be taken to improve the model accuracy and make a major step forward in the modelling of habitat bested on sedimentation dynamics in dune systems.

4.1 Modelling habitat development

4.1.1 Modelling sedimentation dynamics after notching in fore dunes

When compared to the AHN data, the Aeolis model showed it can predict similar sedimentation patterns to what would be expected. However, the outcome shows error in terms of the amounts of sedimentation. Previous research has shown that the local sedimentation in areas directly surrounding the notch may be much higher than the predicted 1.1 cm/year and can reach levels over 5 cm/year (Poortinga et al., 2015; Riksen et al., 2016). Higher sedimentation levels may have different impacts on the existing habitat. As the different habitats are dominated by different plant species, they have different tolerances for how much covering by sand they can handle. White dunes, with predominantly grasses like *Ammophila arenaria* (European marram grass), may cope with higher sedimentation levels than grey dunes (Tonkens, 2022; Van Puijenbroek et al., 2017). An explanation for the underestimation may be the assumptions made regarding the development of vegetation by Aeolis. In current form, Aeolis only knows one type of vegetation, which is based on the properties of *Ammophila arenaria* (European marram grass) (De Vries & Van Manen, 2023), and assumes equal probability of the spread of the vegetation for each area. Looking at the plots made by Aeolis itself (Appendix IV figure 15a), it is seen Aeolis predicts vegetation to overgrow the notch (Appendix IV figure 15b), which captures the sand and lessens the effect of the wind. This may be explained by the way the vegetation is implemented in the Aeolis model, which is based on findings in literature (De Vries & Van Manen, 2023). Studies, however, have shown the importance for incorporating observational data when modelling the development of dunes, as often these models fail to meet the actual developmental patterns of the vegetation (Nolet et al., 2018). For Aeolis to be used as a tool to predict the development of habitat, further development into the vegetation model is needed, by implementing observational data from the field and by introducing more plant species.

Regarding the verification of the Aeolis outcomes, it should be noted that using the AHN data (Actueel Hoogtebestand Nederland, 2022) may be less accurate to the actual elevation changes, because the AHN data is collected on a large scale rather than smaller scale aerial photographs. It was chosen to use the AHN2 and AHN 3 data, and see how they differed, as the AHN data is easily accessible and easily editable. However, for more precise validation steps, it may be advisable to use aerial photographs which contain elevation data. In general, these take more time to process, and are most useful when collected on the same dates used for the start and end dates of the Aeolis run. Since there were no arial photographs of the situation in 2015 and precisely one year later in 2016 and the study was limited in time, it was chosen to use the AHN data.

4.1.2 Integrating the Aeolis model outcome in GIS for processing

The main challenge was the integration of the Aeolis model into ArcGIS Pro. As Aeolis was not intended to be used for these purposes, it was found difficult to load the Aeolis output into ArcGIS Pro. Attempts were made to work around the issue, by directly loading the NetCDF file produced by Aeolis into the ArcGIS software. This proved challenging, as the tools provided by ArcGIS Pro failed at extracting the needed data from the Aeolis files. The approach was therefore shifted, and the data was extracted using Python and transformed using Rstudio, which gave the desired result of having tables which ArcGIS Pro could read. Once loaded in ArcGIS Pro, it was not possible to use georeferencing on the Aeolis output because the Aeolis model works in a gridded format. This means all data is presented in grids, where the X and Y files both start at 0 and work up in steps of 1 meter. This meant the produced data would not correspond to a proper coordinate system within ArcGIS Pro. When reference points are known, ArcGIS Pro can correct the coordinate system and place a dataset in the correct location on the globe. However, no reference points were available for the used Aeolis model data. This meant numerical validation of the data through ArcGIS Pro was not possible, as the data could not be aligned properly.

To improve the methods for integrating the Aeolis model in a GIS environment, a field study prior to creating the Aeolis input could be performed. In the field, the case-study area needs to be covered, and a minimum of 3 but preferably 5 control points need to be set in either the center of determined grid cells, or on the cross point where 4 grid cells meet, used for the Aeolis input. Of these 3 or 5 points, the coordinates must be recorded together with the corresponding grid cells used in Aeolis. This does require precise measurements of the study area, as the exact locations need to be known. Doing so would enable the built-in georeferencing tools by ArcGIS Pro, which would make it possible to align the data to the correct coordinates. This in turn enables the use of tools within ArcGIS Pro to perform numerical validation, which enhances the validation options of the model.

4.1.3 Creating modelled habitat predictions

For exploration purposes, the GIS model was run in a simple form, only taking the predicted sedimentation levels into account, and not yet the existing habitat. The resulting habitat (figure 6) showed mainly white dune areas and areas with baren sand. Given the predicted sedimentation (figure 4), this is in line with the expected development of the vegetation (Tonkens, 2022). However, notching in fore dunes is done by removing vegetation (De Jong et al., 2014; Van der Hagen et al., 2017), thus some form of vegetation can be assumed to be present in the area surrounding the notch. This result thus merely shows the possibility of linking habitat development to sedimentation dynamics modelling.

When introducing existing habitat to the GIS model (figure 8), the newly predicted habitat map showed mainly white dunes and bare sand. These results may be explained by the low inflow of sedimentation, of only up to 1.1 cm/year, by which the habitat is not expected to change (Tonkens, 2022). Because of the low predicted sedimentation, the model expects succession to take over, and change areas from bare sand to white dunes, also within the notch itself (figure 9). As stated before, this may be unrealistic, as the sedimentation dynamics in and around the notch may be much higher than the predicted 1.1 cm/year (De Jong et al., 2014; Riksen et al., 2016). Interestingly, the model predicts small patches of grey dunes and even dunes with *Hippophaë rhamnoides* in the fore dune area. This might again be due to the low predicted sedimentation, where the GIS model predicts succession may take over. However, these areas are in general much more dynamic (Anwar Maun, 2009; Riksen et al., 2016), which often means earlier successional stages of habitat will form (Tonkens, 2022). Given the predicted sedimentation, the model predicts habitat as expected (figure 8), as with low sedimentation levels, succession may take over as more important factor than sedimentation (Anwar Maun, 2009; McGuirk et al., 2022).

The modelled habitat map does show similarity in the general patterns of the habitat to the official habitat map. Starting at the coast (left side of figure 9a), the model mainly predicts the formation of white dunes and areas of bare sand. Pattern wise, this corresponds with the official habitat map used as the basis for the model. More land inwards, grey dunes are predicted to form, which also corresponds to the patterns seen on the official habitat map (appendix III figure 14). This coincides with the literature, as it is known sedimentation rates drop significantly further land inwards, away from the notch (Riksen et al., 2016). The predicted habitat mainly shows differences in the notch itself (figure 9a and 9b), where the GIS model predicts white dunes to start developing, and the Natura 2000 habitat map shows bare sand. This may be explained because of the low predicted sedimentation but may also be caused by not taking into account the relative abundance of habitat types. A consideration can be made regarding the relative abundance of habitat given certain sedimentation levels, as found in the results of a study on Dutch dune biodiversity (Tonkens, 2022). Currently, the model does not take this relative abundance into account. This means the model can only predict one habitat to form per grid cell given the predicted sedimentation. To further expand the model, it could be considered to translate the relative abundance into a probability factor, given the type of habitat present at a certain location and how the predicted level of sedimentation for that location changes the habitat. This may be an improvement for the accuracy of the GIS model.

The habitat map used for the assessment of where the habitat might change was the same map used for a study on the biodiversity in the Dutch dune systems (Tonkens, 2022). This study aimed to link habitat development to sedimentation dynamics based on a field study rather than the creation of a model. This should be taken into consideration, as this may affect the results of this study. As this study is based on the findings by Tonkens (2022), which uses the same study area and habitat map, it may be assumed that this model can work correctly for the Meijendel area. Other factors to consider are the date difference between the model and the habitat map. The model predicts the habitat for the situation of 2016, where the official habitat map was made around 2022, meaning there is a possibility for inaccuracies in the validation. The reason for choosing this habitat map and study area was because of the data availability. The official habitat map was available with meta-data and attribute table. Thus, the map could be used for calculations and processed through the ArcGIS Pro tools. However, as the model was not checked for other areas, it might show inaccuracies when applied to different study areas. Thus, a future step could be to check whether the model is valid for other study areas as well. Also, it may be advisable to use multiple habitat maps for modelling and validation. Currently, the model runs on the same habitat map used for validation due to lack of newer habitat maps. For future studies it is advisable to use multiple field-based habitat maps.

An important factor to consider in habitat formation is the simulation period used by the model. For the Aeolis model, a simulation period of one year was used. This means the habitat model makes its predictions based on one year of data. In general, one year may be considered too short to expect changes in habitat development. Studies specifically aiming at visualizing the changes in vegetation for a certain area show timespans of 20 years (Zhang et al., 2021) and 25 years (Jamali et al., 2015). These studies used remote sensing techniques to assess the changes in vegetation over a time series and noted only small (less than 1%) changes in vegetation per year (Zhang et al., 2021). The study areas of these studies are, however, much larger than the study area chosen in this study. A study which also focused on a smaller area took a time span of 5 years (Zhang & Skarpe, 1995). Considering Aeolis is currently, found most accurate when using simulation periods of up to 3 years (De Vries & Van Manen, 2023), it may be advised to lengthen the run time of the total model to these 3 years. If calculation times with Aeolis could be lowered, and the accuracy for longer runs improved, it would be advisable to stretch the run time to a minimum of 5 years.

Although the modelling of habitat development is found possible, the methods to do so are not yet straightforward, and need improvement if this were to be used as a tool for dune management. Due to the compatibility problems between the Aeolis model and the ArcGIS software, it was not yet possible to create a fully, self-operating GIS model. The current state of the model works on by-hand calculations using ArcGIS Pro's 'reclassify' tool, which bases its information on the Aeolis output and the study on Dutch dune biodiversity (Tonkens, 2022). Ideally the GIS model could directly take the NetCDF file output made by Aeolis and use it as the input for a full GIS model. This model could then be run and produce the predicted habitat development maps.

5. Conclusion

The main goal for this study was to test whether habitat development could be linked to sedimentation modelling. The results of this study show that modelling the development of habitat is possible using sedimentation modelling as underpinning. The Aeolis model shows it can in general predict patterns in sand distribution correctly and gives meaningful insights in the development of dunes after notches have been made. However, in terms of location and levels of sedimentation the model is found to give underestimations, which may be caused by the vegetation response programmed in Aeolis. Currently, outputs from Aeolis are not fully compatible for use with GIS software, making it difficult to use georeferencing and thus numeric validation. Therefore, the overall model lacks in terms of validation. A suggested way to fix this is by a field study prior to modelling to match grid locations of Aeolis to a coordinate system, enabling georeferencing and thus numerical validation. A good addition would be to add the information on relative habitat abundance and calculate this as a probability of how habitat should develop. There is, however, found to be potential for the modelling of habitat based on sedimentation dynamics modelling, and possibilities are present to further expand the model and improve its reliability.

References

Actueel Hoogtebestand Nederland. (2022). *AHN*. Retrieved 28 September 2023 from https://www.ahn.nl/

Adobe. (2023). *Adobe Illustrator*. In (Version 28.1) https://www.adobe.com/

Anaconda Software Distribution. (2016). *Anaconda Navigator*. In (Version 2.3.1) https://www.anaconda.com/

Anwar Maun, M. (2009). *The Biology of Coastal Sand Dunes*. Oxford University Press.

Arens, B., Bos, B., Damsma, P., Geelen, L., Goessen, P., Van der Graaf, S., Groenendijk, D., Harkema, E., Van der Heide, T., IJff, S., Janssen, M., Kooijman, A., Lamers, J., De Meij, T., Meijer, J., Nachbar, N., Nijenhuis, M., Oost, A., Prins, M., . . . Zijlstra, A. (2022). *Handleiding Dynamische Zeereep* 1.0). P. n. e. r. Waddenzee. https://www.rijkewaddenzee.nl/nieuws/checklist-en-handleiding-voor-dynamisering-zeereep/index.htm

Arens, S. M., Van den Burg, A. B., Esselink, P., Grootjans, A. P., Jungerius, P. D., Kooijman, A. M., De Leeuw, C., Löffler, M., Nijssen, M., Oost, A. P., Van Oosten, H. H., Stuyfzand, P. J., Van Turnhout, C. A. M., Vogels, J. J., & Wolters, M. (2009). *Preadvies Duin- en Kustlandschap*.

Argles, A., Moore, J., & Cox, P. (2022). Dynamic Global Vegetation Models: Searching for the balance between demographic process representation and computional tracability. *PLOS Climate*, *1*(9), e0000068. https://doi.org/https://doi.org/10.1371/journal.pclm.0000068

Assendorp, D. (2010). *Classification of pattern and process in small-scale dnamic ecosystems: with cases in the Dutch coastal dunes* Universiteit van Amsterdam]. Amsterdam.

Barrows, C. (1996). An Ecological Model for the Protection of a Dune Ecosystem. *Conservation Biology*, *10*(3), 888-891. https://doi.org/https://www.jstor.org/stable/2387113

De Jong, B., Keijsers, J. G. S., Riksen, M. J. P. M., Krol, J., & Slim, P. (2014). Soft Engineering vs. a Dynamic Approach in Coastal Dune Management: A Case Study on the North Sea Barrier Island of Ameland, The Netherlands. *Journal of Coastal Research*, *30*(4). https://doi.org/10.2112/jcoastres-d-13-00125.1

De Jong, B., Slim, P., Riksen, M. J. P. M., & Krol, J. (2011). *Ontwikkeling van de zeereep onder dynamisch kustbeheer op Oost-Ameland*. https://research.wur.nl/en/publications/ontwikkeling-van-de-zeereep-onder-dynamisch-kustbeheer-op-oost-am

De Vries, S., & Van Manen, M. (2023). Discussing Aeolis. In Personal Communication (Ed.). Delft.

ESRI. (2022). *ArcGIS Pro*. In (Version V3.2.0) Environmental Systems Research Institute. https://www.esri.com/en-us/arcgis/products/arcgis-pro/overview

ESRI. (2023). *World Imagery*. https://livingatlas.arcgis.com/wayback/#active=12457&mapCenter=-115.29850%2C36.06400%2C15

Everard, M., Jones, L., & Watts, B. (2010). Have we neglected the societal importance of sand dunes? An ecosystem services perspective. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *20*(4), 476-487. https://doi.org/10.1002/aqc.1114

Google Earth Pro. (2016). *Imagery. Meijendel nature reserve* Version V7.3.6.9345 (64-bit)).

Heijmans, M., & Berendse, F. (2009). NUCOM: a dynamic vegetation model for peatlands and tundra including nitrogen cycling and mosses. *Proceedings of 4th International WS on C/H2O/Energy balance and climate over boreal regions with special emphasis on eastern Eurasia*, 109-112. https://library.wur.nl/WebQuery/wurpubs/fulltext/12140

Hoornhout, B., Van Westen, B., Cohn, N., & De Vries, S. (2015). *AeoLiS*. In (Version V2.1.1) https://aeolis.readthedocs.io/en/latest/

Jamali, S., Jönsson, P., Eklundh, L., Ardö, J., & Seaquist, J. (2015). Detecting changes in vegetation trends using time series segmentation. *Remote Sensing of Environment*, *156*, 182-195. https://doi.org/10.1016/j.rse.2014.09.010

Kooijman, A. M., Bloem, J., Cerli, C., Jagers op Akkerhuis, G. A. J. M., Kalbitz, W., Dimmers, W., Vos, A., Peest, A. K., & Kemmers, R. H. (2014). N-opslag in organische stof bij hoge N-depositie in kalkrijke en kalkarme duinbodems. *Vereniging van Bos- en Natuureigenaren*.

McGuirk, M. T., Kennedy, D. M., & Konlechner, T. (2022). The Role of Vegetation in Incipient Dune and Foredune Development and Morphology: A Review. *Journal of Coastal Research*, *38*(2). https://doi.org/10.2112/jcoastres-d-21-00021.1

Meijer, L. (2020). *Numerical modelling of Aeolian Sediment Transport, Vegetation Growth and Blowout Formation in Coastal Dunes* Delft University of Technology].

Milhous, R. (1998). Modelling of instream flow needs: the link between sediment and aquatic habitat. *River Research and Applications*(14), 79-94. https://doi.org/https://doi.org/10.1002/(SICI)1099-1646(199801/02)14:1%3C79::AID-RRR478%3E3.0.CO;2-9

Ministerie van Landbouw, N. e. V., ,. (n.d.). *Meijendel & Berkheide*. Retrieved 4 December 2023 from https://www.natura2000.nl/gebieden/zuid-holland/meijendel-berkheide

Nolet, C., van Puijenbroek, M., Suomalainen, J., Limpens, J., & Riksen, M. (2018). UAV-imaging to model growth response of marram grass to sand burial: Implications for coastal dune development. *Aeolian Research*, *31*, 50-61. https://doi.org/10.1016/j.aeolia.2017.08.006

Pisaturo, G., Folegot, S., Menapace, A., & Righetti, M. (2021). Modelling fish habitat influenced by sediment flushing operations from an Alpine reservoir. *Ecological Engineering*, *173*. https://doi.org/https://doi.org/10.1016/j.ecoleng.2021.106439

Poortinga, A., Keijsers, J. G. S., Visser, S. M., Riksen, M. J. P. M., & Baas, A. C. W. (2015). Temporal and spatial variability in event scale aeolian transport on Ameland, The Netherlands. *GeoResJ*, *5*, 23-35. https://doi.org/10.1016/j.grj.2014.11.003

Provoost, S., Jones, M., M., L., & Edmondson, S. E. (2009). Changes in landscape and vegetation of coastal dunes in northwest Europe: a review. *Journal of Coastal Conservation*, *15*(1), 207-226. https://doi.org/10.1007/s11852-009-0068-5

Python Software Foundation. (2023). *Python Programming Language. Python*. In https://www.python.org/

R Core Team. (2023). *R: A Language and Environment for Statistical Computing.* In (Version V4.3.1) R Foundation for Statistical Computing. https://www.r-project.org/

Riksen, M. J. P. M., Goossens, D., Huiskes, H. P. J., Krol, J., & Slim, P. A. (2016). Constructing notches in foredunes: Effect on sediment dynamics in the dune hinterland. *Geomorphology*, *253*, 340-352. https://doi.org/10.1016/j.geomorph.2015.10.021

Ruessink, B. G., Arens, S. M., Kuipers, M., & Donker, J. J. A. (2018). Coastal dune dynamics in response to excavated foredune notches. *Aeolian Research*, *31*, 3-17. https://doi.org/10.1016/j.aeolia.2017.07.002

The Hague. (2023). *Meijendel*. https://denhaag.com/en/meijendel

Tonkens, S. (2022). *Biodiversity in Dutch Dunes: The role of pH in species richness and accumulation* Wageningen Univeristy & Research]. Wageningen.

Tonkens, S. (2023). Discussing Meijendel GIS data. In.

Van der Hagen, H., Ten Napel, G., & Arens, B. (2017). *Grenzen slechten in Meijendel: schuifgeaten in de zeereep* (Holland's Duinen, Issue. https://ecologischeautoriteit.nl/projectdocumenten/011154_5004_grenzen_slechten_in_meijendel_stuifgaten_in_de_ze-hydrotheek_-stowa-_519827.pdf

Van der Valk, L., Arens, S., Koomen, A., & Bakker, M. (2013). *Verkenning herstelmogelijkheden duindynamiek Westduinen (Schouwen)*.

Van Puijenbroek, M. E. B., Nolet, C., de Groot, A. V., Suomalainen, J. M., Riksen, M. J. P. M., Berendse, F., & Limpens, J. (2017). Exploring the contributions of vegetation and dune size to early dune development using unmanned aerial vehicle (UAV) imaging. *Biogeosciences*, *14*(23), 5533-5549. https://doi.org/10.5194/bg-14-5533-2017

Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L. D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T. L., Miller, E., Bache, S. M., Müller, K., Ooms, J., Robinson, D., Seidel, D. V., Spinu, V., . . . Yutani, H. (2019). Welcome to the tidyverse. *Journal of Open Source Software*, *4*(43), 1686. https://doi.org/10.21105/joss.01686

Wickham, H., Vaughan, D., & Girlich, M. (2023). *tidyr: Tidy Messy Data*. In (Version V1.3.0) https://tidyr.tidyverse.org

Zhang, M., Lin, H., Long, X., & Cai, Y. (2021). Analyzing the spatiotemporal pattern and driving factors of wetland vegetation changes using 2000-2019 time-series Landsat data. *Sci Total Environ*, *780*, 146615. https://doi.org/10.1016/j.scitotenv.2021.146615

Zhang, W., & Skarpe, C. (1995). Small-scale vegetation dynamics in semi-arid steppe in inner Mongolia. *Journal of Arid Environments*, *34*, 421-439. https://doi.org/https://doi.org/10.1006/jare.1996.0122

Appendices

Appendix I: Aeolis model parameters

The model parameters used as the input for the Aeolis model can be found in the tables below. Table 1 shows the standard parameter used for land formation predictions using Aeolis. Tabe 2 shows the specific input parameters used for the notch simulations from Meijendel. The parameters used were created by Meijer (2020) for the simulation of blowout features at Meijendel and were reused for the purpose of this thesis.

Table 1: The standard input parameters for land formation prediction in Aeolis (Meijer, 2020).

Symbol	Parameter	Value	Unit
d	Grain size	0.225	*mm*
$n_{fraction}$	Number of sediment fractions	1	-
n_{layers}	Number of bed layers	3	-
h_{layer}	Thickness of bed layers	0.01	*m*
g	Gravitational constant	9.81	m/s^2
v	Air viscosity	1.5 e-5	m^2/s
P_a	Density of air	1.225	kg/m^3
P_g	Density of grains	2650	kg/m^3
P_w	Density of water	1025	kg/m^3
n	Sediment porosity	0.4	-
k	Von Kármán constant	0.41	-
z	Measured hight of wind velocity	10	*m*
Θ_{dyn}	Dynamic angle of response	33	*deg*
Θ_{stat}	Static angle of response	34	*deg*
T	Adaptation time scale for saltation process	1	*s*

Table 2: The specific Aeolis parameter setup used for creating the predictions of the notch and blowout features in Meijendel (Meijer, 2020).

	Symbol	Parameter	Value	Unit
Model parameters				
	n_x	Number of grid cells in x-direction	TBD	-
	n_y	Number of grid cells in y-direction	TBD	-
	Δ_x	Grid cell size in x-direction	1	*m*
	Δ_y	Grid cell size in y-direction	1	*m*
	Δ_t	Time step	TBD	*s*
	k	Bed roughness	1	*mm*
Boundary conditions				
		Offshore boundary	*gradient*	
		Onshore boundary	*gradient*	
		Lateral boundaries	*circular*	
Wind				
	u_w	Wind velocity	TBD	*m/s*
	u_{dir}	Wind direction	TBD	*deg*
	σ_w	Standard deviation of wind direction distribution	TBD	*deg*
Vegetation				
	Γ	Roughness factor for vegetation	TBD	-
	p_g	Possibility of germination per year	1	*1/year*
	p_l	Possibility of lateral expansion per year	0-1	*1/year*
	V_{ver}	Vertical growth of vegetation	0-10	*m/year*
	$\delta z_{b,opt}$	Sediment burial for optimum vegetation growth	TBD	*m/year*
	Y_{veg}	Constant on influence of sediment burial	1	-
	σ_{veg}	Standard deviation in vegetation cover filter	0.8	-
Hydrodynamics				
	z_s	Still water level (sine function of the tide)	-1 to 1	*m*
	H_s	Significant wave hight	0	*m*

Appendix II: GIS tool setup

The most important input parameters for the processing in the GIS are described in the tables below.

Displaying data

For displaying the data, the "X,Y table to point" tool was used. Further parameters can be found in table 3. Environments were used in the default setting.

Table 3: The input parameters used for displaying the table in ArcGIS Pro.

Parameter	Input
Input table	Meijendel data .csv table
Output Feature class	Meijendel_tabletopoint
X Field	X_value
Y Field	Y_value
Z Field	Z_start_value, Z_end_value (in two different runs)
Coordinate system	WGS84

Transforming point to raster data

To transform the data from point data to raster data, the "point to raster" tool was used. Table 4 shows the input settings used for this tool.

Table 4: The parameters used to transform the point data into the different raster sets needed for further calculations.

Parameter	Input
Input Features	Meijendel table to point data
Value field	Z values (start, end, Δ)
Output raster	-raster name-
Cell assignment type	Mean
Priority field	None
Cell size	1
Build raster attribute table	Build

Reclassifying raster sets to the different maps

To calculate the different maps made, the "reclassify" tool was used. Bellow are a set of tables each describing the input settings for the different maps made. In the attribute table, using the add field function, the new values given to each class were given specific names. The captions of the tables describe the names given to each class.

Table 5: The table with input content for the first created habitat map. The recalculation made every value under 0 (erosion) sandy, all up to 0.8 white dune, and all above 0.8 grey dune. This was determined following the data from research by Tonkens (2022).

Parameter	Input
Input raster	ΔZ data
Reclass field	Value
Reclassification	≤ 0.0 = 1; ≤0.8 = 2; ≤1.1 = 3
Output raster	Habitat map without existing habitat
Change missing values to NoData	Data

Table 6: The input used for the creation of the change assessment map. Here, the values below 0.0 were set to be sandy, as they predict erosion. Everything at 0 was set as a point with no level change, indicating low chances of habitat change. Value 3 was given to low sedimentation, and 4 to medium sedimentation.

Parameter	**Input**
Input raster	ΔZ data
Reclass field	Value
Reclassification	< 0.0 = 1; = 0.0 = 2; ≤ 0.8 = 3; ≤ 1.1 = 4
Output raster	Change assessment map
Change missing values to NoData	Data

The creation of the final habitat map was done by manual reclassification, as this was made by using the existing habitat map and the change assessment map. Because of the manual reclassification, no concrete input table is present. Due to the structure of the data, this was found to be the only option to create a habitat map taking into account the existing habitat.

Appendix III: Further maps made during the study

During the study, multiple maps were made using the Aeolis model in- and output. The maps which were not necessarily needed for the results are displayed and explained here, to give extra insight into the data used. The first map (figure 10) shows the visualization of the input Z values used by Aeolis. The input data is shown as elevation data (in meters), where the lowest points are at 0 meters. The higher areas (shown in 1, 2 and 3, figure 10a and 10b) are directly in the foredunes.

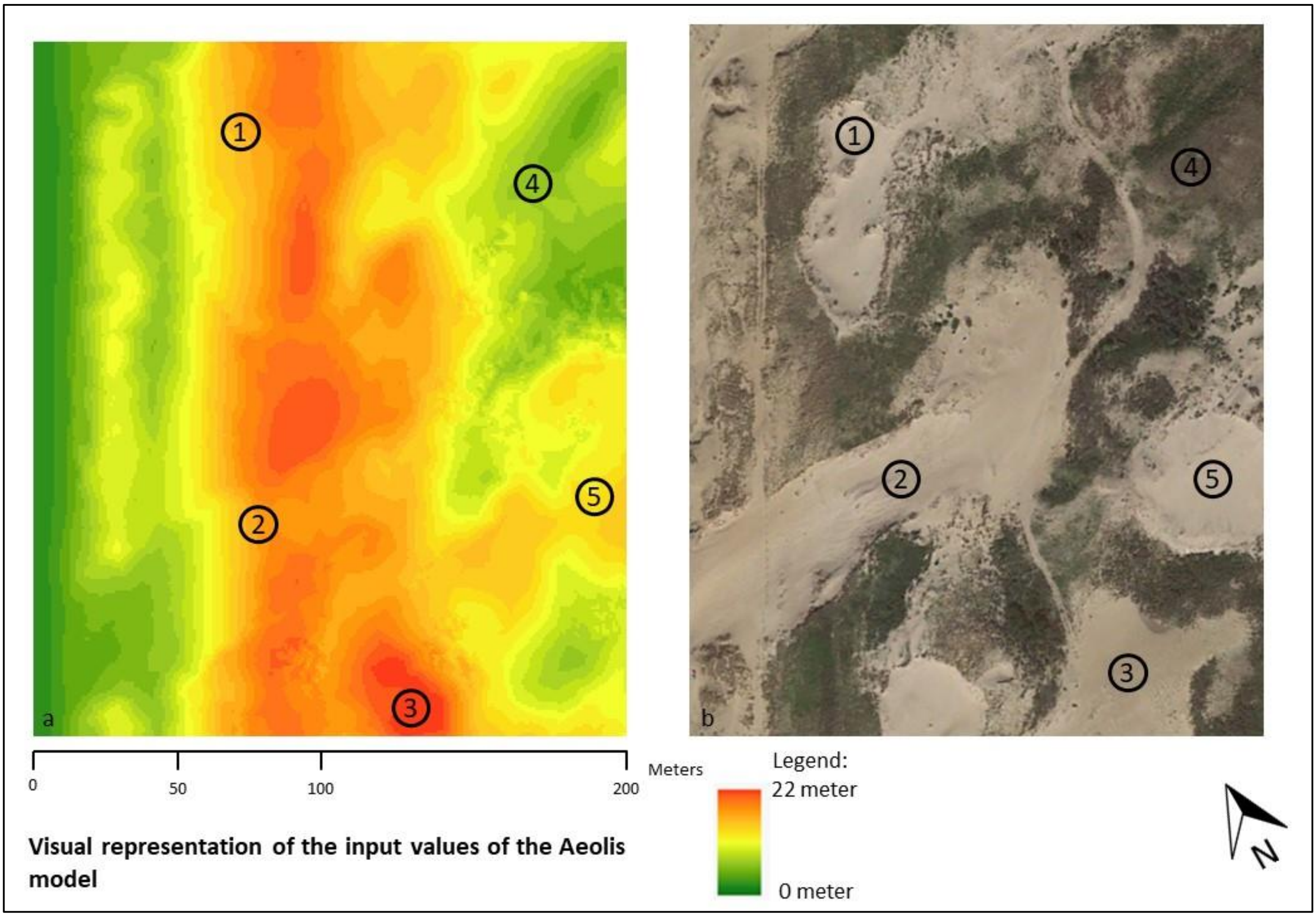

Figure 10: Visual representation of the input values used to run the Aeolis model.

The outcome as calculated by Aeolis (figure 11a) shows more evened out compared to the input (figure 10a). The output does not appear significantly different compared to the input. The main differences can be better spot in the ΔZ map (figure 5).

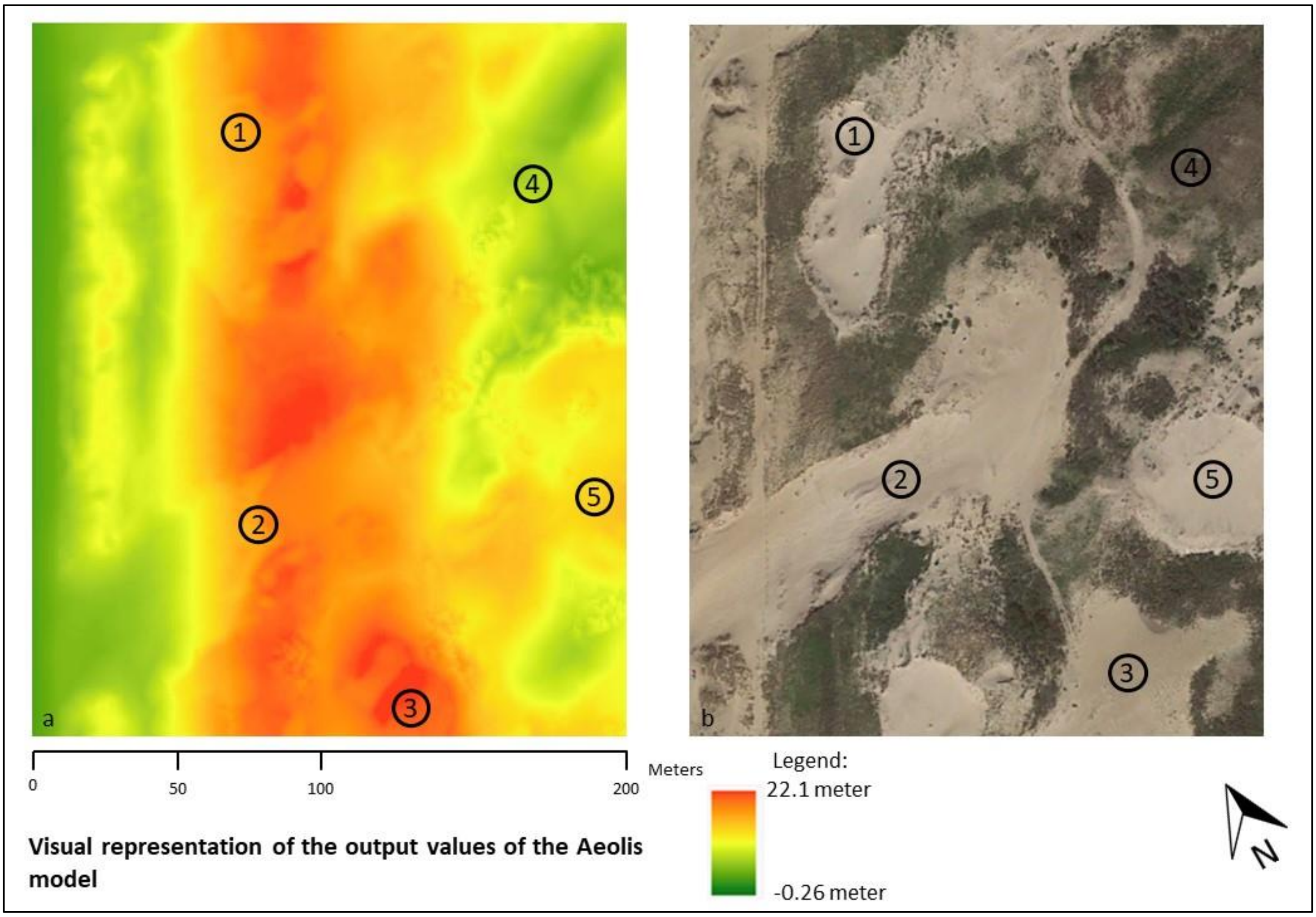

Figure 11: Visual representation of the output values calculated by the Aeolis model.

Comparing the input and output side by side (figure 12) makes it easier to spot the subtle differences. The main difference can again be seen in the smoothness of the output compared to the rougher input data.

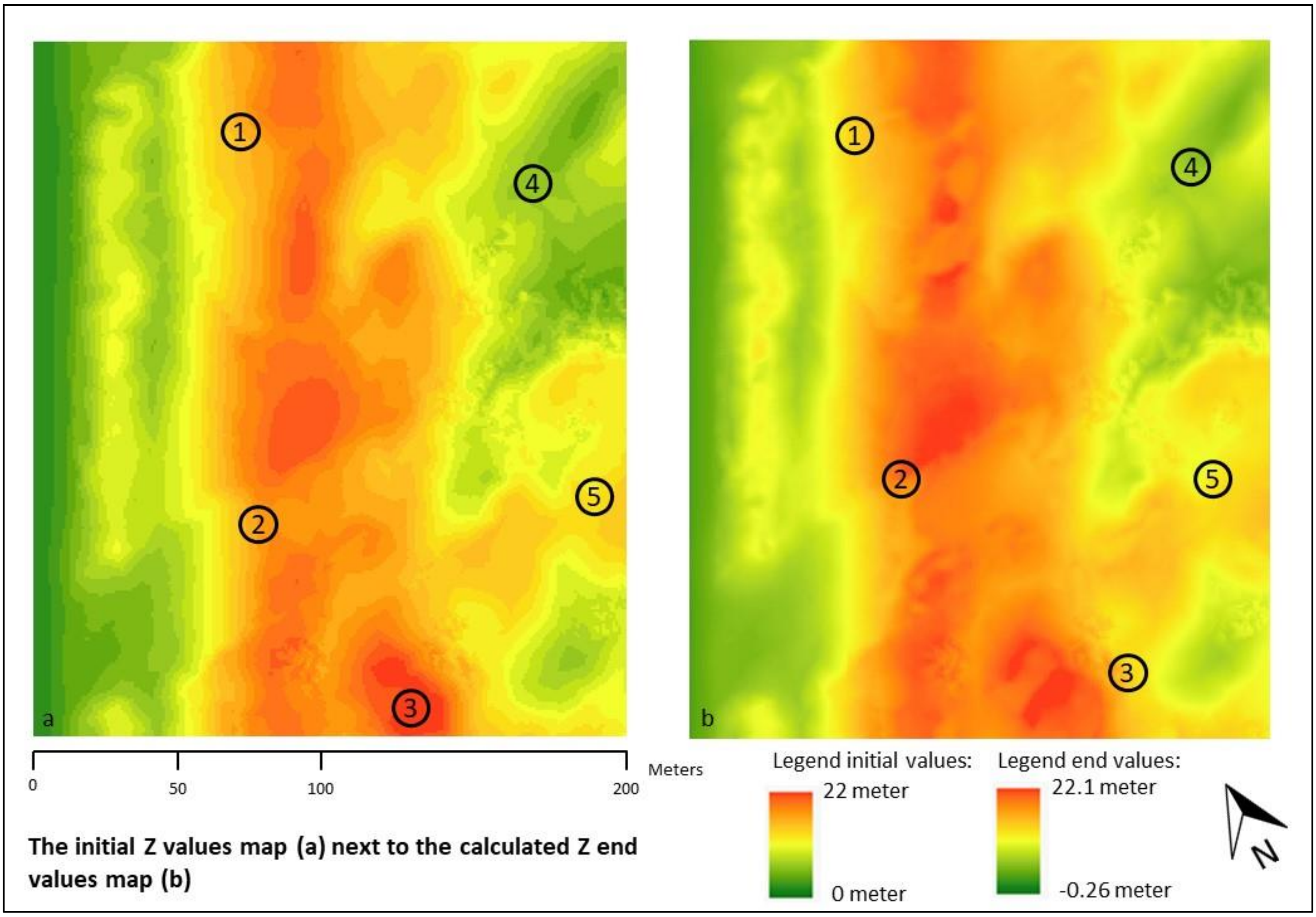

Figure 12: The visualisation of the input and the visualisation of the output of the Aeolis model compared side by side.

The figure below (figure 13) shows the current Natura 2000 classification of the habitat present in the study area. Outlined in red is the study area, which is the notch used for modelling. The left map, however, shows the entire fore-dune system in Meijendel with the habitat currently present.

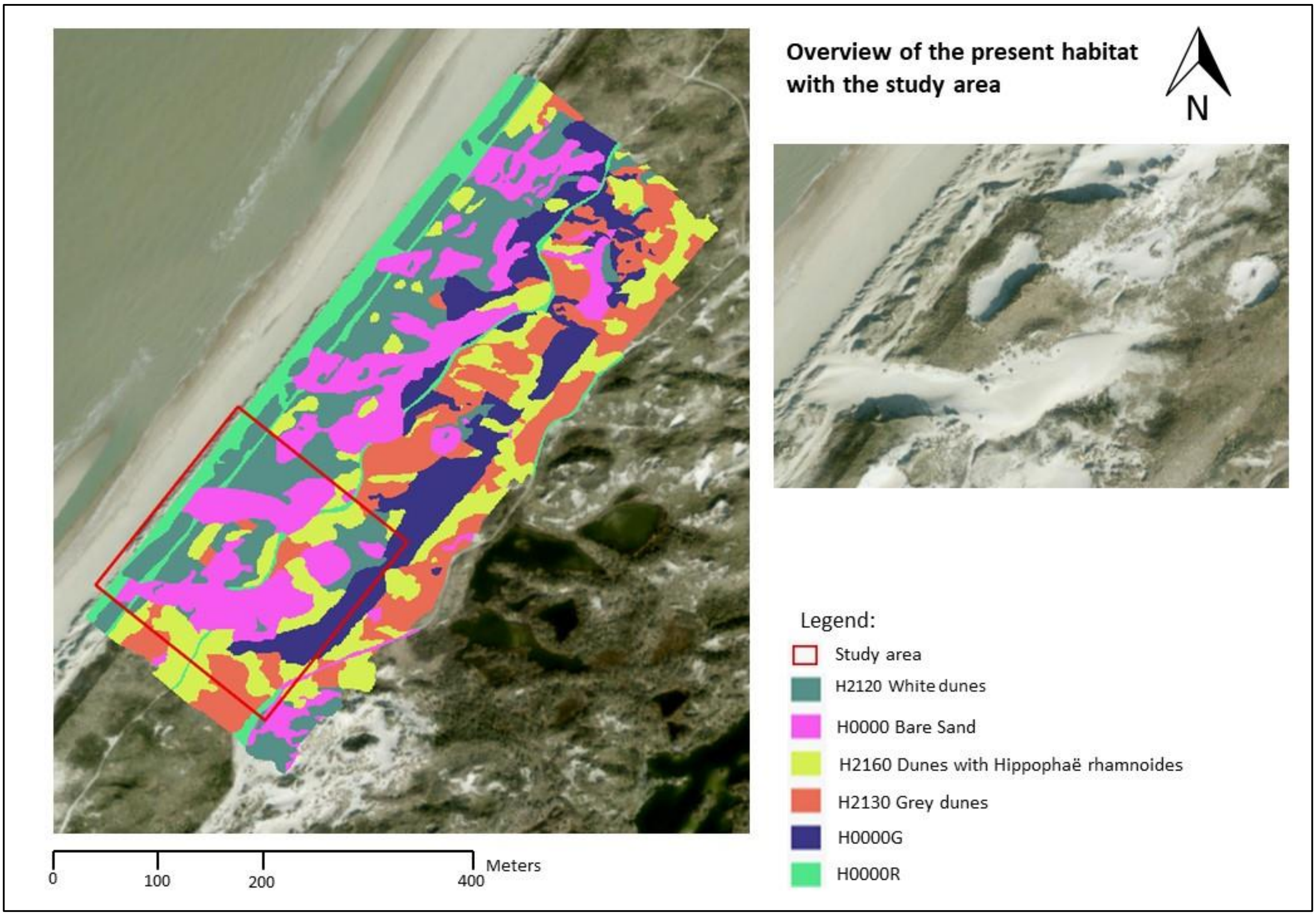

Figure 13: Habitat map of the fore-dunes at Meijendel, classified using the Natura 2000 classification system.

By comparing the habitat map to the change assessment map (figure 14) it was assessed where the current habitat might change and where it would not. The areas where the habitat could change were assessed using the data found by Tonkens (2022), as this study described in detail how habitat would change taking sedimentation into account.

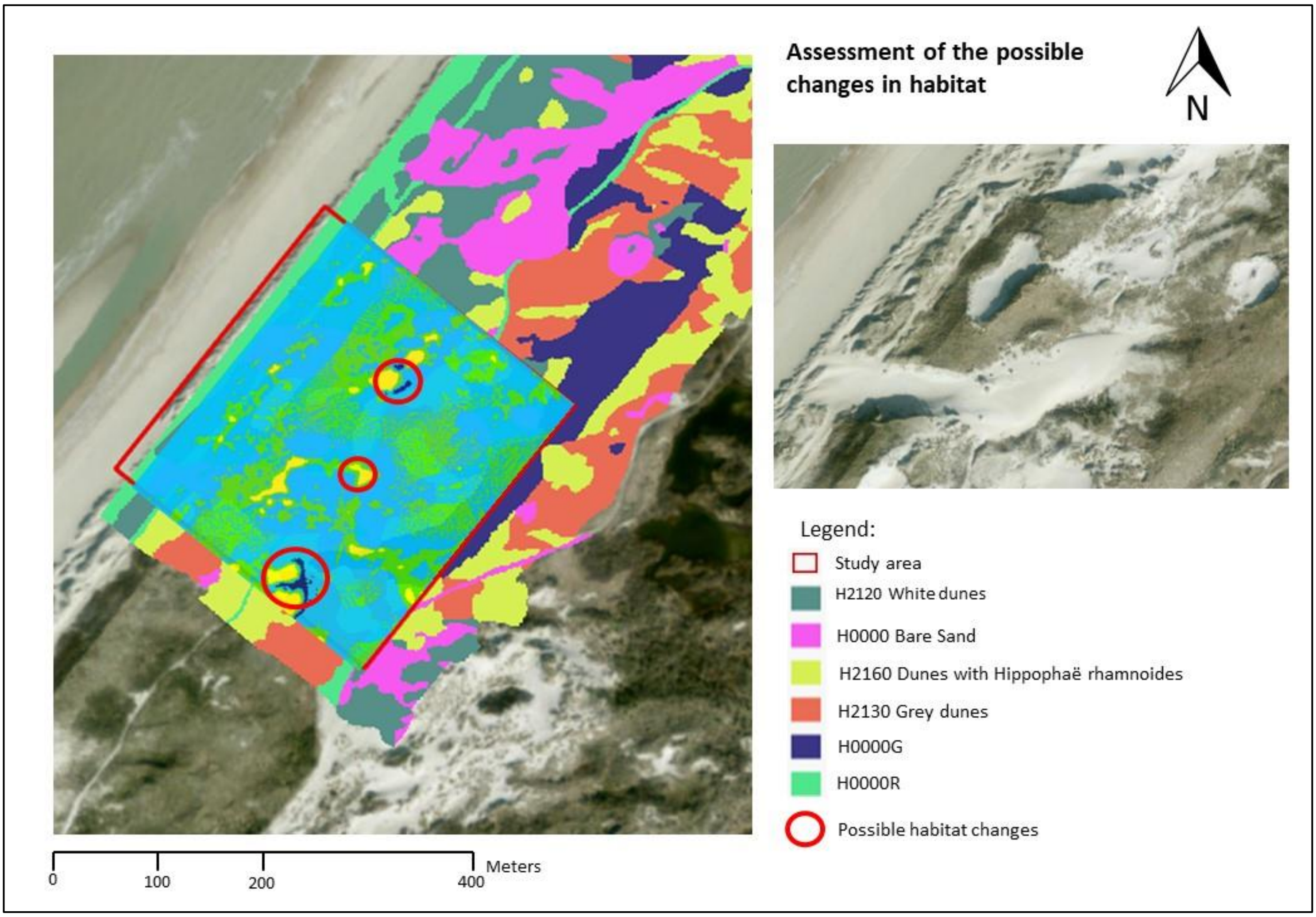

Figure 14: Map showing the areas where habitat might change based on the outcome of the model. Three areas are indicated as areas with highest possibility of changing habitat type.

Appendix IV: Aeolis vegetation predictions

Aeolis itself makes predictions regarding the change in vegetation cover. One of the input files for Aeolis regards vegetation data (figure 15a) (Hoornhout et al., 2015; Meijer, 2020), which is used to predict the flow of sedimentation. Over its run, Aeolis also predicts vegetation output (figure 15b). It is seen Aeolis predicts almost the whole area will be overgrown with vegetation. The change between start and end (figure 16) shows in almost all areas there is an increase in vegetation.

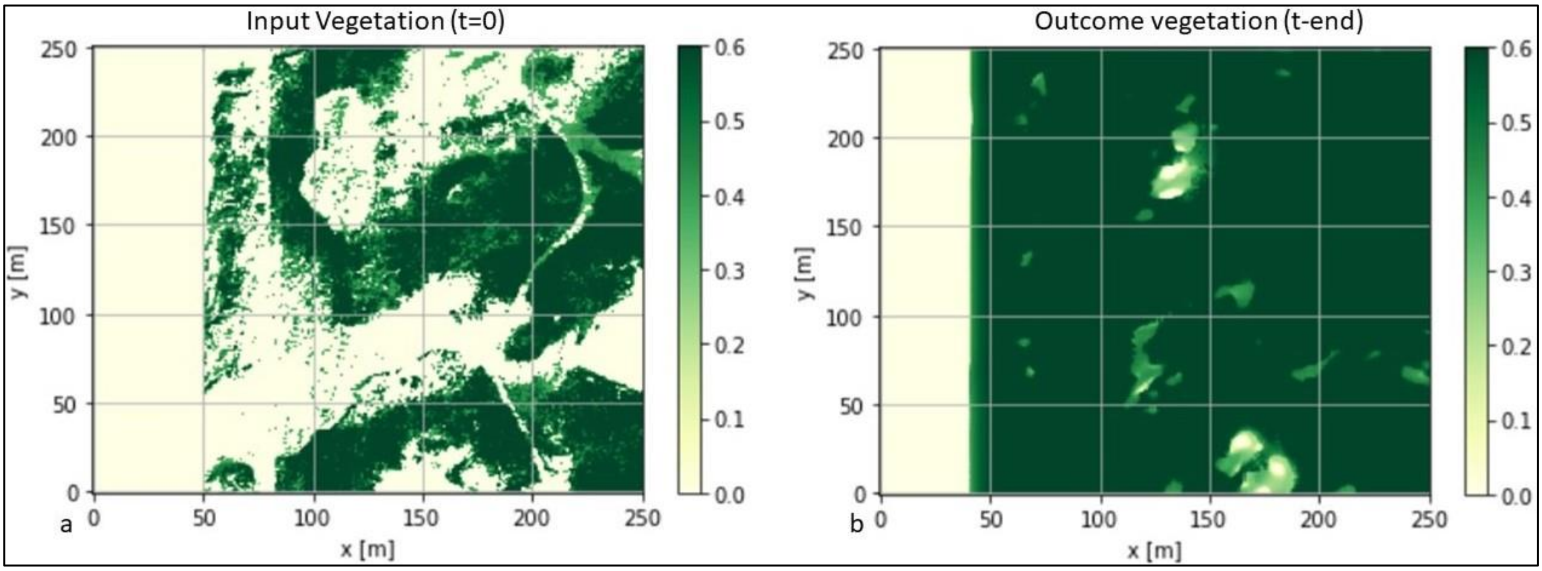

Figure 15: Input (a) and output (b) visualisation of the predicted vegetation cover by Aeolis.

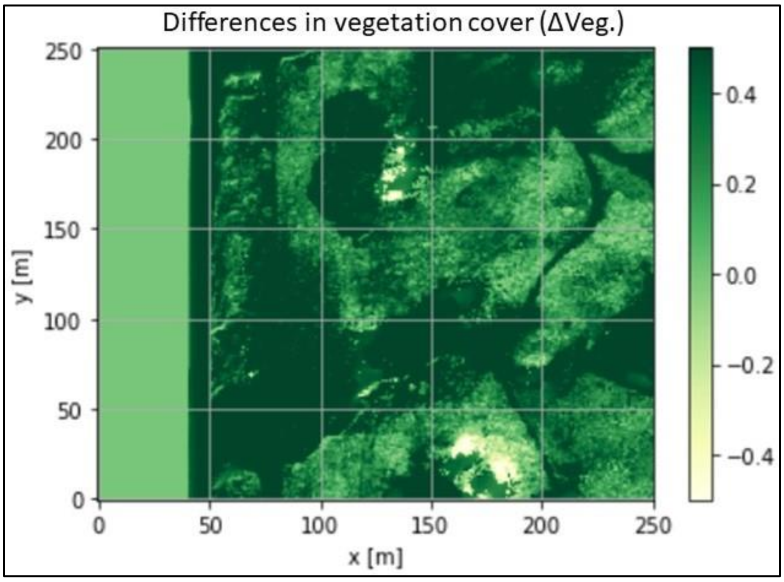

Figure 16: Differences in vegetation cover by increase and decrease compared to t=0 (figure 15a).