# Visual insight into the temporal changes of sand patterns along the Dutch coast

A contribution to detailed point cloud visualization for policymaking and research in coastal management

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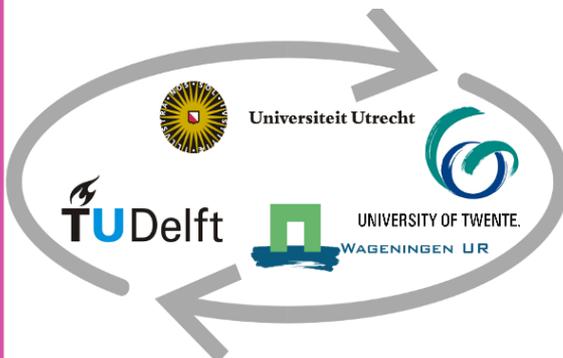
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By

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Abstract

Coastal management in the Netherlands is an important issue to avoid flooding. The coast is a dynamic system which changes through time. Changes in morphology do not only occur on the long term but also on the short term. Through monitoring, data is obtained for research, in this way information can be captured in coastal dynamics. With the use of LiDAR (Light detection and ranging) the elevation along the Dutch coast is measured. In this research is examined to which extend the application and visualization of the original measurements, consisting of point clouds, are useful for policy makers and researchers in providing visual insight into short- and long-term changes of sand patterns along the Dutch coast. Point cloud based visualizations of long term changes along the Dutch coast are visualized in the Hondsbossche Dunes and short term changes are visualized in Noordwijk. Point cloud measurements are possible to be visualized in 3D whereby detailed morphology can be displayed in a very high resolution on a large scale. Furthermore, these point cloud images are really close to reality because there is no information lost or added due to interpolation techniques. In addition, several visualization techniques, like shadow effects and the use of colour scales, are available to increase the quality of the visualization even more. There are however some disadvantages of using point clouds, such as the large volume of the datasets which can make it difficult to work with. There are techniques like point thinning or using continuous levels of detail to overcome this problem. Using point clouds does have an added value when visualizing detailed morphology on a large scale. Especially, on the short term, where changes in morphology are often small and thus need a high resolution to be visualized and where in a short period of time a high volume of data becomes available. Massive 3D point clouds can be updated, integrated, and accessed with much less effort than is required for the normal 3D models.

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List of Abbreviations

ALS	**A**irborne **L**aser **S**canning
CoD	**C**ontinuous Level **of D**etail
DEM	**D**igital **E**levation **M**odel
DSM	**D**igital **S**urface **M**odel
DTM	**D**igital **T**errain **M**odel
GIS	**G**eographical **I**nformation **S**ystems
HHNK	**H**oogheemraadschap **H**ollands **N**oorder**k**wartier
InSAR	**In**terferometric **s**ynthetic-**a**perture **r**adar
LiDAR	**Li**ght **D**etection **a**nd **R**anging
LoD	**L**evel **of D**etail
MLS	**M**obile **L**aser **S**canning
PCA	**P**rincipal **C**omponent **A**nalysis
RWS	**R**ijks**w**ater**s**taat
TIN	**T**riangular **I**rregular **N**etwork
TLS	**T**errestrial **L**aser **S**canner
TNO	**T**oegepast **N**atuurwetenschappelijk **O**nderzoek (Geological Survey of the Netherlands)
UAV	**U**nmanned **A**erial **V**ehicle
UAV-LS	**U**nmanned **A**erial **V**ehicle – **Li**DAR **S**canning

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1. Introduction

Sandy coastal landscapes are constantly changing throughout time. Various influences such as wind flows, and water currents are continuously reshaping beaches and dunes. Sediments are eroded and deposited along the coastline whereby some places become stronger and others more vulnerable. In the Netherlands it is of utmost importance that the coastline is a strong defence from a social and economic point of view. Therefore, the interest for coastal maintenance is high. Visualizing and comparing phenomena like erosion and deposition are very important for decision makers and policymakers in the field of coastal management. For this area of research new tools for visualization can be obtained.

Due to climate change and the resulting accelerated sea level rise, the Dutch coast is becoming more and more vulnerable (Enriques et al., 2019, Hadipour, Vafaie & Kerle, 2020, Vellinga & Klein, 1993, Rijsberman & van Velzen, 1996). The recently drawn conclusion that the melting of the Greenland ice sheet has passed a point of no return only increases that vulnerability (King et al., 2020). This conclusion does not come out of the blue, researchers indicated that the tipping point of melting was almost reached for a while now (Rypdal & Boers, 2020, Schwartz, 2019, Noël et al., 2017). Total melting of the Greenland ice sheet would cause a sea level rise of 2 meter in front of the Dutch coast (de Pater & Katsman, 2007). This will have major consequences for the management and maintenance of the Dutch coast and for the safety of the low-lying areas. Therefore, it is important that the Netherlands is preparing for the effects of sea level rise.

To be able to respond to the sea level rise and to guarantee coastal safety, the Dutch coast is closely monitored. Changes in coastal dynamics can thus be identified in the short- and long-term and actions can be taken if needed. 26% of the Netherlands lay below sea level and 55% is fragile for flooding (PBL, 2007). Therefore, the Dutch coast is protected by dikes and dunes over its entire length. There are several ongoing studies on how the Dutch coast can grow with the sea level rise in a sustainable way (Borsje et al., 2017; Baptist et al., 2019; Aarninkhof, 2017, Wilmink et al., 2019). Sand replenishments take place every year along the coast to keep the coastline with its dunes as it is. These sand replenishments are needed because the balance between supply and demand for sediment along the coastline is overall negative (Mulder & Stive, 2011).

For decision makers it is very important that the Dutch coast is monitored to understand changes in morphology, plant growth and human impacts and their effects on the vulnerability of the coast in the future. Several types of data are collected along the Dutch coast, including height measurements using LiDAR scanners. LiDAR (Laser Imaging Detection and Ranging) data are highly accurate height measurements which consists of large files of point clouds. However, these high-resolution datasets have a large volume and therefore require a lot of computing- and software-power. Raw data are often immediately converted into raster representations which are easier to work with. Nonetheless, during this transformation process, important information could be lost on spatial and semantic level (Poux et al, 2016). In addition, converting the original datasets is prone to errors and it is time-consuming. With the use of raw point cloud data, the coast can be visualized in a high resolution and in 2.5D. This can give more insight into short- and long-term changes on a large scale of sand patterns along the Dutch coast.

1.1 Problem description

As stated in the introduction, coastal safety is increasingly important for the Netherlands. Weak parts of the Dutch coast are strengthened in innovative ways. In this research 2 locations have been chosen which were weak spots along the Dutch coast. These weak spots were reinforced in an innovative way between 2007 and 2015. The first location chosen are the Hondsbossche dunes. Here the coastal system is reinforced through dune formation instead of expansion of the existing dike. The second location is Noordwijk, here a dike in a dune is created to reinforce the coastal defence. By monitoring these areas changes through time can be visualized, so the maintenance of the coastal defences can be based on thoroughly collected facts and experiences. This information can be used in future projects and decision making for coastal defences.

Interpretation and policymaking are mainly based on 2D raster data (0,5m or 2m), that are derived from LiDAR point cloud data. To a certain amount this type of data can cause loss of information. It is not known if the lost information is meaningful for management and maintenance of the system.

1.2 Research objectives

In the research objectives the aim of this research will be discussed whereby the main research question and sub questions will be defined. In addition, the scope and approach of this research will be explained.

1.2.1 Aim of the research

The aim of this research is to find out to which extent the visualization of point cloud data gives more insight into the dynamics of the Dutch coast compared to deduced raster data. Visualization of the dynamics of the Dutch coast can help policy makers and researchers in the field of coastal management to understand coastal dynamics better as an ingredient for better policies that will keep the Netherlands safe from flooding. It will be examined whether the use of raw point cloud data provides more insight in coastal dynamics than the interpolated point cloud data to raster DEMs. By looking at visualizations of short-term changes (days/hours) in sand patterns at Noordwijk and long-term changes (years) in sand patterns at the Hondsbossche dunes, dynamics of the Dutch coast can be better understood. Waterboards and Rijkswaterstaat often immediately convert LiDAR (point cloud) data into raster datasets. The raw LiDAR data consists of extremely large point cloud files, which makes it difficult to work with. However, by converting this data, important spatial information can be lost. This study will examine whether the loss of information is crucial for the temporal analysis of Noordwijk and the Hondsbossche dunes and successively also for other coastal areas in the future.

The following research question has been formulated:
To which extent is the application of point cloud-based techniques useful for policy makers and researchers in the field of coastal management in providing visual insight into short- and long-term changes of sand patterns along the Dutch coast?

The main question can then be subdivided into several sub-questions:
1. What are the significant differences between point cloud visualization and raster visualization?
2. What is the added value of point cloud-based visualization techniques compared to other visualization techniques?
3. What are the limitations of point cloud-based visualization techniques?
4. Which point cloud-based techniques are useful to visualize changes in detailed morphology?

5. What is the best visualization method to display long-term changes in sand patterns along the Hondsbossche dunes while using point cloud data?
6. What is the best visualization method to display short-term changes of sand patterns along the coast of Noordwijk while using point cloud data?
7. What is the added value of detailed point cloud visualization for policymaking and research in the field of coastal management?

1.2.2 Scope of the research

This research has several limitations which define the scope:
- First of all, only two main areas along the Dutch coast are examined and not the whole Dutch coast. For the long-term changes in coastal dynamics, the Hondsbossche dunes are analysed. For visualizations of the short-term changes is the research location of Noordwijk chosen.
- Secondly, for each research location some limitations are defined as well. For the Hondsbossche dunes, only the southern part close to Camperduin is visualized in this research, further details and a figure of this area can be found in chapter 5. This area is chosen because of the high rate of erosion and (sand)dynamics. Attention will be paid to the dunes in front of the dike up to the shore face of the Hondsbossche Zeewering (chapter 5). The (un)depth for the coast is out of the scope, no multibeam data is used in this research. The reinforcement of the Hondsbossche dunes started in 2013 and finished in 2015. Therefore, annual datasets from Rijkswaterstaat are used from the years 2013 up until 2020 for the temporal visualizations. The visualization will be created with point cloud data and focus on the dynamics of the morphology in detail. The raster datasets used in this research will be made from these point cloud datasets or obtained by HHNK.
- The limitations for the Noordwijk location begin with the limited view of the laser scanner. The data of the LiDAR scanner from Coastscan, scans the dunes, beach and tidal area in front of the Hotel Huis ter Duin, this will be the boarders of the research area. The terrestrial laser scanner of Coastscan, scans almost continually (one scan per hour). Instead of looking over a period of years, the time span will be hours or days at this location. More specific, days with stormy weather (storm Ciara) are analysed. First of all, the low tides are visualized from a couple of consecutive storm days. In addition, a couple of consecutive hours before the storm and a couple of hours during the storm at a moment with high windspeeds are observed. In this way change in morphology in a short period can be visualized. Moreover, similar to the Hondsbossche dunes, the focus of visualization at Noordwijk will be on the dynamics of the morphology in detail.
- Lastly, both areas are visualized using raw point cloud data. Point cloud data can be visualized in 2.5D/3D and produce very high-resolution maps. The software programs that are used in this research are ArcGIS Pro and CloudCompare. Visualization techniques for point clouds are the main subject in this research. In addition, point clouds can be subtracted from each other to visualize change in deposition and erosion. The point cloud visualizations are compared to raster visualizations to detect and analyse the differences. As said before, most of the raster visualizations are made with the point cloud datasets of Rijkswaterstaat and raster visualizations of HHNK.

1.2.3 Research approach

For this research, point cloud-based visualizations are compared to raster-based visualizations to find out whether point cloud-based visualizations are more applicable for the visualization of dynamics in detailed morphology. The research area will be the Hondsbossche dunes, for visualizing long-term dynamics and Noordwijk for visualizations of short-term dynamics. How this research will be carried out will be explained in further detail in the methodology chapter (chapter 4).

The research process can be appropriated in four main research steps (Figure 1.1). First a conceptual model was created to get an overview of the key components for the Visualization and Analysis in this research. Hereafter, a theoretical framework is made to answer the first four sub-questions. Then visualizations of the Hondsbossche dunes and Noordwijk are made whereby input is delivered for sub-question 5 and 6. Lastly, the results of the visualizations are analysed and sub-question 7 can be answered.
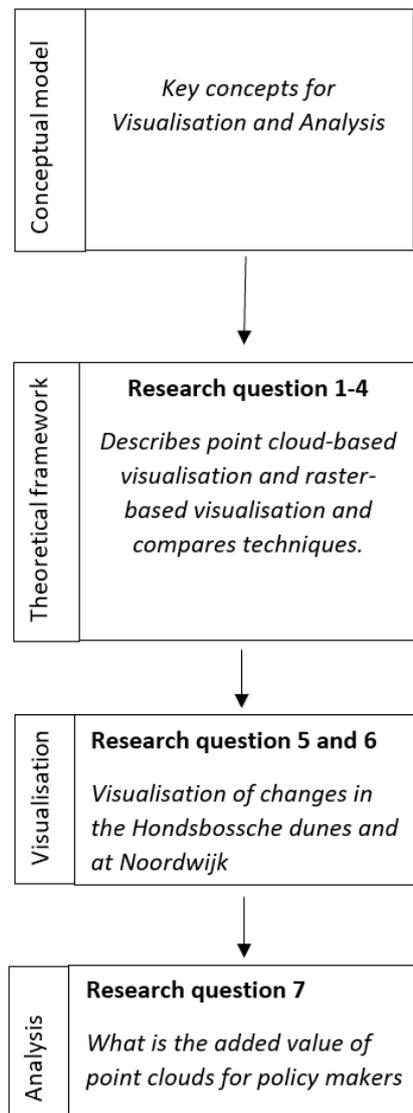
Figure 1.1: Research approach

2. Conceptual model

To provide a good overview of what is involved in this research, a conceptual model has been made (Figure 2.1). The Hondsbossche dunes and Noordwijk are both dynamic coastal landscapes. 3 main components influence the dynamics of these areas: the physical component, biological component and the social component (Wijnenberg et al., 2020). In this research the focus is put on the physical component whereby the changes in geomorphology are visualized using height measurements from LiDAR data. The datasets consist of large point clouds which can be visualized in 2D and 2.5D/3D. The energy input for the physical component are wind, sea currents, tidal currents and human interference.

The Hondsbossche dunes and Noordwijk are closely monitored to gain more insight into the dynamics along the coast. In this research there is looked at data obtained via airborne laser scanners (ALS) for coastal changes on the long term and terrestrial laser scanners (TLS) for coastal changes on the short term. The point cloud datasets retrieved from the airborne and terrestrial laser scanners are often hard to work with due to their large size datasets. They are therefore processed into raster datasets like DEMs (Digital Elevation Model), which reduces the size of the dataset with approximately 98% (when creating raster with cell size 0,5 meter, in datasets from this research). A DEM is a 3D representation of the elevation data which represents terrain. As a side note, two kinds of DEMs exist: the DSM (digital surface model) and the DTM (digital terrain model). A DSM takes objects like houses or trees into account while DTM only focuses on the bare soil. With the software programs ArcGIS Pro and Cloud-Compare several visualizations are made. In this report mainly static maps are visualized. However, animations and visual interaction are also used to understand the data better (Dimopoulos, 2019).
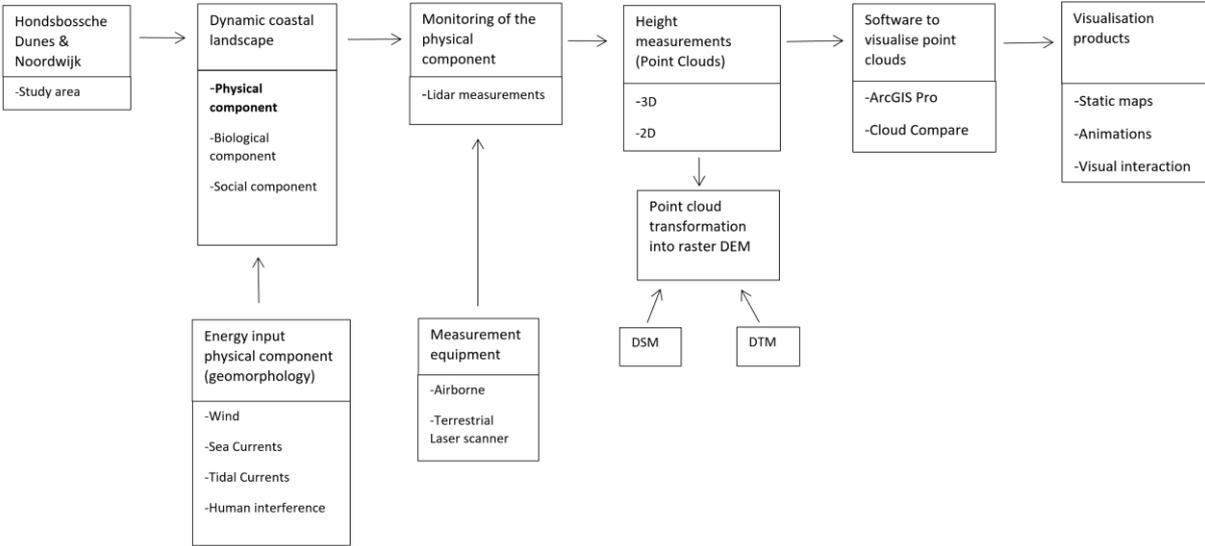
Figure 2.1: Key concepts for the analysis and visualization of the Hondsbossche dunes and Noordwijk

3. Theoretical framework

This chapter connects existing theories and literature to form a basis for investigating the differences between 3D point cloud based- and raster-based visualization for dynamic coastal landscapes. The first section will describe the data types Point cloud and raster. Then, several representation techniques for 3D data including point cloud and raster are explained. Hereafter, visualization techniques for point-cloud data and raster data will be discussed. In addition, the limitations and added value of point cloud-based visualization techniques compared to other techniques will be deliberated. Finally, point-cloud based visualizations will be compared to raster-based visualizations.

3.1 Data types

This first section will describe the two main (2.5D/3D) datatypes that are used in this research. These consists of point cloud data and raster data.

3.1.1 Point cloud data

Remote sensing approaches such as LiDAR are approved methods for capturing the physical world (Richter & Dölner, 2014). These laser scanning devices are capable of creating large point cloud datasets which contain millions of points (Heywood et al., 2011). The points in a point cloud obtain the external surface in three dimensions (3D). Point clouds are therefore widely used in earth surface research (Cheng et al., 2018). The three-dimensional coordinate system of a point cloud can be defined by x, y and z coordinates (Achlioptas et al., 2018). This is important because without the x,y, and z values the spatial information which is captured in the point cloud do not have real meaning e.g. do not reflect the conditions of the real world (Tang et al., 2020).

The point cloud scanned by a LiDAR scanner often contains at least 1 point per m^2, this results in accurate and precise data usage (Zhang et al., 2017). Point clouds often represent the envelope or cover of an object, for elevation data this is only the surface e.g. only the boundary and not the interior of the 'object'. Therefore, the elevation is visualized in 2.5D instead of 3D (Ledoux, Peters & Arroyo Ohori, 2018).

Several types of LiDAR scanning exist. For example, aerial laser scanning (ALS), Terrestrial Laser Scanning (TLS), Mobile Mapping/laser scanning (MLS), Scanning from an universal vehicle (UAV-LS) (Virtanen et al., 2017). Rijkswaterstaat (RWS) uses laser scanning techniques like LiDAR for their coastal management. Yearly measurements are taken from the coastline. In Figure 3.1 an example of a small part of a RWS point cloud dataset is shown. This point cloud is visualized without further visualization techniques e.g. it is the original point cloud dataset. Usually, these dense point clouds are pre-processed by GIS (Geographical Information System) and used as input data for other applications such as environmental monitoring, simulations, disaster management and urban planning (Poux, 2020). In the future, obtaining point cloud data will become easier and cheaper due to improved measurement techniques. This will result in an increase of the amount of up to date data available. Therefore, approaches that will efficiently manage, analyze, visualize, integrate and update 2.5D/3D point clouds will be necessary.
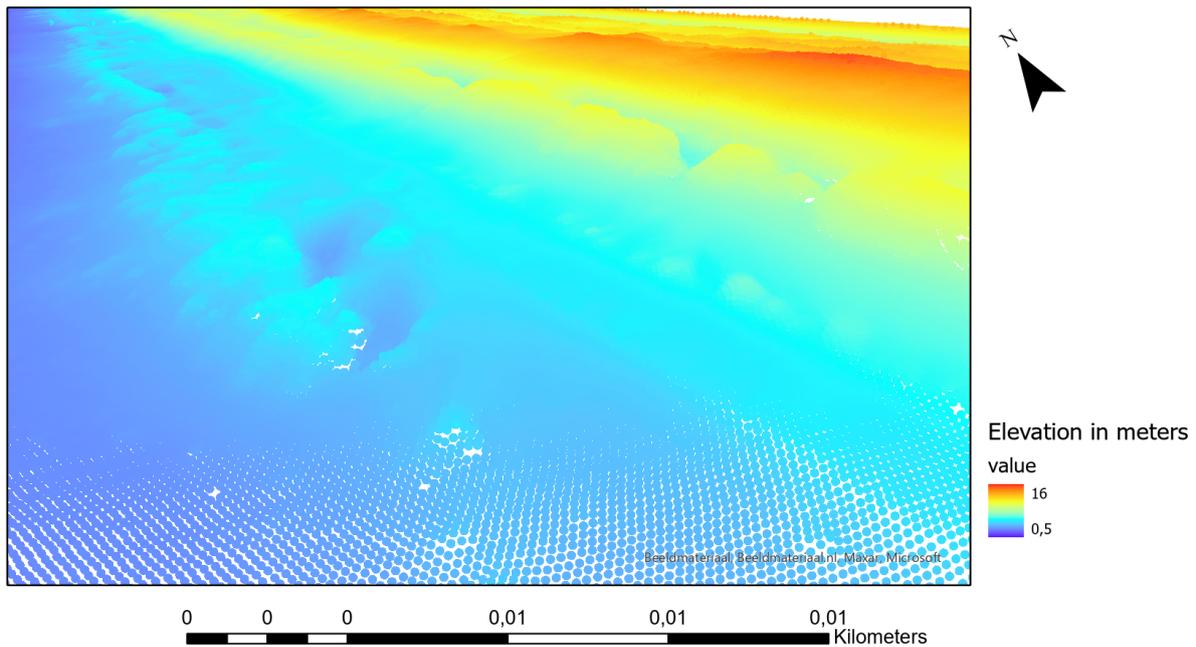
Figure 3.1: Point cloud visualization of coastal LiDAR data from Rijkswaterstaat, south side of the Hondsbossche dunes close to Camperduin. Visualization of las dataset in ArcGIS Pro without further visualization techniques applied to the point cloud. This visualization is on a large scale, in the front the points are visible this visualization consists of.

3.1.2 Raster data

Raster data has a simple matrix data structure which consists of a matrix of cells (pixels) organized into columns and rows (grid) where each cell contains a value representing information. The matrix is often represented by a Cartesian coordinate system in which the columns of the matrix are on the y-axes of the Cartesian plane and the rows on the x-axes of the Cartesian plane (Kokalj & Hesse, 2017).

GIS data are commonly stored as raster data whereby geographical information is encoded in the raster value. Here real-world phenomena are represented in the raster data. The area or surface that is represented by each raster cell consists of the same height and size. An equal portion of the entire surface is thus represented by the raster. For example, a raster which represents elevation (like DEM) may cover an area of 200 square kilometres. If there are 200 cells in this raster, each cell would represent 1 square kilometre of equal height and size (1 km x 1 km).

For the representation of the surface the dimension of the raster cells can be as small or large as needed. For example, possibilities are squared kilometre, square meter or even square centimetre. The cell size of the grid will determine how coarse or fine the features and patterns in the raster appear. The smaller the cell size the more detailed and smooth the raster will look, e.g. the raster cells itself will not be visible when zoomed out. On the contrary, larger cell sizes are more averaged out and raster cells will be visible earlier, this can give a chequered image. However, the greater the number of cells, the longer the processing time will be. In addition, a large number of cells will cause a much higher demand of storage space. When creating a raster dataset with higher resolution the storage space that will be used will increase exponentially when using more raster cells.

When using large cell sizes, spatial information could be lost, or subtle patterns stay obscure. In addition, objects can be visible that are not there. For example, if the cell size is larger than the width of a road, the road will not be visible on the raster map or if the majority (or some other criterion) of the information within this cell is of type 'road', the whole cell will be classified as 'road'.

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Three main types of raster data for visualizing coastal inforamtion exist:
- Continuous data (like temperature and elevation)
- Thematic data (like land use and soil types)
- Pictures (like scanned maps)

So, raster data can be created with digital aerial imagery from satellites, digital pictures, photographs, or even scanned maps. In addition, raster maps can be created through interpolation of point cloud data (Figure 3.2). Raster data, specifically continuous and thematic, are often used for spatial analysis. Raster data are well suited for representing continuous change in dynamic coastal landscapes (Rana & Dikes, 2003). They provide an effective method for storing the continuity as a surface. Also, raster data do provide regularly spaced representation of surfaces. Furthermore, storing the data as a raster gives the ability to perform fast overlays with complex datasets.

However, there are some disadvantages for using raster data as well. First of all, there can be spatial inaccuracies due to limits imposed by the cell dimension of the raster. In addition, when interpolating from point cloud data, information could be lost.
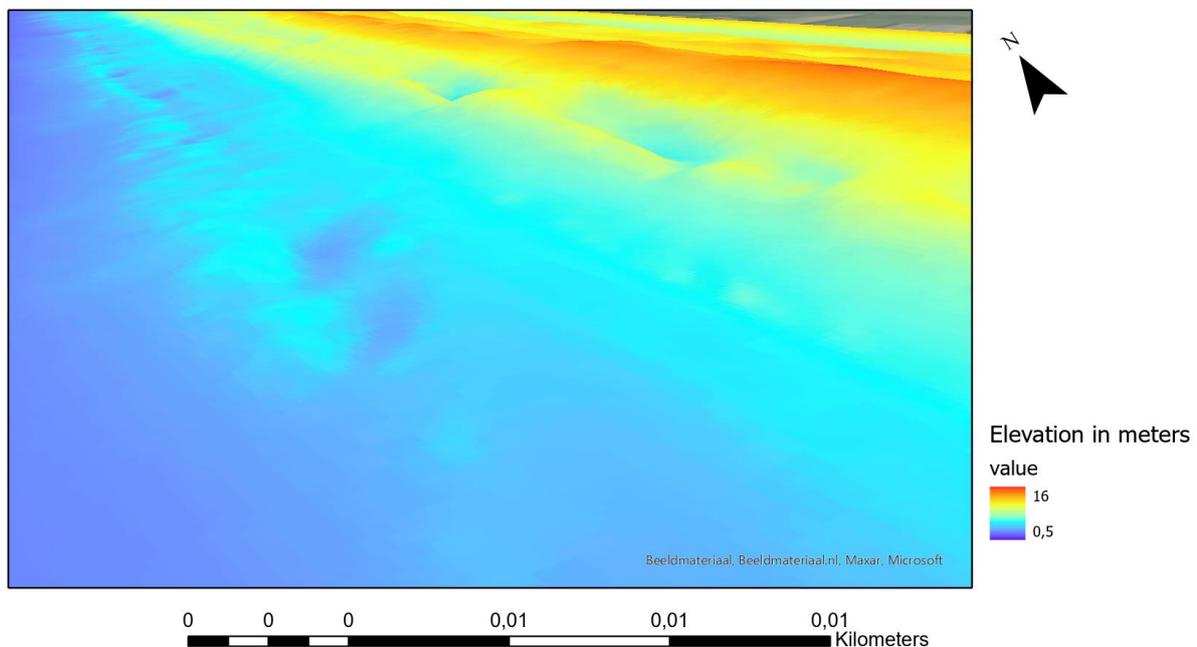
Figure 3.2: Raster visualization (DSM, 0,5m) made from point cloud data of RWS. The figure is made in ArcGIS Pro, using the inverse distance weighted average interpolation of the point cloud tool. This image looks very smooth which is the result of the interpolation. When looking close the grid cells of 0,5 meter are visible.

3.2 Representation techniques of 3D data

To represent point cloud or raster in 3D, several 3D models can be used which can vary both in structure and properties (Figure 3.3). 3D models can be divided in two categories, solid and shell models (also called boundary models). Solid models define the volume of the object that they represent. They are mostly used in medical simulations and in engineering. The solid models are usually built with voxel assemblies or Constructive Solid Geometry (Poux, 2020). The shell or boundary models represent the boundary of the object and not its volume. Almost all visual models which are used in games, films and reality capture workflows are boundary or shell representations.
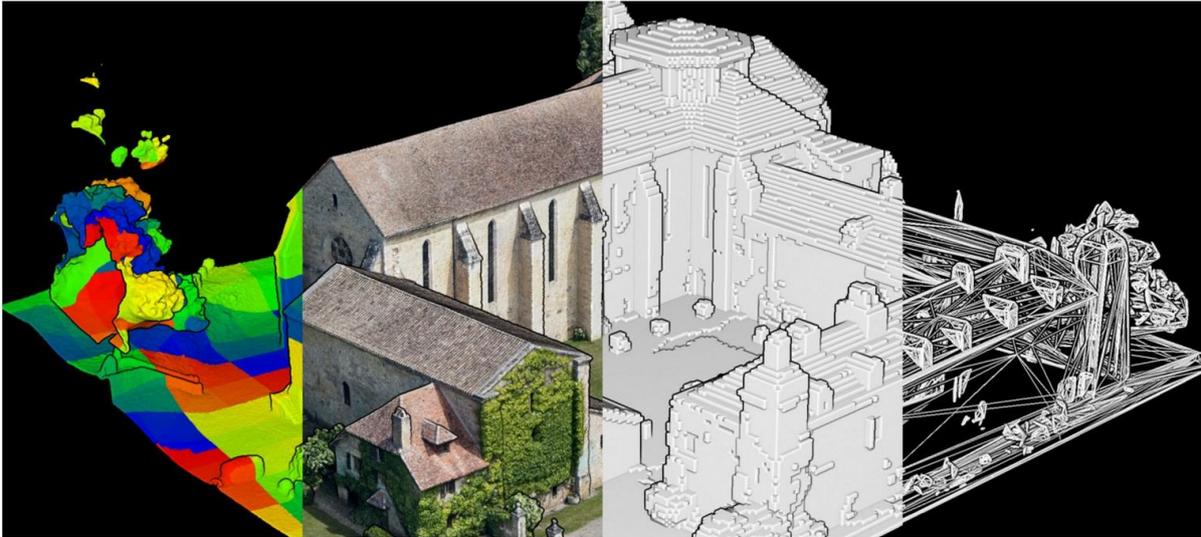
Figure 3.3: Different data representations of 3D point cloud data by Poux, 2020.

There are three main strategies to describe a point cloud through 3D representations (Poux, 2020): Implicit surfaces (Parametric modeling), Boundary representations (B-reps) and Constructive Solid Geometry. B-reps are most commonly used as 3D meshes. Boundary representations are mainly composed of two parts: the geometry (curves, surfaces and points) and the topology (the organisation of elements). In the parametric model parameters are set to a targeted value. This modifies the underlying geometry. Implicit surfaces or parametric models are often used to model walls by setting up their orientation, length, width and height, they will therefore not useful for this research. Constructive Solid Geometry can also be used as meshes and are used to create a surface or object by using Boolean operators.

In the following paragraphs a couple of model representations are discussed. To begin with the point cloud representation. Hereafter, a couple of raster-based representations will be explained. Lastly, there will be elaborated on a mesh-based representation.

3.2.1 Point cloud representations

Point cloud data can be represented in several ways, including in a point cloud model. In a point cloud model, the points are not converted to another datatype like raster or polygons but consist of millions of points. This will give a rather high level of detail in the visualization of the point cloud model. The high level of detail in the visualization, facilitates visibility analysis in different sectors like GIS technology and landscape planning (Figure 3.4) (Zhang et al., 2017). In addition, the original data is used in point cloud models which results in an as close as possible representation of the real-life situation (Cao et al., 2019). Another characteristic of point cloud models is that they sometimes display incomplete information, especially when zoomed in (Figure 3.5). Point clouds are not able to fill in the gaps which occur when there are lack of measurements and thus no data (Haan, 2009). This will ensure that no incorrect conclusions can be drawn during analysis, because the areas with no data are not filled in with for example the average between points.

However, a drawback of using point cloud models can be the huge amount of data points which could give issues with computing power, storage and rendering of the datasets.
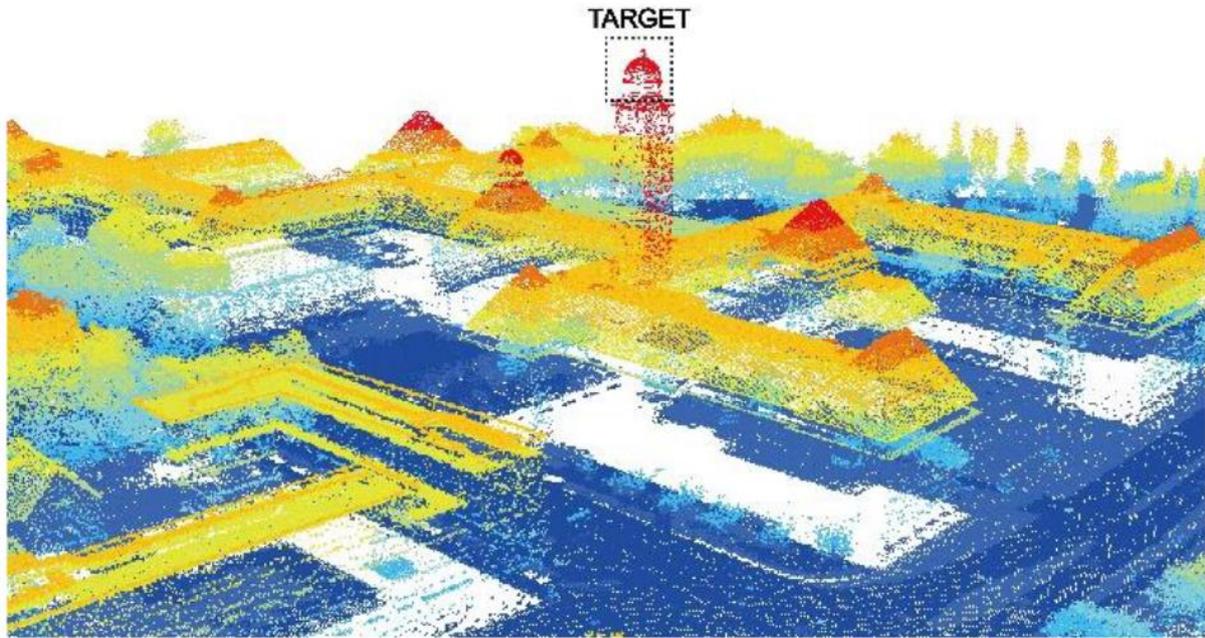
Figure 3.4: High level of detail in point cloud models can facilitate visibility analysis like in the visibility analysis from Zhang et al., 2017. Whereby this tower in Delft is chosen as view target for their visibility analysis.

When the point cloud dataset becomes larger and the number of points increase, the construction of 3D models becomes more time consuming which can pose challenges for analysis. A solution for this is to use generalized 3D models. However, these models have less detail in their 3D representations. Another solution to cope with the point cloud size is to use multiple level-of-detail (LoD) representations which are generated by preprocessing and adaptively removing points (Marton & Gobbetti, 2004). However, spatial information could be lost when removing points. Another possibility is to use a continuous level-of-detail (CoD). No points will be discarded in this case, but unimportant points will have lower values and will not be displayed, unless there is zoomed in or specifically looking for these kinds of points. When using point-based 3D models there is no need to generate new models and corresponding LoDs when new data is available, point-based 3D models can be rapidly updated. The massive 3D point clouds can be updated, integrated, and accessed with much less effort than is required for the normal 3D models especially when working with temporal data. Point cloud data can be directly used to perform visibility analysis, which will shorten the analysis period (Zhang, Van Oosterom & Verbree, 2017).

There are three main operations that can be done with point cloud data (Poux, 2020). First of all, transformations, whereby points in the point list can be multiplied with linear transformation matrices, in this way the coordinate system can be recalculated using a matrix in a numeric computing environment (e.g. mathlab, python). For example, sometimes two point cloud datasets do not align correctly, transformations can help with this problem. Secondly, 'objects' can be combined by merging points list together e.g., points can be put in a list, this list can then be merged to form an object. Lastly, rendering of the point cloud, whereby the points are drawn and projected on an image plane e.g., a series of points are represented in space. As mentioned earlier, there are some advantages and disadvantages when representing point clouds. Benefits are fast rendering and transformations are possible, and the representations are very exact. The main disadvantages are high memory consumption, numerous points (obj., curve, exact representation) and limited combination operations. In table 3.1 the advantages and disadvantages of representing a point cloud are summarized.
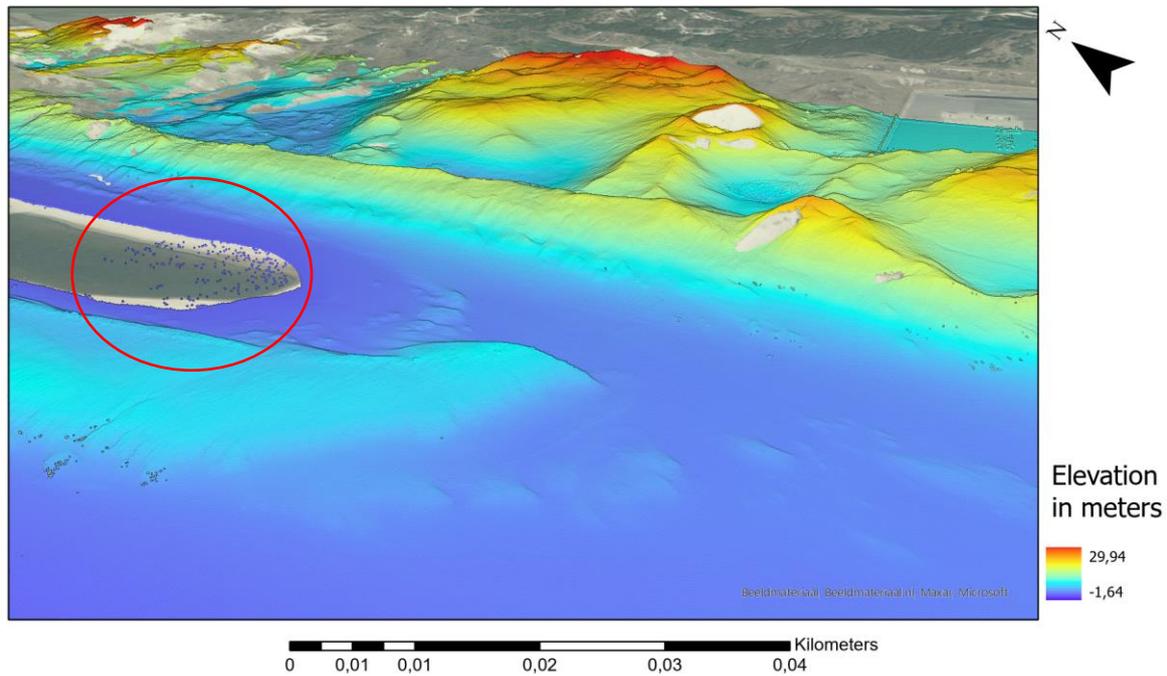
Figure 3.5: Point cloud models do not show data that are not there due to lack of measurements as shown in the red circle.

Table 3.1: Advantages and disadvantages of representing point clouds

Advantages	Disadvantages
High level of detail in visualization	High memory consumption
Fast rendering, data generation, and transformations are possible	numerous points (obj., curve, exact representation)
Representation is close to real life	limited combination operations
Absence of data is not visualized, this will lower the risk that incorrect conclusions during analysis will be made	Empty spaces on the map are not visually attractive for some people
massive 3D point clouds can be updated, integrated, and accessed with much less effort than is required for the normal 3D models	Voluminous data files and data storage are necessary

3.2.2 Voxel-based models

A voxel can also be used to represent a 3D model. A voxel is a 3D based cubical unit. In 2D the pixel, which is the smallest raster unit, is resembling to the voxel. Therefore, the voxel-based model is composed of "3D pixels". This model can be associated with the solid modeling discussed in the previous section 3.2. A famous example of a voxel-based model in the gaming industry is Minecraft (Figure 3.6). In the GIS surrounding voxel-based models are often used to visualize the subsoil. For example, the soil types of the Netherlands are visualized in a voxel-based model from TNO, called the GeoTOP.

In the case of using point cloud data for a voxel-based model, each point can be represented as one voxel with the size x. This will give a 'filled' view without empty spaces between points. Often the data structures of voxels are octrees which permit to average a certain amount of points per voxel unit. This will depend on the level of refinement that is needed. It is practical for rendering and smooth visualization. However, the initial geometry shall be approximated in conjunction with aliasing artifacts. When the volume information is not used correctly it can give false information. Nonetheless, voxel models can

be very handy for processing tasks such as the classification through 3D convolutional neural networks. This is because the voxel model has a very structured grid layout (Poux, 2020).

Figure 3.6: Example of voxel-based model (Minecraft)

3.2.3 Depth map

The depth map is a raster-based point cloud representation. It is an image that consists of information associated to the distance of point constituting the scene from a single viewpoint. The colour-code with intensity values is used for the expression of depth instead of RGB images. Whereby the dark pixels have the lowest values and the bright pixels the highest values. The depth image presents values that visualize the distance to objects whereby the colour of the pixel, the value of the distance from the camera is (Figure 3.7). This form of representing point clouds is fine, only when the surface information is needed, linked to a known point of view. It is a very well-known raster format and transformations are quick and easy. In addition, depth maps have low memory requirements. However, depth maps are essentially a 2.5D representation because two different values for one line sight cannot be visualized in 3D. In addition, the topology of the depth map is relatively weak (Poux, 2020).
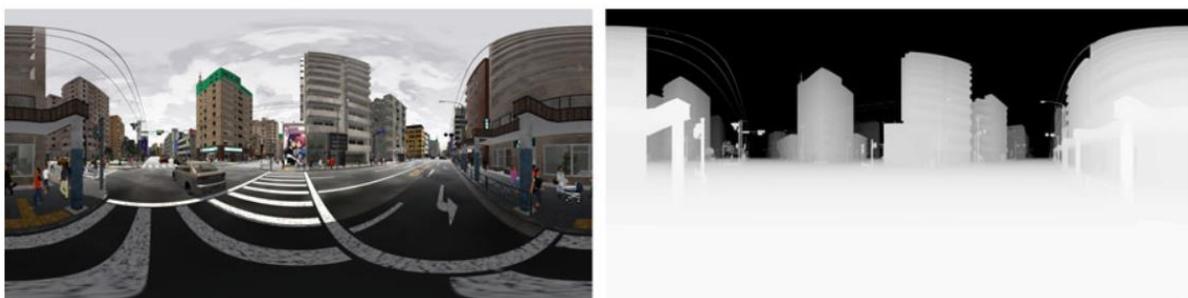
Figure 3.7: Left picture is the original photo (RGB image), right visualization is a depth map. (Takizawa & Kinugawa, 2020)

3.2.4 DEMs

DEMs or digital elevation models are raster maps that represent elevation of a surface. These DEM raster maps are generated by using remote sensing data. Techniques such as LiDAR, photogrammetry, InSAR (Differential interferometric synthetic aperture radar) and land surveying could be used to obtain data for a DEM (Li et al., 2005). As mentioned before LiDAR data consists of points. When creating a DEM, the points in the point cloud are interpolated into a raster map. DEM is often used as a generic term for DSM (digital surface model) and DTM (digital terrain model). A DSM represents the earth's

surface and includes all the objects on it. On the contrary, a DTM represents the bare ground surface, here objects like plants and buildings are filtered out (Figure 3.8).
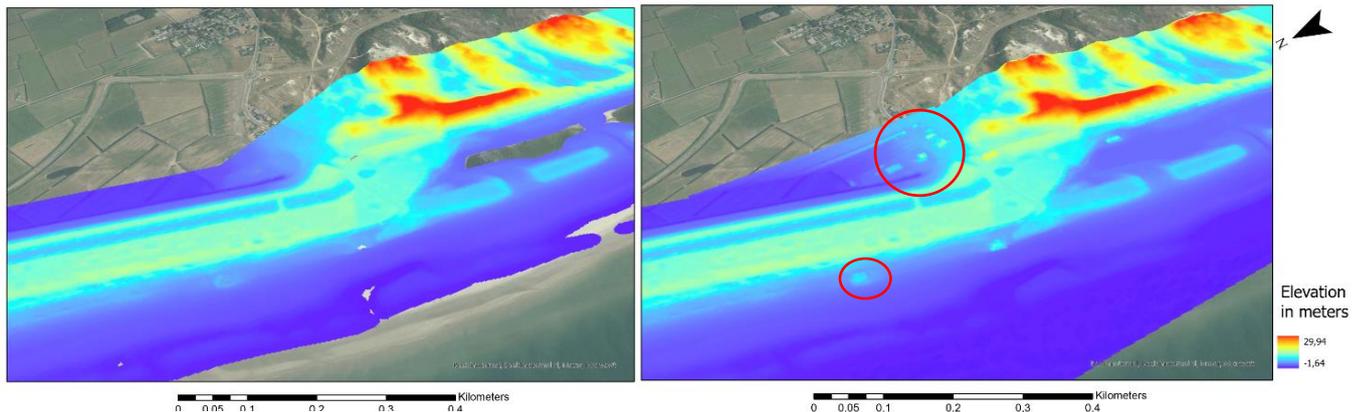
Figure 3.8: Visualization of a DTM (left) which only represents the ground surface and (right) DSM which include objects like buildings (indicated with red circle). Raster with grid size 0,5m.

3.2.5 Projections

3D data can also be projected in a 2D space. The 2D representation captures some of the key properties of the original 3D shape. Multiple projections are also possible where each projection converts the 3D object into a 2D grid with specific information whereby the data is projected in spherical and cylindrical domains. Such projections in these domains help the projected data to be invariant to rotations around the principal axes. In addition, it will ease the processing of the 3D data due to the Euclidean grid structure of the resulting projections. Nevertheless, these representations are not optimal for complicated computer vision tasks like dense correspondence because of the information loss (Poux, 2020).

3.2.6 3D meshes

A mesh is a geometric data structure whereby the surface subdivisions are visualized by a set of polygons. Meshes can be made from LiDAR (point cloud) data as well. Meshes are made up of vertices which are connected by edges making facets of polygonal shape. When these facets are of triangular shape, they are called triangular meshing. These are most common in Reality Capture workflows. An example of a triangular mesh is a Triangular Irregular Network (TIN). This is a form of vector based digital geographic data which are constructed by triangulating a set of vertices (points). They are based on Delaunay triangulation or constrained Delaunay. TINs can represent surface morphology formed with irregularly distributed nodes and lines with three-dimensional coordinates (x, y, and z), these are arranged in a network of non-overlapping triangles (Figure 3.99). By rendering of the triangular facets three-dimensional visualizations are created. In areas where there is little variation of the elevation of the surface, points may be widely spaced. On the contrary, in regions of more intense variation of the elevation the density of points is increased.

For the representation and visualization of the geometry of a point cloud are meshes an excellent option to use. It often reduces the number of needed points as vertices. In addition, the relationship between objects through the faces of connectivity will become clearer. There are several strategies to mesh a point cloud. This often demands some theoretical background to know which parameters are important to adjust for an optimal result.

A TIN which represents the terrain is often called a digital elevation model (DEM) as well. An advantage of using a TIN over a rasterized DEM when visualizing and analyzing terrains, is that the points in a TIN are distributed variably based on an algorithm that determines which points are most necessary to

create an accurate representation of the terrain. The input of data is therefore more flexible and fewer points are needed to be stored than for the raster-based DEM.
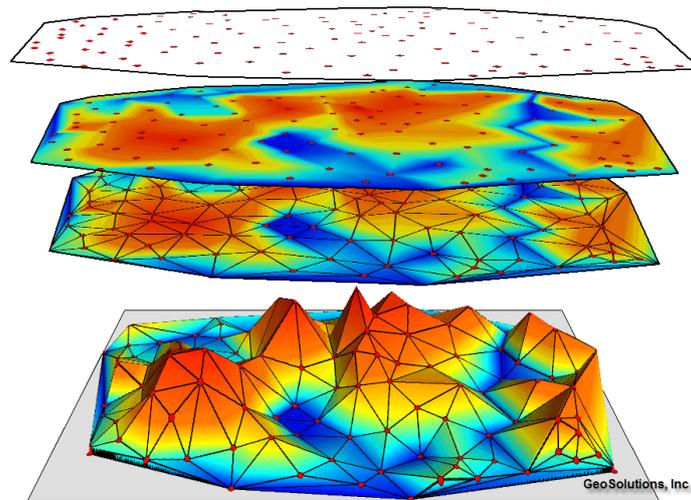
Figure 3.9: Triangular irregulated network represents surface morphology (MyuniGIS,2020)

3.3 Visualization of 3D point cloud and raster data

In section 3.2 it was identified that there are several ways to represent 3D data. However, the representation of data only refers to the form in which the data is stored, processed and transmitted. To be able to analyse datasets it is very important to visualize the data in a proper way. According to Andrienko et al. (2020) there are a couple of principals which are important for creating a good data visualization:

1. Utilise space at first: Taking into account what the analysis tasks are.
2. Respect properties: Make sure that the properties of the visual variables are consistent with the properties of the value domains of the data components.
3. Respect semantics: Knowledge of the domain and common sense should be used in creation of visual displays.
4. Enable seeing the whole: the visualizations need to be designed in a way that it facilitates gaining an overview of all the data items that are shown.
5. Include labels, titles, and legends: The interpretation of patterns strongly depends on explanation of how the data components are encoded by visual means and appropriate labelling of them. For example, when visualizing detailed morphology, continuous colour scale could be used to visualize the elevation.
6. Avoid excessive display ink: avoid visual components that do not communicate useful information.
7. Consider employee redundancy: use redundant ways to communicate important information.
8. Enable looking at data from multiple perspectives
9. Rely on interactivity: this can facilitate comparison and complement visual representation in many other ways.

In addition, there are several cartographic tricks that can be used for better visualizing the elevation (Köbben, 2001).
- Using contour lines
- Using colour scale
- Using shadow effects for better depth perception
- Using multiple perspectives

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There are several benefits for visualizing data. For example, the dataset will be easier to understand and the overview of the data will be more compact. A good visualization helps to discover unexpected patterns and confirm expected patterns. Also, a good visualization will help to understand the distribution of the data. Visualizations are often much more informative and easier to understand than numerical summaries of datasets. Furthermore, visual representations can give more insight into seeing relationships between items. Computational extraction and expression of these relationships will require much more time whereby the results will be harder to interpret. Lastly, graphical visualization facilitates more effective comparison methods. Gleiger et al. (2013) has identified three visual methods:

1. Juxtaposition: where visual representations are placed next to each other applying the strategy of display space partitioning. This can be useful for comparing the overall patterns in two or more distributions.
2. Superposition: this method assists in comparing overlaying things in the same display space, like overlaying multiple annual trends for different years. This technique can be useful for detailed exploration of commonalities and differences.
3. Explicit encoding of distinctions: here the comparison metric is calculated, e.g. the difference, and visually encoded.

In addition, visualizing data in 3D could add extra value to the visualization. People can observe the third dimension by using stereo vision e.g. seeing depth by using your eyes. The brain can determine with this information the relative position of different objects. Furthermore, the properties of objects can also help observe the third dimension. For example, shadow effects, size differences and perspective will help visualize the third dimension. This makes the image even more realistic, small changes are therefore even faster visible (Köbben, 2001).

However, there are also some limitations of the visualization of data which needs to be taken into account. It is generally recognized that the visualization of a dataset alone is often not sufficient for data analysis of the real-world applications (Andrienko et al., 2020). Many statistical summaries assume certain properties of the data, these are not necessarily checked before creating the visual display which could give a wrong interpretation. Another limitation is the lack of visual resolution, when attempting to accommodate all the data items in the display, the space with results can be visually clustered. This will result in a display where items cannot be visually distinguished. It can bury important information, complicates visual perception and recognition, and decreases analytical performance of the users. Filter and zoom interactions could help with this problem. This gives users the ability to remove details or items which are irrelevant for the analyses in mind. However, removing data can lead to losing context. Data reduction/sampling methods like context-aware (semantic) filtering can be used to help with this problem. When a user tries to attach a meaning, thus semantic interpretation, to items created by a visualization technique false patterns could appear. Therefore, visualizations should explicitly highlight distortions.

Several visualization techniques are available to visualize 3D data in different ways. In the next section a couple of these visualization techniques will be discussed for both point cloud data and raster data, whereby the visualization of dynamic coastal landscapes will be the central subject.

3.3.1 Visualization of point cloud datasets

Visualization

Visualization and presentation techniques for massive 3D point cloud data is vital for the communication and understanding of spatial information and simulation results and analysis (Kreylos et al, 2008, Bettio et al., 2009, Kim & Medioni, 2010). According to Bertin (1983), graphical representation is the

encryption of data components by means of visual variables (Andrienko et al., 2020). The most important variable for topographic maps is the variable 'position'. Here the values contain information about the position on some axes. Often visualization types use horizontal (x-axes) and vertical positions (y-axes) within a two-dimensional space, this is called planar dimensions. However, when visualizing 3D data there is a third dimension (z-axes).

To visualize geomorphology, a few visual variables can be used. For example, the variable colour is an important variable to visualize topography. Height values can be visualized from high to low in different colours, for example from light to dark. In addition, classes can be made where every class has a colour and is in between specific height values. Another way to visualize topography is to use contours. These are lines from a specific height. However, these last two options are relatively schematic and therefore not the most optimal solution for the visualization of the elevation in a dynamic coastal landscape.

Although a picture may be worth a thousand words, a static visualization will often be insufficient for a valid analysis whereby a complex subject is fully understood. Therefore, looking from different perspectives will be useful when visualizing a point cloud. This could be done via visual interaction of the point cloud data. A couple of interaction types can be distinguished (Andrienko et al., 2020):
1. The data representation can be changed
2. There can be zoomed in and out, which will give more details
3. Data can be transformed
4. Data can be selected and filtered
5. Corresponding information pieces could be found in multiple views

To enable an interactive visualization and exploration of the point cloud data, point-based rendering techniques can be used (Wimmer & Scheiblauer, 2006, Richter & Döllner, 2010). As discussed in 3.2.1, level-of-detail (LoD) can be used where a hierarchy is built which allows to select the level of detail per node. In addition, out of core rendering and triangle rendering are other techniques that can be used. These rendering techniques can cope with massive 3D point clouds. However, often point- based rendering techniques require direct access to the data. For a large number of users makes this the provision of interactive visualization more complicated. Nevertheless, service-based visualization strategies like Web View Services (WVS) can enable easy data access even on user systems with limited computer capabilities (Parvati & Sanna, 2011), for example the Potree webviewer (Potree, 2020). Visualization through the use of Esri's Storymap can also help for the understanding and communication of the spatial information. Storymaps can combine interactive or static maps with multimedia content such as photos, animations and informative texts.

Point cloud-based techniques to visualize detailed morphology
When visualizing detailed morphology temporal datasets which change spatially are observed. This means that events (e.g. changes in detailed morphology) can happen over a period of time in a certain area. A chronical sequence of the states of these phenomena or events are called time series, these can be visualized in different ways. An example of programs where temporal data can be visualized are ArcGIS Pro and CloudCompare, these programs have several tools to visualize spatial temporal data (further explained in chapter 4.3.1). For example, in ArcGIS Pro, animations can be made of spatial temporal data where time series can be visualized in chronological order. In addition, static maps can be made where maps of different years can be put in chronical order. Furthermore, in ArcGIS Pro layers of different years can be easily put on and off making differences between years easily visible. Via visual interaction changes that occur through time can easily be visualized from different perspectives.
CloudCompare is a software program that supports calculating with large point cloud files. Point cloud datasets of two different years can be subtracted from each other. This will visualize exactly where

points are changed and how much is changed in the period of time between the 2 point clouds. However, it needs to be kept in mind that points from different point clouds never exactly lay on the same spot, this is further discussed in the method section (chapter 4). Comparing 2 point cloud datasets from a coastal environment visualizes erosion and/or deposition. CloudCompare is thus mostly sufficient when calculating with point clouds, the visualization techniques however are of low quality.

As with any kind of data, temporal data may have errors like wrong recorded values, wrong time references and other problems, in particular missing data. Visualization can often exhibit such problems quite prominently (Andrienko et al., 2020). In the visualization of point cloud data areas with no data are shown as empty spaces. This makes point cloud visualizations so close to reality because nothing is displayed that is not there. In addition, the data will not be further processed, in this way no data will be lost. With techniques such as interpolation, information could be lost (Poux et al., 2016).

However, because of the large size of point cloud datasets, which often consists of billions of points, computing and software problems could appear. The huge amount of storage space that is needed can cause very slow transmission times (upload and download) (Jahaveri et al., 2017). To prevent crashing the hardware or software, several operations are available. For example, large datasets which visualize a large area could be cut into smaller parts. This will make the dataset smaller and much easier to work with. When looking at detailed morphology, small areas are analyzed, so cutting the dataset will be a suitable solution.

In addition, the loading and rendering of a large point cloud dataset can take a lot of time. For smaller datasets used in this research, around 400MB, the loading of the dataset in ArcGIS Pro often took around 5 minutes. When panning or zooming in the dataset it took again several minutes to load. Therefore, visual interaction can be challenging when looking at larger areas. However, the loading and rendering time will also be dependent on the hard- and software.

To solve the problem of a longer loading and rendering time the data need to be compressed in some way, because this can lead to data reduction. There are a couple of options to compress point cloud data. The first option is to use kd-trees, binary trees and spanning trees (Schnabel & Klein, 2006, Liao et al., 2012). This exploits high frequency information by thinning the point cloud data in areas with a certain density of the points. In addition, a (continuous) level of detail can be used. A level of detail (LoD) can be seen as a data pyramid with multiple levels (Figure 3.10). Whereby level 0 has a course resolution and a high density of points and level 1 a more detailed resolution and a lower density of points (Van Oosterom, 2019). An LoD is a dimension in spatial data which represents the importance of each point. It helps to leverage the balance between accuracy and efficiency of the applications. When visualizing point clouds, the data is normally rendered at a certain LoD, when more details are required, points with a high LoD value can be loaded and rendered. Nowadays, most point cloud viewers rely on Octree data structures to realize these LoDs. Thus each level in the Octree is representing a LoD. This could give a negative effect for the visualization because the points could pop up in blocks (Figure 3.11). In addition, this causes a large consumption of memory because the extra points are buffered. This is a result of the selection of the blocks instead of the accurate query region. To assure a smooth and natural rendering process, the LoD structure with the Octree structure should be replaced by a continuous LoD structure (cLoD) (Liu et al., 2020).
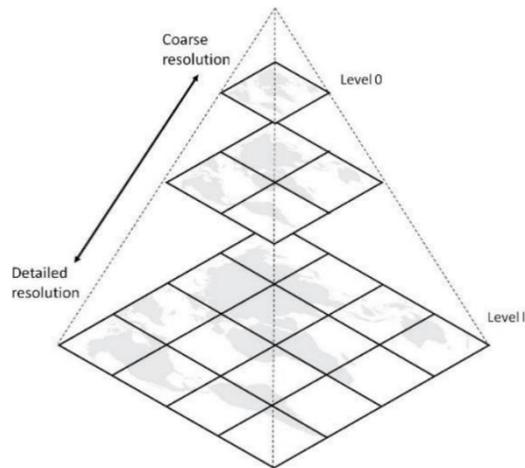
Figure 3.10: Data pyramid for the Level of Detail structure (van Oosterom, 2019)
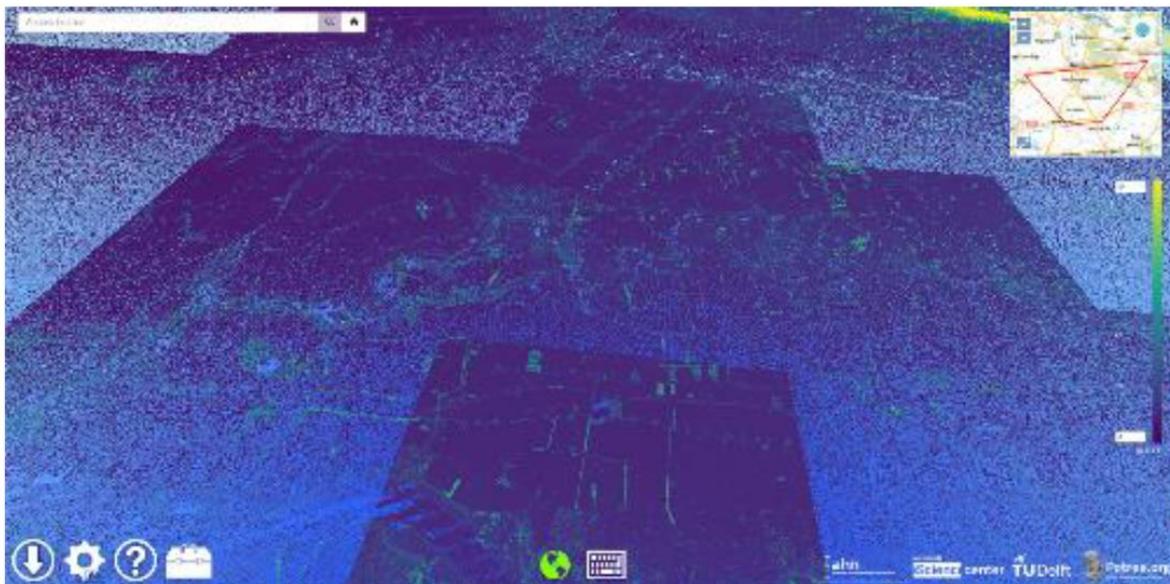
Figure 3.11: Block patterns caused by the octree data structure (Liu et al., 2020)

In the software ArcGIS Pro, thinning can be done with the tool Point cloud scene layer or point thinning. The point cloud scene layer tool removes points causing a lower resolution. The points that are removed are classified as 'unimportant' points such as areas that are overlapped by two fly-overs by the airplane with the laser scanner. Nevertheless, these points could be falsely classified as unimportant. This can result in the loss of potentially meaningful details. Therefore, thinning methods are ideally used in scenarios where the density of the point cloud datasets is high and the time availability is limited (TU Delft, 2018). The point thinning tool in ArcGIS Pro can be used interactively by a slider. When moving the slider to the left a courser surface is shown. With the moving of the slider the density of the points are changed. However, there are no point removed using this tool. Another way to compress point clouds is a simple Octree Compression Scheme and a Graph-based Compression Scheme (Jahaveri et al., 2017). The former uses voxelization, for which a minimum voxel size can be determined, which lowers the output resolution. The voxelization of point clouds will be further discussed in section 3.3.2.

Lastly, there are some techniques to help visualize elevation measurements in a clearer way. ArcGIS Pro has several tools to help visualize the 3D point clouds. For example, adjusting colour schemes, the scale and perspective to better display specific phenomena in the area. Using different colours for

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different heights will give a better understanding of the morphology of the landscape. It is possible to exaggerate the elevation with changing colours (Figure 3.12). In this way, small details will become better visible. Furthermore, a profile can also be created when it is necessary to visualize the elevation from the side when colour alone is not enough to understand the elevation.
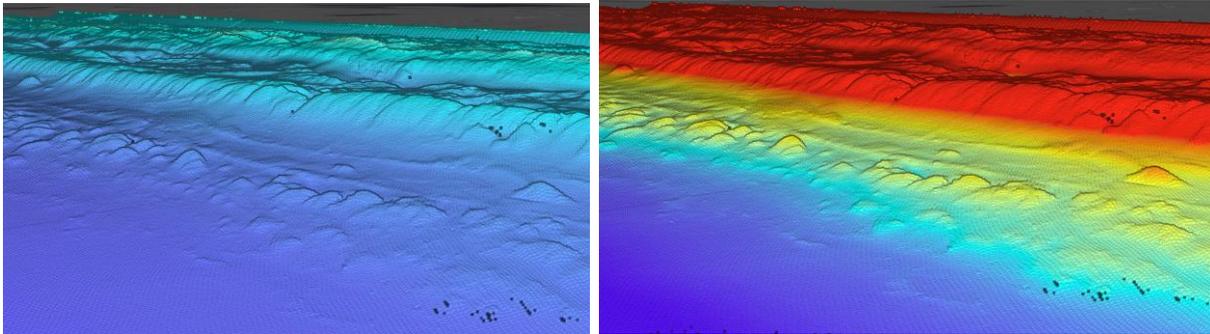
Figure 3.12: The colour can be adjusted for the elevation when something needs to be pointed out. In this case the colour is changed to highlight the small dunes in front of the larger dunes in this point cloud visualization.

In addition, creating shadow effects could make the slopes more visible. In ArcGIS Pro a tool called Eye Dome Lightning is available for point clouds. The output of this technique is similar to the hill shading technique for raster data where shadow effects are also created. However, this technique works fundamentally different. The creation of shadow effects is for users straight forward to interpret, even by non-experts without any training.

Eye-Dome Lightning technique for point clouds is an image-based and non-photorealistic shading technique. It is designed to enhance depth perception in for example geomorphological images. A half-sphere (the dome) centered at each pixel/point (p) is designed as the basic principle of the Eye-Dome Lightning algorithm. The half-sphere or dome is bounded by a horizontal plane. This horizontal plane is perpendicular to the observer direction at point p. The amount of shading is a function of how much of the dome is visible at p, or conversely, how much of the dome is hidden by the neighbors of p. So, a neighbor point will cause that the lightning at p will be reduced if its depth is lower (closer to the viewer) than the one of p. When looking from different perspectives the shadow will be calculated again for the point cloud, thus from every point of view there will be a shadow effect. The amount of shading defined by the previous appointed procedure depends solely on the depth values of the close neighbors. When taking farther neighbor pixels or points into account, a multi-scale approach could be implemented to achieve better shading. This approach will use the same shading function at lower resolutions (most of the time a half quarter image size). In order to limit aliasing induced by lower resolution the shaded images are filtered with a cross bilateral filter. Hereafter, the filtered image is merged together with the full resolution shaded image (Boucheny & Ribes, 2011).

3.3.2 Visualization of raster datasets

Visualization
As discussed before problems can occur when visualizing point clouds due to the large size of the dataset. This problem is mostly resolved when interpolating point cloud datasets to raster-based datasets. When interpolating height measurements obtained by LIDAR scanners, Digital Elevation Maps (DEM) are made in the shape of DTM or DSM.

Raster-based techniques to visualize detailed morphology
Several techniques exist to visualize raster elevation data, in the following section a number of techniques will be discussed.

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The first technique that will be explained is analytical hill shading and hill shading from multiple directions. Hill shading or relief shading is one of the most 'natural', intuitively readable, visual impression of all techniques. This technique describes how the relief surface reflects the incoming illumination which is based on empirical experiences or physical laws. There are several analytical hill shading techniques (Horn, 1981, Blinn, 1977, Batson et al., 1975), however, in most GIS software the techniques of Yoëli (1965) are the standard feature. The output of the hill shading technique is similar to the 'Eye Dome Lightning' technique, both create shadow effects for the visualization of the elevation (Figure 3.13). The images that are created with hill shading by the illumination from several angels are highly correlated. Therefore, it is possible to 'summarize' information by mathematical transformation with the principal component analysis (PCA) (Devereux et al., 2008). Sometimes variables in the data are highly correlated causing duplicate data in other variables. Duplicate data over several datasets can be identified by the PCA. The PCA aggregates only essential information into groups called 'principal components'. When using the PCA, the redundancy can be reduced and a new dataset with only essential information is made (Kokalj & Hesse, 2017).

The hill shading technique that is used for raster maps uses the relative position of the sun for shading the image. To indicate the relative position of the sun, the azimuth and altitude are used for creating the shaded relief. The azimuth is the relative position of the sun along the horizon in degrees. This is 'calculated' clockwise, it starts with 0 degrees at north, east is 90 degrees, south is 180 degrees and west is 270 degrees. The altitude is the angle of the sun above the horizon. This ranges from 0 to 90 degrees, where 0 degrees indicate that the sun is on the horizon and at 90 degrees is the sun directly overhead (Esri, 2020). The hill shading is calculated from one perspective and forms a new layer in ArcGIS Pro. This layer can be made transparent and laid over the original elevation map
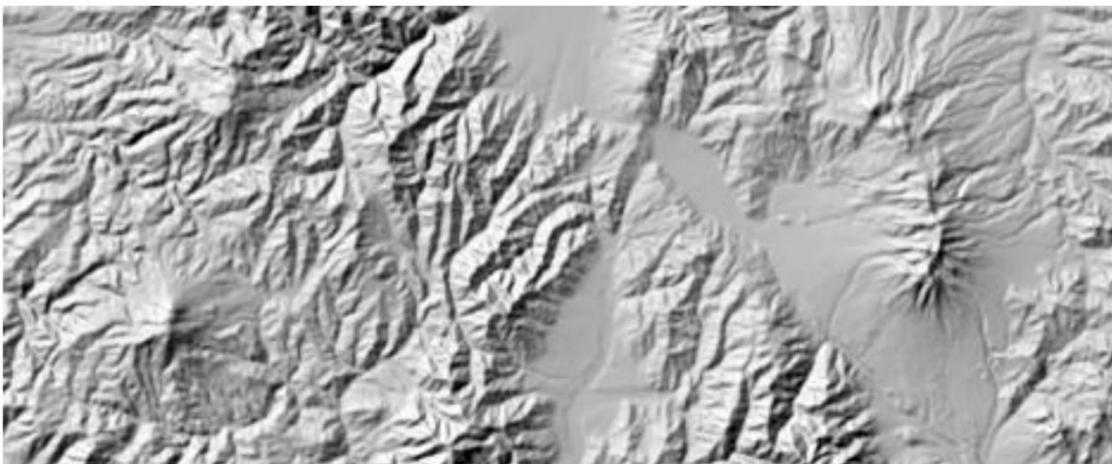
Figure 3.13: Example of the Hillshade technique (Esri, 2020)

A second visualization technique for raster elevation data is calculation and visualization of the slopes (Figure 3.14). The slope, or gradient, is aspect independent and is the first derivative of a DEM. It can be calculated in either the slope in degree or in percentage and it represents the maximum rate of change between each cell and its neighbor cell.
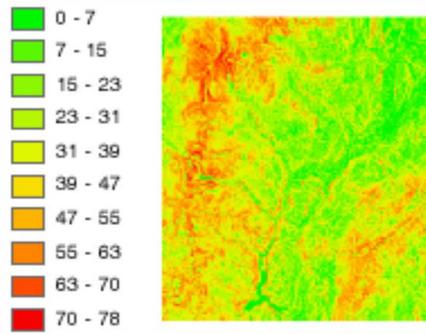
Figure 3.14: Example of the calculation and visualization of the slope from a raster DEM in percentage (slope function) (Esri, 2020)

A third visualization technique is elevation differentiation, this refers to colour coding, constrained colour ramps method or colour cast. This technique consists of controlling the range of values that are presented over a given range of colours or greyscales (Figure 3.15). The technique that is used Figure 3.15 is a histogram stretch whereby the range of the elevation values are stretched to the whole range of the colour of the output image. This can enhance the contrast between raster cells of different elevation. When using colour scales, it is very important to keep the legend as clear as possible. It is therefore advisable to use in some cases classes when visualizing elevation. However, when visualizing detailed morphology this is not the case and multipart colour scheme suffice.
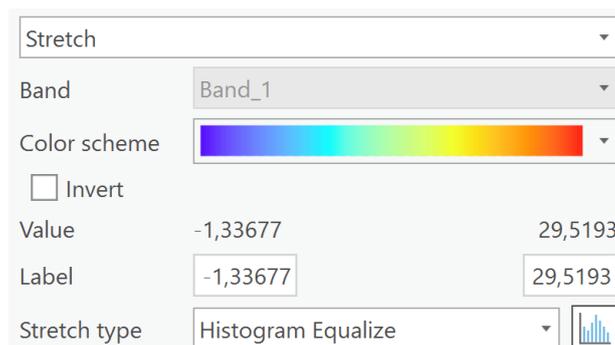
Figure 3.15: Example colour scheme (multipart) with a histogram stretch type.

A fourth visualization technique is a technique that small-scale features can separate from large-scale landscape forms and is called 'trend removal'. Normally, the large-scale trend (large landscape forms) is represented by a smoothed version of the DEM. This can be accomplished by the application of a low pass convolution filter. Through subtracting the smoothed DEM from the original DEM, trend removal can be accomplished. The map that originates will show the local deviations from the overall landscape forms (Figure 3.16).
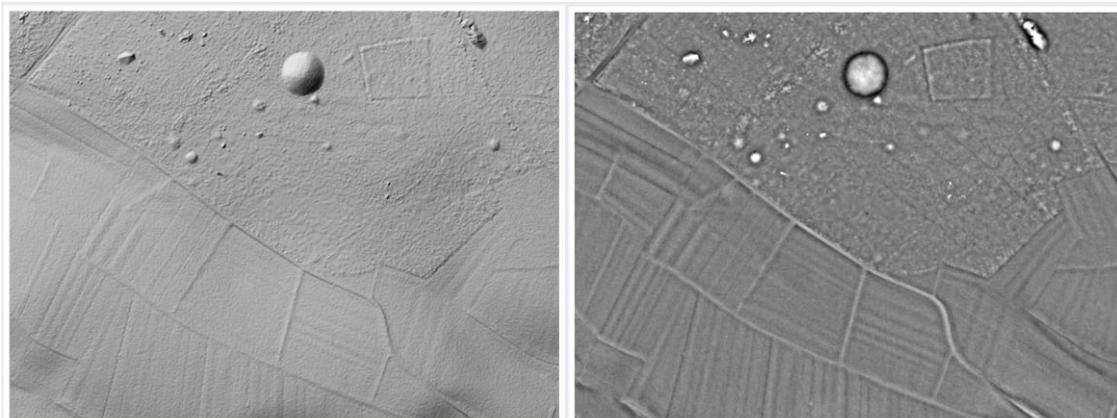
Figure 3.16: The left image shows a DEM whit a burial mountain, in the right image a trend removal from the same image is computed (Hesse, 2013).

The fifth visualization technique consists of using a voxel layer. This layer can represent spatial and temporal information in 3D. It could be used to visualize an underground model (Figure 3.17). There are several capabilities for exploring voxel layers in detail. They can be visualized as surfaces and volumes. An area of interest can be defined using slices to view the volume of this specific area. In addition, sections can be made to understand structures in the voxel layer in a better way.
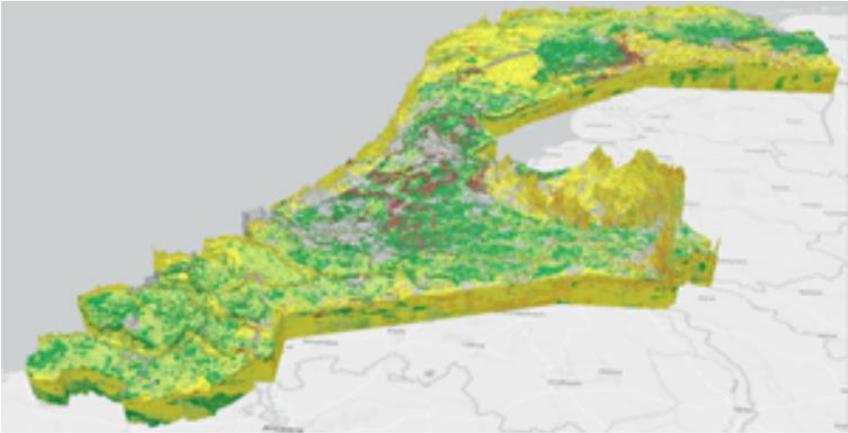
Figure 3.17: Example of a voxel layer of the Netherlands (Esri, 2020)

Finally, to overcome the directional problems of hill shading in relief mapping, Sky-view factors can be used as alternative (Kokalj et al., 20011, Zaksek et al., 2011). This is a geographical parameter which represent a portion of the sky from a certain point (Figure 3.18). A form of Sky-view factor, diffuse solar insolation raster's, are used for the visualization of archeological features (Challis et al., 2011).
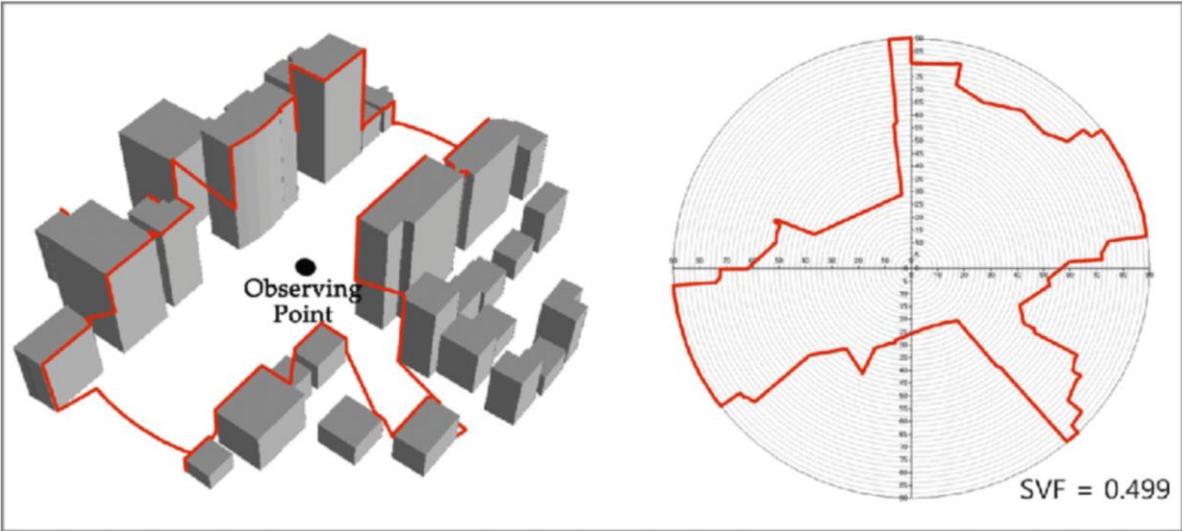
Figure 3.18: Sky view factor is a geographical parameter which represents a portions of the sky from a certain point (Park, Ha, & Lee, 2017)

3.4 Comparison between Point cloud- and raster-based visualization

With all the information discussed in the previous sections of chapter 3, point cloud-based visualization techniques can be compared to raster-based visualization techniques (table 3.2). As mentioned in 1.2.2 raster datasets used in this research are interpolated from point cloud LiDAR data. So, both point cloud and raster visualizations are based on (the same) LiDAR data. However, the raster visualization is processed one step further than the point cloud visualizations. This extra step has advantages and disadvantages in comparison to point cloud visualizations. In the following section point cloud and raster will be compared on a couple components.

Resolution
The first example of an advantage of using the original point cloud dataset for visualization is the high resolution of these datasets. The millions of points in the point cloud provide that very small details can be visualized in a well-defined manner. All the points that are measured with the laser scanner show up in the visualization, in this way no information is lost and information that is not there is not showed. Spaces where there are no measurements taken are empty spaces in the visualization. This makes the visualization as close as possible to the real-life situation.

On the contrary, the resolution of raster cells is much lower and is therefore less detailed. The size of the raster cells can be customized, however, they will probably not become as detailed as a point cloud. It is possible to set the resolution of the raster at 0,1 x 0,1 meter, but this can give other problems in small scale images. First of all, the smaller the grid size the larger the dataset size. In addition, interpolation to a small grid size can display information that is not there. This is because through interpolation the output map becomes nicely covered with no holes where there is no data. However, showing no data can also give insights, for example there are sometimes no measurements because there is water and thus no reflection. With the interpolated raster maps the no data is not shown because the average between points are used to establish this map. In areas where there is no data the closest points are used and in areas where there are more points the average of these points are used. This can give a distorted visualization and important information could be lost or wrongly interpreted.

Interpolation
Another problem that can occur while using raster data, is that when using the same interpolation method to interpolate the point cloud data, but changing the origin of the raster the visualization could change. For example, when the origin moves a raster cell to the left or right, the interpolation is calculated slightly differently, this could form a different visualization. This problem does not occur by using point cloud data itself.

Data size
As described in section 3.2.1 the size of the point cloud datasets can be a draw back for the representation and thus also the visualization. The workload for soft and hardware is often very high because of the huge amount of points in the file. Point clouds are therefore sometimes hard to work with. However, there are techniques available to ease this problem. For example, thinning methods or multiple levels of detail can be used whereby not all points are shown at the same time, in this way the soft and hardware can better cope with the large files. Other tactics involve looking at smaller areas which will decrease the file size as well.

Point cloud data is often transformed to raster data (DEM) because of the difficulties that are involved in the use of large point cloud datasets. Creating a raster from the point cloud will largely decrease the size of the dataset which makes it much easier to work with. However, as discussed before this will not

be an advantage for the resolution of the map and information could be lost due to the interpolation. Especially when small differences in time and space are of interest.

Shadow techniques
As mentioned in section 3.3.1 and 3.3.2 shadow techniques for point cloud and raster are available for a better visualization of the elevation. For point cloud datasets the 'Eye Dome lighting' technique can be used and for raster datasets 'Hillshading' is a possible tool to create shadow effects.

The shadow effect calculated with the Eye Dome lighting is calculated again every time the perspective is changed Figure 3.19). The depth perception created in this way could help to get more insight in the elevation and small morphological phenomena in an coastal area.
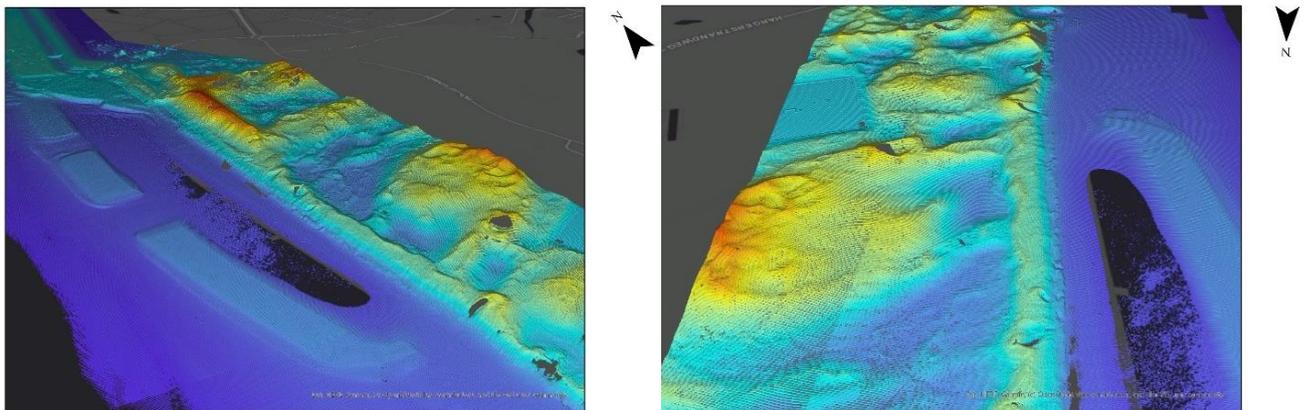
Figure 3.19: Example of shadow effects made with the Eye Dome Lighting tool in ArcGIS Pro from two different perspectives.

The hill shading technique is calculated from one perspective and forms a new layer in ArcGIS Pro. This layer can be made transparent and laid over the original elevation map (Figure 3.20). It is possible that the Hillshading technique could cause disinformation in some cases because the shadow is not dependent of the point of view as is the case with Eye Dome Lighting. Therefore, some areas in the map are always in the shadow zone.
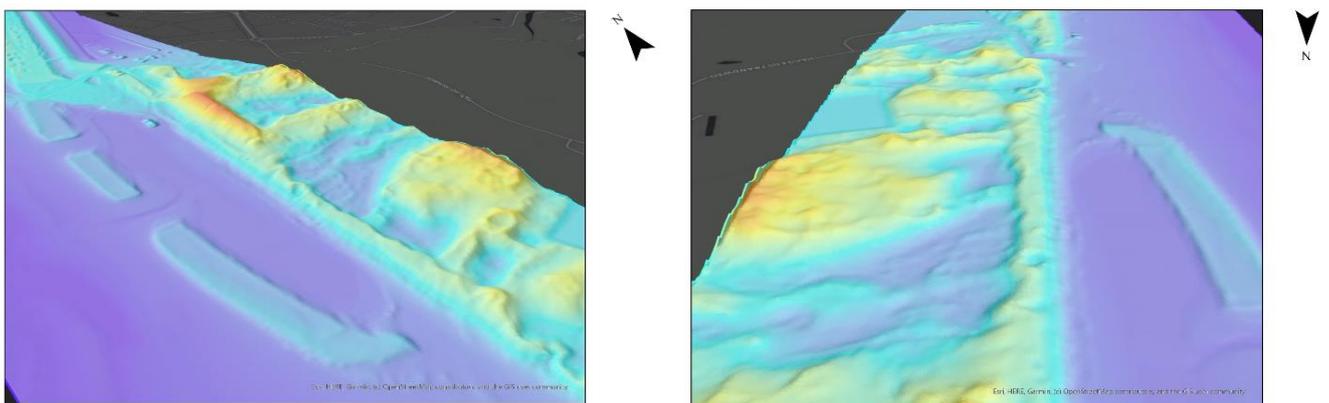
Figure 3.20: Example of shadow effects made with the Hillshade tool in ArcGIS Pro from two different perspectives.

Colour
Another visualization technique are colour coding techniques, these can be used in both cases, point cloud and raster, to visualize the elevation in an easy to understand way. In the results section these techniques will be better compared for point cloud and raster maps.

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Temporal aspect

Temporal point clouds and raster data can both be visualized in several ways. Raster can be easily visualized with a time slider (in ArcGIS Pro). However, point cloud files are too large for this tool to work with. Therefore, point clouds can be animated whereby point clouds of several consecutive years can be visualized. In addition, is it possible in ArcGIS Pro to visualize point clouds and raster data of several years by turning layers on and off. These layers can also be visualized in static maps.

Perspective

The perspective of a visualization can also give more information. Point cloud datasets are 2.5D/3D making it easy to view from different perspectives. Point clouds can not only be visualized from a top view or bird eye view, but also from the side e.g. panorama view (Köbben, 2001). The 2.5D/3D perspective will produce an even closer to reality image and small changes are visible faster. Raster images are often in 2D, when visualizing the DEM in 3D the data needs to be processed even further whereby the surface is based on the point cloud. When visualizing in 2D only a top view is possible. Differences between point cloud and raster will be further shown in the Results section.

Table 3.2 summarizes short the components discussed in the previous section. The important differences between the visualization of point clouds and raster data are listed.

Table 3.2: Differences between point cloud and raster visualization

	Point cloud	**Raster**
Resolution	High resolution	Low resolution
Close to reality	Yes	Not always
Interpolation	Inapplicable	Can give distorted visualization
Data size	Mega bytes	Kilo bytes
Shadow techniques	Available, from different perspectives	Available from one perspective
Colour techniques	Available	Available
Temporal aspect	Visual animation, static map, interaction	Time slider, visual animation, static map, interaction
Perspective	2.5D/3D	2D/3D

4. Methodology

The following chapter will give an outline of the method used to achieve the aim of this research. The objective of this research is: To find out *to which extent the application of point cloud-based techniques are useful for policy makers and researchers in the field of coastal management in providing visual insights into short- and long-term changes of sand patterns along the Dutch coast.*

Figure 4.1 provides a general overview of the workflow for this research. As a first step a conceptual model was created which explains the general key concepts for this research. Secondly, a literature research was executed. Thirdly, data was obtained and prepared to be visualized and analysed. Finally, the data was visualized and analysed.

Conceptual model → Theoretical framework → Data preparation → Visualization → Analysis
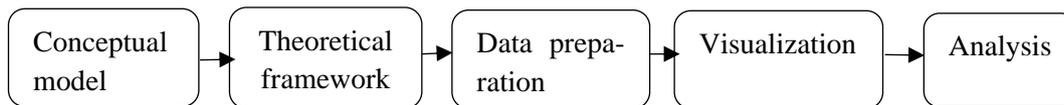
Figure 4.1: Workflow for the research

4.1 Literature research

To be able to start visualizing and analyzing data of the dynamic coastal landscapes a literature research has been carried out. Most of the literature found in this research was obtained by using the snowball method. This means that used articles led to other useful articles through looking at the references. In the theoretical framework, the first 4 sub-questions mentioned in chapter 2.1 are elaborated on.

- Point cloud data and raster data are discussed.
- Several 3D data representations are explained.
- The added value of point cloud-based visualization techniques are compared to other visualization techniques.
- Limitations of point cloud based techniques for visualizing dynamic coasts analyzed.
- Useful techniques to visualize detailed morphology are determined and compared to visualization techniques for raster datasets.

4.2 Data

The next section will elaborate on the acquisition, the preprocessing and the quality of the data used in this research.

4.2.1 Data acquisition

The point cloud data of the Hondsbossche dunes was requested at Rijkswaterstaat. Rijkswaterstaat provides annual height measurements from the Dutch coast which are collected for the dataset "Hoogtegegevens kust". This is a raster dataset of semi-annual height measurements of the entire Dutch coastline. The elevation of the coast is measured by means of LiDAR scanners on board of an airplane, therefore this data is also available in point cloud format. In this study, the datasets with the point cloud format were used for the visualizations. The datasets from 2013 to 2020 were chosen, with measurements taken once a year. The density of these datasets is at least 1 point per 2 square meters, but most points are no further than 0,5 meter from each other. The obtained datasets from Rijkswaterstaat consist of .laz files.

The data used to visualize changes at the coast on a short time period, are data from CoastScan in Noordwijk. This is LiDAR data from a terrestrial laser scanner which stands on the balcony of Hotel Huis ter

Duin (50 meter above ground). A terrestrial laser scanner is a scanner on a static platform (Lindenbergh, 2011). It is a laser scanner with a LiDAR sensor which contains a rotating head and mirror. This makes it possible to get 360x360 degree coverage of the area. The laser emits a focused pulse to a spot on the beach and dunes. The two-way travel time of the pulse can then easily be converted into a range distance where it has a high accuracy. With the orientation and position of the laser scanner, 3 dimensional co-ordinates (x, y, z) of the spot on the beach or dunes can be made (Vosselman & Maas, 2010). The data obtained with the scanner are 3D point clouds where the range can be anywhere between 1m and +/- 2 km (Vos et al., 2017). The laser scanner used at Noordwijk is a Riegl VZ 2000 laser with an accuracy in the order of centimetres (Vos et al., 2020). The point cloud data of Noordwijk consists of 24 measurements per day for the year 2020. This means that a measurement was performed every hour.

Once a day at 12:00 a measurement is taken with a resolution 4x larger than the remainder of the measurements. This study does not use the entire database of 2020 because of the immense amount of data measured during this year. A small part of a couple of consecutive days are chosen to be visualized and analysed. These consecutive days consist of the 9th till the 12th of February 2020. These days are chosen because during this period the storm Ciara took place. Looking at storm data in high temporal resolution with point cloud data is interesting because this is not done before. Measuring during storms is often really hard because of the difficult weather conditions. In addition, one of the largest energy inputs is wind, so during storm a lot of sand displacement takes place. The datasets from CoastScan consist of .asc point cloud files.

4.2.2 Data processing

Before being able to use the obtained coastal data for visualization of the point clouds in ArcGIS Pro or CloudCompare, the data needs to be adjusted. ArcGIS Pro only supports LiDAR datasets that are provided as .las or optimized las (.zlas) files (Esri, 2020). The optimized las, or zlas, is a highly controversial and closed LiDAR format and is thus difficult to work with. Rapidlasso GmbH developed a tool to liberate this closed LiDAR format (rapidlasso GmbH, 2020). The data from Rijkswaterstaat for the Hondsbossche dunes consists of .laz files, this is the compressed version of .las files. To be able to open these datasets in ArcGIS Pro the .laz files need to be decompressed to .las files. However, in Cloud-Compare it is possible to open the .laz files. The decompression of .laz files to .las files can be done using the .laszip.exe e.g. the lastool laz2las. The impact of this decompression is quite large on the storage space, the .laz files are approximately 16 Mb while the decompressed .las version consists of roughly 283 MB.

The data of Noordwijk is from Coastscan. Datasets are used of the low tide (Figure 4.2) from 9 till 12 February 2020. In addition, three hourly datasets before the storm on the 8th of February 2020 are downloaded and three datasets during the storm on the 9th of February 2020 were used. In this way point clouds will be visualized in high temporal resolution. The data of Coastscan consists of point cloud files in .asc format. CloudCompare supports .asc files and the point clouds can be visualized without transformation in this program. However, as mentioned before ArcGIS Pro only supports .las files, so opening these .asc files in ArcGIS Pro is not possible. Therefore, is it needed to convert these .asc files to .las files. But before this can be done the quality of the data needs to be checked.

Februari 2020

		LW		HW		LW		HW		LW		max-Z gaand	begin N gaand	max-N gaand	begin Z gaand	max-Z gaand	begin N gaand	max-N gaand	begin Z gaand	max-Z gaand	begin N gaand	max-N gaand	
		tijd	cm NAP	tijd	cm NAP	tijd	cm NAP	tijd	cm NAP	tijd	cm NAP												
za	1	03:11	-53	07:57	93	15:47	-78	20:18	99			01:35	04:55	07:50	10:20	13:55	17:15	20:10	22:40				
zo	2	03:56	-53	08:41	87	15:27	-74	21:16	91			02:15	05:35	08:30	11:05	14:40	18:10	21:05	23:40				
ma	3	04:48	-52	09:46	79	17:31	-68	22:21	84			03:15	06:40	09:35	12:10	15:45	19:15	22:10					
di	4	05:47	-52	11:02	75	18:41	-65	23:35	82						00:45	04:20	08:00	10:55	13:25	17:00	20:30	23:25	Doodtij
wo	5	06:43	-52	12:12	80	19:51	-64								02:00	05:30	09:10	12:05	14:35	18:10	21:40		
do	6			00:44	85	08:48	-56	13:11	92	21:17	-65			00:35	03:05	06:40	10:05	13:00	15:35	19:10	22:40		
vr	7			01:42	93	09:59	-65	14:02	107	22:23	-67			01:35	04:05	07:40	11:00	13:55	16:25	20:00	23:25		
za	8			02:31	101	10:43	-70	14:46	121	23:12	-65			02:20	04:55	08:30	11:40	14:35	17:10	20:45			
zo	9			03:17	107	11:27	-73	15:28	132	23:45	-62		00:15	03:10	05:40	09:15	12:25	15:20	17:50	21:25			
ma	10			03:59	111	11:59	-77	16:11	139				00:55	03:50	06:20	09:55	13:05	16:00	18:35	22:10			
di	11	01:07	-61	04:42	112	12:41	-83	16:53	142				01:40	04:35	07:05	10:40	13:50	16:45	19:15	22:50			Springtij
wo	12	01:47	-63	05:26	111	13:20	-89	17:37	141				02:20	05:15	07:50	11:25	14:35	17:30	20:00	23:35			
do	13	02:33	-65	06:09	109	14:07	-92	18:23	135				03:05	06:00	08:30	12:05	15:20	18:15	20:45				

Figure 4.2: Water levels of Noordwijk February 2020, tides within the red box are used (NWHW, 2020).

4.2.3 Data quality

The quality of the point cloud data is very important to be able to display a good visualization of the dynamics of the Dutch coast. For the Hondsbossche dune datasets, the quality of the LiDAR datasets was checked before released by Rijkswaterstaat. The main quality demands for the coastal elevation datasets are discussed in "quality document laser altimetry" (Rijkswaterstaat, 2014). Rijkswaterstaat has looked at the following quality aspects: height accuracy, point density, object and water filtering, maximum water level, and disturbing elements.

The height accuracy has been checked by Rijkswaterstaat in 3 different ways. Firstly, a systematic check was performed using the standard deviation of the measured data. The new data was then compared with old data based on reference points such as buildings. And finally, control is performed between overlapping strips created while flying over the area multiple times. In this way it can be checked whether the strips are properly connected.

The point density must be at least 1 point per 2 square meters and evenly distributed. This means that there are no clusters or empty areas in the dataset. However, it may happen that during the measurements some cloud coverage is present, this can cause small areas to be obscured. Usually, these areas are so small that they are resolved during the processing of the data. When the data is interpolated, the holes (with nodata) are filled so that the visualization still gives a complete picture. However, when using the original point cloud data these (no data) holes stay empty. It is also reported that the waterline may be distorted by the reflection. This can cause the point distribution to vary. To ensure the quality of the water and object filtering, it is required that vegetation above 0.5 meters and the water surface are filtered out. In addition, a maximum of 1 object per 1000 ha can be filtered incorrectly.

Lastly, to ensure the planimetric accuracy which is the horizontal precision, the x and y values of the points are controlled. This is done by comparing the x and y values of the point cloud to the BAG (base administration) layers. In this way it can be checked if the point clouds are georeferenced correctly.

Datasets obtained from CoastScan were not processed yet when obtaining the data. First the datasets have been set to transformation and georeferencing. Hereafter, the noise and objects need to be removed (Vos et al., 2020). To georeference the datasets, Mathlab is used. A matrix (Figure 4.3) is used to convert the local coordinate system of the laser scanner to the projected coordinate system for the Netherlands (RD New). In addition, a matrix developed by Sander Vos was used to correct displacements in the point clouds. In this way the z value has a deviation of no more than 3 cm.

```
% Load data and transformation matrix
data=load('200213_010115.asc');
Tm=load('Noordwijk_SOP.dat');
% Extend matrix (add column with 1's. ie. XYZ wordt XYZ1
nn=size(data);
data_ext=[data(:,1:3) ones(nn(1,1),1)];
% Transform data
Tdata=data_ext*Tm';
TTdata=Tdata(:,1:3);
save Td200213_010115.xyz TTdata -ascii
```

Figure 4.3: Matrix to convert the local coordinate system of the scanner in Noordwijk into the projected coordinate system of the Netherlands (RD New)

The .xyz files that are made with the matrix in Mathlab can now be converted to .las files which can be opened in ArcGIS Pro. Again, for this conversion the application of Lastools is used.

In the visualization of the point clouds gaps remain due to shadow effects. The laser scanner measures from a balcony and therefore has a view from the side. The scanner cannot see through objects like buildings or dunes and leaves the area behind such objects empty. Once a month, measurements are taken manually of these areas with a portable laser scanner. These measurements are however not used in this research because of the lower temporal resolution. In addition, even people walking on the beach can give a distorted visualization. This must be taken into account during the analysis.

4.3 Visualization

In order to visualize a dynamic coastal landscape by using point cloud data several techniques are available. In this research two main software programs are used for visualization: ArcGIS Pro and Cloud-Compare.

4.3.1 Software Programs

The software programs used in this research must meet the following requirements: user friendly, fast data loading, easy printing, easy publishing and organizing, possibility to visualize temporal data, support coordinate systems, possibility to zoom and pan through point cloud, possibility to change colours, possibility to select data, make calculations, open point cloud files like .las and visualize in 3D (Boersma et al., 2019, Hathaway, 2014). For the visualization of point cloud datasets of dynamic coastal landscapes ArcGIS Pro is one of the most suitable software packages that meets almost all these requirements. However, ArcGIS Pro struggles with large point cloud datasets and making calculations is not possible. Using the CloudCompare software program for calculations (subtraction of point clouds to measure erosion and deposition of sediment) is a good solution (Boersma et al., 2019).

ArcGIS Pro is an easy-to-use software program where the data can be loaded in an easy and fast way when using the right format (.las). However, the program sometimes has problems with loading large datasets. Luckily as discussed in the literature research, there are some tools available with which this problem can be eased. For example, the dataset can be thinned by using either point thinning or changing the las file into an ArcGIS Pro scene layer.

ArcGIS Pro supports several tools with which point cloud data can be visualized in a temporal way. For example, layers can be turned on and off and animations can be made of time series. ArcGIS Pro also supports a time slider. However, this tool does not support las files. In addition, ArcGIS Pro supports many types of coordinate systems. This is very important to get a good idea of how a dynamic coastal landscape changes spatially over time. Furthermore, this program supports possibilities to pan and zoom through the point cloud and points can be assigned different colours. The latter is very important for

creating a good visualization. By changing colours and being able to look from different angles, the 'story' of the dynamics can be properly conveyed to the reader (Dent, 1999).

As mentioned before, ArcGIS Pro is poor at handling large data sets. Calculations such as comparing 2 point clouds is therefore not possible with this program. CloudCompare will therefore be used for handling this kind of treatment. CloudCompare is designed to perform calculations on large point cloud data. Furthermore, this program also supports coordinate systems, and it is possible to pan and zoom and change colours. However, this program is lacking a geographical way of visualizing the data, because the point cloud cannot be projected on a world map, making it difficult to orientate where in the world the point cloud is located. It is sometimes even hard to tell if one is looking at the bottom or top of the point cloud. In addition, this software program is lacking good visualization techniques like a wide range of colour schemes.

4.3.2 Techniques

The purpose of visualizing (point cloud) data is to convey the creator's message. Cartographic grammar can be used for this, consisting of basic elements that maps contain to make their message clearer. These are elements such as: a legend, a title, scale, boarders and neat lines, credits, mapped and unmapped areas, labelling and symbols and place names (Dent, 1999). However, there is a difference between visualizing 2D and 3D data. For example, with a 3D map, the informational elements must be placed outside the main map because they can otherwise block the 3D view.

Furthermore, it can be difficult to implement form and texture in the map where point clouds are visualized (Struis et al., 2018). But other characteristics such as colour, object information, global height and local height, horizontality (points which are parallel to each other) and surface normal are possible to implement in 3D visualization (Richter et al., 2015).

Tools and techniques for visualizing point clouds in ArcGIS Pro
ArcGIS Pro has several tools and techniques to deal with large point cloud datasets that will be used in this research. First, the point cloud datasets will be cut into the form of the research area. This will result in a smaller amount of points in the point cloud which will help the loading speed of the data. In addition, the point thinning tool is used when loading of the point clouds takes a long time. If there is still trouble with loading the point cloud datasets for visual interaction for example, there is a tool to make a point cloud scene layer. Here the point cloud will be automatically thinned to improve the performance and visibility at greater distance. When zooming in additional features will be displayed until the highest level of detail is reached in the point cloud scene layer.

When looking at smaller areas smaller datasets can be used and the thinning method is not needed. To create a more visual appealing projection of the dataset shadow effects could be added. This tool is called 'Eye-Dome Lightning' in ArcGIS Pro and improves depth perception in the 3D layer as is extensively discussed in paragraph 3.4.

When comparing datasets from one location in different years it is important that the elevation scale is the same in all datasets. The highest and lowest height from all datasets of that location is used for this (excluding high buildings or cranes).
To visualize dynamic coastal landscapes it is important to show the data over time. In ArcGIS Pro this can be done in several ways. The two manners that will be used in this research are static displays of maps and animations. In addition, visual interaction in ArcGIS Pro is used. Layers can be turned on and

off to visualize the dynamics and there can be zoomed in and out and panned through the data. In addition, an animation tool is present whereby visualizations of different years can be played consecutively.

Tools in CloudCompare

To compare two point clouds with each other the program CloudCompare is used. This program has a tool called 'cloud to cloud distance' which measures the Euclidean distance between each point of two point clouds. CloudCompare uses the 'nearest neighbour distance' where for each point in the compared cloud the nearest point in the reference cloud is searched. This will compute their Euclidean distance (Figure 4.4).

Both clouds will have a role, one will be the compared cloud and the other the reference cloud. The compared cloud is the cloud where the distance will be computed on. The distance of each of its points will be computed relatively to the reference cloud. In this way will the scaler field that is generated be hosted by this cloud. The reference cloud will be used as reference, thus the distances will be computed relatively to these points. The reference point cloud needs to be dense enough, if so, approximating the distance from the compared cloud to the underlying surface represented by the reference cloud is acceptable. However, when the reference cloud is not dense enough, the nearest neighbour distance could sometimes not be precise enough. It is then necessary to get a better model of the surface occasionally.

When the nearest point in the reference cloud is determined, CloudCompare can locally model the reference cloud surface. This is done by fitting a mathematical model on the 'nearest' point and several of its neighbours. In this way the distance from each point of the compared cloud to its nearest neighbour of the reference cloud can be replaced by the distance to this mathematical model. Statistically is this more precise and less dependent on the sampling of the cloud. Three models are available, the least square best fitting plane, 2D1/2 Delaunay triangulation or a height function (the latter is the most precise, but also longer to compute). However, using a local model will add to the computation time and has a high demanding of the hardware (Girardeau-Montaut, 2020). The point clouds in this research are relatively dense, together with the high hardware demanding and limited time for computing the research, it is chosen to not use the local model.
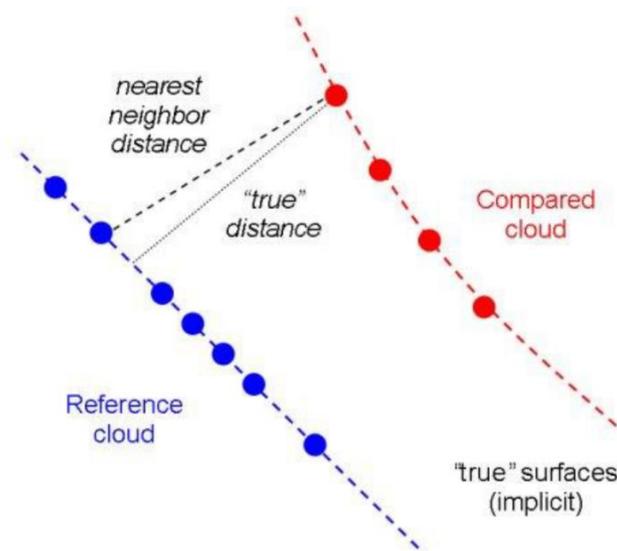
Figure 4.4 Cloud to cloud distance measures the Euclidean distance, the point in the reference cloud is compared to its nearest neighbour in the compared cloud (Girardeau-Montaut, 2020).

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There are a few things to keep in mind when comparing two point clouds without a local model. First, it is important that the reference cloud extends, thus is larger than, the compared cloud. This is to avoid virtually high distances on the boundaries. However, this is not always the case with the used datasets in this research. Especially the data from Noordwijk is sometimes of different sizes at the edges. The measurements from the terrestrial LiDAR scanner used in Noordwijk are sometimes different in size due to weather conditions or the tides. That is why the edges of the maps visualizing differences per hour, cannot always be analyzed equally well.

In addition, it is also important to get the highest density that is possible for the reference cloud, this will influence the accuracy of the results. Lastly, if the reference cloud is very noisy, the least square best fitting plane model will be a good option to consider. On the contrary, if there is not much noise but there is high curvature, the quadratic height function is a possible option to consider (Girardeau-Montaut, 2020).

The octree level used to perform the computation of the real distances is automatically optimized. The octree level is the level of subdivision of the octrees at which the distance computation is performed. Changing this parameter manually only changes the computation time.

The maximal distance can also be changed manually. All points farther than the maximal distance will not have their true distance computed, the threshold value will be used instead. The smaller the value of the maximal distance the more detail is visible in the visualization of the distance between the clouds. For both datasets of the Hondsbossche dunes and Noordwijk the maximal distance is manually set on a value. For the Hondsbossche dunes this was set on 2 meter and for Noordwijk on 0,5 meter. Noordwijk was set on a smaller value because the temporal scale was per hour. The changes per hour are small changes and thus less visible when setting the value of the maximal distance too high.

The aim for comparing 2 point cloud datasets is to visualize change within a certain time period. This change does not only exist of deposition of sediments but also erosion. When computing the cloud-to-cloud distance tool the Euclidean distance is used for a 3 dimensional cloud, the equation for this is: $d(p,q) = \sqrt{((p1 - q1)^2 + (p2 - q2)^2 + (p3 - q3)^2)}$. The square root indicates that there will be no negative values. Thus when comparing 2020 (compared cloud) with 2019 (reference cloud) only the increase (thus deposition) between point clouds will be visualized. However, as said earlier when visualizing change erosion is also an important aspect. The erosion can be visualized by comparing 2019 (compared cloud) with 2020 (reference cloud). In this way two maps are created with positive values, one with the erosion and one with the deposition. These two maps need to be merged together to get a better idea of deposition and erosion in the area. However, before merging these two maps the values of the erosion visualization need to be multiplied by -1 (edit -> scaler field -> arithmetic). In this way, the output map will visualize the erosion in negative values (sediment is gone) and the deposition in positive values (sediment is added).

4.3.3 Visualization of the Hondsbossche dunes dataset

The Hondsbossche dunes dataset consists of two datasets for each year 2013-2020. This is because the research area overlaps two coastal sections of Rijkswaterstaat, namely year_14CZ1 and year_19AN1. From these two coastal sections the research area was clipped with the extract las tool. The extract las tool needed to be used because of the .las format of the dataset. First the research area was made using the editing mode in ArcGIS Pro, a polygon of the research area was drawn. Hereafter, the extract las tool could cut the point cloud whereby only the points inside the polygon would remain. This made the dataset smaller and easier to handle (Figure 4.5). Hereafter, the elevation of all the datasets were set on the same level in the symbology in ArcGIS Pro. The lowest elevation was around -2 meters and the

highest elevation in the dunes was +37 meters, the value of the elevation for all the maps is therefore chosen between these two numbers.
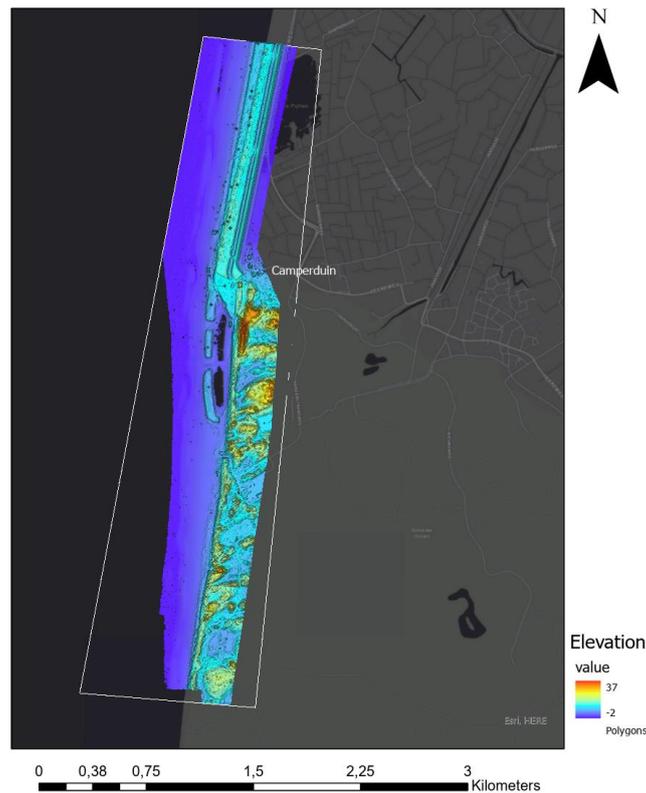
Figure 4.5: The point clouds are cut into the research area (2020) (elevation in meters).

After this, raster DEM visualizations were made from the years 2013-2020 to compare raster and point cloud. The 'interpolate from point cloud' tool in ArcGIS Pro was used to create such raster. The interpolation method used is called inverse distance weighted average interpolation and a DSM and DTM were made for the years 2013-2020 (Figure 4.6). For the DTM only the surface is interpolated whereby ground only points are used (Esri, 2020). The DSM is made using all the points, both ground and above ground points. The cell size of the raster is set on 0,5 meter. To improve the visualization in a way that detailed morphology is better displayed, techniques like 'Eye Dome Lightning' for point clouds and 'Hillshading' for raster are used.

Several static maps and animations are made in ArcGIS Pro of the morphology of the Hondsbossche dunes whereby only the static maps are displayed in this report. Lastly, the raster DSMs of each year were subtracted from each other whereby the 'Minus' (3D analyst) tool from ArcGIS Pro is used. This will result in a difference map whereby it becomes visible where erosion and deposition takes place.
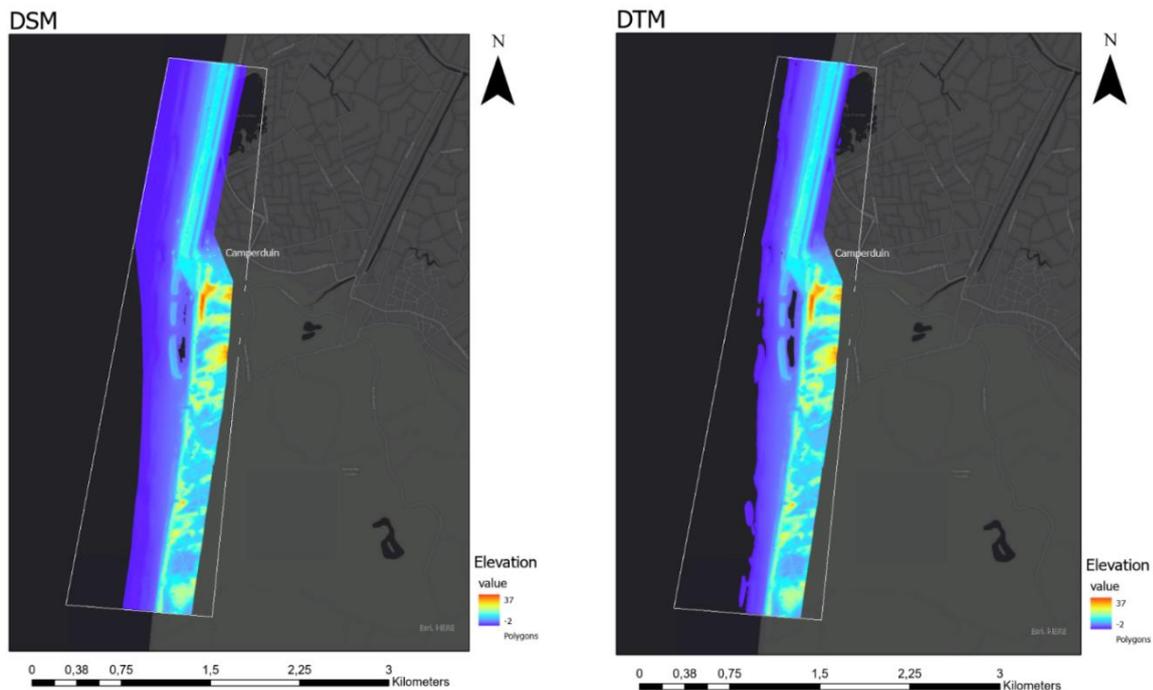
Figure 4.6: DSM and DTM made from point cloud (example is from 2020) whereby the elevation is displayed in meters.

A difference map where erosion and deposition will be visualized is also created for the point cloud visualizations of each year of the Hondsbossche dunes. This is done in the way explained in section 4.3.2. Whereby the 'cloud to cloud distance' tool was used. The change in sediment is visualized between -2 and +2 meters with a continuous colour scale from blue (erosion) to white (neutral) to red (deposition). In this way larger changes are displayed in a darker colour and small changes are visible as well in a lighter colour, this enhances the colour contrast causing making small details better visible.

4.3.4 Visualization of the Noordwijk dataset

For the Visualization of the Noordwijk datasets, the same methods and techniques are used as for the Hondsbossche dunes. The only difference is that the datasets of Noordwijk have a higher temporal resolution. First, all the datasets were set on the same height between the lowest and highest measurement from all the datasets. Then, static visualizations and animations were made of the measurements during low tide in the storm Ciara from 9 till 12 February 2020. Hereafter, the same was done for the hourly datasets of the 8th and 9th of February 2020. For the visualizations where was zoomed in the colour scale was adjusted and shadow effects were used. In addition, erosion and deposition were visualized using the Cloud-to-cloud distance tool of CloudCompare. A continuous colour scheme was from -0,5meter in blue (erosion) to 0, white (neutral) to red, +0,5meter (deposition).

4.4 Analysis

For analysing the result visual interaction with experts of HHNK were undertaken. First, visualizations of the Hondsbossche dunes were displayed in an interactive presentation. Time series of the visualizations of the complete research area and the 5 zoomed in locations were shown through time. People of different fields of interest like coastal experts, data processing, researchers and coastal managers were present. Questions like what kind of sand patterns/ coastal processes are visible on the visualizations and how can detailed point cloud visualisations be of added value for HHNK were discussed. Hereafter, the datasets were viewed in ArcGIS Pro and CloudCompare which made it possible to zoom and pan through the datasets.

Secondly, the visualizations of Noordwijk were discussed in exact the same manner. In this way the added value of using point clouds for visualization of coastal dynamics became clearer.

5. Research area

In this research two main research areas are chosen along the Dutch coast. Firstly, the Hondsbossche dunes are selected for the visualization of coastal dynamics over a longer period. This area changed a lot past years and is highly dynamic. Secondly, Noordwijk is selected as research area when visualizing dynamics over a shorter time span. This area is interesting to look at because here a research project called CoastScan is measuring almost continually with a terrestrial laser scanner which gives a high temporal resolution (Vos et al., 2017). This high temporal resolution is interesting when visualizing highly dynamic phenomena like detailed morphology.

5.1 Hondsbossche dunes in historic perspective

The Hondsbossche Dunes are an 8 km long dune area which lies just in front of the old Hondsbossche Zeewering which was a 5,5 km long dike (Figure 5.1). The area lies in the province of North-Holland between the villages Petten and Camperduin. Historically, dunes were present where the Hondsbossche Dunes are located now as well. Around the year 800 AD the entire coastline was still uninterrupted, whereby Texel was still attached to mainland (Figure 5.2A). However, through large-scale early medieval reclamation of peat areas more and more breaches in the natural coastal defence of dunes occurred. This caused a lot of erosion along the Dutch coast mainly during heavy storms (Bazelmans et al., 2011). A migrating channel in this period, called the Zijpergat, flowed through the dunes into the hinterland, causing a permanently weaker spot in the coastal defence, between Petten and Camperduin. Around 800 AD the strip of dunes was at least a kilometre to the west of the current coast.

In 1248 the dune row where now the Hondsbossche Dunes are situated was badly damaged by a heavy storm, the resulting breach was of such dimension that it would no longer close naturally. During this time the rudiments of the Hondsbossche Zeewering were formed. In the 15th century, the St. Elisabeth Flood (1421) caused another major breach in the coastal defence whereby a large part of the dune strip was destroyed. This allowed the North Sea to flood the hinterland, completely wiping out the village of Petten. Again, efforts were made to restore the coastline and close the breach. However, the North Sea continued to erode the row of dunes at the seaside. Nourishments at the landward side were executed to compensate the erosion on the seaside. This caused the coastline to shift eastward over the years (Barends et al., 2008). During this time the area looked like a tidal area (Figure 5.2B).

In the 16th century, the eastward sift was brought to a halt by constructing poles along the coastline. In addition, beach abutments were added, dams that protrude into the sea at right angles to the coastline. These measures were taken to protect the base of the dune row (Danner, Lambooij & Streefkerk, 1994). However, these measures did not last very long, therefore a sandy dike was constructed at the end of the 18th century. The use of a deck of heavy basalt blocks finally made the seawall resistant to severe storms. All in all, the coastline near the Hondsbossche Zeewering has a dynamic history of a continuing coastal regression with shifting stream channels that flow inland until the end of the 18th century.

In 1981 the dike was raised to delta height at 11.5 m. above NAP. However, in 2004 the seawall was designated as one of the weak locations along the Dutch coast. The dike failure probability and thereby the flood probability was greater than the standard frequency of once every 3000 years (Leenders, Bodde & Verheijen, 2018). Therefore, this coastal defence had to be strengthened again so that coastal safety could be guaranteed. Raising the current dike was not an option, because a part of the village of Petten should have to reallocate. This was conceived to be socially and financially a 'no-go'. That is why waterboard Hollands Noorderkwartier opted for sand reinforcement. This has a great advantage. Dunes can grow with the sea level rise and more space for nature and recreation was created and judged as a

good example of 'building with nature' (Bode et al., 2019). Moreover, growing recreation possibilities had an economical advantage for the village of Petten. The name of the Hondsbossche Zeewering has changed to Hondsbossche dunes because the area is now a dune area with a beach. The reinforcement of the Hondsbossche Zeewering began in 2013 and was completed in 2015. An important part of the economic engine of the Netherlands and 10 million people in the Randstad are safe in the upcoming 50 years because of this project.

Figure 5.1: Aerial visualization of left: the Hondsbossche Duinen and right: The old Hondsbossche Zeewering in blue (ArcGis Pro).
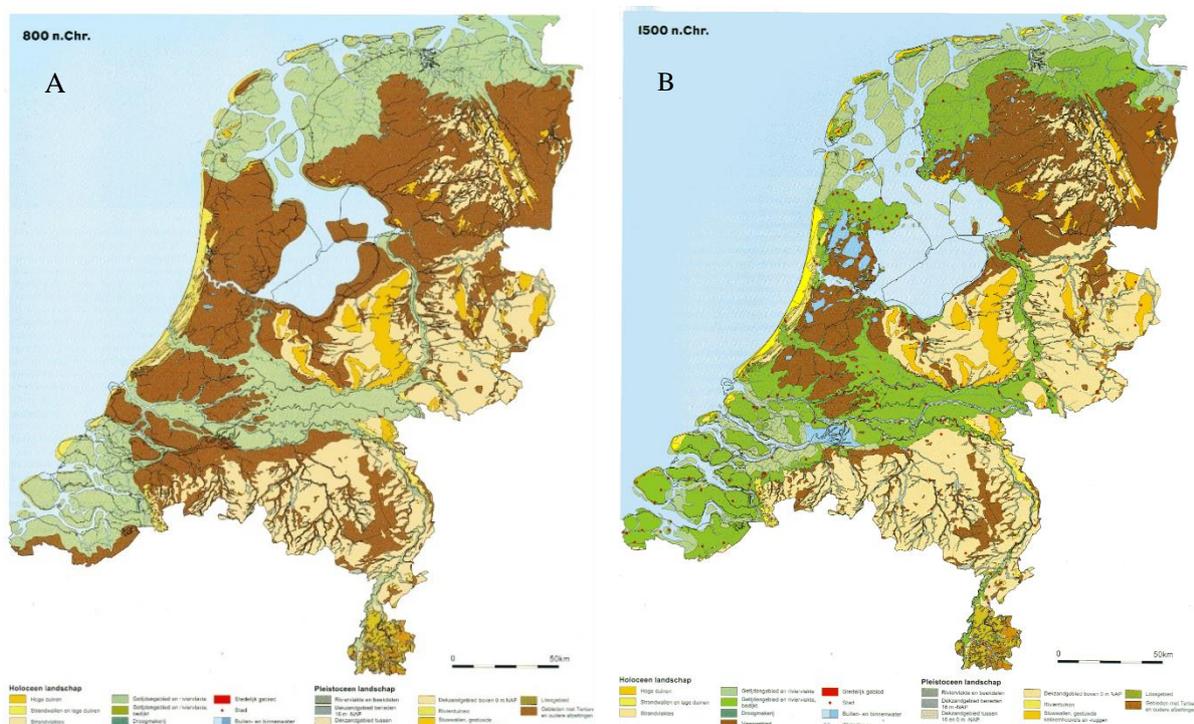
Figure 5.2: Holocene landscape of the Netherlands. A: 800 AD. B:1500 AD (Barends et al., 2011)

Over a distance of 8 kilometres, 35 million m^3 of sand was nourished and dunes were created. This led to a 300-meter shift of the coastline in westward direction. The row of dunes was constructed just before the old sea dike with a 150 m wide beach. The dunes are about 11 m high and 150 m wide over the entire length of the seawall and are reinforced with beach grass. Over the years, the area will require constant sand replenishment, because the area protrudes as to the coastline in north and south direction. This results in a constant erosion due to sea currents and wind. This will mainly happen on the south side of the area, as the main current and wind direction is from south to north along the Dutch coast. However, during storms the wind direction changes often, and more erosion will occur on the north side of the Hondsbossche dunes. To amplify the Recreational demands a lagoon was created on the south side near Camperduin and near Petten a belvedere was created where visitors can view the project.

In this research, the focus is put on the southern part of the Hondsbossche dunes area (Figure 5.3). This area is highly dynamic because of continuous erosion on this side. It is therefore useful to see if higher resolutions in area and time can give more information for management and maintenance. In addition, it might also be useful for the two research programs from the TU Delft called living labs. Here, knowledge about the use of sediments and natural dynamics to improve flood safety and the resilience of our water system has been gathered (Living Labs, 2019).

Figure 5.3: The research area at Hondsbossche Dunes

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5.2 Noordwijk

Noordwijk is a coast village in the Dutch province of South Holland. Noordwijk also has a history of coastal erosion and breakthroughs during storm surges. When the Koningin Wilhelminaboulevard was indicated as a weak link in the Dutch coastal defence, reinforcements were done. In 2007/2008 the coast at Noordwijk was reinforced by adding concrete blocks to the existing dunes over a length of 1,5 km which is called dike in dunes. In addition, the dune area was made approximately 42 meters wider instead of making the dunes higher due to economic reasons. With these measurements the hinterland is protected against flooding. The dunes and dike maintained the height of the existing dunes, in this way the view of the apartments along the boulevard will not change. The area that will be visualized in this research is approximately 500 meters broad (Figure 5.4). The terrestrial laser scanner measures from the balcony of the hotel Huis ter Duin (Figure 5.5). In the field of the viewer of the laser scanner are the beach, intertidal zone, dunes and the beach café Breakers Beach House. The scanner measure one scan every hour for 24 hours per day since 10 July 2019 (Coastscan, 2020).

Figure 5.4: The research area at Noordwijk

Figure 5.5: View from the Balcony of the Hotel Huis ter Duin in Noordwijk where the terrestrial laser scanner is installed (CoastScan,2020).

6. Results

In this chapter the results of the visual analysis of the Hondsbossche dunes and Noordwijk are discussed. First, the two datatypes, point cloud and raster are compared to each other. In addition, several visualization techniques for visualizing elevation which can be used for both point cloud and raster are compared. Hereafter, the Hondsbossche dunes are visualized and analysed with point clouds. First, an overview of the research area is given over the course of a couple of years. Hereafter, the elevation of a couple of interesting areas in the Hondsbossche dunes are visualized in greater detail through time. For every interesting area, the distance between point clouds of different years is calculated. In this way the deposition and erosion of sediment becomes visible.

The same will be done for the Noordwijk dataset, however, the datasets used are of higher temporal resolution. First, an overview is given of the research area over the course of a couple of days. The elevation will be visualized before and after the appearance of storm Ciara. In addition, the difference between the two point clouds will be calculated and erosion and deposition visualized. Hereafter point cloud datasets of Noordwijk measured during low tide from the 9th till the 12th of February are visualized. Here will be zoomed in on detailed morphology close to a beach building. Lastly, hourly data are visualized from consecutive hours on the 8th of February and the 9th of February 2020.

6.1 Comparison between point cloud visualization and raster visualization

For the comparison of point cloud based visualizations and raster based visualizations the .las datasets of the Hondsbossche dunes are used. First an overview of the whole research area in 2020 is given Figure 6.1) in point cloud, DTM and DSM. For these visualizations no further (shadow/thinning) techniques are used. Firstly, what is noticeable is that the point cloud dataset has some difficulties loading when not using thinning techniques. In the south of the research area a square is not loaded correctly. That this problem could occur for large point cloud datasets was already mentioned in the theoretical framework. Loading large point cloud datasets is often time consuming and very demanding for the software as quantified in chapter 3. The point cloud visualization of the full research area consists of two point cloud datasets and covers approximately 5 kilometers by 600 meters. On a small scale not many differences in the use of point cloud or raster-based visualizations can be detected. There are however some small differences between the DTM and point cloud and DSM and point cloud.
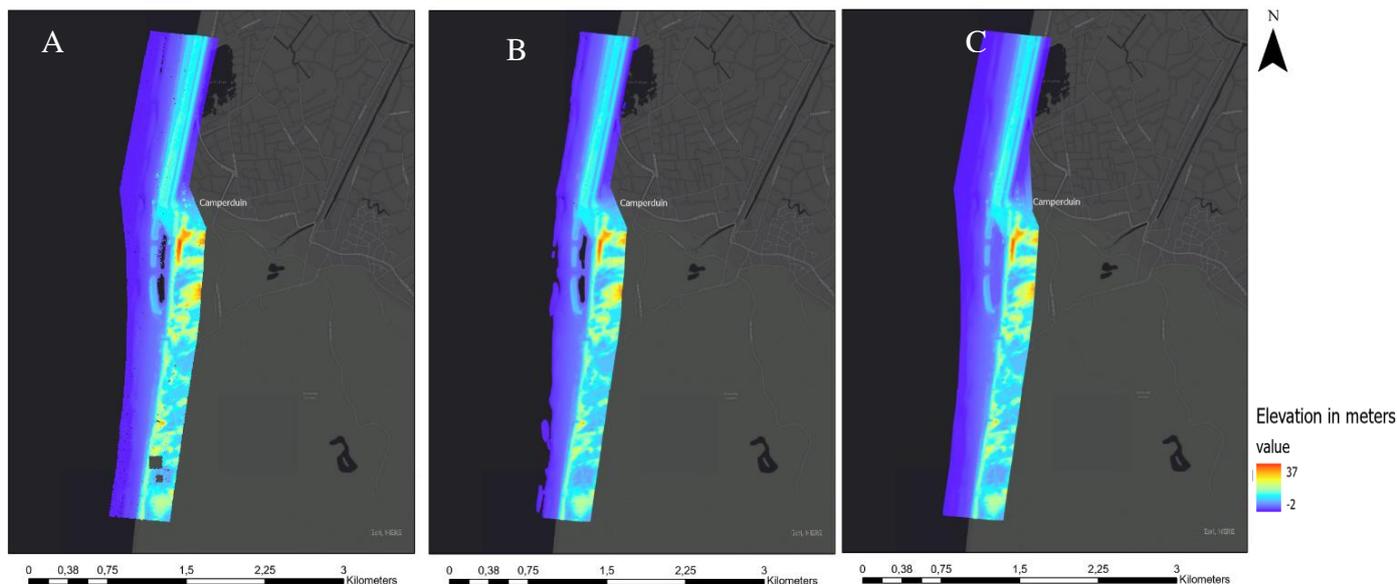
*Figure 6.1: Visualizations of the Hondsbossche dunes research area in 2020. **A**. point cloud visualization **B**. Digital Terrain model (DTM), raster based. **C**. Digital surface model (DSM), raster based. Elevation in meters.*

For example, in the DTM only the bare surface is shown. This means that the buildings and water are filtered out whereby perhaps important information is lost. This is not the case for the point cloud. In the point cloud the circumference of buildings are visible, however, due the angle of the measurement in the airplane it is impossible to see underneath when looking from aside in 3D. This results in no data underneath the buildings. The DTM which visualized the bare ground without any buildings, does visualize the surface underneath, this elevation is interpolated with the points at the side of the building. The elevation underneath these buildings is therefore the average of the values measured at the edge of the building. In some cases, information of the bare surface underneath the beach buildings changes through time and is thus important to know. However, it is often more relevant to know the amount of sediment that moves around a pavilion. In North-Holland beach buildings often stand on stilts. During high tide and storms the sea and wind has free influence on the sediment underneath these buildings (Figure 6.2). In addition, this area is often kept clear of abundance of sediment for storage space and work on pipes. In this case the DTM can give the wrong impression because it looks like there is data underneath these buildings.

As said before in the DTM water is filtered out. Water is often classified as the elevation below 0,5 meters, which is probably not that accurate. In the point cloud water is also not shown, however, this has another reason. The laser from the LiDAR scanner is very limited in penetrating the water surface, therefore deeper water has no data. The small lagoons are a good example of this phenomenon.

Figure 6.2: Beachbuilding Luctor et emergo at Camperduin, beach buildings often stand on poles in the North of Holland. Sediment transport is therefore possible beneath these building, especially during high tide or storm. (photos Petra Goessen)

When comparing the point cloud to the DSM, buildings are shown on both images. However, in the DSM the sides of the buildings are closed, and as said before the buildings stand on poles on the beach causing distorted information in the visualization. The water on the other hand is displayed on the DSM and not visible on the point cloud. The reason why water is not visible on the point cloud is explained before. However, how is the elevation measured beneath the water on the DSM? Again interpolation of the underlying point cloud data in this area is a key factor. For example, the water in the DSM in the small lagoon is interpolated with points from the edge of the lagoon and looks therefore closed. Keeping in mind that the DSM is interpolated from the point cloud data and that in the point cloud data the lagoons are shown as no data, it is not certain whether this area is depicted correctly.

When zooming in on these different datatypes, the differences become clearer. In the point cloud, smaller details are better visible than in the raster-based visualizations. The grid of raster-based images is often set on 0,5 meter or 2 meters. In the images of 0,5 meter more is visible but still not as much as in a point cloud. When comparing the point cloud to the DTM, buildings are visible on point cloud but not on DTM. Therefore, is there no need to take buildings into account while comparing point cloud and DTM. However, when comparing the elevation of the terrain, more details in the point cloud

visualization are present (Figure 6.3). Comparing the point cloud with a DSM in a top view and in perspective difference in detail around the buildings can be detected.
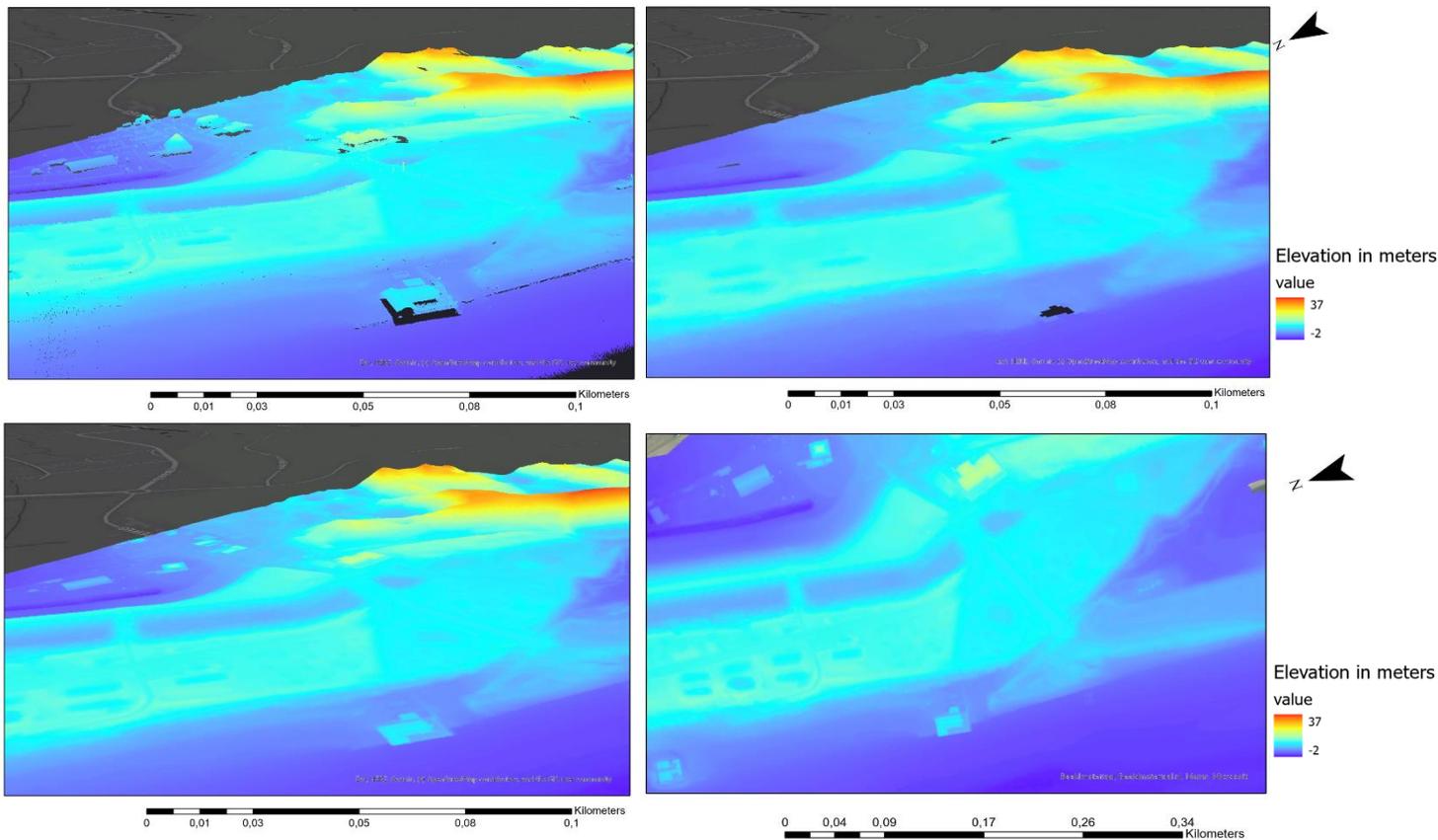
Figure 6.3: On the left top a zoomed in visualization of a point cloud at the Hondsbossche dunes (2020), on the right the same area visualized in raster (DTM) format. On the bottom left a DSM in 2D and right DSM in 3D, raster with grid of 0,5m.

When zooming in even further this difference in detail becomes clearer, even when not using extra visualizations techniques like shadow effects or colour scale the detail in the point cloud dataset is much higher (Figure 6.4). In Figure 6.4 small embryonal dunes are visible in front of the larger dunes, these are less visible on the raster map. The outline of the embryonal dunes is completely vanished on the raster map.
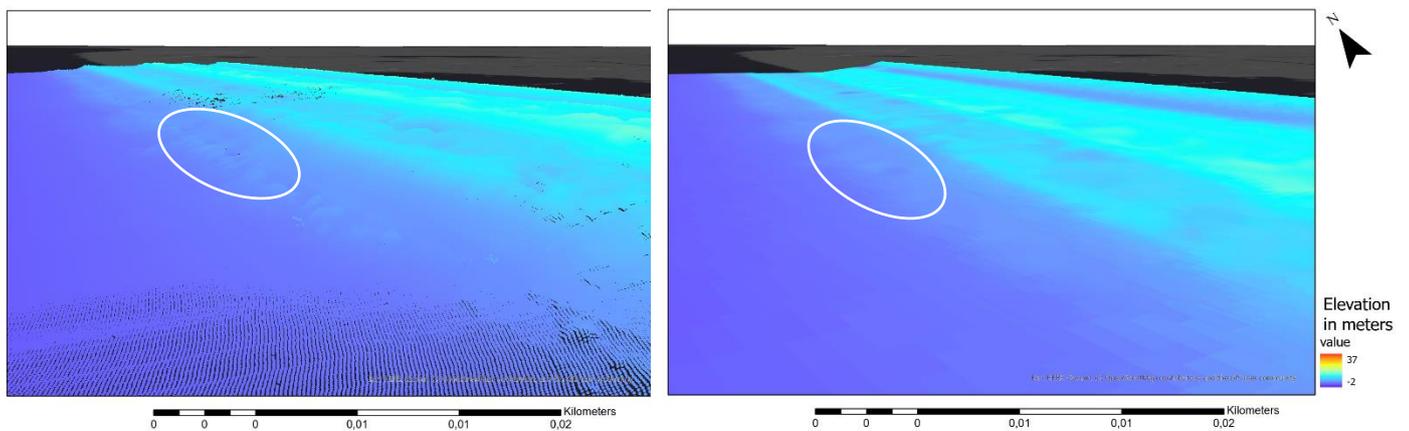
Figure 6.4: On the left a visualization of a point cloud, small embryonal dune in front of the larger dunes are visible. On the right visualization of a raster (0,5m) these embryonal dunes are not visible due to the grid cells. Visualized without extra vis-ualization technique.

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However, the differences between point cloud and raster visualization can be visualized even sharper using some visualization techniques. For example, shadow effects can be used to enhance the depth perception. For point clouds the tool 'Eye dome lighting' is available and for raster-based visualization the tool 'Hillshading'. Eye Dome Lighting is an image-based and non-photorealistic shading technique which uses a dome centered at each point of the point cloud and Hillshading uses the relative position of the sun using the azimuth and altitude. How these techniques work was explained in detail in the theoretical framework (section 3.4). When visualizing point cloud data and raster data with these techniques large differences become clear (Figure 6.5). Visualizing the elevation in these datasets with a shadow technique enhances the level of detail in the point cloud even more.
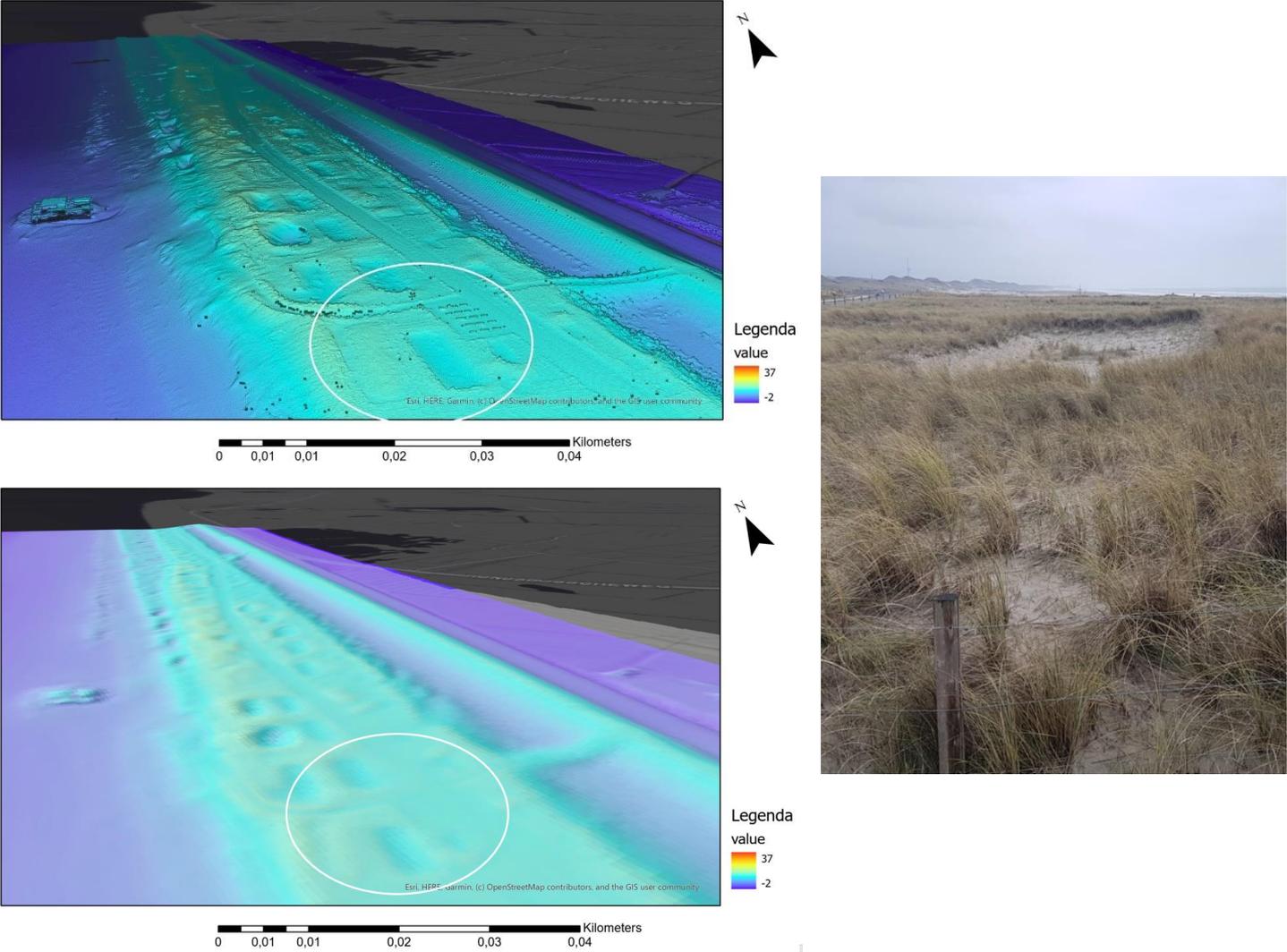
Figure 6.5: Visualization whereby shadow techniques are used, the top left a point cloud, bottom left a raster and on the right real life. Elevation in meters.

Zooming in further, (Figure 6.6) displays how detailed the dune surface is reproduced in the point cloud. Small embryonal dunes can be distinguished in the point cloud but are hardly visible in the raster. In addition, when objects are smaller than 0,5 meter they are not visible on the raster visualization with grid size 0,5 meters (Figure 6.7). On raster visualizations with a grid size of 0,5m, objects will be visible of 1m or larger. Therefore, visualizations for the analysis of the Hondsbossche dunes and Noordwijk are visualized in point clouds with the 'eye dome lightning' technique in section 6.2 and 6.3.
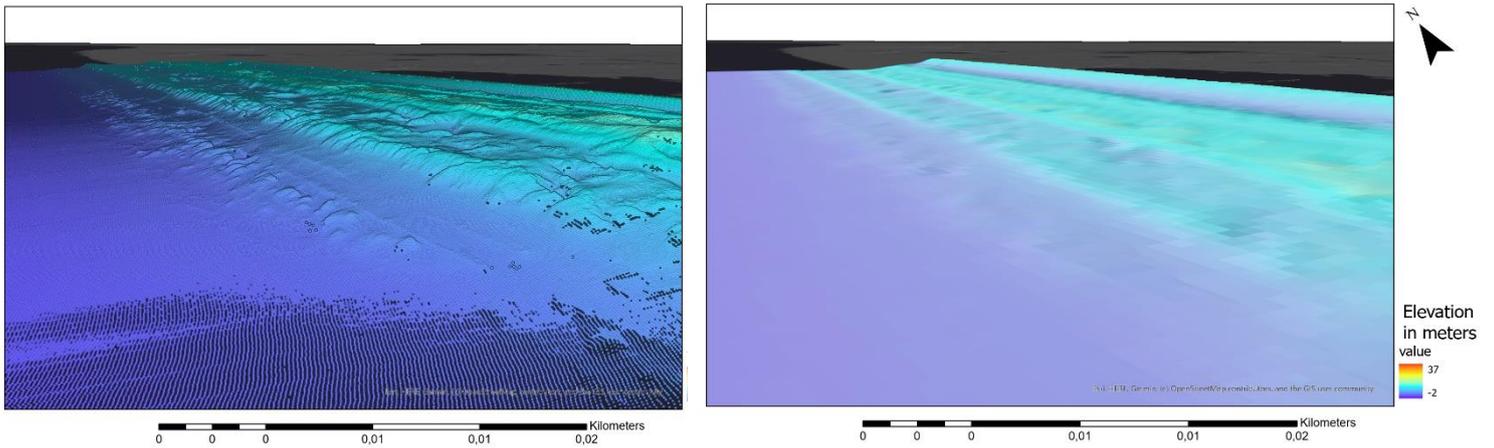
Figure 6.6: Zoomed in visualization of on the left a point cloud and on the right a raster DSM (0,5m).
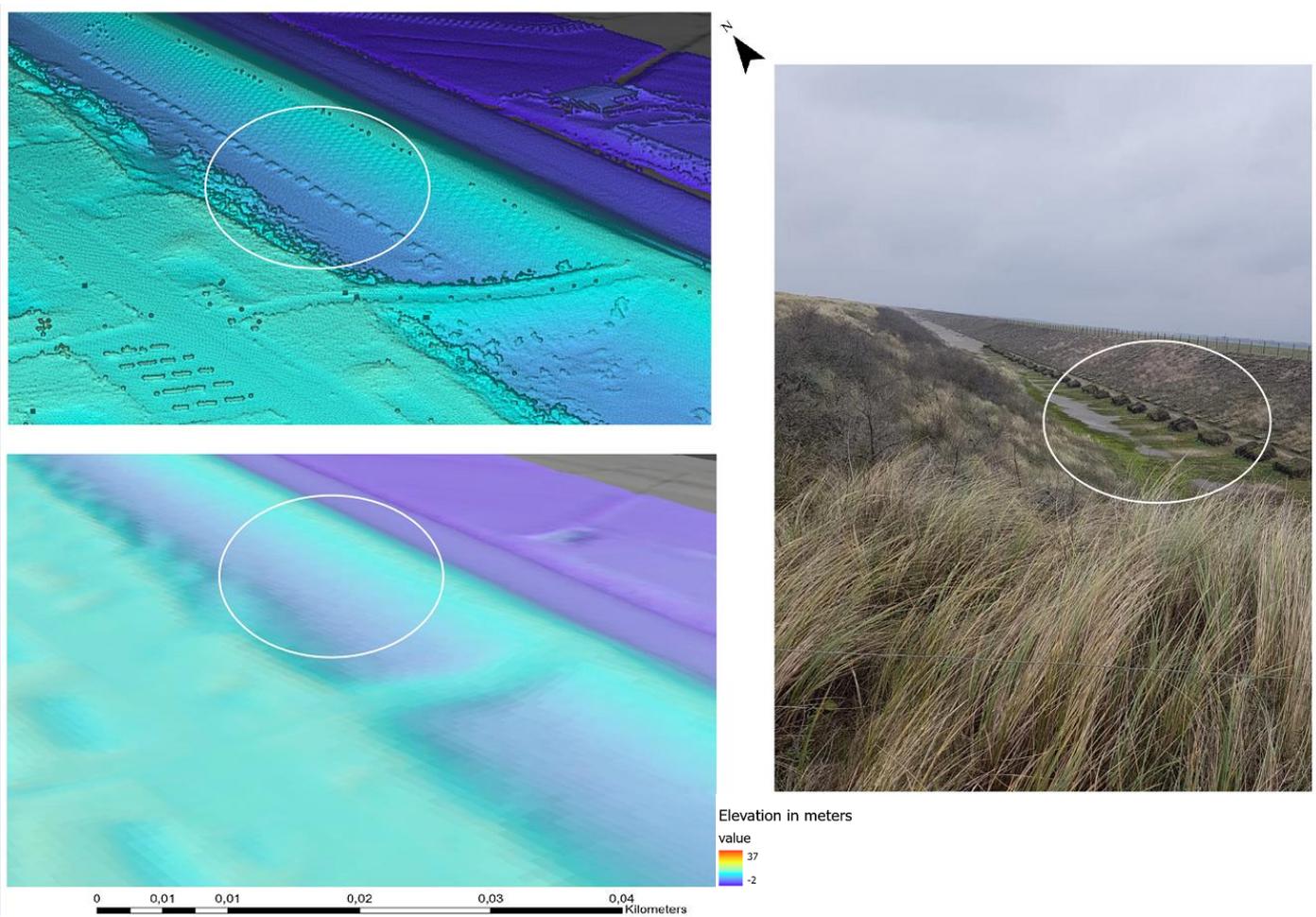
Figure 6.7: Top left visualization of point cloud, bottom left visualization of raster, right picture is the area in real life. The blocks that are visible in real life and in the point cloud data are not visible in the raster dataset (0,5m). Elevation is displayed in meters

Temporal data can be used to compare different periods of time. For example, the year 2017 can be compared to the year 2018. When subtracting these from each other the erosion and deposition of sediment can be visualized. This can both be done for point cloud data and raster data (Figure 6.8). Noticeable differences can be distinguished between the visualization of the point cloud and raster data, applied on the comparison between 2017 and 2018. For example, when comparing both point cloud and raster

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maps a sharp line is visible on the point cloud-based visualization (on the foreground). The raster-based visualization does not show this sharp line in the same distinctive way. Between the years 2017 and 2018 a reed screen was constructed to capture the sand which is probably this sharp line that is visible. The raster visualization that is used for this comparison is created with DTM of HHNK. The raster visualization suggests the inception of a much bigger structure in this area which also could be interpret as dune formation. This could be due to the measurements on which this image is based; they are from a slightly other period of the year 2017 and 2018. But it is more likely that here the interpolation techniques of the raster data are the reason for this fuzzy image. It was intended to visualize both these images in ArcGIS Pro, this was not possible due to communication problems between CloudCompare and ArcGIS Pro.
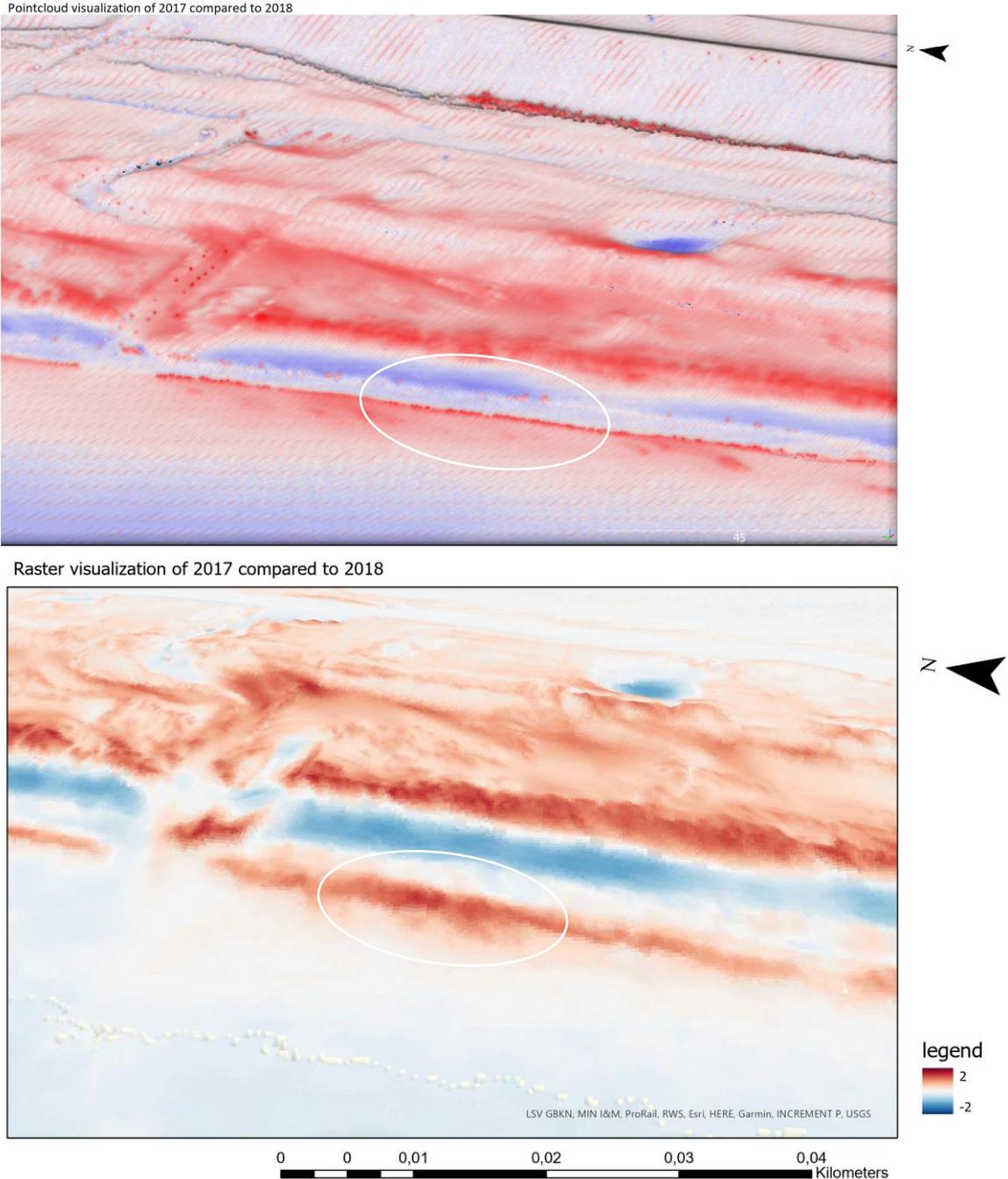
Figure 6.8: Upper visualization is point cloud based, here a sharp line is visible in the white circle, the bottom visualisation is raster based (DTM), the sharp line is less visible. An decrease (blue) or increase (red) in sediment from -2 to +2 meter.

6.2 Long term temporal visualization

In the next section annual datasets of the Hondsbossche dunes are visualized over a course of 7 years. Changes in elevation and erosion and deposition are displayed in several ways. First, changes on a small scale will be visualized where the whole of the research area is displayed. Hereafter, is zoomed in at 5 interesting locations to visualize detailed morphology.

6.2.1 Temporal visualization on a small scale

Temporal changes in the Hondsbossche dunes are visualized from 2013 up to 2020 (appendix I). Each visualization displays the southern part of the Hondsbossche dunes for a specific year. Eight maps are created corresponding to an elevation model, where red represents high areas such as dunes and the lower areas are shown in purple in a continuous colour scale. The elevation ranges from -2 meters to +37 meters. The area is visualized from a bird's eye view to make it possible to see the entire area of interest. There is however a downside of the bird eye's perspective. The 2.5D aspect of the point clouds is not justified from this viewing angle. Using colour scale and shadow effects are therefore chosen to help visualize changes from this perspective. In addition, a topographic base map is added to give a topographic orientation. The datasets used for these visualizations contain a large volume of points. ArcGIS Pro has sometimes difficulties loading the points in these datasets. Therefore, techniques like thinning are used to create these images.

From the bird's eye view of the entire research area it becomes apparent that the area changes over the course of years. In 2013/2014 the Hondsbossche dunes did not exist yet and there was only the Hondsbossche seawall (Figure 6.9). The seawall with its groynes is clearly visible in these images. In 2015 the Hondsbossche dunes are completed. Dunes and a beach were created in front of the seawall and a lagoon was developed in the southern part of the Hondsbossche seawall for recreation. Between 2015 and 2020 no large changes are visible in the geomorphology of the area when viewing the elevation with this colour scale. In this area it is quite difficult to visualize small differences for the whole area on this scale because the elevation has quite a large range from -2 meter to +37 meter. This results in larger steps on the colour scale. For example, small changes of half a meter do not stand out in this way. A different colour scale can be helpful to meet management demands in a better way e.g. a colour scale between 0 and 6 meter could give more insight in changes on the beach. In addition, zooming in will give much more significant detail, whereby the added value of the point clouds can be used.

Even though not much change is visible on the visualisations of this elevation, it is clear that the morphology of the area is changing. It is even better visible on this scale by emphasizing especially on erosion and deposition (Figure 6.10). In these images two point clouds of different years are compared to each other. Displacement per point between the two point clouds has been calculated in CloudCompare resulting in 7 maps (Appendix II, Figure 6.10). Deposition is coloured red and erosion is blue, the range is between +2 meter increase or -2 meter decrease of sediment. Between 2014 and 2015 the largest part of the Hondsbossche dunes is constructed (Figure 6.10). In the years thereafter the beach gets eroded on a large scale, especially in front of the beach building Luctor et Emergo. This area is most affected by currents of the North sea and the main wind direction because here the land protrudes a little further into the sea. It is therefore the weakest point of the area where the heaviest erosion takes place. An exception of this constant erosion takes shape between the years 2018 and 2019, where deposition is visible on the beach. In this year sand replenishments took place to continue to meet the safety requirements for this coastal defence. When looking at the lagoon, southern of the Hondsbossche seawall a variety of erosion and deposition is visible. This phenomenon is not natural either. Every so often the lagoon is deepened out again for recreational reasons. Furthermore, when looking at the whole research

area, it is noticeable that since the construction of the Hondsbossche dunes, deposition takes place in the dune area before the former seawall, especially on the embankment. This is probably very likely a result of a natural process of dune formation.
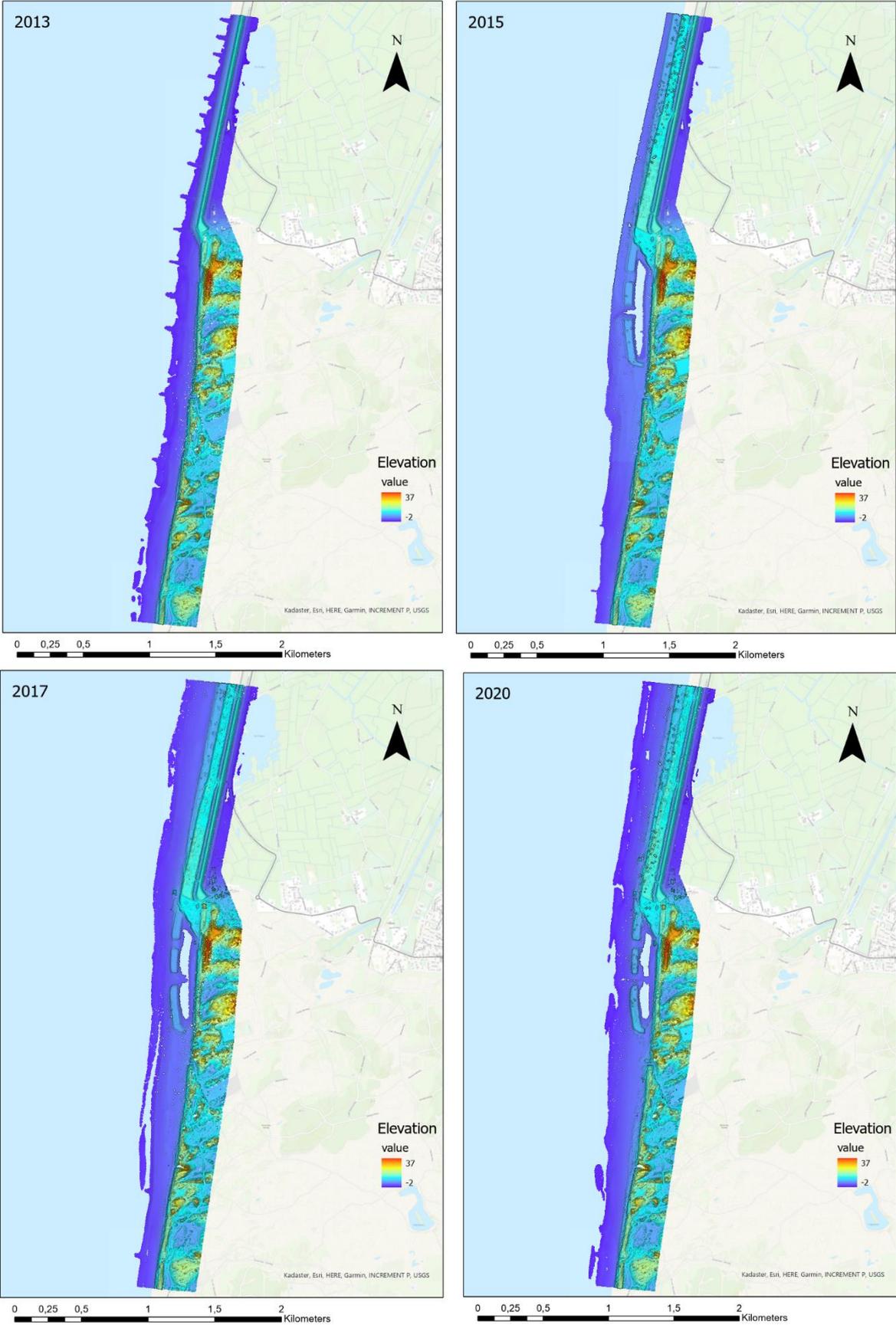
Figure 6.9: Point cloud-based visualizations of the whole Hondsbossche Dunes research area. The elevation is from -2 (purple) to +37 meter (red).
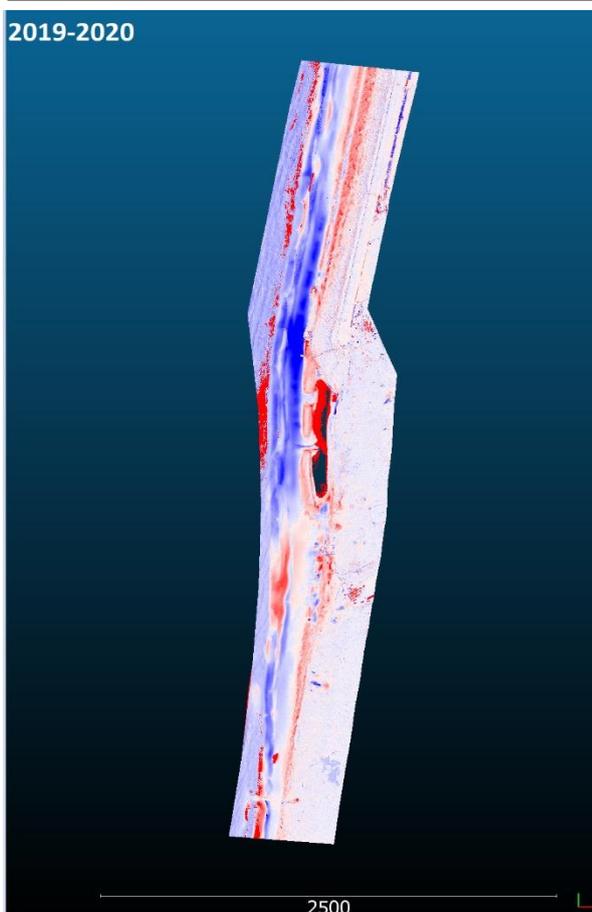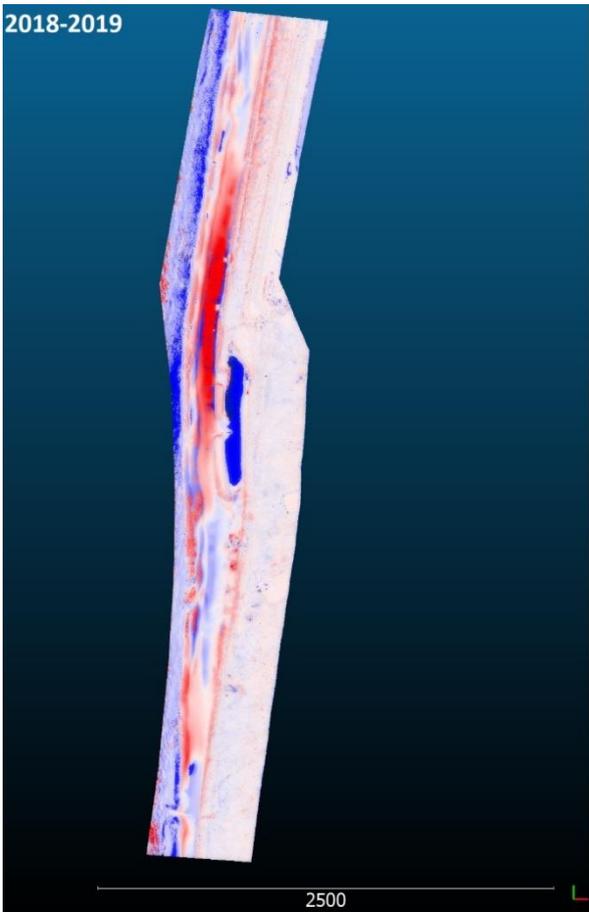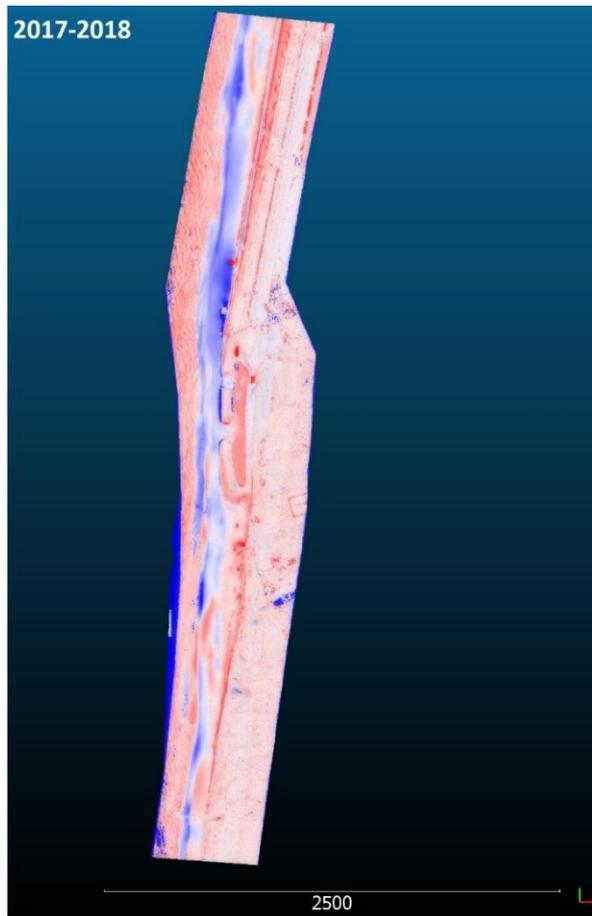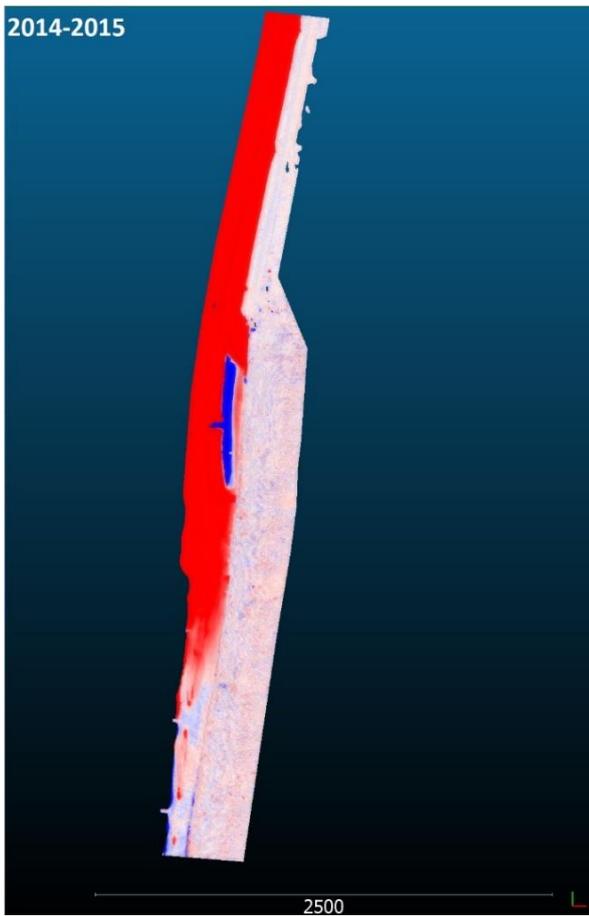
Figure 6.10: Point cloud visualization of erosion and deposition between two years. The colour scale is between red, deposition and blue, erosion. The change is between the -2 meter and +2 meter.

6.2.2 Temporal visualization on a large scale

Five areas in the Hondsbossche dune research area were chosen to look from a closer perspective to show the visualization power of point clouds. Shadow effects are used to increase the depth perception and the colour range is changed in a way the elevation pops out. The zoomed in areas are not visualized from a 90-degree angle anymore but more from the side. This will give the 2.5D aspects of the point cloud a better performance. The first zoomed in visualization is located in the north of the research area (1 in Figure 6.11). The following zoomed in visualizations are up to the south (2, 3, 4 and 5 in Figure 6.11).
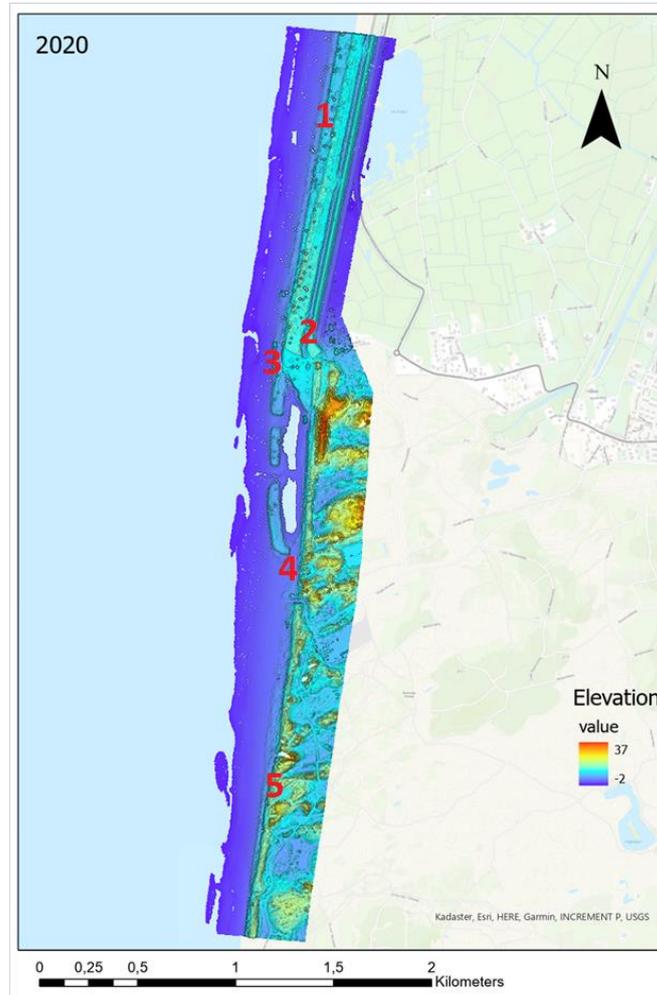
Figure 6.11: Zoomed in locations in the Hondsbossche dune research area. In red the numbers 1 to 5 for the zoomed in locations. (elevation in meters)

Location 1

The first zoomed in visualizations display the old seawall and the new dunes in front of it (Appendix III). The colour scale of these visualizations are adjusted to +2 meters up to +14 meters. In addition, shadow effects are used to create more depth perception. In this way detailed morphology is better visible. Through time a lot of sediment is deposited in this area (Figure 6.12). The dunes in front of the old seawall were constructed around 2014. Through time the elevation of the dune area in front of the seawall becomes higher and higher. In addition, in front of the manmade dunes small embryonal dunes occur from around 2016 which grow larger up to 2020. Change through time can be visualized in another way as well. Two point clouds of different years can be compared to each other, whereby the distance between the two point clouds is measured. The deposition which was visible on the elevation visualizations can also be noticed on these maps where different years are compared to each other (Figure 6.13).

The deposition in the dune area is caused by aeolian transport, wind blows sand from the beach into the dune area. In the dune area vegetation is present, which helps holding the sediment causing the dune area to gradually expand. From 2018 up to 2020 new small embryonal dunes are developing on the beach in front of the dunes that developed around 2017. Furthermore, it looks as if there is a slight acceleration in dune formation between 2016-2017 and 2019-2020.
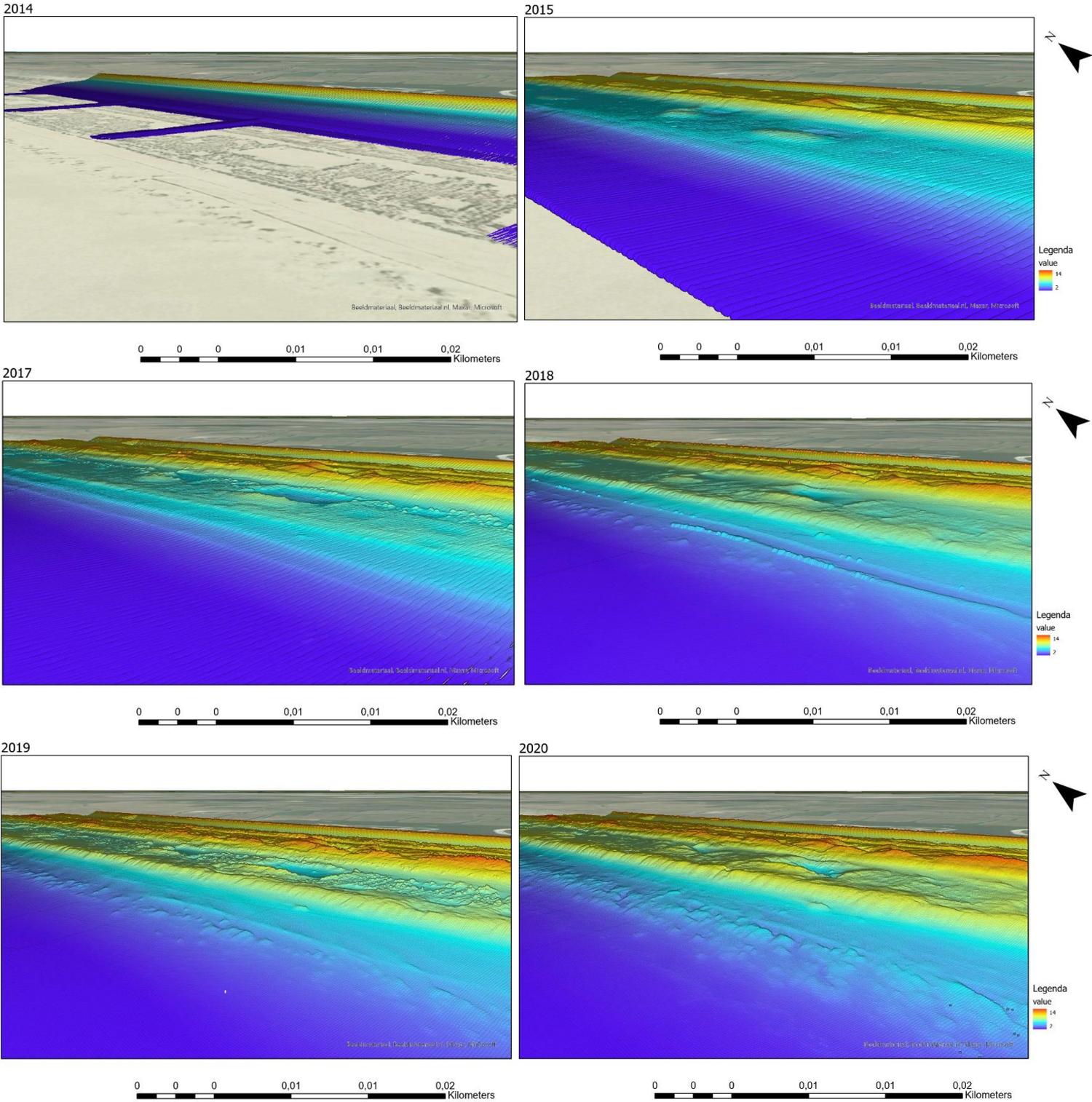
Figure 6.12: Zoomed in point cloud visualization of the elevation of the most northern part of the Hondsbossche dunes. The colourscale runs from 2 (purple) to 14 (red) meters.
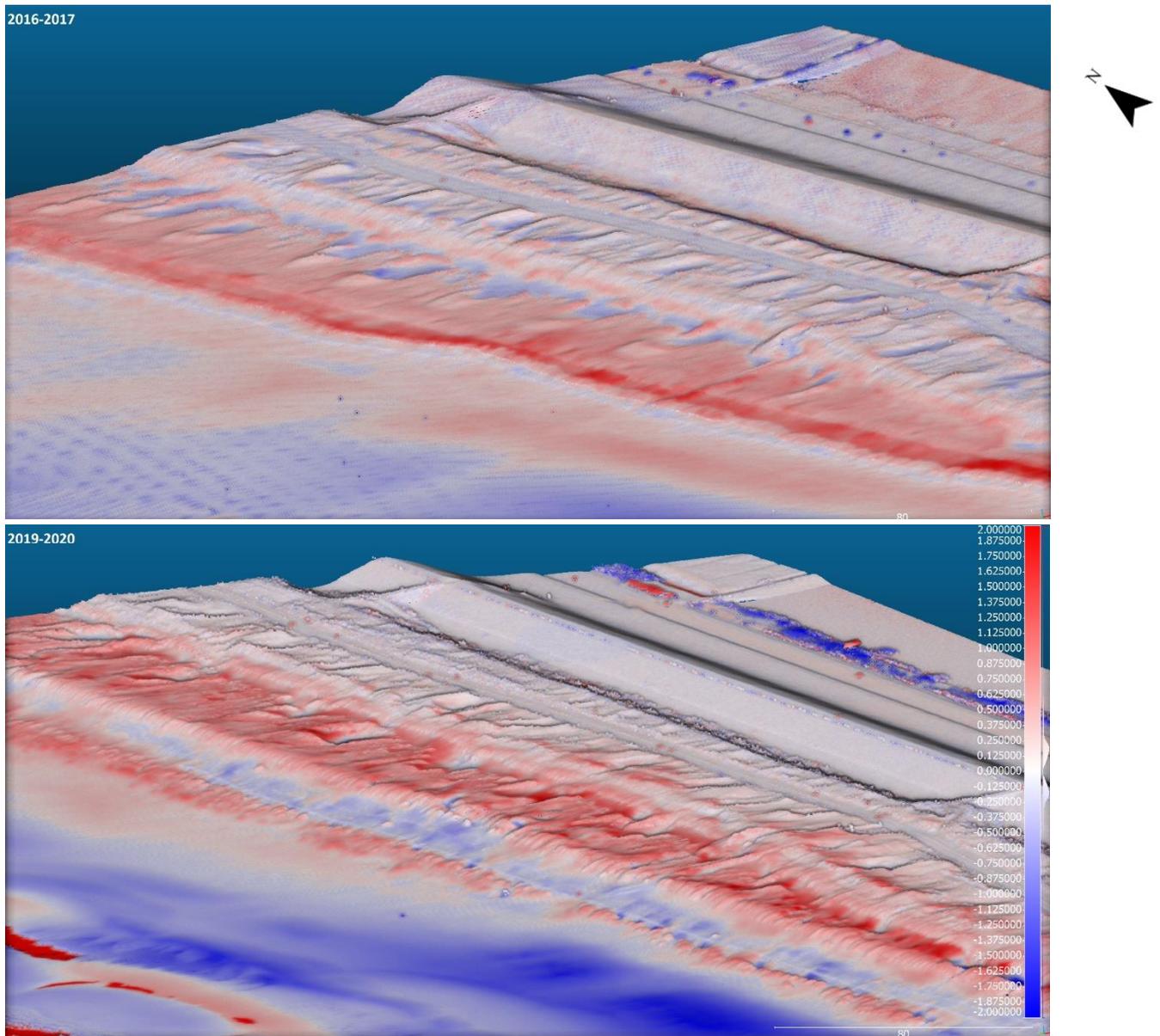
Figure 6.13: Visualizations whereby two point clouds of different years are compared. In the years 2016-2017 deposition is visible in front of the dunes, in 2019-2020 a lot of deposition in this area is also visible and embryonal dunes in front occur. Between 2019 and 2020 there is also more erosion on the beach. (change between -2, in blue, and 2, in red, meters)

Location 2

Moving to the second zoomed in location which is near the beach entrance of the Hookipa Beach building (appendix IV). This is an interesting area because here man-made dust pits are created, visible as squares with a lower elevation. Through the use of shadow techniques and a colour scale from 3 to 15 meters these dust pits are well visible through time with point clouds (Figure 6.14). In 2015 several of these dust pits are created. When moving one year forward some of these pits are gone and other have deepened. The dust pits up north are not only dulled by sand, but the elevation became even higher than its surroundings. In addition, some of the dust pits close to the path of the beach entrance are deepened. Furthermore, embryonal dunes originate in front of the higher dunes. The beach building Hookipa Beach was built in 2018, changes can also be seen around this building over time. On the south and west side of the building is sediment deposited through aeolian sand transport (Figure 6.15). In addition, on the map where 2019 is compared to 2020 it is very well visible that some dust pits are erosional and other depositional.
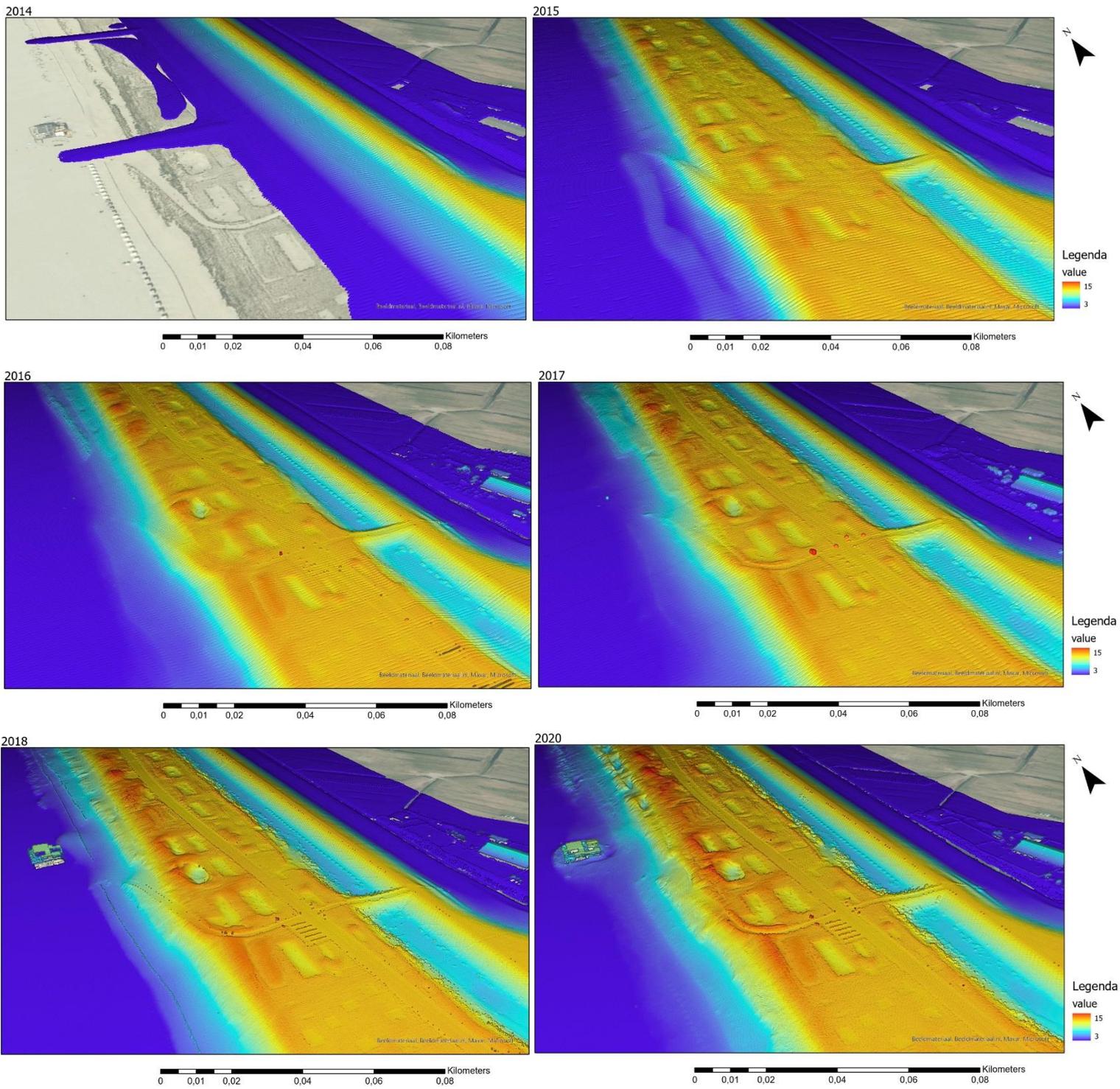
Figure 6.14: Second zoomed in location, point cloud visualization where colour scale is adjusted between 3 and 15 meters. Man-made dust pits are visible, through time some deepen and some fill up. In front of the dunes occur small embryonal dunes through time.
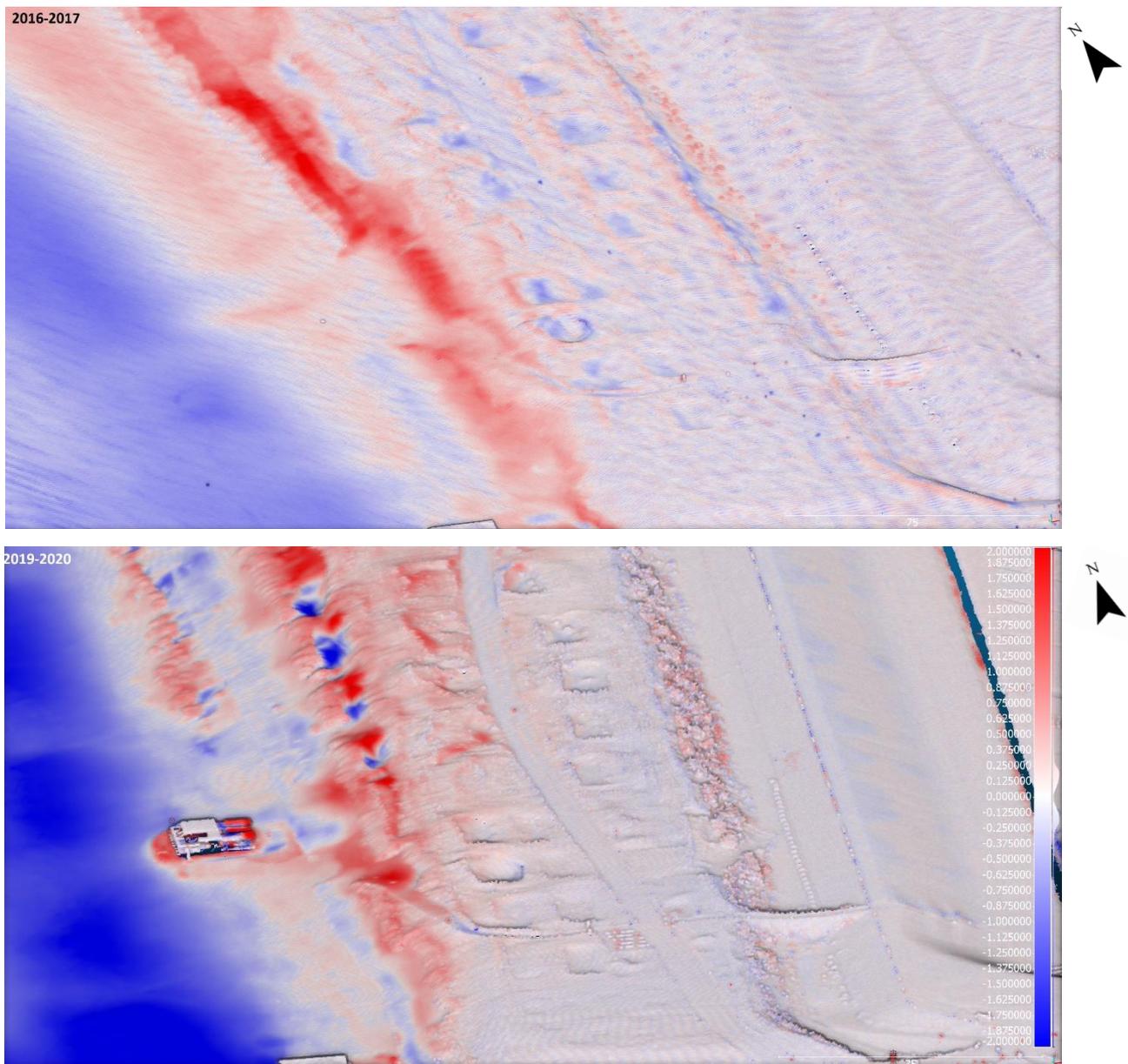
Figure 6.15: Point cloud of 2016 is compared to 2017 and 2019 to 2020. Between 2019-2020 is sediment deposited (red) around some dust pits and in front of the beach building. Erosion (blue) occurs on the beach and in some dust pits close to the beach. In 2016-2017 these dust pits were less visible and the beach building was not yet constructed. (change between -2 and +2 meters)

Location 3

The third zoomed in area is one where the most erosion takes place, the southern corner of the old Hondsbossche seawall close to beach building Luctor et emergo (Appendix V). In this area the wind and sea currents have the most influence on the sediment transport. Small expansions like embryonal dunes do not occur in this area because the elements are too strong (Figure 6.16). However, noticeable is that the dunes to the west of the lagoon, especially on the beach side, get higher over time. The colour scale is set on 0,5 to 17 meters and shadow effects are used again to increase the depth perception. Over a period of three years, from 2015 till 2017, the beach is eroding away fast. Therefore, in 2018 sand replenishment took place again to meet the safety requirements of the coastal defense. This is even better visible on the visualizations where changes per year are visible (Figure 6.17). The change per year is set on a scale from -2 meter to +2 meter.
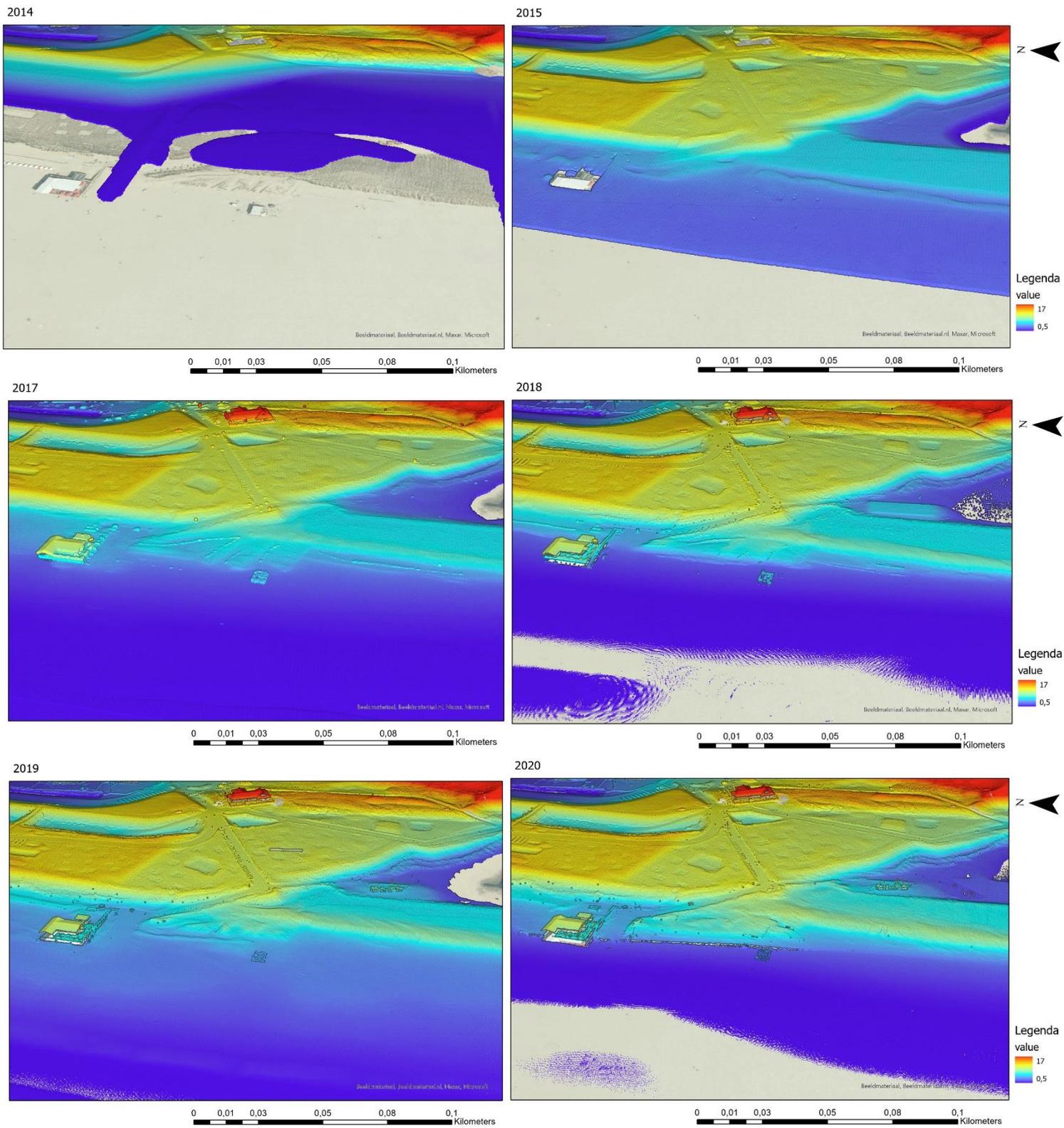
Figure 6.16: Point cloud visualization of third zoomed in location, on the southern corner of the old sea wall close to beach building Luctor et Emergo. In this area there is a lot of erosion because of its location in relation to the sea. However, the dunes next to the lagoon have deposition of sediment on the beach side. Elevation is displayed between 0,5 and 17 meters.
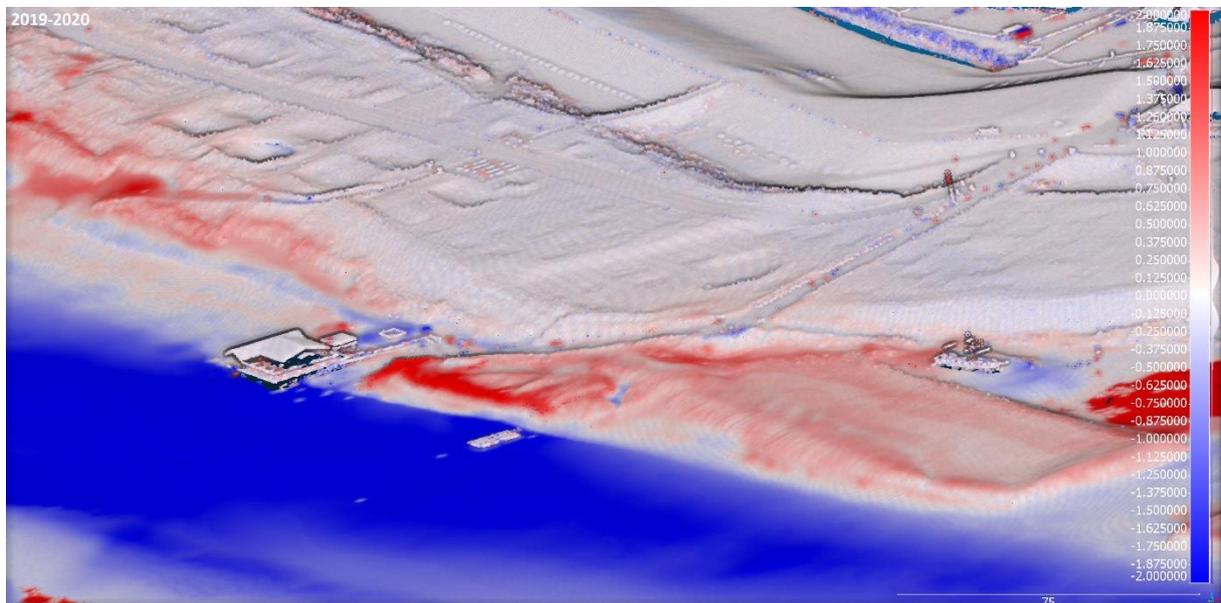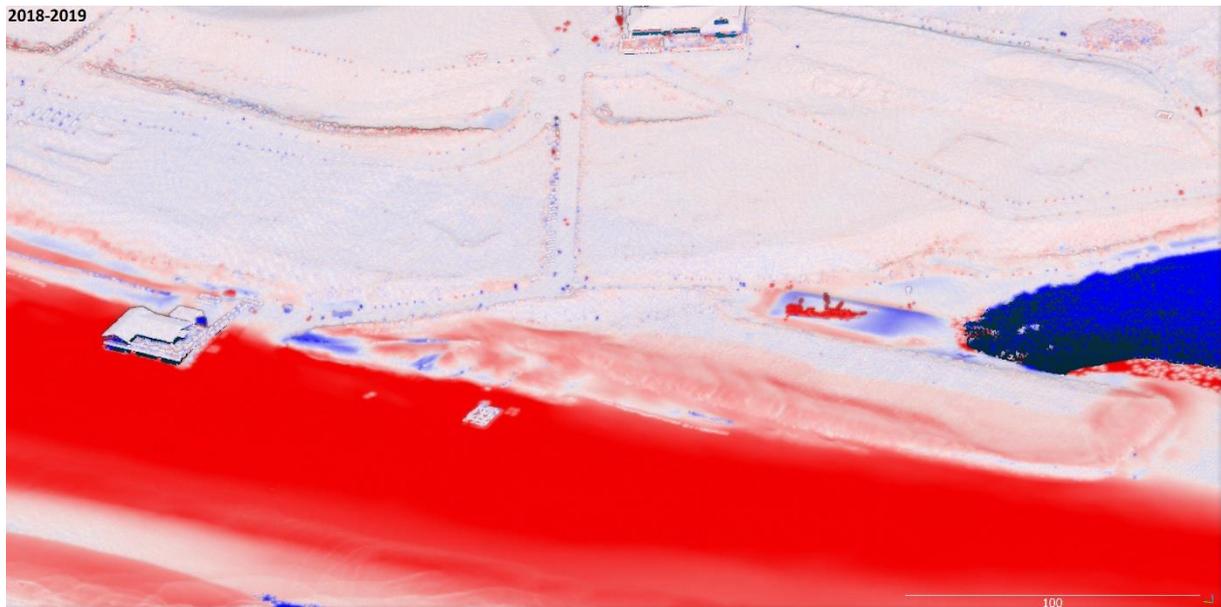
Figure 6.17: Point cloud visualizations of the comparison between 2018 and 2019, and 2019 and 2020. Between 2018 and 2019 a lot of deposition is visible on the beach (large red surface), this is due to sand replenishment. Between 2019-2020 this sand erodes relatively fast (large blue surface). Red, +2 meter, is deposition, blue, -2 meter, is erosion.

Location 4

The fourth area is in the southern corner of the lagoon (Appendix VI). In 2015 a dune was created on the west side of the lagoon. This dune almost touches the original dunes in the east. However, through the years the opening between the original dunes and the new man-made dunes has widened (Figure 6.18). An alteration between erosion and deposition occurs in the following years. First, the dunes that were man made were partly eroded away through aeolian transport. In 2018 deposition has taken place between the dunes. Hereafter, small embryonal dunes occur (Figure 6.19). This is most likely the result of the sand replenishment around 2018. Vegetation like maram grass helps to capture the sediment allowing these small dunes to grow up till 2020.
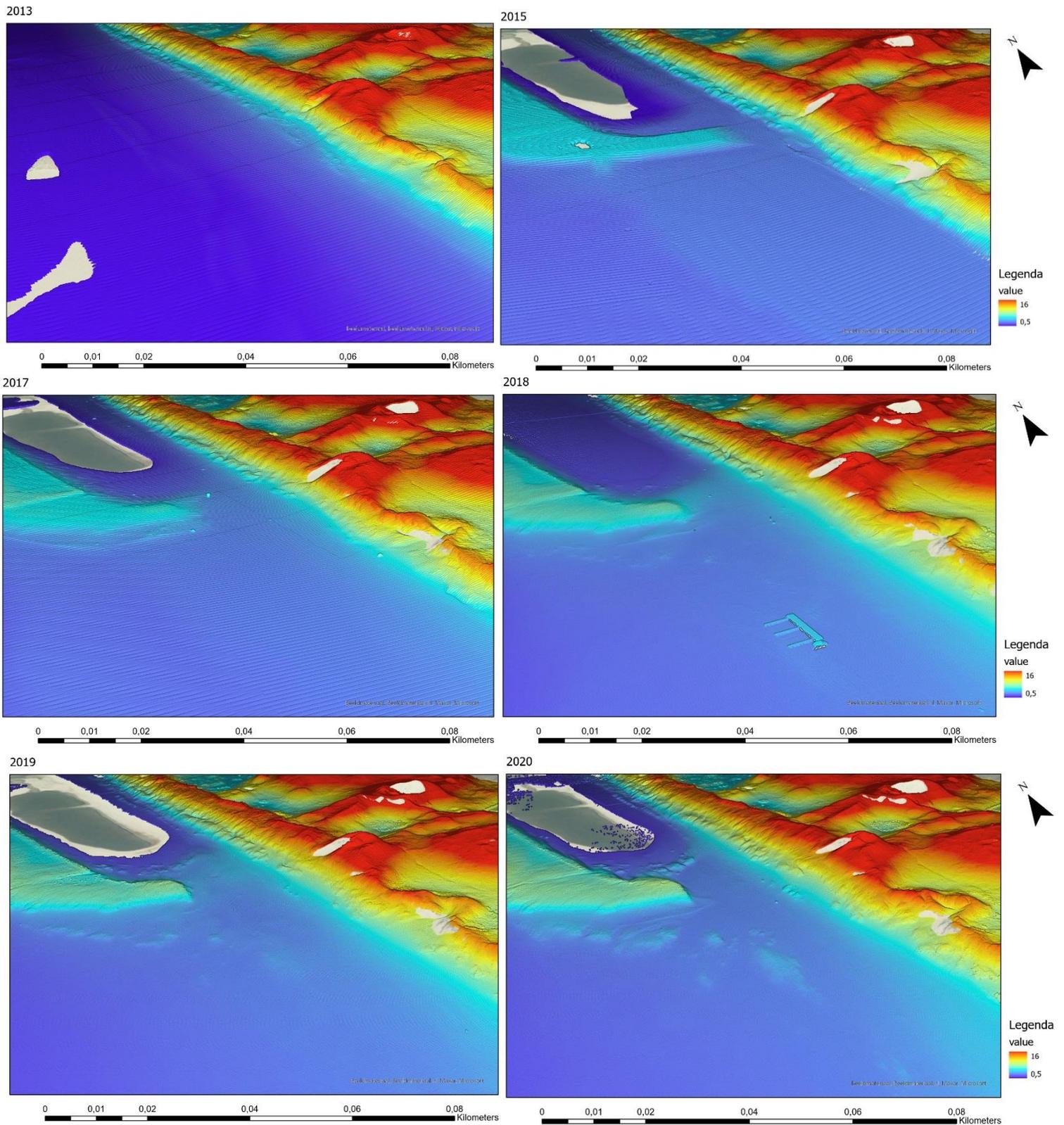
Figure 6.18: Point cloud visualization of 4th zoomed in location of the Hondsbossche dunes. The colour scale is between 0,5 and 16 meters, the man made dunes are eroding and the gap between these lower dunes and the higher dunes is larger. After the sand replenishment small embryonal dunes occur.

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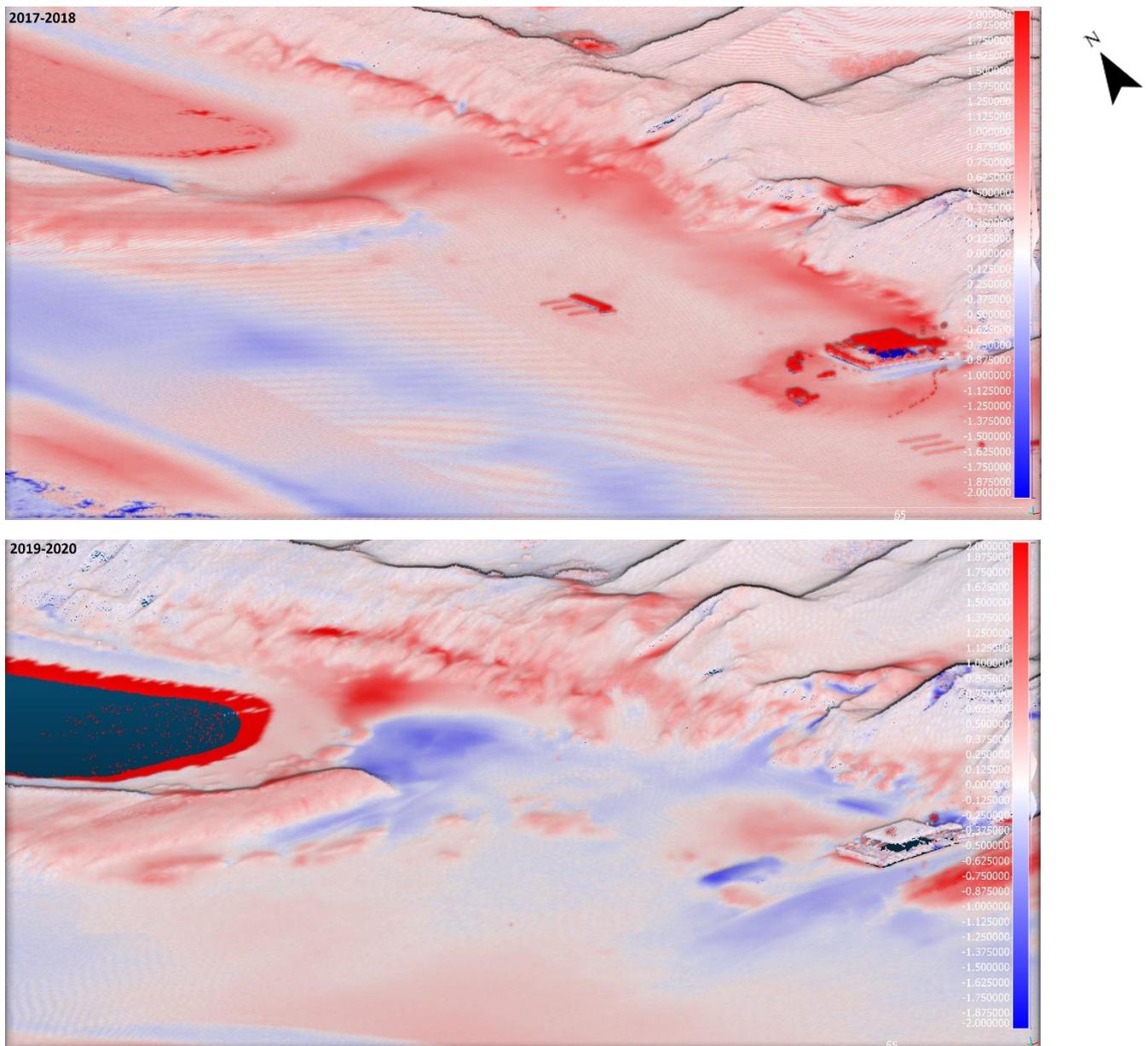
Figure 6.19: Point cloud visualization whereby two years are compared. Between 2017-2018 relatively much sand is deposited (red). However, in 2019-2020 erosion between the smaller and larger dunes is visible (blue). Embryonal dunes are growing south of the lagoon and lower dunes. (change between -2 and +2 meter)

Location 5

The last and fifth zoomed in visualizations are in the most southern part of the research area (Figure 6.20, Appendix VII). In this part of the research area no sand was added during the construction of the Hondsbossche dunes. However, the development of the Hondsbossche dunes has had an effect on this area. From 2014 up to 2020 embryonal dunes occur in front of the excisting dunes. Through time these small dunes grow larger. On the visualizations whereby 2 years are compared to each other (Figure 6.21, appendix VII) it is visible that before the construction of the Hondsbossche dunes erosion occured along the dunes. After the development of the Hondsbossche dunes depositions prevails. On these images changes of -2 meter and +2 meter are visualized with a colourspectrum between blue and red. On the visualisation of 2013-2014 stripes are visible, this is due to less quality of the datasets. The point density is less than in the younger datasets. Streaks in the scan direction of the laser scanner are therefore visible. A solution for this could be to widen the search area for the nearest neighbour in calculation of the point

to point distance. However, when widening the search location smaller changes will be less visible. It is therefore choosen to keep the visualization with the stripes.
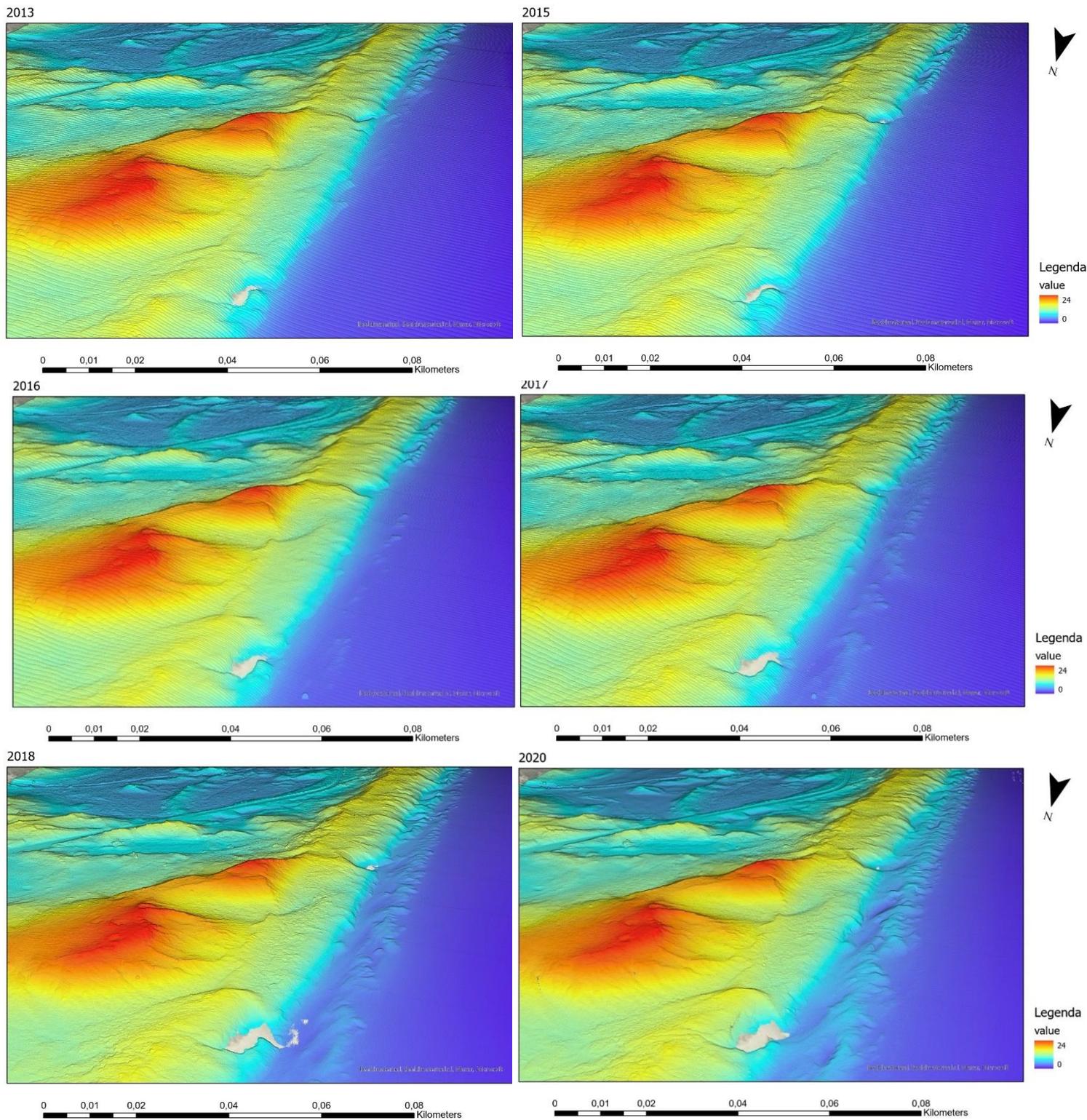
Figure 6.20: Last zoomed in point cloud visualization, colour scale between 0 and 24 meters. Through time embryonal dunes occur in front of the larger dunes.
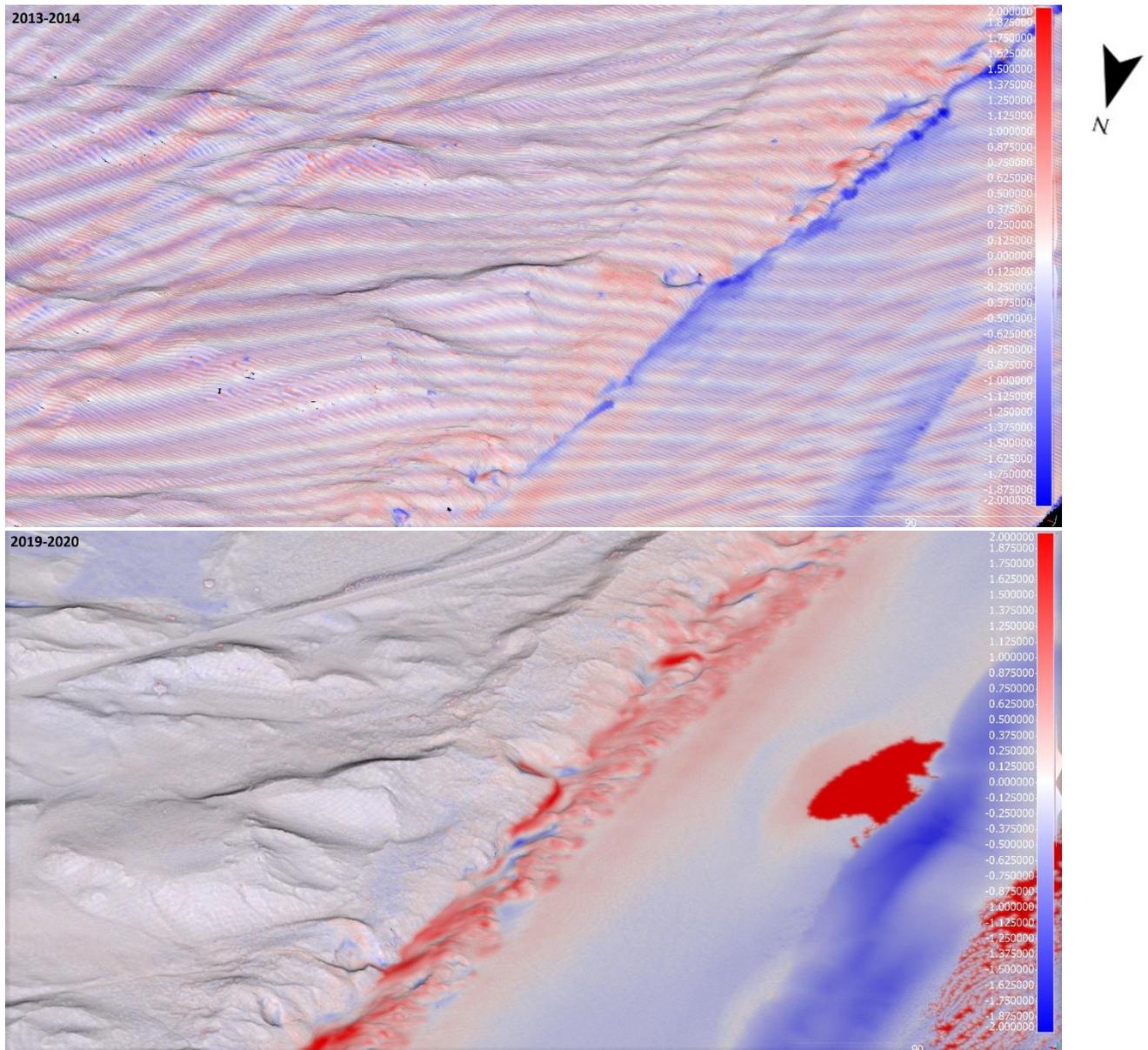
Figure 6.21: Comparison between the two point clouds 2013-2014 and 2019-2020. Before the development of the Hondsbossche dunes erosion occurs in front of the dunes (blue). However, after the development small embryonal dunes appear(red). Change is displayed between -2 and +2 meters. The data from 2013-2014 are of lesser quality, this results in stripes in the scan direction.

6.2.3 Sub-conclusion long-term visualizations

Visualizing changes in coastal landscapes with point clouds over a longer period of time is done in two ways in this research. First of all visualizations of the elevation are made and secondly two datasets are compared by calculating the distance between the clouds. Large scale and small-scale visualization are made. With this material shown, some conclusions can be drawn:

- On a small-scale point clouds and raster visualizations do not differ so much. Raster is, when using a small grid size of for example 0,5, sufficient as well. Comparing point clouds (or raster) between different years can give quick and global insights in deposition and erosion areas. Working with point clouds becomes especially useful when looking at a large scale. As seen in all visualizations above, point clouds has a very high resolution on a large scale.
- With help of a side perspective in 3D, colour range adaption and shadow effects, point cloud visualization is a powerful tool to visualize large scale changes in elevation, erosion and deposition in a dynamic coastal dune area.

- Point cloud visualization is very appropriate to make time (laps) series of coastal geneses on a large scale, interesting for coast morphology research. In addition, the high resolution in point cloud visualization could be very interesting as communication tool for managers in the field. The great details fit better with their experience outside.
- Working with point clouds is more straight forward than with raster because no extra computational steps are necessary to make the visualizations. However, it is of great importance to have enough hard- and software power to process the point cloud data (16GB of working memory is occasionally on the tight side). In addition, calculating with point clouds is even more laborious, because points measured by a LiDAR scanner are never scanned exact on the same place.

6.3 Temporal visualization of Noordwijk

Short term temporal changes in Noordwijk are visualized with point cloud datasets measured during the storm Ciara (9 February 2020 till 12 February 2020). The data is not measured from a view from above as with the aerial measurement from the Hondsbossche dunes. This results in more areas with 'no data' because the scanner cannot look behind higher objects. Though aerial measurements also suffer from this to a smaller extent.

In some places the dunes are relatively high which results in the scanner not seeing the edge of the dune on the beach side and thus show no data. To solve this problem, a manual scan of this area is made every month with a lidar scanner (Figure 6.22). However, the temporal resolution of months is lower than is used for this research where days and consecutive hours are visualized. Therefore, these monthly measurements are not used and it is accepted that holes in the data in front of the dunes and building are visible. For the temporal visualization two temporal resolutions were chosen, days and hours (chapter 4.3.4).

Figure 6.22: Areas that are not measurable for the LiDAR scanner on Hotel Huis Kijk ter Duin are measured manually. (photo of Sander Vos with LiDAR scanner from the TuDelft)

To give a better overview of the research area and period in time the full research area is visualized before the storm and after the storm (Figure 6.23, Appendix VIII). From this distance changes in elevation are not very well visible. However, when looking closer next to the Breakers Beach pavilion a small change is visible. Note the Breaker Beach building does stand on stilts, these are not visible due to a sand banquet specially constructed in front of the building. When comparing these two datasets with the cloud-to-cloud distance tool in CloudCompare (explained in section 4.3.2), the changes close to the

beach building are better visible (Figure 6.24). On the north side up to half a metre of sediment is deposited in front of the dunes (in red). When looking a bit to the south at the next beach entrance, deposition is also visible. However, this deposition does not look natural and is probably made by shovels. Sand that is deposited in front of the entrances of beach buildings through aeolian sand transport during the storm is pushed back to the beach. In the next section there will be zoomed in on the area next to the Breakers beach pavilion where also natural sediment transport took place.
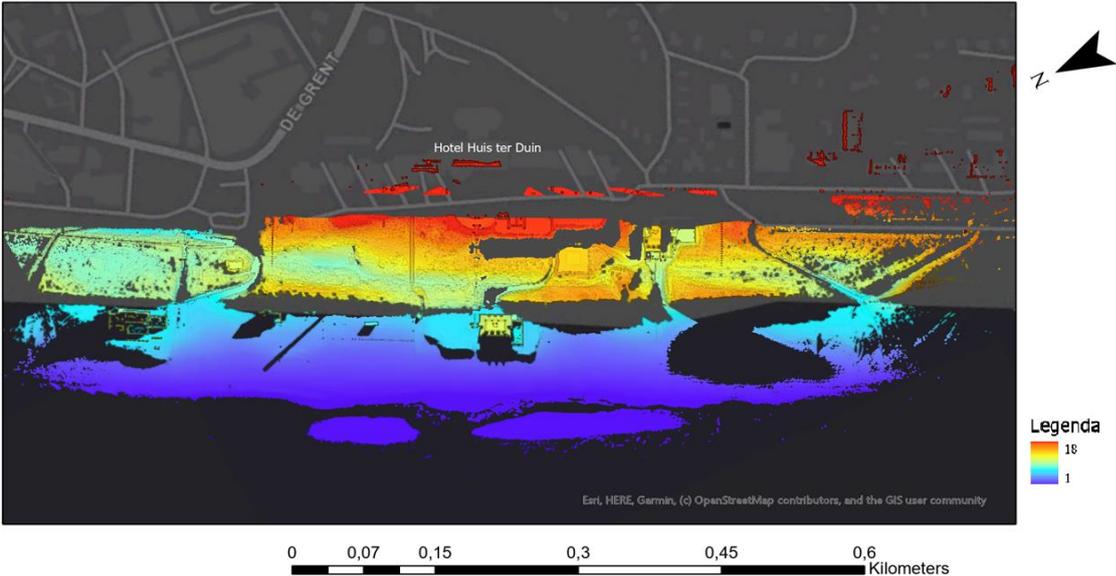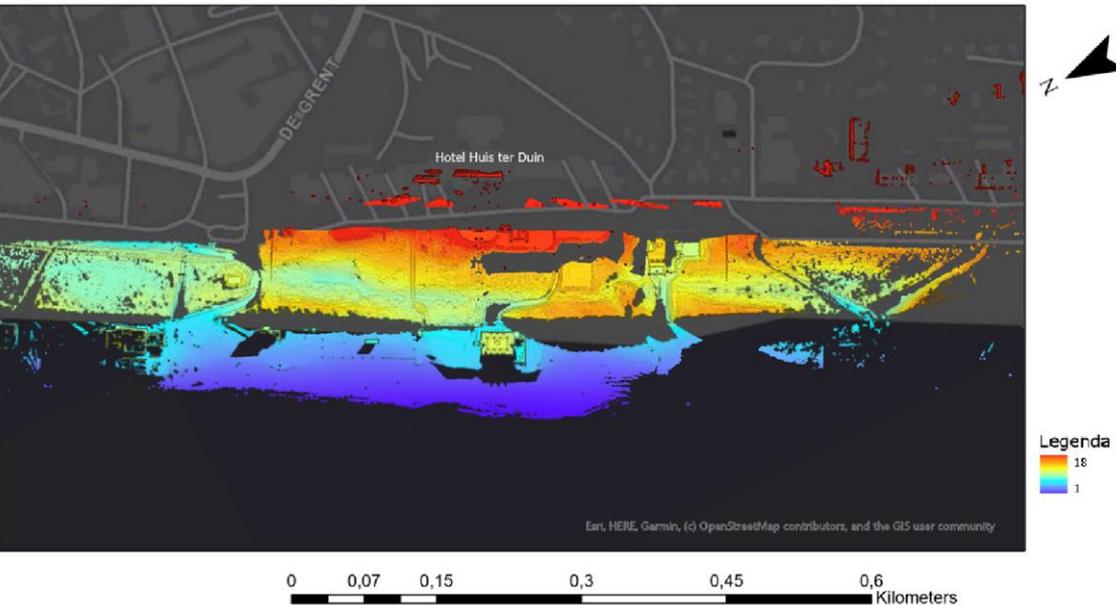
Figure 6.23: Visualization of point cloud measured by the LiDAR scanner from CoastScan. The whole research area is visible before (upper image) and after (lower image) the storm. Elevation is displayed between 1 and 18 meters.
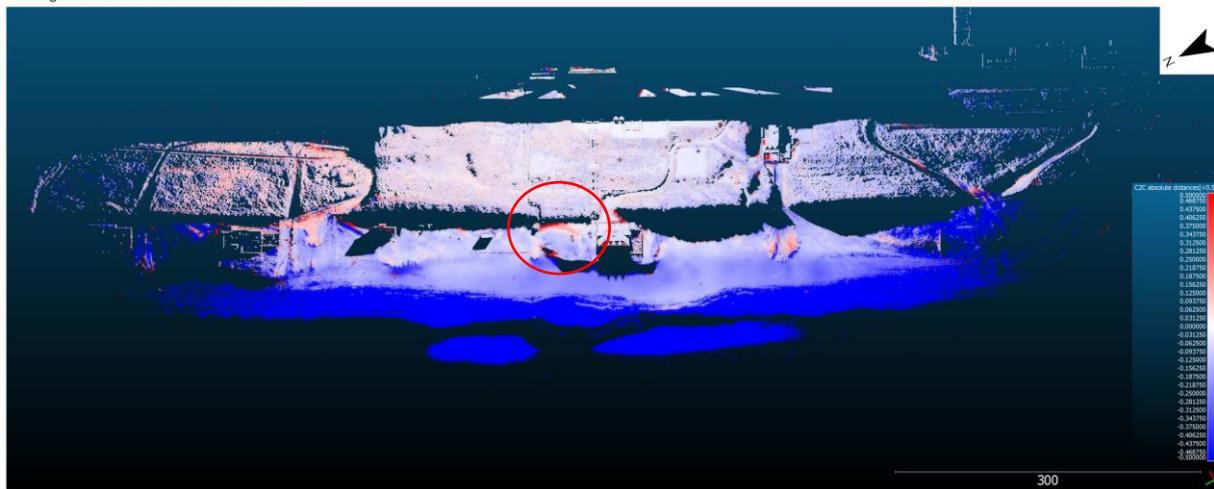
Figure 6.24: Comparison of the point cloud dataset before the storm and after the storm. In the red circle is natural deposition of sediment visible. The colour scale is from -0,5 meter (blue) till +0,5 meter(red).

Zooming in north of the Breakers beach pavilion small changes in elevation can be better visualized. West of the Breakers beach pavilion is no data visible, here the beach is fairly sloping, on the north side of the beach building a man-made plateau is constructed for bathers in the summer season (Figure 6.25). Sediment transport at the time of storm Ciara is visualized during low tide from 9th till the 12th of February (appendix IX, Figure 6.26). The colour scale is adjusted to +5,0 and +6,5 meter, changing the colour scale will make small changes better visible. In addition, the shadow effects are used again to improve the depth perception. However, the form that arises from the sediment is relatively smooth. The shadow effect has a better effect on forms that have sharper edges. Through time sediment deposits in the form of a sand tongue in this area (pers. comm. Sander Vos). Loose sediment is blown from the beach and settled in this form which is probably influenced by the beach building (pers. comm. Martien Witte). The main wind direction during storm Ciara was South West. On the north side of the beach building some areas were in the shelter of the wind. Here sediment could settle. After the storm, sediment that is deposited close to the entrance of the beach building was cleared. On the 12th of February tracks of large equipment for clearing the entrance are visible (Figure 6.26). When comparing these datasets through time it becomes visible that the sand tongue really forms between low tide on 11th of February between 00:00 and 13:00 (Figure 6.27).

Figure 6.25: On the right beach building Breakers, the beach in front is fairly sloping, next to the beach building is it relatively flat for the tourists in the summer.

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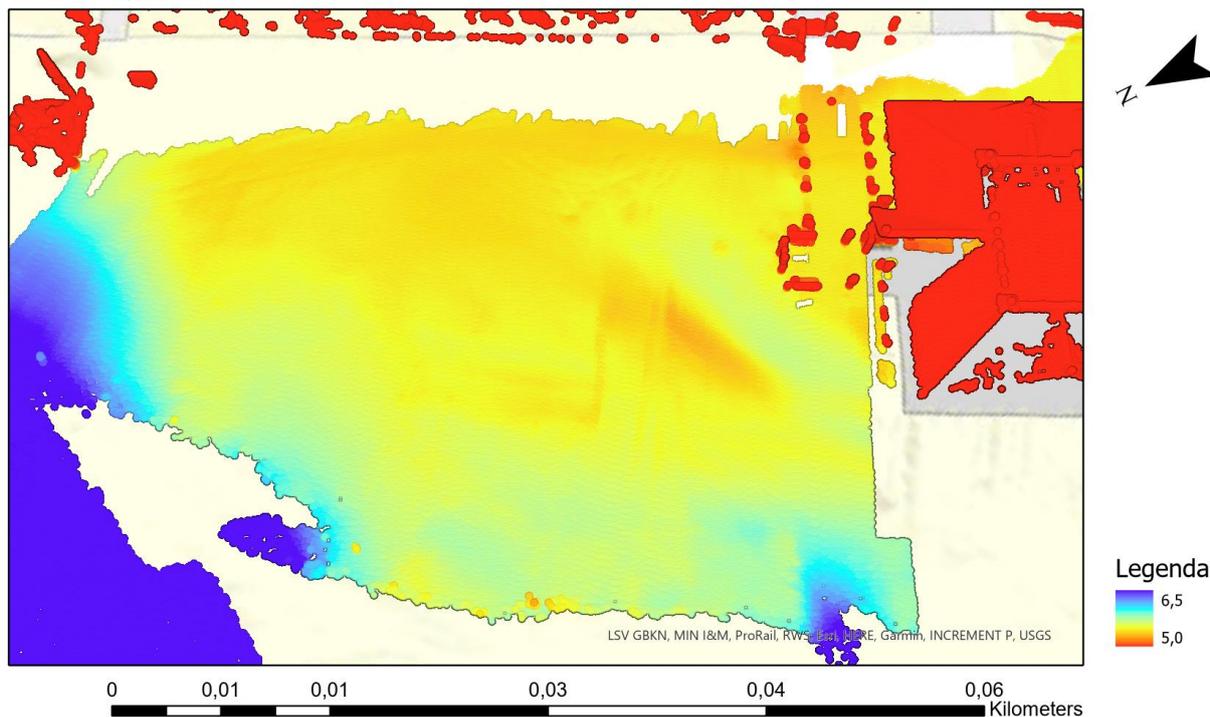
09-02-2020, 13:00

12-02-2020, 13:00
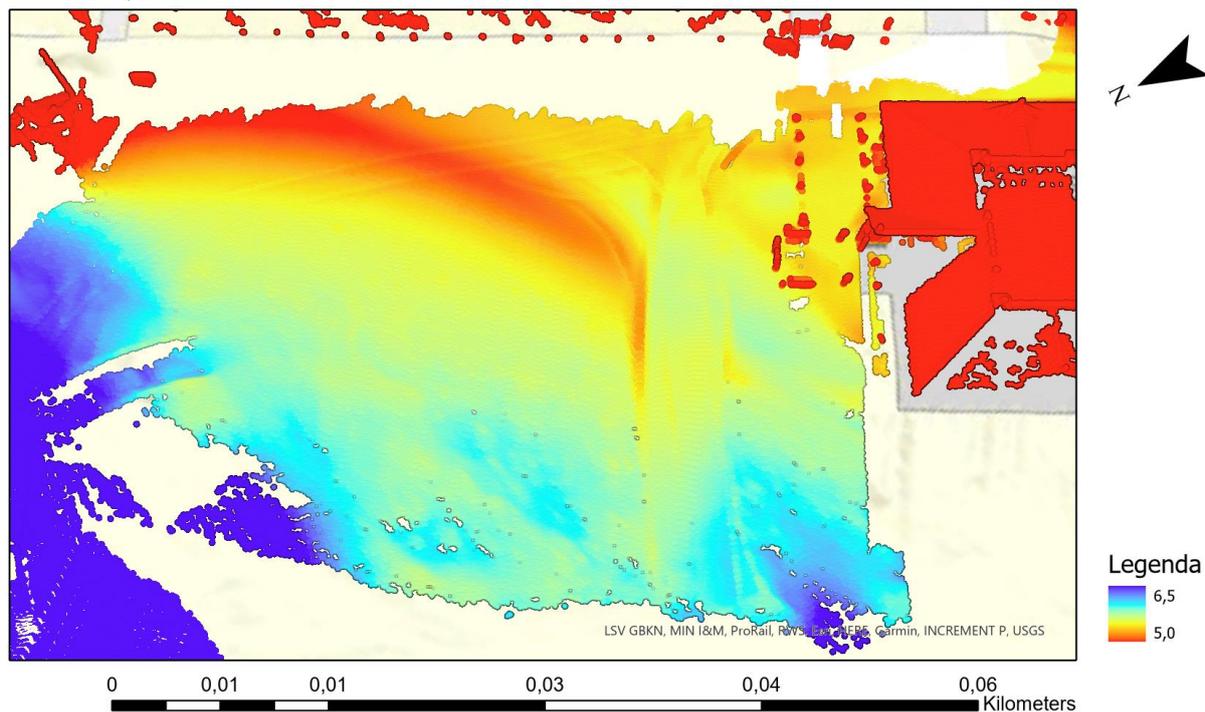
Figure 6.26: Zoomed in point cloud visualisation of the elevation north of the Breakers beach building. Sand is deposited in the form of a sand tongue, loose sediment from the beach is transported through wind and deposited behind the beach building out of the wind. After the storm a shovel moved deposited sand in front of the beach building whereby the sand tongue is deformed. Elevation is displayed between 5 and 6,5 meters.
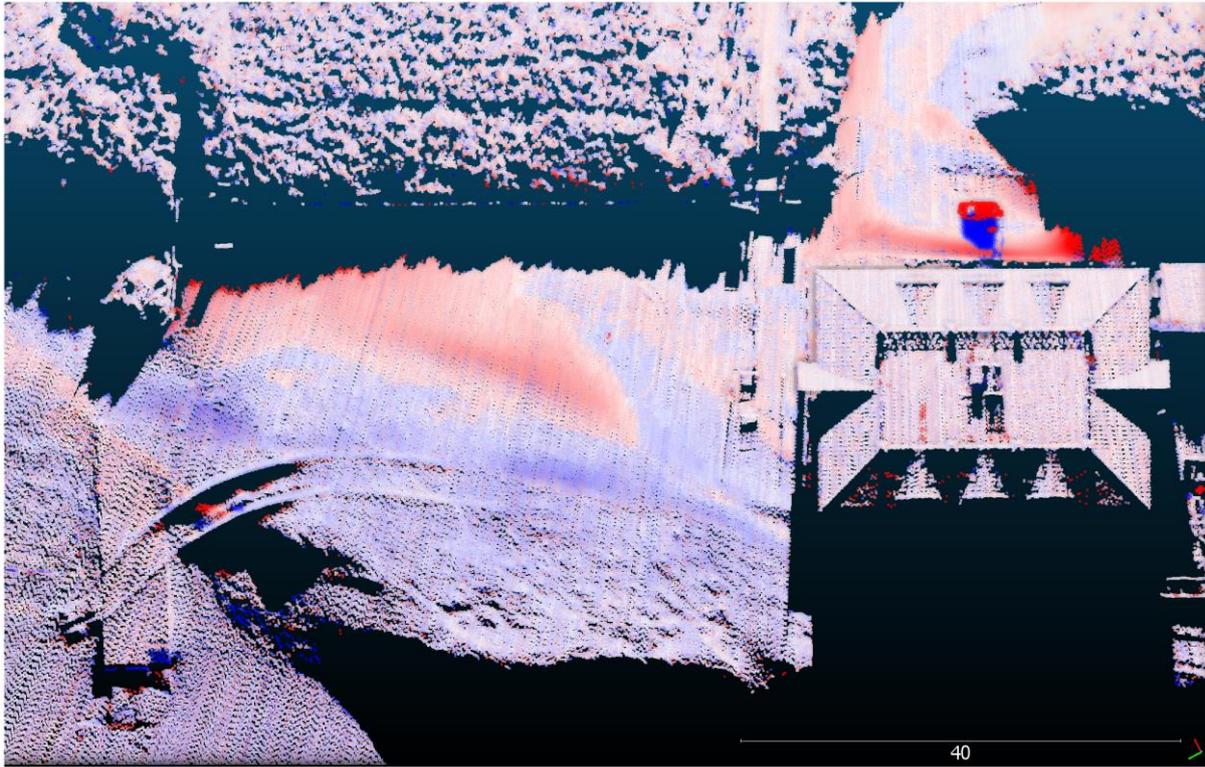
Figure 6.27: The sand tongue really forms between low tide on 11th of February between 00:00 and 13:00. (point cloud in cloud compare image). Change in sediment is between -2 meter and +2 meter.

When visualizing the coast per hour other details become visible. The next visualizations are point clouds measured hourly (Appendix X). First 3 consecutive hours before the storm are visualized and hereafter 3 hours around the time that the storm was at its heaviest (Figure 6.28). Wind speeds of around 120 km per hour have been measured in the coastal provinces during this time. Point cloud datasets with a high temporal resolution are used to visualize changes in elevation that convert quickly. In the visualizations before the storm not much changes can be detected. The north side of the Breaker beach building is visualized and the beach in front of the beach building. However, when visualizing this area during high wind speeds small ripples along the beach can be detected (Figure 6.29). When comparing these hourly datasets it becomes visible that these ripples move slowly from south to north (Figure 6.29). These ripples are only visible in a small period of time, on the 8th of February they are not visible yet and on the 9th of February around 23:00 they are vanished again. These ripples are apparent in the point cloud visualization of different moments (11 AM and 1 PM February 9th) as in the cloud compare visualization between these periods.
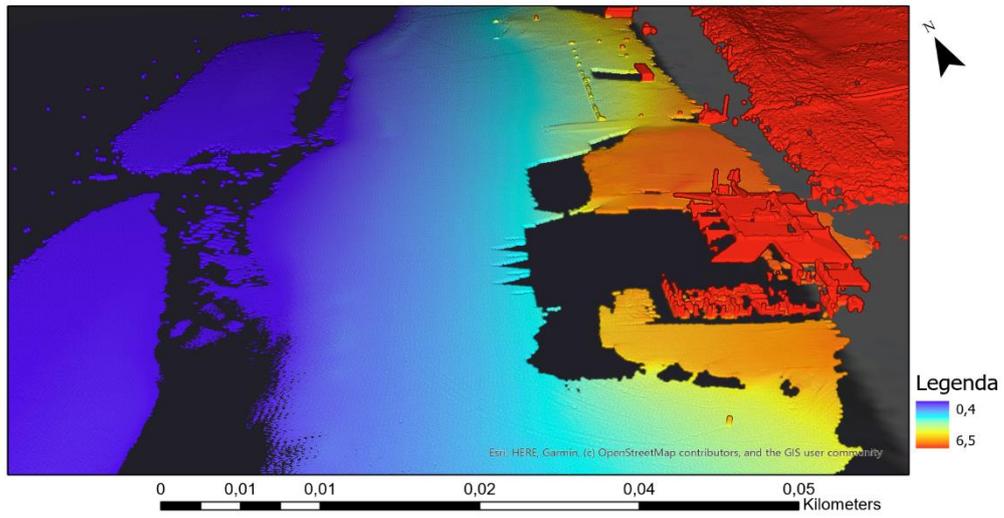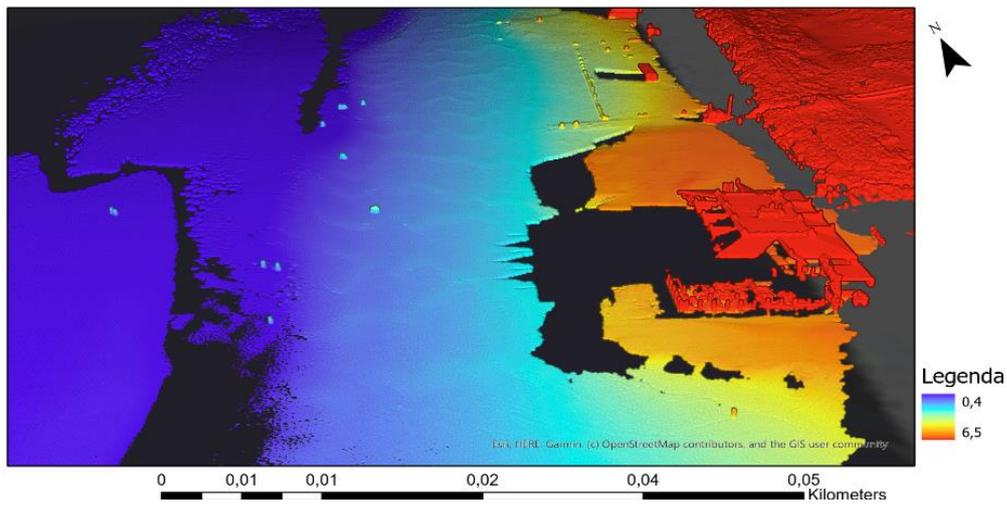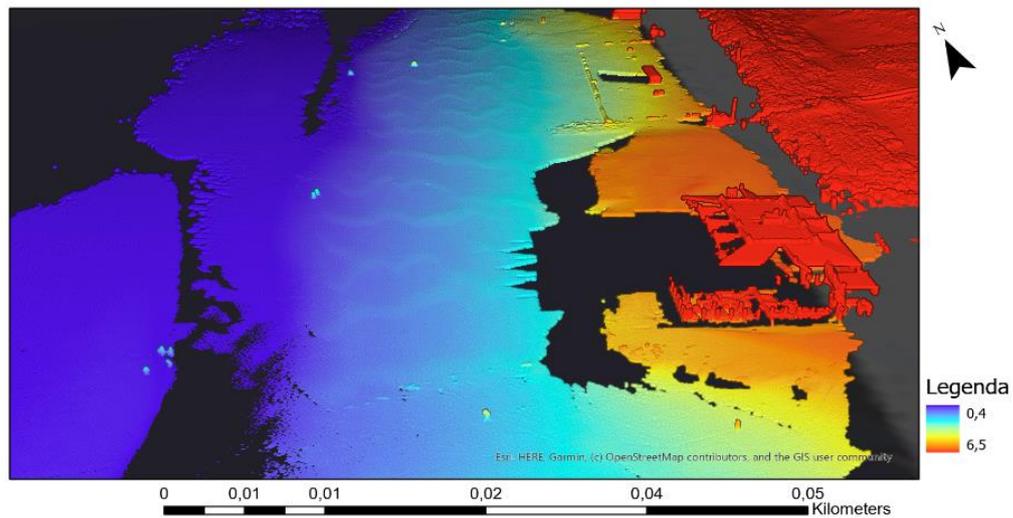
Figure 6.28: Upper point cloud visualization displays the breaker beach building and the beach in front of it on the 8th of February. A relatively smooth beach surface is visible. The middle and lower visualizations show this area on the 9th of February, here beach ripples occur. Elevation is displayed between 0,4 and 6,5 meter.

08-02-2020 between 20:00 and 21:00

Between 08-02-2020 21:00 and 09-02-2020 11:00

09-02-2020 between 12:00 and 13:00

Figure 6.29: The upper point cloud visualization shows consecutive hours on the 8th of February, the middle visualization the difference between the 8th and 9th of February and the lower image two consecutive hours on the 9th of February. In this last image moving sand ripples are visible. Sediment is displayed between -2 and +2 meters change.

6.3.1 Sub-conclusion Short-term visualizations

Visualizing changes in coastal landscapes with point clouds over a shorter period of time is also done in two ways. First of all, visualizations of the elevation were made and secondly two datasets were compared by calculating the distance between the clouds the same as with the visualizations of a longer period of time. Large scale and small-scale visualizations were made. With this material showed, we can draw some conclusions:

- Point cloud visualization is interesting in very small time periods (hours), to show changes in sand patterns during dynamic weather conditions. This opens perspectives to research short term coastal geneses as a part of long-term coast morphology. Activities on the beach and other small changes could also be visualized very well.

- With short term point cloud analysis human interference in sand deposition and erosion can also be made visible. However, for interpretation it is important to have complementary observance by for example photo or video data.

- Again, point cloud visualization is most powerful in large scale cartography because of its high-resolution possibilities. This is ideal for visualizing morphology changes in a short period of time because changes are small on a short time scale.

- However, when calculating with point clouds on this scale and such high resolution in time it is very important that the deviation between the comparing point clouds is minimal. Because of the short period of time, changes in morphology are often small. A deviation between the point clouds that are compared can give a distorted visualization which results in biased small details and problematic interpretations.

6.4 Analysis and application with Waterboard HHNK

Using point clouds for visualizations could have an added value in the future for organizations like HHNK. The high resolution in 2.5D on a large scale provides more insights in small, detailed morphology than the raster data which is used nowadays. It can be a strong new means of communication for the managers outside. Their experiences are better suited to the high resolution of the point cloud visualizations compared to the lower resolution of raster data. In addition, point cloud data is a very interesting tool to use for research of dynamic detailed morphology and thus connecting research on long- and short-term changes in coastal morphology. For example, for research on sediment transport around vegetation or reet screens, or sand transport around beach buildings. It can also be used for research in the dunes where is looked at the development of beach paraboles and 'kerven' (intrusions from the sea).

However, the immense amount of data which will become available when using LiDAR data for research and maintenance of the coastal areas will be a new challenge. The data have to be processed properly. In order to use this data for the proposed purposes, careful consideration will have to be given to storage space and a standardized method of processing. In addition, there are also investments involved. A LiDAR scanner is relatively expensive and has some conditions of use which need to be thought of. For example, when using a LiDAR scanner permanently e.g. standing in a place for a longer period of time the LiDAR scanner needs to have good view of the proposed research area, most of the time the LiDAR scanner needs to be elevated e.g. relatively high above the ground to prevent objects blocking the view.

7. Discussion and Future research

This chapter discusses different challenges that were encountered during this research. Hereby, problems that occurred during the process and plans that were conceived in the beginning but did not happen will be elaborated on. Lastly, some suggestions for new research will be provided.

7.1 Discussion

First and foremost, the quality of the datasets is of significant important when visualizing detailed morphology. Small errors in the data can give large distortions in the visualizations when looking on a large scale. Especially when comparing point clouds to each other, a deviation in the x, y or z direction could give a large impact on the output, this should therefore be done with caution. The datasets of Rijkswaterstaat were quality checked before publishing, it was therefore assumed that the quality of these datasets was good. What stood out was that the datasets from 2013-2016 are of less quality than the datasets from 2017-2020, the point density became higher through time.

The data from Noordwijk came directly from the laser scanner and no quality control was done. Eventually, through transformations which were executed together with Sander Vos the deviation between the point clouds in the z direction was set on 3cm, which is a good result. However, during this process some difficulties occurred.

For this research hourly data was visualized during a storm. Storm often goes hand in hand with heavy rainfall. The LiDAR scanner had some difficulties scanning during heavy rainfall. This can cause less measured points in important locations. For the transformations, three buildings are used. These are hard objects which do not move. In this way the point cloud can be accurately referenced to the cm. However, the datasets which were originally intended to be used were measured during heavy rainfall. Less points were measured on one of the reference buildings during this time, the matrix used for the transformation therefore could not perform the transformation properly. Correcting this in the transformation matrix is possible, however, will take quite some time. It was therefore chosen to pick datasets measured during dry periods.

Secondly, there were some issues with CloudCompare and ArcGIS pro. First of all, during the process of executing the cloud-to-cloud distance tool in CloudCompare it is possible to choose a local model. Point clouds used in the cloud-to-cloud calculation need to be dense enough. Only then, approximating the distance from the cloud that is compared to the underlying surface, which is represented by the reference cloud, is acceptable. When the reference cloud is not dense enough, the nearest neighbor distance could sometimes not be precise enough. In this case it is important to use a local model which makes the calculation more reliable. The point clouds used in this research are relatively dense, however, some are denser than others. It is tried to use a local model, however. The hardware used for this program was not capable to execute the cloud to cloud and crashed several times when trying.

The communication between ArcGIS Pro and CloudCompare turned out to be problematic. The calculations executed in CloudCompare could not be visualized in ArcGIS Pro. ArcGIS Pro has a standard format of the attributes which are possible to choose from in the program. The Cloud 2 Cloud safes in another attribute which was not visible in ArcGIS Pro. To overcome this problem the value of the Cloud 2 Cloud was saved as the z value. In this way it was possible to visualize the layer in ArcGIS Pro. However, this image still did not look the same as the original visualization in CloudCompare. When opening the data whereby the Cloud 2 Cloud value is saved as z value in CloudCompare again, the visualization did not seem right as well. This means that the error occurs after saving the value as z value. The easiest solution is probably to make it possible to use larger datasets in ArcGIS Pro so

calculation can be performed within ArcGIS Pro. Another option is using a different point cloud viewer with good visualization techniques as well. Potree is a free open-source WebGL based point cloud renderer which can visualize large point clouds. With this software it is possible to open the Cloud to Cloud value (see figure).
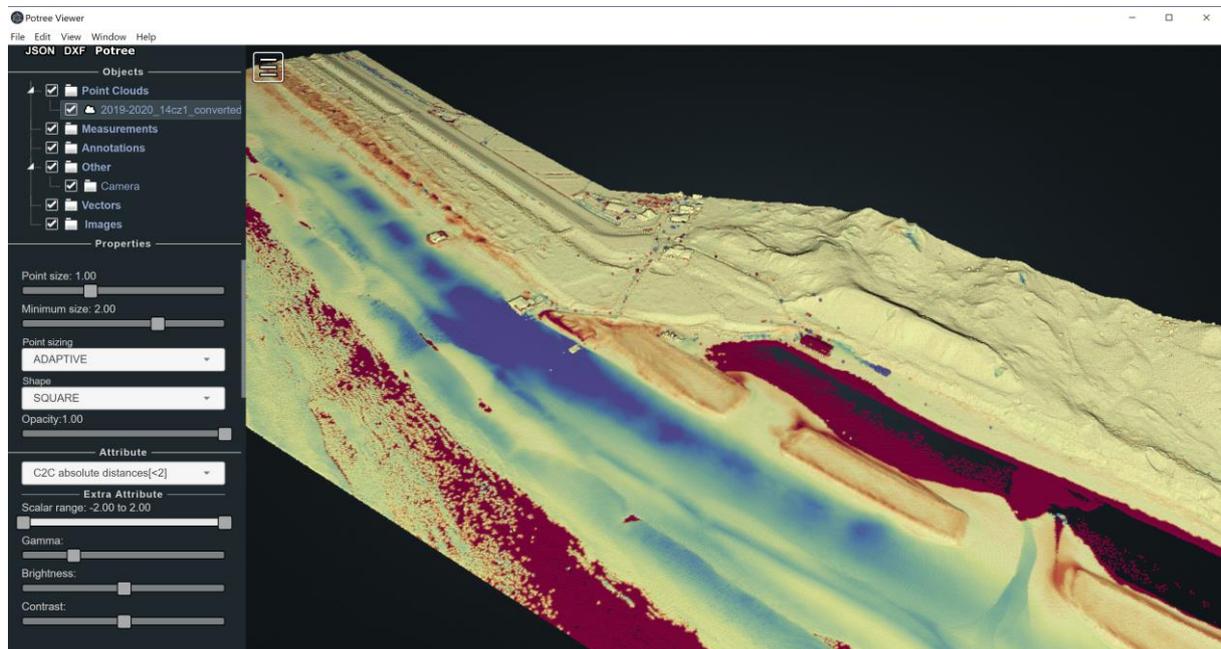
In addition, various types of interpolation techniques exist whereby some are more useful for interpolating elevation than others. In this research no attention was paid to these different types of interpolation. However, it is possible to create a interpolation technique that is especially made to enhance the resolution for specific problems (ver. Comm. Sander Vos). In addition, another problem that could occur while using raster data is that when using the same interpolation method for point cloud data, but changing the origin of the raster, the visualization could change. For example, when the origin moves a raster cell to the left or right, the interpolation is calculated slightly differently, this could form a different visualization. This has not been further investigated in this study either because of the limited time but could be interesting for future research.

Lastly, around mid-December ArcGIS Pro released their new version ArcGIS Pro version 2.7. The old version was automatically updated. Around this period some problems occurred with the visualizations used for this research. The shadow effect Eye Dome Lighting which can be found in almost all visualizations did not work anymore in the layout view. This is the view in ArcGIS Pro where the visualization can be made with a north arow, legend, and scale bar. First the settings were checked for changes, but nothing could be found. Hereafter Esri was contacted. They evaluated the problem and roughly 2 months later it became clear that the exported layout of the 3D Scene using the eye-dome lighting effect displays incorrect results (https://support.esri.com/en/bugs/nimbus/QlVHLTAwMDEz-NTYwOQ==). This bug will be fixed in the next ArcGIS Pro version 2.8 which will be available in the second quarter of 2021. To overcome this problem version 2.7 was deïnstalled and version 2.6 used for this research.

7.2 Future research

During the realisation of this research several new questions occurred. For HHNK calculating the volume of eroded or deposited sediment is very interesting. At the moment this calculation is based on raster data. The point cloud visualizations are higher in resolution and closer to reality. It can be interesting to use point clouds for a more precisely modelling of the volume of sediment transport. In addition, with the high-resolution visualizations of point clouds new questions are rising:

- When and how will sand be retained by plants or reed screens, or simply deposited or eroded on the beach?
- How does sand flows form along objects (like buildings)?

And it is not only interesting to use for the beach but also for the development in dunes.

- How do notches and parabolas develop?

When using this kind of data in an organisation like HHNK, other aspects like costs of measuring equipment, storage of huge amounts of data and analysing time needs to be kept in mind as well. It may be therefore also useful to look at costs and benefits for the use of point clouds. In addition, LiDAR scanners are relatively expensive. Other cheaper measuring techniques could be researched for their functionality as well. For example, photogrammetry. This is another option whereby temporal changes in elevation can be measured and visualized in more dimensions as well. Furthermore, loading, processing, storing and validating of raw data from research can be an important obstacle as well for HHNK. It is therefore important to think about these issues in the future.

When researching the morphology in a dynamic coastal landscape, there is a need at the moment to look more careful to the following aspects (verb.comm. Petra Goessen):

- Measuring more often in the same place
- Measuring in a similar place
- Measuring in places that are not comparable
- Measuring during other circumstances on the same place

This means a lot of measuring. LiDAR scanners are very well capable of scanning over a longer period of time in a high temporal resolution. In addition, a LiDAR scanner need to scan from higher ground to view a large area and over large objects. Otherwise shadows with no data will be present.

8. Conclusion

In par. 1.2.1. of this research several sub-questions were made to eventually answer the main research question. With the information from the theoretical framework the first four questions can be answered. Hereafter, the last three sub-questions can be answered with the information obtained in the results of this research.

8.1 *What are the significant differences between point cloud visualization and raster visualization?*

The main difference between point cloud visualizations and raster visualizations is the difference in resolution. Point cloud visualizations have a high resolution because of the millions of points the point cloud consists of. Raster visualizations in the contrary have a much lower resolution because of the interpolation to raster cells of the same size. This interpolation of point clouds to raster cells makes the visualization less close to reality. Point cloud visualizations display incomplete information, they are not able to fill in gaps where there is a lack of measurements taken. Spaces without measurements show empty on the map, this will ensure that no incorrect conclusions can be drawn during analysis.

On the contrary in raster visualization the areas with no data are filled in when using interpolation. Due to the interpolation the average of points in one raster cell is used to create a map. In areas where there is no data the closest points are used and in area where there are more points the average of these points are used. This can give a distorted visualization and important information could be lost or wrongly interpreted.

There is however one drawback of using point clouds for visualizations, the volume of the datasets. These are often very large and therefore hard to work with. However, there are techniques available to ease this difficulty. For example, thinning methods can be used whereby not all points are shown at the same time, in this way the soft- and hard-ware can better cope with the large files. However, this will not solve the problem of large storage space needed for point cloud data because there always need to be decided which point will be showed and which not and thus the complete point cloud dataset stored. Other tactics involve looking at smaller areas which will decrease the file size. With raster visualizations the size of the files is less of a problem. These datasets become larger when enlarging the resolution. However, they will never be as large as the file size of point clouds.

Lastly, there are for both visualization methods, point cloud and raster, techniques to visualize elevation in a clearer way. For example, using shadow techniques which enhance depth perception. For point clouds 'Eye Dome Lightning' can be used and for raster 'Hill shading' is available. The Eye Dome Lightning technique calculates the shadow effect from different perspectives when zooming in and out and looking from a different angle. On the contrary for the Hill shading of raster maps the shadow effect is calculated from one perspective. Furthermore, for both point clouds and raster, colour techniques are available.

8.2 What is the added value of point cloud-based visualization techniques compared to other visualization techniques?

In the previous section some advantages of using point clouds are already mentioned. Point cloud data are denser and have a higher level of detail (high resolution) than other 3D visualization techniques. Often, point cloud data have a higher density than 1 point/m2. This allows precise and accurate data

usage for visualization and analysis. This makes it possible to visualize certain phenomena that cannot be analysed on such scale by other techniques such as with raster or mesh data. In addition, 'no data' is not shown in the visualization. This together with the high resolution makes the point cloud close to reality.

Another added value for using point clouds for visualization is the fast rendering and transformations that are possible. This will make it easier to provide visual interaction with the dataset. For example, a visibility analysis can easily be performed whereby thinning techniques can be used. In this way, dynamic coastal landscapes can be easily (re)viewed on different scales. In addition, the process of surface generation can be skipped. The point cloud data can be directly used to perform (visibility) analysis, this will shorten the analysis period.

Lastly, massive 3D point cloud datasets can be updated, integrated and accessed with much less effort than is required for the other 3D models.

8.3 What are the limitations of point cloud-based visualization techniques?

The first disadvantage has to do with the point cloud data itself, in many cases point cloud data are noisy, sparse and unorganised. The surface shape of the point cloud can be arbitrary, this can make it hard(er) to create a meaningful visualization. In addition, varying angular and linear rates of the laser scanner can make the sampling density of the points uneven. Moreover, the foreground of the laser scan is often entangled with the background due to limitations of the 3D sensors. Still an efficient point cloud model can be realised if "all the necessary information can be found and easily conveyed without the need for redundant tasks" (Poux et al, 2016).

Another issue related to using point cloud data for visualizing, is the huge amount of data. This will result in a need for high memory consumption and large storage space. The workload for the soft- and hard-ware often are very high. Point clouds are therefore sometimes hard to work with. This will result in a limited possibility for operations and calculations with these datasets.

Lastly, point clouds do not give a continuous or filled visual representation. Areas where there is no data are visualized as empty spaces. For some this can be visually not so attractive, on the other side it prevents that data will be wrongly interpreted easy.

8.4 Which point cloud-based techniques are useful to visualize changes in detailed morphology?

To visualize changes in detailed morphology temporal data are used. Temporal point cloud data can be visualized in several ways. For example, the point cloud can be visualized in an animation of several consecutive years or days. In addition, static maps can be made and be put one after the other. In addition, it is possible to look at temporal point cloud data via visual interaction. In ArcGIS Pro and CloudCompare layers can be turned on and off and consecutive years or days can be displayed in this way.

When visualizing detailed morphology, phenomena are visualized on a large scale. It is therefore sometimes hard to visualize the depth perception. To enhance this, techniques like 'Eye dome lightning' can be used. With this technique shadow effects are created, making the elevation and thereby the detailed morphology, better visible. In addition, it is possible to exaggerate the elevation using different colour scales. In this way, small details will become better visible. Furthermore, a profile can also be created when it is necessary to visualize the elevation from an indirect view.

8.5 What is the best visualization method to display long-term changes in sand patterns along the Hondsbossche dunes while using point cloud data?

Visualizing changes in coastal landscapes with point clouds over a longer period of time only become really interesting when looking on a large scale. Comparing point clouds between different years however can give quick and global insights in deposition and erosion areas. This can give hints to which area's it is interesting to zoom in. A side perspective in 2.5D, colour range adaption and the use of shadow effects in a point cloud visualization are powerful tools to visualize detailed changes in elevation, erosion and deposition in dynamic coastal dune areas. The high level of detail, visible in point cloud visualizations is very appropriate for temporal visualizations of coastal geneses which are interesting for coastal research. However, when calculating with the point clouds one should take caution and take in mind that there is always a deviation when comparing point clouds because the LiDAR scanner never measures exactly on the same place.

8.6 What is the best visualization method to display short-term changes of sand patterns along the coast of Noordwijk while using point cloud data?

Point cloud visualizations are interesting in very small time periods (hours), to show changes in sand patterns during dynamic weather conditions. This opens perspectives to research short term coastal geneses as a part of long-term coast morphology. Using the point clouds will reduce the amount of processing time. Visualizing such short time periods, can give insights in fast changes through time. For example, human interference in sand deposition and erosion will be apparent. However, for the interpretation of fast changing phenomena complementary observance (photo, video) is probably important. Concise, point cloud visualizations are most powerful in large scale utilization because of its high-resolution possibilities. This is ideal for visualizing morphology in a short period of time. However, when calculating with point clouds on this large scale and such high resolution in time it is very important that the deviation between the point clouds is minimal.

8.7 What is the added value of detailed point cloud visualization for policymaking and research in the field of coastal management?

Using visualisations can be of added value when making policy or for research of the coast. It can be a helpful tool for explanation of the policy and for creating more understanding of the technical basis. Data obtained for research is easier to understand and the overview will be more compact when visualizing. It could help to discover unexpected patterns and confirm expected patterns. In addition, visualizations are often much more informative and easier to understand than numerical summaries of datasets. Furthermore, visual representations can give more insight into seeing relationships between items. Visualizations are therefore good to use for communication purposes. In addition, visualizations in high resolution are very interesting for the maintenance of coastal areas. It can help to show where something has changed and to find out what could be the cause of this. This information could be important for maintaining the coastal safety.

Visualizations with point clouds are therefore an interesting basis for long- and short-term policy development and research as establishment of (short-term) changes because of its high resolution. Especially in dynamic areas where morphology changes over a short period occur. For example, to follow sediment displacement in a sand drift pit could be very interesting to get information for long term policy development and maintenance of the area. The high resolution of point clouds is capable to visualize the

smallest changes on cm scale which can be easily linked to the experiences and observations of managers in the field.

An advantage of visualizing with point clouds is that there is not much processing time involved. In principle it is possible to visualize the measurements straight away. However, as said before, for the highest resolution and the closest visualization to reality, transformations should be done, and the quality of the measurements checked. The latter becomes even more important when the sediment transport must be quantified. Small displacements could give large errors in the output visualization of erosion and deposition. On the research side, coupling long term and short-term investigations with point cloud techniques can give new starting points for research on coastal dynamics. For example, long term effects of storms, starting with small scale changes in coast morphology.

There is a good amount of visualization techniques available for visualizing point clouds of dynamic coastal systems. However, the most used program, ArcGIS Pro has difficulties to handle large point cloud datasets. There are some techniques, like point thinning, which are available to overcome this problem. In addition, calculating with point clouds in ArcGIS Pro is not possible because this functionality has not been implemented yet. For these calculations, another program is needed. In this research CloudCompare is used. However, visualization techniques in CloudCompare are not optimal. A downside of using both these programs is the communication between the two. The connection between ArcGIS Pro and CloudCompare need to be improved to get the good of both because calculations done in CloudCompare are not easily visualized in ArcGIS Pro as discussed in the chapter 7.

With all the sub-questions answered the main question can be answered

8.8 To conclude

First of all, the application of point cloud-based techniques is useful for coastal research on a large scale. As mentioned in the discussion when researching the (detailed) morphology in dynamic coastal landscapes there is a need to look more careful to a couple of aspects:
• Measuring more often in the same place
• Measuring in a similar but not the same place
• Measuring in places that are not comparable
• Measuring during different circumstances on the same place

Using LiDAR for these measurements is a convenient option. LiDAR scanners are very well capable of scanning in high temporal resolution over a longer period of time. In addition, visualizing the point clouds could give more insight on small details on a large scale because of the high resolution.

The application of point cloud-based techniques has the most advantages when monitoring changes of sand patterns on a short time period (days, months). On a short time period changes are relatively small and with the visualization techniques available for point clouds, the elevation can be more clearly visualized. Techniques like shadow effects or using different colour scales, can help extract information in detailed morphology. In addition, when looking at a short term, it is possible to have a high volume of data in a limited period. It is possible to visualize point cloud datasets without a lot of effort for preprocessing. However, there are some points of attention:
• Hard- and software have to be able to cope with large datasets.
• Analysing the quality of the data is necessary (e.g. coordinate system, noise).
• Good and reliable data storage and encoding are of utmost importance.

Long-term changes of sand patterns along the Dutch coast can be displayed with point clouds as well. Especially when zooming in on interesting locations, the point cloud has an added value compared to raster visualizations. Thanks to the high resolution of the point cloud and the prevention of information loss due to interpolation. In addition, the visualization techniques for shadow effects like Eye Dome Lighting for point clouds are more advanced than the Hill shading for raster data. Visualizing the changes in the coastal environment in 2.5D are therefore more clearly with point clouds as with raster data. In addition, visualizing in 2.5D gives an added value on visualizing in 2D because in a 3D surrounding, different perspectives of the data can be visualized which results in a better understanding of the area and the ongoing processes.

The detailed information that can be obtained through point clouds is interesting for policy makers, in particular the previously discussed research can be used for policy development. In addition, point cloud visualizations of the elevation are very interesting for field-management. Especially smaller changes through time on a large scale can be used as a check on field management. Minor interventions such as reet fences, are clearly visible in point cloud visualizations. For coastal management it is interesting to see how much these reet fences contribute to capturing sediment. This will ultimately support the coastal safety.

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