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Exploring the potential of explorative point clouds in floodplain maintenance

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MSc thesis in Geomatics

Exploring the potential of explorative point clouds in floodplain maintenance

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Disclaimer

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Abstract

Water management is an integral part of Dutch history, driven by the continuous need to reduce flood risk. Because a large area of the country is located below Normaal Amsterdams Peil (NAP), there is an ongoing challenge to safely discharge all the water to the sea. Therefore, flood safety policy has become crucial to protect the Netherlands from natural hazards. An essential part of this strategy involves the Waardegedreven Onderhoudscontract Uiterwaarden (WOCU) Rijntakken project, which is responsible for managing the floodplains adjacent to the Rijntakken within the Netherlands.

The current lack of efficiency and effectiveness regarding change inspection in the large and sometimes inaccessible areas of the floodplain requires the use of remote sensing change detection to move toward a data-driven maintenance process, in particular, by using point cloud data. This is nowadays a widely used data source in a variety of fields to capture elevations and in this way extract valuable information from terrains. Despite its usage in a variety of applications, the data is often underused since the data is frequently processed directly to other data formats. This research therefore aims to reveal the potential of explorative point clouds in floodplain maintenance.

Light Detection and Ranging (LiDAR)- and multispectral data were acquired at two moments, one before and one after the summer, with a time interval of 45 days. Subsequently, these acquired datasets evolved into an explorative point cloud by adding attributes, including vegetation health, also known as Normalized Difference Vegetation Index (NDVI), and the distance between these two point clouds, the cloud-to-cloud distance. This explorative point cloud with the integrated additional information was visualised to several disciplines involved in the WOCU project. This was done in Three Dimensional (3D) by using Virtual Reality (VR). This collaborative approach revealed the potential use cases of the Red, Green, Blue (RGB), cloud-to-cloud distance, and NDVI point clouds highlighting the potential of explorative point clouds.

Potential use cases that were found are; highly detailed area modeling, vegetation overgrowth monitoring, bank erosion detection, flora status assessment, monitoring of vegetation types, digital inspection of remote sites, participation medium, and identification of atrophied ground patches. Attributes added to point clouds enhanced insights. Especially the RGB point cloud sparked excitement due to its realistic appearance. The Cloud-to-Cloud Distance (C2CD) attribute showed potential, especially for erosion detection. However, due to the short timeframe between measurements, it could not be detected. The NDVI attribute was perceived as less interesting.

The use of explorative point clouds, generated from raw LiDAR point cloud data, offers potential uses and insights for floodplain maintenance. The interdisciplinary value of explorative point clouds was clearly visible. This thesis emphasizes that underused raw LiDAR data, by making it explorative, can act as a valuable resource.

Key words: Explorative point cloud, UAV, LiDAR, VR, flood plain maintenance

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1. Introduction

1.1. Flood plain maintenance: a general overview

Water management is an integral part of Dutch history, driven by the continuous need of reducing flood risk. Because a large area of the country is located below NAP, there is an ongoing challenge to safely discharge all the water through the rivers to the sea. Therefore, flood safety policy has become a crucial part of protecting the Netherlands from natural hazards. An essential part of this strategy involves managing the adjacent floodplains surrounding the rivers. Floodplains are areas to which excess water can flow during high water levels due to heavy rainfall and the annual melting of the Alps. It can also be seen as a natural storage area that offers ecological and social positive benefits in addition to its safety purpose. Ecologically, it provides climate regulation through carbon sequestration, connectivity to improve biodiversity, a new habitat for wildlife and fish, and enhancement of riparian forests and other ecosystem functions. In terms of social benefits, it provides not only flood risk reduction but also improved water and air quality, recreational opportunities and sustainable and intergenerational equity [93].

1.2. Project relevance

It is important to maintain these floodplains regularly by for example preventing excessive vegetation growth to ensure that they retain their flood protection. Van Oord is since this year responsible for the maintenance of several floodplains of the Rijntakken in the Netherlands, as part of the WOCU project. The need for the project has come about due to substantial changes in these areas compared to their initial designated state, or in other words, overdue maintenance. The main core task involved in this project is flood safety, which requires that all aspects of the floodplain are in good condition. Among the assets in the area are channels, bridges, culverts, roads, grids, and spillways, which require various maintenance tasks such as gully maintenance, pruning, mowing overgrowth, and maintenance of objects from baseline measurement, including for example bank erosion.

Maintenance is coupled with change detection with the ability to act where and when needed. It is actually about capturing changes in a particular position between different moments, which can also be seen as a spatio-temporal aspect. At this moment the main concern is the overgrown vegetation that counters the passage of water and hence, it is important to map the area in order to detect new changes. The current state of the floodplains is therefore compared with their initial state. Once all the vegetation and objects within the area have been restored to their original condition, it is planned to carry out periodic checks and perform maintenance work when necessary in the coming years. The inspection of changes currently takes place manually, which is time-consuming. In addition, the expanse of the area and certain areas being inaccessible pose a major challenge. This lack of efficiency and effectiveness calls for the use of other tools, in particular, the use of remote sensing techniques to facilitate change detection in the maintenance process. This is also known as Remote Sensing Change Detection (RSCD) [87]. The use of remote sensing techniques could automate the process, eliminating the need for field inspections and showing more accurately where maintenance is needed, thus making the process more efficient and effective. The idea is to move toward a data-driven maintenance process with the inclusion of such techniques so that these tasks will be based on a flow of acquired data over time.

One of the outputs of these existing remote sensing techniques are point clouds, which are a commonly used data source in a variety of fields nowadays to record heights and in this way extract data from terrains. Despite the fact that point clouds are used for a variety of applications, is the data often underused. This is because the huge size of point clouds is processed to other forms rather quickly. However, these processing steps can also lose important information at both spatial and semantic levels ([73]). So, a raw point cloud can also function as an extensive data resource which might has other potential use cases that are not explored yet. This comes together in the concept of an explorative point cloud which sees the explorative value of point clouds by adding tools, enriching it with semantics, or integrating information flows from different directions. Point clouds can for example be compared with each other, and the Cloud-to-Cloud distance between both datasets can be calculated for each point and then added as an attribute to each point. This can provide insight into the changes that have taken place over time in a given area.

Another remote sensing technique is the multispectral sensor, which allows several spectral bands to be acquired. The advantage of this technique is that with the use of near-infrared and red spectral band data, a NDVI score can be calculated, which is an indicator of the type, density and health of vegetation, which the floodplain is mainly composed of. This can reflect, for example, stress or the state of vegetation after storms or drought. Thus, the point cloud could be enriched by adding more information to each point, namely the NDVI score of the point in question [49; 70].

1.3. Research objective

The related work, which can be found in Chapter 2, elaborated on the current applications concerning point clouds in floodplains and introduced the exploratory approach that can go along with innovative visualization techniques of point clouds. This integration could lead to a new insight into the use of point clouds for decision-making processes during floodplain maintenance. Based on this information, the objective of this research was determined and given the direction of exploring the potential of explorative point clouds in the maintenance of floodplains.

This research elaborates on the potential of explorative point clouds in flood plains. The overarching research question is formulated as follows:

"To what extent are explorative point clouds, generated from raw UAV-LiDAR data, useful in providing insights on change detection for floodplain maintenance?"

The main question is divided into sub-questions.

The following sub-questions will be answered in the literature review of this research.

1. What is the benefit of using a UAV-LiDAR sensor to acquire point clouds of floodplains?
2. What additional attributes are suitable for enriching point clouds of floodplains?
3. What is a suitable algorithm to detect changes in point clouds of floodplains?
4. What is a suitable visualisation technique to display explorative point clouds?

The following sub-questions will be answered from the experimental part of this research.

1. What is the quality of the acquired data?
2. What is a suitable threshold for the maximum cloud-to-cloud distance in visualising changes in explorative point clouds?
3. What are the potential applications of explorative point clouds for different disciplines in floodplain maintenance?
4. What is the most suitable attribute to provide insights into changes in explorative point clouds for floodplain maintenance?

1.4. Scope

1.4.1. Area

The spatial scope of this study is narrowed to a study area that includes the floodplain of Lopik, which is positioned in the Netherlands and part of the Rijntakken WOCU project. The reason for selecting a smaller area is to conduct a more in-depth study, as acquiring data of limited scope is easier and quicker to process. Eventually, if it works on a small scale, the implementation can be extended to larger areas.

1.4.2. Time

In order to compare the point clouds of two different moments in time, it is necessary to choose a time interval between these two moments. This decision is dependent on several factors related to the rate of change of all assets and vegetation present within the floodplain. Moreover, the choice is constrained by the maximum time frame of one month between the two moments given the time limits of this thesis. Specifically, for this study, the acquisition moments are chosen at the beginning and end of the summer season.

1.4.3. Content

In terms of content, this research will mainly focus on acquiring the point clouds, integrating explorative point cloud data on an interactive visualisation interface and integrating new insights.

Moscow In order to define the priorities of this research, there is made use of the MoSCoW method [22]. This method identifies four categories, each with a different priority within, in this case, this research. These include items that must be achieved (must), those that are feasible to achieve (should), those that can be realised if the resources are sufficient (could), and those that do not necessarily have to be foreseen (won't). Figure 1.1 gives an overview of the MoSCoW method applied to this study.

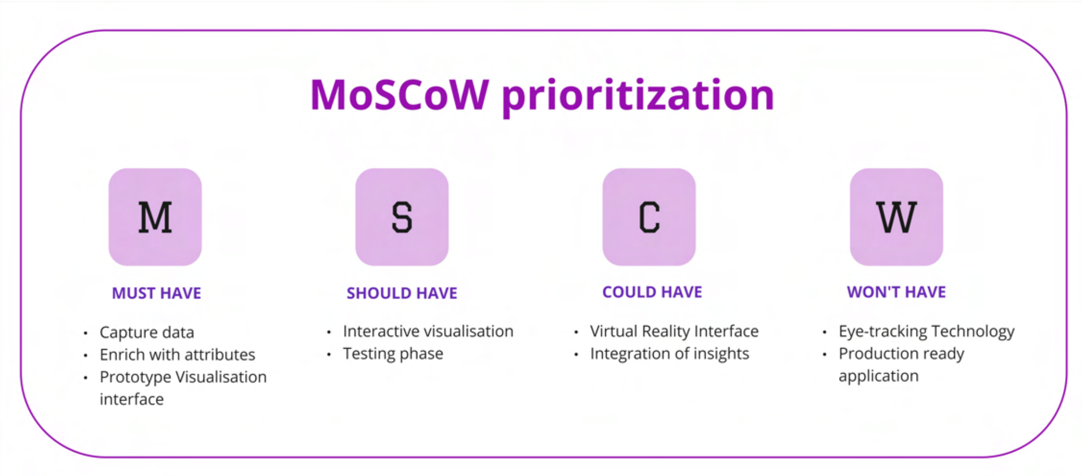


Figure 1.1.: MoSCoW prioritization

Will not do To clarify what this research will not focus on, this section will appoint these items. The research is not concerned with the LiDAR technique. It is assumed that the equipment of the survey department acquires the point clouds correctly, so no attention will be paid to this. In addition, this research will use an existing viewer for the interactive visualisation and no attention will be paid to developing a new one. Furthermore, existing interactive tools will be used and combined, and no attention will be paid to developing a new one. As mentioned earlier, this research will only focus on a pilot study area, and will not look further into implementing on a larger scale after this.

1.5. Thesis outline

This thesis is composed of 8 chapters. Chapter 2 elaborates on the related work of explorative point clouds, visualisation possibilities, and the integration of interdisciplinary insights. Chapter 3 elaborates on the background and context of the project and the research area. Chapter 4 introduces the methodology, including the acquisition, processing, visualisation, and discipline integration. The implementation, including software and tools used, are elaborated on in Chapter 5. Chapter 6 includes the results of this research. Chapter 7 includes the discussion and limitations of this research. Lastly, Chapter 8 concludes this research and gives future research recommendations.

2. Related work

2.1. Floodplain maintenance

Floodplains are part of the river landscape, which are areas to which excess water can flow during high water levels. According to Schmudde et al. [1968], the definition of a floodplain is set as ”a topographic category, which is quite flat and lies adjacent to a stream; geomorphologically, it is a landform composed primarily of unconsolidated depositional material derived from sediment being transported by the related stream; hydrologically, it is perhaps best defined as landform subject to periodic flooding by the parent stream” [4]. Another option is to define these wetlands as areas where the water table is at or above the land surface for long enough each year to promote the formation of hydric soils and to support the growth of vegetation much of which is emergent”. Alexander et al. [1999] combines these definitions of a floodplain as an area of relatively low relief, adjacent to a stream that floods at least once in a given period. Therefore is the management of these adjacent floodplains an essential part in order to keep them functional to protect countries against natural hazards [93]. Figure 2.1 shows an example of a floodplain located along the Rijntakken located in the Netherlands.

Figure 2.1.: Example of a floodplain along the Rijntakken, the Netherlands

One of the main reasons to properly manage the floodplain is flood safety. In the event of high water levels, it is important that the floodplains can still serve as a base of operations. For this, it is necessary to have a good flow from the rivers to these areas. Several local factors influence this flood conveyance, such as high roughness, intensive floodplain aggradation, carrying floodplain width, and vegetation cover [54]. One of these problems, an overgrowth of vegetation, is due to its susceptibility to plant invasions, which increases the roughness of the area and reduces its flood conveyance capacity. Lack of maintenance accelerates the process of this overgrowth and as a result, floodplains cannot function optimally. Kiss et al. modelled flood transport in the case of unmanaged and managed vegetation to identify differences, showing that the one managed floodplain offers up to 86% reduction in roughness by removing invasive plants. [54].

To keep vegetation in floodplains in control, various maintenance tasks including grass cutting and tree pruning are important. In addition, controlling erosion of the banks is crucial. Moreover, there are several essential infrastructure assets, such as inlets and outlets, present in floodplains that need to be inspected on a regular basis to ensure their continued proper functioning. These include repairing any damage or clearing debris.

In the Netherlands, there are two major water managers whose task is to prevent floods within the country, ensure enough ground and surface water and guarantee water quality. These water managers are Rijkswaterstaat and the Waterschappen [103]. Rijkswaterstaat is responsible for managing major bodies of water, such as rivers, while the Waterschappen are responsible for managing regional waters, such as canals. Additionally, Rijkswaterstaat is tasked with monitoring high water levels and providing more space for rivers to flow freely by maintaining floodplains and constructing side channels.

2.2. Introduction to point clouds

Firstly it is important to understand what point clouds are. Point clouds are three-dimensional models that consist of a collection of points with x, y, and z coordinates. However, additional possible properties can also be stored in the point cloud such as intensity, return number, point classification values, RGB color values, and many more [40]. These point clouds can be used to represent certain objects, environments, or spatial phenomena from the real world in a discrete way [29]. The following Figure 2.2 presents an example of a point cloud which is filtered on the basis of its height. The dataset used was obtained via GeoTiles, which provides the ability to download small tiles of the AHN4 dataset. The tile in question is 38EZ1_10, which contains part of the floodplain of Lopik [45].

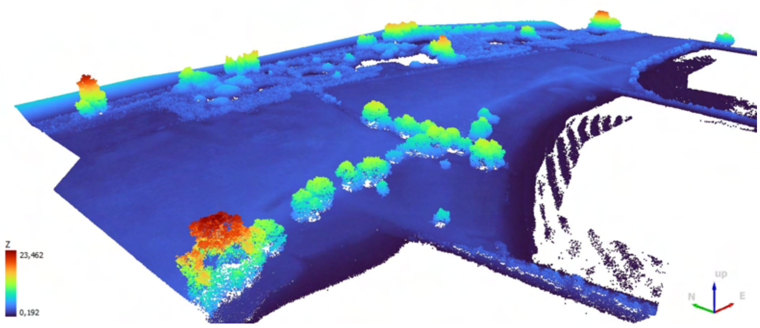


Figure 2.2.: Point cloud of floodplain in Lopik - filtered on height

Developments in the field of 3D point clouds have led to the creation of the national open data source known as the Actueel Hoogtebestand Nederland (AHN). The AHN program was initiated in 1997 and has evolved from the AHN1 to the current AHN4 version [2]. This data source can be used by many different people for a variety of purposes [16]. It is a challenging and expensive process to obtain and process the AHN dataset on a nationwide scale. Therefore are updated AHN dataset versions released on average every five years. Since this time frame is too long for detecting changes within floodplains, it is crucial to have a comprehensive understanding of the acquisition process involved in capturing point cloud data.

Several data collection techniques are available for acquiring 3D point clouds. Among them exist the active and passive forms.

The active techniques emit radiation toward the target by making use of their own energy source and it detects the reflected radiation back from the target. Two active methods are radar remote sensing and LiDAR. Due to the properties of laser radiation, LiDAR has several advantages in areas of dense vegetation and floodplain mapping [101]. One of its benefits is its ability to obtain measurements without being dependent on weather conditions and passing through tree canopy [37]. LiDAR devices make use of laser light pulses being sent to the object and measuring the time to return this signal after hitting the objects in its path. From this, the distance from the scanner to the scanned surface can be computed, allowing the calculation of 3D coordinates (x, y, z). This technique can be seen as the most accurate one.

The exact process of sending and receiving pulses with the LiDAR measurement is as follows. First, a laser beam is formed, which emits in the near-infrared (IR, wavelength 780-3000 nm), visible (390-780 nm) or near-ultraviolet (UV, 200-390 nm) domain. Then it moves through the scanning optics through the air towards the target to be measured. Thereafter an interaction takes place with the target, given that the pulse bounces against it and is thus formed back towards the LiDAR sensor. This is also referred to as an optical flux, which is captured by an optical imaging system. After this, spatial and spectral filtering takes place, which separates the signal into stray flux. After following this optical chain, a photodetector converts the photon flow into an electrical signal, after which it can be digitised. [20].

The exact distance between the sensor and the reflecting point can be measured by using the time-of-flight and the speed of light (see equation (2.1), where *d = distance to the object, c = speed of light, and t = time-of-flight between the light emitted and detected*).

$$d = \frac{c * t}{2} \tag{2.1}$$

The passive techniques measure reflected solar radiation in visible, near-infrared, and mid-infrared wavelengths, or absorbed and then re-emitted solar radiation in thermal infrared wavelengths. Two passive methods are multispectral remote sensing and hyperspectral remote sensing [101]. Photogrammetry techniques enable the generation of a point cloud by combining images from different angles of an object. This is done by identifying overlapping features in the images and determining a 3D point from here. However, this step takes additional time and memory due to the extra processing.

The resulting data of these techniques is also referred to as "raw point cloud" [101]. There are several advantages of laser scanning compared to image-matching photogrammetry techniques. Laser ranging does not depend on surface texture, is less weather dependent than passive optical sensors, has the ability to pass through the tree canopy (unless it is very dense), has a high accuracy, has multiple-return recording, and has no need for ground control.

So to further deepen in the LiDAR technique it is good to know that there are several acquiring techniques, includingAirborne Laser Scanning (ALS), Terrestrial Laser Scanning (TLS), and Mobile Laser Scanning (MLS) techniques. The difference between them is that TLS and MLS are measured from the ground and ALS from the air. Ground-based land measurements are more labor intensive compared to automated aerial methods. In addition, TLS and MLS have limited coverage, while technological developments in ALS have opened up new possibilities regarding conducting accurate and high-density measurements over large areas [75; 27]. As such, LiDAR systems can be carried on board various platforms, including satellites or shuttles, aircraft, helicopters or drones. One of them is the use of LiDAR sensors in Unmanned Aerial Vehicle (UAV), also known as drones. UAV are common platforms that are autonomously operated and have the ability to carry several remote sensors including LiDAR devices and multispectral sensors [8]. A major advantage of integrating these sensors into UAV platforms is their wide range capability, which is needed when mapping and monitoring areas. As mentioned earlier, the ALS gives advantages as multiple pulse echoes are available, allowing the pulse to receive the top of the vegetation as well as the ground because laser pulses can penetrate through canopy. This not only makes the top view of current vegetation available, but also shows the vertical distribution of vegetation in an area making this a commonly used method in areas with a lot of vegetation [71].

Apart from the LiDAR sensor, there is also the possibility of applying photogrammetry during a drone flight, which has the advantage that the flight time is significantly shorter compared to the LiDAR flight. On the other hand, photogrammetry has the disadvantage that image-matching processing takes more time. Thus, both techniques have advantages and disadvantages and this research will compare both methods to make a good trade-off between which technique is most suitable for surveying floodplains.

In order to create a point cloud out of different 2D views, image matching takes place. Several processes exist for creating a 3D model from different views. Among them is structure from motion, where structure refers to the 3D geometry of the scene or object, while motion refers to the camera location and orientation. The geometry is calculated from the moving cameras. In the case of using an imaging sensor under a drone, this means that the camera hangs under the drone that changes position as it follows its flight plan. At the same time as the geometry, the recovery of structure and motion is determined. This is done using bundle adjustment where the sum of squared re-projection errors is minimised. For the bundle adjustment, the input variables are the camera intrinsic and extrinsic parameters and the coordinates of the 3D points. Image matching consists of finding corresponding image points, including key points. With these key points is it possible to identify and match an object that is present in different images. [63].

One of the limitations of LiDAR techniques is its inability to capture the color information of the scanned surfaced due to that the sensor is transmitting a single wavelength. To address this issue is to simultaneously use an imaging sensor. After the acquisition it is possible to resolve and synchronize between the LiDAR and imaging to obtain a colored point cloud data set [59; 110].

After obtaining the point clouds, there are several formats available to manage and exchange them. The LASer (LAS) file format is the most used data format for the dissemination of point cloud data [58]. The American Society for Photogrammetry and Remote Sensing (ASPRS) maintains this binary-encoded standard format that contains information specific to the LiDAR nature of the data and currently operates at version 1.4 [9].

2.3. Explorative point clouds

Point clouds can also be seen as a collection of points in a dimension that holds little significance individually, but if multiple points are presented next to each other, you, as a human being, can easily recognize an object within this set of points. However, to a computer without processing, this remains a set of unrelated points. Using this line of thinking, there are currently used a lot of processing techniques, which are time-consuming for large data sets, to convert the points to other models. In this way, the huge amount of raw data is quickly reduced and important information might get lost [73]. Moreover, the acquisition of point clouds costs not only time but also quite a lot of money. So it is a waste not to look further into the possibilities of the unprocessed raw point cloud and represent it as a model on its own [91]. Point clouds have more value than the derived models since they keep the details. Moreover, it is up to date and each detail is known. However, this added value is to be revealed by the user.

This leads to the introduction of explorative point clouds, which contain enriched information that can be integrated into visualization techniques. The key question then is to what extent additional information and interactive visualisation capabilities make a point cloud explorative. In the case of floodplain maintenance, it involves making decisions about where and when specific operations should take place. Making these decisions is related to decision-making problems. Several factors can influence a decision-making process within flood defences, which include regulatory, financial, technical, and actor perspectives [104]. An important aspect of decision-making processes is that it includes human interpretation.

Understanding human creativity is complicated. Ideas can be unpredictable, or even seen as impossible. Creativity is the generation of new ideas that are seen as valuable. Actually, this creativity happens daily in the virtual aspect of our lives, which is naturally learned. Think for instance of perception, memory, or conceptual thinking. A distinction can be made between three types of creativity, one of which involves the exploration of conceptual spaces in people's minds. This is exactly the type of creativity that is attempted to be achieved with the use of visualisations of raw point cloud data. Exploratory creativity is valuable given that it can lead to someone seeing new possibilities that they did not see before, which opens up the question of the potential of the potency of this approach [14]. But how can this human interpretation be linked to a data-driven process for making certain decisions in floodplain maintenance? That depends on what choices need to be made based on detecting changes in the landscape and confirmed objects. So that detection in turn is linked to the human interpretation, which can be seen as an input factor for the decision-making process. It helps if analysts can explore and play with the point clouds. This comes together in the idea of a spatial decision support tool.

A spatial decision support tool is an interactive system designed to help make decisions when solving a spatial problem [77; 50]. For this, it is important to describe the following two aspects to give a guideline for the requirements of such a type of tool in the case of a maintenance process [Santen]. First, for what, i.e. what exactly the tool should be able to do. In addition, for whom, i.e. which disciplines are involved in the maintenance process. For the first aspect, such a tool should be able to explore where changes are detected. The second aspect concerns the visualisation of the floodplain to the various domains involved within the WOCU project. This results in the question of determining the most suited approach, which involves the various existing visualisation techniques.

2.4. Attributes

The ability of humans to estimate a certain status of an object based on its purposed status is characterized by the phrase "to look is to compare" [10]. The human eye can easily recognize certain patterns or evaluate the status of an object by exploration. This is a skill that in itself is considered very effective, but can be enhanced by advanced aids such as certain additional information added. From this line of thinking, a way to make a point cloud explorative is to enrich it with additional information. This could be done by adding attributes to each point within the point cloud which provides more opportunities to explore the point cloud due to the additional information for each point. The following subsections elaborate on potential attributes that are relevant for the maintenance of flood plains.

2.4.1. Change detection between point clouds

As mentioned in the introduction 1, maintenance and change detection are closely related. Since change detection is about the change of a certain area over time, it can be seen as a spatio-temporal approach. The detection of change determines which elements appeared and disappeared by examining the differences between 3D spaces. Where change itself can be seen as the triple change definition, including positive (objects added), negative (objects removed), or no change [99]. According to Ott et al. [2001] is the main purpose of a temporal aspect in Geographical Information System (GIS) to reproduce temporal processes or events of the real world in a model in such a way that they are accessible for spatial query, analysis and visualization. For instance, there may be visible changes or specific patterns in the landscape that could influence the dynamics of the floodplains. In the case of point clouds, this spatio-temporal aspect involves acquiring point clouds at different time intervals and comparing the obtained points. To determine the exact changes in the acquired area over time, several techniques are available that concern the computation of the distance between the unique neighbour pairs within both point clouds.

One method to achieve this is by using a nearest neighbour distance algorithm, which is known as the simplest and fastest direct 3D comparison method due to the absence of gridding or meshing the data, nor computing surface normals. The change in surface of the point clouds is calculated by using a distance calculation with the Euclidean distance between the two points [47]. CloudCompare has a tool called C2CD, which computes the distances between two point clouds [23]. This is done by comparing the distances for each point within the compared cloud with the reference cloud. Figure 2.3 shows the computation between the two clouds, which results in the nearest neighbor distance for each point within the compared cloud.

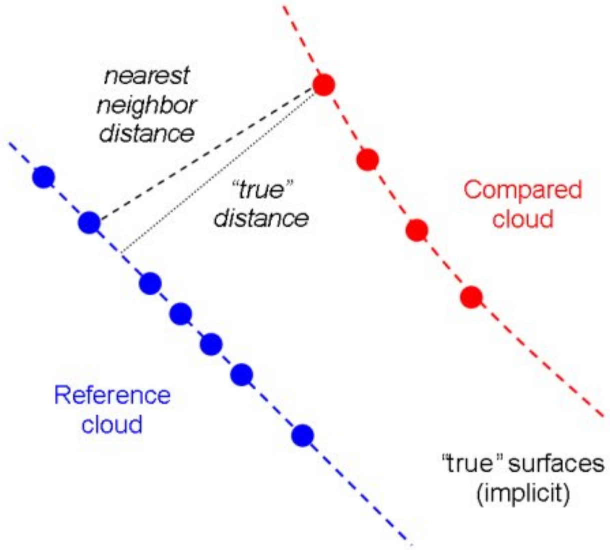


Figure 2.3.: Cloud-to-Cloud Distance computation [47]

Lague et al. [2013] developed the so-called Multi-scale Model to Model Cloud Comparison (M3C2) method which is useful for land cover changes, erosion, flooding, deforestation and changes in the tree canopy. This method enables the user to choose certain core points within the cloud in order to speed up the distance computations. Furthermore, it is possible to set the normal and projection scales parameters to control which points in the cloud will be searched for. The study presented a new algorithm for conducting a direct comparison of the point clouds in 3D. This method seems to offer higher accuracy compared to existing methods and offers an easy workflow due to the absence need of surface meshing.

Vitali et al. [2023] research dives deeper into which of the common methods is most suitable for measuring changes between point clouds regarding the accuracy of calculating inter-point distance. The study tested three different terrains on which of the eight methods, including Cloud-to-Cloud (C2C), also known as nearest neighbour, and M3C2, gives the most accurate result regarding the interpoint distance. This was done by manually manipulating the reference point cloud to a new compared point cloud and comparing the actual change in terms of distance with the outcome of all 8 methods. This revealed that the accuracy of the distance calculation depends on several factors including the nature and size of the clouds, the point density of the clouds, the presence of noise or outliers, and the computational efficiency of the method [28]. One of the tested datasets consisted of a hilly terrain with a lake and nearby vegetation, including shrubs and trees. In this case, all methods work effectively on capturing vertical displacement, but the nearest neighbour, Natural Neighbor Interpolation (NNI), and Inverse Distance Weighting (IDW) methods stood out for accurately representing displacement on trees. While for horizontal displacement, only the nearest neighbour and NNI methods presented a notable performance. Thus, it was found that for terrains, only the nearest neighbour method had good results. [28].

Stilla et al. [2023] describe several change detection techniques for 3D geometries, including point clouds. Several challenges are mentioned, including inconsistent sampling, limited visibility, and missing semantics. In the change detection workflow, three stages are essential, including reference frame registration, geometric difference estimation, and spectral and attribute analysis [99]. Another challenge that is important to consider is the uncertainty of the measurements, given that the measurements are taken at two points in time. This can influence the position of the points, so change detection techniques have to take this into account. An example could be to take into account a certain threshold so that changes are only detected if they are higher or lower than this number.

In addition to detecting positional differences of points, it is also possible to determine the health of the vegetation present within the floodplains and how this might affect the maintenance of the area. This can be done by enriching the point cloud with NDVI values. This brings us to the next subsection in which NDVI is further elaborated on.

2.4.2. Normalized Difference Vegetation Index

As introduced in the introduction (1) is the NDVI a potential attribute to add to each point in the point cloud of floodplain areas. This indicator is in fact widely used for its ability to help make decisions regarding the goals of vegetation maintenance [19]. The NDVI is attractive due to its ability to detect vegetation and various traits, including vegetative stress, assessing plant growth, and estimating crop yields [70; 43]. Additionally, it could be used for analysis of changes in vegetation over time and an understanding of human influences on certain natural processes [55]. These positive contributions from the use of the NDVI create the potential for extending an existing point cloud with additional information by integrating it with this NDVI. Calero et al. [2018] describe a method to integrate the NDVI into a point cloud. The NDVI point clouds can be seen as an innovative method to more easily determine and visualise the health of vegetation [51].

The NDVI is one of the possible applications when using a multispectral remote sensing technique. Multispectral tools include image acquisition and processing techniques. Existing light waves are divided into different bands, depending on their wavelength. If such a light source strikes a material, a certain absorption and reflection occurs depending on the type of material. Figure 2.4 shows the amount of reflection for soil, vegetation, and water.

The intensity of this reflection per frequency light band makes it possible to determine certain properties of a material. These bands can be assembled into a particular band composition to be used for analysis. With these transformations, certain patterns can be visualised, for example, the representation of vegetation. One of these band transformations is the use of Near-Infrared (NIR) and Red (visible) wavelengths to determine the NDVI. [56; 49]. The NDVI is calculated by using the following formula (2.2).

$$NDVI = \frac{NIR - Red}{NIR + Red} \tag{2.2}$$

The NDVI values vary between -1.0 to 1.0, where negative values indicate water, positive values around zero indicate bare soil, positive values between 0.1 and 0.5 indicate sparse vegetation and higher positive values indicate dense green vegetation. The following applies: the higher the index, the healthier the plant is [3].

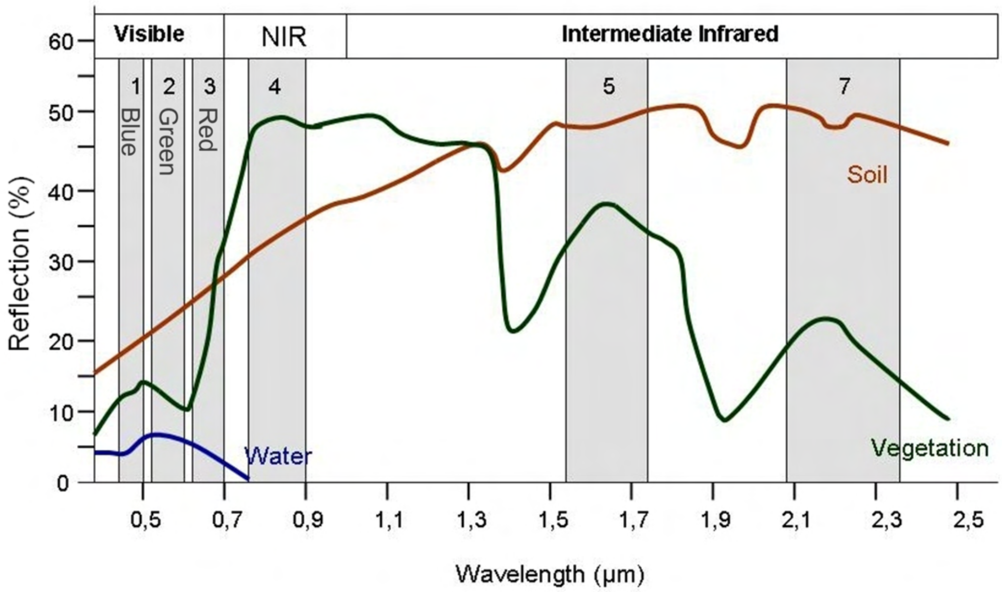


Figure 2.4.: Spectral reflectance of soil, vegetation and water. Adapted from: [95]

There are several factors that contribute to the reflection of NIR and Red wavelengths, which form the basis for NDVI values. NIR operates within wavelengths ranging between 750 and 900 nm and Red ranging between 600 and 700 nm as can be seen in Figure 4.1. The moment the reflected NIR value is higher than the Red value, the NDVI yields a positive value. Conversely, if this relationship is inverted, it means that the NDVI will become negative. The levels of these values depend on the ratios of the reflected NIR and Red wavelengths. The physical factors of vegetation that influence this are as follows. Firstly, the leaf pigment chlorophyll, which is the pigment responsible for photosynthesis in the chloroplast, plays an important role. Chlorophyll absorbs light in the Red part of the spectrum while allowing NIR light to pass through. This results in high NIR and Red values, which means there is a positive NDVI value when there is a lot of chlorophyll present in vegetation. Second, the cell structure of plants impacts the reflection of light. When cells are well hydrated and contain a lot of air, more NIR light is reflected. Conversely, dry, stressed, or deceased leaves contain denser cells leading to reduced NIR light reflection. Furthermore, the structural properties of the leaf, stem and canopy scales affect the scattering of the light. For example, dense vegetation with many leaves tends to absorb more light, and therefore yielding a higher NIR value compared to sparser vegetation. [66].

Besides these physical factors of vegetation, there are other factors that affect the NDVI trend during the year. One of these influences on the NDVI is the change of seasons due to different weather conditions such as dry or wet periods. So, the NDVI value of a plant can change over time with the seasons. Therefore it is important to know at what time the NDVI values are measured in order to check them with the expected trend value of the NDVI value of that moment. Moreover, the type of vegetation can also matter for the NDVI range. For example, heath and dune areas have a higher NDVI value compared to forests in the Veluwe at another time of the year. Given that the types of vegetation in the floodplain can vary, it might appear that certain types of vegetation are healthier relative to nearby other types. A solution could be to extend the NDVI images to multiple times in the year, as certain vegetation structure types may have a high NDVI at another time of the year.

The NDVI values of two moments could also be compared to each other to detect certain changes, which could occur, for example, in case a tree has experienced a lot of stress due to a prolonged period of drought. This could provide insight into increases or decreases in vegetation health at specific locations. First of all, it is important when comparing the NDVI values of two measurements to exclude possible seasonal changes. NDVI values can differ per country and habitat. This could be done by looking at the trend line of the NDVI values of several years at the location in question to see if the increasing or decreasing NDVI values can be attributed to this. Moreover, the change can also be mapped per vegetation type by comparing per vegetation type the NDVI values with the trend NDVI values of the respective vegetation type.

In addition to changes in the position of the points, it is also possible to detect differences in the NDVI values between both point clouds. The NDVI values in both obtained point clouds of the floodplains can be compared to determine whether the health of the vegetation has changed.

The result of both C2CD and NDVI values can be added as an attribute to the point cloud. Visualization is achieved through a color-scaled representation, displaying variations in both distances and NDVI values. This can be utilized for providing a visual representation of the alterations in elevations and NDVI values that have occurred over the time interval of the acquisition of both point clouds. This initiates the exploration of the visualization of the clouds, focusing on identifying an approach that considers a comprehensive representation of the dataset.

2.5. Interactive point clouds

Cartography is seen as ”the set of scientific, technical and artistic activities aimed at the preparation and use of cartographic products” [102]. Presenting spatial data can be made visible in a different way for each application, for instance, consider passive versus interactive representation. For a long time, end-user functional design has been the basis of cartography, creating a communication medium in the form of a map. In the course of the digital revolution, the focus has been more on cartographic representation in the form of user perception and experiences with respect to data visualisation.

Interaction and visualisation are combined into interactive visualisation to view certain data in different ways. The word interactive also has two meanings, one being the interaction between humans and computers, also known as Human Computer Interaction (HCI), and secondly, the interaction between different disciplines. Interactivity is seen as the integration of humans with information in an interface. According to Norman’s stages of action model, there are several steps that are gone through in the process of interaction and thereby better understanding of human action. Namely, the creation of a goal and intention, after which the specification of the action takes place and the execution of this action, then the state of the system is perceived, after which the interpretation takes place and finally the evaluation of the outcome. [65; 81].

Roth [81] focuses on cartographic interaction, in which user manipulation is central and interactivity is seen as actions by the user. Interactions in a digital environment offer the chance to manipulate certain representations. The human being equal to the interactivity of the digital data, allowing for a collaboration between the two. While exploring refers to the act of exploring or investigating something in order to delve deep into the data and potentially extract meaningful patterns or insights, is interactive implying that the data can also be manipulated in real-time by users. This means that the interactive aspect enables the user to have a dynamic interaction in order to obtain engagement. Consider here, for example, navigating through the data to have different perspectives. [108]. To understand changes in landscapes such as floodplains, this must be available in the form of information for exploration and analysis through interactive visualisation as offered by GIS.

As [81] describes the concept of interactive maps, point clouds can also be seen and approached as interactive point clouds, in which the point clouds face the user who interacts through a to-be-determined digital medium such as a 2D screen or 3D visualisation. These interactive point clouds can be seen as a set of individual points, each with their position and possible added attribute, but especially important that their role is to facilitate user interaction and exploration. The main purpose of this is to present users with the data in a dynamic and spatial way and enable them to explore and analyse. When comparing interactive point clouds to traditional cartography, the difference is that maps were seen as static representations while interactive point clouds can respond to specific user needs by querying or manipulating certain data by, for instance, zooming in or changing colour and attribute representation. Making spatial visualisation available through the three dimensions gives the user the power to think visually. For example, the user can integrate observations with existing knowledge, which can spark creativity and positively influence problem solving and decision making. [48]. The effectiveness of such kind of interactive point clouds for the generation of insights will remain an open question.

Taking DiBiase's [1990] swoopy diagram and Tukey's [1977] research on exploratory data analysis into account, four stages have been identified, including exploration, confirmation, synthesis, and presentation. The exploratory stage is mainly located in the early phases of science that require many quantities of human to map representations, so in this research; human to point cloud, in order to encourage visual thinking. With this in mind, MacEachren [1994] has designed a cube framework, the map-use cube, that explains potential map usage on the basis of three axes, which can be seen in Figure 2.5. To convert the idea of interactive maps to interactive point clouds, ”map” in the map-use cube will also be converted to ”point cloud”, thus arriving at the new concept of point cloud-use cube. This adjustment can be seen in Figure 2.6. Using the point cloud-use cube can be a useful guide to uncover the value-added of a particular issue. The three axes are as follows: (1) revealing unknown insights versus presenting known ones, (2) private map use versus public map use, and (3) high versus low human-map interaction. The diagonal axis of the cube shows the area of visualisation and communication. The visualisation is in the position of this cube in which emphasis is placed on exploring and revealing unknowns, high human-point cloud interaction, and private use. This area is also seen as the field of geovisualisation.

Visual thinking is based on three pillars, including seeing, interacting, and reasoning why. Together with the conscious mind and the storage of certain patterns, a person can process certain inputs with existing knowledge. [61; 81]. Seeing certain information is also related to spatial representation, or perceptual capabilities such as, for example, depth in the data. Point clouds can be represented as 3D models, which can fuel another form of visual thinking in users. However, spatial thinking, in addition to perception, depends on several factors

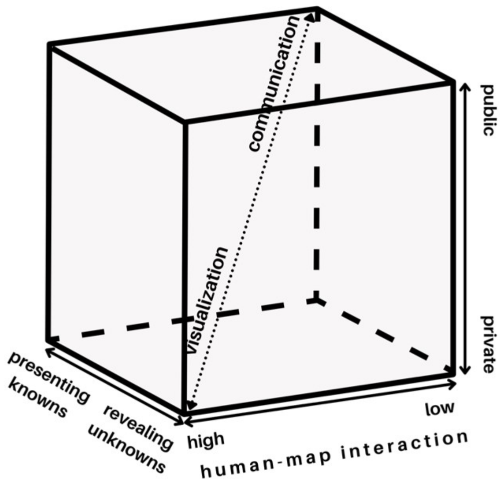


Figure 2.5.: Map - use cube [61]

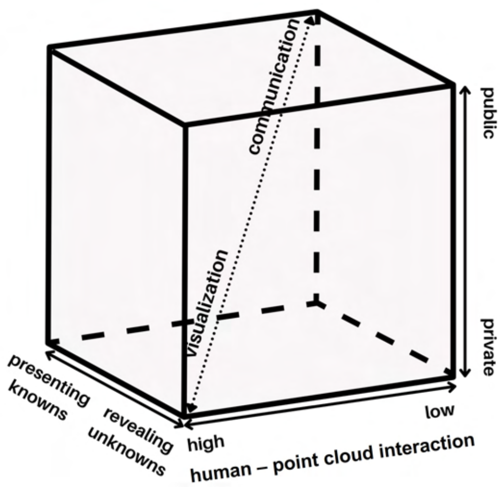


Figure 2.6.: Point cloud - use cube. Adjusted from: [61]

such as cognition and motor skills [81]. Besides spatial thinking, the user's expertise is also important given its potential to make certain connections. Expertise is emphasised earlier in the point cloud-use cube given that this provides a higher level of cartographic interaction. The subfield of geocollaboration concerns the use of mapping interfaces during group interactions such as the field of computer-supported cooperative work.

Andrienko et al. [1999] have also researched interactive maps for visual data exploration. It is mentioned that exploratory data analysis requires highly interactive, dynamic data displays. This can be reapplied for point clouds instead of maps display. Using these interactive techniques, point cloud display manipulation can improve the expressiveness of these clouds to stimulate data exploration. Another finding is that the productivity of an interaction technique lies with the presentation method, as it must be suitable for supporting the appropriate applied analysis operations for the data in question [5]. According to Roth et al. [2008] the success of cartographic interaction depends on the complexity of the interface versus the user's motivation. This means that the user must be engaged with the subject of the information displayed so that the motivation to explore is high enough. It should be taken into account that the complexity of playing with the interface should be manageable so that the ease of use does not have a negative impact.

The provision of geoinformation relies on the WDGM model, developed by van der Schans et al. [1990], which contains all the processes within the geoinformation provision. The WDGM model stands for World, Digital model, Graphic representations, and Mental representation. This model, which can be seen in Figure 2.7, is arranged in the shape of a circle, where the outside consists of two ends, the world, W, and the mental representation of humans, M. In between, sub-processes take place that can run along visible graphical representations, G, and invisible digital models, D. These possible processes form a diagram of possible information increments according to the WDGM model. These processes can be combined to form a series of connecting processes. As shown in Figure 2.7, certain processes take place in the 4 aspects, among which MM stands for human mental processes, communication through gestures and spoken language. GG stands for reprographic processes and exchange of graphics. DD stands for algorithmic-driven processes in digital models, such as analysis. WW equals change processes in the world, such as flooding. Between these aspects, processes can take place. In the case of visualising point cloud data of floodplains, this looks as follows. WW stands for the changes in floodplains, WD stands for the digital data acquisition over the world via artificial sensors (LiDAR and multi-spectral), DG stands for the graphical representation of the digital models, GM stands for viewing a graphical representation of the data, and MM stands for the mental processes of humans after seeing the graphical representation in the form of a point cloud of the floodplains. This can then be linked back from the mental representations of humans to the world, digital model, and graphical representation.

The mental process of humans, "MM," consists of cognitive processes, which are necessary for the representation and processing of information. Cognitive mapping is seen as an abstraction of mental skills needed to collect, organize, store, recall or manipulate information. It is seen as an activity to obtain a grip on understanding the spatial world. An important detail is that a cognitive map, which is an individual representation of the spatial environment, reflects the world in the way a person thinks it is; it does not have to be correct. So this is important to take into account when working with input from a person on a particular issue. [38; 102]

2.6. Visualisation possibilities of point clouds

Visualization techniques have long been used to provide insight into complex data by visualizing it. Applications exist in various fields, including, for example, urban planning, logistics, healthcare, and market research. The domain of information visualisation focuses on graphical representation in an interface with the ability to perform interactive manipulations. The visualisation aspect is also considered a tool for visual thinking or decision-making [39]. One of the information visualisation domains is in the field of GIS, called geovisualisation. This refers to the use of certain tools and techniques to support geospatial

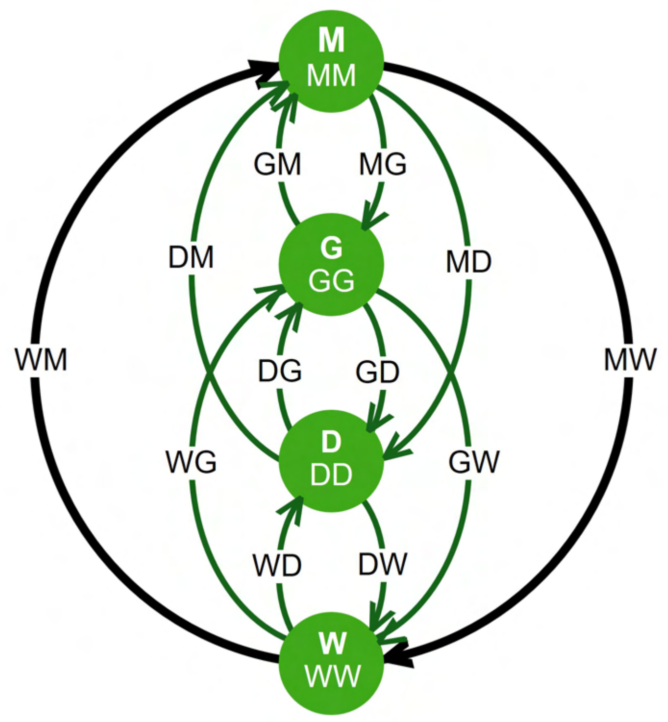


Figure 2.7.: WDGM model [102]

data analysis by integrating interactive visualization. It is widely used for analysis concerning spatio-temporal data and the exploration of landscapes, such as the detection of changes in floodplain areas [98; 21].

The emerging field of geovisualisation draws upon approaches from the discipline of Exploratory Spatial Data Analysis (ESDA), which is a manner to get insights from your data, by making use of tools for the visual exploration, analysis, synthesis, and presentation of data that contains geographic information [39]. The use of such tools makes it possible to examine data in order to obtain a deeper understanding of the phenomena to be investigated and enables the user to test scenarios and investigate possibilities. It contains the relationship within the data and its potential correlation [7].

In the case of multi-dimensional data representation, which includes point cloud data because of its z dimension, several visualisation options are possible. For now, there is no universally appropriate approach for handling and visualising point cloud datasets, especially when exploratory research is involved [11]. As mentioned earlier, point clouds are often processed, into, for example, an elevation grid, before being visualised. However, there are drawbacks regarding the limited level of detail of reality. By processing the point clouds, some data disappears, whereas a point cloud itself can be interpreted as a virtual copy of the real world [114; 115]. Due to this reason, Verbree and Oosterom [2015] recommend direct analysis on point cloud data to avoid such problems. Moreover, Poux [2020] states that direct visualisation of point clouds guarantees a simple application procedure given the elimination of data transformations that are time-consuming. Therefore, existing visualisation capabilities of unprocessed point clouds will be examined.

HCI is the scientific field of identifying the human interaction with computers via for example an interface [42; 13]. To translate multi-dimensional data into an interactive tool, the following factors need to be considered. First, human interaction, its usability, data display, interface, and interactive options to play with the data. The challenge is to create an application which enables several functionalities in a simple and useful interface. It is crucial to consider the lack of knowledge among users of the interface regarding point clouds, which causes the need for an interface that is easy to use and understand, in other words user-friendly. This makes it important to provide assistance where necessary so that users are able to use the application correctly [6; 39].

According to Shneiderman [2003] the starting point of developing an advanced graphical user interface is as follows: overview first, zoom and filter, then details on demand. The most common way is described as follows. By first showing an overview of the data, it is clear what overall view the user is looking at. After this, it is possible to zoom in on objects of interest. The user can then filter out items and obtain certain details of an item. An important aspect is the history task that allows users to recall actions they have performed. In the end, a selection of important findings can be extracted from the data [94].

In addition to the use of visualisation, the exploration of point clouds requires the use of an interactive method for the user. Dykes [2005] argues several examples of interactive visualisation techniques. One of them is dynamic projection, which is an "automated navigation operation in which the projections are dynamically changed in order to explore a multi-dimensional data set". Another method is interactive filtering, which is a combination of select and view enhancement. In this way, a dataset can be divided into sections, allowing a certain focus on objects of interest. The well-known modification technique, zooming, is also mentioned. By using this option, non-important information can be omitted by focusing only on the compressed form of the relevant information. Distortion is a technique that displays some data with a high level of detail while others have a lower level of detail. Two popular techniques are brushing and linking, which are also often combined. Brushing is an interactive selection process and linking allows data to be translated into other views. Another technique used to visualise point clouds is Eye-Dome Lighting (EDL). It is a method, depending on the viewpoint, to enhance depth perception by using shading techniques. Thus, projected depth information is applied to point cloud visualisation [15]. Another possibility is rendering, which is a technique for computing with the attributes of points, such as colour or intensity [78]. Combining different visualisation methods avoids any shortcomings. For example, brushed points can be highlighted in the visualisation, where certain correlations can then be detected. Another advantage is that applying linking and brushing in conjunction with other techniques provides new information.

In the case of maintenance processes, it should be able to show where changes have been observed over measured time. This is so that the user can immediately see which objects have shifted, for example, or grown in the case of vegetation. This could be done through an integrated colour scale that would allow users to more easily recognise certain patterns.

There are several existing interactive visualisation tools that each offer several interactive tools. One of them is the Visualisation Toolkit VTK, which is an open-source software system with a library for various processing and visualisation techniques. Both Python and C++ support the use of this toolkit. Modelling techniques such as contouring or customising the representation of points are possible [111]. CloudCompare is another open-source processing software that can be used for visualising point clouds. Various toolkits are included, such as distance computation, statistics, and more. The software supports read files and provides tools that are allowed during further development of plugins in C++ [24]. An additional open-source visualisation option is Potree, which is a WebGL-based renderer for large point clouds. The presence of a variety of measurement tools provides the ability to validate and analyse raw point clouds without additional processing steps and time [92].

An additional HCI is the use of VR instead of computers [42]. Franzluebbers et al. [2022] present a hybrid immersive headset-and desktop-based VR visualisation and annotation system for point clouds. A comparison is made between different interfaces for annotation and counting tasks oriented towards application on laser scans of vegetation [42]. Some time ago, the use of VR was introduced and promoted as "it offers new and exciting opportunities to visualise 3D GIS data" and that "VR is becoming a popular tool to visualize 3D GIS data" [107]. One of the positive contributions of using VR techniques is that there is potential to improve every phase of a project regarding design, planning, and preparation [100]. Germs et al. [1999] introduced the idea of a multi-view, which included a plan, model, and world view. The data is presented using different angles of information to create an overview that is as complete and realistic as possible. This highly realistic representation provides a 1-to-1 model of reality through its virtual 3D rendering [109]. The study also states that there are three categories concerning visual interaction; orientation and navigation, selection and searching, and manipulation and analysis. To obtain the most functional 3D environment possible, this described functionality must be available. Thus, the virtual world itself can arrange for this capacity to be enhanced by interactive virtual controls [109]. De Haan [2009] and Bochove [2018] also confirm that using VR creates a perception of being in a world comparable to the realistic world, allowing the 3D model to be approached from any perspective. In doing so, the use of VR enables the user to display detailed elements in space, which would not be possible without 3D rendering. If the space provides a realistic representation of the study area, the user of the VR system can genuinely feel like they are in a different environment [107]. Although it is important that the users should be able to control their position and orientation. Additionally, Burwell et al 2012 explore the potential for using 3D visualisation for data exploration of LiDAR point clouds. The article states that a virtual environment is found to be ideal for performing 3D analysis, but that the potential depends on the need and expertise of the participants. In addition, Burwell et al. 2016 also examined the effects of 2D versus a 3D visualization on LiDAR point cloud analysis tasks. This research revealed that each of both have their own strengths and weaknesses depending on the specific objectives. For point cloud data of areas with vegetation, it is debated that a 3D gives a good understanding of the texture and detail of the vegetation. However, it is argued that a 2D versus 3D presentation is even in the interpretation of the object. All in all, the use of 3D in visualisation offers opportunities for the exploration of point clouds by interacting with geographical data.

2.7. Interdisciplinary testing of the interface

The testing of a geovisualisation interface brings several benefits. First of all is it an important aspect in order to ensure the functioning of the interface itself. Consider human-computer interaction, ease of use and clarity of data displayed. But besides this, the aim is obviously to create new insights into the use of explorative point clouds in floodplain maintenance. Bringing together various experts from other areas is a promising approach for this. Combining such expertise is also known as interdisciplinary research, which has the advantage of an enriching perspective from different fields that can potentially lead to new insights. According to Keena et al., [2016] interdisciplinary involves integrating data, concepts, theories, and methods from separate disciplines to enhance understanding of a certain issue. Thus, possible interrelations and their relevance to a problem can be brought to the attention, for which data visualisation offers an approachable way for valuable insights [52]. Also Panagiotidou et al. [2022] argue that data visualisation is seen as a central tool in the field of data-driven collaborative interdisciplinary work. It is important to mention that insights found from a test visualisation cannot be taken as the truth, given an individual's observations are only based on that person's subjectivity. Bringing together insights from different individuals, each with their own expertise, can provide creative insights not found before. However, care will have to be exercised in handling the outcome of such pooled observations and drawing conclusions from them. In addition to gaining ease of use and new insights from the visualisation, it is also important to take into account issues such as the loading time and maximum allowed size of the point clouds. [39]

3. Background and context

3.1. Setting the context - WOCU project

This research on the exploration of explorative point clouds is focused on floodplain maintenance, more specifically the WOCU Rijntakken area. These floodplains, located in the low-lying Netherlands, are an important component of Dutch water management systems. Floodplains are vulnerable and dynamic land areas that need to be well maintained to maintain their function. For this purpose, Rijkswaterstaat, which is responsible for the integrated management and maintenance of the entire water system in the Netherlands according to the Waterwet, has set up the WOCU project. This is done to control the complex task due to the huge area of 64,000 hectares. This project should ensure that the floodplains around the Rijntakken, IJssel, and Maas are maintained through the maintenance contract with various contractors dealing with the maintenance of vegetation, civil engineer management and assets objects such as banks and channels. This project consists of various contract partners involved, including innovation management, digital partners, and domain partners, which includes Van Oord. The project is divided into three plot teams Rijntakken, IJssel and Maas, with Van Oord involved within team Rijntakken. For this, the focus is on the objective of ”safe and natural floodplains for all”. The area Rijntakken runs from the east, near the German border at Lobith, to the west, near Kinderdijk and Dordrecht. The floodplains of this area lie along the rivers de Boven-Rijn, de Waal, de Neder-Rijn, de Lek, de Boven-Merwede, de Beneden-Merwede en de Nieuwe-Merwede, which can be seen in Figure 3.1. [25].

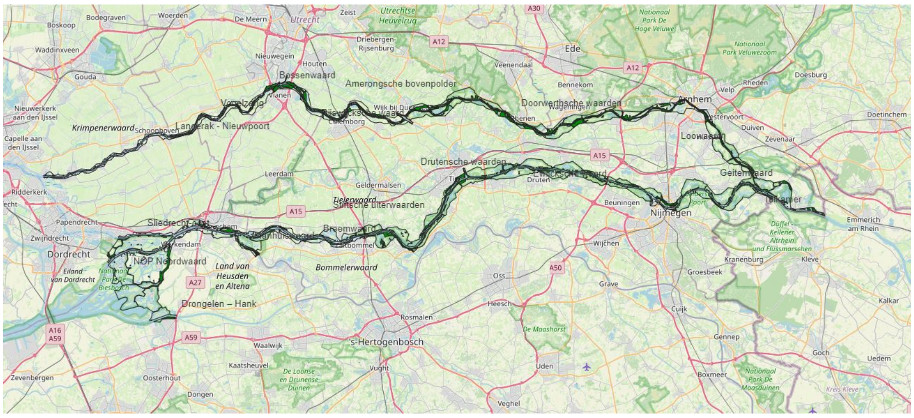


Figure 3.1.: Scope WOCU project - Rijntakken

The sprawling parcel involves a complex stakeholder field with various ownership and management partners, including Rijkswaterstaat, Staatsbosbeheer, local nature associations, and third parties. Each of them has agreed to manage and maintain specific sub-areas within the overall parcel. [25]. The Rijntakken parcel team operates on the basis of the DOEN philosophy with chain cooperation as its focal point. Thus, there are five main elements, including maximum customer value, working from intention, optimal cooperation, fair money for fair work, and learning from and with each other.

The WOCU project is divided into project management, environmental management, strategic asset management, and technical management. Under each of these fall various tasks related to floodplain maintenance, including, for example, vegetation maintenance plans, flood plans, conservation plans, maintenance concepts, monitoring and inspection plans, and system analyses, including, for example, bank erosion. The following section will elaborate on the maintenance tasks within the WOCU project.

3.2. Maintenance tasks

To delve further into the maintenance tasks the WOCU project is involved in, it is important to know exactly what needs to be maintained. When the word floodplain is mentioned, the first thing most of the people will think of is vegetation. You might imagine a piece of land next to the river with some bushes and trees. But apart from the vegetation, many other objects in the floodplain serve different purposes. The inlet and outlet, for instance, play an important role in water management during the high-water season.

All maintenance work within the WOCU project is based on the following core tasks: flood safety, water quality, nature value, and fulfilment of duty of care. Each of these core tasks has its focus related to the overall maintenance project. Ensuring the water quality of the flood plains concerns sufficient freshwater and clean and healthy water. Fulfilling the duty of care includes carrying out tree safety inspection, maintaining natural pumping stations, clearing litter, encroachments and dead fish and birds, controlling invasive species, and controlling diseases and pests. The two important core tasks involved are the regulation of flood safety and the enhancement of the nature value. The following sections will therefore elaborate deeper on what these tasks entail.

Regulating flood safety Regulating flood safety is focused on vegetation maintenance, managing side channels, and other objects present. This regulation involves two main tasks, maintenance of vegetation for proper flow and maintenance of objects involved in flood safety, such as the inlet, outlet, and natural older pumping station. The flood team within the WOCU project is involved and responsible for all work related to high water levels. This is mainly to do with the safety restrictions that have to be met regarding water inflow and outflow. The team is most concerned with changes in the floodplain due to the changing appearance of the floodplain as it may have been underwater. This makes it very interesting to look further into the current scope of work to address potential efficiency issues to implement remote sensing techniques focused on change detection. [25] Therefore the following text will clarify in detail the tasks involved in the vegetation and object maintenance.

The vegetation guidance of the project concerns the requirements for the management and maintenance of vegetation. There is an important requirement in the composition of various types of vegetation in a floodplain, given that this affects the permeability of the water flow. Because of this, there are certain boundary conditions that the floodplain must meet. The WOCU project is currently working on this on the basis of a so-called Vegetation Layer, which shows for each floodplain within the WOCU project the ideal state with respect to the classification of vegetation class. Figure 3.2 shows the vegetation layer of the Lopik study area.

Figure 3.2.: Vegetation Layer - de Vogelzang, Lopik

The Vegetation Layer can be seen as a baseline measurement, of how the distribution of vegetation should actually be. The Vegetation Monitor was developed based on satellite imagery with a resolution of 10 meters to show the difference between the actual and required state of the vegetation in the floodplain. For the Vogelzang floodplain in Lopik, the following status applies which is shown in Figure 3.3.

As an asset owner, Rijkswaterstaat has a certain duty of care that must be fulfilled. There are several objects in the floodplain that are closely involved in the maintenance activities within the WOCU project, given that these objects must function properly for water flow. Common objects include bridges, culverts, inlets and outlets, side channels, weirs, berms, spillways, and sills. This includes tasks such as performing a tree safety inspection, maintenance of roads, bridges, natural pumping stations, and small public facilities, cleaning up litter, obstructions in the channel, dead fish and birds, and controlling invasive species, diseases, and pests. [25]

Enhancing Nature Value The enhancement of the nature objective centres on the value of different nature types. The health of vegetation includes identifying diseases and pests in vegetation, such as fire blight, Dutch elm disease, and oak processionary caterpillar. This makes it important to monitor the health of vegetation to control pests and remove diseased vegetation if necessary. In the case of the oak processionary caterpillar, measures will need to be taken, including control and marking affected sites. For Dutch elm disease, it is important that in addition to control, further infections are prevented in the affected area. Currently, field inspections take place to map vegetation health, but remote sensing techniques bring opportunities to automate this. [25]

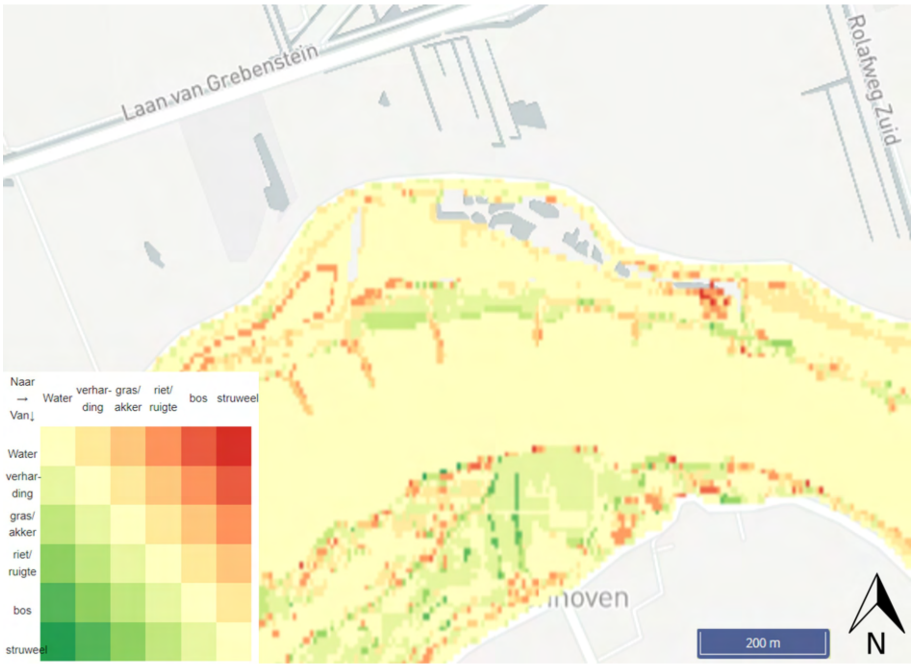


Figure 3.3.: Vegetation Monitor - de Vogelzang, Lopik

The aforementioned core tasks include various concrete requirements that are outlined below.

- The ground bodies of flood refuges should have adequate height and surface area so that they can serve as a refuge for livestock during times of flooding.
- In grazing management, fencing should be in safe and manageable condition and provide proper enclosure/segregation of grazers.
- Paved roads, paved paths and unpaved roads to Rijkswaterstaat (RWS) objects should always be traffic-safe and passable.
- Loose branches, fallen trees and dead trees thicker than 15 cm should be anchored or cleared to prevent them from entering the fairway at high tide.
- Obnoxious (floating) debris that obstructs flow should not be present.
- Dumping and setting stone with constructive function should protect the object to which it belongs from erosion.

After each flood season, all floodplains are checked for the following:

- Are dead trees or other large objects present?
- Is nuisance floating debris present?
- Check whether fencing boundaries are still in place.
- Check whether thresholds are still accessible.

- Check whether locations with flood defences are in place. Such as quays with water retaining function, no water should run along them.
- Are the traffic signs present intact and clean?
- There are no bare spots at ground protection?
  It is not sufficient if there is more than 1 bald spot with a cross-sectional area of bigger than 2 square meters (G-126, high).
- There are no bare patches visible in place of summer quays?
  It is not sufficient if there are more than 6 bare patches with a cross-sectional area of bigger than 0.2 square meters or if there is 1 bare patch with a cross-sectional area of bigger than 0.3 square meters (G-040, high).
- The roads are passable, with no large holes or bank erosion?

The maintenance work of the objects present in the floodplain focuses on controlling these assets and keeping them intact through restoration work. Current tasks include dredging side channels, restoring erosion, repairing deficient bridges, and clearing silted outlets and culverts. The assets that are present within each floodplain should function properly and are checked according to the following:

- The flow capacity must be sufficient: at least 80%
- The bottom height must be sufficient: The bottom height in front and behind the culvert is at least 10 cm lower than the bottom of the culvert.
- Culverts with a check valve should function properly: note as soon as movement is only possible with great difficulty (or not).

All appointed requirements, when they are not met, lead to active tasks to ensure that maintenance is performed here in order to subsequently meet these requirements. These tasks are in turn implemented into the work process of the project.

3.3. Innovation in the project

Innovation is very central to the WOCU project, as potential is seen in making certain work processes more efficient and effective by implementing innovative intermediate steps and integrating this into current working methods. This leaves room to explore the use of new data-related and data-driven applications. To maximise customer value within the range of the budget, asset management is utilized to identify the current status of assets located in the floodplains. By considering the potential risks of an asset, choices regarding maintenance requirements can be made. For instance, remote sensing techniques are used to boost efficiency and effectiveness in the work process. Currently, there are already several conceivable use cases of remote sensing techniques in the field of water safety, natural values, tree safety and other assets. [68]

In the context of flood safety, the aforementioned vegetation monitor, shown in Figure 3.3, has been developed to check the status of an area regarding the roughness of the area based on satellite images with a resolution of 10 metres. This shows the current roughness compared to the ideal state to see where maintenance may be needed. Moreover, the potential is seen in identifying vegetation classes and species to remove the need for field inspections through a more accurate picture of maintenance status. Furthermore, the role of floodplain elevation data is being explored by seeing how it could be used to identify, for example, vegetation classes based on elevation. [68]

The floodplains in the Rijntakken area comprise many Natura 2000 areas with different habitat types and their corresponding specified guidelines on maintaining and improving nature quality. This makes it important to work according to an ecological working protocol that takes into account the habitat types occurring in the area in question. For instance, the possibilities of checking the current status of an area for compliance with Natura 2000 guidelines and nature habitat types are currently being explored. This could potentially reduce the number of field inspections. [68]

Another possible use case is inspecting trees, which is currently done by field inspection. Remote sensing data could potentially determine the location, environmental risk class, and tree species of a tree to work more efficiently. For example, for the environmental risk class, adjacent paths could be mapped to see if a tree could pose a potential risk. [68]

Other assets present in the area could potentially be identified with remote sensing techniques, such as culverts that are not yet in the database. Furthermore, the option of identifying defects such as cracks or corrosion on structures, for example, is being looked at. Furthermore, an oversight could be made of fencing, such as barbed wire, to assess its status. Various defects such as bank erosion, tree root growth, vegetation growth, rutting, turf damage, and erosion could also be identified. [68]

All in all, it is clear that many possible applications have been conceived, but the actual applicability of remote sensing to these possibilities has not yet been mapped. Therefore, exploring one of the common remote sensing techniques, LiDAR, resulting in point cloud data, is a first step in the direction of exploring to what extent this could contribute to the ongoing work process.

3.4. Study area

This study focuses on all floodplains that fall within the WOCU Rijntakken area. To determine a relevant study area within the expansive scope of the project, the following key criteria were considered during the selection process to ensure the relevance and suitability for an in-depth analysis.

Project scope The study area must fall within the WOCU Rijntakken project year plan of 2023, so the pilot area has good integration possibilities. The Rijntakken WOCU project includes all floodplains along the rivers Lek, Nederrijn, Waal, and Merwede.

Drone accessibility The area must allow drone flights, meaning no flight restrictions within the area. For example, it is not allowed to fly over a Natura2000 area. This was assessed by using the interactive Aeret viewer, which shows updated information on which areas are available to fly over with a drone [1]. This restriction is a crucial aspect of aerial surveys in order to acquire data.

Maintenance suitability Vegetation and assets must be present so that any changes over time can be looked at. This since the study involves monitoring to detect certain changes in an area. Therefore it is crucial to have a study area with a dynamic landscape. This was examined using the vegetation monitor, shown in Figure 3.3, which was developed in-house by Van Oord and shows all vegetation and assets that are present in the floodplain.

Erosion potential The area should be located in the outer bend of the river which will most likely cause more change along the lines of water movement, providing valuable insight into erosion dynamics.

The above criteria led to the following established scope of this study, shown in Figure 3.4, positioned along the river Lek within the municipality of Lopik, located in the province of Utrecht, within the Netherlands. Figure 3.5 shows the scope on a large scale. This chosen floodplain, de Vogelzang, lies between the Lekdijk West and the outer bend of the river Lek, making it a relevant focus for the research. The river Lek flows from the Nederrijn near Wijk bij Duurstede to the Nieuwe Maas near Krimpen aan de Lek. The Lek has a length of 62 kilometres, a width of between 180 and 330 metres and a depth of 5.30 metres under NAP. [80].

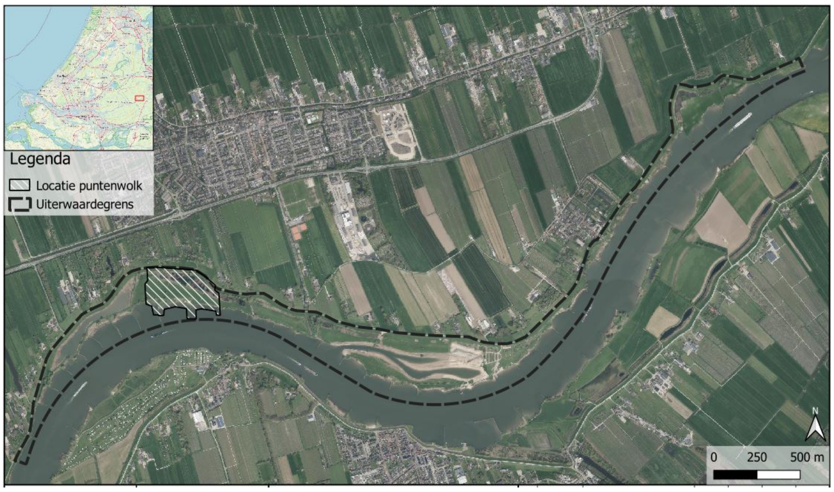
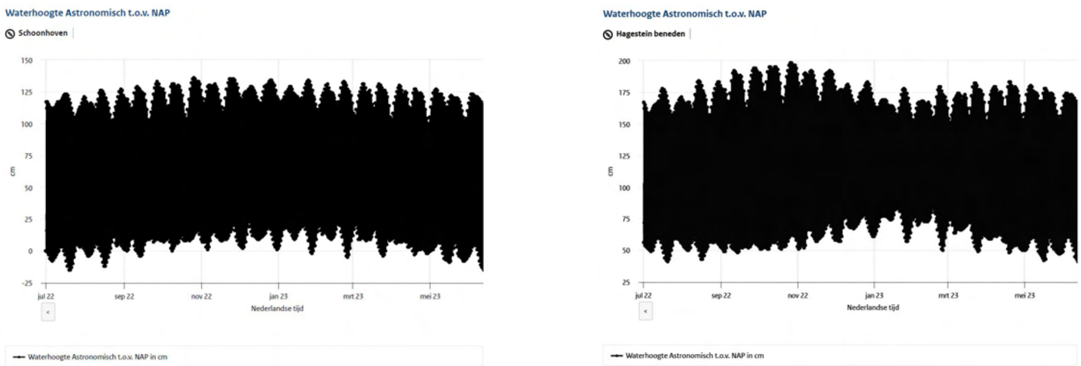


Figure 3.4.: Study area along the river Lek within de Vogelzang of Lopik

The chosen study area has an area of 0.4 square kilometers and is a relatively flat area with elevations ranging from 3 meters above to 1 meter below NAP. The water levels in the Lek River at Lopik vary due to the tide, so the astronomical high and low water levels relative to NAP fluctuate between 10 centimetres and 150 centimetres in the period from July 2022 to July 2023, as can be concluded from Figure 3.6. Lopik is positioned between these two gauging points Schoonhoven and Hagestein, allowing historical atronomic water levels to be estimated.

The floodplain consists of an open cultural landscape with valuable meander values and valuable nature (stream valley grassland). The main course of this floodplain is nature. Groynes are present along the river and the stretch of land. The area consists of grass and field, reed and scrub, forest, scrub, mix class 90/10, mix class, 70/30, water, and paved surface, which can be seen in the vegetation layer of Lopik shown in Figure 3.2. This means

Figure 3.5.: Study area: de Vogelzang, Lopik



(a) Schoonhoven

(b) Hagestein

Figure 3.6.: Astronomical water levels between July 2022 - July 2023

that there is a diverse land distribution within the area. Additionally, tree heights vary from 10 to 20 meters. As already introduced in Section 3.2, various objects are present in floodplains. In the case of this study area, the following objects are present: footpath, inlet and outlet, which are integral to the flood safety function of the floodplain.

Altogether, these characteristics provide a detailed and representative foundation for a comprehensive study of floodplain dynamics within the WOCU Rijntakken project. This enables revealing complex changes over time with a potentially useful contribution of remote sensing techniques to the work process of the overall project.

4. Research methodology

This chapter includes the methodology for the research in order to answer the main- and sub-research questions defined in the introduction (1). The objective of this research is to find out to what extent explorative point clouds, acquired from raw UAV-LiDAR, are useful in providing insights on change detection for floodplain maintenance. This chapter gives an outline of the used method, which includes a workflow of four phases, each consisting of different steps, presented in Figure 4.1. The first phase involves the acquisition of the data. The second phase involves the processing of the data. The third phase consists of the visualization of the point clouds followed by the fourth phase where the integration of knowledge leads to new insights and draws certain conclusions to reach the objective of this research.

A detailed overview of the methodology can be seen in Figure 4.2, which will be referred to in this chapter.

4.1. Phase I - Data acquisition

This phase involves both the preparation and acquisition of the data used in this research, including the data acquisition itself.

4.1.1. Preparation of acquisition

Firstly, the preparation of the acquisition of the data takes place. Various factors must be taken into account.

The initial step consists of determining the precise area within the floodplain of Lopik above which the drone is scanning. Chapter 3 elaborates on the decision of this study area. The study area consists of some vegetation and assets. The floodplains are also located in the outer bend of the river, which might be interesting for monitoring erosion. Furthermore, privacy issues must be taken into account, including the fact that the study area cannot contain any private properties such as houses. All of this taken into consideration has led to the eventual flight area, shown in Figure 3.4 in Chapter 3.

Sensors and drones

In order to know which drones and sensors are required to obtain the correct data, it is important to determine what precise data needs to be acquired. First, a point cloud of the study area must be acquired. As discussed in Chapter 2 this can be created by using photogrammetry or LiDAR technology. It was chosen to use a LiDAR sensor, given its accuracy and the possibility of multiple returns per beam. Second, the NDVI value requires Multispectral

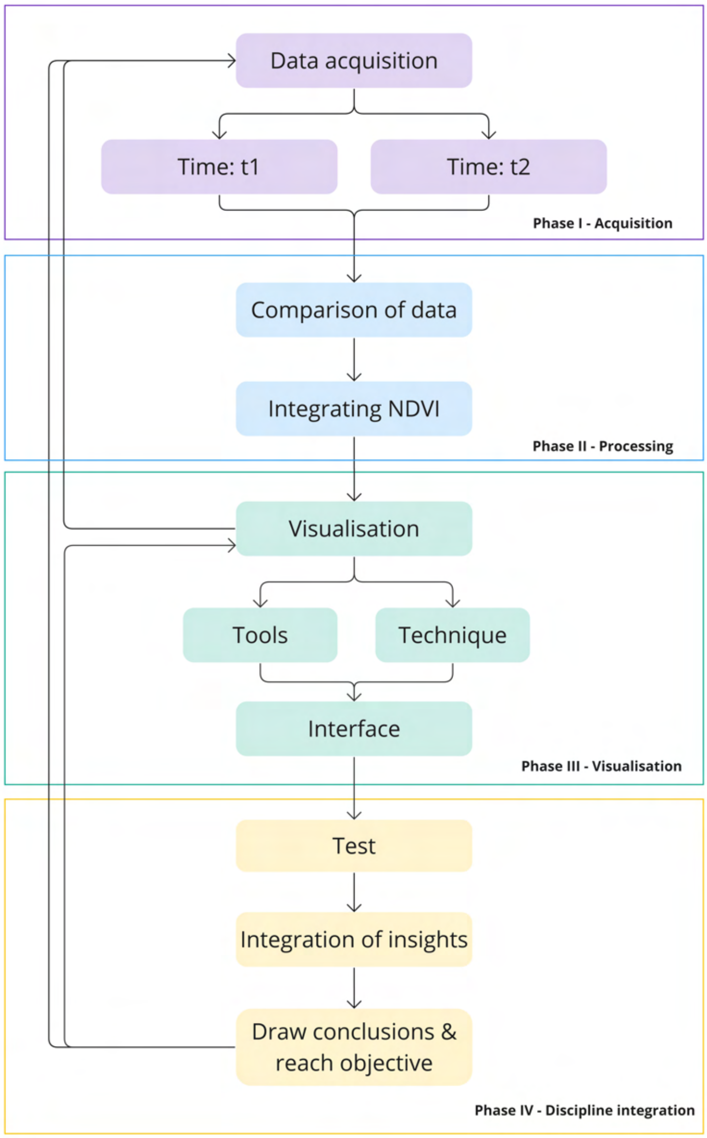


Figure 4.1.: Workflow methodology

Imagery (MSI) data, including the Near-Infrared and Red wavelength bands. For this, a multispectral sensor capable of capturing multiple wavelengths is used. Each of these two types of acquisition requires a specific sensor to acquire the data. The Survey department within Van Oord has several sensors and drones available, including a LiDAR and multispectral sensor and the accompanying drones. The advantage of having these acquisition methods in-house is that the frequency of acquiring the data can be easily determined and altered when necessary. Van Oord has a subscription to the Trimble VRS Now service, which gives instant access to Real Time Kinematics (RTK) corrections on the measured x,y, and z values of the points generated for the point cloud [44]. Using the RTK system, a radio signal from a

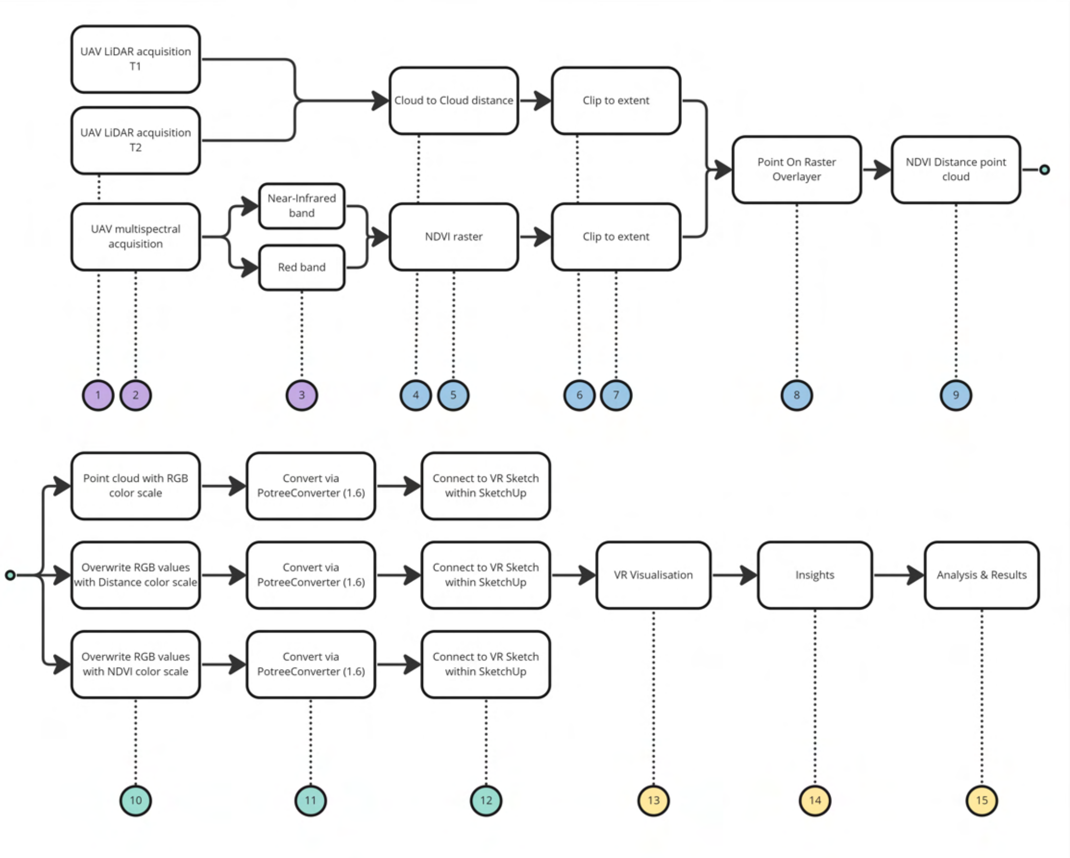


Figure 4.2.: Detailed overview of the methodology

base station provides an additional correction to the collected data that ensures accuracy.

LiDAR: sensor and drone The DJI brand Zenmuse L1 is used for the LiDAR sensor, see Figure 4.3a. This is an integrated Livox LiDAR module with an RGB camera with a 1-inch CMOS on a 3-axis stabilized gimbal, and a very accurate IMU. The sensor has a high Vertical accuracy of 5 cm and a horizontal accuracy of 10 cm. The sensor supports multiple returns, namely three. With this number of returns, is the point rate 480.000 points per second. The detection range is 450 meters. Furthermore has the sensor a high efficiency of 2 squared kilometres covered within a single flight, considering a speed of 13 meters per second, a flight altitude of 100 meters, a site overlap rate of 10%, and a point cloud density of more than 100 points per squared meter. The IP54 Ingress Protection enables the L1 to be operated within a foggy environment and is protected against dust-limited ingress. [36] The drone that matches this sensor is the Matrice 300 RTK drone, see Figure 4.3b. The drone has a maximal flying time of 55 minutes dependent on the payload of the sensor under the drone. The drone is able to operate within temperatures ranging between minus 20 and up to 50 degrees. Furthermore has the drone an IP45 rating, which means that the drone is protected from low-pressure water jets from any direction and protected against solid objects over 1mm. The sensor has a 6-directional sensing & positioning system. The maximal transmission is 15 kilometres. The drone is integrated with a hot-swappable self-heating battery system. The drone has a BS65 Intelligent Battery Station on the ground, which has space for 8 batteries that ensure to perform flights without running out of power. The maximum wind resistance is 12 meters per second. The maximum speed of the drone itself is 23 meters per second. The maximum descend speed is 7 meters per second. All these enhanced flight performance enables a efficienct and stable flight in harsh conditions. The DJI Smart Controller Enterprise connects with the drone, which enables the control of the drone and the setting of all flight parameters. This can be done with the DJI Pilot software that is developed for the M300 RTK drone. [33] Furthermore, DJI Terra, an easy-to-use software program, is used for data processing of the DJI LiDAR point cloud datasets. [35]

Multispectral: sensor and drone For MSI data, the P4 Multispectral drone with an integrated multispectral imaging system is used to provide insight into vegetation health data, see Figure 4.3c. The sensor has a maximum flight time of 27 minutes and the transmission range is up to 7 kilometers with the sensor's OcuSync system. The weight of the drone including the multispectral drone is 1487 grams. The sensor has a built-in visible light (RGB) camera and a multispectral camera array with 5 cameras for the Blue (B), Green (G), Red (R), Red Edge (RE), and Near-Infrared (NIR) bands. Of these, the Red (R), with a wavelength of 650 nm +/- 16 nm, and the Near Infrared (NIR), with a wavelength of 840 nm +/- 16 nm, is used. Furthermore, the drone uses a spectral solar light sensor, which records solar irradiance at the time of day. This contributes to the accuracy and consistency of the acquisition for each part of the day. This allows the most accurate NDVI data to be obtained. The accuracy of the obtained data is of centimetre-level through DJI's TimeSync system which aligns the controller, cameras, and integrated RTK module. For this flight is the DJI GS Pro software used in order to perform the flight mission, including the route planning and setting of all UAV flight plan parameters, and to keep contact with the drone. [34]

Flight parameters

Moreover, this area to be surveyed must be incorporated into the drone's flight path and in doing so, the correct parameters of the flight must be set. These UAV flight parameters are crucial to obtain stable data [113].

LiDAR flight parameters First of all, the specific flight parameters were defined for the Zenmuse L1 LiDAR sensor that is mounted on the Matrice 300 RTK UAV. These parameters will ensure the performance and accuracy of the acquired data during the flight mission.

The altitude of the UAV is set on 80 meters based on the research of Kersten et al. 2022, which is about the influence of the flight altitude on the accuracy of the Matrice 300 RTK UAV equipped with the DJI Zenmuse L1 sensor. In order to activate the IMU calibration, which ensures precise mapping during the data collection, the calibration Flight parameter is turned on. To guarantee a stable take-off of the drone, is the take-off speed set to 10 meters per second, which is the default one. The target surface to takeoff point is set on 0 meters. To provide balance during flight, the speed of the drone during the flight is set to 4 meters per second, which positively affects the point density of the LiDAR data. When the flight is completed, the drone will return to the takeoff site. This eliminates the need for surveyors to move during the flight, and allows them to install all of their equipment at the site.

(a) DJI Zenmuse L1 LiDAR

(b) DJI Matrice 300 RTK

(c) DJI P4 Multispectral

Figure 4.3.: Sensors and drones

In the advanced settings area, for example, flight parameters such as overlap are set. The side overlap is set on 70 %, which is the recommended setting according to the manual of the Zenmuse L1 sensor [31]. The forward (visible) overlap is also set to 70%. The size of these overlaps ensures complete data with no gaps between adjacent fly swaths and paths. In addition, with higher overlap laser pulses, more redundant points are acquired to ensure reliable data. The density of the data is also positively affected because a higher overlap results in more acquired points on the ground. [64] Furthermore is the margin kept at 0 and the course angle is also kept at the default value of 83 degrees.

Furthermore, the payload settings for the LiDAR sensor were defined. First of an important one, namely the echo mode. First of all an important one, namely the echo mode. This parameters is set to triple-echo since there is a need for a higher penetration since the terrain consists of vegetation. This ensures penetration through the leaves of the vegetation, which will provide more points in the LiDAR point cloud. A sampling rate of 160 kHz was employed, since this is the default value for the triple return mode. The scanning mode is set to repetitive scan, since this gives a better accuracy of the positions of acquired points. This setting ensures a pattern that repeats continuously back and forth as the drone moves over the to be scanned area. Lastly, the RGB coloring is put on, which means that each point gets a color due to the integrated RGB camera in the LiDAR sensor, such that a colourised point cloud is obtained. [31]

Multispectral flight parameters Thereafter the flight parameters of the multispectral flight are determined. These are set as follows.

In order to obtain an optimal image capture, the speed of the drone is set to 6.2 meters per second with a shutter interval of 2 seconds. The maximum altitude of the drone is set to 60 meters, which gives a resolution of 3.2 centimers per pixel, enhancing detailed data. Overlap ratios are crucial for a comprehensive capturing of images, which is why it was chosen to set both the front overlap and side overlap ratio at 70 %. The course angle is set to 93 degrees. Additionally, the margin is set to 0 which controls the area margin of the flight. The capture mode is set as an equal time interval, which means that the aircraft will not hover during the flight when flying on the route. The course mode of the flight is set to inside mode, which means that the whole flight path will be within the to-be-mapped area. The shooting angle is course-aligned, which means that the aircraft's nose is always facing the same direction relative to the flight path. Lastly, when the mission is ended the aircraft will be returned to home, which means that after completion, the drone comes back to its take-off point. [30].

Flight permission

The study area was chosen, as discussed in Chapter 3, based on the free zone to fly a drone, but despite the lack of flight restrictions, it is still very important to make sure shortly before the flight that there is permission to fly on the day of the flight. Therefore the Aeret [1] must be checked on the day of flight.

Weather conditions

Another detail is that weather conditions at both measuring times are closely monitored since the drone has a certain allowance of the amount of water in the environment and rainy circumstances might negatively affect the data integrity. So, firstly, rain is strictly set as a no-go weather condition. When operating wind conditions must be closely monitored, with a maximum allowable wind speed of 2.8 meters per second. This must be met for the stability of the drone that ensures the accuracy of the acquired data. Furthermore, the multispectral flight is planned during the daytime during the sunlight hours, considering the working of the sunlight detector of the multispectral drone. Operating during the day guarantees the presence of the sun used as a reference during the operation of the drone creating the multispectral images. This provides the most accurate images while mapping the floodplain.

Spatio-temporal approach

Additionally, the spatio-temporal approach of this research is an important aspect, which is established by the measurement of differences. This means a to-be-determined amount of days must be present between the first and second measurement moment. Given time limitations and restrictions regarding the presence of an authorized surveyor, the maximum available interval days is around 45. It is chosen to conduct the first survey in summer on July 17 2023, the T1 measurement, and the second survey towards the end of summer on August 30 2023, the T2 measurement. The choice is based on the change of vegetation during the summer months, given any drought that may have occurred.

Practical details

There are also some practical details to pay attention to. Firstly, the changing of batteries in the drones. The battery life does not cover the total flight time of the flight, so the battery must be changed while fulfilling the mission. For this purpose, the aforementioned DJI battery box containing 8 rechargeable batteries is used. An aggregate is also carried on to avoid a lack of battery capacity. It is also necessary to bring and wear protective clothing, including safety shoes and a fluorescent vest to comply with Van Oord's safety regulations during data acquisition.

4.1.2. Data acquisition

The acquisition takes place on two designated days, July 17 2023 and August 30 2023. As mentioned in 4.1.1 the in-house Survey department within Van Oord has the appropriate equipment and crew to operate the drones. Prior to the scheduled day of acquisition, there is close coordination with the surveyor in question, Dirk van der Valk, about the final flight plans for both the LiDAR and multispectral surveys, as well as consideration of the weather conditions. For both days, identical flight schedules are prepared depending on weather conditions on the respective day, such as wind speed and rain forecast.

First, a suitable location, identified as the return-to-home spot, is chosen on the Sterke Lekdijk. The spot functions as a designated takeoff and landing spot for the drones, strategically chosen at an inlet on the dike. This allows the drone to return at any time to ensure both safety and minimal traffic disruption, as depicted in Figure 4.4. Before the missions start, this take-off spot is clearly marked such that it is clear where the drone will take off and land to ensure an obstacle-free area.

Figure 4.4.: Take-off location Unmanned Aerial Vehicle

The acquisition day was divided into two different time slots, each assigned to the LiDAR and multispectral sensors mounted under the drones to perform both flight missions.

LiDAR flight The first flight, referred to as number 1 in Figure 4.2, captures point cloud data of the study area, which includes the DJI Zenmuse L1 LiDAR sensor that is mounted on the DJI Matrice 300 RTK drone. The drone is installed at the take-off position, including the attachment of the LiDAR sensor and the insertion of the SD card for data storage. Next, the drone is calibrated after connecting to the DJI Pilot software on the DJI Smart Controller Enterprise. The predetermined flight plan, outlined in Subsection 4.1.1, is loaded into the software, after which the drone starts executing the mission. The performance of the sensor is monitored in real-time via the live stream. A line of sight relative to the drone is maintained throughout the mission.

In case of a low-capacity notification, the drone returns to the take-off point for a quick change of the battery with a new duo set from the BS65 Intelligent Battery Station. After this, the drone will resume the mission at the position where it paused before changing the batteries.

Multispectral flight The second flight, referred to as number 2 in Figure 4.2, captures multispectral data of the study area, which includes the DJI P4 Multispectral drone with an integrated multispectral sensor. Similar installation steps as mentioned above are performed, including installing at the take-off position, SD card insertion, and calibrating of the drone. The main difference is that the drone connects to an installed app, called DJI GS Pro, on an iOS iPad [32]. The iPad serves as the controller of the drone. The performance of the sensor is also monitored in real-time via the live stream. A line of sight relative to the drone is also maintained throughout the mission. Given the shorter duration of the flight, there is no need for battery replacement. After the mission is completed, the drone returns to the take-off location.

After obtaining the point clouds and multispectral images on both scheduled days, it is time for the next phase. Herein, a detailed comparison of the point clouds from the T1 measurement and the T2 measurement is performed and the multispectral data is converted to an NDVI raster for subsequent integration with the point cloud.

4.2. Phase II - Data processing

The second phase concerns the processing of the acquired data, including the change detection between both point clouds, the computation of the NDVI value, and the quality of the collected data. The processing is divided into the preprocessing of the drone data and the processing of the raw data. This includes the creation of the LAS file with the point cloud data. Subsequently, is the change detection computed, through the use of comparison techniques between the acquired point cloud data of the T1 and T2 measurements. For this, it is important to use the most suitable method to achieve the most accurate and reliable results for a relatively flat terrain with vegetation. Furthermore, the NDVI value is computed which concerns the vegetation health. Lastly, the quality of the collected data is elaborated on.

4.2.1. Preprocessing

The acquired LiDAR and multispectral data was processed by the survey department within Van Oord. The LiDAR data of the T1 and T2 measurements are both processed into a LAS file with the raw point cloud data. Furthermore, the multispectral images of the Near Infrared band and Red band were converted to an NDVI raster, referred to as numbers 3 and 5 in Figure 4.2. This was done by subtracting the reflectance values of the NIR and Red wavelength bands and then dividing the residual result by the sum of them. This conversion was performed in the PIX4D software and resulted in an NDVI tiff file.

Both the point clouds and the NDVI grid must have the same extent. All data layers are overlaid and a shapefile polygon ”extent” is manually drawn that overlaps with all three data layers. Both point clouds of the T1 and T2 measurements are clipped based on the created extent polygon, referred to as number 4 in Figure 4.2. The QGIS ”Clip” function within the ”Point cloud data management” processing toolbox is used. The NDVI grid is also clipped based on the extent polygon by using the QGIS ”Clip Raster by Extent” raster tool, referred to as number 7 in Figure 4.2.

4.2.2. Adding of the attributes

After preprocessing, the point cloud can be extended with additional information by adding attributes that make the point cloud exploratory. As mentioned in Chapter 2, maintenance comes from changes that have occurred in a particular field. Therefore, you can compare point clouds from two different times to determine the change in distance for each point. This provides insight into the changes in the terrain and can be added as an attribute to each point in the point cloud. In addition, in the context of floodplains, it is also relevant to determine the health of the floodplain to gain new insights from an ecological perspective. This attribute can again be added to the point cloud so that the point cloud can hereafter be visualized based on this information. The following sections describe how to calculate the distance between the point clouds and also explain the addition of the NDVI values to the point cloud.

Cloud to Cloud Comparison

Different methods were discussed in the related work in order to detect changes between certain point clouds. Considering the research of [28], the C2CD is chosen as it is more simpler method to implement and thereby sufficient for this thesis. In order to implement this method, it has been chosen to make use of CloudCompare, which is an open-source software program. The C2CD calculation is integrated into one of the available tools of the software, which automatically calculates the differences in the position of the points between the two point clouds based on the shortest distance between each pair of points from these point clouds. The input to the method requires exactly two point clouds, the Reference cloud and the Compared cloud. The Reference cloud is used as a reference, which means that the distances are calculated relative to these points computed. However, it is good to make sure that this point cloud also has the highest density compared to the compared point cloud to avoid using a local modelling strategy. The Compared cloud is the one on which the distances will be computed. The distance will be computed for each point in the compared cloud relative to the reference cloud, which is referred to as number 6 in Figure 4.2. [23]

The distance computation requires several parameters. First, the compared and reference cloud must be designated. For this study, the first measurement, the T1 measurement, is considered the reference point cloud and the second measurement, the T2 measurement, is considered the compared point cloud. Next, the general parameters are filled in, in which the octree level is set to auto. The octree level refers to the level of subdivision of the octrees at which the distance computation will be performed. Changing this value will affect the computation time of the calculation. The maximum distance parameter is used to avoid taking into account points that are too far away. Therefore several threshold values, ranging between 0.75 and 4 meters, are tested to find a reasonable value that suits the changes within the spatio-temporal time frame of this research. Moreover, the histogram distribution of the amount of occurring distances throughout the comparison is included to identify the mean and median values of the distance between point clouds. This selectable value causes this threshold value to be set for points that have a distance value greater than this threshold. The multi-threaded is on to ensure that all available CPU cores of the computer are used. The x, y, and z components are not turned on, given that there is no interest in the distance between each compared point and its nearest reference point along each dimension. The reason for this is that local changes are considered, so hence the specific dimension is not relevant. It is not necessary to use local modelling given that the density of both point clouds are identical because the same flight parameters were used during the acquisition of the T1 and T2 measurements. After the calculation is completed, the C2CD is added as an attribute to the reference cloud. Finally, the reference point cloud is exported as a LAS file, having the new attribute "C2CD" added, so that it can be further processed.

NDVI

The vegetation health of the area can be derived from the NDVI values. For this purpose, the multispectral data has been converted into an NDVI grid containing this information. The point cloud can be expanded by adding this information to each point so that an instant overview of the health of the entire point cloud can be displayed. It was chosen to use FME, a geospatial software platform for extraction, transformation, and loading. This program can read and write data from a wide variety of formats. In between reading and writing, the data can be transformed using the so-called transformers. The reason for using the program is that it offers a wide selection of point cloud transformers within the point cloud category.

In the case of creating an NDVI point cloud, two data formats are relevant as input data, namely the point cloud itself and the NDVI raster. The Reference cloud with the added C2CD attribute is used as input point cloud. This point cloud is read by the "ASPRS LiDAR Data Exchange Format (LAS) Reader/Writer". [83]. LAS versions 1.0 through 1.4 are supported. The NDVI raster is in tiff format and is read by the "TIFF (Tagged Image File Format) Reader/Writer" [86]. After both datasets are read in, they can be combined into an NDVI point cloud by implementing different transformers. The points are overlaid on the grid so that each point is assigned the value in the corresponding grid pixel on which it falls. To do this, a so-called "component" must first be created, where the NDVI value of each point will be stored. This is done with the "PointCloudComponentAdder", which requires as input the point cloud feature [84]. This new created component will be the NDVI value for each point, with the component name "NDVI", data type Int32, and value 0. Subsequently, the output of this transformer can be integrated with the NDVI raster by using the "PointCloudOnRasterComponentSetter" [85], which is referred to as number 8 in Figure 4.2. This transformer receives the two sets of input features, the point cloud and the NDVI raster, which must have the same coordinate system. It then assigns a value for each point in the point cloud to the newly created NDVI component based on the location of the underlying NDVI raster. The corresponding band value is extracted and then added to the specified NDVI component of the point. Thus, the output of this transformer is a point cloud feature with an NDVI value added to the NDVI component. This new feature is then written out as a LAS file with the "ASPRS LiDAR Data Exchange Format (LAS) Reader/Writer" [83]. The exported point cloud file contains both the C2CD and the NDVI value for each point, which is referred to as number 9 in Figure 4.2.

Moreover, the NDVI grids obtained from the T1 and T2 measurements are compared to each other to assess global changes in NDVI values. This is done in Quantum-GIS (QGIS) using the Raster Calculator function, where the newest measured NDVI is subtracted from the oldest NDVI value. This difference can then be compared with the NDVI trend line of the difference in NDVI values in the Netherlands between July and August to verify the values obtained against the trend.

With the calculated C2CD and NDVI values, the change in distance and observed vegetation health for each point can be displayed. It is important to include the quality of the data obtained and processed to ensure that correct data is used and displayed from which certain conclusions will be drawn in this study. Hence, data quality is elaborated in the next section.

4.2.3. Data quality

The quality of the data is important to determine the extent to which the collected data represents reality, as the data is used as a visualization of the dynamics of the flood plains. The quality of the raw data and the attributes added during the process will be assessed.

Data quality includes accuracy, resolution, consistency and completeness. The resolution of the data is about the smallest change that can be detected in the measured quantity. For the data collected in this study, spatial, temporal, and spectral resolution are particularly important. These are all relevant to determine the extent to which the acquired and processed data represent reality. [76]

The spatial resolution of the multispectral data is the size of the smallest feature that can be detected in the acquired data [60]. This is dictated by its Instaneous Field of View (IFOV). This IFOV is projected on the ground as Ground Instantaneous Field of View (GIFOV) and represents the Ground Sample Distance (GSD). Ultimately, the pixel dimension of the acquired raster depends on this GIFOV in combination with the sampling rate [76]. For the LiDAR dataset, this is the density of the point cloud. The density of the point cloud depends on the flight parameters, including altitude and overlap. For example, when flying lower and with a large overlap, there will be a greater density of points per square meter. One can imagine that at the moment the LiDAR data is acquired at a higher altitude, the diameter of the beam pulses on the ground surface to be measured will be larger than when flying at a lower altitude. A larger diameter also means a lower accuracy of the actual coordinates of the point being surveyed. Thus, it can be stated that the flight altitude is an important parameter in assessing the quality of spatial resolution.

The spectral resolution is important for multispectral data, which concerns the ability of a sensor to measure specific wavelengths of the electromagnetic spectrum and its width [74]. For the multispectral sensor, DJI Phantom 4, this resolution concerns the Red, RedEdge, Green, Blue, RGB, and NIR wavelengths. In the case where the wavelength bands for the respective channel are narrow, it means a finer spectral resolution. The wavelength bands for the DJI Phantom 4 are presented in Table 4.1 below.

The temporal resolution, denoted by the time interval between the acquisition days, is crucial for analysing the acquired data [97]. It contributes to capturing and understanding changes within this temporal scope, such as vegetation growth. This temporal dimension unveils certain dynamic processes over time within the study area. There are different influences

Table 4.1.: Wavelengths - Multispectral sensor

Band	Wavelength (nm)	+/- (nm)
Red Edge (RE)	730	16
Near-Infrared (NIR)	840	26
Green (G)	560	16
Red (R)	650	16
Blue (B)	450	16

including seasonal variations and environmental fluctuations. Therefore, the temporal resolution of the data must be included in the analysis of the observed trends and influences that provided insights into the natural processes of the study area.

4.3. Phase III - Visualisation of data

This phase consists of the visualisation interface of the point cloud data. As described in Chapter 2, several visualization techniques are available to display point cloud data. The visualization of point clouds consists of the interface, which is positioned between the data and humans, and the available tools that make this interface interactive. The following sections describe the methodology for both aspects.

4.3.1. Interface

In the selection of the most appropriate visualisation interface, both the architecture and the interactive features of an interface are taken into account. The Potree visualisation technology, a WebGL point cloud viewer designed for large data sets, and the utilization of VR technology were compared. Attention has been paid to the representation of the data, including the possibility of using colours to indicate differences more clearly, overlay capabilities to view the point clouds at T1 and T2, and any annotations with further descriptions. In addition, the usability of the interface was assessed in terms of intuitiveness, ease of use and the ability to navigate through point clouds, such as zooming, rotating, filtering and switching screens. Furthermore, the possibility of modifying particular variables to impact the data, such as establishing a threshold, is examined. Virtual reality is chosen as the preferred interface for displaying point clouds in 3D, due to the possibility of interactive exploration by manipulating the position and orientation of a user. Additionally, it has the potential to create a realistic perception of the spatial environment via detailed visualization of the world. Moreover, VR has the potential to enhance every phase of a project as mentioned in Chapter 2.

There are multiple VR headsets available on the market, of which Van Oord has the Meta Quest Pro VR 256 GB headset. This headset is a new design of Meta which allows one to experience the virtual world in a different way due to the different levels of VR intensity. The hardware includes 12GB of RAM and 256GB of storage capacity. With Wi-Fi 6E operating in the 6GHz broadband spectrum, the VR experience can be streamed seamlessly to the computer, achieving a fast throughput of up to 1.6Gbps. Additionally, the headset boasts high-quality imaging of 22 pixels per degree, and multiple users can collaborate with ease. [62] First, it was explored how the point cloud could be represented in this Meta Quest Pro

VR headset. This requires a software application supported by the Meta Quest Pro that is user-friendly, has fast loading speeds for large amounts of data, and also allows movement through the cloud with zoom and rotate functions. VR Sketch is a viable solution as it is an add-on extension for SketchUp, enabling users to create, edit, and view virtual reality models. VR Sketch enables displaying point clouds in the VR headset, by executing the following steps. [96]

It should be noted that currently, the VR Sketch application only allows for reading of the x,y, and z coordinates of a point and its RGB values. This means that no additional attributes can be read yet. So, in order to reveal the custom-added attributes, C2CD and NDVI, a distinct LAS file must be generated for each attribute. The RGB value for each point in the point cloud is replaced with the corresponding color scale for the attribute value of that point. This is done in Feature Manipulation Engine (FME), which is referred to as number 10 in Figure 4.2.

Once the three specific LAS files, including RGB, NDVI and distance, have been processed, the following steps are required to view them through the VR headset. First of all, the LAS files are converted into a POTree format, which is done with the PotreeConverter release 1.6. The LAS files are converted via the command-line tool to a directory structure containing a cloud.js file, which can be read by VR Sketch. This is referred to as number 11 in Figure 4.2. The reason for the conversion is that this format has split the data into multiple files in order to speed up the rendering of the data. The files are organized such that only a fraction of the entire amount of points is loaded at the same time depending on the current position relative to the data. Thereafter, the VR Sketch application is downloaded onto the VR headset. Subsequently, a connection is established between the VR Sketch extension on the computer and the VR Sketch application on the VR headset. An empty SketchUp model is sent to the headset with the ”Send to VR on Oculus Quest”. After VR Sketch is started on the glasses, the 6-digit number is entered, which creates a connection between the SketchUp model and the VR Sketch app on the VR headset. The moment the connection is established, a point cloud can be loaded with the ”View a point cloud” button, which is referred to as number 12 in Figure 4.2. Next, the size of the points can be adjusted, which determines how they will be displayed. This parameter is set to the size 2.5. In addition, the number of points that can be displayed simultaneously can also be adjusted, which affects the rendering time. The number of points is set to 2.5 million. This whole procedure is likely to be time-consuming. Therefore, it is performed initially on a small part of the dataset to verify its efficacy before implementing it to the entire dataset. [96]

4.3.2. Tools

The VR Sketch application used to display the point clouds includes several interactive features for the user to explore. The Meta Quest Touch Pro controllers that come with the system enable the user to easily adjust their position relative to the presented point cloud. The user can scale the point cloud, allowing the 3D model to be zoomed in and out. Furthermore, the model can be rotated so that the model can be viewed from a different angle. In addition, the height of the model relative to the user can be changed by dragging the model down or up. This allows one to view the model exactly from the side, bottom, or top, for example, to obtain a cross-sectional view of the area. Furthermore, the user can move through the point cloud, either by walking through it or flying over it to another location in the field. All in all, it is possible to display the model as if it were a maquette at what position, distance, and size relative to the user wearing the VR headset. Furthermore, the colored points provide an even more detailed reality of the terrain by creating depth. Thereby, objects, for example, a tree, can be recognized more easily. It is not possible to set threshold value ranges for the point cloud. However, the "point cloud" tool can be utilized to hide specific parts of the point cloud. This enables improved visibility behind an object, for instance. It is also possible to draw in the point cloud to highlight certain points of interest, for example. Furthermore, it is possible to record a VR video to review the experience of a user. In addition, the size of the points can be adjusted when loading the point cloud which can enhance the appearance of the 3D model as a whole by slightly increasing the thickness of the points. Furthermore, it is easy to switch between the three attributes, namely RGB, C2CD, and NDVI, by loading the point clouds successively. The user can hold up the headset at that point. Because the position relative to the cloud remains identical, a quick switch can be made the moment the user wants to use the point cloud with a different colour scale. All of these interactive features enhance the exploration of the point cloud by the user.

You could compare the virtual model to the 3D maquette seen in an excerpt from the series Black Adder Goes Forth [41]. In it, it is joked that the maquette shown is the amount of land recaptured since yesterday, to which there is initially a positive response. It is then asked "What is the actual scale of this map?", after which it becomes clear that it is a 1-to-1 life-size representation. Of course, this is brought as a joke, but the reaction of the persons standing around the model can be compared to the participants of this research to whom the 3D model of the floodplains is visualized in VR. As the person in the excerpt says, "It is superbly detailed, look there is a little worm", this can be seen as the interaction between the participant and the virtual 1-to-1 representation of the floodplain in the form of a point cloud. It is then asked about the actual amount of land retaken, after which the person measures the maquette and says "17 square feet". This can be compared to a tool in the VR representation, which stimulates the interaction between the participant and the 3D model.

Once the prototype of the visualization interface is ready, the next phase of discipline integration will commence.

4.4. Phase IV - Discipline integration

This phase consists of identifying involved disciplines, conducting visualisation test days, and integrating the resulting insights. The overall idea of the integration of insights from different disciplines is shown in Figure 4.5. The steps of Norman's stages of action model are followed in the process of interaction to better understand the mental representation of disciplines. This starts with the creation of a goal and intention, then the interaction with the explorative point cloud takes place, after which the interpretation takes place to arrive at an evaluation and outcome [65]. The following sections further explain these taken steps, including the disciplines involved, human interaction, observations and insights.

4.4.1. Involved disciplines

Interactive point clouds are intended to bring new knowledge to the forefront among different disciplines by integrating findings of the expertise in a specific field through a floodplain visualization, in order to progress the floodplain maintenance work process. The first step

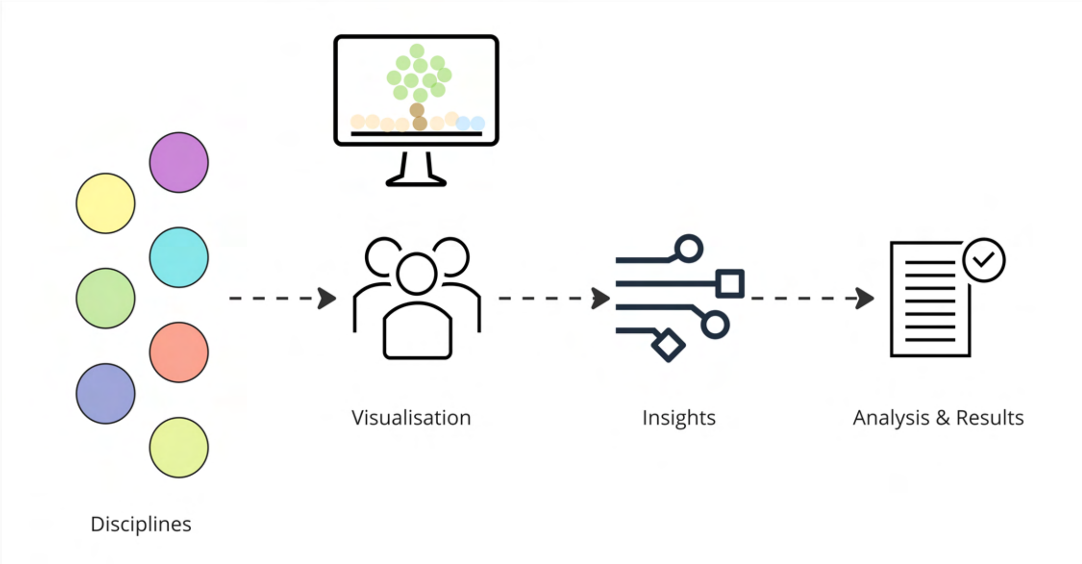


Figure 4.5.: Testing visualisation

is to determine which operational disciplines of the WOCU project will be selected for the visualisation test day. As mentioned in Chapter 2 is the involvement of an interdisciplinary approach effective in tackling complex challenges such as the maintenance of floodplains [52]. To determine who can provide valuable input during a test setup of the interactive viewer, it is important to determine which disciplines are involved in the WOCU project that are concerned with the maintenance aspect. Different parties are involved in the WOCU project, each with their own interests and different inputs. The WOCU project is divided into project management, project management, environmental management, strategic asset management, technical management, contract management, and innovation. Different disciplines and parties are involved in each section. The innovation management is done by Rebel Group. The digital partners are HAL24K Infra and Google. The domain partners are Van Oord, Witteveen + Bos, Prop, and Rijkswaterstaat. Van Oord handles the domain knowledge, is the data provider, and provides the systems. Within the Van Oord company, several departments are involved in the project, including the asset data management department which has an important role within the project. Discussions with the maintenance department revealed that floodplain maintenance relies heavily on a variety of disciplines including ecology, environmental management, civil engineering, project management, asset management, GIS and the area concierge. On the basis of the areas of expertise mentioned, it is possible to identify those who will participate in the testing of the visualisation tool; the list of participants can be found in Table A.1 in the Appendix A. The size of the test group is 16 participants. It is chosen to divide all selected participants into the disciplines from which they were chosen so that they can explore the data together at the same time. The composition of groups can also be found in Appendix A in Table A.1. The decision to group disciplines together is based on the insights of Panagiotidou et al. [2022] on data visualization in interdisciplinary collaboration. The reason this is done is because of the reinforcement effect. Based on geocollaboration principles, it stimulates collaborative dynamics with an emphasis on the shared expertise and contextual relevance within each discipline, allowing for a reinforcement effect [81]. If two test participants from the same discipline are presented with certain information, they can share their interpretations with each other to possibly arrive at new insights.

4.4.2. Testing setup

After this, a plan is made in which way these people are presented with the visualisation, including the communication, composition of participants and the test set-up, including preparation, the moment itself, and the debriefing. This preparation is crucial to obtain suitable insights after the test phase. The test days are scheduled for Wednesday, October 25, and Thursday, October 26, at the Gorinchem location, where the WOCU Rijntakken stakeholders are present. Participants were notified via mail that they had been selected to take part in the testing day of this thesis research and were requested to register at one of the available time slots of 45 minutes. Attention is devoted to participant engagement, given that Roth et al. [2008] show that high levels of motivation correspond with increased willingness to provide input. Therefore, the participants received an education, consisting of an informative flyer, which can be found in Appendix B in Figure B.1, with an explanation of the test setup and background information including the concepts of point cloud, RGB, C2CD, and NDVI. In doing so, it became clear what the purpose of the test day was, so they could approach the participation motivated with this in mind.

While outlining the test, the focus is on what to achieve. The primary aim is to investigate the potential of exploring interactive point clouds in floodplain maintenance. The second objective is to evaluate the ease of use regarding user interactivity with the interface. These two considerations determined the structure of the test setup.

Upon arrival of the participants, a concise presentation is given restating the details outlined in the flyer to ensure a clear understanding of the key concepts and the purpose of the test. In addition, the color scales of the RGB, C2CD, and NDVI attributes will be presented to ensure a clear comprehension of the significance of each color. Here the participant has the opportunity to express possible ambiguities.

The WDGM model, introduced in the related work, can be applied to this research. For instance, floodplains could be seen as worlds and experts from different disciplines as the mental representations of humans. The graphical visible representation (G) would be the 3D model of the point cloud and the digital model (D) the interface, Meta Quest Pro, of the visualisation. The entire process can be seen as follows. The changes in the floodplain (WW) are acquired with LiDAR and multispectral sensors (WD) and representation in a VR 3D model (DG), whereafter they are visualised to the experts during the test days (GM). This stimulates the mental processes of the selected experts (MM), from which insights into the whole process will be obtained. From these mental representations, insights can be translated into a feedback loop to the graphic representative, digital model, and the world itself.

The test setup follows the above concept. The idea is to display the floodplain as a 3D model in the form of a colored point cloud to the experts through the representation in VR glasses, in order to stimulate the mental processes in turn. Furthermore, the principle of visual thinking is utilised, in which the three pillars of observing, interacting, and reasoning are emphasised. The point cloud is observed in the VR model, which enables the interaction with the user, and eventually enables them to use reasoning skills to interpret what they have observed [81]. The exploring and revealing of unknowns is reinforced by the high human-to-point cloud interaction, aligning with the cube framework elaborated on in 2 [61].

Thus, the GM part of the WDGH model contains the visualization of the 3D model to the disciplines, which is referred to as number 13 in Figure 4.2. While displaying the model, the order of interaction between the user and the interface is important. As mentioned earlier in Chapter 2, it is in fact important to provide an overview first, then zoom and filter capabilities and then obtain details on demand. The test setup was devised with this in mind. The moment the participant puts on the VR headset, the 3D model of the floodplain is zoomed out and the user can zoom in and interact with the data. Thus, the concept is followed from large to small to ensure that the user first has a good overview of the area, after which more and more details can be seen.

Guidance will be provided to make the interactivity flow effectively, as the participant may be new to operating the VR controllers.

Meanwhile, the 3D model shown will be streamed from the VR headset to a large 2D screen, on which the other experts present can watch these visuals. This is done to encourage collaborative interaction between the participants. In this way, the person who does not wear the VR headset can still observe the scene to understand the observations and comments of the other participant who is wearing the VR headset. The disadvantage of this form may be that those whose turn it is later to view the 3D model enter the test less blank given they have already been able to see the scene on the 2D screen.

Meanwhile, the participant will be presented with all three point clouds showing the RGB, C2CD, and NDVI attributes. As each cloud is visualised, the participant wearing the VR headset will be asked interview questions. As the research question is exploratory in nature, a semi-schematics interview approach has been selected. This approach consists of some fixed questions in both topic and order, whilst allowing for additional questions to gather more details due to the open-ended nature. The idea of moving from a broad to a more specific perspective is in this way extended to the format of the interview questions. The participant is first asked general questions about their visual perception regarding the point cloud, followed by more detailed questions focused on their area of expertise. Given that several disciplines are interviewed, this has the advantage that different perspectives can be questioned in each discipline to then provide a wide range of insights. So, this means that for each participant there will be four of the same questions for each point cloud shown, but as a result of the interview, the questions will be adjusted for each participant. The questions will be asked during the visualization so that while answering questions the person can simultaneously look at the terrain to come up with new ideas during the interview. The four questions asked for each of the RGB, C2CD, and NDVI point cloud are:

- ”What do you see?”
- ”What do you see from your expertise?”
- ”What potential use cases do you see?”
- ”Do you consider the interface interaction intuitive?”

After both participants have put on the headset, there is room for comments to reach further possible conclusions together with discipline peers. The sessions are recorded, after the approval of the participants, so that these can be reviewed afterwards. The next step involves merging ideas and observations from the disciplines surrounding the explorative point cloud.

4.4.3. Integration of testing

The final step involves the analysis of the human interaction with the visualisation interface and the subsequent iteration integration of the results obtained.

Analysing human interaction

Firstly, a comprehensive analysis is conducted and involves examining insights from the various disciplines regarding change detection in the floodplain area, which is referred to as number 14 in Figure 4.2. The integration of observations into new insights requires reviewing the interviews and categorizing findings of each discipline based on the point clouds attribute, either RGB, C2CD or NDVI. The resulting comprehensive overview distinguishes findings by discipline, demonstrating where each discipline identified observations within point cloud data. Following the categorization, overlapping findings are examined to identify shared observations across disciplines. These potential integrated use cases are shared with project stakeholders to evaluate their applicability in the maintenance project. This will be done in the form of an interactive presentation at Rijkswaterstaat, which is responsible for the WOCU project. This allows the potential of the RGB, C2CD, and NDVI point cloud to be estimated while considering their implementation in the project work process. Subsequently, the research progresses to the final stage, involving the structured reintegration of findings into the phases of data acquisition, visualization, and processing, thereby incorporating them into the overall project process.

Reintegration of results

The reintegration of the results is a crucial step, involving considering feedback and insights from the experts involved, which is referred to as number 15 in Figure 4.2. Determining whether specific insights should adjust the acquisition, processing, or visualization phase is essential. For instance, incorporating a new acquisition technique or adjusting visualisation technique settings might be relevant. Engagement with experts is vital to achieving an optimal workflow, in which collaboration and inclusion of interests are highly relevant. In this way, a continuous feedback loop is generated, ensuring ongoing evaluation for the pursuit of an optimized process over time.

5. Implementation

This chapter includes the details of conducting the T1 and T2 measurements of the required data and the further implementation of the method described previously in Chapter 4, including the visualisation and integration of disciplines.

5.1. Requirements

To support the implementation of this study, a diverse set of software is used, presented in Table 5.1.

Table 5.1.: Overview of used software

Sotware	**Description**
CloudCompare	3D point cloud processing software for processing and visualisation of point clouds
FME	Geospatial integration platform that will be used to transform and manipulate data
LaTex	Software system that will be used for document preparation of the final thesis
PIX4D	A unique suite of photogrammetry software for processing of drone data
PotreeConverter	A converter which generates an octree LOD structure for streaming and real-time rendering of massive point clouds
PotreeDesktop	WebGL-based point cloud renderer for the visualisation of point clouds
QGIS	An open-source geo-information-system that is able to create, edit, visualise, analyse and publish geospatial information
SketchUp	A 3D design software for 3D modelling applications
VR Sketch	A software which is able to display a point cloud in addition to the usual SketchUp model

The software *PIX4D* is For the data processing, there is made use of *PIX4D*, *QGIS*, *CloudCompare*, and *FME* in order to be able to transform and manipulate the data.

For visualising point cloud viewing, *CloudCompare*, *PotreeDesktop*, *VR Sketch*, and *SketchUp* are used.

Latex is used to complete the thesis report, using the template provided by geomatics found at: `https://github.com/tudelft3d/msc_geomatics_thesis_template`.

5.2. Phase I - Data acquisition

As mentioned in Chapter 4, the acquisition consists of two measurements, namely the T1 measurement and the T2 measurement, to be able to identify a change over time. The following sections will provide further details of the days on which the flights were conducted, such as weather conditions.

5.2.1. T1 Measurement

The first measurement was scheduled for the 17th of July, 2023. The weather forecast was closely monitored the day before to ensure optimal conditions for data collection, including the wind direction, wind speed, temperature, and cloud cover. The details can be found in Table 5.2 and Figure 5.1 shows the weather conditions.

The day began with marking the takeoff site so that there was a clear and safe area for drone takeoff, as can be seen in Figure 5.4. The LiDAR flight, was initially scheduled for 2 pm. However, some delay was experienced due to the setup and calibration process of the drone and sensor, as shown in Figure 5.5a.

Some problems were encountered during the replacement of the batteries, which highlights the importance of energy management during the acquisition. The presence of only a single generator led to longer recharge times, which made it necessary to charge the batteries elsewhere which took some time. Eventually, the flight was completed without further problems. Figure 5.5b shows the LiDAR in action.

After the LiDAR flight was complete, the focus shifted to the P4 Multispectral drone. Careful installation and calibration were conducted at the take-off location, as shown in Figure 5.6a. The flight plan and parameters were loaded into the DJ GS Pro application on the iPad. After this, the mission could start to map the study area to obtain the multispectral images. Figure 5.6b captures the drone in action, showing the integrated multispectral camera with the six bands.

Table 5.2.: Weather Conditions - T1 Measurement

Weather condition	**Value**
Wind Direction	North-East
Wind Speed	1.39 m/s
Temperature	26 °C
Cloud Cover	Sunny day with occasional clouds

5.2.2. T2 Measurement

The second measurement was scheduled for the 30th of August, 2023. However, the weather conditions were quite rainy and therefore did not fit within the restrictions of the LiDAR sensor, which cannot override the IP54 Ingress Protection rating. Due to this reason, it has been decided to postpone the acquisition by one day to the 31st of August. The detailed weather conditions of this day can be found in Table 5.3 and Figure 5.3a and Figure 5.3b

Figure 5.1.: Weather conditions - T1 Measurement

show the weather conditions during the day. An important detail is the difference in wind speed which might influence the collected data in terms of the movement of vegetation. Further weather conditions are comparable to the first measurement.

This time the flight day started in the morning around 9 a.m., and again the take-off location was marked as can be seen in Figure 5.4. The LiDAR flight was conducted first and exactly the same flight parameters as during the first flight were set to have comparable accuracy for both datasets. This time no problems were encountered due to battery capacities, given the carrying of two aggregates. Figure 5.2 shows the setup of this battery construction.

Figure 5.2.: Battery construction

After completing the LiDAR flight, the focus shifted to the multispectral flight. Once again, the drone was installed and calibrated and thereafter the flight plan and parameters were loaded via the DJ GS Pro application. After this, the mission was again performed without complications.

Table 5.3.: Weather Conditions - T2 Measurement

Weather condition	**Value**
Wind Direction	North-East
Wind Speed	2.78 m/s
Temperature	16 °C
Cloud Cover	Partly cloudy with occasional sunshine

(a) Begin morning

(b) End morning

Figure 5.3.: Weather conditions - T2 Measurement

Figure 5.4.: Take-off location

(a) Set-up LiDAR (b) LiDAR in action

Figure 5.5.: LiDAR acquisition

(a) Set-Up Multispectral (b) Multispectral in action

Figure 5.6.: Multispectral acquisition

5.3. Phase II - Data processing

The processing of the data consists of several steps, including the preparation and adding of the C2CD and NDVI attributes. The implementation of these steps will be further explained below.

5.3.1. Preparation

The first processing step is to clip all input data to the same extent. The input data consists of the point clouds from the T1 and T2 measurements and the NDVI grid. The extent of this data was determined by overlaying the data layers in QGIS and extracting the overlapping extent. To do this, a new shapefile layer was first created with the geometry type polygon and the same Coordinate Reference System (CRS) as the data. Using toggle editing, a polygon feature is added that involves the overlapping extent. Next, the input data is clipped based on the created extent and the input data is converted to T1_extent, T2_extent, T1_NDVI_extent, and T2_NDVI_extent. This is now the new input data used during the next steps.

5.3.2. Change detection

This step computes the change in the form of the distance between the T1 and T2 LiDAR data. This is done in the software program CloudCompare. First, both LiDAR datasets are loaded. All standard fields, including RGB values, are selected and fields with default values are ignored. The global shift/scale settings can be adjusted. It is chosen to keep the points in the original CRS.

Loading the T1 point cloud takes 244 seconds. Loading the T2 point cloud takes just a little longer, at 347 seconds. For both point clouds, the Time SF has been shifted in order to prevent a loss of accuracy during the loading of the point clouds. Furthermore, all attributes with values that were all the same are ignored, including PointSourceId, UserData, EdgeOfFlightLine, ScanDirectionFlag, and Classification. Next, the LoD acceleration structure for the T1 & T2 clouds is prepared. For The T1 point cloud, the maximum level is 13, with a memory of 147.36 Mb and a duration of 38.9 seconds. For the T2 point cloud, the maximum level is also 13, with a memory of 216.44 Mb and a duration of 42.6 seconds.

After this, the distance between the T1 and T2 points cloud is calculated. For this, a built-in tool that falls under the distance tools of CloudCompare is used. This is the Cloud/Cloud Dist. tool, in which the T1_extent point cloud is set as Reference and the T2_extent point cloud is set as Compared one.

First, an octree is built, and the points are projected with a max depth of 21. The cells are sorted during the building of the octree. Then the distance is calculated and after this, the distance computation settings can be completed. The general parameters are as follows: the multi-threaded is enabled with a max thread count of 40, and the maximum distance is manually set to 1.5 meters since this seems the most appropriate threshold value according to the comparison between the potential threshold values.

The optimal octree level is determined by testing the 21 levels. Thereafter is the octree build and are the cells sorted. The average population of each cell is 29.7 points and the max population is 949 points. In total, there are 6071123 cells created and the optimal octree level is set to 11. The Approx distances between both clouds are computed with a duration of 54.19 seconds. The mean distance is 0.117934 meters with a standard deviation of 0.155468 meters. After this, again the LoD accelarion structure for cloud T2_extent is prepared and the cells are sorted into a max level of 13, within a time frame of 32 seconds and a memory of 213.79 Mb.

Once the C2CD is computed and added as an attribute to the Reference cloud, it is exported as a LAS file. This will be the new input point cloud for the next step.

5.3.3. NDVI point cloud

In the final processing step, the integration of NDVI values into the point cloud was executed using FME software. Initially, both the Reference cloud, containing the C2CD information, and the NDVI raster were loaded as features through the ASPRS reader and tiff reader in FME.

After this, a new Int32 component, called NDVI, was created for the point cloud utilizing the PointcloudComponentAdder. The datatype Int32 is chosen to allow negative values since the NDVI values range between -1 and 1. The output of this transformer is connected to the PointCloudOnRasterComponentSetter transformer. The component settings of this transformer are set to Custom. Band 0 is designated to represent the newly created NDVI component, ensuring the incorporation of NDVI values into the point cloud data. The output of this transformer is exported to a LAS file through a connection with the ASPRS writer. The FME script is executed with a total running time of 2 minutes and 27.4 seconds, from which CPU 73.6 seconds user, and 65.1 seconds system. The peak process memory was 1427156 kB, and the current process memory usage was 117492 kB.

The final product is the Reference cloud with a C2CD and NDVI as added attributes for each point. This point cloud will be used in the next visualization phase.

5.4. Phase III - Visualisation

The visualisation phase concerns launching the point cloud in the VR headset by using the VR Sketch application. The implementation of the required steps will be elaborated on below.

As mentioned in Chapter 4, the VR Sketch application can only display the coordinates and color of each point. This makes it necessary to convert the point cloud with the added attributes into three separate point clouds, namely the RGB, C2CD, and NDVI. This was performed in FME.

The input data in FME is the Reference cloud with the added C2CD and NDVI attributes. These are read with the ASPRS Reader. The "PointCloudFilter" is then used to filter the point cloud based on the value of both attributes. These ranges for both the NDVI and C2CD are shown in Table 5.4.

Then, each range is assigned the corresponding colour value by using the "PointCloudExpressionEvaluator" transformer that overscales the values of the R, G, and B components based on the colour scales of the NDVI and C2CD attributes. The color scale used for the NDVI and C2CD are shown in Figure 5.7. After this, the individual sections with points are combined again into one point cloud for both attributes with the "PointCloudCombiner"

Table 5.4.: Ranges for NDVI and Cloud-to-Cloud Distance

NDVI: ranges	**C2CD: ranges**
-1 and -.2	0 and 0.1
-0.2 and 0	0.1 and 0.15
0 and 0.1	0.15 and 0.2
0.1 and 0.2	0.2 and 0.25
0.2 and 0.3	0.25 and 0.35
0.3 and 0.4	0.35 and 0.45
0.4 and 0.5	0.45 and 0.55
0.5 and 0.6	0.55 and 0.7
0.6 and 0.7	0.8 and 0.9
0.7 and 0.8	0.9 and 1
0.8 and 0.9	1 and 1.25
0.9 and 1.0	1.25 and 1.5

transformer, followed by exporting both the NDVI and C2CD point clouds to a LAS file with the ASPRS writer.

After this, all three of these point clouds were converted via PotreeConverter 1.6 to a cloud.js file so that it could be read by the VR Sketch extension in Sketchup. Before a connection could be made between the VR headset and the computer, a virtual border should be drawn for the movement space in the room for safety reasons. Once the border is drawn, the VR Sketch application can be started on the headset and the connection can be started between the computer and the headset via VR Sketch by sending an empty Sketchup model to the Meta Quest Pro. Then the cloud.js files, including the RGB, NDVI, and C2CD can be easily loaded.

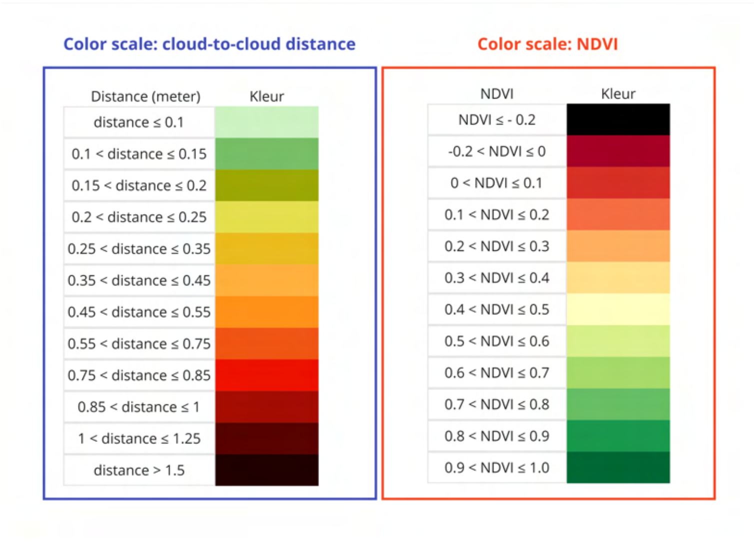


Figure 5.7.: Color scales NDVI and Cloud-to-Cloud Distance with ranges

5.5. Phase IV - Test setup

Test days were scheduled on the 25th and 26th of October, where a total of 11 different disciplines explored the 3D data.

The connection between SketchUp and VR Sketch in the Meta Quest Pro succeeded. However, the moment the VR headset had not been on for a while, it disconnected because the application assumed the user was no longer active. This caused some delay in switching test persons. The point clouds were easily and quickly rendered. Switching between the point clouds in the VR headset also proceeded without difficulty. However, there were some complications while streaming the live images from the VR headset to the computer due to an unstable internet connection. This affected the resolution of the streamed live view, making it more difficult to watch.

6. Results and analysis

This chapter describes the results of the acquisition of the data, the processing of the attributes, and the integrated insights of the conducted VR visualisation tests.

6.1. Acquired data

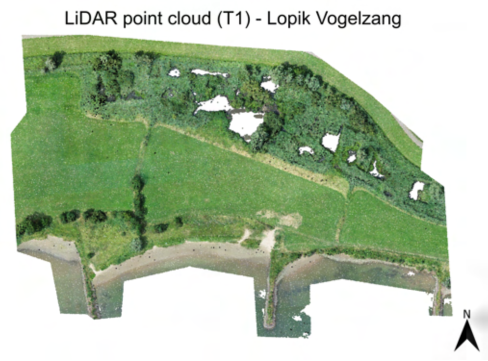
While the point clouds are not a result in themselves, the potential use of these point clouds is an important result of this research. As a result, it is essential to the permibility and continuity of this report to consider this data. This section therefore shows the results of the obtained LiDAR and multispectral data, giving a global overview, including the properties of the data.

6.1.1. LiDAR point clouds

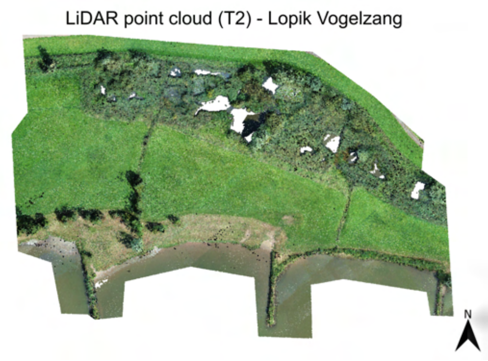
Figures 6.1a and 6.1b show the point clouds of the T1 and T2 measurements of the clipped extent area. These LiDAR point clouds are acquired with the Zenmuse L1 sensor. The point cloud of the T1 measurement has a total of 153.987.778 points, while the point cloud of the T2 measurement has a total of 180.320.911 points. This means that there is an increase in points of 26.333.133 points, which equals 17,1%. This could be due to grown vegetation, which resulted in more points being collected. The two point clouds of the T1 and T2 measurements are also visualized based on their height in Figures 6.2a and 6.2b. The points within the T1 point cloud range from a minimum of -0.5025 z value to a maximum of 82.8192. The mean z value for the T1 point cloud is 2.4374 metres and the median is a bit lower, namely 2.0877. For the points within the T2 point cloud, the z values range between a minimum of -0.1374 and a maximum of 62.8726 The mean z value for the T2 point cloud is 2.5996 and the median is again a bit lower, namely 2.0764. This means that the mean z value for the T2 point cloud increased by 0.1222 metres, while the median remained almost the same with a small decrease of 0.0113 metres compared to the T1 point cloud. To provide a visual representation, Figure 6.3 shows a histogram for both the T1 and T2 measurements by displaying the point distribution per range.

In the realm of point cloud data exploration, the human eye proves to be a valuable tool. When conducting a comparative analysis of the differences between the T1 and T2 measurements, certain distinctions can be revealed easily with the naked eye. Navigating through the point cloud data unveils several structures, patterns, and subtle transformations. This exploration of comparisons led to the following identified elements that are considered as changed over time, as illustrated in the following Figure 6.4. These elements provide insights into the dynamic evolution captured within the point cloud data.

First of all, the overall color difference between the two point clouds is immediately noticeable. The points in the T1 measurement appear lighter green compared to the points in the

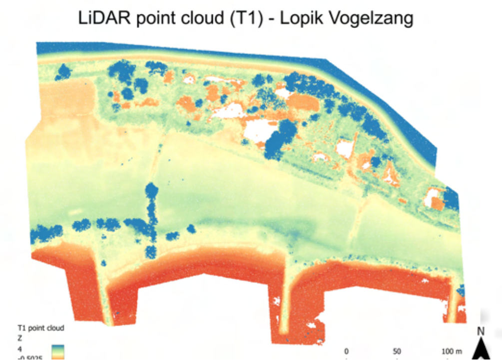


(a) T1 Point cloud - RGB

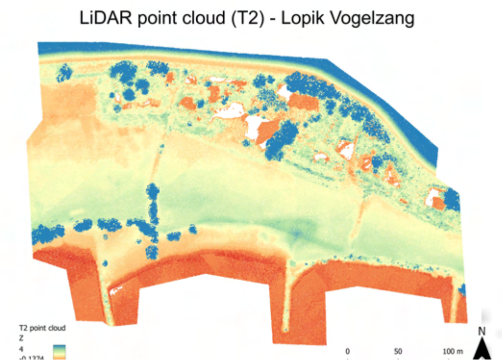


(b) T2 Point cloud - RGB

Figure 6.1.: RGB point clouds

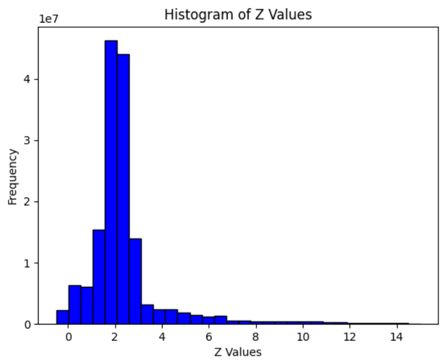


(a) T1 Point cloud - Z value

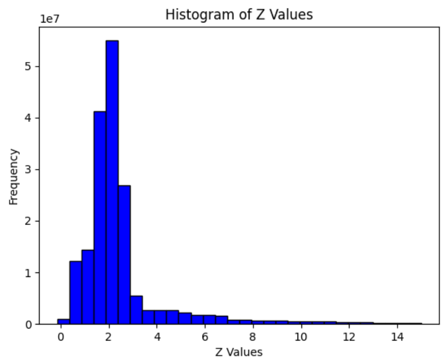


(b) T2 Point cloud - Z value

Figure 6.2.: Point clouds - Z value

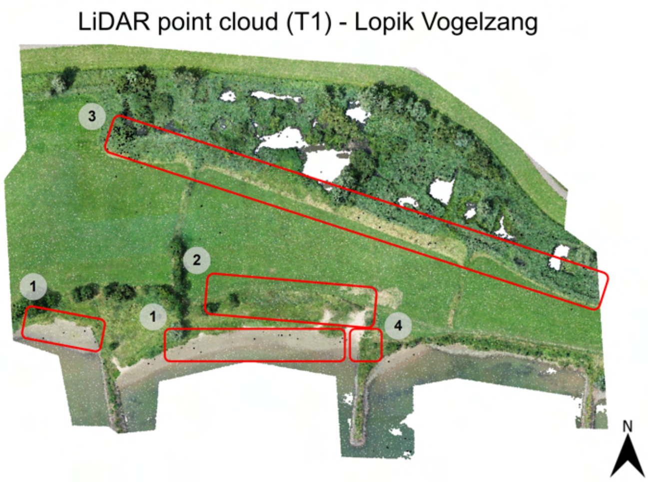


(a) T1 Point cloud

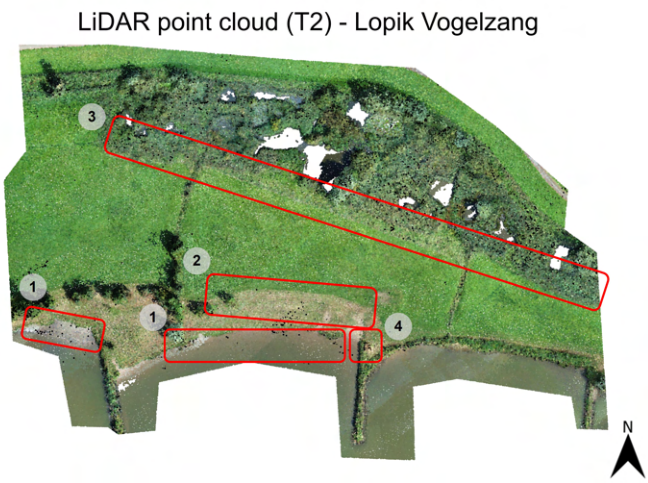


(b) T2 Point cloud

Figure 6.3.: Histogram Z value



(a) Differences in T1 point cloud



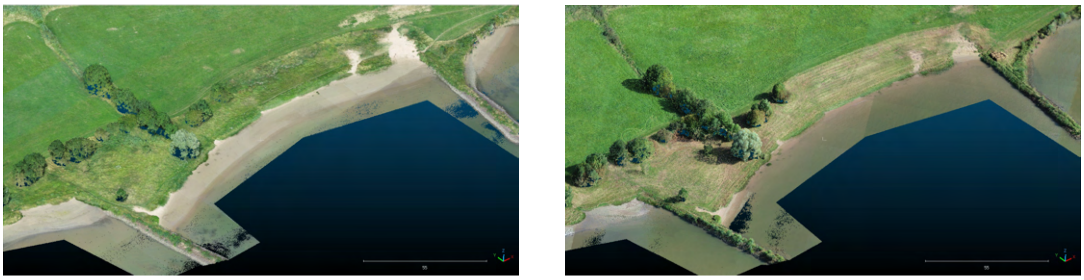
(b) Differences in T2 point cloud

Figure 6.4.: Differences between T1 and T2 point cloud

T2 measurement, which come out darker green. This is probably due to seasonal variations, where the T1 measurement took place in mid-July and the T2 measurement towards the end of summer.

Additionally, it can be seen as number 1 in Figure 6.4 that the water level was higher during the T2 measurement than the T1 measurement. Therefore, less sand is visible around the shoreline. This indicates that the point cloud accurately maps the fluctuating waterline given that the separation between land and water is clearly visible. The following Figure X shows this from a side view, so it can be seen more clearly.

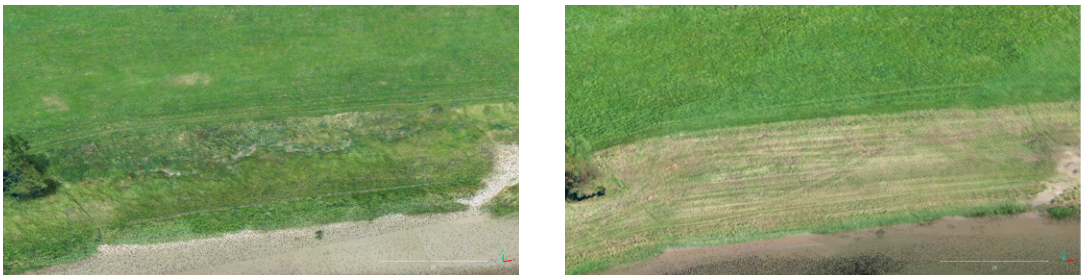
Moreover, it can be seen at number 2 in Figure 6.4 that the region above the middle crib is atrophied over time. Comparing the initial T1 measurement, which depicts a greener



(a) Water level - T1 point cloud (b) Water level - T2 point cloud

Figure 6.5.: Number 1: Side view of water level (RGB)

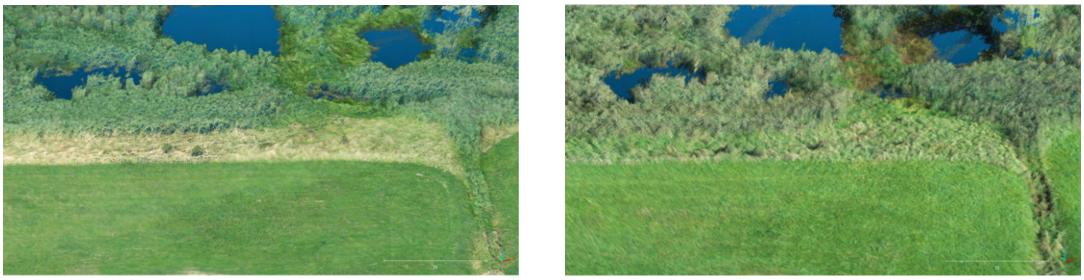
area, with the T2 measurement where the grass has changed to a more sandy area, indicates atrophication. The following Figure 6.6 shows this from a side view, so it can be seen more clearly.



(a) Atrophication - T1 point cloud (b) Atrophication - T2 point cloud

Figure 6.6.: Number 2: Side view of atrophication (RGB)

Furthermore, at number 3 in Figure 6.4, located beneath the area with taller trees, there is a horizontal strip with yellow and brownish points during the T1 measurement. While this strip of points actually became greener over time toward the T2 measurement. The following Figure 6.7 shows this from a side view, so it can be seen more clearly.



(a) Yellow and brownish strip - T1 point cloud (b) Yellow and brownish strip - T2 point cloud

Figure 6.7.: Number 3: Side view of the yellow and brownish strip (RGB)

Furthermore, a very clear example of difference has been the laying down of hay bales in between the two measurements, located in front of the middle crib at number 4 in Figure

6.4. These hay bales were not there during the T1 measurement, and are now clearly visible as points in the T2 measurement. This is therefore a good case that can be considered in the added attributes, to see how these deposited hay bales influenced the data. The following Figure 6.8 shows this from a side view, so it can be seen more clearly.

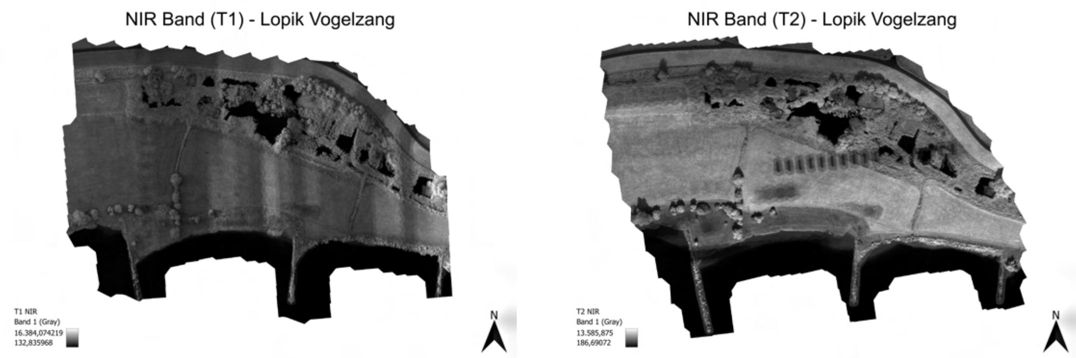
(a) Hay bales - T1 point cloud

(b) Hay bales - T2 point cloud

Figure 6.8.: Number 4: Side view of hay bales (RGB)

6.1.2. Multispectral bands

The multispectral sensor acquired the 6 bands, including Red Edge, Near Infrared (NIR), Green, RGB, Red, and Blue at both T1 and T2 measurements. The NIR and Red spectral bands are required for the NDVI. Figures 6.9a and 6.9b show the Near Infrared bands of both T1 and T2 measurements. Figures 6.10a and 6.10b show the Red band of both T1 and T2 measurements. The Near Infrared and Red bands are converted into a NDVI raster for both T1 and T2 measurements.

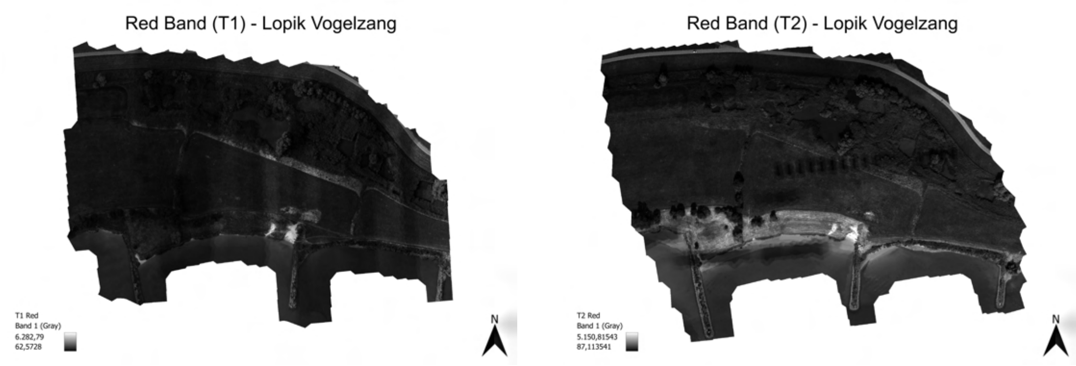


(a) T1 NIR band

(b) T2 NIR band

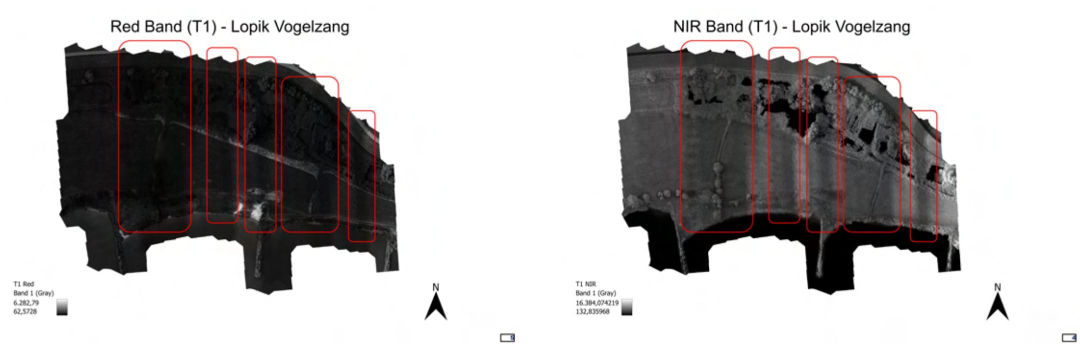
Figure 6.9.: Multispectral: NIR band

The NIR and Red bands of the T1 measurement, shown in Figures 6.9a and 6.10a, seem to have certain vertical colored areas as streaks visible, as marked in red in Figure 6.11. This could be due to a strong lightning incidence that could have caused a certain mirror-like reflective effect through the vegetation canopy. As a result, it could have led to light from one side and shadows on the other side, making streaks of gradients visible in the reconstruction of images.



(a) T1 Red band (b) T2 Red band

Figure 6.10.: Multispectral: Red band



(a) T1 Red band (b) T1 NIR band

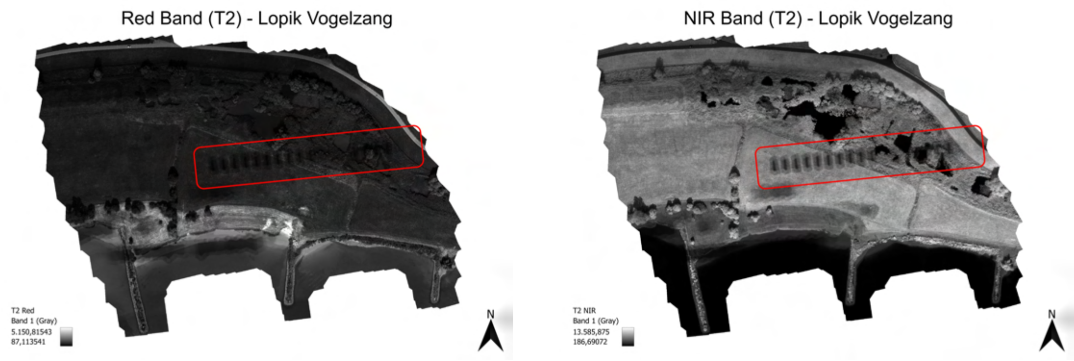
Figure 6.11.: Shadows T1 multispectral bands

The NIR and Red bands of the T2 measurement, shown in Figures 6.9b and 6.10b, indicate the presence of camera noise in the form of a repeating homogeneous pattern visible at the center of the area on a horizontal line, marked in red in Figure 6.12. Consequently, the position of the original raw multispectral images captured, illustrated in Figure 6.13, was evaluated.

This showed that certain duplicate overlapping images were acquired, which probably caused an erroneous merging of the grid. To resolve this issue, the duplicate images were removed from the raw data, and the grids of the 6 bands were restructured in DJI Terra. The result of this process was favourable, as can be seen in Figure 6.14 showing the NIR and Red bands of the T2 measurement without these aforementioned duplicated images.

6.2. Processed data

The raw acquired data was processed into an NDVI grid, which was then integrated into the point cloud. In addition, the raw point cloud data of T1 and T2 was also compared and



(a) T2 Red band

(b) T2 NIR band

Figure 6.12.: Distortion T2 multispectral bands

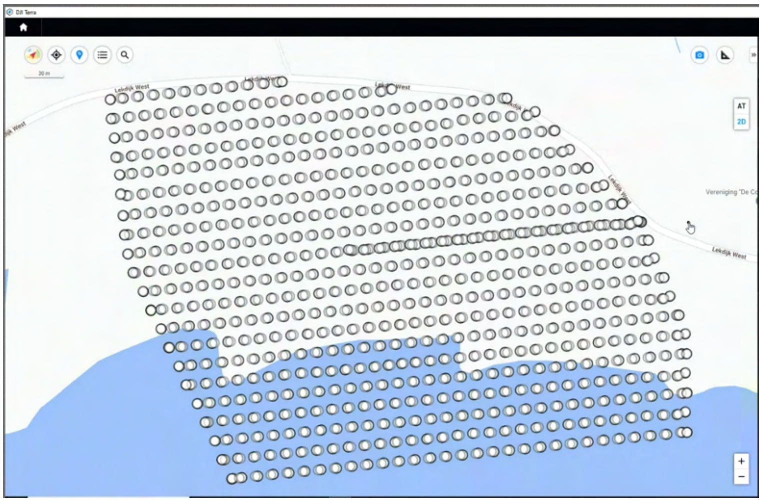


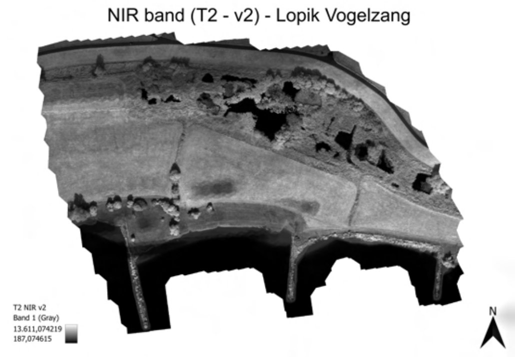
Figure 6.13.: Distortion multispectral images

formed into a point cloud with the C2CD attribute added. The following sections show the results of this processed data.

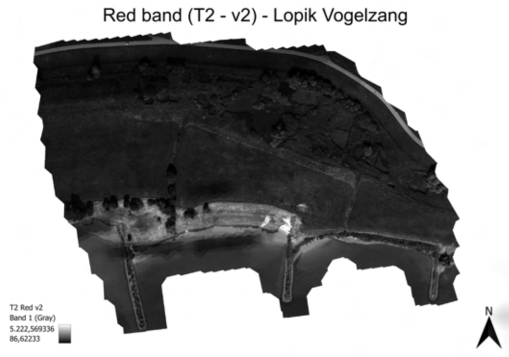
6.2.1. Cloud-to-cloud distance

The T1 point cloud, the Reference cloud, was compared to the T2 point cloud, the Compared cloud. As indicated in Chapter 4, the maximum distance threshold between the two point clouds has been tested to determine the optimal one. The results of the different thresholds that were set are shown in the following Figure 6.16, with thresholds of 0.75, 1, 1.5, 2, 3, and 4 metres. The color scale used runs from light green to red, with light green representing no change and red representing the most change. This color scale can be found in Figure 6.15.

Some appropriate features, including the hay bale on the middle crib, were monitored. It



(a) T2 NIR band (v2)



(b) T2 Red band (v2)

Figure 6.14.: Multispectral: NIR & Red bands (v2)

Figure 6.15.: Color scale: Cloud-to-Cloud Distance

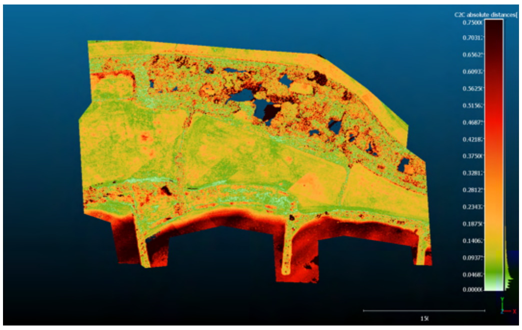
can be seen that the difference in threshold gives a different picture in Figure 6.16. It has been examined where the haybale stood out, given that this has been an actual change. It is not expected that much greater changes have occurred than the height of the haybale, which is around one meter. Moreover, the C2CD distribution is included, which can be seen in the histogram in Figure 6.17. This shows that most distances are under 1 meter. In addition, the temporal resolution of 45 days is taken into account, and as a result, the threshold of 1.5 metres seems the most appropriate for this data. Because of this, the minimum distance is 0 metres and the maximum distance is 1.5 metres. The mean distance is 0.1168 metres, while the median lies at 0.0675 metres. The standard deviation is 0.1364 metres.

When exploring this point cloud, visualised based on the C2CD of each point, with the human eye, certain observations become apparent due to the changed interplay in colors. These observations are shown and numbered in Figure 6.18

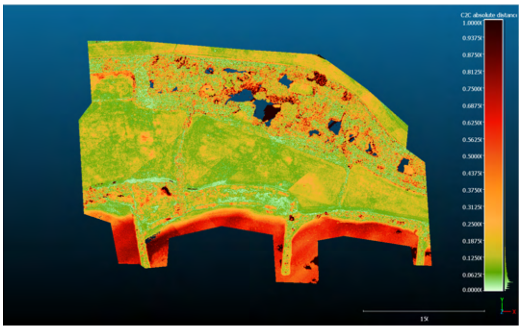
First of all, shown as number 1 in Figure 6.18, the water level immediately stands out due to the variation in colours on the shorelines, ranging from orange to red, indicating a clear difference larger than 0.5 meter. As a result, it is possible to determine that there was a difference in water level during the T1 and T2 measurements, as was also observed in the comparison of the RGB T1 and T2 point clouds. The following Figure 6.19 shows this from a side view, so it can be seen more clearly.

Furthermore, it is clear that no change seems to have occurred on the walking paths along the river bank line, shown as number 2 in Figure 6.18. This is because a clear path is visible, which is shown by the light green colored points, which is equivalent to a maximum distance of 15 cm. The following Figure 6.20 shows this from a side view, so it can be seen more clearly.

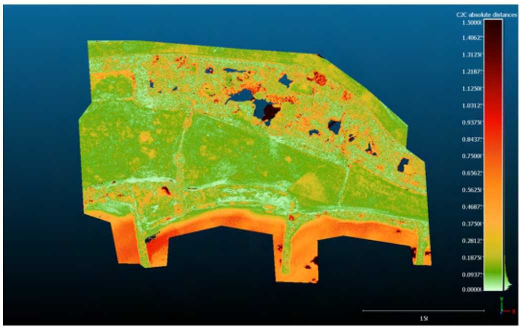
Furthermore, it is clearly visible that the tops of the trees, at the top of the study area, have undergone changes. This can be seen by the orange to red colored tips of the tree tops,



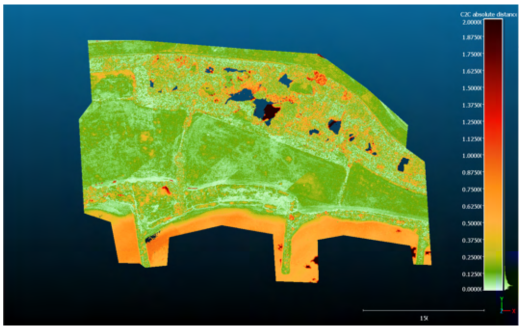
(a) Threshold: 0.75 meter



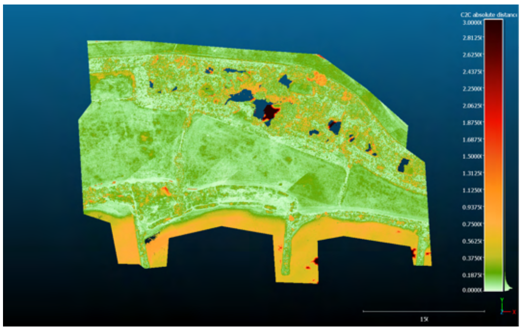
(b) Threshold: 1 meter



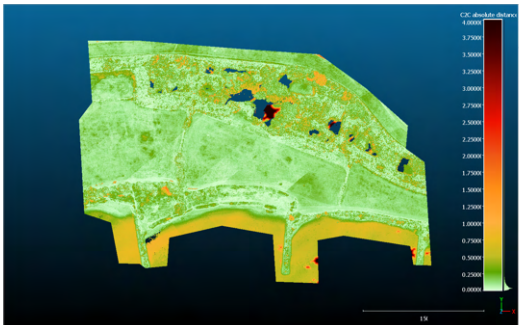
(c) Threshold: 1.5 meter



(d) Threshold: 2 meter



(e) Threshold: 3 meter



(f) Threshold: 4 meter

Figure 6.16.: Cloud-to-Cloud Distance thresholds

shown as number 3 in Figure 6.18. The following Figure 6.21 shows this from a side view, so it can be seen more clearly.

The example with the hay bales placed in front of the middle crib is also clearly visible in the C2CD point cloud, shown as number 4 in Figure 6.18. The orange color of the points denotes a distance of around 1 meter between the T1 and T2 measurements, indicating the detection of hay bales positioned placed over time. The following Figure 6.22 shows this from a side view, so it can be seen more clearly.

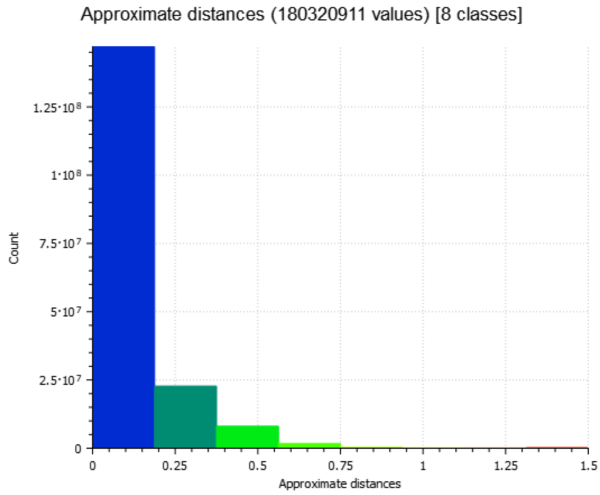


Figure 6.17.: Histogram Cloud-to-Cloud Distance

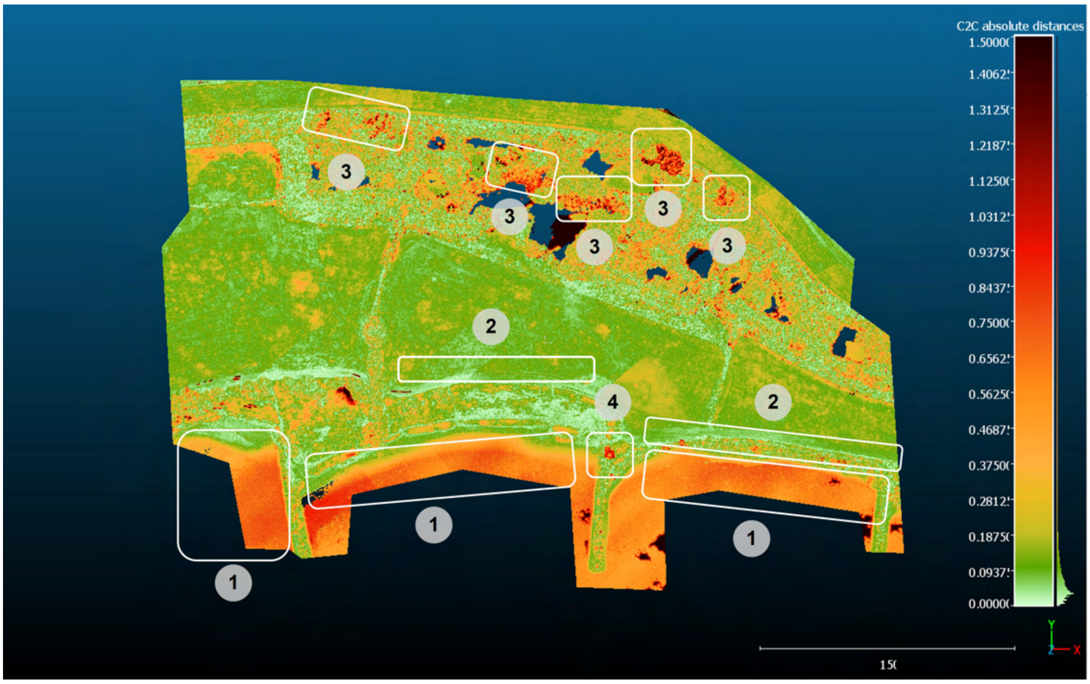


Figure 6.18.: Cloud-to-Cloud Distance with a threshold of 1.5 meters

6.2.2. Normalized Difference Vegetation Index

The NIR and Red bands, shown in Section 6.1.2, are merged into a NDVI raster. These can be seen in Figures 6.23a and 6.23b. It can be seen that difference in NDVI values occurred between the two time points. The difference in NDVI between these two time moments can be seen in Figure 6.24. The color scale used to show the differences runs from red to green,

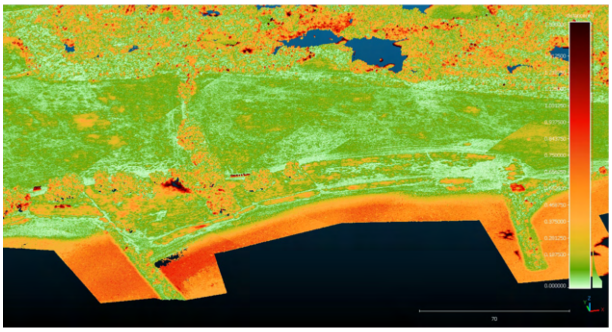


Figure 6.19.: Number 1: Water level (Cloud-to-Cloud distance)

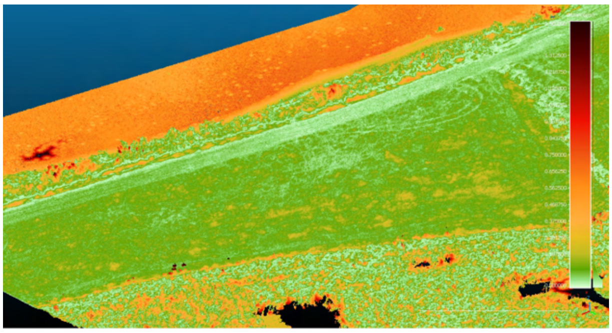


Figure 6.20.: Number 2: Walking path (Cloud-to-Cloud distance)

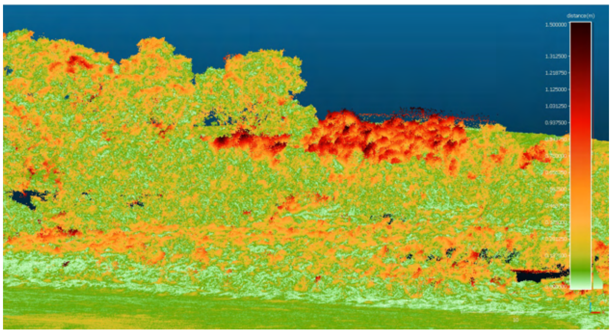


Figure 6.21.: Number 3: Tops of trees (Cloud-to-Cloud distance)

where red represents negative differences in the NDVI values, and where green actually represents positive changes in the NDVI values. For example, it can be seen that around the shoreline the vegetation turns orange, meaning that the NDVI value has decreased. In contrast to the edge below the forested area, where the pixels turn dark green, thus meaning the NDVI here has gone up. This map shows at a glance how the NDVI has changed at time spatial resolution.

The above NDVI of the T2 measurement, see Figure 6.23b was integrated into the Reference cloud with the C2CD attribute already added earlier. This resulted in an NDVI point cloud, which can be seen in Figure 6.25. The point cloud is colored based on the value of the NDVI

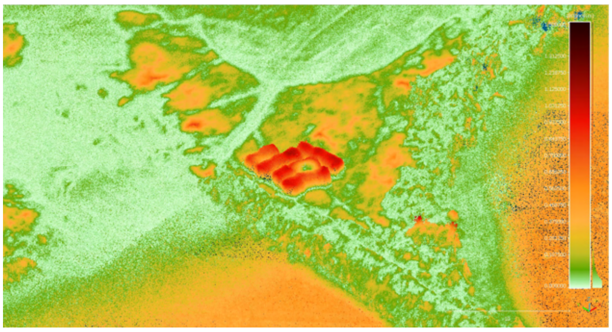
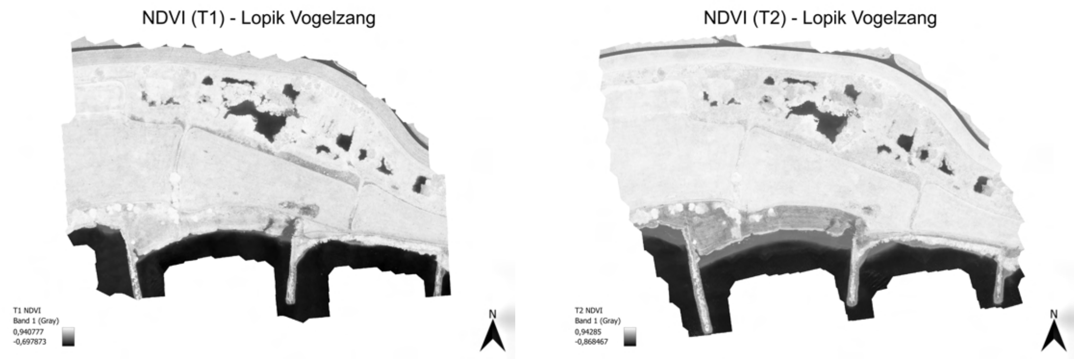


Figure 6.22.: Number 4: Hay bales (Cloud-to-Cloud distance)



(a) T1 NDVI

(b) T2 NDVI

Figure 6.23.: NDVI raster

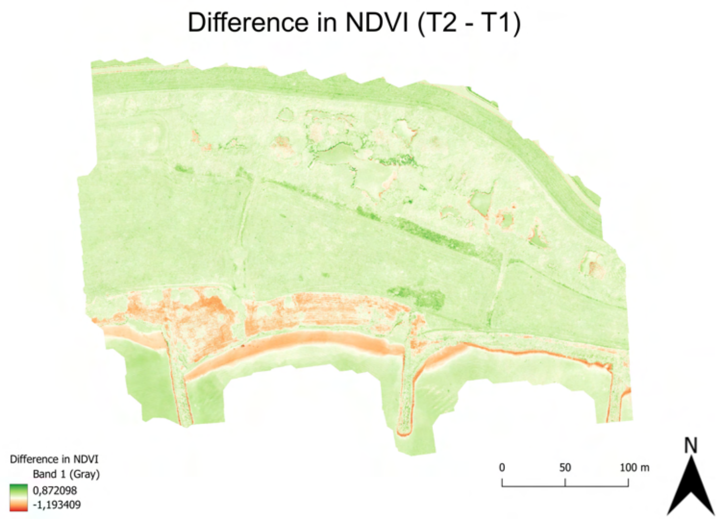


Figure 6.24.: Difference in NDVI

of each point.

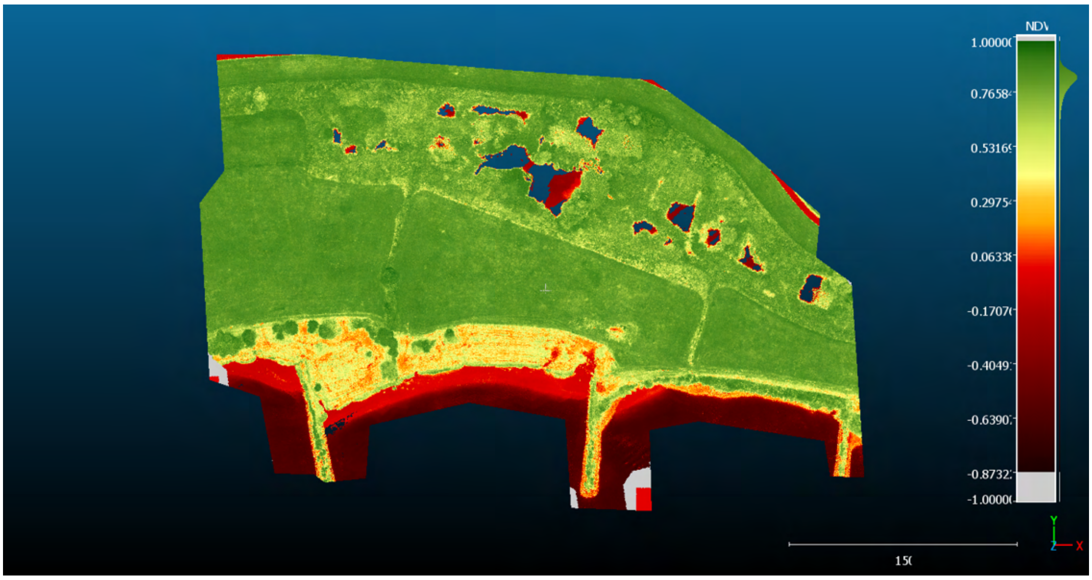


Figure 6.25.: NDVI point cloud (Reference cloud)

The color scale used for the NDVI attribute runs from dark red to to bright green, with dark red representing a NDVI value of minus 1 and bright green representing a NDVI value of 1. This color scale can be found in Figure 6.26.

Figure 6.26.: Color scale: NDVI

The NDVI point cloud was also explored based on observations with the human eye. The following notable features are numbered and shown in Figure 6.27. These are elaborated on further below.

First of all, it is clearly visible that the water turns dark red, representing negative NDVI values, which is indeed correct considering water is supposed to give negative NDVI values as opposed to vegetation which is supposed to be green. This is shown as number 1 in Figure 6.27. The following Figure 6.28 shows this from a side view, so it can be seen more clearly.

In addition, tire tracks and footpaths are visible given a clear pattern of orange dots is present in these areas, shown as number 2 in Figure 6.27. In both cases, the lower field has been dented while walking or driving a vehicle, reducing the vegetation in NDVI. As a result, the points in the line of hiking trail and tire tracks have lower NDVI relative to the immediately adjacent points. The following Figure 6.29 shows this from a side view, so it can be seen more clearly.

Moreover, the NDVI value around the shoreline lights up by the pale yellow dots, indicating the sandy surface. This is shown as number 3 in Figure 6.27. The following Figure 6.30

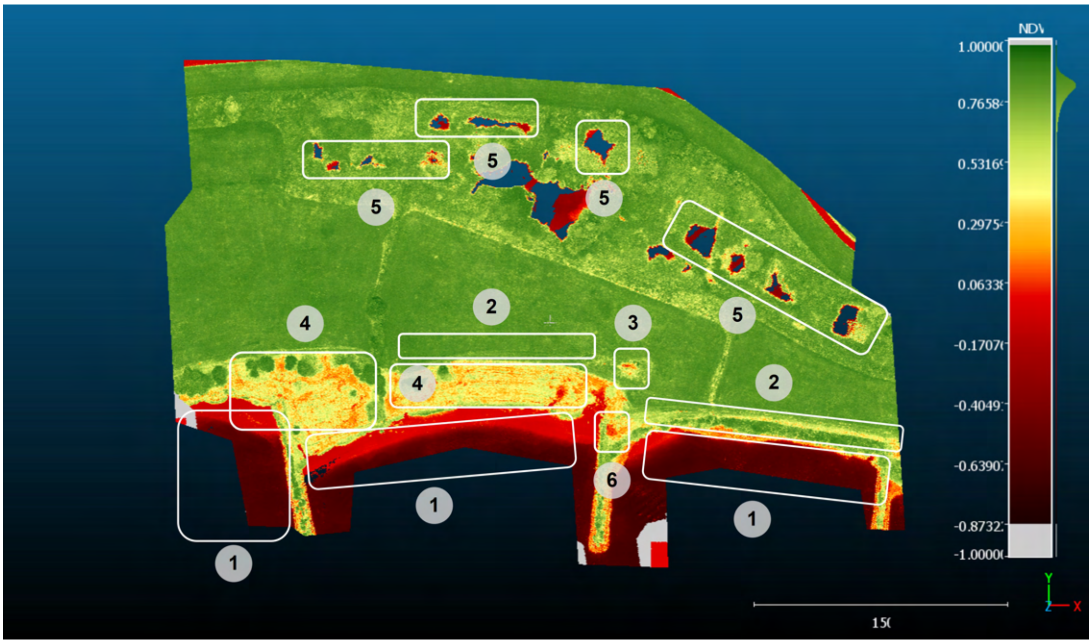


Figure 6.27.: Observations in NDVI point cloud (Reference Cloud)

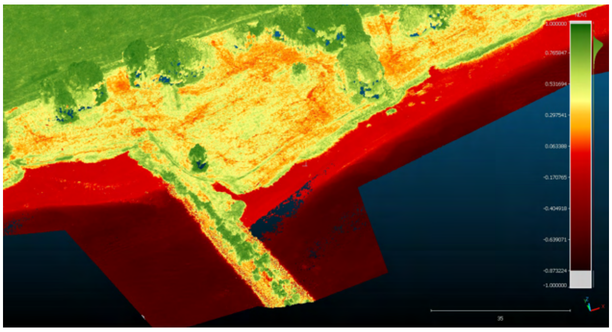


Figure 6.28.: Number 1: Waterline (NDVI)

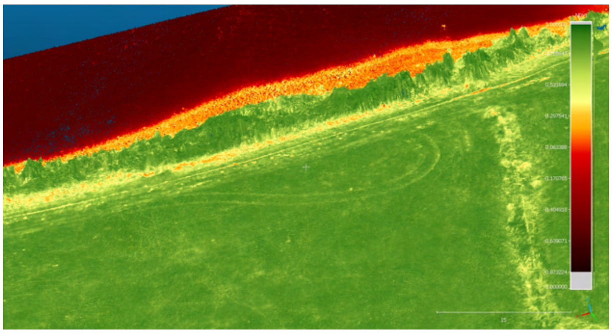


Figure 6.29.: Number 2: Tracks (NDVI)

shows this from a side view, so it can be seen more clearly.

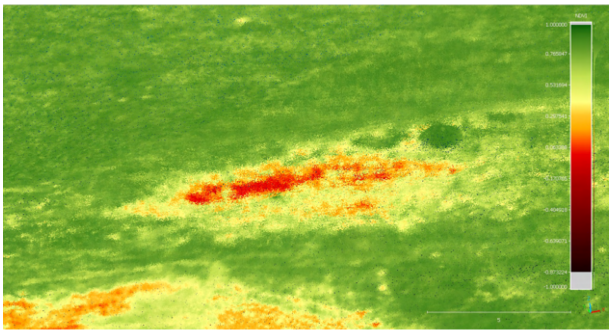


Figure 6.30.: Number 3: Sandy surface (NDVI)

Furthermore, yellow to orange spots are also visible in the field where the attenuated areas were also noted in the RGB point cloud. This is shown as number 4 in Figure 6.27. The following Figure 6.31 shows this from a side view, so it can be seen more clearly.

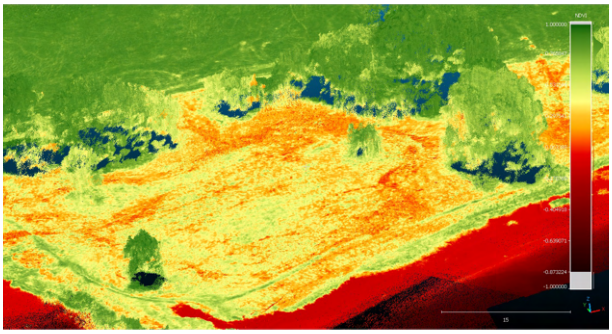


Figure 6.31.: Number 4: Attenuated areas (NDVI)

In the floodplain itself, water is present in some places, around which the edges turn red, signifying a negative NDVI. This is shown as number 5 in Figure 6.27. This will be because this vegetative most likely has a lot of moisture in view. The following Figure 6.32 shows this from a side view, so it can be seen more clearly.

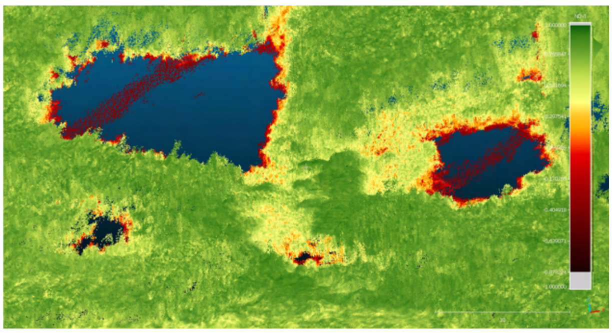


Figure 6.32.: Number 5: Vegetation around water (NDVI)

The example of hay bales also is useful in the NDVI point cloud, shown as number 6 in Figure 6.27. The top of the hay bales turns red, which means that the vegetation is not alive. This is correct since the hay bales have most likely been lying in the sun for some time and thus the reflected NIR and Red band are negatively influenced regarding the NDVI value of the points. The following Figure 6.33 shows this from a side view, so it can be seen more clearly.

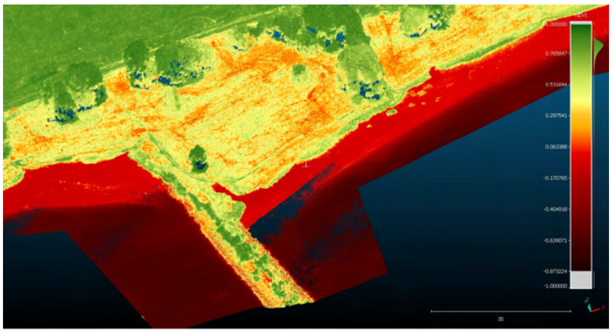


Figure 6.33.: Number 6: Hay bales (NDVI)

6.3. Quality of the data

The quality of the data is important to determine the extent to which the collected data represents reality, as the data is used as a visualization of the dynamics of the flood plains. The quality of both the raw data and the quality of the attributes added during the process is elaborated below.

6.3.1. Raw data

The accuracy of the acquired data is dependent on several aspects, including weather conditions, flight parameters, and usage of the RTK network.

The LiDAR flight contains a DJI Terra Quality Report for LiDAR Point Cloud Processing, containing the input data overview, parameters, performance overview, and warning message.

The following LiDAR quality information applies to the T1 and T2 mission. The point cloud data collection time was 1 hour and 2 minutes. The point cloud density has a high value. There has not been an accuracy check. The point cloud effective distance was 250 meters. The optimised point cloud accuracy has been turned on, the same as for a smooth point cloud. There is a warning message for the T1 measurement noting that only 2 or less than 2 reference satellite systems were available for the base station. This means that the solution could be affected. The warning message for the T2 measurement notes that some points are removed due to incorrect positions or orientations.

The multispectral flight has produced a quality report of the mission. This provides an overview and appoints various quality aspects regarding the aerotriangulation and 2D reconstruction of both the T1 and T2 mission.

The following multispectral quality information applies to the T1 mission.

The overview contains the proportion of calibrated images. The number of images is 609, of which the number of calibrated images is 539. This is a total of 88.51% of the images. The total consumption time was 27 minutes and 4 seconds, of which the aerotriangulation took 4 minutes and 35 seconds and the 2D reconstruction took 22 minutes and 29 seconds. The flight parameters includes the average flight altitude of 64.49 meters which gave a GSD of 3.329 cm/px. The aerotriangulation coverage area is 0.09879 squared kilometers.

The Aerotriangulation quality report gives the reconstruction accuracy, stating that there is 1 connected component, for which 539 maximum number of component images were used. There were 1070196 projections and 230136 tie points. The projection Error RMS is 0.918 px and the georeferencing RMSE is 0.023 meters. The reconstruction parameters are as follows. The computation method is a standalone one. The feature point density is high. The distance to ground is 100 meters. The camera calibration information shows the image residuals for the camera, shown in Figure 6.34.

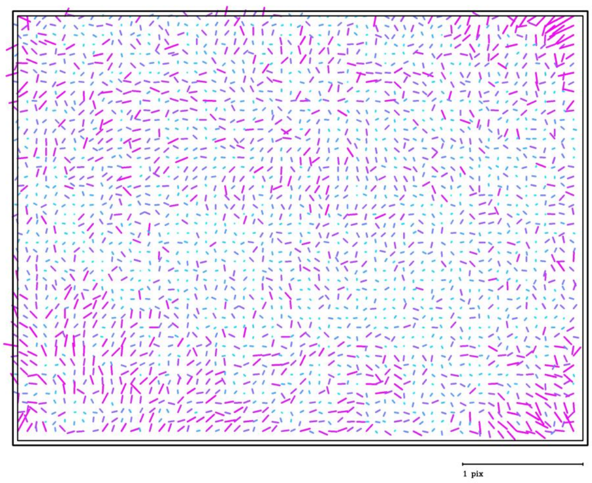


Figure 6.34.: Image Residuals for Camera - T1

The initial and optimized intrinsic parameters of the camera are presented in Table 6.1. The covariance matrix is presented in Table 6.2.

Table 6.1.: Camera intrinsics parameters - T1

Parameters	**Focal Length**	**Cx**	**Cy**	**K1**	**K2**	**K3**	**P1**	**P2**
Initial	1947.51	784.071	638.07	-0.415079	0.38648	-0.445856	0.0008509	0.008509
Optimized	1947.013	796.318	640.936	-0.411775156	0.321045039	-0.267171279	0.000705701	-0.000205393
Difference Value	-0.497	12.247	2.866	0.00330384	-0.065434961	0.178684721	-0.000145199	-0.001056293

The quality report of the 2D reconstruction is as follows. The 2D reconstruction consumption time was 22 minutes and 29 seconds, including 26 seconds for image distortion correction and color correction, 58 seconds for densification, and 21 minutes and 5 seconds for TDOM generation. For the reconstruction parameters, the resolution was set to high and the mapping scene was set to multispectral. The scene overlap is visible in the following Figure 6.35.

Table 6.2.: Covariance matrix - T1

	Focal Length	*Cx*	*Cy*	*K1*	*K2*	*K3*	*P1*	*P2*	*Error*
Focal Length	1	-0.014	-0.232	-0.355	0.081	-0.049	0.476	0.023	0.248
Cx	-0.014	1	0.006	0.004	-0.001	-0.001	0.004	-0.341	0.072
Cy	-0.232	0.006	1	0.068	-0.005	-0.002	-0.444	-0.01	0.064
K1	-0.355	0.004	0.068	1	-0.937	0.881	-0.15	-0.018	0.000295194
K2	0.081	-0.001	-0.005	-0.937	1	-0.984	0.018	0.015	0.002029124
K3	-0.049	-0.001	-0.002	0.881	-0.984	1	-0.008	-0.015	0.004228373
P1	0.476	0.004	-0.444	-0.15	0.018	-0.008	1	0.037	0.000005456
P2	0.023	-0.341	-0.01	-0.018	0.015	-0.015	0.037	1	0.000005012

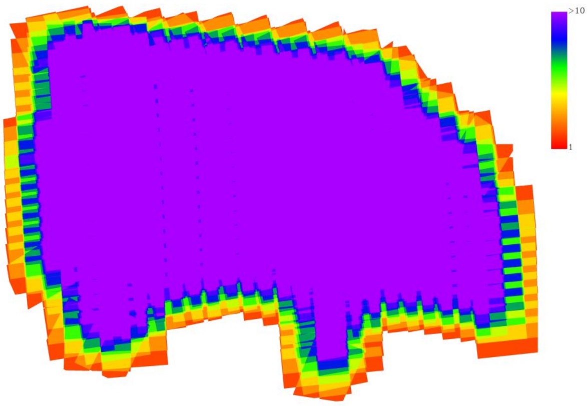


Figure 6.35.: Scene Overlapping - T1

The following multispectral quality information applies to the T2 mission.

The overview contains the proportion of calibrated images. The number of images is 675, of which the number of calibrated images is 620. This is a total of 91.85 % of the images. The total consumption time was 23 minutes and 47 seconds, of which the aerotriangulation took 3 minutes and 36 seconds and the 2D reconstruction took 20 minutes and 11 seconds. The flight parameters include the average flight altitude of 64.64 meters which gave a GSD of 3.33 cm/px. The aerotriangulation coverage area is 0.110392 squared kilometers.

The Aerotriangulation quality report gives the reconstruction accuracy, stating that there is 1 connected component, for which 620 maximum number of component images were used. There were 1277891 projections and 245004 tie points. The projection Error RMS is 0.905 px and the georeferencing RMSE is 1.175 meters. The reconstruction parameters are as follows. The computation method is a standalone one. The feature point density is high. The distance to the ground is 100 meters. The camera calibration information shows the image residuals for the camera, shown in Figure 6.36.

The initial and optimized intrinsic parameters of the camera are presented in Table 6.3. The covariance matrix is presented in Table 6.4.

The quality report of the 2D reconstruction is as follows. The 2D reconstruction consumption time was 20 minutes and 11 seconds, including 8 seconds for image distortion correction and color correction, 1 minute and 22 seconds for densification, and 18 minutes and 41 seconds for TDOM generation. For the reconstruction parameters, the resolution was set to high and

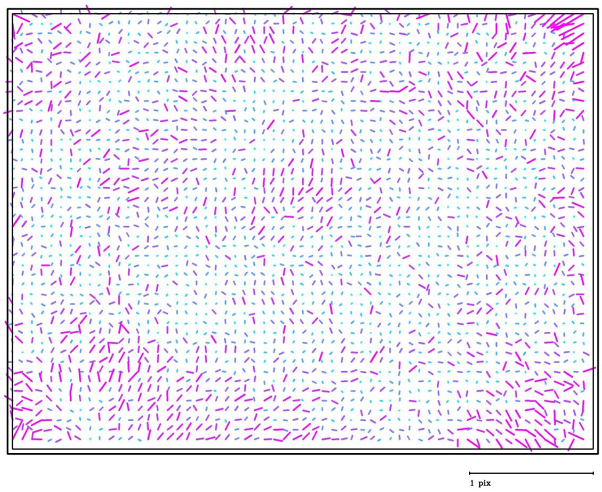


Figure 6.36.: Image Residuals for Camera - T2

Table 6.3.: Camera intrinsics parameters - T2

Parameters	**Focal Length**	**Cx**	**Cy**	**K1**	**K2**	**K3**	**P1**	**P2**
Initial	1947.51	784.071	638.07	-0.415079	0.38648	-0.445856	0.0008509	0.008509
Optimized	1946.934	796.373	641.376	-0.411415375	0.320000293	-0.265232018	0.000696893	-0.000253779
Difference Value	-0.576	12.302	3.306	0.003663625	-0.066479707	0.180623982	-0.000154007	-0.001104679

Table 6.4.: Covariance matrix - T2

	Focal Length	*Cx*	*Cy*	*K1*	*K2*	*K3*	*P1*	*P2*	*Error*
Focal Length	1	0.032	-0.231	-0.388	0.09	-0.055	0.477	-0.078	0.242
Cx	0.032	1	-0.05	-0.015	0.005	-0.004	0.03	-0.375	0.063
Cy	-0.231	-0.05	1	0.072	-0.005	-0.002	-0.469	0.017	0.058
K1	-0.388	-0.015	0.072	1	-0.929	0.871	-0.167	0.025	0.000264181
K2	0.09	0.005	-0.005	-0.929	1	-0.984	0.024	0.001	0.00178034
K3	-0.055	-0.004	-0.002	0.871	-0.984	1	-0.012	-0.007	0.003687512
P1	0.477	0.03	-0.469	-0.167	0.024	-0.012	1	0.017	0.000005031
P2	-0.078	-0.375	0.017	0.025	0.001	-0.007	0.017	1	0.000004639

the mapping scene was set to multispectral. The scene overlap is visible in the following Figure 6.37.

6.3.2. Processed data

The processed data includes the quality of the C2CD and of the NDVI values. For both attributes, temporal resolution is important given the time gap that existed between the acquisition days. This time frame was 45 days which affects the changes detected in the C2CD. In addition, weather conditions influenced the data, considering it was more windy on the second day. This may have particularly affected the C2CD, due to possible differences that were actually due to the wind. Therefore, drawing of the results should take this into account.

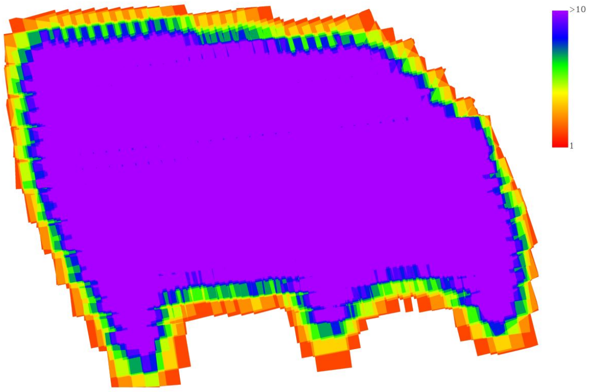


Figure 6.37.: Scene Overlapping - T2

6.4. Use cases of explorative point clouds

As the world and mental representation of humans are opposed to each other in the WDGM model, the interactive point cloud has functioned as a means of connecting the two. Therefore, it is important to look at how this was accomplished by reflecting on the outcomes of the potential use cases and feedback. The dynamics of the flood plain, also referred to as WW, were combined and presented in the form of a point cloud (G). The digital tool to visualize these is the VR headset that has provided a 3D virtual world that brought together the World and Mental representation of humans. The eyes of the human have been able to explore the point cloud interactively in this way, stimulating the mental and creative processes to arrive at insights. The insights equivalent to MM in the WDGM model were identified in the form of answers to interview questions. These insights, arising from the mental representations of humans (MM), can then, as an iterative process, be fed back to the world (W) itself, e.g. in the form of carrying out certain work in the floodplain, the digital model (D), e.g. by obtaining additional information, and the graphical representation (G), e.g. by an alternative visualisation method. In this way, it remains an iterative process, with a continuous loop with possibly different routes through the WDGM model. The next subsections will elaborate on these insights to analyze the interactivity in the virtual representation between the world and the mental representation of humans.

6.4.1. Insights from disciplines

The testing sessions yielded valuable insights into the potential use cases of the explorative point clouds and the incorporation of possible additional input sources. The findings from all participants per discipline have been summarized in Figure A.1 in Appendix A. To document observations on the point clouds, the interviews were re-listened from which keywords were extracted. The frequency of these keywords was examined, and the recurring insights were subsequently formed into topics. Finally, these topics were put down in the following Table 6.5. From this table, the following use cases are further described for the RGB, cloud-to-cloud distance, and NDVI point cloud.

Table 6.5.: Potential use cases of point clouds

Findings potential use cases point clouds		
RGB	**C2CD**	**NDVI**
Participation tool	Bank erosion	Assessment flora status
Detailed model of reality	Vegetation overgrowth	Attenuation of a natural area
Plot boundaries in 3D	Controlling work activities	Vegetation types/species
Digital remote site inspection	Linking vegetation layer	
Consultation opportunities for stakeholders		
Limited visibility solution		

Use cases: RGB point cloud

The RGB point cloud could serve as a tool for participation in projects involving multiple stakeholders. In certain project sites, stakeholders might hold conflicting interests, and the use of a 3D model can serve as a tool to provide enhanced clarity on divergent perspectives.

Furthermore, it is often mentioned that the point cloud is very similar to reality due to the many details visible. The large point density and the integrated RGB colors seem to outline reality in great detail.

It is mentioned that during maintenance it is sometimes difficult to determine cadastral boundaries, or: Which tree belongs to our maintenance area and which does not? The point cloud can offer a solution for this since it is easier to look through the vegetation to determine which exact areas belong to the maintenance area and which do not.

In the current work process, maintenance is performed by externally hired companies. Checking the work performed is often difficult given the time and cost constraints due to the size of the area. The use of a 3D model of the maintenance area can offer a solution because it can immediately see what the floodplain looks like. Thus, the inspection could be done digitally.

At the time when employees are working outside, communication with personnel in the office tends to be difficult because there is no direct view of certain difficulties that have arisen. For example, point clouds would provide an opportunity for consultation between different parties during a work through the representation of reality.

It is indicated that there are sometimes limitations regarding visibility while performing certain activities behind high vegetation such as reeds, for example. For this, the 3D point cloud could again provide a solution by making visible certain areas or objects that were previously blocked.

Use cases: Cloud-to-Cloud Distance point cloud

An important aspect of maintaining floodplains is bank management. This involves paying attention to the occurrence of bank erosion along rivers. These are places where the bank is eroding away. The difference in measured z values between two points could offer the potential to detect bank erosion. It is noted that the time period of 45 days is too short to detect bank erosion, but suggested that with an annual LiDAR measurement, there would be potential to detect weak spots along the bank.

As mentioned in Chapter 3, it is important that floodplains have enough flow opportunities to make space in case of high water. For this, it is important to remove excess vegetation regarding the coarsening restrictions on time when needed. Because of this, it is seen potential to use the C2CD point cloud as a difference map between the two measuring moments to detect where vegetation may have grown, and then use this to determine whether this is within or outside the agreed restrictions. This could be incorporated into the current work process so that possible maintenance trajectories are automatically triggered if a danger zone arises.

As mentioned earlier in the potential use cases of the RGB point cloud, completed work could be inspected digitally. The RGB point cloud displays a realistic and detailed representation of reality. However, when combined with the C2CD, differences could reinforce and confirm the observations made in the RGB point cloud. However, it should be taken into account that the current C2CD cannot indicate whether the elevation has increased or decreased. This is because the method considers points from all directions in the computation process of determining the difference in distance between the two sets of point clouds. Therefore, it would be more satisfactory to use an alternative method which identifies work completed by focusing on the distance between two sets of point clouds in relation to the z-axis. In this way, a negative distance would equal decreased height, which would mean that maintenance may have occurred. While positive distances equal increased height, which would represent vegetation growth. In this way, an inspection of work can be simplified.

Use cases: NDVI point cloud

The NDVI point cloud was perceived as very clear given its distinct colors. Nevertheless, the concrete applications were not seen directly due to some disciplines being further removed from an ecological point of view.

However, it was observed that the NDVI point cloud has the potential to serve as a discussion initiator, considering that the stakeholders involved in the project are assessed on the flora status of the floodplain. This could for example indicate that certain areas require a minimum level of healthy vegetation.

Additionally, it was noticed that yellow areas were present, indicating atrophied areas. This could be interesting for identifying areas of attenuation, as areas sometimes need to be attenuated precisely to restore and enhance the biodiversity of a particular piece of land. The NDVI point cloud could serve as a tool for checking the attenuation status of a certain area.

6.4.2. Iteration integration of additional information

Besides immediate concrete use cases, the creativity of all individuals also stimulated alternative ideas to implement in the current work process of the WOCU project. In other words, what relevant information was lacking that would be relevant for the floodplain maintenance process. This information was thus not yet linked to the point clouds at the time of showing. Two distinct use cases have arisen, one involves the integration of the the vegetation layer for identifying coarsening. Second, there was interest in distinguishing vegetation types. The following sections further explain both aspects in more detail.

Vegetation Chart

The Vegetation Chart indicates where which vegetation is allowed for the entire scope of the WOCU floodplain area from the point of view of flood safety and water quality. Figure 3.2 shows the vegetation chart of the Vogelzang floodplain within Lopik. The occurring vegetation types range from water, paved surface, grass and field, reed and scrub, forest, thicket, mix class 90/10, mix class 70/30, to mix class 50/50. The order of these classes regarding roughness is: grass and field, reed and rough, forest, and thicket. There are some rules regarding permitted deviation from this vegetation layer. Namely, solitary trees may be grown. Existing hedges and hedgerows may grow into linear thickets. If an area is classified as homogeneous, a coarser class may be created provided the area does not exceed 500 square metres. Lastly, the mixture classes contain percentages of maximum allowable rough vegetation and minimum presence of grass and field. [79]

If this Vegetation Chart is included in the existing workflow of the project, it can offer the potential for detecting excessive coarsening in certain areas. For this, a maximum allowed height can be linked per vegetation class for each season to the entire Vegetation Chart. The measured heights in the LiDAR point cloud can be assessed against these allowed heights. The vegetation layer will be divided into quadtrees, where each cell is assigned a maximum allowable height. Subsequently, the point cloud will be partitioned into octrees with the same resolution as the quadtrees, checking for each voxel what the mean z value is of the points inside. This can be done by principal component analysis that can determine the main modes of variation of the mean z-scores. It can then be examined whether these z values of the voxels are higher or lower than the admitted z values in the quadtrees that have the same x and y position. The distance between these two z values is then computed and assigned as an attribute to all points that lie within the respective voxel in the octree. After this, the point cloud can be displayed based on this newly added attribute, indicating the amount of excess coarsened vegetation. In this way, it would be possible to see at a glance where maintenance has to be carried out regarding the exceeded heights. This could then be integrated into the work process of the entire project by bringing these identified areas to the forefront.

Vegetation type classification

Different vegetation types and plant species can be distinguished. Participants are interested in classifying point clouds based on these vegetation species. In this way, distinctions can be made automatically for purposes such as environmental monitoring or examining the biodiversity of a particular area. There is currently a lot of research being done on identifying vegetation types and species, so it would be a great way to integrate this information into the point clouds in order to identify and display species directly in a point cloud.

6.5. Added value of the explorative point cloud

This research focuses on the use of an explorative point cloud in floodplain maintenance. The potential of explorative point clouds for detecting changes in this dynamic environment depends on various factors. The explorative region in the point cloud - use cube [61], depends on several factors including data representation, interaction, and audience. The explorative point cloud is presented in the form of a very realistic 1-by-1 model. The representation in 3D gives the user the power to think visually and combine existing knowledge with new observations. The experts go in blank which provides the opportunity to reveal certain unknown insights. In this research, interaction techniques are seen as a medium to stimulate the connection between humans and virtual reality, in the form of an explorative point cloud. The point cloud responds to the specific needs of the user by querying or manipulating data. This means that the degree of presence of interactive tools influences this effect. Moreover, the productivity of a specified interaction technique depends on the presentation method of the data, given that it must be accessible to support certain issues in question [5]. In other words, the dynamic changes of the floodplain require a dynamic representation of the data. As a result, an interactive representation offers more possibilities. In addition, the success of this kind of interaction also depends on the relationship between the user's motivation and the complexity of the visualisation interface [82]. In the case of this study, all participants were highly involved in floodplain maintenance, which gives room for the complexity of the interface. So it can be stated that this did not have a negative influence on the success of the interactive representation of the explorative point cloud.

7. Discussion & Limitations

This chapter discusses the findings of this research, including several inadequacies, improvements, and challenges that were encountered. Furthermore, there is elaborated on all limitations.

7.1. Discussion

Some discussion points are discussed in detail in the following sections.

7.1.1. Representation of raw point clouds

Firstly, the issue of the representation of raw point clouds is considered. Utilizing raw point cloud data means retaining all points of the acquired data in order to present a complete overview of the floodplain. This inclusiveness is seen as advantageous for applications where details are of great importance. For example, distinguishing between water and land is vital for hydrologists or detecting weak areas for erosion, and the detailed representation allows for a true-to-reality 1:1 model. Furthermore, the responses of participants highlighted that the 3D model was perceived of high level of detail and realistic. This level of detail might not be achievable if the raw point cloud data would be processed by removing certain outliers during the processing of the data. Additionally, the unprocessed nature of the raw data enables the ability to analyze the data based on specific characteristics without the limitations imposed by pre-filtered data.

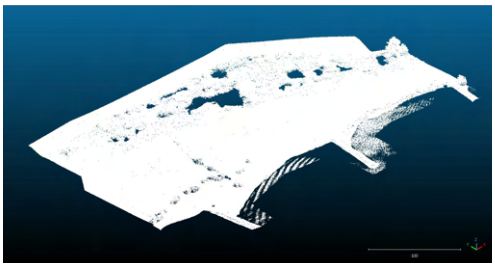
However, certain drawbacks were experienced in preserving these details. The significant amount of information in raw point cloud data leads to large file sizes compared to filtered and processed variants. Managing these huge data sets requires memory capacity. Moreover is the rendering time negatively affected due to the volume of the raw point cloud data, requiring computing capabilities for the visualisation of the data. There is also a limit to how many points can be displayed simultaneously in the VR headset, and there is a loading time the moment a user moves to another area in the point cloud. This complication of rapid switching in the displayed image requires robust capacities. Also during the analysis of the raw data and the incorporation of the additional information of the NDVI and C2CD were certain limitations in terms of computer capabilities encountered. Nowadays, many studies focus on a **cLoD!** (**cLoD!**) to render point clouds without data density shocks to enable an interactive real-time visualisation [105]. Similarly, research has been done on the use of Continuous Level-of-Detail (cLOD) in immersive environments, as it significantly reduces the number of points to be rendered [116]. This means that although there is potential for better processing of the massive point cloud datasets in terms of rendering time, data management needs to be adapted for use in this study.

Taking all these factors into account emphasizes the importance of determining the specific needs of visualizations and considering the corresponding application of the point cloud data with respect to the balance between detail and feasibility. This consideration is crucial for determining the level of detail that is needed to be retained based on the requirements of the needs of the application.

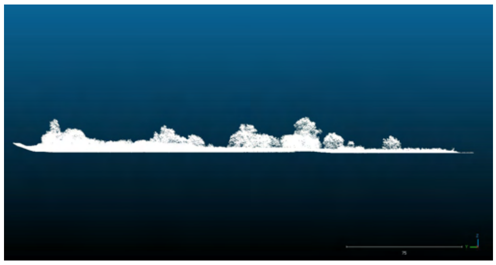
7.1.2. Size of study area

Secondly, the size of the study area will be discussed. The study area is slightly smaller than 0.5 square kilometers poses considerations regarding the research outcomes. Initially, the intention was to capture a larger area, which contained the whole flood plain de Vogelzang. However, due to difficulties given the battery charge of the drone during the flight, this was not accomplished and led to the selection of a smaller test area within the floodplain. Despite the reduced size, the area was chosen to contain important features such that vegetation and groynes are present, and that it lies in an outer bend of the river.

Within the WOCU Rijntakken project, a recent development involved surveying the Rijntakken area by Kavel10. The acquired data set was compared with the point cloud data of this study regarding density, and a large difference of factor 1:150 was found. Whereas the point cloud of the study area of this research included around 150 million points, it was only 1 million points for the Kavel10 point cloud. In addition, the decision was not made to integrate the acquired point clouds with an RGB value, so this means that the visualization will be a lot less clear. Figure 7.1 shows the floodplain of the Vogelzang surveyed by Kavel10, with each point having the same color due to the absence of RGB values. However, the points are classified by their return number, so it is possible to visualise the cloud based on this attribute which is visible in Figure 7.2. It can be seen to give a little more depth, but when this point cloud is compared with the UAV LiDAR point cloud used in this study, the difference in resolution and detail is very large.



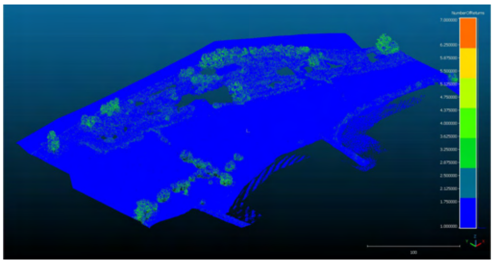
(a) Side view



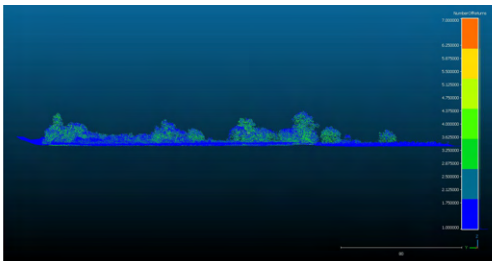
(b) Cross-section view

Figure 7.1.: Point cloud Lopik acquired by Kavel10

The RGB value could, of course, be integrated later, but will cause additional processing steps. Moreover, an analysis must be performed regarding the usability of this data. First, it is necessary to see if it can serve the same potential use cases as the drone point cloud given the difference in density and thus detail. In addition, it needs to be examined whether this density in the VR headset gives the same details as before and the points will need to be colored first to give a better picture of reality. A cloud-to-cloud analysis between this point cloud and the AHN4 data can also be performed to experience possible issues regarding the reduced density of the data.



(a) Side view



(b) Cross-section view

Figure 7.2.: Point cloud Lopik acquired by Kavel10 visualised on its return number

In conclusion, the expansion of the study area size is a critical consideration, due to potential complex challenges that might occur. Ensuring that this new data fits the outcomes of these results should therefore taken into account.

7.1.3. Spatio temporal aspect

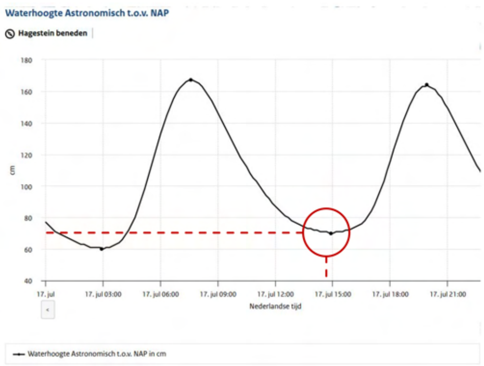
The spatio-temporal aspect plays an important role in this study. Between the two measurements, there is a time frame of 45 days, on which the C2CD depends. Hence, the extent to which outcomes are realistic should be considered given this relatively short timespan. During the interviews, for example, participants expressed that a longer time span is needed to detect bank erosion. It is therefore necessary to consider for each potential use case whether the difference in time frame has an impact. Furthermore, it should be taken into account that if the visualization showed data with a longer time frame, alternative uses might have been found. A follow-up study could see to what extent this affects the findings.

In addition, it was also clearly visible that the tides differed between measurements due to the difference seen in the C2CD in Figure 6.18. This corresponds to the measurements of the tides of the Lek River. The tides of the Lek River are measured in Hagestein, upstream of the location of Lopik, and in Schoonhoven, slightly beyond Lopik. Figure 7.3 and Figure 7.4 show the water height during the T1 and T2 measurements, in which it can indeed be seen that the tides differ from each other. The estimated difference in water height is shown in Table 7.1. Although this is a rough estimation of the water heights, it gives an indication of the difference which could be expected. Given the measured C2CD, which can be seen in Figure 6.18, this estimate agrees fairly accurately.

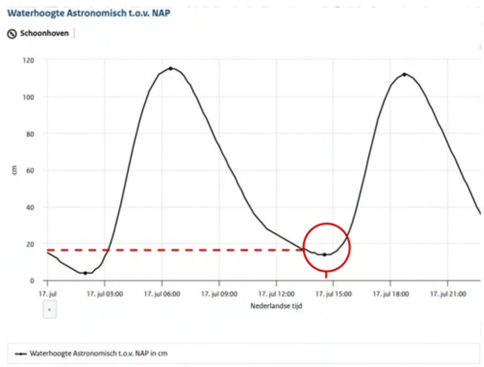
Table 7.1.: Estimated difference in water height in Lopik

Location	T1 height	T2 height	Difference
Hagestein	70	150	+ 80
Schoonhoven	18	75	+ 57
Estimated height in Lopik	44	112,5	+68,5

Moreover, the NDVI value also includes a temporal aspect. This is due to the fact that the NDVI value changes over the season. In addition, the NDVI can be different by plant type. To observe the seasonal difference of the NDVI, the measured NDVI value during the T1 and T2 measurements can be compared with the trend of the NDVI through the years in the province

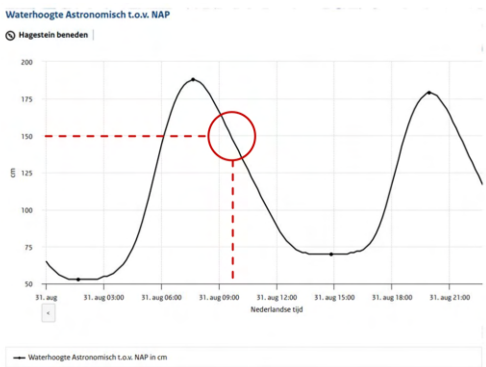


(a) Getij de Lek: Hagestein - T1



(b) Getij de Lek: Schoonhoven - T1

Figure 7.3.: Getij de Lek - T1



(a) Getij de Lek: Hagestein - T2

(b) Getij de Lek: Schoonhoven - T2

Figure 7.4.: Getij de Lek - T2

of Utrecht, in which Lopik is located. The Long Term Average (LTA) value for the NDVI of the province of Utrecht is shown in Figure 7.5 and is based on the years between 1984 and 2015. According to the trend value, the average NDVI value in Utrecht during the T1 measurement on July 17 would be around 0.75 and for the T2 measurement, it would be around 0.76 as well. The measured NDVI values for the Vogelzang floodplain in Lopik are shown in Figure 6.23. For the T1 measurement, using the RasterStatisticsCalculator in FME, a median of 0.757 and a mean of 0.510 were computed as NDVI values. For the T2 measurement, a median of 0.772 and a mean of 0.480 were computed. Table 7.2 shows the differences in the NDVI value between the LTA and the measured NDVI values. Herein, it can be seen that the median of the measured NDVI value has barely any difference for both the T1 and T2 measurements compared to the LTA. In contrast to the mean, where there is a slightly larger difference with a decrease of 0.25 compared to the LTA. This could possibly be because the LTA of the NDVI is based on the crop area or because the resolution of the LTA is 1 kilometre, which is significantly larger than the resolution of the acquired NDVI grids measured with the multi-spectral drone. In addition, the difference in NDVI value between the T1 and T2 time points can also be seen for both the LTA and the measured NDVI values. The table shows for both the LTA and the measured mean and median NDVI values that there is hardly any increase or decrease between both time points, which could be because both measurements were taken in the summer and therefore there was no seasonal change which could have influenced this.

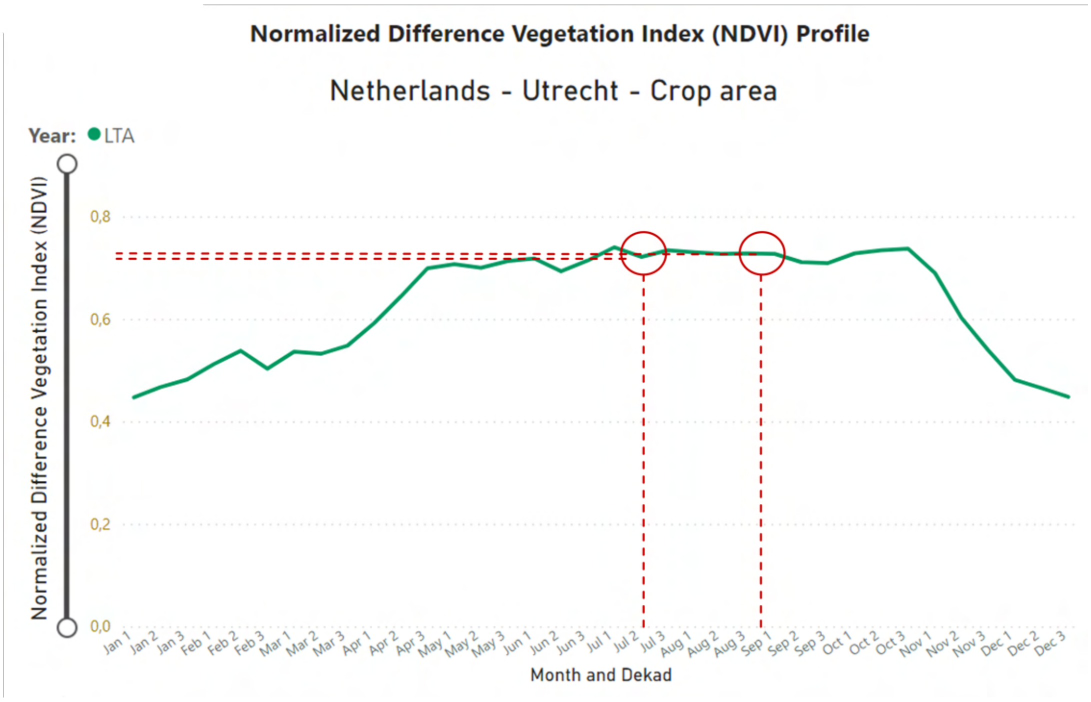


Figure 7.5.: Long Term Average NDVI Utrecht

Table 7.2.: Measured versus Long Term Average values of NDVI in Lopik

Value	T1	T2	Difference
LTA NDVI - Utrecht	0.750	0.760	+ 0.010
Measured NDVI (mean)	0.510	0.480	- 0.030
Measured NDVI (median)	0.757	0.772	+ 0.015
Difference LTA vs Measured (mean) NDVI)	- 0.240	- 0.280	
Difference (LTA vs Measured (median) NDVI)	+ 0.007	+ 0.012	

7.1.4. Representativeness of study area

The selected study area is within the scope of the WOCU Rijntakken project and includes various elements that are crucial to floodplain maintenance. These include different types of vegetation, the outer bend of the river, and notable objects such as a hiking trail. However, the question is to what extent this selected floodplain is representative of the characteristics of the other floodplains located within the WOCU project. It is plausible that other floodplains have different characteristics in terms of varied vegetation species or unique objects. As a result, the lack of these specific features in the study area could have unconsciously limited the creativity and diversity of the insights of the participants. In other words, it is important to examine more closely how this specific floodplain in Lopik relates to the other floodplains within the scope. This would require additional research to compare the specific characteristics of the chosen floodplain with those of other floodplains in the WOCU project.

7.1.5. Weather influences

The acquisition of the data was influenced by weather conditions, including wind. First of all, wind was present at both times, which influenced the position of some points in the point cloud due to wind speed and wind direction. Secondly, wind speed and wind direction differed at both measurement times. Since this study computes the C2CD between the two collected datasets, the wind will affect the result of this distance. In other words, to what extent was there actually a difference or was this (partially) due to the wind? During the T2 measurement, there was an increase in wind speed of 5 kilometres per hour. There was no change in wind direction between the T1 and T2 measurements. These possible changes introduce the dynamic factors during the acquisition process that may affect the data.

7.1.6. Validation of potential use cases

The exploration of potential use cases for point clouds in floodplain maintenance is a pivotal aspect of this research. However, it is necessary to validate these use cases to determine their effectiveness and usability. The considerations concerning the validation process include participant representation, sample size, and potential validation methods.

Firstly it is crucial to assess the representativeness of the participants who provided insights concerning the visualized explorative point cloud of the flood plain. All participants had a full contextual understanding of the dynamics of the floodplains, confirming their technical expertise and input. The interdisciplinary selection of participants accumulated a diverse perspective from eight different disciplines. For the validation of potential use cases, it would be valuable to involve more in-depth specialized disciplines relevant to each use case.

Furthermore, the reliability of the results of the identified use cases depends on the number of participants, which in the case of this study was 18. As previously mentioned in 4, ”a truth is not the truth”, underlines the importance of cautious interpretation. In other words, it cannot be assumed that what someone says is true. This makes it very crucial to further validate certain identified use cases for applicability within the floodplain maintenance process. An effective method might be to organize a feedback session, in which the representatives of the disciplines involved can jointly review the feasibility of the proposed use cases to provide fresh input again. This joint session can also encourage interdisciplinary insights for refining the details of these use cases. Despite the need for further validation, the variety and amount of input insights form a foundation, indicating that it can be stated that there are certainly linking opportunities to be included in the process. The needs of the project should drive this explorative point cloud.

7.1.7. VR headset

The use of a VR headset provides an immersive experience as participants can move through the point cloud in a three-dimensional space. The alternative was the use of a conventional 2D screen which has limitations regarding perception of depth. The choice to use the VR headset as a visualization medium was explained in 2, but may have affected the insights provided by the participants.

Firstly, the choice between the VR headset and the 2D screen influences the interaction between the human and the data, i.e. the HCI. This interaction is also referred in the WDGH model as ”GH”, which represents the viewing of the visualization, and results in ”MM”, the mental processes of humans that lead to possible insights. The VR experience provides a vibrant playing field by allowing individuals to experience the real world in a highly realistic 1:1 model of the world. The usage of VR allows the 3D model to be approached from any perspective enabling a representation of all detailed elements in space [26] In general, feedback on the use of the VR headset was very positive due to the impressive detail of the floodplain shown.

In contrast, the 2D screen would have offered alternative interaction tools, making it easier to see height profiles, for example. In addition, the user-friendliness played a role, given the comfort of the VR glasses due to potential fatigue. One of the test participants suffered from nausea, which disrupted and negatively affected the interaction. Some participants were less enthusiastic and slightly sceptical about putting on the VR headset than others, which may have slowed down the mental thought process of these participants during the visualisation test.

7.1.8. Interactivity of the interface

In this research, interaction techniques are seen as a medium to stimulate the connection between humans and virtual reality, in the form of an explorative point cloud. The degree of presence of interactive tools influences the perception of the user. Looking back at the interactive capabilities of the VR Sketch application, this is open to debate. On the one hand, the very realistic 1-to-1 model combined with all possible navigation options offers a complete experience for the user to move through the point cloud. The ability to switch between the attributes of the explorative point clouds to view additional information is also very positive. However, other interactive features are absent, such as the use of an intersection line, brushing and linking, EDL, and history tasks view back. This raises the question of whether the trade-off between a 2D computer display and an interactive VR display would give different outcomes in this study.

7.2. Limitations

The study encountered some limitations regarding the lack of battery of the UAV, the temporal resolution of the data acquisition, distortion of the multispectral sensor, computer memory, technical difficulties of the VR headset, and the limited participants of the visualisation.

Data acquisiton The study experienced practical limitations, concerning battery restrictions and wind conditions. The lack of sufficient battery caused a smaller study area to be covered. Moreover, the significant increase in wind speed during the second measurement, compared to the first measurement, was an accuracy limitation concerning the position of the points and therefore in the computed C2CD.

Temporal resolution A significant constraint concerns temporal resolution, with a restricted time interval of only 45 days due to time limitations within the scope of this thesis. This temporal limitation affects the computed cloud-to-cloud analysis. Consequently, not all temporal variations in the floodplain dynamics may have been observed, possibly resulting in incomplete results. In addition, both measurements took place during the summer season, which introduces the constraint of capturing dynamic changes across seasons and differences due to the flood season.

Distortion The T2 measurement of the multispectral data has encountered challenges. Distortion in the form of duplicate images in the raw data has caused a regressed pattern in NIR and Red bands. This limitation has been resolved, although caution should be taken when scaling up to the entire project scope.

Computer memory A limitation was experienced concerning the computational resources, particularly during the processing of the expansive point cloud data. The initial used computer encountered challenges related to memory capacity, which limited the seamless processing and visualization of the data. This highlighted the fact that raw point cloud data is enormous. It was crucial to address this challenge, by accessing a remote server with robust computing capabilities to continue the research. Although this limitation was resolved during the research, it led to delays in the timeline.

VR headset There were technical problems with the VR headset, including the disconnection between the VR Sketch app and the VR Sketch plugin in Sketchup when the VR headset was inactive for 5 minutes. This resulted in interruptions during the switching between participants. Moreover, the limited available toolset in the VR Sketch up requires as consideration of functionality versus the detailed immersive experience of the VR headset compared to a 2D screen.

Participants Despite the diversity of the perspectives present within the group of participants, the absence of a dedicated ecologist introduces a potential limitation in the comprehensive understanding of ecological knowledge within floodplain dynamics. This inadequacy might have led to implications, particularly for the identification of potential use cases for the NDVI point cloud. Moreover, the limited size of the participant group, consisting of 18 individuals, imposes a constraint. Although there was at least one represented per discipline, the relatively small sample size of this study may have affected a restriction in-depth of insights obtained.

8. Conclusions

This research is concluded by assessing each research sub-question, providing answers to both the literature review and the experimental phase of this research. These questions will be answered in logical order following the progression from data acquisition to storage, processing, and visualisation. On this basis, the main research question, generated in Chapter 1, is addressed.

- What additional attributes are suitable for enriching point clouds of floodplains?

Enriching raw point clouds of floodplains with additional attributes to enhance their explorative and interactive potential to provide valuable insights for maintenance purposes. Exploration refers to the use of interactive visualization tools and techniques, which stimulate the creativity needed to explore particular insights and patterns within a spatial context. In this way, intrinsic details are preserved and even emphasized through the integration of additional attributes. The consideration of which attributes are then appropriate as enrichment for a point cloud of a floodplain includes the following factors. Firstly, the acquired LiDAR point cloud that was already integrated with RGB values provides a very detailed representation of reality, which led to this being selected as an attribute. Secondly, recognizing that maintenance is closely linked to changes and that the automatic detection of such changes may offer the potential to indicate certain maintenance activities. Therefore, a valuable attribute is the change of point clouds over time in the form of distance between the position of points, also called the C2CD. Lastly, given that a floodplain is mostly composed of vegetation, understanding its health and status is relevant, especially considering the changes in high and low water seasons through which vegetation has a lot to endure. Therefore, integrating the NDVI as an attribute in a point cloud provides insights into vegetation stress, growth, and understanding of environmental changes in the floodplain over time.

- What is the benefit of using a UAV LiDAR sensor to acquire point clouds of floodplains?

The use of a UAV-LiDAR sensor offers several advantages for creating point clouds in a dynamic area such as the floodplain. First, the use of a UAV, which belongs to the ALS techniques, is advantageous compared to ground-based techniques such as the TLS and MLS techniques. This is because ground-based techniques have limited coverage and are also labor-intensive. ALS technology, on the other hand, offers the possibility of conducting accurate and high-density measurements of large areas. The advantage of a UAV over an airborne is that it is unmanned and generally cheaper. In addition, a drone can fly lower, allowing a higher density to be achieved. The choice to use LiDAR as opposed to photogrammetry is based on the fact that LiDAR is less weather dependent, does not depend on surface texture, has high accuracy, and offers multiple-return recording because it can penetrate through tree canopy. In particular, the last advantage is very relevant for a floodplain since there is a lot of vegetation present and in this way, points can both be collected on top as under vegetation.

- What is the quality of the acquired data?

The quality of the acquired data is relevant to determine the extent to which the results represent reality and can be used to draw certain conclusions. Data quality is assessed in terms of accuracy, resolution, consistency, and completeness. For the LiDAR data, the Zenmuse L1 LiDAR sensor under the Matrice 300 RTK UAV was used. This sensor offers an accuracy of about 5 centimetres vertical and 10 centimetres horizontal. For both the T1 and T2 flight, the UAV was flown at an altitude of 80 meters, used a side overlap ratio of at least 70 percent, and used the integrated RTK network. By using the RTK system, a radio signal from a base station provides an additional correction to the collected data that ensures accuracy. The resulting resolution, in terms of density, was 100 points per square meter. Regarding consistency between the T1 and T2 measurements, there was a difference in wind speed of 1.39 meter per second. Furthermore, completeness is the same for both measurements. For the multispectral data, the Phantom 4 sensor was used, which offers an accuracy of about 3 cm. In addition, the RTK network was used, ensuring the accuracy of the position of the acquired data. For both the T1 and T2 flights, it was flown at an altitude of 60 meters with a side overlap ratio of 70%. The resulting resolution involves a GSD of 3.3 centimetres per pixel for the T1 and T2 measurements. The consistency was affected by weather conditions, where it was sunnier during the T1 moment and more windy during the T2 measurement. This resulted in vertical shadow lines in the T1 data and a distortion pattern of duplicate images in the T2 data, which could be corrected. From this, it can be said that the data collected is reliable to use for this research and drawing results.

- What is a suitable algorithm to detect changes in point clouds of floodplains?

A suitable algorithm for detecting change in point clouds of floodplains involves a spatiotemporal approach. Once point cloud data has been collected at different time intervals, these two sets can be compared. There are several techniques to compute the distance between a unique neighbour pair within both point clouds. The research conducted by Vitali [28] compared these techniques for a hilly terrain with a lake and nearby vegetation, including shrubs and trees, which matches the characteristics of a floodplain. The results showed that the most effective method for identifying changes in both vertical and horizontal directions is the nearest neighbor, which is also known as the C2CD. This method uses the nearest neighbor distance algorithm, which is known as the simplest and fastest direct 3D comparison method because the data does not need to be gridded or meshed, nor does it require the computation of surface normals. The change in the surface of the point clouds is calculated by using a distance calculation with the Euclidean distance between the two points [47].

- What is a suitable threshold for the maximum cloud-to-cloud distance in visualising changes in explorative point clouds?

To visualise the changes in the floodplain, a threshold for the maximum cloud-to-cloud distance between the compared point clouds has to be determined as this value cannot be adjusted by the user in the VR environment. Determining the optimal threshold for the C2CD attribute for visualizing changes in the explorative point cloud depends on the distribution and amount of change detected in the study area. This threshold ensures that only changes up to a certain value are identified, which ensures that incorrect distances are not included in the C2CD. Different values (0.75, 1, 1.5, 2, 3, and 4 meters) were tested to determine the most appropriate value for the test area. Figure 6.16 shows the impact of the different thresholds on the visual representation of change in the area, using a color scale (running from light green, no change, to red, most change). The distribution of C2CD was analyzed, showing that the majority of distances are below 1 meter. Also given the relatively short time frame of 45 days, it was considered that changes up to 1.5 meters could be relevant for identification of differences in the floodplain and hence this value was chosen as the threshold used.

- What is a suitable visualisation technique to display explorative point clouds?

The use of VR is a suitable technique for visualizing explorative point clouds. Both the field of geovisualization, ESDA, and HCI emphasize the importance of having a user-friendly interface while providing interactive exploration capabilities. VR displays a very detailed, almost 1-to-1, three-dimensional model. Moreover, it is a dynamic representation because the user has the ability to change its position and orientation relative to the model. This creates a lifelike reality, boosting the experience of the user. Ultimately, the immersive nature of VR provides a unique interaction between the user and the point clouds, which is beneficial for in-depth analysis and complete understanding of the study area displayed. In particular, the Meta Quest Pro was used as a VR headset with VR Sketch as the application rendering the point clouds by connecting to the VR Sketch plugin in SketchUp Pro. This method includes several interactive features that users can explore by allowing them to interactively view virtual reality 1-to-1 models. These include scaling the point cloud, zooming, rotating, walking through it, hiding specific parts of the cloud, recording a video, increasing the thickness of points, switching between attributes, and taking notes in the point cloud.

- What are the potential applications of explorative point clouds for different disciplines in floodplain maintenance?

Different parties and disciplines are involved in the maintenance of the floodplains within the WOCU Rijntakken project, with the WOCU Rijntakken project divided into project management, environmental management, strategic asset management, and technical management. Discussions with the maintenance department revealed that floodplain maintenance relies heavily on a variety of disciplines including ecology, environmental management, civil engineering, project management, asset management, GIS and the area concierge. By showing the visualization of exploratory point clouds (RGB, C2CD, and NDVI) to these involved disciplines, the following potential applications were found for the use of exploratory point clouds for floodplain maintenance. The RGB point cloud offers potential for consultation opportunities with stakeholders, a detailed model of reality as an impression of an area, measuring of objects, improved view of parcel boundaries, a solution to limit visibility, digital inspection of a remote site, usage for work preparation, and as a participation medium. The C2CD offers potential for monitoring work, spotting overgrowth, detecting height differences around built objects, and detecting bank erosion if a longer time frame is taken. The NDVI point cloud offers the potential for identifying atrophied patches of ground, assessing flora status, and identifying sand in floodplains. In addition to these current potential co-benefits that an explorative point cloud can provide for floodplain maintenance, it was noticed that individuals also came up with alternative ideas to implement in the current work process of the WOCU project. First, by using the Vegetation Chart, which shows the permitted vegetation for the entire scope of the project. If integrated, this chart may offer the potential to monitor excessive coarsening. Second, there was interest in classifying the points based on vegetation species for the examination of the biodiversity of a particular area.

- What is the most suitable attribute to provide insights into changes in explorative point clouds for floodplain maintenance?

The added attributes to the exploratory point clouds each brought their value regarding insights into floodplain changes. However, most of the disciplines got excited about the interaction with the RGB point cloud. This was because the addition of the colors realized a very realistic 1-to-1 model. This gave the impression that every detail was visible and stimulated creativity for a variety of applications. Moreover, participants were also enthusiastic about the possible potential of the C2CD, but given the short time frame, it was not possible to be able to detect erosion in the point cloud. In addition, despite potential applications, the NDVI was currently considered the least interesting, but this could also have been due to the lack of an area ecologist as a participant.

Based on this information, the main research question can be answered:

- *To what extent are explorative point clouds, generated from raw UAV-LiDAR data, useful in providing insights on change detection for floodplain maintenance?*

The use of explorative point clouds, generated from raw LiDAR point cloud data, offers potential uses and insights for floodplain maintenance. The term explorative, when added to the point cloud, refers to the integration of additional information to the points and the use of interactive visualization tools and techniques to allow users to explore the point cloud. The emphasis of explorative point clouds is on fostering creativity through interactive visualisation, with this being a valuable tool for the extraction of valuable insights and patterns within a spatial context. The interactive experience with the visualised explorative point cloud in the VR headset stimulated the creativity of the participants, as evidenced by the diverse insights gained from experts involved in the WOCU project. These insights could be implemented in the current workflow of the project by making use of these linking opportunities. This implies that there is value in looking at explorative point clouds from an interdisciplinary perspective and that explorative point clouds could certainly provide insight into the dynamics of floodplain maintenance. The level of success regarding the potency of explorative point clouds depends on the interaction possibilities that take place between the human's mental representation and the visualisation shown. This thesis highlights that an explorative point cloud can thus be seen as a chameleon for a versatility of uses within maintenance projects, making raw LiDAR data which is often underused, a valuable resource.

9. Future research

Any inadequacies and improvements that formed new questions are used for the following further recommendations of this research. This chapter delves into these recommendations and formulates possible research questions that arise for each identified research topic.

Validation use cases Future research should prioritize the validation process for the identified potential use cases in this study. An investigation is required into the feasibility of these use cases within the WOCU project, coupled with an examination of the specific benefits they can provide. Additionally, an in-depth examination is required to determine whether any modifications or new datasets are essential for the implementation process of these use cases. Application scenarios could be used to determine the effectiveness of each of the identified use cases. Investing in a robust validation process will expand the utility of point cloud data into a versatile data source that offers co-occurrence opportunities within a project. The integration of these linking opportunities into existing work processes has the potential to optimize workflows through efficiency and effectiveness. The following research directions should be explored:

- What is the feasibility of the indicated potential use cases of explorative point clouds for floodplain maintenance?
- Is there additional information required to fulfil the implementation process of certain use cases?
- What is the effectiveness and added value, in terms of costs and time, when implementing the use cases?
- How can these potential use cases be optimally integrated within the existing workflows?

Roughness index As introduced in Chapter 6, the reintegration of the roughness of the terrain has been seen as highly promising. Determining the locations for maintenance based on the roughness of the particular piece of ground is therefore the next step of this research. Further research should further develop the proposed idea in Chapter 6. The following research directions should be explored:

- How can the roughness of the terrain be integrated into the explorative point cloud to visualize overgrown vegetation?
- Should a difference be made for the permissible roughness per period for the year?
- What time of the year is the most appropriate for collecting the LiDAR data?

Cost-benefit analysis The moment this research is further implemented in the work process of the WOCU project, certain costs will be involved. Hence, it is important to conduct a comprehensive cost-benefit analysis that takes into account factors such as acquisition costs and time. This also includes the consideration of using a drone or aircraft with a LiDAR sensor in terms of costs. These costs must be set against the benefits of the potential use cases that can, for example, in turn, reduce several labor time and costs. These actual benefits must be quantified, to what extent they contribute, for example, to early detection of erosion, efficient flora status monitoring, or increased stakeholder involvement to ultimately lead to a beneficial strategic floodplain management. The following research directions should be explored:

- Do the benefits of implementing a use case outweigh the costs of the potential use cases?
- At what point is a tipping point reached that the costs incurred are recovered in terms of effectiveness and efficiency benefits?
- Is acquired LiDAR data with an aircraft accurate enough to perform all found use cases from a UAV point cloud?

Upscaling Expanding the study area to cover additional floodplains within the extensive scope of the WOCU Rijntakken project, certain challenges must be considered. First, there are flight restrictions in certain locations in the Netherlands, so it may not be possible to fly a drone everywhere without problems. Furthermore, challenges for up-scaling of the area must be considered in terms of computer storage, processing and capacities should be thoroughly explored. In addition, the issue of to what extent a larger area can be displayed in the VR headset with the VR Sketch is important. This is therefore something that should be considered in a follow-up research. In addition, it is questionable whether it is financially realistic to fly into every floodplain with a drone given the time span of around 1 day per floodplain. An alternative method could be considered, such as using an aircraft with a LiDAR sensor. Other flight parameters will then have to be taken into account, such as the altitude at which the aircraft is flown, which will influence the density of the point cloud. The following research directions should be explored:

- How can the whole project area be smoothly visualised within the VR headset?
- Is the data resolution of aircraft LiDAR data sufficient enough compared to UAV LiDAR data?

Computer memory As the study area scales up, the point cloud data will naturally expand in size. The increase in scale poses data management challenges concerning memory issues due to the increase in gigabytes of data. To ensure a successful processing, visualising, and analysing of this data, future research should thoroughly consider the importance of having sufficient computing power. For this, the processing of all data could for example be divided into tiles per floodplain. Current developments on compression techniques might contribute in terms of the storage challenges of the raw point clouds. The following research directions should be explored:

- How can the size of the explorative point clouds be minimised to scale up the study area to the entire project area?

- How can data management be implemented for the point cloud data of the entire project?

Time interval Future research should focus on determining the most appropriate time interval between the acquisition moments of the data. It is important to examine factors such as flight frequency (e.g. perhaps on an annual basis) and strategic timing (e.g. before or after the flood season). This strategic trade-off ensures that the selected acquisition moments of the point cloud data will yield the most in terms of changes over time. The following research direction should be explored:

- What is the most appropriate time interval between the acquisition moments to optimize the detection of change for floodplain maintenance?

Participants Including ecological expertise could possibly lead to worthwhile insights regarding possible unexplored ecological aspects within the dynamics of the floodplain. Future research should delve deeper into the understanding of certain complexities of floodplain maintenance by incorporating a broader range of experts and expanding the size of participants. This would enhance the richness of insights and nuanced exploration of the potential use cases of point clouds. The following research directions should be explored:

- Is the possible relationship between the insights of the participants by discipline relevant for further implementation?
- Which disciplines are relevant in exploring additional potential use cases?
- What additional information might be relevant to enrich the explorative point clouds with?

Visualisation method Further research could compare the effectiveness of VR and 2D visualization methods regarding the influence on the quality and depths of the potential insights and the user experience. A hybrid approach may be considered, where an initial overview is presented on a computer screen, followed by a detailed exploration using a VR headset for specific areas that require further attention. The following research directions should be explored:

- How would hybrid 2D and 3D visualisation of exploratory point clouds best be implemented in the WOCU project?
- What requirements determine the extent to which a particular floodplain needs extra attention for 3D viewing in VR?

Toolset in VR Sketch Exploring the integration of additional tools into VR Sketch has the potential to enhance the interaction between users and the 3D model. The current toolset may be expanded for further exploration possibilities in the point cloud by including for example features like the option for intersection of height profiles. This contributes to rendering the virtual environment more suitable for direct analysis. The following research directions should be explored:

- Which additional tools have priority to be available for exploring point clouds in VR?

- Are there any other interactive opportunities that could further stimulate the exploration?

Weather conditions This study did not consider the influence of wind due to time constraints, but future research could look at a possible correction factor based on the difference in wind speed and wind direction between the two measurements. This would add to the accuracy of the actual measured differences between point clouds. However, it should be considered whether this correction takes place in the raw data, or whether it can be integrated into the computed C2CD. Also, it must be taken into account that not all points are susceptible to wind speeds, such as objects made of stone compared to trees. The following research directions should be explored:

- How can a correction factor for the possible changes due to wind influence be implemented in a change detection method between two point clouds?
- For which points within the point cloud should this correction be applied?

Explorative point clouds in other projects While the primary focus of this study was on the explorative point cloud for floodplain maintenance, future research has the potential to extend the scope of applications. This expansion can be done by exploring the added value across several purposes in other sectors to obtain a broader understanding of their potential. Consider, for example, the urban planning, infrastructure and disaster management sectors. The following research directions should be explored:

- How to determine which additional information per purpose is suitable for an explorative point cloud in question?
- Is it relevant to identify points as part of a particular object?
- Is the potential of explorative point cloud equivalent for other purposes in various sectors?

A. Insights

Discipline	Who	Group	RGB	Cloud-to-cloud distance	NDVI	3D bril experience	New data	Comments
Werkvoorbereider Civiel en Water	Christiaan Velzen	1	Ik kijk net naar een manquette, prachtig. Onder de indruk van de details. Impressie van de omgeving, inclusief begroeiing is duidelijk. Civiele objecten. Veel steenbestorting is gegroeid. Goede indruk hoe het erbij ligt.	Civiele objecten verschil identificeren. Erosie aanpak in ons gebied. Sedimentatieproces en de afkalving zou je kunnen volgen als je de lidar metingen frequent laat inwinnen.	Goed overzicht van direct impressie. Evt. Dooie takken opsoren. Verder niet heel relevant.	Legenda mist. Tijd slider om interval in te stellen zou goed kunnen zijn.		Te korte intervallen voor bijvoorbeeld detectie van erosie -> compleet seizoen willen doorlopen
Asset management	Arjen Vos, Jurre Klein	2	Slechtere plekken in zand, bosjes beter zichtbaar. Goed overzicht vanaf bovenaf -> zo is er meer te zien. Soorten bomen niet te zien, duikers en inlaten ook niet te zien. Verruiging in relatie tot de gemaaide gebieden valt op. Informatie zou op deze manier gedeeld kunnen worden.	Rode vlekken vallen direct op, bij de strekdammen en naast bomen. Richting gras vel ook verandering, nuttig omdat je het beter ziet dan wanneer je het veld in gaat. Langer tijdsinterval waarschijnlijk nuttiger. Gebouwde objecten kan hoogteverschil relevant zijn en vegetatie rond bouwwerken. Verruiging is goed te zien. Waterstand ook zichtbaar. Potentie voor berekening of verruiging te groot is, in RGB kan je goed zien waar verruigde stukken zitten -> mooi als je dat hier direct kunt zien adhv de vergelijking met T1.	Hek valt op, rond het hek is niet gemaaid. Rond gebouwde objecten wil je geen objecten ivm wortel groei. Gemakkelijk overzicht groot gebied. Mogelijk plekken waar flora het zwaar heeft goed in kaart te brengen. Kan van belang zijn omdat er beoordeeld wordt op situatie van flora. Plekken die moerassiger zijn, daar gaat het mis als het droog is. Kan gespreksopening zijn met partner. Afvaldumping wellicht zichtbaar (ook wellicht in verschilkaart)	Gebruiksgemak eenvoudig. Kan eventueel optie zijn om te overleggen met externe partij. PROP kan je ook goed controleren ipv in het veld te staan. Inspectie zou ook gedaan kunnen worden van geulen, afkalving en bomengroei op randen. Arbeidsintensieve opdrachten. Groot op scherm is fijner, maar met bril kan je wel makkelijker inzoomen. Scherm is weer makkelijker te delen met collega's. Dus een optie om het beide te gebruiken zou goed zijn.	Vegetatielegger gebruiken. Water niveau in GIS omgeving even hoog brengen. Afkalving en oevererosie op gestortte oevers.	
Hoofduitvoerder Groen	Geert Pleivier	3	Vraag of grenzen kunnen worden weergegeven, bijvoorbeeld perceelgrenzen.	Zichtbaar wat veranderd is tussen twee momenten is handig, om te laten zien dat er onderhoud is uitgevoerd bijvoorbeeld	Kan het ook per type vegatie/soort		Vegetatielegger gebruiken	
Gebiedscongierge	Dennis Boomkamp	3	Herkent uiterwaarden. Ziet verwijdering van riet, de werkzaamheden die buiten zijn geweest. Gaat sneller dan te voet. Ook handig om nieuwe werkzaamheden in te kunnen schatten. Je kan over bepaalde vegetatie in het terrein heen kijken.	Water valt direct op. Oeverosie kan goed te zien zijn. Voor en na hoogwaterseizoen vliegen			Vegetatielegger gebruiken. Warmtebeelden om nest in boom te spotten.	
Natuurontwikkeling	Lianne Ruijven	3	Omgevings aspect zijn aanrijroutes releveant. Zie je in RGB.	Niet heel duidelijk.	Verschralen van gebieden. Kan relevant zijn, moet je ook resten weghalen en niet alleen maaien.	Veel detail zichtbaar. 2D scherm kan je beter samenwerken met collega's. Maar hier kan je beter orienteren door de uiterwaard heen.	Vegetatielegger gebruiken. Grenzen ook weergeven van gebied.	
Technisch Manager	Erwin Suijkerbuik	3		Hoogtekaarten lijken handig voor verruiging in kaart te brengen.	Toepassing voor vegetatietype en soorten zijn handig.		Vegetatielegger gebruiken	
Operationeel omgevingsmanager	Richard Commandeur	3	Handig om greppels te zien, kan je zien waar je kunt rijden.					
Gebiedsspecialist	Rene Vonder, Retze Talsma, Arno Slager	4	De hoogte van bomen en struiken vallen goed op. Zou handig zijn voor het inmeten van bepaalde objecten of om een beter beeld te krijgen door alle details. Goed om in te schatten met beeld vanaf alle orientaties waar mogelijke bottlenecks zitten, zoals bijvoorbeeld waar wordt het smaller of is er meer begroeiing.	Verschraling van grond te zien. Goede optie om verschil te meten. Kijk goed naar de threshold van de puntenwolk, wellicht aan te passen voor specifieke doeleinden.	Goed om idencatie te hebben waar aandacht aan besteed moet worden. Of zichtbaar waar geen vegetatie aanwezig is, zoals bijvoorbeeld zand.	Vraag of de kaart altijd horizontaal blijft. Start van de bril opzetten duurde even, maar naar verloop van tijd ging het goed.		Vraag waarom er geen punten zijn bij water. Uitleg gegeven.
Project Manager	Jan Span	5	Makkelijk om te overleggen door anders te kijken naar het gebied in 3D -> voor participatie van omgeving	Waterpeil verschil valt op. Combineer vegetatielegger met lidar data en laat dit zien in VR bril -> wat voor verruiging treed er daadwerkelijk op.	Goede indicitatie van de status van een uiterwaard.	Heel gaaf, werkt goed. Je kunt makkelijk navigeren door de puntenwolk.	Vegetatielegger gebruiken	
Strategisch Assetmanager	Jantien Buysse	6	Gebruik voor participatie in projecten.	Identificeren van oevererosie zou relevant zijn.	Verschraling van gebied.			
Projectleider Civiel en Water, Adviseur Klachten	Ton van de Sande	7	Voorbereiding van werk, door middel van tonen van de desbetreffende uiterwaard. Communicatie met persoon in het veld	Bossages zie je gegroeid en gras dat gemaaid is.	Zand zichtbaar.	Best tijdrovend in vergelijking tot normaal scherm.		
	Jasper Cornelissen	7	Veel detail zichtbaar, wat er gemaaild is bijvoorbeeld.	Je kunt zien waar gemaaid is, dit is relevant.	Twee momenten vliegen in het voorjaar en najaar.-> vegetatiestatus van een gebied vergelijken. Soms willen we dat iets verschraald, en is dat juist goed.			
System Engineer	Eureka Marahani	8	Veel detail zichtbaar. Makkelijk dat je niet naar buiten hoeft. Z hoogte is toegevoegde waarde door extra informatie.		Type planten verschillen de NDVI waardes wellciht. Schraal gebied is goed zichtbaar in beeld	Legenda toevoegen zou van toegevoegde waarde zijn. Ook eventueel het includeren van notities.		

Figure A.1.: Findings - VR visualisation

B. Flyer

Figure B.1.: Flyer - Participants involvement

C. Reproducibility self-assessment

C.1. Marks for each of the criteria

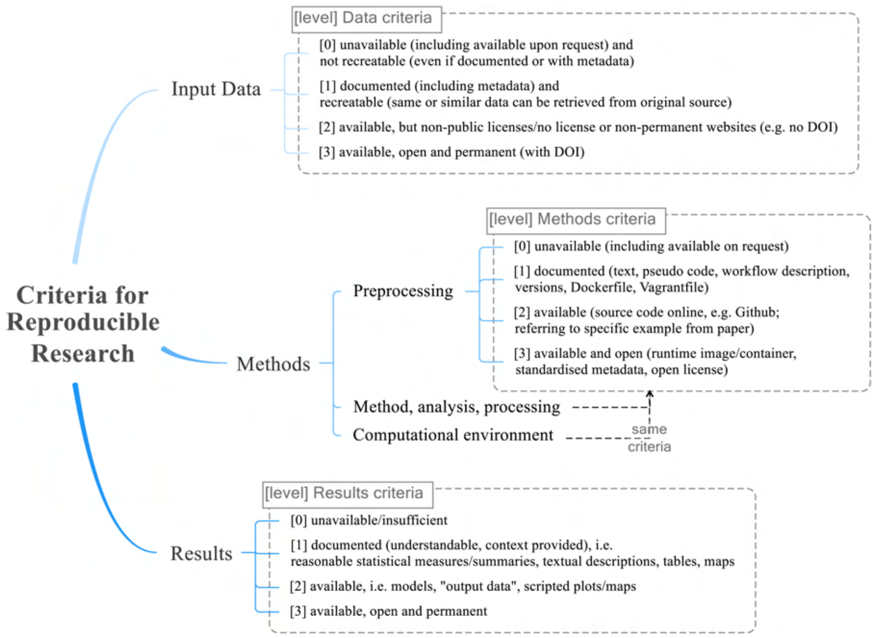


Figure C.1.: Reproducibility criteria to be assessed.

The following Table C.1 shows the reproducibility of this research focused on the input data, method, and results based on the criteria shown in Figure C.1.

Table C.1.: Evaluation of reproducibility criteria

Category	Criteria	Grade
1. Input data	Point clouds	0
	NDVI	0
2. Method	Pre-processing	0
	Processing	2
	VR Visualisation	2
3. Results		3

C.2. Self-reflection

Input data The point cloud and NDVI data of the T1 and T2 measurements are acquired in-house by Van Oord with the Zenmuse L1 and Phantom 4 Multispectral sensors. However, the dataset is not available to the public due to its proprietary nature as it is part of the WOCU project. Therefore, the data is not made available to anyone outside of the project. While this limitation is necessary for the confidentiality of the project, it does affect external validation and further exploration of the exploratory point cloud data.

Method The methodology and implementation of this research are described in detail in Chapter 4 and 5.

The pre-processing of the data is done in DJI Terra software, which is not open-source.

The processing of the attributes is done in QGIS, FME, and CloudCompare. QGIS and CloudCompare are both open-source GIS software programs that are used for clipping the point cloud data, and computing the cloud-to-cloud distance between both T1 and T2 point clouds. FME, which is not an open-source GIS software, is used to integrate the NDVI values in the point cloud.

The VR visualisation requires the Meta Quest Pro headset, Sketchup software, and VR Sketch software. The Sketchup and VR Sketch software are both not open-source software programs.

Results The results drawn are open and permanently available in the form of this document and serve as a valuable contribution to the existing knowledge in the field of explorative point clouds.

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Colophon

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