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TANGIBLE LANDSCAPE: A DESIGN TOOL FOR DUTCH WATERWAYS

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Tangible Landscape: a design tool for Dutch waterways

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Abstract

Tangible Landscape (TL) is a projection-augmented sandbox powered by a Geographical Information System (GIS) for near real-time geospatial analysis of design options. TL is an example of a Tangible User Interface (TUI) where data is manipulated by human interaction instead of relying on a Graphical User Interface (GUI). The objective of this thesis is to develop design tools to be able to use TL during workshops to collaboratively design waterways. A mock-up of a study area at the *Overijsselse Vecht* was already made. The up-scaling of the set-up is investigated to increase the collaborative aspect. To realize this objective, the question how to design and realize a design within TL has been investigated. TL could be the new approach to landscape design as design tools have been developed to stimulate iterative design processes. A thread has been used to intuitively design a waterway that is subsequently analyzed providing visual feedback and numerical feedback to the user by calculating important parameters for designing waterways. The developed tools functioned well and proved to be robust and quick as several configurations of the thread were tested. With the near real-time iterative results - both visually and numeric - a design was evaluated within seconds, decreasing the needed effort and time, stimulating the planning and design process. Moreover, by using a TUI GIS is made more accessible, ultimately increasing informed collaborative decision processes.

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List of abbreviation

AHN Algemeen Hoogtebestand Nederland

AR Augmented Reality

BwN Building with Nature

DEM Digital Elevation Model

DTM Digital Terrain Model

GIS Geographic Information System

GUI Graphical User Interface

GCP Ground Control Point

LiDAR Light Detecting And Ranging

RTD Research Through Design

TL Tangible Landscape

TUI Tangible User Interface

VL Virtual Landscape

VR Virtual Reality

Contents

1 Introduction

1.1 Background and context

Tangible Landscape (TL) is a projection-augmented sandbox powered by a Geographical Information System (GIS) for real-time geospatial analysis and simulation (Petrasova et al., 2018). It is used to study and change a landscape intuitively, to explore ideas and test hypotheses with real-time computational feedback. Changing the landscape is done by changing the physical mock-up model by removing, adding or displacing sand. TL couples a physical mock-up model with a digital model in near-real time by using 3D sensing, enabling users to apply geospatial modeling, simulation and visualisation. By changing the the mock-up model, the visualized spatial data is altered. TL is an example of a Tangible User Interface (TUI). Initially, spatial data was manipulated using line-driven command interfaces. Later Graphical User Interfaces (GUI) were introduced, which already provided more interactive manipulation of spatial data (Ratti et al., 2004a). The development to use GUIs for GIS was driven by a need for a more natural interface to handle geospatial data to make it more accessible (Cartwright et al., 2001). In line with this, TUI were introduced as a new alternative (Ullmer and Ishii, 2000). This new interface enables users to physically interact with the digital environment (Ishii and Ullmer, 1997) removing the need for interaction with a mouse and keyboard by shifting to manipulation by touch and feel.

Other examples of TUIs which were key for the development of TUIs, are: Illuminating Clay (Piper et al., 2002),SandScape (Ishii et al., 2004), Phoxelspace (Ratti et al., 2004b), Efecto Mariposa (Vivo, 2011), Augmented Reality (AR) Sandbox (Reed et al., 2014), Rapid Landscape Prototyping Machine (Robinson, 2014) Cantrell and Holzmann 2016), Inner Garden (Roo et al., 2016) and The Augmented REality Sandtable (ARES) (Amburn et al., 2015). However, compared to TL these examples are not powered by a GIS.

TUI aims to bridge the gap between physical forms of representation and its digital counterpart of representation and analysis (Ishii and Ullmer, 1997). Especially between the different design steps of exploring possibilities and simultaneously conducting spatial analyses on different design steps (Ishii et al., 2004). Such design steps are important, for example, in the field of landscape architecture. In landscape architecture, GIS is mostly used as a mapping tool to visualize and document spatial data but often not to increase spatial knowledge by spatial analyses due to its complexity and the lack of knowledge of the possibilities of GIS for landscape architecture (Nijhuis, 2017).

TL has proven to be an effective tool for accurately modeling topography and physically making changes. It is possible to give ideas form, to perform quantitatively testing and to use an iterative design process to model a topography using a digital reference (Harmon et al., 2018). It increase the understanding of concepts of topography, e.g.reconstructing a historical landscape flooded by a dam (Rengifo, 2018), the flow of water (Harmon et al., 2016), effects of changing hydrology conditions (Rahman et al., 2017), and the understanding of the difference between real and abstract representations (Jermann and Dillenbourg, 2008). It is also used in education to understand better the impact of changes on topographic features (Millar et al.,

2018). It has been used for ecological design where an interdisciplinary problem had to be solved concerning the design of land forms, hydrological systems, planting, and a trail network (Tabrizian et al., 2017). Moreover, it was used to facilitate decision-making processes focusing on collaboration between stakeholders to solve a common problem (Tonini et al., 2017). Recently, it has been used for participatory modeling by studying the spread of Sudden Oak Death (Gaydos et al., 2019).

There are several advantages to using a TUI such as TL, especially in the field of landscape architecture. It integrates the physical and digital representations, it enables physical spatial modeling, it improves the collaboration and communication and it can be used as a preliminary usability study (Ishii et al., 2004). Moreover, it allows for continuous feedback to the user by analyzing each change, supporting the iterative design processes of envisioning and weighing of possibilities (Lynch et al., 1984) with the aim of proposing intentional change (Steinitz, 1995) to a landscape. TL is able to continuously visualize and evaluate these intentional geomorphological changes with the added benefit of comparing these changes to a reference.

1.2   Problem definition

The landscape architect intends to redesign a landscape, by using workshops with different stakeholders where TL is used as a mobile platform as a mean for communication. A previous study using TL has been carried out by Wageningen Environmental research (van Buuren and Keijsers, 2018). This study tested whether it was possible to set up TL, explored the possibilities and served as an pilot study. Testing was done by using a small scale mock-up of 25 x 25 cm. To enhance communication with designers and stakeholders, the question arose whether it is possible to use TL on a larger scale. For this case a mock-up of 75 x 100 cm will be used. This mock-up was made of a study area located at the *Overijselse Vecht* (see section 3.2. Initial testing showed that fitting the reference DEM to the physical mock-up resulted in a mismatch of which the cause is unknown and thus investigated in this thesis. Also, correctly initializing and calibrating the system proved to be challenging. These problems have to be solved as we intend to use TL as a mobile sandbox in the context of having workshops with stakeholders, using TL as a design tool.

Using TL, waterways could be designed in a different way by providing near real-time analyses and feedback, this is of interest due to importance of water in Dutch landscape design. As of yet, no tools have been developed to 1) analyze a waterway design using compatible with TL, and 2) to provide the user with specific feedback during the design of waterways with analysis and visualization. GIS tools – to construct or extract a waterway center line and describe the profile – do exist (Schwenk et al., 2019), but are not compatible with TL. Thus, such tools have to be developed. Due to the nature of TL, the tools to be developed must rely on the user interaction with TL instead of a GUI. That is to say, the interaction occurs solely with the mock-up and not with the GIS.

A new approach to design with TL will be tested where 1) the spatial data is altered by using a tactile instrument to design the waterways, and 2) using this altered spatial data as a reference to physically alter the mock-up. Such an approach to landscape design with TL has not been performed. Either a landscape is formed which is not based on a reference to study theoretically the subject at hand (Millar

et al., 2018; Tabrizian et al., 2016), or a landscape is formed from scratch using a reference DEM as a guide (Harmon et al., 2016; Harmon, 2016; Harmon et al., 2018; Millar et al., 2018). If the starting point of design is a mock-up of a study area, spatial analysis is performed without changing the mock-up itself, but rather time series models are visualized (Tonini et al., 2017) or additional materials are used as tools for analysis (e.g. markers (Gaydos et al., 2019; Tonini et al., 2017), laser pointer (Tabrizian et al., 2016)). One study used TL for design, where coloured velt was used to visualize different tree species with VR (Tabrizian et al., 2017)). However, the mock-up is used as a reference but not physically altered during design as is the case in this thesis.

1.3 Objective and research questions

The objective of this research is to develop TL design tools which will be used in workshops to re-design (Dutch) waterways in the context of re-introducing meandering rivers. The tools will be used for designing possible waterway interventions and to model the proposed design. As the tools will be used for collaborative design during workshops, there is a need for mobility, and a larger scale as well as a mock-up model to be used as a reference model.

The objective will be achieved by answering the following research questions:

RQ1 How to improve the alignment of the digital reference model to the physical model?;
RQ2 How to make a waterway design with Tangible Landscape?;
RQ3 How to realize waterways in Tangible Landscape?

1.4 Reading guide

This thesis describes how TL can be used with larger morphologic/topology mock-ups and the process of developing tools for designing (Dutch) waterways. In the previous section the background and context is explained as well as the problem definition and research questions. The problem definition defines the challenges which will be solved by answering the research questions stated in section 1.3. Chapter 2 describes the relevant concepts and provides a literature review. In chapter 3 the materials and methods used during this thesis are described, primarily showing the development of the design tools. Chapter 4 shows the results of the alignment of the digital model to the mock-up as well as the performance of the developed tools. Chapter 5 provides a discussion on the results and evaluates the working of the tools and their limitations. In chapter 6, the conclusions of this thesis are drawn and recommendations and future work is discussed.

2 Literature review

Before digital techniques were available, landscape architects and planners communicated their ideas with hand-drawn sketches and small mock-ups. Since then 3D visualization has come a long way as challenges such as complex expensive graphics are tackled (Danahy and Wright, 1988). Recently, research in virtual environments, a form of virtual reality (VR), such as on-site display of data on mobile devices (Gill and Lange, 2015) or augmenting the real world with digital 3D data visualization (Haynes and Lange, 2016) has been conducted. VR can be defined as an event or entity that is real in effect but not in fact (Heim, 1994). With regards to Virtual Landscape (VL), where the entity is the landscape itself, a primary visual model with a characteristic geographic setting is visualized (Prechtel et al., 2013). However, in the above mentioned cases the environment is not tangible in a sense that the data visualized can not be altered by physical human interaction. Data can be made Tangible through Tangible User Interfaces (TUIs)(Ishii and Ullmer, 1997). Examples of such interfaces are: Illuminating Clay (Piper et al., 2002), SandScape (Ishii et al., 2004), Phoxelspace (Ratti et al., 2004b), Efecto Mariposa (Vivo, 2011), Augmented Reality Sandbox (Reed et al., 2014), Rapid Landscape Prototyping Machine (Robinson, 2014), Inner Garden (Roo et al., 2016) and The Augmented REality Sandtable (ARES) (Amburn et al., 2015). An overview of these examples and of the different studies in which TL has been used is depicted in table 1. The advantage of using our physical abilities to manipulate the data are many fold. Physical interaction can advance the design process (Mitasova et al., 2006), enabling deeper learning (Ishii and Ullmer, 1997), increase understanding of spatial relations (Kim and Maher, 2008; Cuendet et al., 2012; Rengifo, 2018) and reduce the spatial cognition load (sources), increase collaboration among designers and technologists (Tabrizian et al., 2017; ishii1997; Rengifo, 2018) and lead to more informed decision-making (Mitasova et al., 2006; Tabrizian et al., 2017).

Table 1: Overview of the literature review of comparable projects to Tangible Landscape. The three main functions of TL defined for this thesis: the use of a reference, the ability to change a mock-up and the feedback given is compared to other projects

Paper	How changed?	use of reference		Feedback
Illuminating clay	Interaction with clay surface	could be based on mock-up		DEM, certain analyses
SandScape	Interaction with glass beads	No		Through DEM visualisation
PhoxelSpace	various materials	No		By projecting results
Efecto Mariposa	Interaction with ash	no reference		Several visualisation layers
Augmented Reality Sandbox	move sand by hand	No reference, No GIS		contour lines, other layers
Rapid Landscape Prototyping Machine	via control interface	No		several projections
Inner Garden	move sand by hand	No		Visual change by breathing and heart-rate, sound is used
The Augmented REality Sandtable	move sand by hand , more used for projecting only	nno GIS	included	AR goggles, gesture tracking
(Gaydos et al., 2019)	not changed	mock-up		placing markers
(Harmon et al., 2018)	sculpted using elevation and contour map	reference DEM		different spatial analyses
(Millar et al., 2018)	Change by hands	reference DEM, for forming landscape from scratch		different spatial analyses
(Tabrizian et al., 2017)	Not changed	No		VR; coloured velt representing tree species
(Tonini et al., 2017)	Not changed	mock-up		markers; time-series
(Tabrizian et al., 2016)	freely sculpted	No		VR; ponding or trails designed with laser pointer
(Harmon et al., 2016)	freely sculpted by hand	reference DEM		simulated water flow, depression, difference analytic

Using TL, this thesis aims to develop tools which support landscape design - specifically for designing waterways - with the aid of GIS and near real-time visualization. Fundamental to this approach is the work of Ian McHarg in *Design with Nature* (Ian McHarg, 1969) as this prompted the theory and methodology to use GIS for landscape design. The main idea is to, through design, solve spatial problems. The

spatial problems will be analyzed through an iterative process of analyses, synthesis and evaluation (Lawson and Dorst, 2013). The analyses is founded upon a conjunction of spatial data provided by a GIS and on the expertise of the architect to interpret this data. TL provides near real-time numeric and spatial output to support the synthesis of a design and its evaluation. In essence, TL and the developed tools support visual landscape research (Nijhuis, 2017) by providing an interface to observe the landscape, apply landscape design and planning concepts and harnesses the power of GIS methods and technologies. Within the context of TL and this thesis, to design means to apply the following iterative process:

– Changing the physical mock-up model by human interaction;
– Receiving feedback on the interaction;
– Using a reference to know what has been changed, compared to the original situation.

To develop the appropriate tools, it is key to understand how a landscape architect designs a water way. For designing we need a certain approach. *Design with Nature* (Ian McHarg, 1969) presents, for his time, a new way of thinking by depicting various abiotic, biotic and human characteristics of the landscape as separate layers (Van den Brink et al., 2016). Following this discourse, Steinitz and Rogers (1970) proposed a methodology that follows an iterative process of designing spatial configurations and testing them for their impact on, for example, hydrology, biodiversity and land use (Van den Brink et al., 2016). Such an approach requires spatial data such as height maps, flow models and DEM derived landscape characteristics. A framework, called Geodesign (Steinitz, 2012), has been developed to guide the methods used by landscape architects to analyse a landscape, test interventions and support decision making processes. Different types of models are used during the iterative process which require data that can for a large part be supplied by a GIS. Research Through Design (RTD) methods are applied in engineering-oriented landscape architectural projects - such as designing waterways - where design will usually be tested with computer simulations or mock-ups, evaluated, and tested iterativly until an optimized solution is found (Van den Brink et al., 2016). Another important factor of designing is to take into account the cultural knowledge of the decision makers. Often, designs are also assessed by experts or citizens for their cultural, aesthetic and ethical value (Van den Brink et al., 2016). This shows the need for collaboration during the design process. TL can be used as a platform to support such collaboration. Next to design approaches, it is of importance to know how to design with water and, in the context of this thesis, how to design waterways. Developing new rivers or re-introducing meanders requires a clear understanding of the natural water processes at hand (Prominski et al., 2017). The aim is to (re-)introduce natural morphodynamic processes, to create a more dynamic starting point for the rivers further development. Self-dynamic development - such as Building with Nature (BwN) (de Vriend et al., 2014) - requires sufficient space. Rivers in similar landscape context can serve as an example to design a new river. If located in the study area, an original course could be reconstructed using old maps or surveying historical landscape features. TL supports water way design by offering a platform for viewing and analyzing spatial data to be used for Geodesign, to test designs using RTD methods using a mock-up and stimulate collaboration during decision-making processes.

To design waterways, with a GIS, one must be able to describe such waterways spatially. This can be done by applying several concepts. Van den Berg (1995) found that braided and meandering rivers are geometrically shaped by only three variables; the grain diameter of the substrate, the gradient of the valley, and the yearly or biyearly highest flow rate. The first two variables are determined by the composition of the soil and topography, while the flow rate depends on hydrological characteristics of the catchment. All variables are independent of the pattern of the river, and thus can be used to empirically predict the geometry of a water way.

The geometry can be predicted by using hydraulic-geometric equations (Leopold and Maddock, 1953) which relate the flow rate Q to a certain width and depth, with the following relations:

$$width = a * Q^b \tag{1}$$

$$depth = c * Q^f \tag{2}$$

with the coefficients a,c, and the exponents b,f being dependable on the type of river and climate. An overview of these parameters and the following mentioned parameters can be seen in Figure 1. The variation in the exponents is little, in most cases $b = 0.5$ and $f = 0.4$ are used (Makaske and Maas, 2015). Based on research of Knighton (1987), Hobo (2006) used a value of $a = 5.62$ for sandy banks and $c = 4$ for clayey banks for the *Overijselse Vecht*. If $f = 0.4$, Knighton (1987) found values of $c = 0.54$ for sandy banks and $c = 0.58$ for clayey banks. Hobo (2006) used again these values for the *Overijselse Vecht*. The wavelength and amplitude of a meandering river can also be used to describe the geometry of the river. These variables can be approximated using the following relations (Leopold and Wolman, 1960):

$$wavelength = 11 * w^{1.01} \tag{3}$$

$$amplitude = 3.0 * w^{1.1} \tag{4}$$

With w denoting the width of the river. Moreover, the hydraulic radius, which can be used as a good estimation for the depth for design (Makaske and Maas, 2015) is described as (Brownlie, 1983):

$$\text{Hydraulic radius} = S^{-0.2542} * 0.3724 * D_{50} * Q *^0 .6539 * \sigma_s^{0.1050} \tag{5}$$

$$\sigma_s = \sqrt{\frac{D_{50}}{D_{16}} + \frac{D_{84}}{D_{50}}} \tag{6}$$

With S denoting the gradient of the waterway, D_x the diameter for grain sizes with a weight lower than x percent of the weight of the substrate, Q the flow rate and σ_s the composition of the soil of the waterway. Using the described values for a, b, c, and f, to calculate width, depth, wavelength and amplitude for the case of the *Overijselse Vecht* will result in an underestimation of the actual geometry. If the valley gradient is used as oppose to the gradient of the water way, the hydraulic radius is underestimated as well. Contradictory, an underestimation is desired as this leaves room for the river to develop itself towards natural geomorphology (Makaske and Maas, 2015). The hydraulic-geometric relations have been used in the design process of Dutch waterways before, namely at two meandering projects at *Hagmolenbeek* and *Overijsselse Vecht*(Makaske and Maas, 2015). Outside of the Netherlands, research

has been done in tidal marsh areas (Williams et al., 2002). Using these relations, among others, a restoration case study has been carried out in *Whitemarsh Run*, Maryland (Soar and Thorne, 2001).
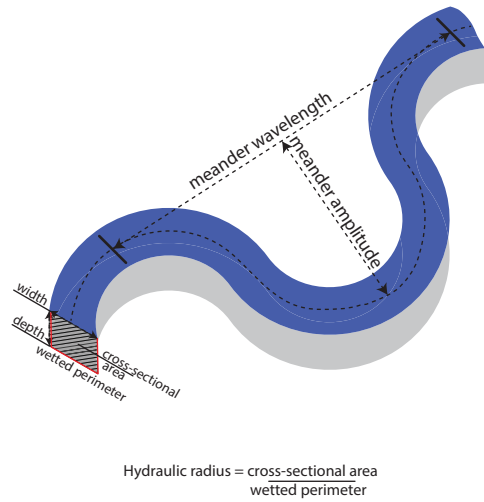

Figure 1: Schematic overview of the above mentioned relations: width (Eq 1), depth (Eq 2), wavelength (Eq 3), amplitude (Eq 4), hydraulic radius (Eq 5)

3 Materials and methods

This chapter describes the methodology used for this research. First, in section 3.1, the set-up of TL as used in this study is described. In section 3.2, the study area and the process of creating the mock-up is described. Section 3.3 describes the process of aligning the digital model to the mock-up and studying the performance on the large scale. Section 3.4 entails the analyses of a waterway and the calculation of important parameters for design. The waterway design will be initiated by a thread. Section 3.5 concerns the realization of the proposed design of a waterway by providing guidelines to alter the mock-up and subsequently analyzing these changes. The methodology is presented per research question. Figures 4, 5 and 6 shows the methodology of each research question respectively. All development is done by using open source coding.

3.1 Set-up

3.1.1 Hardware

TL uses affordable, common hardware: a 3D scanner, a projector and a computer. In the coming section the current hardware that has been used is listed. Due to rapid development and possible alternatives, other solutions could be used in later research outside the scope of this thesis. For more detailed information on the hardware *Tangible Modeling With Open Source GIS* (Petrasova et al., 2018) can be consulted.

3D scanner The 3D scanner scans the mock-up as it is modified by the user. A Kinect is used as it is one of the most affordable 3D scanners available. It provides real-time, high resolution depth and color information. The scanner uses Time-of-Flight (ToF): a technique used in Light Detecting and Ranging (LiDAR) technology (Remondino and Stoppa, 2013). The sensor indirectly measures the time it takes for a near-infrared laser light to travel from the sensor to the mock-up and back. The accuracy and precision of the Kinect is investigated by Wasenmüller and Stricker (2016), Andersen et al. (2012) and Lachat et al. (2015). Wasenmüller and Stricker (2016) found that central pixels showed a similar accuracy while the corners deviated. He also confirmed the long warm-up time needed for the Kinect to achieve reliable results. They do however recommend to apply many pre-processing to compensate for random noise, however the noise is already reduced compared to the Kinect v1 as well as improved depth measurements (Lachat et al., 2015). In this research the Kinect for Xbox One is used.

Projector A projector was used to project the geospatial data on the mock-up. The projector itself is not part of the processing loop. This means that the projected image can only be aligned manually by visual interpretation and not automatically with the use of software. The configuration and placement of the projector is important as they affect the coverage, distortion, and visibility of the projected image. The actual data represented by the image is not affected. The needed resolution and possible distortions are of importance for selecting a projector. The projector

must also be able to generate a bright scene. Such a scene is needed as otherwise the projected data might not be visible. This is especially true for bright lighted rooms, such as offices. The developers recommend higher resolution projectors that offer at least WXGA (1280x800) (Petrasova et al., 2018). Concerning the brightness, they recommend brighter projectors of at least 3000 Lumen. For this research the NEC NP405 projector was used equipped with a NP14LP lamp. This projector offers XGA (1024x768) and 2600 Lumen.

Computer requirements To be able to use TL, the computer needs to meet certain requirements. The computer is used for 3D scan processing and spatial modeling. These are both intensive computational processes that require high performance and enough memory. The developers recommend a multi-core processor, at least 4 GB of memory and a good graphics card. The software of the Kinect scanner is written to work on specific operating systems. For this purpose, Libfreenect2 (Xiang et al., 2016) is used. The preferred operating system is GNU/Linux distribution Ubuntu as this is what TL was initially developed for.

3.1.2 Software

The software used for TL consists of the following packages:

(1) GRASS GIS (Neteler and Mitasova, 2013): an open source GIS and the processing engine providing all the algorithms and libraries used for spatial analyses.

(2) Module r.in.kinect, a GRASS GIS module that obtains depth and color information from the Kinect scanner. Point cloud data from the scanner is subsequently processed into a DEM and RGB rasters provided in separate layers respectively. This module takes care of the calibration of the scanning angle by scanning first an empty table and computing the angular deviation. A plane segmentation algorithm (Rusu and Cousins, 2011) was used to extract the part of the point cloud representing the empty table. A rotation matrix was derived from the angular deviation between the scanner axis and the vector perpendicular to the empty table. Using Rodrigues rotation formula (Belongie, 2019) a rotation matrix was derived to be used to rotate every scan.

(3) GRASS GIS Python API (PyGRASS) was used to build workflows by executing in order GRASS GIS modules. To develop the different analyses for this thesis, the Python Scripting Library is used.

(4) Tangible Landscape Plug-in for GRASS GIS. This plug-in coupled the software of the sensor to GRASS GIS. It provides a GUI in which the user can select processing parameters of the scan and specify a reference DEM. It automates the process of scanning and enables the user to specify workflows by selecting its corresponding python file.

3.1.3 Physical set-up

The experimental set-up of TL at Wageningen University and Research (WUR) is depicted in figure 2 as was used during this thesis.
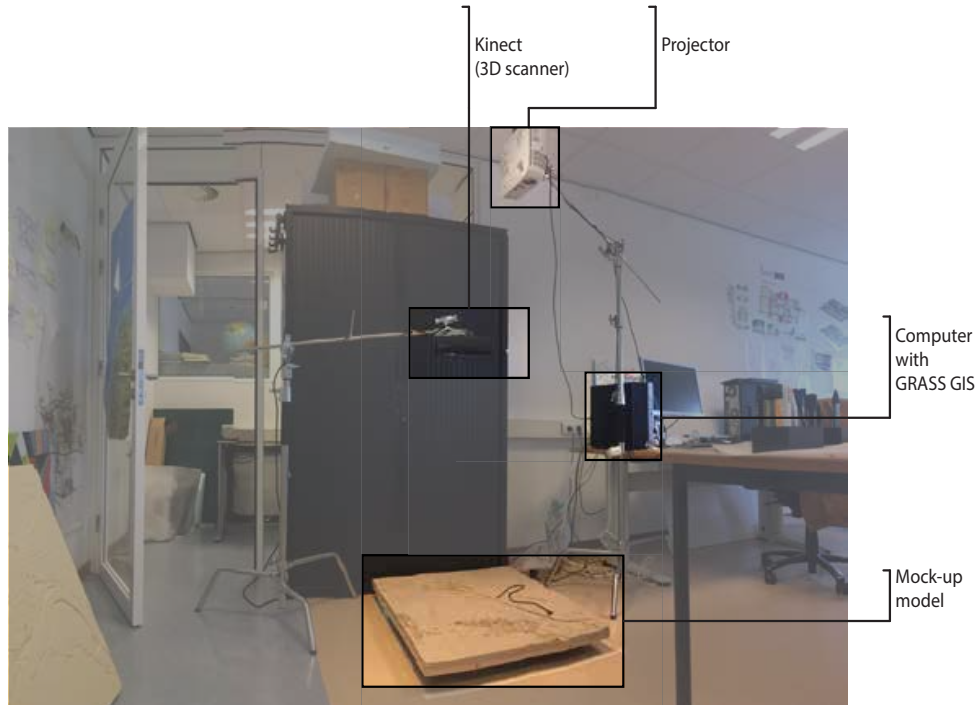
Figure 2: Experimental set-up of Tangible Landscape at the *atlier* at Wageningen University and Research. The hardware components; 3D scanner, projector, computer with GRASS GIS are depicted as well as the mock-up

3.2 Case study and mock-up

study area For this thesis a study area was defined. The study area is located at the *Overijselse Vecht* at Junne, in Overijssel, the Netherlands (for reference see figure 7A. There, Wageningen University and the waterboard have been working on extending the secondary channel by re-introducing a meander (Maas et al., 2018). This secondary channel has been designed with BwN (de Vriend et al., 2014) in mind. This means to design infrastructure that works in line with natural processes and that is adaptable to environmental chancing conditions (de Vriend et al., 2014). This project was part of *Boeiende Beekdalen* as part of the LUMBRICUS programme (Maas et al., 2018). Now we want to test if TL could be used for such a design problem. TL will then be used as an exploratory tool to analyses a possible design. For designing a waterway with certain parameters describing the substrate through which the waterway flows as well as the flow rate are needed. The following parameters are needed as well and are known for this study area (see section 2): a, b, c, f, and the composition of grain diameters of the waterways bed, e.g. sandy, gravel or clayey.

mold   To represent the study area a mock-up of the study area was made by using a mold of 100 x 75 cm. The production of this mold is the result of previous work done by WUR and not part of this thesis. The mold is based on a DTM (Digital Terrain Model) provided by the Actueel Hoogtebestand Nederland (AHN), a Dutch national survey to map the Netherlands using LiDar with a resolution of 0.5 meters. It is published as open data. This DTM was used as a reference DEM during this thesis. However, to create a mold the height of this DTM had to be inverted to correctly model the topography of the resulting mock-up. The actual height of the DTM is exaggerated by 8 times to increase the contrast so that height differences are more easily visible to the human eye as well as to the scanner. The height had to be increased by such an amount due to the flat topography of the study area as well as the size of the mock-up. TL software build-in functionality has been used to account for this exaggeration in height during geospatial computations.

mock-up   To re-design the study for the use of TL, a mock-up was made (see figure 2. A mock-up is a scaled model of a certain object used during designing, in this context a physical landscape. The mock-up was created using the mold. The mold was put into a rectangle frame which was slightly higher to allow room for the addition of kinetic sand. Kinect sand was placed into the rectangular frame until it was uniformly filled to the top. A plate was fitted on top of the leveled sand bed. Next, the whole frame was flipped upside down. The plate and mold were removed to reveal the mock-up.

Figure 3: the mold: an inverted DEM of the study area, z-values have been 8 times exaggerated

3.3   Alignment and pre-processing

In this section the alignment of the digital model to the mock-up is described. Before the alignment of the digital model to the mock-up, the up-scaling of the model was tested by conducting a compactness study based on scans made by the Kinect. After this, the scan was georectified to better fit the mock-up. Lastly, the reference DEM

was processed to be able to calculate the difference between the reference DEM and the scanned DEM. A schematic overview of this section is depicted in figure 4.

Research question 1

Reference DEM

Mock-up model

Make sandbox with
mold based on
Reference DEM

Scanned DEM

Scan
Mock-up

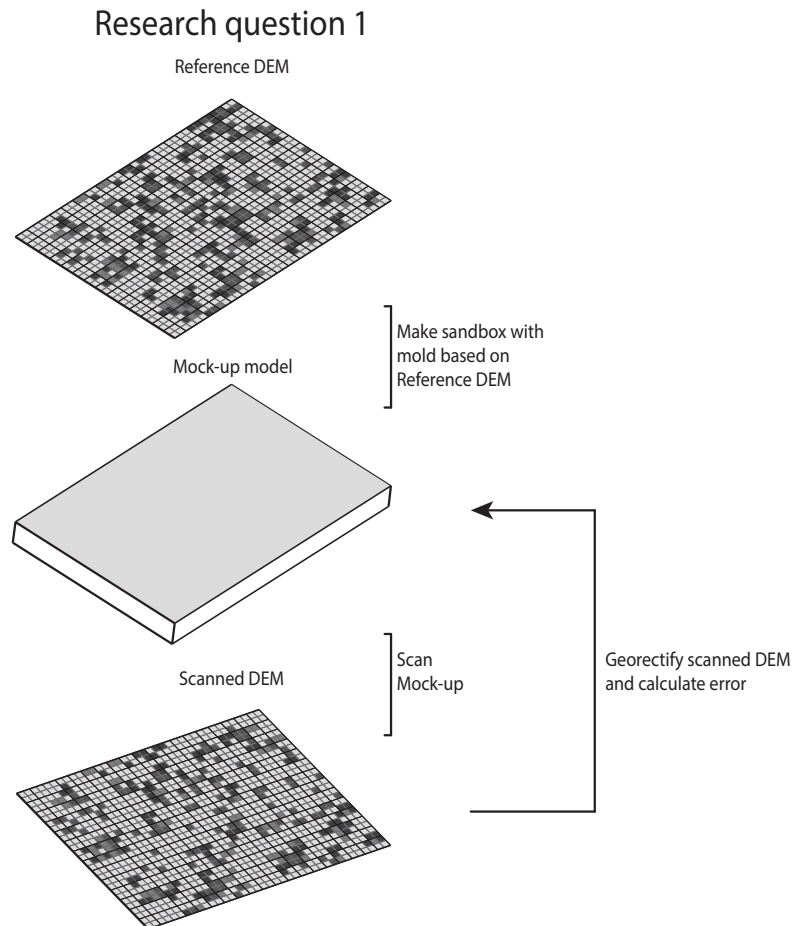Georectify scanned DEM
and calculate error

Figure 4: schematic overview of the alignment process. First, a mock-up was made using the mold described in section 3.2. Then, this mock-up model is scanned to generate a DEM. Finally, the scanned DEM was fitted to the mock-up by goerectifying the scanned DEM using the reference DEM of the study area

3.3.1 Compactness study

As a mismatch was observed when initially testing TL on the larger scale of 100 x 75 cm, the performance of the Kinect scanner was tested by conducting a compactness study. The compactness (C) (Gravelius, 1914) is a way to describe the shape of an object. Using the compactness factor, shapes can be compared with each other (Wentz, 1997). The compactness ratio is defined as follows:

$$\text{Compactness ratio} = \frac{\text{perimeter}}{2 * \sqrt{\pi * \text{area}}} \tag{7}$$

First, a test has been done on a small scale model of 25 x 25 cm which has been used in previous research at Wageningen University and Research (van Buuren and Keijsers, 2018). For this test a wooden base plate of 25 x 25 cm was used. Using several wooden plates of 12.5 x 12.5 x 2 cm, the compactness of these plates was calculated using different configurations. In this way possible distortions and trends were investigated in all three dimensions. After these tests, the same test was carried out using the scale of 100 x 75 cm. Here the smaller wooden plates were placed on each edge as well as in the center. Each configuration was tested using the Kinect scanner facing in the longer axis or facing the smaller axis to exclude the possible effect of deformations caused by the orientation of the scanner.

3.3.2 Alignment

For aligning the scanned DEM to the reference DEM, georectification is applied. First, Ground Control Points (GCP) were selected using the GCP Manager extension in GRASS GIS. Using this manager the user can interactively select the GCPs. An affine (first-order) polynomial transformation was applied to shift and scale the raster data set. For this transformation a minimum of three GCPs were used. The forward and backward errors in the X and Y dimension were calculated. In this way the degree of fit of the digital model to the mock-up was assessed. A tool was developed to automatically georectify each scan. This tool applied the affine transformation on all consecutive scans after the initial phase of defining the GCPs. This tool applied the algorithm developed in GRASS GIS to rectify a scan (Enslin, 2013).

3.3.3 Difference DEM

A difference DEM is the difference between the reference DEM and the georectified scanned DEM. Before a difference DEM could be calculated, pre-processing steps were necessary. The reference DEM was re-sampled, to be able to compare the scanned DEM to the reference DEM. Re-sampling was done using bilinear interpolation as a DEM is continuous data. Bilinear interpolation was also used as it requires less computational power and less smoothing is applied compared to cubic convolution. Due to how to mock-up was created, the landscape represented by the mock-up is an east-west mirrored representation of the reference DEM. The reference DEM was mirrored in the east-west direction to be compared to the scans of the mock-up. After the initial processing, the difference was calculated. This

difference was calculated by subtracting the scanned DEM from the reference DEM. By analyzing this difference DEM, differences in representation of the landscape between the scan and reference were assessed. Also, this difference was used as a measure for the noise of the scanner. The noise of the scanner is caused by the inaccuracy of the scanner, meaning that although no change has occurred to the object, the outcome will of the next scan will differ to some degree. This difference, and especially the mean of this difference was used to take into account this noise during further analyses.

3.4   Designing a waterway

This section describes the development of a tool to design a waterway by the use of a thread. A black thread with a diameter of 0.5 centimeter was used. The thread was laid on top of the mock-up, shaped by the user to represent a possible design with the course of the waterway represented by the entire length of the thread (figure 5, first raster). The thread had to be cut to a specific length fit to the study case as the entire thread was scanned and considered to be a waterway. To use a thread as a design tool had several reasons. First, it is a highly bendable, yet retains it desired shape and can intuitively be used and is widely available. A methodology was needed where a intervention to the landscape could be proposed, before actual changing the mock-up as returning to the state before the change required time and effort and would ultimately slow down the iterative design process which was striven for.

The analyses of a waterway that is represented by a thread can be split up into two parts. First, the center line of the proposed waterway was constructed (figure 5, steps 1-5). Second, a raster representing the waterway was constructed (Figure 5, 6-10). Finally, parameters for design such as the length and the hydraulic-geometric parameters were calculated. To use this tool certain initial input was needed. First, the preferred flow rate and composition of the sediment of the proposed waterway bed had to be defined. These parameters are location specific, related to soil and catchment characteristics. As mentioned in chapter 2 Van den Berg (1995) already found that these parameters - in combination with the valley gradient - determine the geometry of braided and meandering rivers. These inputs were used for the hydraulic geometric equations to predict the geometry of a waterway fitted to such a catchment and geomorphology.

Research question 2

1] Scan
    (scanned DEM)

2] Filter

3] Thin

4] Vectorize

5] Clean

Calculate with 3D points
- length
- valley gradient
- sinuosity

6] Rasterize

7] Give width

Calculate with width:
- meander wavelength
- meander amplitude
- hydraulic radius

8] Give depth
    calculated with
    hydro-geometric relation
    in relation valley gradient raster

9] Substract waterwayraster
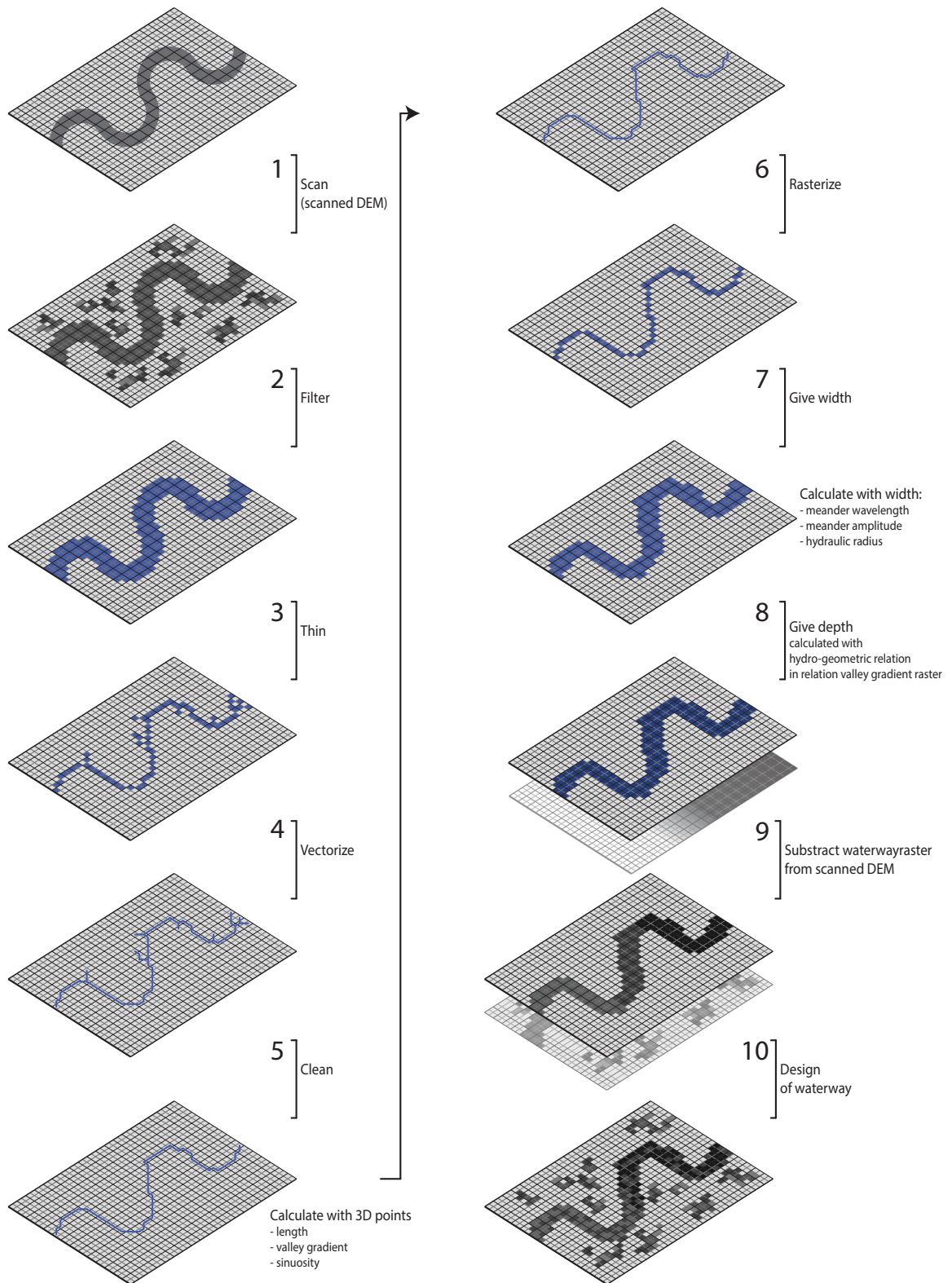   from scanned DEM

10] Design
     of waterway

Figure 5: schematic overview of the process of designing a waterway using a thread.

3.4.1   Constructing the center line

To describe the shape of the proposed waterway the center line of a waterway was constructed. First, the raster cells representing the thread were filtered from the scanned DEM (figure 5, step 2). A black colored thread was used to contrast the light brown color of kinetic sand. As the scanner is able to register color, the thread was delineated using a color specific threshold. All selected cells were given a value of 1, all unselected cells were classified as no data. The raster selection did not always result in a continuous surface following the shape of the thread, but often contained gaps or discontinuities. To fill these gaps and to connect all selected raster cells, cells were added around all perimeters of all areas to a certain degree by using a growing algorithm (Marjorie Larson, 2019). Next, a thinning algorithm was applied (figure 5, step 3). This algorithm reduced non-null cells that denote linear features in a raster to a single cell. In literature this process is known as skeletonization (Blum et al. (1967); Saha et al. (2016); Sintunata and Aoki (2017)). The tool used in GRASS GIS for thinning uses the thinning algorithm described in *Analysis of Thinning Algorithms Using Mathematical Morphology* (Jang and Chin, 1990). They define the thinning process as "successive removal of outer layers of pixels from an object while retaining any pixels whose removal would alter the connectivity or shorten the legs of the skeleton". The algorithm uses an iterative process, peeling off the outside pixels of an object after each iteration. A known issue with this approach is the creation of possible small spurs or "dangling lines" (Waupotitsch, Olga, 2015). At a later stage in this methodology, these were removed.

To further analyze and clean the intermediate result, the raster was converted to vector line features (figure 5, step 4). To remove small spurs or dangles a cleaning algorithm was used (Gerdes, David and Blazek, Radim and Landa, Martin, 2016) (figure 5, step 5). This toolset considers a vector line to be a dangle if no other vector line is on at least one end node. For this tool a threshold had to be defined. The tool removed a dangle if the length was shorter than the value of the threshold. Finally, the multiple vector lines were converted into one single line to ensure a correct topology by assigning all lines to one polyline.

3.4.2   From center line to waterway raster

Using the constructed center line, a waterway raster was constructed using the flow rate and gradient depended width and depth given by the hydraulic geometric equations (see section 2). To give the center line the appropriate width, the center line was converted from a vector line to a raster (figure 5, step 6). Using the same growing algorithm as before, cells were added around the perimeter of the raster using the width as the diameter (figure 5, step 7). A raster format was used because the final waterway raster needed to be compatible to the scanned DEM. To calculate the given width, the raster was converted to a polygon. A vector approach was used as the width given to the final raster is not equal to the calculated width with the hydraulic geometric relations. This difference is caused by the resolution of the scanner, as the width is bound by the raster resolution. Transects, lines running orthogonal in respect to the center line, were constructed along the center line and were clipped to the waterway polygon. The waterway raster was transformed to a polygon feature to be used for clipping the transect lines. The spacing of the

transects is set by the user. From these transects the mean length was calculated. The mean length of the transects is a direct measurement of the width of the design of the waterway.

Next, the depth of the design was calculated and integrated into the scanned DEM (figure 5, steps 8-10). To calculate the depth of the designed waterway raster, the depth given by the hydraulic geometric equation was used. This depth indicates the depth of the waterway bed in relation to the top of the waterway, but not the actual depth in relation to the scanned DEM. To calculate the depth of the waterway in relation to the DEM more processing steps were needed (figure 5, step 8). Water flows from high elevation to low elevation according to the valley gradient. To simulate this flow, a raster plane was constructed over the entire extent of the study area. This raster plane started with the height of the starting point of the designed waterway. The height of this raster plane decreased according to the calculated valley gradient in the direction of the end point of the waterway. To construct such a plane, the gradient, aspect and starting point were needed. The gradient was calculated by selecting the begin and end node of the center line. The begin and end node of the center line were the centroids of the first and last raster cell of the waterway raster constructed before. These 2D points were transformed to 3D points by sampling the scanned DEM using bilinear interpolation. The gradient was then calculated by using the following relation:

$$\text{valley gradient} = \frac{180}{\pi * \arctan 2(\frac{\Delta h}{\Delta d})} \tag{8}$$

where delta d is the euclidean distance between the 3D points, and delta h the height difference. The euclidean distance, d, was calculated by using the Pythagorean formula:

$$\text{euclidean distance} = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \tag{9}$$

Then, the aspect (the slope direction) between the start and end node was calculated as follows:

$$\text{aspect} = \frac{180}{\pi * \arctan 2(\frac{\Delta x}{\Delta y})} \tag{10}$$

where dx is the difference between the x-coordinates of the node, and dy the difference between the y-coordinates.

From this raster plane the depth calculated by the hydraulic geometry equation (equation 2) was subtracted to derive the depth of the waterway in relation to the valley gradient (figure 5, step 9). This raster covered the entire extent of the mockup. To integrate this raster which depicted the depth of the designed waterway into the scanned DEM a mask was used. Using the previously calculated waterway raster as a mask, the calculated gradient raster with the designed depth was re-sampled. Finally, a composite raster was created by patching the scanned DEM and the re-sampled waterway raster (which now contained the depth of the designed waterway), filling the no data present in the waterway raster map with values from the scanned

DEM (figure 5, step 10). By creating this composite raster the waterway design was integrated into the scanned DEM.

3.4.3 Calculating other parameters concerning design

An important parameter for design is the length of the proposed waterway along the center line. As it was not possible to directly extract the length, the constructed center line was converted to vertices. Then, the euclidean distance of each set of following vertices was calculated. the distances were summed, to calculate the total length of the course of the waterway. Next, the parameters concerning meandering rivers were calculated; wavelength, amplitude and hydraulic radius according to relations 3, 4, 5 respectively as mentioned in section 2. Another parameter used to describe meanders is sinuosity, or tightness of the meander bend, which is expressed as the ratio of the length of the waterway in a given curve to the wavelength of the curve (Leopold and Wolman, 1960). In other words, the ratio of the length of the waterway and the euclidean distance between the begin and end point of the waterway (Williams, 1986):

$$\text{sinuosity} = \frac{\text{length center line}}{\text{euclidean distance}} \tag{11}$$

3.5 Realizing a waterway design

In section 3.4, the method to design a waterway with a piece of thread is described. This section describes the methodology of realizing a design of a waterway. To visualize the needed changes to the mock-up to realize a design, another tool was developed. Important to note here is the change of the used reference DEM. In this case, the waterway design calculated in the section 3.4 was used as a reference instead of the initial reference DEM to create the mock-up. The difference between each consecutive scan of the mock-up and the new reference was calculated during the process of changing the mock-up to realize the design (figure 6, steps 1-3, iterative process). In this way, the calculated difference indicated where to change the mock-up, by either taking away sand by supplying sand. By using this difference as a guide, a waterway design was realized (Figure 6).

It is important, while changing the mock-up to realize a design, to receive feedback on the geometry of the waterway. For this purpose, again a center line and waterway raster had to be constructed. The same methodology was applied as was used for the tool developed previously (section 3.4, except for the steps delineating the waterway from the scanned DEM. As the input changed from a piece of thread to a registered small differences of the mock-up by the scanner, the algorithm to decide which raster cells represented a waterway had to be altered as well. For this new algorithm, new functionality was needed.

For this new algorithm, a function which defined a threshold for selecting a raster cell was developed. The threshold only depended on the scans itself to ensure that the user does not have to interact via a GUI but only interacted with the mock-up. In section 3.3.3the mean of the difference DEM - the difference between the first scan before changing the mock-up and the initial reference DEM - was calculated.

Research question 3
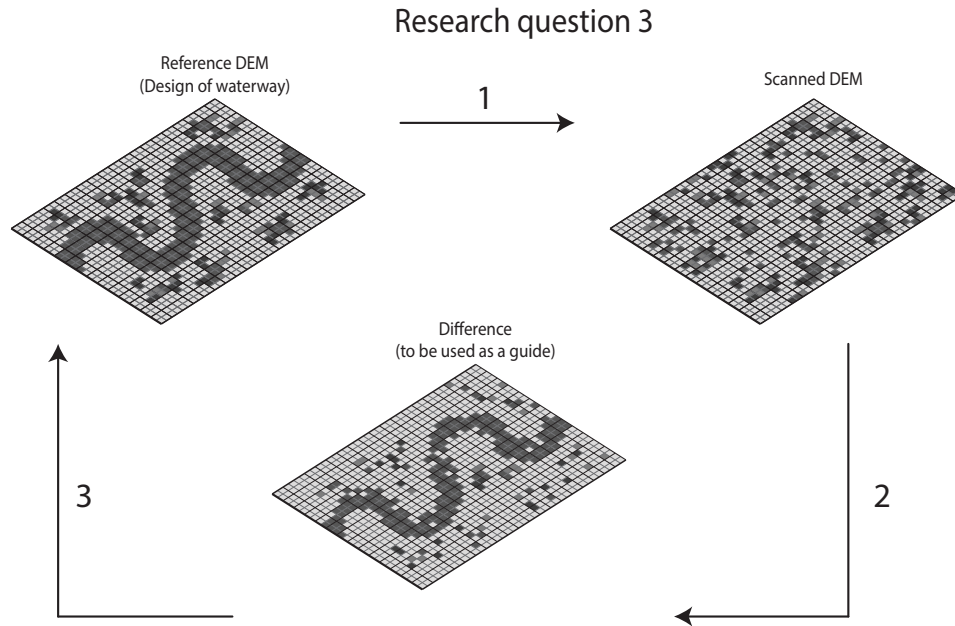
Figure 6: schematic overview of the process of realizing a design of a waterway. Important to note here is that the waterway raster is used as a reference during the process instead of the reference DEM used during the previous processes.

For this function, this value was used as the mean initial difference. This value is used to take into account the inherent inaccuracy of the scanner. The threshold was defined as follows:

$$\text{threshold} = (\text{current difference} + \text{mean initial difference}) * [0 - 1] \quad (12)$$

Using this threshold raster cells were selected which represented the realized waterway, by applying the following relation:

$$\text{waterway raster} = \text{current difference} > \text{threshold} \quad (13)$$

After the cells were selected and classified as waterway raster, the same methodology was applied as mentioned in section 3.4

4 Results

This chapter discusses the results of this research. In section 4.1 the results answering the first research question are addressed. Section 4.2 entails the second research question. Finally, the results of the proposed methodology of the third research question are discussed in section 4.3.

4.1 Optimizing the reference data

The aim of the first research question was to investigate the cause of the error in the data representation on the larger scale which was observed in the initial stages of this thesis. Also, the possibility of up-scaling and the possible challenges were analyzed.

4.1.1 Compactness study

To study the ability of the scanner to represent certain shapes, a compactness study was carried out (table 2). First, the small scale of 25 x 25 was considered as previously used by van Buuren (van Buuren and Keijsers, 2018). The extent of this scale was represented by object B. Object A is the wooden plate as mentioned in section 2. no differences were found for object A and B by comparing the compactness of real objects to the compactness of the same objects registered by the scanner. Second, the large scale of 100 x 75 cm was considered which was the same scale as the mock-up. The scale of the mock-up was represented by object C. Differences were found between the real compactness of object A and C compared to their scanned compactness. A difference of 0.002 units for object C was found. On the same scale, a difference of 0.001 units was found for object A. Comparing the representation of object A on the small to the representation on the large scale, a difference 0.001 units was found.

The scanner measured distances in units. The actual size of a unit depended on the extent of the scanned area. The scale was always defined as a x,y,z plane from 0 units to 1 unit. To relate a unit to its actual size, the ratio was calculated (table 2). At the small scale 1 cm is equal to 0.038 units. On the large scale 1 cm is equal to 0.027 units. Object A has an actual height of 1 cm. On the small scale a difference in height of 0.001 units was found, on the larger scale no difference in height was found. No differences were found for changing orientation of the scanner which either faced the short or long axis. Thus, a possible effect of orientation on the representation of objects can be excluded.

Table 2: The results of the compactness study investigating the representation of objects on the small and large scale by the Kinect scanner

Object	Dimension (cm)	Scan (unit)	Compactness object	Compactness scanned object	Difference between compactness
Small scale					
Object B	25 x 25	0.77 x 0.768	1.128	1.128	0
Object A	12.5 x 12.5 x 1	0.384 x 0.373 x 0.039	1.128	1.128	0
Ratio	1	0.038			
Large scale					
Object C	100 x 75	0.873 x 0.642	1.140	1.142	0.002
Object A	12.5 x 12.5 x 1	0.107 x 0.103 x 0.027	1.128	1.129	0.001
Ratio	1	0.027			

4.1.2 Mismatch reference DEM

During the course of this thesis a fundamental error concerning the initial data was found. Initially, it was assumed that the reference DEM provided was the same DEM used to create the mock-up. Through visual inspection it was found that the reference DEM used was shifted by 100 meters to the east compared to the mock-up. By adjusting the old reference DEM, a new correct reference DEM was made.

Scans of the mock-up were georectified to the old reference DEM and the adjusted reference DEM. The forward errors and backward errors were calculated (table 3). The adjusted DEM showed lower errors. forward error of the adjusted reference DEM approached more the target resolution compared to the old forward error. Comparing the georectification of the old reference to the newly adjusted DEM, a difference of 2.48 was found for the forward error. A difference of 2.51 was found for the backward error.

Table 3: Forward and backward errors of the old reference DEM and adjusted reference DEM.

Reference	Source resolution [m]	Target resolution[m]	Forward error	Backward Error
old reference DEM	5.5	0.5	3.46	3.52
adjusted reference DEM	5.5	0.5	0.98	1.01
difference	-	-	2.48	2.51

4.1.3 Analyzing scanned DEM of adjusted reference DEM

Comparing the georectified scanned DEM (fig7B) with the reference DEM (fig7A) similarities and differences were observed. The scanned DEM showed a coarser grid due to the difference in resolution between the reference DEM and the scanned DEM. With respect to the z dimension the scanned DEM raster values ranges from 3.0 to 18.3 meter. The reference DEM raster values ranged from 2.6 to 18.5 meters, Comparing the range of the reference to the range of the scanned DEM, the scanner was not able to capture a part of the higher values and lower values. Comparing the histogram of the reference DEM and the scanned DEM, it was found that the scanned DEM tended to overestimate the height values. This was also confirmed

by the right skewed histogram and the shift of the predominant values (peaks) to higher elevation (fig7B).

Next, the representation of the mock-up by the scanner was analyzed. The overall course of the river and its meanders was captured well (fig7B). The scanned DEM tended to overestimate the height of the higher laying area to the north and northeast of the river. The higher values present in the west of the reference DEM were underestimated in the scanned DEM. Also, the higher values of the ridge in the south tended to be underestimated resulting in more smoothed representation of the landscape. These differences were also analyzed using the difference between the scanned DEM and the reference DEM (fig7C). Positive values denote an underestimation of the height while negative values represent an overestimation. The histogram tended to be left-skewed, showing the tendency to overestimate the height. As stated before, this was predominantly true for the area to the north. The peak of the histogram was located around -2.0 meter, meaning that in most cases the scanner made an overestimation of 2.0 meters The most dominant underestimations were observed in the high elevated peaks located in the south and southwest. The vast majority of the over-estimations were made uniformly over the extent, meaning that the morphology of the reference was captured well by the scanner. In contrast, larger differences were found on edges of terraces in the landscape where a large height difference occurs. For example, the transition from low laying land to higher laying land to the west and east of the main channel of the river (fig7A). These differences are also depicted as linear lighter colored features in the difference DEM (fig7C). Along the river itself and the meanders this pattern was also observed.
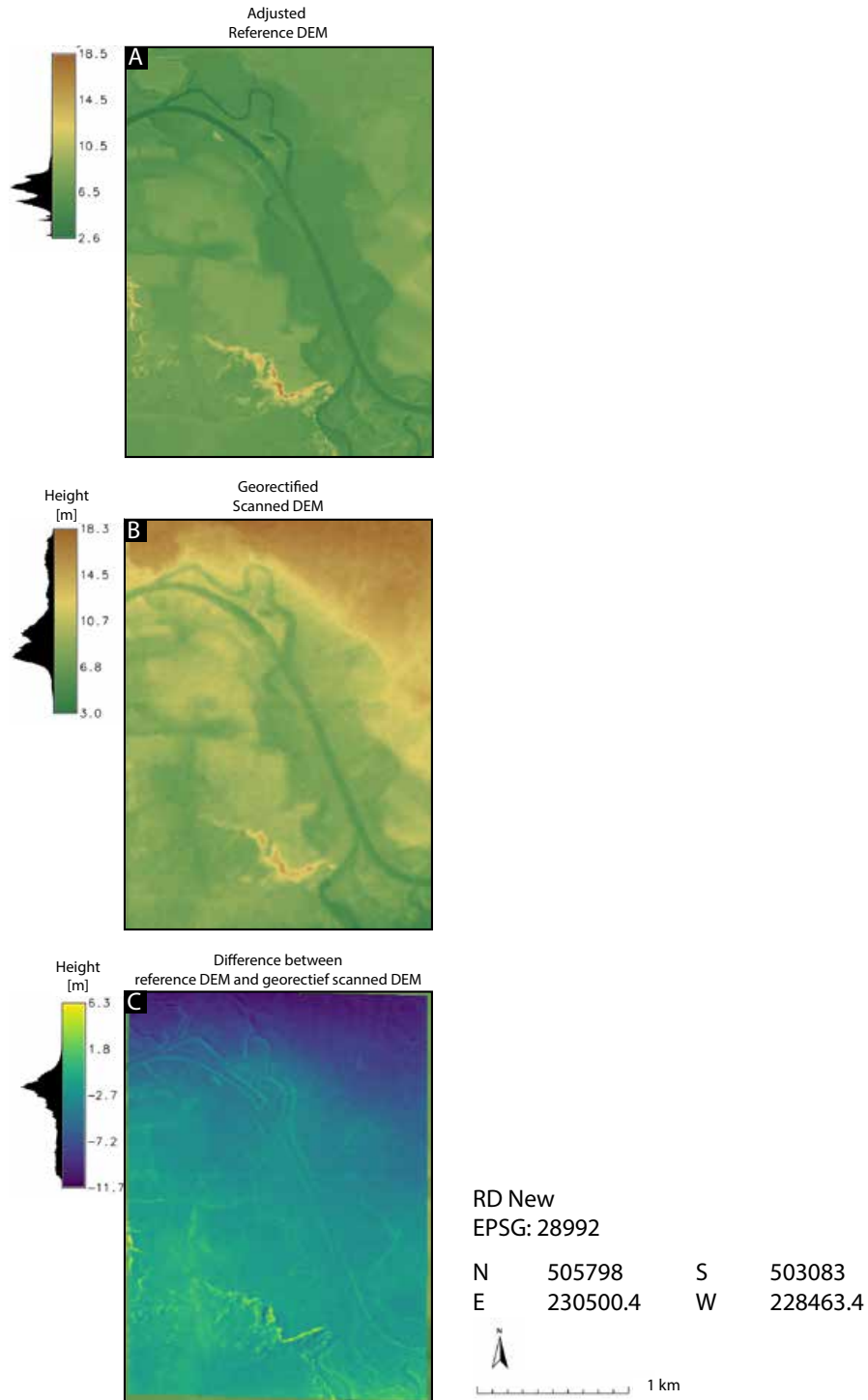
Figure 7: A: shows the adjusted reference DEM. B: is the result of scanning the mock-up. The scanned DEM was georectified to the adjusted reference DEM. C: shows the difference between the adjusted reference DEM and the georectified scanned DEM.

4.2 Designing a waterway

To answer RQ2, the numeric and spatial outcome of the developed algorithm to design a waterway was carried out for several flow rates (table 4). This resulted in several rasters (fig 8A1, 8B1 and 8C1) which were projected on top of the mock-up. A close up of the designed waterways for a flow rate of 3, 9 and 15 cubic meter per second is shown in figure 8A2, 8B2 and 8C2 respectively. The algorithm proved to work consistently while alternating the placement of the thread. Doing so, different cases with changing geometry; length, direction and degree of bending were tested. Each model run took around 10 seconds to complete.

Comparing the calculated width to the scanned width a trend was observed. The scanned and calculated width of the waterway increased with increasing flow rate. In all cases the algorithm overestimated the width of the waterway as the scanned width was larger than the calculated width. At higher flow rates, the overestimation was found to be higher than 1 meter. The depth of the waterway was observed to follow the calculated gradient of the valley as intended. It did not follow the height profile of the scanned DEM (figure8A2 to C2) as then it would have a constant depth equal to the calculated depth corresponding to the flow rate. However, the depth is not constant along the course of the design. In all cases, the scanned length was overestimated compared to the actual length. The sinuosity, which is directly related to the length, stayed consistent as well. The calculated gradient had a tendency to fluctuate but an underestimation was observed at 9 m3/s. Both the meander length and meander amplitude increased with increasing flow rates as is expected from the relations equation 3 and equation 4 respectively.

Table 4: Results of the algorithm which calculates important parameters based on the placed thread. The flow rate increases per step.

Flow rate m3/2	Calculated width	Scanned width	Calculated depth [m]	Scanned mean depth [m]	Actual length [m]	Scanned length [m]	Gradient m/m	Sinuosity [-]	Meander wavelength [m]	Meander amplitude [m]
3	6.93	7.68	0.84	1.57	1617.4	1436.64	0.0016	1.29	77.72	25.23
9	12.00	13.57	1.3	2.08	1617.4	1586.69	0.0012	1.28	135.32	46.16
15	15.49	17.68	1.6	2.46	1617.4	1533.68	0.0005	1.31	175.12	61.12

Visually the designed waterway was represented as a change in the DEM (figure 8A2, 8B2 and 8C2). A new meandering channel was constructed by placing a thread on the mock-up. Using the calculated width, depth, and course of the waterway, the raster cells coinciding in this area were changed accordingly. The proposed geometrical changes increased with increasing flow rate, as indicated by the increase in negative values for the course of the waterway if the flow rate increased (figure 8A2, 8B2 and8C2). The scale of the changes were small compared to the scale of the model. The highest flow rate of 15 m3/s was easier to interpret due to the increase in scale of the design. The increase in change is visualized by a deepening of the depth of the waterway indicated by increasingly darker colors. Moreover, the increase in width with increasing flow rate was indicated by the growing extent of the design. The increase in meander length and meander amplitude with increasing flow rate had no spatial effect as the course of the waterway was not altered. Using the same algorithm, tests have been carried out using a thread with a smaller diameter to see if it was possible to work with finer detail. However, the scanner was not able to see a the smaller diameter resulting in not registering the thread not in parts or entirely.
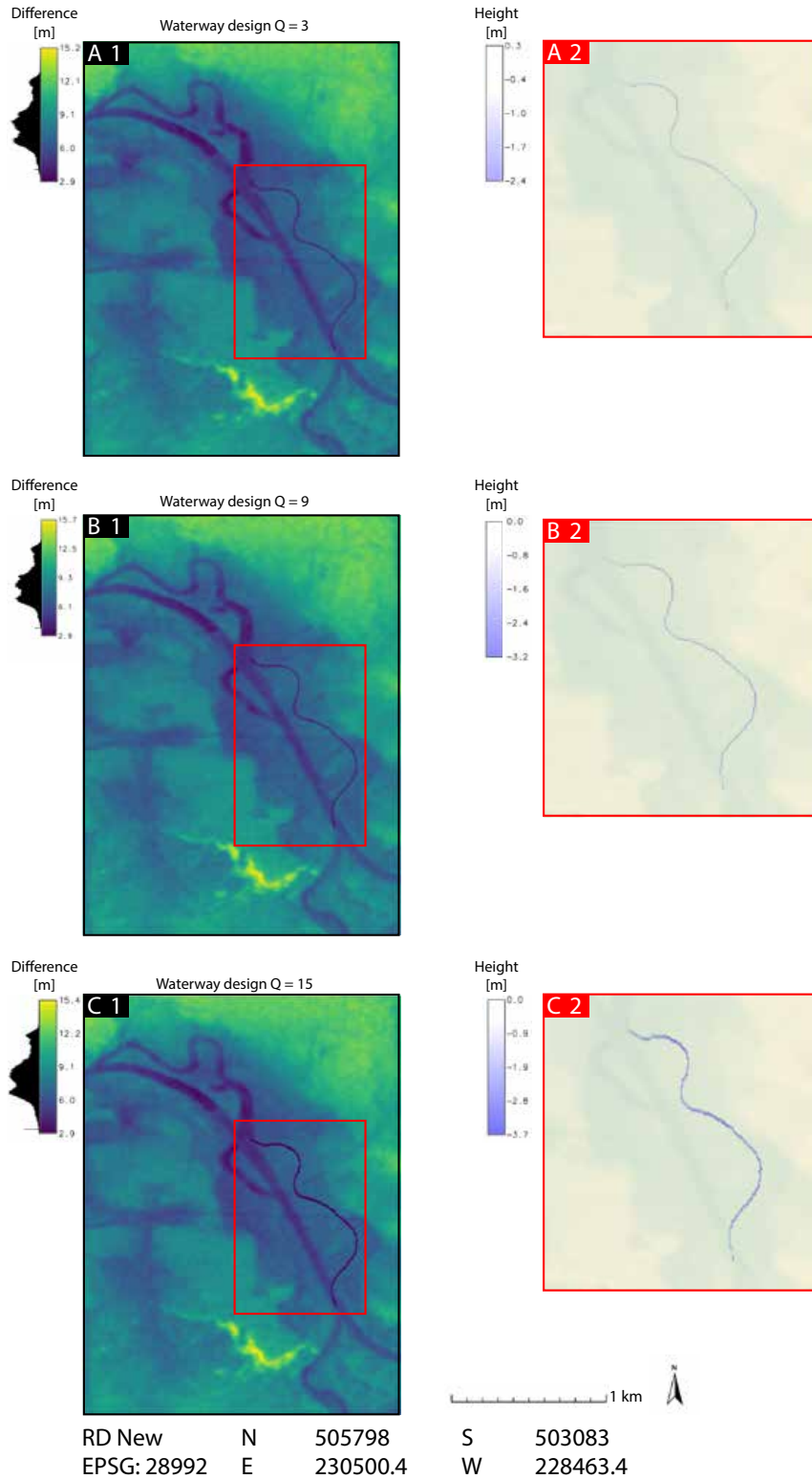
Figure 8: A1-C1: the waterway design integrated in the scanned DEM is shown. A2-C2: a detailed view of the designs is given as well as the raster values only for the raster cells of the waterway. From top to bottom, the waterway is designed for a flow rate of 3 (A1) ,9 (B1) and 15 (C1) cubic meter per second respectively.
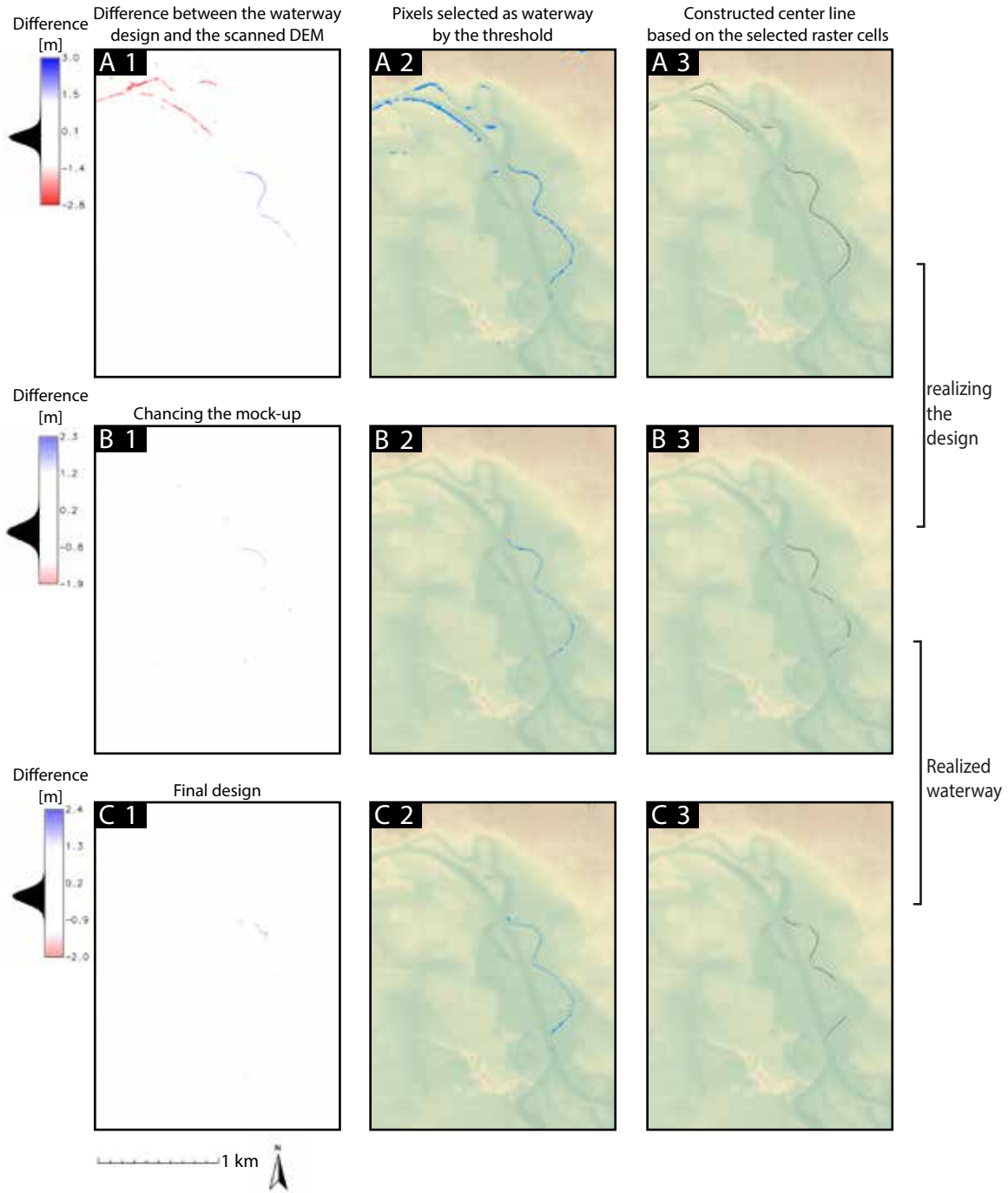
4.3   Realizing a waterway design

Waterways were designed by using the algorithm developed in RQ2. The design of the waterway for a flow rate of 3 m3/s was used as input for the algorithm developed for RQ3. Using this algorithm, the waterway design was realized in the mock-up by taking away sand or adding sand on the specified areas. The specific areas were visualized on top of the mock-up to be used as a guide (9A1). Positive (blue) values indicated that sand had to be removed while negative (red) values indicated that sand had to be added. White indicates that no sand has to be removed or added. Sand was only removed or added at the location around the waterway. The design was indicated in blue (fig 9A1). The output of RQ2 was used as a reference for each scan made during the process of changing the mock-up. Each model run took around 25 seconds to complete. Before changing the mock-up, a waterway design was calculated using a flow rate of 3 m3/s (figure 9A1). This had to be done as the thread was removed from the mock-up to ensure that only the mock-up itself was scanned. Moreover, the thread had to be removed to be able to alter the mock-up on the same spot. As the thread was not used as input anymore, a new algorithm was developed where the differences between a reference - in this case the resulted waterway design of RQ2 - and a scanned DEM would be used as an input.

After changing the mock-up a certain amount, a new scan was made to indicate where to add or take away sand (fig 9B1). The differences were measured in meters relevant to the scale of the mock-up. In some areas outside of the designed area, negative (red) values were present which indicated a change that was not needed. Also, positive values were found where no changes were made. Each time the difference of the waterway compared to the reference became smaller indicated by more and more white. Due to the small scale of the needed changes, the visuals were difficult to interpret while being projected on the mock-up.

The result of the selection of raster cells representing the realized waterway during the process of changing the mock-up is shown in figure 8A2, 8B2 and 8C2 in blue. As the waterway was more and more constructed the selected cells depicted more and more the initial design described by the thread. The final selection of raster cells of the realized waterway (figure 9C2) closely represents the design. This can be seen by comparing figure 8A2 to figure 9C2 as well as the abundance of white in figure 9C1 or the near absence of either positive and negative values. Constructing the center line of the realized waterway was not successful before changing the mock-up (figure 9A3, depicted in black), during the process (figure 9B3) or after finalizing the design (figure 9C3).

As with designing a waterway (RQ2) the same parameters were calculated during the model runs for realizing the design (RQ3). As the constructed center line is never fully connected, the calculations on the realized design never succeeded.

Figure 9: A1-C1: visual guide for realizing a waterway design. Positive (blue) values indicated that sand had to be removed while negative (red) values indicated that sand had to be added. White indicates that no sand has to be removed or added. A2-C2: selected waterway raster cells. A3-C3: constructed center line based on the selected waterway raster cells

5 Discussion

In this section the results of this research will be discussed according to the order of the research questions. In section 5.1 the results of up-scaling and alignment of the reference DEM to the mock-up are discussed. Then, the process of designing with a thread is discussed in section 5.2. Lastly, the realization of a waterway design using the developed design tools is discussed in section 5.3.

Although the benefits of using the developed tools for designing water ways are clear, the question remains when to move from hand-drawing sketches to the application of TL in the design process. TUI and TL aims to make GIS more accessible but whether the implementation of TL will be a success, and accepted as a new approach to landscape design remains to be seen. The investment of calibrating the system, defining the necessary parameters before the user can design a waterway might be too big a drawback. Moreover, the ease of use of GRASS GIS as a software and its development environment for possible new tools might prove to be a burden to the less experienced user.

5.1 Up-scaling and improving alignment

The goal of the first research question was to attempt to find the cause for the mismatch found during up-scaling of the mock-up to 100 x 75 cm and to evaluate the results of the scanner on this scale. Results from the compactness study showed minor differences on both the small and larger scale. These differences could be explained by the inaccuracy of the scanner, but does not explain the mismatch itself. Important to remember for the visualization of data on top of a mock-up using TL, is that the data itself might be correct while the visualization of the data might not be. Adjusting the projected image has to be done manually. The visualization of the data is influenced by several factors such as position and viewing angle which cause the keystone effect (Yadav and Agrawal, 2013): distortion of an image caused by attempting to project an image onto a surface at an angle. Another factor is the position of the scanner in respect to the mock-up, a small change of the position or projecting angle can result in large differences. The magnitude of these differences increases with scale as finer detail is visualized. The position and viewing angle are also important as - in essence - 2D data is projected on a 3D surface causing inherent distortions such as stretching and compressing.

Unexpectedly, visual analyses showed that the reference DEM did not match with the DEM that was used for the production of the mold. Therefore, the reference DEM was manually adjusted, which resulted in lower errors for goerectification of 1.0 meters instead of 3.5 meters. After the adjustment the rectification only resulted in a small shift. The error of 1.0 meters is acceptable in relation to the scanners resolution of 5.5 meters, making it possible to present data on this scale. Moreover, in research done by the developers of TL (Gaydos et al., 2019; Harmon et al., 2018; Millar et al., 2018; Tabrizian et al., 2017; Tonini et al., 2017; Tabrizian et al., 2016; Harmon et al., 2016; Harmon, 2016) no rectification is preformed, as it is inclusive in the software. However, during the use if TL this part of the software often did not function well and calibration was carried out manually. It remains questionable if this rectification step is necessary. Moreover, studies which applied TL on a larger

scale comparable to the one used in this thesis (Gaydos et al., 2019; Tonini et al., 2017) do not report georectification or a discussion on the performance of the scanner on this scale.

Results from the difference DEM show an overall good representation of the modeled terrain (figure7C). The overestimation of predominantly 2.0 meters over the extent might be due to a incorrect configuration of the system. Because of this, the defined base height is possibly elevated compared to the actual base height of the reference DEM. Large differences - over-estimations - were found in the north. Although spatial uniform deformations were observed at the borders during the compactness study, it remains questionable if this could explain the over estimations in the north, as no such over estimations were found at the other borders of the scanned DEM. The large differences on the terraces, or locations were rapid height differences occurred could be explained by the resolution of the scanned DEM. With a resolution of 5 meters the height difference could not be always detected well. Combined with an inherent inaccuracy, the scanner might overshoot or undershoot the peaks causing a lower elevation to be detected.

During this thesis the set-up was not consistent because no rigid structure was developed yet. Striven was to not change the described set-up in figure 2. However, the scanner, projector and mock-up are free standing in space, meaning that scanning and viewing angles can differ quickly due to accidents from users or stakeholders/bystanders making small changes to the configuration are probable. This already happened over the course of this thesis, where the set-up was in a safe and secure experimental environment, and will happen more often in collaborative settings. I should state here that due to the use of this TL in different session outside of the study room, the set-up had to be rebuild several times.

5.2   Designing a waterway with a thread

To answer the second research question concerning designing waterways using TL, design tools have been developed. The developed tools functioned well and proved to be robust as several configurations of the thread were tested. With the near real-time iterative results - both visually and numeric - a design was evaluated within seconds, decreasing the needed effort and time, stimulating the planning and design process. The tools were able to extract and generate a vectorized center line from a scanned DEM where a thread was used to indicate the shape of the designed center line. Using this center line, a waterway design was made for the user-defined flow rate taking into account topography. Designing with a thread proved to be a straightforward process but entails drawbacks as well. Intuitively, the problem with representing a waterway by a piece of thread is that the physical representation itself is the complete opposite of the phenomena that is represented. While a thread is an elevated structure, a waterway is an excavated structure. A thread has a minimum diameter which the scanner is still able to register, limiting the level of detail possible to the resolution of the scanner. Moreover, as the thread is registered over the entire extent it has to be cut to the desired length for each design.

In practice, the resolution of the scanner was too low to be used effectively on this scale. The proposed changes with a flow rate fitting to the study area (3 m3/s) only had effect on 1-2 pixels along the designed waterway. Decreasing the scale

would scale wise increase the proposed changes as 1 pixel does not represent 5 meters but, for example, 15 meters. A consequence however would be that the surrounding landscape - the context - in which these changes would take place is not modeled, making it more difficult to assess the impact of the design on the surroundings. Because of the small scale of the proposed changes to the mock-up it remains questionable if the results are intuitively understand. For one, the changes are hard to see due to the thread obstructing the design as both cover the same extent. Moreover, the resulted depth changes are small compared to the vertical scale making the visual distinction between the proposed changes and the surrounding landscape more difficult. It remains questionable if the calculated depth represents well the intended change due to the use of a thread. As the scanner scans the mock-up, it also scans the thread that is placed on top. This could alter the generated scanned DEM as the height of the physical thread is also taken into account. Including the thread in the scan could lead to an underestimation of the depth. Fortunately, under-sizing of design leaves room for the waterway to shape itself via morphodynamic processes (Makaske and Maas, 2015).

As the width is related to the flow rate, an increased flow rate resulted also in an increased width (see hydrological-geometry relations section 2, equation 1). In all cases results show an overestimation of the calculated width. Unsure is why the width is over-estimated and why it increases with increased flow rate. The cause might be the applied methodology used to calculate the width. The scanned width is defined by a buffer along the constructed center line of the placed thread by using transect lines that are clipped to the buffer. Arguable, the exact width of the design is the width given by the amount of raster cells from the raster generated by converting the constructed center line. However, this width is not measured. Using this width is challenging as it is limited by the increments of the raster resolution. For example with a resolution of 5.2 meters, a width of 7.3 meters can either be represented by 1 raster cell (thus being 5.2 meters) or by 2 rasters cells (thus being 10.4 meters).

The proposed changes are only represented in 2D on top of the mock-up. To make the spatial results more intuitive, cross-sections of the waterway could be presented alongside the mock-up to give a sense of the 3D impact and show the general shape of the design bedding. It is beyond the scope of this study, but changing the mock-up could directly be executed by altering the terrain using a programmable shape changing interfaces (Coelho and Zigelbaum, 2011) such as Surflex (Coelho et al., 2008) and PneUI (Yao et al., 2013).

5.3   Realizing a waterway design

The third research question concerned the methodology how to realize a waterway design. To do so, the design resulting from the previous research question is used as a reference instead of the initial reference DEM. Results show that realizing a waterway design is possible by guiding the iterative process with visualization, however subsequently analyzing the realized waterway was unsuccessful. Change was also proposed not only on the design but also on other parts of the landscape. This shows the inaccuracy of the scanner by detecting change where no change had occurred or has to occur. The design was difficult to realize as the proposed changes

were small in width and depth due to the used scale, morphology and hydrology of the study area. Precision and carefulness was needed in removing sand as only small amounts had to be removed.

The algorithm to classify raster cell as a waterway is based on a degree of change between the waterway design and the scanned DEM during the realization process. The proposed changes were in the order of magnitude of the inaccuracy of the scanner, making it difficult to visualize the iterative changes and subsequently analyze the realized waterway. If the waterway is not classified correctly, a center line is incorrectly constructed causing the analyses to fail. Therefore, evaluating the realized waterway by comparing it to the initial design was not possible. For further cases, it might be better to take into account the topography surrounding the changed area as a mean to classify the waterway raster instead of a difference. In this regard a lot of research already has been conducted outside of the scope of TL. The profile scan technique (Chorowicz (1984); Kim, 1985) might be of use as it can classify elevations, slopes and curvatures. These geometric properties can be used to characterize a terrain surface (Gelbman and Papo, 1984) such as river bedding. Another option might be to apply (semi) automated linear feature extraction to vectorize information from DEMs (Doucette et al., 1999) by applying an unsupervised classification with DEM derivatives (Seijmonsbergen et al., 2011), or the algorithm proposed by Rieger (1993). Alternatively, rivers could possibly automatically be recognized from LiDAR data via edge extraction and skeleton generation (Lin, 2008) or be extracted as an anthropogenic feature using statistical operators as thresholds (Sofia et al., 2014).

6 Conclusion and recommendations

TL can be used for design by using a thread as a design tool, applying hydro-geometric relations and calculating important parameters for design during an iterative process. Designing in such a way proved to be robust and reliant. By defining the desired flow rate the design is given a certain width and depth in relation to the reference DEM.

The proposed methodology could be a new approach for designing waterways in the context of Landscape architecture. Especially due to the application in an iterative design process, providing near real-time feedback on possible designs in the context of a mock-up. On the aspect of scale, applying TL on a larger scale is possible to enlarge to use as a mobile sandbox during workshops but challenges with possible level of design detail arose. Using a mock-up on such a scale increases the spatial awareness and offers more information compared to a 2D map.

A design could be realized, however this required effort and deemed challenging due to the small proposed changes which follow from the Dutch context due to low gradients and low water flow rates. The proposed changes are in the same order of magnitude as the noise of the scanner limiting the possibility to correctly visualize the difference - showing where to take away sand - between the reference DEM and scanned DEM. Not only limited this the visualization and realization but also the analyses in near real-time during the iterative process of taking away sand.

This concept could be improved by working on the following three aspects: develop a more ridged set-up, using a scanner with a higher resolution and add more functionality to the developed tools. First, to improve the mobility and ease of use of this sandbox, a ridged structure has to be constructed. This construction would ensure a fixed configuration of the scanner and projector in relation to the mock-up. This in turn simplifies the configuration process and ensures a better model fit to the mock-up. This could stimulate the process of moving from an experimental phase to put it into practise as the current set-up is too vulnerable. Second, TL is restricted by the available software for scanners, only the Kinect scanner can be used. New software could enable the use of a scanner with a higher resolution making it possible to achieve a higher level of detail on larger mock-ups. However, a higher resolution also imposes a higher computational burden affecting the iterative process.

For future work we are looking into combining the developed tools with other models. SOBEK (Deltares, 2019) a model used to simulate water currents and related processes is currently being investigated. The challenge there is how to couple the GIS environment of TL to the model interface of SOBEK which is based on a succession of cross-sections of the waterway. User interaction is the dominating factor of a TL success. A tight coupling with sophisticated models must be aligned with response times concerning the process of interaction and participation.

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Appendices

A   Table of Content of the ZIP file

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