Modelling Historical River Landscape Evolution in Virtual Reality (VR)

Geomatics Master Project

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Abstract

This project explores the visualization of temporal river landscape evolution through 3D techniques in a Virtual Reality setup. Historical topographic maps are used as the data basis to create digital elevation models and textures. Using Unity and the High-Definition Render Pipeline, photorealistic landscapes are generated and integrated into an immersive VR environment. The workflow is designed to be automated and reproducible, with potential applicability to other historical maps. The resulting interactive VR application allows users to interactively explore the historical evolution of river landscapes, focusing on a study site in Laupen BE, Switzerland. While the workflow automates many steps, some manual preprocessing remains necessary.

1 Introduction

Natural landscapes form a complex construct of various factors and are influenced and defined by human, animal and plant life. Landscapes transform and change constantly over time. The ever-accelerating development and spread of technological advances of humankind requires an understanding of the historical and future temporal changes of natural landscapes due to various reasons [1]: understanding diversity and identity loss [2], preserving cultural heritage [3] or solving environmental problems like floods and landslides [4].

An effective method for capturing the form and evolution of landscapes, which has been used for centuries, are topographic maps. Of course, 2D visualisation have certain disadvantages, as a three-dimensional environment has to be packed into a two-dimensional representation. 3D visualisations make it possible to avoid this problem and can provide substantial advantages over 2D visualisations, e.g. for convincing stakeholders about river and reservoir restorations [5][1] or for planers in case of a scenario testing by providing a sense of familiarity and interactivity using realistic 3D visualizations [6]. However, new difficulties arise with 3D visualizing technologies, especially regarding the handling of technologies embedding such 3D visualizations. Finding a clear advantage for one or the other visualisation technique turns out to be difficult, as multiple reviews ([7], [8]) show. Nevertheless, it can be assumed that having more dimensions to represent requires more advanced visualisation techniques. This work explores how the temporal evolution of river landscapes can be visualised using 3D visualization techniques in a virtual reality (VR) setup. Building on research about 3D landscape visualization technologies ([9][10][3][11][12]), this work introduces two key innovations: the representation of temporally changing landscapes using VR and extensive automation for creating such representations solely based on historical topographic maps.

1.1 Background

In Switzerland, the damming of rivers was and is still today a widespread issue. The construction of dams and canals has not only destroyed habitats but also disrupted the regulatory function of natural river courses, which are vital for managing changing water levels. Since 2011, Swiss law has obliged both cantons and the federal government to renaturalise and revitalise bodies of water as much as possible to address these problems [13]. Visualisations of historical landscapes are particularly useful for such projects, as they can help to highlight the issues of dammed rivers and biodiversity loss by showing how the landscape might have appeared before human intervention [14]. Further, temporal landscape visualizations can give insides into future trends of landscapes and how they may evolve. They can potentially reveal whether a river network will be altered after uplifts or if erosion is likely in certain regions [4]. In such cases, structural interventions would be the natural response. 4D visualizations can persuade stakeholders and planners by illustrating the positive and negative effects of landscape changes [1].

Thanks to the first two major map series, the Dufour maps (1845-1865) [15] and the Siegfried maps (1870- 1926) [16], the historical map base of Switzerland was already established in good quality well into the past. Especially Siegfried maps had an outstanding accuracy for that time [16], which therefore nowadays can still be valuable for extracting topographic information of that time. The Siegfried maps as well as historical national maps will be used in this project to extract elevation models, which build the basis for digital landscape visualizations.

Digital landscape visualization has been explored previously. De Boer et al. [17] applied a combination of image segmentation, GIS and 3D rendering software but mainly based on a manual approach. Joye et al. [11] included more automated processes but focused primarily on settlements and cities rather than natural landscapes and used images as base data.

On the one hand, this project is intended to make up for the lack of automation in most approaches and, above all, to take the final visualisation one step further thanks to VR technology.

1.2 Objectives

The objective of this project is to develop a virtual reality platform that enables users to journey through time and witness the evolution of river landscapes in an immersive way. A workflow is to be created and implemented, which shows the process to get from a historical topographic map to a 3D-modelled landscape in a VR environment. The workflow should be reproducible, automated and allow it to be used for different areas of interest and with different historical maps.

This work focuses on the technical implementation of a VR application that allows us to witness the temporal evaluation of river landscapes. The effectiveness of such a visualization, also compared to topographic maps, is not part of this work.

2 Methods

The development process of the virtual reality platform for 3D visualizations can be divided into three work packages:

1. WP1: Map to DEM
2. WP2: Generating temporal landscapes
3. WP3: Immersive visualization and storytelling in VR

The following chapters explain the underlying data, preprocessing steps and the development of the three work packages. A simplified workflow, shown in Figure 1, shows the overall process and is taken up again in the respective chapters by means of a number in brackets (e.g. *(12)*) corresponding to the numbered processing steps in the illustrated flowchart diagram. For a detailed view, appendix A shows a complete illustration with all functions, intermediate steps and results. WP1 and WP2 are implemented entirely based on Python, WP3 using Unity and C# scripts.

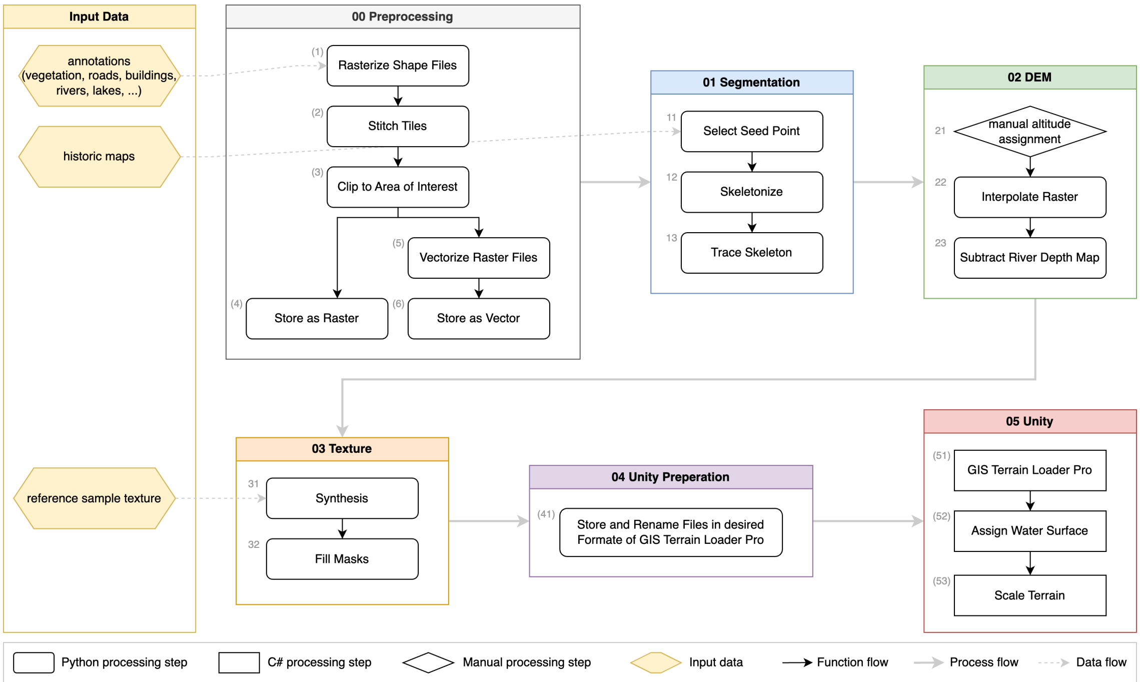

Figure 1: Illustrated simplified process workflow.

2.1 Data

The workflow to be created should take a, one could say any, map as input and create a 3D representation from it [1]. Historical topographical maps of Switzerland are used for the development. More precisely, for the years 1870-1926 the Siegfried maps [16] and subsequently from 1935 until the end of the century the old national maps are used [18]. All maps are available as raster files (GeoTIFF). Additionally, preextracted features, such as rivers, lakes, vegetation and roads are provided by the Chair of Cartography (ETH Zurich) for each of the available historical maps.

A study site is selected for development. Based on the interest in visualizing a site with strong temporal changes in the landscape, different regions in Switzerland are investigated. The following rivers and regions show potential:

- Aare river (channelization and dam construction)
- Rhone river (flood control and agriculture development)
- Thur river (agriculture development)

[1] The workflow is being developed and tested based on the mentioned topographic maps. Other topographic maps with similar features and representation may lead to similar results, however, this has not been tested and can therefore not be guaranteed.

- Saane river (channelization and dam construction)

An area around Laupe BE and Bösingen shows strong changes from 1888, where the river flows in a natural meandering form, until this date when the river is fully channelized without any natural flow left. This area, displayed in Figure 2, stretching over 2.8x3.8 km, is therefore selected as the study site.

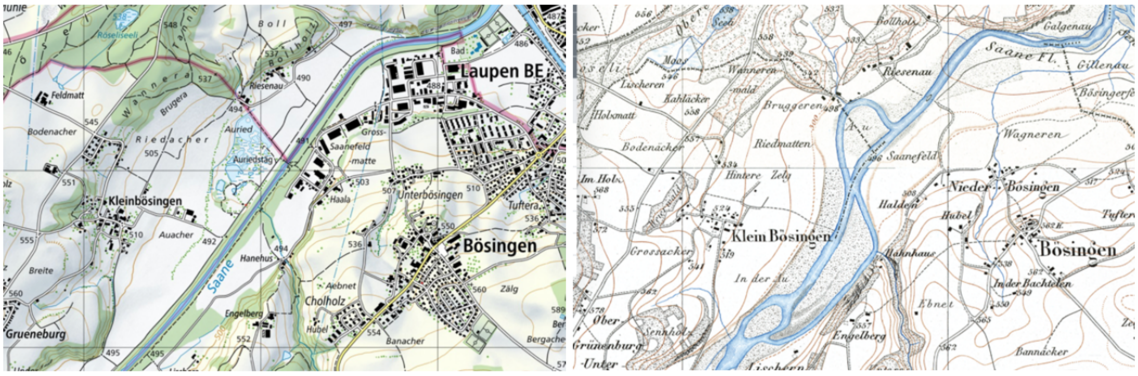

Figure 2: Selected Study Site: Saane, Laupen BE, 2024 (left) vs. 1888 (right). (source: swisstopo)

2.2 Preporcessing

The data is available in different data formats and naming conventions and stored in predefined tiles. The different map tiles contain parts of the area of interest. Tiles are available for different states of time. Multiple preprocessing steps are needed, to prepare the data for the actual workflow.

All files are brought into a raster file format (GeoTIFF). This includes rasterizing some vector features *(1)*. Based on that, the area of interest is extracted from the maps as well as the annotation features. The tiles are merged with the nearest time intervals (not all neighbouring tiles are available for the same year) and stitched together *(2)*. The area of interest is then cut out *(3)*.

2.3 Map to DEM

The essential features of a map containing height information, are the contour lines. They are defined as lines of constant height and are in this case specified on the map for every 10 metres of height difference. In a first step, the contour lines have to be extracted from the map. The lines are shown in orange on the map and are therefore easy to distinguish from other features. The simple but effective segmentation algorithm is therefore used. The lines are roughly masked with simple thresholding and then refined with a flood fill algorithm [19] based on a selected seed point on the map *(11)*. Similar pixels within a tolerance of the seed value are selected. The resulting pixels are then skeletonized *(12)* and a vector shape is created using the skeleton tracing *(13)* algorithm of [20].

In a second step, altitute values need to be manually assigned to the contour lines *(21)*. The altitude is assigned using GIS software (e.g. QGIS). An implement script helps to speed up this tedious manual work by assigning height values based on the nearest neighbour of already existing contour lines (e.g. contour lines of the most recent national map).

The third step involves the creation of the digital elevation model (DEM) by interpolating the contour lines *(22)*. For this purpose, the vector contour lines are rasterized again in a single-band unit8 format with the normalized height information as pixel values. Two different approaches are tested for creating the DEM: simple linear grid interpolation and a Unity-based AI model. For the linear grid interpolation the *scipy* library [21] is used. The Unity-based AI model is a provided pre-trained C# model for interpolating heights.

As the maps do not contain any information about the depths of rivers and lakes, these features show the same altitude as their surrounding terrain. However, the DEM should represent the actual ground also for the waters, as the riverbeds and lakes are later "filled" with water as a part of the visualization process in Unity. Therefore, hydrology depth maps are calculated and subtracted from the DEM *(23)*. The depth maps are calculated on the basis of a distance-to-edge algorithm. The nearest distance to a non-flow pixel is calculated for each flow pixel and this value (scaled) is selected as the depth of the flow. This creates a linear gradient down to the deepest point i.e. the point furthest from the edge. Thresholding is used to limit the depth to a maximum value (stream 1m, river 4m, lake 20m).

2.4 Generating temporal landscapes

Before creating the terrains, the spatial alignment between the temporal maps and DEMs is checked. Alignment forms the basis for the best possible perception of temporal changes in the landscape. As the underlying data, the historical maps, are already georeferenced with sufficient accuracy and consistency for this area, no further measures were required for the alignment.

The 3D terrain is created in Unity based on the DEM and textures. This second work package is about the generation of meaningful textures, the creation of the terrain and the design of the landscape based on the vector annotations, such as vegetation and water elements.

The texture-synthesis technique is used to stitch together patches of existing images with seamless transitions. The goal of this method is to create arbitrarily large textures based on a small-sized input sample of a texture. An existing algorithm [22] was used for the implementation *(31)*. The resulting textures have the same image dimension as the DEM and annotation raster files and can therefore be clipped *(32)* by the annotation (e.g. clip vegetation texture by vegetation annotations).

The texturisation of bodies of water deserves special mention. Here, not a water texture is chosen, as one might assume, but the texture of the bottom of the water, i.e. stone-like textures. The reason for this is that in the subsequent modelling with Unity, water bodies with real physical properties are placed in the river and lake beds. The bottom texture will then be slightly visible through the water and a realistic impression can be achieved.

The creation of the terrain is done in Unity using the *GIS Terrain Loader Pro* package [23]. This package takes the following three files as input:

- DEM (raster)
- Texture (raster)
- Vector features, such as roads, buildings, trees, grass and custom geopoints (vector)

These files need to be stored in the package-requested format and with the requested naming convention *(41)*. If the data is available in the required structure, a complete terrain, including texture, buildings and vegetation, can be created with just a few clicks *(51)*. The vegetation is represented using 3D models of trees and grass. Both are placed randomly with a predefined density inside the defined area.

Unity 6, released in October 2024 [24], is chosen for development. A High-Definition Render Pipeline (HDRP) is used to create photorealistic landscapes. The HDRP setup comes with a water system, allowing the creation of physical-based water bodies easily [25].

2.5 Immersive visualization and storytelling in VR

The last work package is about the development of an interactive VR application. Unity and the XR Interaction Toolkit are used to create the virtual interactive environment. The Meta Quest headsets are selected as the devices to be executed for the software and the interactions are adapted accordingly to the available controllers and interactives. The application is developed with the following functions in mind: allowing the user to jump between different temporal landscapes, switch between a small-scale *(53)* and a full-scale environment and explore the landscape at different (geographic) locations.

3 Results

The result of this work is an interactive application for VR headsets allowing the user to experience historical river landscape evolution. Further, this work results in an automated workflow for the creation of such 3D landscapes, that can be reproduced or even reused for other historical maps.

3.1 Contour Line Extraction

The chosen segmentation approach for the extraction of the contour lines produces acceptable results, considering the simplicity of the approach. Acceptable means that the contour lines are extracted automatically to such an extent that manual digitisation is significantly reduced. In flat terrain, where the contour lines are further apart (Figure 3 right), the algorithm can extract the contour lines almost perfectly. However, if the terrain is steep (lines close together), the extracted lines merge, which leads to unsightly results (Figure 3 left). In this case, significantly more manual effort is required to correct and enhance the contour lines.

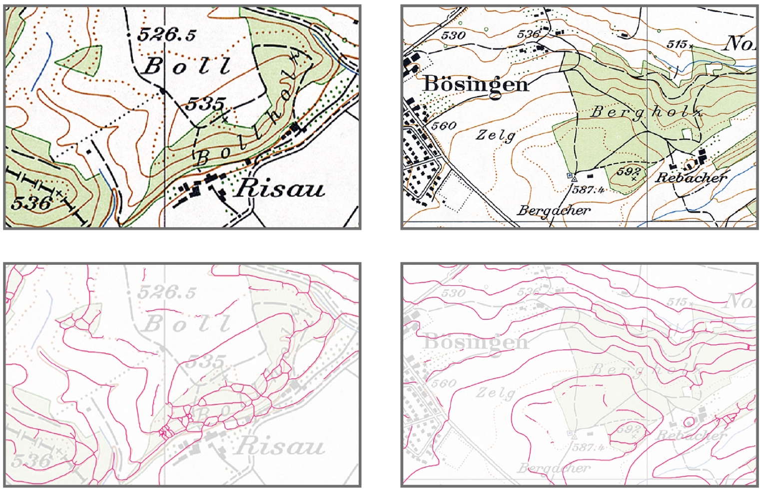

Figure 3: Contour line segmentation results. Poor performance in steep terrain (left column), acceptable performance in flat terrain (right column).

3.2 Grid Interpolation

Figure 4 shows the current DEM of swisstopo [26] and the results from the Unity AI model and linear grid interpolation. The linear grid interpolation clearly outperforms the model. The limitation of the AI model lies in its scalability, as the model can only process tiles of 512x512 pixels. The effect of this is clearly visible in the resulting DEM due to the raster-like artefacts and the poor large-scale interpolation of the height values.

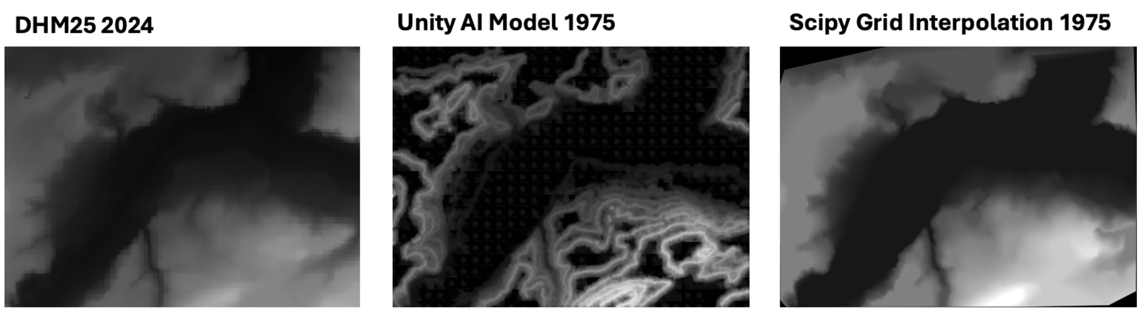

Figure 4: From left to right: current DHM25 DEM (2024), Unity AI model resulting DEM (1975) and linear grid interpolation resulting DEM (1975).

3.3 Temporal River Landscapes

The river landscapes were created for the four selected years 1899, 1912, 1930 and 1975. Only these years were deliberately implemented, as the manual assignment of the contour lines entailed considerable effort and was not the focus of this work. Figure 5 shows one of the resulting river landscape models, i.e. the landscape from 1899. The texture displays grass/vegetation, river beds, streets and light beige for the unknown areas. The water bodies are animated with a flow direction, transparency and reflection on the water surface. The trees move slightly in the wind. A sky with clouds and sun completes a realistic animation and representation of the landscape (see Figure 7). This 3D visualization thus makes it possible to clearly identify and experience the evolution of the river landscape (see Figure 6).

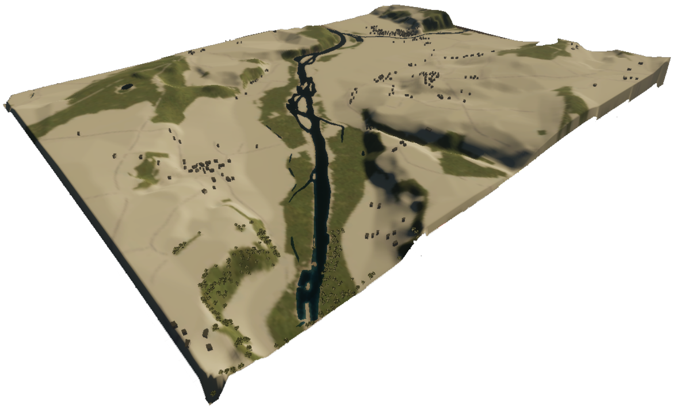

Figure 5: Modelled river landscape of Laupen BE in 1899.

Figure 6: Evolution of the river landscape in Laupen BE between 1899 and 1975.

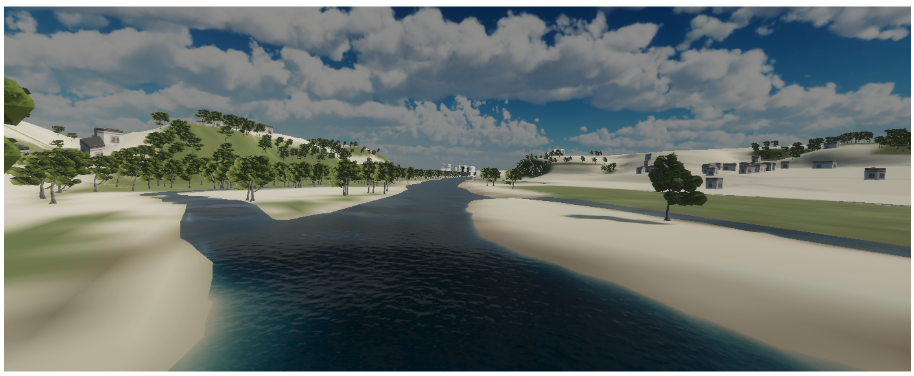

Figure 7: Full-scale environment visualization of river landscape in Laupen BE at 1899.

3.4 VR Application

The application starts in the small-scale environment (see Figure 8). A kind of table is visible on which the terrain or river landscape is located. The scaling factor was set to 0.001, resulting in a model of 2.8x3.8 metres (real size dimensions). A dialog panel shows the current year. The so-called 'jump buttons' can be activated with one controller button on the dashboard. The 'jump buttons' are buttons that have been placed at various locations (see red buttons on the terrain in Figure 8) within the landscape. By selecting a button, the user can jump to the respective location in the full-scale environment. The full-scale environment is a 1:1 scale environment of the landscape. The user can move around freely, explore the landscape and return to the small-scale environment (see Appendix B).

Figure 8: First person view inside the application: Virtual small-scale environment and the interaction controllers.

4 Discussion

The chosen approach to turn historical maps into an immersive and interactive 3D representation contains many individual, sometimes elaborate, steps. With the developed workflow, many of these tasks could be automated. Due to the complexity and sheer number of processing steps, it was not possible to achieve satisfactory results for all of them. The various results and aspects are discussed in the following list:

- **Acceptable contour line extraction:** The segmentation of the contour lines is done based on simple thresholding and connected components algorithms. For many areas on the map, this approach achieved good results and could extract the contour lines well. However, the limitations of this approach are visible for areas with dense information on the map, e.g. in steep terrain where contour lines are close to each other or where other map information such as text, other line features or pointed lines are shown. With morphological operations, some of the smaller artefacts (small, unconnected line segments) could be removed using erosion, however, at the same time, dilation is needed to fill the eroded lines again, which itself leads to new wrongly connected components. This tradeoff already explains the difficulties and limitations of such simple image-processing algorithms. As a result, manual labour was required to correct the contour lines.

- **Manual altitude assignment:** One of the more difficult image processing tasks is the extraction and classification of text. As the extraction of height information from the historical maps was only one part of one of the three work packages, the development of an algorithm extracting the altitude and assigning it to the contour lines was abandoned. The consequence was some tedious manual work, assigning each line an altitude. In terms of automation, an improvement in this part could probably bring about the most significant acceleration of the process.

- **DEM raster interpolation:** The achieved results with linear grid interpolation can be considered satisfactory. A quantitive analysis of the goodness of the resulting DEM is difficult to make, as no 'true data' for reference is available from this time. However, visual comparison to the current DHM25 model shows, that this method works quite well, especially on an overall scale. On the other hand, the limitations and problems of the Unity AI model are immediately visible and can be explained by the limited scalability of 512x512 pixel-sized tiles, that the model takes as an input. By having only the information of such a small tile, the model lacks context beyond the border of each tile and therefore cannot create a meaningful DEM.

- **Allignment of temporal landscapes:** The terrain can be assumed to be largely static over the period of just a century under consideration. The main changes in the landscape over this period are due to the evolution of the course of the river (natural and human-influenced changes) and changes in the vegetation. In order to best visualize and perceive these landscape changes, a good geographical alignment within the temporal landscapes is important. This is mainly based on the underlying data, in this case, the historical maps. For the selected area in Laupen BE, the maps allign well, which consequently leads to a successful impression of the evolution of the landscapes. The main source of error or limitation in quality results from the extraction of elevation information. Be it inaccuracies in the segmentation algorithm, in the manual assignment of heights or in the interpolation, the terrain sometimes shows unreliable or even incorrect structures.

- **Terrain texture:** The terrain texture is purely based on vector annotations. These annotations are extracted from the historical map only. No other maps, such as land coverage maps, are considered. Therefore, the information basis for creating textures is limited to the available information from the historical maps, i.e. forests, roads, rivers, lakes and wetlands. For all other coverages, the resulting texture could not be created. This limitation affects the overall impression and perception of the visualized landscape.

- **Representation quality of 3D objects:** The 3D objects, such as buildings and trees, are created and placed by the *GIS Terrain Loader Pro*. The packages allow to define different textures for the building's walls and different tree objects. The standard textures and tree objects are used here. The accurateness of the resulting representation in relation to the landscape at the selected location therefore leaves certain doubts. The visualization could be considerably improved with an analysis of historical buildings and the growing vegetation in this area. The trees are placed randomly on the predefined areas. This can be both an advantage and a disadvantage. On the one hand, it is not possible to obtain more precise information about vegetation and its density from the topographic map anyway. With a random placement of trees, plausible visualizations can be achieved. On the other hand, variability of different tree species or visual effects of forest edges (thinning of tree density) is more difficult to realise with this method. In general, it can be concluded, that 3D objects make a significant contribution to realistic visualization.

- **VR interactivity:** The interactivity of the application was deliberately kept simple. The use and handling of VR headsets and controllers require a higher level of cognitive understanding than conventional applications with a screen and mouse. For this reason, only three main functions are possible within the application: changing the year, jumping between small-scale and full-scale and moving freely within the environment. To always know which virtual year one is currently in, a dialogue window with the displayed year floats below the (virtual) feet. The intuitiveness as well as possible errors and difficulties when using the application have not yet been tested within the scope of this work.

5 Conclusion

According to limited research, two significant new aspects were investigated and developed in this project. On the one hand, there has hardly been any focus on an automated workflow from (historical) maps to a 3D visualisation and, on the other hand, little work has been published on the visualisation of temporal changes in landscapes using 3D render machines and VR applications.

It must be said, however,it was not possible to create a fully automated application for the visualisation of landscapes. Some manual intermediate steps limit a simple and user-friendly application and further development and improvements would be necessary. In this regard, it should also be mentioned that in the end the major part, at least in terms of time, was taken up by preprocessing.

Probably the most interesting question from this work is what the benefits and effectiveness of such novel representations of temporally changing landscapes are. Since this question was not declared in advance as part of this work, no research was carried out in this regard. Nevertheless, I would like to raise some points of interest for future work.

Such a visualisation can have potential for planning or educational purposes. As some studies have already shown ([1],[27]), 3D visualisations can help to understand past processes and take measures for the future. In particular, such visualisations can help to demonstrate possible measures to stakeholders who are less experienced and familiar with the subject matter of specific landscapes and convince them of their importance. With regard to educational purposes, such an application could be used to improve spatial understanding. The points just mentioned are only assumptions and therefore it would be important to investigate and verify them in a potential further work based on user studies.

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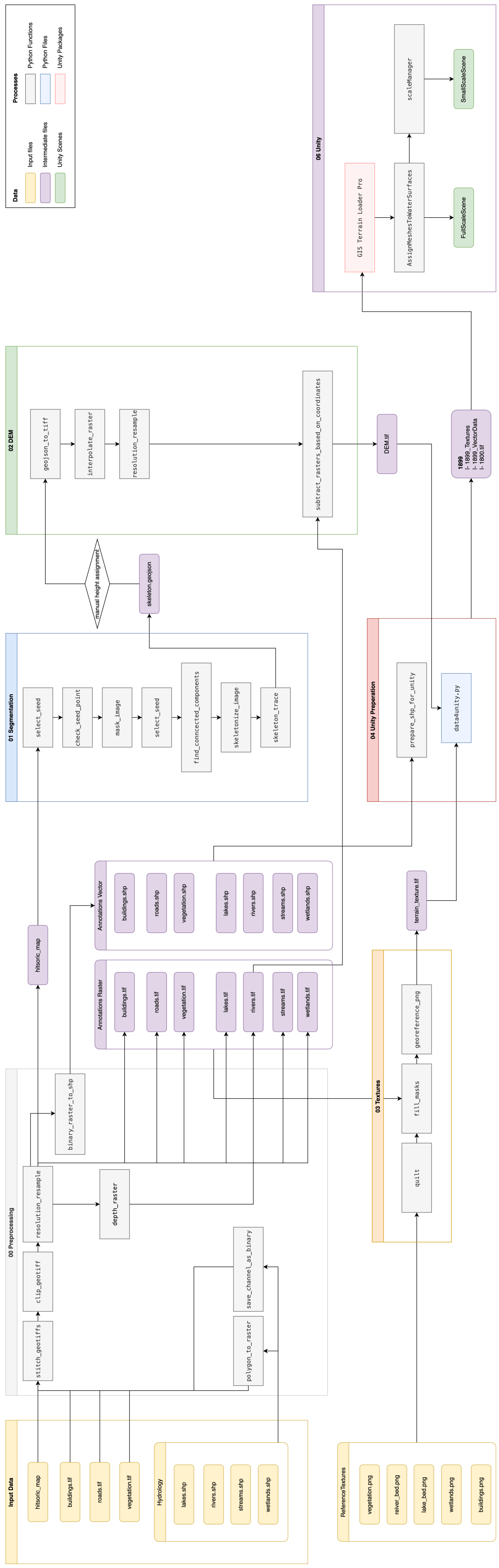
Appendix

A Full Process Workflow



B Full-scale VR envrionment

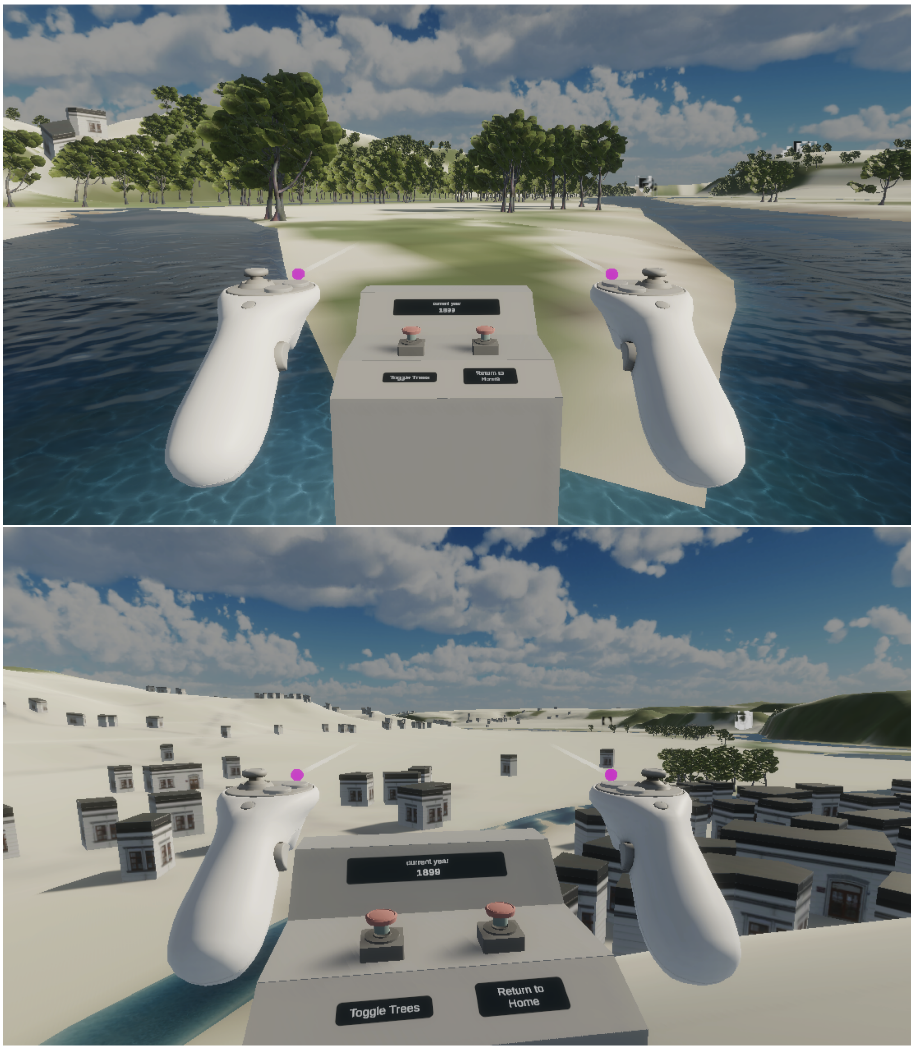


Figure 9: VR application: Inside the full-scale environment.