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Detecting the Displacement of the Baltic Basin's Ancient Shorelines by Clustering of Terrain and Distance Data along the Glacio-Isostatic Uplift Axis

Identifier le déplacement des anciennes lignes de rivage du bassin de la mer Baltique par le clustering *des données de terrain et de distance le long de l'axe du soulèvement glacio-isostatique*

Edijs Breijers, Edyta Kalińska, Māris Krievāns

Abstract: The successive development phases of the Baltic Sea basin have affected areas that are nowadays exposed, giving rise to numerous ancient shoreline landforms. In present-day Latvia, on the eastern shore of the Baltic Sea, however, these are only vaguely traceable. In order to grasp the dynamic relationship between ancient human activities and the ever-changing shorelines, a case study was carried out on the ancient Ventspils lagoon, north-western Latvia, where several Mesolithic and Neolithic settlements have been investigated. Using an automated LiDAR data-processing method, a highly detailed digital terrain model was created. It has served as the main data source for detecting the ancient shorelines; firstly, for deciphering the most pronounced ridges, and, secondly, as the input data for cluster analysis as elevation data, adjusted according to glacio-isostatic uplift direction and rates. The adjusted ridges were clustered (k-means clustering), and after manual filtering, 25 ancient water levels corresponding to 10 shores in four time periods during the Ancylus Lake and Littorina Sea stages were modelled as trend surfaces. These trend surfaces were then compared with the modern-day terrain to delineate the ancient shores. While the results correspond well with previous findings of shoreline remnants and could be detected in the field, the models show a disconnection from consensual studies in the area when it comes to the positioning of the stages' maximum water levels due to glacio-isostatic uplift. Also, the 25 new ancient water levels reveal a discrepancy with previous studies, where only one or two levels per stage were considered. The methodology developed and the results have various applications in the field of archaeology at sites impacted by glacio-isostatic uplift and with a highly variable water level.
Keywords: Highly detailed digital terrain model, Ancylus Lake, Littorina Sea, Mesolithic, Neolithic.

Résumé : Les phases successives de développement du bassin de la mer Baltique ont affecté des zones qui sont aujourd'hui exondées, donnant naissance à une multitude d'anciennes lignes de rivage. Le long des côtes de l'actuelle Lettonie, sur la rive orientale de la mer Baltique, ces rivages anciens ne sont que vaguement traçables. Afin de saisir la relation dynamique entre les anciennes activités humaines et l'évolution des littoraux, une étude de cas a été réalisée sur l'ancienne lagune de Ventspils, au nord-ouest de la Lettonie, là où plusieurs établissements mésolithiques et néolithiques ont été étudiés. En utilisant une méthode automatisée de traitement des données LiDAR, un modèle numérique de terrain très détaillé a été créé ; il a servi de source principale de données pour détecter d'anciennes lignes de rivage. Les crêtes littorales les plus prononcées ont tout d'abord été identifiées, puis leur altitude a été ajustée en tenant compte de la direction et des taux du soulèvement glacio-isostatique. Les crêtes ajustées ont ensuite été regroupées (*clustering k-means*), et, après un filtrage manuel, 25 anciens niveaux d'eau ont été modélisés au cours des stades du lac Ancylus et de la mer à Littorines. Si les résultats correspondent bien aux découvertes antérieures de vestiges de rivages et ont pu être identifiés sur le terrain, les modèles montrent une déconnexion avec les travaux faisant consensus sur le territoire lorsqu'il s'agit de positionner les niveaux d'eau maximum des stades, et cela en raison du soulèvement glacio-isostatique. De même, les 25 nouveaux niveaux de paléo-rivages montrent un décalage avec les études précédentes, où seuls un ou deux niveaux par étage étaient identifiés. La méthodologie développée et les résultats obtenus ont différentes applications dans le domaine de l'archéologie, particulièrement sur des sites affectés par le soulèvement glacio-isostatique et de fortes variations du niveau d'eau.

Mots-clés : modèle numérique de terrain à haute résolution, lac Ancylus, mer à Littorines, Mésolithique, Néolithique.

INTRODUCTION

Postglacial isostatic rebound started in the Baltic Sea basin right after the Last Glacial Maximum (LGM), around 20 ka BP, and continues to the present day, with a maximum rate in the Gulf of Bothnia of ca. 1 cm a^{-1} (Ojala et al., 2013). Nevertheless, the uplift rate has been irregular both spatially and temporally. The major components driving this specific spatiotemporal aspect of the development of the Baltic Sea basin are the changes in the global mean sea level and, regionally, the changes triggered by glacio-isostatic adjustment (Björck, 1995).

Once the Fennoscandian ice sheet retreated, the inflow of viscous mantle started raising the terrain back to its original state, thus resulting in a complex pattern of shoreline development. The development of the coasts and shoreline displacement has been extensively studied for years along the Baltic Sea, in its eastern (Tikkanen and Oksanen, 2002; Miettinen, 2004; Ojala et al., 2013; Rosentau et al., 2013), western (Lambeck, 1999; Berglund et al., 2005; Hansson et al., 2019; Kalińska-Nartiša et al., 2017) southern (Schumacher and Bayerl, 1999; Schwarzer et al., 2003; Uścinowicz, 2006; Lampe and Lampe, 2020) and central parts (Svensson, 1991; Wastegård et al., 1995). The first glacio-isostatic rebound rate map for the whole Baltic Sea region, based on the analysis of gravity measurements, levelling data and tide gauge records, was created by M. Ekman (1996). Its general validity has been demonstrated by the correlation with several subsequently created models, such as the latest NKG2016LU model (Vestøl et al., 2019), with some changes in radiality and uplift rates.

While a part of the Baltic coast has been thoroughly studied with respect to tracing ancient shorelines, until now, the Latvian coast of the Baltic Proper is under-studied except for some older studies followed by the later works of G. Eberhards (2003) and G. Eberhards and V. Brenners (2010). The ancient Ventspils lagoon, near the present-day port town of Ventspils, constituting the central-northern part of Latvia's west coast, provides valuable information on the geomorphological and geological development of this area and its surroundings, which can be related to ancient human activity. There have been several previous studies, with E. Grīnbergs developing the initial ideas (Grīnbergs, 1957) and I. Veinbergs continuing the work (Veinbergs, 1979 and 1996) on the geomorphological aspects, while V. Podgurskis and his team carried out geological mapping of the area (Podgurskis et al., 1987). Despite these studies, the developmental stages and corresponding shorelines have not been well identified in the Ventspils lagoon. This is because the relatively calmer conditions in the lagoon compared with the open sea were not favourable for the formation of distinct shorelines, and also because of the present-day conditions in the area of the ancient lagoon, where several types of erosion have affected the site during the time since the active lagoon stage. Consequently, ancient shorelines were poorly developed and are thus difficult to trace in this area.

This study aims to provide the first high-detail digital terrain model of the ancient Ventspils lagoon in order to detect the past shorelines along the coast of western Latvia. The work proceeded in two steps: (1) deciphering the most pronounced ridges, followed by (2) cluster analysis of adjusted elevation data.

1. REGIONAL GEOLOGICAL BACKGROUND AND THE STUDY AREA

The Ventspils lagoon was located on the eastern coast of the present Baltic Sea, in north-western Latvia (fig. 1). The emergence of this ancient waterbody was related to the retreat of the Fennoscandian ice sheet after the Late Glacial Maximum (LGM) and at the end of the Weichselian glaciation. The development of the present Baltic Sea started with the formation of the Baltic Ice Lake through the merging of several proglacial lakes in the region at around 16 ka BP (Houmark-Nielsen and Kjær, 2003). However, a fully-developed water body, which also encompassed the lowest-lying parts of the present-day dry-land area of Latvia, formed at around 14 ka BP (Vassiljev and Saarse, 2013). Since the coasts of the Baltic Ice Lake stages are 40-60 m above the present sea level in the vicinity of the study area, whereas stretches of the shorelines of the lagoon have been detected at much lower heights (Grīnbergs, 1957), it is safe to assume that the actual formation of the Ventspils lagoon took place after the rapid drainage of the Baltic Ice Lake near Mt. Billingen (Björck 1995) and even after the Yoldia Sea stage, which took place approximately between 11.7 ka BP and 10.7 ka BP, when the coastline formed 5-15 m below the present sea level near the location of the lagoon (Veinbergs, 1979). A freshwater Ancylus Lake started to develop right after the damming of Närke strait, south-eastern Sweden, which was induced by glacio-isostatic rebound (Jensen et al., 1999; Björck, 2008). The rising water level of the Ancylus Lake and continuing longshore sediment drift gave rise to the first coastal formations of the Ventspils lagoon, still detectable in the modern terrain and sediment (Grīnbergs, 1957; Veinbergs 1996). After the initial transgression, which put the Ancylus Lake approximately 10 m above the global mean sea level for 500 years, a rapid regression ensued, signifying the end of the Ancylus Lake stage and the start of the Littorina Sea stage in the Baltic basin (Andrén et al., 2011). The onset of the Littorina Sea stage occurred gradually due to the shallow connections with the North Sea. This stage is often characterized as being marked by several distinct transgressions, with the maximum at about 7.6 ka BP (Björck et al., 2008; Bendixen et al., 2017). Previous studies indicated two traceable Littorina Sea stage transgression coasts in the modern terrain of the ancient Ventspils lagoon (Grīnbergs, 1957; Veinbergs, 1996), while other studies in areas close to the lagoon, for example on the Ruhnu Island (Muru et al., 2018) and in Pärnu Bay (Rosentau et al., 2011; Rosentau et al., 2020), have detected only one major transgressive episode. As the Ventspils lagoon diminished, with a gradual lowering of the water level to its present level, the Littorina Sea stage ended and the present-day Baltic Sea stage commenced.

The Ventspils lagoon spanned ca. 45 km in length and ca. 20 km in width. The present-day Venta river, with several terraces and numerous oxbow lakes, meanders through the ancient lagoon from south-east to north-west and enters the sea in Ventspils harbour. The lowermost parts of the Ventspils lagoon lie between ca. 2.5 and 4.6 m a.s.l. and are occupied by bogs and the coastal lake of Būšnieki. The higher ground, 9.5-19.2 m a.s.l., constituted a set of ancient islands and peninsulas with some pronounced margins, which in many cases provided suitable locations for an ancient human settlement.

According to archaeologists, the unique circumstances that dictated the region's geomorphological and geological development partly explain the somewhat unusual pattern of human settlement during the Stone Age. Since the lagoon served as a very important resource area for fishing, the first human inhabitants created their settlements near the shores of the lagoon, and since the water level in the lagoon fluctuated, there was a need for the inhabitants to shift their settlement locations. Several artefacts that indicate recurring occupation of the same sites have been identified and dated, for example, the Sise site in the southern part of the lagoon (fig. 2) has yielded artefacts correlating temporally with both the Ancylus Lake and the Littorina Sea maximums (Bērziņš et al., 2016). Reuse of some settlements has also been noted at other sites around the ancient lagoon (fig. 2) and, likewise, in the Pärnu Bay area (Rosentau et al., 2011; Rosentau et al., 2020), showing a unique pattern of shifting settlement and suggesting that further investigation of the palaeogeographical setting could lead to the discovery of more similar archaeological sites.

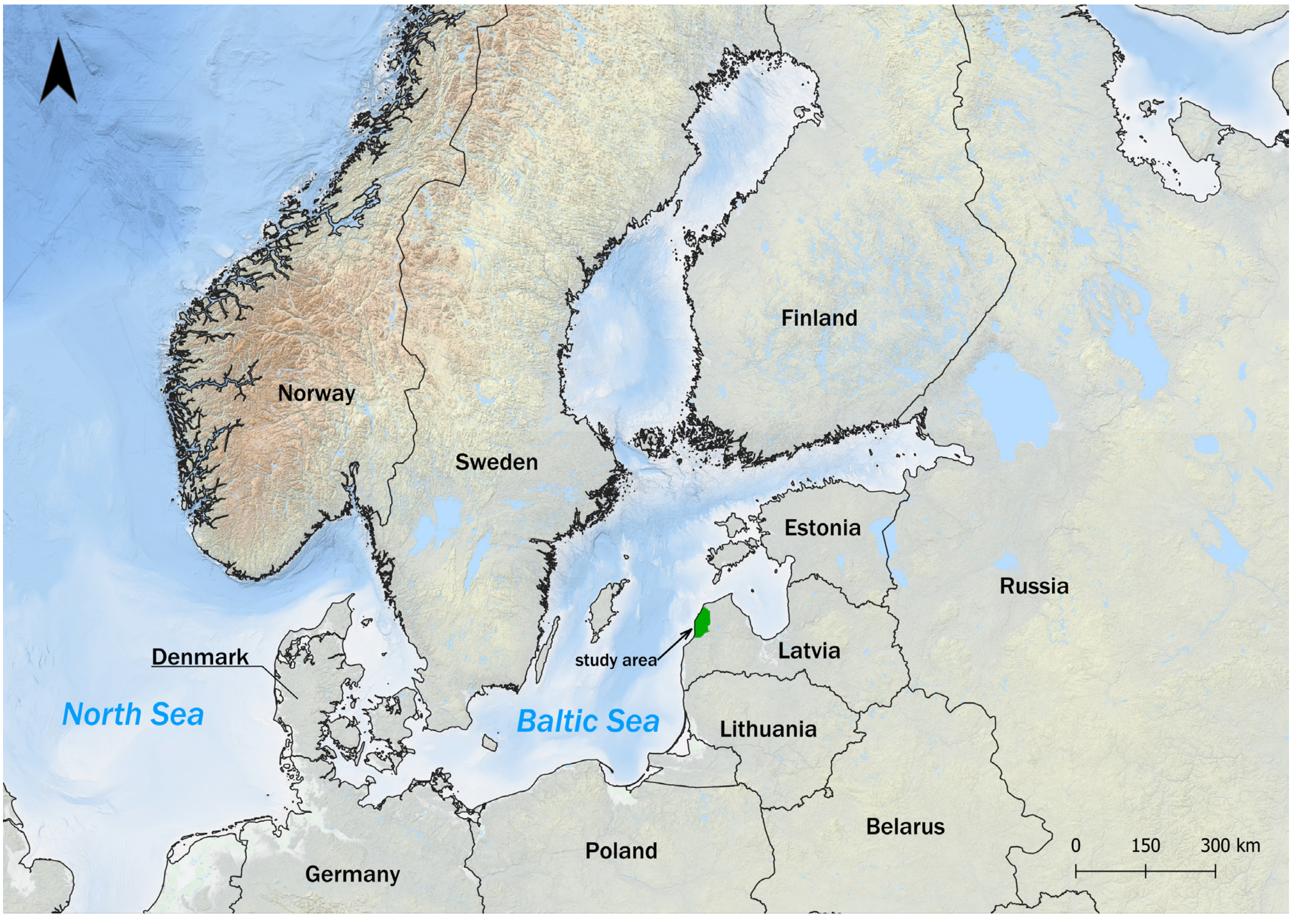

Fig. 1 – The location of the ancient Ventspils lagoon, marked in green (map EMODnet Bathymetry Consortium, 2020).
***Fig. 1** – En vert: emplacement de l'ancienne lagune de Ventspils (carte EMODnet Bathymetry Consortium, 2020).*

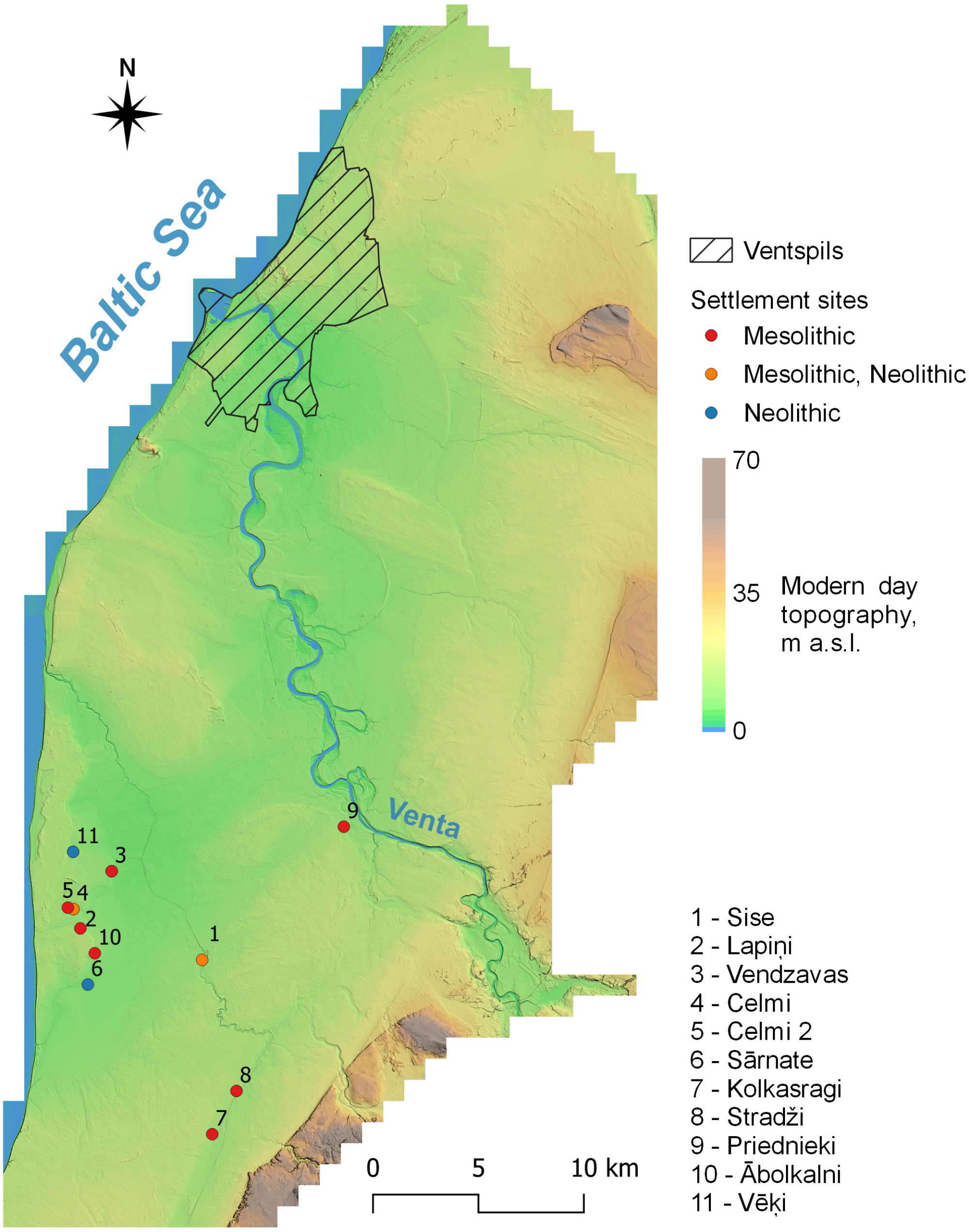

Fig. 2 – Stone Age settlements in the vicinity of the ancient Ventspils lagoon.
Fig. 2 – *Sites préhistoriques situés à proximité de l'ancienne lagune de Ventspils.*

2. MATERIALS AND METHODS

After examining the various studies on the development of the Baltic basin and the impact of glacio-isostatic adjustment in the region, and studies on the ancient Ventspils lagoon itself, a set of materials and methods was compiled to detect the ancient shorelines. Our approach involved, (1) determining the research area and creating a Digital Elevation Model (DEM) and (2) generating the palaeogeographical models to detect the suspected remnants of ancient shorelines in the field. Since this approach is considered valid for application to other similar sites, automatization tools for data acquisition, processing and analysing were built with highly customisable open source tools for work with open data.

2.1. DEM creation and cleaning

With LiDAR remote sensing technology becoming more readily available, the Latvian Geospatial Information Agency has published its survey results as open data in LAS format (LGIA, 2016). In order to acquire the data needed to build the DEM, a simple data download script was created in *Python 3* with *urllib* and *tqdm* libraries, for making URL requests and monitoring progress, respectively. Since the data is stored in 1 km^2 map tiles according to TKS-93, a topographic map system under the coordinate system for Latvia (LKS-92), which is not easily accessible for large regions, the input for the script is a simple list of the specific map tiles, which are selected based on water levels of previous studies in the region and the underlying geology of the lagoon. The tiles list is then iteratively processed, compiling web request links according to the storage template and subsequently downloading and storing each LAS data tile needed for further processing.

After acquiring LiDAR data for the whole study area, each LAS file is classified and filtered in order to obtain the ground points with the Simple Morphological Filter (SMRF) implementation in the Point Data Abstraction Library (PDAL; Pingel et al., 2013; PDAL Contributors, 2018). The ground points are then converted to a point cloud format used by the System for Automated Geoscientific Analyses (SAGA) GIS software and subsequently gridded into a raster format at 5 m resolution, using the Natural Neighbour method. Each resultant raster data file is converted from a SAGA GIS proprietary raster format to *GeoTiff* format using the Geospatial Data Abstraction Library (GDAL) translate function. The creation of the DEM for the study area is automated in *Python 3* using the *subprocess* library to sequence the above-mentioned processing tools, which are packaged in the open source *OSGeo4W* distributions. The terrain models for each of the LiDAR data tiles are obtained and combined (fig. 2) using the GDAL virtual raster format driver (GDAL/OGR contributors, 2019).

2.2. Palaeogeographical modelling

While similar studies (Leverington et al., 2002; Ojala et al., 2013) rely on manually digitizing and grouping ancient shoreline ridges and combining them with various chronological data to obtain ancient water level trend surfaces, this study focuses on terrain changes resulting from glacio-isostatic adjustment. This is done because the ancient shoreline ridges of the lagoon themselves are not prominent enough to be definitive. According to the most successful principles developed in the palaeogeographical reconstructions in the region (Rosentau et al., 2011; Habicht et al., 2017; Rosentau et al., 2020), the water level trends modelled in this study were also compared to the actual terrain.

For a precise analysis and interpretation based on the palaeogeographical models, any major changes to the terrain subsequent to the existence of lagoon conditions in this area, such as dune formation, bog development and various anthropogenic modifications, needed to be excluded. This was done by digitizing the most prominent of these forms from the geological maps (Podgurskis et al., 1987) and the terrain, then rasterizing the polygons and removing them from the DEM with a raster calculator. Holes in the resultant DEM were then closed with the SAGA GIS *Close Gaps* tool.

An ancient shoreline can be detected in various ways, e.g. by carrying out a survey in the field or by marking specific ridge points in the DEM, but the size of the study area, the characteristics of the formation of lagoonal coastal ridges, and even the specific pattern of development of the study area along with the development of the Baltic basin are all limiting factors for implementing the previously established approaches. To detect the potential shoreline ridges in the present-day DEM, downslope index analysis with a drop factor of 1.5 m was carried out using the *WhiteboxTools 1.1.0.* plugin in *QGIS 3.17.0.* The index is output as metres, so the lower the index, the nearer it is to the set 1.5 m drop (fig. 3).

The downslope index, originally created for quantifying topographic impact on local drainage basins, has several other applications in the fields of hydrology, biochemistry and geomorphology (Hjerdt et al., 2004). In this study, this index was used to limit the terrain model to ridges by constraining the index output to 300 m, thus returning only those DEM raster cells that show a relative downward change in elevation by 1.5 m within the nearest 300 m (fig. 4), analogous to current beach ridges in Latvia at sites with similar lowland morphology, and to account for erosion. The set values were empirically acquired to optimally highlight the potential ancient shorelines in the terrain model.

Since the azimuth of glacio-isostatic uplift in the study area is at about 335° (Rečs, Krievāns, 2013), a raster map (d), representing relative distance in the direction of the uplift, was created for the study area. The elevations of the detected ridges (k) were adjusted with the raster calculator according to the uplift rates (g) in the Pärnu Bay area (Saarse et al., 2003; Rosentau et al., 2011). This results in input data needed for further analysis for each stage of interest (P_x, 1.):

$$P_x = \frac{k-(d_{max}-d)*g}{1000}; \quad (1.)$$

since the lagoon existed during the Ancylus Lake and Littorina Sea stages, uplift rates of 0.272 m/km (initial Ancylus Lake stage, approx. 10.5 ka BP), 0.256 m/km (Ancylus Lake maximum, approx. 10.2 ka BP), 0.129 m/km (Littorina Sea maximum, approx. 7.3 ka BP) and 0.106 m/km (post-maximum Littorina Sea, approx. 6.0 ka BP) were used (Saarse et al., 2003; Rosentau et al., 2011). For each of the uplift rates, the adjusted ridge height raster, depicting the palaeoelevations of the ridges, was clustered with the *K-Means Clustering for Grids* tool from SAGA GIS. After several tests with various cluster numbers, division into 30 clusters was chosen. This made it possible to remove invalid clusters depicting, for example, portions of the Baltic Ice Lake stages that might have appeared in the terrain model or riverbanks (fig. 4), while keeping the number of clusters to a manageable level. Each cluster represents the raster cells closest to the respective palaeoelevation centroid, which is determined iteratively by the k-means algorithm, in accordance with the initial cluster number. The hill-climbing method, originally developed to tackle biological taxonomy problems (Rubin, 1967), was used for clustering, rather than the iterative hierarchical minimal distance method (Forgy, 1965), since it yielded more precise results than the full

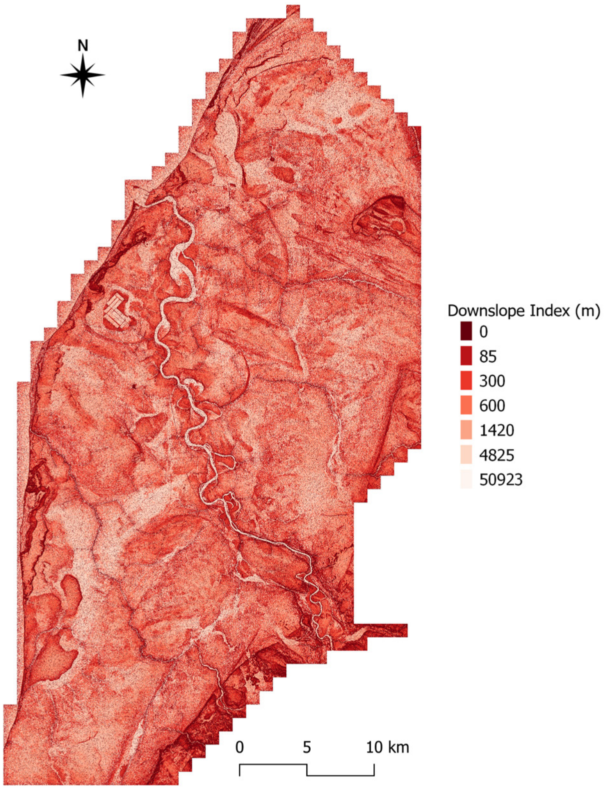

Fig. 3 – Downslope index output for the study area.
Fig. 3 – *Indice de pente descendante pour la zone d'étude.*

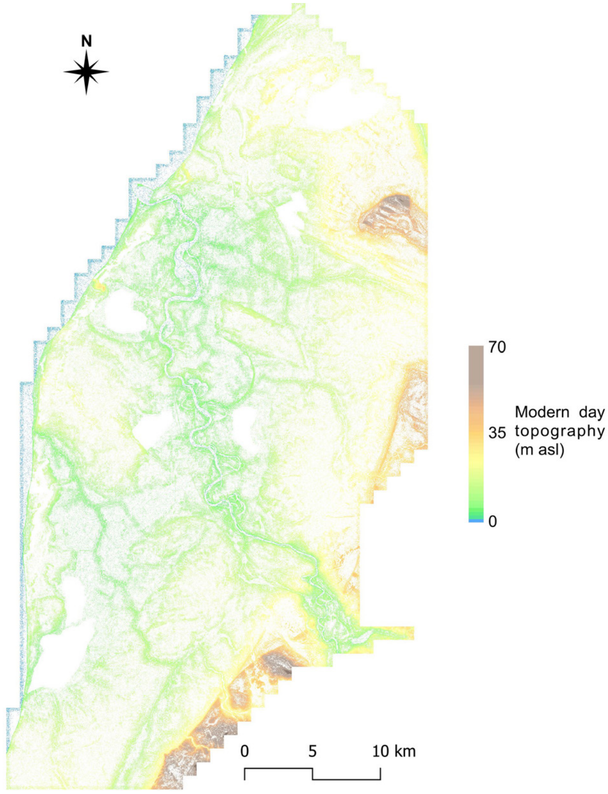

Fig. 4 – Initial terrain raster cells acquired by filtering downslope index values.
Fig. 4 – *Cellules raster de terrain acquises par filtrage des valeurs de l'indice de pente descendante.*

terrain model. Both of these methods are available in the SAGA GIS tool.

After clustering each of the adjusted ridge height rasters, the results were used in an automation script for shoreline detection. The *Python 3* script was written to operate with *QGIS 3.17.0* environment variables by initializing *QGIS* resources, e.g. *qgis.core* and *qgis.analysis* modules alongside the *processing* framework (Graser and Olaya, 2015). By building a standalone script and initializing the *QGIS* resources separately, modularity could be maintained, permitting the addition of external operators to the workflow, like the *WhiteboxTools Python* library (Lindsay, 2014). Once the environment was set and all the required tools imported, the overall script variables were set, such as the number of clusters to be created (or specific clusters to be created for testing purposes) and paths to the cluster raster file, the terrain data file and the output folder. The cluster raster files for each uplift rate were then iteratively processed cluster by cluster, defining paths for temporary data layers and for the resulting data in raster and vector formats. Present-day terrain values were assigned to the cluster's raster cells with GDAL's raster calculator from the *QGIS processing* framework by obtaining the clustered cells and multiplying them by the DEM. A linear trend surface for each surface was computed with the *TrendSurface* tool from the *WhiteboxTools* library. A first order polynomial linear trend was chosen, because of the relatively small size of the study area in terms of glacio-isostatic adjustment, where the models show linearity in the current adjustment rate at the ancient Ventspils lagoon (Ekman, 1996; Vestøl et al., 2019). The initial trend surface was compared with the input data in the raster calculator to narrow it down to ± 0.4 m before the final trend surface analysis using the *TrendSurface* tool. By comparing the final trend surface of each cluster with the terrain model in the raster calculator, the extent of the lagoon at the given cluster and, therefore, the respective shoreline, can be derived. Since the expression is set up to return a value of '1' for the raster cells 'submerged' at the time of the cluster, and a value of '0' for terrestrial cells, the result can be extracted as both vector and raster data, which are useful for faster verification workflows and storage saving, and for quality visualisation rendering, respectively. The script allows the shorelines to be described as polygons, using the GDAL *Polygonize* tool coupled with several simplification tools, such as *Keep N biggest parts*, *Simplify geometries* and *Delete holes*. Respective water levels and adjusted terrain raster data are generated by carrying out operations in the raster calculator, e.g. by subtracting the trend surface from the present-day DEM to get the terrain situation at the time of the specific water level. After processing a cluster, temporary data layers are deleted to clean up the workspace. The full palaeogeographical modelling workflow is shown in figure 5.

To validate a cluster, its trend surface data of glacio-isostatic rebound rate and the direction of the surface uplift, calculated trigonometrically from the trend surface regression coefficient values reported by the *TrendSur-*

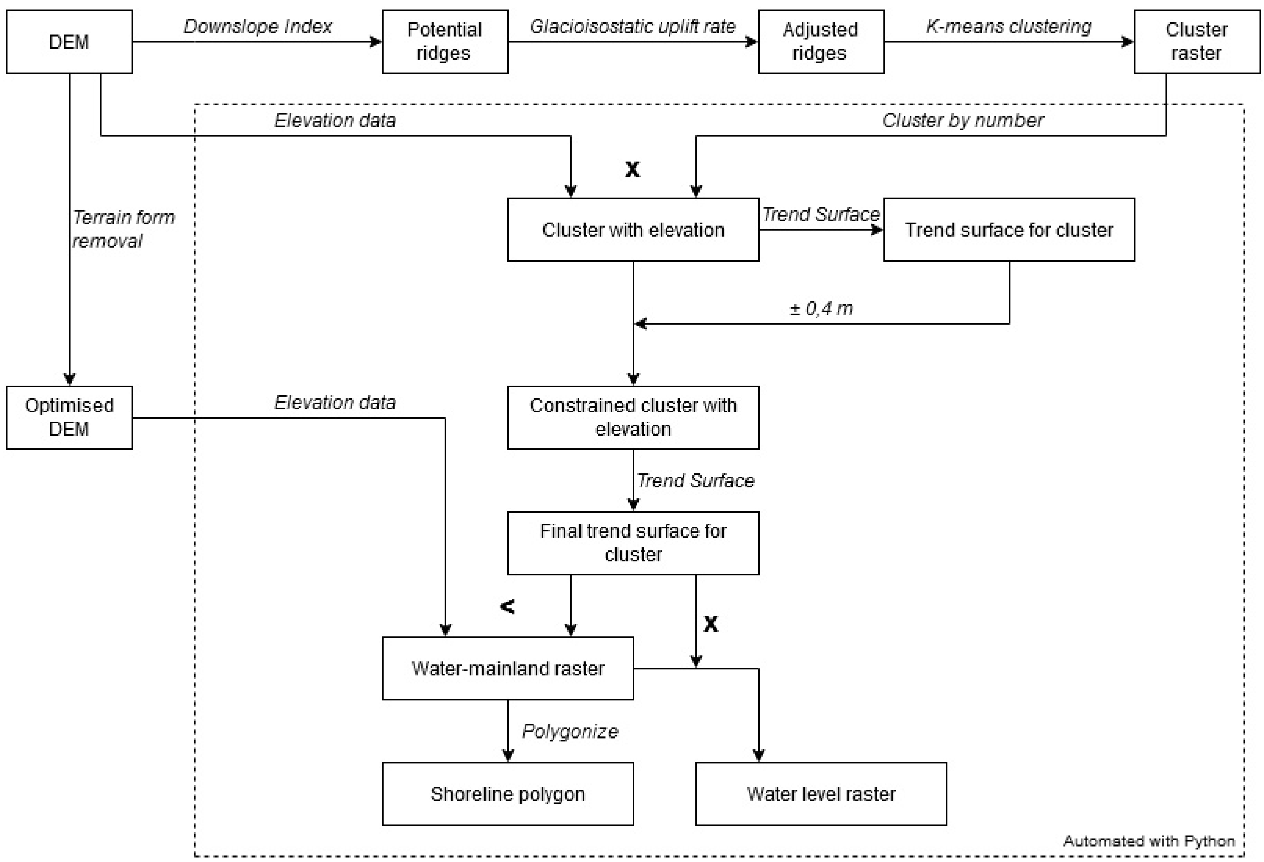

Fig. 5 – Palaeogeographical modelling workflow developed by the authors in the course of the study.
***Fig. 5** – Workflow de modélisation paléogéographique développé par les auteurs au cours de l'étude.*

face tool, are compared to the original input rebound rates and direction data. Additionally, manual verification using the *Profile Tool* plugin in *QGIS* was carried out to determine the conformity of clusters and the DEM. In the example shown in figure 6, the terrain profile is shown in black and the coloured line represents the clusters, which show a good fit for the fourteenth and twenty-first clusters, as they depict a zone in the terrain that resembles a water level right by the shoreline ridge.

3. RESULTS AND DISCUSSION

Several elements were comprehensively developed over the course of this study: (1) the DEM for the study area as a base for this and further studies, (2) a workflow for the detection of ancient shorelines applicable in situations with known glacio-isostatic uplift rates and directions, along with (3) various workflow automation scripts. These three elements have contributed to the building of palaeogeographical models for different time/stage slices, which not only serve to validate the workflow but are also of use with archaeological data, since correlations could be drawn between the obtained models and the previously known settlement sites located on the same shore and relating to the same time (fig. 6).

3.1. Terrain creation and optimisation

Data acquisition was automated, which saved an estimated 9 hours of manual work for the 1257 km^2 of the study area and ensured that no human error could occur during the download of the required data, which can otherwise lead to downloading superfluous data or incomplete download of the required data. The workflow regarding DEM creation is constituted by several steps utilising several open source tools, which all have to be engaged for each of the LiDAR data tiles. Since this workflow was automated in our study, it omitted steps that would normally require thousands of manual actions. The removal of relief forms post-dating the lagoon stage of the area from the DEM (fig. 7) essentially provided not only the basis for palaeogeographical reconstructions, but also data for further archaeological investigations in the area.

3.2. Palaeogeographical modelling

With a view to possible application to other sites, the highly customisable automation script, which chains together 13 different open source tools, creates a palaeogeographical model with all of the requested data, e.g. a terrain raster for the specific period or the shoreline polygon, in approximately 4 minutes. Four specific time slices are considered in the Baltic Sea basin: initial Ancy-

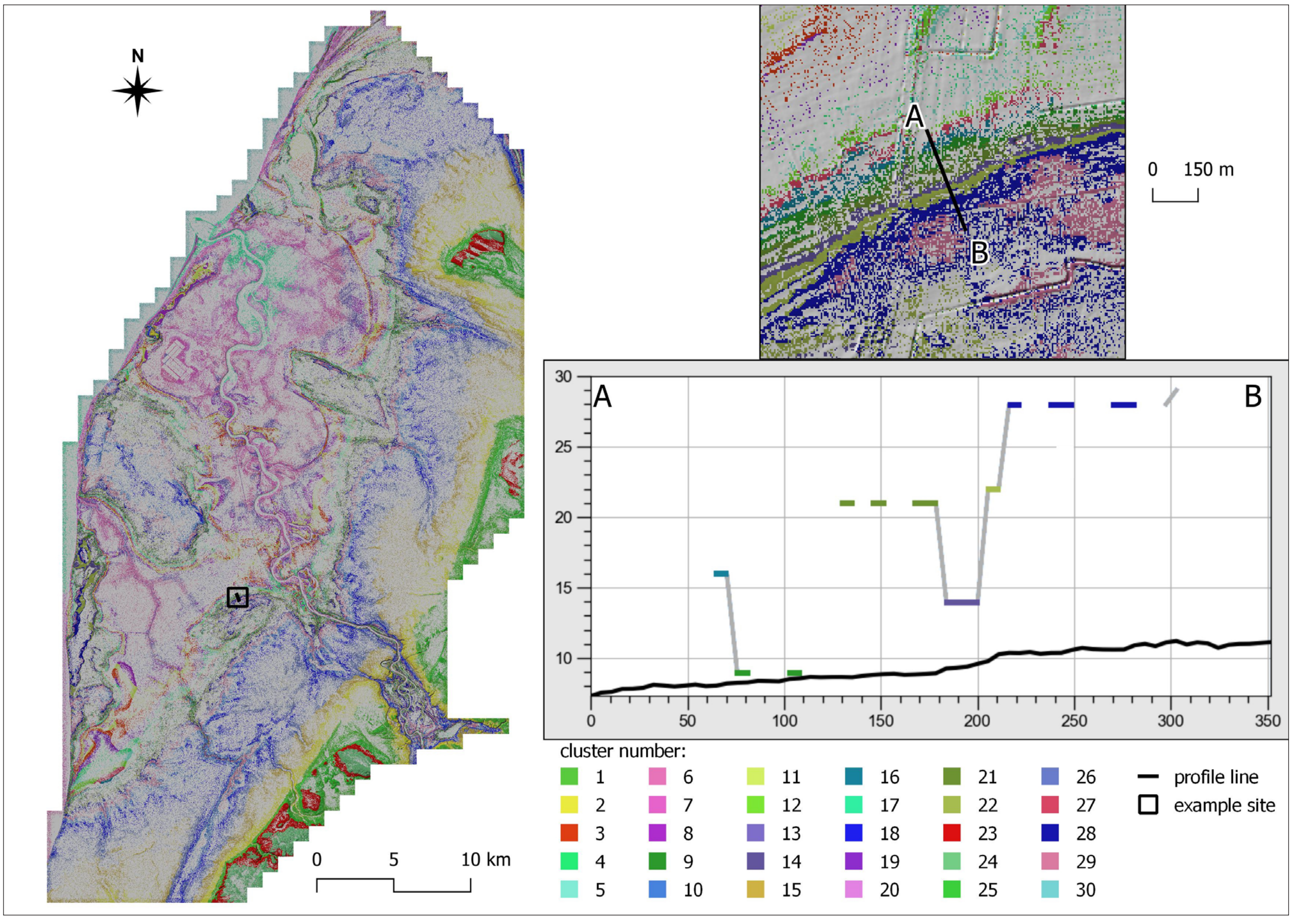

Fig. 6 – An example of manual verification process using the profile tool (green, blue, red, deep pink areas show resultant clusters).
***Fig. 6** – Exemple du processus de vérification manuelle à l'aide de l'outil de profil (les zones vertes, bleues, rouges et rose foncé montrent les clusters résultants).*

lus Lake (approx. 10.5 ka BP), Ancylus Lake maximum (approx. 10.2 ka BP), Littorina Sea maximum (approx. 7.3 ka BP) and post-maximum Littorina Sea (approx. 6.0 ka BP; Saarse et al., 2003; Rosentau et al., 2011), and these were selected for reconstruction in this study. Each time frame was clustered into 30 clusters, and the automatic process of creating these 120 (4 x 30) initial variants took ca. 8 hours.

After comparing the trend data with the input data and manual verification, 25 out of 120 models were determined to be valid for use in this study. For the initial Ancylus Lake stage, there are four shorelines, belonging to a single stable period, most likely depicting a part of the transgressive phase of the Ancylus Lake stage because this occurred before and is located below the maximum stage. A large proportion, namely eleven out of the 25 valid models align with the Ancylus Lake maximum, grouping into five distinct shoreline groups. Six of the models are grouped into three stable groups belonging to the Littorina Sea maximum, and finally the four remaining models belong to one stable shore during the post-maximum Littorina Sea stage. The results of our modelling work disagree to some extent with previous studies, which considered only one or two shorelines per stage (Grīnbergs, 1957; Veinbergs 1996).

Although deciphering from the relative displacements of the shorelines in this way does present some difficulties due to readability issues, when viewed together, the overall relations of the modelled time period shorelines can be interpreted (fig. 8). For example, a closer look at the northernmost part of the Ventspils lagoon reveals the highest modelled shorelines for each modelled period (fig. 8).

With the start of the Ancylus Lake stage, when a separate water body developed, several islets were formed (fig. 8), and a rapid water level rise took place over the course of a few hundred years in the Ventspils lagoon. A similar rise is also known in the literature in connection with the development of the Baltic Sea basin (Björck, 1995; Andrén et al., 2011) and from the investigation of the archaeological record of the Ventspils lagoon itself (Bērziņš et al., 2016). The existence of a separate water body can also explain the relatively large difference in the elevations of modelled shorelines corresponding to the Ancylus Lake stage. After the retreat of the Ancylus Lake, when the water level in the region fell below the present sea level (Rosentau et al., 2020), the Littorina Sea stage commenced, with a number of islands emerging in the Ventspils lagoon (fig. 8). After reaching its maximum, the water level fell gradually, since the height difference

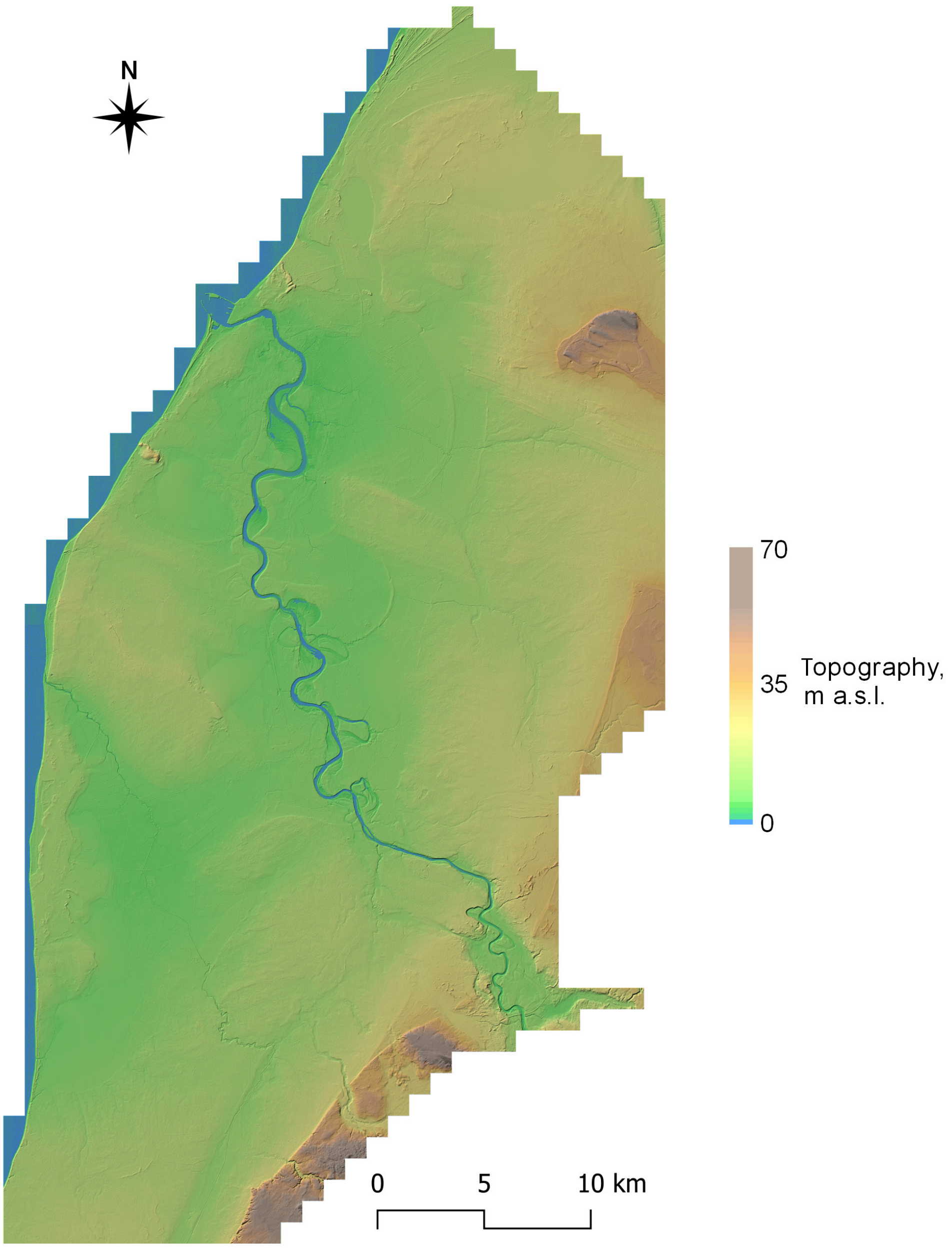

Fig. 7 – Optimised terrain model for palaeogeographical modelling, where relief forms post-dating the lagoon (major dune formations, raised bog, etc.) have been removed.

Fig. 7 *– Modèle de terrain optimisé pour la modélisation paléogéographique ; les formes de relief postérieures à la lagune (formations dunaires majeures, tourbières hautes, etc.) ont été supprimées.*

between the Littorina Sea maximum and the post-maximum Littorina Sea periods, corresponding to approximately 1.3 ka, is relatively small (fig. 8).

Even though the ancient shoreline fragments, detected at several sites across the area of the Ventspils lagoon (Grīnbergs, 1957; Veinbergs 1996), fit very well with the models height-wise, the apparent consensus view, according to which the Ancylus Lake stage is generally positioned above the Littorina Sea stage, cannot be confirmed. This is because several Littorina Sea stage maximum models are above some of the Ancylus Lake maximum models in the southern part of the lagoon, while the same models show an inverted hypsometric relationship in the northern part of the area, with some fragments overlapping. Looking at the highest modelled shorelines that mark maximum stages reveals the differences in shoreline displacement and an apparent impact of glacio-isostatic uplift. In the southern part of the lagoon, the shorelines are virtually the same, whereas on the northern side, the Ancylus Lake maximum is substantially higher than the Littorina Sea maximum compared with modern-day topography. Situations like these cause difficulties for the task of precisely placing the modelled shorelines in time by dating techniques. While the ridges in the southern part of the ancient lagoon can be visually detected in the field, there is no guarantee that a particular

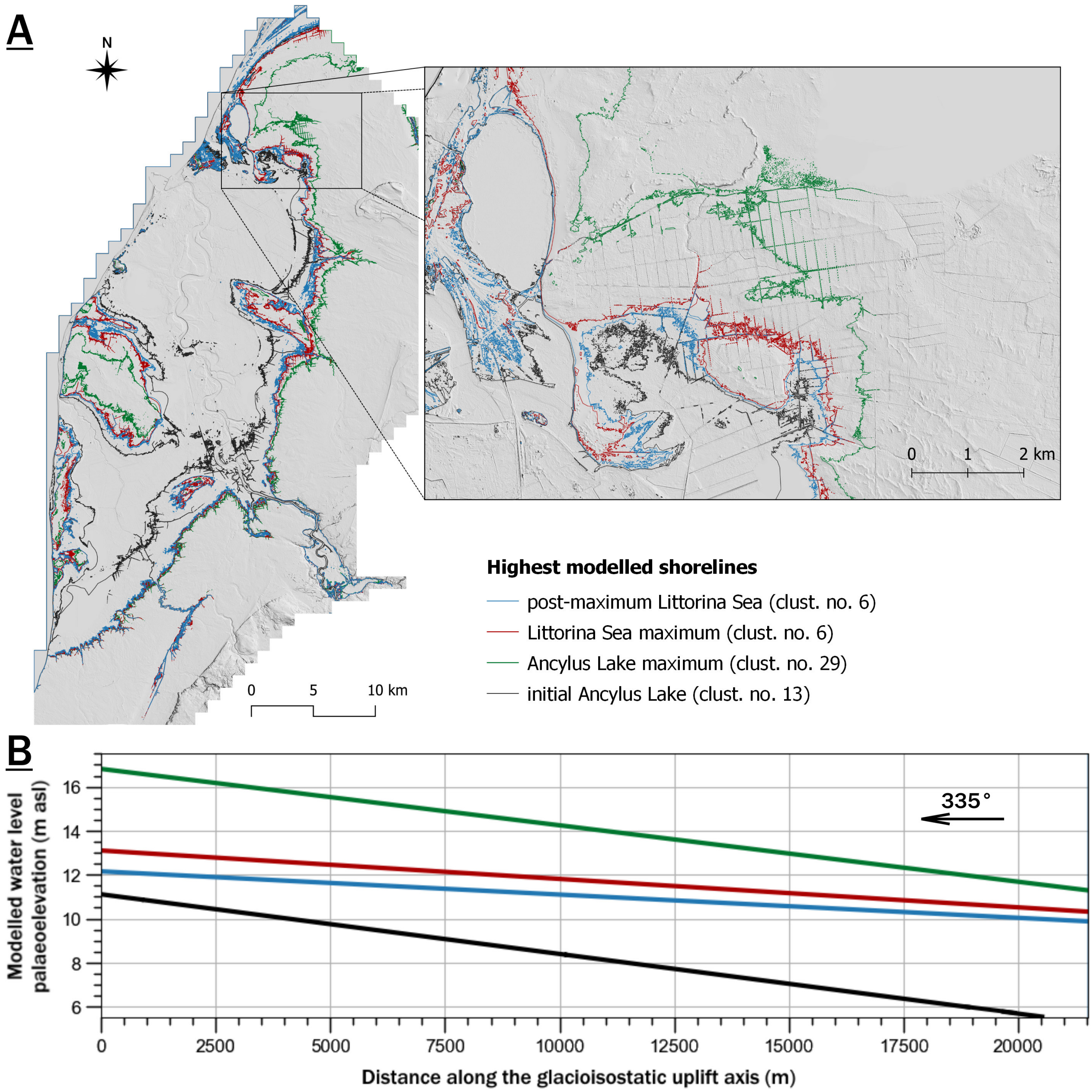

Fig. 8 – Highest shorelines for each modelled time period (A) and their respective water level trends along the glacioisostatic uplift axis (B).

Fig. 8 *– Lignes de rivage les plus élevées pour chaque période modélisée (A) et leurs tendances respectives du niveau d'eau le long de l'axe du soulèvement glacioisostatique (B).*

ridge corresponds to the maximum of the Ancylus Lake stage or the maximum of the Littorina Sea stage, since the models overlap (fig. 9).

3.3. Archaeological context

The model could have a wide range of applications in archaeology: it will permit a more comprehensive understanding of Stone Age settlement dynamics and living conditions, in particular with respect to fishing and other subsistence activities, which are influenced by the terrain and water depths; it extends the possibilities of targeting specific locations over the course of future archaeological prospection aimed at discovering Stone Age sites; and it enables the correlation of dated sites with sites that have not been dated, by comparing their geographical association with particular shorelines. For example, at the Lapiņi site (Bērziņš and Doniņa, 2014) and Sise site (Bērziņš et al., 2016), artefacts have been recovered that correspond to the onset of the Ancylus Lake stage, which occurred ca. 10.5-10.2 ka BP (Rosentau et al., 2011). The Priednieki site has not been dated yet, but it is thought to be Middle Mesolithic, i.e., 10.3-8 ka BP (Damlien et al., 2018). If we assume that this site was located by one of the Ancylus Lake maximum shorelines (fig. 10), then the model helps to narrow down the age of this site.

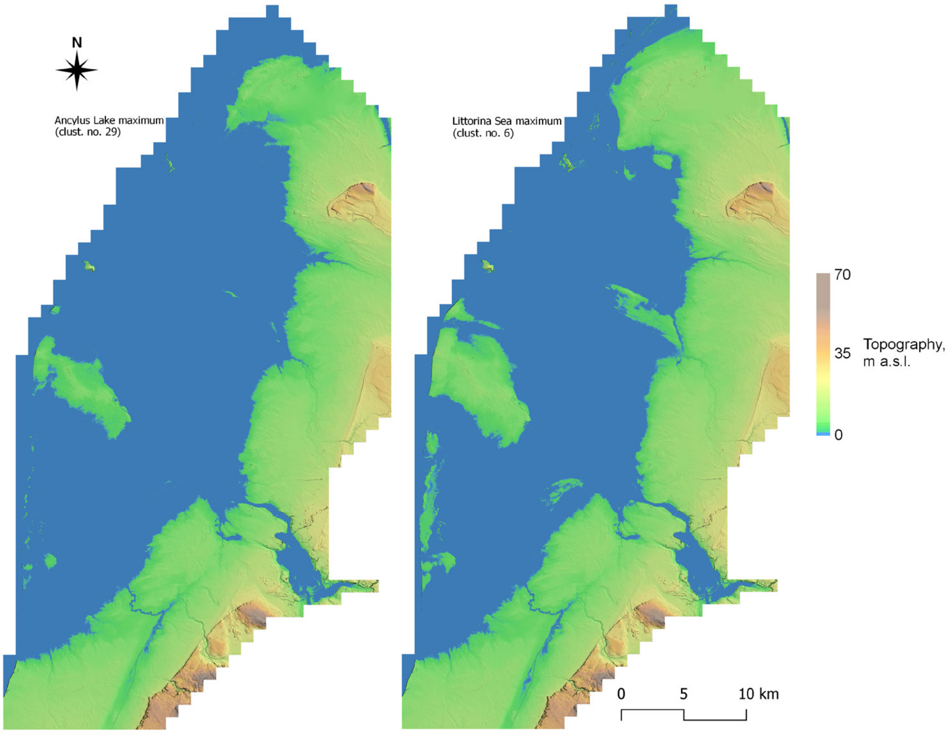

Fig. 9 – Comparison of the highest modelled shoreline palaeogeographical models for the Ancylus Lake maximum (cluster no. 29) and the Littorina Sea maximum (cluster no. 6) periods.

Fig. 9 *– Comparaison des modèles paléogéographiques des plus hauts rivages modélisés pour les périodes du maximum du lac Ancylus (cluster n° 29) et du maximum de la mer à Littorines (cluster n° 6).*

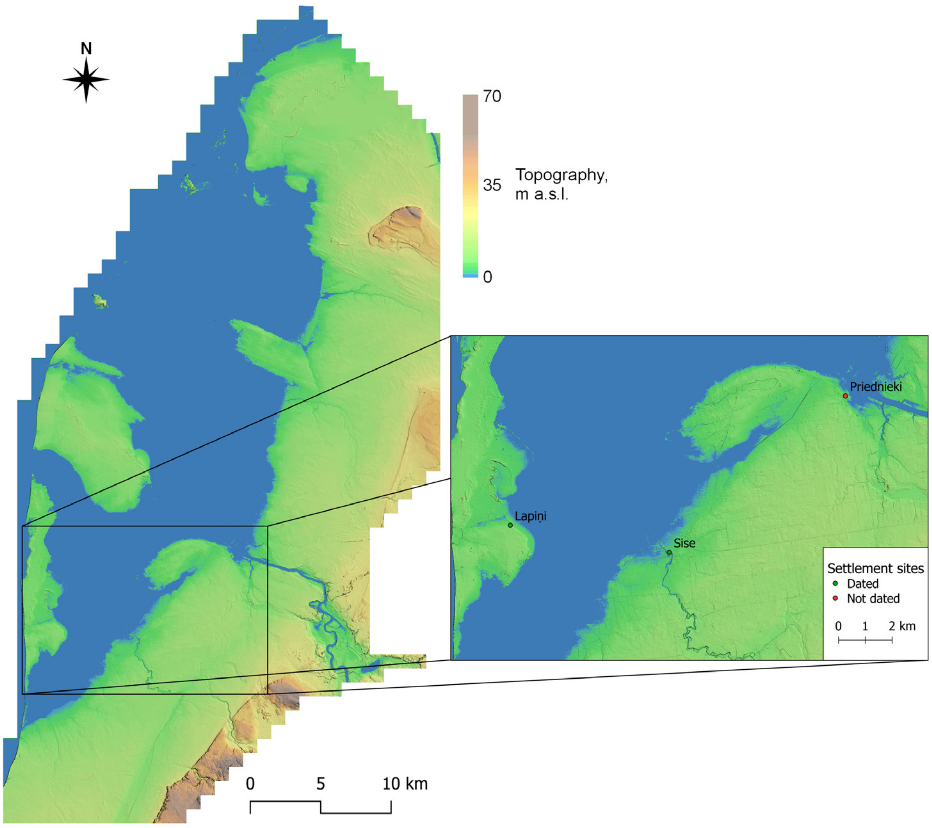

Fig. 10. The position of the Lapiņi, Sise and Priednieki sites in relation to the Ancylus Lake maximum (cluster no. 27) palaeogeographical model.

Fig. 10. *Position des sites de Lapiņi, de Sise et de Priednieki par rapport au modèle paléogéographique du maximum du lac Ancylus (cluster n° 27).*

CONCLUSIONS

The development of automation scripts enables the workload to be reduced. For example, approximately 9 hours of manual work was eliminated during the data acquisition phase alone. Furthermore, the automation of processes gives a degree of leeway when experimenting with various values during the methodology -building phase. Making the scripts modular allows the user to acquire the resultant data in the formats as desired for overview, analysis, or visualisation purposes.

In the vicinity of the ancient Ventspils lagoon, 25 shorelines, which are divided into 10 relatively stable shore phases, corresponding to four selected periods of time during the Ancylus Lake and Littorina Sea stages, have been identified in this study. This contrasts with previous studies, where only one or two shorelines per development stage were considered and further correlated with the maximum phases of the Ancylus Lake and Littorina Sea. Our study reveals that these stages are not so homogeneous, and that parts of the Littorina Sea stage models could be detected relatively higher than parts of the Ancylus Lake stage models, due to the impact of glacio-isostatic adjustments. Nevertheless, the models correlate well with the previously described heights of ancient shoreline remnants.

Our results have a wide application and can be used for archaeological interpretations and studies in nearby regions. The results could also be used for narrowing down the age of ancient settlements, although further investigations are needed in this regard to warrant the spatiotemporal connection of settlements located beside the same modelled shorelines.

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