

MERLE MURU

GIS-based palaeogeographical
reconstructions of the Baltic Sea shores
in Estonia and adjoining areas during
the Stone Age



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Department of Geography, Institute of Ecology and Earth Sciences,
Faculty of Science and Technology, University of Tartu, Estonia

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Supervisors: Assoc. Prof. Dr. Raivo Aunap,
Department of Geography,
Institute of Ecology and Earth Sciences,
University of Tartu, Estonia

Dr. Alar Rosentau,
Department of Geology,
Institute of Ecology and Earth Sciences,
University of Tartu, Estonia

Opponent: Prof. Vincent Gaffney
School of Archaeological Sciences
University of Bradford, United Kingdom

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LIST OF ORIGINAL PUBLICATIONS

This thesis is based on the following original research papers.

- Paper I Rosentau, A., **Muru, M.**, Kriiska, A., Subetto, D.A., Vassiljev, J., Hang, T., Gerasimov, D., Nordqvist, K., Ludikova, A., Lõugas, L., Raig, H., Kihno, K., Aunap, R., Letyka, N. (2013). Stone Age settlement and Holocene shore displacement in the Narva-Luga Klint Bay area, eastern Gulf of Finland. *Boreas* 42: 912–931.
- Paper II **Muru, M.**, Rosentau, A., Kriiska, A., Lõugas, L., Kadakas, U., Vassiljev, J., Saarse, L., Aunap, R., Küttim, L., Puusepp, L., Kihno, K. (in press). Sea level changes and Neolithic hunter-fisher-gatherers in the centre of Tallinn, southern coast of the Gulf of Finland, Baltic Sea. *The Holocene*, doi: 10.1177/ 0959683616678462.
- Paper III Preusser, F., **Muru, M.**, Rosentau, A. (2014). Comparing different post-IR IRSL approaches for the dating of Holocene coastal foredunes from Ruhnu Island, Estonia. *Geochronometria* 41 (4): 342–351.
- Paper IV **Muru, M.**, Rosentau, A., Preusser, F., Plado, J., Sibul, I., Jõelett, A., Aunap, R., Bjursäter, S., Kriiska, A.. (manuscript). Fore-dune chronology for reconstructing Holocene shore displacement and Stone Age palaeogeography on Ruhnu Island, Gulf of Riga, Baltic Sea.

Author's contribution:

- Paper I The author participated in the data collection and analysis and the writing of the manuscript and is primarily responsible for the palaeogeographical models.
- Paper II The author participated in the study design and data analysis, is responsible for the palaeogeographical models and led the writing of the manuscript.
- Paper III The author led the data collection, preparation and interpretation and participated in the data analysis and the writing of the manuscript.
- Paper IV The author led the study design, data analysis and interpretation and the writing of the manuscript, participated in the data collection and is primarily responsible for the palaeogeographical models.

1. INTRODUCTION

Since the last deglaciation, the shores of the Baltic Sea have undergone significant changes due to marine/lake transgressions and regressions induced by the melting of the continental ice sheets, the up-damming and drainage of the basin and the glacial isostatic land uplift. A large number of Stone Age sites with the evidence of shore-connected settlement are presently located at the seabed or tens of metres above sea level.

In the southern Baltic Sea region, Stone Age coastal settlement sites lie at the present seabed due to Holocene sea-level rise (Fischer, 2011; Lübke et al., 2011). In contrast, in the northern Baltic Sea region, prehistoric coastal settlements have been uplifted due to post-glacial rebound (Siiriäinen, 1982; Halen, 1995; Vaneeckhout, 2008). In transitional areas, as in Estonia, these have also been uplifted and are presently located inland; however, Mesolithic sites are sometimes buried under lake or marine sediments due to the up-damming of the Baltic basin or the mid-Holocene sea-level rise, which temporarily exceeded the rate of the land uplift in this region (Jussila and Kriiska, 2004; Veski et al., 2005; Gerasimov et al., 2010).

Palaeoenvironmental reconstructions have been found to be highly important for understanding the prehistoric settlement pattern and its changes because solely archaeological material does not allow sufficient conclusions about the environment of the settlement sites, and therefore multi-proxy data and methods of natural sciences are applied in the interpretation of cultural heritage. Depending on the location of the sites and availability and characteristics of the data, different kinds of palaeogeographical methods have been used (e.g. Gaffney et al., 2007; Bailey and King, 2011; Siart et al., 2012; Stock et al., 2014; Westley et al., 2014; Breeze et al., 2015). In the case of prehistoric coastal settlement in the Baltic Sea region and elsewhere, the setting regarding the past shore level, the type of the past water body and coastal features are the main questions in many studies (e.g. Miller et al., 1997; Jussila and Kriiska, 2004; Ling, 2004; Schmölcke et al., 2006; Wikell et al., 2009; Dolukhanov et al., 2010; Rosentau et al., 2011; Berzins et al., 2016; Habicht et al., 2016; Hansson et al., 2016). These questions can be addressed via methods of analytical geography and relief analysis, which are now conducted in geographic information system (GIS). GIS is an excellent tool for putting data from several research disciplines into spatio-temporal relations to draw new interdisciplinary conclusions. Assembling archaeological, sedimentological, chronological, geomorphological, topographical and other relevant data is a way towards new knowledge about prehistoric settlement in the context of its natural environment.

The changes of the past sea level and the Holocene evolution of the coastal zone of the Baltic Sea in Estonia and adjoining areas around the Gulf of Finland and the Gulf of Riga have been studied actively (Saarse et al., 2003; Saarse et al., 2010; Grudzinska 2015). At the same time, there is solid archaeological

evidence of shore-bound subsistence strategy of humans in these areas in the Mesolithic and the Neolithic times (Kriiska, 2001; Kriiska et al., 2016; section 2 of this thesis). However, site-specific knowledge about the natural environment that was surrounding the settlements as well as the choice of settlement locations regarding the past shoreline and type of coast needs to be advanced.

The aim of this thesis is to reconstruct palaeogeography for some of the most important sites with indications of Stone Age coastal settlement in Estonia and adjoining areas by implementing GIS-based methods and thus provide new insight into the Stone Age settlement pattern in the context of Holocene relative sea level changes. Comprising four scientific papers, the study gives landscape context to the development of Mesolithic and Neolithic settlement on different types of palaeo-coasts: in Narva-Luga area, in northeastern Estonia and north-western Russia (Paper I), in the city centre of Tallinn, on the southern coast of the Gulf of Finland (Paper II) and on Ruhnu Island, in the middle of the Gulf of Riga (Paper III; Paper IV).

To achieve this aim, the following tasks were set:

1. to reconstruct the Holocene relative sea level changes and shore displacement for the Stone Age settlement sites;
2. to define the relationship between the locations of the archaeological sites, which indicate shore-connectedness, and their contemporary coastal setting by means of palaeogeographical methods;
3. to test the timing of Stone Age coastal settlement and the idea of relatively late abandonment of coastal settlement in the eastern Baltic Sea region by applying GIS-based palaeogeographical modelling; and
4. to advance the methodology of GIS-based palaeogeographical reconstructions.

This thesis is a contribution to Estonian Research Council projects (ETF7294, 9011 and PUT 456) investigating relationships between Stone Age settlement and shore displacement in the eastern Baltic Sea region, conducted at the Institute of Ecology and Earth Sciences, University of Tartu.

2. DEVELOPMENT OF THE BALTIC SEA AND PREHISTORIC SETTLEMENT ON ITS SHORES

In the early phases of cultural development, human populations in the Baltic Sea region experienced times of significant marine/lake transgressions and regressions owing to the melting of the Scandinavian Ice Sheet, the up-damming and drainage of the basin and glacial isostatic land uplift.

Deglaciation of the Scandinavian Ice Sheet produced a huge volume of meltwater and led to formation of an ice-dammed lake in the Baltic Sea basin at c. 16.0 cal. ka BP (Andrén et al., 2011). The **Baltic Ice Lake** had several stages of advancement and retreat until the final rapid drainage of c. 25 m within 1–2 years, when the connection to the ocean opened through central Sweden in Billingen at c. 11.7 cal. ka BP (Björck, 1995; Andrén et al., 2011). As a result of the differential isostatic land uplift, the Baltic Ice Lake coastal landforms, formed just before the drainage, are presently located at about 30–60 m above present sea level (m a.s.l.) in Estonia (Saarse et al., 2003) but below zero in the southernmost Baltic Sea region (Figure 1a). During the Baltic Ice Lake period, human groups from surrounding areas started to colonize ice-free margins of the retreating ice sheet. These were **Palaeolithic** reindeer (*Rangifer tarandus*) hunters, who established their **camp sites along game migration routes**, which were mostly located inland (Terberger, 2006). Their migration was highly dependent on ice and water barriers. At the end of the last glaciation, Palaeolithic communities occupied an area from the southern Baltic Sea region to southern Scandinavia and the eastern Baltic Sea Region to the River Daugava and Lielupe terraces in Latvia (Zagorska, 2007; Zvelebil, 2008). In Estonia, no human settlements of that time have been found, although there is evidence of the habitation of reindeer (Ukkonen et al., 2006).

After the Billingen drainage, a partially brackish phase of the ancient Baltic Sea called the **Yoldia Sea** started when, due to the rapid rise of the ocean level, saline water entered the Baltic Sea basin through the straits formed in central Sweden (Figure 1b). The northern shore of the sea was still marked by the glacier, but most of the Baltic basin was already deglaciated by the Yoldia stage (Andrén et al., 2011). The relative sea level in the southwestern part of the Baltic Sea basin was lower than today, whereas southern Scandinavia and the eastern Baltic Sea region experienced the emergence of new land as a result of the land uplift. The Yoldia Sea in Estonian territory was regressive, with the lowest levels around 25 m in northern Estonia (Heinsalu and Veski, 2007) and around zero or even below in southwestern Estonia (Veski et al., 2005; Talviste et al., 2012). Since the early Holocene, at about 11.5 cal. ka BP, **rapid amelioration of climate** and the spread of forests provided more varied subsistence for people, including fish, marine and terrestrial mammals, plants, fruits, etc. (Bell and Walker, 2005; Jöns, 2011). Emerged archipelagos, mainly in the western part of the Baltic Sea, provided many favourable locations for the first coastal settlements, where the earliest evidence of communities specialised on marine

resources have been found. The establishment and end of these **Late Palaeolithic/Early Mesolithic** settlements was highly dependent on local relative sea level changes (Fischer, 1996; Kindgren, 1996; Gustafson, 1999).

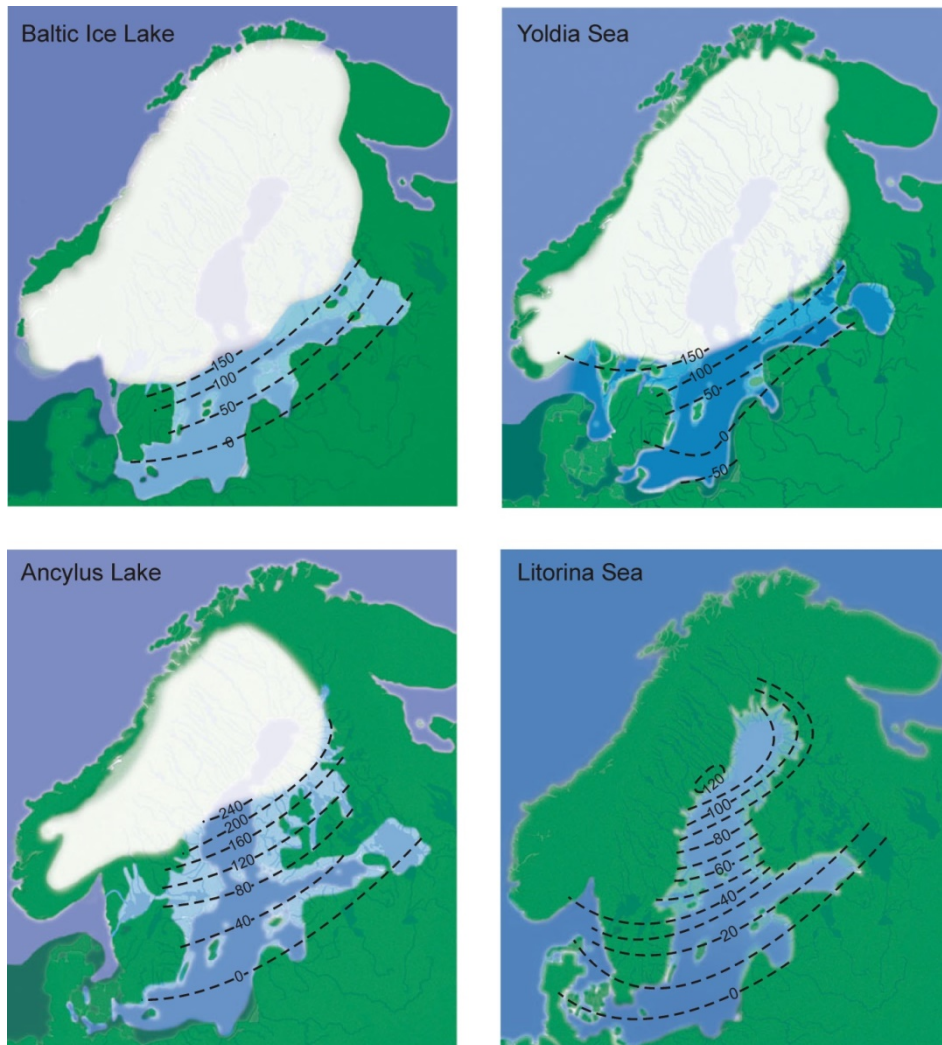


Figure 1. Late and postglacial development of the Baltic Sea. a) Baltic Ice Lake at c. 11.7 cal. ka BP. b) Yoldia Sea at c. 11.1 cal. ka BP. c) Ancylus Lake at c. 10.5 cal. ka BP. d) Litorina Sea at c. 7.5 cal. ka BP. Palaeogeographical reconstructions of past Baltic Sea shorelines according to Andren et al. (2011), water level isobases according to Eronen (2001).

The slightly brackish phase was short, as, due to the intensive isostatic land uplift caused by deglaciation, the connecting straits shallowed and the connection to the ocean ended at about 10.7 cal. ka BP. The water was up-dammed again and the freshwater **Ancylus Lake** formed in the Baltic Sea basin (Andrén et al., 2011; Figure 1c). The lake was fed by the quickly melting ice sheet and additions from rivers, and its water level rose for about 500 years, flooding coastal areas all around the basin. In Estonia, Ancylus Lake transgression reached 5–45 m a.s.l. at c. 10.2 cal. ka BP (Saarse et al., 2003). Human settlements spread everywhere around the Ancylus Lake coasts and inland at that time. The **Mesolithic** people were generalists who adapted their economic strategies to the **exploitation of many different kinds of resources** available in their vicinity (Zvelebil, 2008; Jöns, 2011). At that time, the **earliest known human settlements in Estonia**, seasonal hunting and fishing camps, were established in Pulli and in Kunda Lammasmägi (Åkerlund et al., 1996; Lõugas, 1996, 1997; Poska and Veski, 1999; Kriiska and Tvauri, 2007). Archaeological material and palaeogeographical reconstructions show that the Pulli settlement, dated to 10.8–10.2 cal. ka BP was located near the river and forest, several metres above Ancylus Lake level and several kilometres from the shoreline. The site was later flooded by the waters of Ancylus Lake (Lõugas, 1997; Poska and Veski, 1999; Veski et al., 2005; Rosentau et al., 2011). The Kunda Lammasmägi settlement, where the earliest habitation started around 10.7 cal. ka BP, was located on a small island in a palaeo-lake or wetland clearly above Ancylus Lake level (Åkerlund et al., 1996; Karukäpp et al., 1996; Sander, 2014).

At about 9.8 cal. ka BP, the waters of Ancylus Lake found an outlet through the Danish Straits, and the lake level lowered to that of the ocean in about 200 years. The earliest evidence of saline water ingress, the start of the **Initial Litorina Sea** phase, is documented in the southern Baltic Sea at about 9.8 cal. ka BP (Andrén et al., 2000; Berglund et al., 2005). The Scandinavian Ice Sheet was fully melted, and the people settled all areas around the Baltic Sea basin (Zvelebil, 2008). The sea level rose, and the brackish environment reached throughout the Baltic Sea basin around 8.5 cal. ka BP, marking the start of the **Litorina Sea** (Andrén et al., 2011; Figure 1d). At that time, remarkable changes in the ecosystem took place as the climate warmed and the global sea level rose, widening the connection to the ocean and making the Litorina Sea saltier over time, thus increasing primary production and the number of species. This created favourable conditions for development of the **maritime economy** of humans, with seal and porpoise hunting as the prevailing subsistence strategy and abundant shore-bound settlement everywhere on the coasts of the Baltic Sea (Andersen, 1993a; Christensen, 1995; Larsson, 1997; Kriiska, 2000; Kriiska and Lõugas, 2009; Jöns, 2011). These **Mesolithic and Neolithic** coastal settlements, from the period c. 10.5–6.0 cal. ka BP, are presently located at different elevations because of differential regional glacial isostatic land uplift and eustatic sea level rise (see Figure 2 for relative sea level changes in different parts of the Baltic Sea basin). In the southern Baltic Sea region, a number of

settlement sites have been found lying in the present seabed because of relative sea level rise (Fischer, 2011; Lübke et al., 2011). In contrast, in the northern Baltic Sea region, prehistoric coastal settlements have been uplifted because of post-glacial rebound; the older the site, the higher the altitude has become (Siiriäinen, 1982; Vaneeckhout, 2008). In transitional areas in the eastern Baltic Sea region, coastal settlements have also been uplifted and are presently located inland; however, Mesolithic sites are sometimes buried under marine sediments because sea level rise temporarily exceeded the land uplift in this region (Jussila and Kriiska, 2004; Veski et al., 2005; Gerasimov et al., 2010; Rosentau et al., 2011). In Estonia, the transgression lasted until c. 7.5 cal. ka BP (Veski et al., 2005, Saarse et al., 2009) with its highest shoreline reaching 5–25 m a.s.l. (Saarse et al., 2003). Afterwards, relative sea level lowering appeared, evidenced by coastal formations (Rosentau et al., 2013) and isolated lake basins (Grudzinska et al., 2013) found on gradually lower elevations in the coastal areas. In the eastern Baltic Sea region, the beginning of maritime lifestyle and the selection of settlement sites on the coast started during the second half of the Mesolithic period at about 9.8–8.5 cal. ka BP and continued in many areas also during Neolithic (Comb Ware) times (Gerasimov et al., 2010; Jöns, 2011; Kriiska, 2001). The settlement locations followed the shoreline regression (Kriiska, 2001; Jussila and Kriiska, 2004). Based on archaeological material, geological studies and a few palaeogeographical reconstructions, it has been concluded that the preferred locations for settlements were associated with former river mouths (Nunez and Okkonen, 1999; Rosentau et al., 2011), sheltered bays and archipelago systems (Kriiska, 2003a) and coastal lakes and lagoons (Kriiska, 1999; Bērziņš, 2008). A change in this settlement pattern and an important shift in prehistoric human subsistence strategy took place with the introduction of **agriculture and animal husbandry** to the Baltic Sea region around 6.0 cal. ka BP (e.g. Andersen, 1993b; Ahlfont et al., 1995). In many locations, settlements were moved to arable farmlands away from the coast (Schmölcke et al., 2006; Jöns, 2011). However, in the eastern Baltic Sea area, many settlements were still established on the seashores. This is reflected in the discoveries of fishing and hunting tools and large numbers of bones of marine mammals, together with pottery, and the absence of farming indicators until the Late Neolithic period (Kriiska, 2003a; Veski et al., 2005; Bērziņš, 2008; Gerasimov et al., 2010).

When the climate cooled again and sea level rise slowed down, water exchange between the Baltic Sea basin and the ocean gradually decreased, and the environment became only slightly brackish and less productive, marking the start of the **Post-Litorina Sea** (Limnea Sea) at about 4.5 cal. ka BP (Hyvärinen et al., 1988; Grudzinska 2015). The coastal zone, which had lost its centrality for the inhabitants' nutrition after the introduction of farming, gained new importance for trade and communication. Since then, the Baltic Sea, together with rivers and lakes, formed a prehistoric **transportation network** (Jöns, 2011). The remains of harbours and jetties provide information about the late Holocene sea level changes (e.g. Miller et al., 1997).

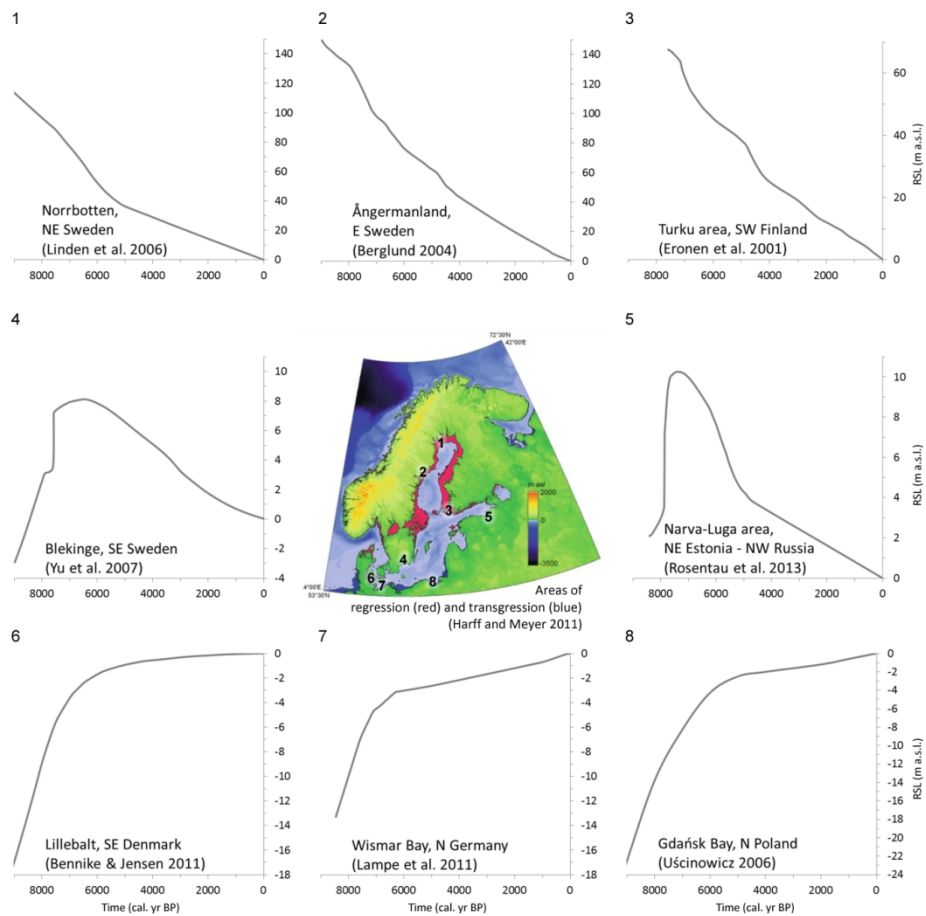


Figure 2. The change of relative sea level in different parts of the Baltic Sea basin since the onset of the Litorina transgression at about 8.0 cal. ka BP. Figure from Rosentau et al. (2017).

3. MATERIALS AND METHODS

3.1 Description of study areas

The study areas are located in the peripheral zone of the glacial isostatic land uplift in the eastern Baltic Sea region (Figure 3), where the Holocene relative sea level history has been complex, with alternating transgression and regression periods (Figure 2). Two of the study areas, Narva-Luga Klint Bay and Tallinn city centre, are located on the southern coast of the Gulf of Finland, and one, Ruhnu Island, in the middle of the Gulf of Riga. The apparent land uplift rates (relative to rising sea level) for the last century are 0.9 mm/a in Ruhnu, 0–1 mm/a in Narva-Luga and c. 2.5 mm/a in the Tallinn study area (Ekman, 1996), and the present absolute rebound rates are 1.5 mm/a, 1.8–2.3 mm/a and 3.1 mm/a respectively (Agren and Svensson, 2007).

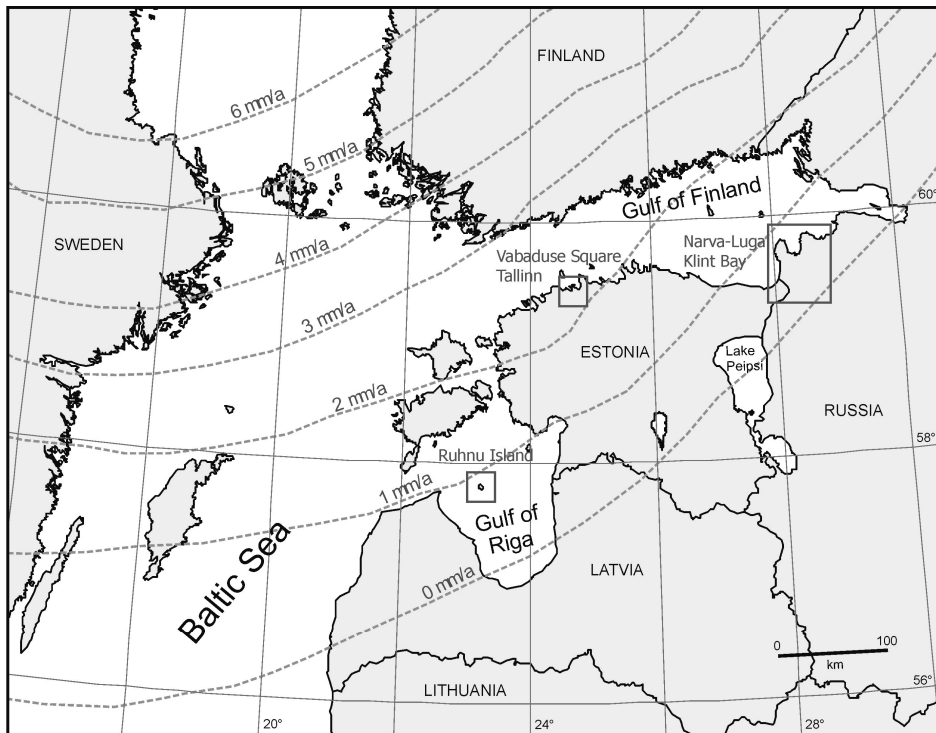


Figure 3. Location of study areas: Narva-Luga Klint Bay, Tallinn city centre and Ruhnu Island; and apparent land uplift (relative to rising sea level) isobases (Ekman, 1996).

Narva-Luga Klint Bay is a lowland with plateau-like morainic hills, peatlands and large meandering rivers, situated in northeastern Estonia and northwestern Russia. The study area is about 2000 km². To the south and to the east, the area

is contoured by the Baltic Klint bedrock escarpment tens of metres high. The low areas between the uplands and the escarpment created favourable conditions for the development of near-shore bars, spits and beach ridges intersected by lagoons presently filled with organic and silty-sandy deposits. The Stone Age human occupation, represented by more than 60 settlement sites in the area, dates back to the pre-ceramic Mesolithic period c. 8.5 cal. ka BP and continues through Narva-type and Combed Ware ceramic times to Late Neolithic Corded Ware settlements (Kriiska et al., 2016).

The study area in Tallinn is a heavily built-up city centre near the coast of Tallinn Bay. The area (1.2 km²) comprises a limestone bedrock hillock in the west and continuously lowering topography in the east and north. A sandy sediment layer with Middle and Late Neolithic Combed ware and other artefacts and animal bones indicating coastal settlement at around 5.0 cal. ka BP have been found beneath the medieval and modern cultural layers in Vabaduse Square (Kadakas et al., 2010).

Ruhnu Island, with an area of 12 km², forms an above-water top to a northwest-southeast oriented sandstone bedrock ridge in the middle of the Gulf of Riga. Around the flat circular-shaped centre of the island, sequences of foredune ridges parallel to the former shorelines mark the former backshores and beach progradation. Traces of Late Mesolithic and Late Neolithic human habitation have been found on the island in seven and one sites, respectively, and the settlement phases dated to around 7.2, 6.2 and 4.7 cal. ka BP (Kriiska and Lõugas, 2005; Konsa and Ots, 2009).

3.2 Chronology and shore displacement reconstruction

In two study areas, the Narva-Luga and Tallinn, shore displacement was reconstructed on the basis of radiocarbon-dated sediment stratigraphies sampled during fieldwork and of previously published studies available for the areas. The dates were calibrated using the OxCal program (Bronk Ramsey, 2001, 2009) and calibration curves IntCal09 and IntCal13 for terrestrial and limnic sediments and a combination of Marine09 and IntCal09 calibration curves for Litorina Sea sediments (Reimer et al., 2009, 2013; Sandgren et al., 2004). In Narva-Luga (Paper I), the elevations of the dated sites were corrected against the differential land uplift according to the methodology described in Rosentau et al. (2011). Interpolated surfaces of water levels with different shoreline tilting gradients calculated from databases of Estonian coastal formations for Baltic Ice Lake stage III, Ancylus Lake maximum level, Litorina Sea maximum level (Saarse et al., 2003, 2007) and the modern Baltic Sea about 100 years ago (Ekman, 1996; Figure 3) were used as palaeo-water level reference surfaces. For all other time slices, relevant water-level surfaces were interpolated between the reference surfaces considering linear decay in water level tilting. This method of spatio-temporal interpolation was used in shore displacement modelling as well as in palaeogeographical reconstructions. In the Tallinn area,

all the sites were chosen from the same Litorina Sea level isobase, and therefore additional corrections were not necessary (Paper II). The shore displacement curves for the Narva-Luga and Tallinn area were drawn for the depiction of the relative water level changes in the study areas over the Holocene period.

In the Ruhnu Island study area, shore displacement reconstruction was based on 10 luminescence dates of undisturbed sandy sediments gathered from the ditches on the seaward slopes of the shore-parallel foredune ridges in a sequence from the southern coast to the centre of the island. The ages were determined by the post-IR IRSL protocol for feldspar grains (Paper III). The best protocol was chosen according to the best fit with radiocarbon dates from the island and previous studies on Holocene relative sea level changes on the coasts of the Gulf of Riga (Saarse et al., 2009; Rosentau et al., 2011). Elevation of each sample was corrected to correspond to the elevation of the lower limit of aeolian sediments of the sampled foredune, inferred from ground penetrating radar survey and sediment cores. In this way the displacement of backshore was modelled for the Litorina Sea regression period.

For the chronology of Stone Age settlement, previously published and new radiocarbon dates from archaeological material (charcoal, bones, artefacts, etc.) were used for each study area. Additionally, typologically dated sites were used in palaeogeographical reconstructions. All of the sites are presently located inland, away from modern seashores.

3.3 Palaeogeographical reconstructions

The palaeogeographical reconstructions were based on the GIS approach, according to which the palaeo-water level surfaces were subtracted from the digital elevation model (DEM) of the modern land surface to produce palaeo-land surfaces.

The reference water level surfaces (section 3.2) were used for modelling palaeogeographies for their times. For other time slices relevant to the analysis of Stone Age settlement pattern, the palaeo-water level surfaces were interpolated between the reference surfaces and their elevations corrected to corresponding water levels on shore displacement curve, as described in Rosentau et al. (2011). Elevation H_{ni} of every grid cell n for a certain time period i was calculated using the following equation:

$$H_{ni} = A_n + \frac{A_n - L_n}{T} T_n + d_i$$

where A_n and L_n are the section's older and younger reference surfaces, respectively, T is the length of time between stages A_n and L_n , T_i is the time from the initial stage A_n , and d_i is the difference of the sample site from the linear trend line in the water-level change curve.

The raster DEMs of modern land surfaces were generated by the Triangulated Irregular Network (TIN) model with smoothing interpolation, using elevation data from different sources and of different precisions for each study area. For Narva-Luga Klint Bay, the DEM with a grid size of 20×20 m was based on the digitized elevation data of Estonian and Soviet Topographic Maps in the scales 1:25000 and 1:50000, provided by the Estonian Land Board. The elevation data for the Gulf of Finland were taken from the bottom topography dataset of the Baltic Sea (Seifert et al., 2001). For Tallinn centre, the data of pre-medieval surface elevations from available geological records (Zobel, 2009) as well as the data measured during the Vabaduse Square excavations were used and the DEM with a resolution of 2 m created. Additionally, a detailed DEM of the Stone Age excavation plot with a resolution of 0.2 m was generated to enable detailed description of the microtopography of the settlement site. The latter elevation data originated from tacheometry and levelling measurements of the Stone Age cultural layer upper surface during the archaeological excavations (Kadakas, 2010). For Ruhnu Island, airborne LiDAR elevation point data with a point density of approximately 0.45 points per m², collected in the years 2008 and 2012 by the Estonian Land Board, were used, and the 5 m resolution DEM interpolated.

The reconstructed palaeoshoreline positions were corrected against the inaccuracies arising from the various sediment deposits accumulated later than the time being modelled. In the Narva-Luga area, the corrections were based on Quaternary geology maps (by Ministry of Natural Resources of Russian Federation in scale 1:200000 and Estonian Land Board in scale 1:50000), topographic maps and aerial images (by Estonian Land Board and Google Inc.). The shoreline as initially modelled was repositioned landward on major peat or sand accumulations and seaward on locations with presumably younger river erosion. In Tallinn, the thickness of anthropogenic sediments (c. 2–2.5 m of medieval and modern cultural layers and landfills) had previously been removed from the elevation data using information from sediment cores, surfs and excavations in the city centre (Zobel, 2009).

On Ruhnu Island, palaeoshorelines were reconstructed based on morphological analysis of relief. The palaeo-beach zones were indicated following the seaward foot of the dated foredune ridges and that of the ridges with similar foot altitude around the island. The widths of the beaches were estimated based on modern analogues (Rosentau et al., 2013), ground penetrating radar survey and coring data. The ridges younger than the time modelled were removed by lowering their altitude to modelled palaeo-sea level. For the morphological profile of the oldest settlement phase, the later re-deposited dune ridge was eliminated by lowering its elevation to the level of surrounding flat land and a foredune ridge modelled at its supposed original location. The reconstructions of the island were compared to relative sea level curve from a previously published study about Pärnu Bay area on the northeastern coast of the Gulf of Riga (Rosentau et al., 2011). The land surface altitudes of the coastal areas

around the Gulf of Riga were calculated based on water level surface of Litorina Sea maximum level (Saarse et al. 2003).

The setting of each archaeological site was defined by the comparison of its location with the position of its contemporary shoreline, its relative sea level and the type of coast inferred from the palaeogeographical reconstruction and sedimentary proxies.

4. RESULTS AND DISCUSSION

4.1 Narva-Luga Klint Bay during the Mesolithic and Neolithic times

The palaeogeography of the Narva-Luga area was studied using the shore displacement reconstruction and GIS-based modelling presented in Paper I in order to clarify how Mesolithic and Neolithic people faced Holocene shoreline changes in this coastal area.

The reconstructed shore displacement curve for Narva-Luga Klint Bay displays three regressive phases in the Baltic Sea history, interrupted by two rapid Ancylus Lake and Litorina Sea transgressions at c. 10.9–10.2 cal. ka BP and c. 8.5–7.3 cal. ka BP, respectively (Figure 4). During the Ancylus Lake transgression, the lake level rose 9 m at an average rate of about 13 mm per year in the centre of the study area. The highest shoreline of Ancylus Lake at an altitude of 8 m a.s.l. in the southern and 17 m a.s.l. in the northern part of the study area was formed around 10.2 cal. ka BP. During the Litorina Sea transgression the sea level rose 8 m at an average rate of about 7 mm per year and the highest shoreline of the Litorina Sea was formed at an altitude of 6 m a.s.l. in the southern and 14 m a.s.l. in the northern part of the study area at around 7.3 cal. ka BP. Since then the relative sea level lowered continuously.

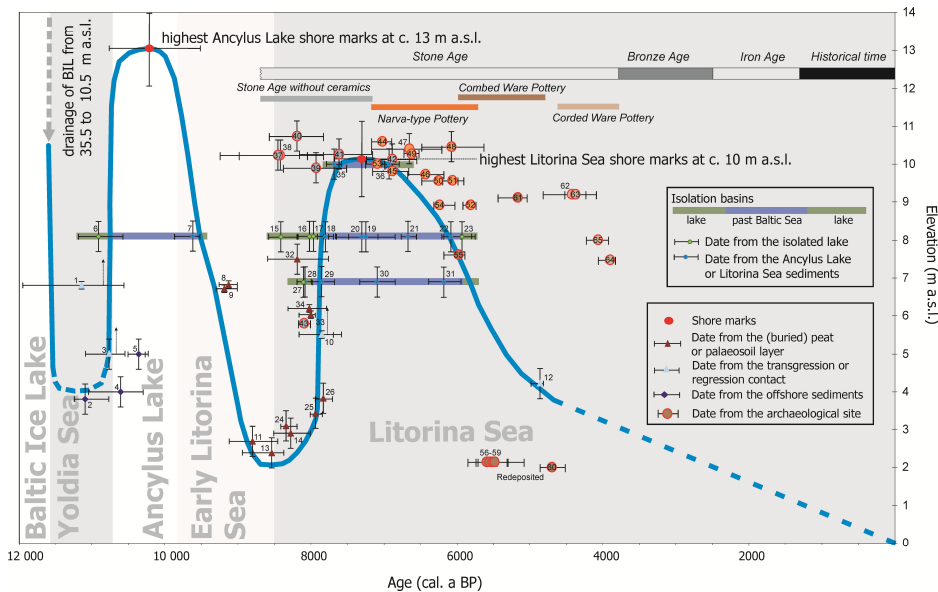


Figure 4. The Holocene relative water level change curve for the Narva-Luga Klint Bay area. Water level elevations of all sites were corrected against the differential land uplift. Baltic Sea stages according to Andrén et al. (2011). Figure published in Paper I.

The palaeogeographical reconstructions show an open water environment during the Baltic Ice Lake and Ancylus Lake highest water level times followed by the emergence of dry land, river and peatland development during the Initial Litorina Sea, the inundation of the area during Litorina Sea transgression and the lagoon environment afterwards until the overgrowing of the lagoon for the time of the Post-Litorina Sea.

The oldest traces of human activity, dated to 8.5–7.9 cal. ka BP, are associated with the palaeo-Narva River in the period of low water level at the beginning of the Litorina Sea transgression (Figure 5a). Only three locations with archaeological finds of the period are known; more settlements may have existed, but none have been preserved or found due to the burial and/or re-sedimentation during the transgression. At the time of the Litorina Sea transgression, a large semi-enclosed lagoon formed in Narva-Luga Klint Bay, opening new habitation possibilities for humans (Figure 5b). The palaeogeographical reconstructions, together with sedimentary evidence, show that the lagoon was protected from the open sea by a coastal landform system in the west, and the high-energy wave regime never extended into the southern part of the lagoon (Paper I; Rosentau et al., 2013). The coastal settlement associated with the lagoon, represented by 33 Stone Age sites at the time of the study, existed there for about 2500 years. The lagoon shores were preferred living environments for hunter-fisher-gatherer groups exploiting both forest and marine-lagoonal resources during the Narva-type Pottery and Combed Ware Pottery periods. The coastal settlement started in the southern part of the lagoon at c. 7.1–7.0 cal. ka BP and spread up to the northern part of the lagoon within about 1000 years (Figure 5c). The settlement pattern clearly indicates the avoidance of the open coast of the Litorina Sea and preference for the sheltered shores of the lagoon, sometimes at the mouths of rivers and streams. However, abundant finds of bones of cod (*Gadus morhua*) and harp seal (*Phoca groenlandica*) evidence trips to the open sea. Such Neolithic coastal sites, dominated by bones of seal (*Phocidae*) and often also wild boar (*Sus scrofa*) are known from several places around the Baltic Sea (Jonsson, 1986; Lõugas, 1997; Storå, 2001). Specialized seal hunting developed here, as well as in many other areas around the Baltic Sea, during the Litorina Sea stage (Lõugas, 1997; Kriiska, 2000; Storå, 2001; Seitsonen, 2008). The flourishing of the coastal settlement coincides with the Holocene Thermal Maximum and the most saline phase of the Baltic Sea. Since about 5.0 cal. ka BP a clearly different habitation pattern develops in the study area – the settlement concentrates along ancient rivers (Figure 5d). A similar situation is documented in other areas around the Gulf of Finland for that period of time (Edgren, 1984; Lang, 1996; Kriiska, 2000). Bones of domestic animals and pollen of cereal plants in deposits (Kriiska, 2009) suggest that the change from a hunter-fisher-gatherer economy to agriculture and animal husbandry at the Corded Ware period was the reason for the new settlement pattern, which occurs simultaneously with the overgrowing of the lagoon at c. 5.5–4.5 cal. ka BP.

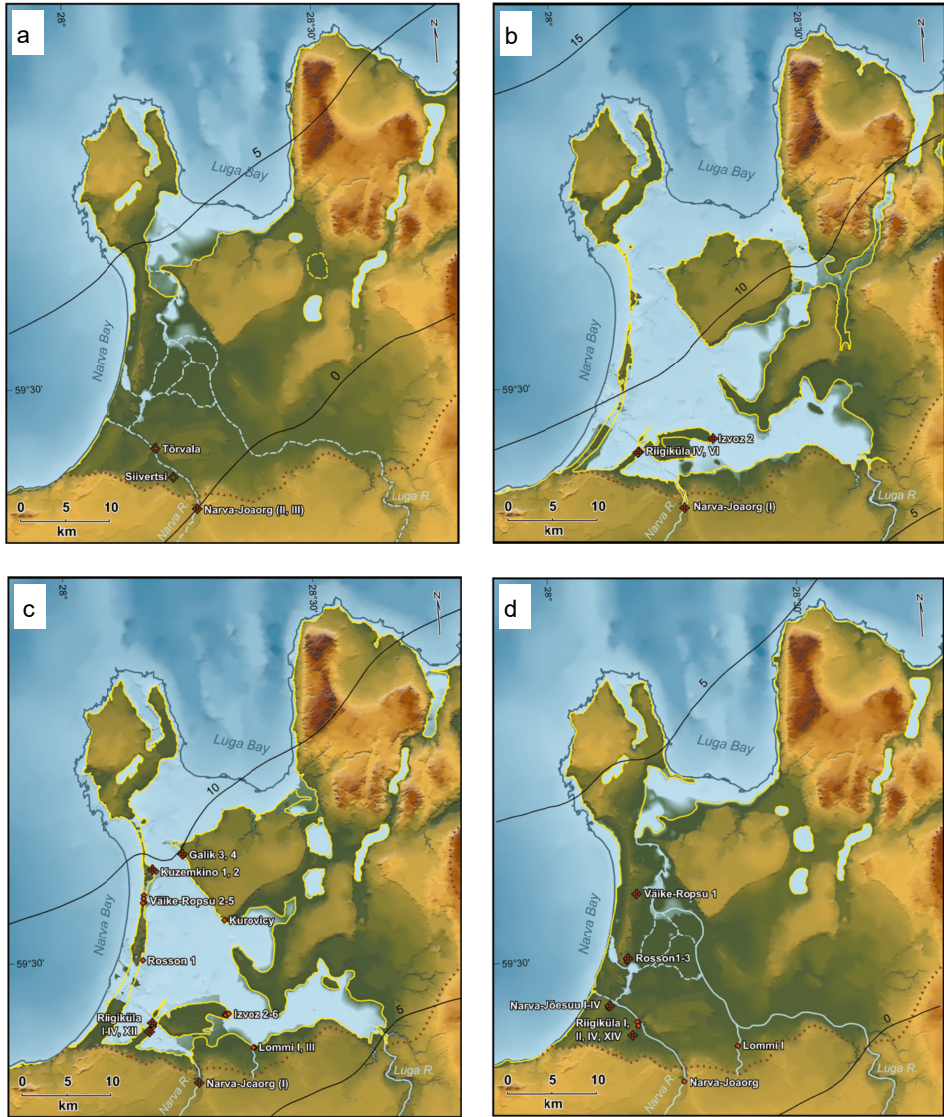


Figure 5. Palaeogeographical reconstructions of Narva-Luga Klint Bay. a) The Litorina Sea at the beginning of the transgression and the earliest known Stone Age sites in the area at c. 8.0 cal. ka BP. b) The Litorina Sea after the transgression and the beginning of the coastal settlement at c. 7.0 cal. ka BP. c) The Litorina Sea lagoon environment and hunter-fisher-gatherers' coastal settlements c. 6.0 cal. ka BP. d) The Post-Litorina Sea, overgrowing of the lagoon and Neolithic farmers' riverbank settlements c. 4.5 cal. ka BP. Figure reproduced from Paper I.

The palaeogeographical reconstructions show that the study area (presently at 15.5–16.5 m a.s.l.) was isostatically uplifted from the Litorina Sea at about 5.8 cal. ka BP and, at the time of the Middle Neolithic habitation at about 5.0 cal. ka BP, it was an open bay environment in the wave and wind shadow of a 28-m-high Toompea bedrock hillock (Figure 7a). The settlement site was established c. 100 m from the shoreline. The detailed reconstruction of the palaeotopography of the settlement site reveals the seaward-inclining palaeo-beach surface at c. 1.5–3.5 m above its coeval sea level, where the concentration of finds decreases towards the past seashore (Figure 7b, c). The settlement was probably established higher than wave run-up, as close to the shoreline as possible. As indicated by the faunal remains and the reconstructed palaeogeography, the settlement site presented a good location for seal and porpoise hunting trips into the former Tallinn bay and to the open sea. In the eastern Baltic Sea region, the preferred settlement locations of these Stone Age maritime economy times have been associated with sheltered palaeo-bays and archipelago systems (Kriiska, 2003a), former river mouths (Nuñez and Okkonen, 1999; Rosentau et al., 2011), major palaeo-lagoonal systems (Paper I) or coastal lakes (Bērziņš, 2008; Kriiska, 1999), and only in a few cases with the shores of open bays (Kriiska, 2003a, 2007; Carpelan et al., 2008) as in the Vabaduse Square site. Later, when the shoreline retreated towards the northeast, the Middle Neolithic hunter-fisher-gatherers abandoned the settlement. However, a few Corded Ware pottery fragments suggest that it was re-exploited to some extent by Late Neolithic farmers, when, according to the palaeogeographical reconstructions, the seashore had retreated several hundred metres from the site. A similar pattern of re-habitation is recognized in some other settlement sites in the eastern Baltic Sea region (Kriiska, 2003b).

The detailed reconstructions suggest that the settlement probably continues to non-excavated areas parallel to the modelled shoreline and does not spread further seaward (Figure 7b). The knowledge acquired from this study provides a better prediction of the locations and discoveries of similar Neolithic open seashore sites in the eastern Baltic Sea region.

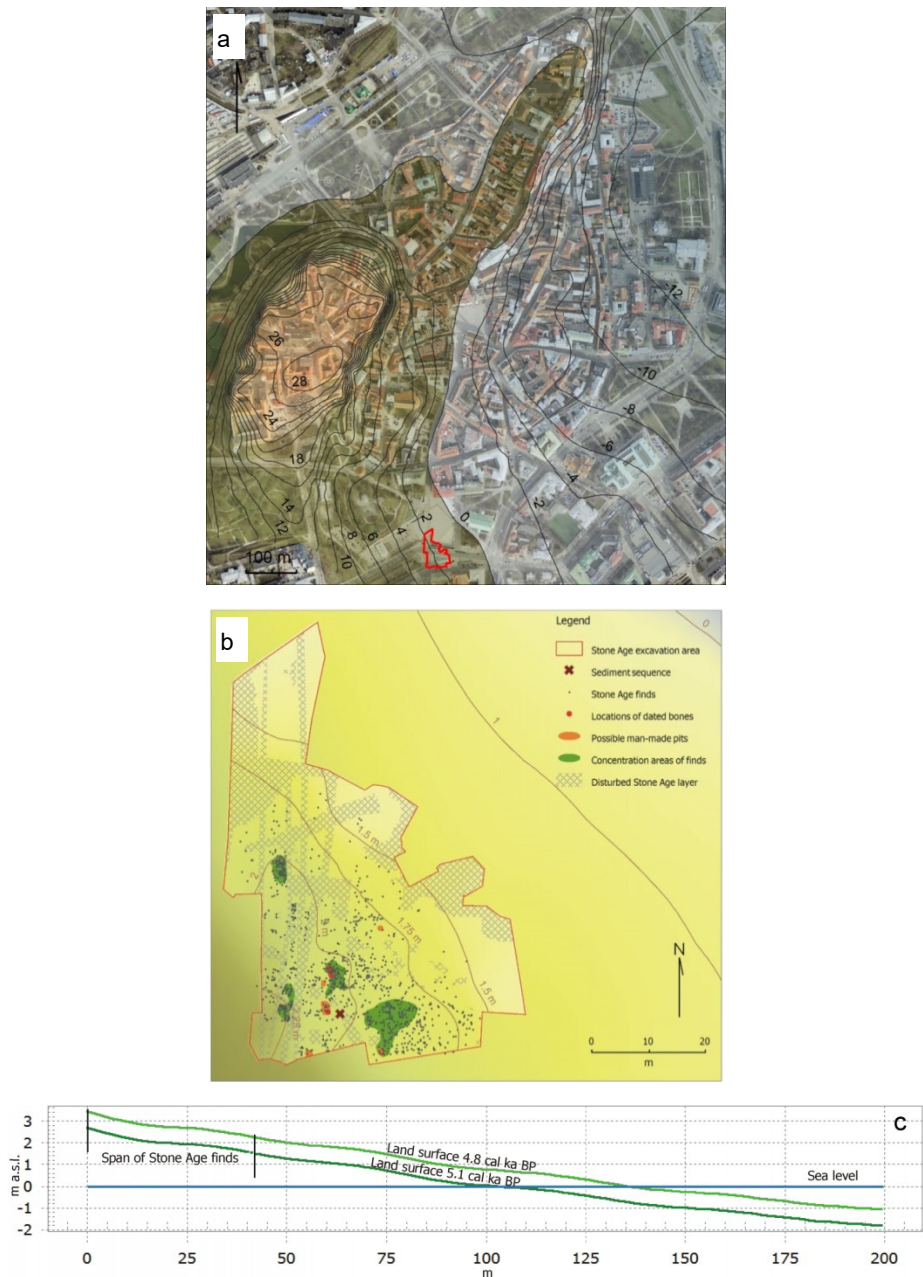


Figure 7. a) The reconstruction of the Litorina Sea coast and Neolithic hunter-fisher-gatherers settlement on its shore at about 5.0 cal. ka BP. The location of the study area is presently in a densely built-up city centre. Vabaduse Square excavation plot (red polygon) marked on orthophoto (Estonian Land Board). b) Detailed palaeotopographical reconstruction of the Vabaduse Square Neolithic settlement site at c. 5.1 cal. ka BP. c) Profile illustrating the elevation and distance of the settlement from its coeval shoreline. Figure reproduced from Paper II.

4.3 Ruhnu Island: Coastal progradation and Stone Age settlement

The palaeogeography of Ruhnu Island was studied using shore displacement reconstruction and landscape modelling based on data from foredune succession presented in Papers III and IV in order to clarify the geomorphological development of the remote island and its colonization by Mesolithic and Neolithic people.

The Post-IR IRSL dating shows that the studied foredune sequence sampled along a 1.6-km-long transect from the coast to the centre of the island, consisting of 38 ridges, was formed between 6.91 ± 0.58 ka and 2.54 ± 0.19 ka ago and represents a period of falling relative sea level (Paper III). Considering the uncertainties of the ages, the start of the foredune succession corresponds well with the shift from the Litorina Sea transgression to the regression in the region (Figure 8). This study shows that foredune progradation, with an average rate of c. 0.4 m per year, was controlled by glacial isostatic land uplift, which caused continuous withdrawal of shorelines into lower elevations. As evidenced by sediment cores and ground-penetrating radar analysis, the foredune ridges are built of well to very well sorted fine- to medium-grained aeolian sand and underlain by seaward dipping foreshore sediments. The contact between foreshore and aeolian sediments below each ridge, indicating the landward swash limit at the foredune formation time, decreases from 9.5 m a.s.l. to 3.5 m a.s.l. between 6.9 and 2.7 ka ago.

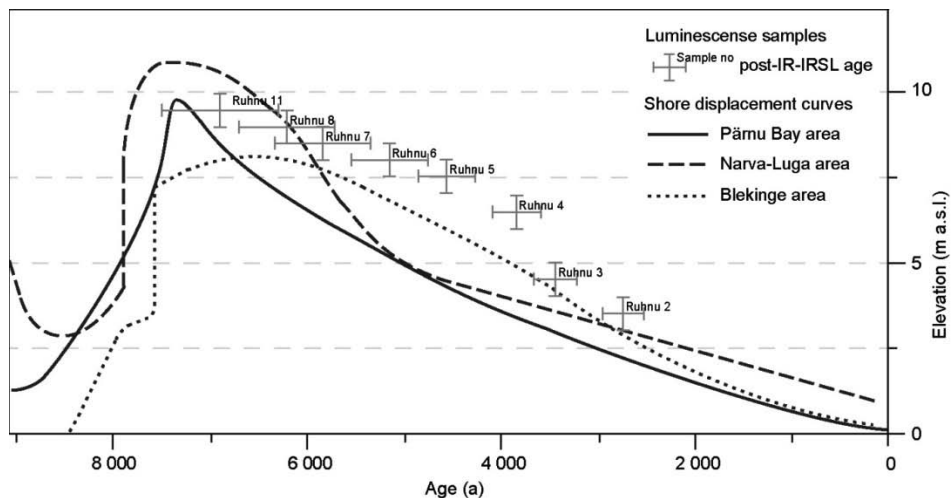


Figure 8. Luminescence ages and corrected elevations of foredune samples indicating former backshore limits on Ruhnu Island. Elevations of the samples were corrected according to ground penetrating radar and coring data, and represent contact of foreshore and aeolian deposits. The Holocene shore displacement curves for peripheral zone of the Scandinavian Ice Sheet post-glacial land-uplift area in Narva-Luga area in northeastern (Paper I) and Pärnu Bay area in southwestern Estonia (Rosentau et al., 2011) and Blekinge area in southern Sweden (Yu et al., 2007) for comparison. Figure from Paper IV.

Using the high-resolution LiDAR DEM made it possible to delineate foredune foot lines and track the backshore limit of the same age at nearly constant altitude and thus reconstruct the coastal zone and the shape of the island in the course of Litorina Sea regression. Difficulties in the delineation of the beach zones appeared in locations where foredune feet were not clearly exposed and the ridges were united or eroded.

Palaeogeographical reconstructions of Ruhnu Island, together with morphological profiles across foredunes, suggest that during the oldest Late Mesolithic settlement, the seal hunters' camps were established on the centremost foredune ridge in the former backshore zone at c. 4 m above the mean sea level at about 7.2 cal. ka BP (Figure 9). The colonization coincides with the Litorina Sea level highstand. For c. 1000 years Ruhnu Island remained a very small islet consisting of one encircling coastal ridge and an emerging flat area in the centre of the island. Based on tool material and pottery type (Kriiska and Lõugas, 2005) the first settlers of Ruhnu Island originated from the already-inhabited Saaremaa Island, which, according to palaeogeographical reconstruction of the Gulf of Riga, was located c. 70 km northward at that time. Dates from the Ruhnu II site indicate that the island was revisited again at about 6.2 cal. ka BP, when the sea level had become c. 2 m lower, but the wave run-up still reached the feet of the same foredune ridges. Probably at that time, in the southern part of the island, a new settlement (Ruhnu IV) was established on the leeward side of a recently formed foredune ridge in the vicinity of coastline, c. 4 m above mean sea level and 2–3 m above swash limit (Figure 9). The second settlement phase coincides with the time of the major re-blowing event, which was luminescence-dated to 6.29 ± 0.46 ka. It is therefore possible that forest clearance caused by humans contributed to sand movements. These sites were located somewhat higher from the mean sea level than other similar Mesolithic seasonal camp sites in the eastern Baltic Sea region (Rosentau et al., 2013; Kriiska, 2003a). This can be explained by the location of the island in the middle of the gulf, with stronger winds and higher waves, which forced people to establish settlements higher from the mean sea level compared to locations on protected coasts.

The reconstruction shows that at about 4.7 cal. ka BP, the island had gained a compact shape with an area of 2.5–3 km², and a Late Neolithic settlement was established hundreds of metres from the shoreline at c. 8 m above its coeval sea level on the flat central plain of the island, which is a clearly different pattern from the earlier coastal settlement. The find material and location of this Late Neolithic site is similar to other Late Neolithic Corded Ware sites in the eastern Baltic Sea region, where this kind of change in settlement pattern (away from the shore) has been linked to the intensification of agriculture and animal husbandry (Kriiska, 2001, 2003b; Paper I).

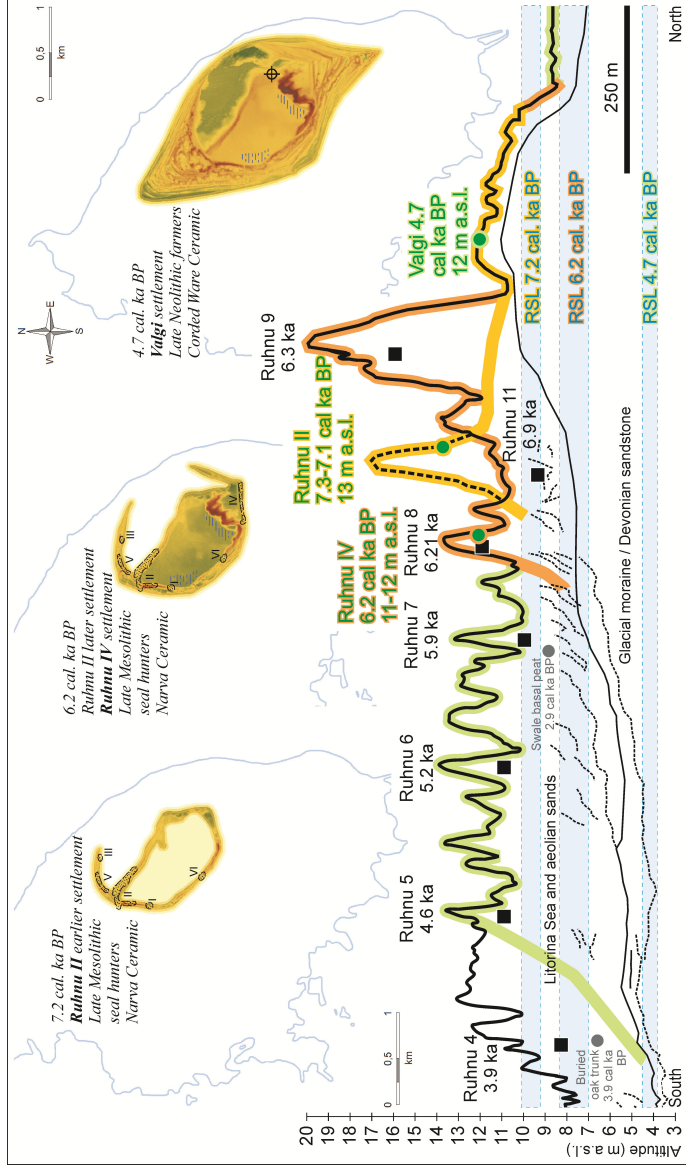


Figure 9. Progradation chronology and profile of the studied foredune sequence together with principal locations of Stone Age settlements and the corresponding palaeogeographical reconstructions of Ruhnu Island for time slices 7.2 cal. ka BP, 6.2 cal. ka BP and 4.7 cal. ka BP. Black squares mark the locations of the IRSL sampling sites. Prominent seaward dipping reflectors are drawn in dashed lines, and sedimentary units marked as interpreted on ground penetrating radar image. Vertical scale is exaggerated ~32 times. Relative sea levels (RSL) according to Rosentau et al. (2011) and Paper I. Figure from Paper IV.

4.4 Methodological aspects of GIS-based palaeogeographical reconstructions

In Estonia and the adjoining coastal areas, shore displacement and palaeoshoreline positions have been studied previously by several authors, starting from as early as the beginning of the 20th century by Ramsay (1929), Markov (1931) and Kents (1939) and continued, among others, by Kessel (1963), Kessel and Raukas (1967), Hyvärinen et al. (1992), Miidel (1995), Lepland et al. (1996), Saarse et al. (2003), Miettinen et al. (2004), Sandgren et al. (2004), Veski et al. (2005), Saarse et al. (2009, 2010), Saarse and Vassiljev (2010), Rosentau et al. (2011), Grudzinska et al. (2013, 2017), and Habicht et al. (2016). The most recent of these studies use applications of DEM and GIS, among other methods, for shore displacement and landscape modelling. However, for the most part, interpretations of landscapes around Stone Age sites have been made in archaeological studies (e.g. Jussila and Kriiska, 2004; Kriiska and Lõugas, 2005; Gerasimov et al., 2010), which have made little use of geoscientific methods. For Narva-Luga Klint Bay, Tallinn and Ruhnu Island the palaeogeographical reconstructions presented in this thesis are the first that use GIS-based modelling and integrated geoscientific proxies specifically for addressing questions and testing ideas raised from archaeological data and interpretations about these study areas.

Advantages of GIS. Reconstruction of past shorelines and water bodies based on terrain elevation and glacial isostatic adjustment data in GIS goes back a few decades (Mann et al., 1998; Leverington et al. 2002). In this thesis, the implementation of GIS enabled compilation, analysis, improvement and visualization of data originating from several research disciplines, mainly archaeology, geology, palaeobotany and palaeozoology, cartography, remote sensing and geodesy. The methodology developed in Rosentau et al. (2011) formed the initial basis for the palaeogeographical modelling and was advanced by adding morphological analysis of relict coastal ridges, foreshore sloping and microtopography, and adapting the methods to small-sized study areas with detailed elevation data. The GIS workflow, starting from the compilation of shore displacement curves and the spatio-temporal interpolation of water level surfaces and proceeding with the calculation of past terrain altitudes, removal of younger sediments, modelling palaeoshorelines positions and their comparison with archaeological data, resulted in detailed palaeogeographical reconstructions that provided new knowledge about the development of the coasts and improved the understanding of living customs of Stone Age people in the eastern Baltic Sea region (sections 4.1–4.3). The use of GIS and the high quality input data enabled detailed description and visualization of the palaeoshorelines and palaeolandscape of the study areas as well as the calculation of previously unapplied indicators like the distance of the settlement site from the shoreline or the angle of beach slope (Paper II; Paper IV). Using high-accuracy LiDAR elevation data in DEM-based analysis, made it possible to detect landforms indicating palaeoshorelines, which were difficult to notice in cartographic data

or in the field, and model palaeogeography based on morphological analysis (Paper IV). GIS provided the tools for linking and expanding scarce point source information from sediment cores and archaeological sites over an entire area using interpolation techniques (Paper I; Paper II). On the other hand, it enabled modelling based on vast data sets (altitudinal, bathymetric and geophysical data) and overlaying it for analysis in the context of this scarce point data (Paper I; Paper IV).

The GIS-based methods with this modelling logic developed in this study are universally applicable, but the detail level and fidelity of the results depends largely on the quality of input data. Therefore, although the generation of palaeogeographical reconstructions of areas with archaeological finds is mainly motivated by the need for better understanding of cultural heritage, the first task is to collect adequate data through geological investigation.

Shore displacement data. As the shore displacement data is a primary variable in the palaeogeographical reconstructions of coastal areas, a relative water level curve based on the up-to-date assessment and analysis of previously published and newly collected data was compiled for the Narva-Luga and Tallinn study areas and the detailed analysis of beach progradation based on foredune sequence chronology conducted for Ruhnu Island (Figure 4, 6, 8). Around the Baltic Sea, the important factor directing the shore displacement and the geomorphological development of the coastal areas is the glacial isostatic rebound. As the land uplift rate is the highest in the centre of the Fennoscandian rebound zone at Botnian Bay and decreases towards its periphery (Figure 1, 3), the past water surfaces are tilted. This results in the relict coastal formations of the same age located presently at different altitudes. The mean tilting gradients of these water-level surfaces decrease exponentially over time as a result of the deceleration of the land uplift (Lambeck et al., 1998). Therefore, considering the differential land uplift and tilting of the past surfaces is inevitable in palaeoshoreline and coastal palaeoenvironmental studies. Paper I shows that even in the periphery of the uplifting region, the differences of the past shoreline elevations are from c. 0.27 m/km at Ancylus Lake and c. 0.20 m/km at Litorina Sea maximum water levels to c. 0.12 m/km at the end of the Stone Age period at c. 4500 years ago. Therefore, it is necessary to estimate the shoreline tilting and the correction of relative sea level for each modelled Stone Age settlement phase.

Elevation data. In all studies conducted for this thesis, palaeogeographical reconstructions were based on the digital elevation data of the highest precision and accuracy available for each area and used in the form of DEMs of the optimal resolution, considering the detail level of the data itself and the particular purpose of the research. The use of elevation data from different sources and of different precisions enabled the comparison of and therefore conclusions about advantages and disadvantages of these data with regard to palaeogeographical reconstructions and shore displacement studies.

For Narva-Luga Klint Bay, the DEM based on the digitized elevation data of the Estonian and Soviet Topographic Maps from the first half of the 20th century

provided modelling for the relief as it was before the excavation of the major quarries and creation of the water reservoirs and other recent man-made features in the area, which have strongly influenced the original natural landscape in some locations. Furthermore, the Soviet Topographic Maps elevation data package at the scale 1:25000 is the most precise presently available that uniformly covers the whole area on both sides of the national border. For reconstructing the geomorphological development of the area, as large as c. 2000 km², the data density of the maps with elevation isobases every 2.5 m was found sufficient, and the resolution of 20 m was considered optimal. The disadvantages of the data were the artefacts, originating from the inevitably clustered nature of the data along the elevation contour lines and the uneven distribution of data, with the density of data points being high in areas with varying relief and steep slopes, while flat areas are represented by fewer points. This was overcome by using different smoothing parameters for different areas according to their data point density after initial TIN interpolation (Muru et al., 2011). Under this method, actual narrow features and abrupt changes in elevation were retained in the DEM. In nature, the former often mark abrasion terraces and the latter dunes, which, due to their narrow form, are often flattened out in DEMs covering large areas. Both of these landforms are associated with relict coastlines. Methods like Natural Neighbour and Inverse Distance Weighting interpolation tended to produce unnatural terraces on the locations of contour lines and overestimated trends in elevation values. The generated DEM showed high consistency with the airborne LiDAR data (available for Estonian part of the study area by Estonian Land Board) and known locations of coastal and other landforms. The knowledge about DEM smoothing acquired from this study was taken into account and the same interpolation method used when generating land surface models in the following palaeogeographical studies of Tallinn city centre and Ruhnu Island.

The study about Tallinn shows that data from the relatively dense geological records can be used for generating DEM of the prehistoric relief of a presently built-up urban area. In urban environments, geological data is often the only data representing past natural relief. Additionally, the study showed that detailed elevation data originating from tacheometry and levelling measurements during archaeological excavations provides a unique possibility to reconstruct the microtopography of the ancient land surface (Figure 7). The high resolution (0.2 m) DEM of the Vabaduse Square excavation plot, 2200 m² wide, led to the conclusion that the Stone Age finds were located most densely in the flattest (gradient of <1°) section immediately inland from the steepest (gradient 1.5°–2.0°) section of the seaward dipping palaeo-beach, probably right above the wave run-up elevation. The continuation of the gently sloping foreshore into the shallow sea was detected on the lower resolution reconstructions of Tallinn palaeo-bay (Paper II).

In the case of Ruhnu Island, the high-resolution LiDAR elevation data provided a reliable source for the analysis of the development of coastal areas and shore progradation on the basis of detailed analysis of relief and morphology of

the landforms. The LiDAR data were available and applicable in palaeo-terrain analysis for the whole area having only a few man-made features in the natural landscape. LiDAR DEM-based relief analysis applied together with luminescence chronology of foredune sequence, enabled considerably reliable reconstruction of shore displacement in this case, when organic material was not available for determining the age of past sea levels. The DEM used in the shore displacement reconstruction and the delineation of the coastal zones was generated in less detail than the original LiDAR data to avoid excessive small-scale variations that might have disturbed the modelling of the main relief features and inhibited accurate assessment of the overall geomorphological development of the island. Many authors have addressed the resolution/scale issue in landscape analysis (Dikau, 1990; Thomson et al., 2001; Hengl and Evans, 2009). The generalization of the DEM was kept at a level (5 m resolution) that enabled the measurement of individual coastal landforms (foredunes) and the detailed characterisation of beach progradation history. By means of DEM-based morphological analysis, supported by ground-penetrating radar image, sediment stratigraphy and chronology (Paper III), the distinctive changes in coastal advancement were detected and associated with possible climate changes in the Baltic Sea region and prehistoric human influences on the island (Paper IV).

Proving the Stone Age shore-bound settlement in the eastern Baltic Sea region. Using as many proxies as possible made conclusions about the Stone Age settlement pattern more reliable and more in detail than those before. These detailed GIS- and DEM-based palaeogeographical reconstructions of coastal landscapes made it possible to prove the shore-connectedness and marine lifestyle of the Mesolithic and Neolithic hunter-fisher-gatherers from c. 7200 to 5000 years ago and the disappearance of the settlements from the shores thereafter in relation to the development of agriculture in the eastern Baltic Sea region. Until now these ideas were mainly based solely on archaeological and osteological material found from the studied sites. Furthermore, it was possible to map the settlement pattern in its contemporary landscape and define the configuration of the shore and (with some reservations) the type of coast at the time of its prehistoric habitation (Figures 5, 7, 9). These reconstructions show that during the Stone Age coastal settlement and marine subsistence times, the people established their settlements as close to the shoreline as possible and, although sheltered bays and lagoon shores were the most favourable locations for habitation (Paper I), seasonal hunting and fishing camps were also established on the beach zone of a large open bay and on a remote islet (Paper II; Paper IV). In addition to a better understanding of the reasons behind prehistoric settlement patterns, based on these discoveries it is also possible to predict more accurately the locations of potentially undiscovered Stone Age sites in different types of coastal landscapes and specify the ages of undated settlements considering both their elevation above their contemporary sea level and the type of coast. There have been attempts to search for possible coastal settlement locations based on general information about past relative sea levels and, only at a limited number of locations, based on specific palaeoshoreline

reconstructions (Teiter, 2000; Habicht et al., 2016). The most favourable locations for potential settlements were proposed in Paper I and the probable extension of the camp site predicted in Paper II. With the help of knowledge about coastal features, several new Stone Age sites have been discovered in Narva-Luga Klint Bay in recent years (Kriiska et al., 2016). In all three study areas, the palaeogeographical reconstructions support the idea of the disappearance of the settlements from the coastal zone in Late Neolithic times, less than 5000 years ago, which is documented and linked to the development of farming in previous archaeological studies of the eastern Baltic Sea region (Kriiska, 2003b; Bērziņš, 2008; Gerasimov et al., 2010). This is notably later than on the southern and western coasts of the Baltic Sea, where similar change in subsistence strategy and settlement pattern took place about 1000 years earlier (Schmölcke et al., 2006; Jöns, 2011). In case of the Vabaduse Square site as well, the re-exploitation of the previously coastal settlement by Late Neolithic farmers, at a time when the seashore had retreated far from the site, was shown by the palaeogeographical reconstructions.

Further development. Provided with accurate suitable input data and tested methods in GIS, palaeogeographical reconstructions for several time slices can be produced with relatively little effort and time using repeated semi-automated computing. As stated above, besides the quality of input data, the fidelity of the reconstructions depends on the logic of the modelling methods – how the available sedimentary, hydrological, topographical or other data is used for DEM manipulations or shore level corrections or modelling sedimentary processes. However, in each case, exceptions exist whereby an expert scientific assessment is necessary due to the lack or qualitative nature of the data or other reasons making it unsuitable for mathematical operations. This was the case when correcting palaeoshoreline positions by means of topographical, aerial and geological maps, when the exact thicknesses and deposition times of sediments and the formation of river valleys were ambiguous in the Narva-Luga study area (Paper I) and when tracking the backshore limit of Ruhnu Island in locations where the foredunes were re-worked (Paper IV). Questions remain about the landscapes preceding major transgressions, which erode and deposit sediments, as relevant to the case of reconstructing Narva-Luga Klint Bay during its initial settlement at c. 8500–8000 years ago (Fig. 5a). In these cases, DEM-based modelling provided only the starting point for further manual editing. The further development of the palaeogeographical methods presented in this thesis should be towards dynamic models of shore displacement and landscape evolution as well as improvement of the techniques for deposition-erosion modelling, automated identification of the landscape settings with high probability for prehistoric settlement, and attractive (3D) visualization.

5. CONCLUSIONS

The reconstructed shore displacement and palaeogeographies provided new insight into the development of Baltic Sea shores and the natural environment of the Stone Age settlements in Narva-Luga Klint Bay, in Tallinn City centre and on Ruhnu Island. For the first time for these areas, integrated proxies and methods of geosciences and GIS were used to test ideas raised from archaeological data and interpretations about the study areas. The results led to the following main conclusions.

- The palaeogeographical reconstructions, generated by compilation of relative sea level, land surface elevation, sedimentological and archaeological datasets and spatio-temporal modelling of coastal changes, improved the interpretation of Stone Age settlement pattern. GIS-based methods made it possible to model shoreline positions corresponding to the time of the existence of any settlement. The results confirm the shore-connected lifestyle and abundant coastal settlement of hunter-fisher-gatherers since c. 7.2 cal. ka BP as well as the disappearance of settlements from the sea-shores since c. 4.7 cal. ka BP in Estonia and adjoining areas.
- For Narva-Luga Klint Bay, the palaeogeographical reconstructions show that the oldest known traces of human activity, dated to 8.5–7.9 cal. ka BP, were associated with riverbanks in the period of low water level at the beginning of the Litorina Sea transgression. As seen from the shoreline modelling, abundant Stone Age settlement, represented by sites with ages from c. 7.1 to c. 5.0 cal. ka BP, was located on the shores of Litorina Sea lagoon. Coinciding with the time of the overgrowing of the lagoon, the change from hunter-fisher-gatherer economy towards farming induced the transformation from coastal settlement back to river settlement at c. 5.0–4.5 cal. ka BP in this area.
- In Tallinn city centre, the palaeogeographical reconstructions showed that the area emerged from the Litorina Sea at about 5.8 cal. ka BP, and the Neolithic seal hunter's camp, presently c. 16 m a.s.l. and under urban deposits 2.5 m thick on Vabaduse Square, was established on a gently sloping sandy beach of the large Tallinn palaeo-bay at around 5.1–4.8 cal. ka BP. In comparison to previous archaeological studies, this kind of setting is rare in eastern Baltic Sea region and thus the results expand the knowledge about Neolithic coastal settlement in this region.
- The palaeogeographical reconstructions of Ruhnu Island show that seal hunters inhabited the coastal zone of the island during the two phases of Late Mesolithic habitation at about 7.2 cal. ka BP and 6.2 cal. ka BP. At that time, the Litorina Sea shore of Saaremaa Island, where the settlers probably originated, was located c. 70 km northeast. Compared to other study areas and previous studies, these camps on the remote islet were established higher above their coeval sea level (4 m a.s.l.) than similar settlements on more

protected coasts. Reconstruction of the time c. 4.7 cal. ka BP confirms that Late Neolithic settlement was founded in the centre of the island, hundreds of metres away from the shore, indicating a shift in subsistence strategy.

- Elevation data from different sources and of different precision enabled different relief modelling approaches. High-resolution LiDAR data enabled detection and delineation of landforms indicating palaeoshorelines and modelling of coastal progradation based on morphology. Detailed elevation data from archaeological excavations made it possible to reconstruct micro-topography of the Stone Age site and assess previously unapplied variables like beach sloping and swash limit. Under the DEM-based methods, complications appeared when reconstructing landscapes and landforms preceding deposition or erosion events.
- The palaeogeographical methods advanced in this study, together with the new knowledge about Stone Age settlement preferences gained from the palaeogeographical reconstructions of the study areas provide better prediction of possible undiscovered settlement sites based on similarities in palaeolandscape.

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SUMMARY IN ESTONIAN

Eesti ja lähinaabruse kiviaegsete rannikualade geoinfosüsteemipõhised paleogeograafilised rekonstruktsioonid

Läänemere nõos on pärast mandrijää taandumist liustiku sulavete ülespaisutamiste ja mahajooksude ning piirkonna glatsiaal-isostaalilise maatõusu ja kerkiva maailmameretaseme tõttu aset leidnud märkimisväärsed veetasememuutused (joonised 1 ja 2), mis on kujundanud rannikumaastikke. Eestist ja lähialadelt on teada rohkesti kiviaegseid asulapaiku, mis viitavad rannasidusale elatusviisile, kuid asuvad tänapäeval merest kaugel.

Selleks, et paremini interpreteerida arheoloogilisi leide ja mõista varase inimasustuse ajalis-ruumilist paiknemist, on oluline teada seda asustust ümbritsenud looduskeskkonda. Käesoleva väitekirja eesmärgiks on rekonstrueerida kiviaegse rannasidusa asustuse seisukohast oluliste piirkondade paleogeograafia ja Läänemere veetaseme muutused Eestis ja lähinaabruses, kasutades geoinfosüsteemidel (GIS) põhinevaid lahendusi andmete analüüsiks ja maastike arengu modelleerimiseks. Uuritud aladeks (joonis 3) olid Narva-Lauga klindilaht (Rosentau et al., 2013 – Artikkel I), Tallinna kesklinn ja Vabaduse väljak (Muru et al., trükis – Artikkel II) ning Ruhnu saar (Preusser et al., 2014 – Artikkel III; Muru et al., käsikiri – Artikkel IV). Väitekirja ja selle tulemused annavad panuse Läänemere regiooni idaosa kiviaja asustust ja rannikualade muutuseid käsitlevatesse uurimisprojektidesse ETF 7294, 9011 ja PUT 456.

Jääajajärgse maatõusu intensiivsuse erinevuste tõttu asuvad kiviaja asulakohad sõltuvalt piirkonnast ja asustuse vanusest erinevatel absoluutkõrgustel, mistõttu on paleorannavööndite modelleerimiseks vajalik teada piirkonnas aset leidnud aastatuhandetetaguseid veetasememuutusi. Töö üheks eesmärgiks oli rekonstrueerida veetasememuutused eraldi iga uurimisala jaoks. Selleks dateeriti setteläbilõikeid ning kasutati varemavaldatud dateeringuid (Artikkel I; Artikkel II). Setete ja arheoloogilise materjali dateerimisel kasutati radioaktiivse süsiniku meetodit, rannikuluidete puhul luminescentsmeetodit (Artikkel III). Paleogeograafiliste rekonstruktsioonide teiseks oluliseks sisendiks oli digitaalne maapinna kõrgusmudel (DEM), mille loomiseks kasutati Narva-Lauga uuringualal 20. saj. I poolest pärinevatelt topograafilistelt kaartidelt digitaliseeritud kõrgusinfot, Tallinna kesklinna puhul geoloogiliste ja arheoloogiliste uuringute infot kultuurkihi aluspinna kõrguste kohta ja Ruhnu saarel aero-LiDAR-mõõdistuse andmeid. Koostatud veetaseme muutuste kõverate ja paleoveepindade juhttasemete (mis põhinevad Antsülusjärve ja Litoriinamere kõrgeimate veetasemete rannamoodustiste ning 20. saj. merevaatlusjaamade andmetel) alusel modelleeriti kiviaja asulakohtade vanustele vastavad paleoveepinnad. DEM-i ja paleoveepindade rasterarvutuste tulemusena rekonstrueeriti kiviaja rannajooned ja paleomaapinna kõrgused. Vaadeldavast ajahetkest hiljem aset leidnud erosiooni ja akumulatsiooniga piirkondades korrigeeriti modelleeritud rannajoone

asukohta geoloogiliste ja topograafiliste kaartide, setteläbilõigete ning reljeefi morfoloogia alusel.

Käesolevas töös valminud paleogeograafilised rekonstruktsioonid on nende piirkondade kohta esimesed, kus on kasutatud geoloogilistele ja geomorfoloogilistele andmetele tuginevat geoinfosüsteemipõhist modelleerimist selleks, et testida arheoloogilistest uuringutest tulenevaid järeldusi.

Narva-Lauga klindilahe paleogeograafiliste rekonstruktsioonide (joonis 5; Artikkel I) põhjal järeldati, et esmane teadaolev inimtegevus selles piirkonnas 8500–7900 aastat tagasi langeb perioodi, mil meretase oli sarnane tänapäevasele (joonis 4) ja tollane asustus oli seotud Narva jõe kallastega. Litoriinamere veetaseme tõustes kujunes klindilahes laguun, mille kaldail oli rannasidus küttide-kalurite-korilaste asustus alates u. 7100 a.t. kuni laguuni kinnikasvamiseni u. 5000 a.t. Seejärel kujunes merest kerkinud klindilahe alale taas jõgedega seotud asustus, mille algus langeb ajaliselt kokku Neoliitilise põllumajanduse ja loomakasvatuse intensiivistumisega Läänemere regiooni idaosas. Narva-Lauga piirkonna uurimistulemused kinnitavad varasemaid arheoloogilisel leiumaterjalil põhinevaid interpretatsioone kiviaja inimese elupaigaeelistuste kohta ning täpsustavad rannasidusa elatusviisi ajavahemikku.

Tallinna kesklinna ala paleogeograafilised rekonstruktsioonid näitavad, et tänase Vabaduse väljaku alt välja kaevatud küttide-kalurite-korilaste asula rajati u. 5100–4800 a.t. toona sinnani ulatunud lahe rannale, u. 100 m kaugusele ja 2,5 m kõrgusele veepiirist (joonis 7; Artikkel II). Detailse paleoreljeefi rekonstruktsiooni ja setteläbilõike andmete alusel järeldati, et asula paiknes liivasel rannanõlval vahetult lainete ulatuse piirist kõrgemal. Läänemere idaosa kiviaja rannasidusate asulakohtade kontekstis on selline paiknemine avatud lahe rannal suhteliselt haruldane.

Ruhnu saare paleogeograafilised rekonstruktsioonid tõestavad, et esimesed inimasulad, mis on raadiosüsinik-dateeritud u. 7200 a. vanuseks ja viitavad hülgeküttimisele, rajati seal Litoriinamere rannavööndisse u. 4 m kõrgusele tolleaegsest meretasemest (joonis 9; Artikkel IV). Sarnast paiknemist paleomeretaseme suhtes, kuid madalamatel absoluutkõrgustel, näitas ka Ruhnu järgmine asustusjärk ajast 6200 a.t. Võrreldes teiste selle perioodi rannikuasulatega Eestis, paiknevad Ruhnu asulad paleoveetaseme suhtes mõnevõrra kõrgemal, kuid reljeefianalüüsi ja paleorekonstruktsioonide järgi siiski tollase ranna vahetus läheduses. Ligikaudu 4700 a.t. rajatud asula paikneb aga paleorekonstruktsiooni kohaselt saare keskosas, rannast eemal ja 8 m veetasemest kõrgemal, viidates elatusviisi muutusele.

Koostatud rekonstruktsioonid kinnitavad, et rannasidusa asustusjärgu ajal hilis-mesoliitikumist kesk-neoliitikumini rajati asulad rannajoonele nii lähedale kui võimalik, arvestades ranna ja veekogu tüüpi ning sellest tulenevaid isearasusi nagu lainete ulatus jms. Kõigi kolme uuringuala tulemused kinnitavad Eesti ja lähinaabruse kiviaegse asustusmustril olulist muutumist alates u. 4700 a.t., mil elupaigaks hakati valima merest kaugemaid piirkondi seoses nõorkeraamika kultuuri leviku ning üleminekuga küttimisele-korilusele baseeruvale elatusviisilt põlluharimisele ja loomakasvatusele.

Geoinfosüsteemipõhiste meetodite ja detailsete veetasememuutuste andmete kasutamine ning ajalis-ruumiline interpoleerimine võimaldas rekonstrueerida eraldi iga leiukoha dateeringule vastava rannajoone, mistõttu sai võrreldes varasemate teadmistega täpsustada kiviaegsete rannasidusate asualade paiknemist. Erineva täpsusastme ja detailsusega kõrgusandmed tingisid erineva lähenemise reljefianalüüsile iga uuringuala puhul. LiDAR-andmestik võimaldas rannikulitestiku morfoloogia alusel modelleerida rannavööndi arengut Ruhnu saarel ja hinnata paleorandade ulatust (Artikkel IV). Arheoloogilistest kaevamistest pärinev detailne mõõdistusandmestik võimaldas rekonstrueerida kiviaegse laagripaiga mikroreljeefi ja hinnata näitajaid nagu nõlvakalle või kaugus veepiirist (Artikkel II). Rekonstruktsioonide usaldusväärsus on suurem piirkondades, kus ei ole toimunud hilisemat setete kuhjumist (nt. raba või luidete moodustumise läbi) ega ärakannet (nt. ranniku- või jõgede erosiooni tõttu).

Narva-Lauga klindilahe, Tallinna kesklinna ja Ruhnu saare uurimistöodes arendatud paleogeograafilise modelleerimise meetodika ja saadud tulemused ning nende põhjal tehtud järeldused aitavad paremini mõista Läänemere idaosa kiviaegset asustustrit seoses rannikualade maastike muutustega ja prognoosida võimalike senileidmata asulakohtade paiknemist.

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PUBLICATIONS

CURRICULUM VITAE

Name: Merle Muru
Date of birth: April 5 1983
Citizenship: Estonian
Address: Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, 46 Vanemuise St, 51014, Tartu, Estonia
E-mail: merle.muru@ut.ee

Education:

2007–2017 doctoral studies in geoinformatics, University of Tartu¹
2001–2007 BSc in geoinformatics and cartography, University of Tartu
1998–2001 Tallinn Secondary School of Science, golden medal
1989–1998 Saku Gymnasium

Professional employment:

2013–... specialist in geoinformatics, University of Tartu, department of geography
2005–2012 cartographer, Hendrikson & Ko
2004 surveyor, Estonian Agricultural Registers and Information Board
2003 interviewer, Tartu city government / University of Tartu

Additional education:

2016 e-course „Programmeerimisest maalähedaselt“, University of Tartu, institute of computer science
2016 summer school „Natural resources management: from data processing to web publishing“, International Society for Photogrammetry and Remote Sensing
2015 course „Paleokliima: meetodid ja interpretatsioonid“, University of Tartu, department of geology
2015 course „Kvaternaarisetete dateerimismetodid ja nende rakendamine“, University of Tartu, department of geology
2014 course „3D modelleerimine geoloogias“, University of Tartu, department of geology
2013 professional training in luminescence dating laboratory at Stockholm University
2012 course „Quaternary Stratigraphy and Dating Methods“, Stockholm University
2011 course „Läänemere paleorannajoonte modelleerimine“, University of Tartu, department of geology

¹ incl. 24.12.2007–24.12.2010 maternity leave

Research interests:

palaeogeography, palaeoenvironment, relief analysis, geoinformatics

Scientific publications:

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Other scientific activities:

- 2012–... instruction of practical trainings at courses “Re-cultivation of mining areas” and “Natural resources and mining technologies”, University of Tartu, department of geology
- 2017 development of e-course “Geoinfosüsteemid maavara varude arvutustes”, University of Tartu, department of geology
- 2016 exhibition “Viikingiaja aarded Eestist”. Reconstruction of Viking Age palaeoshoreline of North-Estonia. Estonian Maritime Museum.
- 2016 permanent exhibition “Kohtumised”. Modelling of Stone Age coastal areas of Estonia. Estonian National Museum.
- 2015–2016 applied research “Flooding maps of inland waterbodies of Estonia” for Estonian Insurance Association
- 2015 applied research “Assessment of climate change impacts and elaboration adaption instruments in the field of planning, land use, health and rescue management” for Estonian Ministry of the Environment.
- 2013 short course “LIDAR-based palaeogeographic reconstructions of the Baltic Sea”, University of Tartu, department of geology, an organizer
- 2012 exhibition. Modelling and animation of palaeotopography of Tallinn city centre. Tallinn City Museum
- 2012 training school “Palaeo-coastlines of the Baltic Sea and Stone Age coastal settlements”, COST Action TD0902, Pärnu-Riga-Klaipeda, an organizer
- 2012 exhibition. Maps of post-glacial development of Pärnu region. Pärnu Museum.

Awards and scholarships:

- 2015 Lev Vassiljev memorial scholarship, University of Tartu Foundation
- 2013 Short Term Scientific Mission grant, COST Action TD0902
- 2012, 2013, 2015 travel grant, Doctoral School of Earth Sciences and Ecology
- 2011, 2012, 2013, 2014 scholarship, ESF DoRa T8

ELULOOKIRJELDUS

Nimi: Merle Muru
Sünniaeg: 5. aprill 1983
Kodakondsus: Eesti
Aadress: Geograafia osakond, Ökoloogia ja Maateaduste Instituut, Tartu Ülikool, Vanemuise 46, 51014, Tartu
E-post: merle.muru@ut.ee

Haridus:
2007–2017 doktorantuur geoinformaatika erialal, Tartu Ülikool¹
2001–2007 BSc geoinformaatika ja kartograafia erialal, Tartu Ülikool
1998–2001 Tallinna Reaalkool, kuldmedal
1989–1998 Saku Gümnaasium

Teenistuskäik:
2013–... geoinformaatika spetsialist, TÜ ÖMI geograafia osakond
2005–2012 kartograaf, OÜ Hendrikson & Ko
2004 põllumassiivide hindaja ja mõõdistaja, Põllumajanduse Registrate ja Informatsiooni Amet
2003 küsitleja, Tartu Linnavalitsus / TÜ geograafia instituut

Erialane täiendõpe:
2016 e-kursus „Programmeerimisest maalähedaselt“, TÜ arvutiteaduse instituut
2016 suveülikool „Natural Resources management: From data processing to web publishing“ Rahvusvaheline Fotogrammeetria ja Kaugseire Ühing
2015 kursus „Paleokliima: meetodid ja interpretatsioonid“, TÜ geoloogia osakond
2015 kursus „Kvaternaarisetete dateerimismeetodid ja nende rakendamine“, TÜ geoloogia osakond
2014 kursus „3D modelleerimine geoloogias“, TÜ geoloogia osakond
2013 enesetäiendus Stockholmi Ülikooli luminestantsdateerimise laboris
2012 kursus „Quaternary Stratigraphy and Dating Methods“, Stockholmi Ülikool
2011 kursus doktorantidele „Läänemere paleorannajoonte modelleerimine“, TÜ geoloogia osakond

¹ sh 24.12.2007–24.12.2010 akadeemilisel puhkusel lapse hooldamiseks

Uurimisvaldkond:

paleogeograafia, paleokeskkond, reljeefianalüüs, geoinformaatika

Teaduspublikatsioonid:

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Muu erialane tegevus:

- 2012-... praktikumide juhendamine ainetes „Kaevandusalade rekultiveerimine“ ja „Maavarad ja kaevandustehnoloogiad“, TÜ geoloogia osakond
- 2017 e-kursuse „Geoinfosüsteemid maavara varude arvutustes“ loomine ja läbiviimine, TÜ geoloogia osakond
- 2016 näitus „Viikingiaja aarded Eestist“. Põhja-Eesti viikingiaegse rannajoone rekonstruktsioon. Eesti Meremuuseum.
- 2016 püsinäitus „Kohtumised“. Eesti kiviaegsete rannikualade modelleerimine, Eesti Rahva Muuseum.
- 2015–2016 rakendusuuringu „Eesti siseveekogude üleujutuskaartide koostamine“, Eesti Kindlustusseltside Liit, üks koostajatest
- 2015 rakendusuuringu „Kliimamuutuste mõjude hindamine ja kohanemismeetmete väljatöötamine planeeringute, maakasutuse, inimestervise ja päästevõimekuse teemas“, üks koostajatest
- 2013 lühikursus „LIDAR-based palaeogeographic reconstructions of the Baltic Sea“, TÜ geoloogia osakond, üks korraldajatest
- 2012 näitus, Tallinna kesklinna paleoreljeefi modelleerimine ja animatsioon, Tallinna Linnamuuseum
- 2012 koolitus „Palaeo-coastlines of the Baltic Sea and Stone Age coastal settlements“, COST Action TD0902, Pärnu-Riia-Klaipeda, üks korraldajatest
- 2012 näitus, Pärnu ümbruse maismaa jääaja järgset arengut kujutavate kaartide koostamise, Pärnu Muuseum.

Uurimistoetused ja stipendiumid:

- 2015 Lev Vassiljevi mälestusstipendium, Tartu Ülikooli sihtasutus
- 2013 Short Term Scientific Mission grant, COST Action TD0902
- 2012, 2013, 2015 välisvisiidi toetus, Maateaduste ja ökoloogia doktorikool
- 2011, 2012, 2013, 2014 stipendium, ESF DoRa T8

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