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Rock head elevation model of northern Estonia

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Abstract. The last rock head elevation model covering the whole of Estonia was compiled about 40 years ago. This model relied on data from 2500 boreholes and excavations and geophysical data. Using the freely accessible present information about more than 34 640 borehole datapoints from the carbonate area, we updated the 40-year-old model. The Devonian sandstone area was disregarded in this work as it needs a different approach of interpolation due to a considerably lower data density and a different behaviour of erosional processes. During this work, the data were filtered for identifying errors and the filtered dataset was interpolated numerous times using the Topo to Raster and Spline methods available in ArcGIS software. The results were compared statistically and by employing the available rock head elevation models. The results from the Topo to Raster method proved to be superior in the correlance next to the partially mapped 1:50 000 rock head elevation model, and the best-suited model was applied to the outcrop area of carbonate rocks in Estonia. Compared to the last rock head elevation model, the new one describes the carbonate bedrock topography in much more detail. It does not match the 1:50 000 scale geological map in all places, possibly due to a much more detailed data set but also because of the errors that may have passed the filtering process during the early stages of work. The rock head elevation model is an important part of GIS-based geological mapping and one of the first steps in producing 3D geological models.

Key words: rock head elevation, stratigraphy, Estonia, 3D modelling.

INTRODUCTION

The latest complete rock head elevation (RHE) model of Estonia was published in the early 1980s (Tavast & Raukas 1982). The same model was addressed at the end of the 1990s by Rõõmusoks et al. (1997) using the same data set. Additionally, a partial RHE model was produced in the course of geological mapping at a 1:50 000 scale carried out in northern Estonia (EGS 2018).

The old complete RHE model was based on only a limited number of core sections although their total number was already reaching tens of thousands. As the location of old boreholes has been justified and much of old data made available, the accuracy of the data has improved since 1990. This fact necessitated the elaboration of a new RHE model that could substantially improve our knowledge about bedrock geology, create a better understanding of the landscape history and support the ongoing geological mapping carried out by the Estonian Geological Survey.

This paper presents an analysis of the new RHE model in the carbonate outcrop area of Estonia using data from public databases and publications. The study is limited to the outcrop area of the Ordovician and Silurian carbonate rocks because South Estonia with relatively poor data coverage and commonly crossing valleys requires a different methodological approach.

PREVIOUS WORK

The development of the RHE model of Estonia was summarized by Tavast (1994). Schmidt (1854, 1865) was the first to describe the cuesta-like topography of the bedrock surface in Estonia. The first schemes of the bedrock topography in the North Estonian denudation area and Middle and Upper Devonian uplands were published by Tammekann (1928). Later he added the depressions of the Gulf of Finland, Gulf of Riga, Lake Peipsi and Lake Võrtsjärv, and the North Estonian Klint and Middle Estonian Plain (Tammekann 1949). His study was continued by Orviku (1955). The establishment of the Geological Survey in 1957 initiated the medium-scale geological mapping. A map of bedrock topography with 20 m isolines was created by Kajak (1966, 1970). He distinguished some smaller topographic forms like the Ahtme Upland and the Luuga–Narva and Ojamaa lowland areas. A bedrock topography map with 10 m isolines was published by Raukas et al. (1971). Data from older maps, 2500 boreholes and excavations and geophysical investigations were used for compiling the bedrock elevation map with 10 m isolines to the set of complementary maps of the geological map of Estonia at a scale of 1:200 000 (Tavast 1978), with a number of newly defined positive and negative landforms.

The investigation of the Baltic Sea floor was started by Sviridov et al. (1976) and continued by Amantov et al. (1988). The structure of the depression of Lake Peipsi was studied by Rähni & Tavast (1981) and of the Gulf of Finland by Tavast & Amantov (1992). The latest studies of bedrock geology of Lake Peipsi, which added resolution to the bedrock topography model, were carried out by Miidel et al. (2001).

The bedrock elevation map is one of the standard layers of geological maps of 1:50 000 scale. This map is at present covering North Estonia and also small isolated areas in other parts of the country. No attempts have been made up to now to integrate all available data from the sources listed above. The latest comprehensive bedrock topographic model was created in 1982 (Tavast & Raukas 1982), and thus it is almost 40 years old.

GEOLOGICAL BACKGROUND

Estonia is located on the southern slope of the Fennoscandian Shield. The crystalline basement is covered by the latest Proterozoic to early–middle Palaeozoic sedimentary rocks. In northern Estonia, the thickness of the sedimentary cover reaches about 100 m and increases to more than 800 m in southeastern Estonia (Puura & Vaher 1997). The initial thickness of the sedimentary cover was likely higher (Kirsimäe et al. 1999) but the rocks were later subjected to extensive erosion. The resulting bedrock topography displays cores of several uplands that can be observed in modern topography, and the depressions of lakes Peipsi and Võrtsjärv and the Gulf of Finland (Tavast 1997). The erosion of sedimentary bedrock in the course of the Quaternary shaped the modern topography of the bedrock by removing up to 60 m from its surface (Tavast 1997).

ANCIENT VALLEYS CARVED BY GLACIERS

The greatest challenge in this field is reconstructing ancient valleys. Most of these valleys represent ancient river beds which were further eroded by glaciers and their meltwaters and were subsequently filled with sediments that can vary in composition and morphology (Raukas & Kajak 1997).

The mapping of buried valleys usually consists in research into their age and interactions, and modelling of the slopes and bases of the valleys. The knowledge about the relative ages of valleys is more certain in the case of crossing valleys. In North Estonia, the valleys are usually not crossing, which makes the determination of their age more difficult and less feasible. In this case, the modelling of valleys includes investigating the modern digital elevation model (DEM; ELB 2019), borehole data (ELB 2017), outcrop belts of the formations in a 1:400 000 geological map (EGS 2018) and literature data about the previously identified buried valleys (Tavast & Raukas 1982). Some buried valleys are also shown in the 1:50 000 and 1:400 000 geological maps.

MATERIAL AND METHODS

The present study is based on the following sources:

- drill core data in the borehole database of the Estonian Land Board (ELB 2017);
- well database at the Environment Agency of Estonia (VEKA);
- published data (Tavast & Raukas 1982; Miidel et al. 2001);
- Estonian Geological Base Map (1:400 000 and 1:50 000; EGS 2018).

The RHE model was generated with ArcGIS software using the Topo to Raster interpolation method. The first part of data, 13 103 localities describing carbonate RHE under Estonian soil, came from the borehole database of the Estonian Land Board. Additional 21 537 data points were filtered from the VEKA database. As the VEKA database has no dedicated row for RHE, this information was extracted using a Python script that identified the upper boundary of the uppermost bedrock unit and validated the obtained depth value, comparing it with the available RHE data within a buffer zone of 100 m. Altogether 34 640 data points describing RHE of the carbonate area were used (see the supplementary materials at https://doi.org/10.15152/GEO.489).

Additional data from bedrock elevation mapping within the depression of Lake Peipsi (Miidel et al. 2001) were used to get more accurate results in the eastern part of the region. Devonian outcrop areas were excluded from the study due to the scarcity of data. Future interpolation of this region requires a different approach and the results would be of lower accuracy.

Some controversial data were also discovered in the transition zone between the Devonian sandstones and the Ordovician–Silurian carbonate rocks. Judging from the 1:400 000 geological base map and the core documentation, 65 drill cores located in the outcrop area of carbonates penetrated the Devonian sandstones in the uppermost part of the succession (and 398 drill cores in the Devonian outcrop area hit the carbonates first). This might be due to small isolated outliers that are not mapped or incorrect coordinates of the respective sections. In some cases the anomalous data points were located up to 20 km off the main distribution area of the respective rocks. The overwhelming majority of data points with anomalous rock placement (54 of 65) originated from the VEKA database. Such data points were not used for modelling.

The density of data points in Estonia is the highest (Fig. 1) within the outcrop area of carbonate rocks. In some areas a more complicated approach than just interpolation is still needed to reveal the extent of buried valleys. Although the borehole density is mostly more than adequate for geological modelling, the data point density is strongly influenced by wetlands. The wetlands created large gaps in the mapping grid that lowered the reliability of the RHE model in these areas.

Occasionally the borehole coordinates may have uncertainty that is bigger than the grid value of the interpolated RHE model. To reduce the effect of this issue, the altitude values of all data points were analysed next to the maximum and minimum of the altitude values in the standard 20 m grid size DEM (ELB 2019) within the buffer area of 100 m. If the altitude of a data point deviated more than a metre from the values within the buffer zone, the point was discarded. Altogether 26 222 out of 34 630 data points passed this filter. Filtering the raw data was aimed at improving the reliability of the generated RHE model. The distribution and density of data points are illustrated in Fig. 1.

The greatest challenge was interpreting carved valleys which are abundant on glacially eroded rock head. The interpolation algorithm chosen for this purpose had to be able to generate continuous and reliable surfaces in areas where the data points are of low density. According to Bergonse & Reis (2015), only two interpolation algorithms can successfully interpret partial data where some extrapolation is needed. These are the Spline and Topo to Raster methods. The Topo to Raster approach is based on the ANUDEM algorithm (Hutchinson 1989) and is a more complex method of creating a hydrologically correct

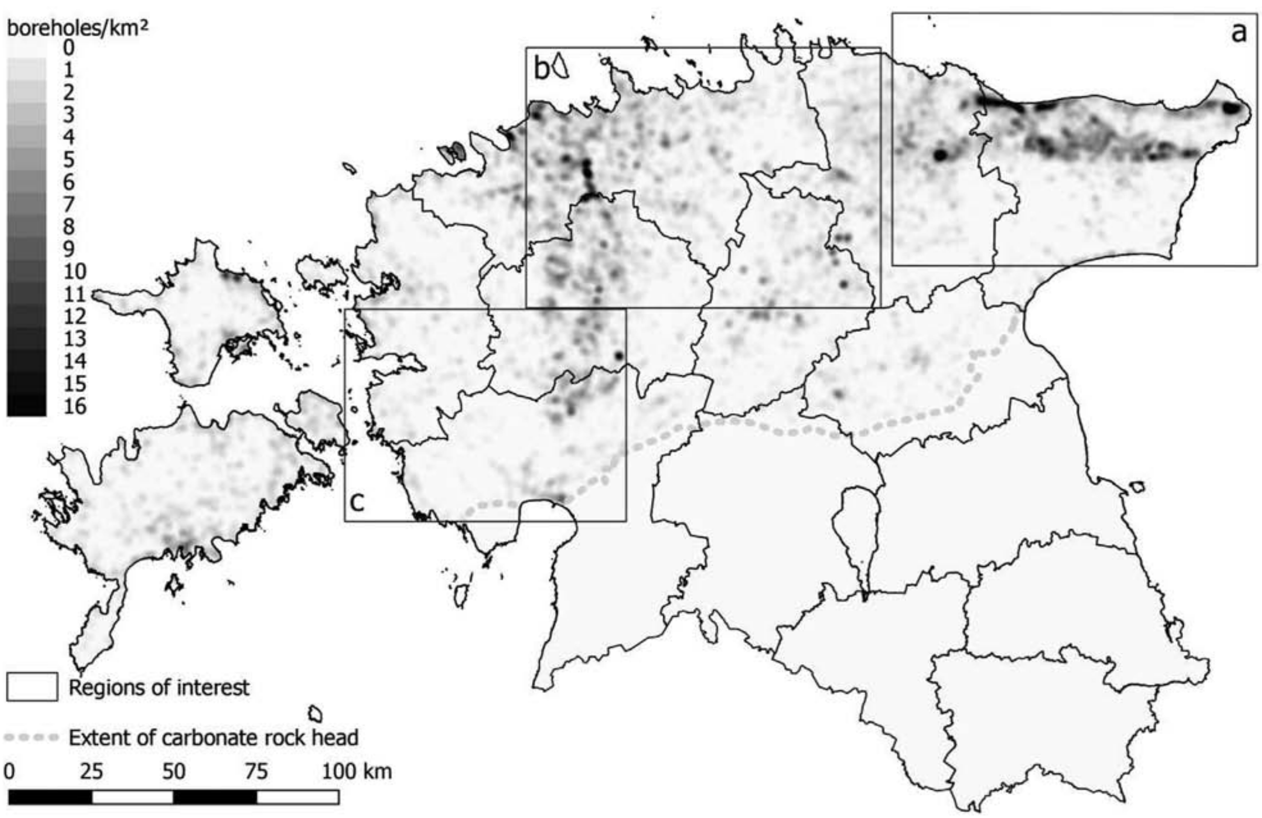


Fig. 1. The area of carbonate rock head and the density of the available borehole data averaged to 2 km^2. Areas a, b and c (respectively Figs 8, 9 and 10) show specific locations of comparisons visualizing the similarities of the model in different areas next to Estonian Land Board data about buried valleys.

DEM, which makes it more suitable for simulating glacially eroded strata and creating concave shapes of the valleys. As the outcome depends largely on the interpolation method and its parameters, a quantitative study based on special script was performed to find the best suitable interpolation parameters. This script compared the interpolated surface to the 1:50 000 bedrock topography map layer (Fig. 2) where this information is available for North Estonia. Altogether 6437 Topo to Raster interpolated surfaces were generated during this process and statistical fitting analysis was performed. In parallel, 126 interpolations using the Spline method were generated, with variable weight value changes on the logarithmic scale and using both Regularized and Tension based algorithms. The results of the standard deviations between different models generated using different parameters stayed between 3.2 and 3.8 for the Topo to Raster method (Fig. 3) and 7.16 and 37.8 for the Spline method (Fig. 4). Of numerous generated models with standard deviation up to 3.2, the lowest values were based on Iterations = 4, Margin = 1 and Roughness penalty = 1. Enforcing the sink parameter did not affect the results. The value of iterations has certain effect on the number of sinks in the interpolated raster image and needs to be greater than or equal to zero. The iterations value is 20 by default and higher values are used to clear more sinks and to generate more ridges and streams to output. The margin value determines the distance of interpolating beyond the specified extent of output and is 20 by default. The roughness penalty value needs to be greater than or equal to zero, being determined as an integrated squared second derivative. Normally its values over 0.5 are not recommended, although our best results had this value between 0.5 and 1.

The enforce parameter is used to define drainage enforcement. It can be set to remove all sinks or depressions and create hydrologically sound surface models. The value of ‘enforce’ attempts to remove all sinks, ‘no enforce’ leaves the sinks unfilled and ‘enforce_with_sink’ does not alter the depressions existing in the input data but this is useful only if dedicated input data do exist. The generated RHE models have 100 m raster resolution, which does not allow visualizing steep slopes. The resolution of 5 m would produce a 45 degree angle slope in case of 5 vertical metres

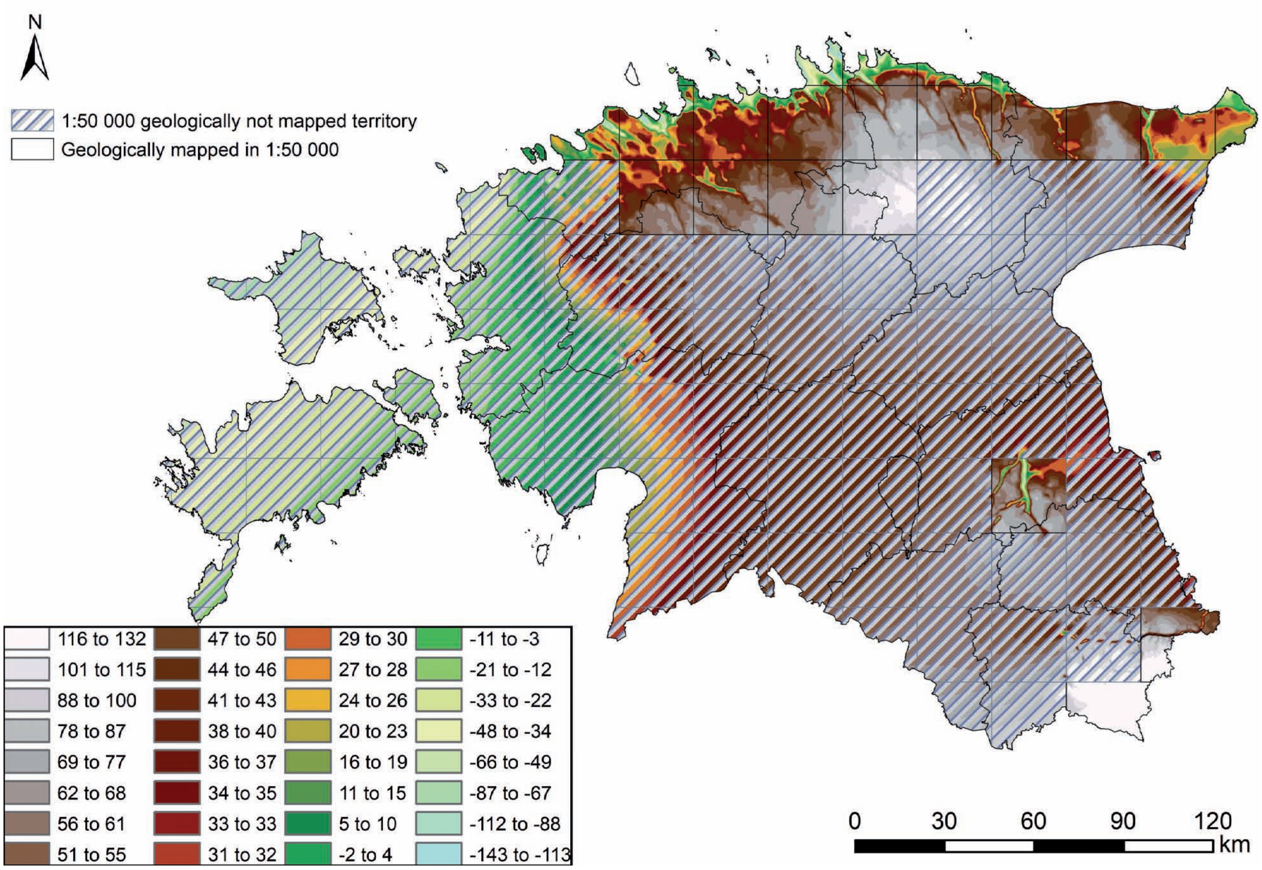


Fig. 2. The bedrock model of the geological map of Estonia (1:50 000) (EGS 2018) and the mapped area. Surface values are metres above sea level.

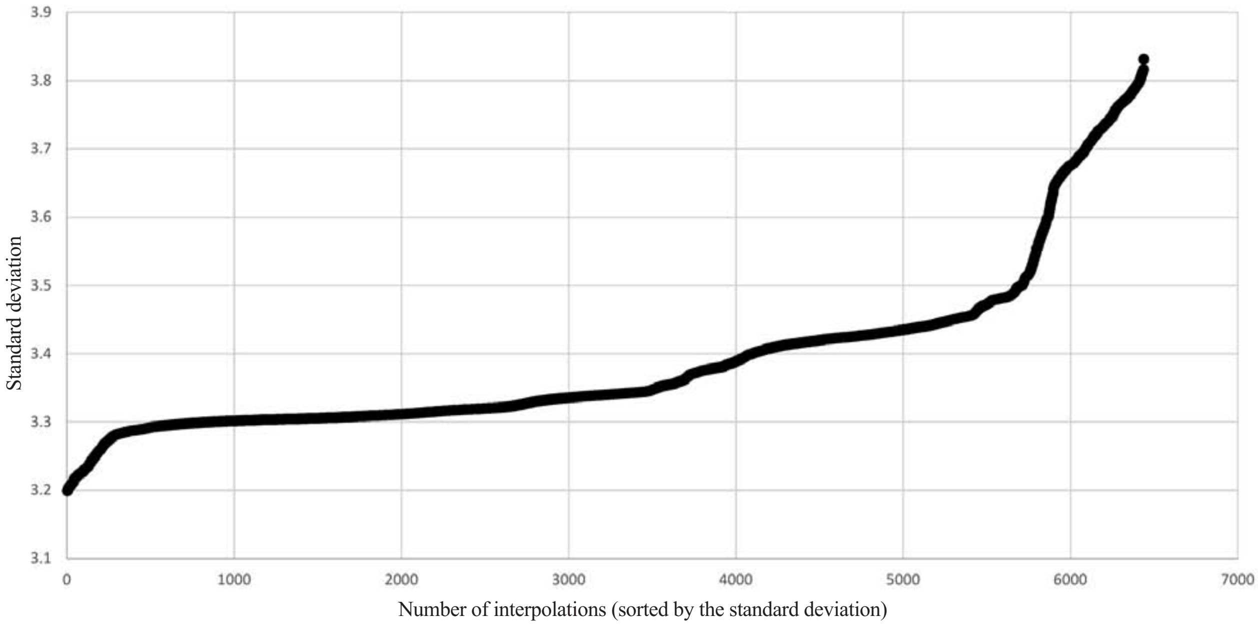


Fig. 3. The chart of standard deviation values of all the interpolated surfaces by the Topo to Raster method.

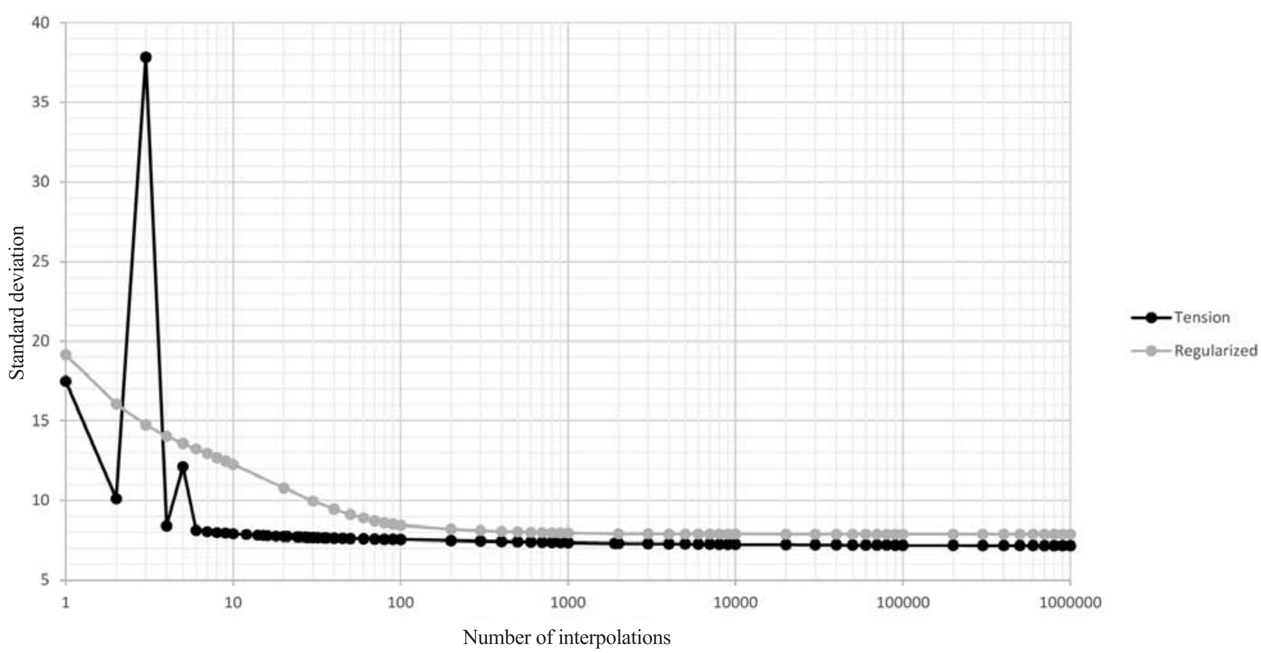
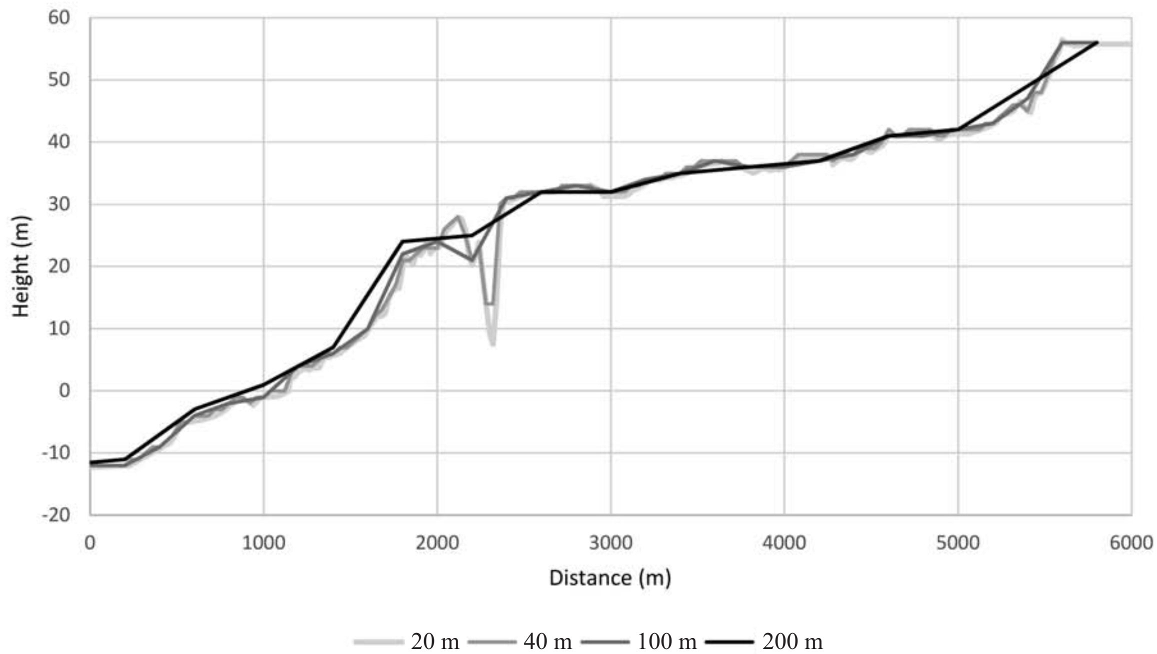


Fig. 4. The chart of standard deviation values of all the interpolated surfaces by the Spline method.

per 5 m horizontally. In order to obtain the same result using 100 m resolution, an altitude difference of 100 m for 100 m distance is needed for getting the same effect in a model. The steepest and highest slope in northern Estonia is the North Estonian Klint. Its effects in the digital terrain models of different resolution are demonstrated in Fig. 5. At 20 m resolution the escarpment produces angles up to 26 degrees but in the 100 m DEM the same altitude difference appears as a 2.5 degree angle. This points to a problem with interpreting buried valleys and other steep slopes found in the RHE model. Based on the working model, all the significant steep slopes must be derived from 2–3 degree angles. This also means that the interpretation made solely on a raster image may contain errors.

A



B

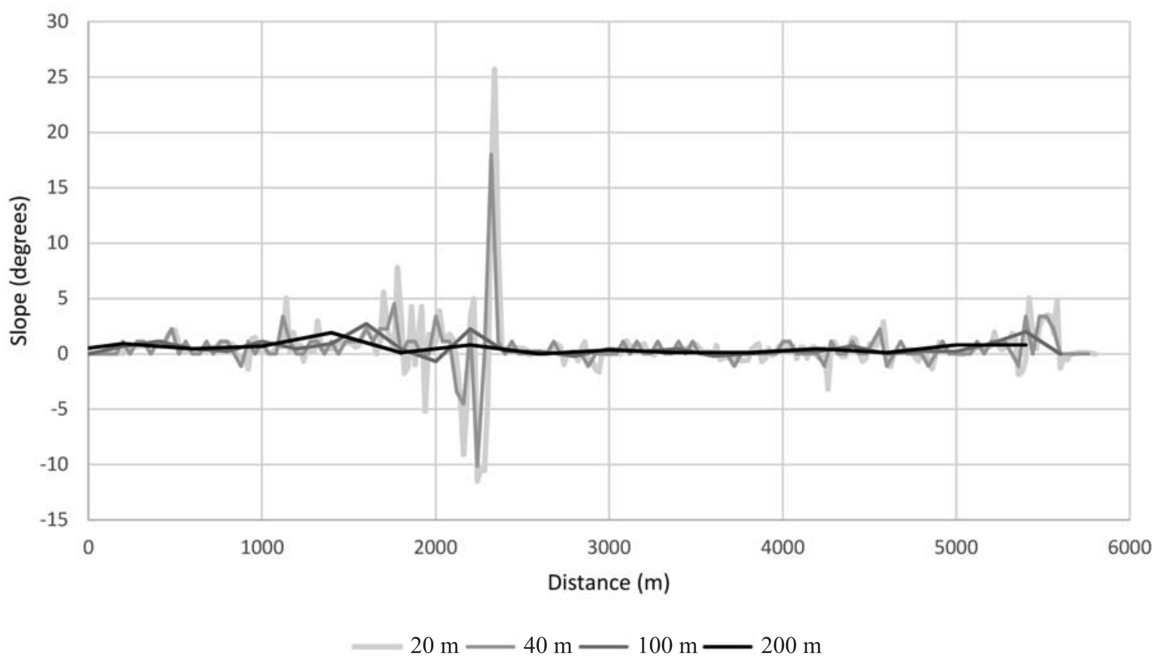


Fig. 5. A sample cross section based on the North Estonian Klint visualizing the loss of detail (**A**) and slope angles in degrees (**B**) at the resolutions of 20, 40, 100 and 200 m. At the resolution of 100 m in the new rock head elevation model, 2–3 degree angles mark steep slopes like the North Estonian Klint, buried valleys and uplifts.

The RHE model covering the entire northern Estonia benefits from the opportunity of comparing different versions of digitally created RHE models with the older partial models in the areas where such information is available. This is adding reliability to the RHE model in the areas of lower-density data coverage or the areas where different models are in conflict. The created RHE model is likely the best possible approximation to the real RHE morphology in the study area for the time being.

COMPARISON OF THE ROCK HEAD ELEVATION MODELS

As the pixel size of the new RHE model (Fig. 6; see also https://doi.org/10.15152/GEO.489) is 100 m, it is difficult to draw a completely new map of buried valleys but the RHE model can be compared with previous low-resolution models. The comparison with the geological map of a scale 1:50 000 (EGS 2018) is possible only within the area of coverage (Fig. 2). The second model (Fig. 7) is the old complete RHE model for the whole of Estonia (Tavast & Raukas 1982). It was created before digitalization and was influenced by the security requirements of the former USSR that forced lower accuracy of data.

The RHE model (Fig. 7) by Tavast & Raukas (1982) is a masterpiece of its era. Based on data from 2500 boreholes and geophysical data, it presents more or less accurately the principal geomorphological features in most regions. Although the geographical accuracy of the old model does not allow a one-to-one comparison, it is still reflecting the principal valley systems. While the old RHE model (Fig. 7) is originally presented as 20 m isolines, the accuracy and level of detail of the new RHE model (Fig. 6) are remarkably better. For this reason, the observed system of buried valleys of the Pandivere region in the new RHE model is different from the old one (Figs 6, 7). The level of detail in western Estonia, especially on the islands, is also much higher. In some parts, the older model is not entirely supported by the new model. An example is the valley beginning about 3 km north of Lehtse and ending in Kopli Bay (Fig. 7). The new model confirms that this valley reaches up to Kose only and displays also another meridionally oriented valley through Aegviidu (that would cross the Lehtse–Kopli buried valley of the old RHE model).

The primary data for generating this valley in the old model are not available. Some NNW–SEE trending buried valleys across the Pandivere upland are also not supported in the old RHE model.

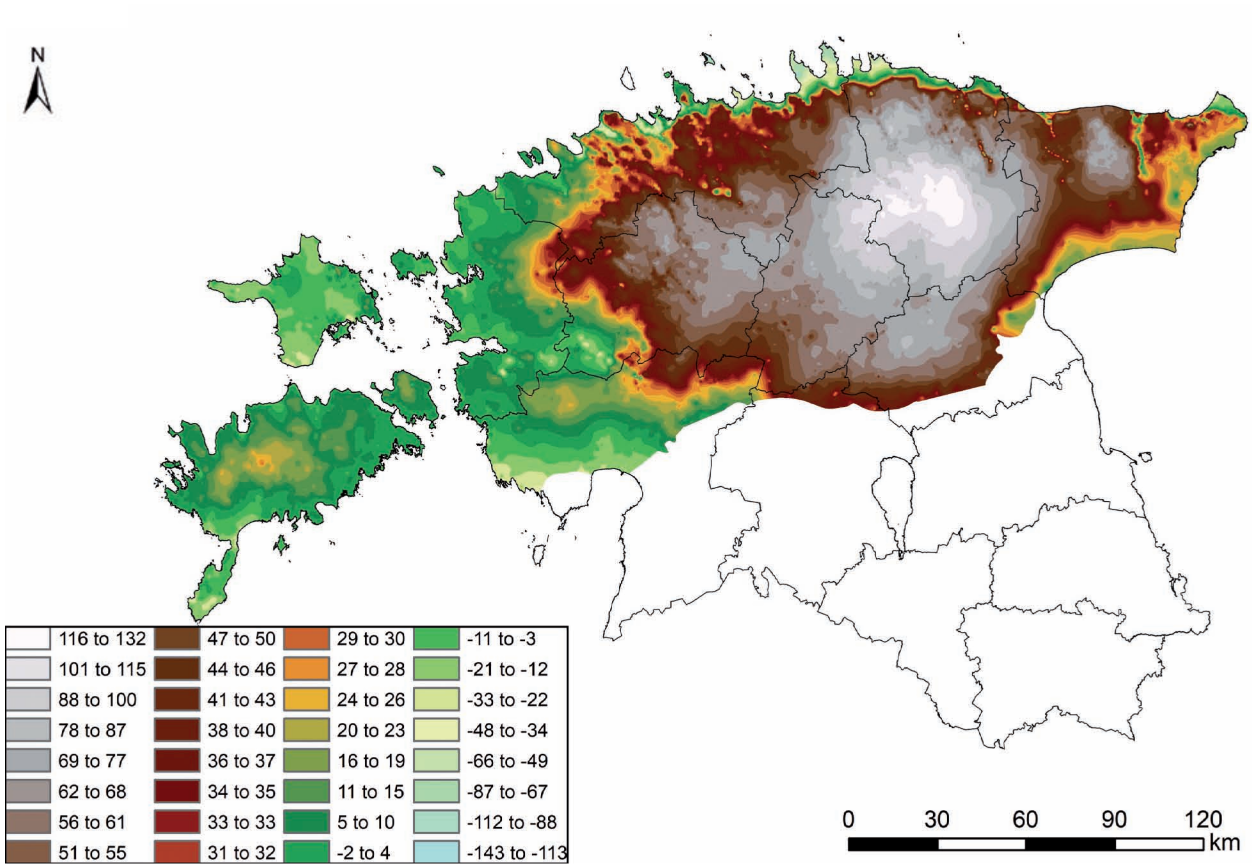


Fig. 6. The interpolated model of rock head elevation of the carbonate area. Surface values are metres from sea level.

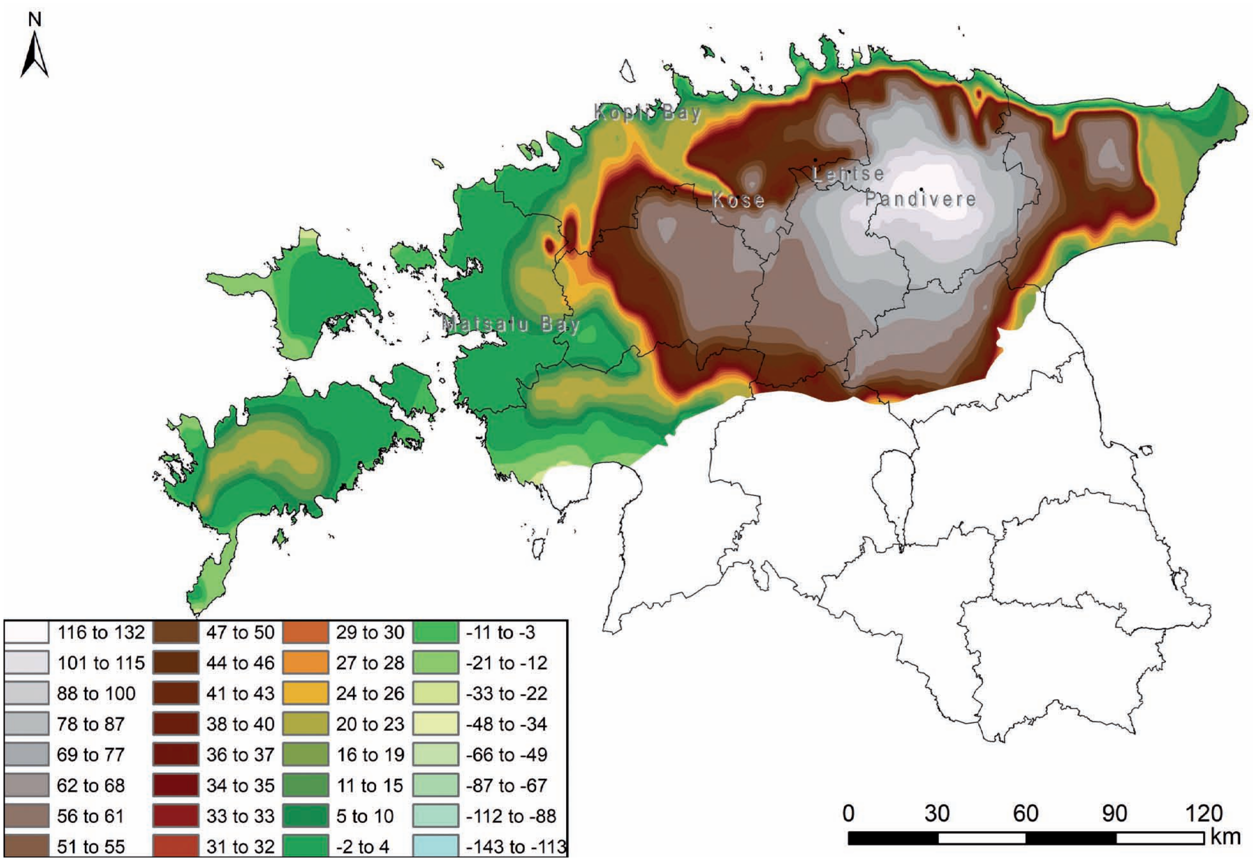


Fig. 7. The digitalized rock head elevation model of bedrock by Tavast & Raukas (1982). Surface values are metres above sea level.

GEOLOGICAL BASE MAPS ON THE ESTONIAN LAND BOARD WEBSITE

The Estonian Land Board holds the basic data on Estonian geology. The 1:50 000 and 1:400 000 geological base maps of Estonia are available for everyone. The 1:400 000 map is based on the primary data of the 1:200 000 base map which was created during 1957–1975, thus being older than the RHE model by Tavast & Raukas (1982). Basic information about the RHE on this map is derived from the distribution of rock units and buried valleys (EGS 2018) on the 1:400 000 geological map. As no elevation data are available, the comparison was difficult in problematic cases. There is a mismatch against both the Tavast & Raukas (1982) and new RHE models in the Matsalu Bay area regarding the continuity and shape of buried valleys. Some more problems are encountered in Lääne County, where the borehole data do not confirm the existence of some buried valleys. Some more mismatches are recorded in northern Estonia as well.

The geological map at a scale of 1:50 000 reveals a general pattern of buried valleys and bedrock topography height patterns (Fig. 2). This is the most accurate RHE information but it has limited coverage.

As 1:400 000 and 1:50 000 geological maps also come with layers of buried valleys, it is possible to compare the data of two older models with the new interpolated one. Three areas of interest (Ida-Viru, Harju and Lääne counties) were chosen to show similarites and differences between these models. In Ida-Viru County (Fig. 8), the borehole density is high and the differences are small. The interpolated slope angles tend to be higher in areas where there are buried valleys present on the geological maps. The greater borehole density also reveals more terrain roughness in some areas. Harju County (Fig. 9) has less dense borehole data and the buried valleys correlate less between the interpolated results and geological maps of different scale. The calculated slopes of the new RHE model have more chaotic distribution and the correlation with buried valley patterns of the previous models is good in the areas represented by enough data. In some cases, the lack of borehole data hinders proving all valleys present in the previous models. The heaviest problem of match was recorded in Lääne County (Fig. 10), where the

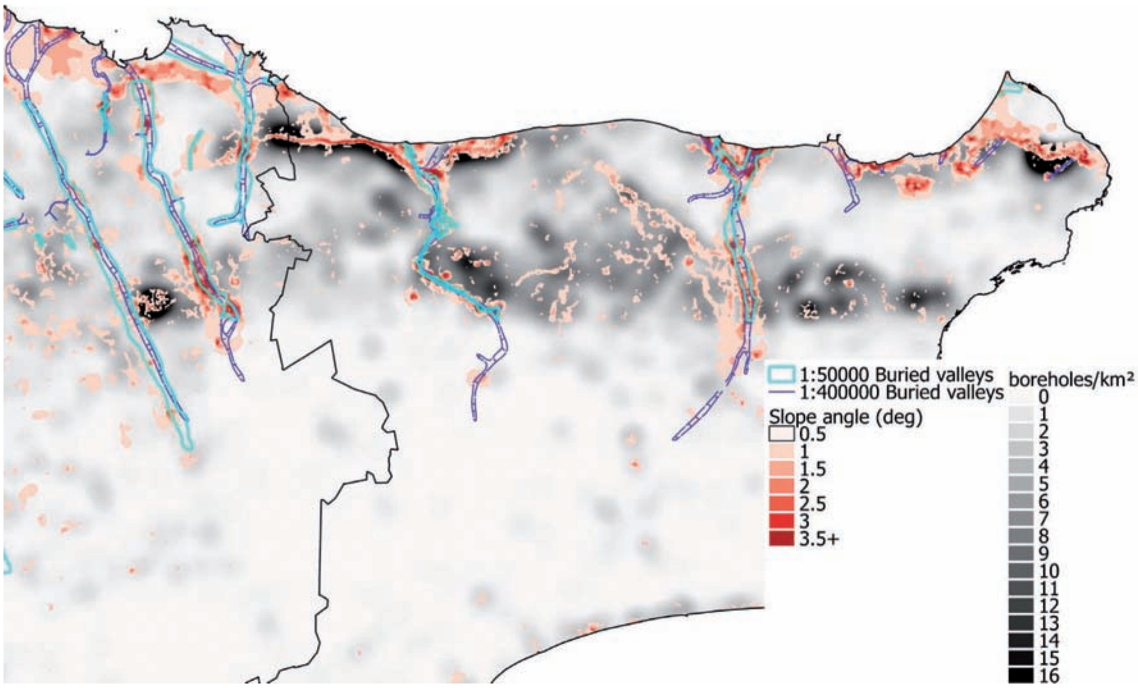


Fig. 8. The rock head elevation (RHE) model of Ida-Viru County next to the mapped buried valleys (area a in Fig. 1). The area is characterized by a high density of borehole data and the interpreted buried valleys from the geological maps (1:50 000 and 1:400 000) agree well with the interpolated slope data from the RHE model.

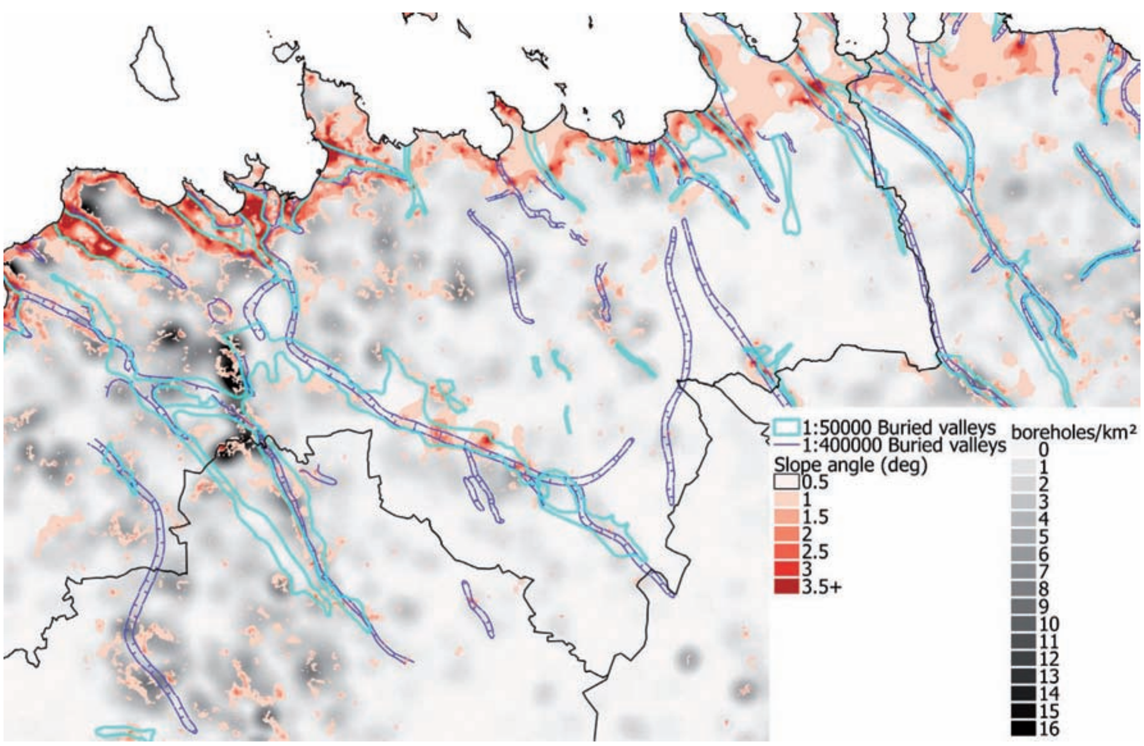


Fig. 9. The rock head elevation (RHE) model of Harju County (area b in Fig. 1). This area has a more varying borehole density and shows good correlation of the slope data with the mapped buried valleys only in the areas with high borehole density. The extent of some buried valleys gains only partial support from the RHE model and the continuity of some valleys can be questioned.

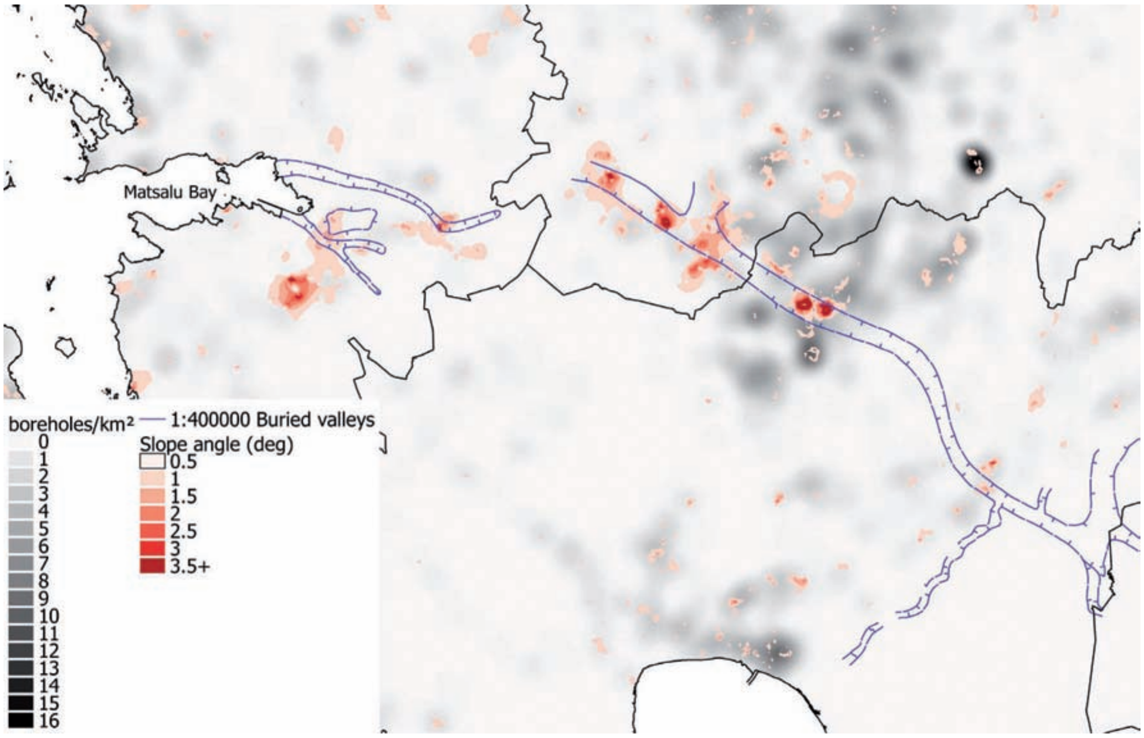


Fig. 10. The rock head elevation (RHE) model of the border area of Pärnu and Lääne counties (area c in Fig. 1). The density of boreholes in this area is low and questions arise about the true locations and directions of the buried valleys of older models. The mapped valleys proceeding east of Matsalu Bay are not supported by the RHE model whilst some steep slopes south of the bay could point at undetected buried valleys.

buried valley beginning from Matsalu Bay has no proof in the interpolated RHE model but some buried valleys supported also in the DEM seem to be present south of the bay. As the borehole density is low, the actual situation remains problematic in the area.

DISCUSSION

Previous information about buried valleys was mainly derived from surface topography, boreholes and geophysical studies. The newly proposed RHE model allows us to draw a less continuous valley system than proposed in earlier studies (Tavast & Raukas 1982; EGS 2018). Quite obviously the valley morphology and general pattern of valleys is dependent on the physical properties and composition of rocks and karst features. As the dipping of strata is insignificant in northern Estonia, erosional processes were likely the dominant factor in shaping the irregularities of the bedrock surface topography.

Considering the practical need for an up-to-date RHE model, we have to conclude that the older models lack sufficient precision and detail. The RHE model created in the course of large-scale (1:50 000) geological mapping is carefully elaborated but does not cover western mainland and the western islands where the results of large-scale geological mapping are not converted into digital format and not made widely available. The present RHE model for northern Estonia was created with the same settings that gave the best fit to the existing partial model but it covers the whole area from the northern coast up to the southern limit of the distribution area of the Ordovician and Silurian rocks. This is adding reliability to the new RHE model in the areas where the results of large-scale geological mapping are not available yet.

Lääne County and wetlands where the data are scarce should still be considered problematic. Some indirect indication of bedrock topography could be derived from the papers and reports dealing with the geological structure of wetlands and information on the thickness of peat deposits but these data are insufficient for reconstructing the valley systems in these areas. This gap could be filled in by future geophysical studies.

The present study provides an up-to-date approximation of RHE in northern Estonia. However, due to the lower density of data points in some areas it is likely that there are more unrecorded valleys that could be recovered in the course of future field work or geophysical investigations. The same is needed for resolving controversies between different models in some problematic areas.

CONCLUSIONS

After more than 150 years since the first and about 40 years from the last publication on Estonian RHE, a new bedrock RHE model was created, based on all publicly available data. The new ArcGIS-based RHE model integrates much more data and was created using an optimized set of interpolation parameters. The data points were carefully selected after multiple procedures of validation. Using the Topo to Raster and Spline methods, 6563 interpolations were performed and validated. A cluster of interpolations ended up with standard deviation of about 3.2, making them good candidates for the final model. The new model is capable of showing all the main features known from the previous ones and has greater accuracy. A few disagreements were still recorded between different models that could be resolved by adding more data points from unpublished sources or by performing additional geological and/or geophysical investigations. The new model showed less continuity in the pattern of buried valleys compared to the older models and narrows the features down. Comparison with the results of large-scale (1:50 000) geological mapping in the area where such data are available shows a good fit and adds reliability to the newly generated model in the areas where mapping data are missing or unavailable. As the RHE model is an important part of GIS-based geological mapping, this work has a potential of facilitating this activity in future.

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Supplementary online data

Supplementary online material to this article can be found at https://doi.org/10.15152/GEO.489. It consists of filtered borehole GIS data and three raster data files of the final result.

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Põhja-Eesti aluspõhja reljeefi mudel

Tavo Ani ja Tõnu Meidla

Esimene Eesti aluspõhja reljeefi mudel valmis 150 aastat tagasi ja viimane ligikaudu 40 aastat tagasi. Antud töö raames valmis esmakordselt kogu Eesti karbonaatset avamust käsitlev mudel, mis tugineb aluspõhja käsitlevatel vabalt kättesaadavatel andmetel. Uus mudel loodi, kasutades ArcGIS-i tarkvara ja selle interpolatsiooni meetodeid. Andmete interpolatsioonil lähtuti meetoditest Spline ja Topo to Raster. Kokku loodi ja analüüsiti 6563 erinevat aluspõhja reljeefi mudelit. Üldse leidus 148 interpoleeritud pinda, mille puhul standardhälbe väärtus oli ligikaudu 3,2. Nimetatud mudeleid võib nimetada aluspõhja reljeefi mudeli parimateks kandidaatideks. Uus mudel on piisavalt detailne, näitamaks aluspõhja reljeefi iseärasusi ja pakkumaks varasematest töödest suuremat täpsust. Siiski leidub mudelis kohati piirkondi, kus morfoloogia erineb tunduvalt varasemates töödes kirjeldatust. Antud iseärasusi on võimalik lahendada, lisades mudelisse andmeid avaldamata allikatest või geoloogiliste ja/või geofüüsikaliste välitöödega. Vanemate mudelitega võrreldes on uue mudeli järgi aluspõhja reljeefis leiduvad orud kitsamad ja nende järjepidevus lünklikuma iseloomuga. Uus mudel näitab ka head korrelatsiooni geoloogilise 1:50 000 kaardistamise raames loodud aluspõhja reljeefi mudeliga ja lisab teadmisi piirkondade kohta, kuhu 1:50 000 kaardistamine pole veel jõudnud. Kuna aluspõhja reljeefi mudel on oluline osa GIS-põhisest geoloogilisest kaardistamisest, on sellel tööl potentsiaali olla tulevikus osa täiemahulisest geoloogilisest 3D-mudelist.