J Paleolimnol (2019) 62:53–71
https://doi.org/10.1007/s10933-019-00075-3

ORIGINAL PAPER

Reconstructing Lake Onego evolution during and after the Late Weichselian glaciation with special reference to water volume and area estimations

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Received: 13 March 2018 / Accepted: 19 March 2019 / Published online: 28 March 2019

Abstract GIS-based reconstructions of Lake Onego development in the Late Pleistocene and the Holocene are presented. Reconstructions originated from the ideas of the Lake Onego depression deglaciation model proposed by I. N. Demidov and the isobase data of E. I. Devyatova. Twelve digital paleogeographic maps were developed and now are available on-line. The reconstructions for different time periods were unified, had a spatial resolution 90 m and a strict geographic conjunction. Paleogeographic maps were verified in relation to hand-drawing images of I. N. Demidov and E. I. Devyatova and by matching lake shoreline with a position of archaeological sites both in qualitative and quantitative manner. Area, volume, maximum, mean depth and dynamics of water fluctuation of Lake Onego was determined at twelve stages of its development. The discrepancies in ice-marginal positions and time scales were found to be major factors affecting the area and volume uncertainties between present and previous studies. Awareness of the lake's shoreline position allows us to determine areas where human settlement was possible, which increases our chances of discovering new archaeological sites.

Keywords Lake Onego · Lake Onega · Morphometric characteristics · GIS reconstruction · Late Pleistocene · Holocene

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s10933-019-00075-3) contains supplementary material, which is available to authorized users.

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Introduction

After the last glaciation maximum the ice sheet retreating reshaped the landscape cardinally, the formation and development of large proglacial lakes caused a series of changes in regional climate (Krinner et al. 2004), global ocean-climate system (Björck et al. 1996; Jakobsson et al. 2007) and early human history as a result (Boyd et al. 2003). The most well-studied ice-lakes are Glacial Lake Missoula (Baker and Bunker 1985), Glacial Lake Agassiz (Thorleifson 1996) and Glacial Lake Algonquin (Schaetzl et al. 2016) in North America, Baltic Ice Lake (BIL)

(Björck 1995) in Europe. BIL was formed as an ice-dammed lake in the process of melting of the southern part of the Scandinavian Ice Sheet (SIS). However, the history of relatively small ice-lakes associated with southeastern and eastern (continental) flanks of the SIS, as well as meltwater volumes and drainage routings remain unclear (Mangerud et al. 2004; Lyså et al. 2011; Larsen et al. 2014).

Lake Onego (Fig. 1) (61°42′ N, 35°25′ E; 33 m asl) is the second largest lake in Europe with volume 295 km^3 and surface area 9720 km^2 (Filatov 2010). The lake is located in the deep tectonic depression in the suture zone of the Fennoscandian Shield and East European Platform. Mainly tectonic forces formed the Lake Onego depression; however, Pleistocene Scandinavian glaciations significantly affected its structure. The lake depression was repeatedly enveloped by the ice streams during glaciations and by fresh and sea waters during the interglacial periods (Svendsen et al. 2004; Hughes et al. 2016; Stroeven et al. 2016). In the Late Weichselian time, the lake depression was filled with the Onego ice stream of the White Sea ice stream complex (Kalm 2012) located in the southeastern part of the SIS. The retreat of the Onego ice stream in the

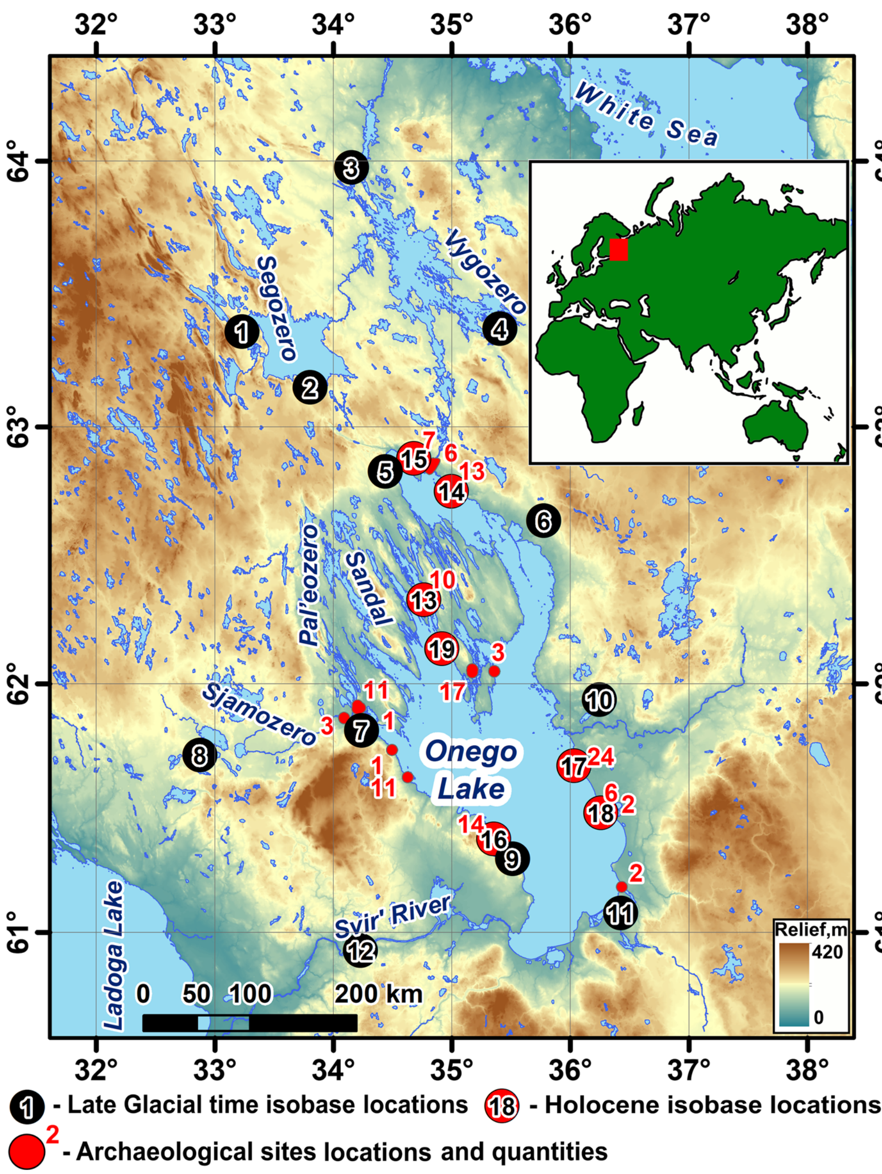

Fig. 1 The studied region, modern relief DEM, isobases and locations of archaeological sites used for verification of the model. Late Glacial period (isobases for 13.3 cal ka BP employed): **1&2** (Segozero)—Biske (1959); **3** (Nadvoitsy)—Ekman et al. (1991); **4** (Vygozero), **6** (Nemina), **7** (Sulazhgora), **12** (Svir')—Demidov (2005, 2006a); **5** (Perguba), **9** (Rybreka)—Biske et al. (1971); **8** (Garjusuo)—Saarnisto et al. (1995); **10** (Pudoz)—Wohlfarth et al. (1999); **11** (Vytegra)—Poryivkin (1960). Holocene period (since 11.5 cal ka BP): **13** (village Pegrema), **14** (Ornavolok peninsula), **17** (Besov nos peninsula)—Devyatova (1986); **15** (village Pindushi), **18** (lake Muromskoe)—Devyatova et al. (1987); **16** (village Sheltozero)—Devyatova (1984); **19** (Zaonezhskij peninsula)—Elina et al. (2000)

Late Glacial time led to the formation of the proglacial lake and its evolution during and after the ice sheet retreat.

Several original models of the Lake Onego depression deglaciation in the Late Glacial period are presented by Biske et al. (1971), Kvasov (1976), Saarnisto et al. (1995) and Demidov (2005). The models differently assessed sizes of the lake, glacioisostatic uplift of the territory, and location and altitude of drainage thresholds. Demidov's (2005, 2006a) model was created on the basis of a comprehensive study of ancient costal landforms and lake bottom sediments, used new and previously obtained data on the geological and geomorphological structure of the Lake Onego depression, paleomagnetic and radioisotope dating of sediments (Ekman et al. 1991; Wohlfarth et al. 1999; Saarnisto and Saarinen 2001). This model contains the latest available isobase values as well as new paleo dates (Fig. 1) and is the most detailed model at present time.

In the Holocene period the Earth's crust glacioisostatic uplift began to play a key role in lake development. At this time, around 10.5–10.0 cal ka BP humans began to populate the shores of the ancient Lake Onego. However, the glacio-isostatic changes in the local topography had been substantial enough that the ancient coastal terraces together with archaeological sites associated with them were left far away from the present shoreline. Thus, archaeological and geological studies of this period were closely intertwined (Zemlyakov 1935, 1936; Devyatova 1984, 1986; Devyatova et al. 1987). The history of the Lake Onego shoreline archaeological assessment goes back to the 19th century when the Lake Onego petroglyphs were discovered in 1848. Now more than 800 archaeological sites have been discovered, and many of them have been excavated over the area more than 100 m^2.

The development of the lake Onego shorelines during the Holocene was comprehensibly studied by geologist E. I. Devyatova in collaboration with archaeologists V. F. Filatova, N. V. Lobanova, U. A. Savateev and A. P. Zhuravlev. The key segments of the Lake Onego shoreline were assessed during this work (Devyatova 1984, 1986; Devyatova et al. 1987) where patterns of relief, water body, vegetation and climate changes were considered in their connection with human settlement activities. The study was focused on assessing lake terraces, which allowed the researchers to define particular chronostratigraphic stages and provided the material for paleographical reconstructions. The conclusions were based on stratigraphy of sedimentary deposits of archaeological sites and surrounding locations, pollen analysis and radiocarbon dating. The field surveys were conducted on several key locations (Fig. 1) where well-known archaeological sites were densely situated. The maximum and minimum water levels were established for every key location for six climatic periods: Younger Dryas (YD; ca. 12.3–11.5 cal ka BP), Preboreal (PB; ca. 11.5–10.5 cal ka BP), Boreal (BO; ca. 10.5–8.9 cal ka BP), Atlantic (AT; ca. 8.9–5.5 cal ka BP), Subboreal (SB; ca. 5.5–3.0 cal ka BP), Subatlantic (SA; ca. 3.0 cal ka BP—present time).

Today, progress in digital elevation modeling with geographical information systems (GIS) software provides a new potential for reconstructing the ice-lake's development (Leverington et al. 2002b) allowing estimation of lake areas and water volumes, which is essential to understand the role of these lakes in the meltwater budget. GIS methods have been widely applied to reconstruct changes in the bathymetry, area and volume of glacial Lake Agassiz (Mann et al. 1999), Baltic Ice Lake (Jakobsson et al. 2007) and others. GIS-based reconstruction of proglacial lakes was recently created for the continental part of the Late Weichselian SIS (Gorlach et al. 2017). Although the latter study also includes the Lake Onego depression, it was implemented with a small-scale spatial resolution near 1000 m (GTOPO30 model was used in Lake Onego region) which was quite enough for broad scale estimation, but probably insufficient to assess the relatively small proglacial Lake Onego. Thus, the broad time-scale Lake Onego development has never been reconstructed using GIS instruments with spatial resolution enough for precise shoreline position, area and volumes estimations until now.

Taking into account all the above, the shoreline contours of the entire lake in the Late Pleistocene and Holocene can be reconstructed by interpolation of glacio-isostatic rebound data, published by Demidov (2006a), Devyatova (1984, 1986) Devyatova et al. (1987) and Elina et al. (2000) in combination with Earth's modern topography. The latter is expedient to be utilized from high resolution digital elevation models (DEMs).

Only three freeware DEMs with spatial resolution less than 100 m are available for now: USGS STRM DEM 3′ (Rodriguez et al. 2006), ASTER GDEM 1′

(Tachikawa et al. 2011) and ALOS World 3D30 (Tadono et al. 2014). However, different specific issues, coupled with capabilities of the remote sensing technologies applied are inherent to each of them. USGS STRM DEM 3′ only partly covers the studied region, ASTER GDEM 1′ despite the good spatial resolution and broad coverage has lots disturbances and artifacts of spatial data, that considerably hampers it application for modeling purposes (Tadono et al. 2014). ALOS World3D30 is currently under development and although some data are ready to use, it has patchy coverage in studied region (Tadono et al. 2014). The necessary alternative to these models is global DEM developed by Jonathan de Ferranti (JdF DEM) (Kirmse and de Ferranti 2017). To fulfill the voids and uncovered areas of 3″ USGS STRM DEM the author involved external data from topographic maps and plans, ASTER GDEM data and other public sources to form the global 3′ DEM (Ferranti 2017; Tait 2010). The region of interest northward of N60° was previously uncovered by 3″ USGS STRM DEM and has been digitized from Russian topographic maps and converted into a DEM by Jonathan de Ferranti (Kirmse and de Ferranti 2017; Fredin et al. 2012). Although this data source is relatively new and still is not used commonly, it was effectively applied in tracing the ice marginal moraines in NW Russia (Fredin et al. 2012), assessing spatiotemporal variations of glacier flow (Nobakht et al. 2015) and calculating prominence and isolation of mountains all over the world (Kirmse and de Ferranti 2017). Independent assessment of this global DEM showed its good fit for Tanzania region (Ulotu 2017), northern Norway and NW Russia (Fredin et al. 2012).

Late Atlantic–Subatlantic water levels on the south part of the Onego Lake were lower than at present, as confirmed by archaeological data (Savateev 1984). For this reason, the contemporary underwater topography of the Lake needs to be involved to adequately reconstruct shoreline in the southern part of the lake and estimate the lake volume in different time periods.

In this paper, glacioisostatic uplift data, published by Demidov (2005), (Devyatova 1984, 1986; Devyatova et al. 1987) and Elina et al. (2000) were assimilated together with modern topography and bathymetry to develop the model of Lake Onego deglaciation and development in the Holocene and the Late Pleistocene. The shape and the shoreline position, area, volume, maximum and mean depth estimations for twelve stages of its development beginning from 14.5 cal ka BP until the present will be presented. The Lake Onego development in YD period will be discussed as a result of ice sheet margin movement, water discharges and catastrophic drops during ice sheet melting, while lake evolution in later periods will be assessed in the light of Earth's crust isostatic uplift and shoreline human settling.

Materials and methods

The studied area lies in North-West part of Russian Federation between the coordinates 60° N, 30° W and 65° N, 39° W and covers 570 km from North to South and 502 km from West to East (Fig. 1). To reconstruct such a wide region it is advantageous to use a GIS method, proposed by Leverington et al. (2002b). To implement such an approach it is required to generate a single data layer for each (1) modern topography and (2) rebound surfaces. Both data layers must be georeferenced to each other and must be resampled to a common grid resolution, and contain values expressed with respect to a common datum (Leverington et al. 2002b). Modern topography layer needs to contain modern elevations together with contemporary lakes bathymetry resampled in uniform coordinate system, projection, datum and common grid. The historical water plane can be generated by subtracting the rebound surfaces (2) from the modern topography (1) (Leverington et al. 2002b; Krist and Schaetzl 2001).

Modern elevations DEM

The primary source of the modern elevations was the JdF DEM with spatial resolution three arc seconds (Kirmse and de Ferranti 2017). This is the first freeware global elevation model with spatial resolution less than 100 m with coverage of the studied region. The independent assessment of this DEM for Tanzania region showed its vertical mean deviation from GPS control heights in 0.1 m with standard deviation (STD) 10.9 m (Ulotu 2017). Additional quantitative assessment of the vertical DEM's error in the Onego Lake region will be presented further.

The DEM of the studied region was combined from 45 single tiles covered a space 1° × 1° each and was converted to UTM WGS 84 zone 36 N projection

(EPSG: 32636). The same projection was used for other mapping features.

Modern Bathymetry DEM

The database of the Lake Onego depression bathymetry was compiled using depth measurements, digitized manually from navigation charts of Lake Onego and the River Svir' (Onezhskoe ozero 1988). Modern shoreline and islands positions were digitized manually from satellite images (Landsat 4) with spatial resolution 50 m. Modern lake bathymetry DEM was calculated with GIS Surfer 11 software using ordinal kriging method with barriers on grid 20 × 20 m. The vertical scale of the modern lake bathymetry DEM was converted into the Baltic Sea level datum and combined with modern elevation DEM by raster cells substitution. Thus, modern topography DEM of lake watershed and its depression was obtained.

To account for the water volumes of other smaller lakes situated within the largest stage of the lake development, the depressions of 125 lakes were incorporated into modern topography DEM. They included original detailed bathymetric maps of lakes Vygozero, Segozero, Pal'eozero, Seleckoe, Songo, Maslozero, Oster, Sundozero, Vendjurskoe and Urozero, developed by authors by means of georeferenced echo sounder surveys. Relief of 15 relatively large lakes (Konchozero, Kroshnozero, Lizhmenskoe, Lizhmozero, Munozero, Peldozhskoe, Pertozero, Pyalozero, Sandal, Shotozero, Sjamozero, Svyatozero, Ukshozero, Vagatozero, Yandomozero) was digitized from hand-drawings (Filatov and Kuharev 2013). Depressions of another 99 small lakes were interpolated based on shoreline topography and maximum depth from (Filatov and Kuharev 2013). To account for other local depressions, now filled with small lakes, peatlands and other flat quaternary entities, the modern topography DEM was converted into isoclines and then isoclines were converted backwards into DEM without sinks filling using 'Topo to Raster' tool from ArcGis toolbox with 'Type of drainage enforcement' feature set to 'No enforce' (Hutchinson 1989). Quantities of sediment deposition and erosion in the lake basin were not accounted during the generation and interpretation of results, because taking them into account resulted in only 1% larger lake volume, as shown earlier for neighboring locations (Jakobsson et al. 2007). Geo-referenced calculations and map algebra operations with DEMs were implemented within ArcGIS 10.2.2 software with the Spatial Analysis package. The spatial resolution of the combined DEM, involving modern topography and bathymetry, was 90 m.

Ice margins positions

Ice margin positions were used only for proglacial stages of the lake development in the Late Glacial time (14.5–13.2 cal. years. BP). The general ice margins configurations were derived from those of Demidov (2006a) with minor modifications. The first two stages of the proglacial lake formation were evolved by Demidov (2006a) using the Luga (14.5 cal ka BP) and the Neva (14.0 cal ka BP) ice margins positions (Saarnisto and Saarinen 2001). The next two stages (13.3 and 13.2 cal ka BP) were evolved by Demidov (2006a) based on interpretations of moraine and stratigraphic evidence.

Ice margins were digitized in form of multilines from the preliminary georeferenced sketches. Later they were adjusted in accordance with glacial and fluvio-glacial landforms locations using topographic maps and geomorphological charts. The Ice margins multilines were complemented with the borders of the studied region and converted into Ice Sheet polygons.

Isobase values

Isobase values for Late Pleistocene period were adopted from study of Demidov (2005). The slope of the lake depression 13.3 cal ka BP was used for entire Late Pleistocene (14.0–12.3 cal ka BP) employing twelve isobase values (Fig. 1). Glacioisostatic uplift was not used for period 14.5 cal ka BP, because only one point of water level was available.

For the Holocene period seven isobase values were employed to reconstruct every climatic period (Fig. 1). Isobases were obtained from relict shoreline terraces (Devyatova 1984, 1986; Devyatova et al. 1987; Elina et al. 2000), marking the highest and the lowest water planes for every climatic period. Thus, we employed these minimum and maximum water marks to estimate spatial dispersion in shoreline position and to evaluate an uncertainty in area and volume calculation for every reconstructed period.

Rebound surfaces

The mean water plane of the present day Onego lake (33 m asl) (Filatov 2010) was used as the reference level to calculate the Rebound Surfaces, which were interpolated in a form of inclined planes. Thus, the present day water level (33 m asl) was subtracted from each isobase value (asl) for each reconstructed period and the results were interpolated with the first order 3D polynomial using Surfer 11 software forming the Rebound Surfaces. In the next stage Rebound Surfaces were subtracted from the modern topography & bathymetry DEM (Leverington et al. 2002b) to calculate the paleo-DEM for each reconstructed period. For the Late Glacial time (14.5–13.2 cal. years. BP) the paleo-DEM grid cells underlying the ice sheet polygon were increased up to 1000 m asl to model ice sheet position.

Generally, the modelled shoreline was depicted as the 33 m isocline on the paleo-DEM, however vertical measurements uncertainty and water plane correction made this boundary slightly vague. While only one Rebound Surface (13.3 cal ka BP) was used for the periods from 14.0 to 12.3 cal ka BP, the water levels for each of them were plotted higher or lower by the mean difference between isobase values at 13.3 cal ka BP and the modelled stage.

Cumulative vertical error estimation

The cumulative vertical error (Δh) is derived from uncertainty in (1) relief vertical height estimation during remote measurements, (2) isobase values estimation, (3) rebound surface interpolation process.

DEM (1) confidence interval ($\pm \Delta h_{Rel}$) was calculated by using mean-square deviation between modern elevations DEM values and regular geodesic network marks, obtained from topographic map (1:200,000). Overall, 399 marks were implemented and probability α = 0.05 was used to calculate confidential interval. Discrepancy (2) generally occurs during field measurements and includes methodological uncertainties in evaluation of water levels by the heights of lake terraces, wave-cut bluffs and spits, and instrumental errors, which occur during their height measurements. To account them, we used maximum and minimum water levels for every period, where this data was available (generally for the Holocene).

Rebound surface interpolation errors (3) were estimated as confidence interval ($\pm \Delta h_{Int}$) of mean-square deviation between isobase values used for interpolation and interpolated values at the same positions with probability 0.05.

The cumulative vertical error (± Δh) was calculated as follows:

$$-\Delta h = -\Delta h_{Rel} - \Delta h_{Int}$$

$$+\Delta h = +\Delta h_{Rel} + \Delta h_{Int}$$

Thus, the paleolake shoreline for each reconstructed period is deemed to be situated between two contour lines depicted on the paleo-DEM grid at heights 33 + Δh (maximum modelled water level, m) and 33 − Δh (minimum modelled water level, m).

Human settlements

The data of total of 131 archaeological sites' positions was used for model verification (Fig. 1). Most of sites contain several diachronic components (complexes). These complexes are dated according to the current typo-chronological scheme of Karelian antiquities, which is based on available radiocarbon dates made of organic materials from excavations, mostly during previous investigations (Kochkurkina 1991; Lobanova and Filatova 2015; Tarasov et al. 2018; Tarasov 2018). Generally, the sites selection process was aimed to cover all key locations and all periods studied.

The sites with direct GPS reference were preferred, however GPS positioning has been involved into the Karelian archaeological practice only a decade ago and initially a number of sites with precise spatial reference is still quite small. Together with recently discovered archaeological sites (German 2014; Tarasov 2015; Ivanishcheva et al. 2015), the spatial reference was established for settlements discovered in last decades in the Besov Nos and the Ornavolok peninsulas, Pindushi, Derevjannoe and Sheltozero villages (Fig. 1) during sites' inventory and monitoring for heritage protection management. Several archaeological sites were georeferenced using schematic maps from field surveys and publications (Zhuravlev 1991; Kosmenko 1992; Zhulnikov 1999; Tarasov et al. 2007; Melnikov and German 2013) to fulfill the gaps in studied key locations and periods.

Georeferenced settlements data has also been obtained from available archaeological field reports.

Model verification

Paleogeographic maps were verified in two ways. The first one was implemented by comparison of maps with hand-drawn images of Demidov (2005) and Devyatova (1986, 1984; Devyatova et al. 1987). Shoreline contours and island sizes were compared. The second way of verification was carried out by matching the lake shoreline with a position of archaeological sites. The lake shoreline position for each reconstructed period was compared with a position of archaeological sites dated by this period.

The proximity of the fresh water sources was required for human settling during the Stone Age and the Early Metal periods with hunting and fishing-based economies. This distance for the Onego Lake region can be established by the remoteness of the archaeological sites from small and medium inland lakes, which retained relatively stable water plane after the glaciation. The majority of prehistoric settlements discovered near such lakes and included in the data set (Kochkurkina 2007) were situated within the 100 m distance from the shore. Considering this, we may suppose that archaeological sites had to be situated on the shore, within the same distance from the reconstructed shoreline.

Quantitative analysis of the sites distancing from the modelled shoreline was conducted using 'Near' tool from ArcGis 10.2.2 toolbox. The tool indicates the distance from the point feature (archaeological site) to polygon delineating the area of water plane fluctuation for each reconstructed climatic period. The sign of the distancing for sites situated under the lowest modelled water plane was additionally changed into the negative. Thus, the sites situated within the water level fluctuation during particular climatic period had zero distancing, while the sites situated onshore above the highest water plane had the positive value. The negative value of distancing indicates that the corresponding site remained underwater or couldn't exist according to our model in the particular climatic period.

Area and volume calculations

Area and volume calculations were implemented using ArcGis 10.2.2 software with spatial analysis package. The shoreline contours were converted into polygons and enclosed islands were cutout from them. Thereafter areas of polygons, representing water surface, were calculated using ArcGis tools.

To calculate the water volume, the raster data below the modeled water surface was extracted to a separate grid file. Next, the grid file was reclassified into integer form ("Reclass by table" tool applied) with the one-meter step and "Zonal statistics as table" tool from spatial analysis package was applied to calculate the area between neighbor isoclines. Then the sum of areas of all underlying depths was calculated for each isocline. The volume of each isocline layer as a product of area and isocline depth was calculated. The total water volume was assumed as a volume under the last isocline.

Results

Paleoreconstructed maps of twelve periods in the Late Pleistocene (Fig. 2) and Holocene (Fig. 3) are available online (http://arcg.is/0Kyr9a).

DEM vertical error

The heights of the modern terrain DEM were observed to be on average 1.65 m lower, than elevation marks of the geodetic control net. The standard deviation was 5.89 m. Confidence interval (Δh_{Rel}) was $\pm$ 0.55 m ($\alpha = 0.05$; $n = 399$) and true height value lay in a range from − 1.1 to − 2.2 m.

Interpolation error

Determination coefficients for polynomials interpolated vary significantly from 0.19 to 0.99, and were 0.76 in average (ESM1). The lowest coefficients (0.19, 0.34) were observed for the latest climatic period (SA) where isobase values were nearly the same as the modern DEM error. In any case, low values of determination coefficients were balanced by consideration of interpolation errors, which were varied from $\pm$ 0.57 m for BO_{min} up to $\pm$ 4.3 m for DR_1.

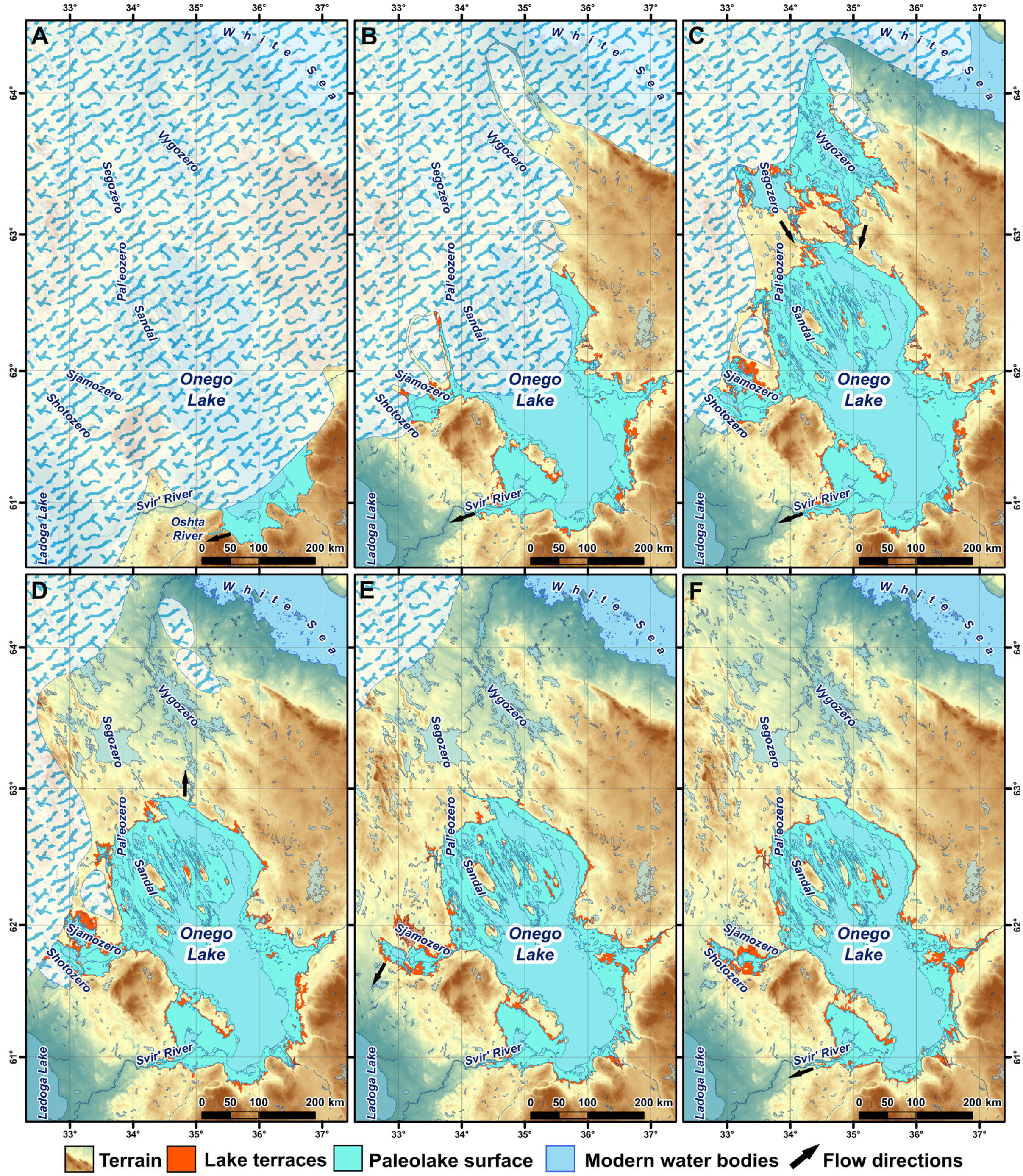

Fig. 2 The Onego Lake development in the Late Pleistocene: **a** 14.5 cal ka BP; **b** 14.0 cal ka BP; **c** 13.3 cal ka BP; **d** 13.2 cal ka BP; **e** 12.4 cal ka BP; **f** 12.3 cal ka BP

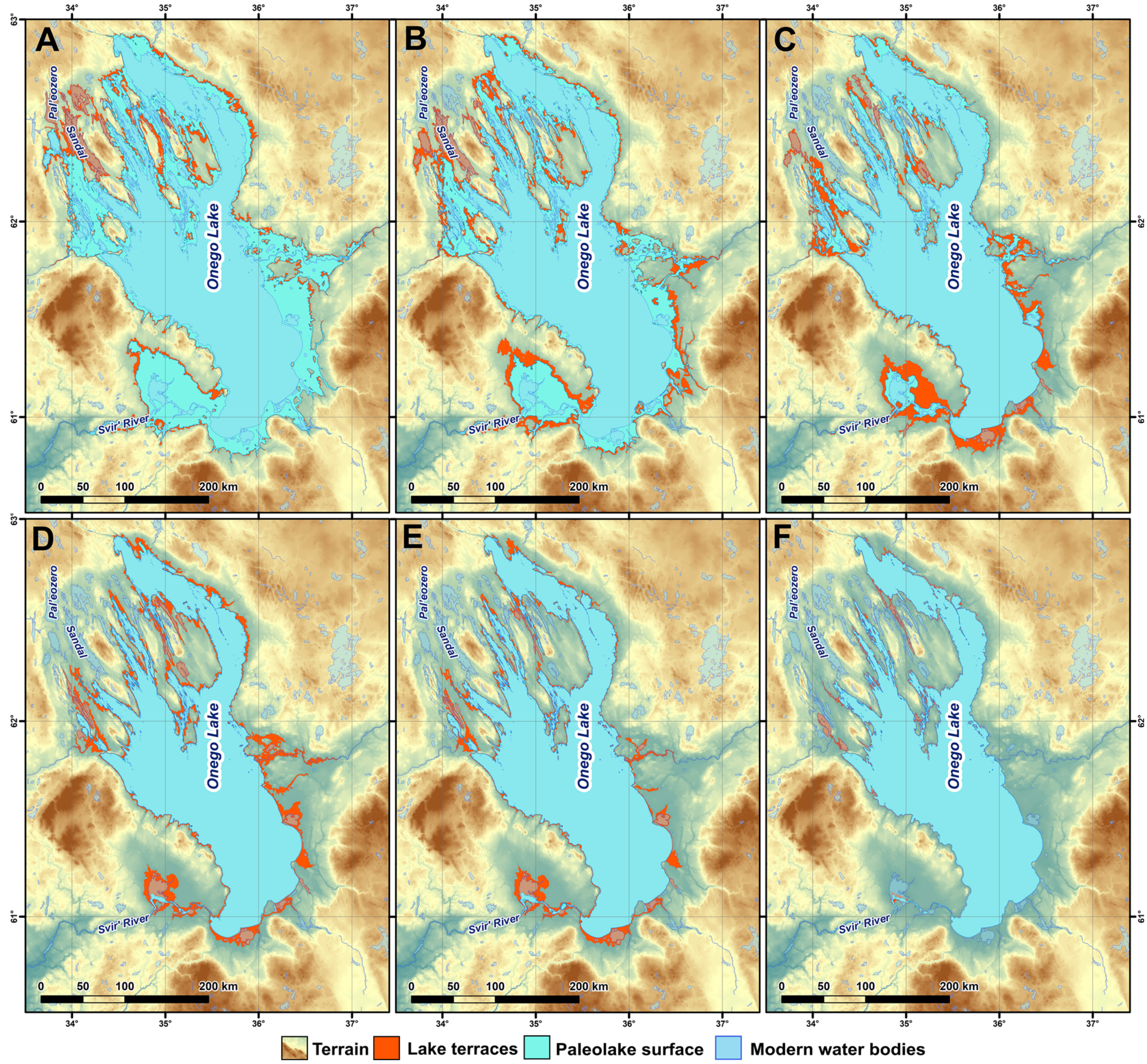

Fig. 3 The Onego Lake development in the Holocene: **a** YD (12.3–11.5 cal ka BP); **b** PB (11.5–10.5 cal ka BP); **c** BO (10.5–8.9 cal ka BP); **d** AT (8.9–5.5 cal ka BP); **e** SB (5.5–3.0 cal ka BP); **f** SA (3.0 cal ka BP–present)

Area, volume and bathymetry

Volumes, areas, mean and maximum depths for twelve stages of Lake Onego development from 14.5 cal ka BP until present are given in Table 1.

Palaeogeographical verification

Reconstructions of Lake Onego development in the Late Pleistocene period were compared with schematic hand-drawn images of I. Demidov (Filatov 2010). General shoreline and islands configurations, ice margins and discharge positions were very similar on our maps and earlier images (Fig. 4). However, our reconstructions were found to be considerably detailed: while sketches were designed to present basic principles of shoreline formation and discharge events, our maps contains detailed information about shoreline configuration and position with strict spatial reference.

The high definition maps obtained during this study enabled us to find-out and refine the boundaries of secondary relief formations: unflooded islands and uplands, ancient bays and straits. The existence of the

Table 1 Volumes, areas, mean and maximum depths of Lake Onego in different time periods. Confidential interval with α = 0.05

Period, cal ka BP	Threshold location	Threshold height, m ASL	Volume, km^3	Area, km^2	Mean depth, m	Max depth, m
14.5	Oshta-Tuksha- Oyat' Rivers	106[a]	180 ± 5	2711 ± 64	66.5 ± 0.5	114 ± 2
14.0	Svir' River	80[b,c]	795.5 ± 72.5	14,785 ± 684	53.5 ± 2.5	168 ± 5
13.3	Svir' River	80[b,c]	1639.5 ± 166.5	32,328 ± 1484	50.5 ± 2.5	184 ± 5
13.2	Onego-Vygozero threshold	115-110[a,c]	1201 ± 117	24,879 ± 1078	48.5 ± 2.5	174 ± 5
12.4	Gar'jusuo peatland	110[d,c]	1080 ± 112	22,590.5 ± 1168.5	47.5 ± 2.5	169 ± 5
12.3	Svir' River	75[b,c]	967 ± 105	21,483.5 ± 1148.5	44.5 ± 2.5	164 ± 5
12.3−11.5	Svir' River	–	695.5 ± 56.5	17,728 ± 1040	39 ± 1	144.5 ± 3.5
11.5−10.5	Svir' River	–	546.5 ± 67.5	15,562 ± 1213	35 ± 2	137.5 ± 4.5
10.5−8.9	Svir' River	–	427 ± 50	13,018 ± 1231	33 ± 1	130 ± 4
8.9−5.5	Svir' River	–	349.5 ± 43.5	11,194.5 ± 1156.5	31 ± 1	122 ± 4
5.5−3.0	Svir' River	–	323 ± 27	10,633.5 ± 763.5	30.5 ± 0.5	119 ± 3
3.0-present	Svir' River	–	301 ± 19	9597.5 ± 272.5	31 ± 1	116 ± 2
Current	Svir' River	31.5[e]	295[e]	9720[e]	30.0[e]	120[e]

[a]Kvasov (1976), [b]Poryivkin (1960), [c]Demidov (2005), [d]Saarnisto et al. (1995), [e]Filatov (2010)

large bay in the area of the Ivinskaya Lowland in the south-west part of the Lake Onego from 14.0 cal ka BP was confirmed by our reconstructions (Fig. 4a). The Bay was situated in the South-West part of the lake and was separated from them with a Shoksha ridge (heights up to 205 m), which formed a large island at 14.0–12.4 cal ka BP. The island was separated from the land in the South with a wide straight in the Svir' river valley and with a thin one in the North. Presently this channel is retraced with a small lake system.

To validate the reconstructions in the Holocene, the shoreline positions were compared with hand-drawn images of E. I. Devyatova (Devyatova 1984, 1986; Devyatova et al. 1987). These local field studies were conducted on relatively small shoreline segments (from hundreds of meters to a few kilometers long). Using a uniform methodology, including levelling surveys (5–10 levelling lines), photographic aerial surveys and its interpretation, geological and geomorphological profiling (Devyatova 1986), the authors prepared detailed maps for every studied shoreline fragment for every climatic period. As the shoreline segments were small enough to consider them as isostatically uniform and were detailed sufficiently thanks to aerophotograph basemap, they can pose as a reference for our whole-lake glacioisostasy model. Modelled shoreline and islands contours were compared with ones depicted on the hand-drawn images of the crucial shoreline segments. Islands' sizes specified by E. I. Devyatova were also compared with our reconstructions.

The Orov Bay region (Fig. 5) is shown as an example of comparison. Devyatova et al. (1987) suggests that instead of the Ornavolok peninsula presently situated here, only two small islands elevated over the lake surface in YD (Fig. 5a). Later, in PB they were expanded and joined (Fig. 5c). In BO period (not shown) the area of the joint island raised and it achieved 1.2 km in length. Our reconstruction reproduces these changes in general, however due to a higher uncertainty in height determination, in YD two small islands were already joint and potentially could be flooded during high water levels. In PB, general island configuration conforms to Devyatova et al. (1987). Our data suggests that in BO the island length increased and was between 1.4 and 1.7 km and is close to ones, established by Devyatova et al. (1987).

The similar roughness were evident at the other key segments of the Lake Onego shoreline: Lake Muromskoe, Besov Nos Peninsula, Pegrema and Sheltozero villages (Fig. 1). However, general shoreline configurations and large island sizes were close to

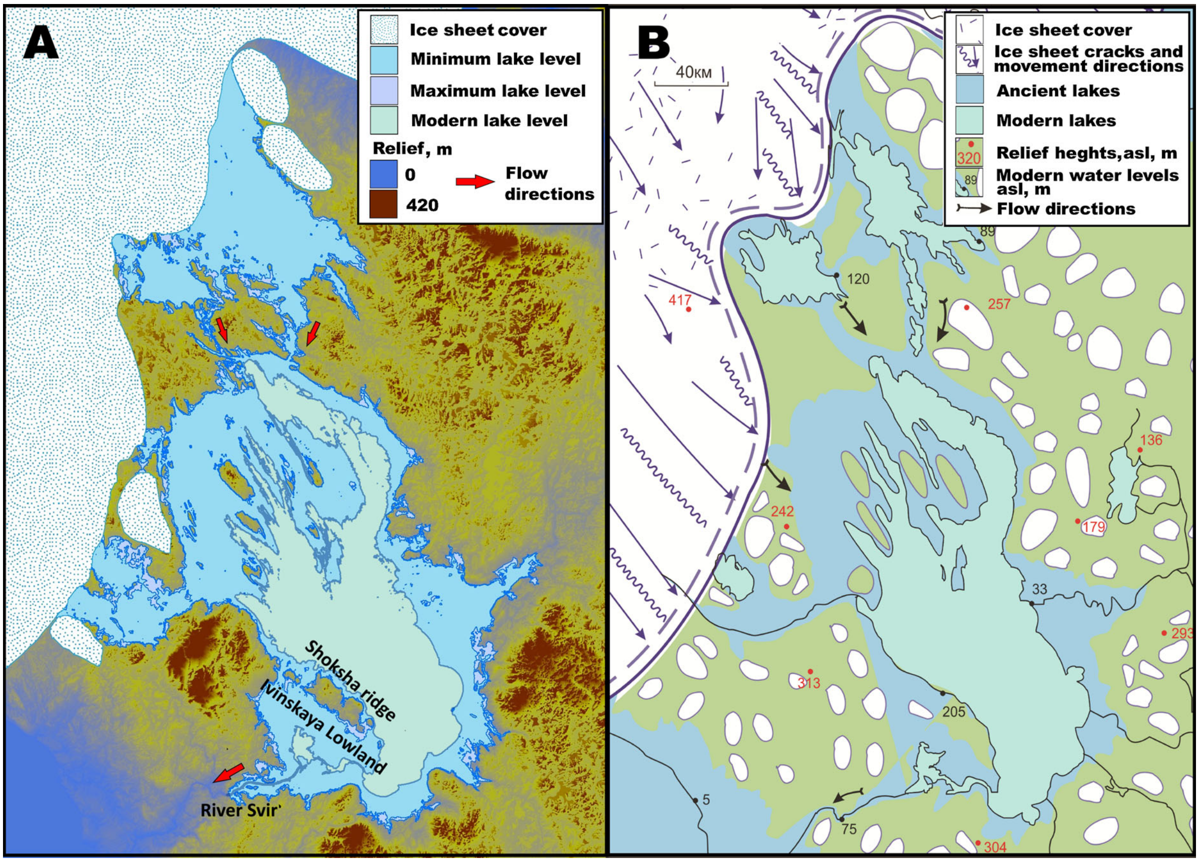

Fig. 4 The comparison of our reconstructions (**a**) and hand drawing of I. Demidov (**b**) (Filatov 2010) for period 13.3 cal ka BP

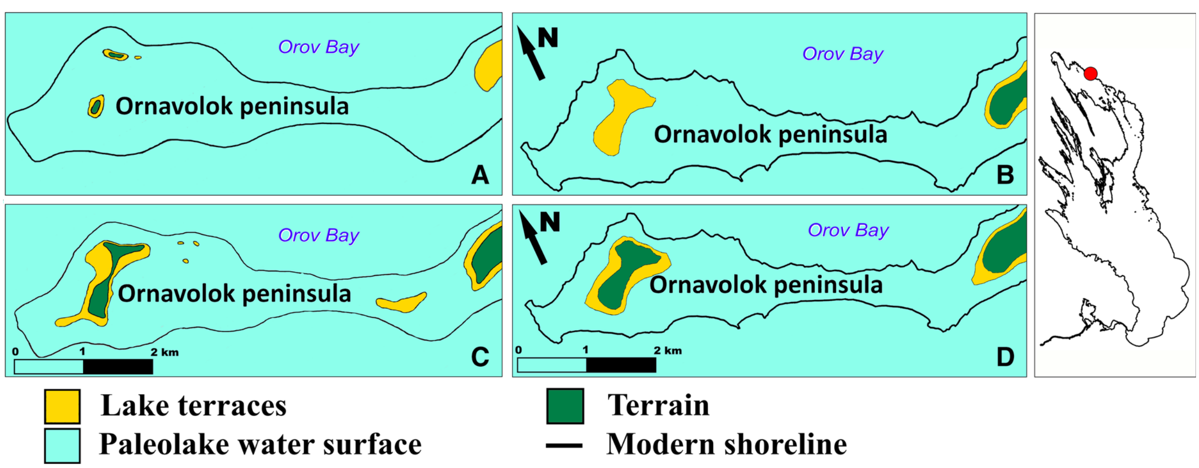

Fig. 5 The comparison of hand-drawings of Devyatova et al. (1987) (**a**, **c**) with our reconstructions (**b**, **d**) for the late Dryas (**a**, **b**) and Preboreal (**c**, **d**) for Orov-bay region

descriptions and hand-drawings of Devyatova (1984, 1986) Devyatova et al. (1987).

Archaeological verification

Substantially in all cases, where archaeological sites had strict GPS reference and dating, they were situated on the shore or within a range of water level fluctuation. In a few cases, archaeological sites were positioned on the lake surface, but not further than 62 m from the lowest water plane. That was due to the horizontal DEM error, because this type of error was not considered during vertical error estimation. Since horizontal DEM error was assumed as a ½ of DEM mesh size and lies around 45 m (Rodriguez et al. 2006), such a deviation is reasonable.

The region of the Besov Nos Peninsula with high density of archaeological sites, both settlements and rock art locations, has been extensively studied by archaeologists (Zemlyakov 1936; Lobanova and Filatova 2015). In total, 23 precisely georeferenced settlement sites from the Besov Nos Peninsula and adjacent localities of the Kladovets Peninsula and Chernaya River mouth were used (Fig. 6). The sites contain complexes from the Mesolithic period till the Middle Ages whose relative dating covers the timespan from the BO (possibly) till the SA periods, ca. 10.0–1.0 cal ka BP.

Only in one case the archaeological site was significantly distanced outshore (near 100 m), apparently because the strict GPS reference was absent for this site and spatial reference was specified using only one available hand-drawing scheme map.

In four cases, archaeological sites were situated far away onshore. Two of them were nearby sites located on a distance more than 1 km away from the coast. However, our reconstructions showed that they were situated on a coast of a small lake, which is currently transformed in a peatland (Fig. 7a). The other two archaeological sites extensively distanced from reconstructed lake shoreline were associated with the River Povenchanka and the River Shuya (Fig. 7b, c). Since all of these sites were situated near the water bodies, which possibly were used as water supplies for these settlements, they have been excluded from further consideration. In any case identified deficiencies with only five sites represent 4% only of all sampling data set (131 site) and do not affect a general trend, thus quantitative assessment could be implemented.

A quantitative analysis of the site distancing is presented in a form of matrix array (Table 2) where cells contain statistical information about the distance from the dated site to modelled shoreline (mean, SD, maximum and minimum) while the columns and rows represent the particular climatic periods of sites and shorelines plotted against each other.

Discussion

Onego lake development in Late Pleistocene

The results allow us to track back the quantitive changes that took place in the Lake Onego basin beginning from the Last Glaciation, when the maximum fluctuations of water volume and area were observed (Figs. 2, 8). They generally resulted from ice sheet melting and opening of new water thresholds during the glacier retreat to the North. Our reconstructions for the Late Pleistocene period confirmed

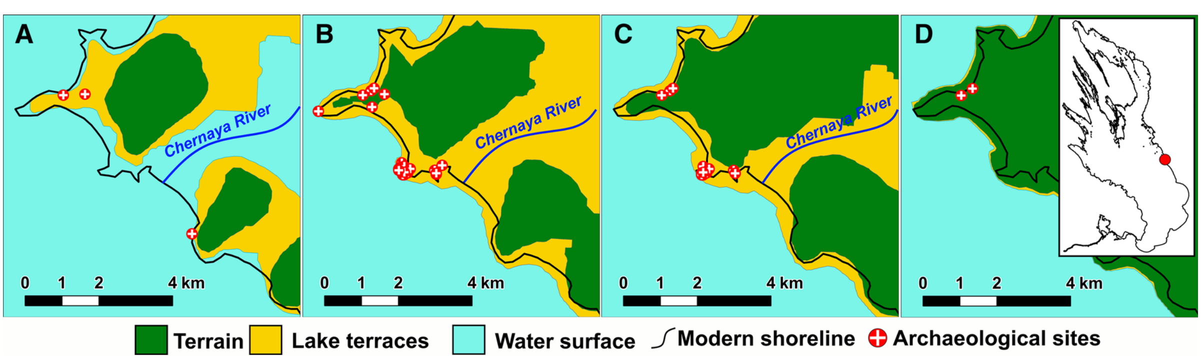

Fig. 6 Spatial distribution of archaeological sites, lake terraces and shoreline at the Besov Nos Peninsula region in the different periods **a** Boreal (BO), **b** Atlantic (AT), **c** Subboreal (SB), **d** Subatlantic (SA)

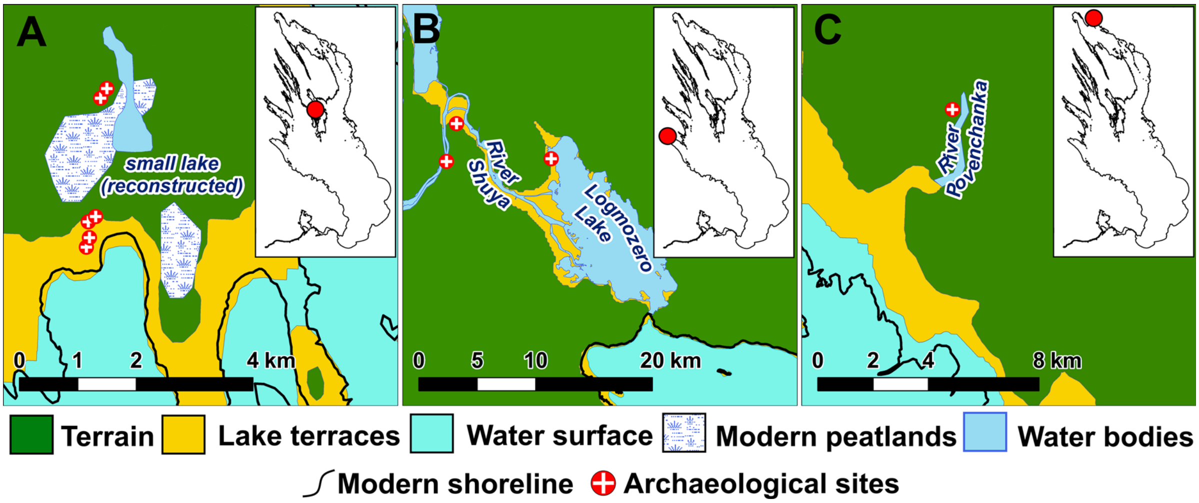

Fig. 7 Deficiencies of the shoreline and archaeological sites positions. **a** Reconstructed small lake (SB); **b** the River Shuya region (SA); **c** the Povenets region (AT)

the discharges directions and formation of Lake Onego through six main stages proposed by Demidov (2006a). The formation of the proglacial lake began in the south part of the modern Lake Onego from the opening of water divide into the Baltic Sea basin through stream ways of modern rivers Oshta-Tuksha-Oyat' (Fig. 2a) near 14.5 cal ka BP at height 120 m asl (Kvasov 1976). Later the threshold was eroded by a stream, that was cut into loose deposits down to 106 m asl. The volume and area was the smallest for the considered period (Figs. 2a, 8), even smaller than contemporary. Together with a glacier retreatment to the North 14.3 cal ka BP (Kvasov 1976; Saarnisto and Saarinen 2001) a new threshold was opened through a Svir' river valley (Fig. 2b) and the level was dropped down to 85–75 m asl (Demidov 2006a). However, since the retreating glacier released new territories which were submerged at once, the level drop didn't significantly affect its overall size. The rise of the lake continued due to the glacier retreatment and reached almost three times the current volume of water and surface area by a factor of 1.5.

By 13.3 cal ka BP, the lake had reached its peak development and expanded northwards far beyond the modern watershed (Figs. 2c, 8). It was still dammed by glaciers and low drainage thresholds at North-East were hold by ice blocks. The glacier continued to extensively feed the lake and lake reached more than five times the current volume of water and surface area at least thrice. The rise of lake volume through the all stages of its growth was not connected with dramatic discharge events; it was relatively constant and maintained at values 120 km^3 per 100 years.

Through 13.2–12.3 cal ka BP a chain of dramatic discharge events took place, which resulted in a more than 40% volume and 33% area reduction. In the end of the Allerød—beginning of Younger Dryas an extensive regression of the Onego proglacial lake occurred and dramatically changed the shoreline position and the structure of bottom sediments (Demidov 2006a). At the first stage (13.2 cal ka BP), the lake acquired a new runoff to the White Sea basin (Figs. 2d, 8), and the lake level was dropped by 10 m as a result (Demidov 2006a). It was the largest regression for the lake history after the last glaciation, and resulted in a one-third area reduction of the lake and more than 440 km^3 of fresh water was discharged into the White Sea. The hydrochemical situation at the bottom-water interface changed dramatically because of the regression and redirection of currents in the lake (Demidov 2006b). According to the hypothesis of Demidov (2006b) the changes resulted in the oxidation of the top layer of bottom sediments and the formation of the "pink" stratum of varved clays 10–15 cm thick throughout the all ice-dammed lake.

The second stage of the regression was relatively slower, occurring over 800 yrs. This time the proglacial lake attained another runoff threshold across the northern part of the Onego-Ladoga water divide (Figs. 2e, 8) through Gar'jusuo peatland—

Table 2 Archaeological sites dating and distancing (in meters[a]) from the modelled shoreline in different climatic periods

Sites periods (sites quantity) \ Shoreline periods	PB	BO	AT	SB	SA
PB (n = 2)	Mean: 26 SD: 37 Min: 0 Max: 53	Mean: 173 SD: 150 Min: 66 Max: 279	Mean: 625 SD: 385 Min: 353 Max: 897	Mean: 1321 SD: 1252 Min: 436 Max: 2207	Mean: 3046 SD: 209 Min: 2898 Max: 3194
BO (n = 14)	Mean: − 323 SD: 472 Min: − 1609 Max: 53	Mean: 29 SD: 79 Min: − 23 Max: 279	Mean: 113 SD: 244 Min: 0 Max: 897	Mean: 808 SD: 1167 Min: 0 Max: 2736	Mean: 2148 SD: 2840 Min: 40 Max: 7085
AT (n = 97)	Mean: − 578 SD: 527 Min: − 2565 Max: 53	Mean: − 271 SD: 410 Min: − 2212 Max: 279	Mean: 8 SD: 41 Min: − 50 Max: 353	Mean: 122 SD: 297 Min: − 25 Max: 1284	Mean: 549 SD: 868 Min: 0 Max: 3671
SB (n = 60)	Mean: − 1144 SD: 1070 Min: − 4565 Max: 0	Mean: − 682 SD: 787 Min: − 2995 Max: 41	Mean: − 7 SD: 46 Min: − 281 Max: 71	Mean: 13 SD: 38 Min: − 62 Max: 162	Mean: 267 SD: 474 Min: 0 Max: 3671
SA (n = 13)	Mean: − 892 SD: 926 Min: − 3741 Max: − 292	Mean: − 408 SD: 846 Min: − 2995 Max: 0	Mean: − 13 SD: 47 Min: − 169 Max: 0	Mean: 6 SD: 28 Min: − 62 Max: 51	Mean: 120 SD: 100 Min: 0 Max: 302

[a]Zero distance means the site situated in the range of lake level fluctuation; positive value have sites situated onshore, while negative ones indicates submerged sites

Nyalma River–Vidlitsa River (Saarnisto et al. 1995). The lake level dropped by around 15 m, and then steadied out for a long time period covering nearly the entire Younger Dryas. The water volume reduction this time was near 150 km^3 k $year^{-1}$.

At the end of the Younger Dryas, when the drainage pathway via the Svir' River to Lake Ladoga was reopened (Figs. 2f, 8), another regression happened. By that time, the lake had already lost its connection with the glacier, which had retreated westwards (Demidov et al. 2006). The regression caused a drop of the lake level by around 20 m, resulting in the drainage of large areas near the shore and considerable downcutting of rivers. The volume was reduced over 113 km^3 per 100 years.

Currently only one other model of Lake Onego development by Gorlach et al. (2017) with area and volumes estimates is available. The model suggests two stages of Onego proglacial lake development, that contrast with ours at 14.4 and 13.8 cal ka BP. The first one is proglacial lake formation stage in the south part of the lake depression and the second one represents partial depression deglaciation. Taking into account linear trend of area and volume rising in this period (Fig. 8) we can estimate the volume and area at the same periods as Gorlach et al. (2017). The data comparison shows high discrepancy in the results: our model suggests that 14.4 cal ka BP the area and volume of the proglacial lake were 5080 km^2 and 304 km^3 in average, while Gorlach et al. (2017) reports 820 km^2 and 21.95 km^3 respectively. At

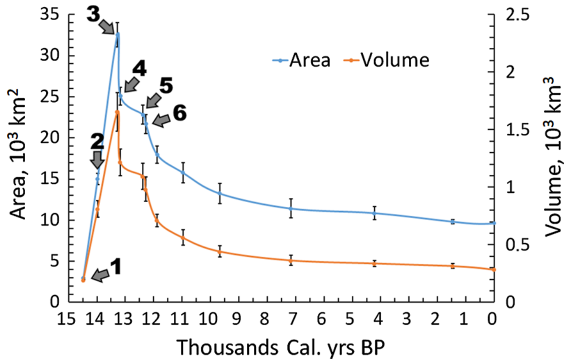

Fig. 8 Dynamics of area and volume changes from 14.5 cal ka BP until present. Main thresholds and associated catastrophic drops are shown with numbers: 1—first stage of deglaciation, discharge into the Baltic Sea basin through stream way of modern rivers Oshta-Tuksha-Oyat'; 2, 3—Into the Ladoga lake depression through pra-Svir' streamway; 4—Into the White Sea basin through the Onego—Vygozero threshold; 5—into the Ladoga Lake depression through Gar'jusuo peatland over rivers Nyalma—Vidlica streamways; 6—Into the Ladoga Lake through Svir' River

13.8 cal yrs BP our results show the area of 19,900 km^2 and volume 1033 km^3, while Gorlach et al. (2017) reports 6852 km^2 and 131.91 km^3 only.

Despite the numerous simplifications employed by Gorlach et al. (2017), namely the usage of the robust GTOPO30 DEM data in the studied region and modest glacioisostatic uplift interpolation between 19.0 and 12.0 cal ka BP followed by Ågren and Svensson (2007), the observed strong discrepancies seemed only partially linked with them.

It seems that the largest discrepancies are coupled with the ice margins positions, as it was shown in Leverington et al. (2002a). Gorlach et al. (2017), as well as our model, applied end-moraine positions from Saarnisto and Saarinen (2001) and Demidov (2006a). However, the ice margins were interpreted differently over the lake surface: for both stages, the ice margins by Gorlach et al. (2017) were southward from ones evolved by Demidov (2006a). As a result, relatively small differences in the ice margins positions led to manifold variation in the area and volume estimations. Since the edge of the glacier retreated with time, it is possible to compare the time scale in the work of Gorlach et al. (2017) with our research.

In Gorlach et al. (2017) 14.4 cal ka BP—the initial phase of the first deglaciation stage—was reconstructed. At that time the ice margin remained southward from the current lake shoreline coinciding with 14.6 cal ka BP of our model. For 14.5 cal ka BP we reconstructed the last phase of this stage, when the ice margin was northward from the current shoreline, but the Svir' outlet was still dammed by the ice. It is also valid for the second stage (13.8 cal ka BP), where the initial phase of the lake surface deglaciation was reconstructed in Gorlach et al. (2017) and coincides with 14.3 cal ka BP phase in our model. Thus, the last phase of this process (14.0 cal ka BP) was shown on our reconstructions and demonstrates the stage where the ice sheet released most part of the lake surface, but its tongue remained on the Zaonesh'skii Peninsula. This way the ice margins positions and discrepancies in time scales of the different deglaciation models were deemed to be the major factors of the area and volume uncertainties between these two independent studies.

Onego Lake development in Holocene

During the Holocene Lake Onego transgressions alternated with regressions. Water level fluctuations were driven by climatic change namely by the rainfall amount, as well as by the lake depression glacioisostatic uplift, erosion and soil slip processes at Svir' threshold outlet (Devyatova 1986; Elina et al. 2000). The erosion process seemed to be the most important in the end of YD, when the volume reduction achieved 68 km^3 per 100 yrs. Later a vital role in the lake evolution was held by glacioisistatic uplift process, which was the fastest in PB period (Fig. 8), when the lake volume reduction is estimated as 166 km^3 k year^{-1}. This process slowed down later, reaching 92 km^3 k year^{-1} in BO and 31 km^3 k year^{-1} in AT. Beyond the SB period the volume reduction faded out from 9 km^3 k year^{-1} to 7 km^3 k year^{-1} until the present time.

Degradation of the Baltic Ice Sheet and subsequent climate warming finally led to peopling of the Lake Onego region. Human habitation in the Eastern Fennoscandia in general started at the turn of PB and BO periods. Many archaeological sites dated to the Late PB—Early BO time (ca. 10.8–10.0 cal ka BP) have been investigated in the last few decades in South-Eastern Finland and the Karelian Isthmus (Kriiska et al. 2016; Pesonen et al. 2014; Gerasimov et al. 2010).

According to paleogeographical investigations, ecological conditions on the shores of Lake Onego became favorable for human settlement from the end of the PB period (Fig. 3b), when forested tundra landscapes with birches dominating among tree species, mostly in a form of bushes, and subordinate pines appeared in the region (Devyatova 1984, 1986; Devyatova et al. 1987; Elina et al. 2000). In the BO period (Fig. 3c), this landscape was replaced by forests of northern taiga type with dominating birch and pine trees (Devyatova 1986, Devyatova et al. 1987; Elina et al. 2000). However, data confirming habitation before the Late BO period were lacking until recently. The first reliable dates for this period were obtained during the last two years. Radiocarbon dates made of burnt animal bones from sites at the northern shore of the lake showed an Early Boreal Age, ca. 10.4–10.1 cal ka BP (Tarasov 2018). Therefore, the Lake Onego region definitely was included in the Early Holocene migration processes in the Eastern Fennoscandia. At the moment there are no Late PB dates, but we can expect that they will be obtained in the future.

As it can be seen from the quantitative analysis of archaeological sites distancing from the reconstructed shorelines (Table 2) in most cases the cornerwise cells contain close to zero values of mean, SD, max and min (marked with green color), which indicates that the sites dates correspond to the modelled shoreline and our model runs well in most of cases. Only in one case analysis showed a better fit for none-cornerwise cells (SB shoreline against SA sites, marked with yellow), but not conversely. This indicates the peculiarity of the sites dataset in conjunction with water level fluctuation, which was slightly lower in SA time compared with SB and the present time. Owing to the fact that all the sites have been discovered only recently when many of SA sites were already submerged, only high-up sites could be discovered and presented in the dataset for SA period, which in its turn showed shorter distances compared with SB period. However, the mean distance between archaeological sites dated with SB period and the shoreline modelled for this period was still in the accepted 100 m interval.

From PB to SB periods the mean sites distance didn't exceed 100 m from the shore, which is in agreement with our previous consideration and indicates the good model fit. Only in one case (SA–SA crossing, marked with orange color) the mean distance did exceed this range. This can be a consequence of both of mentioned above data set specificity or of the transformation of hunting- and fishing-based economies to the agricultural ones, or at least, to a complex economy integrating hunting and gathering with agriculture and pastoralism, when the proximity to arable land was becoming as important as the proximity to the local water sources. The latter can be expected since the first millennium AD.

From the perspective of the foregoing analysis, the model is sufficiently adequate and accurate to make both qualitative and quantitative assessment. In this article, the information concerning the dating and location of archaeological sites was used for digital reconstruction and verification of the shoreline formation during the Holocene period. However, this can work in an opposite manner as well, as the model can be used for prognostic purposes during archaeological surveys. With this model, we get a new tool for predicting location of yet undiscovered sites, especially the sites belonging to the earlier periods.

One of the directions of future work might be the search for submerged sites on the southern coast of the lake. The idea of southern coast encroachment was proposed quite a long time ago (Savateev 1984), and is supported by numerous stray finds dated to the AT–SA periods (Neolithic–Iron Age) that can be collected along southern shores, especially after storm events. These artifacts definitely originate from submerged human settlements. Our model also confirmed the possibility of their existence: the ancient shores were found to be situated up to hundreds meters outshore from the modern shoreline position.

Conclusions

GIS-based reconstructions of Lake Onego development in the Late Pleistocene and the Holocene were presented in the paper. Reconstructions were originated from the ideas of the Lake Onego depression deglaciation model proposed by I.N. Demidov and the data of E.I. Devyatova concerning Lake Onego depression isostatic uplift in the Holocene. GIS-modeling was performed using ArcGIS software on the base of original digital elevation model of the Onego lakebed, its watershed and other 125 lakes depressions. The reconstructions for all periods were unified, had spatial resolution 90 m and a strict geographic conjunction. Twelve digital paleogeographic maps available on-line were developed as a result (http://arcg.is/0Kyr9a).

Paleogeographic maps were verified by using hand-drawing images of I.N. Demidov and E.I. Devyatova and by matching lake shoreline with a position of archaeological sites. Compared with hand drawings of I.N. Demidov, our maps were considerably more detailed and had strict geographic reference. On the contrary, in comparison with E.I. Devyatova reconstructions, our maps roughed the fine relief forms. The main reason for this was a higher vertical error of DEM used. Even so, the common shoreline configuration and dimensions of large islands conform to sketches and descriptions of E.I. Devyatova. Considering this, the reconstruction presented new data about shoreline position on the unstudied areas, which cover most of the lake shoreline. The maps have been produced for the whole lake surface, which was not conducted earlier.

Based on our reconstructions the area, volume, maximum and mean depth of the lake were determined at different stages of its development. The dynamics of water fluctuations are also presented. The discrepancies in ice margins positions and/or time scales were found to be major factors of the area and volume uncertainties between Gorlach et al. (2017) model and ours.

The high definition maps obtained during this study are able to support foregoing field surveys with detailed georeferenced data about relict lakes positioning. They can be applied for qualitative estimation of bottom deposits stratigraphy and lakes origin in the area of Onego proglacial lake. Awareness of the lake's shoreline position in Holocene allows us to determine areas where human settlement was possible, and increases our chances of discovering new archaeological sites.

Acknowledgements The study has been financially supported by the Presidium RAS program #19 "Fundamental problems of geology-geophysical studies of lithospheric processes" (50%) and by the Russian Science Foundation #18-17-00176 (40%). Part of paper writing by Tarasov A. was completed within the current research project of the Department of Archaeology of the Institute of Linguistics, Literature and History of the Karelian Research Centre of Russian Academy of Sciences, state registration number #0225-2014-0014 (10%). The authors are especially grateful to A.M. Zhulnikov, N.V. Lobanova, M.V. Ivanishcheva, and K.E. German for providing georeferenced data for archaeological settlements on Onego Lake shoreline.

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