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Sedimentation dynamics in the littoral zone of Lake Peipsi

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Abstract Bottom sediments of Lake Peipsi proper were mapped in the 1970s' from the research vessel but for technical reasons near shore areas were not investigated. The present work is the first attempt to fill this gap. Based on the surface sediment mapping of the whole lake basin, we identified 11 key areas of the littoral zone and provided a detailed survey of the sediments. By the grain-size, the surface sediment samples can be separated into three groups: coarse-grained (predominantly sands in the near shore areas and in the southern part of the lake), fine-grained (mainly silts) and clayey sands, both in the central deeper part of the lake within the 8 m depth contour. Because of a complicated system of currents, the granulometry of deposits shows distinct spatial distribution. Long-term observations have shown that the water level in Lake Peipsi changes cyclically, i.e. years with a low water level alternate with years with a high water level. This phenomenon causes fast erosion in some years and exuberant growth of reed and bulrush and accumulation of fine material in the coastal zone in other years. Water-level fluctuations affect the sediment characteristics and aquatic vegetation assemblages and have influence on the land use, fishery and recreation.

Keywords *• Near shore sediment • Littoral zone • Shore types • Erosion and accumulation • Protection of the coasts • Lake Peipsi*

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INTRODUCTION

Lake Peipsi (L. Peipsi) (Fig. 1) is large (3,555 km^2) inland body of water on the border of Estonia and Russia. It belongs to the Baltic Sea catchment and is located south of the Gulf of Finland into which it drains via the Narva River. The average depth of the lake is 7.1 m and the maximum 15.3 m. The northernmost and largest part of the lake is shallow Peipsi proper (Big Lake or Lake Peipsi *sensus stricto* – L. Peipsi *s.s.*). It is connected to the southernmost part, Lake Pihkva (Pskov) via the narrow strait like Lake Lämmijärv ("Hot Lake"). L. Peipsi is of great economic significance, first, in terms of water transport, fishery and energy production (Kangur *et al*. 2012). The bottom deposits hold great reserves of curative mud and building materials, and the waters cool the huge kettles of the Baltic and Estonian Thermal Power Plants and drive the turbines of the Narva Hydropower Station. Beaches of the lake, especially northern beach of the L. Peipsi *s.s.,* have a high recreational value (Tavast, Raukas 1996).

The first scientific studies of the lake were initiated after the catastrophic floods of the 1840s', which caused great damage to adjacent areas. As the fish breeding in the lake required regulation, the first studies focused mostly on the hydrology and biology of the lake. Karl-Ernst von Baer (1860) guessed that meliorative works and forestry cutting in the watershed have caused catastrophic floods. To avoid big floods, Helmersen (1864) proposed to lower the water level of lake about 1 m, dredging the upper course of the Narva River. Lowering the lake's water level became a topical matter again after the extremely water-rich years at the beginning of the 1920s'. In Nina Village on the western coast of L. Peipsi south of Kallaste Town (near Pusi site), local

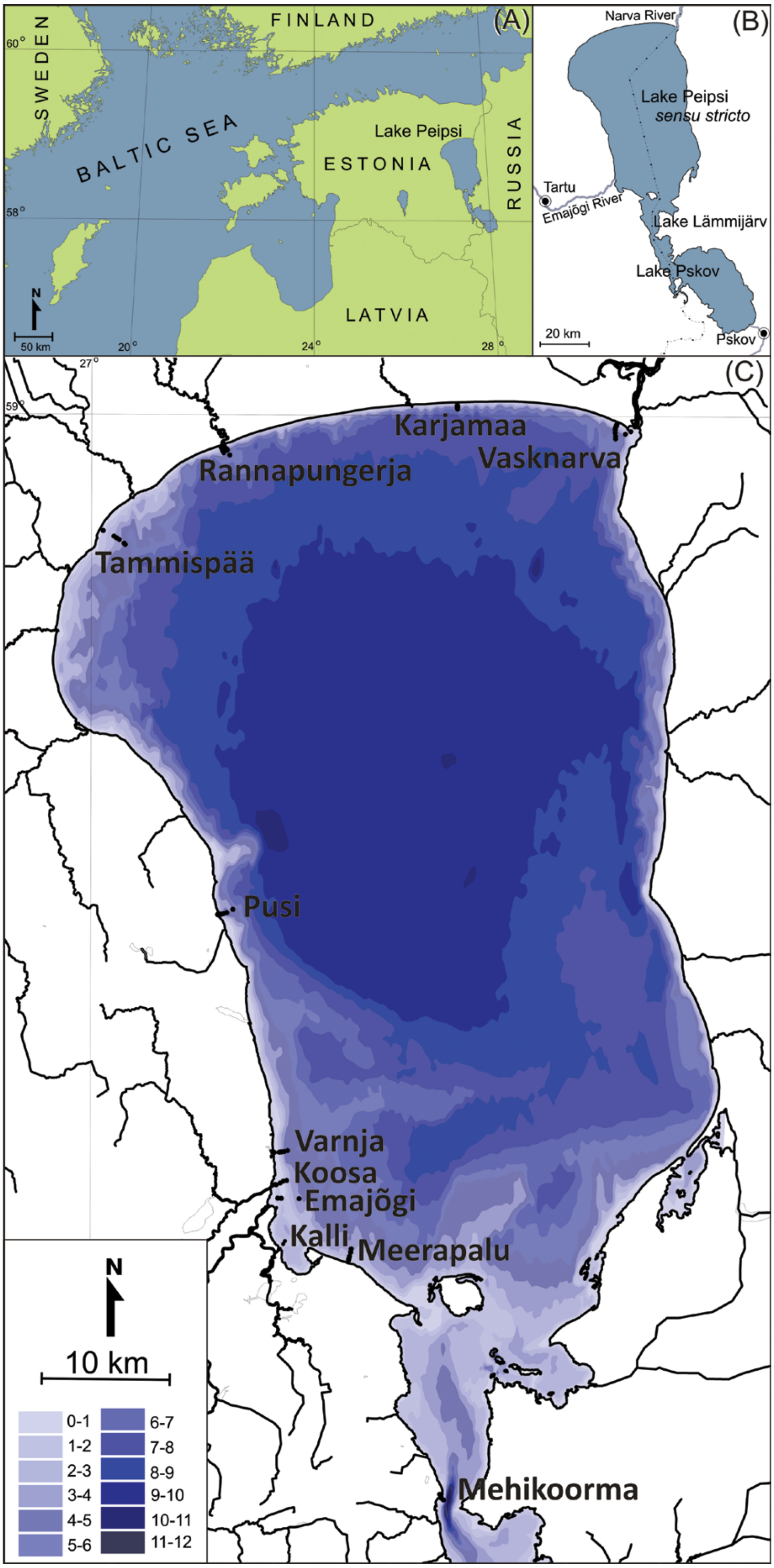

Fig. 1 Location of Lake Peipsi (A), Lake Peipsi *sensu stricto* (B), and studied sites, lake depths, inflows and outflows (C). Compiled by J. Terasmaa, 2013.

inhabitants had to be resettled and shore defence constructions were built (Vichmann 1929).

Bottom sediments of L. Peipsi were mapped in the 1970s' from the research vessel of the Institute of Geology of the Estonian Academy of Sciences (Raukas 1981; Raukas, Rähni 1981). The draught of the vessel was 1.4 m. Therefore, near shore areas were not investigated. This work is the first effort to fill this gap. Together with the latest L. Peipsi *s.s.* surface sediment map (Punning *et al*. 2009) it will give a complete overview of the lake deposits. The studies of surface sediments have scientific and practical value, as they are the basis for understanding the sediment dynamics. Particles in shallow lakes may repeatedly settle to the bottom and be re-suspended throughout the water column (Luettich *et al*. 1990).

SEDIMENTATION CONDITIONS

Helmersen (1864) presented the first classification of lake shores. During last decades, several new classifications have been proposed and the coasts of the lake are described in detail (Tavast 1984, 1999; Raukas, Tavast 1989, 2005).

Recent classifications distinguish the abrupt cliffed shore (an abrasional escarpment in Devonian sandstone), erosional scarp shore (an abrasional bluff in sand, till or peat) and flat erosional-accumulation shore. The last one can be divided into (1) till shore – an abrasional shore with a protective cover of boulders, sometimes with a thin layer of sand, (2) gravel shore – an accumulation shore with pebbles and gravelly sediments, (3) sandy shore – an accumulation sandy beach with a ridge of foredunes, (4) silty shore – an accumulation shore with silty-clayey sediments, and (5) artificial shore with man-made structures. Our key areas for the study of littoral processes were chosen at different shore types in different hydrological conditions close to the state monitoring stations (Raukas, Tavast 2011).

Changes in the hydrological regime and fluctuations of the lake level alter the lake morphometry and transform the characteristics of sedimentation zones of the lake floor thereby they directly influence sedimentation and resuspension (Davis, Ford 1982; Bloesch 1995; Shteinman, Parparov 1997). The wealth of information exists about the water level fluctuations in L. Peipsi over hundred years. This gives the potential for carrying out the prognosis of the future water levels and possible damages of the coast in the coming decades.

Long-term observations have shown that the water level in L. Peipsi changes greatly (Jaani 1973, 2001) that complicates water transport, shore protection and recreational possibilities around the lake. Both, water erosion and hummock ice have changed the coasts. The regional glacioisostatic uplift (0.4 mm yr^{-1} in Rannapungerja) and sinking (–0.8 mm yr^{-1} in Mehikoorma) of the lake basin (Miidel 2008) has caused slow movement of the water masses to the south. This means that erosion of the northern coast will diminish and large areas in the southern coast will be flooded in the coming future.

The small depths, large surface and drainage areas make L. Peipsi extremely sensitive to climatic fluctuations and other environmental changes occurring in its drainage basin. Seasonal and especially long-term water level fluctuations in L. Peipsi (Jaani 1973, 2001) are considerable and rather well studied. Distinct rhythmicity has been observed in lake-level fluctuations. In the recent past during 1959–1977, the water level in the lake was lower than the long-term average. In the water-rich period 1986–1991, it was 0.5 m above the long-term average. Since 1992, the water level has been constantly lowering. In 1996, the water level in the lake was extremely low and in some places the lake floor was exposed for hundreds of metres. Recently, a new high-water period has started, as it was expected by several publications (Jaani, Reap 2001).

Because of these lake characteristics, erosion and damages on the coast is highly depending on the water level. During the low water-level periods, erosion is not so notable. When the water level rises, the lake shores are intensively eroded and serious damage occurs. At the same time, due to drastic shoreline changes, it is difficult to compare the results of grain-size and mineralogical analyses of different years.

Wind-drift and wind gradient (compensation, flow, seiche and internal pressure streams (Kallejärv 1973) exist in L. Peipsi. The surface water moves in the direction of the wind in the northern part of L. Peipsi *s.s.*, and anticyclonic and cyclonic circulation is characteristic for the southern part. Near the bottom of the northern part of L. Peipsi *s.s.*, the compensation streams are formed; in the shallow southern part, the surface currents reach the bottom.

Waves in L. Peipsi *s.s.* are steep and short and at the wind force of 8 m/sec, their height are 60–70 cm (Sokolov 1983). Waves of this height are most common (57%) in L. Peipsi *s.s.* The highest waves (240 cm) were recorded in 1961 and 1962 with the wind force of 20 m/sec.

Because of the shallow depth, the lake ice, which lasts 114 days in average, plays a great role in the sedimentation and resedimentation of bottom and coastal deposits. Almost every spring, ridges of pressure ice, which are up to 10 m high, are pushed forward against the shore, shaping the coast, redepositing older sediments and transporting huge boulders (Fig. 2). Lake ice and small icebergs can carry coarse material to the area of fine-grained sediments. The effects of ice-push are greatest on sandy beaches on the northern and western coast of the lake where deep furrows are often formed on the beach.

In deeper areas, fine-grained organic rich sediments occur and water-level fluctuations cause their resuspension. Fine-grained organic-rich sediments are very cohesive and play the main role in the circulation of various inorganic and organic pollutants such as nutrients and xenobiotics. L. Peipsi acts as a regional sink for atmospherically transported particles and chemical compounds as well as those originating from the catchment (Punning *et al*. 2008). Because of the

Fig. 2 Hummocky ice on Lake Pepsi *s.s.* coast in Nina Village near Pusi site. Photo by E. Vabamägi (15 April, 2010).

cohesive character of sediments, the lake floor could be subject to episodic erosion and resuspension during certain meteorological events (changes in the water level etc.). This may cause remobilisation of nutrients from muddy sediments and their return to the lake ecosystem. During the Soviet period (1940–1991), a great quantity of pollutants from industrial and agricultural sources was deposited into the lake which has resulted in an intensive growth of reed and bulrush that formed up to 150 m wide belts on the foreshore (Mäemets, Mäemets 1999).

METHODS OF INVESTIGATION

The whole near shore area was sampled and eleven study sites were selected for more detailed investigation (from south to north: Mehikoorma, Meerapalu, Kalli, Emajõgi, Koosa, Varnja, Pusi, Tammispää, Rannapungerja, Karjamaa and Vasknarva, Fig. 1C). Sediment samples were taken with a grab sampler. Samples were stored in previously numbered and weighed plastic boxes. Ninety-one sampling points were determined using *GPS Garmine Oregon* (horizontal accuracy 3–5 m). We took the samples from near shore underwater slope from rubber boat equipped with Sonar system that also provided information about the bottom topography. Winter sampling was done from ice. On the backshore, we used level equipment to measure the profiles.

All analyses were made by authors in the laboratories of Institute of Ecology at Tallinn University. Dry matter in sediments was determined by drying the samples at 105°C to constant weight. Organic matter was measured as loss-on-ignition (LOI) upon heating at 550°C for 210 min. The carbonate content was calculated from the loss of weight after burning the LOI residue at 950°C for 150 min (Heiri *et al*. 2001). We treated the fine-grained sediment samples with organic matter with hydrochloric acid and hydrogen peroxide (Konert, Vandenberghe 1997; Vaasma 2008). After that, the grain-size spectra for particles were measured using a Fritsch Laser Particle Size *"Analysette 22"*. Coarse-grained compounds, larger than 250 µm, were extracted prior to laser spectrometry. To avoid flocculation, an ultrasonic disperser and addition of sodium hexametaphophate (Calgon) were applied. Grain-size of the sandy samples was determined by wet sieving using a Vibratory Sieve Shaker *„Analysette3" PRO*. The results were given as median diameter of particles as defined by the Udden-Wentworth grain-size scale (Last 2001). To provide information about each set of observations describing the studied sites, statistics are presented as five number summaries. Five number summaries include sample minimum, the first quartile, the median, the third quartile and the sample maximum.

STUDIED SITES AND MEASUREMENT RESULTS

Eleven studied sites are distributed along Estonian coast of L. Peipsi (Fig. 3). The distance between sampling points within profile was in average 180 metres. The water depth varied from zero to 6.5 m (mean depth 2.9 m). All samples are minerogenic (from 87.0 to 99.9%, mean value 98.3%) and dominated by sand (biggest share between 100–200 µm) (Fig. 4).

Mehikoorma site is characterized by sandy beach. It is located in the vicinity of the deepest part of L. Peipsi (>15 m). Site contains seven sampling points with in average 2.0 m water depth. Their maximum distance from the coast is 595 m. Sediment mineral matter content varies between 97.7 and 99.0% (average 98.5%) and grain-size varies from fine to medium sand (median between 108.1 and 305.7 µm). Standard deviation of this dataset is around average (σ = 88.5) compared with other studied sites. Nearcoast shallow water sediments are coarser than sediments farther away from the coast.

Meerapalu site contains six sampling points in up to 4.0 m deep water (average 2.4 m), up to 1070 m away from the shoreline. Mineral matter content is between 95.7 and 99.6%; grain size varies from very fine to medium sand (median 96.7–295.2 µm). The standard deviation is below the average (σ = 67.4).

Kalli River site is situated south from the mouth of the Emajõgi River. Water depth of the sampling points varies between 1.5 and 2.8 m (average 2.0 m); maximum distance from the coast is 890 m. Sediment mineral matter content is between 96.1 and 98.0%. Grain size varies from very fine sand to fine sand (75.4–145.6 µm), so variations are low (σ = 38.2).

Emajõgi River site is located in the mouth of the Emajõgi River; water depth varies between 1.4 and 4.5 m (average 3.1 m) and maximum distance from the coast is 1860 m. In comparison with other sites, mineral matter content is lowest (from 91.1 to 96.8%, in average 94.6%), probably because of the river inflow. Grain size varies from very fine sand to find sand (median 70.8–152.8 µm). Variations are similar to the Kalli River site (σ = 39.9).

Koosa River site is located north from the Emajõgi River mouth and water depth is between 1.2 and 3.3 m (average 2.1 m). The furthermost sampling point is situated 1860 m from the coast. Sediment mineral mater varies between 95.9 and 99.0%. Grain size distribution mean shows fine sand (median 137.7–159.3 µm). Standard deviation is one of the lowest (σ = 10.3).

In Varnja site the water depth varies from 1.0 to 5.5 m (average 3.5 m) and maximum distance from the coast is 1190 m. Sediments are rich of mineral matter – one of the highest within studied sites (between 99.3 and 99.7%). Grain size is mainly fine sand (median 135.8–167.2 µm), with low standard deviation (σ = 12.3).

Pusi site is covered with vegetation. Water depth is between 0.5 and 6.5 m (average 3.5 m), maximum distance from the coast is 1290 m. Mineral matter content varies from 98.9 to 99.7%. Grain size distribution is characterized by fine sand (median 139.7–167.2 µm), with lowest standard deviation (σ = 9.1).

Tammispää site is located in the northwestern coast

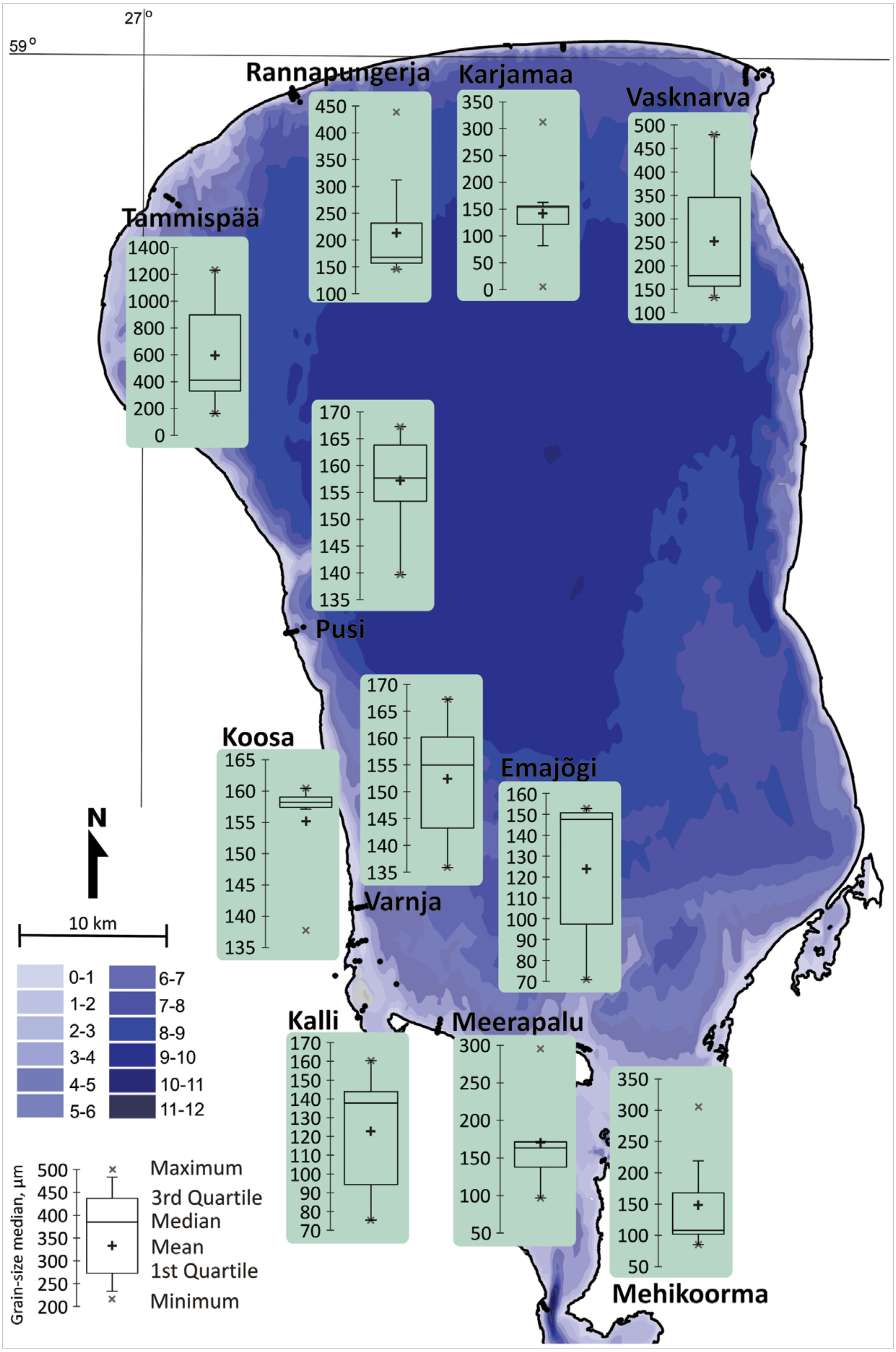

Fig. 3 Descriptive statistics (maximum, 3[rd] Quartile, median, mean, 1[st] Quartile and minimum) of the grain size on investigated sites. Compiled by J. Terasmaa, 2013.

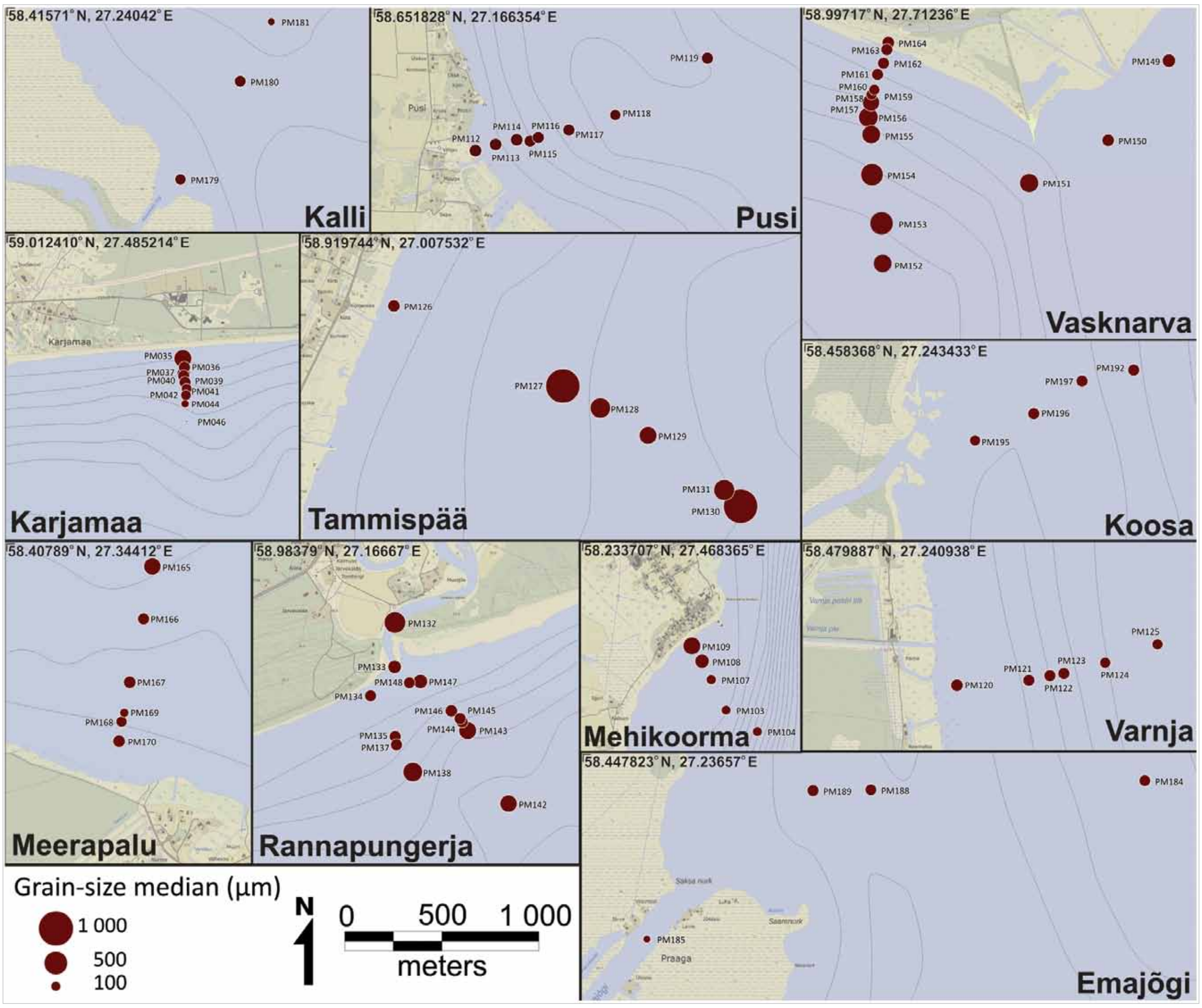

Fig. 4 Grain size median values of sampling points on studied sites. Dashed lines show the water depth with 1 m step. Compiled by J. Terasmaa, 2013.

of the lake. Water depth varies between 0.9 and 5.8 m (average 3.9 m) and maximum distance from the coast is 2130 m. Mineral matter content is between 96.9 and 99.6%. Grain size distribution varies from very fine to the very coarse sand (median 162.7–1231.1 µm). Large variations lead to the greatest standard deviation (σ = 437.5).

Rannapungerja site is located in the mouth of the Rannapungerja River. Because of the difficult geomorphological conditions (inflow channel and underwater ridges), the sampling method was modified – 12 samples were taken in two parallel profiles and one sample was extracted from the river bottom. Water depth of sampling points range between 0.8 and 6.3 m (average 3.1 m) and maximum distance from the coast is 830 m. Mineral matter content varies from as low as 95.1 to 99.8%. Grain size is distributed from fine sand to medium sand (median 145.6–438.3 µm), with greater than average standard deviation (σ = 98).

Several underwater sandy ridges (Fig. 5) characterize Karjamaa site in sandy beach. Water depth varies from 0.1 to 5.3 m (average 2.2 m); maximum distance from the coast is 323 m. Sediment mineral matter content is in average 97.4%. Grain size is from fine to medium sand (median 142.1–312.1 µm) with average standard deviation (σ = 81.3).

Vasknarva site is located near the outflow of the Narva River. Several underwater sandy ridges (Fig. 5) characterize also this site in sandy beach. In addition to the sampling profile, three sampling points are located in the direction of the outflow. Water depth is between 0.1 and 6.2 m (average 2.9 m) and maximum distance from the coast is 1160 m. Mineral matter content is highest and varies between 98.9 and 99.9%. Grain-size distribution is from fine sand to the medium sand (median 132.1–479.0 µm), with great standard deviation (σ = 122.8).

DISCUSSION

In the shallow coastal regions of L. Peipsi *s.s.*, sediments are relatively coarse-grained (see Figs 3 and 4), and predominantly consist of sands that are similar to the beach deposits and the river inflow. The largest amount of material seems to originate from the erosion of the coastal zone, from both above and below the lake level, determined mainly by the complicated current system in the lake. Sediment in the mouth of the River Emajõgi (study sites Emajõgi, Kalli and Koosa; see Fig. 3) is rather fine-grained (from very fine sand to fine sand) and well sorted. Another important sediment source in the southern part of the lake is the inflow through Lake Lämmijärv. Lake Lämmijärv has relatively fast flow rate (sometimes more than 50 cm/s) and acts as a river where the matter is transferred from Lake Pskov to the L. Peipsi *s.s.* Compared to L. Peipsi *s.s*. and Lake Pskov the bottom topography of Lake Lämmijärv is very variegated and coastline intended. There are two deeper and several shallower hollows, therefore, sedimentation in this part of the lake is complicated and the distribution of sediments is mosaic. In Mehikoorma and Meerapalu sites, grain-size varies from very fine to medium sand. This sandy area covers south-western shallow part of the lake (from the Meerapalu site to the Pusi site).

Shoreline changes and beach erosion have been caused by several geological (initial rocks and sediments, tectonic movements, slope gradient) and hydrometeorological (hydrology, wind regime, wave-action, ice-push) factors and human activity. The south-westerly and southerly (45–50%) winds predominate in the depression of the lake, causing high rises in the water-level in the northern part of the depression and intensive erosion of the coast (Raukas, Tavast 2005). Wind-generated waves serve as most important energy-transfer agents changing the coast and transporting sediments. In the near shore area, the erosion of sandy shore sediments with clear long shore transportation exists (Punning *et al.* 2009). As a result of long shore erosion, modern lake sediments are absent in extensive areas in north-western and northern coasts, or till and varved clays are covered with a thin layer of residual sediments ranging from several to some tens of centimetres in thickness. Till in the Tammispää site consists of unsorted material. The deposits contain also a sizeable fraction of coarse (>1000 µm) material such as fragments of shells, gravel and conglomerate.

Erosion of the sandy beach in the foreshore on the northern coast of the lake has produced well-sorted fine- and medium-grained sand, rich in quartz (72–95%) and feldspars. Decrease in the amount of carbonates and increase in the quantity of quartz, zircon and tourmaline in a southerly direction should be pointed out as the main quantitative differences (Raukas 1999). Importantly, L. Peipsi *s.s.* sediments do not bear direct relationship to the local bedrock (Silurian carbonate rocks in the north and Devonian sandstones in the south); instead, the minerals are carried to the lake through the Quaternary deposits, hence, just after recurrent redeposition.

The influence of the rivers is clearly visible in the mouth of the Rannapungerja River. Strong river flows form underwater ridges of the river sediments at 600 m distance from the coast and sediment movement is

Fig. 5 Orthophoto of the Rannapungerja study site. Inflow of the Rannapungerja River and underwater sandy ridges (after X-GIS . Estonian Land Board, 2009).

forced by the river current (Fig. 5).

The activity of coastal processes and storm impact are controlled by coastal geomorphology: near shore topography, shoreline configuration and exposure to the waves. After heavy storm in November 1987, the sandy scarp near Alajõe retreated 4 m and a new high bluff formed in ancient dunes. Also, the coast near Kuru Village, typically characterized by the accumulation processes, retreated 3 m (Raukas, Tavast 2005). The coastal scarp at Remniku (near the Karjamaa site) on the northern shore retreated for 7 metres during 1981–1994. As a result, the great amounts of the backshore sand were eroded to the lake. Material is moving to the east, in the direction of outflow of the Narva River, causing clogging of the outflow (Fig. 6). At present, the sand drift is directly carried into the river, where it accumulates both, in the river channel and in the upper portion of the Narva Reservoir (Jaani 1999). If we consider that the amount of sand between jetties near the outflow of the Narva River is 600 000 m^3 (Jaani 1999) and the time of accumulation is 70 years, then the accumulation rate of sand is 8571 m^3 yr^{-1} (not considering the transit material).

The lithological characteristics reflect clearly an impact of the current systems of the lake. In the near shore area, erosion of sandy coastal sediments with clear long shore transportation occurs. In the central deeper area, deposition of fine-grained particles, transported by the complicated current system from the near shore areas and mixed with autochthonous organic material, play the most important role. In the shallow coastal regions, sediments are relatively coarse-grained and consist, for the most part, of sands. Long shore drift in the shallow water is limited and its occurrence is significant only at the northern coast of the lake. Here, the Narva River, the only outflow from the lake, promotes clear long shore drift from the west to the east, gradually blocking the outflow area. Furthermore, because of the long shore erosion, modern lake sediments are largely absent in this area, or, the till and varved clay are covered with a thin layer of residual sediments, with thickness ranging from several millimetres to some tens of centimetres. Erosion of the sandy beach in the foreshore between the Rannapungerja and the Narva rivers has produced well-sorted fine- and medium-grained sand, tens of centimetres up to several metres thick. The sands overlay directly on the Pleistocene deposits that crop out during low water periods.

Fig. 6 Ortophoto of the Vaskvarva study site. Outflow to the Narva River, underwater sandy ridges and clogged up jetties (after X-GIS. Estonian Land Board, 2009).

CONCLUSIONS

The study presented results of detailed sampling of near shore sediments of L. Peipsi *s.s.* and discussed the coastal processes that influence the sedimentation dynamics of the littoral zone. The findings have importance not only for better understanding of the lake history and prognosing future changes, but also to solve practical problems related to the socio-economic use and management of the lake.

All investigated near shore sediments are minerogenic (from 87.0 to 99.9%, mean value 98.3%) and dominated by sand. Near shore deposits have a distinct spatial distribution, determined mainly by the current system in the lake. The main source of bottom sediments is the erosion of the lake bottom and shores. The sediment load of the rivers and brooks to the lake is moderate and reflects the sediment load in rivers. Long-term observations have shown that the water level in L. Peipsi changes cyclically, i.e. years with low water level alternate with years with high water level. This phenomenon causes fast erosion in some years and exuberant growth of reed and bulrush and accumulation of fine material in the coastal zone in other years. Both processes can reduce the recreational value of the coasts and influence to the water transport. Near the outflow of the Narva River, the movement of sand masses from the west to the east causes blocking of the lake outflow.

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