INFORMATION
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Figure 1. Location scheme of Lake Peipsi and the measurement site (star) near the village of Sääritsa. Depth isolines are drawn at 20 m, 16.5 m, 13 m, 9.5 m, 6 m, 2.5 m, and 0.05 m.

2001a, 2001b). Although the instantaneous water level varies greatly, its average is stable; it was the same (29.97 m over the
mean water level of the Baltic Sea) during 79 years (1921–1999) and 115 years (1885–1999) (Jaani, 2001b). In 1930–1984 the
water input into the lake (0.7–13.2 km³) slightly exceeded the output (10.7–13.1 km³) (Gronskaya and Jaani, 2001). This caused a
slight increase in the water level. During the first 15 years of XXI century this long-term trend will apparently be replaced by
long-term decrease in the water level (Jaani and Reap, 2001).
The movement and mixing of waters in Lake Peipsi are strongly related to quasi-stationary seiches. Uninodal seiches (duration 4 h 57 min, amplitude 5–7 cm) (Jaani, 2001c) have an almost equal period with those in the largest lake in the Europe, Lake Ladoga, Russia (4 h 40 min, 8–10 cm) (Malinina, 1973) but are much shorter than the open Baltic Sea seiches (17–30 h) (Jönsson et al., 2008).

Somewhat surprisingly, the existing pool of studies contains quite a little information about climatology of wind wave fields in
this water body (Jaani and Reap, 2001; Raukas and Tavast, 2011). The only estimates of the spatial distribution of wave properties in
the offshore have been derived for a small selection of wind speeds and using simple fetch-based models (Sokolov, 1983).
According to these estimates the overall maximum wave height should not exceed 2.5 m in the central part of the lake and 2 m in
the nearshore areas. Generally, wave height varies in the range of 0.4–0.6 m for weak winds (3–5 m s⁻¹), reaches 1.2–1.3 m for
winds of 10 m s⁻¹, and rarely achieves 2.3–2.4 m under very strong winds (20 m s⁻¹) (Jaani, 2001d).

Wave impact itself, and its joint action with human activity may dramatically change nature of the shoreline and cause beach
erosion. It is a major problem for shallow inland basins as Lake Peipsi where breaking storm waves are the intense driver for
shoreline modification and the absence or weakening of the wave

METHODS AND DATA
The properties of waves were measured in 2002 in southern part of the lake (not indicated), in 2004 and 2005–2007 (Figure 2) during ice-free periods near the western coast of the lake about 300 m from the coast in about 3 m deep water. Since 2004 the site was located near the village of Sääritsa, about 10 km to the north of Kallaste township (58.75°N, 27.1°E, Figure 1). The campaigns mostly covered the end of summer and autumn. This time of the
year is usually relatively windy in this region and hosts the
second-highest waves in the eastern Baltic Sea (Lopatukhin et al., 2006).
The measurements were performed using an autonomous water level recorder constructed and manufactured by PTR Group
(Tallinn, Estonia). The device is basically a pressure gauge based on a Keller pressure sensor with extended memory capacity. The
sensor was mounted according to the classical scheme in the water column about 1.5 m below water surface, using a suitable
buoyancy and anchor to stabilize its position with respect to the lake bed.
The analysis of the pressure data follows the classical procedure of establishing the surface wave properties from the pressure time series (Dean and Dalrymple, 1990; SBE, 2002). The continuous pressure data series (recorded with a frequency of 4 Hz) was divided into sections with duration of 20 min. The mean pressure and the linear trend were first eliminated from the each section of
the pressure time series. The mean pressure was used for calculating the instrument depth. A Hanning window was applied next to suppress the spectral leakage that occurs when the data contain a periodic signal with a frequency that does not coincide with any of the exact frequencies of the Fast Fourier Transform (FFT) for the particular record. This process was followed by a
multiplication by a proper scale factor (SBE, 2002) in order to keep the total energy of the wave field in the particular section,
and performing the standard FFT of the record. As the pressure fluctuations caused by short waves rapidly decrease with depth,
the amplitudes of waves with the frequencies exceeding a certain threshold were set to zero. Doing so is the standard way to prevent measurement noise from being mapped into unrealistic short wave heights. The truncated spectral density of the pressure was converted to the wave energy spectrum using the pressure attenuation rates for the given sensor position, water depth, and wavelength.

As the estimates of water surface time series, obtained by inverting of the described procedure, not necessarily represent the actual water surface elevations, we only consider the parameters of waves that can be adequately retrieved from the analysis of pressure data: mean wave height, significant wave height \( H_s \) (historically associated with the average height of one third of the highest waves and called simply wave height hereinafter), and mean period (equivalent to \( T_{1/3} \)).

Wave parameters were recorded 72 times a day. The total number of the relevant 20 minute long sections containing adequate wave data is 19,228 on 263 days. During the years 2005–2007 the summer and autumn seasons (July–November) are represented (Figure 2). The wave data contains several gaps. July and November are not well represented and the data set does not cover the period from May to June. As these two months are the calmest ones of the whole year in this region (Soomere et al., 2012), the established wave climatology eventually is biased towards rougher wave conditions.

The maximum monthly data coverage (in terms of the percentage of time covered by successful recordings) is in August (83%). Records of September and November cover about 77–78% of days. The lowest percentage of days is covered by measurements in July (about 20%) and in November (44%). The success rate in July 2002 and 2004 is about 1–5%. Because of a small number of measurements in 2002 and 2004, this data is not considered while establishing characteristics of wave climate in Peipsi Lake.

Most of the recordings (except for the day of deployment and retrieval of the instrument) cover full calendar days. In order to reach the maximum coverage we also use data from these days. As there is certain diurnal variation in the wave properties, we use daily average wave height as recommended in (Zaitseva-Pärnaste et al., 2009; Soomere et al., 2012).

Wave climate

According to data from the Tiirikoja hydrometeorological station (located at the north-western coast of Lake Peipsi, Figure 1) weak and moderate south-western (SW) and southern (S) winds dominate during 45–50% of the year. According to Tavast and Raukas (2002), the average wind speed is 4–5 m s\(^{-1}\) and rarely exceeds 20 m s\(^{-1}\). It is therefore not unexpected that the long-term average significant wave height at our measurement site remains below 0.3 m and that the proportion of practically calm seas (\( H_s \leq 0.2 \) m) and situations in which the wave height is in the range of 0.2–0.4 m both form about 1/3 of the entire data set. Consequently, quite calm seas with wave height \( H_s < 0.2 \) m are common for Lake Peipsi. They form up to 70% and 65% of all seas in summer and in autumn, respectively (Figure 3).

Wave heights larger than 1 m were only observed in autumn (3%). A few records of quite large wave heights are probably related to special atmospheric conditions in October–November 2005 and 2007. The roughest seas \( H_s = 1.98 \) m during the measurement interval 2005–2007 was recorded in autumn 2005. On the one hand, a comparison of this result with the estimates of (Sokolov, 1983) suggests that the historical estimates of the wave parameters probably underestimate the roughness of wave conditions in this water body. On the other hand, such a large wave height in shallow water is at the threshold of the wave heights for this depth (60% of the water depth according to (Massel, 1996) or 54% according to Nelson (1994)) or even exceeds it to some extent.

A distinctive feature of the wave fields in question is their high intermittency: relatively long almost calm intervals are interspersed with comparatively short wave storms that start abruptly and decay somewhat more slowly (Figure 4). This feature is also consistent with the relatively small extension (about 125×70 km) of this lake. Even though the water depth is moderate and the group speed of waves relative low, both the reaction time and memory duration of the wave systems are comparatively short.
The wave properties exhibit strong seasonal variability. In summer, the wave height did not exceed ~1 m, while in autumn it reached 1.98 m. The maximum of wave height in our measurements in autumn 2005–2007 (~2 m whereas the north-north-western wind at Tiirikoga at this time was only 7.1 m s\(^{-1}\)) is close to the biggest instrumentally measured maximum wave height in this lake (2.1 m in NNW wind over 12–13 m s\(^{-1}\) (Jaani, 1996)). According to Tavast (2009), in this part of Estonia much larger wind speeds may occur (10-min average wind speed over 25 m s\(^{-1}\); short wind events up to 35–40 m s\(^{-1}\) were recorded in 1954, 1969 and 2005). This suggests that wave heights in this lake may be considerably larger than estimated in the existing sources. Unfortunately, no data of wave height for these situations in Peipsi Lake is available.

Mean wave heights vary not only seasonally but also annually (Figure 5). The patterns of variations may be different in different years. Thus, autumn 2005 hosted relatively rough seas (\(H_s = 0.33\) m on average) while \(H_s\) in autumn 2006 and 2007 was 0.08 cm and 0.13 m, respectively. Such an annual variability is clearly visible on Figure 4.

While in 2005 the months hosting, on average, the roughest seas were October and November, seasonal variations were less clear in 2006–2007 (Figure 5). This not necessarily means that the seasonal cycle was negligible in these years. As the measurement site was located in the vicinity of the western coast of the lake, it may have been to some extent sheltered with respect to a part of predominant westerly wind and to give a somewhat distorted representation of the seasonal cycle for some years.

Interestingly, long-term trends (1921–2005) of water level fluctuations in Peipsi Lake suggest that the highest water levels usually occur from April to July (Raukas and Tavast, 2011). Our results suggest that this cycle is shifted by several months with respect to the annual cycle of wave intensity. This means that the most intense waves normally occur during average or low water levels in this water body. Therefore, waves usually do not impact on unprotected sediments far beyond the average waterline. Such a shift of the two cycles is not unexpected as the water level fluctuations in this lake are mostly related to cycles of dry and wet years that are strongly influenced by solar activity and general atmospheric processes (Jaani et al., 1998) while the wave properties are governed by the seasonal wind cycle in the region.

As an interesting peculiarity, we also note a feature of the diurnal cycle of wave intensity: the highest waves tend to occur in the evening in summer, and in the morning in autumn. The reasons for such a cycle are unclear.

Common directions of highest waves depend on directions of strong winds. A direction of strong winds also play important role in increase of wave height by wave set-up.

Wave Periods

The distribution of occurrence of mean wave periods has a bell shape (Figure 6). Mean wave periods are mainly concentrated in a narrow range of 1.5–2.5 s that is characteristic for coastal areas of semi-sheltered domains with a depth less than 10 m (Soomere et al., 2012). The well-defined peak at about 2 s is observed from July to November. Although wave fields with periods below 1.5 s often occur at the measurement site, a secondary peak at 1–1.5 s is apparently related to the limitation of the above-described procedure of derivation of wave properties from the pressure data series and probably has no physical background. The fraction of seas with periods exceeding 3 s is negligible, about 0.2% in summer and about 0.02% in autumn. This is expected for this shallow inland lake of moderate dimensions.

Differently from the Baltic Sea (where the distribution of wave periods has a skewed shape; see (Soomere et al., 2012) and references therein), this distribution has an almost perfectly symmetrical shape and matches well a Gaussian distribution. The large fraction of waves with periods about 2 s is typical for Lake Peipsi (Sokolov, 1983). It is apparently related to its limited size but the shallow water depth may play a role here as longer waves exert relative strong interaction with the bottom. Interestingly, high frequencies (periods less than 1.5 s) were only observed in October–November 2005 (Figure 7) probably because the sensor was positioned somewhat closer to the water surface than in other sessions.

Joint Distribution of Heights and Periods

Scatter diagrams (2D distributions characterizing the frequency of occurrence of different combinations of wave properties) are recognized as a powerful tool to estimate roughly the combinations of wave heights and wave periods during the strongest storms (Lopatukhin et al., 2006) and are widely applied for Baltic Sea (Soomere et al., 2012)

The overall shape of the distribution of combinations of wave heights and periods first reflects the limited size and shallow depth
Table 1. The basic parameters of wave climate at Sääritsa:
median, 90 %-tile, 95 %-tile, and 99 %-tile.
<table>
<thead>
<tr>
<th>Hs (m)</th>
<th>Tm (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median</td>
<td>0.207</td>
</tr>
<tr>
<td>90%</td>
<td>1.782</td>
</tr>
<tr>
<td>95%</td>
<td>1.881</td>
</tr>
<tr>
<td>99%</td>
<td>1.96</td>
</tr>
</tbody>
</table>

of this water body (Figure 7). Generally, the combinations are concentrated in a range of short (1.5 < Tm < 2.5 s) and small waves (Hs < 0.5 m) (Table 1). As mentioned above, the branch of waves longer than Tm > 3 s is almost missing. There are few records of small waves with periods more than 3 s in summer. In almost all cases the wave height was well below 0.1 m. Only in one occasion waves with period of 3.5 s had a height of 0.3 m. Given the small size of Lake Peipsi and intensity of its use, a part these records may be associated with vessel waves that frequently have periods 5–7 s (Soonere, 2007).

Moderate and rough seas with 1 < Hs < 2 m and 1 < Tm < 2 s are mainly recorded in autumn. Interestingly, the highest measured wave fields had very small mean periods. For example, the overall roughest wave field (Hs = 1.98 m) had a mean period of only 1.5 s (Figure 7). The relevant waves were extremely steep and apparently already in a breaking stage.

Wind data from coastal stations in 1966–2007 (Suursaar et al., 2010) show that in 2005–2007 along Estonian coast of the Baltic sea strongest storms occurred in winter (January 2005 and 2007) when Lake Peipsi/Chudskoe was covered with ice. During experiment in 2005–2007 at Sääritsa we managed to catch storms in October 2005 (Hs up to 1.98 m, 1 < Tm < 2 s) and October 2007 (Hs up to 1.93 m, 1.9 < Tm < 7.3 s) (Figure 4). According to FuL-Berlin (2012), several depressions were registered in the Northern Europe in October 2005 (Claus 11/10, Danny 18/10, Eberhard 19/10, Franci 20/10, Günther 21/11, Heido 23/10, and Innocentius 24/10) and October 2007 (Ingo 3/10, Julius 7/10, Karl 9/10, and Lupus 10/10) that could be responsible for these waves.

**CONCLUDING REMARKS**

Analysis of wave climate in fetch-limited wind conditions in shallow water basins like Lake Peipsi/Chudskoe is important for many engineering and environmental applications. For example, the importance of the combination of the sea and lake water level change together with variations in the wave intensity for coastal climate in large and shallow lakes (Soomere, 2007). The overall largest wave height 1.98 m at our measurement location near the western coast of Lake Peipsi signifies that much higher waves are eventually possible in central parts of the lake. Another interesting feature is the extreme steepness of rough seas in this lake. It is well known that wave spectrum in very shallow lakes is different from the one in deeper waters (Young and Babanin, 2006). Wave observations in a near-constant, finite-depth Lake George, Australia showed that waves will not break unless some average background steepness exceeds a threshold value (Banner et al., 2000; Babanin et al., 2001). Further studies into wave properties in Lake Peipsi might explain whether this effect is limited to very shallow basins or may become evident also in somewhat deeper areas. Also, numerical analysis of short-term and long-term trends of total wind-wave energy flux in addition to wave parameters (wave height, wave period) in Lake Peipsi could substantially improve our understanding of wave climate in large and shallow lakes.

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