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LONG-TERM CHANGES IN HYDROLOGICAL REGIME OF THE LAKES USMA, BURTNIEKS AND RĀZNA

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Changes in the hydrological regime of the lakes of Latvia have been caused by several natural and human factors. This publication summarises the results of research on the long-term and seasonal changes in the water level, and thermal and ice regimes of the three biggest lakes of Latvia (Usma, Burtnieks, and Rāzna) and their regional features in the period from 1926 to 2002. The levels of the lakes Usma and Rāzna have been controlled, but it can be considered that changes of the water level in Lake Burtnieks have been due to the impact of natural factors during the period from 1947 to 2002. Global climate warming has caused considerable changes in the hydrological regime of the lakes during the last decades, as the water level and temperature have increased and the number of days with ice cover and the thickness of ice have decreased. A positive trend in the freezing data and statistically reliable negative trend for the ice break-up date were observed for all the lakes. Lake Usma is located in the western part of Latvia, therefore, its hydrological regime, in particular, the thermal and ice regime, differs from those of lakes Burtnieks and Rāzna which are located in the northern and eastern part of Latvia, respectively.

Key words: *lake, water table, water temperature, ice, long-term and seasonal changes.*

INTRODUCTION

The territory of Latvia is rich in lakes. There are 2256 lakes with a surface area larger than 1 ha. The majority of lakes in Latvia are small. Only 16 lakes have an area larger than 1000 ha or 10 square kilometres (Tidriķis, 1995). Still, they account for 40% of the total area of the lakes. Most lakes are located in highlands (approximately 40% of the lakes occur in the highlands of Latgale and Augšzeme). The lowest number of lakes occur in Zemgale where the low plain and numerous rivers do not allow accumulation of water. The total area of lakes in Latvia is about 1000 square kilometres. This area amounts to about 1.5% of the area of Latvia, and the proportion is similar to that in Lithuania but considerably less than in Estonia (5%), Sweden (8.5%) or Finland (9%). In Latvia there are many lakes, as glaciers covered this territory in not so far distant past. The ice-cover and water resulting from its melting caused formation of a terrain rich in hilly and depressions, which facilitated flow of water from raised parts and its accumulation in lower areas. Lakes formed by pools in marshes and bogs are not recorded in Latvia, but their number could be above ten thousand. In the 20th century, the number of lakes decreased due to overgrowing, drainage projects and merging of lakes.

Lakes are one of the most common landscape elements in Latvia and in the Baltic region, which includes also some highlands with lakes in Lithuania, Poland and Northern Germany. Lakes are a natural indicator that reflects the water regime of the region and its variability. The dynamics of the condition of a lakes over time is best characterised by the water level regime and its changes brought about by natural and anthropogenic factors. Similar to fluctuation of the volume of discharge of waters, cyclic and periodic changes over the span of centuries are characteristic also for fluctuation lake levels. These cyclic fluctuations are caused by various macroprocesses, such as atmospheric circulation, changes in the solar radiation which determines the thermal and ice regime of the lakes, and the amount of precipitation (Glazačeva, 1975).

The history of the modification of the hydrological regime of lakes by human activity in Latvia started already in the 18th–19th centuries. The largest changes occurred in the 20th century, with increased alteration made by land drainage, hydro-energy projects, fisheries and other management types that affected the level of lakes.

Wide research on the hydrological regime of Latvian lakes and its changes were carried out in the 1930s, for example, investigations on large lakes near Rīga by Stakle (1935) and on morphometric elements and regimes by Slaucītājs (1935; 1937; 1938). In the 1950s to 1970s, studies were carried out on the morphometry of the Latvian lakes, etc. (Котов и др., 1958) and on the thermal and ice regime of rivers and lakes by Glazacheva (Глазачева, 1964; 1965;

Glazačeva, 1975). The publications by Tidriķis (1995) and Glazačeva (2004) are among the last reviews on the hydrological regime of Latvian lakes and its changes. It should be noted that lately no broad research on this topic has been carried out, and generally, since 2003–2004, regular monitoring of Latvian lakes is no longer performed.

The objective of this study was to analyse long-term changes of hydrological regime, i.e. water level and temperature, ice occurrence, and regional features of the three largest Latvian lakes: Usma, Burtnieks, and Rāzna.

MATERIALS AND METHODS

Studied lakes. The three biggest lakes of Latvia (Usma, Burtnieks and Rāzna) that had long series of observation data and different physical geographic location (Fig. 1) were selected for the study. The main characteristics of the lakes are presented in Table 1.

Lake Usma (57°12'N 22°10'A) is located in the western part of Latvia at 20.6 m a.s.l. (Eipurs, 1998) in the Ugāle plain of the Kursa lowland, in the Irbe river basin. The surface area of the lake is 37.2 km^2. Usma Lake is a remnant of the Baltic Ice Lake. The lake bed stretches from the North to South with length 13.5 km; the widest part (6 km) is in the middle part of the lake. Usma Lake is the second biggest lake in Latvia from the point of view of the water volume (190 mill. m^3) and the estimated water turnover is two years. It discharges to the Baltic Sea at its north-western end via the Engure River — Puzes Lake — and then Rinda and Irbe Rivers. In comparison to the other studied lakes, Lake Usma has a high average and maximum depth (5.4 m and 27 m, accordingly).

Table 1

MORPHOMETRIC PARAMETERS OF STUDIED LAKES (Tidriķis, 1995)

Lake	Watershed, km^2	Surface area, km^2	Volume, mill. m^3	Maximum depth, m	Average depth, m
Usma	396	37.2	190	27	5.4
Burtnieks	2215	40.1	88	3.3	2.4
Rāzna	221	57.6	405	17.0	7.1

Burtnieks Lake (57°44’ N 25°14’ A) is the fourth biggest lake in Latvia. It is located at 39.5 m a.s.l. in the northern part of Latvia in the Tālava lowland (Tidriķis, 1994). The water surface area is 40.06 km^2. The lake bed is of glacial origin and stretches in the direction from the North West to the South East. Its length is 13.3 km, and maximum width is 5.5 km. Lake Burtnieks is a shallow lake with average depth 2.2 m and maximum depth 3.3 m. This lake represents a flow lake, as water turnover takes place on average six to seven times per year (in spring once every 2–3 weeks and in summer once in three months). It discharges to the Riga Gulf via the Salaca River at the north-western end of the lake where the width at the discharge is 25–30 m. Lake Burtnieks has the biggest basin (2215 km^2), which exceeds its water surface area (40.06 km^2) by 55 times. This factor causes large seasonal fluctuation of the water level.

Lake Rāzna (56°19’ N 27°27’ A) is located in the South East part of Latvia on the highest part (163.4 m a.s.l) of the Latgale highland in the Rāznava hilly section (Lumane, 1997). This is the second biggest lake of Latvia from the aspect of the water surface area. Its area is 57.6 km^2, and in 1956–1974, following the lowering of the level of Lubāna Lake, it became the biggest lake in Latvia. In terms of the water volume, Lake Rāzna is the biggest lake in Latvia. The total volume is 405 mill. m^3 or 1/5 of the aggregate volume of all lakes of Latvia. The lake bed is of glacial origin, rounded with a slight straighter stretch from the East to the West. Its length is 12.1 km and the largest width is 6.9 km in the east part of the lake. The average depth is 7 m and maximum depth is 17 m. Lake Rāzna is a flow lake, and average discharge is 240 mm. The discharge of the lake occurs in the western part via the Rēzekne River — Lake Kaunata. If the water level is high, discharge occurs also in the north-western part of the lake via Lake Zosnas and Kazupe River to the Malta River.

Data and methods. In the analysis of the hydrological regime of the studied lakes the hydrological monitoring data

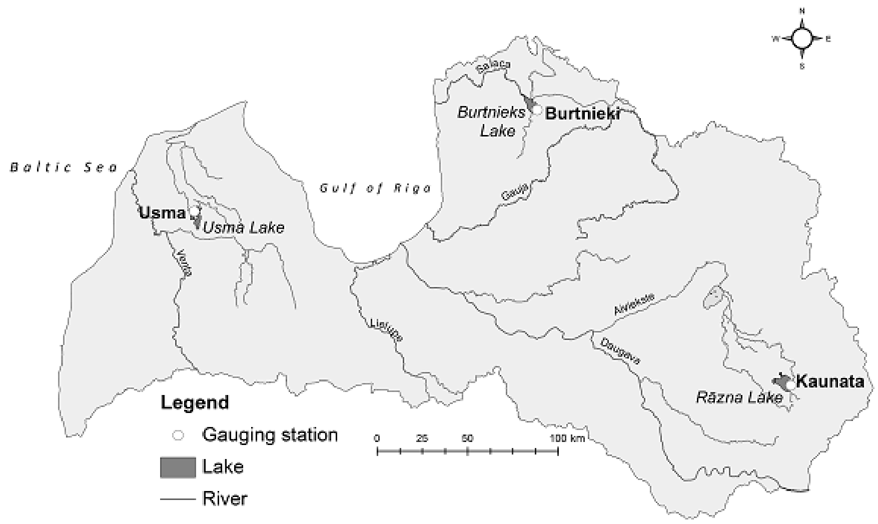

Fig. 1. Location of the studied lakes.

Table 2

STUDY PERIODS OF UTILIZED HYDROLOGICAL DATA

Data	Lake Usma	Lake Burtnieks	Lake Rāzna
Water level, cm	1926–2002	1947–2002	1948–2002
Water temperature, ^{o}C	1946–2002	1946–2002	1948–2002
Ice thickness, cm	1929–1939, 1946–2002	1946–2002	1948–2002
Number of days with ice	1926–2002	1946–2002	1948–2002
Date of freezing	1926–2002	1946–2002	1948–2002
Date of ice break-up	1926–2002	1946–2002	1948–2002

from the funds of the Latvian Environment, Geology and Meteorology Centre (Anonymous, 2011) and the publication of the Marine Board by Stakle and Kanaviņš (1941) were used. For the purpose of analysis of the water levels, the monthly mean data in centimetres above the zero post mark have been used and the observation periods for the studied lakes differ in this case (Table 2). Systematic monitoring of the water level of Lake Usma was started in September 1926 at Usmaciema hydrological station that was established by the Latvian Sea Department. The gauging station „Usma" is located 4 km to the North East of the mouth of the Engure River (Fig. 1). Its location and the zero mark of the post at 20.38 m a.s.l. have remained unchanged during the period of study. In the analysis of the water level of Lake Burtnieks the observations from the gauging station „Burtnieki" at the South East coast of the lake have been used, the zero mark of the HNS „Burtnieki" is located at 37.84 m a.s.l. In the case of Lake Rāzna the gauging station „Kaunata" is located at the east part of the lake and the mark of the zero post is at 160.57 m above the sea level.

In the analysis of the long-term trends of the water temperature the mean monthly data are used: for lakes Usma and Burtnieks from March to December, and for Lake Rāzna from April to December.

For the analysis of the ice regime the data on the ice thickness and duration days, freezing and break-up dates were used. The measurements of the thickness of the lake ice usually are performed from October to April six times per month, i.e. on the 5th, 10th, 15th, 20th, 25th and the last date of the month, and as from the winter of 1975/1976 there have been individual periods or years when the observations were performed only three times per month. In the study measurements of the ice thickness in the middle of the lake are used, and in the case of Lake Burtnieks the missing data from the winter of 1969–1970 were replaced by inshore ice thickness observations that are not essentially different from the measurements of the central part of the lake. Afterwards, the mean and maximum annual ice thickness were calculated. In the present study, the date of freezing is the first day of ice occurrence, the date of ice break-up is considered as the date of disintegration of the ice cover in the period with regular ice observations, and the number of days with ice is calculated as the actual number of days on which ice occurred. For possibly immediate assessment of the climate changes in the Latvian lakes the severity index was calculated by Sztobryn *et al.* (2009). The index was used for the seasonal number of days with ice and the probability of ice occurrence.

The multivariate Mann-Kendall test (Lettenmaier, 1988; Loftis *et al.*, 1991) was used to detect the trend shift in monthly and annual data analysis. The test was applied separately to each variable at each site, at a significance level of $P \leq 0.05$. The trend was considered statistically significant at the 5% level, if the test statistic was above 1.96 or below –1.96.

In studies of hydro meteorological time series in the Baltic Sea area by Kļaviņš *et al.* (2007) and Stips & Lilover (2010) the so called breakpoints during the 20th century were found. One of them refers to year 1987, which could have determined the long-term changes in hydro-climate patterns during last decades. Therefore, in our investigation the entire study period was divided into two periods: until 1987, with "no substantial" climate change impacts, and the period from 1988, with "substantial" climate change impacts on hydrological processes in Latvian lakes.

RESULTS

Changes in water level. In Latvia the big lakes have been regulated in recent or not so recent past, therefore, the long-term changes in their water level depend not only on the natural factors, mainly climate-related factors, but also anthropogenic activities. Concerning Lake Burtnieks during the study period from 1947 to 2002 there are no data about the works performed by humans in regulating the water level. Therefore, the long-term changes in the lake level can be deemed to be natural. This is confirmed by the comparison of the long-term changes in the lake level with the cycle of the changes in the flow of the Salaca River from 1951 to 2002. As it can be seen in Figure 2, two periods can be distinguished in the water regime of Lake Burtnieks and the Salaca River: low water from 1947 to 1977 and high water from 1978 to 2002. The long-term mean water level of the lake for numerous years was 40.1 m a.s.l., and 39.9 m during the low water period and 41.1 m during the high water

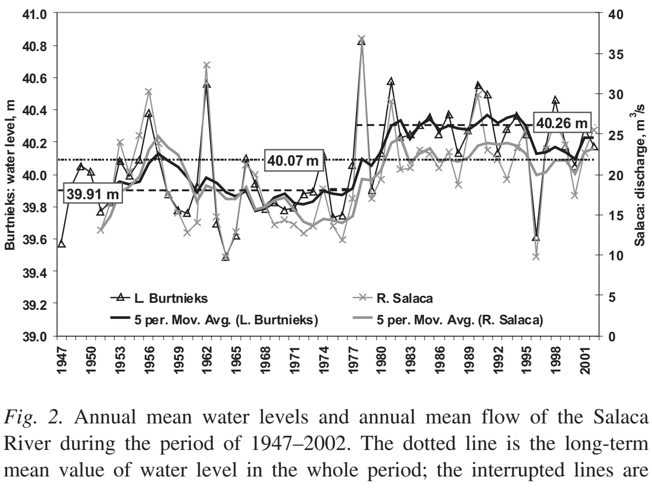

Fig. 2. Annual mean water levels and annual mean flow of the Salaca River during the period of 1947–2002. The dotted line is the long-term mean value of water level in the whole period; the interrupted lines are long-term mean values of water level of the studied periods 1947–1977 and 1978–2002.

period. The long-term seasonal analysis showed that the statistically reliable positive trend at a significance level of $P \leq 0.05$ could be observed for the water level of the lake from January to March and from June to September, but in the flow of the Salaca this trend could be observed only from January to March.

Lake Usma is peculiar concerning the fact that the regime of its water levels has been impacted by direct human activity. In 1969, on the Engure River not far from its mouth the eel catching device was constructed (Fig. 3). The water level in the lake was raised on average by 20 cm. These changes are also reflected very well in the long-term changes in the mean water level where during the period from 1927 to 1968 it was 21 m and from 1969 to 2002 it was 21.2 m a.s.l. (Fig. 4). Thus, during the study period from 1927 to 2002, a statistically reliable positive trend could be seen from January to September, and during the period from 1927 to 1968, a reliable positive trend could be identified only in March and April, when the level fluctuations were caused mainly by the natural conditions.

Lake Rāzna was regulated for several times (Fig. 5). During the period from 1951 to 1955, Sprukti hydro power station

Fig. 3. The eel catching device on the Engure River not far from its outflow from Lake Usma. (Photo by Mārtiņš Kriķītis, 2010).

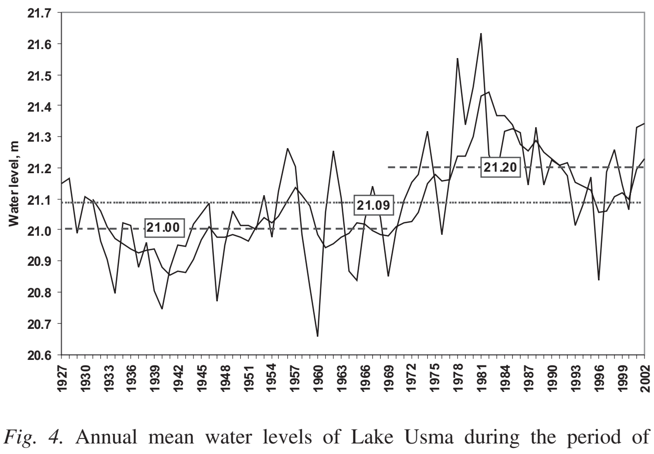

Fig. 4. Annual mean water levels of Lake Usma during the period of 1927–2002. The dotted line is the long-term mean value of water level of the whole period; the interrupted lines are long-term mean values of water level of the studied periods 1927–1968 and 1969–2002.

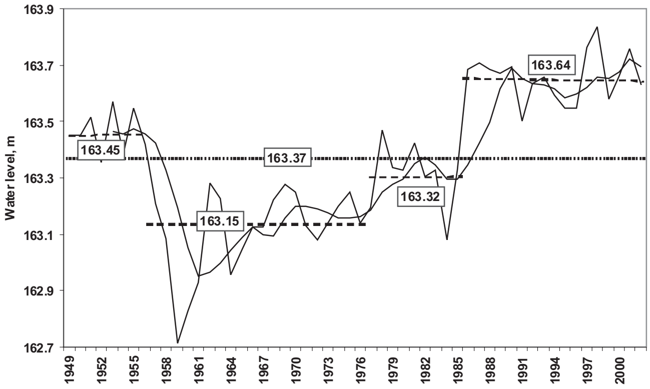

Fig. 5. Annual mean water level of Lake Rāzna during the period of 1949–2002. The dotted line is the long-term mean value of water level of the period 1949-2002; the interrupted lines are long-term mean values of water level of the studied periods 1949–1955, 1956–1977, 1978–1984 and 1985–2002.

(HPS) was built and it was in operation until 1977. During the period from 1956 to 1962, the flow of the lake was deepened along the section Lake Rāzna — Lake Kaunatas and on the upper course of the Rēzekne River to direct higher volumes of water to the Rēzekne River for the operation of Sprukti HPS. Following the deepening of the outflow the level of the lake decreased by 0.3 m. After closing Sprukti HPS, the natural water level was restored at the lake for a couple of years from 1985 to 1992 (on average, up to 163.32 m a.s.l.), when the eel catching device was constructed and the level was raised by 29 cm. During the period from 1993 to 2002, the Kaunata gates and Sprukti HPS were reconstructed and resumed power generation in 1996. The gates continue to maintain the level of the lake at the artificial level which was raised by another 5 cm following their reconstruction.

Changes in water temperature. The thermal regime of lakes is determined by the location of the lakes, climatic conditions, size and depth, inflow of underground and surface waters (streams, rivers). Lakes of the temperate latitude: in summer — direct, in winter — reverse stratification. In springs the water warms up slowly, later it accumulates the warmth, and during other seasons, the water is often warmer than the air. The water temperature is the highest in July and August and the lowest during the period of formation of the ice cover. In summer the upper layers of the deep lakes at the depth of 4–6 m warm up, the temperature practically does not change at other depth layers.

The results of the study of the water temperature demonstrated that the long-term mean temperature was the highest for Lake Usma where it amounted to 10.3 ^{o}C, followed by Lake Burtnieks with 9.6 ^{o}C and Lake Rāzna with 9.1 ^{o}C (Fig. 6.). During the time period until 1987, the long-term mean temperatures in all the lakes were lower than during the time period from 1988 to 2002, when the climate warming could be observer. For lakes Usma and Rāzna the water temperature had increased by approximately 1 ^{o}C. The long-term seasonal analysis demonstrated that the statisti-

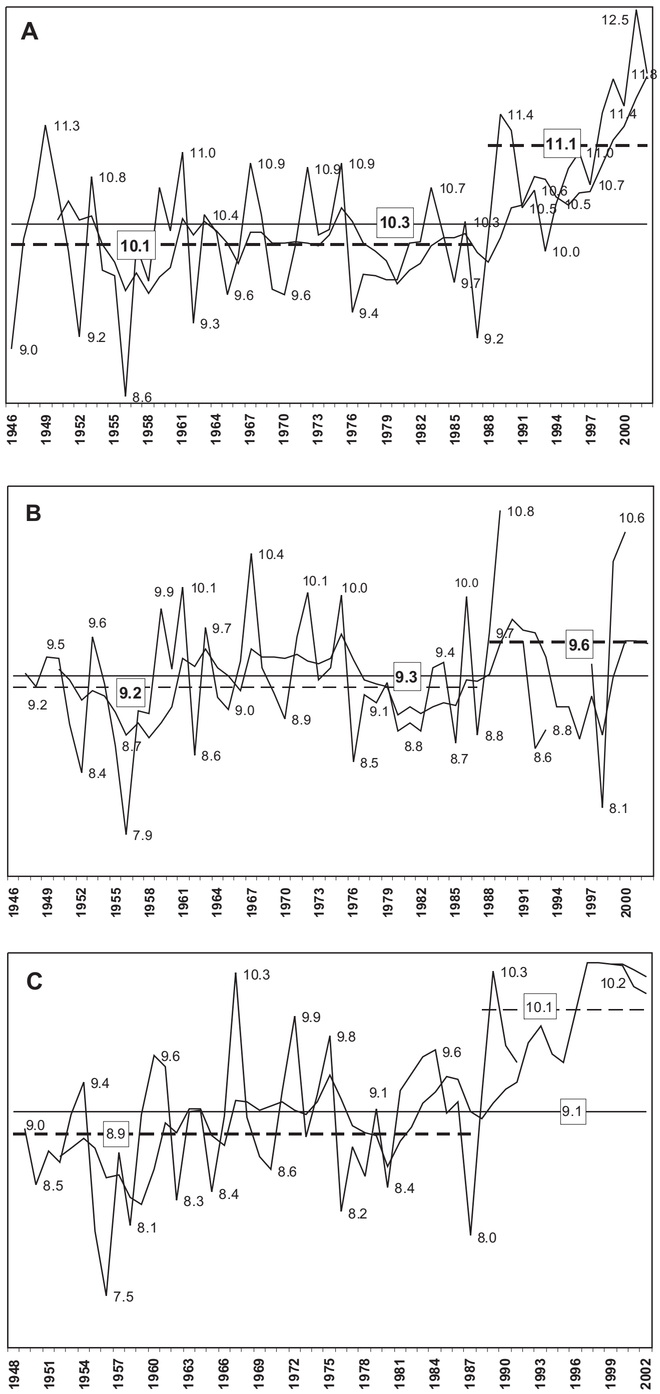

Fig. 6. Long-term water temperatures in lakes Usma (A), Burtnieks (B) and Rāzna (C). The uninterrupted horizontal line is the long-term mean value of water temperature of the whole study period; the interrupted lines are long-term mean values of water temperature of the studied periods 1946–1987 (A, B), 1948–1987 (C) and 1988–2002 (A, B, C).

cally positive trend could be seen during spring months March – April, and for Lake Rāzna also in July, August, and December.

Changes in ice freezing and break-up date. The ice formation in the Latvian lakes depends on the length of the period between the move of the daily mean temperature below 0 °C and cooling of the water in the lake to 0 °C. Stable ice cover forms within 2–20 days after the first ice elements have appeared. At the highlands in the north and east part of

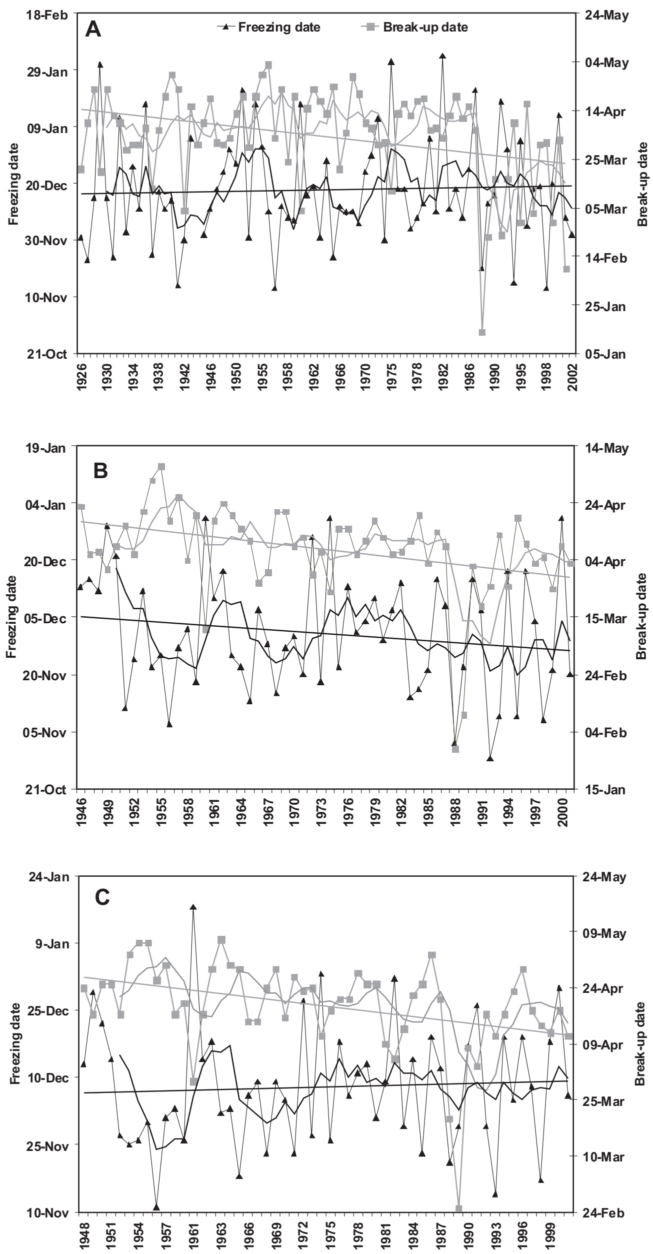

Fig. 7. Long-term freezing dates and break-up dates for lakes Usma (A), Burtnieks (B) and Rāzna (C). The horizontal lines are long-term mean values of freezing dates and break-up dates during the whole period.

Latvia the ice cover starts to form in the 2nd half of November (Burtnieks — from the 25th November to the 4th December, Rāzna — from the 27th November to the 8th December), and in the West and middle part of Latvia — in the 1st half of December (Usma — from the 2nd to the 10th December). It breaks up during the period from the 2nd half of March to mid-April (Usma: the 31st March – the 13th April, Burtnieks: the 6th–11th April, Rāzna: the 18th–25th April), and within ten days after that the ice melts at the site. The climate warming resulted in the ice break-up already in mid-March or end of March, for example in the case of Lake Usma the mean date was the 17th March, for Burtnieks it was the 25th–30th March and for Rāzna it was the 12th April. As it can be seen from Figure 7, the trend that during the study period the ice formation date is later

Table 3

EXTREME YEARS WITH THE EARLIEST AND THE LATEST DATE IN FREEZING AND BREAK-UP

Lake Usma (1926–2002)		Lake Burtnieks (1946–2002)		Lake Rāzna (1948–2002)	
earliest freezing	latest freezing	earliest freezing	latest freezing	earliest freezing	latest freezing
13.11.1998,	01.02.1975,	29.10.1992,	31.12.1960,	11.11.1956,	17.01.1961,
13.11.1956,	03.02.1982,	02.11.1988,	31.12.1974,	14.11.1993,	02.01.1975,
14.11.1941,	31.01.1930	07.11.1956	31.12.2000,	17.11.1998,	01.01.1983
15.11.1993			29.12.1949	18.11.1995	
earliest break-up	latest break-up	earliest break-up	latest break-up	earliest break-up	latest break-up
05.01.1989,	03.05.1956,	29.01.1989,	07.05.1956,	25.02.1990,	07.05.1964,
09.02.2002	29.04.1941,	10.02.1990,	02.05.1955,	20.03. 1989,	06.05.1955,
	29.04.1955,	11.03.1961	26.04.1958,	30.03.1961	06.05.1956,
	28.04.1969,		24.04.1963,		03.05 1987,
	23.04.1929,		23.04.1947		03.05.1954,
	23.04.1931,				29.04.1997
	23.04.1942,				
	23.04.1958,				
	23.04.1963,				
	23.04.1966,				

can be seen for all the lakes, i.e. there is a positive trend, but it is not statistically significant. The ice break-up date is earlier, i.e. there is a negative trend and it is statistically significant at the $P \leq 0.05$.

The extreme freezing and break-up dates are summarised in Table 3. The variation of the dates among the studied lakes is higher in case of the freezing and lower in case of the ice break-up. It can be seen very well here that in 1961, 1989, 1990 the earliest break-up dates could be observed in all the lakes and in 1955, 1956, 1958, 1963 the latest break-up dates could be observed.

Changes in the numbers of days with ice cover and severity index. Until the year 1998, it could be observed that on average the ice cover was maintained in the Latvian lakes for 3.5–5 months or 6 months during severe winters. As it can be seen in Figure 8, the length of the ice cover varies among the studied lakes. The shortest ice cover length refers to Lake Usma and it equals to 107 days (104 days during the period 1945–2002), and the longest period refers to Burtnieks and equals to 128 days and to Rāzna where it equals to 133 days, i.e. 21 and 26 days longer, accordingly. During last 14 winter seasons (1988/89–2001/02), in comparison to the preceding study period (1926/27–1987/88), the number of days with ice cover had decreased on average by 14–33 days. It has decreased most for Lake Usma and least for lakes Burtnieks and Rāzna. Statistically significant long-term changes at the $P \leq 0.05$ were identified only for Lake Rāzna. Seasons with the longest and the shortest duration of ice cover are summarised in Table 4.

In order to establish the character of winter from the point of view of severity the severity index was calculated. As it can be seen in Figure 9, the severity index varies among the lakes: it is higher for the lakes located in the North and East

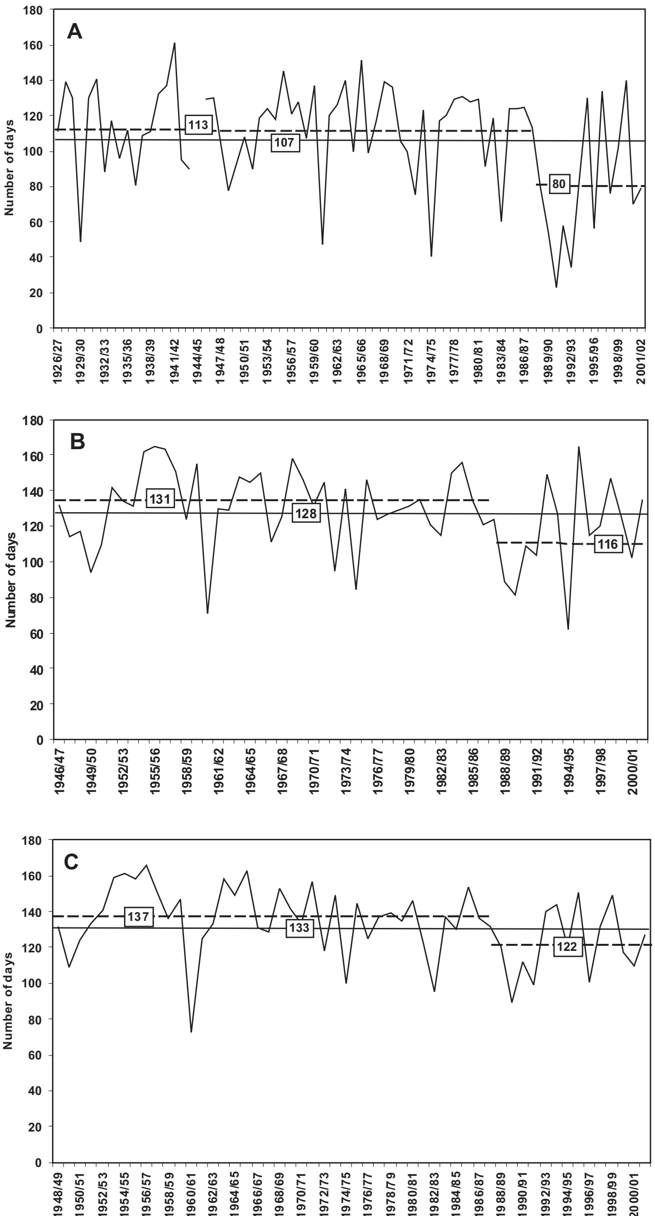

Fig. 8. Long-term numbers of days with ice cover of the lakes Usma (A), Burtnieks (B) and Rāzna (C). The uninterrupted line is the long-term mean value of the number of days with ice cover of the whole study period; the interrupted lines are the long-term mean values of the number of days with ice cover of the studied periods 1926/27–1987/88 (A), 1946/47–1987/88 (B), 1948/49–1987/88 and 1988/89–2001/02 (A, B, C).

of Latvia, which are Burtnieks and Rāzna, and it is lower for Lake Usma located in the western part. Based upon the calculated severity index the most severe and warmest winter seasons correspond to the seasons with the longest and the shortest duration of ice cover. The most severe winters could be observed from 1954/55 to 1958/59, 1965/66, 1968/69 and 1995/96 seasons, and the warmest winters were in 1960/61, 1974/75, 1988/89, 2001/01 seasons. The statistically reliable negative trend at a significance level of $P \leq 0.05$ was found only for Lake Rāzna.

Changes in ice thickness. The changes in the ice thickness of the studied lakes can be described as pseudo-cycles, where periods with thicker and thinner ice cover alternate

Table 4

SEASONS WITH THE LONGEST AND THE SHORTEST DURATION OF ICE COVER

Lake Usma (1926–2002)		Lake Burtnieks (1946–2002)		Lake Rāzna (1948–2002)	
season	number of days	season	number of days	season	number of days
The longest duration of ice cover					
1941/42	161	1955/56, 1995/96	165	1956/57	166
1965/66	151	1956/57	163	1965/66	163
1955/56	145	1954/55	162	1954/55	161
1931/32	141	1968/69	158	1953/54	159
1963/64, 1999/00	140	1984/85	156	1955/56	158
The shortest duration of ice cover					
1990/91	23	1994/95	62	1960/61	73
1992/93	34	1960/61	71	1989/90	89
1974/75	40	1989/90	81	1982/83	95
1960/61	47	1974/75	84	1991/92	99
1929/30	49	1988/89	89	1974/75, 1996/97	100

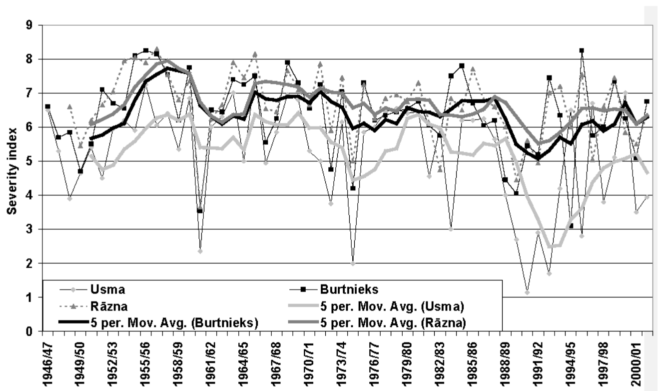

Fig. 9. Long-term severity indexes of the lakes Usma, Burtnieks and Rāzna.

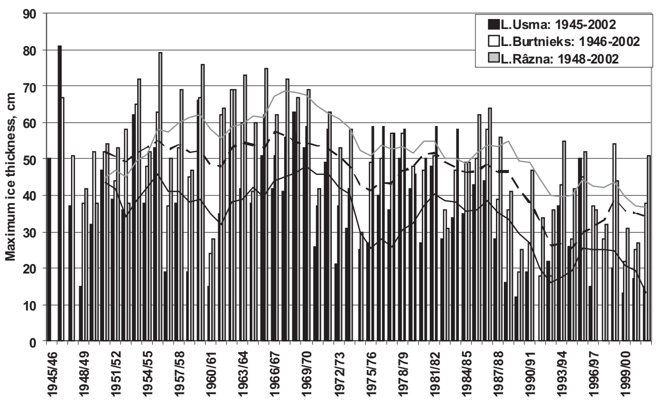

Fig. 10. Long-term annual maximum ice thickness of winter-spring season.

(Fig. 10). Ice thickness was pronouncedly higher during the period 1945–1973 when the maximum ice thickness levels were observed: in Lake Usma 81 cm in the season of

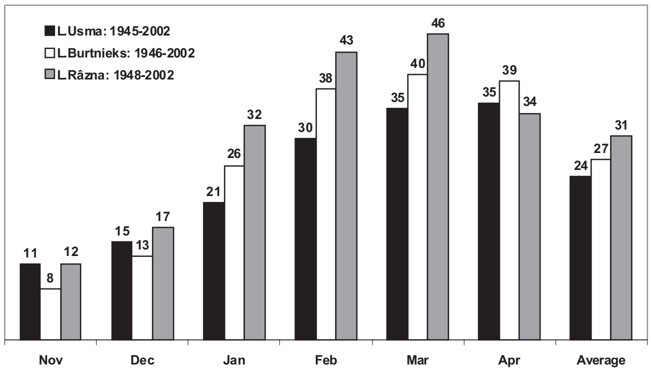

Fig. 11. Long-term monthly mean ice thickness.

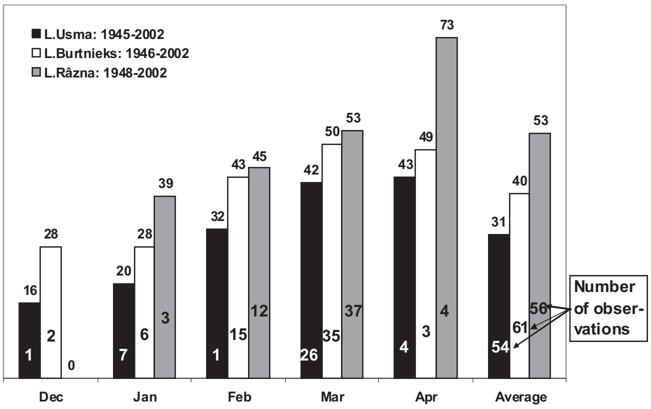

Fig. 12. Long-term monthly maximum ice thickness.

1946/47, in Lake Burtnieks 69 cm in the season of 1962/63, in Lake Rāzna 79 cm in the season of 1955/56. The period of 1988–2002 is characterised by lower ice thickness, this was the period when the warming of the climate was observed and during this period also lower maximum ice thickness levels were observed: in Usma 12 cm and in Rāzna 25 cm in the season of 1989/90, in Burtnieks 18–19 cm in the seasons of 1989/90, 1991/92 and 1992/93. However, a statistically negative trend was identified only for the annual maximum ice thickness.

It is natural that in the Latvian lakes the mean and maximum ice thickness increase in the direction from west to east, it is 24–31 cm and 54–56 cm, accordingly (Figs. 11 and 12). The highest mean and maximum ice thickness can be observed in March, but they can occur also in February and April. This depends on the heat exchange balance of the particular year and the climatic conditions of the year that determine the changes in the thermal and ice regimes of the lake.

Regarding observation of the mean ice thickness of lakes no statistically significant long-term changes were identified at the significance level of $P \leq 0.05$. In turn, concerning the maximum ice thickness data reliable negative trends were identified in November, January and February for Lake Burtnieks and March for Lake Usma and a positive trend was identified only for November for Lake Usma.

DISCUSSION

The long-term hydrological changes of the Latvian lakes have been determined by the set of the natural, mainly climatic, and human activities factors. The adjustment works have been performed in all the three studied lakes, and they have served as an essential determinant of the long-term changes in the water level. Changes in the climatic conditions, in turn, have more defined the changes in the water temperature and the ice regime, as well as the changes in the water regime. From year 1929 to 1930, the water bed of the Salaca River was deepened along a section of 7 km from its mouth. In this relation the level of Lake Burtnieks was lowered by 1 m (Glazačeva, 1975). Regarding the study period from 1947 to 2002 there are no data about the water level adjustment works performed by a human at Lake Burtnieks. Therefore, these could be considered natural processes which have taken place mainly under the impact of the climate change and due to the lake itself naturally trying to restore the water level to the initial level (Fig. 2).

The long-term variation of the hydrological regime of the lake (water level, temperature and ice conditions) is strongly related to climatic variables. The air temperature is the dominant variable determining the hydrological processes and is also correlated to some extent with other relevant meteorological driving variables such as solar radiation, relative humidity and snowfall (Livingstone *et al.*, 2010). For example, statistically, air temperature is often able to explain 60–70% of the variance in the timing of the break-up (ice-off) on lakes (Livingstone, 1997). In Latvia the latest study by Lizuma *et al.* (2007) has found that the annual mean air temperature has increased by 1.4 ^{o}C during last 50 years. In the study period from 1950 to 2003, the highest increase in the mean air temperature was recorded in spring (March, April and May) and early winter (November and December). Also the mean annual maximum temperature increased more rapidly in April and May, while the minimum temperature increased more rapidly in winter. In lakes the annual and long-term water temperature changes resemble the changes in the air temperature (Glazačeva, 1975), which is proven also by the results of our study. During the ice-free period from 1988 to 2002 the water temperature had experienced a long-term increase by up to 1 ^{o}C. Statistically reliable positive trends of the water temperature were found during the spring month, which indicate a faster removal of the ice coverage and faster warming up of the water.

Livigstone *et al.* (2009) pointed out that on interannual to interdecadal time-scales, the timing of ice-out, the temperature of rivers and lake surfaces and the discharges rates of streams are all directly influenced by regional climatic forcing. They consequently exhibit a high degree of coherence that is linked to the regional-scale special homogeneity of the relevant meteorological driving variables. The air temperature, which exhibits the highest degree of special homogeneity, is responsible for much, but not all, of the observed coherence. It was found by Livingstone and Dokulil (2001) in spring and summer; the coherence in lake surface water temperature was found to be reinforced by a regional coherence in meteorological driving forces other than air temperature (e.g., wind speed in spring and high-altitude cloud cover in summer). We can conclude that also we have found some regional differences in the surface water temperature among the studied lakes Usma, Burtnieks and Rāzna. Comparatively higher long-term average temperature was characteristic for Usma (10.3 ^{o}C) followed by Burtnieks with 9.6 ^{o}C and Rāzna with 9.1 ^{o}C.

Another factor which is referred to by many studies is the North Atlantic Oscillation (NAO) (e.g. George, 2000; Livingstone and Dokulil, 2001; Weyhenmeyer 2004; Kļaviņs *et al.*, 2009). Since air temperatures in the larger part of Europe in winter and spring are strongly influenced by the climate prevailing over the North Atlantic, it is not surprising that physical lake surface and rivers variables at these times of year are strongly linked to the NAO. As the NAO affects a number of meteorological driving variables, its influence on lakes is typically greater than that of any single variables (Livingstone *et al.*, 2009).

The global warming during last decades has had an essential impact in determining the changes in the water regime of the lakes of Latvia: later freezing and earlier break-off dates can be seen, thus the number of days with ice coverage and the average and maximum thickness of ice have decreased. The climatic factors are the most important ones which determine the regional differences between the thermal and ice regimes which are, in turn, determined by the length of the period between the change in the average daily temperature below 0 ^{o}C and cooling of water to zero degrees in lakes; this depending on the size and depth of the lake, its geographic location, water exchange there, etc. (Glazačeva, 1975). Thus, small differences between the changes in the thermal and ice regime of the lakes appeared in the study, where by comparing Lake Usma of the west part of Latvia to the lakes of the east part of Latvia (Burtnieks and Rāzna) a slightly higher long-term average water temperature could be seen, and also the ice-coverage period and thickness of ice were lower at the place where winters are warmer and milder.

The results of our study on the long-term changes in the ice regime of lakes Usma, Burtnieks and Rāzna are similar to those in the Northern countries (Korhonen (2006) in Finland and Weyhenmeyer *et al.* (2004). The results of the analysis clearly showed that there is a statistically significant change towards earlier ice break-up in Finland from the late 19th century to the present time. There is also a significant trend towards later freezing in the longer series, and thus also towards a shorter ice cover duration. The series of maximum thickness of ice showed both decreasing trends in the southern part of the country and increasing trends in the central and northern regions. These trends were statistically significant for approximately 50% of the observation sites. At the same time Weyhenmeyer *et al.* (2004) pointed out that the timing of ice beak-up responds much more strongly to the interannual variations in the air temperature in southern Sweden, where winters are relatively mild and duration of the ice cover usually varies between 0 and 125 days, compared to the northern Sweden where winters are more severe and ice cover usually lasts for 200 to 250 days. Similar study results have been obtained on the phenology of the river ice in the Baltic region by Kļaviņš *et al*. (2006; 2007; 2009), Stonevicius *et al*. (2008) and Šarauskienė and Jurgelėnaitė (2008). A decreasing linear trend indicates the decrease of the ice cover duration and shifting of the date of ice break-up to earlier dates, and indicates strong shrinkage of the ice cover duration in the studied rivers compared to early studies periods. Kļaviņš *et al*. (2009) pointed out that the time of ice break-up depends not only on meteorological conditions in a particular year and the distance from the Baltic Sea, but also on the global climate change.

This study indicated also the regional differences of the hydrological regime of the lakes. Lake Usma is located in the west part and there is a greater impact on hydrological regime by meteorological processes occurring over the North Atlantic and the Baltic Sea than in relation to the other part of Latvia. Therefore, the climatic conditions are milder in winter and its hydrological regime, in particular, the thermal and ice regime, are different from that of lakes Burtnieks and Rāzna which are located in the north and east parts of Latvia. The results of the study have proven that Lake Usma has comparatively higher water temperature during the ice-free period and the ice forms later, breaks up earlier and stays for a shorter time period, and the ice cover is thinner.

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USMAS, BURTNIEKU UN RĀZNAS EZERU HIDROLOĢISKĀ REŽĪMA ILGTERMIŅA IZMAIŅAS

Latvijas ezeru ilgtermiņa hidroloģiskā režīma izmaiņas ir noteicis dabisko un cilvēka darbības faktoru kopums. Šajā publikācijā ir apkopoti pētījuma rezultāti par trīs Latvijas lielāko ezeru — Usmas, Burtnieku un Rāznas — ilgtermiņa un sezonālās ūdens līmeņa, termiskā un ledus režīma izmaiņām un to reģionālajām īpatnībām no 1926. gada līdz 2002. gadam. Usmas un Rāznas ezeru līmenis ticis regulēts, bet Burtnieku ezeram ūdens līmeņa izmaiņas pētījuma periodā no 1947. gada līdz 2002. gadam notikušas dabisku faktoru ietekmē. Globālā klimata pasiltināšanās ir noteikusi būtiskas izmaiņas ezeru hidroloģiskajā režīmā pēdējās dekādēs, paaugstinoties ūdens līmenim un ūdens temperatūrai, kā arī samazinoties dienu skaitam ar ledstāvi un ledus biezumiem. Visiem ezeriem ir atrasta pozitīva tendence aizsalšanas datumam un statistiski ticama negatīva tendence ledus uzlūšanas datumam. Usmas ezers atrodas Latvijas rietumu daļā, tādēļ tā hidroloģiskais režīms, jo īpaši termālais un ledus, ir atšķirīgs no Burtnieka un Rāznas, kuri atrodas Latvijas ziemeļu un austrumu daļā.