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INFLUENCE OF HYDROLOGICAL CONDITIONS ON THE ECOLOGICAL STATE OF SHALLOW LAKE VŐRTSJÄRV

A. Järvet: *Influence of hydrological Conditions on the Ecological State of Shallow Lake Vőrtsjärv.* – Geografie – Sborník ČGS, 109, 2, pp. 129–144 (2004). – Lake Vőrtsjärv as a very shallow (mean depth 2.8 m) water-body and considerable water level fluctuations cause changes in both the surface area and volume of the lake. Due to the shallowness of the lake, low level periods are accompanied by several phenomena detrimental to its ecosystem, like cyanophyte blooms, overgrowing with macrophytes, resuspension of phosphorous compounds, restricted spawning places for pike and winter fish kills. In the years of low water level the perspectives to catch in established fishing sites using particular gear as well as access to harbours are hindered. Causal relations between the water regime and ecological state of the lake Vőrtsjärv have been discussed in this paper.
KEY WORDS: shallow lake – water regime – ice cover – ecological state – water management.

1. Introduction

L. Vőrtsjärv (Fig. 1) as a very shallow (mean depth 2.8 m) lake and considerable water level fluctuations cause changes in both the surface area and volume of the lake. During the highest (35.28 m) level, its surface area was estimated at 326 km^2, and the volume at 1.213 km^3. At the lowest water-stand (32.20 m), these values were 237 km2 and 0.383 km^3, respectively. Thus, the surface area of the lake may vary by the value of 89 km^2 and the volume by 830 km^3. The shallowness together with the large amplitude of water level fluctuations (annual mean 1.38 m, annual maximum 2.20 m, absolute range 2.92 m) cause fish kills in severe winter, intensive resuspension of sediments, intensive growth of macrophytes and cyanophyte blooms during low-level periods. In 1965 macrophytes covered only 15 % of the lake's area, since then their area has expanded remarkably (Haberman et al 1998). Due to the prevalence of westerly winds, the reed belt (mainly *Phragmites australis* and *Schoenoplectus lacustris*) is continuous and lush at the sheltered western shore and broken at the open eastern shore. The narrow southern tip of L. Vőrtsjärv is fully covered with macrophytes (*Nuphar lutea* and *Potamogeton lucens* are prevailing).

Hydrological observation data of shallow lakes are valuable indicators of long-term variation not only of water regime, also ecological conditions. Over the years the lake varied considerably with respect to depth and volume and as result to surface area. During the last ten-twenty years, the influence of hydrological factors on the ecological state on L. Vőrtsjärv has come into focus. A second reason for the increasing interest is that lake restoration (lake management) by connected measures of hydrological regulation and biological manipulation seems more effective than separated activity.

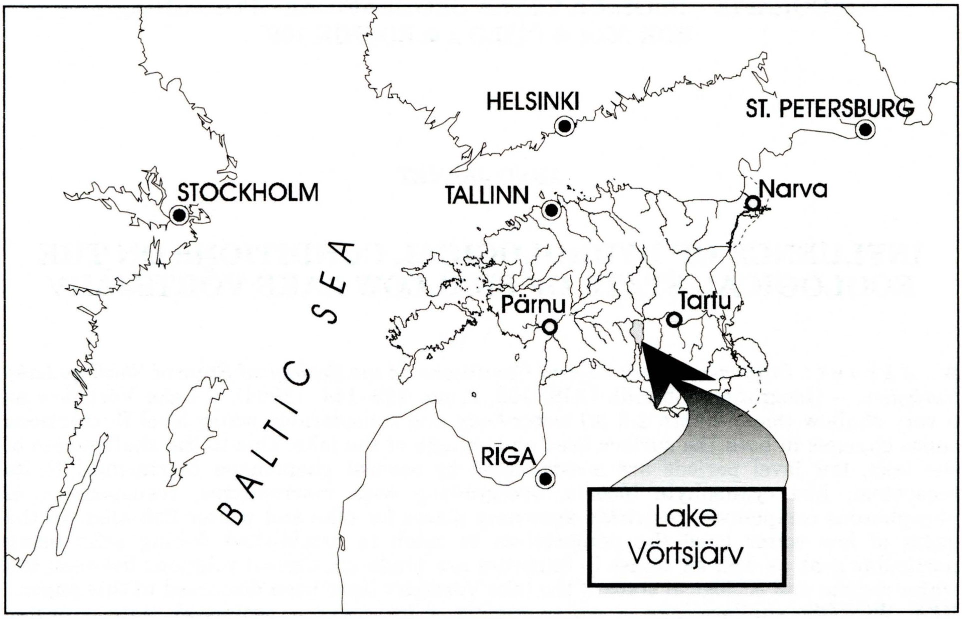

Fig. 1 – Location map of Lake Võrtsjärv

Changes of climatological conditions, which are reflected by cyclic fluctuation in the water regime and ice conditions over the long period, influence obviously to hydrophysical, and also hydrochemical and hydrobiological processes in the lake. The state variables of water quality are connected with hydrometeorological factors directly or indirectly. For example, an increase of the average depth of the lake results in a decrease of bottom irradiance and in the reduction of water column irradiance (Reinart 1999). The temporal variation of both quantity and type of ice influence the amount and type of light entering a lake, which in turn effects such processes as photosynthesis and oxygen production in the water masses under ice cover.

The main objectives of this study were:

1. Due to flat shores and small depth, fluctuations in the water level of L. Võrtsjärv are expressed with the changes large differences in morphometry and ecological conditions of lake.
2. According to shallowness, the ice cover has an important role in the formation of lake ecological conditions in a winter period. By hydrological characteristics it is possible to explain the winter condition of L. Võrtsjärv by active volume, and corresponding mean depth.
3. The annual cycle of weather conditions of water environment can be divided into seasons, which are described by qualitatively different climatological characteristics. The criteria for climatic seasons of lakes based on seasonal variability of water temperature and ice phenomena characteristics.
4. The ecological state of a Lake Võrtsjärv can be improved with the regulation of water level, because the strong dependence of ecological state on the water level is characteristic for relatively dry years and seasons.

It can be reported that water level has a very clear effect on the oxygen concentration during low water and long ice cover period. The increasing height of the water level was the single independent environmental factor demonstrating a clear fluctuations behaviour. Other environmental factors being rather constant, this smooth continuous trend offered a unique possibility to follow changes in the ecosystem (Nõges et al 1998). The characteristic features of the annual hydrological cycle of L. Võrtsjärv are a low water level in winter and a high water level in spring, which decreases gradually during summer and early autumn and is followed by a smaller peak in late autumn. The daily variation of the water level is within the range of centimetres, the monthly variation within the range of decimetres, but the annual amplitude exceeds 2 m.

The seasonal behaviour of nutrient compounds and their ratio (NO_3/N_{tot}, PO_4/P_{tot}) is different under changed hydrological conditions, because shallow lakes are more efficient in converting the available phosphorous and nitrogen into phytoplankton biomass (Nixdorf, Deneke 1997). For example, the proportion of mineral nitrogen in L. Võrtsjärv had its maximum (40–75 % of N_{tot}) in January and decreased gradually to about zero in the end of summer (Nõges et al 1997). The high winter water level of PO_4/P_{tot} dropped sharply in May, shortly after the ice break.

Optical properties of water as well as the mixing depth and resuspension rate of sediments, all determined by the water level, come to the forefront in the case of shallow and turbid L. Võrtsjärv where light limitation plays a major role in controlling phytoplankton growth (Nõges 1995). The influence of changes in the water level on different trophic levels is either direct or mediated by cascading effects in the food chain.

2. Long-term fluctuations of water level

The water level in the lake is fluctuating continuously in response to external factors. Variations in the level may be either relatively rapid, as in the case of seasonal variation, or long-term with a duration of several years. These differences vary in time, due to different precipitation, evaporation, in- and outflow patterns. Changes in the water level can be observed most clearly and most rapidly in shallow lakes whose catchment area exceeds the lakes surface at least 5–10 times. For L. Võrtsjärv with the catchment area of 3 104 km^2 this index is 11.5 at mean water level.

The harmful effect on the hydrological factors on the ecological and shoreline zone management becomes apparent under the following hydrological conditions:

- flood – monthly mean water level above 34.50 m;
- small depth of the lake – monthly mean water level below 33.00 m.

Both extremely high (over 35.00 m) and extremely low water level (below 32.50 m) have detrimental effects. In summer, during shallow water periods, small depth and lake volume and intensive primary production are a problem, and during floods the land use in the shoreline area and the traffic on small roads become complicated.

The aim of the analysis of long-term water regime was to detect statistically significant changes since 1871. The periodicity in long-term series of climate indicators of lakes is a very interesting and important issue for forecasting and economic purposes. Cyclic changes observed in nature have their sources in the global and regional variability of atmospheric circulation. Fluctuations in the water level in L. Võrtsjärv over the years are

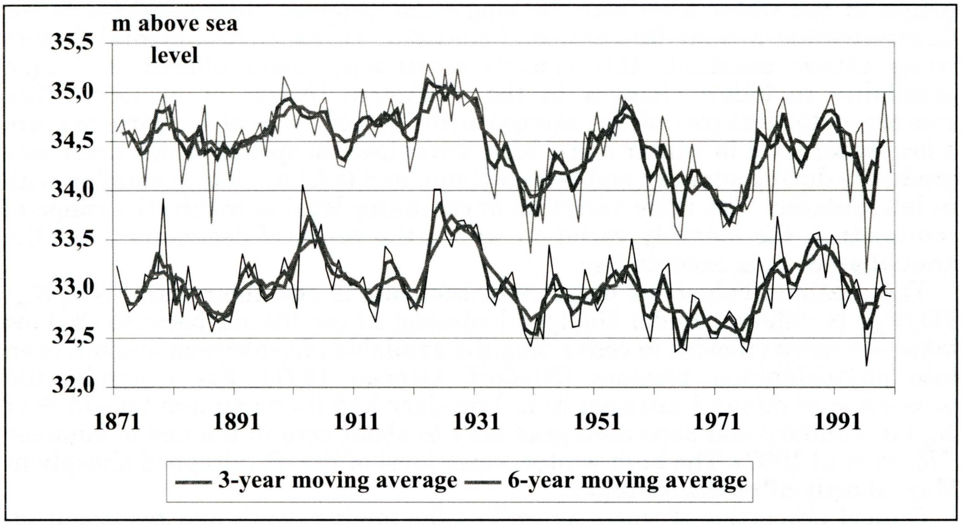

Fig. 2 – Long-period changes in annual maximum and minimum water level of Lake Võrtsjärv

considerable and seemingly quite random. Long-term water level measurements in L. Võrtsjärv show a sinusoidal alternation of low and high water states. Long-term changes in water regime can be seen most clearly in the dynamics of the minimum water level of a year (Fig. 2).

In order to demonstrate periodicities or cycles, spectral analysis is used. Using this method makes long-term periodicities visible and several periods can be identified. Figure 3 presents the results of the spectral analysis. Several peaks appear in the spectra. Altogether three groups of periodicity were detected:

1. short periods with a spectral peak at 3.6 years
2. medium periods at 6.4 years
3. long periods with a length between 24 and 32 years.

The spectral peak at 25.6 years seems to have an exceptional position. The identified very long periodicities – 64 and 128 years – are questionable in comparison with shorter spectral peaks, because the length of the time series was 128 years. Periodic fluctuations of water level with a 25–33-year period are characteristic of not only Estonia, but also of a much larger area in North Europe (North-West Russia, Latvia, Lithuania, southern part of Finland). Several authors (Libin, Jaani 1989; Behrendt, Stellmacher 1987; Hiltunen 1994) reported similar results for different large lakes in the northen part of Europe. Fluctuations with approximately the same time period were found for lakes Peipsi (Jaani 1996) and Ladoga and also in recent studies of river runoff change in Finland (Hiltunen 1994) and in the runoff coefficient in Estonia (Järvet 1995). Reap (1986) concluded on the basis of spectral analysis of L. Peipsi water level time series that the cycles of 6.1–6.4, 10–11 and 80–90 years are more evident, because the difference of main features of water regime between the two lakes is not significant.

The period since the beginning of the 1960s has been relatively dry compared with the earlier time, which is reflected by the long-term water level curve, with more frequent and longer low level (below 33.00 m) periods. Provided that the same periodicity continues, it is possible to forecast the

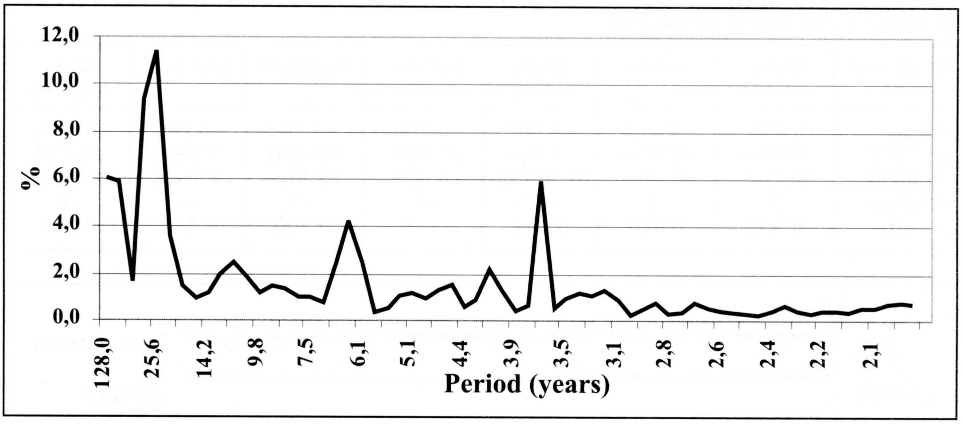

Fig. 3 – Spectrum of annual minimum water level in L. Võrtsjärv in 1871–2000

water regime in the near future. The negative phase (lower water level) if should last until the end of the 2010es, in the case of the 30-year fluctuation.

An analysis of the changes in the water level a six-year shift shows that periodic fluctuations have quite a stable character. It appears from a visual comparison (Fig. 2) that strong periodicity exists for periods of about 30 years. Level changes over the 20th century show a general tendency to a decrease, although periodic increases can be observed.

There is a strong connection between the periodic fluctuations of precipitation and changes in the hydrological regime in Estonia. Significant periodical changes in the water level of lakes are closely related to changes in precipitation and, to a lesser extent to the amount of evaporation. Data on the shifts of the spectral behaviour of water level can be obtained from the precipitation time series. The corrected time-series of spatial mean annual precipitation in Estonia indicates a clear periodicity (Jaagus 1998): cycles of 50–60, 25–33 and 5–7 years were detected. Temporal variability of evaporation is much lower than that of the runoff of rivers and water level of lakes. When annual precipitation in Estonia is less than 650 mm, then water level will depend on precipitation, and evaporation is stable (Järvet 1998). Based on the comparison of water balance elements, it can be concluded that the temporal variability of the water level of Lake Võrtsjärv is much higher than the variability of precipitation.

3. Long-term trends in thermal conditions

Typical variables of water climate, such as monthly mean water temperature, are not the best variables to describe ecological conditions associated with annual cycles in the organic activity in lakes. Therefore, climatic seasons, characterized by their start date and duration, are applied (Järvet 2000, 2001). Seven climatic seasons of water-bodies have been distinguished in Estonia. The climatic seasons of lakes are defined by water temperature and ice cover characteristics (date of the beginning and the end ice phenomena and ice cover). The seasons of colder half-year (late autumn, winter, early spring) determined only by ice data. A closed annual cycle consists of a sequence of regularity alternating ecological phases, which are

Tab. 1 – Statistics of temporal variability for start date of climatic seasons of Lake Võrtsjärv by linear trend line in 1946–2000

Statistics	Early winter	Winter	Early spring	Spring	Summer	Autumn	Late autumn
Slope	0.016	–0.013	–0.339	–0.160	–0.132	–0.047	–0.094
in 1946	13 Nov	28 Nov	17 Apr	21 Apr	29 May	7 Sept	29 Oct
in 2000	14 Nov	27 Nov	31 March	13 Apr	22 May	5 Sept	25 Oct
Change	1	–1	–17	–8	–7	–2	–5
p value	0.882	0.920	0.014	0.018	0.200	0.511	0.312

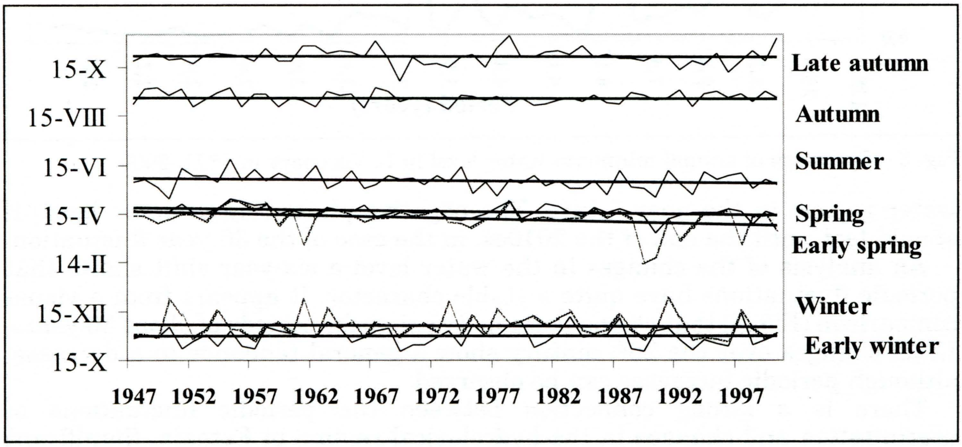

Fig. 4 – Long-term series and linear trends for start dates of climatic seasons L. Võrtsjärv

expressed using beginning dates, duration and intervals. The thermal characteristics of lakes are particularly responsive to changes in the weather and frequently amplify the effects of regional-scale variations in the circulation of the atmosphere.

Results of linear regression analysis of long-term series indicate the presence of some long-term changes. Changes in trend in Table 1 are differences between trend-line values calculated for years 2000 and 1947. Positive changes show a tendency for climatic seasons to start later and vice versa (Tab. 1).

Climatic seasons of Lake Võrtsjärv for the whole year tend to begin earlier, except early winter and winter, which start at same time. A statistically significant trend was determined only for the start date of early spring (beginning of break-up of ice-cover), also for the beginning of spring (daily mean water temperature increase above 4 °C). Start dates of early spring have shifted on L. Võrtsjärv from 17 April to 31 March.

The summer period (from spring to late autumn) has lengthened by 1 week during the 55year period. Most significant trend was obtained for winter (ice cover period). The shortening of the winter season by 17 days is calculated. A statistically significant trend was determined only for the beginning date of early spring – significance at $p<0.05$ level. Other clearly trends were obtained for early winter and autumn, but statistically not significant due to the high temporal variability of the time series (Fig. 4).

The summer half year (period from the beginning of spring to the end of late autumn) has lengthened during 55 years on L. Võrtsjärv 9 days. The periods of rapid warming tended to occur earlier in the year and there was an associated extension in the length of the biological summer. The shortening of the winter season by 18 and 16 days is statistically significant. All the long-term tendencies observed in Estonian large lakes are in a good accordance with the trend of increasing mean air temperature during winter and spring seasons, and with the trend of decreasing spatial mean snow cover duration (Jaagus, Ahas 2000).

4. Influence of summertime hydrological conditions on the ecological state

Quantitative responses of the biota to increased nutrient loading are adequate in a nutrient-limited environment but can differ in a wide range in the case of other limitations. Optical properties of water as well as the mixing depth and resuspension rate of sediments, all determined by the water level, come to the forefront in the case of shallow and turbid L. Võrtsjärv where light limitation plays a major role in controlling phytoplankton growth (Nõges 1995). Despite the rather stable nutrient content the biological indices of the trophic state fluctuate strongly depending on water richness. The influence of changes in the water level on different trophic levels is either direct or mediated by cascading effects in the food chain.

Wind-exposed northern and eastern coasts of the lake are bordered with a mostly continuous belt of *Phragmites australis* (Cav.) Trin. ex Steud., followed by submerged *Potamogeton perfoliatus* L. at a depth of about 2 m. Only in places exposed to the strongest wave action, the reed-beds become narrow or fragmentary, often separated from the shore by a shallow open water area. The western coast is richer in vegetation. The zone of floating-leaved plants – *Nuphar luteum* (L.) Smith – is distinct in places, while the zone of submerged vegetation is everywhere well formed. The southern corner of the lake is fully overgrown with macrophytes. Depending on fluctuations in the water level the abundance and distribution boundaries of different species vary greatly. Besides eutrophication, also lasting low-level periods in dry years contribute to the broadening of reed-bed areas.

Water level controls phytoplankton biomass in L. Võrtsjärv both through light conditions and nutrient availability. During periods of high water level, large amounts of phosphorus are accumulated in the sediments while phytoplankton is mainly light-limited. In the periods of low water level, light conditions improve and sediment disturbance enriches the water more with phosphorus than with nitrogen. As a result, nitrogen limitation is switched on, and nitrogen-fixing species get an advantage in competition (Nõges et al, 1998).

Water level is one of the main factors determining to a great extent the success of spawning and hence the abundance and catches of many fish species. In L. Võrtsjärv water level has a particular significant effect on the abundance of pike, which lays its eggs in overflooded shallow places (as a rule, up to 0.5 m), mostly on dead vegetation. In the case of high water level, the spawning areas of pike are rather extensive, which lays a firm foundation for the formation of a strong pike generation. There is an evident positive correlation ($r = 0.45$; $n = 30$; $p < 0.01$) between mean water level in spring and pike catch in the lake (Järvalt, Pihu 2002). As a rule, abundant pike catches

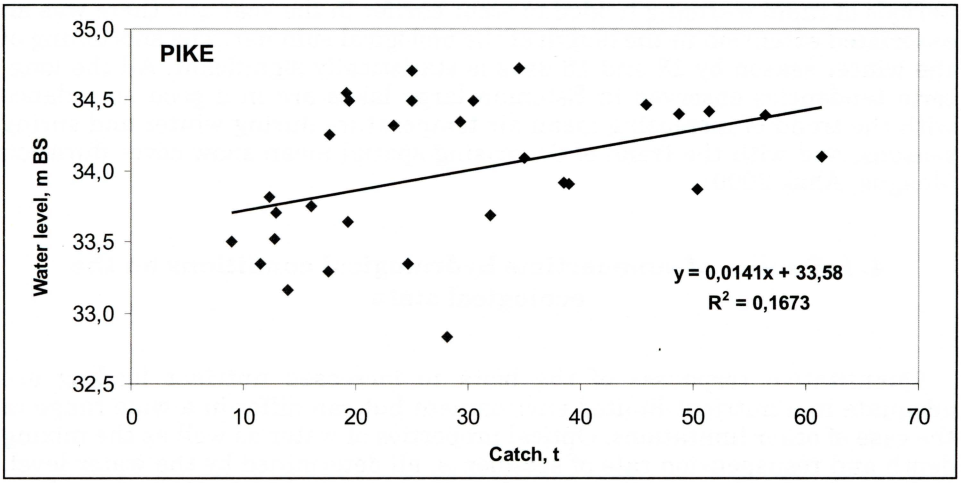

Fig. 5 – A correlation between annual pike catch and mean water level

follow, with a 4–5year delay, periods of high water level, and small catches occur, with a similar delay, after periods of low water level. This is in accordance with the age composition of pike catches in L. Võrtsjärv, where usually 4–5year-old specimens are dominating. On the ground of an experimental trawl catch a still stronger positive correlation ($r = 0.61$; $n = 23$; $p < 0.01$) was found between the abundance of a particular pike generation and water level in the spawning period (April–May) in the lake (Fig. 5; Järvalt, Pihu 2002).

5. Influence of wintertime hydrological conditions on the ecological state

Investigation about long-term changes of water and ice regime on L. Võrtsjärv gives some information not only about the hydrological conditions, but also about the trends and changes of ecological conditions caused by ice cover and water retention time. Winter conditions of a lake, especially the oxygen amount and concentration in water depend upon the duration of ice cover, thickness of ice and snow.

Ice cover has an essential part in the formation of lake ecological conditions, especially in a winter period (Fig. 6). Several winter fish kills (in 1939, 1948, 1967, 1969, 1978, 1987) have been documented on the L. Võrtsjärv during this century. Most of them (1939, 1948, 1967, 1969) coincided with low-level periods and, hence, with a higher primary production in the preceding summer and oxygen depletion during winter. Important indices of water-body climate factors are the duration and thickness of ice cover and from a lake volume point the ice volume.

To calculate a changes in lake morphometry, the lake volume, surface area, and average depth were determined at maximum ice thickness, which corresponds with wintertime minimum water level. By hydrological characteristics it is possible to explain the wintertime ecological conditions of lake by active volume, and corresponding mean depth. In calculating active

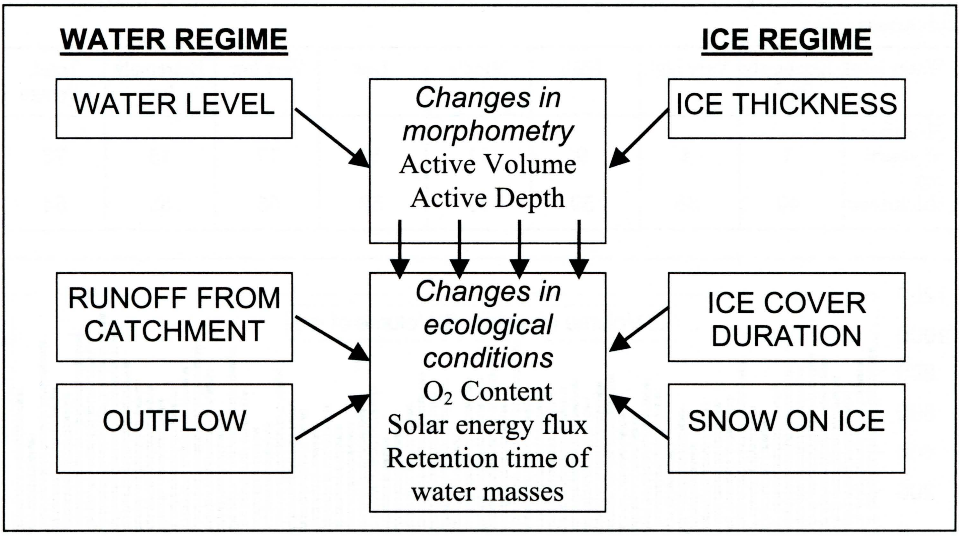

Fig. 6 – A principal scheme of wintertime hydrological factors influence on the morphometry and ecological conditions of shallow lake

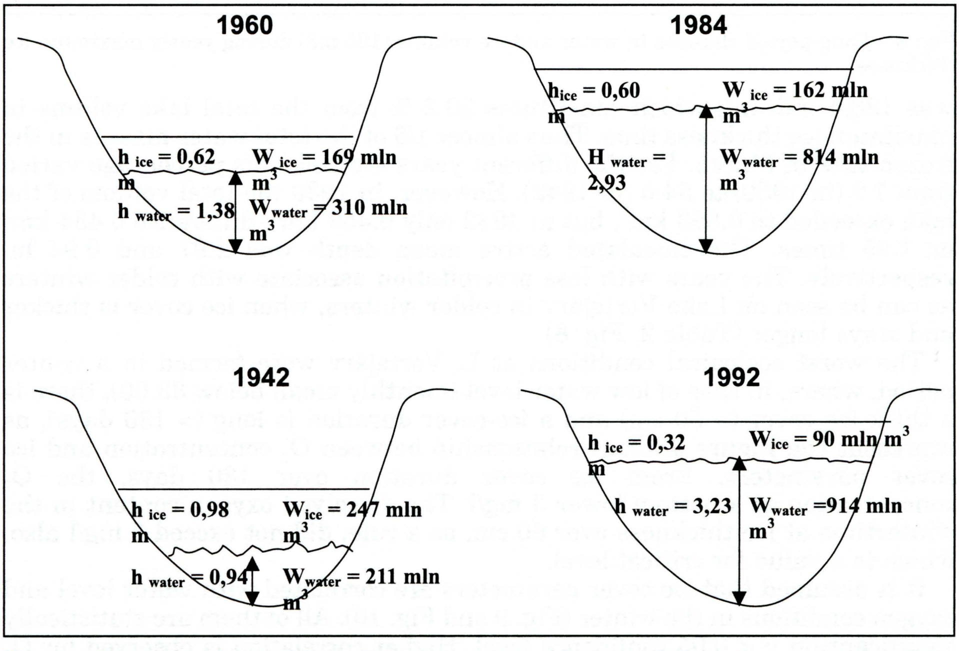

Fig. 7 – Examples about of Lake Võrtsjärv active volume in different water level and ice thickness conditions

volume the ice volume (or dead volume) is subtracted from the total volume, as the volume of ice is actually temporary unused water for the lake ecosystems (Fig. 7).

The annual maximum ice volume ranges from 69.7 mil m^3 (in 1961) to 247.5 mil. m^3 (in 1942). The mean ice volume (in 1925–1997) on L. Võrtsjärv

Tab. 2 – The duration of years by minimum wintertime water level and maximum ice thickness (cm)

Water level	Extremely high	Very high	High	Middle	Low	Very low	Extremely low	Total, average
Number of years	1	4	9	11	16	17	15	73
Ice thickness	40	38	59	53	52	53	62	54

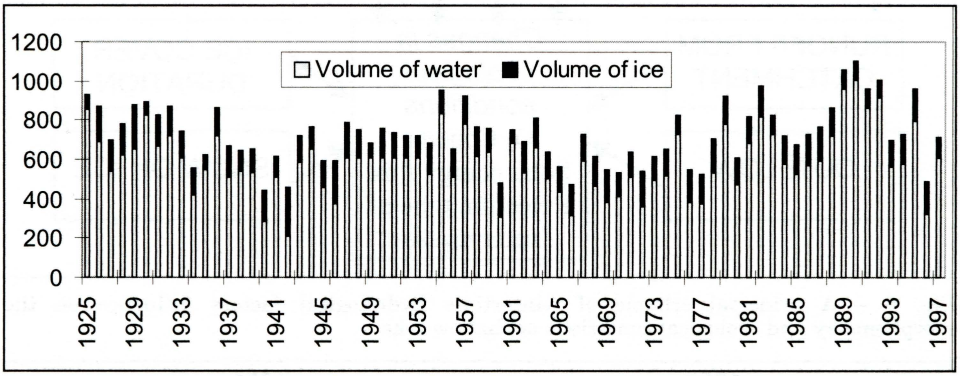

Fig. 8 – Long-period changes in water and ice volume (106 m3) during yearly maximum ice thickness

was 138.4 mil. m^3, which constitutes 20.2 % from the total lake volume in maximum ice thickness time. Thus almost 1/5 of the total water mass is in the frozen sate in March. For the different years studied, this percentage varied from 7.9 (in 1930) to 54.0 (in 1942). However, in 1930 the total volume of the lake exceeded to 0.893 km^3, but in 1942 only 0.459 km^3; difference 0.434 km^3 or 1.95 times. The calculated active mean depth was 2.97 and 0.94 m, respectively. The years with less precipitation associate with colder winters as can be seen on Lake Võrtsjärv in colder winters, when ice cover is thicker and stays longer (Table 2, Fig. 8).

The worst ecological conditions at L. Võrtsjärv were formed in a winter period, where, in case of low water level (monthly mean below 33.00), there is a thick ice cover (> 50 cm) and a ice-cover duration is long (> 130 days), as represent the Figure 9 about relationship between O_2 concentration and ice cover parameters. From ice cover duration over 130 days, the O_2 concentration at a bottom lower 3 mg/l. The dissolved oxygen content in the wintertime at ice thickness over 60 cm, as a rule, did not exceed 3 mg/l also, which is a value for critical level.

It is assumed that ice cover parameters are correlated with water level and oxygen conditions in the winter (Fig. 9 and Fig. 10). All of them are statistically significant on $p < 0.05$ confidence level. Higher correlation is observed for O_2 content in bottom layer (Table 3) than in surface part. At a bottom the concentrations of O_2 were always lower measured in the upper layers. It can be explained by the fact that there are often observed the depletion of O_2 for bottom sediment oxidation and surface layer is characterised sometimes in March by photosynthetical aeration – the algal activity just under the ice.

The winter of 1995/1996 has been another example of the disastrous consequences of the low water level. After the highly productive summer of

Tab. 3 – Regression equations relating ice cover duration (days) and maximum ice thickness (cm) to O_2 minimum concentration (mg/l) in water (n = 28)

x-variable	Equation	r	p
	Surface layer		
Ice cover duration	$y = -0.06x + 17.67$	0.366	0.055
Ice thickness	$y = -0.15x + 16.91$	0.417	0.027
	Bottom layer		
Ice cover duration	$y = -0.10x + 16.76$	0.486	0.009
Ice thickness	$y = -0.21x + 15.22$	0.533	0.003

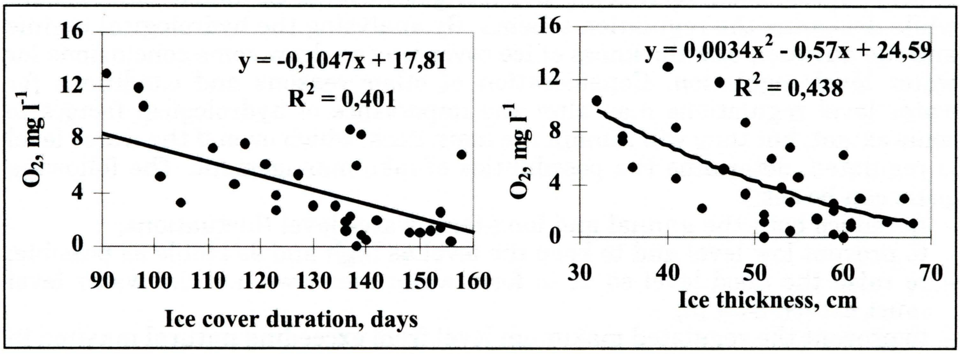

Fig. 9 – The correlation between ice cover characteristics and wintertime minimum dissolved O_2 content (mg/l) in water: left – duration (days), right – thickness (cm) in 1968–2000

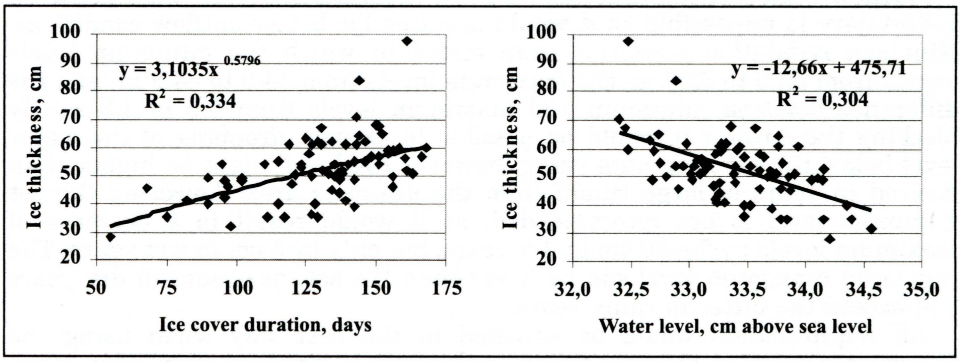

Fig. 10 – Correlation between ice cover characteristics and a minimum water level in winter

1995 the lake was frozen at an extremely low level. The winter has been cold and the lake has been covered by thick ice (~0.6 m) and snow (~0.3 m). There have been no thaws from mid-December till the beginning of March. The lowest oxygen concentrations during the studied 30 years (2.3 mg.l^{-1} just below the ice, 0.4 mg.l^{-1} in the bottom layer) were registered on 1st March.

Very low oxygen concentration in L. Võrtsjärv in the winter of 1996 can precisely be explained by low water level and a large amount of ice (31.5 % from total water mass of the lake). The lowest oxygen concentrations during the last 35 years (2.3 mg.l^{-1} just below the ice, 0.4 mg.l^{-1} in the bottom layer) were registered on 1 March 1996 (Nõges et al 1998). The winter of 1986/1987 has been an example of the disastrous consequences of a long winter, thick ice and snow cover. After the highly productive summer of 1986 the lake was frozen in November. The winter has been cold and the lake has been covered by thick ice (0.64 m) and the thickness of snow cover was recorded in the beginning of March 0.41 m.

6. Improving the ecological state by water level regulation

Lake Võrtsjärv with its large drainage area, bad outflow conditions and flat shores is a complicated object for water level regulation. The requirements of fishery, agriculture, recreation and navigation must be taken into account while designing the regulation scheme. By analysing the hydrological regime and the duration and thickness of ice cover we can draw some conclusions for water level regulation. Consideration of other reasons and conditions for water level regulations may alter the importance of hydrological factors to some extent, but they will remain the main ones, which even if the water level is regulated, determine the possibilities of lake management. The following goals can be set:

- to reduce both the annual and long-term water level fluctuations;
- to prevent low level and to keep the level as high and as stable as possible;
- to raise the flood level so as to form water-meadows, i.e. the water level must exceed 34.4 m;
- to prevent the regulated maximum level from exceeding natural maxima in order to avoid flooding of buildings and roads;
- to guarantee the sanitary minimum flow in the River Emajõgi (outflow L. Võrtsjärv).

Outflow calculations showed that a constraint level regulation of L.Võrtsjärv is impossible as it would requires far better outflow conditions. Nineteen regulation scenarios were tested in which the minimum levels varied from 33.0 to 33.7 m, the maximum levels from 34.0 to 34.8 m, and the difference between minimum and maximum levels from 0.6 to 1.8 m. By blocking the outflow it would be possible to prevent dropping of the water level below the set minimum value, however the level might be higher than desired in years of large runoff from the drainage area. Lowering the set minimum level is not recommended, as it would result in a decrease of maximum levels by 30–50 cm in dry years, but only by 5 cm in wet years. The regulated maximum level can be lower than the set maximum in dry years and exceed the latter in rainy years.

All requirements would be satisfied in the best way when using the following regulation scheme: filling of the lake proceeds in April-May when the regulator is closed. Lowering of the water level starts in the second half of May at the maximum flow rate determined by the outflow conditions, until it reaches the set minimum (usually in September). The water level would increase slightly in November and December. In years when the lake cannot be regulated due to the high level in the outflow, or due to excessive inflow, the regulator would be opened and the natural regime established. It would be reasonable to keep the minimum level at 33.7 m which is the long-term average and to which the level can be lowered in most cases (75 % of years). The regulated maximum water level is to be 34.8 m in which case forced maxima would reach 35.6 m.

As a result of regulation measures water level dynamics does not change much. It will generally follow the natural pattern but will proceed at a higher level and will have a smaller amplitude. The level will be about 1 m higher during low-water periods. Extraordinary high levels do not exceed much natural maxima, as the natural level equals at 1 % probability 35.50 m and the regulated level 35.6 m. The annual mean amplitude of level fluctuations will decrease by 0.3 m (from 1.4 to 1.1 m), the annual maximum amplitude by more than 1 m.

7. Conclusions

The most important problem of L. Võrtsjärv is the fluctuation of its level. The lower level is the result of climate change causing both decreased river inflow and increased effective evaporation. Low water periods, making up 10 % of the total number of days according to the observation data, are harmful to the ecological conditions of the lake. The active volume of the lake is the smallest with shallow water level (mean below 33.00 m in March) and thick ice cover in winters, which may cause a decrease in the oxygen content below the critical level, i.e. <2-3 mg/l.

Lasting low-water periods in L. Võrtsjärv are accompanied by a number of adverse biological phenomena consisting generally in destabilizing of the ecosystem. An increase in phytoplankton and bacterioplankton biomass deteriorates the transparency and gas regime of the lake. Low-level periods accelerate the overgrowing of shallow coastal areas with macrophytes and deteriorates the spawning conditions for pike by restriction of spawning places and for pike-perch by the spawn being buried under sediments. Greatest success would be achieved by reducing sediment resuspension and by strengthening light limitation on phytoplankton, which would control primary production and the amount of particulate matter in the water.

The analysis of the factors that influence the ecological state of Lake Võrtsjärv in winter, confirm that the main cause of variability are the water level and ice thickness. The results indicate that water level has a very clear effect on the O_2 content during low water-stand and long ice cover period. The active volume of the lake is the smallest with shallow water level (mean below 33.00 in March) and thick ice cover (> 50–60 cm) in winters, which may cause the decrease of oxygen content below critical level – <2–3 mg/l. But even a small change in ice cover and water level characteristics during mild winters has a significant positive influence on a ecological state.

With high water level, the overflooding of large areas causes problems mainly for agriculture and forestry. By means of the regulation of the water regime, by raising the minimum and maintaining the optimum level, conditions in the lake can be improved. Regulation of water level, especially by raising the minimum level, would have the positive effects on the ecological state of the lake. To decreasing the ice cover influence on L. Võrtsjärv ecosystems it is necessary to keep regulated winter water level on 33.50–33.70, as recommended. Water level regulation (i.e. low water elevation) can favourably affect L. Võrtsjärv, but the construction of regulating facilities mostly depends on economic factors. Taking into consideration the very small slope of the outflow Emajõgi R., the water level regulation of the lake by an early-planned scheme is aggravated at least by 50 % of years. It is not possible to avoid inundations by regulation facilities. Their danger and duration may even increase with regulated higher water level.

References:

BEHRENDT, H., STELLMACHER, R. (1987): Long-term changes in water quality parameters of a shallow eutrophic lake and their relations to meteorologic and hydrologic elements. In: The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. No. 168, pp. 535-544.

HABERMAN, J., NŐGES, P., NŐGES, T., PIHU, E., KANGUR, K., KANGUR, A., KISAND, V. (1998): Characterization of Lake Vőrtsjärv. Limnologica, 28, No. 1, pp. 3–10.

HILTUNEN, T. (1994): What do hydrological time series tell about climate change? Publications of the Water and Environment Research Institute, 17, pp. 37–50.

JAAGUS, J., AHAS, R. (2000): Space-time variations of climatic seasons and their correlation with the phenological development of nature in Estonia. Climate Research, 15, pp. 207–219.

JÄRVALT, A., PIHU, E. (2002): Influence of water level on fish stocks and catches in Lake Vőrtsjärv. Proc. Estonian Acad. Sci., Biol. Ecol., 51, No. 1, pp. 74–84.

JAANI, A. (1996): Hydrology and water balance of Lake Peipsi. Hydrobiologia, 338, pp. 11-23.

JÄRVET, A. (2002): Climatological calendar of Estonian lakes and its long-term changes. Nordic Hydrological Programme Report, 2, No. 47, Ånund Killingtveit), pp. 677–687.

JÄRVET, A. (2001): Climatological calendar of lakes in Estonia and its long-term changes. Proceedings of 9th International Conference on the Conservation and Management of Lakes, Japan, 5, pp. 51-54.

JÄRVET, A. (1999): Influence of Ice Cover on the Ecological Conditions of Shallow Lake Vőrtsjärv. Publications of Second Workshop on the Baltic Sea Ice Climate. Publicationes Instituti Geographici Universitatis Tartuensis 84, pp. 92-100.

JÄRVET, A. (1998): Long-term changes in time series of water balance elements. In.:Tarand, A., Kallaste, T. (eds.): Country Case Study on Climate Change Impacts and Adaptation Assessments in the Republic of Estonia. Stockholm Environment Institute Tallinn Centre, pp. 69-71.

JÄRVET, A. (1995): The variation of runoff coefficient in Estonia. In: Meteorology in Estonia in Johannes Letzmann`s Times and Today. Estonian Academy Publishers, Tallinn, pp. 180-189.

LIBIN, I., JAANI, A. (1989): Vozdeistvije izmenenij solnenoj aktivnosti na geofizieskie I gidrologieskie processy. Proc. Acad. Sci. Estonian SSR, Biol., 38, pp. 97-106 (in russian).

NIXDORF, B., DENEKE, R. (1997): Why "very shallow" lakes are more successful opposing reduced nutrient loads. Hydrobiologia, 342/343, pp. 269-284.

NŐGES, P., NŐGES, T., LAUGASTE, R., HABERMAN, J., KISAND, V. (1997): Tendencies and relationships in the pelagic environment and plankton community of Lake Vőrtsjärv in 1964-93. Proc. Estonian Acad. Sci., Biol. Ecol., 46, No. 1/2, pp. 40-57.

NŐGES, T., NŐGES, P., KISAND, A., KISAND, V., TUVIKENE, L., ZINGEL, P., PŐLLUMÄE, A., HABERMAN, J. (1998): Ecological studies. In: Huttula, T., Nőges, T. (eds.): Present state and future fate of Lake Vőrtsjärv. Tampere, pp. 79-112.

NŐGES, P. (1995): Long-term decrease in phyto- and bacterioplankton abundance in shallow, strongly eutrophic Lake Vőrtsjärv (Estonia): Seeming or real improvement of the trophic state? Proc. 6th Intern. Conf. Conservation & Management Lakes. Kasumigaura'95, 2, pp. 818-821.

REAP, A. (1986): O vozmoznostjah sverdolgosronogo prognosa vodnosti udsko-Pskovskovo ozera. In: Problemy i puti racionalnovo ispolzovanija resursov I ohrana prirody. Antropogennoje vozdeistvije na ecosistemy I problemy monitoringa. Vilnius, p. 80 (in russian).

REINART, A. (1999): Photosynthetically available radiation in Lake Vőrtsjärv at winter by the model of incident solar radiation. Publicationes Instituti Geographici Universitatis Tartuensis, 84, pp. 72–80.

Shrnutí

VLIV HYDROLOGICKÝCH PODMÍNEK NA EKOLOGICKÝ STAV MĚLKÉHO JEZERA VÖRTS

Jezero Vörts v Estonsku je velmi mělké (průměrná hloubka vody 2,8 m) a značné kolísání jeho úrovně vyvolává změny jak pokud jde o jeho rozlohu, tak pokud jde o jeho objem vody. Při nejvyšším stavu vody (35,28 m) je jeho plocha odhadovaná na 326 km^2 a objem na 1.213 km^3. Při nejnižším stavu vody (32,20 m) činí tyto hodnoty 237 km^2 a 383 km^3. Tedy rozloha plochy se liší o 89 km^2 a objem o 830 km^3.

Změny klimatických podmínek, které se promítají v cyklickém kolísání vodního systému a ledových podmínek po dlouhé období, ovlivňují zřetelně hydrofyzikální a také hydrochemické a hydrobiologické procesy v jezeře. Proměnlivý stav kvality vody je spojen s hydrometeorologickými faktory přímo nebo nepřímo. Například zvýšení průměrného stavu vody v jezeře vede ke snížení ozáření dna a ke snížení ozáření vodního sloupce. Přechodná změna jak množství, tak druhu ledu, ovlivňuje množství a druh světla pronikajícího do jezera, což působí na takové procesy jako je fotosyntéza a produkce kyslíku ve vodních masách pod ledovou pokrývkou. Optické vlastnosti vody stejně jako měnící se hloubka a měnící se podíl usazenin, což je určováno stavem vody, vystupuje do popředí v případě mělčin a zakalení jezera Vörts, kde nedostatek světla má velkou roli při regulaci růstu fytoplanktonu.

Vliv změn stavu vody na různých trofických úrovních má přímé nebo zprostředkované stupňovité účinky na potravní řetězec.

Škodlivý účinek hydrologických faktorů na ekologickou a mělčinovou oblast nastává zřetelně v důsledku následujících hydrologických podmínek: záplavy – měsíční úroveň vody nad 34,50 m, malá hloubka jezera – měsíční úroveň vody pod 33,00 m.

Jak extrémně vysoký (nad 35,00 m), tak i extrémně nízký stav vody (pod 32,50 m) mají škodlivé účinky. V létě během období nízkého stavu vody, se malá hloubka a objem jezera a intenzivní primární produkce stává problémem a během záplav také.

Ke znázornění periodicity cyklů byla využita spektrální analýza. Použití této metody zviditelnilo dlouhodobou periodicitu a některá období mohla být identifikována. Tabulka 3 uvádí výsledky spektrálních analýz. Ve spektru se objevují některé vrcholy. Současně byly zjištěny tři skupiny periodicity: krátká období se spektrálním vrcholem za 3,6 roku, střední období za 6,4 roků, dlouhá období o délce mezi 24 a 32 roky.

Zdá se, že spektrální vrchol za 25,8 let má výjimečné postavení. Byla zjištěna velmi dlouhá periodicita – 64 a 128 let –, což je problematické ve srovnání s kratšími spektrálními vrcholy, protože délka časových řad byla 128 let.

Ledová pokrývka je základní součástí při tvorbě ekologických podmínek jezera, zejména v zimním období. Několik zimních úhynů ryb (v letech 1939, 1948, 1967, 1969, 1978, 1987) bylo v jezeře Vörts dokumentováno během minulého století. K většině z nich (1939, 1948, 1967, 1969) došlo v obdobích s nízkým stavem vody a z důvodu vyšší základní produkce v předcházejícím létě a vyčerpání kyslíku během zimy. Důležitými ukazateli klimatických faktorů stavu vody je délka a síla ledové pokrývky a poměr objemu vody jezera k objemu ledu.

Odhady změn v morfometrii jezera, objemu vody v jezeře, rozsahu plochy a průměrné hloubky vycházely z maximální síly ledu, což odpovídá zimnímu minimu úrovně vody. Hydrologickými charakteristikami lze vysvětlit zimní ekologické podmínky jezera pokud jde o pohyblivý objem vody a odpovídající hloubku. Při výpočtu pohyblivého objemu je objem ledu (čili pevný objem) odečten od celkového objemu, protože objem ledu je dočasně nevyužitá voda pro udržování ekosystémů.

Roční maximum objemu ledu se pohybuje od 69,7 mil m^3 (v roce 1961) do 247,5 mil. m^3 (v roce 1942). Průměrný stav objemu ledu (v letech 1925 – 1997) na jezeře Vörts činil 138,4 mil m^3, což činí 20,2 % z celkového objemu jezera v době maximální ledové pokrývky. Téměř 1/5 celkové masy vody je zmrzlá v březnu. Bylo vypočteno, že toto procento v různých letech kolísalo od 7,9 (v roce 1930) do 54,0 (v roce 1942). Avšak v roce 1930 celkový objem jezera převyšoval 893 km^3, zatím co v roce 1942 činil pouze 459 km^3, rozdíl tedy představoval 434 km^3 čili 1,95násobek. Vypočtená hloubka pohyblivé vody činila v příslušných letech 2,97 a 0,94 m. Byly to roky s nižšími srážkami ve spojení s chladnějšími zimami, jak to bývá na jezeře Vörts v chladnějších zimách, kdy ledová pokrývka je silnější a vydrží déle.

Horší ekologické podmínky na jezeře Vörts vznikaly v zimním období, kdy v případě nízkého stavu vody (měsíční průměr nižší než 33,00), je zde ledová pokrývka o síle > 50 cm) a vydrží déle (> 130 dní) jak uvádí tabulka 9 o vzájemných vztazích mezi koncentrací kyslíku a parametry ledové pokrývky. Při ledové pokrývce trvající déle než 30 dní je koncentrace u dna nižší než 3 mg/l. Obsah kyslíku v zimním období při síle ledu vyšší než 60 cm, jak je pravidlem, nepřesahuje také 3 mg/l, což je hodnota na kritické úrovni.

Odhaduje se, že parametry ledové pokrývky odpovídají úrovni vody a kyslíkovým podmínkám v zimě. To lze statisticky vyjádřit vzorcem $P < 0,05$ počtu pravděpodobnosti. U dna byla koncentrace kyslíku vždy nižší než v horních vrstvách. To může být vysvětleno jako skutečnost, že je zde často pozorováno vyčerpání kyslíku pro okysličení usazenin u dna a vrchní vrstva je někdy v zimě charakterizována fotosyntetickým provzdušněním – rozmnožováním řas přímo pod ledem.

Při rozboru hydrologického režimu a trvání a síly ledové pokrývky můžeme dospět k některým závěrům o regulaci úrovně vody. Požadavky rybářství, zemědělství, rekreace a plavby musí vzít v úvahu stanovení regulace systému. Jezero Vörts s širokou odtokovou oblastí a nevhodnými odtokovými podmínkami a mělkými břehy je komplikovaným objektem regulace úrovně vody. Zvážení těchto důvodů a podmínek regulace stavu vody může usměrnit význam hydrologických faktorů do určité míry, ale ty zůstávají hlavní,a ty, dokonce i když je úroveň vody regulována, určují možnosti správy jezera.

Následující cíle mohou být dosaženy: snížení jak ročního, tak dlouhodobého kolísání stavu vody, předcházení snížení stavu vody a udržení stavu vody tak vysoko jak je to možné, zvýšení míry zaplavování tak, aby byly zaplavovány louky, tj. stav vody musí převýšit 34,4 m, regulací maximálního stavu vody předcházet odhadovanému přirozenému maximu, aby se předešlo zaplavování budov a silnic.

Výpočet odtoku potvrdil, že nucená regulace úrovně jezera Vörts není možná, protože by to vyžadovalo mnohem lepší odtokové podmínky. Bylo testováno devatenáct scénářů regulace, ve kterých se minimální stav vody pohyboval od 33,0 do 33,7 m, maximální stav od 34,0 do 34,8 m a rozdíl mezi minimálním a maximálním stavem od 0,6 do 1,8 m.

Blokování odtoku by bylo možné, aby se předešlo snížení stavu vody pod míru minimální hodnoty, avšak stav vody by mohl být vyšší než žádoucí v letech s velkými srážkovými odtoky z přítokové oblasti jezera. Snížení míry minimální úrovně se nedoporučuje, protože by vedlo nejen ke snížení maximální úrovně o 30–50 cm v suchých letech, ale dokonce o 5 cm v deštivých letech. Regulovaná maximální úroveň může být nižší než maximum v suchých letech a později může být překročena v deštivých letech.

Všechny požadavky by byly nejlépe uspokojeny uplatněním následujícího schématu regulace: naplnění jezera v dubnu–květnu, kdy je regulační zařízení částečně uzavřeno. Snižování stavu vody zahájit v druhé polovině května na míru maximálního odtoku určovanou odtokovými podmínkami až dosáhne minimální míry (zpravidla v září). Stav vody by se mohl mírně zvýšit v listopadu a prosinci. V letech, kdy jezero nelze regulovat kvůli systému průtoku nebo kvůli nadměrnému přítoku, regulační zařízení by mělo být uzavřeno a zaveden přirozený režim. Bylo by rozumné zachovat minimální stav 33,7 m, který je dlouhodobým průměrem a na který může být snížen. V největším počtu případů (75 % let). Regulovaný maximální stav vody by mohl být 34,8 m, při čemž by se maximálně mohl zvýšit na 35,6 m.

V důsledku regulačních opatření by se dynamika stavu vody příliš nezměnila. Následovala by přirozený vzor, ale postupovala by na vyšší úrovni a měla by menší amplitudu. Mimořádně vysoký stav by překračoval přirozené maximum pouze o 1 %, protože přirozený stav by činil 35,5 m a regulovaný stav 35,6 m. Roční amplituda kolísání stavu vody by se snížila o 0,3 m (z 1,4 m na 1,1 m) roční amplituda maxima o více než 1 m.

Obr. 1 – Mapa polohy jezera Vörts
Obr. 2 – Dlouhodobé změny ročního maximálního a minimálního stavu vody v jezeře Vörts
Obr. 3 – Spektrum ročního minimálního stavu vody
Obr. 4 – Dlouhodobé řady a lineární trendy trvání klimatických sezón jezera Vörts
Obr. 5 – Vzájemné vztahy mezi ročními srážkami v povodí a stavem vody v jezeře
Obr. 6.– Základní schéma vlivu zimních hydrologických faktorů na morfometrii a ekologické podmínky mělkého jezera
Obr. 7 – Příklady pohyblivého objemu vody jezera Vörts při různém stavu vody a různé síle ledu
Obr. 8 – Dlouhodobé změny objemu vody a ledu (106 m^3) během ročního maxima síly ledu
Obr. 9 – Vzájemný vztah mezi charakteristikami ledové pokrývky a zimní minimální úrovní rozpuštěného obsahu kyslíku (mg/l) ve vodě: vlevo – trvání (dny), vpravo – síla ledu (cm) v letech 1968–2000
Obr. 10 –Vzájemný vztah mezi charakteristikou ledové pokrývky a mezi stavem vody v zimě.

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