Article

Changes in water temperature and chemistry preceding a massive kill of bottom-dwelling fish: an analysis of high-frequency buoy data of shallow Lake Võrtsjärv (Estonia)

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Abstract

Although massive fish kills are wide-spread and can be economically devastating, there is little information on exact causal mechanisms of fish kills in nature. In large shallow Lake Võrtsjärv, sporadic fish kills have been registered mainly in cold winters, yet in 2013, an unexpected fish kill occurred beginning mid-June. At the time of the fish kill, an investigation was conducted to determine species composition, number, and sizes of dead fish along the lake shore. To determine possible causes of the fish kill, we analysed the dynamics of key physical and chemical parameters of lake water, including diurnal fluctuations of water temperature (WT), pH, dissolved oxygen (DO), ammonium ion concentrations (NH_4-N), and the development of water stratification, during the growing season of 2013 using high-frequency water quality monitoring buoy and monthly manual monitoring data. Environmental data between 2010 and 2012 were used as a reference because no fish kill occurred. The results suggest that the fish kill was induced by a combination of successive and co-occurring extreme water parameters such as high WT (up to 24.5 °C), pH (up to 9.2), and NH_4-N (up to 0.13 mg L^{-1}), short-term stratification, and low DO concentration in the bottom water (0.49 mg L^{-1}, saturation 5.4%) induced by quick warming of this shallow lake after a long ice-covered period and leading to a likely ammonia poisoning and hypoxia. The main target species was the bottom-dwelling ruffe (*Gymnocephalus cernuus*), indicating that the summer kill started at the bottom of the lake. The event highlights the significance of short-term disturbances on fish populations, which can be detected only using high-frequency monitoring data.

Key words: bottom-dwelling fish, extreme weather events, high-frequency water parameter fluctuations, large shallow lake, massive fish kill, short-term stratification

Introduction

A few dead fish floating on the surface of a lake during the growing season is not necessarily cause for alarm, but problems arise when large numbers of fish are found dead and dying over a longer period of time (Helfrich and Smith 2009). In the Nordic countries, sporadic fish kills have been registered mainly in cold winters as a result of a significant decline in dissolved oxygen during long periods of ice cover (e.g., Järvalt et al. 2005, Hurst 2007, Ruuhijärvi et al. 2010). Similarly, extreme heat (Mundhal 1990), high water temperature, massive cyanobacterial blooms (American Fisheries Society 1992, Kangur et al. 2005, 2013), oxygen deficit (Jeppesen et al. 1998, Zhu et al. 2008, Moss et al. 2011, Kangur et al. 2013), and high pH and ammonia concentrations (Rodger et al. 1994, Randall and Tsui 2002) have been reported to cause sudden massive fish die-offs in ice-free lakes. Despite the global occurrence of unexplained massive fish kills and the rising public concern (Snyder 2013), little knowledge exists on exact causal mechanisms explaining fish kills in nature. Nevertheless, such a massive fish die off can result

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in a complete restructuring of the fish community (Vanni et al. 1990, Balayla et al. 2010, Kangur et al. 2013) and even abrupt, unexpected transitions in the aquatic ecosystem (Dakos and Hastings 2013).

Seasonal mean conditions are typically used to predict the behaviour of lakes; however, certain events, such as summer fish kills, are likely more closely dependent on stochastic extreme events (Kann and Smith 1999). Heat waves, periods of high algal photosynthesis, toxic blooms, and other events (Kann and Smith 1999, Havens 2008) may play a key role in causing water quality to change within hours (Helfrich and Smith 2009), creating temporary anoxia or building short-term potentially lethal peaks in pH. Therefore, high-frequency monitoring buoy data can be useful for tracing the exact factors triggering fish kills.

In large shallow eutrophic Lake Võrtsjärv, a high-frequency water monitoring buoy has operated since 2009 in parallel with monthly manual monitoring of water chemistry, revealing sudden shifts in different water parameters that may cause summer fish kills. Recording the exact occurrence of the first dead fish on the lake shore and the intensification of the fish kill was possible because the Centre for Limnology (on the shore of Lake Võrtsjärv; Fig. 1) research staff is constantly observing the lake. Hence, the 2013 fish kill in Lake Võrtsjärv provided a unique opportunity to detect shifts in water parameters that can trigger massive fish kills.

Beginning mid-June 2013, a mass fish kill occurred in Lake Võrtsjärv. We operatively started comprehensive investigations to clarify the causes of this unexpected, ecologically critical, lethal event in the lake. We hypothesised that (1) the fish kill was linked with an acute temperature change (quick warming after the ice-covered period) and rapid shifts in the lake water quality, and (2) the summer fish kill started at the bottom of the lake where the habitat first became unsuitable for fish. Specific objectives of the study were to (1) clarify the causes of the unexpected, critical condition of the lake that was lethal to fish; (2) analyse differences in environmental conditions between "fish kill" and "ordinary" years; and (3) assess the number of fish killed and identify the target species. We summarise the results of these investigations and explore factors that determine the likelihood of summer fish kills in large shallow lakes.

Study site

Lake Võrtsjärv (58°16′N, 26°02′E), located in the central part of Estonia (Fig. 1), is a shallow turbid waterbody with a mean depth of only 2.8 m, a maximum depth of 6 m, and a surface area of 270 km^2. Its water level fluctuates by an annual average of 1.4 m, and the absolute range of water level fluctuations (3.2 m) even exceeds the mean depth (Järvet et al. 2004). Changing water level strongly affects the functioning of all levels of the ecosystem in Lake Võrtsjärv (Nõges and Järvet 2005); nevertheless, according to the monitoring data, the 2013 water level was close to the long-term average. Commonly, Võrtsjärv does not stratify; the mean difference between the surface and the bottom temperatures over the ice-free period is ~0.1 °C, with exceptional short-term maxima reaching 4 °C on single calm days (Laas et al. 2012).

Based on nutrient concentrations, the central part of the lake can be considered highly eutrophic, whereas the narrow and sheltered southern part is hypertrophic. Over the last decades, the mean concentration of chlorophyll *a* (Chl-*a*) is 24 µg L^{-1}, mean total phosphorus (TP) is 54 µg L^{-1}, and mean total nitrogen (TN) is 1.4 mg L^{-1} (Tuvikene et

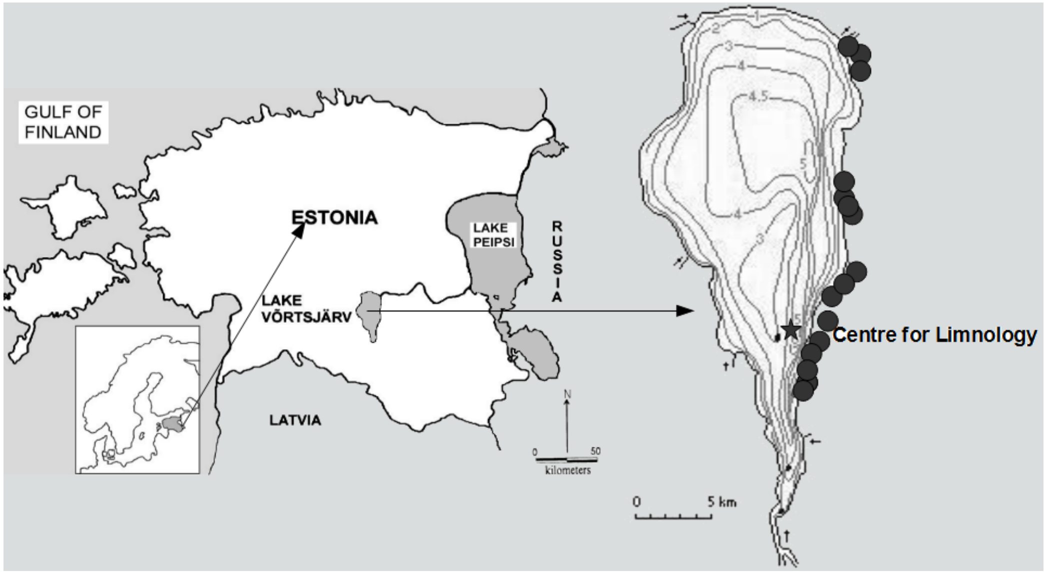

Fig. 1. Location of Lake Võrtsjärv, Estonia.★ represents the buoy and ● the locations of fish analyses on the lake shore.

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al. 2004, Nõges et al. 2010). In Lake Võrtsjärv, the dominant cyanobacteria, *Limnothrix planktonica*, *L. redekei*, and *Planktolyngbya limnetica*, cannot fix N_2, and the main N_2-fixing taxa, *Aphanizomenon skujae* and *Anabaena* spp., commonly do not dominate. Overall, nutrient loading to Lake Võrtsjärv has decreased since 1990, the water quality has improved, and the present ecological status seems to be mostly controlled by climatic factors through changes in water level (Nõges et al. 2007).

Material and methods

Sampling and dataset

We analysed some weather parameters (e.g., wind speed) and the dynamics of key physical and chemical parameters of lake water, including diurnal fluctuations of water temperature (WT), pH, dissolved oxygen (DO), fraction of unionised ammonia (NH_3), and water stratification, during the 2013 growing season using high-frequency water quality monitoring buoy and monthly manual monitoring data. Overall, water quality monitoring data from 2010, 2011, and 2012 were used as reference in data analysis. In CUSUM analysis, data from 2010 and 2011 were used as a reference to compare with the 2013 “fish-kill” year because there were data gaps in 2012 caused by malfunctioning of some sensors.

High-frequency buoy data of WT, pH, and DO were collected at 10–15 min intervals near the deepest point of Lake Võrtsjärv (Fig. 1), which has been considered generally representative of lake-wide conditions (Nõges and Tuvikene 2012). In 2013, ~2.5 m of water was under the buoy in spring and in the beginning of summer. Since 2009, measurements were conducted in the open-water period at 1 m depth with a multiparameter sonde (YSI model 6600 V2-4). Since January 2013, 2 PME miniDOT loggers recording DO and WT 0.5 m from the surface and 0.5 m from the bottom at 10 min intervals were added to the measuring system to capture micro-stratification periods in summer. Concentrations of different nutrient forms (PO_4-P, TP, NH_4-N, NO_2-N, NO_3-N, TN), sulfate ion (SO_4), biochemical oxygen demand (BOD_5), and Chl-*a* were measured at the buoy location in frames of monthly monitoring. Monthly monitoring methods are described in more detail by Nõges and Tuvikene (2012). Wind speed was measured by a weather station on the shore of Lake Võrtsjärv at the Centre for Limnology.

The appearance of the first dead fish and the broadening of the fish kill were observed by the research staff of the Centre for Limnology. To evaluate the extent of the fish kill and the number of fish killed, we conducted 4 surveys at 16 sites along the shore (Fig. 1) from 18 to 23 July 2013. Because the lake is mostly bordered with a reed belt, surveys were conducted on the eastern side of the lake where access to the shores is possible. Dead fish were identified, counted, and measured once on 5 m transects at each site.

Data analysis

Abrupt ecosystem changes often result from nonlinear dynamics (Andersen et al. 2008). Therefore, to ascertain possible reasons behind the fish kill we first used the CUSUM approach (Gilbert 2010) to detect structural changes in WT, pH, and DO in the fish-kill year of 2013 compared to the ordinary years (2010 and 2011). We used 2010 and 2011 as reference years in CUSUM because data gaps occurred in 2012 caused by the malfunctioning of some sensors. In the CUSUM analysis, trends were calculated for the 2-month high-frequency data records (Jun and Jul) for WT, pH, and DO. The approach herein applies the *z*-score CUSUM method (Gilbert 2010). First, all data for which CUSUM scores were calculated were first transformed to *z*-scores by calculating mean values and standard deviations for all parameter time series. Each data point was normalised by first subtracting the mean and then dividing the result by the standard deviation. The second step in the CUSUM approach is to sum all *z*-scores over time to obtain a long-term trend. The effect of this manipulation is to filter fluctuations, thereby revealing the patterns in the data. Absolute CUSUM values are not important to the understanding of relationships and will change, depending on the length of the time series, because inclusion of additional data will change the mean and standard deviation. According to Gilbert (2010), downward trends in CUSUM charts indicate values below the long-term mean and upward trends indicate values above the long-term mean.

We estimated differences between the monthly water parameters (pH, WL, WT, BHT_5, NH_4-N , NO_3-N, NO_2-N, Chl-*a*, TP, TN, SO_4, PO_4-P) in the fish-kill year (2013) and in the ordinary years (2010, 2011, 2012) using an ANOVA Tukey test to evaluate the significance of the differences in investigated years. Moreover, the June 2013 monitoring data (on WL, WT, pH) were also compared with June 2013 buoy data to ascertain that the buoy data were comparable to monitoring data. To evaluate whether wind speed had an effect on the fish kill, we then used an ANOVA Tukey test to compare wind speed during periods with “normal” DO and pH and no large fish kills (period 1) with a “fish-kill” period of low DO and high pH (period 2). In our study, data from 15 and 26 June were treated as period 2. All analyses were conducted using procedures provided by programme R 3.0.0 (R Development Core Team 2013) at a significance level of 5%.

Calculation of the fraction of unionised ammonia

In aqueous solution, toxic unionised ammonia (NH_3) exists in equilibrium with ammonium and hydroxide ions. We calculated the fraction of unionised ammonia according to Emerson et al. (1975) as a function of pH, temperature, and the ionic strength of the aqueous solution. Within the temperature range of 0–50 °C and a pH range of 6.0–10.0, this function is given by the following expression:

$$f = 1/(10^{(pK_a - pH)} + 1), \quad (1)$$

where pK_a is a function temperature in Kelvin, and:

$$pK_a = 0.0901821 + 2729.92/T_k. \quad (2)$$

Results

Numbers and species of fish killed

Thousands of dead fish, mostly ruffe (*Gymnocephalus cernuus*) were observed on the shore of the lake beginning 15 June, mostly in the pelagic part of the lake, with dead fish accumulating in shallow water and along the shore. As a result of the decrease in the water level and changes in wind direction, the dead fish formed multiple strips on the shore, indicating a lengthy duration of the fish kill.

The highest concentration of dead ruffe (up to 168 specimens per 1 m of shoreline) along the open eastern coast was observed at the Centre for Limnology (Fig. 2; observation station 5). In addition to ruffe, we found a few (1–2) large dead specimens of northern pike (*Esox lucius*), Eurasian perch (*Perca fluviatilis*), common bream (*Abramis brama*), and asp (*Aspius aspius*) on the shore and at the water edge.

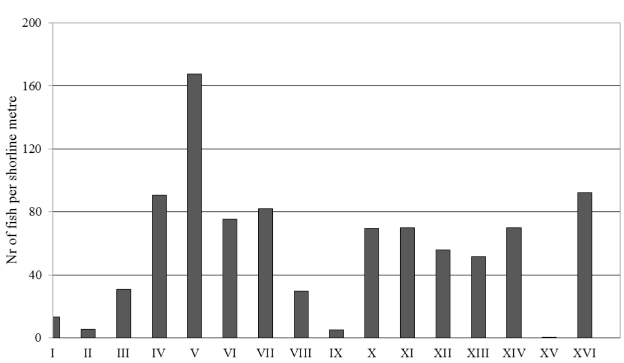

Fig. 2. Total number of dead ruffe in different observation stations per 1 m of shoreline of Lake Võrtsjärv, Estonia. The observation stations (see on Fig. 1) are ordered from south to north.

In July 2013, we measured on average 57 (range 1–168) specimens of dead ruffe per 1 m of shoreline. The average total length of dead ruffe was 10 cm (range 6–13 cm) and the total weight ~14 g. Regarding the average number, the total length and weight of dead ruffe, and the approximate length of the investigated shoreline (about 40 km), the number of dead ruffe in this part of the lake was at least 2.28 million specimens (about 32 tonnes). The total length of shoreline of Lake Võrtsjärv is about 109 km (Järvet et al. 2004). Unfortunately, the number of dead fish that remained on the bottom of the lake or that were consumed by scavengers is unknown.

Variation in water temperature, pH, dissolved oxygen, and ammonium ion content

Manual lake monitoring took place on 18 June 2013, a few days after the detection of first dead fish. These monitoring results were comparable with the data obtained from the buoy and data from previous years. According to the ANOVA Tukey test, except for Chl-*a*, which had a significantly ($P = 0.016$) higher concentration in the year of fish kill, no significant difference was found in other water parameters (pH, TN, TP, NH_4-N) between the fish-kill year (2013) and the ordinary years (2010–2012) under investigation.

Nevertheless, the CUSUM analysis of the high-frequency data revealed significantly ($P < 0.05$) higher pH and WT and lower DO in the fish-kill year (2013) compared to the ordinary years (2010–2011). The largest difference between the years was noted when the residuals of pH and WT were compared, with the most significant difference in pH occurring 20–30 June (Fig. 3). The CUSUM analysis revealed the change-points in pH and WT; in 2013, pH rose quickly from the beginning of June and remained high through June and July. In 2010 and 2011, however, pH values did not peak until mid-July. Similarly, WT in 2013 was high from the beginning of June, followed by a short, cooler period, but the end of June and the beginning of July were considerably warmer in 2013 than in 2010 and 2011 (Fig. 3).

In spring 2013, after the ice break-up on 26 April, the lake warmed rapidly, reaching a WT of 23.5 °C by 21 May (Fig. 4). Concurrently, pH reached the highest values (9.2) of the year and remained high (around 9) until mid-July (Fig. 4). From mid-June 2013, WT rose significantly (Fig. 4), and by the end of June an 8-day period of high WT (up to 24.5 °C) co-occurred with high pH (average 9.1). Thereafter, days with extremely warm water (WT 26–29 °C) continued until the end of July (Fig. 4).

Moreover, in 2013 extremely low values of DO were recorded in the near-bottom water in the evenings of 15, 26, and 27 June (0.49, 2.8, and 2.9 mg L^{-1}, with corre-

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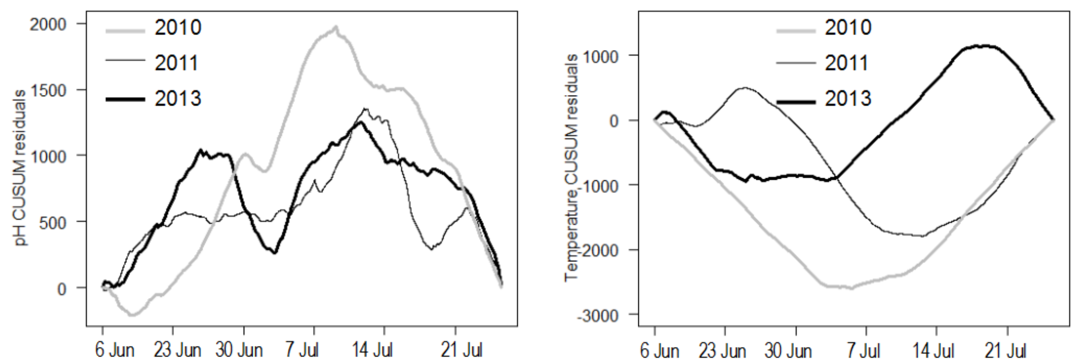

Fig. 3. CUSUM test residual values as a function of time for the water pH and temperature in June and July of "ordinary" years (2010 and 2011) and the "fish-kill" year (2013) in Lake Võrtsjärv, Estonia.

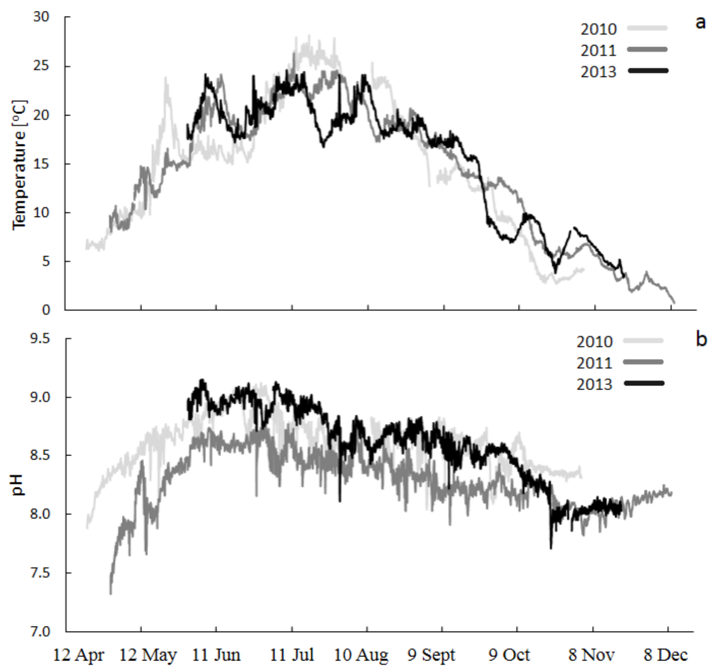

Fig. 4. High-frequency buoy data of surface water temperature (a) and pH (b) in the growing season of 2010, 2011, and 2013 in Lake Võrtsjärv, Estonia.

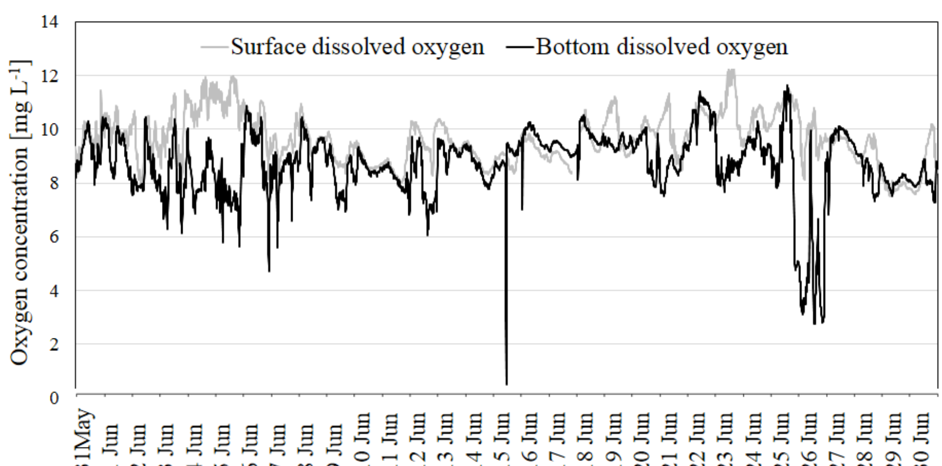

Fig. 5. High-frequency buoy data of dissolved oxygen concentrations in the near-bottom water and in the surface water in June 2013 in Lake Võrtsjärv, Estonia.

sponding saturation levels of 5.4, 30.8, and 31.7%, respectively; Fig. 5). Such extremely low DO concentrations occurred in periods with extraordinarily ($P < 0.001$) calm weather, which allowed short-term stratification of the lake. By late evening of 15 June, the average wind speed had reduced considerably, from ~5.6 m s^{-1} in the day to 1.3 m s^{-1} in the late evening, when slight wind was interrupted by periods of complete calm. On 26 and 27 June, average wind speeds were 1.1 and 1.4 m s^{-1}, respectively.

The calculated fraction of unionised ammonia nitrogen in the surface layer reached highest values (>40% of total ammonia N, the sum of NH_4-N and NH_3-N) in the first week of June, with 2 other peaks in the last week of June and first week of July (Fig. 6). These periods coincided with the formation of temporary thermal stratification during which temperature differences between the surface and bottom layer exceeded 4 °C, and the corresponding DO concentrations differed by >4 mg L^{-1}.

Discussion

The high-frequency buoy data indicated that the summer fish kill in 2013 in Lake Võrtsjärv was likely induced by a combination of successive and co-occurring extreme phenomena. The quick warming in May created a short-term stratification and low DO concentration in the bottom water in mid-June, followed by an 8-day period of co-occurring high WT and pH that potentially triggered toxic NH_3 formation. Finally, a long period with extremely high temperatures followed. Such extreme events probably led to hypoxia and ammonia poisoning of fish. Thus, a combination of factors such as high WT, low DO, high pH, and toxic ammonia concentration were probably responsible for the mass mortality of fish over a longer period.

In shallow lakes (like Lake Võrtsjärv), hypoxia should seldom occur because of regular mixing of surface and bottom waters and sufficient exchange between water and atmosphere (Zhu et al. 2008). Nevertheless, short-term stratification of shallow lakes creating low DO concentrations in the bottom water is possible, like that observed in Lake Võrtsjärv in mid-June 2013 when the first dead fish appeared. According to Zhu et al. (2008), all hypoxic events in large, shallow, and eutrophic Lake Taihu (China) occurred during calm periods when average wind speeds were <2.6 m s^{-1}. Similarly, in Lake Võrtsjärv the fish kill was accompanied by calm weather and low DO concentrations.

The fish kill in Lake Võrtsjärv was not complete; the main target species was ruffe (>90% of dead fish). Similarly, ruffe was also the main target fish during the previous fish kills in 2002 and 2010 in the nearby large eutrophic Lake Peipsi (Kangur et al. 2005, 2013). This small bottom-dwelling shoaling fish is acknowledged to be sensitive to extremely low oxygen conditions (Kováč 1998). Moreover, when stratification of the waterbodies occurs, densities of ruffe can decrease rapidly in an anoxic hypolimnion (Hölker and Thiel 1998). The preferred oxygen concentration for ruffe is 5–6 mg L^{-1} (Kováč 1998). The fish kill in June 2013 in Lake Võrtsjärv affected mainly ruffe, indicating that the mortality of fish likely started at the bottom of the lake where low DO concentrations occurred during the calm dawn.

The fish die off in Lake Võrtsjärv intensified at the end of June 2013 as the temperature and pH rose significantly, and the period with highest temperature (24–25 °C) and pH (about 9) lasted up to 8 days. This period differed significantly from ordinary conditions in the lake. Ruffe prefers lower temperatures than other percids because its temperature optimum is between 15 and 20 °C (Hölker

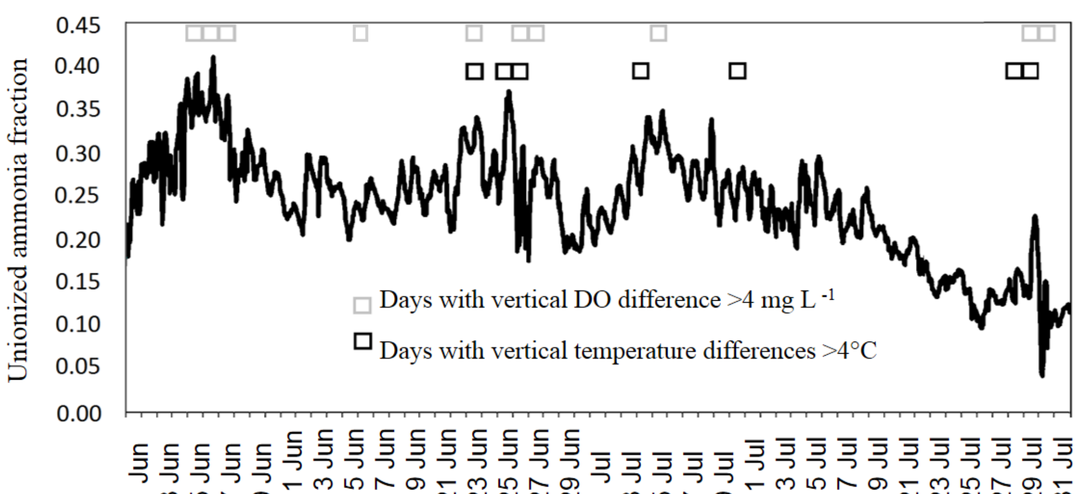

Fig. 6. Unionised fraction of total ammonia nitrogen in Lake Võrtsjärv, Estonia, in summer 2013 and the days of temporary thermal stratification.

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and Thiel 1998, Henson and Newman 2000), and it has a slower physiological response to increasing temperature (Henson and Newman 2000). Additionally, ruffe has a low tolerance for high pH (Rask and Tuunainen 1990), similar to many other fish species for which pH values >9 are lethal (Falter and Cech 1991). Although, data are unavailable on the direct pH effect on ruffe, ruffe do not avoid areas with high pH because they cannot sense pH difference in water (Tuvikene and Kreitzberg, unpubl. data). Thereby, an extraordinary period with high temperature and pH probably deepened and extended the fish-kill phenomenon in Lake Võrtsjärv.

Elevated pH further affects fish populations because the frequency of sublethal and lethal concentrations of unionised ammonia increases with increasing pH and temperature (Kann and Smith 1999). Toxicity, expressed as total ammonia (the sum of NH_3 and NH_4) in the environment, increases with water pH, and with WT to a minor degree (Randall and Tsui 2002). Histopathological investigations of fish deaths during cyanobacterial blooms in the UK indicated that the cause of death was mostly from gill damage caused by the high pH and higher levels of ammonia from the decomposition of the cyanobacteria (Rodger et al. 1994). Although we do not have total ammonia measurements for this period, a toxic effect of unionised ammonia on fishes can still be assumed because the conditions supported a high proportion of the total ammonia to be in the unionised form.

Co-occurring high pH and WT with occasionally low DO concentrations at the bottom caused by temporary thermal stratification can therefore have a dramatic effect on the ruffe population because it does not seek refuges. In shallow eutrophic lakes, bottom-dwelling fish have no refuge from deoxygenation during still, warm summer nights (Kangur et al. 2013). Additionally, even in the case of survival, fish are stressed, and their populations are often restricted to limited areas of tolerable water quality where food limitation and crowding may lead to negative effects on fish success, as reflected in reduced survivorship, growth, and reproduction (Beitinger 1990).

The fish-kill event highlights the significance of short-term disturbances on fish populations of northern shallow lakes, which can be detected only using high-frequency buoy data because monthly data are too sparse for this purpose. Co-occurring unsuitable extreme environmental conditions may have significant impacts on fish populations and fish community structure, and thereby affect the whole lake ecosystem through the food web. The frequency of these extreme events related to local weather situations may increase with climate change in the future (IPCC 2013, Christidis et al. 2015) and could trigger a major regime shift in the fish habitat, reducing the resilience of the system.

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