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Spatial and annual variability of environmental and phytoplankton indicators in Lake Võrtsjärv: implications for water quality monitoring

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Abstract. Monitoring purposes determine the selection of variables, location of sampling sites, and sampling frequency. The selection should provide the best signal to noise ratio for the parameters of interest. For trend and surveillance monitoring, the deepest point of a lake, where different inputs to the lake are integrated, is frequently selected. However, the representativeness of a single site is often questioned, especially for large lakes. Based on data collected from 10 sampling points during 11 survey expeditions in August 2001–2011 to the large shallow Lake Võrtsjärv, Estonia, we studied the spatial and annual variability of environmental and phytoplankton variables and analysed the representativeness of a permanent sampling station for the whole lake conditions. The two southernmost stations under the influence of the main tributary deviated clearly from the homogeneous group of the other eight stations, which we termed 'Võrtsjärv Proper'. Among the stations of Võrtsjärv Proper, the year-to-year variability dominated strongly over the spatial variability, the latter being almost negligible for most of the variables. Surface water temperature and water level explained approximately half of the total variability in parameters commonly used in ecological status assessment of lakes. This has serious implications for using these variables to detect human impacts in Võrtsjärv. Our study showed that the deep sampling site, which was characterized by the lowest average variability of the parameters measured and was representative of more than 90% of the lake aquatory, possesses all necessary qualities required of a permanent surveillance monitoring station.

Key words: water level, natural variability, large lake, representative sample, design of monitoring network.

INTRODUCTION

Any environmental metric included in a monitoring programme of water bodies is subject to four general types of variation: spatial, temporal, their interaction (meaning that a particular temporal effect operates differently in some locations than others), and variation caused by sampling and measurement error (Ellis & Adriaenssens, 2006). Any of these types of variation operates at different scales, for example temporal differences include diurnal and seasonal dynamics (both regular and stochastic), year-to-year differences, and multiannual cycles; spatial differences involve horizontal and vertical differences, differences between different parts within a water body, and differences between water bodies within a smaller or larger area.

Depending on the purpose of monitoring, the intrinsic variability of metrics can be successfully exploited in some cases as a signal to discover certain impacts on the system or relationships within the system, but in other cases it acts as a noise complicating the detection of the signal of interest. A typical case to exemplify this dilemma is the monitoring of water bodies with two different aims: detecting human impacts with the effect of natural variability minimized or climate change impacts for which anthropogenic changes represent confounding factors. In both cases the success of monitoring rests on the researcher's ability to select good specific indicators that are sensitive to the underlying conditions of interest but insensitive to other factors (Patil, 1991).

Besides the selection of right indicators, wise and targeted selection of monitoring sites and timing of sampling are the next key issues to determine the efficiency of monitoring. Cavanagh et al. (1998) formulated the principles for site selection in environmental monitoring. For trend monitoring, the location of sites should be such as to provide an indication of change in the water quality within the basin as a whole. A good site for this purpose is the deepest point of the lake where different inputs to the lake are integrated. The same is valid for survey monitoring where the purpose is to establish the general overall condition of the water body. For impact assessment monitoring, on the contrary, sites should be established near the shore adjacent to the development whose impact is studied or at the mouths of tributaries and at the outlet if the impact of sub-catchments is addressed. In this case it is also recommended that one site should be located at the deepest point of the lake to monitor overall conditions.

The number of monitoring sites needed per lake depends on various factors including the purpose of sampling, lake size, stratification, morphometry, flow regime, and tributaries (EPA, 1997), which together determine the strongly lake-specific area for which a station can be considered representative. Long-term records from lakes often originate from a single mid-lake station (e.g. the series on phytoplankton from four lakes of the English Lake District (George et al., 2004) or on zooplankton from Lake Kinneret, the largest freshwater lake in Israel (Rachamim et al., 2010)). Although there are potential problems associated with sampling only a single site (Reckhow & Chapra, 1983), long-term data are increasingly sought for many purposes, such as evaluating responses to climate change, experimental manipulations, or management interventions. However, given the large uncertainty related to the representativeness of data from a single station, publishing single site data, especially if conclusions are drawn for the lake as a whole, is often met by strong reservation from reviewers.

The bulk of the nearly 50-year data on plankton and hydrochemistry from the large Lake Võrtsjärv, Estonia, has also been collected from the single permanent sampling station located at the deepest site of the lake. Experientially the narrow southernmost end of the lake has been described in several studies (Nõges et al., 2004; Laas et al., 2012) as a part clearly differing from the remaining homogeneous part of the lake (which we may call Võrtsjärv Proper), but until now there is no analytical proof for that. The long-term monitoring site located in the deepest area of the lake close to the Centre for Limnology has been considered generally representative of lake-wide conditions for a number of variables such as phytoplankton abundance and composition (Nõges et al., 2004), bacterioplankton numbers (Tammert & Kisand, 2004), and dissolved oxygen concentrations (Toming et al., 2009); however, also these statements are empirical.

The aims of the present paper are (i) to assess the dissimilarity between different sampling stations and delineate the more homogeneous lake proper and parts of the lake that significantly differ from it in hydrochemical, hydrooptical, and phytoplankton variables; (ii) to analyse the partitioning of variance between spatial (sampling stations) and temporal (years) components within the lake proper for different variables; (iii) to assess the role of temperature and water-level changes in the variability of the monitored parameters; and (iv) to evaluate the representativeness of the main monitoring station for characterizing Võrtsjärv Proper and to discuss the necessity of continuing the August whole-lake surveys.

MATERIAL AND METHODS

Site description

Võrtsjärv (catchment area 3104 km^2, surface area 270 km^2) is a highly eutrophic lake located in the southern part of Estonia in a shallow depression of preglacial origin (Järvet et al., 2004). The lake is ice covered on average 135 days a year, from the end of November to late April. Altogether 18 rivers and streams flow into the lake while the Emajõgi River is the only outflow (Fig. 1). The water retention time is one year.

Due to its shallowness (mean depth 2.8 m, maximum depth 6 m), significant annual and inter-annual water-level fluctuations with concurrent changes in the surface area and volume by 89 km^2 and 0.83 km^3, respectively, are characteristic for lake Võrtsjärv (Nõges et al., 2003; Järvet et al., 2004). The mean difference between surface and bottom temperatures during the ice-free period is around 0.1 °C; short-term differences of up to 4 °C can develop only when calm weather lasts for several days (Laas et al., 2012). Measurements of currents made in 1995–1996 (Kivimaa et al., 1998) showed that strong currents caused by moderate wind velocities (2.9 m s^{-1}, maximum 13.2 m s^{-1}) mix the water well also horizontally. Still, in the narrow southern end of the lake, the influence of dominating southerly and south-westerly winds is much weaker, and abundant macrophytes restrict water exchange with the other parts of the lake.

Changing water levels affect strongly all components of the lake ecosystem. The low-water periods along with wind action increase the resuspension of fine-grained sediments (Raukas, 1995) and accelerate nutrient cycling, which in turn leads to massive growth of phytoplankton and macrophytes. The water contains

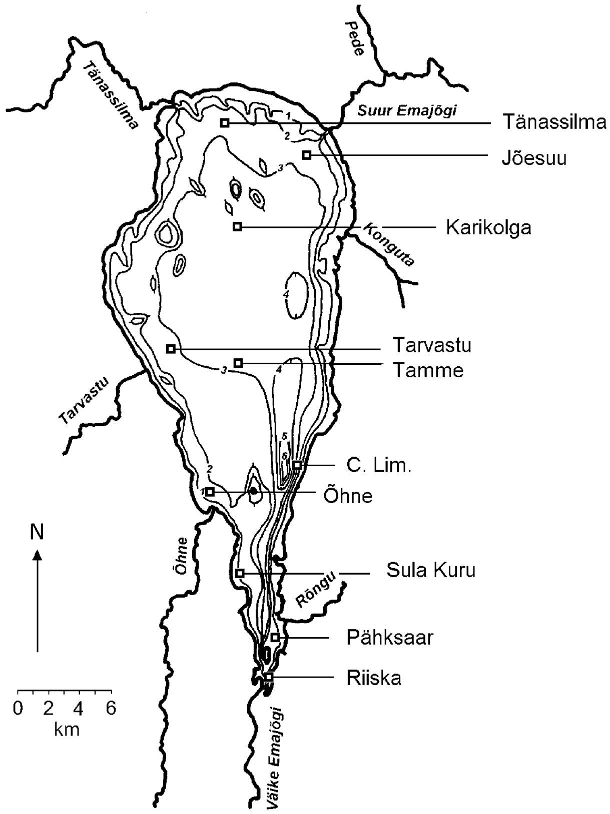


Fig. 1. Bathymetric map of Võrtsjärv with main inflows and sampling stations.

much seston and the mean transparency of the lake is less than 0.8 m during summer. At the mean water level, 19% of the lake area is covered by macrophytes (Feldmann & Mäemets, 2004). An emergent and submerged plant zone surrounds the open water area of the lake, being widest in the southern and western parts of the lake protected from winds from the main directions (Feldmann & Nõges, 2007). Cyanobacteria form up to 95% of the phytoplankton biomass during the ice-free period.

Discharge of total nitrogen (TN) and phosphorus (TP) to the lake has decreased since 1980 (Järvet, 2004; Pall et al., 2011). Monitoring data show a clear increasing trend in permanganate oxygen demand in the lake whereas TN and TP concentrations have decreased since the 1980s, especially in summer and autumn, reaching annual mean values of 1.38 mg L^{-1} for TN and 47.8 µg L^{-1} for TP in the period 1994–2010.

Since 1992 monthly year-round state monitoring has been performed at the sampling station C. Lim. and in 2001 nine more stations around the lake (Table 1) to be monitored in August were added to the programme.

Table 1. Main characteristics of Lake Võrtsjärv monitoring stations

Sampling station	Geographical coordinates	Distance (km) from the nearest river mouth or shore of the lake	Bottom sediments (Raukas & Tavast, 2002)	Influence of macro-phytes, yes/no	Influence of river inflow, yes/no	Openness to wind influence, yes/no
Riiska	58°06′20″N, 26°04′38″E	0.6	Sapropel	yes	yes	no
Pähksaar	58°07′33″N, 26°04′46″E	0.65	Sapropel	yes	yes	no
Õhne	58°12′07″N, 26°01′06″E	0.9	Sapropel	yes	yes	no
Tänassilma	58°23′06″N, 26°00′27″E	1.8	Sandy clay and clay	yes	yes	no
Tarvastu	58°16′43″N, 25°58′06″E	1.5	Sapropel	yes	yes	no
Jõesuu	58°22′51″N, 26°06′57″E	0.9	Till	no	no	yes
Sula Kuru	58°09′26″N, 26°02′40″E	0.5	Silty sand	yes	no	no
Tamme	58°16′21″N, 26°02′41″E	5.2	Sapropel	no	no	yes
Karikolga	58°20′14″N, 26°02′44″E	4.9	Sandy and silty sapropel	no	no	yes
C. Lim.	58°12′40″N, 26°06′20″E	0.15	Sandy silt	no	no	yes

Data

We used lake monitoring data on pelagic parameters such as water temperature, Secchi depth, hydrochemistry, and phytoplankton (chlorophyll *a* (Chl-*a*)) collected from 10 sampling points during 11 lake surveys in August (2001–2011). Data on phytoplankton composition (Table 2) were collected during the last four surveys (2008–2011). Secchi disk depth (Secchi), water surface temperature (Temp), dissolved oxygen (DO) content, and pH were measured in situ, the rest of the chemical analyses were performed at Tartu laboratory of the Estonian Environmental Research Centre. Chlorophyll *a* and phytoplankton samples were analysed at the Centre for Limnology of the Estonian University of Life Sciences. Data on the lake's water level (WL) for the survey dates were obtained from the Estonian Meteorological and Hydrological Institute (EMHI).

Table 2. Field and laboratory methods used for different variables

Variable	Abbreviation	Unit	Method	Reference
Physical and chemical variables				
Water level	WL	cm	EMHI Hydrometric Station	
Secchi disk depth	Secchi	m	Visual	
Water surface temperature	Temp	°C	YSI Professional	
Dissolved oxygen	DO	mg L^{-1}	YSI Professional	
Active reaction	pH		YSI Professional	
Carbonate alkalinity	HCO_3^-	mmol L^{-1}	EVS-EN ISO 9963-1	
Total phosphorus	TP	µg L^{-1}	ISO 15681-2	
Soluble reactive phosphorus	PO_4-P	µg L^{-1}	ISO 15681-2	
Total nitrogen	TN	mg L^{-1}	EVS-EN ISO 11905-1	
Nitrate nitrogen	NO_3-N	mg L^{-1}	EVS-EN ISO 13395	
Ammonium nitrogen	NH_4-N	mg L^{-1}	EVS-EN ISO 11732	
Nitrite nitrogen	NO_2-N	mg L^{-1}	EVS-EN ISO 13395	
Chemical oxygen demand	COD_{Mn}	mg L^{-1}	SFS 3036	
Sulphate	SO_4^{2-}	mg L^{-1}	EVS-EN ISO 10304-1	
Chloride	Cl^-	mg L^{-1}	EVS-EN ISO 10304-1	
Calcium	Ca^{2+}	mg L^{-1}	SFS 3003	
Total hardness	Hard	meq L^{-1}	SFS 3003	
Water colour	Colour	°	EVS-EN ISO 7887	
Total suspended solids	TSS	mg L^{-1}	EVS-EN 872	
Biochemical oxygen demand	BOD_7	mg L^{-1}	EVS-EN 1899-2	
Total iron	TFe	mg L^{-1}	ISO 6332	
Sodium	Na^+	mg L^{-1}	EVS-EN ISO 11885	
Potassium	K^+	mg L^{-1}	EVS-EN ISO 11885	
Magnesium	Mg^{2+}	mg L^{-1}	SFS 3003	
Specific conductivity	Cond	µS cm^{-1}	YSI Professional	
Silicon	Si	mg L^{-1}		Grasshoff, 1976
Phytoplankton variables				
Chlorophyll *a*	Chl-*a*	µg L^{-1}	Spectrophotometry	Jeffrey & Humphrey, 1975
Total biomass	Btot	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958
Number of species	Nsp		Microscopic counting	Utermöhl, 1958
Biomass of cyanobacteria	Bcya	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958
Biomass of diatoms	Bdia	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958
Biomass of chlorophytes	Bchl	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958
Biomass of chrysophytes	Bchr	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958
Biomass of cryptophytes	Bcry	g WW L^{-1}*	Microscopic counting	Utermöhl, 1958

* WW – wet weight.

Statistical methods

Because frequency histograms of the metrics studied showed that the inorganic forms of nitrogen (NO_2-N, NO_3-N, and NH_4-N) were strongly negatively skewed as many of the values were reaching the lower detection levels for these variables and even a log-transformation could not noticeably improve the spread of the data, we left them untransformed. Therefore, results concerning these variables should be taken with reservation. Among other variables, TP, PO_4-P, HCO_3, Secchi, total suspended solids (TSS), and biomass of cryptophytes (Bcry) were slightly negatively skewed, while specific conductivity (Cond) and number of species (Nsp) were slightly positively skewed. As all data were collected in August, the skewness of the variables was much less pronounced than commonly observed in seasonal data. Considering that transforming part of the data (e.g. by taking logarithms for right skewness or raising to a power >1 for left skewness) would have disturbed the homogeneity of the data, these series, though slightly skewed, were not transformed prior to further analyses.

In order to make the variability ranges of all variables comparable, we calculated their variation coefficients (C_{var}) over the study period as the per cent ratios of their standard deviation to mean values.

Aiming at separating the more homogeneous 'Võrtsjärv Proper' from the deviating stations, we clustered the ten stations using the joining (tree clustering) method in STATISTICA 8.0 (StatSoft, Inc. 1984–2007) with Euclidean distance as the distance measure and the Single Linkage amalgamation rule based on the 'nearest neighbour'. Separate clusterings were made for single years based on two groups of variables, one based on chemical and physical (for the years 2001–2011) and the other on phytoplankton variables (2008–2011). For the final result for the two groups, the distance matrices of variables were averaged over years.

Among the eight more homogeneous stations revealed by cluster analysis and defined as Võrtsjärv Proper, we ran the Variance Components analysis of STATISTICA 8.0 to study the role of spatial and interannual components of variability in the total variability of variables within this area. We used the factorial design with the Expected Mean Squares method and defined 'Year' and 'Station' as the random factors. For consistency of the 'Year' effect, we included in the analysis only the variables measured during all 11 surveys and skipped the shorter time series. We checked the randomness of the yearly measured values by calculating their autocorrelations with a 1-year lag. Among the 33 variables analysed, 4 were autocorrelated at most of the stations due to trends in their time series (negative trends for nitrates, sodium, and chloride and a positive trend for water colour). Due to autocorrelation, the temporal variability of these variables could be slightly underestimated, but for homogeneity reasons we preferred not to skip them from the analysis.

To have an insight into the impact of climate variability on the variables used in lake monitoring, we analysed the effect of water level and water temperature (as proxies for precipitation and thermal variability) on variables measured within Võrtsjärv Proper using Spearman correlation and multiple linear regression analyses.

Finally, to solve the question on the representativeness of the long-term sampling station (C. Lim.) for the whole lake in water chemistry and plankton studies, we ran Student's *t*-tests to discover significant differences between measurement results at that station and all the other stations.

RESULTS

Among the chemical and physical variables, the inorganic forms of nutrients (NO_2-N, NO_3-N, NH_4-N, Si, and PO_4-P), total iron (TFe), and TSS were relatively most variable with average C_{var} values equal or exceeding 50% (Table 3). Low variability was characteristic of pH, major cations, Temp, DO, and WL. General phytoplankton characteristics, such as Nsp, Chl-*a*, and total biomass (Btot) were less variable than the biomasses of single algal classes. The long-term permanent sampling site, C. Lim., located in the deepest part of the lake had the smallest average C_{var} and the southernmost station Riiska the largest average C_{var} among the stations.

The average C_{var} for phytoplankton variables was twice as high as that for physical and chemical variables and decreased towards the central part of the lake (Fig. 2). As a characteristic pattern, C_{var} for phytoplankton variables was elevated at the stations affected by major inflows. No such effect was observed for the mean C_{var} for physical and chemical variables, which was rather equal for all stations.

Two distinct clusters of stations were distinguished in Võrtsjärv both by physical/chemical and by phytoplankton variables (Fig. 3). The two southernmost stations under the influence of the Väike Emajõgi River deviated clearly from the rather homogeneous group of the other eight stations, which we termed 'Võrtsjärv Proper'. If to draw a provisional boundary between these two clusters at the latitude of the mouth of the Rõngu River (see Fig. 1), Võrtsjärv Proper would occupy 98% of the lake area.

Among the stations of Võrtsjärv Proper, the year-to-year variability dominated strongly over the spatial variability, the latter being almost negligible for most of the variables (Fig. 4). For variables such as Temp, carbonate alkalinity (HCO_3^-), total hardness (Hard), Cl^-, NO_2-N, water colour (Colour), and K^+, the inter-annual variability accounted for more than 80% and for SO_4^{2-} and Si even for 90% of the total. The highest contributions of spatial variability reaching 14–15% of the total, were found for Ca^{2+}, specific conductivity (Cond), DO, and biochemical oxygen demand (BOD_7). The variability explained by the combined effect of 'Year' and 'Station' (and including also the error term) ranged between 6% and 86% of the total variability among the eight stations.

The two major proxies for the climatic (natural) variability, Temp and WL, explained 1–74% of the total variability in the monitored variables (Table 4). The natural variability affected most strongly variables commonly used in ecological status assessment of lakes, such as TSS, TP, Chl-*a*, Secchi, and TN.

Table 3. Variation coefficients (in %) of variables in Võrtsjärv survey data from August over the study period. Variables within the two blocks and the stations from left to right are given in descending order of the average variation coefficient

Variable	Riiska	Pähksaar	Õhne	Tänassilma	Tarvastu	Jõesuu	Sula Kuru	Tamme	Karikolga	C. Lim.	Average over stations
					Chemical and physical variables						
NO_2-N	161	118	170	160	143	204	147	128	132	165	**153**
NO_3-N	101	126	98	46	61	55	55	61	55	57	**71**
Si	22	32	85	53	65	68	94	74	70	66	**63**
TSS	66	78	59	74	68	53	65	58	57	33	**61**
NH_4-N	49	57	73	66	62	60	35	41	81	47	**57**
TFe	89	39	65	63	69	55	51	53	31	48	**56**
PO_4-P	56	70	45	45	48	49	54	46	50	27	**50**
HCO_3^-	23	26	43	45	47	47	38	47	46	4	**37**
TP	21	26	39	54	46	39	36	42	31	28	**36**
Colour	55	39	43	37	26	32	28	27	32	30	**35**
Hard	34	32	29	35	32	36	31	32	36	34	**33**
BOD_7	48	55	24	21	24	16	25	25	14	21	**27**
Secchi	22	32	24	32	27	26	27	32	27	23	**27**
SO_4^{2-}	14	13	28	25	27	28	23	26	27	27	**24**
TN	29	35	21	15	20	17	12	26	18	15	**21**
COD_{Mn}	42	20	19	11	13	13	12	22	22	13	**19**
Cl^-	16	14	14	10	13	14	15	11	12	10	**13**
WL	11	11	11	11	11	11	11	11	11	11	**11**
Na^+	14	13	18	10	9	9	12	8	9	9	**11**
Mg^{2+}	16	15	11	8	9	6	21	6	8	10	**11**
DO	25	15	8	8	9	6	9	9	8	10	**11**
Ca^{2+}	7	6	9	13	7	8	11	7	8	20	**10**
Temp	11	10	8	10	9	8	9	8	8	9	**9**
K^+	9	14	9	8	6	7	6	6	6	8	**8**
Cond	6	5	5	7	3	33	5	3	3	3	**7**
pH	2	2	2	2	2	2	2	2	2	2	**2**
					Phytoplankton variables						
Bchr	197	114	66	171	116	118	74	181	145	122	**130**
Bcry	112	112	167	126	161	86	91	84	105	106	**115**
Bdia	140	106	121	76	81	63	68	49	49	64	**82**
Bchl	143	107	64	18	35	34	81	70	54	52	**66**
Bcya	116	122	77	79	29	51	51	17	31	29	**60**
Btot	143	61	70	67	25	37	42	10	25	17	**50**
Chl-*a*	63	59	34	53	42	30	36	36	28	30	**41**
Nsp	24	59	46	4	14	9	11	7	12	7	**19**
Average over variables	**56**	**48**	**47**	**43**	**40**	**39**	**38**	**37**	**37**	**34**	**42**

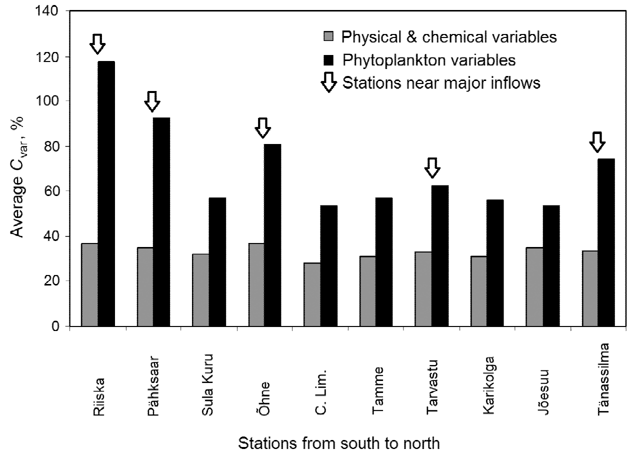


Fig. 2. Year-to-year variability of physical and chemical variables (for the period 2001–2011) and for phytoplankton variables (for the period 2008–2011) at monitoring stations in Võrtsjärv as revealed by surveys in August. For list of variables see Table 2.

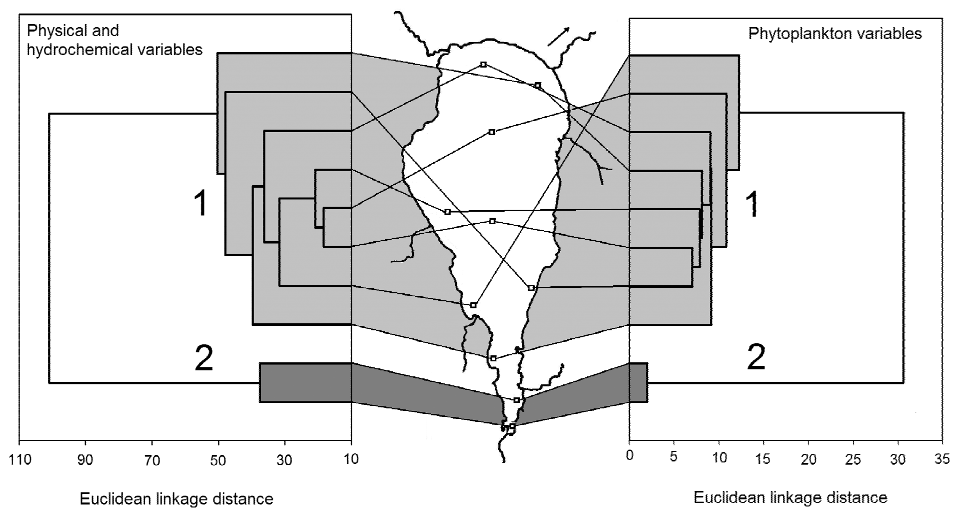


Fig. 3. Clusters of monitoring stations in Võrtsjärv based on physical and chemical variables (for the period 2001–2011) and for phytoplankton variables (for the period 2008–2011) measured in August: 1 – Võrtsjärv Proper, 2 – southern end. For list of variables see Table 2.

Although the biomass of three phytoplankton groups, cyanobacteria, diatoms, and chrysophytes (Bcya, Bdia, and Bchr, respectively), correlated significantly both with Temp and WL, the multiple regression model relating these groups with the climate proxies remained non-significant.

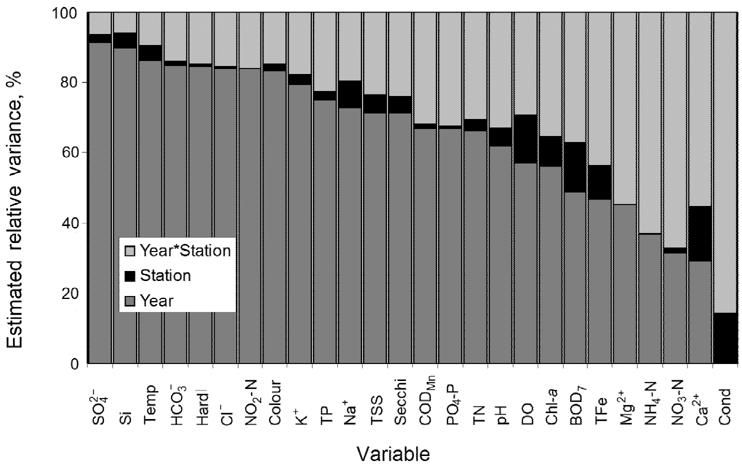


Fig. 4. Relative role of temporal variability (years), spatial variability (stations), and their combination (year*station) in the total variability of physical and chemical variables in Võrtsjärv Proper in August 2001–2011.

Table 4. Effect of water temperature and water level in determining the variability of monitoring data in Võrtsjärv Proper. r – coefficients of Spearman correlation of variables with water temperature (Temp) and water level (WL); β – standardized coefficients of multiple linear regression showing the relative contribution of temperature and water level in the prediction of the dependent variable; * – $p < 0.05$; ** – $p < 0.01$; R^2 – determination coefficient of the regression model. Variables are given in the descending order of R^2

Variable	r(Temp)	r(WL)	β(Temp)	β(WL)	R^2
TSS	−0.206	−0.426**	−0.531**	−0.937**	0.742**
TP	−0.152	−0.420**	−0.500**	−0.884**	0.659**
Chl-*a*	−0.338**	−0.193	−0.666**	−0.710**	0.550**
Secchi	0.238*	0.281**	0.583**	0.697**	0.484**
TN	−0.160	−0.356**	−0.461**	−0.728**	0.461**
HCO_3^-	0.158	0.243*	0.674**	0.259**	0.375**
TFe	−0.215*	−0.196	−0.480**	−0.573**	0.373**
Cl^-	0.124	−0.490**	−0.242*	−0.657**	0.357**
K^+	−0.150	−0.196	−0.401**	−0.604**	0.322**
Na^+	0.483**	−0.678**	0.173	−0.461**	0.310**
Mg^{2+}	0.494**	−0.626**	0.245*	−0.389**	0.292**
Si	0.464**	0.191	0.571**	0.289**	0.271**
Ca^{2+}	−0.157	0.518**	0.046	0.529**	0.261**
SO_4^{2-}	−0.004	−0.385**	−0.353**	−0.538**	0.254**
Colour	−0.384**	0.467**	−0.259*	0.329**	0.246**
COD_{Mn}	−0.474**	0.398**	−0.402**	0.126	0.221**

Continued overleaf

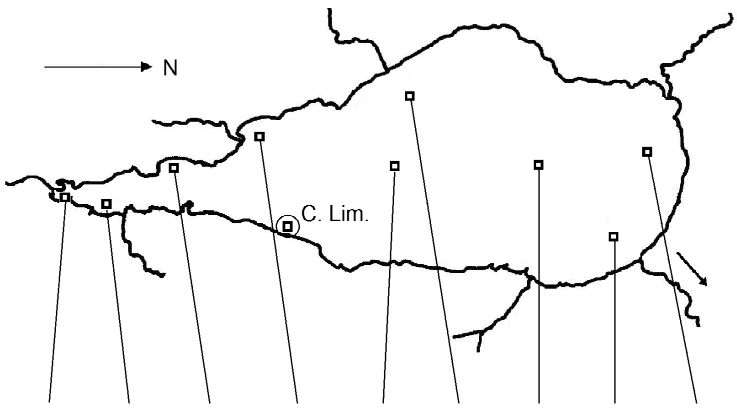
Table 4. *Continued*

Variable	r(Temp)	r(WL)	β(Temp)	β(WL)	R^2
NO_3-N	0.497**	−0.708**	0.085	−0.394**	0.190**
BOD_7	0.138	−0.299**	−0.073	−0.419**	0.155**
DO	−0.042	0.286**	0.103	0.380**	0.122**
Hard	0.039	0.291**	0.262*	0.357**	0.117**
Bcya	0.435*	−0.360*	0.253	−0.112	0.117
Bchr	0.387*	−0.387*	0.207	−0.149	0.109
Bdia	−0.366*	0.432*	−0.406	0.002	0.072
Bcry	−0.167	−0.097	0.223	0.351	0.061
Nsp	0.251	−0.116	0.069	−0.170	0.051
NO_2-N	0.060	−0.268*	−0.182	0.073	0.050
Btot	0.318	−0.239	0.120	−0.099	0.041
PO_4-P	−0.137	0.041	−0.137	−0.189	0.033
NH_4-N	−0.239*	0.124	−0.155	−0.146	0.026
pH	0.167	0.014	0.139	0.082	0.016
Cond	−0.060	0.389**	0.124	0.092	0.014
Bchl	0.052	0.033	−0.126	−0.110	0.008

Confirming the results of cluster analysis, also Student's t-test showed that the mean values of most of the parameters monitored at the long-term permanent monitoring station C. Lim. differed significantly from those at the two southernmost stations, Riiska and Pähksaar (Fig. 5).The area deviating from the main monitoring station extended also to Sula Kuru and Õhne stations only for Cond and DO. None of the mean values of the remaining 31 variables measured at C. Lim. differed significantly from those measured at any of the other seven stations of Võrtsjärv Proper.

DISCUSSION

In this section we will analyse the requirements that the specific features of Võrtsjärv pose to its monitoring programme and how the objectives, sampling design, and variable selection of this programme correspond to the principles of adaptive monitoring, a new paradigm for long-term research and monitoring introduced by Lindenmayer & Likens (2009). According to these authors, successful and effective monitoring programmes should (i) address well-defined questions that are specified before the commencement of a monitoring programme, i.e. be driven by a human need, which assigns them a management relevance, (ii) be underpinned by rigorous statistical design, and (iii) be based on a conceptual model of how the components of an ecosystem that are targeted for monitoring might function.



Group	Variable	Riiska	Pähksaar	Sula Kuru	Õhne	Tamme	Tarvastu	Karikolga	Jõesuu	Tänassilma
Physical and chemical	Cond	+ ($p < 0.001$)	+ ($p < 0.001$)	+ ($p < 0.001$)	+ ($p < 0.05$)					
	TSS	- ($p < 0.001$)	- ($p < 0.001$)							
	pH	- ($p < 0.001$)	- ($p < 0.001$)							
	Ca^{2+}	+ ($p < 0.001$)	+ ($p < 0.001$)							
	Secchi	+ ($p < 0.001$)	+ ($p < 0.001$)							
	BOD_7	- ($p < 0.001$)	- ($p < 0.001$)							
	Na^+	+ ($p < 0.001$)	+ ($p < 0.001$)							
	NH_4-N	+ ($p < 0.001$)	+ ($p < 0.001$)							
	HCO_3^-	+ ($p < 0.001$)	+ ($p < 0.01$)							
	Cl^-	+ ($p < 0.01$)	+ ($p < 0.001$)							
	Mg^{2+}	+ ($p < 0.01$)	+ ($p < 0.01$)							
	TP	+ ($p < 0.01$)	+ ($p < 0.05$)							
	Si	+ ($p < 0.01$)	+ ($p < 0.05$)							
	COD_{Mn}		- ($p < 0.01$)							
	TN	- ($p < 0.05$)	- ($p < 0.05$)							
	DO	- ($p < 0.05$)		- ($p < 0.05$)						
	NO_3-N	+ ($p < 0.05$)								
	Hard	+ ($p < 0.05$)								
	TFe		+ ($p < 0.05$)							
	PO_4-P									
	Temp									
	SO_4^{2-}									
	NO_2-N									
	K^+									
	Colour									
Phytoplankton	Chl-*a*	- ($p < 0.001$)	- ($p < 0.001$)							
	Btot	- ($p < 0.001$)	- ($p < 0.001$)							
	Bcya	- ($p < 0.001$)	- ($p < 0.001$)							
	Nsp	- ($p < 0.001$)	- ($p < 0.01$)							
	Bdia	- ($p < 0.05$)	- ($p < 0.05$)							
	Bchl	- ($p < 0.05$)								
	Bcry									
	Bchr									
	Median *p*	0.005	0.009	0.414	0.546	0.607	0.654	0.713	0.640	0.557

$p < 0.001$ | $p < 0.01$ | $p < 0.05$ | non-significant

+/− Mean value higher / lower compared to that at the station C. Lim.

Fig. 5. Differences in monitored variables between the main monitoring station C. Lim. and other stations in August. The comparison is based on eleven surveys of physical and chemical variables (in 2001–2011) and four surveys of phytoplankton variables (in 2008–2011).

Research questions and management relevance

Often monitoring programmes have been planned on the 'collect now, think-later' principle (Roberts, 1991), which may lead to unfocussed, ineffective monitoring. The questions asked and study objectives set depend on the purpose of monitoring. Common reasons for monitoring include baseline setting, trend detection, status survey, compliance checking, and impact analysis (Cavanagh et al., 1998), each of them implying a different sampling design and set of target variables.

With the establishment of the Võrtsjärv Limnological Station (presently Centre for Limnology) in 1960, regular monitoring of Võrtsjärv for scientific purposes began. Such monitoring has continued until today with at least monthly frequency, which considerably exceeds the frequencies suggested by the Water Framework Directive (WFD) (EC, 2000) for surveillance monitoring. However, also the EU Framework Programme 5 project EUROLAKES (http://www.hydromod.de/Eurolakes/results/pol-brief-strategies.jpg) envisages monthly monitoring as the minimum advisable frequency enabling to detect most crucial events determining the ecological status of lakes.

The research questions for Võrtsjärv have changed over time or evolved into new questions, which is typical of adaptive monitoring (Lindenmayer & Likens, 2009). From mainly producing background information for the fisheries research in the 1960s and 1970s, the focus of Võrtsjärv monitoring has shifted over decades to support studies on trophic relations in the planktonic food chain (e.g. T. Nõges et al., 1998; Blank et al., 2010), trend detection in ecological status (Nõges et al., 1997; Nõges & Laugaste, 1998; T. Nõges et al., 2010), as well as climate change impact assessment (Nõges et al., 2007; P. Nõges et al., 2010a, 2010b). Changing research needs through successive projects have added new variables, changed analytical approaches, and created a high complexity of the monitoring programme, which has caused increasing costs and partly compromised the clarity of the overall objective. Still, the high complexity and the maintenance of the integrity of the long time series (another principle of adaptive monitoring) have proven to be the main strength of the programme that has enabled a process-based approach in the ecological research, fulfils various requirements of the WFD, and has started to pay back also in the climate change impact studies. Considering its long-term data, Võrtsjärv has been included as a model lake in various EU financed projects.

Statistical design and representativeness of sampling stations

Beyond defining the monitoring objectives, the location of permanent sampling sites is the next most critical issue in the design of a monitoring programme. For trend and survey monitoring (which can be still defined as the main purpose of Võrtsjärv monitoring), a station located at the deepest point of the lake is expected to provide the most integrated picture of all changes least affected by local impacts from point sources (Cavanagh et al., 1998). In many lakes the deepest point is located far from the shores, which complicates its accessibility, especially in rough weather. The location of the deep area of Võrtsjärv close to the eastern shore was a lucky coincidence, which enabled to satisfy the requirements of both representativeness and logistics and was one of the main arguments for selecting the position for the present Centre for Limnology in the 1950s (Timm, 1973).

Our study showed that the deep sampling site C. Lim., characterized by the lowest average variability of the parameters measured and being representative for more than 90% of the lake aquatory, possesses indeed the necessary qualities required of a permanent surveillance monitoring station. Although the number of sampling stations has varied over years from one to ten, the station at the deepest area of the lake has been continuously included in the programme and has the most complete data series. The revealed homogeneity of Võrtsjärv Proper was so high that it may raise the question of redundancy of monitoring the other seven pelagic stations within the area. The highest spatial variability, reaching 14–15% of the total for Ca^{2+}, Cond, DO, and BOD_7, was still marginal compared to the year-to-year variability and could be attributed to the effect of the Sula Kuru and Õhne stations characterized by a higher submerged macrophyte cover.

Selection of variables

Lindenmayer & Likens (2009) list several factors that have compromised the credibility of long-term research and monitoring programmes. Besides the lack of focus and poor design, which undermine the statistical power to detect trends or reveal contrasts between impacted and unaffected sites, a crucial question is what to monitor. Measuring the wrong things sidetracks the monitoring programmes (Karr & Chu, 1997).

The high variability of the common water quality parameters, such as TSS, TP, Chl-*a*, Secchi, and TN in Võrtsjärv and, especially, their strong dependence on climatic forcing, creates problems for their direct use in water quality and ecological status monitoring. Ecological status indicators should reflect the effect of the pressure to be assessed, but they must not be affected by natural variability factors (Hering et al., 2006). One way to overcome the high natural variation of the parameters mentioned above is the statistical elimination of the climate depending component of the variability by de-trending the data series. De-trending of the common water quality parameters for the effect of WL in Võrtsjärv (Tuvikene et al., 2011) caused a more than ±40% change of some seasonal mean values, showing the high importance of WL changes in shaping these variables. On the other hand, the impact of anthropogenic pressures depends also on climatic conditions and may be either amplified or dampened by the latter. Given the position expressed by the IPCC (2007) that most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in anthropogenic greenhouse gas concentrations and the complex effect of temperature on most of the climatic and ecological processes, it becomes more and more complicated to distinguish between the intrinsic natural variability and the anthropogenic variability. This situation creates the necessity to develop more universal biological metrics for assessing global change impacts on ecosystems.

In our data, the variance of phytoplankton parameters was nearly twice as high as that of the chemical and physical parameters. As biological parameters often include larger methodological errors compared to chemical and physical parameters, it has been common to consider biological parameters too variable to monitor. Indeed, as Karr & Chu (1997) showed, some biological attributes, in particular abundance, density, and production, vary too much even at low levels of human influence, and only a few biological attributes provide reliable signals about biological conditions. In fact, the increase of variance of some biological indices itself can reflect anthropogenic stress owing to the fact that biological systems subjected to high human disturbance are less resilient to environmental change (Fore et al., 1994). Although the plankton variables used in Võrtsjärv monitoring (except the number of species) belong to the criticized above biological attributes, their increased variability near the river mouths showed their high sensitivity to detect changes.

In the present paper we used only data from one month avoiding so the problems caused by seasonal variability of data, which is another serious cause of variation in the monitoring data. Standardization of the data by removing seasonality (e.g. by converting each measurement to a virtual ‘seasonal average’ value through predefined regression formulas) has shown to have several advantages if the data are used for ecological status assessment (Tuvikene et al., 2011).

CONCLUSIONS

- One of the main aims of Võrtsjärv monitoring since its commencement has been providing data for the numerous research projects run in this model lake. This has caused higher complexity and higher sampling frequency than commonly required for surveillance monitoring. The maintenance of the integrity of the long time series is the main strength of the programme that has enabled a process-based approach in the ecological research, fulfils various requirements of the WFD, and has been increasingly valued in the climate change impact studies.
- Based on chemical, physical, and phytoplankton data from 10 monitoring stations, Võrtsjärv can be divided into two distinct parts: the narrow southernmost part under the influence of the main inflow, the Väike Emajõgi River, represented by two stations and forming only 2% of the lake’s total area, and the homogeneous Võrtsjärv Proper represented by eight stations.
- Within Võrtsjärv Proper, the inter-annual variability markedly exceeded the spatial variability for most variables monitored. The highest spatial variability,

reaching 14–15% of the total for Ca^{2+}, Cond, DO, and BOD_7, was still marginal and could be attributed to the effect of the larger submerged macrophyte cover at two of the southern stations of this otherwise homogeneous area.

- The location of the permanent sampling station at the deepest site in Võrtsjärv is excellent both by its statistical properties (smallest variability of measured parameters, good representativeness for the pelagic part of the lake, insensitivity to local factors or inflows) and logistics (close to the shore and laboratory facilities).
- The selection of variables monitored in Võrtsjärv is excellent for climate change impact research as many of them show strong relationships with changes in water level and temperature, which can be considered good proxies for precipitation and thermal variability for this lake. The strong dependence of TSS, Chl-*a*, TP, TN, and Secchi in Võrtsjärv on climatic variability strongly compromises their usefulness in detecting human influence. One way to overcome this problem is the de-trending of data for known variability factors, which has already been tested in Võrtsjärv with success. Still the search for new indicators sensitive to human influence but insensitive to extraneous factors should continue.

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REFERENCES

Blank, K., Laugaste, R. & Haberman, J. 2010. Temporal and spatial variation in the zooplankton:phytoplankton biomass ratio in a large shallow lake. *Estonian J. Ecol.*, **59**, 99–115.

Cavanagh, N., Nordin, R. N., Pommen, L. W. & Swain, L. G. 1998. *Guidelines for Designing and Implementing a Water Quality Monitoring Program in British Columbia*. Ministry of Environment, Lands and Parks. Government Publication No. 7680000554. http://www.ilmb.gov.bc.ca/risc/pubs/aquatic/ (visited 2012-04-27).

EC. 2000. Directive 2000/60/ EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *OJ L* 327, 22.12.2000.

Ellis, J. & Adriaenssens, V. 2006. *Uncertainty Estimation for Monitoring Results by the WFD Biological Classification Tools*. WFD Report. Environment Agency, Bristol.

EPA. 1997. *Guidelines for Preparation of the Comprehensive State Water Quality Assessments (305(b) Reports) and Electronic Updates: Supplement*. EPA-841-B-97-002B. U.S. Environmental Protection Agency, Washington, DC.

Feldmann, T. & Mäemets, H. 2004. Macrophytes. In *Lake Võrtsjärv* (Haberman, J., Pihu, E. & Raukas, A., eds), pp. 185–205. Estonian Encyclopaedia Publishers, Tallinn.

Feldmann, T. & Nõges, P. 2007. Factors controlling macrophyte distribution in large shallow Lake Võrtsjärv. *Aquat. Bot.*, **87**, 15–21.

Fore, L. S., Karr, R. & Conquest, L. L. 1994. Statistical properties of an index of biotic integrity used to evaluate water resources. *Can. Fish. Aquat. Sci.*, **51**, 1077–1087.

George, D. G., Maberly, S. C. & Hewitt, D. P. 2004. The influence of the North Atlantic Oscillation on the physical, chemical and biological characteristics of four lakes in the English Lake District. *Freshwater Biol.*, **49**, 760–774.

Grasshoff, K. (ed.). 1976. *Methods of Seawater Analysis*. Verlag Chemie, Weinheim and New York.

Hering, D., Feld, C. K., Moog, O. & Ofenböck, T. 2006. Cook book for the development of a Multimetric Index for biological condition of aquatic ecosystems: experiences from the European AQEM and STAR projects and related initiatives. *Hydrobiologia*, **566**, 311–324.

IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* (Solomon, S. et al., eds). Cambridge Univ. Press, Cambridge, U. K.

Järvet, A. 2004. Pollution load to Lake Võrtsjärv. In *Lake Võrtsjärv* (Haberman, J., Pihu, E. & Raukas, A., eds), pp. 151–171. Estonian Encyclopaedia Publishers, Tallinn.

Järvet, A., Karukäpp, R. & Arold, I. 2004. Location and physico-geographical conditions of the catchment area. In *Lake Võrtsjärv* (Haberman, J., Pihu, E. & Raukas, A., eds), pp. 11–26. Estonian Encyclopaedia Publishers, Tallinn.

Jeffrey, S. W. & Humphrey, G. F. 1975. New spectrophotometric equations for determining chlorophylls a, b, c_1 and c_2 in higher plants, algae and natural phytoplankton. *Biochem. Physiol. Pfl.*, **167**, 191–194.

Karr, J. R. & Chu, E. W. 1997. *Biological Monitoring and Assessment: Using Multimetric Indexes Effectively*. EPA 235-R07-001. University of Washington, Seattle.

Kivimaa, R., Huttula, T. & Podsetchine, V. 1998. Hydrodynamical studies. In *Present State and Future Fate of Lake Võrtsjärv. Results from Finnish–Estonian Joint Project in 1993–1997* (Huttula, T. & Nõges, T., eds). Vol. 209, pp. 60–77. The Finnish Environment, Helsinki.

Laas, A., Nõges, P., Kõiv, T. & Nõges, T. 2012. High-frequency metabolism study in a large and shallow temperate lake reveals seasonal switching between net autotrophy and net heterotrophy. *Hydrobiologia*, **694**, 57–74.

Lindenmayer, D. B. & Likens, G. E. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. *Trends Ecol. Evol.*, **24**, 482–486.

Nõges, P. & Laugaste, R. 1998. Seasonal and long-term changes of phytoplankton in L. Võrtsjärv. *Limnologica*, **28**(1), 21–28.

Nõges, P., Kägu, M. & Nõges, T. 2007. Role of climate and agricultural practice in determining the matter discharge into large shallow Lake Võrtsjärv, Estonia. *Hydrobiologia*, **581**, 125–134.

Nõges, P., Nõges, T., Haberman, J., Laugaste, R. & Kisand, V. 1997. Tendencies and relations in the plankton community and pelagic environment of Lake Võrtsjärv during three decades. *Proc. Estonian Acad. Sci. Biol. Ecol.*, **46**, 40–57.

Nõges, P., Laugaste, R. & Nõges, T. 2004. Phytoplankton. In *Lake Võrtsjärv* (Haberman, J., Pihu, E. & Raukas, A., eds), pp. 217–231. Estonian Encyclopaedia Publishers, Tallinn.

Nõges, P., Mischke, U., Laugaste, R. & Solimini, A. G. 2010a. Analysis of changes over 44 years in the phytoplankton of Lake Võrtsjärv (Estonia): the effect of nutrients, climate and the investigator on phytoplankton-based water quality indices. *Hydrobiologia*, **646**, 33–48.

Nõges, P., Nõges, T. & Laas, A. 2010b. Climate-related changes of phytoplankton seasonality in large shallow Lake Võrtsjärv, Estonia. *J. Aquat. Ecosyst. Health Manage.*, **13**(2), 154–163.

Nõges, T., Kisand, V., Nõges, P., Põllumäe, A., Tuvikene, L. & Zingel, P. 1998. Plankton seasonal dynamics and its controlling factors in shallow polymictic eutrophic Lake Võrtsjärv, Estonia. *Int. Rev. Ges. Hydrobiol.*, **83**(4), 279–296.

Nõges, T., Nõges, P. & Laugaste, R. 2003. Water level as the mediator between climate change and phytoplankton composition in a large shallow temperate lake. *Hydrobiologia*, **506–509**, 257–263.
Nõges, T., Tuvikene, L. & Nõges, P. 2010. Contemporary trends of temperature, nutrient loading, and water quality in large lakes Peipsi and Võrtsjärv, Estonia. *J. Aquat. Ecosyst. Health Manage.*, **13**(2), 143–153.
Pall, P., Vilbaste, S., Kõiv, T., Kõrs, A., Käiro, K., Laas, A., Nõges, P., Nõges, T., Piirsoo, K., Toomsalu, L. & Viik, M. 2011. Fluxes of carbon and nutrients through the inflows and outflow of Lake Võrtsjärv, Estonia. *Estonian J. Ecol.*, **60**, 39–53.
Patil, G. P. 1991. Encountered data, statistical ecology, environmental statistics, and weighted distribution methods. *Environmetrics*, **2**, 377–423.
Rachamim, T., Stambler, N., Zohary, T., Berman-Frank, I. & Gal, G. 2010. Zooplankton contribution to the particulate N and P in Lake Kinneret, Israel, under changing water levels. *Hydrobiologia*, **655**, 121–135.
Raukas, A. 1995. Estonia. In *Nature*. Valgus, Tallinn.
Raukas, A. & Tavast, E. 2002. The Holocene sedimentation history of Lake Võrtsjärv, Central Estonia. *Geol. Quart.*, **46**(2), 199–206.
Reckhow, K. H. & Chapra, S. C. 1983. *Engineering Approaches for Lake Management. Volume 1. Data Analysis and Empirical Modeling*. Butterworth Publishers, Boston.
Roberts, K. A. 1991. Field monitoring: confessions of an addict. In *Monitoring for Conservation and Ecology* (Goldsmith, F. B., ed.), pp. 179–212. Chapman & Hall.
Tammert, H. & Kisand, V. 2004. Bacterioplankton. In *Lake Võrtsjärv* (Haberman, J., Pihu, E. & Raukas, A., eds), pp. 207–215. Estonian Encyclopaedia Publishers, Tallinn.
Timm, T. (ed.), 1973. *Võrtsjärv*. Valgus, Tallinn.
Toming, K., Arst, H., Paavel, B., Laas, A. & Nõges, T. 2009. Spatial and temporal variations in coloured dissolved organic matter in large and shallow Estonian waterbodies. *BER*, **14**, 959–970.
Tuvikene, L., Nõges, T. & Nõges, P. 2011. Why do phytoplankton species composition and “traditional” water quality parameters indicate different ecological status of a large shallow lake? *Hydrobiologia*, **660**, 3–15.
Utermöhl, H. 1958. Zur Vervollkommnung der quantitativen Phytoplanktonmethodik. *Mitt. int. Ver. Theor. Angew. Limnol.*, **9**, 1–38.

Keskkonna ja fütoplanktoni näitajate ruumiline ning aastatevaheline muutlikkus Võrtsjärves vee kvaliteedi seire seisukohast

Peeter Nõges ja Lea Tuvikene

Seire eesmärgid määravad, millised näitajad, proovikohad ja milline proovivõtu sagedus on meid huvitava info saamiseks kõige ökonoomsemad. Ülevaate- ja uuriva seire kohaks valitakse tavaliselt järve sügavaim koht, eeldades, et seal avalduvad järve kui tervikut iseloomustavad omadused kõige paremini. Suurte järvede puhul tekitab aga ainult ühe proovipunkti kasutamine sageli küsimuse, kas see on kogu järve iseloomustamiseks piisavalt esinduslik. Uurisime suure, madala Võrtsjärve kümne proovikoha augustikuisel seirel aastatel 2001–2011 saadud keskkonnanäitajate ja fütoplanktoni andmete ruumilist ning aastatevahelist varieeruvust,

et selgitada, kas üks püsivaatluskoht on kogu järve iseloomustamiseks küllalt esinduslik. Kaks kõige lõunapoolsemat proovikohta, mis on Väikese Emajõe mõjualas, eristusid selgelt ülejäänud kaheksast proovikohast. Viimaste hulgas oli aastatevaheline varieeruvus märkimisväärselt suurem kui ruumiline. Veetaseme ja pinnakihi temperatuuri muutustega oli Võrtsjärves seletatav ligikaudu pool järvede ökoloogilise seisundi iseloomustamiseks tavaliselt kasutatavate parameetrite kogumuutlikkusest. See tekitab viimaste kasutamisel inimmõju hindamiseks Võrtsjärvele tõsiseid probleeme. Võrreldes teiste proovipunktidega on järve sügavas kohas asuva proovipunkti näitajate keskmine varieeruvus madalaim. See proovipunkt sobib iseloomustama 90% järve akvatooriumist ja selle kasutamine Võrtsjärve ülevaateseire statsionaarse seirekohana on õigustatud.