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19

INFLUENCE OF HYDROLOGICAL FACTORS AND HUMAN IMPACT ON THE ECOLOGICAL STATE OF SHALLOW LAKE VÕRTSJÄRV IN ESTONIA

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ABSTRACT

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This thesis is a study of the hydrological conditions and pollution load impact on the ecological state of a shallow non-stratified eutrophic lake in Estonia. This dissertation first presents a review of the hydrological regime of Lake Võrtsjärv in regard to long-term fluctuations of water level and the estimation of climatic seasons, then analyses the influence of hydrological factors on the ecological state of the lake, including possible climate change impact, and finally gives recommendations for lake regulation and water management planning in the catchment area.

Causal relations between the water regime and the ecological state of Lake Võrtsjärv have been discussed. Both water balance and pollution load components were estimated and compared with the observed data characterising the ecological state of the lake. Due to its small depth (mean 2.8, maximum 6 m) and relatively large surface area (270 km^2) and drainage basin (3104 km^2), Lake Võrtsjärv reflects sensitively the changes occurring in its watershed as well as in the climate and in hydrology.

The main objectives of the Ph.D. dissertation were: 1) to study the influence of hydrological factors on the ecological state of Lake Võrtsjärv and on its long-term fluctuations, 2) to investigate long-period and seasonal variability of hydrological conditions in relation to climate parameters and analyse various criteria for determining the climatic seasons of water bodies and their temporal changes, 3) to develop water balance and balance of substances calculations for the lake for detecting the temporal changes between inflow and outflow, and 4) to carry out research for integrated water management planning on the river basin principle and for water level regulation in Lake Võrtsjärv.

For the study, mainly two types of data were used: a) the long-term series of hydrological observations, such as water level, river runoff, ice phenomena, etc., of Estonian Meteorological and Hydrological Institute, and b) the chemical monitoring data of river waters, the sampling strategy for which was developed by the author of this thesis since the 1970s.

The lake ecosystem and the surrounding areas are strongly affected by fluctuations of the water level in the lake, which is the most important factor influencing the ecosystem and management of a shallow lake. The low-water periods are more dangerous to the lake ecosystem and fishery, especially during wintertime. They cause an increase in resuspension, accelerate nutrient cycling, and improve the water column illumination. This leads to a massive growth of planktonic algae and of submerged macrophytes.

The annual cycle of weather conditions of the water environment can be divided into seasons that are described by qualitatively different climatological characteristics. The criteria of climatic seasons and the climatological calendar for lakeshas been developed and 7 climatic seasons have been distinguished.

In order to demonstrate periodicities or cycles of water level change, spectral analysis is used. This method makes long-term periodicities visible and several periods can be identified, among which the spectral peak at 25.6 years seems to have an exceptional position.

This thesis demonstrates that the impact of hydrological factors on the ecological state of shallow Lake Võrtsjärv is larger than previously assumed. It is assumed that ice cover parameters are correlated with water level and oxygen conditions in the winter. The worst ecological conditions in L. Võrtsjärv are formed in a winter period where, in conjunction with a low water level (monthly mean below 33.00), the ice cover is thick (> 50 cm) and the ice-cover duration is long (> 130 days). But even small changes in ice cover and water level characteristics during mild winters have significant positive effects on ecological state.

To calculate a change in lake morphometry, the lake volume, surface area, and average depth were determined at maximum ice thickness, which corresponds to wintertime minimum water level. In regard to hydrological characteristics it is possible to explain the wintertime ecological conditions of the lake by active volume and the corresponding mean depth. In calculating active volume the ice volume is subtracted from the total volume, as the volume of ice is actually temporarily unused water for the lake ecosystems.

The most important problem of L. Võrtsjärv is the fluctuation of its level. Low water periods, making up, on average, 10% of the year according to the observation data, are harmful to the ecological conditions of the lake. By 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 a positive effect on the ecological state of the lake. 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. To decreasing the influence of ice cover on L. Võrtsjärv ecosystems it is necessary to keep winter water level between 33.50–33.70, as recommended.

Considering also other reasons and conditions for regulating the water level, the importance of hydrological factors may change to a certain extent, but they would still remain the key factors in defining the prospective use and protection needs of the lake even in the case of regulated water level. Provided that the same periodicity of water level fluctuation continues, it is possible to forecast water regime in the near future. The low level phase of 25–30-year fluctuation started in 1992 and it should last until 2006–2007.

LIST OF PUBLICATIONS INCLUDED IN THE THESIS

I Nõges, P., **Järvet, A**., 1998. The role of Lake Võrtsjärv in the matter circulation of the landscape. *Limnologica*, **28**: 13–20.

II Nõges, P., **Järvet, A**., Tuvikene, L., Nõges, T. 1998. The budgets of nitrogen and phosphorous in shallow eutrophic Lake Võrtsjärv (Estonia). *Hydrobiologia*, **363**: 219–227.

III Mander, Ü., **Järvet, A.** 1998. Buffering Role of Small Reservoirs in Agricultural Catchments. International Review of Hydrobiology, **83**: 639–646.

IV **Järvet, A**., 2000. Water regime of Lake Võrtsjärv. In: T. Kaare and J.-M. Punning (eds.), Estonia. Geographical Studies, **8**. Estonian Academy Publishers, Tallinn: 72–88.

V Nõges, P. & **Järvet, A**., 2002. Response of a natural river valley wetland to supplementary run-off and pollutant load from urban wastewater discharge. In: Ü. Mander & P. Jenssen (eds.), Natural Wetlands for Wastewater Treatment in Cold Climate. *Advances in Ecological Sciences*, **12:** 139–158.

VI **Järvet, A**., Mander, Ü., Kull, A., Kuusemets, V. Nutrient runoff change in a rural catchment in South Estonia. Large Rivers, vol. **13**, No. 3–4. *Arch. Hydrobiol. Suppl*., 141/3–4: 305–319.

VII **Järvet, A**., Mander, Ü. Classification of chemical status of rivers for water management planning in Lake Võrtsjärv catchment area, Estonia. In: C.A. Brebbia (ed.), River Basin Management II. *International Series on Progress in Water Management*. **WIT**PRESS: 251–260.

Author's contribution

Publication (I): This study was initiated and designed by the author. He also participated in the analysis of results and in the preparation of the manuscript.

Publication (II): The paper presents results from a collaborative lake ecosystem study with scientists from Võrtsjärve Limnological Station. The author participated in the general design of the study and was responsible for the external load calculations and partly for writing the manuscript.

Publication (III): The author is partly responsible for the data collection and analysis, and participated in writing the manuscript.

Publication (IV): The author is fully responsible for this publication.

Publication (V): The author is principally responsible for the collection and evaluation of the hydrological, wastewater and chemical data and the analysis of the results obtained in the study. He also participated in the preparation of the manuscript.

Publication (VI): The author is principally responsible for the evaluation of this study. He is fully responsible for the data collection and analysis. He also participated in the preparation of the manuscript.

Publication (VII): The author is fully responsible for the data collection and analysis. He also participated in the preparation of the manuscript.

The results of these studies have been presented by the author at several international and local scientific conferences, seminars and workshops, and have been widely applied in the establishment of integrated protection and management for L. Võrtsjärv and other waterbodies in its catchment area, including water management planning and as proof of the need to regulate the lake's water level.

MAIN ARGUMENTS PROPOSED FOR DEFENCE

1. In shallow lakes the hydrological conditions are the principal factors influencing to the ecological state. Due to flat shores and small depth, fluctuations in the water level are reflected in large changes in the morphometry and ecological conditions of the lake. Therefore, different hydrological criteria, such as water level, lake volume, retention time, water temperature and ice cover characteristics, can be used to analyse the ecological state of a shallow lake.
2. Due to its shallowness, the ice cover has an important role in the formation of the lake's ecological conditions in the winter period. Important indices of waterbody climate are the duration and thickness of the ice cover and, from a lake volume aspect, the ice volume. In regard to hydrological characteristics, it is possible to explain the winter condition of L. Võrtsjärv by active volume and corresponding mean depth.
3. The northern temperate zone is characterized by high variability of climatic seasons, which is one of main factors influencing the ecological conditions of waterbodies. The annual cycle of weather conditions of the water environment can be divided into seasons that are described by qualitatively different climatological characteristics. Here, I propose the criteria for climatic seasons of lakes based on 1) seasonal variability of water temperature and 2) ice phenomena characteristics.
4. The difference between hydrological and chemical parameters is a reflection of the processes going on in the lake. The lake acts as an accumulator in its drainage area landscapes, though the influx and efflux of substances can almost be balanced during short periods. The seasonal pattern of the external budget of substances is strongly affected by the water balance of the lake. Lake Võrtsjärv as a large waterbody exerts an essential influence on the matter circulation of the landscape.
5. 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. Different criteria, such as water height below ecologically accepted level and duration of low-level periods, can be used to estimate the water level regulation scheme. Hydrological studies also provide information required for the analysis associated with the management decision processes regarding the lake and its catchment area.

1. INTRODUCTION

The ecological situation in shallow lakes is determined by the joint influence of many factors, including change in water level and local climatic conditions. Water level fluctuation is regarded to be an important factor for lake ecosystem functioning and management. Additionally, the anticipated effects of climate change may significantly alter the functioning of shallow lakes. Extreme water levels may cause shifts between the turbid and the clear, macrophyte-dominated state (Coops *et al*, 2003).

Due to its small depth (mean 2.8, maximum 6 m), Lake Võrtsjärv reflects sensitively the changes occurring on its watershed as well as climate. The revealed long-term trends and periodicity in hydrological factors are seen in the lake ecosystem as drifts in chemical and biological regimes. In these conditions the human impact may become more acute or, on the contrary, may be eclipsed by changes in the physical environment (Huttula & Nõges, 1998). Long-term changes in the ecosystem of Lake Võrtsjärv can be attributed to three main groups of factors:

1) variability of large-scale atmospheric circulation patterns through their influence on water level and ice regime;
2) climate variability in combination with the watershed management that shapes the external load of nutrients and organic matter on the lake;
3) human impact on fishes cascading down to lower trophic levels.

Considerable water level fluctuations cause changes in both the surface area and volume of the lake. Change in water level is the most important factor influencing the ecosystem and management of a shallow lake. Due to the shallowness of lake Võrtsjärv, low-level periods are accompanied by several negative phenomena in the lake ecosystem, such as cyanophyte blooms, overgrowing by macrophytes, restricted spawning places for pike, and winter fish kills. During the low water-level years the possibilities to catch in established fishing sites and with established methods (gears) and the entering to harbours are embarrassed.

Hydrological observation data of shallow lakes is a valuable indicator of long-term variation not only of water regime, but also of ecological conditions. Knowledge about the structure of hydrological time series as well as their variability in time may be useful for evaluating the development of ecosystem parameters in time and in relation to the main influencing factors (Stellmacher & Mende, 1991).

Changes in hydrological conditions, which are reflected by cyclic fluctuation in the water regime over a long period, obviously influence hydrophysical, as well as hydrochemical and hydrobiological processes in the lake. Water quality variables are, either directly or indirectly, connected with hydrometeorological factors. For example, an increase in the average depth of the lake results in a decrease in bottom irradiance and water column irradiance (Reinart, 2000). In a seasonal aspect, phytoplankton growth is dependent upon the release rate of mineral nitrogen, under the best light conditions due to the low water level. Lasting low-water periods in dry years result in the expansion of reed-bed areas and in the deterioration of the water quality.

During the last ten years, the influence of hydrological factors on the ecological conditions in shallow lakes in Estonia has come into focus. The associated ecological problems have recently appeared in Lake Võrtsjärv, where the lowest recorded water level since the 1870s was registered in 1996. A second reason for the increasing interest is that lake restoration (lake management) using combined measures of hydrological regulation and biological manipulation seems to be more effective than the implementation of separate measures. Ecologically-based regulation requires careful investigations and interpretation of the results before any recommendations can be given (Hellsten, 2000). The great value of long-term investigations of Lake Võrtsjärv is obvious, since this lake has several common features with other European shallow lakes such as L. Balaton or Nuesiedler See in Central Europe. The importance of investigations into hydrological and biological connections concerning shallow lakes has been underlined in an international workshop held in Hungary in May 2002 (Coops *et al*, 2003). There special attention was paid to the role of water level fluctuations in the structure and function of shallow lakes.

Due to its small depth (mean 2.8, maximum 6 m), relatively large surface area (270 km^2) and drainage basin (3104 km^2), Lake Võrtsjärv reacts sensitively to the changes occurring in its watershed as well as those in climate and hydrology. Being situated in a mainly rural environment, human impact on the lake is expressed first of all as eutrophication. The impact of different hydrological factors is combined in this lake. During recent decades, since the 1960s, it has experienced problems connected with eutrophication and nutrient loading from the catchment area. Eutrophication causes frequent algal blooms; deterioration of the oxygen regime has resulted in several fish kills in the second half of the 20th century. The sediment accumulation caused by high productivity enlarges the macrophyte zone. Finally, the reed belt enlarges due to vegetative colonisation of new shallow regions as well as generative reproduction in emerging dry areas. This leads to a gradual overgrowing and causes problems for fishery, navigation and recreation.

Lake Võrtsjärv's water is optically turbid and the concentration of all optically active substances is large when compared with other Estonian lakes (Reinart *et al*, 2003). Besides the optical properties of the water, light climate is very strongly affected by the lake's water level and ice conditions. If a low oxygen reserve is accompanied by thick snow cover, stressful conditions for aquatic life may occur in the lake at the end of the winter, and a severe reduction in dissolved oxygen can lead to total anoxia. The importance of the transparency of ice-snow cover for the ecological conditions in the shallow eutrophic Lake Võrtsjärv is confirmed by long-term monitoring data of limnological parameters including the oxygen content in the water.

Water level controls phytoplankton biomass in L. Võrtsjärv through both light conditions and nutrient availability. During periods of high water, large amounts of phosphorus are accumulated in the sediments since phytoplankton is mainly light-limited. In the periods of low water, light conditions improve and sediment disturbance enriches the water more with phosphorus than with nitrogen. As a result nitrogen limitation occurs and nitrogen-fixing species are given an advantage in competition (Nõges *et al*, 1998). The solution L. Võrtsjärv's various problems and the prediction of its water level is a complex task, but it may be successfully resolved by combining the efforts of a wide range of specialists. Therefore, analysis of water regime and other hydrological factors is very useful for lake management, especially from a restoration point of view.

Võrtsjärv's shallow lake ecosystem and the surrounding areas are strongly affected by fluctuations of the water level in the lake (mean annual amplitude 1.4 m). At a high water level large areas surrounding the lake are flooded. This causes problems mainly for agriculture and forestry. The low-water periods are more dangerous for the lake ecosystem and for fishery, especially during wintertime. Low water causes an increase in resuspension, accelerates nutrient cycling and improves the water column illumination. This leads to massive growth of planktonic algae and of submerged macrophytes. Low water level also causes winter oxygen depletion due to a significantly smaller oxygen storage capacity and a higher amount of easily degradable organic material produced during the vegetation period.

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

The revealed long-term trends and periodicity in climatic factors are seen in the lake ecosystem as drifts in hydrological, thermal, chemical and biological regimes. In these conditions the human impact may become more acute or, on the contrary, may be eclipsed by changes in the physical environment. Study of the ecological processes in the lake in combination with the hydrological conditions and changes in the watershed is the only way to discover such combined effects, and to understand and predict the behaviour of the lake ecosystem. By this means it is possible to assess protective measures, to maintain the water quality and even to restore the lake to some reasonable extent.

The author of this thesis began studying the connections between the hydrological and ecological factors affecting Lake Võrtsjärv and rivers of its catchment area after the massive fish kills in the lake in the spring of 1987 (Tiidor *et al*, 1987). Chemical monitoring data proved that the river water discharging into the lake could not be the direct cause of the fish kills despite the fact that the concentration of organic matter and biogenic compounds was higher than recommended by ecological standards. A special monitoring project was developed by the author at the beginning of 1988 (Järvet & Laanemets, 1990; Järvet, 1993; 1994). The next studies were instigated on the basis of the results of the data analysis of the first period (Järvet, 1991; Järvet & Nõges, 1994) and research activity has continued until today.

Main objectives of the current dissertation are as follows:

- To apply integrated principles for the investigation of ecological state on shallow lake for water management purposes.
- To study the influence of hydrological factors on the ecological state of Lake Võrtsjärv and its long-term fluctuations.
- To investigate long-period and seasonal variability of hydrological conditions in connection with climate parameters, and to analyse various criteria for determining the climatic seasons of water bodies and their temporal changes.
- To investigate the possible climate change impact on the hydrological conditions of the Lake Võrtsjärv and its drainage basin under different GCM scenarios and using the method of analogous years and climate seasons.
- To compare different weather types and meteorological characteristics that are affecting pollution load and to explain the intensity of pollution load under different hydrological conditions and human impacts.
- To develop water balance calculations and balance of substances of lake for detecting the temporal changes between inflow and outflow.
- To carry out special research into integrated water management planning according to the river basin principle and into water level regulation in Lake Võrtsjärv.

This thesis summarises the hydrological and environmental studies carried out by the author in collaboration with limnologists from Võrtsjärve Limnological Station and collegues from the Department of Geography of the University of Tartu. The main objective of this thesis has been to alleviate the general scarcity of knowledge concerning the relationship between hydrological and ecological conditions in shallow lakes. The requirements of these studies were also influenced by the fact that much observational data about Lake Võrtsjärv itself and its catchment area has already been collected and it was being studied by many researchers. The thesis does not concentrate on advanced mathematical modelling, but it tries to

1) evaluate the applicability of selected hydrological parameters in planning water management strategies for improvement of the ecological state of Lake Võrtsjärv;
2) create a simple system of activities that are needed for the improvement of water quality, not only in the lake, but also in its catchment area, and present recommendations for lake restoration;
3) provide adequate recommendations for decision makers and water management authorities planning practical water protection measures.

Although the possibilities to reduce negative impacts to water quality and ecological state of Lake Võrtsjärv (regulation of water level, especially by raising the minimum level in winter) have been discussed in this thesis.

2. MATERIAL AND METHODS

2.1. Study area

Lake Võrtsjärv is the second largest lake in the Baltic countries and the largest domestic water-body in Estonia. It is located in the southern part of Estonia in a shallow depression of preglacial origin (Fig. 1)[1]. The submeridionally elongated (57°50'-58°30' N and 25°35'-26°40' E) drainage basin of the lake covers 3374 km^2 (including the lake itself), of which 3275 km^2 is on Estonian territory and 99 km^2 is in Latvia The axial length of the lake is 34 km and the maximum width is 13 km. Through the outflowing Emajõgi River its drainage basin is connected to the watershed of Lake Peipsi (47,800 km^2).

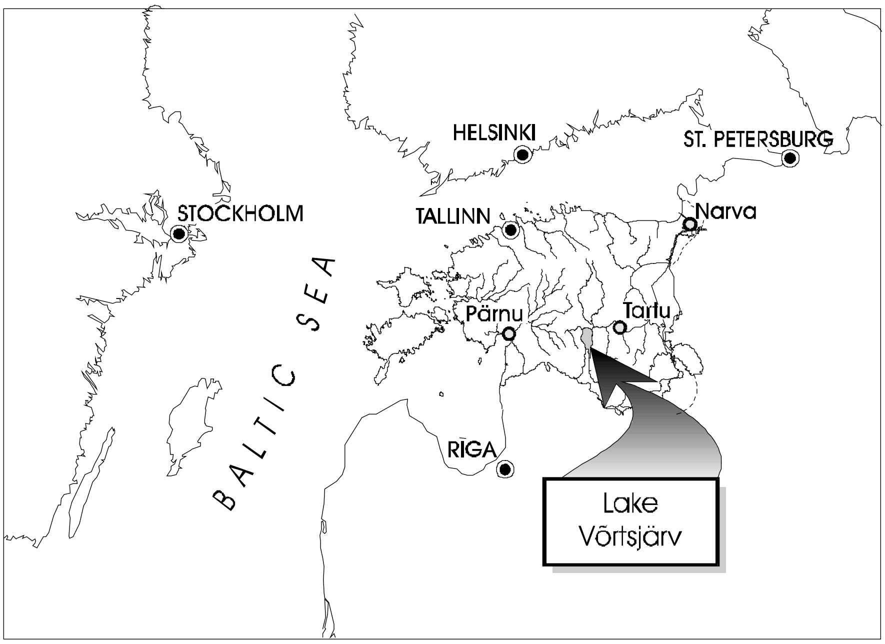

Figure 1. Location map of Lake Võrtsjärv.

L. Võrtsjärv as a very shallow (mean depth 2.8 m) lake and significant 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 its volume at 1.213 km^3. At the lowest water level (32.20 m), these values were 237 km^2 and 0.383 km^3, respectively. Thus, the surface area of the lake may vary by a value of 89 km^2 and the volume by 0.830 km^3.

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[1] Figures indicated in this style, are included in the text. Figures indicated as (**FIG. …**), could be found in the part COLOUR PLATES.

2.1.1.Geology and topograhy

Lake Võrtsjärv has a complicated geological history that was influenced by deglaciation processes and tectonic movements. The base rock is formed of Middle Devonian deposits, mainly sandstone, which is denuded in places along the eastern shore. The glaciers denuded and widened the basin and piled up drumlins on the eastern and northern coasts of the glacial lake. The birth of Contemporary Võrtsjärv is traditionally held to be the time when the outflow to the west finally closed and the outflow to the east via the Emajõgi Valley opened some 7500 years ago. Lowering of the lake level followed and little by little the lake acquired its present contours.

It has been stated that the rate of tectonic uplift in the Võrtsjärv Lowland is lower than in northwestern Estonia. During the last 10 000 years the uplift in the northern part of the lake basin has been 10 m greater than in the southern portion (Moora *et al*, 2002). At the present time, the annual rate of uplift in the northern part of the lowland is 0.6 mm greater than in the southern part, and it changes abruptly in the NE-SW oriented zone, which coincides with a tectonic fault. Due to the uneven land uplift, Lake Võrtsjärv is steadily retreating southwards, inundating new areas in the mouths of the Väike Emajõgi, Õhne and Tarvastu rivers. The thickness of the river deposits in the mouth of the Väike Emajõgi River exceeds 15 m (Miidel *et al*, 2003). Geodetic data shows that the uneven uplift is still in progress. In about 2000 years, the northern part of the lake will be dry and the southern part swampy.

The area surrounding L. Võrtsjärv is covered with till, glaciofluvial sand and gravel, glaciolacustrine silt and clay, gyttja, lake marl and peat. In some places, aeolian and alluvial sandy-silty sediments occur. The thickness of the deposits is mostly 5–10 m, seldom more, being greatest (20–25 m) in the Kolga-Jaani drumlin field (Miidel *et al*, 2003). Peat is the most important mineral resource on the lowland. Sapropel and lake marl can also be used on a local level.

The drainage basin of Lake Võrtsjärv does not form a geomorphological unit. Almost all the authors who have dealt with the geology of Lake Võrtsjärv maintain that the main topographical features of the Võrtsjärv Lowland were formed by the continental ice. The drumlinization pattern is the most typical feature of the area. The lineated pattern of drumlin topography indicates the glacial dynamics of the Võrtsjärv lobe. The orientation of the longitudinal axes of drumlins reflects the direction of the glacial ice movement. Due to their low topographical position most of the drumlins were buried partly or entirely under the glaciolacustrine or lake and bog deposits (Karukäpp & Moora, 2003).

The lakeshore areas can be divided into four main landscape types:

- moraine plains and terrains mostly used for agriculture;
- lacustrial abrasion and accumulation plains (higher parts under fields and cultivated grasslands);

- sandur-areas, covered mostly with heath and sandy heath pine-woods;
- marsh localities — fens, peat-bogs, water-meadows and swampy forests.

The small drumlins in the Kolga-Jaani drumlin field occur in the north-western part of the lowland, forming an island of arable land surrounded by the forests and bogs. The river basins in the lake catchment area mainly represent a till-plain landscape type with land use typical of South Estonia (**FIG. I**).

The flatness of Võrtsjärv Lowland is reflected in the topography of the lake bottom. The majority of the lake depression is lying on a level of 30.0–30.5 m (corresponding to a depth of 2.5–3.0 m), with no division into separate basins. The only deep site is located close to the eastern shore in the southern part of lake. The small slope of the shore prevents strong abrasion by large waves during high water level. Examples of erosional activity can be seen on the central part of the eastern shore, between Ubesoo and Tamme.

Coastal erosion and sediments transported by rivers and streams are the principal sources of material for the bottom deposits of Lake Võrtsjärv. Some of the material is also provided by wind and drifting ice, and the redistribution of this by waves is controlled by the bottom topography and the highly fluctuating water level. In the southern part of the lake the sediments are much thicker than in the northern part, indicating a gradual rise in water level due to local subsidence in the southern portion of the basin (Raukas, 2003).

About 2/3 of the lake bottom is covered with mud lying on marl; the latter is exposed only at the bottom of the deepest part of the lake. The thickness of mud and marl increases towards the south (up to 7 and 4.7 m, respectively). Their total amount in the lake is 360 million m^3 (Veber 1973). Varved clays lying under marl are exposed in the form of a sandy, muddy-sandy or clayey bottom, mostly in the northern part of the lake. In places, underwater accumulations of boulders can be found.

2.1.2. Hydrography

154 streams belonging to the drainage basin of L. Võrtsjärv have been included in the official register of Estonian running waters. The rivers and brooks are numbered in the order in which they drain into the lake starting from Väike Emajõgi River and moving clockwise around the lake. These streams have a total length of 1431 km within the drainage basin. The inventory of Estonian watersheds carried out recently on the basis of 1:25 000 and locally 1:10 000 topographic maps distinguished 409 elementary watersheds in the L. Võrtsjärv drainage basin. There are 40 rivers and brooks with a length over 10 km. The longest is the Õhne River (94 km) and the largest, Väike Emajõgi River. Its basin occupies 1273 km^2 or 40.9% of the total lake basin area (Fig. 2).

Many river courses have been regulated and/or canalised to some extent. However, large-scale river reclamation activities have only been carried out since the 19th century in order to improve the water regime of agricultural areas. The most intensive regulation of rivers took place during Soviet times (particularly in the 1950s and at the beginning of the 1960s), when large-scale amelioration programmes were undertaken. Natural riverbeds have been completely destroyed in several regions. Still, the main rivers have natural flow regime. To drain wetlands, many rivers are dredged or cut, and the water level of some lakes has been reduced.

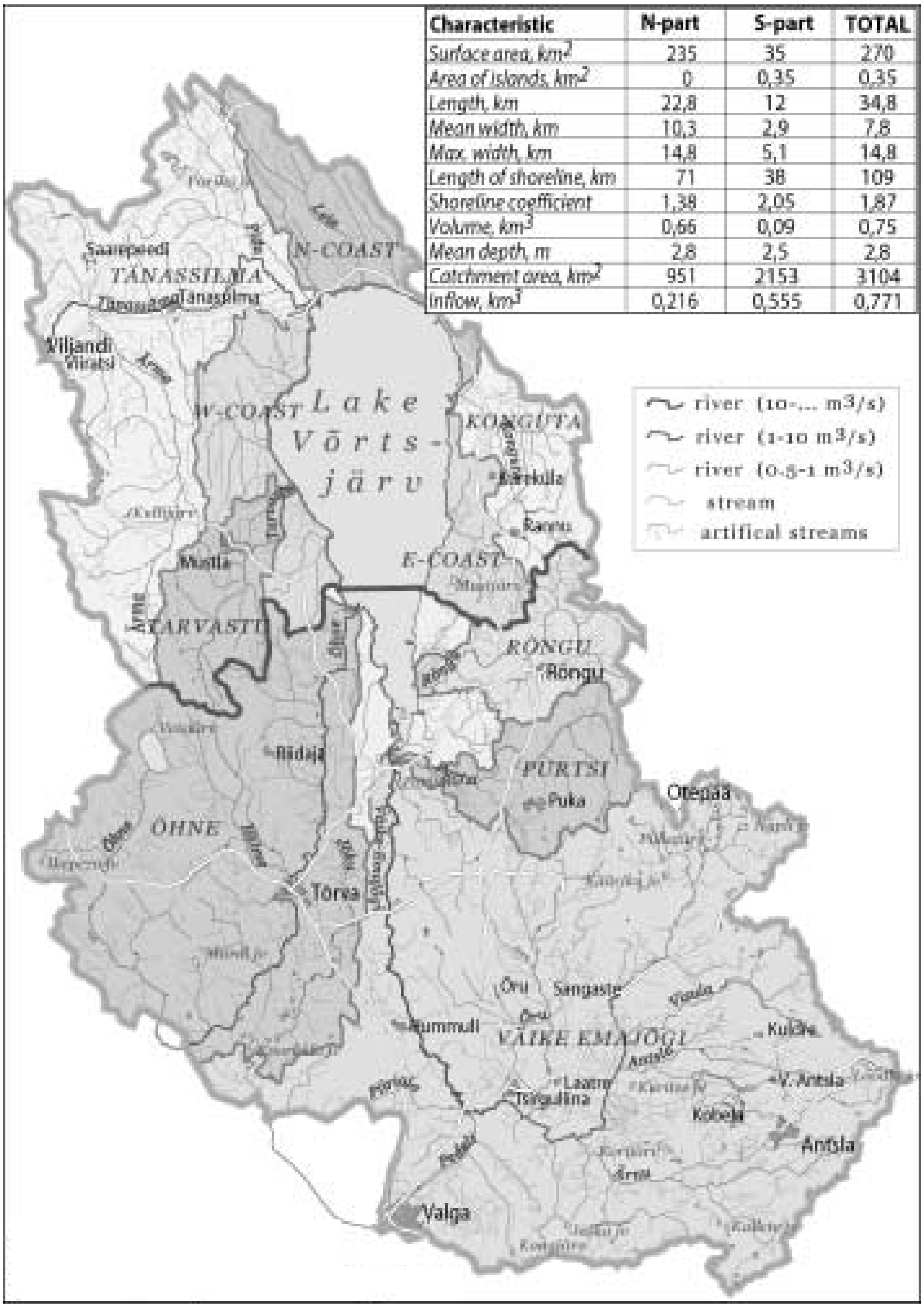
The Emajõgi River channels outflowing waters into L. Peipsi (Peipus; 3555 km^2, the fifth lake in Europe by area). During the spring high water period the direction of this flow in the upstream part may become reversed due to water-rich tributaries entering the Emajõgi River in the upper course. In this case, 13 days a year on average, the lake has no outflow.

L. Võrtsjärv basin can be divided into seven major subbasins: Väike Emajõgi, Õhne, Tarvastu, Tänassilma, Konguta, Rõngu, and Purtsi, according to the hydrographic network (Table 1, Fig. 2). Most of the other basins have an area less than 50 km^2. Despite the small size of the Võrtsjärv drainage basin there is a remarkable variability of hydrological parameters both in space and in time. Only three rivers (Väike Emajõgi, Õhne and Tänassilma) have an average runoff at the river mouth of more than 2 m^3/s. Most of the water discharging into L. Võrtsjärv flowed through the Väike Emajõgi River, whose basin occupied 1270 km^2, or 40.9% of the total lake basin area.

Table 1. Main river basins and their agricultural land-use on the Lake Võrtsjärv catchment area (km^2)

River basin or catchment	Area, km^2	Agricultural land, km^2	% of agri-cultural land	Agricultural drained land, km^2	Bogs, km^2
Väike Emajõgi	1173	418.2	35.6	267.2	45
Õhne	575	279.9	48.9	116.8	75
Tarvastu	108	51.7	47.8	30.3	4
Tänassilma	454	247.1	54.4	122.1	51
Konguta	97	62.8	64.8	60.9	5
Rõngu	109	58.8	54.0	42.1	8
Purtsi	107	43.4	40.6	34.2	3
W-coast	162	62.2	38.4	50.3	15
N-coast	101	36.9	36.5	31.6	23
E-coast	118	52.9	45.3	36.3	14
TOTAL	3004	1313.9	39.6	799.0	243

The population density is relatively low, 22.5 inhabitants km^{-2} and towns, settlements and roads cover a small part of the drainage basin. About 30–40% of the studied catchments may potentially be used as arable land. However, during the 1990s arable land has decreased from 41 to 34%. In wooded areas, the forest covers 66% of the land and consists of coniferous and mixed forests.



Characteristic	N-part	S-part	TOTAL
Surface area, km^2	235	35	270
Area of islands, km^2	0	0,35	0,35
Length, km	22,8	12	34,8
Mean width, km	10,3	2,9	7,8
Max. width, km	14,8	5,1	14,8
Length of shoreline, km	71	38	109
Shoreline coefficient	1,38	2,05	1,87
Volume, km^3	0,66	0,09	0,75
Mean depth, m	2,8	2,5	2,8
Catchment area, km^2	951	2153	3104
Inflow, km^3	0,216	0,555	0,771

Figure 2. Southern and northern part of Lake Võrtsjärv and its drainage basin.

Also, the creation of small water reservoirs was actively pursued in the 1980s. At the beginning of the 20^{th} century, waterpower was used by 36 water mills and small hydroelectric power stations. At present, 4 of these still function. These artificial lakes were usually of a small regulating volume and did not significantly influence rivers' runoff regime. Some of the wetlands are drained directly through the construction of agricultural drainage systems and open ditches in forest.

There are more than 120 natural and artificial lakes in the drainage basin of Lake Võrtsjärv. These artificial lakes were usually of a small regulation volume anf did not significantly influence rivers' runoff regime. The largest natural lake is Lake Veisjärv (surface area 4.8 km^2, maximum depth 4.0 m). The second largest is Pühajärv (2.7 km^2, 8.5 m deep). About 80% of the lakes are shallow with an average depth of 1 to 5 m. Only 6 small lakes are deeper than 10 m. Many lakes are eutrophicated at present.

2.2. Hydrological and water quality investigations

Lake Võrtsjärv, together with the watercources in its drainage basin, represents one of the most intensively investigated inland aquatic systems in Estonia. Occasional hydrological research on Lake Võrtsjärv began at the beginning of the 20^{th} century. The lake level has been recorded daily at Rannu-Jõesuu in the northeast part of the lake since November 1921. Results of biological and chemical investigations carried out in L. Võrtsjärv in the 1950s are resumed in a collection of papers (Hydrobiological investigations I, 1958, in Russian). In this collection the first overview about bottom sediment types and a bathymetric map was published.

A new period in lake research started in the 1960s, after the foundation of Võrtsjärve Limnological Station. The regular investigation of lake hydrochemistry was started in 1968. A monograph on L. Võrtsjärv including chapters on the geological history of the lake, on hydrology, hydrochemistry, biology, fishery and on human activities was published after some years of continuous investigations (Timm 1973). Later a collection of short papers and a special issue of the journal "Eesti Loodus" (Estonian Nature, 11, 1990, in Estonian) have been published. Unfortunately, the distribution of those papers to a broader scientific audience was limited, as both were published in Estonian. The latest changes that have taken place in the biota and water quality have been analysed in a special issue of the international journal "Limnologica" (Nõges (ed.), 1998). The most profound monograph on L. Võrtsjärv was published in 2003 (in Estonian, 536 p.), edited by J. Haberman, E. Pihu and A. Raukas, in which four chapters were written by the author of this thesis.

2.2.1. Hydrological observations

The hydrometric network for lake water level registration at the outflow in Rannu-Jõesuu and runoff measurements in Tõlliste (Väike Emajõgi River) was established by the Estonian Hydrological Board in 1921 (**FIG. II**). This means that regular hydrological data on L. Võrtsjärv has been collected during more than 80 years. The number of observation points reached a maximum in the1980s and diminished gradually during 1996–1997 (Table 2).

Still, more important than the length of the time series is the size of the area covered by discharge measurement stations and their location in subcatchments. The hydrologically investigated area embraces about 1500 km^2, which constitutes 49% of the total area of L. Võrtsjärv's drainage basin (Table 2). There are 2 runoff stations (Tõlliste and Tõrva with a total catchment area of 1323 km^2) at which the time series exceed 60 years. The data from such stations reflects in the best way the runoff regime of rivers in the drainage basin of L. Võrtsjärv. Between 1961 and 1969 a maximum total area of watersheds was monitored — 1631 km^2 (52.5% of the total drainage basin), while the area of monitored watersheds was the smallest (1323 km^2; 42.7%) in 1970–1976 and at present (Fig. 3). The rest of the inflow into the lake must be calculated by the hydrological analogy method.

Table 2. Hydrological network for rivers' runoff in the L. Võrtsjärv basin

River	Station	Latitude	Longitude	Area, (km^2)	Period
Inflow					
Väike Emajõgi	Tõlliste	57.85	26.13	1054	1921–
Õhne	Tõrva	58.00	25.92	269	1945–
Helme	Tõrva II	58.00	25.92	95	1977–1996
Tarvastu	Linnaveski	58.23	25.90	95	1977–1999
Tänassilma	Tänassilma	58.40	25.85	309	1955–1969
Outflow	*R.-Jõesuu*	*58.38*	*26.13*	*3374*	*1961–*

All presented discharge stations are operated as combined stations where both water level and discharge are measured. Flow in other streams (Tänassilma, Purtsi, Rannu and Rõngu rivers) was calculated by using earlier regression equations. The mean specific runoff of the observed area was applied to calculate the runoff from the shore areas (10% of the watershed). At the beginning of the 1990s a computerized database of the observed daily runoff data with monthly extreme values was created by the author of this thesis.

The number of open-water observation points on the lake varied in space and time depending on the focus of research. For example, in the 1960s special measurements of currents and vertical temperature changes along the dynamic axis of the lake was carried out. At the same time, regular hydrochemical observations were started in 1962. **FIGURE II** demonstrates the network of stations set up for the joint monitoring of L. Võrtsjärv drainage basin by the Estonian Meteorological and Hydrological Institute and the Estonian State Environmental Programme during the 20. century.

The regular monitoring of the ice and snow regime of L. Võrtsjärv was begun in 1924, and water temperature in 1946. The water temperature was measured manually two times a day in the outflow of the lake. The data from the measurement site at Rannu-Jõesuu is considered to characterize the areal coverage of the whole lake. The ice regime observations consist of:

- measurements of ice thickness carried out every 5th day and on the last day of the month;
- registration of dates and the character of freeze-up and ice break-up.

The long-term series of annual minimum and maximum water level in Lake Võrtsjärv was computed over a 132-year period (1871–2002). Until 1921 it was calculated from data recorded on the Emajõgi River in Tartu. The data set from this observation point starting from 1867 represents the longest continuous water level record in Estonia since 1871. The annual typical water level characteristics in the Emajõgi R. and in L. Võrtsjärv are very strongly correlated (Table 3).

The precipitation estimate for the lake basin has been obtained by means of averaging precipitation interpolated into the grids of a calculation network. A grid network of 6–7 km was used. The mean annual amount of precipitation for the period 1925–2002 was 665 mm. The absolute long-term range in the precipitation was 419 mm. The maximum recorded was 884 mm in 1928 and the minimum, 435 mm in 1940. During the years of the last decade the lowest amount of annual precipitation was observed in 1996 — only 439 mm. Data on wind speed and direction were obtained from the meteorological station located at Tõravere (20 km distant from the lake in an easterly direction).

2.2.2. Water quality monitoring.

For 30 years the basic hydrochemical sampling site of the lake has been located near the western coast at the deepest (6 m) point of the lake (**FIG. II**). From 1995 on the monitoring station was moved about 1 km to the North, to a site corresponding better to the average depth of the lake (~3m).

Water samples from 4 larger rivers were collected once a month since 1974. In 1988–1991, water samples from the mouths of 9 larger inflowing rivers and streams, from 4 drainage canals of polders, and from the outlet were collected once a month. The part of the lake drainage area not monitored by the sampling stations in 1988–1991 made up only 9.7% and from 1992 to 2003, 23% of the total catchment area (Fig. 4).

Water from the monitored rivers and streams was sampled once a month and analysed in the South-Estonian Laboratory of Environment Protection in

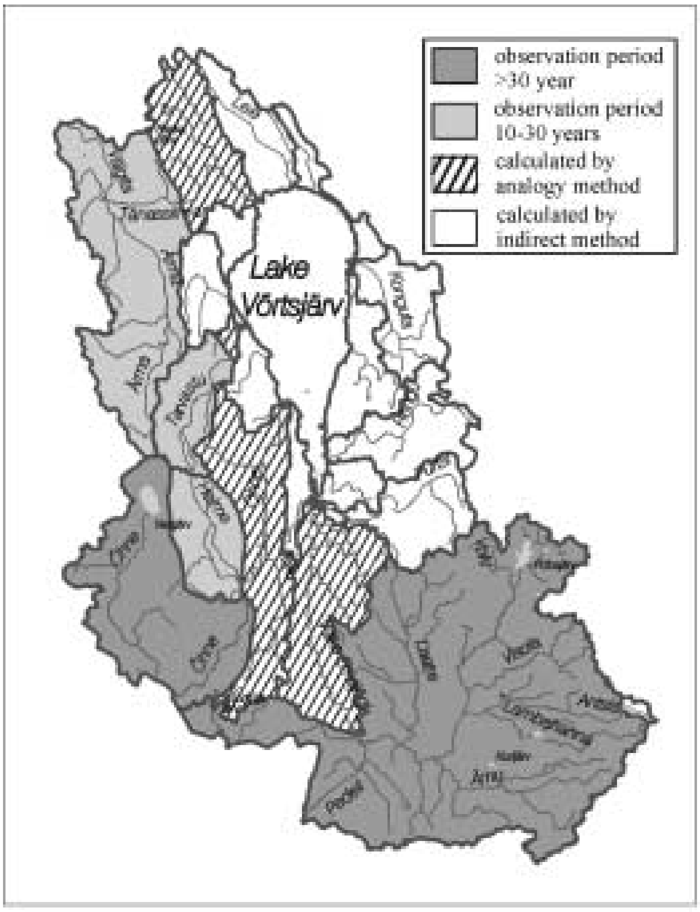


Figure 3. Measured and calculated runoff area.

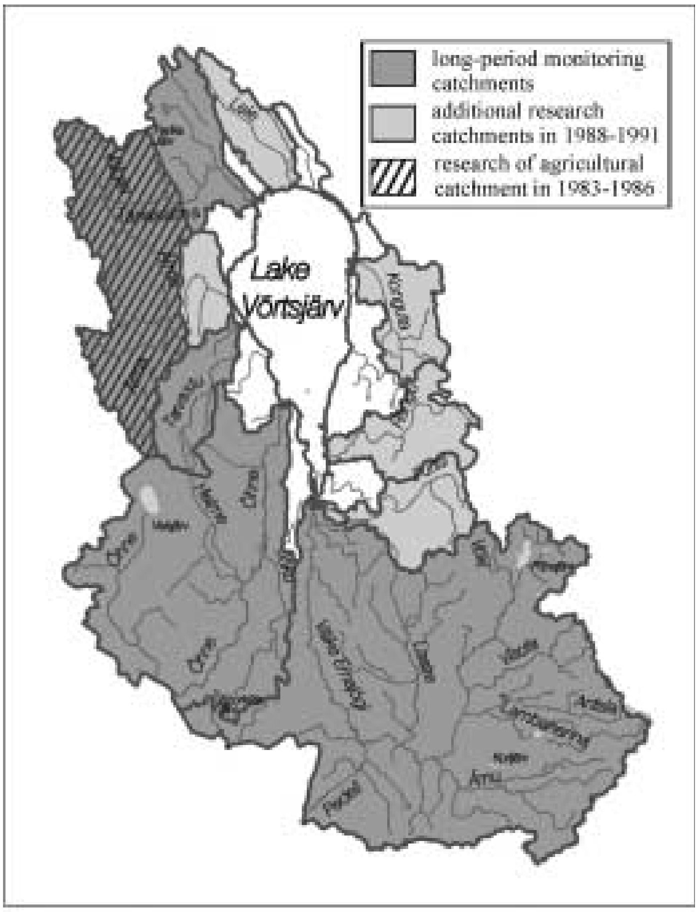


Figure 4. Rivers water clemical monitoring catchments.

Tartu. In the case of the first detailed investigation period of external pollution load in Lake Võrtsjärv, the sampling period was 1988–1991. After that the number of sampling sites was reduced, which coincided with the Estonian rivers chemical monitoring programme.

The samples were analysed for BOD, NH_4-N, NO_2-N, NO_3-N, total N, PO_4-P, and total P. TIN (total inorganic nitrogen) has been calculated as the sum of NH_4-N, NO_2-N and NO_3-N. The measurements of TP and TN began in 1985, and in the rivers, in 1987. In the first period, until 1987, mainly the mineral forms of nutrients (ammonium, nitrites, nitrates, phosphates) have been measured. All water analyses were made following the international methods for examination of water and wastewater quality.

The existing more than 25-year–long databases represent a good background for trend investigations, but the monthly time interval is sometimes too long to build a correct mass budget of substances or to follow causal relations between the variables of the lake. In order to increase the reliability of the data on the seasonal dynamics of the measured parameters, a complex dataset with a one-week sampling interval was collected in 1995, and with a two-week interval, in 1996, in the framework of a Finnish-Estonian cooperative project (Huttula & Nõges, 1998). Regular weekly sampling of nutrients from six main inflows, from the lake and from the outflow enabled the building of correct external and internal nutrient budgets and the calculation of internal phosphorus loading and denitrification rate (Nõges *et al*, 1998).

Catchment areas, also hydrological stations and sampling sites, are coded using the first five letters of the river's official name and three numbers indicating the distance (km) from gauge (sampling sites) to the mouth of the river. For example, TARVA006 indicates a catchment area at the 6th km of the Tarvastu River mouth.

3. HYDROLOGY OF LAKE VÕRTSJÄRV

3.1. Water regime

The water level in the lake is fluctuating continuously in response to external factors, depending largely on regional climate conditions. 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 water level can be observed most clearly and most rapidly in shallow lakes whose catchment area exceeds the lake's surface area by at least 5–10 times. For L. Võrtsjärv, with a catchment area of 3104 km^2, this index is 11.5 at mean volume.

Today the water regime of Lake Võrtsjärv is relatively well described owing to regular measurements carried out within the framework of a national hydrological network program. Data from the Tartu station on the Emajõgi River (the oldest Estonian inland hydrological station) was used for characterizing the water regime of L. Võrtsjärv, the time-series of the annual mean, maximum, and minimum water levels being extended from the year 1871 to 1921 by correlation. The linear correlation coefficients, 0.85, 0.96 and 0.89 (Table 3), of the annual maximum, mean and minimum water levels of the Emajõgi R. and L. Võrtsjärv, respectively, demonstrate a close connection between the water regimes of these two water bodies (Fig. 5). All water level measurements recorded as values above measurement zero were converted to the same geodetic height level (above sea level) according to the Baltic system.

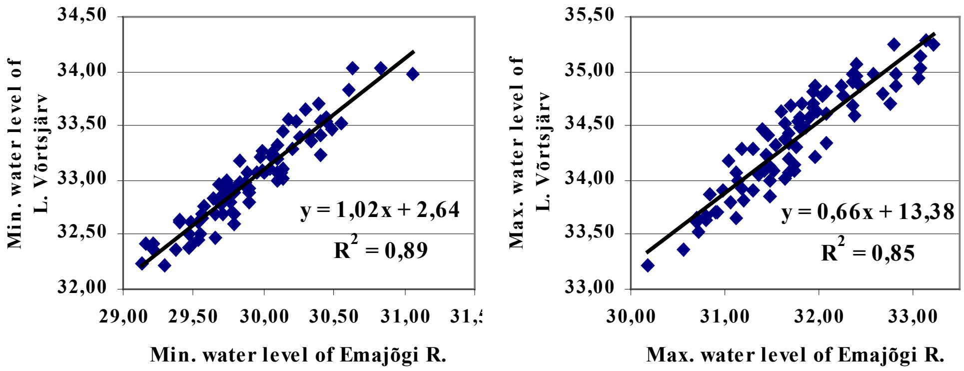


Figure 5. Relationship between annual minimum and maximum water levels in the Emajõgi River (station Tartu) and Lake Võrtsjärv in 1923–2003.

Table 3. Relationship between the water level of the Emajõgi R. (*x*) and L. Võrtsjärv (*y*)

Characteristic	Regression equation	R^2	*SE*	*SE* % from observed variance
Maximum level	$y = 0.66x + 13.38$	0.85	0.25	12.0
Mean level	$y = 0.92x + 5.46$	0.96	0.11	5.5
Minimum level	$y = 1.02x + 2.64$	0.89	0.19	10.4

The present study is based on: a) analysis of general water regime, e.g. seasonal variability of water level, and b) analysis of periodicity and cycles of a long-time series beginning in 1871. To give a better graphic representation of regularities, two simple data processing techniques were used:

1) smoothing of time-series with a simple moving average or by the normalizing time series;
2) spectral analysis of time-series.

In both cases the simplest version of the method was used. To eliminate short-term fluctuations and make long-term ones more evident (in a given context), smoothing of time series by the moving average method is used. Integral curves of deviations are calculated by yearly deviations from long-term mean values. Thus, in general, the integral curve of deviations does not directly show the temporal course of some phenomenon, but the temporal position of the phenomenon with regard to the mean value.

In addition to visual analysis of water level series, the occurrence of hidden periodicity was studied with the help of the standard method of spectral analysis. Using Fourier's transformation of the correlation function, spectral density can be determined. A graphic representation of the correlation function enables the correlation maxima and the respective periods to be assessed.

3.1.1. General features of water regime

According to data from the Rannu-Jõesuu hydrological station, the long-term (1922–2003) mean water level of L. Võrtsjärv is 56 cm above measurement zero (33.07), or 33.63 m above sea level according to the Baltic System. In 1996 the water level dropped to the lowest value ever recorded in L. Võrtsjärv and at the beginning of September, the lowest daily water level was observed (Fig. 6). This was 87 cm below zero, or 32.20 m. The highest water level in L. Võrtsjärv (35.28 m) was recorded in 1928 and the annual maximum (34.64 m or 1 m higher than the long-term period average) in the same year.

A mean daily water level distribution is characterized by left asymmetry: median – 33.58 m, average – 33.62 m, mode – 33.33 m (such a level had occurred on 244 days in total); the radius of asymmetry is –30. The difference between the arithmetic mean of 33.62 m and median 33.58 m is significant. Consequently the frequency distribution shows two maximum values – at 33.50

m and 34.00 m. In comparison with the data from the years 1923–1966 (Jaani, 1973) an essential change has taken place in median replacement and the opposite evidence of asymmetry. In the first period there was right side, but now left side asymmetry (Fig. 6). The median is situated 14 cm lower than the 33.72 m level; the long–term mean water level is 5 cm lower. It shows that a dry period started after the mid–1960's, which is confirmed by statistics. In the last 38-year period there have been more dry years and the long-term changes in the lake water level confirm it.

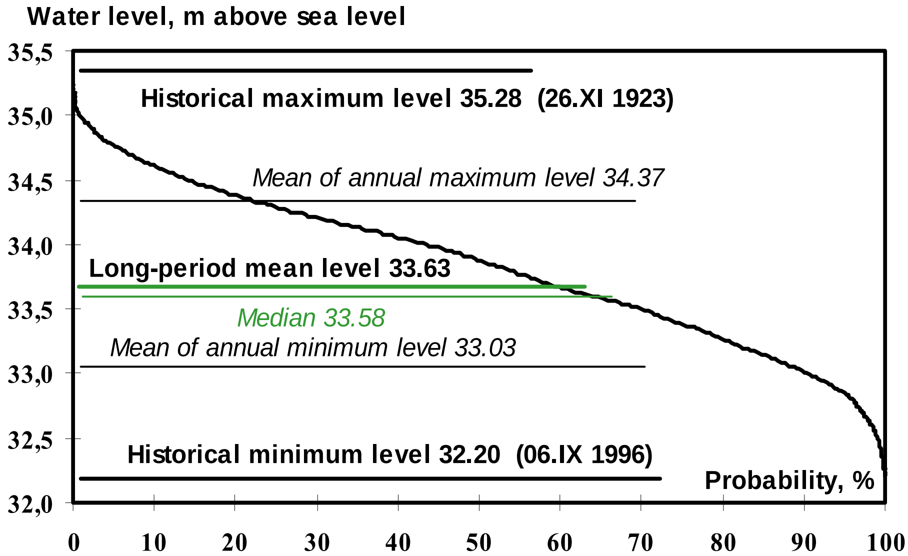


Figure 6. Integrated curve of Lake Võrtsjärv daily mean water levels.

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 (Fig. 7). The daily variation in water level is measured in centimetres, the monthly variation in decimetres, but the annual amplitude exceeds 2 m. The average annual fluctuation amplitude of the water level is 1.34 m. The maximum value was recorded in 1951 (2.02 m), the minimum value in 1925 (0.75 m). The absolute amplitude for the observation period since 1922 was 3.08 m, with the maximum water level of 35.28 m on 26 November 1923 and the minimum of 32.20 m on 6 September 1996 (Fig. 6).

During the period studied, the discharge of the rivers normally peaked in the 1st decade of April, while the level in the lake lagged by one month, reaching its maximum normally in the 1st decade of May. During the spring maximum runoff period the changes in the water level of L. Võrtsjärv were mainly caused by hydraulic conditions in the outflow, as the lake level is hydraulically predominantly connected with the water level in the Emajõgi R. and in L. Peipsi. Because of a great inflow in April (25% of the annual inflow) and very low outflow (0.7% of the annual outflow), the water level remained above the annual mean level until the beginning of August (Fig. 7). Spring high water level affected the level during the next 4–5 months, since the decline in the level after the peak period in May lasted until mid-September, and it also had a causal effect on the autumn maxima in November and December.

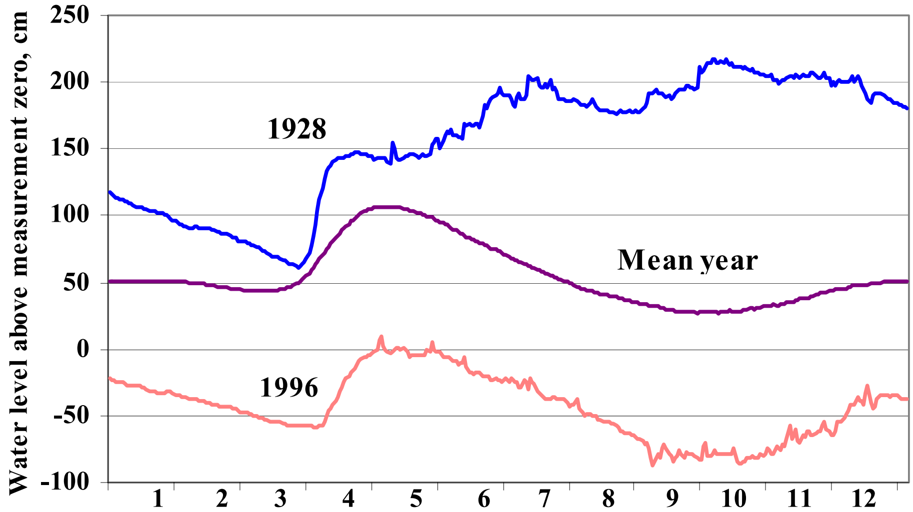


Figure 7. Seasonal change in water level of L. Võrtsjärv in hydrologically extreme years and long period mean.

Minimum water level

The low water level occurs in two periods: (a) summer–autumn and (b) winter. The summer–autumn minimum level is the most essential and has the longest duration. For example, in 1996 the low water level lasted until the end of the year and continued in winter 1997. In July and August, evaporation exceeded the water input (river inflows + precipitation). The winter low water level is higher than the summer–autumn low level and it has a much shorter duration.

The number of days with a low water level (below 33.00) make up 9.4% of the long-term (1922-2003 period, inc. the days with a very low level (below 32.50), which make up 1.63%. The water level is regarded to be lower than the ecologically acceptable level when its mean monthly value drops below 32.50, i.e. more than 57 cm below measurement zero. The regulation of water level can mainly help avoid periods of low water level. In such regulation, short low–level periods (up to one week) can be neglected. The total number of days in the short periods is a little less than 10% of all low–level days and their influence on the need to regulate water level is not important.

Maximum water level

In comparison with low water level (below 32.50 m), the duration of the high level (above 35.00 m) was short: 0.81% of the days in long–term period. The number of days with a level over 34.50 m is already up to 14.2%. On L. Võrtsjärv, spring and autumn floods can be distinguished. During 63 of the 81 observed years the highest water level occurred in spring and during 18 of them, in autumn. During the observed years, the maximum water level in the lake normally occurred in April. The spring flood has mainly been caused by snow melting, but in some years, rain has added to the water level rise. The unfavourable conditions of the outflow – the small slope of the Emajõgi River and bifurcation in its upper course during flooding – lead to prolonged high water periods with extensive flooding of shoreline areas. Autumn brings about a water level rise every year, which may last until the lake is frozen. This is caused by an increase in the amount of precipitation and a decrease in evaporation.

The flood area around L. Võrtsjärv was specified on a 1:10000 topographic map and relief isolines were digitized. The area between the topographic shoreline and the 35 m isoline was taken as a flooded area with a relatively long-term water level stand with 1% probability. The boundary of the flood area is the Tartu–Viljandi road at the outflow and the Pikasilla bridge on the Väike Emajõgi R. mouth in the south. In the observed period the water level reached 35.00 m or higher on 202 days. The submerged area exceeds 22.76 km^2, of which the largest part, 15.80 km^2 or ca 70%, is situated in Viljandi County. Among rural municipalities, Tarvastu has the largest flooded area – 9.72 km^2. A submerged area of 18.3 km^2 corresponds to the high water value of 34.37 m in an average year during the long-term period. The maximum submerged area in the case of the observed maximum water level, 35.28 m, was calculated by the water level *vs* surface area relationship curve as 57 km^2, but this area is difficult to measure on a topographic map.

3.1.2. Long-term fluctuations

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 an interesting and important issue for forecasting and economic purposes. While studying the changes in long-term low (LW), mean (MW), and high water (HW) levels, it became evident that the changes in all three parameters are similar. 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 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 annual water level.

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 8 presents the results of the spectral analysis. 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.

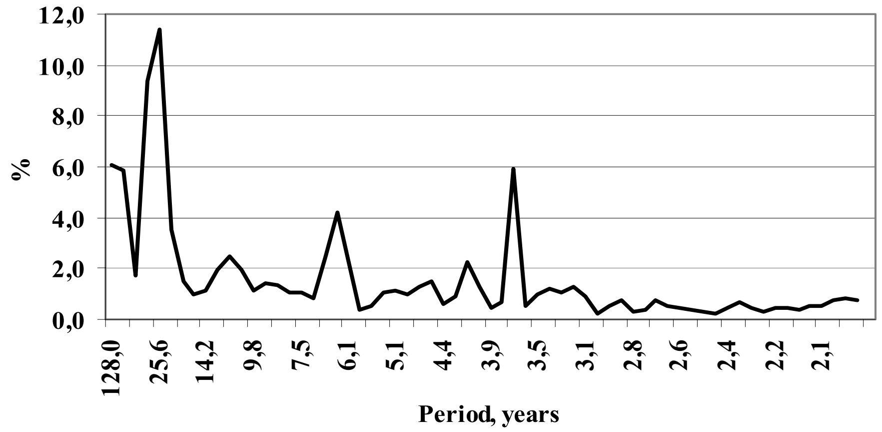


Figure 8. Spectrum of annual minimum water level in L. Võrtsjärv.

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 not only of Estonia, but also of a much larger area in northern Europe (North-West Russia, Latvia, Lithuania, southern part of Finland). Several authors (Jaani, 1996; Либин & Яани, 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 by Jaani (1973) for lakes Peipsi and Ladoga and also in recent studies of river runoff change in Finland (Hiltunen, 1994), and in the runoff coefficient in Estonia (Järvet, 1995). These fluctuations are caused by natural variations of precipitation, which are amplified by drainage basin characteristics (Behrendt & Stellmacher, 1987). 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.

The period since the beginning of the 1960s has been relatively dry in comparison with earlier times, which is reflected in 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 water regime in the near future.

Real cyclic changes occur as a result of all oscillations with different periods and amplitudes. The following long-term cycles of annual minimum water level can be distinguished in L. Võrtsjärv (from minimum to minimum):

1. 1855–87. Duration: 32 years (close to the Brückner cycle). The beginning is established by data from Lake Ladoga; however, it may have started somewhat earlier (Jaani, 1996). It is hard to determine the actual start and structure of the cycle. However, the water-rich years of the 1840s (not exactly observed) probably belonged to the preceding cycle.

2. 1888–1913 (or 1921?). Duration: 26 (34) years; in accordance with the Brückner cycle. The cycle seems to consist of two parts (Fig. 6): 1888–1901 and 1902–13.

3. 1914–1940. Duration: 26 years, among them the wettest year (1928, annual precipitation amount 884 mm) and the driest year (1939, annual precipitation amount 435 mm) in Estonia in the 20th century.

4. 1941–1976. This period is characterized by a small variation of annual rainfall, ranging from 490 mm in 1941 to 800 mm in 1962 (average value 635 mm per year, SD 89 mm); as a result, changes in the water level in L. Võrtsjärv were not great.

5. From 1977 onwards. This cycle has already lasted for 26 years and its duration should also be about 30 years. Starting from the second half of the first decade of this century a new water-rich period should begin.

There is a strong connection between the periodic fluctuations in 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. The corrected time-series of spatial mean annual precipitation in Estonia indicates a clear periodicity (Jaagus 1992, 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 the water level of lakes. When annual precipitation in Estonia is less than 650 mm, lake water level depends on precipitation, and evaporation rate is stable (Järvet, 1998). When precipitation is higher, evaporation increases with a rising amount of precipitation. Based on the comparison of water balance elements, it can be concluded that the temporal variability of the water level of large lakes is much higher than the variability of precipitation.

An example of another comparison using the long-term series of hydrological characteristics is the investigation of the relation of the normalized time series of annual maximum (H_{max}) and minimum (H_{min}) water levels to possible climate changes. The above quantities were normalized with respect to multi-annual values and presented in a dimensionless form:

$$i_n = \frac{i - i_{min}}{i_{max} - i_{min}}$$

where i - the value of the indicator (water level) in a given year,

i_n – dimensionless value of the normalized indicator,

i_{min} – lowest value of the indicator observed in the investigation period,

i_{max} – maximum value of the indicator in the investigation period.

For smoothing, 6 year filters, the closest value to the main period of 6.4 years calculated by spectral analysis, were used. The temporal variation of H_{max} and H_{min} is shown in Fig. 9. The fluctuations of the water level are probably reflections of variations of zonal atmospheric circulation and this is the response of the lake (water level) to the climate changes.

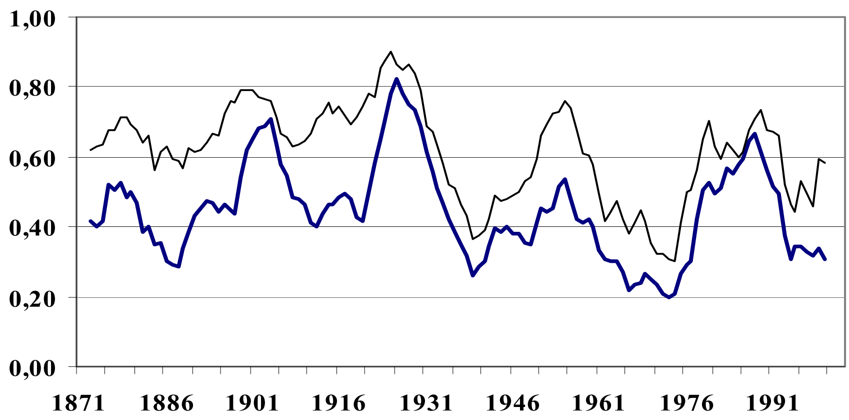


Figure 9. Long-term variation of annual maximum (normal line) and minimum (bold line) water level of L. Võrtsjärv in 1871–2003, smoothed by a 6-year filter.

The variation of both indicators is similar, but amplitudes in the period from the 1870s to the 1920s differ. This subperiod has been characterized as a relatively long wet period and therefore the annual minimum water level reflects multi-annual variation better than the maximum level.

3.2. Water balance

The evaluation of the water balance of Lake Võrtsjärv is one of the principal objectives of the hydrological investigation. The basic method involves the accurate measurement of the precipitation, inflow, outflow and changes of water accumulation in the lake, and the calculation of evaporation rate from lake surface. In our computations, the groundwater component has not been taken into consideration due to its small value and the difficulties associated with its measurement.

The water balance of L. Võrtsjärv can be written as the following simple equation:

$$Q_{in} + P - Q_{out} - E \pm A \pm \Delta s = 0,$$

where Q_{in} – surface inflow into the lake,
P – precipitation on the surface of the lake,
Q_{out} – outflow from the lake through the Emajõgi River,
E – evaporation from the water surface of the lake,
A – accumulation (capacity difference in the water storage of the lake);
Δs – balance error (or discrepancy).

Precipitation.
The accurate estimation of areal rainfall is not easy, as its temporal and spatial heterogeneity is relatively high. The number of long-term rainfall records available from rain gauges within the catchments is insufficient for conventional estimationn of mean lake surface precipitation for any time interval. In this study, precipitation was measured using a daily precipitation series collected by ground-level gauges at 3 stations situated near the lake: Rannu-Jõesuu, Linnaveski and Ranna. The average monthly precipitation for the lake surface was estimated by the Theissen method. In this way we took into account the decreasing effect of Sakala Upland on rainfall in the Võrtsjärv lowland and on the lake surface.

Inflow.
The discharge observations of the rivers in the lake catchment are not complete enough to allow a direct calculation of inflow into the lake. The Estonian Hydrological Board established a water level registration and runoff measuring network of two sites in 1921 (Table 2). Other sites were steadily added to the network, and discharge is measured at the 5 hydrological observations sites located on major and minor streams throughout the whole catchment area. These gauged watersheds had a maximum total area of 1631 km^2 (52.5 %) from 1961 to 1969 and a minimum of 1324 km^2 (42.7 %) from 1970 to 1976 and from 1999 to today. The reduction of hydrometric stations has created problems for the reliable determination of runoff from the total lake basin. If we take into consideration the runoff stations with time series of over 30 years, their total number is only 2 (Tõlliste and Tõrva) and their total catchment area is 1287 sq. km. Such stations with fairly long time series reflect best the runoff regimes of rivers of the L.

Võrtsjärv drainage basin. There are many instances where runoff data has not been measured, or where the available streamflow monitoring series are too short to afford a reliable estimate for the parameter of interest. In such circumstances, regression equations are commonly used to estimate runoff parameters (Table 4).

Table 4. The comparison of monthly mean specific runoff from the observation catchments on the drainage area of L. Võrtsjärv (l s^{-1} km^{-2}). Relationships that were used for discharge calculations are marked in bold.

Basic station	Computing station	Period of comparison	Regression equation	R^2
NAVES015	**TÄNAS016**	**1955–1969**	**y = 0.89x - 0.26**	**0.89**
ÕHNE_036	TÄNAS016	1955–1969	y = 1.27x - 1.75	0.73
ÕHNE_036	**TARVA006**	**1978–1999**	**y = 0.90x - 0.51**	**0.84**
ÕHNE_036	**HELME000**	**1977–78; 1987–96**	**y = 1.08x - 1.33**	**0.91**
VEMAJ036	ÕHNE_036	1961–2000	y = 1.03x + 1.12	0.90
VEMAJ036	**PIIRI000**	**1977–1980**	**y = 0.98x – 1.50**	**0.92**
ÕHNE_036	PIIRI000	1977–1980	y = 0.76x – 1.12	0.88

The observation sequences of ungauged catchments have been restored by the analogy method. For the unobserved area of the drainage basin, also for river Tänassilma, R. Navesti (outside of Lake Võrtsjärv drainage basin) was selected as the analogy river, and the monthly mean value of specific runoff (l/s per km^2) of selected analogy rivers (Table 5) were used for discharge calculations. Runoff from hydrologically non-investigated area (Fig. 3), about 700 km^2, was calculated using monthly mean specific runoff values of investigated catchments.

Evaporation.

The rate of evaporation depends on the availability of energy and water, and a number of factors (e.g. micrometeorological conditions) influencing evaporation process. Lake evaporation is the most crucial component in the water balance equation, because no direct evaporation measurements were available at the lake surface. From several indirect methods the following aerodynamic formula presented by Russian State Hydrological Institute in the 1960es was selected by the Estonian hydrological service:

$$E = 0.14n(e_0 - e_2)(1 + 0.72w_2),$$

where

E – evaporation, mm/month;

n – number of days in month;

e_0 – saturated vapour pressure at surface water temperature, mb;

e_2 – air vapour pressure at a height of 2 m, mb;

w_2 – wind velocity at a height of 2 m, m/s.

The daily evaporation was calculated using meteorological data observed in three-hour steps, and then averaged over a month.

Accumulation component.

For assessing the water mass in the lake, the lake level records at Rannu-Jõesuu hydrological station in the north-east shoreline, where water level has been recorded daily since November 1921, are used. Changes of the volume of the lake can be predicted when the depth-volume relationship for the lake is known. The volume of Lake Võrtsjärv can be calculated as a function of lake level W = f(H), where H is the water level at the station in Rannu-Jõesuu. Seiches, hydrodynamic gradient, and storm surges can all affect lake level records and can cause significant errors when estimating volume changes. For this reason, water level records of the first day of every month were analysed in detail to determine accident deviations from the normal curve.

Outflow and reverse disharge.

Lake Võrtsjärv outflow has been measured since 1961 at Rannu-Jõesuu hydrological station. The lake is regulated naturally so effectively that maximum flows of the outflow occur during 40...50 days after maximum runoff of inflows (Fig. 10). During the higher water period the direction of the flow may become reversed in the upper course of the river. This complicates the calculation of correct water balance. In principle the reverse discharge of the Emajõgi River is added to the inflow component of the water balance.

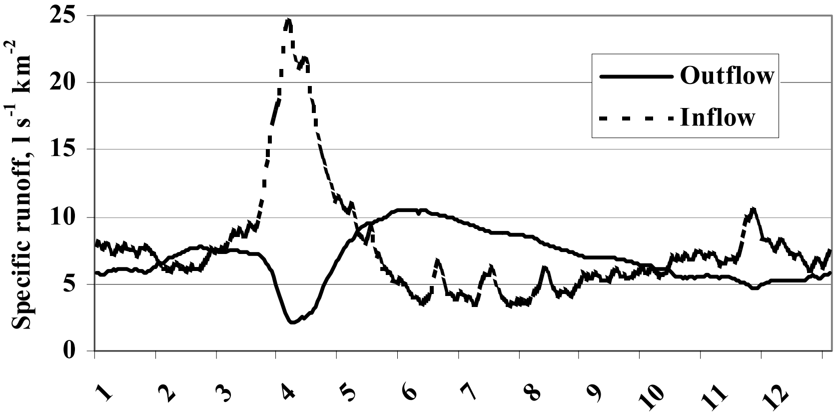


Figure 10. Comparison of long-term daily mean inflow and outflow of Lake Võrtsjärv.

The upstream part of the Emajõgi River (6 km) and the mouth of the Pede River constitute a hydrologically interesting region in Estonia. Owing to its small slope, during floods the Emajõgi River can flow in the reverse direction back into Lake Võrtsjärv. The amount of reverse discharge is greater, the lower the water level in L. Võrtsjärv is at the beginning of the high water period. In addition to that, during the high water period a large area adjacent to the Emajõgi River is flooded, covering an estimated 92 km^2 during the period of maximum water level.

Since 1961 the Emajõgi River has flowed in the reverse direction in 33 years. Between 1961 and 2003 there have been 560 days of reverse flow and an additional 128 days when the water has flowed in neither direction (Fig. 11). The annual average reverse discharge into L. Võrtsjärv has been estimated as 20.1 million m^3, which constitutes 2.8% of the mean annual total inflow into the lake. The maximum daily reverse flow was measured on April 1, 1968 as 48.5 m^3/s. Since 1978, cases of reverse discharge have decreased, since this has been a period of relatively high water level in the lake, and when the water level of the lake is comparatively high at the beginning of floods there is less possibility for reverse discharge from the Emajõgi River.

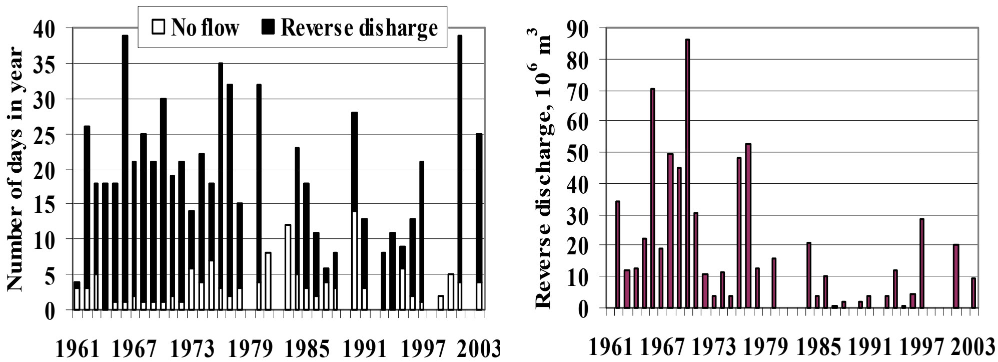


Figure 11. Number of days (*left side*) and annual discharge *(right side*) of Emajõgi reverse direction flow in 1961–2003.

Thus, in the presented water balance equation, a time period of 40 years (1961–2000) was used and monthly intervals turned out to be most satisfactory. Some water level and discharge series were much longer, exceeding 82 years, but sufficient data for water balance calculation was not available until 1961 when runoff measurements in the outflow of L. Võrtsjärv were initiated. The mean monthly values of the water balance parameters are given in Table 5. Similarly, inflow and outflow vary by a factor of nearly 0, but monthly and annual differences are important (**FIG. III**). The discrepancy was larger for the months of the spring maximum runoff period (Table 5), when the inflow substantially exceeded the outflow and the accumulation was higher than the sum of the other months. However, it is impossible to completely rule out the inaccuracy in evaporation estimates as one cause of the “imbalance”.

Tabel 5. Annual mean water balance of Lake Võrtsjärv in 1961–2000 (10^6 m^3)

Balance components	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Input													
Inflow	59	37	77	178	76	36	33	39	47	53	64	72	771
Precipitation	2	3	16	19	12	16	19	21	15	13	12	4	153
TOTAL	60	40	93	197	88	52	52	60	62	66	76	76	924
Output													
Outflow	57	64	62	34	85	89	81	67	58	52	43	47	739
Evaporation	0	0	1	6	17	26	31	25	19	12	5	1	143
TOTAL	57	64	63	40	102	115	112	92	77	64	48	48	882
Accumulation	2	-29	27	147	-22	-65	-63	-38	-15	8	27	21	-3
Balance error	2	5	3	10	9	11	3	6	0	-6	1	7	52

3.3. Climatological calendar of Lake Võrtsjärv

The northern temperate zone is characterized by a high variability of meteorological conditions, which is one of main factors influencing the natural conditions of water-bodies. Water climate can be analyzed using not only simple quantitative variables but also qualitative ones. Seasonal variability in nature is caused by seasonality of weather conditions. The annual cycle of weather conditions can be divided into seasons, which are described by qualitatively different climatological characteristics.

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. A closed annual cycle consists of a sequence of regularly alternating ecological phases, which are expressed using beginning dates, duration and intervals. A climatological calendar contains a complex of common descriptive statistics (beginning date and duration of climate season) that describes the temporal variation of climate seasons and ecological conditions. The duration of climatic seasons was calculated as the difference between the start dates of 2 successive seasons.

The sinusoidal representation of the annual distribution of water temperature in lakes is preserved most clearly in the surface layer of up to a couple of metres in depth. This layer constitutes the most sensitive part of the lake, which is susceptible to changes in meteorological conditions. On the basis of the observations carried out on the thermal structure of Polish lakes, it has been found that lake water temperature at a depth of 0.4 m best characterizes the thermal relations of the surface water layer (Skowron, 2001).

Climatic seasons can be used as good indicators that can contribute new information to studies on climate change influence on lakes. It proceeds from the fact that seasonal variability of lake ecosystems strictly follows annual cyclicity.

In the present study, observation materials from the EMHI concerning daily mean values of surface water temperature (0.3–0.5 m depth) and the occurrence of ice phenomena were used. Regular observation data has been collected from the mid-1940s, when water temperature measurements were begun.

3.3.1. Determination of climatic seasons of lakes

A climatic season can be defined as an independent stage in the annual cycle of the climatic component of the geographical environment. Every season has its specific complex of natural conditions for water-bodies. The influence of weather (temperature) conditions on the seasonal development of the ecosystems of a lake is the leading criterion for dividing a year into climatic seasons. Determination of seasons must also be as simple as possible, using uniform criteria. Climatic seasons of the warm-half year are determined according to the pattern of daily mean water temperature, and the winter period seasons according to ice phenomena (Fig. 12). These recommendations permit the use of a large data set and minimize subjectivity in the determination of start dates of climatic seasons.

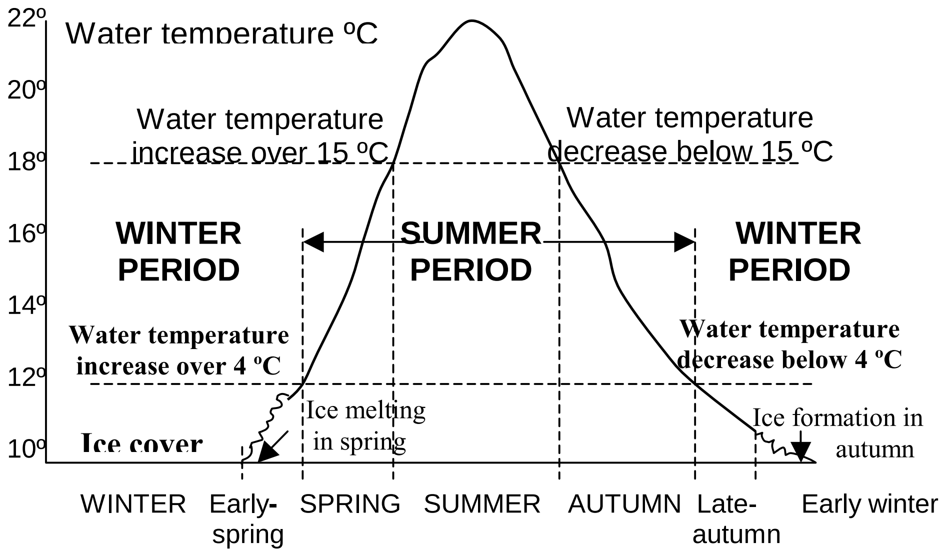


Figure 12. Determination of climate seasons of lakes in Estonia.

It is assumed that the basic criterion for the division of the year into thermal seasons is the transition of water temperature through the stipulated values (levels).

Two essential threshold temperatures are passed during the warming and cooling periods in spring and autumn, respectively: 4^{O}C and 15^{O}C. 4^{O}C is the temperature of the highest water density and 15^{O}C separates intensive biological summer from spring and autumn. This corresponds to a period where water temperature is consistently higher than 15^{O}C. Above this temperature level intensive vegetation of macrophytes and diatoms begins. It is also the transition point from spring to summer phytoplankton, and from cold-water zooplankton to warm-water type.

Applying the above-mentioned criteria and methods, the following climatic seasons (thermal periods) in lakes have been accepted (Table 6). Seven climatic seasons of water-bodies have been distinguished in Estonia (Järvet, 2001a, 2001b). The climatic seasons of lakes are defined by water temperature and ice cover characteristics (date of the beginning and the end of ice phenomena and ice cover). The seasons of the colder half-year (late autumn, winter, early spring) are determined only by ice data. Ice cover is the main factor determining climatic seasons during the cold half-year.

Table 6. Determination of climate seasons of lakes in Estonia

Climate seasons	Determining of climate seasons
Early spring	Period from the break up the ice cover up to the period of mean daily water t^{O} above 4^{O}C
Spring	Period of mean daily water t^{O} from 4^{O}C to 15^{O}C
Summer	Permanent increase of diurnal mean water temperature above 15^{O}C
Autumn	Period of mean daily water t^{O} from 15^{O}C to 4^{O}C
Late autumn	Period from the end of daily water temperature above 4^{O}C up to the beginning of ice phenomena
Early winter	Period from the beginning of ice phenomena up to the beginning of ice cover
Winter	Period with permanent ice cover

The first occurrence of ice is regarded as the beginning of late autumn. On the land surface this period corresponds to late autumn (determined by the first formation of snow cover) and additionally to early winter. Winter as the main season of the colder half-year begins when permanent ice cover occurs. Early spring is mainly a period of ice melting. Spring, which begins after the permanent increase of daily mean water temperature above 4^{O}C, indicates the beginning of the intensive thermal warming season. Spring and autumn enclose the period before and after summer when water temperature is permanently below 15^{O}C.

3.3.2. Temporal variability

Start date and duration of the climatic seasons of lakes in Estonia are characterised by a remarkable temporal variability (Table 7). Temporal range here means the difference between the earliest (longest) and the latest (shortest) values during the observation period.

Climatic seasons of Estonian large lakes reflect the climatological conditions in continental part of Estonia, mainly in south-Estonia. They vary remarkably from the climatic season characteristics in west-Estonia. Thermal influence of the Baltic Sea is the main factor in the formation of territorial differences. For example, in the spring, the "green wave" migrates over Estonia from south-east to north-west during 12 weeks (Jaagus and Ahas, 2000).

Table 7. Statistics of temporal variability for start dates and duration of climatic seasons determined at L. Võrtsjärv between 1946 and 2000.

Climate seasons	Average		Range		St dev	
	Start date	Duration	Start date	Duration	Start date	Duration
Early spring	07 Apr	9	78	56	13.9	12.0
Spring	17 Apr	38	43	52	7.2	11.3
Summer	26 May	103	49	56	10.8	12.3
Autumn	06 Sept	51	28	62	7.5	11.8
Late autumn	27 Oct	17	57	53	9.7	12.6
Early winter	15 Nov	14	59	48	12.6	13.3
Winter	29 Nov	129	83	108	15.7	22.9

Temperature conditions of L. Peipsi are quite different in comparison with L. Võrtsjärv. Lake Võrtsjärv is very shallow (mean depth 2.8 m) and its volume at mean water level is estimated at 0.97 km^3. The largest (northern) part of L. Peipsi, the thermal conditions of which are characterised by Mustvee hydrological station, has a mean depth of 8.4 m and a water capacity of 21,79 km^3. Therefore, L. Peipsi accumulates a larger amount of heat in summer. Also, it cools down slowly, freezes later and opens later in spring than L. Võrtsjärv. The shallow L. Võrtsjärv warms up and cools down considerably faster. Warming from the break-up of ice cover to 15^{O}C takes 49 days in L. Võrtsjärv and 60 days in L. Peipsi. Cooling from 15^{O}C to the formation of permanent ice cover takes 84 days in L. Võrtsjärv, but 103 days in L. Peipsi. During long and stormy meteorological late autumn, the whole water mass of both lakes cools down to 0^{O}C.

The lowest year-to-year variability is typical for the start dates of spring and autumn. The smallest standard deviation (11.3 days) of the beginning dates occurred for spring. This is probably due to the rapid change in the length of the day, solar radiation, and air temperature during equinoxes at high latitudes. Seasonal changes at that time are the fastest and most fixed in time in comparison with other times of the year. The highest temporal variability is characteristic for the beginning of early spring, early winter and winter.

Temporal variability of the duration of climatic seasons is even higher than that of start dates (Table 7). Duration is determined by 2 start dates and this increases its temporal variability. The duration of winter and early winter are the most variable. The range of variation of the three winter seasons together is several months; maximum value of standard deviation exceeds 33 days (Järvet, 2001).

3.3.3. Long-term trends

The thermal characteristics of lakes are particularly responsive to changes in the weather, and frequently amplify the effects of regional-scale variations in the atmospheric circulation. Results of linear regression analysis of long-term series in Estonia indicate the presence of some long-term changes. Changes in trend in Table 8 are differences between trend-line values calculated for years 1947 and 2000. Positive changes show a tendency for climatic seasons to start later and *vice versa*.

Climatic seasons of Lake Võrtsjärv for the whole year tend to begin earlier (except early winter and winter, which start at the same time), while the seasons of Lake Peipsi have undergone different changes. A statistically significant trend was determined only for the start date of early spring (beginning of break-up of ice-cover), for L. Võrtsjärv, also for the beginning of spring (daily mean water temperature increase above 4^{O}C). Start dates of early spring have shifted one month earlier on L. Peipsi (from 19 April to 19 March), from 17 April to 31 March on L. Võrtsjärv.

The summer period (from spring to late autumn) has lengthened by 1 week during the 55-year period (**FIG. V**). The most significant trend was obtained for winter (ice cover period). The shortening of the winter season by 17 days is indicated. A statistically significant trend was determined only for the beginning date of early spring – significance at $p<0.05$ level. Other clear trends were obtained for early winter and autumn, but these were statistically non-significant due to the high temporal variability of the time series.

Table 8. Statistics of temporal variability for start date of climatic seasons of L. Võrtsjärv by linear trend line between 1946 and 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

The summer half year (period from the beginning of spring to the end of late autumn) has lengthened during 55 years on L. Võrtsjärv by 9 days, respectively. The periods of rapid warming tended to occur earlier in the year and there was an associated extension in the length of biological summer. The shortening of the winter season by 16 days is statistically significant. All the long-term tendencies observed in Estonian large lakes are in good accordance with the trend of increasing mean air temperature during the winter and spring seasons (Jaagus, 1996), and with the trend of decreasing spatial mean snow cover duration (Jaagus & Ahas, 2000).

As a graphical summary of the results of the climatological calendar trend analysis, several annual circles can be drawn. **FIG. VI** presents the annual cycles of both large lakes in Estonia. The inner cycle represents the mean distribution of the seasons by trend at the beginning of the observation period, and the outer cycle, at the end. The cycle is oriented so that the winter solstice is located at the bottom, and the summer solstice is at the top. Time progresses counter – clockwise.

The obvious lengthening of summer seasons and shortening of the winter period can easily be observed. It is in good accordance with changes in the general climatic calendar in Estonia (Jaagus & Ahas, 2000), because the period 1945 to 1998 is characterised by a remarkable tendency for late winter and early spring to begin earlier (by 32 and 18 days).

Results of linear regression analysis demonstrate changes in the climatological calendar reflecting the influence of global warming. Similar trends have been observed in the whole Nordic region of Europe. T. Gronskaya *et al* (2000, 2001) have assessed the impact of changing weather patterns on the dynamics of several lakes in Russia and Finland.

4. ECOLOGICAL STATE IN WINTER CONDITIONS

Over the years, the ecological state of the Lake Võrtsjärv has varied considerably with respect to climatic conditions and morphometry (depth and active volume). Ice cover also plays an essential role in the formation of the lake's ecological state. Under the ice, primary production is controlled mainly by light availability. The amount of solar radiation in water depends upon a number of factors: the values of the total radiation incident onto the surface of the water body and the surface albedo, the thickness and transparency of the ice and snow cover, and the optical properties of water.

4.1. Winter conditions

The purpose of this section is to present a general survey of hydrological factors connected with ice cover in estimating L. Võrtsjärv ecological conditions in wintertime. Ice cover plays an essential role in the formation of the lake's ecological conditions, especially in the winter period. Important indices of water-body climate factors include the duration and thickness of ice cover and the ice volume. Changes in climatological conditions, which are reflected by cyclical fluctuations in the water regime and ice conditions over a long period, obviously influence hydrophysical and also hydrochemical and hydrobiological processes in the lake (Fig. 13).

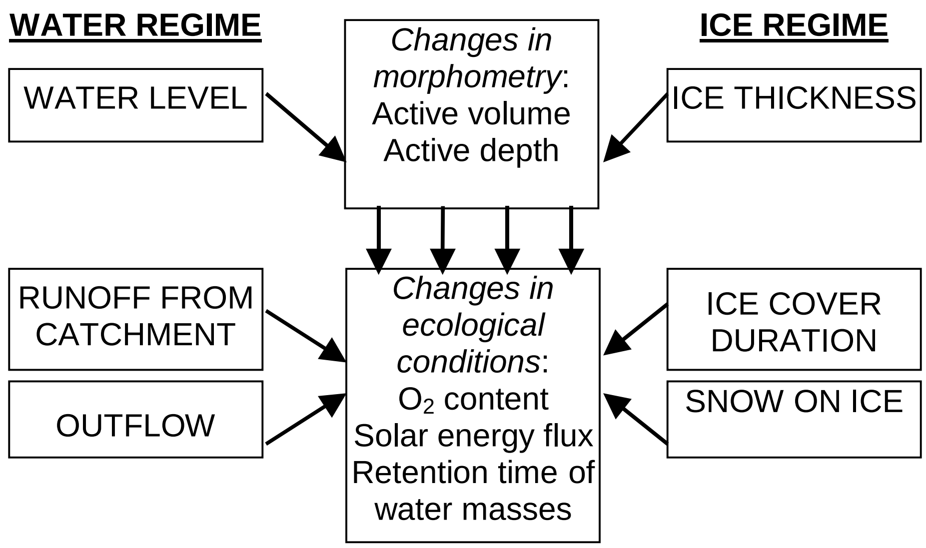


Figure 13. The principal scheme of wintertime hydrological factors that influence the morphometry and ecological conditions of a shallow lake.

The temporal variation of both quantity and type of ice are important from an applied point of view. The winter conditions of a lake, especially the amount and concentration of oxygen in water, depend upon the duration of ice cover and the thickness of ice and snow. One of the ways in which the snow and ice cover development of a lake in winter influences a lake's ecosystem is its effect on light entering the water mass. The ice and snow cover and the wintertime radiation conditions of L. Võrtsjärv are characterised by the observation series, the results of which are presented in the papers by Järvet & Reinart (1997) and Järvet (1999).

4.1.1. Ice and snow observations

The observation series of the Estonian Meteorological and Hydrological Institute (EMHI) were used to analyze the lake's ice and snow cover conditions. The regular survey of ice and snow regime, including thickness measurements, was started in 1923. The ice regime observations consist of:

1) measurements of the thickness of ice and snow on the ice. The thickness of the ice cover is recorded every 5th day and on the last day of each month.
2) Observations of ice freeze-up and break-up — the dates and character of freeze-up and break-up are observed.

The thickness of ice has been measured almost continuously at 1 km from the shore since then. Within this program, the snow and ice cover of a lake are represented by a single set of measurements from one site close to the lakeshore, with additional visual observations of conditions on the lake. The data of the measurement site at Rannu-Jõesuu (the north-east coast of the lake) are considered to characterize the areal coverage of the whole lake. The results of the first decades of observations have been published (Jaani, 1973) in the monograph on L. Võrtsjärv presenting the results of complex investigations until 1966.

4.1.2. Dates and duration of ice cover

The ice cover on Lake Võrtsjärv is characterized by variability in the thickness of the ice, and also by the times and extent of disappearance of ice cover on the lake. The freezing of the lake usually begins in the middle of November, and by the end of April the lake ice is gone (Table 9). The table offers the average, the earliest and the latest dates of ice phenomena in autumn and in spring. There was an extremely cold winter in 1941/42, and mild winters in 1960/61 and 1989/90. The lake was covered with ice for an average of 131 days a year (Table 10). Ice grows until March and then quickly breaks up. Ice thickness in March is mainly 45–65 cm, with a mean of 52 cm. In the very warm winter of 1960/61 the ice thickness only reached 26 cm, but it was still there in March. During the long winter of 1956 there was thick ice even in April (49 cm on 25 April). The maximum ice thickness — 98 cm — was observed in 1941/42, and the period of thick ice in Estonian conditions (> 50 cm) exceeded 132 days — until the end of April.

Table 9. Seasonal variations in the formation of ice cover on Lake Võrtsjärv in the period 1923–2000.

Character.	**Oct**	**Nov**			**Dec**			**Jan**	**Feb**	**March**	**April**			**May**
Decade		*I*	*II*	*III*	*I*	*II*	*III*				*I*	*II*	*III*	
First ice phenomena	14	15	21	16	6	3								
Beginning of ice cover		6	19	22	12	10	5	2						
End of ice cover									2	14	25	25	8	1
Last ice phenomena										4	7	24	27	13

The thickness of snow cover varies greatly during winter and to a small extent also in different parts of the same lake. Lake snowpack has an original stratigraphy and distribution, which are the result of the natural conditions of falling snow and its deposition (Leppäranta *et al*, 2003). We suppose that the ice in Lake Võrtsjärv is like normal lake ice, with the main layers from the top down being: 1) relatively opaque, usually snow-derived snow (white) ice; 2) the layer of clear columnar congelation (blue) ice which is formed by the direct freezing of lake water. The thickness of white ice is 0–15 cm in a normal year, and this depends on the snowfall history, but does not exceed more than one third of the total thickness of the ice. Table 10 represents the main results of ice and snow cover duration and thickness analyses: average and extreme values.

Table 10. Ice cover duration on L. Võrtsjärv in the period 1923–2003

	Autumn and winter			***Spring***		
	Beginning of steady ice cover	*Duration of freezing processes (days)*	*Ice-covered period (days)*	*Bracing up of ice*	*Floating of ice*	*Ice-free period (days)*
Mean	29. XI	12	131	27. III	27. IV	234
Earliest or Maximum	04.XI 1940	63 (1960)	168 (1995/96)	21. II 1990	10. IV 1938	314 (1990)
Latest or Minimum	30. I 1930	1 (1933)	55 (1929/30)	3. V 1942	14. V 1942	192 (1956)

Snow cover. The lake's snowpack, like that on land, has an original stratigraphy and distribution, which are the result of the natural conditions of snowfall and the duration of their deposition. However, the effects of wind and temperature must be taken into consideration. In addition, the thinning of snow cover in all or part of the lake occurs whenever the ice sheet is flooded. Such flooding, which can have various reasons, is a normal hydrological event in most snowy lake ice regions. Great variations in spatial patterns can occur from one period to another. These spatial and temporal variations of both quantity and type of snow are extremely important from an applied point of view. They greatly influence the amount and type of light entering a lake, which in turn affects such processes as photosynthesis and oxygen production in the water body. The losses of light in ice vary from 4% in December to 22% in November and March (**FIG. VII**). In January, February and March, the losses of incident light are mostly caused by thick snow, 40% to 60% accordingly (Reinart, 1999).

4.2. Light climate under the ice cover

Ice and snow cover plays an essential role in the formation of the light conditions of L. Võrtsjärv, which freezes over almost every winter. For example, they 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 the ice cover.

The amount of solar radiation in water during winter depends upon a number of factors: the height of the sun, the length of the day, the duration of the ice cover period, surface albedo, and the thickness and transparency of the ice and snow cover. The albedo of fresh snow is the highest (80–90%), but the albedo of ice depends upon its thickness and internal structure, ranging from 10% (young ice) to 60% (thick ice with scabrous surface) (Leppäranta *et al*, 2003).

Light conditions that might be found in Lake Võrtsjärv during winter were simulated with ice and snow thickness for mild, average and cold winters. On the basis of the average, maximum and minimum thickness of snow and ice, the results for three hypothetical variants of winter (average, cold and warm) can be determined (Fig. 14). The dividing of ice into layers is hypothetical in our case, taking into account usual weather conditions. The proportion of snow ice to total ice thickness was 0 in November, 0.07 in December, 0.25 in January, 0.35 in February, 0.28 in March and 0.06 in April (Reinart, 2000).

The transmittance *T* of the photosynthetically active radiation (PAR, 400–700 nm) is calculated as the ratio of irradiances under and below the snow-ice cover. Higher *T* values are related to the lack of snow and thin ice cover (**FIG.**

VII). When the thickness of the ice and snow cover increases, light transmission declines (from Nov. to Feb.). If snow starts to melt, the scattering decreases and the transmittance increases until the snow is gone (March, April). From January to March, the losses of incident light are mostly caused by attenuation in thick snow (40–60%). The attenuation of light in ice with average ice conditions varies from 4% in December to about 26% in March. In warm winters *T* values are around 10% during the whole period of ice cover, while in cold winters only less than 0.1% from incident PAR is transmitted through the ice and snow cover. Consequently, the reflection conditions and thickness of snow are the most important factors influencing the transmission of PAR through the ice cover.

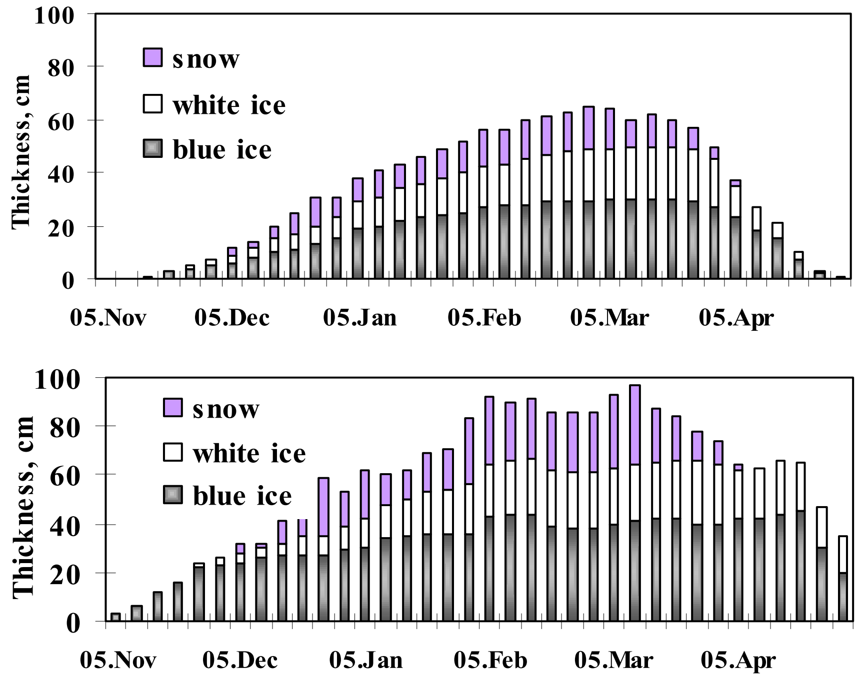


Figure 14. Change in ice and snow cover thickness during an average (*above*) and very cold winter (*below*).

Incident PAR increases from December to April, but because of the properties of the ice cover, minimal values of under-ice PAR occur in February and March (**FIG. VII**). The low values of irradiance under the ice from December to February are caused not only by low incident irradiance, but also by the greater albedo of snow than that of bare ice. Very low values of PAR under the ice in February and March even in average winters are caused by the small transmittance of the snow-ice cover.

4.3. Changes in lake morphometry

To calculate a change in lake morphometry the lake volume, lake area, and average depth were determined at maximum ice thickness, which corresponds with the wintertime minimum water level. On the basis of hydrological characteristics it is possible to explain the wintertime ecological conditions of the lake by active volume, and corresponding mean depth. In calculating active volume, the ice volume is subtracted from the total volume, as the volume of ice is actually temporary unused water or dead volume for the ecosystems. Using active volume in characterising a winter period offers the possibility to calculate the morphometrical and water retention characteristics of the lake, which depend on volume, and in wintertime only active volume (Fig. 15). This figure illustrates the relatively constant ice cover thickness on the lake morphometry in different water level conditions.

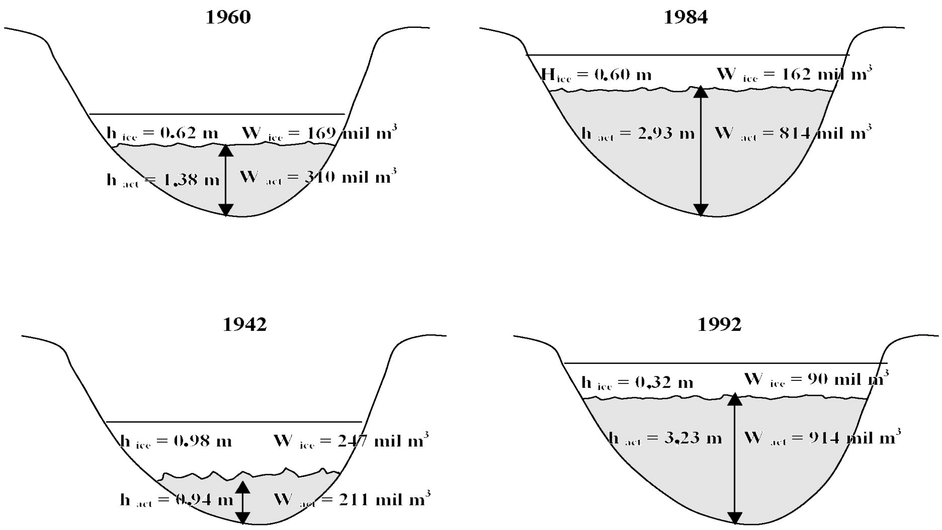


Figure 15. The examples of impact of ice cover on the morphometric characteristics of L. Võrtsjärv in extreme hydrological situations. *Left side* — dry years, *right side* — wet years.

For purposes of comparison, the characteristics of the lake volume in March are estimated for every winter since 1924/25 (Fig. 16). March is chosen for characterising winter months, as ice cover reaches the maximum thickness, on the average, on 10 March, and in a normal year the minimum winter water level is also observed in March (the second decade), directly before the beginning of the spring snow melting period.

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 was 138.4 mil. m^3, which constitutes 20.2% of the lake's total volume in the period of maximum ice thickness. Thus almost 1/5 of the total water mass is in a frozen state 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 0.893 km^3, but in 1942 it was only 0.459 km^3 — a difference of 0.434 km^3 or 1.95 times. The calculated active mean depth was 2.97 and 0.94 m respectively.

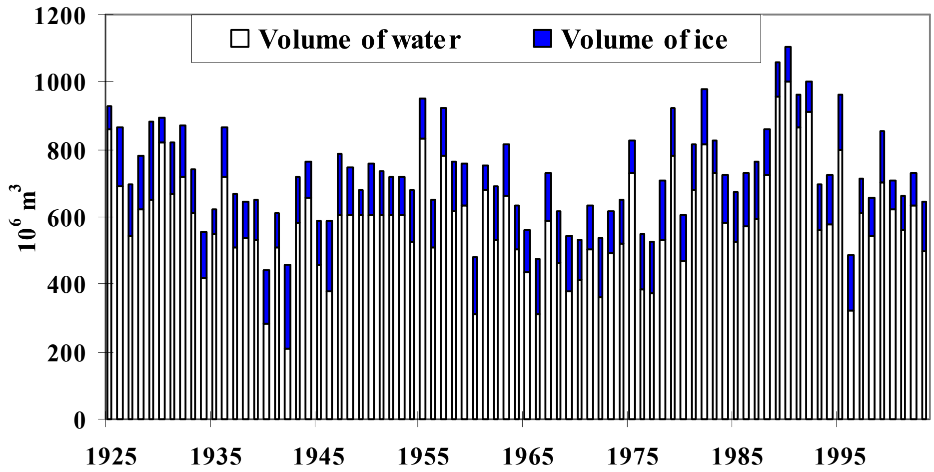


Figure 16. Long-term changes in annual maximum ice volume and corresponding active volume of Lake Võrtsjärv.

4.4. Changes in oxygen conditions

The winter conditions of a lake, especially the oxygen amount and concentration in water, depend on the duration of ice cover and the thickness of ice and snow. The worst ecological conditions at L. Võrtsjärv occurred in a winter period with low water level (monthly mean below 33.00) accompanied by thick ice cover (> 50 cm) of long duration (> 130 days), as represented in Figure 17 about the relationship between O_2 concentration and ice cover parameters. In the event of ice cover duration over 130 days, the O_2 concentration in the bottom layer was lower than 3 mg/l. The dissolved oxygen content in winter at ice thickness over 60 cm also did not generally exceed 3 mg/l, which is the value for the critical level. The active volume and mean depth of the lake are smallest in the case of a low water level (monthly mean level in March below 33.00) and thick ice cover in winters, which at the end of winter may cause a reduction in oxygen content below the critical point (< 2 mg/l).

It is assumed that ice cover parameters are correlated with oxygen conditions in the winter. All of them are statistically significant at $p < 0.05$ confidence level. Higher correlation is observed for O_2 content in the bottom layer (Table 11) than in the surface part. At the bottom the concentrations of O_2 were always lower than that measured in the upper layers. This can be explained by the fact that the depletion of O_2 is often observed for bottom sediment oxidation, and in March the surface layer is sometimes characterised by photosynthetical aeration — algal activity just under the ice.

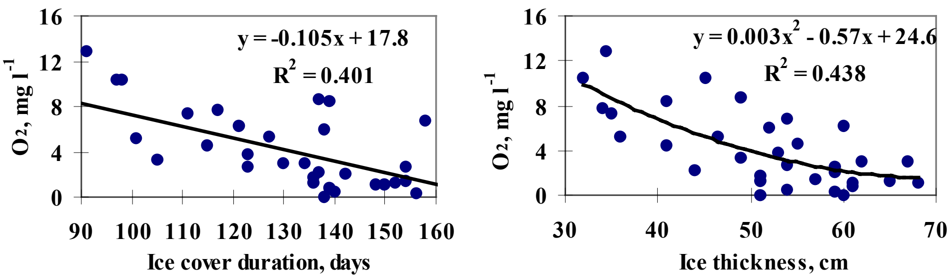


Figure 17. The correlation between ice cover characteristics and wintertime minimum dissolved O_2 content (mg l^{-1}) in water: *left side* — duration (days), *right side* — thickness (cm).

Table 11. Regression equations relating ice cover duration (days) and maximum ice thickness (cm) to minimum O_2 concentration (mg/l) in water (n = 28).

x-variable	Equation	R^2	*p*
	Surface layer		
Ice cover duration	y = –0.06 x + 17.67	0.366	0.055
Ice thickness	y = –0.15 x + 16.91	0.417	0.027
	Bottom layer		
Ice cover duration	y = –0.10 x +16.76	0.486	0.009
Ice thickness	y = –0.21 x + 15.22	0.533	0.003

Very low oxygen concentration in L. Võrtsjärv in the winter of 1996 can be explained precisely by the low water level and large amount of ice (31.5% of the 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 was cold and the lake was covered by thick ice (0.64 m); at the beginning of March the thickness of snow cover was recorded at 0.41 m.

In the event of the coincidence of low water level and severe winter, serious fish kills may occur in L. Võrtsjärv. Thus in the early spring of 1996, when the water level was only 0.5 m above its absolute minimum and after an extraordinarily cold winter, the southern and southwestern shallow parts of the lake were frozen down to the bottom. The lake was covered with thick ice (0.6 m) and snow (0.3 m), and the lowest oxygen concentration (2.3 mg l^{-1} just below the ice, 0.4 mg l^{-1} in the bottom layer) during the 30 years examined was registered (Nõges & Nõges, 1998). As a result of this extreme disaster, about 20 t of hibernating eels was killed in the very shallow southern basin of lake. Other more or less active fish were able to escape in time and survived.

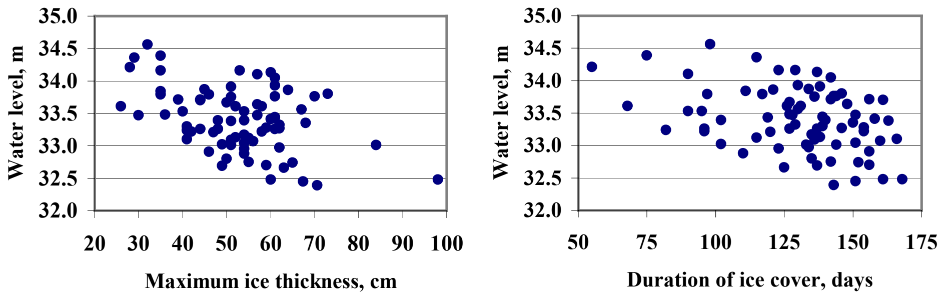


Figure 18. Correlation between minimum water level in winter and maximum ice thickness (*left side*) and ice cover duration (*right side*).

In the following winter conditions the harmful influence of the above-mentioned hydrological factors begins to influence the criteria connected with ice cover and water level, which can be determined as follows:

- long ice cover period — over 150 days;
- thick ice cover — over 60 cm;
- small depth of lake — the mean water level in February and March is less than 33.00 above sea level.

5. POLLUTION LOAD

By most of the trophic characteristics (PP, Chl *a*, nutrient concentrations) Lake Võrtsjärv can be regarded as eutrophic, but, according to Secchi depth and plankton composition, it falls into the hypertrophic range. High turbidity is caused by sediment resuspension, and permanent mixing increases nutrient turnover by keeping diffusive fluxes in the steep concentration gradient at the sediment-water interface high (Nõges *et al*, 1998). In addition to nutrient availability and the associated trophic state, the functioning of lake ecosystems is controlled by the quantity and periodicity of the water resource, independent of lake morphometry, climate, and basin management (Coops *et al*, 2003).

Due to the shallowness and the large wind-exposed area L. Võrtsjärv is unstratified and turbid – Secchi depth from 0.5 to 1.0 m during the ice-free period. According to the mean concentrations of total nitrogen (2 mg l^{-1}) and total phosphorous (about 50 µg l^{-1}) the lake is regarded as eutrophic. In turbid water, phytoplankton growth is limited mainly by light (Nõges & Järvet, 1995). Annual primary production was 224 g C m^{-2} in 1995.

5.1. Changes of nutrient concentrations

Nitrogen export from agricultural areas and phosphorus load of wastewater outlets of small towns and food processing enterprises were major problems in the eutrophication of waterbodies of the catchment area of Lake Vőrtsjärv. A decrease in both nitrogen and phosphorous annual mean concentration and discharge was observed in the study area (whole catchment of Lake Võrtsjärv) during the period 1980–2002 (Fig. 19, Table 12). This decrease was significant for all the concentrations (p<0.05). The most remarkable trend was found for ammonium nitrogen – diminishing from 0.86 mgN l^{-1} in 1980 to 0.04 mgN l^{-1} in 2002.

Table 12. Statistics of the temporal trend for annual mean flow-weighted concentration of BOD_5 and nutrients (mg l^{-1}) in the total inflow of Lake Võrtsjärv in 1980–2002.

Characteristics	BOD_5	NH_4-N	NO_3-N	TIN	N_{tot}	PO_4-P	P_{tot}
Average	2.8	0.44	1.92	2.37	3.51	0.066	0.098
±StDev	1.3	0.37	0.93	1.05	1.70	0.034	0.039
Min	1.4	0.05	0.94	1.03	1.34	0.026	0.052
Max	6.6	1.41	4.48	4.92	7.58	0.176	0.223
Start-concentration*	4.4	0.86	2.69	3.55	5.35	0.104	0.137
End-concentration*	1.2	0.04	1.15	1.18	1.91	0.029	0.058
Change in trend	3.2	0.82	1.54	2.39	3.44	0.075	0.079
p-value	*0.05*	*<0.01*	*0.04*	*<0.01*	*<0.01*	*<0.01*	*<0.01*

**Start- and end-concentrations according to trendline.*

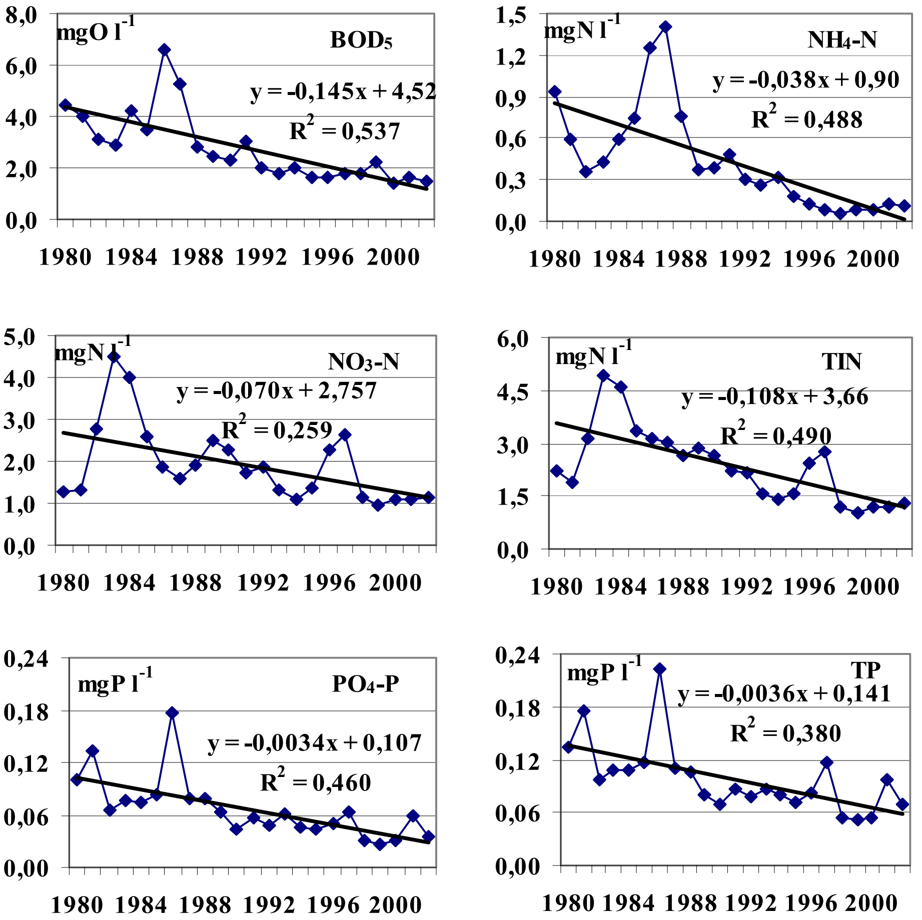


Figure 19. Variation of annual mean concentration (mg l^{-1}) of BOD_5 and nutrients in the rivers of the Lake Võrtsjärv catchment (external load of L. Võrtsjärv) in 1980–2002.

Changes in nutrient concentrations during the period 1980–2002 are most probably related to a decline in fertilization and animal husbandry. It can be assumed that leaching of ammonium and nitrate nitrogen from agriculture was the main source of inorganic nitrogen in the studied rivers. During the period 1980–2002, the percentage of arable lands in the studied area decreased from 42% to 32%. The intensive fertilization that was practiced up to the end of the 1980s (120 kg N, 50 kg P, and 80 kg K ha^{-1} yr^{-1} on arable lands and cultivated grasslands) resulted in the highest leaching of nutrients in the second half of the 1980s. The decrease in mineral fertilizer usage started in 1988 and continued until 1997–1998. Compared to the level at the end of 1980s, only 5–10% of the N, P and K mineral fertilizers and 30% of the manure were applied to agricultural lands at the end of the 1990s.

To analyse temporal changes of the studied trends, the whole research period was divided into 2 equal parts: (1) 1980–1991 and (2) 1992–2002. When comparing the two periods, we can see a significant difference in nutrient concentrations: the concentration of N-compounds has decreased by a factor of 2 and the concentration of P-compounds by 30–50% (Fig. 20).

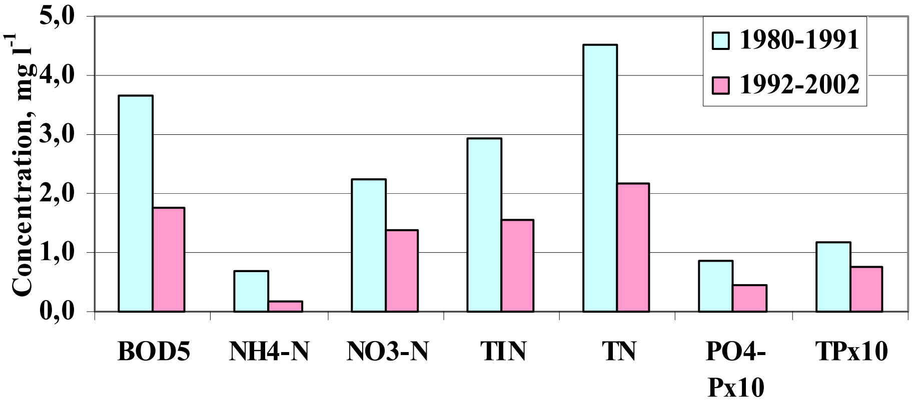


Figure 20. A comparison of mean annual concentrations of BOD_5 and nutrients in 1980–1991 and 1992–2002 (mg l^{-1}, PO_4-P and TP x 10mg l^{-1}).

Nutrient losses from the whole catchment area of Lake Võrtsjärv in the last decade were extremely low in comparison with the results recorded in the 1980s, when mean annual losses were 12.5 kg ha^{-1} yr^{-1} and 3.11 kg ha^{-1} yr^{-1} for total nitrogen and total phosphorous, respectively. The strongest indications of falling trends in concentrations and riverine loads of nitrogen (TIN and TN) were found in the agriculturally dominated Väike-Emajõgi and Tänassilma river basins (Fig. 21; **FIG. VIII**).

The fall in phosphorus runoff in the studied rivers was rather different (Table 13). This is a result of higher wastewater pollution load and intensive animal breeding in the Tänassilma and Tarvastu river basins. However, the phosphorous runoff from the Tarvastu River basin was significantly higher in the period from 1987–1991 and dropped at the end of the 1990s to the mean level (PO_4–P 0.045 mg $l^{-1}$and Ptot 0.076 mg l^{-1}) for the whole Lake Võrtsjärv catchment area (**FIG. IX**). Four main inflows, the rivers Väike Emajõgi, Õhne, Tarvastu and Tänassilma made up 70–75% of the water discharge into the lake, and 80–85% of the total load of monitored substances. Difference was mainly due to the large nutrient runoff into the Tänassilma River. The phosphorous pollution originated mainly from the urban sewage of the town of Viljandi and from the Viiratsi pig-breeding farm, which spread slurry on the fields all the year round. The Õhne River was the cleanest of the large inflows into Lake Võrtsjärv. Its role in the budget of all substances was less significant than its proportion in the water discharge.

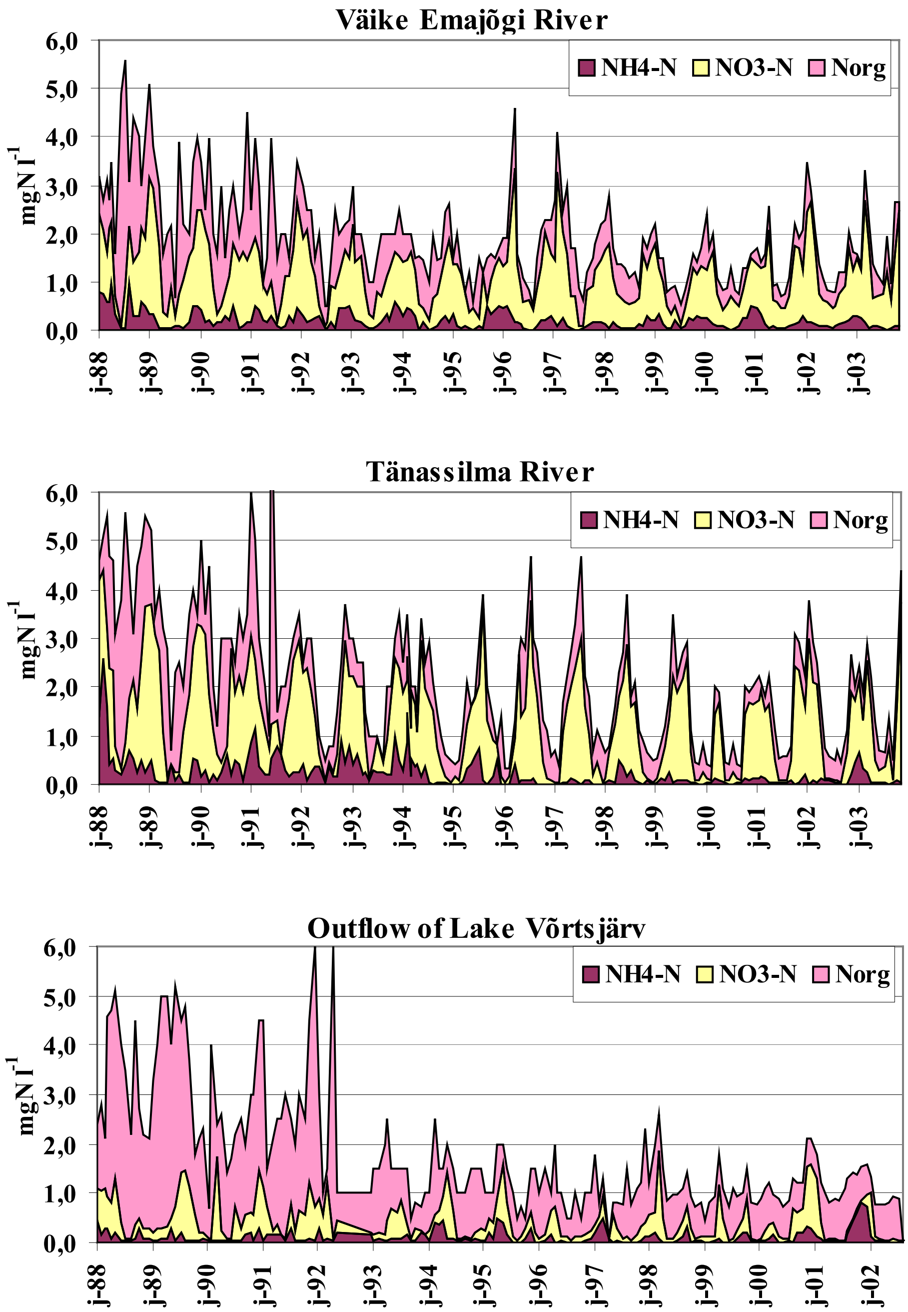


Figure 21. Dynamics of concentrations of nitrogen in main inflowing rivers and outflow of Lake Võrtsjärv in 1988–2002 (mgN l^{-1}).

Table 13. Comparison of runoff and nutrient flow-weighted mean concentrations (mg l^{-1}) of main rivers in the Lake Võrtsjärv catchment area during 1980–2002.

River, Period	Specific runoff, l s^{-1} km^{-2}	BOD_5	NH_4-N	NO_3-N	TIN	TN	PO_4–P	TP
Väike Emajõgi								
1980–1991	8.89	2.9	0.55	1.83	2.40	3.51	0.074	0.110
1992–2002	8.05	2.2	0.19	1.15	1.35	2.04	0.048	0.079
Decrease, mg l^{-1}	0.84	0.7	0.36	0.69	1.05	1.47	0.027	0.031
Decrease, %	9	24	65	37	44	42	36	28
Õhne								
1980–1991	10.45	2.6	0.44	1.30	1.75	2.79	0.041	0.058
1992–2002	9.78	1.6	0.14	1.16	1.29	1.95	0.030	0.057
Decrease, mg l^{-1}	0.67	1.0	0.30	0.15	0.45	0.83	0.011	0.001
Decrease, %	6	37	69	11	26	30	26	1
Tarvastu								
1980–1991	9.84	5.1	0.62	2.81	3.45	4.40	0.101	0.138
1992–2002	7.87	2.1	0.18	2.07	2.34	3.10	0.043	0.073
Decrease, mg l^{-1}	1.97	3.0	0.44	0.75	1.12	1.30	0.058	0.065
Decrease, %	20	59	71	27	32	30	58	47
Tänassilma								
1980–1991	10.68	3.2	0.67	2.31	2.99	4.21	0.112	0.158
1992–2002	8.36	1.9	0.21	1.24	1.46	2.17	0.069	0.095
Decrease, mg l^{-1}	2.32	1.2	0.46	1.06	1.53	2.04	0.044	0.063
Decrease, %	22	39	69	46	51	48	39	40
Total catchment								
1980–1991	8.96	3.6	0.69	2.52	3.23	4.98	0.087	0.119
1992–2002	8.07	1.9	0.20	1.54	1.75	2.50	0.045	0.076
Decrease, mg l^{-1}	0.89	1.7	0.49	0.98	1.47	2.49	0.042	0.043
Decrease, %	10	47	71	39	46	50	48	36

In comparison with earlier years, the water quality of the rivers has improved. According to the proposed classification of Estonian river water quality, about 70% of the water samples analysed in the last five years were found to be in class II, *i.e.* the water quality in these river profiles was “good”. About 20% of samples were found to be in class III, which indicates “fair chemical status”, and only 10% (Tänassilma River) were in class IV, which represents “poor chemical status”.

5.2. Changes in riverine discharge

Lake Võrtsjärv is a highly eutrophic lake, receiving nutrients from the catchment area, mainly via four main rivers. The nutrient transport of each river reflects specific land use activities (including point and nonpoint pollution) within the catchment, and, moreover, meteorological and hydrological conditions and biogeochemical processes in the soil, sediment and surface water. The seasonal dynamics of the nutrient load from the watershed depended on the dynamics of the hydrological load to a greater extent than on the changes in nutrient concentrations in the inflowing water. Significant changes in land-use and agricultural practice have been observed. Statistical analysis has indicated that annual runoff has remained almost unchanged, however, the maximum and minimum discharges have changed significantly in 1980–2002 (Järvet *et al*, 1998).

To facilitate interpretation of temporal changes in riverine loads of nutrients we calculated flow-normalised loads. For each river basin we calculated flow-weighted mean annual concentrations by the following equation:

$$c_{mean} = \frac{(Q_1 * k_1 + Q_2 * k_2 + \ldots Q_n * k_n)}{(Q_1 + Q_2 \ldots + Q_n)}$$

where k_1, k_2 and k_n denote the concentrations of sampling days and Q_1, Q_2, and Q_n denote daily flow. Annual load L is calculated by multiplying c_{mean} with total annual flow

$$L = (\Sigma Q) * c_{mean}$$

In addition to the change of land use pattern and fertilization intensity, variation in hydrological conditions plays an important role in nutrient and organic matter runoff from rural catchments. However, this influence varies for different nutrients. For instance, on the studied catchments, the annual runoff correlated positively with BOD_5, NO_3–N and TIN ($p < 0.01$), but there was no statistically significant correlation between stream discharge and NH_4–N and PO_4–P transport. Multiple regression analysis showed that the most important factor characterising the nitrogen runoff in the studied catchments was the rate of fertilisation (Järvet *et al*, 2002). Also, the complex land use factor correlated significantly with both N and P runoff.

When comparing the load of two periods, we can see a significant difference in total amount of nutrients transported by rivers from the Lake Võrtsjärv catchment. The results of calculations show that the mean annual runoff of NH_4–N, NO_3–N, TIN, TN, PO_4–P and TP in 1992–2002 was 35–71% smaller than during the period 1980–1991. At same time, no significant trends in the water discharge of the main rivers – Väike Emajõgi and Õhne rivers were observed (Fig. 22); the differences of the average annual specific runoff of the 2 periods exceed 0.84 and 0.67 $l\ s^{-1}\ km^{-2}$, respectively. Annual mean specific runoff for the whole catchment of Lake Võrtsjärv by calculated linear trend diminished from 1981 to 2000 by only 0.45 l s^{-1} km^{-2}, although the difference between the two compared decades exceeds 0.89 l s^{-1} km^{-2} or 10%.

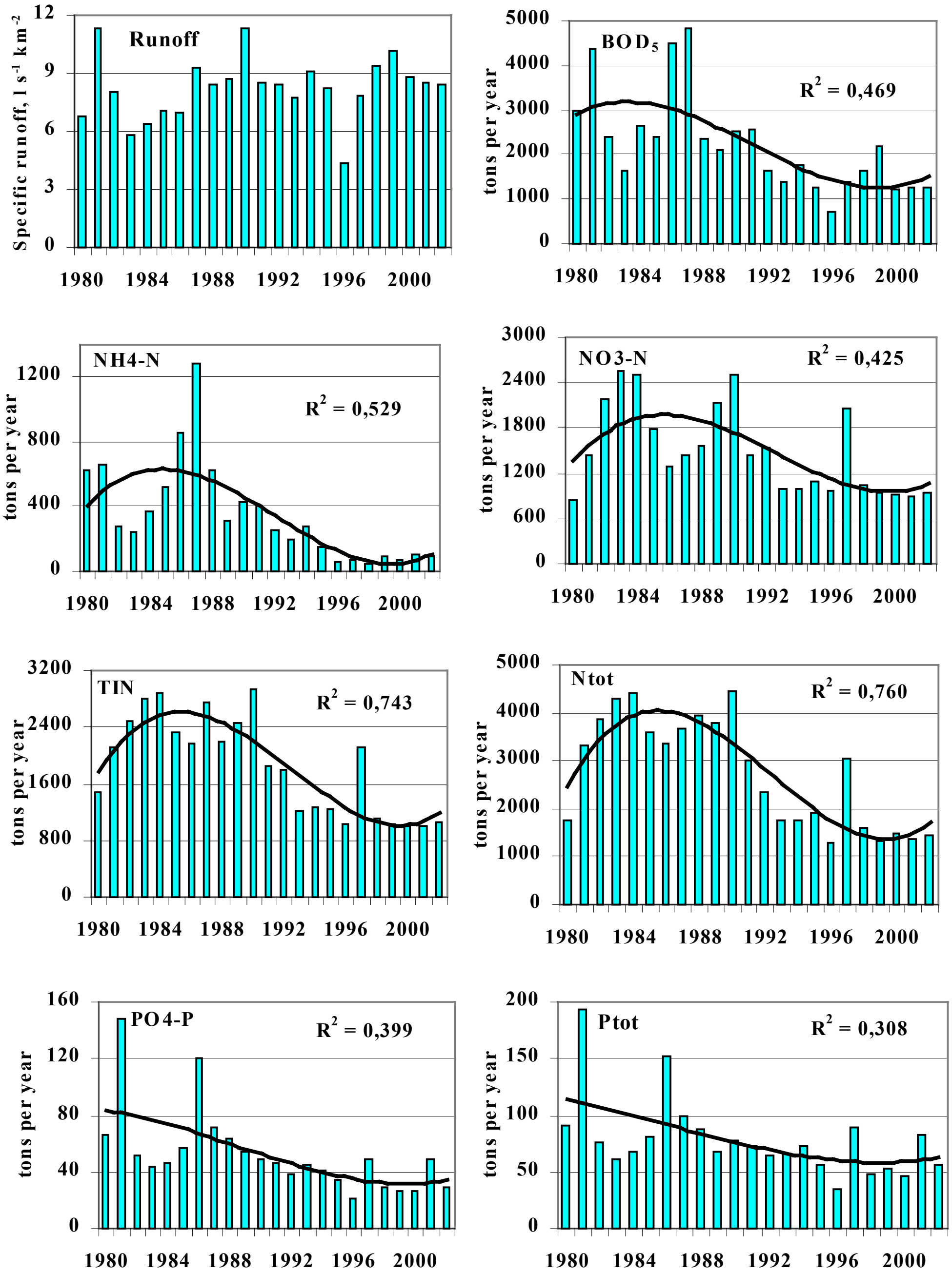


Figure 22. Change in total annual runoff of nutrients (tons yr^{-1}) in the whole Lake Võrtsjärv catchment area in 1981–2002.

5.3. External load of Lake Võrtsjärv

Measurements of the nutrient load at sufficiently close intervals of time to serve as a reliable base of estimation were started in 1980. Considering the entire lake, most of the substances were discharged through the tributaries; the pollution originating from the atmosphere was small. The results of upward fluxes of nutrients, calculated as the sums of net budgets and trap catches are presented in Nõges *et al*, 1998, and are not analysed in this work. The existing data allowed the calculation of correct internal net budgets only for 1991 and 1995–1996.

5.3.1. External budget of substances

Lake Võrtsjärv as a large waterbody exerts an essential influence on the matter circulation of the landscape. The substances carried along with runoff waters from the drainage area or precipitated or washed out from the atmosphere are, to a greater or lesser extent, involved in the internal metabolism of the lake. Some of them accumulate in sediments, others are released in gaseous form, while the remainder pass through the lake and exit through the outflow. Most of the interannual variation in the input of nutrients to the lake seems to be related to natural changes in runoff.

The external budget (EB) showing the retention (sedimentation, transformation, denitrification) was calculated as the difference in the input-output fluxes:

$$EB = L_{in} - L_{out}$$

where L_{in} – external (riverine + atmospheric) loading,
L_{out} – outflow.

The atmospheric loading was taken into account only for NH_4–N, NO_3–N and PO_4–P by applying the results of environmental monitoring measurements in Lahemaa National Park (N-Estonia).

It should be mentioned that the monthly mean upward fluxes of nutrients increased gradually together with the decrease in the mean depth of the lake. The variables selected by regression procedure demonstrated that wind-induced sediment resuspension plays the major role in the formation of nutrient upward flux and thus in the formation of the temporal pattern of nutrients during the ice-free season. Other fluxes, such as the external loading or new sedimentation of autochthonous production, are overcome and masked by the powerful resuspension – sedimentation cycle, exceeding the former by one or two orders of magnitude (Nõges *et al*, 1998). In general, the internal net budgets of substances had large fluctuation amplitudes exceeding the ranges of external budgets by a factor of 3–10. The seasonal dynamics of internal net budgets were determined, to within 88–99%, by the dynamics of internal budgets (Nõges & Järvet, 1998).

External budget (Σ outflux – Σ influx) corresponds to the "black box" concept and demonstrates the influence of the lake on the quality of the water coming from the drainage area. Negative values express the retention of substances, which is reflected in a smaller outflux in comparison with the influx. Positive values express the apparent addition of substances to the water during its passage through the lake.

Nutrients

Nutrient cycles through production and destruction processes play a substantial role in the functioning of water ecosystems. Besides BOD_5 and particulate matter, nutrients (N and P) were most affected by the lake. In comparison with the influx, a distinct decrease in the mineral forms of nutrients was revealed in the outflow (Table 14). Since Lake Võrtsjärv is an efficient nutrient trap, most of the incoming inorganic N and P load from the drainage basin was reduced during transport through the lake (Fig. 23; Table 14).

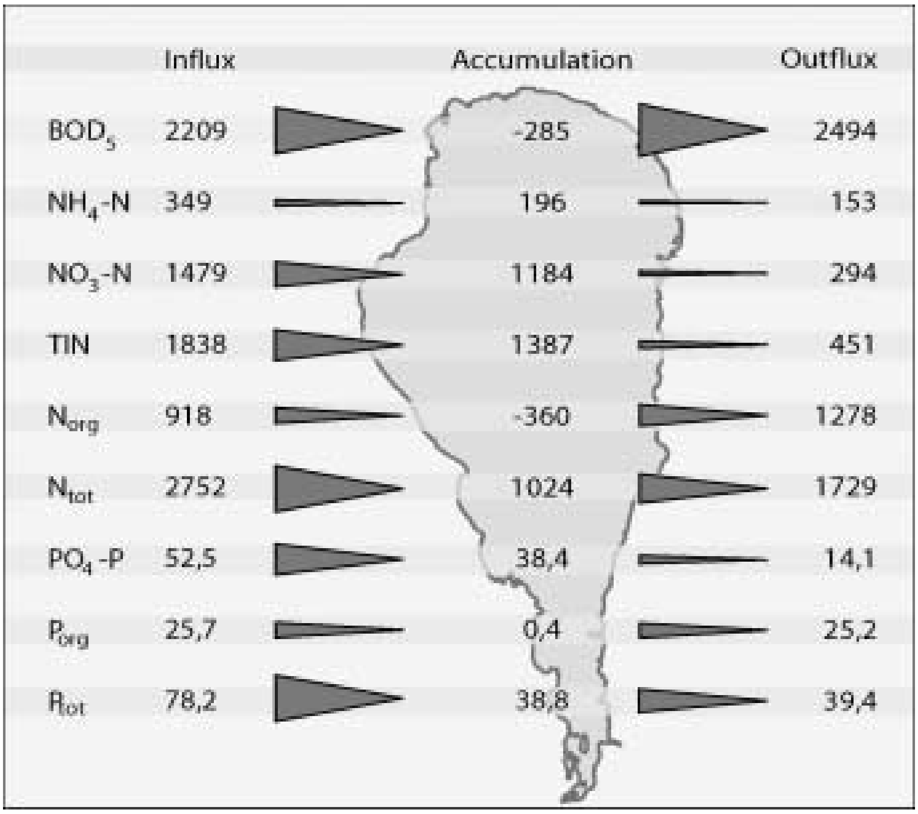


Figure 23. External budget of BOD_5 and nutrients for Lake Võrtsjärv (annual average for 1988–2002).

Annually 2752 tons (10.2 g m^{-2}) of total nitrogen entered the lake, both from the watershed and by direct atmospheric precipitation. Two thirds of this loading was in dissolved inorganic form (TIN). Atmospheric input formed 11 % of TIN and 7 % of the total nitrogen loading. The annual outflow of Ntot was 1729 t and only 26% of that was contributed by TIN. As nitrogen of the organic compounds forms the major part of the difference TN - TIN, it was conventionally named organic nitrogen (N_{org}). The annual loss of TIN was 76 %. The relatively smaller decrease in TN was the result of the high N:P ratio of the inflowing water, which exceeded several times the optimal level for biological requirements. The retention of NH_4^+–N and NO_3^-–N, as the main forms of TIN, was almost proportional, forming 56% and 80%, respectively, though the absolute decrease of nitrates exceeded that of ammonium by a factor of 6. At the same time the amount of N_{org} increased by 39% from 918 to 1278 t.

In the annual phosphorus loading (78 t or 0.30 g m^{-2}), 67 % was accounted for by soluble reactive phosphorus expressed by PO_4 and 33 % by organic phosphorus (P_{org}, calculated as TP - PO_4–P). The atmospheric loading of P (only PO_4 data was available) formed 10 % of the inorganic phosphorus and 7 % of the TP input. The annual decrease of PO_4, forming 67 % of the loading, was mostly accounted for by transformation of soluble reactive phosphorus into organic P. In some years (1999, 2002) the outflow of TP exceeded the inflow (largest negative retention -31 % was calculated for 2002). Partially the retention ability of the lake in certain years was underestimated (in 1988, 1991–1992) or overestimated (in 1989, 1990, 1996) due to the unbalanced water budget, as the volume of the lake in the beginning of the year was remarkably smaller or larger than at the end. If the external budget showed a continuous retention of phosphates in the lake, the internal net budget revealed several periods with prevailing internal phosphorus loading (March, July, December). These periods were followed by phosphate consumption and the precipitation of organic phosphorus (Nõges & Järvet, 1998). As a result of the decrease in the external load of phosphorus and nitrogen compounds since the beginning of the 1990s, the concentrations of all nitrogen and phosphate forms, but not of TP, have decreased (**FIG. IX**) in the outflow. The mean concentration of total phosphorus in the outflow (0.043 ±0.026 mg l^{-1}) has been seasonally and annually quite stable (Fig. 24).

Nutrients were accumulated during the phase of lake volume increase from January to May and predominantly flushed out from June onwards. The outflow exceeded the load for the shortest time in the case of TIN (June, July). The external budgets of TN, TP and PO_4–P were negative from June till October, while N_{org} and P_{org} were predominantly being flushed from the lake until the end of the year. During low flow periods in dry summers, most of the rivers switched over to groundwater feeding. This reduced drastically the nutrient inflow in August and September. In the late autumn rainfalls and the increased surface runoff made the external budgets of inorganic and total nutrients turn positive again, despite the continuing decrease in lake volume.

Table 14. Annual difference between influx and outflux of BOD and nutrients in L. Võrtsjärv (10^3 kg y^{-1}, runoff 10^6 m^3 y^{-1})

YEAR	RUNOFF	BOD_5	NH_4-N	NO_3-N	TIN	Norg	TN	PO_4-P	Porg	TP
1980	130	2082	415	689	1111	-183	928	50,0	-2,8	47,2
1981	299	1920	483	1358	1847	486	2333	110,9	4,7	115,6
1982	-346	-640	44	1927	1976	-155	1822	33,8	-1,6	32,2
1983	-234	-1015	15	2289	2309	-67	2242	35,2	8,9	44,1
1984	-61	127	207	2365	2579	848	3427	37,3	8,2	45,5
1985	-71	-86	247	1704	1959	251	2210	37,8	-10,1	27,7
1986	-130	1630	598	680	1288	-1421	-133	107,7	8,9	116,6
1987	-30	2741	497	648	1151	-1174	-25	58,7	-1,7	57,0
1988	-119	-633	463	1144	1613	-781	834	48,4	4,6	53,0
1989	-130	-1769	240	1535	1782	-1049	733	28,0	2,7	30,6
1990	66	-514	293	1948	2250	-879	1370	35,6	9,9	45,5
1991	-260	-772	288	852	1149	-1382	-304	33,0	2,8	35,8
1992	-107	-1038	153	1255	1411	-134	1276	29,2	-5,2	24,0
1993	56	-697	101	815	920	-149	771	28,6	5,0	33,6
1994	131	-304	177	762	946	-60	885	28,8	12,7	41,5
1995	-86	-1730	118	856	981	101	1082	27,7	-21,6	6,1
1996	33	-449	4	818	833	-97	732	16,4	-7,7	8,8
1997	143	-593	44	1756	1807	412	2219	45,2	21,1	66,3
1998	112	-847	-1	878	885	-152	734	25,6	-15,4	10,2
1999	-57	-888	60	654	718	-456	263	-11,1	9,9	-1,2
2000	164	-1233	21	803	832	6	838	19,9	-5,7	14,2
2001	168	-741	64	769	840	-476	715	41	-19	56
2002	-56	-1110	-30	737	709	-2517	-1409	15	-60	-17
Mean	-17	-285	196	1184	1387	-392	1024	38	-2	39

5.3.2. Changes in nutrient loading

The annual mean nutrient input to L. Võrtsjärv is calculated as 10.2 g m^{-2} y^{-1} TN, 6.8 g m^{-2} y^{-1} TIN and 0.29 g m^{-2} y^{-1} TP and 0.19 g m^{-2} y^{-1} PO_4–P (Fig. 23). These loading figures can be considered rather low. The mean nitrogen load for 69 shallow Danish lakes was 142 g m^{-2} y^{-1} (median 52). Annual TP loadings reaching several grams per square meter have been reported for several German, Polish and Russian lakes (Nõges *et al*, 1998).

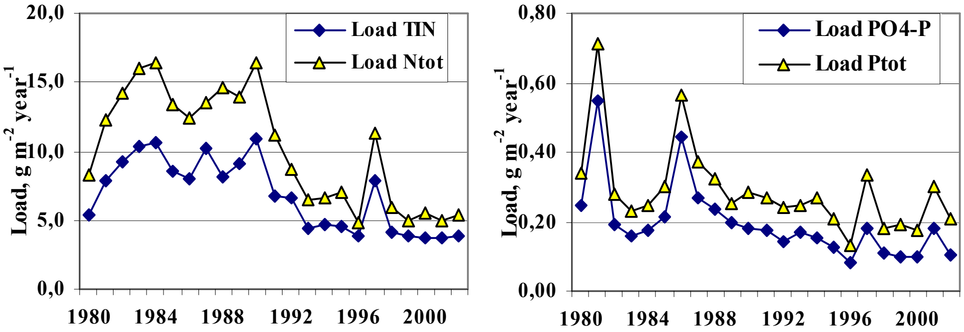


Figure 23. Changes in long-term nutrient loads on the Lake Võrtsjärv surface. All annual loads were calculated according to lake surface area 270 km^2.

The loading on L. Võrtsjärv is small due to the large area and long residence time of water, but still exceeds the transition range between oligo- and eutrophic conditions (0.056...0.112 g m^{-2} y^{-1} TP) calculated according to Vollenweider (1976). The annual water discharge correlated positively with runoff of BOD_5, NO_3–N and TIN ($p<0.05$), but there was no statistically significant correlation between stream discharge and NH_4–N and PO_4–P transport for monthly time series. As TN loading decreased faster than TP loading, the TN/TP ratio in the loadings decreased.

It is remarkable that the concentrations of TN and TP in the lake water depend more on the loadings of NO_3–N and PO_4–P than on the total loadings of these elements. Obviously, a substantial proportion of TN and TP in the riverine discharge is in particulate form that settles to the bottom near the rivers mouth as the flow rate decreases and does not actively participate in the nutrient cycle. Examination of long-term trends in nutrient loads in individual rivers confirmed that, at most of the investigated sites, since 1991–1992 a natural variation in runoff was the main cause of interannual variation in riverine loads of nutrients.

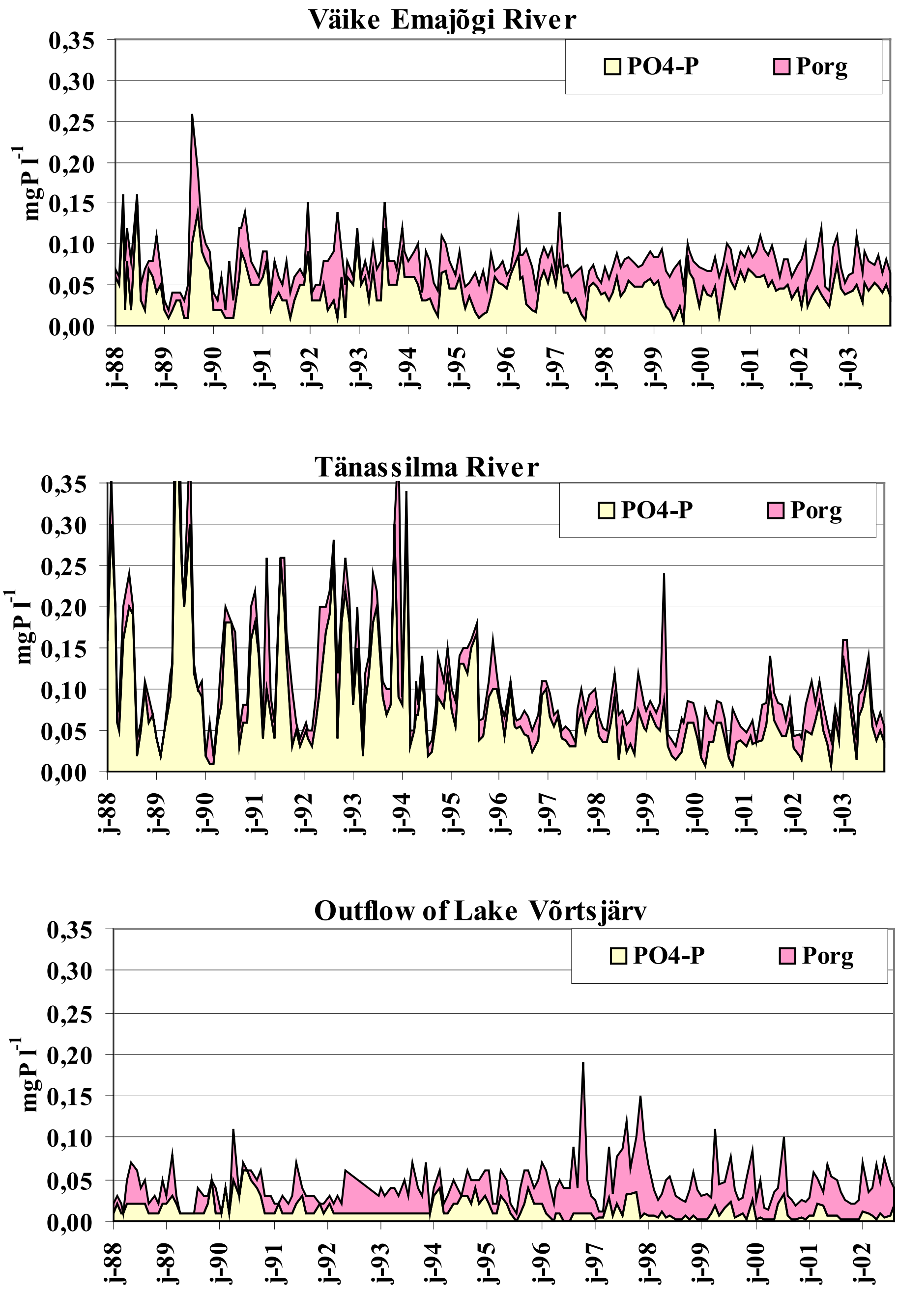


Figure 24. Dynamics of concentration of phosphorus in main inflowing rivers and outflow of Lake Võrtsjärv in 1988–2002 (mgP l^{-1}).

N/P ratio

Some authors (Forsberg, 1979; Uhlmann, 1982) have confirmed many years ago that the elementary composition of phytoplankton biomass, both in inland and marine waters, can roughly be approximated by an average atomic ratio of $C_{106} : N_{16} : P_1$. This simple characteristic has proved to be useful in water quality and ecological state assessment. River and lake waters, when they are nonpolluted, are not in biogeochemical equilibrium – the portion of P relative to N and C is normally much lower.

The C: N : P ratio of the dissolved inorganic compounds in the rivers, lakes and reservoirs is also a reflection of the antropogenic influence on the watershed. Both concentration and amount of N and P can normally be attributed to different sources. It is generally agreed that the lakes in a temperate climate are, in their natural condition, most frequently limited in P, and that N becomes the limiting factor as a consequence of a higher pollution level. This is explained by the fact that the N/P ratio in streams is much higher than the ratio in which these two nutrients are required by algae. In wastewater recipients, the proportion of P to N is much higher than in the streams of intensive agricultural land-use catchments.

For management purposes, it seems reasonable to express this deviation by a dimensionless concentration with N-overplus as a multiple and N-deficiency as a fraction of 16. According to Uhlmann (1982), a level of dimensionless concentration of N or TIN higher than P or PO4–P indicates P-limitation ($N/P \geq 1.6$), and a level of N (TIN) lower than P (PO_4–P) indicates N-limitation ($N/P \leq 0.7$). Identification of the critical nutrient element by this simple method is less expensive and can also be performed for water management practice. Thus the significance of point and diffuse loadings may already be indicated by the N : P ratio.

As Fig. 25 illustrates, in the drainage basin of L. Võrtsjärv, the flux of nitrogen (TIN) by the rivers into the lake was normally so high that it caused a nitrogen overplus until 1991. This coincides with a low Ptot and PO_4–P concentration (mainly 0.010–0.030 and 0.030–0.060 mg/l, respectively) in the outflow. It is very probable that phosphorus represented the critical nutrient element until the end of the 1990s. In the case of the eutrophic Lake Võrtsjärv, the curves expressing the annual changes in P and N-concentrations during the last 10–11 years are much closer to each other and nearer to the zone representing a harmonic N : P composition dimensionless concentration = 1. Low N/P ratio loadings would promote the dominance of nitrogen-fixing blue-green algae.

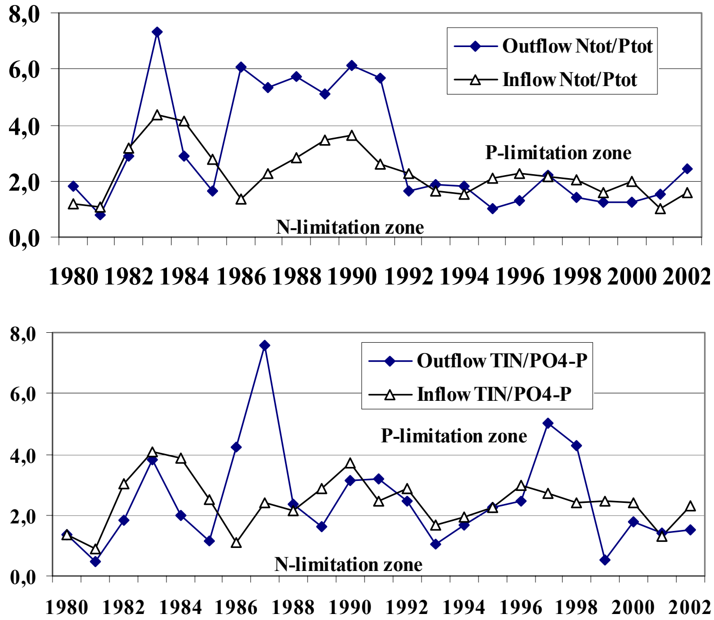


Figure 25. Changes in annual mean dimensionless concentration of total nitrogen *versus* total phosporus (*above*) and total inorganic nitrogen *versus* phosphate phosphorus (*below*) of Lake Võrtsjärv inflow and outflow during the research period: 1980–2002.

Organic matter

Organic matter in the lakes is either of autochthonous or allochthonous origin. The mostly inorganic particulate matter carried along by inflowing rivers as suspended solids precipitates rapidly in the lake as the flow velocity falls. As a result of the high productivity of L.Võrtsjärv, the increase in the amount of particulate matter due to the formation of phyto-, zoo- and bacterioplankton exceeds the losses due to the deposition of inflowing particles. On annual average, by calculations of external budget, the amount of particulate matter increased by 17% and the biochemical oxygen demand (BOD_5) by 48% as water passes through the lake.

BOD_5 at Rannu-Jõesuu station is the highest in summer during the period of intensive photosyntesis, due to the high amount of phytoplankton. Organic matter produced in this highly eutrophic lake is the main factor causing a relatively high biochemical oxygen demand and organic nitrogen and phosphorus concentrations in the R. Emajõgi. As a result of phytoplankton degradation, upstream biochemical oxygen demand in summer-autumn (5–7 mgO_2/l) can be even higher than downstream BOD at Kavastu station, near the Tartu wastewater outlet (Loigu & Leisk, 2001). In general the present level of BOD in most rivers of the L. Võrtsjärv drainage basin is quite low compared to the end of 1980es. The mean value of BOD_5 in the other rivers varied between

1.0–2.0 mgO l^{-1}. Only in the Väike Emajõgi River it was about 2.5 mgO l^{-1} as the mean value of 1992–2002.

Formally, judging by BOD values, the out-flowing water of Lake Võrtsjärv can be classified as highly polluted, however, such estimation is unjustified since organic matter is not derived from pollution but is of autochthonous character. Therefore, the high level of BOD_5 at the Rannu-Jõesuu station does not indicate direct organic pollution. According to other indices, like dissolved oxygen or N- and P-compounds, the upstream of the Emajõgi River can be considered to be among the cleanest of the monitored South-Estonian running water-bodies. The content of inorganic nitrogen and phosphorus at the outlet from L. Võrtsjärv is low because it has been transformed to organic nitrogen and phosphorus during the photosynthetic processes in the lake. Organic nitrogen forms on average 72% of TN, and the content of nitrates is higher only in the spring flood period.

The total content of organic matter is characterized by dichromate oxidizability. In 1995–1996 the dichromate oxygen demand (COD_{Cr}) of the inflow varies mainly from 15 to 40 mgO l^{-1}, and that of the outflow, from 20 to 40 mgO l^{-1}. The seasonal distribution of the riverine COD load (calculated for the year 1995) was characterised by a pronounced peak during the spring floods and a comparatively low concentration in late autumn and winter (Fig. 26). The lowest concentration in rivers is measured in mid-winter. Seasonal variation in COD_{Cr} was relatively well expressed both in inflow and outflow.

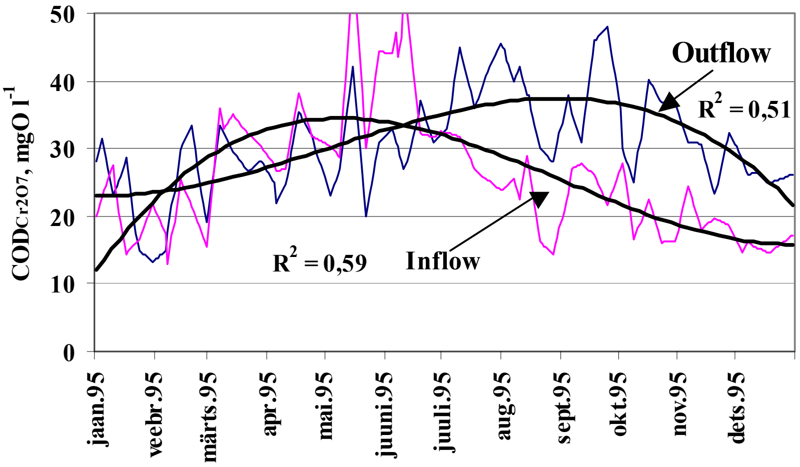


Figure 26. Seasonal variability of COD_{Cr} concentrations in the total inflow and outflow of Lake Võrtsjärv in 1995.

The concentration of COD in inflow is significantly smaller than in outflow in autumn and winter. The lake water is comparatively rich in organic matter from July to November. The seasonal trend in concentration of COD in outflow is consistent with changes in increase of phytoplankton biomass in lake.

6. CLIMATE CHANGE IMPACT

Global climate change due to the increase of greenhouse gas concentration in the atmosphere is a factor expressing the anthropogenic stress on the water environment. The greatest warming is expected to take place in high latitudes. Water resources are very sensitive to climate change, and studies on this topic have been carried out for many regions in Europe. Understanding the sensitivity of water resources is the first and most important step in climate change integrated impact assessment (Fig. 28).

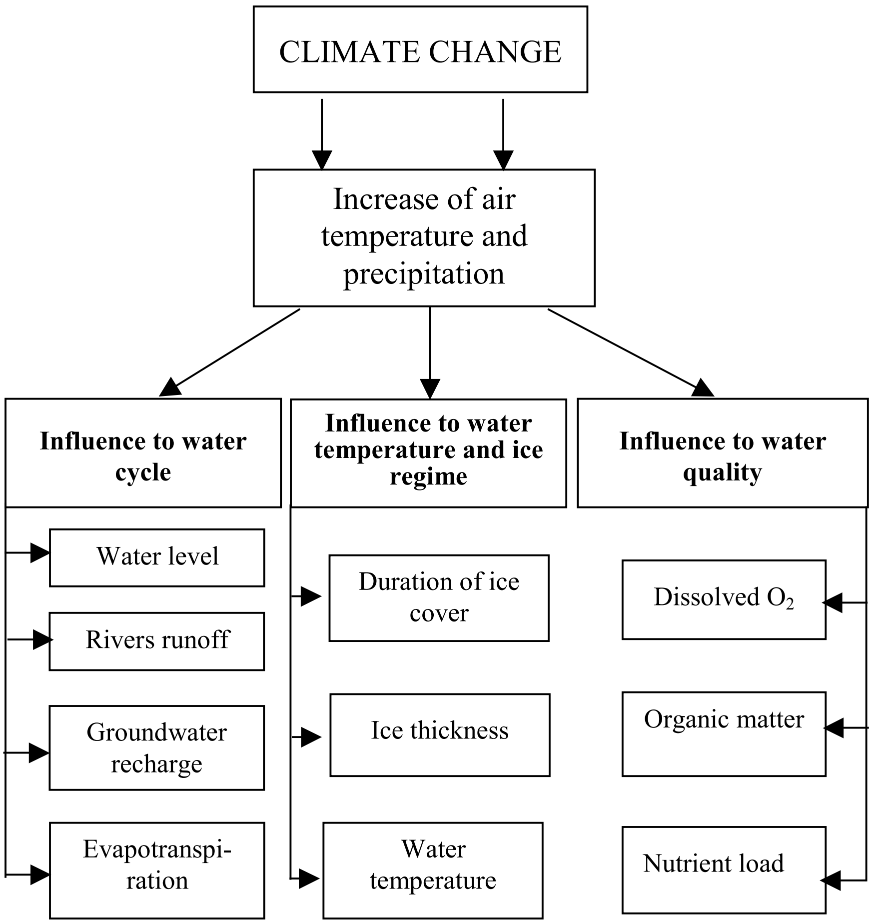


Figure 28. A simplified scheme of climate change impact assessment on the lake and its catchment area in sub-boreal zone.

There are two main study areas concerning investigations of climate change: 1) it is important to analyse the existing time-series of climate and related hydrological variables and to detect possible changes, 2) there is an obvious necessity to develop climate change scenarios for study future climate for vulnerability assessment. Impact research needs to address these problems, including the development of 1) a more physically based understanding of hydrological processes and their interactions, 2) hydrological parameter measurement and estimation techniques for application over a range of spatial and temporal scales, and 3) modular modeling tools to provide a framework to facilitate water management research (Leavesley, 1994).

The first estimations of climate change impact on water resources in Estonia have been obtained within the U.S. Country Studies Program in 1995–96 (Järvet, Jaagus, 1996). From 1996 to 1998 a second national climate change impact assessment was carried out for the Estonian National Policy Plan on the UN Framework Convention on Climate Change (Fig. 29). The study was financed by the UNEP (Järvet *et al*, 2000; Järvet *et al*, 1998), and this dissertation presents the main results connected with rivers in the Lake Võrtsjärv drainage basin.

Figure 29. Location map of climate change study areas (Järvet *et al*, 2000).

6.1. Modelled changes in the annual runoff of rivers

The point model WATBAL is applied to simulate river runoff using a monthly modelling time step. This model — realized as an MS Excel macro — is considered to be a suitable tool for climate change assessments of river basin runoff (Yates & Strzepek, 1994; Yates, 1997). The general calibration and validation of the WATBAL model for Estonia was performed during a first study (Järvet & Jaagus, 1996), while more detailed analysis was presented by (Järvet *et al*., 1998 and Roosaare & Jaagus, 1998).

Using the WATBAL model, changes in river runoff in the case of the four climate change scenarios were calculated for 36 studied river basins including the Väike Emajõgi and Õhne rivers in the Lake Võrtsjärv catchment area (Järvet *et al*, 1998). The modelled changes in the annual mean runoff by different scenarios in Väike Emajõgi River range from 62% to 21% and on the Õhne River from 59 to 19% (Table 15).

Table 15. Hydrologic vulnerability assessment for the Väike-Emajõgi River by different climate change scenarios. Baseline period 1961–1990.

Scenario	Change in precipitation (%)	Change in temperature (°C)	Change in runoff (%)	Runoff coefficient
GISS	35	3.9	68	0.43
GFDL30	24	4.9	45	0.41
CCCM	16	4.1	24	0.37
GFDL transient, 4th decade	5	1.2	8	0.36
GFDL transient, 7th decade	4	3.1	8	0.36
GFDL transient, 10th decade	20	4.3	41	0.41
Incremental	0	4.0	–4	0.34
Incremental	10	4.0	14	0.36
Incremental	20	4.0	33	0.39
Incremental	–10	4.0	–20	0.31
Incremental	–20	4.0	–35	0.28

The model results indicate a substantial variability in the rivers discharge. The GISS model gives the highest increase in precipitation and runoff, while the CCCM gives the lowest mean value. Higher sensitivities of discharge to climate change are observed in the Väike-Emajõgi River and in the whole hydrologically studied area of Estonia. It is necessary to emphasize that according to the transient scenario, the most essential increase in annual runoff would occur during the last quarter of the transient period. The maximum runoff in November would become the highest during the whole year instead of the observed monthly maximum in April. This is caused by the expected increase of precipitation in autumn.

These estimates are made using the Priestly-Taylor method for calculation of potential evapotranspiration. The values obtained by this method are 15–18% lower than the values obtained using the Thorntwaite and the modified Penman methods. The model results using the Thorntwaite method show lesser changes in the rivers discharge. The runoff model results using the Priestly-Taylor method are not sensitive to an increase in temperature and potential evapotranspiration. Changes in runoff depend mainly on the changes in precipitation. The Thorntwaite method, on the contrary, shows very accurately the changes in temperature. The increase in mean temperature of 1°C will cause the decrease in mean annual discharge by 2–4%. The modified Penman method gives intermediate results and some calculated values are presented in Fig. 30.

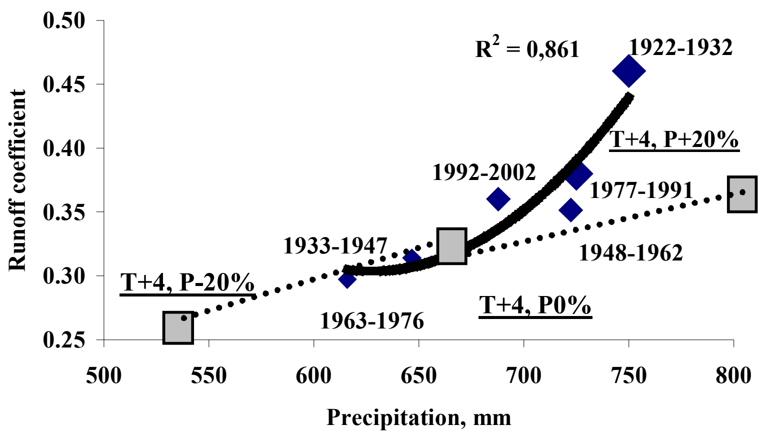


Figure 30. Relationship between precipitation and runoff coefficient on the Väike Emajõgi River basin by the observed and predicted climate change data.

Not only total increase of annual runoff, but also its seasonal distribution, is important. In most of the impact studies, the consequences of the greenhouse effect on runoff are analysed and discussed, while seasonal patterns of runoff have received less attention, especially concerning their regularity. Modelling results demonstrate the possibility of significant changes in the annual course of monthly runoff in the eastern part of Estonia, including the Lake Võrtsjärv catchment area (Fig. 31). Maximum runoff is more sensitive than minimum runoff. The shift of the spring runoff maximum at an earlier time will result in the longer duration of the summer low water period and in the reduction of total runoff during the vegetation period (from April to September) in many river basins of Estonia. The area of increased runoff in summer is located in southeastern Estonia, and that of decreased values covers the rest of the territory.

The most important changes should take place during the cold half of the year. Higher temperature in winter will be caused by increasing cyclonic activity in the Northern Atlantic and by more frequent inflow of warm Atlantic air masses. This will lead to less stable weather in Estonia. Storms and periods of melting will occur more often. As a result, a substantial increase in river runoff in winter is the most general impact of climate warming. Frequent melting periods cause less accumulation of snow during winter. Consequently, the beginning of the snowmelt in spring should shift earlier, and the runoff maximum will be less intensive. The danger of floods will decrease.

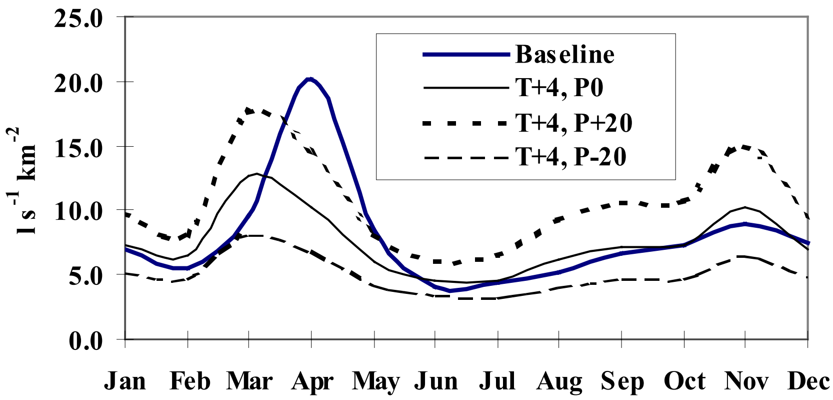


Figure 30. Changes in monthly runoff in Väike Emajõgi River basin by different temperature and precipitation change scenarios.

The increase of river runoff in autumn is directly caused by a significant increase of autumn precipitation predicted by both of the GCM's scenarios. Possible change in annual course of runoff should be more substantial in western part of Estonia, in regions of maritime climate. Instead of two maxima (spring, autumn) and two minima (winter, summer) there will occur only two main hydrological seasons: maximum during the cold half-year (November–April) and minimum during the warm period (May–October). The similar water regime is typical for Western Europe at the present time. In eastern part of Estonia, maximum autumn runoff would not exceed maximum spring runoff. The geographical belt in which the season of maximum runoff moves from spring to autumn, is ***Intermediate Estonia***, the demarcation zone of which crosses Estonia diagonally from SSW to NNE.

6.2. Interactions between groundwater recharge and rivers' runoff

In the case of natural hydrogeological conditions, changes in groundwater level are affected by climatic conditions. The spatial variation for the annual groundwater level fluctuations is controlled by the recharge-discharge mechanism, which is mainly dependent on the climate. Numerous studies deal with the effects of global climate change on river runoff, soil moisture and evapotranspiration. There are not, however, many investigations on the effect of climate changes on aquifer storage and groundwater recharge.

In the Lake Võrtsjärv drainage basin, the uppermost water-bearing formation is connected with Quaternary deposits consisting mostly of till and glaciolacustrine sand or sandy loam. The water in the Quaternary sediments is mainly unconfined. The next principal water-bearing formation is represented by Paleozoic sandstones, the waters of which having a hydraulic connection with waters in river beds. The unconfined aquifers are recharged by the percolation of rain and melt water through unsaturated soils. Intensive infiltration starts in spring and lasts until the snow has melted. Later the amount of groundwater mostly decreases due to the evapotranspiration. Intensive infiltration recurs in autumn attending the rainfall period. During a cold winter the amount of groundwater predominantly decreases since infiltration is restricted by the freezing of precipitation.

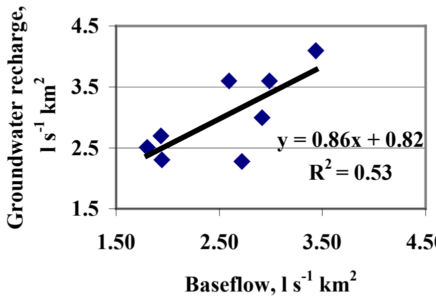
The data of the long-term river runoff and groundwater recharge have quite a close correlation in Estonia if one groups the rivers' catchments on the basis of similar hydrological and hydrogeological conditions (Table 16, Fig. 32). Previous studies (Vallner, 1980) showed that the value of the corresponding correlation coefficient for a group of catchments in south-Estonian hydrological region consisting of 8 stations was 0.66.

Global climate change was simulated through a set of hypothetical scenarios of temperature increases coupled with precipitation and river runoff changes. The interaction between streamflow and groundwater recharge was expressed by the ratio of the two variables on a seasonal and monthly basis (Järvet & Vallner, 1998). The methodology of conceptual hydrological simulation was adopted to explore the sensitivity of groundwater–streamflow interaction on projected climate changes over medium-sized catchments (mainly from 300 to 5500 km^2).

The influence of possible climate change on the groundwater recharge and its seasonal variability are estimated through the changes of river runoff, whose values were calculated using the WatBal model. The modelling results of river runoff have been used for estimating possible groundwater recharge changes in the future, because in natural conditions, changes of the groundwater regime are affected by climatic factors.

Table 16 and **Figure 32**. The regression relationship between the mean annual flow parameters of rivers in the southern Estonian hydrological region from 1961–1990, l s^{-1} km^2. Q_t – total runoff, W – groundwater recharge, Q_{base} – baseflow.

River	Station	Q_t	W	Q_{base}
V. Emajõgi	Tõlliste	7.81	2.70	1.93
Õhne	Tõrva	8.31	3.00	2.92
Piigaste	Piigaste	8.18	2.30	1.94
Ahja	Koorvere	7.84	4.10	3.44
Ahja	Ahja	6.40	3.60	2.99
Võhandu	Himmiste	7.27	3.60	2.59
Võhandu	Räpina	7.16	2.20	2.72



The impact of climate change on groundwater recharge was determined by substituting the increment of the modeled surface runoff as *x* into the regression equation. For the prediction of the values of HADmid, HAMmid, HAMmax, and HADmax, scenarios were used. The calculations carried out show that in result of climatic change, excepted the increment of the groundwater recharge in Väike Emajõgi and Õhne rivers catchment area will be very different (Table 17, Fig. 33). The relative increment of groundwater recharge will vary from –7 to 54% and –47 to 111% on the V. Emajõgi and Õhne catchments respectively.

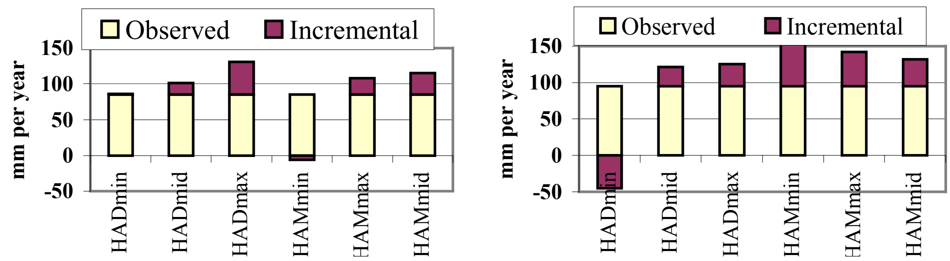


Figure 33. Increment of annual groundwater recharge calculated on the basis of different climate change scenarios on the river basins Väike Emajõgi (*left*) and Õhne (*right*).

According to transient simulations realized by a time step equal to 10 days, an additional groundwater recharge will mostly take place in late winter and autumn. In these periods contemporary infiltration is usually restricted because of low air temperature, which prevents snow melting. The warmer and wetter climate means more rainfall than snowfall, thus making more moisture available during winter and early spring. The water level in spring and autumn will rise, and floods will begin earlier. If the climate is warmer, precipitation will mostly reach the ground surface as rain capable of instant percolation into the unfrozen soil. Therefore groundwater recharge will significantly increase during a warm autumn and winter. At the monthly level, the most prominent effect of the climate change on groundwater regime is caused by the scenario *T*+4, *P*+20 (temperature increases by 4°C and precipitation increases by 20%). The climate change scenario of temperature increase by 4°C and precipitation decrease by 20% predicts the smallest water level rise.

In the catchment of the Väike Emajõgi R. the groundwater recharge will be high in HAD-scenarios, but he HAM-scenarios conduce comparatively greater infiltration in the catchment of the Õhne R. basin. Despite the differences in infiltration rates, the spatial distribution of groundwater recharge will be practically the same in both HADmid and HAMmax scenarios. Owing to climate change, the ratio of groundwater recharge to total surface runoff will increase from 30% to 40%. Since groundwater recharge and surface runoff are positively correlated in Estonia, the reduced surface runoff will cause a very small decrease in the annual groundwater recharge compared with the present.

Table 17. Increment of annual groundwater recharge in river basins of L. Võrtsjärv

River basin	HADmin	HADmid	HADmax	HAMmin	HAMmid	HAMmax
Väike Emajõgi						
mm per year	1	16	46	–6	23	30
%	1	19	54	–7	27	35
Õhne						
mm per year	–45	26	30	105	47	37
%	–47	27	32	111	49	39

The predicted possible changes in climate conditions will be favourable for the restoration of groundwater resources. The modelling results indicated that the climate change will be followed by a rise of long-term annual mean groundwater level of about 0.2–0.4 m in the Lake Võrtsjärv drainage basin (Järvet & Vallner, 2000).

6.3. Climate change impact on water management

Possible changes in river runoff caused by climate change will certainly have an influence on water management (Becker & Lahmer, 1996). The problems arising for instance with low-flow and flood periods will be solved at the watershed (catchment) level, not only by administrative units (counties). Data on minimum runoff are needed, particularly in water supply and water quality control. Climate warming will be followed by positive as well as negative consequences for water management. Problems of water management associated with changes in river runoff arise mainly during low-flow and flood periods. They are estimated taking into account local conditions in different parts of Estonia (Table 18). This regionalization is made on the basis of hydrological parameters (annual range of monthly mean, maximum and minimum runoff, the character of its seasonal course) following general landscape peculiarities in Estonia.

There are great differences in the ratio of minimum and maximum runoff between hydrological regions in Estonia, although the difference between modelled and observed monthly minimum runoff has a low regional variation. It indicates that remarkable change in minimum runoff is not projected in the case of climate warming, but the reduction of maximum runoff may be significant. The Highest values of maximum monthly runoff are typical for eastern and western Estonia and for the Western Estonian Archipelago, and the lowest ones — for southern and northern Estonia.

The ratio between maximum and minimum monthly runoff will decrease greatly. Therefore seasonal fluctuations of runoff will remarkably diminish due to climate change. Low flow characteristics of rivers are important for different water-based human activities such as water supply, water quality and quantity estimates. If minimum runoff increases, it will act as a positive factor for the water management of rivers, especially for wastewater discharge, navigation and recreational use. In the next studies in Estonia, it may be useful to practise hydrologically and ecologically connected analysis such as that which has been performed in the Netherlands (Claessen *et al*, 1994).

Table 18. Ratios between maximum and minimum monthly runoff (mm d^{-1}) for the baseline period and modelled for the year 2100 using HADMID scenario

Catchment	Baseline (1961–1990)			Modelled for 2100			Modelled-observed		
	Max	Min	Max/ Min	Max	Min	Max/ Min	Max	Min	Max/ Min
South Estonia	1.64	0.34	5.07	1.44	0.45	3.36	–0.20	0.10	–1.71
V. Emajõgi R.	1.66	0.34	4.88	1.42	0.46	3.09	–0.24	0.12	–1.80
Õhne R.	1.65	0.45	3.67	1.47	0.51	2.88	–0.18	0.06	–0.78
East Estonia	2.44	0.27	9.55	1.80	0.33	5.78	–0.64	0.06	–3.78
North Estonia	1.87	0.39	5.13	1.59	0.46	3.61	–0.27	0.06	–1.52
West Estonia	2.33	0.27	8.8	1.79	0.34	5.35	–0.53	0.07	–3.45
W-E Archipelago	2.11	0.25	8.44	2.01	0.24	8.38	–0.10	–0.01	–0.06

Changes in hydrological conditions in Estonia should also be translated into changes in the ecology of water-bodies, because a number of ecological processes are dependent on hydrological factors (Järvet, 1998). It can be concluded that the positive impacts of climate warming on the ecological state of Lake Võrtsjärv are dominant (Table 19), and that all these modelled changes can be considered to be inside the observed natural variation of water balance elements during the baseline period from 1961–1990.

In general, all climate change scenarios for Estonia forecast mild winters, a decrease in snow cover and an increase in the duration of dry periods in mid–summer. The predicted global warming will cause more changes in the water balance elements in the cold period than in the warm season. Modelled annual runoff and its seasonal variability in the study area on the Lake Võrtsjärv catchment area are not very sensitive to climate change. Under the impact of climate change, a long-term series of annual precipitation will continue with a periodicity of 25–35 years. This will cause long-term fluctuations in hydrological regime and also the future alternation of wet and dry periods. No significant changes in the hydrological regime (annual runoff) of rivers in the drainage area of Lake Võrtsjärv caused by global climate changes have been observed.

Table 19. Comparison of climate change impacts on water bodies and water regime

Changes	**Positive impacts**	*Negative impacts*
Increase in minimum winter runoff	Favourable oxygen conditions in water bodies	Unstable ice cover
Decrease in maximum spring runoff	Diminishing of floods in spring	Lengthening of the period with minimum runoff in summer, diminishing of water capacity in soils
Lengthening of the period with minimum runoff in summer	Better conditions in drained forest areas	Increase in productivity of high plants and algae in lakes and water reservoirs, increasing of evaporation from water surface
Increase in maximum runoff in autumn	Favourable ecological conditions in water bodies	More floods in autumn and inadequate drainage of agricultural land
Changes in agricultural discharge	Smaller peak flow in spring, diminishing of pollution load and wash-out of fertilisers	Problems for farmers during the harvest period in autumn
Water level changes	Decrease of flooded areas around shallow lakes during high water periods	Possible drop of water level below the ecologically optimal limit in shallow lakes for the second half of summer
Storage of lakes	Increase of total and active storage of lakes during winter period	

6.4. Consequences of the climate changes on the state of lake ecosystem

It is clear that the scale of climate change predicted in the future will significantly alter the functioning of shallow lakes and seasonal patterns of water quality (Carvalho & Kirika, 2003). The North Atlantic Oscillation (NAO), which is defined through the variability of air pressure differences between the North (Iceland) and South (Azores), dictates climate variability over a large area of the Atlantic, North America and Europe, especially during winter (Hurrell *et al*, 2001). The variation in heat and moisture transport between the Atlantic and surrounding continents affects the water balance components of lakes, such as precipitation, riverine inflow and evaporation, resulting in changes in the water level. If present trends continue, limnologists believe that weather changes will have a major effect on the dynamics of lakes throughout Europe (Dokulil & Teubner, 2003). Most seriously, ecological changes should occur in the southern part of Europe, where a significant decrease in the mean monthly runoff for months is estimated, and the highest decrease in runoff will be during summer and especially during June (Mimikou *et al*, 2000).

Typical climate-related problems include increases in lake productivity, increases in water colour and the increased frequency and severity of algal blooms. Many water quality problems that were once assumed, to be driven by the local weather are now known to be influenced by climatic events that operate on a global scale (Dokulil & Teubner, 2003).

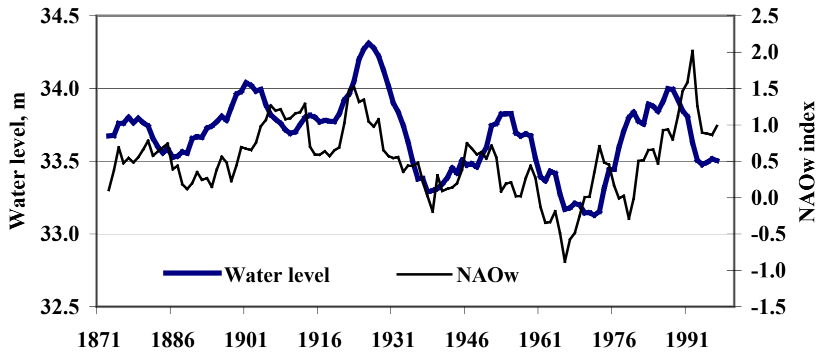


Figure 34. Relationship between NAO index for winter and annual mean water level in L. Võrtsjärv presented as 7-year moving average values.

The ecosystem of L. Võrtsjärv is sensitive to water level fluctuations, which follow the pattern of the North Atlantic Oscillation (NAO) index, reflecting changes in climate in the northern hemisphere (Fig. 34). Phytoplankton biomass was significantly lower in years of high water level and the changes were unrelated to nutrient loading. In low-water years, better water column illumination and increased release of phosphorus from resuspended bottom sediments results in substantially higher phytoplankton biomass than in high-water years (Nõges *et al*, 2002).

For the ecosystem of L. Võrtsjärv, the warmer and wetter climate could bring about higher water levels in winter. The deeper the mixed water column, the lower the average light intensity, causing reduced phytoplankton biomass (Nõges & Nõges, 1998). In the deeper water both resuspension and denitrification rates are lower, the first reducing the phosphorus release from the bottom sediments and causing lower P concentration while the second causes increased nitrogen concentration (Nõges & Nõges, 1999). Consequently, in a warmer world the N/P ratio in Lake Võrtsjärv would be higher and N_2-fixing cyanobacteria would have less chance to develop (Fig. 35). Due to climate warming, the highest mean monthly nutrient losses in spring are shifted from the 1990s to an earlier period (from early April to mid March) and despite the lower intensity of land use, the winter nutrient losses may be almost as high as during previous years.

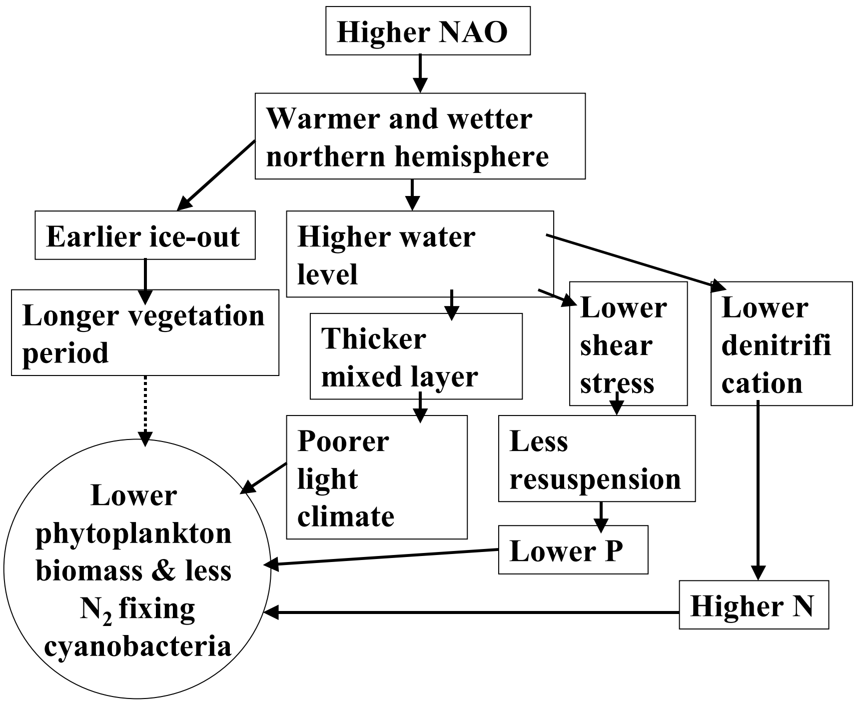


Figure 35. The assumed consequences of global warming on the phytoplankton of Lake Võrtsjärv (Nõges *et al*, 2002).

The successions of phytoplankton composition were caused by changes in light and nutrient availability in the fully mixing environment (Nõges *et al*, 2003). At high water level in summer and autumn, light limitation is the main negative feed-back mechanism resulting in lower phytoplankton biomass. At lower water levels with more light available, nutrient limitation takes control of phytoplankton. The mixed water column is better illuminated while the N:P ratio decreases, due to both increasing P concentration and decreasing N concentration.

6.4.1. Climate change impact on the ice regime

In northern Europe, winter is the most critical period in the context of weather and climate change, as the greatest change in air temperature and precipitation are expected to occur during this period. The shift towards earlier spring events in lake ice cover is a global phenomenon that can be observed in lakes of the Northern hemisphere (Magnusson *et al*, 2000). On a global scale, lake ice parameters such as thickness, freeze-up and break-up dates and ice cover duration are good indicators of regional climate change in high-latitude regions. Earlier findings suggested a substantial impact of the North Atlantic Oscillation (NAO) on winter ice cover (Livingstone, 1999). In particular, the interannual variability of late-winter and early-spring temperature in Europe shows an association with the phases of the NAO. The positive phases of the NAO are associated with warmer and rainy late-onset winters and earlier springs in Estonia.

Correlation between circulation indices and ice regime parameters

The circulation indices for Estonia calculated by O. Tomingas (2003) were used as a measure for regional-scale circulation. The zonal circulation indices are calculated using daily 5x5 degree gridded sea-level pressure data. It is the difference between standardized average pressure anomalies at three stations located in the south (52.5°N) and north (62.5°N) of Estonia. Positive values of the zonal index represent above-normal westerly circulation, and negative values indicate below-normal westerlies or even easterly airflow. The SW-NE index was calculated as a difference between the SLP at the southeastern and northwestern sides. The SE-NW index was calculated similarly, as a difference between the standardized SLP in the northeastern and southwestern corners of Estonia.

The impact of atmospheric circulation on ice cover duration acts indirectly through air temperature and snow cover conditions in winter. Local meteorological conditions such as type of snow cover and melting-refreezing sub-periods influenced the length of the ice cover period more strongly than the large-scale NAO. In the same conditions, air temperature and warm rainfall significantly affect the timing of snow cover, but do not have too much of an impact on ice break-up in the lake. In general, the ice break-up dates of Lake Võrtsjärv cannot be statistically connected with large-scale atmospheric circulation. Some statistically significant correlations between zonal circulation indices and ice cover parameters have been detected only for the ice thickness parameter (Fig. 35).

The correlation between the zonal circulation index and ice thickness in Lake Võrtsjärv is negative from December to March (the highest correlation – 0.44 in December) and for the winter season (D-J-F). The SW-NE index has a significant negative correlation with ice thickness in December, as well as for the winter season (D-J-F). The correlation between the SE-NW index and ice thickness is positive in January, February and during the winter (D-J-F). The meridional index had no significant correlation with ice thickness. These results can be explained by the influence of the meridional circulation index, which in most meterological stations in Estonia is statistically not correlated with winter temperatures (Tomingas, 2003). Our results indicate that the timing of ice break-up dates and the duration of ice cover were not closely associated with zonal circulation indices.

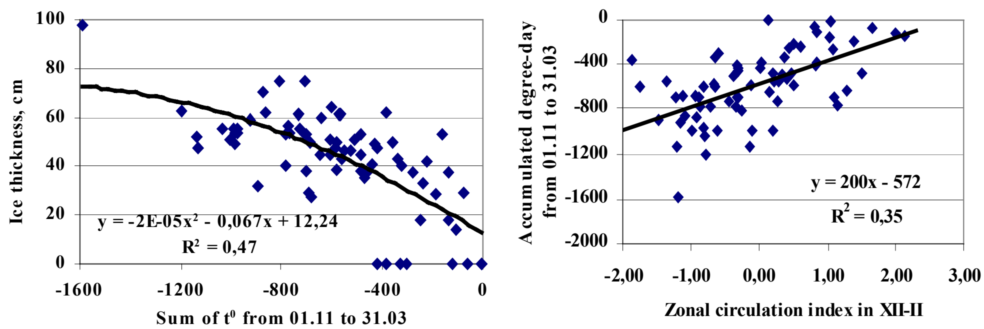


Figure 36. Correlation between zonal circulation index and accumulated degree-day.

Perhaps in some cases it is possible to obtain a better understanding of the dependence of ice-freeze and ice cover break-up dates and ice seasons by using daily circulation indices. For example, an accumulated degree-day analysis based on daily temperatures offers a relatively good correlation with ice thickness (Fig. 37) and zonal monthly circulation indices (Fig. 35). The formation and break-up of the ice cover is assumed to occur when in every year the accumulated degree-day reaches a critical value (Yoo and D`Odorico, 2002).

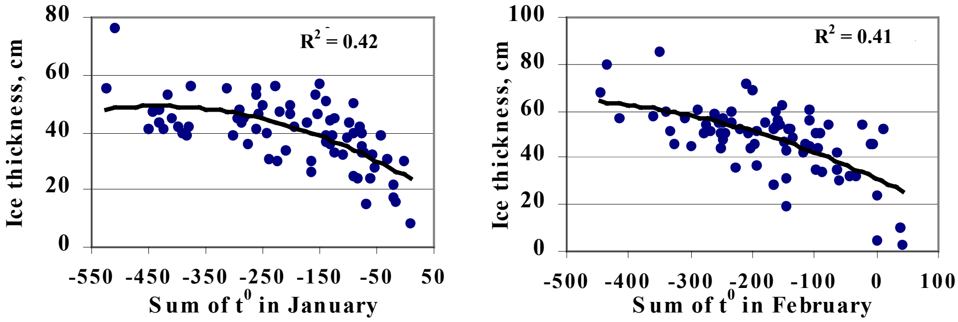


Figure 37. Ice thickness dependence at the ends of January (*left side*) and February (*right side*) from accumulated degree-day.

Nor was the correlation between the snow cover data and the meridional index statistically significant. Since ice formation in winter is closely connected to fluctuations in air temperature, the correlation between wintertime circulation indices and ice thickness in Lake Võrtsjärv follows a similar pattern. Nevertheless, it is obvious that the relationship between ice thickness and regional atmospheric circulation in winter is much more complicated than the direct relationship between atmospheric circulation and air temperature. Maximum lake ice thickness is not a very good direct measure of the severity of a winter, but rather a complicated function of snowfall and temperature patterns. Even with exactly similar frost sums and snowfall totals, the maximum thickness of lake ice may vary considerably (Kuusisto, 1994).

7. LAKE VÕRTSJÄRV AS PART OF A WATER MANAGEMENT SYSTEM

The integrated catchment management presented by the EU Water Framework Directive (WFD) and Estonian water legislation introduces a new approach in water management. The overall goal is the achievement of good and non-deteriorating status for all waters. The directive institutionalises ecosystem-based objectives and planning processes at the level of the hydrographic units as the basis for water resources management. River basin management is a relatively new approach in the countries of western Europe, but in Estonia this principle was applied from the 1960s.

Effective river basin management requires sound data, information and knowledge, including surface and groundwater data (quantity and quality) and also social and economic data. For these purposes the most spatially detailed data should be used, and planning by elementary catchments as spatial units is recommended. An areal interpolation is needed for the correct mapping of all data, and the GIS of the Lake Võrtsjärv basin is now being prepared. Such mapping enables improved understanding of the regularities in hydrological and water resource use characteristics, the finding of territorial contradictions and the integration of water with other landscape components and land use.

The catchments constitute a hierarchical structure and should be used for a planning and management system by the same principle. The main aims of this water management policy are:

- to develop a water management system based on hydrographic units instead of the present system based on administrative boundaries;
- to expand the scope of water interests (protection) to all waters, including ground water aquifers;
- to set water quality objectives and criteria for legislative implementation;
- to elaborate a management plan and a program of measures for each river basin having a catchment area over 100 km^2.

Based on long-time monitoring data that consisted in gathering water quality information from rivers in the Lake Võrtsjärv catchment area, classes of rivers were devised with regard to water quality. Secondly, a priority list of different water use and protection measures, including maps at the river basin level to be used in integrated water management planning, was developed by the author of this thesis.

7.1. Water protection in the catchment area

Phase I of the L. Võrtsjärv catchment area water management plan is oriented towards a description of surface and groundwater status, including an analysis of human impact on the quality of water and water bodies. One of the most important and also problematic issues for river basin management planning is the designation of water bodies and the establishment of relevant water quality objectives (Fig. 38). This is very closely connected with the improvement of monitoring programmes. The EU Water Directive describes in detail how ecological assessment should be performed, including which quality elements must be used.

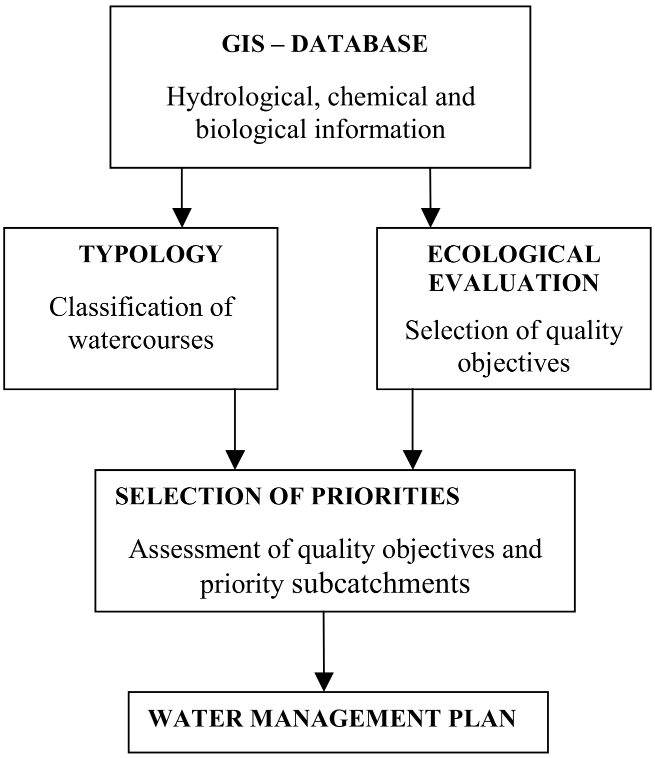


Figure 38. Steps in the methodology for the assessment of water quality for water management planning.

Under the guidelines of the EU WFD, integrated catchment management is adopted as an important aspect in water policy in the interests of achieving good water status. The Directive established the general objectives of achieving good water status as a minimum goal. It also requires specially detailed measures for rivers of poorer quality. Good status means that the ecological status achieved conditions in which human activity did not have a significant effect on a balanced and sustainable ecosystem. The status "good" that should be reached can be defined through numerical and biological criteria. Numerical criteria are the statistical averages of certain chemical or other values.

The EU Water Framework Directive devotes close attention to the ecological assessment of surface water and the measure of achievement of implementation programmes. Quality elements for assessment are divided into biological elements (e.g. composition and abundance of flora and fauna), hydromorphological elements (e.g. quantity and dynamics of runoff, river depth and width variation) and supporting physico-chemical elements (e.g. oxygenation conditions, nutrients, etc.) for all water bodies. Each authority should set standards for the elements most relevant to the pressures faced by the water body under its responsibility and classify waters accordingly (Kallis & Butler, 2001).

During the last decade much research has been devoted to the ecological quality of catchments and watercourses (Cude, 2001; Leentvaar, 2002; Schneiders *et al*, 1999). The evaluation of water quality was based on physico-chemical monitoring data. Each parameter was compared with the quality criteria. As a quality score, the summarised Chemical Index (C.I.) was used. The C.I. gives a score based on five parameters, i.e.: saturation of dissolved O_2, BOD_7, NH_4–N^+, N_{tot} and P_{tot}. It has been used to describe the state and changes of water quality by chemical classification. The chemical classification divides rivers into five classes and C.I. ranging from 1 (higher quality) to 5 (bad quality) for each parameter. For all rivers studied, the quality assessment was made along the whole length (Fig. 39).

The water with higher quality parameters is typical of Estonian natural waters that are not directly influenced by human activity. For the second class (II), a certain anthropogenic impact is allowed, but quality is still good and suitable for the river ecosystem (Loigu and Leisk, 2001). Rivers that are moderately, significantly or strongly influenced by human activities correspond to a quality situation belonging to classes III, IV or V classes respectively. The goals for the five-class system were linked to different quality requirements.

The present level of biological oxygen demand (BOD_7) in most of the rivers of the L. Võrtsjärv basin is quite low in comparison with the 1980s, when the amounts of wastewater discharged into the rivers reached the highest levels. The BOD_7 of natural river water that is not directly influenced by human activity is generally less than 3.0 mg O_2 l^{-1}. BOD_7 3–5 mg O_2 l^{-1} indicates moderate human impact, and values continuously above 5 mgO_2/l indicate obvious pollution. During the last decade, the BOD_7 level in the rivers of the L. Võrtsjärv basin has generally been classified as good (class II) or moderate (class III) (**FIGURE X**). The fluctuation of annual 90% values is also quite low, which shows the high efficiency of wastewater treatment in the towns and large villages of the basin.

The rather high BOD_7 in the Tarvastu and Tänassilma rivers, especially upstream of the Tänassilma River, was caused by wastewater pollution from the town Viljandi. Additionally, the upper reaches of Tänassilma River run through agricultural areas characterised by large amounts of slurry spreading in the fields, even in winter. The self-purification processes in the Tänassilma River (mineralization of organic matter) also cause this high eutrophication level by inorganic nitrogen, especially by NH_4–N and low O_2 concentration. This explains why the high level of NH_4–N at the mouth of the Tänassilma River does not indicate direct local nutrient pollution.

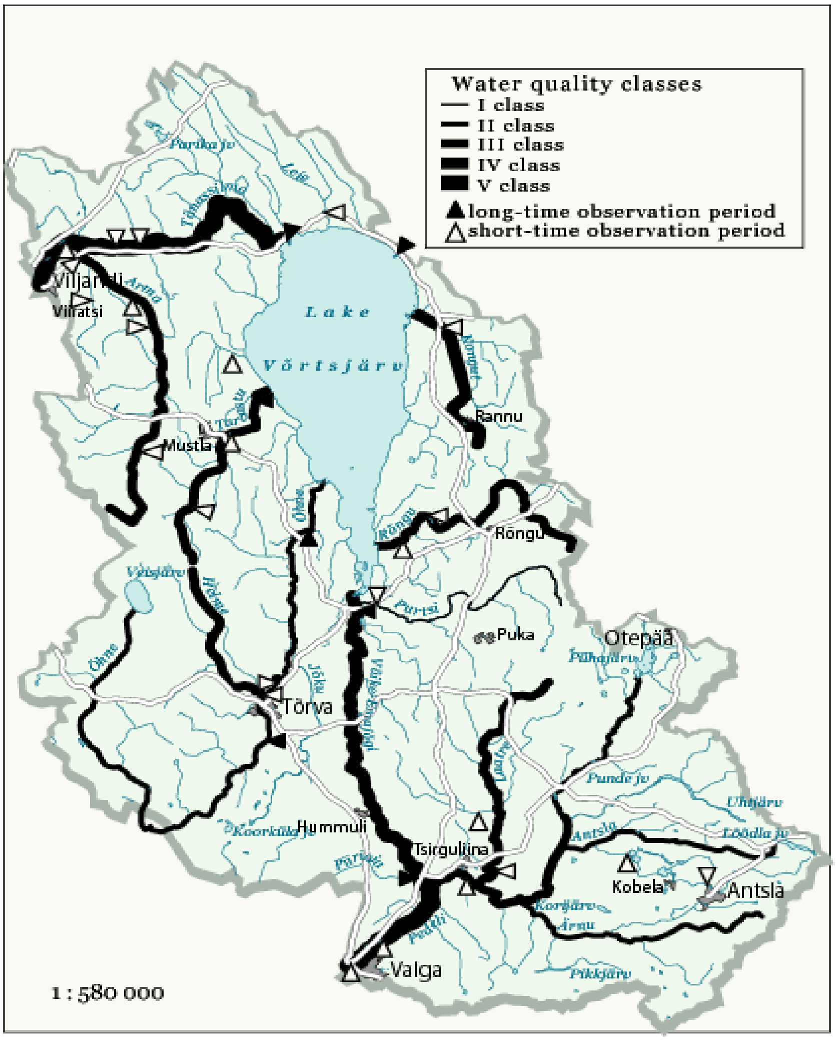


Figure 39. Monitoring sites and water quality classes of rivers in the Lake Võrtsjärv catchment area.

In comparison with other rivers, the water quality score of the Õhne River was high: in the 1980s the annual mean C.I. was 2.5 and in the 1990s C.I. was 1.5. In general, the water quality class moved from **fair** to **good** (Fig. 40). The ecological quality of the Väike Emajõgi River falls quickly after receiving incoming water from the Pedeli River (Fig. 38), which is a recipient of insufficiently treated wastewater from the town of Valga (14,300 inhabitants). Therefore the downstream section had poor water quality (class IV) until 2002.

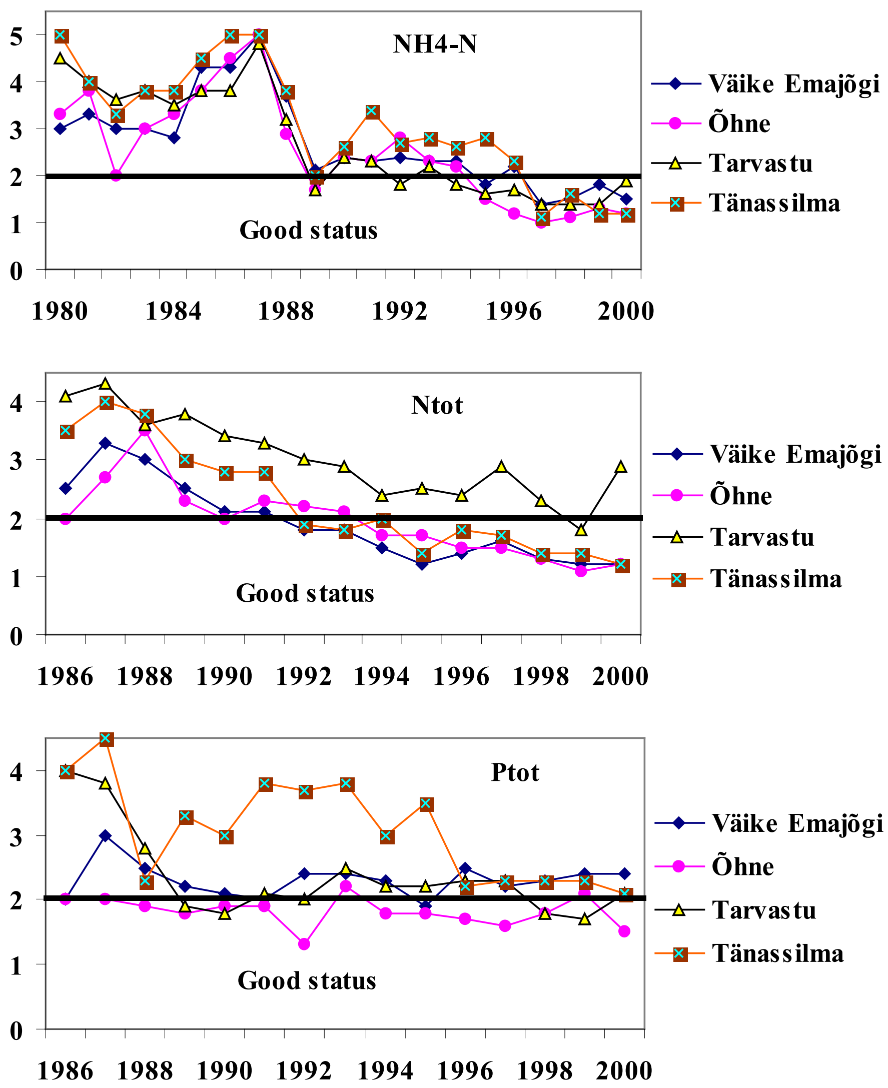


Figure 40. Dynamic of water quality classes in 1980–2000 by the chemical parameters of the main rivers in the Lake Võrtsjärv catchment area.

To improve the river's water quality, the environmental authorities initiated wastewater treatment programmes in the mid-1990s. Recently, extensive reconstruction of wastewater treatment plants remained locally important so as to reach the basic quality standards for water bodies.

The total current ecological value of river water quality in the L. Võrtsjärv catchment area as assessed by overall chemical parameters is relatively low, and falls into quality class III. The Õhne River and some smaller brooks (Purtsi, Visela, Antsla) in the eastern part of the catchment area have good water quality. For the Tänassilma River, class III will be the maximum attainable level in the near future. Despite chemical quality, overall water quality should guarantee the migration of fishes from Lake Võrtsjärv to the downstream sections of main rivers (excluding the Tänassilma River), which have been established as important spawning sites.

The long-term possibilities for water protection and river restoration could be considered. For this purpose, catchment areas with higher priority for river restoration programmes will be selected in respect to water management planning. The assessment of quality elements could be transformed into a policy map for river water quality improvement programmes. Based on their ecological value to the fishery, the highest priority in integrated management is held by rivers with water quality classified by the Chemical Index as <2.5. The lower part of the Õhne River is in urgent need of restoration of its natural variety, focused primarily on small fragments of valuable habitats. These fragments can be designated as ecologically core areas of the river valley. It is typical that in countries with lower population density and large uncultivated areas, restoration programmes are primarily oriented towards naturally degraded sites.

7.2. Lake Võrtsjärv water level regulation

The great role of physical processes in regulating the L. Võrtsjärv ecosystem is obvious. This fact has been mentioned by most earlier investigators. Intensive sediment resuspension as the main factor causing low water transparency was shown by Mühlen & Schneider (1920). Pihu (1959) related the spawning success of pike with differences in the height of the spring flood. He also cited the observations of local fishermen concerning the rapid expansion of reed areas after the low water period in 1939–1940.

The shallow Lake Võrtsjärv ecosystem and the surrounding areas are strongly affected by large fluctuations of the water level in the lake (mean annual amplitude 1.4 m). At a high water level, large surrounding areas are flooded. This causes problems mainly for agriculture and forestry. The flooding of meadows surrounding L. Võrtsjärv starts at the water level of 34.47 cm BS (Pihu, 1959). Low levels cause significant changes in the littoral, which is the most visible part of the lake ecosystem for normal lake and shoreline zone users. Lakeside areas are usually inundated from mid-April to the second half of June. In 1965 macrophytes covered only 15% of the lake area (Mäemets, 1973), since then, their area has expanded remarkably (Haberman et al., 1998). Due to the prevalence of western winds, the reed belt (mainly *Phragmites australis* and *Schoenoplectus lacustris*, is continuous and lush on the sheltered western shore, and broken on the open eastern shore. The narrow southern end of L. Võrtsjärv is fully populated with macrophytes (*Nuphar lutea* and *Potamogeton lucens* prevail).

7.2.1. Reasons for regulation

Ecological state.

Due to the shallowness of the lake, low-level periods are accompanied by several unfavourable phenomena such as overgrowth by macrophytes, restricted spawning area for pike, and winter fish kills (Nõges & Nõges, 1998). The low-water periods are more dangerous to the ecosystem. They cause an increase of resuspension, accelerate nutrient cycling and improve water column illumination. This leads to massive growth of planktonic algae and submerged macrophytes. The reed belt enlarges due to vegetative colonisation of new shallow regions as well as generative reproduction in emerging dry areas. Low water level also causes winter oxygen depletion due to a significantly decreased oxygen storage capacity and higher amount of easily degradable organic material produced during the vegetation period. The years with less precipitation are associated with colder winters, when ice cover is thicker and stays longer (Table 20).

Table 20. The distribution of years by minimum wintertime water level and ice cover parameters

Characteristic	Extr. high	Very high	High	Middle	Low	Very low	Extr. low	Total, *Mean*
Number of winters	1	10	16	18	16	8	10	79
Mean ice thickness cm	29	40	49	51	50	53	60	53
Mean ice cover duration, days	115	126	129	130	127	132	143	130

External loading to Lake Võrtsjärv has long been high, leading to a nearly hypereutrophic state with very high internal loading. Therefore the reduction of external loading alone is not efficient to improve the situation. The enhancing of the reduction of internal loading is needed for the restoration of the lake. The most effective method of restoration that can be implemented in practice is the prevention of excessively low water levels. To a certain extent, water-level management can provide a useful tool for lake restoration. It has been found that water levels should not fall below the value of 33.00 m. In very dry years this is impossible, but by means of regulation it is possible to reach a favourable water level from the point of view of trophic status. However, efforts should also be made to reduce external loading.

Water level and fishery.
Water level is one of the main factors determining the success of spawning and therefore the abundance and catches of many fish species. In L. Võrtsjärv, the water level has a particularly important influence on the prosperity of pike, which lays its eggs in shallow flooded places (generally up to 0.5 m), mostly on dead vegetation. As the water level is kept relatively low during the early spring, the spring flood is much lower. This mainly affects the reproduction of spring spawning fish, because most spawning areas are not available during the spawning period.

In the event of high water levels, the spawning areas of pike are quite extensive, which lays a firm foundation for the formation of strong pike generation. There is an obvious positive correlation ($r=0.45$; $n= 30$; $p <0.01$) between the mean water level in spring and the pike catch in the lake (Järvalt & Pihu, 2003). As a rule, abundant pike catches follow, with a 4–5-year delay, periods of high water level and small catches occur, with the some delay, after periods of low water level. This is in accordance with the age composition of pike catches in L. Võrtsjärv, where 4–5-year-old specimens are usually predominant. On the basis of data obtained from an experimental trawl catch, a still stronger positive correlation ($r=0.61$; $n=23$; $p<0.01$) was found between the abundance of a certain pike generation and the water level in the lake during the spawning period (Järvalt & Pihu, 2003).

Several winter fish kills in Lake Võrtsjärv (in 1939, 1948, 1967, 1969, 1978, 1987) have been documented during 20. century (Table 21 and 22). 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.

Table 21. Hydrological parameters of Lake Võrtsjärv during fish-kill winters. All data are presented as deviations from long-term mean values

Year	Δh of max. ice thickness, cm	ΔW of total volume, 10^6 m^3	ΔW of active volume, 10^6 m^3	Δh of active depth, cm
1939	+10	–71	–95	–0.28
1948	+4	–234	–238	–0.74
1967	+1	+3	+3	+0.02
1969	+6	–183	–208	–0.64
1978	+15	–21	–57	–0.17
1987	+14	+40	+5	+0.02
1996	+7	–240	–268	–0.84
Long-term mean	53	727	588	2,25

Table 22. Water level and ice cover conditions during fish-kill winters

Year	Water level	Ice thickness	Duration of ice cover	End of ice cover	O_2 in bottom, mg l^{-1}
1939	Very low	Very thick	Medium	Medium	*
1948	Extremely low	Thick	Long	Medium	*
1967	Very low	Medium	Long	Medium	*
1969	Extremely low	Thick	Very long	Late	0.3
1978	Low	Very thick	Long	Vary late	1.1
1987	Medium	Very thick	Medium	Late	0.8
1996	Extremely low	Thick	Extr. long	Vary late	0.0

* *No data*

The unfavorable discharge conditions — the small slope of the Emajõgi River, the silting up of the mouth of the river and bifurcation between the beginning of the Emajõgi River and the Pede River cause long-term annual high water periods. The high water floods extensive coastal areas, hindering the agricultural use of those lands. However, this situation is rather favorable for the natural regulation of the discharge of the Emajõgi River. **FIGURE IV** illustrates the variation in the number of days of high water and low water. The figure points out the need to regulate Lake Võrtsjärv, especially to raise its low water level, since years of low water tend to go in succession.

7.2.2. Principles of water level regulation

In order to define the regulated water levels on a month-by-month basis, the following important factors are considered:

- ecological and fishery-related recommendations for achieving as high spring and summer water levels as possible;
- reducing the seasonal and long-term fluctuations in the water level;
- seasonal variations in the natural water level of the lake;
- raising the minimum water level without raising maximum water levels;
- use of lakeshore areas.

The level of spring high water is the most important regulated water level, which also affects water levels in the following months. In order to guarantee favorable conditions for fish spawning (i.e. the existence of extensive low water areas), the average water level in April should be 34.50 meters above sea level (Fig. 41). During the second half of May, the water level can already be much lower. The recommended regulated mean water level for May is therefore 34.00 meters.

During the low water seasons, both in summer and autumn as well as in winter, it is important to maintain the water level at a minimum of 33.50 meters.

Months considered to have such water level are February, July and August. The regulated water levels of the remaining months are seen as transition levels from high and low water situations, considering the natural peculiarities of the Lake Võrtsjärv water regime, such as the slow change in water level, especially in the fall high water period. In order to have the recommended water level of 33.50–33.70 meters for winter (January, February and March), the water level has to be at least 34.00 meters in November and December. The mean annual regulated water level of 33.80 is an average of recommended monthly water levels.

The author of this thesis has conducted a comparison between the natural long-term water level of Lake Võrtsjärv (from 1922 to 2002) and the recommended regulation levels (Fig. 41). The need to regulate Lake Võrtsjärv can be drawn from the comparison between recommended water levels and the actual water levels of the observation period. That will give us an overview of the period during which the water level is below the recommended level. Considering the relatively slow fluctuations in the water level of Lake Võrtsjärv and the unfavourable discharge circumstances, the comparison is based on mean monthly water levels.

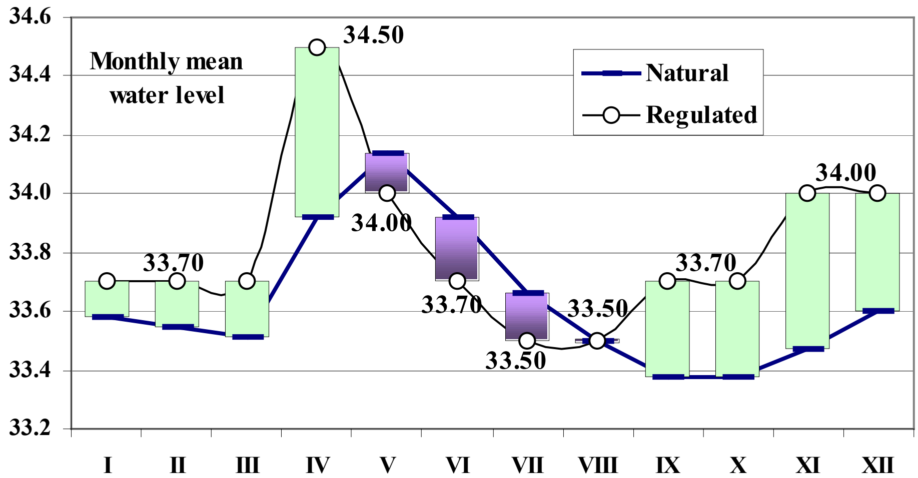


Figure 41. Seasonal variability of natural and recommended monthly mean water level on Lake Võrtsjärv.

The regulated water level would follow natural conditions but at higher levels and in a more regular way. The projected water level during the summer low water period would be 50–60 cm higher than the natural level. However, the use of a very precise and flexible regulation scheme is not possible because of the limited penetrability of the Emajõgi River.

There has not been much discussion of the increasing risk of flooding during water-abundant periods if the water level of Lake Võrtsjärv is raised above the natural level. The regulation facilities will not be able to avoid the damage caused by floods, and the risk of flooding could even increase to a certain extent. Despite the fact that in water-abundant years, when Lake Võrtsjärv would not be regulated because of the high water levels of the upper course of the Emajõgi River and its tributaries, Põltsamaa and Pedja, the natural regime would be maintained, extensive floods could not be avoided.

When one also considers other reasons and conditions for regulating the water level, the importance of hydrological factors might change somewhat, but would still remain the key factors in defining the prospective use and protection needs of the lake, even in the case of a regulated water level.

In a very long-term perspective, the natural conditions of the discharge of Lake Võrtsjärv could deteriorate because of neotectonic movement, as the land uplift on the northern coast of the lake exceeds the uplift in the southern part by 0.2–0.3 mm a year. Neotectonic uplift is also the reason for the paleogeographical lowering of the northern part of the lake and the slow inclination of the water towards the south.

7.3. Water management regionalization

Considering the natural features of the lake, its catchment area and administrative divisions (counties and local municipalities), the Lake Võrtsjärv catchment area can be divided into 5 water management zones for special planning related with water resources (**FIGURE XI**). The zones are differentiated on the basis of their relation to and distance from the lake, and to a lesser extent on administrative and political factors. Such regionalization can be seen as functional zoning of water management, since all the zones face somewhat different objectives. One of the main principles for Lake Võrtsjärv basin water management regionalization is that the lake is a core water-body (planning unit), which also needs water protection measures for the whole catchment.

Zone I covers the lake surface area (270 km^2) and the additional flood area, which is 57 km^2, according to the historically highest water level of 35.28 m. During the high water period, the influence of water extends even farther, since soils also become moist in areas away from the flooding line.

Zone II is the area bordering the lake, determined by the Master Plan for the Võrtsjärv area (AS ENTEC, 2001). It forms a roughly 10-km-wide zone around the lake, and has a close relation with the lake itself. The planned area also includes Zone I of functional planning and therefore the territory of Zone II, including the lake area, is 733 km^2.

Zone III is made up of the seven local municipalities bordering Lake Võrtsjärv that are outside the area determined by the Master Plan. The territory of the zone is 541 km^2. The whole territory of the municipalities comprises

1587 km^2, of which 1331 km^2 or 84% belong to the Lake Võrtsjärv catchment area. They have established the Võrtsjärv Foundation in order to better organize common activities, since for these municipalities the lake is quite central to the organisation of local life.

Zone IV encompasses the rest of the catchment area within the borders of the Estonian Republic, with a territory of 1688 km^2. These are local administrative units that only have a hydrographical relation to the lake, since they are situated in the catchment area. Some can affect the lake directly; for instance the towns of Viljandi and Valga, which influence the lake with municipal wastewaters. These administrative units lack direct socio-economic links to the lake.

Zone V is a 99-km^2 area on Latvian territory and can therefore be seen as an object of transboundary cooperation between the two countries. Hydrographically, most of the area is located in the drainage basin of the Pedeli River; a small part (9 km^2) also belongs to the Õhne River drainage basin.

The first three zones make up the **active zone**, and have a territory of 1601 km^2; the fourth and fifth zone together form the **passive zone** with an area of 1773 km^2 (including the area belonging to Latvia), as far as the water management of the Lake Võrtsjärv catchment area is concerned. Considering the ecological condition of the lake, the bigger polluters located farther away, such as the towns of Valga and Viljandi, are as influential for the lake as areas in the proximity of the lake. Just as significant is agricultural land use, which can bring about increased diffuse pollution.

8. CONCLUSIONS

Changes in hydrological conditions should also be translated into changes in the ecology of waterbodies, because a number of ecological processes are dependent on hydrological factors. Due to its small depth, Lake Võrtsjärv reflects sensitively the changes occurring in its watershed as well as in climate and hydrology. Long-term changes in the ecological state of Lake Võrtsjärv can be attributed to two main groups of factors: 1) variability of the large-scale atmospheric circulation patterns through their influence on water level and ice regime; 2) climatic variability in combination with drainage basin management, which shapes the external pollution load. Change in water level is the most important factor influencing the ecosystem and management of the shallow Lake Võrtsjärv.

Due to its shallowness, ice cover has an important role in the formation of lake ecological conditions in the winter period. It is assumed that ice cover parameters are correlated with water level and oxygen conditions in the winter. Low water level causes winter oxygen depletion due to a significantly smaller oxygen storage capacity. The worst ecological conditions in L. Võrtsjärv are formed in a winter period where, in conjunction with a low water level (monthly mean below 33.00), there is thick ice cover (> 50 cm) and the ice-cover duration is long (> 130 days). But even a small change in ice cover and water level characteristics during mild winters has a significant positive effect on ecological state.

The analysis of long-term changes (from 1980–2002) in nutrient and BOD_5 concentrations and the riverine load in the whole catchment area of the lake are presented. Nutrient losses from the total catchment area of Lake Võrtsjärv in the last decade were extremely low in comparison with the results recorded in the 1980s, when mean annual losses were 12.5 kg ha^{-1} yr^{-1} and 3.11 kg ha^{-1} yr^{-1} for total nitrogen and total phosphorous, respectively. The strongest indications of downward trends in riverine loads of nitrogen (TIN and TN) were found in the agriculturally dominated Väike-Emajõgi and Tänassilma river basins. The seasonal dynamics of nutrient load from the watershed depended on the dynamics of the hydrological load to a greater extent than on the changes in nutrient concentrations in the inflowing water. In comparison with earlier years, the water quality of the rivers has improved. According to the proposed classification of Estonian river water quality, about 70% of the analysed water samples from the last five years belonged to class II, *i.e.* the water quality in these river profiles was "good". About 20% of samples belonged to class III, which is "fair chemical status", and only 10% (Tänassilma River) belonged to class IV, which represents "poor chemical status".

To analyse temporal changes of pollution load, the whole research period was divided into 2 equal parts: (1) 1980–1991 and (2) 1992–2002. When comparing the two periods, we can see a significant difference in nutrient concentration: the concentration of N-compounds has been halved and the concentration of P-compounds has decreased by 30–50% .

External nutrient budgets for the lake were calculated for the period 1980–2002. Lake Võrtsjärv acts as an efficient trap for nutrients, accumulating more than a half of the external N load and about one third of the external P load during the annual cycle. Lake Võrtsjärv as a large waterbody exerts an essential influence on the matter circulation of the landscape and acts as an efficient trap for inorganic form of nutrients. The annual accumulation of TIN was 76%. The relatively smaller decrease in TN was the result of the high N:P ratio of the inflowing water, which exceeded several times the optimal level for biological requirements. The retentions of NH_4^+–N and NO_3^-–N as the main forms of TIN were almost proportional, forming 56% and 80%, respectively, though the absolute decrease of nitrates exceeded that of ammonium by a factor of 6. The annual decrease of PO_4, forming 67% of the loading, was mostly accounted for by transformation of soluble reactive phosphorus into organic P.

This thesis demonstrates that the impact of hydrological factors on the ecological state of shallow Lake Võrtsjärv is larger than previously assumed. It can be concluded that positive impacts of climate warming on the ecological state of Lake Võrtsjärv are prevailing and all these modelled changes can be considered to be within the observed natural variation of water balance elements during the baseline period from 1961 to 1990.

L. Võrtsjärv's greatest problem is the fluctuation of its water level. Low water periods, making up 10% of the average year according to the observation data, are harmful to the ecological conditions of the lake. 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 a positive effect on the ecological state of the lake. In order to decrease the influence of ice cover on L. Võrtsjärv ecosystems it is necessary to keep winter water level between 33.50 and 33.70 m, as recommended.

Considering also other reasons and conditions for regulating the water level, the importance of hydrological factors may change to a certain extent, but will still remain the key factors in defining the prospective use and protection needs of the lake, even in the case of a regulated water level.

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11. SUMMARY IN ESTONIAN

Hüdroloogiliste tegurite ja inimtegevuse mõju madala järve ökoseisundi kujunemisele Võrtsjärve näitel

KOKKUVÕTE

Käesolevas uurimistöös on vaadeldud hüdroloogiliste tegurite ja inimtegevuse mõju madalaveelise Võrtsjärve ökoseisundi kujunemisele. Analüüsil on kasutatud riikliku hüdroloogiateenistuse (praegu Eesti Meteoroloogia ja Hüdroloogia Instituut) vaatlusandmeid nagu järve veetase, jäänähtuste esinemise aeg ja jää paksus, jõgede äravool jt. Reostuskoormuse arvutamiseks on kasutatavad vooluveekogude riikliku keemilise seire andmed, kusjuures väitekirja autor oli vastava seiresüsteemi väljatöötaja.

Võrtsjärvel on umbes kolmekümneaastase sammuga kordunud kõrge ja madala veeseisu perioodid. Täpsemalt on Võrtsjärves veetaseme pikaajalist muutlikkust väljendava tsükli pikkus 25,6 aastat, millele järgnevad tsüklid kestusega 6,1 ja 3,6 aastat. Viimaste aastate vaatlusandmed näitavad, et selline tsükliline muutumine jätkub. Viimane kõrgveeperiood kestis 1992. aastani ning praegu jätkub madalveeperiood. Veetaseme perioodiliselt selget kõikumist saab arvestada järve kasutamise ja kaitse korraldamisel, sest madal- ja kõrgveeperioodid vahelduvad pikaajaliselt küllaltki korrapäraselt.

Võrtsjärve kui madala veekogu ökoloogiline seisund sõltub suuresti hüdroloogilistest teguritest — madalast veetasemest (probleemiks on järve väike sügavus ja maht ning suviti kinnikasvamise oht), jääkatte kestusest ja paksusest (mõjutavad järve talvist ökoseisundit, eriti vees lahustunud hapniku hulka. Kõrgest veeseisust põhjustatud üleujutused raskendavad aga järve lähisümbruse (kaldavööndi) looduskasutust — järveäärsete alade põllu- ja metsamajanduslikku kasutamist ning väiksemate teede läbitavust.

Hüdroloogiliste tegurite otsene kahjulik mõju järve ökoseisundile hakkab avalduma üleujutuse (kuukeskmine veetase üle 34,50 m ümp), madalvee (kuukeskmine veetase alla 33,00 m), pika jääkatteperioodi (üle 150 päeva) ja paksu jääkatte (üle 60 cm) korral. Kõige halvemad ökoloogilised tingimused kujunevad talvel siis, kui veetase on madal, jääkate paks ja jääkatteperiood pikk. Veevaestel aastatel võib jääoludega seotud ebasoodsaiks tegureiks lugeda madalat veetaset ja paksu jääkatet. Nende näitajate omavaheline seos ei ole põhjuslik, sest veerohkemaid aastaid põhjustab atmosfääri intensiivsem tsirkulatsioon. Veevaestel aastatel on ilmastik püsivam ja talved külmemad, see tingib paksema ja mõnikord ka kestvama jääkatte.

Võrtsjärv on biogeenide ja orgaaniliste ainete maastikulise ringe mõjutaja. Biogeenide transformatsioon ilmneb kõige selgemalt mineraalse lämmastiku ja fosfori ning kergesti lagunevate orgaaniliste ainete (väljendatuna BHT_5 kaudu) ja hõljumi võrdlemisel väljavoolus ja sissevoolus. Järve saabuvast 78,0 t-st fosforist aastas seotakse veekogusiseste protsesside käigus 30,4 t ehk 39%, 2752 tonnist lämmastikust 1023 t ehk 37%. Lämmastiku suhteliselt väiksem kahanemine on tingitud sellest, et sissevoolavas vees on olnud N-ühendite sisaldus N ja P biogeokeemilise tasakaalu tasemest (16:1) kõrgem. Ainult suvisel madalveeperioodil on N_{inorg} ja PO_4 suhe Tänassilma jõe suudmes lähedane eespool nimetatud tasakaalule. Teiseks seotakse veetaimestiku poolt õhulämmastikku, mis muudab lämmastiku bilansi koostamise üldse keerukaks ja ebatäpseks.

Järve kanduv mineraalne lämmastik transformeerub suures osas orgaaniliseks lämmastikuks. Aastas saabuvast 2336 t-st N_{inorg} "lahkub" Emajõe kaudu ainult 450 t ehk veidi alla 20% sissetulnud inorgaanilisest lämmastikust. Mineraalse lämmastiku põhivormidest on eriti suur NO_3 sidumine järves — 80%; NH_4 vähenemine ulatub 57%-ni. Sealjuures on nitraatlämmastiku sidumine järves absoluuthulgalt ligi 6 korda suurem kui ammooniumlämmastikul. Samal ajal N_{org} hulk suureneb 918 tonnilt 1278 t-le — tõus sissevoolu suhtes 39%. Järve intensiivsest primaarproduktsioonist tingituna suureneb väljavoolus märgatavalt orgaanilise hõljumi hulk, mis tõstab ka BHT_5 kontsentratsiooni. Jõgedega sissevoolava hõljuvaine, esmajoones mineraalse hõljumi suhtes toimib järv setitajana. Tekkinud fütoplankton suurendab väljavoolavas vees üldhõljumi sisaldust rohkem kui jõgedega sissekanduvaid hõljuvaineid setib. Järves tekkinud füto- ja zooplankton suurendavad bilansiliselt BHT_5 hulka — tõus aasta keskmisena 10%. Seetõttu on järvest väljavoolavas vees eriti kõrge hõljuvainete ja BHT_5 kontsentratsioon suvekuudel — keskmisena vastavalt 23 ja 4,1 mgO l^{-1}.

Võrtsjärv on tugevasti eutrofeerunud veekogu, kuid järve väline reostuskoormus on hakanud viimastel aastatel vähenema. Eriti märgatav on olnud inorgaanilise lämmastiku ja fosfaatse fosfori koormuse vähenemine, mille tulemusena jõgede veekvaliteedi klass on paranenud keskmiselt 1,5 ühiku võrra. Kõige suurem reostuskoormuse vähenemine on toimunud Väikese Emajõe, Tänassilma ja Tarvastu jõe puhul.

Veetaseme reguleerimisega on mõnevõrra võimalik parandada Võrtsjärve ebasoodsat ökoseisundit ja vähendada madalast veetasemest põhjustatud kalamajanduslikku kahju. Kavandatud veeseis oleks madalaveelisel suve- ja talveperioodil 50–60 cm kõrgem looduslikust tasemest. Väga täpset ja paindlikku reguleerimise skeemi Võrtsjärve puhul pole siiski võimalik kasutada Emajõe piiratud läbilaske tõttu. Reguleerimisrajatiste abil ei ole võimalik vältida suurveest põhjustatud kahjulikke üleujutusi Võrtsjärve ümbruses. Arvestades ka veetaseme reguleerimise teisi põhjusi ja tingimusi, võib hüdroloogiliste tegurite tähtsus mõnevõrra muutuda, kuid need jäävad ikkagi peamisteks, mis määravad ka reguleeritud veetaseme korral järve perspektiivsed kasutamisvõimalused ja kaitse vajadused.

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1985–1988 Tartu State University, courses for Candidate of Science
1993–1998 University of Tartu, Institute of Geography, PhD studies

Professional employment

1973–1983 Tartu Amelioration Board, Head of Department
1983–1988 Tartu Water Use and Protection Agency, Head
1989–1993 Ministry of Environment and Environmental Research Centre, researcher
1993– Institute of Geography, University of Tartu, lecturer

Professional membership

- Nordic Hydrological Association (NHF), board member 2002–
- International Association of Hydrological Sciences (IAHS), member
- Estonian Geographical Society, board member 1996–
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- Estonian Nature Conversation Society, member

Grants and scholarships

- UNESCO Hydrological Courses for 2 months study at Moscow University, Russia in 1986.
- Department of Geophysics, University of Helsinki (Finland) in 1994–1995, 2 weeks.
- Department of System Ecology, University of Stockholm (Sweden) in 1994 (2-week seminar).
- Department of Landscape ecology, University of Munich (Germany) in 1995, 2 weeks.
- Department of Geography, University of Bochum (Germany) in 1998, 1 week.

Research Interests

- Hydrology of lakes and rivers
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- Integrated water management planning
- Climate change impact assessment on water resources
- Physical geography and landscapes of Estonia

Major projects

- Grant No. 675 of Estonian Science Foundation in 1994–1995: Influence of landscape factors on the river runoff and water quality in the L. Võrtsjärv watershed, principal investigator.
- U.S. Country Studies Program: Support for Climate Change Studies in Estonia (1994–1995), investigator.
- Ministry of Environment of Finland (Häme Environmental Research Centre): Modelling Nutrient Loading of Lake Võrtsjärv (1995–1998), investigator.
- Water resources subproject leader of UNO Environmental Programme Research Project (GF 2200-96-45): Country Case Study on Climate Change Impacts and Adaptation Assessments in the Republic of Estonia (1996–1998).
- Estonian Ministry of Environment: Implementation of river basin principle in water management planning in Estonia (1999), contractor and investigator.
- EUROPEAN FRESHWATER PROGRAMME: Water and Wetland Index for Estonia (2000), Estonian national expert.
- Estonian Ministry of Environment: The Nitrates Directive Designation of Vulnerable Zones in ESTONIA (2001), member of working group.
- Ministry of Environment of Estonia (Environmental Board of Viljandi county): Water management planning on the Lake Võrtsjärv catchment area (2001–2004), project leader and principal expert.
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1993– Tartu Ülikooli geograafia instituut, lektor

Teadusorganisatsiooniline ja -administratiivne tegevus

- Põhjamaade Hüdroloogiaassotsiatsioon (NHF), juhatuse liige 2002–
- Rahvusvaheline Hüdroloogiateaduste Assotsiatsioon (IAHS), liige
- Eesti Geograafia Selts, juhatuse liige 1996–
- Eesti Veeühing, liige, juhatuse liige 1998–2000
- Õpetatud Eesti Selts, liige
- Eesti Looduskaitse Selts, liige

Uurimistoetused ja stipendiumid

- UNESCO Rahvusvalised Hüdroloogiakursused Moskva Ülikoolis 1986. a., kaks kuud
- Helsinki Ülikooli geofüüsika instituut 1994–1995.a., 2 nädalat.
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- Müncheni Ülikooli maastikuökoloogia instituut 1995.a., 2 nädalat.
- Bochumi Ülikooli geograafia instituut 1998.a., 1 nädal.

Teadusvaldkonnad

- Jõgede ja järvede hüdroloogia
- Valglate, järvede ja veehoidlate reostuskoormus
- Integreeritud veemajanduslik planeerimine
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Tähtsamad projektid

- Eesti Teadusfondi grant No. 675: Maastikuliste tegurite mõju jõgede äravoolule ja veekvaliteedile Võrtsjärve vesikonnas (1994–1995), granti hoidja.
- USA Kliimamuutuste uurimisprojekti Eesti Rahvuslik Uurimisprogramm (1994–1995), töögrupi liige.
- Soome Keskkonnaministeeriumi (Häme Keskkonnauuringute Keskus): uurimisprojekt "Võrtsjärve toitainete koormuse modelleerimine" (1995–1998), töögrupi liige.
- ÜRO Keskkonnaprogrammi uurimisprojekt: Country Case Study on Climate Change Impacts and Adaptation Assessment in the Republic of Estonia. UNEP/GEF project GF/2200-96-45 (1996–1998), veeressursside töörühma juht.
- Keskkonnaministeerium: Valglaprintsiibi rakendamine Eesti veemajanduses (1999), vastutav täitja.
- EUROOPA MAGEVEE PROGRAMM: Eesti Vee ja Veekogude Indekseerimine (2000), Eesti rahvuslik ekspert.
- Keskkonnaministeerium: Reostustundlike suublate nimekirja ajakohastamine (2000), vastutav täitja.
- Keskkonnaministeerium: Eesti nitraaditundlike alade määramine (2001), töögrupi liige.
- Keskkonnaministeerium (Viljandimaa Keskkonnateenistus): Võrtsjärve vesikonna veemajanduskava koostamine (2001–2004), projektijuht ja peaaekspert.
- Eesti Teadusfondi grant No. 5425: Kalade noorjärkude mõju zoo- ja fütoplanktonile Eesti suurjärvedes ja selle sõltuvus sesoonsest ja pikaajalisest temperatuuri dünaamikast (2003–2004), alltäitja.

Publications related to this dissertation

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