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The Roles of Natural and Anthropogenic Factors of Ecological State in the Lake Peipsi

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***Abstract*—**In this paper we discuss the problems of the long-term management policy of Lake Peipsi and the roles of natural and anthropogenic factors in the ecological state of the lake. The reduction of the pollution during the last 15 years could not give significant changes of the chemical composition of the water, what implicates the essential role that natural factors have on the ecological state of lake. One of the most important factors having impact on the hydrochemical cycles and ecological state is the hydrological regime which is clearly expressed in L. Peipsi. The absence on clear interrelations of climate cycles and nutrients suggest that complex abiotic and biotic interactions, which take place in the lake ecosystem, plays a significant role in the matter circulation mechanism within lake.

***Keywords*—**Lake Peipsi, ecosystem, eutrophication, water fluctuation, NAO.

I. INTRODUCTION

THE European Union Water Framework Directive (2000/60/EC) (WFD) sets the legal framework for integrated river basin planning and has established it as the key instrument for water management based on the River basin principle. The WFD aims to ensure "good quality" status of all water bodies throughout Europe by 2015, and this is to be achieved by implementing management plans at the river basin level. The Directive requires evaluation of the ecological status of surface water as well as risk assessment of pollution coming from watershed as measured by the condition of specific biological, hydromorphological and chemical and physico-chemical quality elements. By other words, we must be able to forecast how different kind of anthropogenic pressure will affect water ecosystem in every specific case. According to the WFD all biological assessment procedures are reference-based, i.e. the ecosystem of every evaluated waterbody has to be compared with the ecosystem of the so called reference water body. In the case of such large and unique lake as Lake Peipsi this means that the state of the lake ecosystem before intensive human impact should be reconstructed in order to right determination of "good status".

It is well known that the dynamics of ecosystems are influenced by fluctuation of natural conditions and human impact. Natural variances include climatic changes, hydrological regime, and vertical movements of the earth's crust, short–term effects like forests fires [1], [2]. In addition, the natural processes in the lake ecosystem, for example, such as lake aging also lead to changes of the ecosystem structure. The environmental processes in some cases preponderate over human impact. The study of the acting mechanism and relations between the impact on ecosystems and its results is extremely complicated and need joint efforts from scientists from different fields to be revealed. It is very rarely possible to reconstruct the correct state of studied past ecosystems because lack of data. The existing monitoring data allow evaluate trends during last fifty years only for limited number of chemical and biological parameters and interpretation of those data can only provide a short-term forecast of the situation.

The understanding of the natural forces regulating the development of ecosystem, its sensitivity and resistance are the key problems for planning of sustainable management of natural resources [3]. Therefore, to obtain better insights in environmental planning increased research efforts to investigate the interactions between natural and anthropogenic processes are required. This is important for management of water bodies and in particular for management of transboundary water bodies where in compiling management plans a lot of additional difficulties will arise.

The sharing of catchment areas between countries can cause problems for initiating coordinated water management plans. The underlying nature of such problems is usually due to different economic standards, and/or political structure.

The aim of this study is to discuss problems related to the long-term management policy of the Lake Peipsi. We present data about the history of this transboundary lake and discuss aspects that are related to the natural environmental and the man-made impact on the development of the ecosystem of the lake.

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II. HISTORICAL AND GEOGRAPHICAL SETTING

The name Lake Peipsi (or Peipus, as used in English in different maps and publications) is generally used for the whole lake aquatory including the lakes Lämmijärv and Pskov. Different names are used in Russian: L. Chudskoe or Tchudskoe, L. Tyoploe and L. Pskovskoe. Nowadays, both English and Estonian versions (L. Peipsi, L. Lämmijärv and L. Pihkva) are used in English publications. Geographically Lake Peipsi belongs to the Baltic Sea watershed and locates south of the Gulf of Finland (Fig. 1). The catchment basin of L. Peipsi (47 800 km^2 including lake 3555 km^2 surface) extends from 59^{o}13′ to 56^{o}08′ N and from 25^{o}36′ to 30^{o}16′ E. This is the fourth largest lake after the Ladoga, the Onega, and the Vänern with respect to the surface area and the biggest international lake in Europe. Nowadays its watershed is shared between Russia (27 917 km^2), Estonia (16 323 km^2) and Latvia (3 560 km^2) [4].

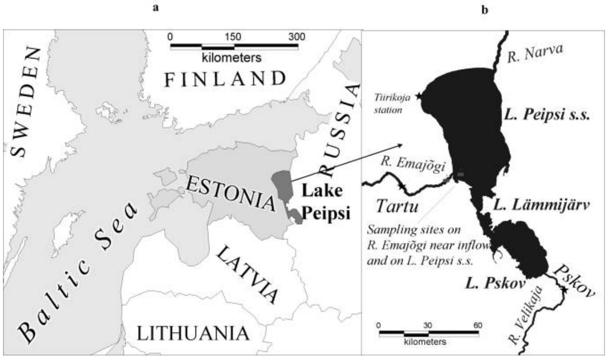

Fig. 1 (a) L. Peipsi is a biggest transboundary lake in Europe, being also the eastern border of EU; (b) L. Peipsi commits of 3 different parts (L. Peipsi *s.s.*; L. Lämmijärv; L. Pskov)

The average depth of L. Peipsi is 7.1 m, maximum depth 15 m and the residence time of water is about two years [5]. Its basin capacity is more than 25 cubic kilometers of yet relatively clean water. The lake is submeridionally elongated and consists of three limnologically different parts called (from north to south): the largest and deepest northern part L. Peipsi *sensu stricto* (*s.s.*), the middle strait-like part L. Lämmijärv, and the southern part L. Pskov (Fig. 1b).

According to Samuel P. Huntington [6] the great historical line that has existed for centuries separating Western Christian peoples from Muslim and Orthodox peoples runs along what are now the borders between the Baltic states (Estonia, Latvia) and Russia. L. Peipsi could be presented as a "Classical" transboundary lake with a geographical position as a natural border during the centuries. The coasts of L. Peipsi attracted man as early the Mesolithic [7]. As the L. Peipsi and its catchments have been rather attractive for different ancestors the L. Peipsi region has experienced a large number of wars. In the 9th century it was struck by an attack from the Vikings. Then the Teutonic Order ruled Estonia and the Estonians accepted Christianity (13th cent.). Aliise Moora [8] stated that in the 13th century the Narva River was a natural border between North-Estonia and Novgorod-Pskov Region. During all following centuries until 1721 the state borders of Russian and Estonian geographical territories were going through the lake. In the 13th century the Danes owned the Estonian territory, and subsequently Sweden gained rule over the land. As a result of the Northern War (Treaty of Nystad, 1721), Sweden lost Estonia, Livonia, Ingria, and part of Karelia to the Russian Empire. In 1920-1940, as a result of the Tartu peace treatment L. Peipsi again became a transboundary lake between Estonia and Russia. From 1992 onwards the lake has been again as a border between the Estonian Republic (ER) and the Russian Federation (RF) and as of May 2004 Peipsi is the western border of European Union.

Nowadays, the lakeside municipalities, especially in Russia, are peripheral areas for countries; unfavorable demographic situation, economic recession, and undeveloped infrastructure are specific for those areas. All these municipalities rank below the national average living standard and their development potential is related with the lake and local small and medium size entrepreneur-ship focusing on fishery, organic farming and tourism. For Estonia L. Peipsi has especially high importance, because its catchment embraces ca 25% of Estonian territory.

III. HUMAN IMPACT ON THE STATE OF THE LAKE ECOSYSTEM

The principle objective of the WFD is to return all surface waters to good status. But how and to what degree the ecological status of L. Peipsi can be improved by implementation of different water protection measures remains subject of discussion? It, first of all, is important to understand the role of natural and anthropogenic factors in the formation of the present ecological state of the lake. Mankind influenced this ecosystem in direct (fishing, recreation, water transport) and indirect ways (human activities on the watershed which cause contamination of surface waters). The natural factors are more complex and include for example changes in the hydrological balance, climatic fluctuations and interior processes of development of the lake's ecosystem.

One of the widely used integrated parameters to determine the health of lake ecosystems is the state of the fish population. Historically L. Peipsi was a smelt-bream lake. The main fishes catched from L. Peipsi for commercial purposes during 1931-1940 were smelt, roach, perch and bream. During the period 1998-2002 also catch of smelt dominated, followed by pikeperch, bream and perch. During 20 century the commercial catch in the lake has been decreased approximately twofold [9], [10]. It seems that intensive fishery is one of the most important factors affecting fish population. Already in 1860 K. E. von Baer published the first information on the fishery of the lake during 1851-1852 [11]. He was the first who presented a project on fishing (1859), which came as a first decision on fisheries management in the L. Peipsi with aim preservation of fish stocks, as well as the first official regulation on fishing in Russia. Changes of the ichthyocoenosis structure due to transformation of food chains and spawning conditions as a consequence of the water pollution or fluctuations of water level in the lake may be significant as well. However, the relationships between the fish population and water pollution combined with water fluctuation are insufficiently investigated. Also, the construction of the dam of the Narva hydropower station in 1955-56 [12] influenced the fish population by blocking the route of migrating fish (e.g. natural route for eel from the Baltic Sea to the water bodies of the L. Peipsi basin).

At present the eutrophication of the lake is the most important problem under discussion. The evaluation of the trophic level based on the concentration of total phosphorus, chlorophyll, and water transparency shows that the situation in all three parts of the lake is different. L. Peipsi *s.s* is a eutrophic lake; the state of L. Lämmijärv is close to hypertrophic, whereas L. Pskov is considered to be hypertrophic [13]. However, according to a another classification system [14], the values of mean concentrations of total nitrogen and phosphorus, chlorophyll *a* and water transparency during last decade allow all parts of L. Peipsi to be considered eutrophic. The investigations of macrophytes communities confirm the negative changes related with eutrophication. The most obvious consequence of eutrophication for macrovegetation of L. Peipsi has been the expansion of reed belt along the lakeshore. Increase of reeds *Phragmites australis* (Cav.) is especially remarkable in the larger formerly mesotrophic northern part (L. Peipsi *s.s.*), where the overgrowing with reeds began in second half of the 20th century. The biomass of reed has increased at least tenfold over the last 30 years [15]. The changes in species composition and distribution of macrophytes communities also can affect traditional spawning places of fish.

According to the current opinion, discharged wastewater and intensive use of mineral fertilizers in agriculture during the 20th century were the main reasons caused rapid enrichment of surface waters by nutrients (nitrogen and phosphorous) and eutrophication as a result [16], [17]. The long-term changes of the phosphate and nitrate content in water indicate that the remarkable eutrophication of L. Peipsi began in the early1970s [13]. After World War II, growth of the population on the Peipsi catchment area followed by an increase of volume of industrial and agricultural production has resulted to increased contamination in the region. Anthropogenic pressure on the lake was maximal at the end of 1980th. After dissolution of Soviet Union the economic situation in the region was changed. The significant decrease of industrial production (including food industry) and the mass construction of the wastewater treatment plants facilitated reduction of pollution from point sources. The use of commercial fertilizer in Estonia showed a strong upward trend since the beginning of 1960s until 1987/1988. But since 1989/90 to 1995 the application of nitrogen fertilities declined nearly by a factor 6 and phosphorus 15 times. It has been evaluated that at the beginning of the 1990s the run-off from agriculture on the Estonian part to L. Peipsi formed approximately 60% of the total annual nitrogen load and 40% of the total phosphorus load on the surface water [18]. However, the drastic decrease in number of farm animals and use of commercial and organic fertilizer due to the economic crises at the end of 1980-ies and simultaneous reduction load from point sources have not led to the expected retaliatory significant reduction of pollution load from watershed [19], [20].

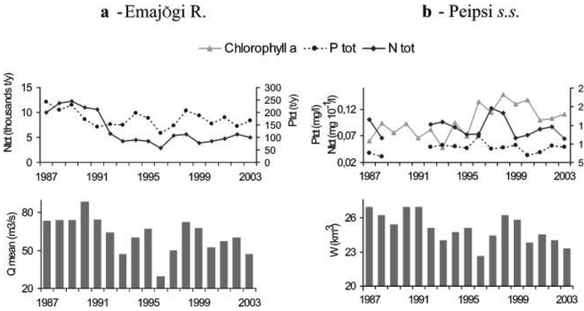

Fig. 2 (a) Pollution load via River Emajõgi (Q_{mean} – average annual runoff, P_{tot} – load of total phosphorus, N_{tot} – load of total nitrogen); (b) mean annual concentrations of chlorophyll "*a*", total phosphorus (P_{tot}), total nitrogen (N_{tot}) in L. Peipsi near inflow of R. Emajõgi and average annual water volume (W). Schematic sampling sites see on Fig. 1(b)

No doubt that the eutrophication processes in the lake is related with the anthropogenic load from the watershed. The fact, that the long-term annual average water inflow in the lake is about 12.5 km^3, what is equal to half of the mean water volume in the lake [4], points to an important role for inflow from rivers on the hydrochemical regime in the lake. It could be expected that the hydrochemical regime of the lake would follow changes of nutrient load due to water exchange time of 2 years. However, inspite of the fact that nutrients load a little decreased in the 1990s [19] the phosphorus concentrations in Lake Peipsi remain high due to the accumulation of a large P-pool in the bottom sediments [21], [22]. The lack of a direct relationship between the pollution load and the lake ecosystem state can be illustrated by an example of the Emajõgi River (Fig. 2a). The River Emajõgi was selected because it is one of the largest rivers on the Peipsi watershed and has been relatively trustfully monitored for a long time. According to assessments performed during the mid 1990s [20], approximately 85% of total phosphorus and 80% of total nitrogen load from the watershed has come into the lake via two main rivers: Velikaya (catchment area 25 200 km^2) and Emajõgi (9 745 km^2). Those rivers have two big cities, Pskov and Tartu, respectively, located on their shores. The dynamics of nutrient load entering with river water (Fig. 2a) and content of chlorophyll *a* and concentration of nitrogen (N_{tot}) and phosphorus (P_{tot}) in the L. Peipsi water near Emajõgi mouth during 1987-2003 are presented in Fig. 2b. Since the load varied from year to year and is dependent on water runoff mainly, the mean annual water discharge of the Emajõgi River is also presented. It is shown in Fig. 2a that at the beginning of the 1990ies the load of total nitrogen via Emajõgi R. had a visible downward trend whereas at the same time the reduction of the phosphorous load was small. The dynamics of the total nitrogen- and total phosphorus concentration in L. Peipsi near the inflow of Emajõgi R. do not show a clear relation to the load coming with river water. At the same time despite of some reductions of pollution load the content of chlorophyll *a* have has been increased since beginning of

1990. This suggests that the nutrient load from watershed is not a main factor generated mass growth of phytoplankton.

The growth of algal blooms is the most serious negative consequences of lake eutrophication. However, the presence of algal blooms was noticed already at the end of 19th and during the 20th century in the different parts of L. Peipsi [23]. This fact also indicates that water blooms may not always be caused by deterioration of water quality. The structure of the phytoplankton community changed considerably and biomass of phytoplankton (particularly cyanobacteria) displayed an increasing trend in L. Peipsi *s.s.* during 1992-2001 [22]. Decrease of phosphorus to low levels is no guarantee that cyanobacterial populations will also follow suit [24] and the appearance of cyanobacterial blooms is usually caused by hydrophysical (temperature, hydrology) and weather conditions [25]. Once the physical requirements of algae are satisfied, then the questions of chemical resources arise. The moderately calcareous water of L. Peipsi appears to be highly favorable for growth of cyanobacteria.

The existing information allows to relate the increase of the nutrient pollution load from the watershed with acceleration of eutrophication processes during 1970th –1980th, but the above given example suggests the absence of an one-way cause-consequence relationship between pollution load and the response of the lake ecosystem. The process of accumulation of nutrients in the lake ecosystem depends on many factors such as the specifics of the nitrogen and phosphorus cycles in the lake. The processes taking place in the lake ecosystem are very complex. Therefore, it is very difficult to reveal relationships between the state of the lake ecosystem and the anthropogenic impact. The lack of long-term hydrochemical and biological observations in the lake also impede investigations.

IV. CLIMATE-RELATED EFFECTS

One of the most important factors having impact on the hydrochemical cycles and ecological state is the hydrological regime in the lake. The changes in hydrological conditions, which are reflected by cyclic fluctuations in the water regime an over long period, were discussed already at the end of the 19th century. The first written records describing L. Peipsi dates back to 1839 [26]. Regular monitoring on L. Peipsi water fluctuation started already in 1902 and more complex studies of lake level fluctuations were initiated in the 1920s. The measurements at the Tiirikoja hydrometric station in Estonia started in 1921 and the data are most accessible and have the longest sets of the best quality. The mean annual water levels for 1885-1902, and 1918-1921 were reconstructed on the base of average summer levels at Tartu (the Emajõgi R.) [27].

The specific cycles of water level fluctuations are clearly expressed in L. Peipsi. There are two seasonal low-water periods (winter and summer) and two high-water periods (spring and autumn). Beside that, the water regime depends also on the weather conditions of the year; the years may differ both in water-abundance and the annual distribution of the rainfall. Short timely fluctuation of water level associated with heavy storms during the high stands of water reached up to 3.04 m in the past 80 years [27]. It also makes causes to extension of lakes' surface even up to the 4000 km^2 during short time. Due to water level fluctuations (annual average) reaching a maximal amplitude of 1,5 m, the surface area of L. Peipsi varies from 3500 km^2 to 3850 km^2 and water volume has varied from 22.3 km^3 to 27.4 km^3 in the past 100 years. The fluctuations of L. Peipsi volume in relation to the annual average amount of water in the lake have been in the amplitude from +11 % to –15% in the past 100 years.

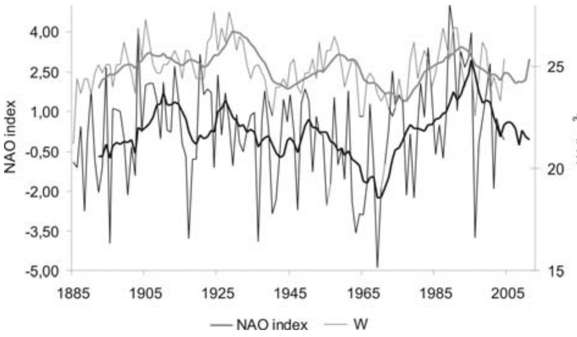

Fig. 3 The L. Peipsi water volume (W) fluctuation and the North Atlantic Oscillation (NAO) index cycles (with moving average 8 year); the source of the NAO index [34], [35]

The cycles of the hydrological regime in the Northern Hemisphere have attracted investigators for centuries. Many researchers have studied the variations and revealed variations with cycles of 2 up to 1850 years [28]–[30]. The data show that the lake level fluctuations have a rather regular character but the length of the periods differs in the various regions. The different factors such as cycling changes in solar radiation, climate variability over a large area of the Atlantic, North America and Europe, especially during winter have been main arguments to explain the water balance components of lakes [31], [32]. P´erez-Peraza *at al.* [33] has confirmed the relation between water volumes (included L. Peipsi) and solar activity. There are different external and internal factors that cause variations of the water masses. Indeed, the external factors could be one of the determinative, that corroborate the smoothed variations with the North Atlantic Oscillation (NAO) indexes, which represents the dominant climate pattern in the North Atlantic region [34], [35] (Fig. 3). Also the NAO index since the late 1960s shows a significant 8-year oscillation in wavelet analysis [36]. Fig. 3 shows the changes in the average annual water volume and its 8-year moving averages based on data from the Tiirikoja hydrometric station. By using different methods, various authors [37]–[40] have distinguished periods in the cyclicity with the duration of 2-3, 5-6, 10-11, 21-22, 26-28, 33 and 80-90 years of the water amount in L. Peipsi. Consequences of hydrological regime fluctuations for the lake hydrochemistry must be taken into consideration for the development of the river basin management plan.

It is natural to predict that such large variation of the water volume will have impact on the ecological state of the lake. As example, the relationships between concentrations of phosphate (PO_4–P) in L. Peipsi *s.s.* (the annual mean) and the change of water volume (in %) of lake have been analyzed (Fig. 4). The monitoring of PO_4–P in lake covers the years 1960-2004. The concentrations of PO_4-P varied in a broad range and emerged some cyclicity during 1960-2004. In the 1960ies the phosphorous concentration in the water was relatively low and reached maximum values at the end of 1970ies followed by a rather sharp decrease and relatively stabile concentrations since beginning of the 80ies. The Fig. 4 shows poor correlation between the water fluctuations and phosphate concentration in the lake. At the same time, the PO_4-P concentration in the L. Peipsi *s.s.* during 1960-2004 also is not in accordance with the dynamics of anthropogenic pollution load (for example, Fig. 2).

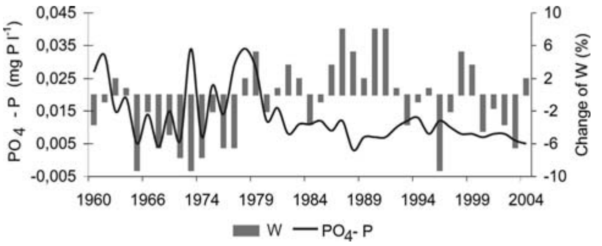

Fig. 4 The phosphorus concentration variation in L. Peipsi *s.s.* and the change of the average annual water volume (W) calculated as % of average annual water volume during 1960-2004 (W=24.91 km^3)

The fact of influence both hydrological regime and pollution load from watershed on the hydrochemical regime is not subject to doubt. The absence on clear interrelations on above mentioned factors and phosphate concentration only suggest that complex abiotic and biotic interactions, which take place in the lake ecosystem, plays a significant role in the matter circulation mechanism within lake. For example, the decrease of runoff from the catchments can also decrease input of total phosphorous in the lake. Also, the lake flooding and internal loading of nutrients (also mixing sediments) are having great influence. As showed the Estonian small lakes research, this influx that we can compare with the human impact could to call forth the increasing of eutrophication [41].

The investigation of the influence of the common global climatic cyclic processes and the L. Peipsi water level oscillation on the function of the lake ecosystem using methods of paleoecological analyses may give new variances in the investigation and prediction of the development of the ecosystem. It is important to know how quickly the ecosystem has responded to changes in the past and how resilient they may be to changes forced by current and future threats [42].

Despite the long history of investigations and the involvement of a large number of researchers, many problems of topical interest in the development of the ecosystem are still under discussion. The changes in water volume may affect sedimentation processes, chemical composition of the water near the bottom and consequently chemical processes in the water and bottom sediments interface. Those processes are insufficiently studied. To separate the impact of the long-term lake-level fluctuation with registered human impact there is a need for scientifically based comprehensive sediment studies.

V. CONCLUSION

From aforesaid we see that natural processes could have essential impact on the function and development of the lake's ecosystem. Consequences of hydrological regime fluctuations for the lake hydrochemistry can exceed the human impact at the certain developmental stages, and also magnify or modify the anthropogenic factor. The reduction of the pollution during the last 15 years did not result in significant changes of the chemical composition of water. To improve the situation or to prevent the negative changes in the lake's ecosystem it is necessary to analyze the role of all factors, which affect the ecosystem of the lake. Most of the projects financed by the European Commission are focused on the relationship between the pollution load resulting from human activity on the watershed and the quality of the water in the ecosystem. Other important factors such as processes in the ecosystem and its internal control mechanisms are investigated very insufficiently. The coordination and integration of Estonian and Russian scientists is needed to successfully investigate and manage the water quality of L. Peipsi. This will also help to develop an appropriate water management plan. It is also the lack of harmonized monitoring strategies that makes an assessment of L. Peipsi very difficult and the uncertainties in available data should be mentioned. To make a reasonable forecast it is necessary to know the main reasons of ecosystem's change.

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