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Ecohydrological evolution in the catchment of Lake Drūkšiai, Lithuania, under anthropogenic pressure

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The catchment area of Lake Drūkšiai (the Ignalina Nuclear Power Plant cooling basin) is exposed to severe anthropogenic pressures due to urbanization, industrialization and, to a smaller scale, to agricultural development. Ecological changes in the lake are investigated in connection with the water balance of Lake Drūkšiai and the interaction of surface water and groundwater in the catchment. The main sources which contribute to the most active water exchange in the lake are total surface runoff, precipitation and artificial circulation of water used in the cooling system of the reactor turbine condensers of the INPP. According to the observation and model results, natural groundwater flow does not influence significantly the water exchange in the lake. However, groundwater, particularly of the confined Upper-Middle Devonian aquifer, is the basic source of centralized water supply in the region and indirectly has become the most significant chain of nutrient transport to the lake. Due to this impact, the trophic state of the lake has changed from (oligo)mesotrophic to almost eutrophic within twenty years of operation of the INPP. The increase of the water surface temperature and alteration of vertical thermal stratification have stimulated the main ecological changes in Lake Drūkšiai.

Key words: Lake Drūkšiai, water balance, surface water and groundwater interaction, stable isotopes and radioisotopes, thermal pollution, nutrient load, ecological changes

INTRODUCTION

The water resources (both surface and groundwater) of the catchment of Lake Drūkšiai have been and are intensively exploited. The catchment is exposed to severe anthropogenic pressures due to urbanization, industrialization and, to a smaller scale, to agricultural development. These pressures manifest themselves mainly as a thermal load originating from the Ignalina Nuclear Power Plant (INPP) cooling system and as a nutrient load originated from a municipal (Visaginas town) waste water treatment plant. It has caused evident changes in the whole ecosystem of Lake Drūkšiai and in the surrounding area of the INPP.

The aim of the present paper is, first, to evaluate the water balance of Lake Drūkšiai and the interaction between surface water and groundwater in the catchment applying isotope data; secondly, to determine trends of ecological changes in Lake under the anthropogenic pressure. Data for water balance calculations and evaluation of ecological changes were collected from various sources including reports on environmental monitoring performed by the INPP.

STUDY AREA CHARACTERIZATION AND METHODOLOGICAL APPROACH

The study area, comprising the catchment of Lake Drūkšiai, is located in the northeastern part of Lithuania and includes adjacent territories of Belarus and Latvia. Today the catchment area of Lake Drūkšiai is 613 km^2, 50% of it being included in the Lithuanian territory, 32% in Belarus, and 18% in Latvia (Fig. 1).

The hydrographic network of Lake catchment had undergone considerable changes in the 20th century (Lasinskas, 1991). In about 1912, while building a water-mill, a canal was dug out between Lakes Drūkšiai and Stavokas (a small lake located very close to Lake Drūkšiai). Some water from the lake flew through the new channel (crossing Lakes Stavokas and Obole) directly into the Drūkša r. A runoff regulation sluice was installed after building a hydroelectric power plant (HEPP) with a capacity of 300 kW downstream from Lake Stavokas in 1953. In the same year, the Drūkša (Drisviata) r. downstream the Apyvardė r. mouth was dammed. After that, the entire Apyvardė r. runoff was turned directly into Lake Drūkšiai, increasing the catchment area by 25%.

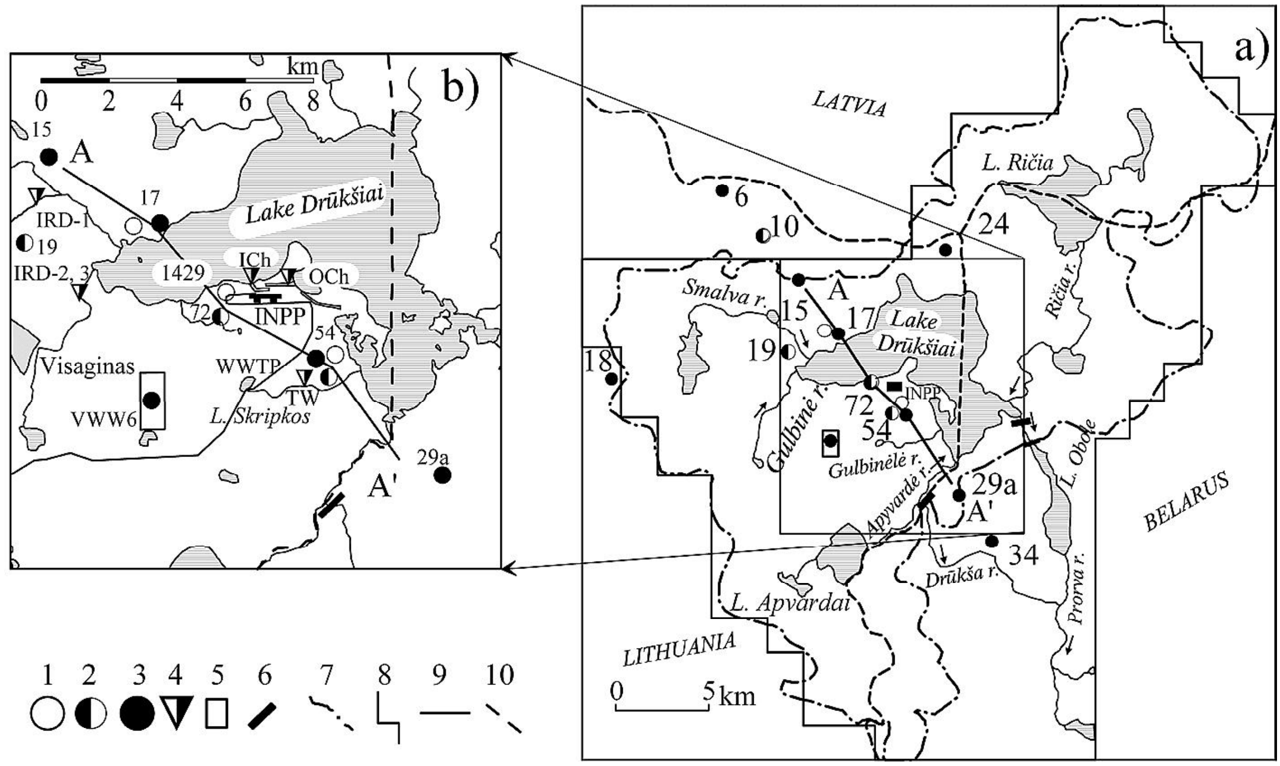

Fig. 1. Study area location with Lake Drūkšiai catchment (a), sampling points in Lake Drūkšiai catchment (b): 1–3 – observation well and its number (1 – unconfined aquifer, 2 – semi-confined aquifer, 3 – confined aquifer); 4 – surface water sampling point; 5 – wellfield of Visaginas waterworks; 6 – dam; 7 – boundary of Lake Drūkšiai catchment area; 8 – modelling area; 9 – line of hydrogeological cross-section AA'; state borders
(IRD – industrial rainwater drainage of town, ICH – cooling water inlet channel, OCH – cooling water outlet channel, WWTP – waste water treatment plant, TW – partially treated water outlet, VWW6 – extraction well No 6 of Visaginas waterworks wellfield).

The area of Lake Drūkšiai is 49 km², the maximum depth being 33.3 m and the average depth 7.6 m; the total water volume reaches 369 million m³ by water level at 141.6 m above sea level (Таутвидас, Ласинскас, 1986). The natural lake basin has the altitude of 141.2 m. There are 11 tributaries to the lake, including small channels and four bigger streams such as the Ričianka, Apyvardė, Smalva and Gulbinė rivers. The Prorva river takes the outflow from Lake Drūkšiai.

The artificial regulation of the water level reaches 0.9 m (140.7–141.6 m a. s. l.) and corresponds to water volume of 43 million m³. The HEPP was closed in 1982. The INPP Unit 1 was started at the end of 1983 and the Unit 2 in 1987. Since then, the water of Lake Drūkšiai has been used for cooling the reactor units (electric power capacity 1500 MW of each unit) of the INPP. Unit 1 was shut down at the end of 2004.

From the hydrogeological point of view, Lake Drūkšiai catchment belongs to the eastern part of the Baltic artesian basin (Marcinkevicius, Laskovas, 1995, Mažeika, Petrošius, 1998). The main hydrogeological features of the catchment along the line AA' are presented in Fig. 1. The zone of fresh groundwater (thickness about 250 m) occurring in the Middle Devonian (*Narva*) regional aquitard includes about 20 aquifers; six of them (unconfined aquifer, four semi-confined aquifers in intertill deposits and confined Upper-Middle Devonian aquifer) are most important aquifers from the point of view of water supply. The intertill semi-confined aquifers (layers of sand and gravel 5 to 35 m thick) make from 20 to 50% of the total thickness of the Quaternary deposits. Three of the six aquifers – Q_{III-II}, Q_{II} and Q_{II-I} – are particularly widespread. Aquifer Q_{II} lies at a depth of 40–60 m (altitude 80–90 m above sea level). Almost over the whole region, this aquifer is covered by g Q_{II} aquitard (basal till, thickness 10–40 m). The underlying aquifer Q_{II-I} is separated from the mentioned aquifer by layers of loam and clay. However, these layers are spread not everywhere (thickness varies withing the range of 0–30 m). The transmission capacity of the Quaternary (Q_{III-II}, Q_{II} and Q_{II-I}) aquifers is 40–120 m²/day and the effective porosity is 0.05. The hydraulic conductivity of confining layers varies between 5×10^{-5} and 5×10^{-4} m/day.

The Upper-Middle Devonian confined aquifer is widespread in the whole region, except deep palaeo-valleys in pre-Quaternary bedrock, filled by Quaternary deposits (Fig. 2). Therefore, the hydrodynamic integrity of the aquifer in them is not interrupted. The thickness of the aquifer makes up 80–110 m. It consists of

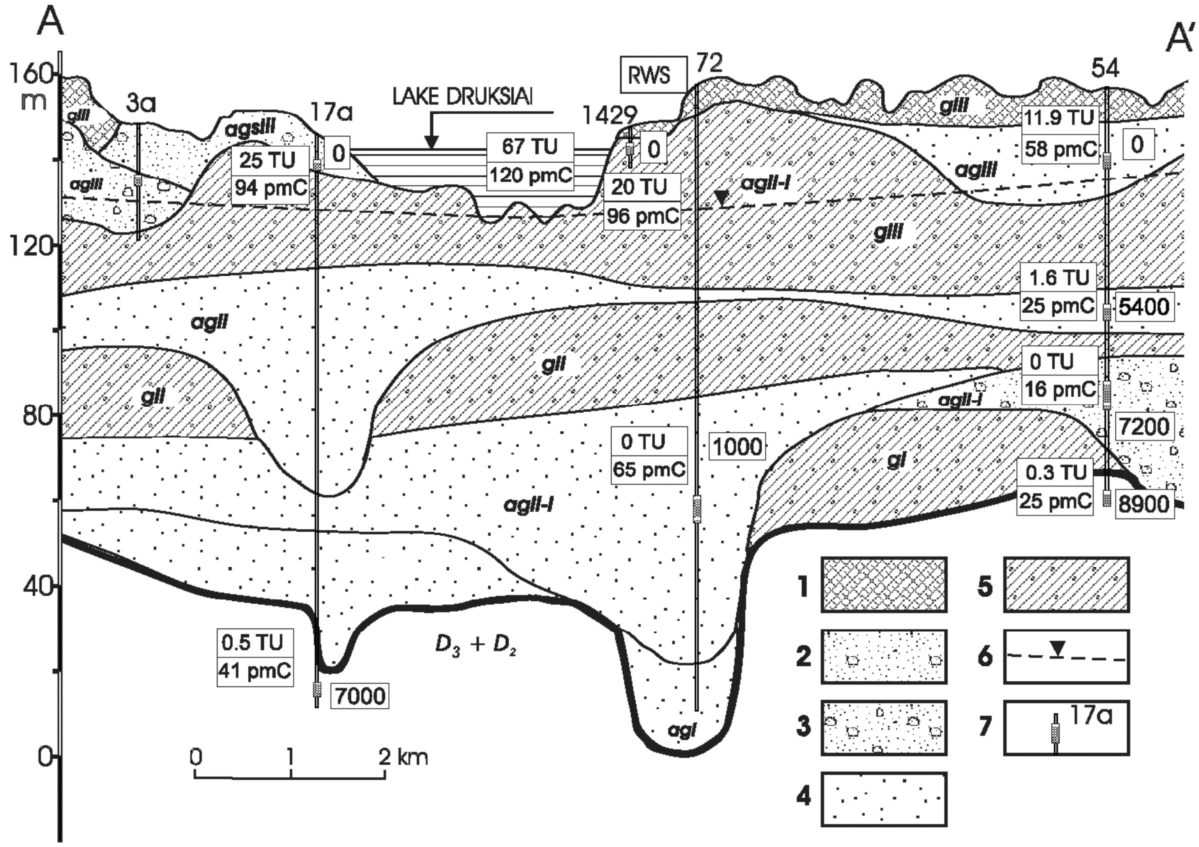

Fig. 2. Hydrogeological section of Lake Drūkšiai catchment (line of section is shown in Fig. 1) with ^{3}H and ^{14}C data: 1 – fissured till deposits; 2 – unconfined aquifer (fine sand with gravel); 3 – unconfined and semi-confined aquifer (various sand with gravel); 4 – semi-confined aquifer (various sand with gravel and interlayers of silt and clay); 5 – aquitard (till deposits); 6 – groundwater level of semi-confined aquifer agII-I; 7 – observation well with filter interval and its number; 8 – upper boundary of confined Devonian aquifer

fine-grained sand and sandstone (60%) and of clay layers. The hydraulic conductivity of sand and sandstone varies within 2–8 m/day, the transmissivity of the aquifer within 100–900 m^2/day, and the effective porosity is 0.1.

The hydrodynamic situation of Lake Drūkšiai catchment is characterized by modern recharge, when at increase of depth in the aquifer the altitudes of water level are lowered. The unconfined aquifer, in which the local flows occur, makes an exception. The water levels of the Upper-Middle Devonian aquifer under natural conditions lower toward the Daugava River valley from 145–150 m up to 137–140 m above sea level.

The INPP is the main user of Lake water and particularly of groundwater in the catchment area. When two reactor units were operating, the maximum discharge of heated water in summer time used to be 160 $m^3 \times s^{-1}$. Recently, the discharge of heated water has been reduced approximately to 63 $m^3 \times s^{-1}$. The thermal heat load on Lake is 0.06 $kW \times m^{-2}$ when only one reactor is operating. For 18 years (1981–1999), under a wide range of different weather and INPP capacity conditions, the Lithuanian Energy Institute had been investigating the thermal state of the lake. After the INPP starting, the hydrothermal regime of Lake Drūkšiai has changed, because the discharged heated water raised the average monthly surface temperature of the lake by 3–4° C (Šarauskienė, 2002).

The main pollution sources forming the nutrient and even chemical load are related to the INPP and the attending Visaginas town. The lake receives treated waste water used for the household needs of the town and for the needs of the INPP and untreated water from the Visaginas and INPP rainwater sewers. The rainwater from the outbuildings of the INPP (8×10^6 $m^3 \times year^{-1}$) and drainage water (1.5×10^6 $m^3 \times year^{-1}$) extracted by lowering the groundwater level in the site of the INPP through a closed collector is turned into a rainwater sewer which disposes it into Lake Drūkšiai.

The waste water treatment plant is designed for full biological treatment and complementary cleaning with sand filters. The capacity of facilities is up to 9.5×10^6 $m^3 \times year^{-1}$. Treated municipal water is disposed into Lake Drūkšiai through the Gulbinėlė stream. Around 5.5×10^6–8.5×10^6 m^3 of pretreated water gets into the lake every year with mean annual concentrations of nitrogen 37.7 mg N/l and phosphorus 3.5 mg P/l.

Only groundwater is used for household needs of the town and by the INPP. The eastern part of Lithuania, compared to the rest of the territory, contains the highest resources of fresh groundwater related to several semi-confined Quaternary inter-till aquifers and to the main productive confined Upper-Middle Devonian aquifer. The same aquifers are exploited in the Latvian and Belarusian territories of the Lake Drūkšiai catchment.

For considerations of the water balance of the Lake Drūkšiai catchment, the water flows have been divided into measured flows (precipitation, evaporation from the lake, groundwater extraction, and groundwater lowering in site), the ones calculated from hydrological balance (surface water inflow, evaporation from catchment, industrial losses and evaporation) and the ones calculated by groundwater flow models (groundwater recharge, base flow to streams and lakes, and leakage among the aquifers).

RESULTS AND DISCUSSION

Water balance

Approximate water balance calculations for Lake Drūkšiai had been made for a few years after starting two INPP reactor units (Gailiušis et al., 1995). The water discharge from tributaries to Lake Drūkšiai is occasionally measured by field expeditions. Therefore we can only have a general long-term view of discharges to Lake Drūkšiai and of the other water balance elements.

Water level fluctuations. When the HEPP was started in 1953, the natural lake water level raised by 0.3 m (to 141.6 m) and the mean annual amplitude of water level fluctuation became 0.8 m or even 1.3 m. Before Lake damming it had been 0.6 m. After the starting of the INPP, the annual water level fluctuation amplitude decreased to 0.19–0.59 m (mean 0.4 m), though the mean annual water level increased from 141.48 to 141.69 m. Following the regulations of lake water use and preservation, the annual lake water level fluctuation amplitude should not exceed 1.2 m to reduce the hazards of shore abrasion. However, most of the shores of Lake Drūkšiai are bogged up and have a small inclination. An artificial lake water rise and maintenance of small fluctuations amplitude (Fig. 3) have reduced the area of periodically inundated and drying lake-shores.

Precipitation. The variation of annual precipitation in the catchment of Lake Drūkšiai is small. The greatest amount of precipitation is characteristic of summer months (32%) and the smallest of spring (19%). For Lake water balance model, the average annual

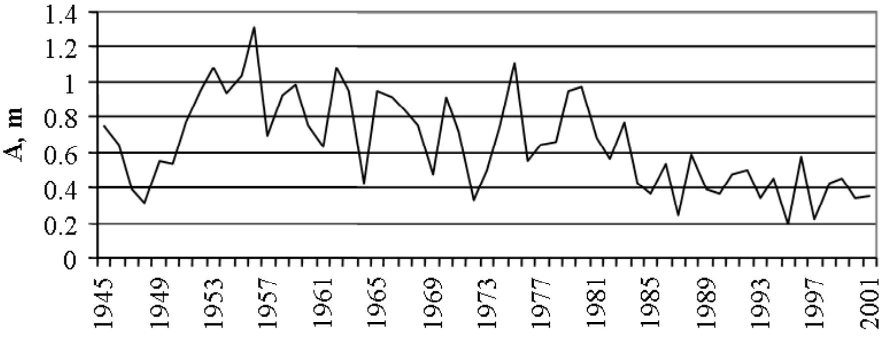

Fig. 3. Amplitude (A, m) of Lake Drūkšiai water level fluctuation

precipitation (718 mm or 440.2×10^6 m^3) was derived from the data of precipitation measurement in four pluviometers (1923–2000) located in Lake Drūkšiai or near its catchment.

Evaporation. The season of evaporation from the water surface lasts for six months (from the ice cover melting on average on April 19 till the new ice cover formation on average on December 5) according to Lake Drūkšiai observation data of 1944–1975. In 1976–1988, most important parameters, such as water temperature, evaporation intensity, precipitation and other, have been investigated at a hydrological-meteorological station equipped at the lake (Януkенене, 1989). Before the operation of the INPP (1976–1981), during seven months (V–XI), Lake Drūkšiai would lose 520 mm (or 25.5×10^6 m^3) of water through evaporation. After starting the INPP (1984–1988), the measured average annual evaporation from the water surface increased up to 46.8×10^6 m^3 (Януkенене, 1992) because of the increased average monthly surface temperature of the lake.

The summary evaporation from the land of the lake Drūkšiai catchment has not been specially investigated. According to the water balance method, summary evaporation from land was calculated in Lake Drūkšiai area (Gailiušis et al., 2001). The accepted annual evaporation from the land for lake water balance consideration is 500 mm (or 282×10^6 m^3).

Surface inflows and outflow. Almost the entire surface runoff through the Apyvardė (36.9×10^6 m^3) and Ričianka streams (22.1×10^6 m^3) gets into the southern part of the lake. In this part, water for the INPP needs is taken and discharged again. The most intensive water circulation takes place in the southern part of the lake. The runoff (Prorva stream) in the water balance consideration is 100.4×10^6 m^3. This value was derived from the annual runoff measurements and was revised according to the long-term measurements in the nearby catchments (Таутвидас, Ласинскас, 1986).

Isotope data around Lake Drūkšiai. Isotope (^{3}H, ^{14}C and δ^{13}C, δ^2H and δ^{18}O) and chemical data for wells are presented in Tables 1, 2 and 3. The stable isotope composition of groundwater oxygen around Lake Drūkšiai changes from –11.9‰ to –9.0‰ and does not significantly differ from isotope patterns of Lithuanian groundwater attributed to the active exchange zone (Rozanski et al., 1993; Mažeika et al., 1999). The most negative values of δ^{18}O are characteristic of the western part of Lake Drūkšiai Region and together with the highest piezometric level of groundwater indicate a recharge area. The most positive values of δ^{18}O are characteristic of the eastern part of Lake Drūkšiai Region in the area close to the tectonic fault zones where the piezometric level distribution in consequent aquifers shows groundwater leakage through confining beds from deep-er aquifers to subsurface. These areas have been qualified as regional discharge areas with relatively positive δ^{18}O values in the Upper-Middle Devonian aquifer formed of sandstone. The recharge and discharge areas have different values of 'groundwater age' parameters estimated by radioactive isotope (^{3}H and ^{14}C) methods.

Radiocarbon age (^{14}C) of groundwater was determined by using the matrix exchange Fontes–Garnier model (Fontes and Garnier, 1979). For age correction, the

Table 1. **Stable isotope data for wells in the Lake Drūkšiai catchment**

Well	Aquifer lithology	Screen interval (m)	Date	δ^{18}O (‰ SMOW)	δ^2H (‰SMOW)
1428 (next to No 1429)	Q_3, loam, till, unconfined	2–5	5/28/90	–11.9	n/m
262 (close to Salakas in Zarasai district)	Q_{3-2}, sand, intertill, semi-confined	30–40	5/28/90	–10.8	n/m
258 (close to Salakas in Zarasai district)	Q_{2-1}, sand, intertill, semi-confined	70–77	5/28/90	–10.9	n/m
263 (close to Salakas in Zarasai district)	D_{3+2}, sandstone, confined	100–105	5/28/90	–11.0	n/m
1443 (next to No 34)	Q_3, loam, till, unconfined	2–5	5/28/90	–11.7	n/m
119 (next to No 34)	Q_{3-2}, sand, intertill, semi-confined	25–30	5/28/90	–10.4	n/m
188 (next to No 34)	Q_{2-1}, sand, intertill, semi-confined	67–72	5/28/90	–10.4	n/m
121 (next to No 34)	D_{3+2}, sandstone, confined	103–109	5/28/90	***–9.0***	n/m
189 (next to No 34)	D_{3+2}, sandstone, confined	134–145	5/28/90	***–9.6***	n/m
69 (close to Dūkštas in Ignalina district)	Q_{2-1}, sand, intertill, semi-confined	156–165	11/18/92	–11.3	–83
6	D_{3+2}, sandstone, confined	131–134	6/12/92	–10.6	–79
79 (close to Dūkštas in Ignalina district)	D_2, sandstone, confined	104–110	11/18/92	–11.0	–80
24	D_2, sandstone, confined	124–129	11/18/92	–11.0	–82

n/m – not measured.

Table 2. **Isotope data for wells in Lake Drūkšiai catchment. ^{14}C activities are uncorrected for the difference between –25‰ and $\delta^{13}C$ of the sample. ^{3}H values 0 TU fall within counting error**

Well	Date	$\delta^{13}C$ (‰ VPDB)	^{3}H (TU)	^{14}C (pmC)	^{14}C age (years)*
		Unconfined Quaternary			
1429	6/5/94	–12.8	17.4±1.2	95.9 ± 0.9	modern
	5/26/95	–14.1	17.6 ± 1.2	94.6 ± 0.8	modern
	5/15/02		19.5 ± 2.4		
		Semi-confined Quaternary			
54v	6/13/92	–6.4	3.6 ± 0.7	57.9 ± 0.7	modern
	5/23/02		11.9 ± 0.5		
54b	9/9/92	–10.7	3.3 ± 0.3	24.9 ± 0.5	5400
	5/23/02		1.6 ± 0.2		
54a	9/9/92	–9.5	3.2 ± 0.3	16.3 ± 0.4	7200
	5/23/02		0		
19	9/1/94	–0.7	0	56.5 ± 0.5	indefinite
	5/23/02		1.0 ± 0.3		
72	9/25/93	–10.9	10.2 ± 2	64.6 ± 0.8	1000
	5/15/02		0		
	5/26/95	–12.7	5.1 ± 0.4	63.9 ± 0.9	
		Confined Devonian			
VWW6	6/3/94	–13.8	0	44.6 ± 0.5	2300
17	9/25/93	–17.9	0.8 ± 0.4	40.7 ± 0.7	7000
	5/23/02		0.5 ± 0.1		
18	9/23/93	–7.5	0	34.4 ± 0.6	indefinite
	5/23/02		1.1 ± 0.2		
6	6/3/94	+2.3	0.8 ± 0.2	51.3 ± 2	indefinite
54	9/8/92	–14.6	2.2 ± 0.2	25.3 ± 0.5	8900
	5/23/02		0.3 ± 0.2		

* Corrections are made using Fontes–Garnier model and chemical data presented in Table 3.

Table 3. **Dissolved ions in groundwater (mg/l) of Lake Drūkšiai catchment. Blank indicates a not analyzed parameter**

Well	Date	$Na^{+}+K^{+}$	Mg^{2+}	Ca^{2+}	NH_4^{+}	NO_3^{-}	Cl^{-}	SO_4^{2-}	HCO_3^{-}
Unconfined Quaternary									
1429	5/26/95	5.3	2.4	108	0.04	2.6	3.5	28.6	317
Semi-confined Quaternary									
54v	01/93	10.0	18.0	84.0	0.2	4.0	10.0	5.0	345
54b	01/93	65.0	14.0	56.0	1.0		7.0	4.0	397
54a	08/92	68.0	21.0	60.0	0.1	4.0	3.5	1.0	458
19	11/02	20.0	38.0	83.0	0.17	2.85	9.0	4.0	441
72	5/26/95	34.3	19.5	72.0	0.4	3.0	5.3	6.6	440
Confined Devonian									
VWW6	5/29/95	14.6	21.9	80.0	0.65	0.69	5.3	12.1	415
17	11/92	29.0	24.0	65.0	0.1		10.0	5.0	372
	5/23/02	45.1	23.4	47.5	1.5	0.6	14.2	4.5	342
18	01/93	20.0	20.0	44.0	0.2		7.0	4.0	272
6	11/02	23.0	15.0	29.0	0.98	0.37	7.0	4.0	207
54	01/93	47.0	20.0	42.0	0.4		8.0	6.0	333

measured $\delta^{13}C$ in groundwater and additional carbon isotope parameters selected from similar geochemical systems according to Clark and Fritz (1997) were used: $\delta^{13}C$ of the soil CO_2 in the recharge zone equals to –24.7‰ PDB (Галимов, 1966); $\delta^{13}C$ of the dissolved calcite equals to 0‰ PDB; isotope enrichment between the soil CO_2 and calcite equals to –10.4‰ PDB). The groundwater age in the studied wells varies from modern to 8900 years, characterizing the hydrodynamics of the DIC system with retardation processes. Sometimes, the radiocarbon age of groundwater could not be estimated due to complicated geochemical patterns and has an indefinite value. Extreme $\delta^{13}C$ values (mostly enriched) of DIC in groundwater of the confined Upper-Middle Devonian aquifer were observed in some cases (for example, for well 6 $\delta^{13}C=+2.3‰$). The influencing factors could be the dissolution of carbonate minerals and calcite precipitation (Clark and Fritz, 1997).

The main data on water balance indicating an interaction between surface water and groundwater in the Lake Drūkšiai catchment are presented in Fig. 4. The main forming elements of the Lake Drūkšiai catchment water balance (1990–1995) are the following: surface water inflow 76.5×10^{6} $m^{3}\times year^{-1}$, precipitation to the lake 35.2×10^{6} $m^{3}\times year^{-1}$ and groundwater base flow to streams and lakes 22.4×10^{6} $m^{3}\times year^{-1}$ (direct baseflow to Lake Drūkšiai 3.2×10^{6} $m^{3}\times year^{-1}$). Groundwater extraction from Visaginas waterworks for household needs of the town and for different needs of the INPP makes 8.9×10^{6} $m^{3}\times year^{-1}$, the water output from waste water treatment plant being 8.5×10^{6} $m^{3}\times year^{-1}$ and the technological water losses about 0.4×10^{6} $m^{3}\times year^{-1}$. The zone of groundwater active exchange, including unconfined aquifer, semi-confined Quaternary aquifers and confined Devonian aquifer, covers 99% of the total in the exchange volume of groundwater (Jakimavičiūtė ir kt., 1999; Mažeika, Petrošius, 1998). The water flow in the Quaternary unconfined aquifer under steady-state conditions with the Visaginas waterworks operation and groundwater lowering in the INPP site contains 48×10^{6} $m^{3}\times year^{-1}$ (about 2.87 $l/(s\times km^{2})$). About 19.2×10^{6} $m^{3}\times year^{-1}$ of water reaches the Devonian aquifer and 14.7×10^{6} $m^{3}\times year^{-1}$ of water flows out outside the Lake Drūkšiai catchment. Considering the main water balance members ($\times10^{6}$ $m^{3}\times year^{-1}$), the following water balance equation could be derived for Lake Drūkšiai:

$$35.2[P] + 98.9[IF(S)] + 3.2[DGWF] + 1.5[GWD] + \\ + 8.5[WWT] = 46.8[E] + 100.4[OF(S)] + 0.1[LL],$$

where P is precipitation on the lake surface, IF(S) is surface water inflow including groundwater base flow to rivers, DGWF is a direct groundwater base flow to the lake, GWD is the artificial drainage of the INPP site, WWT is the water inflow to the lake after waste water treatment, E is evaporation from the lake surface, OF(S) is surface water outflow from the lake, LL is leakage from the lake to the aquifer.

Nutrient balance and ecological changes in Lake Drūkšiai

Heat discharges, water level management as well as groundwater extraction during the operation of the INPP have significantly influenced the natural hydrological, hydrochemical and hydrothermal regimes in Lake Drūk-

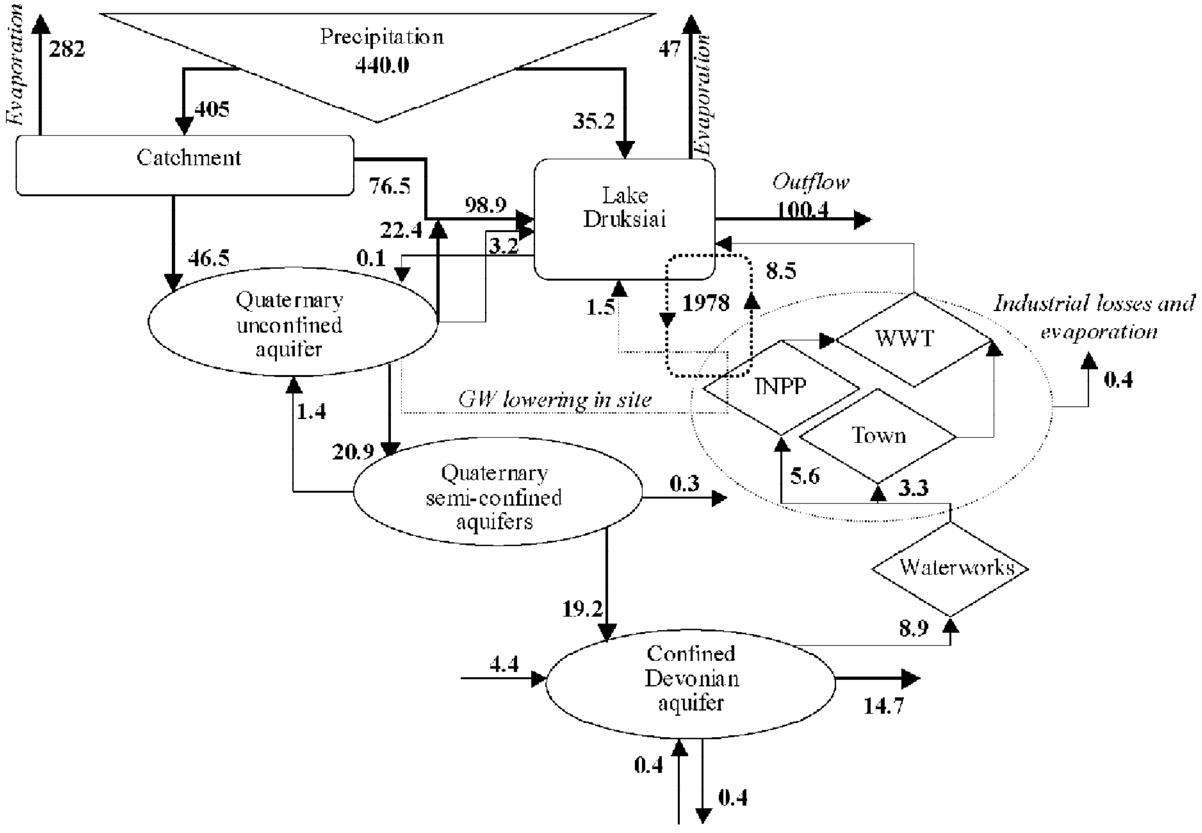

Fig. 4. Generalized surface water and groundwater interaction (recharge and discharge flows, $\times10^{6}$ $m^{3}\times year^{-1}$) in Lake Drūkšiai catchment

Table 4. **Long-term averaged balance (1991–2000) of nutrient load on Lake Drūkšiai (initial data have been taken from the INPP environmental monitorig reports)**

Sources	N_t, t (N) year^{-1}	P_t, t (P) year^{-1}
Domestic and industrial waste water	**85.53**	**15.291**
Industrial rainwater drainage of the INPP site (IRD-1, 2)	1.663	0.244
Industrial rainwater drainage of the INPP site (IRD-3)	0.335	0.081
Treated water after the Visaginas and the INPP waste water treatment plant (S/WWTP)	81.625	14.720
Industrial rainwater drainage of Visaginas town (IRD-2 town)	0.617	0.046
Industrial rainwater drainage of Visaginas town (IRD-1 town)	0.416	0.04
Industrial rainwater drainage of the site of spent nuclear fuel storage (IRD–SNF)	0.870	0.16
Natural runoff	**62.02**	**3.88**
Total input	**147.54**	**19.17**
Prorva (output)	**98**	**14.11**

šiai. On the other hand, the groundwater from the confined Upper-Middle Devonian aquifer being used for household needs and in the INPP became indirectly the most significant chain of nutrient transport to Lake. Up to 1000 tones of organic carbon, 700 tones of nitrogen and 50 tones of phosphorus had been entering Lake annually with municipal waste water treatment and some other discharges with maximum values in 1990–1991. Using the evaluated water balance and nutrient monitoring data, different contributing sources to nutrient balance in the catchment of Lake Drūkšiai have been calculated (Table 4).

The nutrient load from Visaginas and INPP municipal waste water treatment plant has decreased within the last decade due to implementation of new technological facilities. According to recent evaluation, more than 50% of nitrogen and more than 70% of phosphorus come into Lake through the waste water treatment discharges (Paškauskas et al., 1999).

However, a decrease of the annual N_{total}/P_{total} ratio from 21:1 in 1983 to 8:1 in 1997 evidently indicates well-defined changes of the trophic state of Lake from (oligo)mesotrophic to almost eutrophic (Fig. 5). After starting the INPP, the mean annual concentration of N_{total} in the water of Lake Drūkšiai has increased up to 1.53 mg N/l in comparison with that of the pre-starting period (1.29 mg N/l) (Atominė energetika…, 1997). Later on, immobilization and organic export as well as high denitrification activity of microorganisms in bottom sediments led to some elimination of this element from the hydroecosystem. It was evaluated that ca. 310 tons of N_{total} annually had been removed from Lake Drūkšiai during the period of 1985–1997 due to benthic denitrification which exceeds 40% of the annual nitrogen load. At present, the annual extents of N_{total} concentration have a lower range and reach 1.14–1.26 mg N/l. On the contrary, the concentration of P_{total} had an evident tendency to increase and already in 1997 exceeded 0.15 mg P/l.

The fluctuations of phytoplankton primary production and mineralization of organic matter in the course of year show an evident tendency to increase in most parts of Lake Drūkšiai. Annual rates of primary productivity increase during the period of 20 years up to 130 g C/m^2 (Fig. 5e). In the recent years, the mean values of phytoplankton primary production during active vegetation periods range from 470 to 590 mg C/m^3 day^{-1}. The highest values of primary production (1290 mg C/m^3 day^{-1}) and most intensive total benthic organic matter decay rates (up to 1590 mg C/m^2 day^{-1}) were determined in the most eutrophicated south-eastern part of the lake where treated waste waters and discharged. Exactly in this part of the lake bottom, sediments are richest in organic matter (C_{org} up to 12.4%), contrary to more mineralized sediments in the zone where heated water from the INPP discharges (C_{org} ca. 2.5%) (Пашкаускас и др., 2000).

The increase of the water surface temperature changes in the natural vertical thermal stratification and appearance of distinct temperature gradients due to the unstable water usage regime induced the main ecological changes in Lake Drūkšiai. The amount of species of the prevailing plankton organisms in 1993–1997 decreased 2–3 times versus the pre-starting period: phytoplankton – from 116 to 40–50, zooplankton – from 233 to 139. The amount of chlorophyll *a* increased also and reach-ed 70–113 µg/l in 1996–1997. One seasonal maximum of planktonic organisms' abundance and biomass became characteristic. The average biomass of phytoplankton during the active vegetation period reached 4.5 mg/l and that of zooplankton 1.0 mg/l. Zebra mussels (*Dreissena polymorpha*) introduced accidentally in the lake in 1981–1982 have spread rapidly, influencing the trophic structure of communities and changes of water quality. The expansion of reeds has influenced the decline of rare macrophyte species, especially in the most euthrophicated parts of the lake. The rates of fish community succession were ten times as high as those in natural lakes. An exchange of the dominant species took place: the abundance of stenothermal cryophylic fish has decreased significantly, but the abundance of euritherms and euribionts has increased.

Various toxic and/or polluting impacts (oil products, heavy metals, sulphur compounds and even radionuclides)

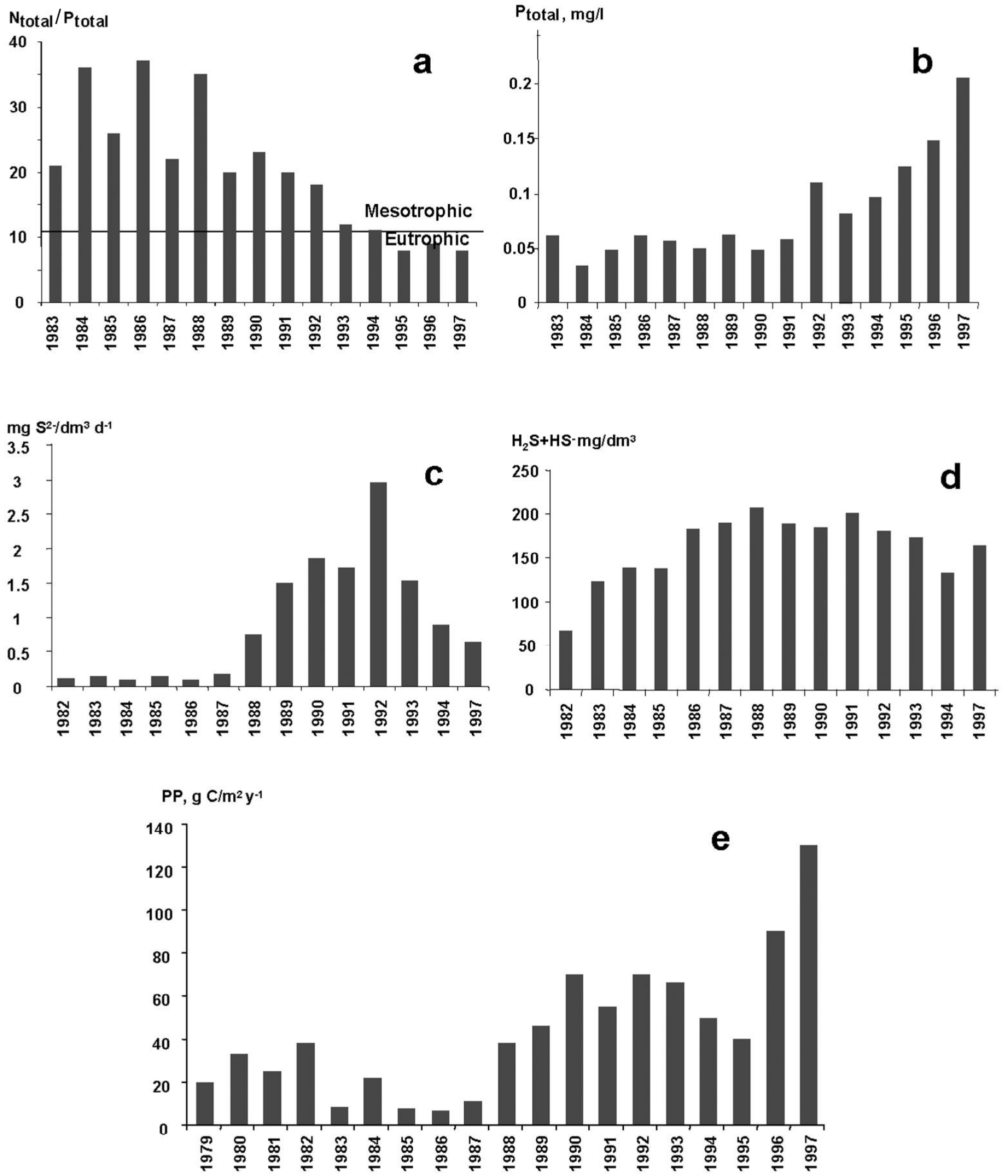

Fig. 5. Change of the annual N_{tot}/P_{tot} ratio (a) and P_{tot} concentration (b) in water, sulphate reduction rate (c) and hydrogen sulphide (d) in bottom sediments as well as primary productivity rates (e) of Lake Drūkšiai

which came to Lake Drūkšiai via municipal and INPP site rainwater drainage outlets take place as well. Nonetheless, only natural hydrocarbons dominate in the bottom sediments of the lake. Technogenic pollution with oil products was identified only in 3.9% of the bottom area, whilst the areas with intermediately and sediments highly polluted by heavy metals are bigger (Atominė energetika…, 1997). One of the most evident changes that have happened during the construction and operation of the INPP was a rapid increase of sulfates in the lake water and bottom sediments – from 8 mg/l in 1982 to 17–19 mg/l in 1997 and from 20–25 mg/dm^3 DW to almost 125 mg/dm^3 DW respectively. The main sources of sulphates are the low-salt water treatment facilities for the main circulation circuit of reactor units as well as domestic effluents from the production area and the Visaginas town. This led to an intensification of microbial sulphate reduction in bottom sediments in a very short time and eliminated methanogenesis, another terminal process. Therefore, already in 1982, quite a high amount of hydrogen sulphide was observed in bottom sediments. The highest rate of sulphate reduction, up to 3.8–4.3 mg S^{2-}/dm^{-3} d^{-1}, was measured in 1992. The process of sulphate reduction in bottom sediments decreased from 1.60 in 1993 to 0.67 mg S^{2-}/dm^3 per day in 1997 because of the distinct decrease of sulphate concentration in water and bottom sediments of the lake in comparison to previous years. Later on, the intensity of these processes decreased, but it still is comparatively high in most parts of the lake (Fig. 5c.).

Due to the anthropogenic thermal and chemical load, several different ecological zones have formed in Lake Drūkšiai:

the most eutrophicated *south-eastern part* of the lake, where the main eutrophicating factor is domestic waste waters with a high content of nutrients (N, P), the increased amount of all groups of planktonic organisms, as well as an enhanced activity of production–destruction processes were determined in this area;

the *heated water outflow* zone, where water temperature in many cases exceeded 28 °C (ecological limit), the lowest abundance and variety of most of planktonic organisms (phytoplankton and protozooplankton) as well as decreased production processes and increased destruction processes of organic matter were determined in this area;

the *pelagic part* of Lake, including the deep and medium deep zones, where various impact factors manifest sporadically, depending on the operating regime of the INPP, wind direction, waves, etc.

CONCLUSIONS

The water balance of Lake Drūkšiai consists of several main sources. The total surface runoff, precipitation and artificial circulation of the water used in the cooling system of the reactor turbine condensers are the main sources and processes that contribute to the most active water exchange in the lake (water exchange coefficients are 0.22, 0.09 and 5.4 respectively). Groundwater does not influence significantly the water exchange in the lake (the water exchange coefficient with respect to the unconfined groundwater equals to 0.009).

However, groundwater, particularly of the confined Devonian aquifer, is the basic source of water supply in the region and indirectly has become the most significant chain of nutrient transport to the lake after being used for household needs and at the Ignalina NPP. More than 50% of nitrogen and more than 70% of phosphorus enter the lake by this way, causeing eutrophication problems; within less than twenty years Lake Drūkšiai has become an almost eutrophic water body. Additional heat load supplied by the INPP cooling system stimulated the main ecological changes as well as favoured the spatial heterogeneity of ecological conditions in Lake Drūkšiai.

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DRŪKŠIŲ EŽERO BASEINO ANTROPOGENINĖ EKOHIDROLOGINĖ RAIDA

Santrauka

Drūkšių ežero – Ignalinos atominės elektrinės (IAE) aušintuvo – baseinas laikui bėgant patiria didelį antropogeninį poveikį, kurį sukelia urbanizacijos, pramonės ir mažesniu mastu žemės ūkio plėtra visoje baseino teritorijoje. Todėl ekologiniai pokyčiai Drūkšių ežere tyrinėti atsižvelgus į ežero vandens balansą ir paviršinio bei požeminio vandens sąveiką ežero baseino teritorijoje. Pagrindiniai šaltiniai, turintys įtakos vandens apykaitos procesams ežere, yra paviršinis nuotėkis, krituliai, IAE turbinų aušinimo sistemoje naudojamo vandens cirkuliacija. Pasirėmus sukauptais duomenimis ir atlikta analize, galima teigti, jog gamtinio požeminio vandens nuotėkis į Drūkšių ežerą menkai veikia vandens apykaitos procesus ežere. Tačiau požeminis vanduo iš Viršutinio-Vidurinio Devono vandeningojo komplekso yra pagrindinis centralizuoto vandens tiekimo regione šaltinis. Šis vanduo, suvartotas buityje ir ūkyje, patenka į nuotekų sistemą ir tampa biogeninių medžiagų pernašos į ežerą grandimi. Dėl šio poveikio per 20 IAE ir Visagino miesto nuotekų sistemos eksploatacijos metų ežero trofinė būklė pasikeitė nuo (oligo-)mezotrofinės iki beveik eutrofinės. Trofinės būklės pokyčiai, taip pat vandens paviršiaus temperatūros didėjimas, vertikalios temperatūrės stratifikacijos kaita sąlygojo ekologinius pokyčius Drūkšių ežere.

Raktažodžiai: Drūkšių ežeras, vandens balansas, paviršinio ir požeminio vandens sąveika, stabilūs ir radioaktyvūs izotopai, šiluminė tarša, biogenų prietaka, ekologiniai pokyčiai