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WATER SYSTEM OF THE LAKE DRUKSIAI TRANSBOUNDARY CATCHMENT UNDER ANTHROPOGENIC PRESSURE

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Abstract. The study is devoted to evaluations of surface water and groundwater balance and interaction in the transboundary catchment of Lake Druksiai, which is located in the northeastern Lithuania and includes adjacent territories of Belarus and Latvia. The water resources (both surface and groundwater) of the catchment have been and are intensively exploited. The catchment is exposed to severe anthropogenic pressures due to urbanisation, industrialisation and, on a smaller scale, to agricultural development. These pressures manifest themselves mainly as thermal load originated from Ignalina Nuclear Power Plant (INPP) cooling system, and as nutrient load originated from municipal (Visaginas town) waste water treatment plant as well as chemical pollution of the lake from point and non point sources. From the hydrogeological point of view, Lake Druksiai catchment belongs to the eastern part of Baltic artesian basin. Groundwater does not influence significantly the water exchange in the lake (water exchange coefficient in respect to unconfined groundwater equal to 0.009). However, groundwater particularly of confined Upper-Middle Devonian aquifer is the basic source of water supply in the region and indirectly became most significant chain of nutrient transport to the lake after being used in household needs and in INPP.

Key words: water balance, surface–groundwater interaction, Lake Druksiai.

Abstrakt. Praca poświęcona jest ocenie bilansu wód powierzchniowych i podziemnych w transgranicznej zlewni jeziora Druksiai, znajdującej się w północno-wschodniej Litwie i obejmującej także przyległe obszary Białorusi i Łotwy. Zasoby tych wód były i są intensywnie eksploatowane. Zlewnia podlega silnej antropopresji z powodu urbanizacji i uprzemysłowienia oraz w mniejszym zakresie z powodu rozwoju rolnictwa. Ta presja powodowana jest głównie przez gorące wody pochodzące z chłodzenia elektrowni atomowej w Ignalinie, przez zanieczyszczenia wypływające z miejskiej oczyszczalni ścieków (miasto Visaginas) oraz przez zanieczyszczenia chemiczne pochodzące ze źródeł punktowych i rozproszonych. Z hydrogeologicznego punktu widzenia zlewnia jeziora Druksiai należy do wschodniej części bałtyckiego basenu artezyjskiego. Wody podziemne nie wpływają poważniej na wymianę wód jeziora (współczynnik wymiany tych wód z nie izolowanymi wodami podziemnymi wynosi 0,009). Z drugiej strony wody podziemne, pochodzące zwłaszcza z izolowanego zbiornika górnego środkowego dewonu, są głównym źródłem zaopatrzenia całego regionu w wodę i w ten sposób pośrednio stają się najważniejszym nośnikiem dostarczanych do jeziora składników organicznych, pochodzących z gospodarstw domowych, jak i gorących wód z ignalińskiej elektrowni atomowej.

Słowa kluczowe: bilans wód, wzajemne oddziaływanie wód powierzchniowych i podziemnych, jezioro Druksiai.

INTRODUCTION

The study area comprising the catchment of Lake Druksiai (the largest lake in Lithuania) is located in the northeastern Lithuania and includes the adjacent territories of Belarus and Latvia (Fig. 1). Though catchment of Lake Druksiai is not wide (613 km^2), its water resources (both surface and groundwater) have been and are intensively exploited. The catchment is exposed to severe anthropogenic pressures due to urbanisation, industrialisation and, on a smaller scale, to agricultural development.

The aim of this paper is to present the results of the evaluation of the water balance of Lake Druksiai and the interaction of the surface water and groundwater in the catchment, applying the groundwater flow modelling and isotopic data.

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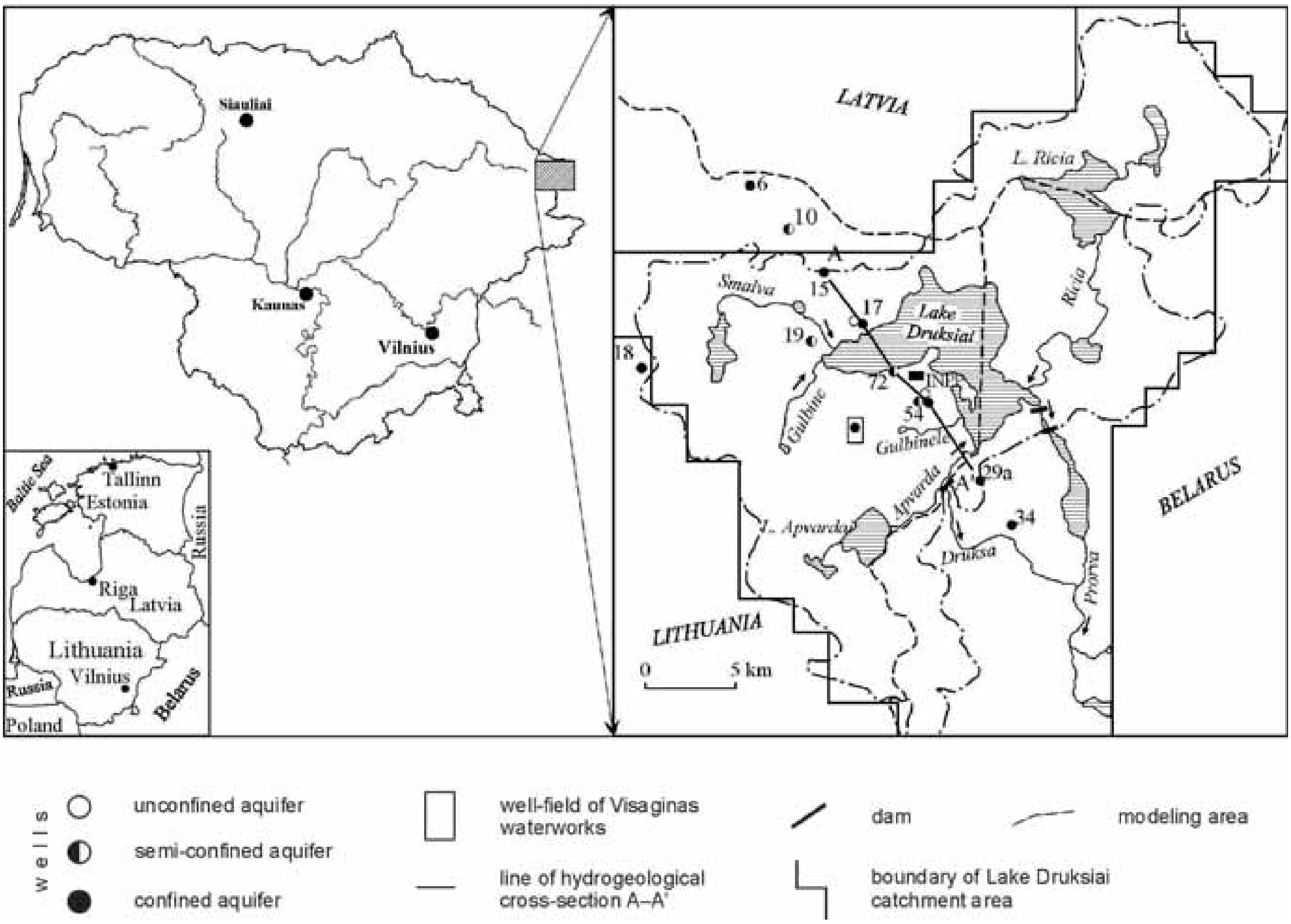

Fig. 1. Location of study area

GEOLOGICAL, HYDROGEOLOGICAL AND HYDROLOGICAL SETTINGS

Many specialised geological and hydrogeological investigations have been performed in the region of Lake Druksiai. Their results have been submitted in detailed reports and maps of different scale (from the review one up to 1:50,000) (Marcinkevicius, Laskovas, 1995).

Overlying the basement of crystalline rocks (granite-gneisses) of block structure, occurring at a depth of 700–750 m, the cover of sedimentary deposits is composed of four formations: Cambrian–Vendian sandstone and gritstone — average thickness 200 m; Silurian–Ordovician carbonates and clays — average thickness 250 m; Devonian sandstone, marl and clay — average thickness 200 m; Quaternary sand-loam — average thickness 100 m.

A system of palaeo-valleys, determined by drilling and different geophysical methods, has inherited the location predetermined by a spatial distribution of tectonic faults on the top of the Middle Devonian bedrock. This link can be explained by the fact that river valleys had developed along the terraces of tectonic faults which are in majority of cases predominated by easily weathered and abraded rocks.

From the hydrogeological point of view, Lake Druksiai catchment belongs to the eastern part of the Baltic artesian basin. Main hydrogeological conditions of the catchment along line A–A' are presented in Figure 2.

A zone of fresh groundwater (thickness about 250 m), occurring above the Middle Devonian (Narva) regional aquitard, includes about 20 aquifers; 6 of them (an unconfined aquifer, four semi-confined aquifers in intertill deposits, and one confined Upper–Middle Devonian aquifer) are the most important aquifers for water supply.

The unconfined groundwater in the Lake Druksiai catchment is lying at a depth of 3–4 meters, on average. This depth appreciably varies depending on the surface topography and also on the origin and lithological composition of the aquifer. In the lakes and rivers valleys, and pits, unconfined groundwater frequently comes close to the earth's surface. The deepest unconfined groundwater occurs in hills and close to deep valleys. The glacial aquifer is most widespread in the Lake Druksiai catchment. However, it does not occupy continuous areas because groundwater circulates only in interlayers and

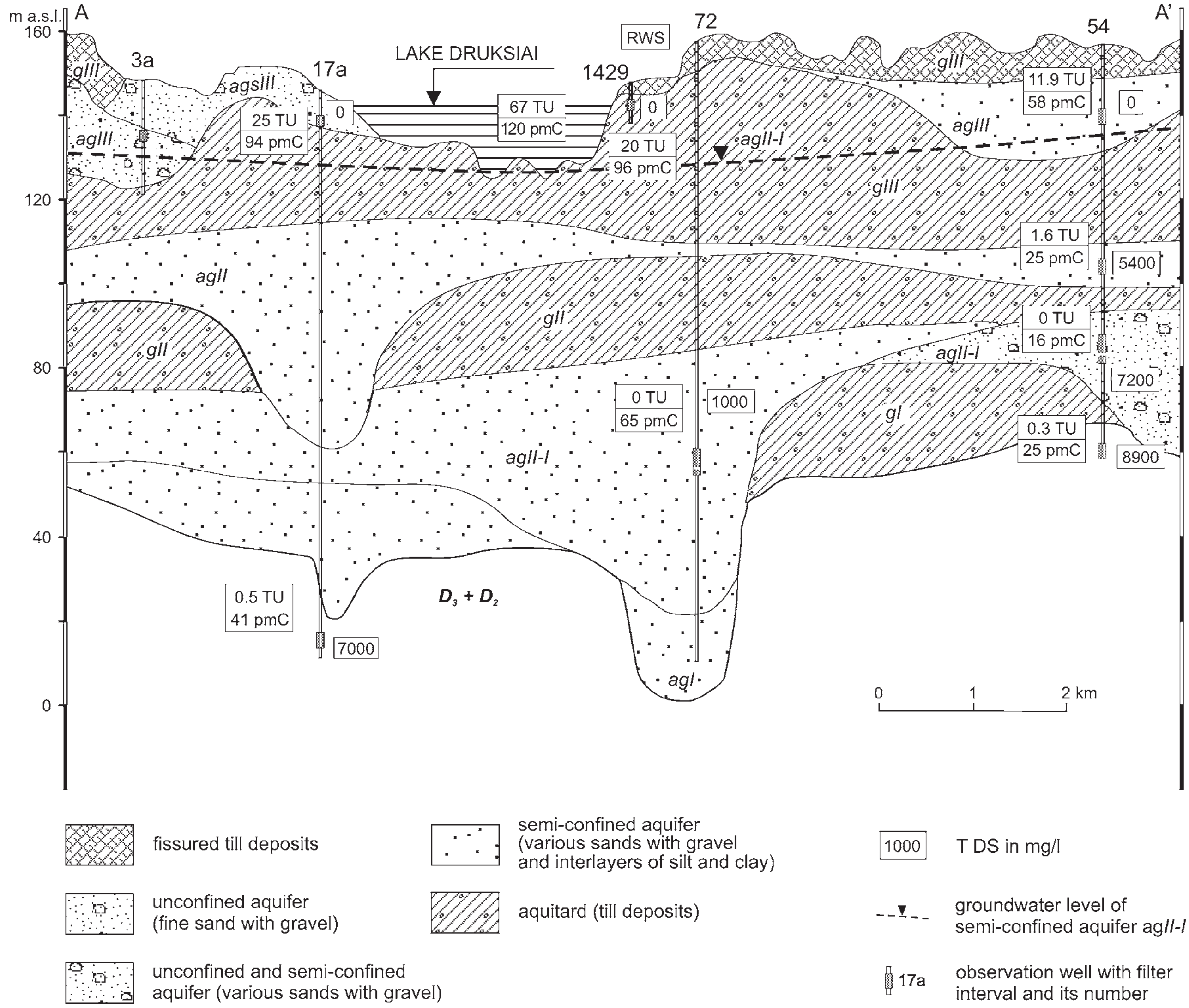

Fig. 2. Hydrogeological section of Lake Druksiai catchment with ^{3}H and ^{14}C data

Line of section is shown in Figure 1

lenses of sand and sandy loam, which are intervened in firm till loam. Usually, water yield in glacial aquifer is very small (0.002 l/s and less). The thickness of the Quaternary formation makes up 80–100 m but within the zones of palaeo-valleys in pre-Quaternary bedrock, reaching the regional aquitard, it increases up to 200–230 m.

The confined Upper–Middle Devonian aquifer is widespread in the whole region, with an exception of deep palaeo-valleys in pre-Quaternary bedrock, filled by the Quaternary deposits. Therefore, the hydrodynamic integrity of their aquifer is not interrupted. The thickness of the aquifer makes up 80–110 m. The aquifer consists of fine-grained sand and sandstone (60%) and layers of clay. The hydraulic conductivity of sand and sandstone varies within the interval of 2–8 m/day, the transmission capacity of the aquifer is 100–900 m^2/day, and effective porosity is 0.1.

The hydrodynamic situation in the Lake Druksiai catchment is characterised by modern recharge, when with the increase of the aquifer depth the altitudes of water level are lowered. The unconfined aquifer, in which the local flows occur, is an exception. The water levels of the Upper–Middle Devonian aquifer, in most cases, are the lowest. Under the natural conditions, they are dipping towards Daugava river valley, from 145–150 m up to 137–140 m a.s.l.

Due to isolation of aquifers from above by aquitards with low hydro-conductivity properties, the vulnerability of groundwater could be assumed as low. This presumption could be confirmed by isotope and helium data indicating the features of groundwater formation, residence in aquifers and hydrogeological significance of tectonic faults (Figs. 3, 4).

Today the catchment area of Lake Druksiai is 613 km^2, 50 of it being included in the Lithuanian territory, 32 — in Belarus, and 18 — in Latvia. The hydrographic network of the lake catchment has undergone considerable changes in the 20th century (Lasinskas, 1991). In about 1912, during the construction of a water-mill, a canal was dug out between Lakes Druksiai and Stavokas. Some water from the lake flew through the new channel (crossing Lakes Stavokas and Obole) directly into Druksa river. A runoff regulation sluice was installed after building a hydroelectric power plant (HEPP) with

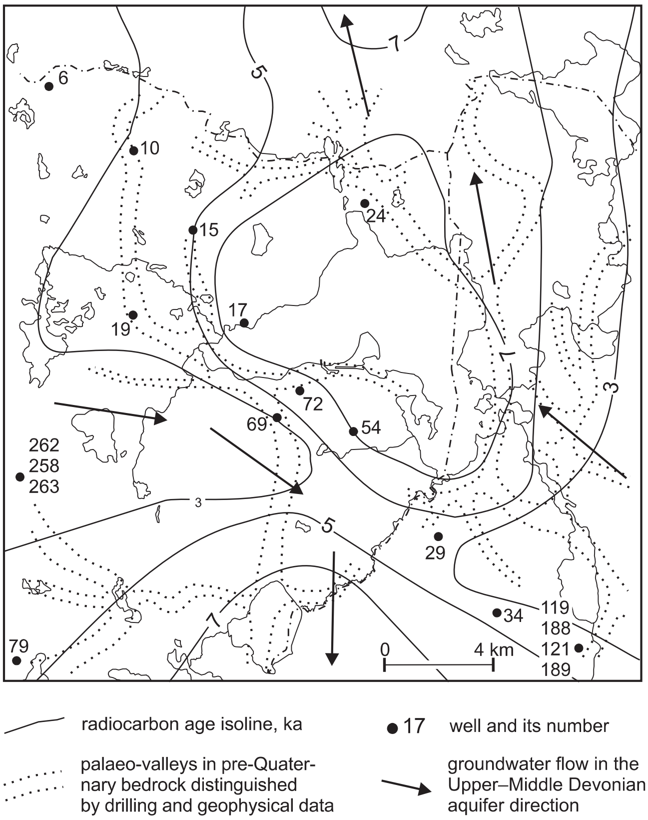

Fig. 3. Radiocarbon age of groundwater from the Upper–Middle Devonian aquifer (data source on palaeo-valleys — Geological Survey of Lithuania)

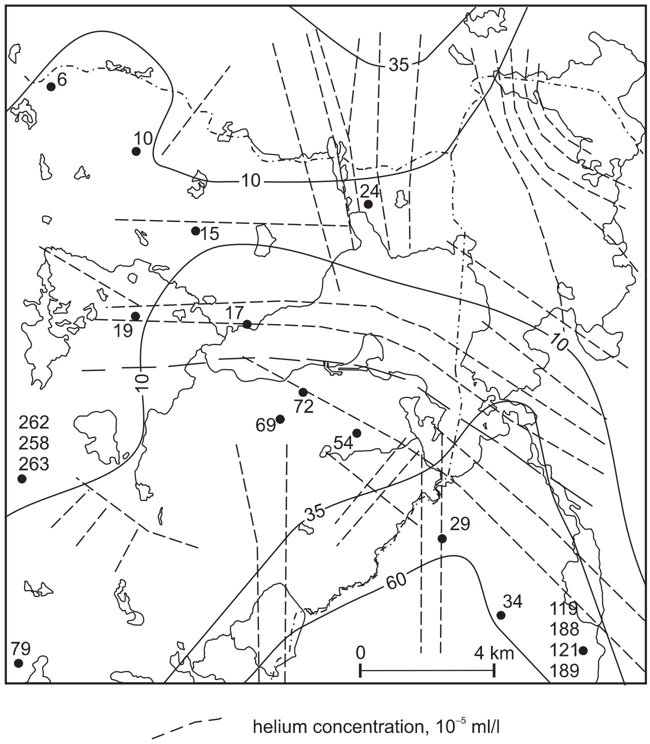

Fig. 4. Helium content in groundwater from the Upper–Middle Devonian aquifer (data source on tectonics — Geological Survey of Lithuania)

capacity of 300 kW, downstream from the Lake Stavokas in 1953. In the same year, the Druksa (Drisviata) river downstream the Apyvarde river mouth was dammed. After that, the entire Apyvarde river runoff was turned directly into the Lake Druksiai, increasing the catchment by 25% and, consequently, increasing the area of intensively used agricultural lands in the catchment of Lake Druksiai.

The area of the Lake Druksiai is 49 km, the maximum depth 33.3 m, the average depth 7.6 m, and the total water volume reaches $369 \cdot 10^6$ m^3 at 141.6 m above sea level (Tautvydas, 1989). The natural lake basin has the altitude of 141.2 m. Above this level the water overflows the lakeside bogs. There are 11 tributaries to the lake including small channels and four bigger streams, and only one river has the outflow from the Lake Druksiai.

Artificial regulation of water level reaches 0.9 m (140.7–141.6 m a.s.l.) and it corresponds to water volume of $43 \cdot 10^6$ m^3. The HEPP was closed in 1982. The first INPP reactor unit started to operate at the end of 1983, the second — in 1987. Since then water of Lake Druksiai has been used for cooling the reactor units (electric power capacity 1500 MW of each unit) of Ignalina Nuclear Power Plant (INPP).

ANTHROPOGENIC LOAD AND WATER MANAGMENT IN THE CATCHMENT

INPP is the main user of the lake water and particularly of the 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/s. Recently, the discharge of heated water has been reduced approximately to 63 m^3/s, the two reactor units operating in turn. Thermal heat load on the lake is 0.06 kWm^{-2} when only one reactor is operating.

During the warm periods (May–August) of 1993–1997, the monthly averaged surface temperatures have not exceeded 23°C, i.e. not exceeded the permissible limits. The ecological limit for daily averaged water surface temperature in the warmest month is 28°C. During 1993–1997, the lake surface water temperature reached 28°C quite rarely forming overheated area that constituted 60% of the total lake area (Sarauskiene, 2002).

The main pollution sources forming the nutrient and even chemical load are related to INPP and Visaginas town. The lake receives the treated waste water used for household needs of the town and of the INPP, and the untreated water from Visaginas and INPP rainfall sewers. The rainwater from the outbuildings of INPP ($8 \cdot 10^6$ m^3/year) and drainage water ($1.5 \cdot 10^6$ m^3/year), extracted by lowering of groundwater level in the INPP site through a closed collector, is turned into the rainwater sewer, which disposes it of into the Lake Druksiai. The waste water treatment plant is designed for full biological treatment and complementary cleaning with sand filters. The capacity of facilities is up to $9,510^6$ m^3/year. The treated municipal water is disposed into the Lake Druksiai through Gulbinele stream. Around $5,510^6$–$8,510^6$ m^3 of pre--treated water gets to the lake every year with mean annual concentrations of nitrogen being 37.7 mg N/l and phosphorus — 3.5 mg P/l.

Only the groundwater is used for household needs of the town and 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 intertill aquifers and to the main productive confined Upper–Middle Devonian aquifer. The same aquifers are exploited in the Latvian and Belarus parts of the Lake Druksiai catchment.

On the Lithuanian side of the Lake Druksiai catchment only the Visaginas waterworks are located. In adjacent territories several centralised waterworks are in operation: in the territory of Lithuania – Ignalina, Zarasai, and Dukstas waterworks; in the territory of Latvia – two waterworks: Daugavpils I and II. There are no centralised waterworks in the Belarus territory of the catchment.

SURFACE WATER AND GROUNDWATER INTERACTION BASED ON HYDROLOGICAL OBSERVATION, ISOTOPE DATA AND GROUNDWATER FLOW SIMULATION

WATER BALANCE

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

Water level fluctuations. When HEPP started in 1953, the natural lake water level raised by 0.3 m (till 141.6 m) and the mean annual water level fluctuation amplitude became 0.8 m or even 1.3 m. Before the lake damming, it had been 0.6 m. After starting the INPP operation, 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 fluctuations amplitude should not exceed 1.2 m to reduce the hazards of shore abrasion (Fig. 5).

Precipitation. Variation of annual precipitation in the Lake Druksiai catchment is small. The greatest amount of precipitation is characteristic of summer months (32%), the smallest — of spring (19%). For the lake water balance model, the average annual precipitation (718 mm or $440.2 \cdot 10^6$ m^3) was derived from the data of precipitation measurement in the Lake Druksiai or near the catchment, where four pluviometers measured the amount of precipitation in 1923–2000.

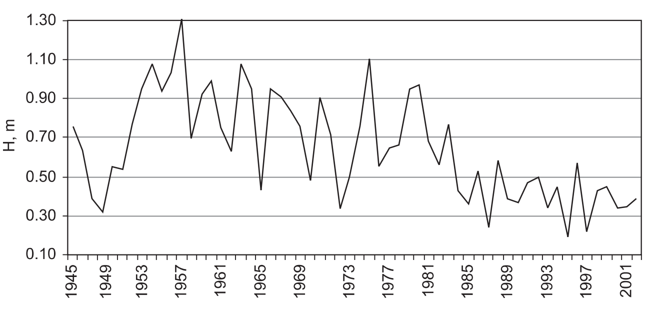

Fig. 5. Amplitude of Lake Druksiai water level fluctuation

Evaporation. During seven months (V–XI) before the operation of INPP (1976–1981) the Lake Druksiai lost 520 mm (or $25.5 \cdot 10^6$ m^3) of water through evaporation (Janukeniene, 1989). Since the beginning of the operation of INPP (1984–1988), the measured average annual evaporation from the water surface has increased up to $47 \cdot 10^6$ m^3 (Janukeniene, 1992) due to increase of average monthly surface temperature of the lake. The accepted annual evaporation from the land for lake water balance consideration is 500 mm (or $28.2 \cdot 10^6$ m^3) (Gailiusis *et al*., 2001).

Surface inflows and outflow. Almost the entire surface runoff through Apyvarde ($36.9 \cdot 10^6$ m^3) and Ricianka streams ($22.1 \cdot 10^6$ m^3) gets into the southern part of the lake. In this part, water for INPP usage is taken and discharged again. The runoff (Prorva stream) in the water balance consideration is $100.4 \cdot 10^6$ m^3. This value was derived from the annual runoff measurements and was revised according to long time measurements in nearby catchments (Tautvydas, 1989).

ISOTOPIC DATA

Stable isotope composition of water molecule oxygen for groundwater around Lake Druksiai changes from –11.9‰ to –9.0‰, and does not significantly differ from isotope patterns of Lithuanian groundwater attributed to active exchange zone. The most negative values of ^{18}O are characteristic of western part of Lake Druksiai region and together with the highest piezometric level of groundwater indicate recharge area. The most positive values of ^{18}O are characteristic of southeastern part of region of Lake Druksiai, in the area close to tectonic fault zones where piezometric level distribution in consequent aquifers shows groundwater flow through confining beds from deeper aquifers to the subsurface. These areas have been qualified as local discharge areas with relatively positive ^{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 (Fig. 3, Table 1).

Table 1

Isotope data from wells in region of Lake Druksiai

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

^{14}C activities are uncorrected for the difference between –25‰ and ^{13}C of the sample; ^{3}H values 0 TU fall within counting error

MODELLING INTERACTION BETWEEN SURFACE WATER AND GROUNDWATER

The first models of local scale were applied to Lake Druksiai catchment with ^{3}H data on groundwater monitoring in site of radioactive waste storage of INPP (Mazeika, Petrosius, 1998; Jakimaviciute *et al*., 1999). In these studies, very local environs of radioactive waste storage with increased ^{3}H activity (up to 30,000–60,000 TU) in unconfined shallow groundwater have been simulated. A very distinct trace of ^{3}H opened a possibility to calibrate model parameters (mainly recharge rate and hydraulic conductivity), and to recover the groundwater levels and ^{3}H activities corresponding to measurements data of 1990–1995.

The regional Middle Devonian aquitard was identified as the lower boundary of the flow area in the section. In a plan, the flow area was limited by the territory of Lake Druksiai catchment with different boundary conditions (impermeable, constant hydraulic head). The influence of lakes and rivers (permeability parameters of beds, pits and constant or varying on the known mode water levels), and waterworks (actual or designed yields) was considered as well. In first iteration, during the groundwater flow simulation, the input parameter values from summarised reports (Table 2) have been selected. In further stages, initial values were calibrated in order to get the best coincidence of simulated and observed in 1990–1995 values of piezometric levels.

The data on conductivity of aquifers and confining layers, groundwater levels, yields and drainage by the rivers (underground runoff) were used for calibration of the model. Some parameter values were corrected based on isotope data: recharge rate according to the mean residence time of ^{3}H in the unconfined groundwater, and hydraulic transmission capacity of aquifers according to ^{14}C age difference between two points along the water flow path line. The application of isotope methods has not essentially changed parameter values in the groundwater flow models but has confirmed groundwater transit times derived from the flow models.

The main data on water balance indicating an interaction between the surface water and groundwater in the Lake Druksiai catchment are presented in Figure 6. The main forming elements of the Lake Druksiai catchment water balance (1990–1995) are the following: surface water inflow — $76.5 \cdot 10^{6}$ m^3/year, precipitation to lake — $35.2 \cdot 10^{6}$ m^3/year, underground inflow to streams and lakes — $22.4 \cdot 10^{6}$ m^3/year (direct underground inflow to Lake Druksiai — $3.2 \cdot 10^{6}$ m^3/year). The groundwater extraction from Visaginas waterworks for household needs of the town and for different use by INPP makes $8.9 \cdot 10^{6}$ m^3/year, water output from waste water treatment plant — $8.5 \cdot 10^{6}$ m^3/year, technological water losses — about $4 \cdot 10^{6}$ m^3/year.

The zone of groundwater active exchange, including unconfined aquifer, semi-confined Quaternary aquifers, and confined Devonian aquifer, covers 99% of total in an exchange presented volume of groundwater. The water flows in the Quaternary unconfined aquifer under steady-state conditions with Visaginas waterworks operation and groundwater lowering in the site of INPP contain $4.8 \cdot 10^{6}$ m^3/year (about 2.87 l/s km^2). $19.2 \cdot 10^{6}$ m^3/year of water reach the Devonian aquifer from above, $14.7 \cdot 10^{6}$ m^3/year of water flows out outside the Lake Druksiai catchment. Extraction of water from the Upper–Middle Devonian aquifer in the Visaginas town waterworks causes depressions of piezometric surfaces of this aquifer and of Quaternary aquifers. It causes an increase (20–30%) of the exchange with adjacent aquifers (in the majority from above) and reduction of the lateral flow. As the used groundwater comes back into the Lake Druksiai, the extraction of groundwater does not have an appreciable influence on the surface run-off. The Lake Druksiai incurs losses due to leakage into aquifers only by operation of Visaginas town waterworks in an intensive mode, and even in this case the inflow of water from the lake into aquifers is very small (36,500–255,500 m^3/year).

Table 2

Main parameters used in groundwater flow simulation

Parameter	Values (from geological mapping reports according to Marcinkevicius and Laskovas, 1995)	Values calibrated in simulation	Values corrected by using radioisotope data	Formulas used in recharge rate (q) and hydraulic transmissivity (T) calculation according to tritium residence time (τ) and radiocarbon age difference (t) along water pathline
Recharge rate [m/day]	$0–8\cdot10^{-4}$	$1\cdot10^{-4}–7\cdot10^{-4}$	$4.7\cdot10^{-4}–7.7\cdot10^{-4}$	$q = \frac{\varepsilon \cdot H}{\tau}$, where: q — recharge rate, ε — effective porosity, H — thickness of unconfined aquifer, τ — residence time of ^3H in aquifer (residence time for sandy aquifer — 3.4 years, for loamy aquifer — 8.8 years basing on statistically data attributed to region of Lake Druksiai)
Hydraulic conductivity of Upper Quaternary unconfined aquifer (1 aquifer) [m/day]	0.1–8	0.1–2	n/c	
Hydraulic transmissivity of Lower Quaternary confined aquifer (2 aquifer) [m^2/day]	30–270	40–120	120–200	
Hydraulic transmissivity of Upper–Middle Devonian (D_{3+2}) confined aquifer (3 aquifer) [m^2/day]	100–900	250–500	400–590	
Effective porosity of Quaternary aquifers (1 and 2)	0.05	0.05	n/c	$T = \frac{\varepsilon \cdot L^2 \cdot b}{\Delta h \cdot \Delta t}$, where: T — transmissivity, L — water pathline length between two observation wells with ^{14}C and hydraulic head data, b — aquifer thickness, Δh — hydraulic head gradient, Δt — radiocarbon age difference (main ^{14}C data plotted in Fig. 2)
Effective porosity of Upper–Middle Devonian (D_{3+2}) aquifer (3)	0.10	0.10	n/c	
Leakage through confining bed between 1 and 2 aquifers [1/day]	$5\cdot10^{-6}–2\cdot10^{-4}$	$5\cdot10^{-6}–2\cdot10^{-4}$	n/c	
Leakage through confining bed between 2 and 3 aquifers, [1/day]	$1\cdot10^{-5}–5\cdot10^{-4}$	$1\cdot10^{-5}–5\cdot10^{-4}$	n/c	

n/c — not corrected

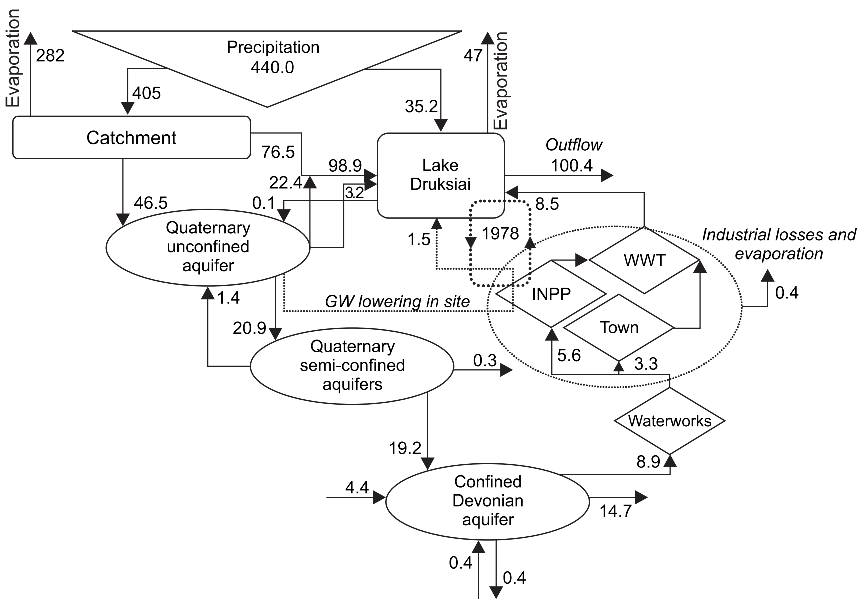

Fig. 6. Simulated surface water and groundwater interaction (recharge and discharge flows, $\times10^6$ m^3/year) in the catchment of Lake Druksiai

REMARKS

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

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