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Research Article

CONCENTRATION OF URANIUM IN WATERS OF THE BIGGEST LAKES OF THE TYWA RIVER DRAINAGE BASIN

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ABSTRACT

The paper presents the results of research of uranium concentrations in its different kinds – suspended and dissolved – in waters of the largest lakes located in the catchment area of the River Tywa – Strzeszowskie Lake, Dłużyna Lake, Długie Lake and Dłuzec Lake. Small (or the order of several 0,01 μg/l) variations in concentration of uranium in different lakes were noted. The study has also shown a seasonal variation – in a similar range – in concentrations of the above species of uranium, as well as total uranium. The content of dissolved uranium was highest in the autumn and winter, lower in the spring and summer. Overall, total uranium was found in greatest concentrations during the fall, in other seasons concentrations were lower and similar to each other. Suspended uranium was found in largest concentrations in autumn and summer, in lower ones in spring and winter. Concentrations of the different species of uranium during the study period showed a small variation – variation coefficient below 10% for total uranium and dissolved uranium, and about 25% for suspended uranium. The observed concentrations of uranium were typical of uncontaminated unpolluted water.

Keywords: Tywa River, Dłużec Lake, Długie Lake, Strzeszowskie Lake, Dołgie Lake, uranium, uranium concentration in water.

INTRODUCTION AND RESEARCH OBJECTIVES

Uranium is a heavy metal, generally regarded by the public as rare – however, in the environment it is in fact more common than such elements as cadmium or selenium [Bowen 1979]. Uranium occurs naturally in earth's crust at concentrations of approximately 4 ppm; such concentrations are similar to those characteristic of arsenic, boron or other lanthanides, and an order higher than some non-heavy metals, for example silver and mercury. Uranium is found in varying concentrations in all soils, rocks, minerals, as well as food and water (Kabata-Pendias, Kabata, 1999).

Tests of 3700 water samples collected in Ontario (Canada) in 1990–1995 showed the mean uranium content was 0.05–4.21 μg/l, and in treated potable water – 0.40 μg/l. Average uranium concentration in drinking water in New York was in the range of 0.03–0.08 μg/l. In five Japanese cities, the mean level of uranium in drinkable water was 0.9 μg/l. However, there have been cases of occurrence of uranium at much higher concentrations, especially in small supplies. For example, concentration of 700 μg/l was found in a small private water supply in Canada. Research conducted in Finland in waters used to supply drinking water to the populace, the median concentration was found at the level of 28 μg/l. In a study of 476 Norwegian groundwater samples, 18% of them had uranium concentrations in excess of 20 μg/l. Concentrations in excess of 20 μg/l have also been found in groundwater in New Mexico, USA and in central Australia [WHO 2011].

Uranium present in natural water reservoirs comes primarily from anthropogenic sources, such as: fertilization with phosphate fertilizers, processing of apatites, production of construction materials (cement), manufacturing pigments for glass and ceramics industry. The use of phosphate fertilizers is a major source of anthropogenic uranium (fertilizers contain up to 390 mg of U/kg, depending on production technology, raw materials used and the fertilization dose applied) because of high uranium content in phosphate ores (uranium in apatite: 30–120 mg/kg) [Zielinski et al. 1,997; Kratz and Schnug 2006]. Other anthropogenic sources include uranium mining waste, burning of coal and petroleum products, emissions from nuclear power plants and military uses of uranium. Also coal-fired power plants are one of its significant sources in the environment, as coal and peat are characterized by high uranium content, of up to 200 mg/kg [Bowen 1979]. Sources of uranium in the marine environment include atmospheric precipitation of terrigenous material, as well as inland waters inflow [Skwarzec et al. 2002].

CHARACTERISTICS OF THE RESEARCH AREA

Landscape of the Tywa River basin, as well as the whole West Pomeranian Lakeland was shaped in the last Scandinavian glaciation, during glacier stagnation in the Pomeranian stage [Kondracki 2001]. Southern parts of the Tywa River drainage basin are located in the Myślibórz Lake District; its northern parts belong to the Wełtyń Plain, while the estuarine segment is located within the Lower Oder Valley [Kępińska-Kasprzak et al. 1997, Raczyńska 1999, Kondracki 2001].

Tywa River – with a length of 47,9 km and catchment area of 264,5 km ^{2} – is a right tributary of the East Oder. SNQ reliable flow calculated for the section of the mouth of the river is 0.71 m^3/s. Tywa catchment area is located in the geographical terrain where the share of underground water and lakes water recharge is estimated at more than 60% of the total runoff. Average specific runoff of the Tywa River in the years 1961–1985 was 3,41 $l/s/km^2$ [Duda et al. 1991].

Lakes, especially in the middle section of the river, are the dominant component (2.8%) of the landscape of the Tywa River drainage basin [Kępińska-Kasprzak et al. 1997, Duda et al. 1991, Raczyńska 1999] – 30 lakes were counted in the Tywa catchment area (18 with the surface of less than 10 ha). Tywa runs through eight ribbon lakes; only 4 of them have the surface exceeding 50 hectares – the series of lakes: Strzeszowskie, Dołgie (Dłużyna), Długie (Swobnickie) and Dłużec, where the present study was conducted. The lakes are situated in the western part of the Myślibórz Lake District, within the Chojna-Moryń Lake Group [Piskorski, 1979, Kondracki 1994, 2000, Kubiak 2003]. The aquifers are located among forests, and are used for tourism and recreation purposes, as well as lake fishing. The lakes' morphometric characteristics are presented in Table 1, while the uses of the catchment area are shown in Table 2. A detailed description of the general limnological and geographical characteristics is given by Kubiak et al. [2009, 2013].

Table 1. Morphometric characteristics of the studied lakes

No	Indicator	Strzeszowskie Lake	Dołgie Lake	Swobnickie Lake	Dłużec Lake
1	Latitude	52°59.6'	53°00.5'	53°03.7'	53°07.3'
2	Longitude	14°36.9'	14°37.3'	14°38.6'	14°39.4'
3	Maximum length (m)	1900	1850	3900	2400
4	Maximum width (m)	1150	450	1200	500
5	Average width (m)	670	304	882	355
6	Elongation ratio	1.6	4.1	3.2	4.8
7	Maximum effective length (m)	1900	1700	3900	2200
8	Maximum effective width (m)	1150	450	1200	600
9	Shoreline length (m)	5750	4350	9000	5875
10	Shoreline development index	1.44	1.64	1.37	1.79
11	Water table surface (ha)	127.2	56.3	344	85.2
12	Volume (thous. m^3)	9499	1700	14485	5228
13	Maximum depth (m)	14.2	6.6	6.8	10.4
15	Average depth (m)	7.4	3.1	4.2	6.1
16	Depth indicator	0.52	0.47	0.62	0.58

Table 2. Uses of catchment areas of the studied lakes

Lake	Swobnica				Dłużec				Strzeszowskie				Dłużyna			
Usage	Direct drainage basin		Total drainage basin		Direct drainage basin		Total drainage basin		Direct drainage basin		Total drainage basin		Direct drainage basin		Total drainage basin	
	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%	km²	%
Forests	3.9	34.1	26.8	26.0	0.5	4.3	28.4	22.8	0.1	2.2	1.8	15.7	4.7	59.5	12.9	23.2
Grazing land	-	-	5.4	5.3	0.4	3.2	7.0	5.6	0.5	10.4	0.5	4.6	0.2	2.0	4.6	8.3
Waters	3.4	30.4	5.1	5.0	1.0	7.9	6.1	4.9	1.3	25.6	1.4	12.7	0.6	7.6	0.9	1.6
Arable land	3.8	33.3	62.7	60.9	9.5	79.5	79.1	63.4	2.6	52.6	6.8	60.8	2.4	29.9	36.1	65.2
Other	0.3	2.2	2.9	2.8	0.6	5.1	4.1	3.3	0.5	9.2	0.7	6.2	0.1	1.0	1.0	1.7
Total	11.3	100	102.9	100	12.0	100	124.7	100	5.0	100	11.3	100	7.9	100	55.4	100

The lakes Strzeszowskie, Dłużec near Banie and Dołgie are eumictic, periodically presenting tachymictic features, while the lake Długie (Swobnickie) is polymictic. Oxygen systems in these lakes are proof of their high trophic index [Kubiak et al. 2009].

Tywa River drainage basin is characterized by fairly significant differences in hypsometric terms. In the area of the Myślibórz Lake District, where the tested lakes are located, the landscape is hilly – however, the moraine hills of this lake district only in a few instances exceed the height of 100 m above sea level, with relative heights of 20 to 40 m. The Tywa drainage basin is situated at the average altitude of 57m above sea level, longitudinal slope from the source to the river mouth is 2,2‰, while the average slope is of 8‰ [Duda et al. 1991, Raczyńska 1999].

Surface lithology of the Tywa River catchment area is mainly made up of rock material left behind after the last ice age. Glacial till extends over most of the Tywa River basin, only its lower parts are covered with glacial sands. The majority of the Tywa drainage basin area is covered with podsolic soils (about 67% of the total surface of the basin), extending mainly over the central and estuarial part of the catchment area. Light to medium brown earths are present in the upper section of the drainage basin (about 27% of the total surface) [Duda et al. 1991].

The discussed catchment area is rich in natural plant communities; synanthropic species are only a small share of the plant life, pointing to low contamination of the Tywa River waters. The quality of water in the river makes it a habitat of salmonid fish; also eutrophication index has not been exceeded in water.

Given the low degree of contamination of lake waters in the Tywa River catchment area, as well as a limited number of available publications on the presence of uranium in the Polish lakes. The key objective of the present study was to determine the content of this metal in the waters of the largest lakes in the Tywa River catchment area.

METHODOLOGY

Tests of samples from the lakes Strzeszowskie. Dołgie (Dłużyna). Długie (Swobnickie) and Dłużec were conducted in all seasons. Every year from 2008 to 2010. Water samples were taken at varying depths in the deepest areas of the lakes. For measuring uranium contents ICP-MS spectrometer – Elan DRC from Perkin-Elmer company (detection of <0.1 μg/l) was used. It is a fast and exact procedure for determination of uranium concentration. Even of the order of ng/l in drinking water and mineral waters (Himiri et al. 2000. WHO 2011). Uranium was measured in samples both non-filtered and filtered through a fiberglass filter of 0.45 μm retention. After digestion with nitric acid; this procedure allowed the author to measure the total uranium content as well as the levels of dissolved uranium – the difference in these two concentrations was used for calculation of the suspended uranium concentration.

In order to determine the impact of metabolic processes on the presence of uranium in waters of the tested lakes studies of other hydro-chemical indicators were carried out in parallel. Taking into account the above impact and variability of concentrations of different species of uranium between the aquifers as well as their seasonal fluctuations statistical analysis of the obtained results was performed using the Statistica 10.0 software [StatSoft Inc. 2009].

PRESENTATION AND DISCUSSION OF THE RESULTS

Uranium is one of the most important – in geochemical terms – radioactive elements; it is found in waters usually in small amounts. The highest concentrations are known to occur in acidic waters of igneous rocks and in some types of sedimentary rocks. Concentrations of uranium in seawater vary between 1 and 4 μg/l and remain stable – groundwater uranium contents, which usually do not exceed μg/l, are equally stable. In mineral waters, uranium levels can reach 500 μg/l. In water supplied from uranium deposits the concentrations exceeding 1 mg/l are frequent – although in such areas concentrations to the order of 15 mg/l were also recorded. Average content of uranium in groundwater of temperate climate is 2.1 μg/l (Birke et al. 2009). Uranium levels in the flowing waters of Germany vary between 0.007 and 43.7 μg/l. with a median of 0.33 μg/l (Birke et al. 2009). Earlier publications stated that in the surface waters on the German, uranium concentrations were within the range of 0.007 to 52.7 μg/l (median 0.65 μg/l). At that time highest values were recorded around uranium mines and in areas known for intensive use of phosphate fertilizers [Birke et al. 2003].

The solubility and mobility of uranium compounds in the aquatic environment are a complex issue and depend on the ionic form in which uranium is present [Merkel et al. 2002]. Water migration of uranium is also dependant on oxidation-reduction conditions to a large extent; with an increase in Eh, uranium content in water grows as well. In an oxidizing environment. the element is present in the form of easily migrating uranyl ion. UO_2^{+2}. Uranium shows a marked tendency to binding, forming larger compounds, for example with ions: carbonates. fluorides. sulphates. phosphates and hydroxyl ions [Bernhard, 2004]. Most of the generated cationic, anionic or neutral complexes are very mobile in aqueous solution [Merkel, Sperling, 1998]. Hence, the ubiquitous nature of uranium, particularly in well-oxygenated water and subsurface groundwater. Water migration is restricted by water sorption processes; as soluble uranium compounds are readily adsorbed by silica gels. iron hydroxides and aluminum hydroxides as well as clay minerals [Bernhard, 2004]. In a reducing environment, the reduction of U (VI) to U (IV) results in removal of autogenic uranium from the water to the bottom sediments, as it is then only very weakly soluble [Skwarzec et al. 2002. Bernhard, 2004]. The uranium exchange in the lakes between the bottom sediments and water is described by Chappaz et al. [2010], who further explain that in the anaerobic environment in hypolimnion uranium is reduced to its stable insoluble species and precipitates down to the bottom sediments.

The uranium content in the Oder River waters around Gozdowice was at 1.5 μg/l [Birke et al. 2009]. Different studies conducted in 1999 and 2000 showed that in the Oder River water in the area of Krajnik uranium concentrations (U^{234} and U^{238}) were 1.89 and 1.58 μg/l respectively, while the suspended uranium contents of same isotopes were 0.39 and 0.35 μg/l [Pietrzak-Flis et al. 2004]. The quoted data refer to the waters of the River Oder adjacent to the Tywa River drainage area. In the above years analyses of concentrations of the two isotopes of uranium in waters of lakes Drawsko, Wadąg and Wigry were also carried out. In the Drawsko Lake recorded concentrations were at 0.31 μg/l (1999) and 1.18 μg/l (2000) for the dissolved uranium species. and – respectively for U^{234} and U^{238} – at 0.34 and 0.37 μg/l for suspended uranium. More uranium-rich were found to be the waters of the Wadąg Lake – concentrations of 1.32 and 1.52 μg/l of dissolved uranium and 0.81 and 0.39 μg/l of suspended uranium were recorded in the samples. These studies have also shown that only a negligible proportion of the total uranium amount is made up of the isotope U^{235} [Pietrzak-Flis et al. 2004]. In the Baltic Sea waters (1996–1998) uranium was present at concentrations of 6.11 μg/l in the area of the Gdańsk Deep and 3.96 μg/l in the region of the Bornholm Deep [Skwarzec et al. 2002].

The studies carried out clearly point to the conclusion that in waters of the largest lakes in the Tywa River drainage area uranium is present only at low concentrations (Table 3), similar to those naturally occurring in surface waters [Skwarzec 2002, Pietrzak-Flis et al. 2004]. In the Tywa River waters uranium contents varied within the range of 0.49–2.42 μg/l. The mean concentration of uranium was at 1.26 μg/l in the river water and at 1.19 μg/l in the lakes. In most instances, uranium levels in the studied lake waters were contained within the range of 1.0–1.2 μg/l – frequency of 57.7% of the samples.

Dissolved uranium in waters of all the studied lakes of the Tywa River drainage basin was most frequently measured at within the range

Table 3. Concentrations of different forms of uranium in waters of the studied lakes in the Tywa River drainage area

Lake	Indicator	N	Mean	Confidence interval	Confidence interval	Median	Min	Max	Range	Variation coeff.	Max. freq. range	Freq. (%)
All lakes: total	U dissolv.	272	0.88	0.87	0.89	0.89	0.59	1.18	0.59	10.4	0.8–0.9	48.5
	U total	272	1.19	1.17	1.20	1.19	0.77	1.65	0.80	9.8	1.0–1.2	57.7
	U susp.	272	0.31	0.30	0.32	0.30	0.10	0.58	0.48	28.7	0.3–0.4	42.3
	U dissolv/total (%)	272	74.5	73.7	75.2	75.0	58.3	90.3	32.0	8.5	70–75	31.9
	U susp./total (%)	272	25.5	24.7	26.2	25.0	7.5	41.7	34.2	24.7	20.–25	34.0
Dłużec	U dissolv.	46	0.87	0.85	0.88	0.88	0.75	1.00	0.25	6.7	0.8–0.9	54.3
	U total	46	1.16	1.13	1.19	1.17	1.00	1.42	0.42	7.7	1.1–1.2	41.3
	U susp.	46	0.30	0.29	0.32	0.30	0.20	0.42	0.22	20.4	0.2–0.3	52.1
	U dissolv/total (%)	46	74.1	72.5	75.7	73.1	61.6	82.6	21.0	7.4	70–75	34.8
	U susp./total (%)	46	26.2	24.6	27.7	26.8	17.4	38.4	21.0	19.9	25–30	32.6
Dołgie	U dissolv.	92	0.90	0.89	0.92	0.90	0.70	1.17	0.47	9.2	0.8–0.9	46.7
	U total	92	1.23	1.22	1.25	1.23	1.09	1.65	0.50	6.8	1.1–1.2	39.1
	U susp.	92	0.33	0.31	0.34	0.33	0.17	0.50	0.34	22.3	0.3–0.4	46.7
	U dissolv/total (%)	92	73.4	72.3	74.6	74.4	58.3	87.6	29.3	7.5	70.75	38
	U susp./total (%)	92	27.0	25.9	28.0	26.0	12.9	41.7	28.8	18.6	20–25	39.1
Swobnica	U dissolv.	45	0.86	0.82	0.90	0.84	0.65	1.18	0.60	15.1	0.8–0.9	28.9
	U total	45	1.13	1.09	1.17	1.12	0.77	1.45	0.68	12.5	1.1–1.2	40
	U susp.	45	0.27	0.25	0.30	0.30	0.10	0.46	0.37	30.4	0.2–0.3	42.2
	U dissolv/total (%)	45	76.4	74.3	78.5	77.2	59.2	90.3	31.1	9.2	75–80	37.8
	U susp./total (%)	45	23.6	21.5	25.7	22.8	9.7	40.8	31.1	29.7	20–25	37.8
Strzeszowskie	U dissolv.	89	0.88	0.86	0.90	0.89	0.59	1.11	0.52	9.9	0.8–0.9	57.3
	U total	89	1.18	1.15	1.20	1.18	0.81	1.52	0.71	10.6	1.0–1.21	31.5
	U susp.	89	0.30	0.28	0.33	0.30	0.11	0.58	0.47	35.3	0.2–0.3	42.7
	U dissolv/total (%)	89	74.8	73.3	76.2	75.0	60.9	89.7	28.8	9.2	70–75	28.1
	U susp./total (%)	89	24.5	23.0	26.1	25.0	7.5	39.1	31.6	29.5	20–25	25.8

of 0.8–0.9 μg/l (frequency 48.5%). with mean concentration of 0.88 μg/l and concentration extremes of 0.6 and 1.2 μg/l. Average suspended uranium contents was of 0.31 μg/l (maximum frequency range 0.2–0.3 μg/l. frequency of 42.3%) (Table 3). Dissolved uranium is very mobile in well oxygenated waters [Merkel. Sperling. 1998], hence the different variability of uranium concentrations – lower for total uranium and dissolved uranium (variation coefficient <10%). and higher for suspended uranium (variation coefficient ~ 25%). Overall, the element was present in the tested waters mainly in the form of dissolved uranium; on average nearly 75% of the total uranium content in the samples was its dissolved species (Tables 3 and 4).

The geographical differences in the occurrence of uranium are mainly due to the lithology variations of the catchment areas of individual aquifers and anthropogenic factors impacting the lakes and their basins. Maximum concentrations are usually observed in the surface waters in old mining districts. High uranium contents are found also in loess soils areas under intense agricultural exploitation (concentrations correlated positively with utilization of phosphate fertilizers) [Birke et al. 2009]. Ground water contains uranium usually in the range of 2 to 12 μg/1; the lowest uranium levels are recorded generally in the humid climate regions and the highest – in dry climates [Birke et al. 2009].

Consistent geological structure of the Tywa River drainage basin [Mikołajski, 1964] and evenly-spread human pressure in the area [Kubiak et al. 2013] mean that no significant statistical differences in uranium concentrations between the waters flowing in and out of the studied lakes occurred, and that only low variation (of the order of hundredths of a μg/l) in uranium concentrations in the different lakes were recorded. Similarly

Table 4. Concentrations of different forms of uranium in waters of the studied lakes in the River Tywa drainage area in different seasons

Season	Indicator	N	Mean	Confidence interval	Confidence interval	Median	Min	Max	Range	Variation coeff.	Max. freq. range	Freq. (%)
All lakes: total	U dissolv.	272	0.88	0.87	0.89	0.89	0.59	1.18	0.59	10.4	0.8–0.9	48.5
	U total	272	1.19	1.17	1.20	1.19	0.77	1.65	0.80	9.8	1.0–1.2	57.7
	U susp.	272	0.31	0.30	0.32	0.30	0.10	0.58	0.48	28.7	0.3–0.4	42.3
	U dissolv./total (%)	272	74.5	73.7	75.2	75.0	58.3	90.3	32.0	8.5	70–75	31.9
	U susp./total (%)	272	25.5	24.7	26.2	25.0	7.5	41.7	34.2	24.7	20–25	34.0
Spring	U dissolv.	73	0.87	0.85	0.88	0.9	0.7	1.0	0.3	7.0	0.8–0.9	58.9
	U total	73	1.15	1.13	1.17	1.2	0.8	1.3	0.5	8.3	1.1–1.2	45.2
	U susp.	73	0.29	0.27	0.31	0.3	0.1	0.5	0.4	31.2	0.2–0.3	45.2
	U dissolv./total (%)	73	75.2	73.8	76.7	75.0	60.9	90.3	29.4	8.4	70–75	30
	U susp./total (%)	73	24.9	23.4	26.3	25.0	9.7	39.1	29.4	25.1	20–25	42.5
Summer	U dissolv.	87	0.87	0.85	0.90	0.9	0.6	1.2	0.6	14.3	0.8–0.9	28.7
	U total	87	1.20	1.17	1.23	1.2	0.8	1.5	0.7	12.2	1.1–1.2	28.7
	U susp.	87	0.33	0.31	0.35	0.3	0.1	0.5	0.4	28.8	0.3–0.4	48.3
	U dissolv./total (%)	87	72.6	71.1	74.1	72.0	58.3	89.7	31.4	9.7	70–75	26.4
	U susp./total (%)	87	27.6	26.1	29.1	28.0	10.3	41.7	31.4	25.3	25–30	27.6
Epilimnion	U dissolv.	39	0.90	0.86	0.95	0.9	0.6	1.2	0.6	15.0	0.8+0.9	28.2
	U total	39	1.23	1.18	1.28	1.2	0.8	1.5	0.7	12.3	1.2–1.3	30.8
	U susp.	39	0.33	0.30	0.36	0.3	0.1	0.5	0.4	29.7	0.3–0.4	48.7
	U dissolv./total (%)	39	73.2	71.0	75.4	72.9	62.7	85.8	23.2	9.3	70–75	25.6
	U susp./total (%)	39	26.9	24.7	29.1	27.1	14.2	37.3	23.2	25.5	25–30	25.6
Metalimnion	U dissolv.	17	0.85	0.80	0.91	0.8	0.6	1.0	0.4	13.0	0.8–0.9	41.2
	U total	17	1.19	1.12	1.25	1.2	0.9	1.4	0.5	10.3	1.2–1.3	35.3
	U susp.	17	0.33	0.27	0.38	0.4	0.1	0.5	0.4	33.6	0.3–0.4	36.3
	U dissolv./total (%)	17	72.2	67.9	76.6	69.2	61.9	89.7	27.8	11.7	60–65	23
	U susp./total (%)	17	27.7	23.4	32.1	30.8	10.3	38.1	27.8	30.4	35–40	35.4
Hypolimnion	U dissolv.	31	0.85	0.81	0.89	0.9	0.6	1.0	0.5	13.4	0.9–1.0	35.5
	U total	31	1.18	1.12	1.23	1.2	0.8	1.5	0.7	12.9	1.1–1.2	35.5
	U susp.	31	0.34	0.30	0.37	0.3	0.1	0.5	0.4	25.9	0.3–0.4	54.8
	U dissolv./total (%)	31	72.0	69.5	74.4	72.0	58.3	87.4	29.1	9.3	70–75	38.7
	U susp./total (%)	31	28.4	26.0	30.7	28.0	12.6	41.7	29.1	22.7	25–30	41.9
Fall	U dissolv.	47	0.91	0.88	0.94	0.9	0.8	1.2	0.4	10.3	0.8–0.9	42.3
	U total	47	1.24	1.20	1.27	1.2	1.1	1.6	0.5	8.6	1.2–1.3	27.7
	U susp.	47	0.34	0.31	0.36	0.3	0.2	0.6	0.4	24.0	0.3–0.4	42.6
	U dissolv./total (%)	47	73.5	71.7	75.3	73.8	61.6	87.6	26.0	8.1	70–75	31.9
	U susp./total (%)	47	25.9	24.0	27.8	25.2	7.5	38.4	30.9	25.2	20–25	34.6
Winter	U dissolv.	65	0.89	0.88	0.91	0.9	0.8	1.0	0.2	6.2	0.8–0.9	67.6
	U total	65	1.17	1.15	1.19	1.2	1.0	1.3	0.3	6.8	1.1–1.2	40
	U susp.	65	0.27	0.26	0.29	0.3	0.2	0.5	0.3	22.0	0.2–0.3	67.7
	U dissolv./total (%)	65	76.2	74.9	77.4	75.0	61.5	83.3	21.8	6.7	70–75	41.5
	U susp./total (%)	65	23.7	22.5	24.9	25.0	16.7	33.3	16.6	20.1	24–28	41.5

Measuring unit: µg/l

low variation was found depending on the seasons of the year (Table 4). Because uranium is not an element essential for the functioning of hydrobiocenosis, no correlation was found between the uranium contents and levels of biological production indicators (%O_2 chlorophyll "a" total organic carbon) [Kalff, 2002].

Waters of the Dołgie Lake was richest in dissolved uranium, where the mean concentration was 0.90 μg/l. the results ranged between 0.70 – 1.17 μg/l, and the maximum frequency range was 0.8-0.9 μg/l – at 46.7% frequency. The smallest dissolved uranium concentrations were found in the waters of Swobnica Lake, where the mean dissolved uranium content was of 0.86 μg/l and the range between 0.65 – 1.18 μg/l, with the maximum frequency range of 0.8-0.9 μg/l (frequency 28.8%). Waters of the remaining two reservoirs showed intermediate concentrations of dissolved uranium although the maximum frequency ranges for all samples were the same for all lakes (Table 3 and 4). Similar variations were found for total uranium content, as well as suspended uranium - the average total uranium content varied from 1.23 μg/l in the Dołgie Lake and 1.18μg/l in the Strzeszowskie Lake to 1.13 μg/l in the other two tested aquifers. The total uranium concentration maximum frequency range was of 1.1-1.2 μg/l – for suspended uranium the range was between 0.2-0.3 μg/l (only for the Dołgie Lake, the maximum frequency range was of 0.3-0.4 μg/l) (Tables 3 and 4).

The study revealed that uranium contents in the waters of the studied lakes of the Tywa River drainage basin varied in different seasons with same changes noted for all aquifers. Dissolved uranium levels were highest in the autumn (mean of 0.91μg/l) and winter (0.89 μg/l); they were lower in the spring and summer (0.87μg/l). Highest total uranium contents were also recorded in the autumn (1.24 μg/l); in other seasons concentrations were similar (1.16 μg/l in winter. 1.15 in spring and 1.20 μg/l in the summer. respectively). The largest concentrations of suspended uranium species were found in the autumn as well (average 0.34 μg/l) and in the summer (0.33); they were lower in the spring and winter (mean contents of 0.29 and 0.27 μg/l. respectively) (Tables 3-4).

Seasonal and vertical variation in uranium contents in the samples was the same in all the studied lakes. In all the aquifers throughout the year no uranium concentration variation dependant on sampling depth was found for any uranium species. In the summer epilimnion waters contained 1.23 μg/l of total uranium on average, 0.90 μg/l of dissolved uranium and 0.33 μg/l of its suspended species. In the other layers, i.e. metalimnion and hypolimnion concentrations were of 1.19. 0.85 and 0.33 μg/l for total dissolved and suspended uranium in metalimnion and – respectively – of 1.18. 0.85 and 0.34 μg/l for hypolimnion; the recorded differences were not statistically significant (Tables 3 and 4).

No vertical differentiation in uranium concentrations was due to significant water dynamics in the tested bodies of water mass and the fact that uranium is not a biophile element, thus, vertical changes in the intensity of metabolic processes in lakes did not result in formation of vertical variation of uranium contents [Wetzel 2001, Kalff 2002].

CONCLUSIONS

The conducted studies allow for drawing of the following conclusions regarding the presence of uranium and its various species in lakes waters in the Tywa River drainage area:

1. In the studied aquifers uranium was present in low concentrations similar to those naturally occurring in surface waters.
2. There was no correlation between the concentrations of uranium and intensity of biological production indices.
3. On the basis of studied samples it was found that there is a small variation in uranium concentrations (of the order of hundredth of a μg/l) between different lakes. The most uranium-rich waters were those of the Dołgie Lake, while the lowest levels were recorded in the Swobnica Lake.
4. In the waters of the studied aquifers uranium content varied depending on the season. Dissolved uranium contents were highest in autumn and lowest in the spring and summer. Also total uranium concentrations were found to be greatest in the fall, in other seasons concentrations were lower and similar to each other. Highest suspended uranium levels were recorded in the autumn and summer they were lower in the spring and winter.
5. In the studied lakes no vertical variation in the sample uranium contents was noted.
6. There were no significant statistical differences in uranium concentrations between the waters flowing in and out from the four lakes.

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