PRACE GEOGRAFICZNE, zeszyt 143

Instytut Geografii i Gospodarki Przestrzennej UJ
Kraków 2015, 33–46
doi: 10.4467/20833113PG.15.024.4625

THE DYNAMICS OF FLUVIAL TRANSPORT OF SOLUTES IN THE FLUVIAL-LACUSTRINE SYSTEM OF THE LEWIŃSKA STRUGA STREAM (WOLIN ISLAND, WEST POMERANIA)

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Abstract: The presented results constitute a summary of a five-year study conducted from 2009 to 2013 in the upper catchment of the Lewińska Struga stream. Weekly research on the physical and chemical properties of Lewińska Struga waters at the Domysłów profile was combined with seasonal hydrochemical studies conducted in the following five flow-through lakes: Warnowo, Rabiąż, Czajcze, Domysłowskie and Żółwińskie. Across young glacial areas of the Polish Lowland, a drainage network is often produced by a fluvial-lacustrine system, in which a river links subsequent lakes via short sections. In such cases, this fluvial transport of solutes is sometimes disturbed in lakes, which are both their source and deposition area. The main research strategy of the paper was aimed at determining the functioning of the fluvial-lacustrine system of Lewińska Struga stream on Wolin Island. This paper also discusses the dynamics of fluvial transport of solutes carried with Lewińska Struga waters.

Keywords: river-lake system, water quality, seasonal fluctuations, denudation

Introduction

At young glacial areas within fluvial-lacustrine systems, water circulation is determined by (1) meteorological conditions which affect the supply of water and solutes into a catchment area, and by (2) physical and geographical characteristics of a catchment itself (including size, terrain, land use, soil conditions, lake density index). They regulate a range of circulation and outflow of water and matter from a catchment. Fluvial-lacustrine systems within the Baltic Sea Coast are typically composed of shallow lowland lakes. The biodiversity and water quality in these fluvial-lacustrine systems of water circulation are affected by numerous factors: relatively short retention times of lake waters, stage of a lake development, physical and chemical properties of water and high ion load provided by a river (Milner *et al.* 2007). Natural eutrophication of fluvial-lacustrine geoecosystems may lose balance as a result of anthropopressure, especially in an effect of providing additional energy and matter which may pose a threat to keeping stability and natural trophism of lakes (Bajkiewicz-Grabowska, Zdanowski 2006).

Water reservoirs play an important role in the circulation of solutes within fluvial--lacustrine systems. River-transported matter coming from chemical denudation is partially accumulated in lakes which accelerates their evolution. At the same time the transit of waters through lakes contributes to supply biogenic substances to river sections below water reservoirs. There is a number of positive and negative interactions between a lacustrine geoecosystem and a water-course flowing through it, however, it is very difficult to clearly identify how these two systems interact (Hillbricht-Ilkowska 1999; Marcarelli, Wurtsbaugh 2007). Lakes are characterised by longer hydraulic retention times compared to rivers which causes that accumulation and sedimentation of allochthonous matter prevails within them (Kling *et al.* 2000; Neal *et al.* 2008).

Chemical denudation is a relevant determinant of the circulation of elements in the nature. It depends on geology, lithology, soil cover, hydrogeological conditions and land use. However, it is crucial to keep the circulation of water in the catchment system because it has the largest impact onto the geoecosystems and their changes. Repeated and regular monitoring of the physical and chemical properties of surface waters of the upper Lewińska Struga is very relevant to determine the direction and rate of geomorphic development and to determine the human impact on the chemistry of the analysed waters.

The research problem of the article was to determine the functioning of the fluvial-lacustrine system of Lewińska Struga on Wolin Island. The work shows the dynamics of fluvial transport of solutes carried with the Lewińska Struga waters and identified quality of surface waters of Lewińska Struga catchment.

The present article presents the specificity of transport of solutes in the fluvial--lacustrine system of the upper Lewińska Struga waters and shows some regular impacts of lake retention onto the quantity and quality of material discharged from the catchment. The results are based on the hydrochemical studies conducted in the hydrological years: 2009–2013 within the following lakes: Warnowo, Rabiąż, Czajcze, Domysłowskie and Żółwińskie as well as at the Domysłów measurement profile at the Lewińska Struga waters.

Study area

The upper catchment of the Lewińska Struga is located in north-west Poland on Wolin Island, in the western part of the Warnowo-Kolczewo Lake District within the Wolin National Park (Fig. 1). According to the division made by Kondracki (2000) the research area is located within the Central Lowland province, Central-European Coastline sub-province, Szczecińskie Coastline macro-region, Uznam and Wolin Islands mezo-region. The area is characterised by the following features: coastal location, almost complete forestation, predominantly podsols created on glacial sediments, moderate anthropopressure in the lakes area.

The upper catchment of the Lewińska Struga with its area of 11.6 km^2 and lake density index at 12.2% is covered predominantly with low permeable sediments (clays and dusts). Sandy areas of valley floors and glacial channels in the south-eastern

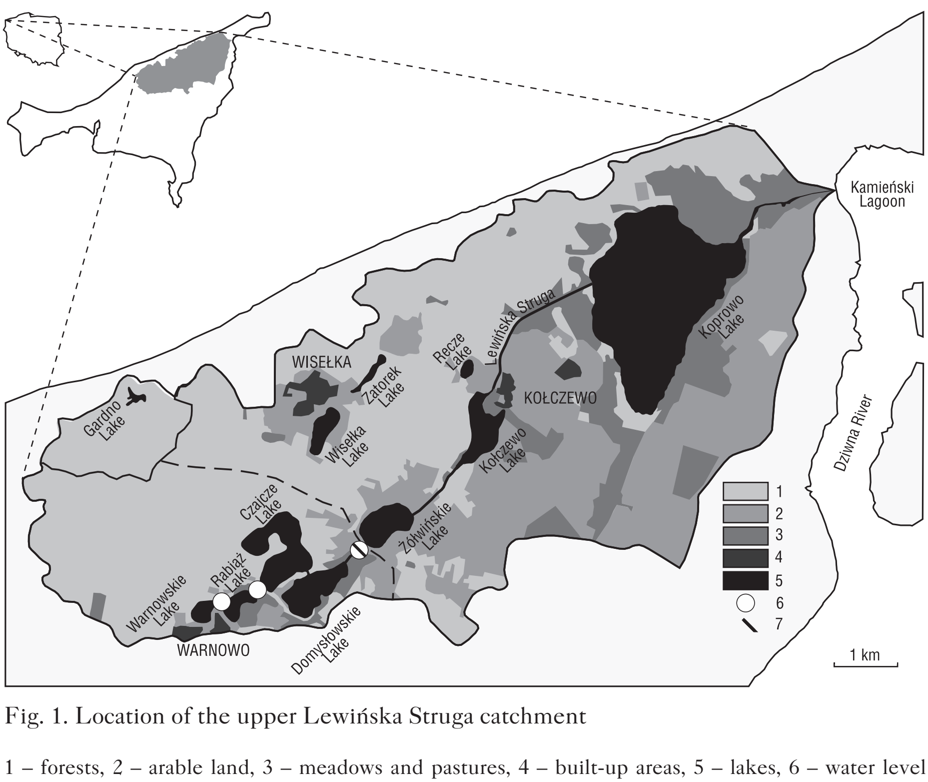

Fig. 1. Location of the upper Lewińska Struga catchment

1 – forests, 2 – arable land, 3 – meadows and pastures, 4 – built-up areas, 5 – lakes, 6 – water level measurement, 7 – hydrometric profile

Source: authors' own study.

part is used for agriculture (7.8% – arable lands, 5.2% – meadows and pastures), built-up areas can only be found in the vicinity of the Warnowo and Rabiąż Lakes (1.8%), while the remaining area (73%) is forested (Samołyk, Ścisłowska 2014).

The Warnowo, Rabiąż, Czajcze, Domysłowskie and Żółwińskie Lakes are shallow, ribbon post-glacial reservoirs supplied with precipitation, surface run-off and groundwaters (Grzegorczyk *et al.* 2008; Samołyk 2013). The Lewińska Struga runs through these lakes and transport waters further through the Kołczewo and Koprowo Lakes to the Kamieński Lagoon.

The average depth of the studied lakes is 2.0 m and it is much lower than the average depth of Polish lakes (7.02 m) specified by Choiński (1995). None of the analysed lakes (Samołyk 2013) reaches the average shore-line development index as identified by Choiński (1995) for Poland at a level of 1.85. This is characteristic to small lakes of post-glacial origin.

The Lewińska Struga is a linear watercourse, with little shore-line development at a level of 1.07 m a.s.l. and its very small gradient of 0.11‰. Average flow of Lewińska Struga at Domysłów profile is 0.06 $m^3 \cdot s^{-1}$, maximum water depth is 0.7 m and the width of this valley is about 2 km. The structure of land use in the close proximity to the river-bed is dominated by grassland and arable lands (Samołyk 2013; Tylkowski 2014). Due to this small gradient of the river bed, low capacity (performance), considerable width of the valley and considerable growth of vegetation within the upper Lewińska Struga (forestation 73%), a flow of water at the point closing Domysłów is often imperceptible and stagnant in its nature. The upper Lewińska Struga has a length of 3.0 km, 0.6 km of which is beyond the lakes.

Materials and methods

The lakes (Warnowo, Rabiąż, Czajcze, Domysłowskie and Żółwińskie) and the upper Lewińska Struga were studied on the basis of 10 water quality indicators which allowed to determine the spatial and temporal variability of physical and chemical properties: pH, specific electrical conductivity (SEC) at 25°C, ions HCO_3^-, Na^+, K^+, Mg^{2+}, Ca^{2+}, SO_4^{2-}, NO_3^- and Cl^-. Samples of lake waters were collected in years 2009–2013 from within subsurface water layers (0.3 m below the water level) at the deepest depth profile at least twice per year (the minimal acceptable sampling was limited to spring and autumn mixing of lake waters). Water samples from Lewińska Struga were collected once per week directly from the mainstream, half the depth of the water-course. River water levels were recorded every 10 minutes at the water-gauge profile in Domysłów by means of a limnimeter and flow measurements were made with the application of the conductometric method (Stach 1992). Reaction and electrical conductivity were measured directly in the field and the content of ionic components was determined at the Environmental Monitoring Station laboratories in Biała Góra and the Geoecological Station in Storkowo. The procedures developed by Hermanowicz *et al.* (1999), Kudelska *et al.* (1994) and Namieśnik *et al.* (1995) were followed while conducting these measurements and works.

Results and discussion

During some repeated field studies the average monthly levels of the lakes (Czajcze, Domysłowskie) and water-course (the Lewińska Struga, three measuring points) waters were correlated ($R^2 = 0.71 \div 0.97$) and fluctuated within a minor range (Fig. 2). The water-gauges within the area of the Wolin National Park – located between the Warnowo Lake and the Rabiąż Lake as well as between the Rabiąż Lake and the Czajcze Lake – recorded an amplitude of their water levels at 20 cm in five-year observations. The lowest levels were recorded every year from May to July, and the highest – from November to the end of February. The water-gauge at the end of the partial catchment in Domysłów showed similar regularities while the recorded fluctuations had the largest range here – up to 26 cm (Samołyk, Ścisłowska 2014).

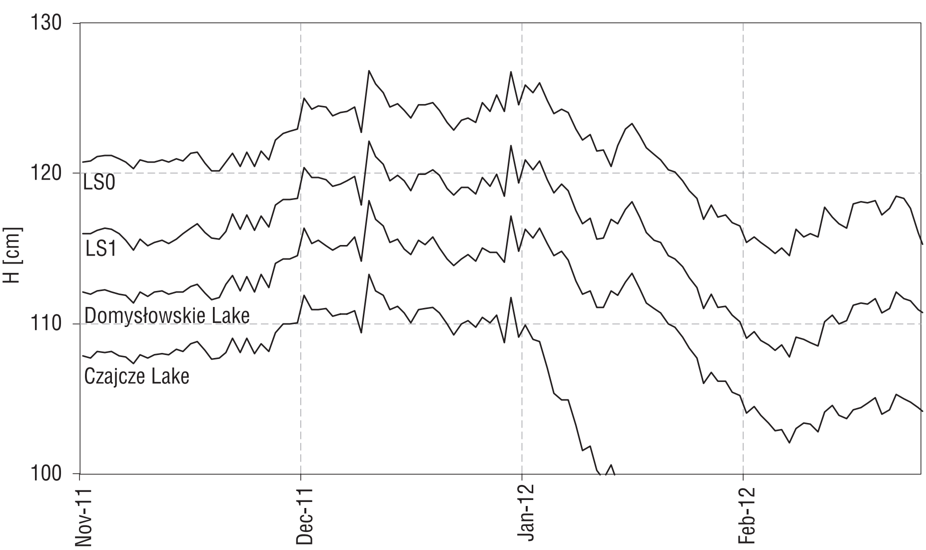

Fig. 2. Daily water levels in the Lewińska Struga catchment (7.11.2011 to 29.02.2012)
Source: authors' own study.

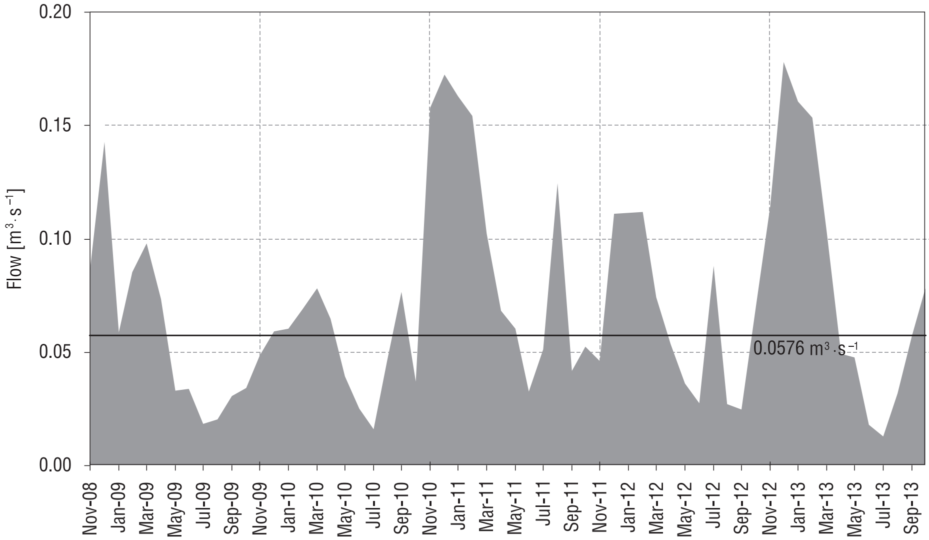

Fig. 3. Average monthly flows in the Lewińska Struga at the Domysłów profile ($m^3 \cdot s^{-1}$) in the hydrologic years: 2009–2013

Source: authors' own study.

The average daily flow measured at the water-gauge profile in Domysłów (Fig. 3) was equal to 57.6 $dm^3 \cdot s^{-1}$ and its variability ranged from 5.1$dm^3 \cdot s^{-1}$ to 221.8 $dm^3 \cdot s^{-1}$. Relatively small outflows from the discussed area result from significant forestation of the catchment area, considerable width of the valley, little length of the water--course and above all the mentioned flow-through lakes.

It showed a strong hydrochemical correlation ($R^2 > 0.6$ for SO_4^{2-}, Na^+, Mg^{2+}) of the Lewińska Struga with the lakes which it flows through (Tab. 1). The chemical composition of all the studied waters is determined by soil cover, lithology and land use. High concentrations of bicarbonate and calcium ions are affected by clay ground, chemoautotrophic bacteria, photosynthesis and an influx of dead biomass. Plant remnants decomposing in anaerobic conditions are a source of sulphates and indirectly nitrates (Samołyk, Ścisłowska 2014).

In the hydrological years (2009–2013), electrolytic conductivity being a measure of water mineralization changed from 20.1 $mS \cdot m^{-1}$ (the minimum value registered in the Domysłowskie Lake) up to 40.8 $mS \cdot m^{-1}$ (the maximum value recorded in the Żółwińskie Lake) with its average value ranging from 25.4 $mS \cdot m^{-1}$ up to 31.4 $mS \cdot m^{-1}$. The seasonal variability of concentration of solutes in the lakes fits – to a large extent – the variability observed in the river waters. The lower mineralization

Table 1. Results of research on the quality of surface waters from the Warnowo, Rabiąż, Czajcze, Domysłowskie and Żółwińskie lakes and the Lewińska Struga (2009–2013)

			Warnowo Lake	Rabiąż Lake	Czajcze Lake	Domysłow-skie Lake	Lewińska Struga	Żółwińskie Lake
Data for years			2009–2013	2009–2013	2009–2013	2009–2010	2009–2013	2009–2013
Number of samples			22	18	26	12	199	19
Water quality index [units]								
pH	[–]	minimum	6.44	6.71	6.70	6.29	6.33	6.67
		average	7.05	7.26	7.30	6.98	7.14	7.29
		median	7.04	7.22	7.29	7.06	7.16	7.33
		maximum	7.55	7.80	7.77	7.27	8.07	7.82
		standard deviation	0.31	0.28	0.32	0.26	0.52	0.41
		coefficient of variation	0.04	0.04	0.04	0.04	0.07	0.06
specific electrical conductivity	[$mS \cdot m^{-1}$]	minimum	22.0	24.0	21.7	20.1	23.1	21.0
		average	30.5	31.4	28.8	25.4	30.7	28.6
		median	29.9	31.0	29.5	23.6	31.6	27.5
		maximum	38.9	37.8	40.3	39.6	37.3	40.8
		standard deviation	5.6	4.9	4.7	5.8	3.3	5.7
		coefficient of variation	0.18	0.16	0.16	0.23	0.11	0.20
HCO_3^-	[$mg \cdot dm^{-3}$]	minimum	130.58	125.66	111.05	128.14	134.49	109.80
		average	173.26	174.82	166.37	161.81	164.24	162.96
		median	176.95	177.23	169.94	159.87	163.45	170.24
		maximum	214.78	214.72	187.32	201.36	199.04	197.64
		standard deviation	27.97	28.35	16.42	21.80	14.75	28.21
		coefficient of variation	0.16	0.16	0.10	0.13	0.09	0.17
Ca^{2+}		minimum	25.65	40.08	34.07	28.06	46.89	24.05
		average	51.29	49.47	50.27	44.67	53.40	48.83
		median	52.21	48.81	49.30	47.09	52.81	51.70
		maximum	78.16	57.11	64.13	54.51	62.44	63.13
		standard deviation	12.23	5.22	5.91	7.96	3.77	10.24
		coefficient of variation	0.24	0.11	0.12	0.18	0.07	0.21

			Warnowo Lake	Rabiąż Lake	Czajcze Lake	Domysłow-skie Lake	Lewińska Struga	Żółwińskie Lake
Data for years			2009–2013	2009–2013	2009–2013	2009–2010	2009–2013	2009–2013
Number of samples			22	18	26	12	199	19
Water quality index [units]								
Cl^-	$[mg \cdot dm^{-3}]$	minimum	17.16	19.19	16.78	14.08	14.39	14.63
		average	21.02	21.08	18.69	18.05	17.35	18.29
		median	21.30	21.01	18.10	17.49	17.15	18.05
		maximum	24.15	23.37	22.36	27.76	21.02	22.09
		standard deviation	1.81	1.17	1.37	3.69	1.37	1.91
		coefficient of variation	0.09	0.06	0.07	0.20	0.08	0.10
NO_3^-		minimum	0.28	0.56	0.81	1.43	0.41	0.27
		average	2.25	1.36	2.36	3.88	2.03	3.68
		median	2.51	1.12	2.16	3.58	1.86	3.83
		maximum	5.10	3.71	4.31	5.96	4.18	8.45
		standard deviation	1.52	0.75	0.94	1.24	0.94	2.48
		coefficient of variation	0.68	0.55	0.40	0.32	0.46	0.67
SO_4^{2-}		minimum	21.06	26.23	20.94	14.99	15.36	22.40
		average	27.67	31.55	25.47	20.78	20.40	25.96
		median	27.88	31.75	24.39	21.08	20.43	25.77
		maximum	41.37	36.82	41.37	26.71	25.69	30.34
		standard deviation	4.60	2.80	4.08	3.24	2.33	2.33
		coefficient of variation	0.17	0.09	0.16	0.16	0.11	0.09
Na^+		minimum	8.93	8.98	8.63	8.01	8.17	8.21
		average	9.51	9.65	9.40	9.55	9.41	9.34
		median	9.42	9.64	9.28	9.59	9.26	9.17
		maximum	10.65	10.67	10.79	11.13	11.09	11.10
		standard deviation	0.49	0.51	0.53	0.91	0.83	0.83
		coefficient of variation	0.05	0.05	0.06	0.09	0.09	0.09

			Warnowo Lake	Rabiąż Lake	Czajcze Lake	Domysłow-skie Lake	Lewińska Struga	Żółwińskie Lake
Data for years			2009–2013	2009–2013	2009–2013	2009–2010	2009–2013	2009–2013
Number of samples			22	18	26	12	199	19
Water quality index [units]								
K^+	$[mg \cdot dm^{-3}]$	minimum	1.78	2.87	2.20	2.04	1.98	2.38
		average	2.79	3.49	2.31	2.39	2.48	2.81
		median	2.37	3.52	2.26	2.38	2.31	2.83
		maximum	5.95	3.80	2.84	2.79	4.21	3.27
		standard deviation	0.98	0.23	0.14	0.23	0.42	0.24
		coefficient of variation	0.35	0.07	0.06	0.10	0.17	0.09
Mg^{2+}		minimum	5.72	6.13	4.94	4.43	5.25	4.82
		average	6.75	6.94	5.92	5.57	6.04	6.06
		median	6.87	7.02	6.04	5.61	6.01	6.25
		maximum	7.46	7.51	6.88	6.20	6.86	6.68
		standard deviation	0.49	0.37	0.47	0.54	0.41	0.46
		coefficient of variation	0.07	0.05	0.08	0.10	0.07	0.08

Source: authors' own study.

of the Lewińska Struga waters was observed during high outflows, and the highest – during low outflows.

A drop in the concentration of HCO_3^- and Ca^{2+} being dominant in the ion-balance was the main reason for their lower mineralization at the maximum outflows. The presence of these ions in the river outflow is mainly related to lithological conditions, underground supplies and intensive chemical weathering. The diversity of HCO_3^- andCa^{2+} at the longitudinal profile in the Lewińska Struga is limited: from 161.8 mg·dm^{-3} to 174.8 mg·dm^{-3} for HCO_3^- and from 44.7 mg·dm^{-3} to 53.4 mg·dm^{-3} for Ca^{2+}. Calcium ions are captured by the lakes as a result of precipitation of poorly soluble calcium compounds to bottom sediments. The concentration of Ca^{2+} shows the highest variability in the lakes (standard deviation from 5.2 mg·dm^{-3} up to 12.2 mg·dm^{-3}) reaching the lowest recorded value at 24.05 mg·dm^{-3} in the Żółwińskie Lake and the maximum of 78.16 mg·dm^{-3} in the Warnowo Lake. At the same time, the concentration of carbonate ions in the Lewińska Struga varies from 46.9 mg·dm^{-3} up to 62.4 mg·dm^{-3} (standard deviation = 3.8 mg·dm^{-3}).

A high level of concentration of chloride and sodium ions in these waters is conditioned by an increase in the supply of marine aerosols. The total average share of Na^+ and Cl^- in surface waters increased from 9.7% for the Warnowo and Rabiąż Lakes up to 10.4% in the Lewińska Struga and the Żółwińskie Lake.

Levels of sulphates remained more or less the same within all the studied waters. However, it should be noted that the average annual concentration of SO_4^{2-} in the Lewińska Struga waters slightly decreased from 22.1 mg·dm^{-3} in 2009 up to 18.2 mg·dm^{-3} in 2013. SO_4^{2-} ions may be supplied through the oxidation of sulphides contained in the ground, from organic elements within the upper level of soil and from plant residuals released from the lakes.

In 2009–2013 the chemical composition of the lake waters was subjected to minor changes providing an evidence on stable circulation of waters and solutes within the studied geoecosystem and little anthropopressure. A change in the ion concentration was observed only during snowmelt, increased rainfall or winter water stagnation periods.

The concentration of potassium remained at a similar level throughout the research period at all the research positions. This ion is very mobile. It occurs in this environment as a result of mineral weathering and biochemical processes in soils.

The share of biogenic elements (NO_3^-, NO_2^-, NH_4^+, $PO_4^{3-}{}_{diss}$, P_{tot}) in the lakes within the upper Lewińska Struga (Grzegorczyk *et al.* 2008) is more than 40 times smaller compared to ions derived from chemical denudation (Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-}, HCO_3^-). The most common sources of biogenic elements in the river outflow are as follows: atmospheric supply of biogenic elements together with atmospheric precipitation and inflows of pollutants from urban and agricultural areas (their number within the discussed catchment in minor).

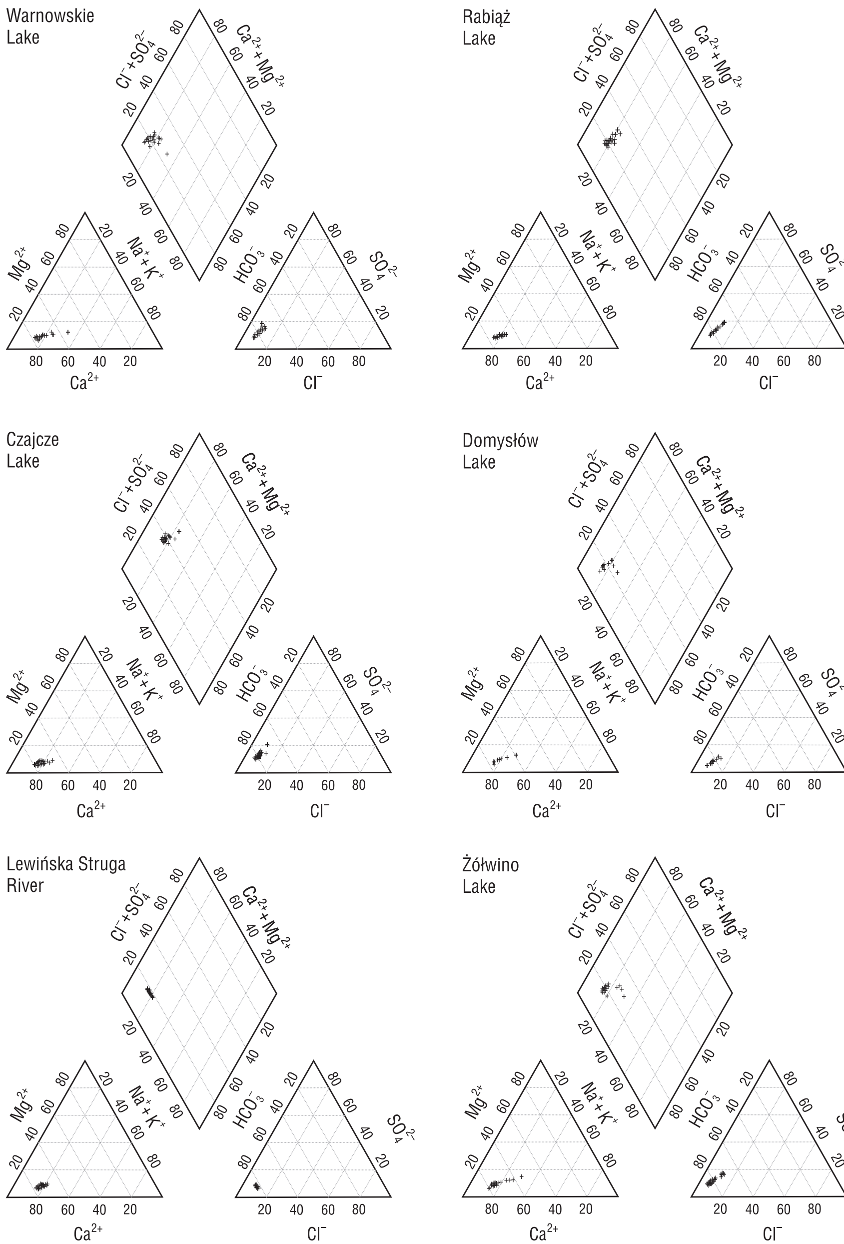

Fig. 4. Differences in surface water chemistry in the upper Lewińska Struga in the hydrologic years: 2009–2013

Source: authors' own study.

The analysed variability of the chemical composition of surface waters within the upper Lewińska Struga waters (Fig. 4) allows the classification of the studied waters (in terms of their ionic composition) as bicarbonate-calcium waters. Regardless of the season (and also regardless of the intensity of outflow in case of the Lewińska Struga) a range of changes on the chemistry of these waters is minor. The content of ions, mineralization and pH are closely related to lithology, soils, land cover and use land. It is worth noting that none (out of all the analysed 200 water samples from the Lewińska Struga) differs from others. It indicates the buffering role of the lakes in shaping the chemistry of the river waters.

On the basis of the flow curve and concentration of solutes on the Lewińska Struga, loads of ions drained in 2009–2013 within the catchment area were calculated. 3050.8 tons of solutes flew away together with the Lewińska Struga (the least – 466.1 tons in 2010, and the most – 827.1 tons in 2011). The river waters drained from the catchment area were dominated by bicarbonate ions (1833.6 tons) and calcium ions (584.4 tons). They were followed by sulphate ions (222.7 tons), chloride ions (191.5 tons), sodium ions (103.0 tons), magnesium ions (68.1 tons), potassium ions (26.8 tones) and nitrate ions (20.7 tons).

Within the catchment of the Gardno Lake (Kostrzewski *et al.* 2015) the average atmospheric supply of solutes ranges from 0.47 $g \cdot m^{-2}$ at stem-flowing through 6.20 $g \cdot m^{-2}$ at atmospheric precipitation up to 7.69 $g \cdot m^{-2}$ at through-falling. The geoecosystem of the Gardno Lake reflects the present conditions of the alimentation area of the upper Lewińska Struga. Therefore, it must be assumed that the atmospheric supply of solutes to the catchment ground within the upper Lewińska Struga amounts to 14.36 $g \cdot m^{-2}$. When considering the whole catchment area, the average annual supply of water amounts to 166.5 tons.

The chemical denudation in the upper Lewińska Struga catchment can be derived (calculated in its simplified form) from a variance in the atmospheric supply and loads drained by the river waters. Thus the annual factual chemical denudation in the catchment area of the upper Lewińska Struga amounts to 38.3 tons per km^2 on average.

Conclusion

The dominant concentration of bicarbonate and calcium ions is characteristic to areas where the natural process of ground weathering/leaching is the main source of supply of solutes. High concentrations of HCO_3^- and Ca^{2+} provide evidence on the high intensity of chemical denudation processes in the catchment area of the Lewińska Struga, which is justified by its lithological conditions and availability of solutes. Larger fluctuations in the concentration of carbonate ions in the lakes with smaller changes within the Lewińska Struga provides evidence on precipitation of Ca^{2+} deep in the lake.

The slight gradient of the Lewińska Struga and the presence of flow-through lakes explains that the chemistry of the river waters is subject to little change during the year. They are made by little flow fluctuations and deposition of more-difficult soluble ions within the lake bottom sediments. Confronted with little dynamic fluvial outflows the average daily load of solutes carried with the upper Lewińska Struga waters amounted to 144 $kg{\cdot}km^{-2}$. After taking into account the supply of ions at their atmospheric stage the actual chemical denudation amounts to 105 $kg{\cdot}km^{-2}{\cdot}a^{-1}$.

The concentration of all the discussed ions changed in the lakes most (where both the standard deviation and coefficient of variation reached higher values compared to the Lewińska Struga). The lakes are large recipients of deposits which capture solutes. In spite of the fact that the discussed lakes do not belong to a group of large reservoirs, they significantly regulate the transport of substances within the catchment area of the Lewińska Struga. It is reflected in minor outflows and fluctuations of the river waters as well as in the very stable chemical composition of the Lewińska Struga.

It should be emphasised that the parameters of the fluvial-lacustrine system of the Lewińska Struga – in terms of water drainage and transport of dissolved matter – are only slightly variable. The river outflow from the catchment area is stabilised by the lakes. As a result, the system is less susceptible to extreme phenomena such as high rainfall, rapid thawing, drought. It is also associated with a significant forestation of the catchment area, a small percentage of land used for agriculture and built-up areas.

Acknowledgements

The study was co-financed by the NCN research project no. N N304 274340 entitled: “The current state and functioning of the natural environment within the selected areas of West Pomerania region under climatic changes and increased anthropopressure”.

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