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CALCIUM ION MIGRATION IN AGRICULTURAL AND AFFORESTED LAKE CATCHMENTS

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Abstract: The research on circulating of calcium in the agricultural-forest drainage areas were carried out on the Olsztyn lake district in 2004–2006 years. Three lakes were marked out for examinations about diversified anthropogenic interacting with their drainage areas.

Ardung lake is situated in the centre-western part of the Mazurian lake district, its surface amounts to 26.2 ha and the average depth is 1.8 m. The drainage area of examined lake has the surface of 1539 ha and forest communities are covering it in the form of pine forests about the high level of the naturalness.

Drainage area of Bukwałd lake is situated 20 km to the north of Olsztyn. Lake covers 36.2 ha of the surface and its average depth is 5.0 m. The total drainage area of lake is taking the surface of 1156 ha, in which the arable land constitutes the 60 % with the little surface area of the land filled by wasteland (9 %) and forests (31 %) and with low-density housing.

Lake Sunia is situated about 30 km to the north of Olsztyn. The surface area of lake amounts to 111.6 ha and its average depth is 3.9 m. The total surface of the drainage area amounts to 450 ha, out of which 97 % is going to the intensively agriculturally used lands, while the rest part constitute wastelands and forests.

Comparing the individual research years one should state that in 2005 the lowest values of flows were recorded in the rising tides and ebb tides from Lakes Sunia and Bukwałd, however the highest were observed in the year 2004; a situation developed differently in the drainage area of Ardung lake, in which, in the sequence of the entire research period, comparatively levelled values of flows were recorded in all rising tides and the ebb tide of lake.

Comparing flows off from the examined drainage areas one should state that the waters running off from the exploited agricultural drainage areas of Bukwałd lake were characterised by the highest Ca^{2+} contents (114.3–126.3 mg $\cdot$ dm^{-3}), however the lowest were found in waters running off from the boggy area of the same lake (25.0 mg $\cdot$ dm^{-3}).

Higher contents of calcium in the waters running off from the agricultural areas is connected with more intensive washing this element out of arable cultivated soils periodically deprived of the plant cover. Considerable de-equalisations occurring in the drainage areas of lakes can also contribute to the faster outflow of biogenes increasing this way their content in the waters flowing into the reservoir.

Keywords: lakes, catchment, biogenes, calcium

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The circulation of matter in the landscape, including pollutants, eutrophicating substances and other vital components for ecosystems, takes place in the catchments. The runoff of biogenic substances from the catchment area to surface and underground water is determined by various factors, in particular relief features, soil coherence and fertility, land use type, water relations and climate conditions, primarily precipitation volume and distribution.

Together with magnesium, hydrogencarbonates and sulfates, calcium determines the hydrochemical type of most water resources in the catchment areas of young glacial zones. Intense leaching of calcium from the soil is responsible for the high calcium content in surface water [1]. Calcium is intensively washed out from farming areas in a moderate climate zone, mainly due to the acidification of precipitation water which also causes soil acidification. For this reason, calcium fertilizers should be applied to compensate for the loss of this nutrient and to create a supportive environment for plant growth. Calcium concentrations in water must be kept at an adequate level as calcium has buffering properties and it plays an important role in primary production by ensuring sufficient CO_2 concentrations for photosynthesis [2].

The objective of this study was to determine the effect of catchment use on calcium migration in surface water, in particular on its concentrations and load transported to the lake.

Materials and methods

The research on calcium migration in lake catchments was carried out in the Olsztyn Lakeland in the catchment areas of the lakes Sunia, Bukwałd and Ardung, between March 2004 and February 2007.

Lake Sunia (N 53°58’, E 20°17’) is situated around 30 km to the north of Olsztyn in the rural district of Świątki. The lake has an area of 111.6 ha and an average depth of 3.9 m. Its total catchment area is 450 ha, including a tributary area of 70 ha. It is surrounded mostly by arable land (97 %), with barren land and woodland accounting for only 3 % of the total area. The catchment area comprises predominantly loamy and sandy soils with heavy loamy sands and light sandy loams of soil quality class IVa, IIIa and IIIb.

The catchment of Lake Bukwałd (N 53°58’, E 20°16’) is in the vicinity of the village of Bukwałd, rural district of Dywity, around 20 km to the north of Olsztyn. The lake has an area of 36.2 ha with an average depth of 5.0 m. The lake catchment has an area of 1156 ha, and it is occupied by arable land (60 %), barren land (9 %), forests (31 %) and dispersed development. Lake Bukwałd is fed by 4 tributaries. Northern tributaries no. 1 and no. 2 intersect arable land and have a total catchment area of 322 ha. South-western tributaries comprise tributary no. 3, which flows through wasteland (catchment area of 63 ha) and emerges from a water-logged area, and no. 4 which flows mostly through woods (catchment area of 516 ha). The lake is fed from a hilly area with significant height differences reaching 23.5 m. The catchment area comprises mostly light and heavy loamy sands of soil quality class IVa, IVb and, locally, IIIa and IIIb.

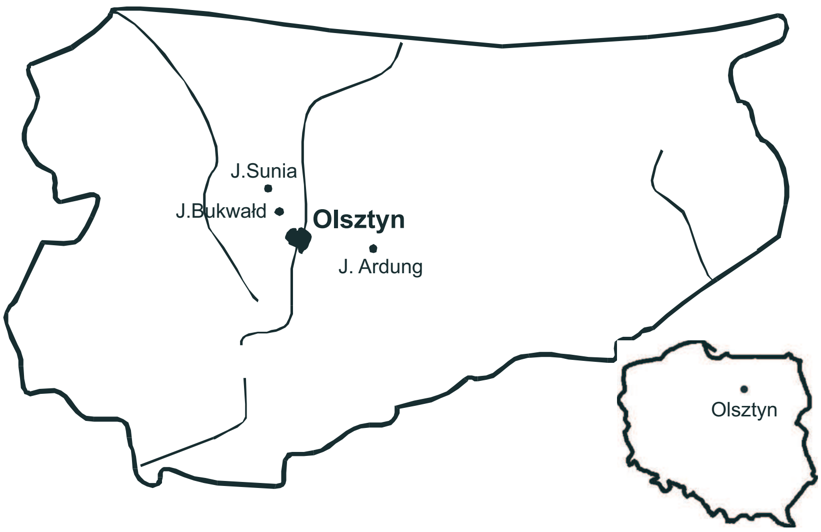

Fig. 1. Location of the study area

Lake Ardung (N 53°45', E 20°55') is situated in the central-western part of the Masurian Lakeland. It has an area of 26.2 ha and an average depth of 1.8 m. The lake catchment has an area of 1539 ha, of which 505 ha is occupied by the direct catchment. The lake is fed by 3 tributaries and 2 head streams. Tributaries no. 1 and 2 are found in the north-eastern part of the lake. Tributary no. 1 has an afforested catchment, while tributary no. 2 flows through an afforested catchment featuring a small number of settlements and a fish pond. Tributary no. 3 enters the lake on the south-eastern side. In the upper part, the catchment comprises several interior basins where seven small lakes play a focal function in the process of ground and underground water recirculation. The lower part of the catchment is afforested in 90 %. The predominant type of soils in this area are podzols overgrown with pine woods characterized by a high degree of naturalness. All three types of podzols are locally encountered in this area: podzolic soils, rusty soils and podzols of different morphological sub-types and varieties [3].

The study included hydrological measurements and laboratory analyses. The flow of watercourses feeding into the lake (4 into Lake Bukwałd, 1 into Lake Sunia, 2 into Lake Ardung) was measured once a week at approximately 50 m above the lake outlet. Flow measurements were performed with the use of a VALEPORT electromagnetic flow-meter and by the volumetric method at a low flow rate (below 2 $dm^3 \cdot s^{-1}$). Runoffs per area unit for each partial catchment area were computed based on mean annual measurements. Water was sampled for physical and chemical analyses once a month at the place of flow monitoring. The Ca^{2+} content of water was determined by atomic absorption spectrophotometry. Analyses were conducted in accordance with the universally accepted methodology [4].

The volume of calcium migration from the analyzed catchment was computed as the total product of calcium levels and the corresponding mean monthly flows.

Results and discussion

Water runoff from each catchment area was strongly determined by the type of land use. The lowest fluctuations were observed in the afforested catchment of Lake Ardung where the observed values were relatively stable in both the inflow and the outflow of this water body. The above could be attributed to the high retention capacity of the investigated catchment, covered by forest vegetation. In the catchments of the remaining lakes, the highest average flow values were noted in 2004, and the lowest – in 2005 which was marked by a complete absence of runoffs in the summer (Table 1).

An analysis of runoffs per area unit in each catchment showed the highest fluctuations in respect of outflows from the agricultural catchment of Lake Bukwałd (0 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the summer and autumn of 2005 to 44.0 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the winter of 2006). The noted high variations in surface runoffs from the agricultural catchment could be due to a high level of water uptake by the farmed crops. The catchment's heavy soils inhibited surface water filtration into the soil profile. Runoff was supported by significant altitude differences and the periodic absence of vegetation cover.

An analysis of runoffs from the investigated lakes per area unit indicates the highest fluctuations in the outflow of Lake Bukwałd (0 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the autumn of 2005 to 20.6 $dm^3 \cdot s^{-1} \cdot km^{-2}$ in the winter of 2004). Significantly lower fluctuations were observed in Lake Sunia (0–13.4 $dm^{-3} \cdot s^{-1} \cdot km^{-2}$) and Lake Ardung (4.2–8.8 $dm^{-3} \cdot s^{-1} \cdot km^{-2}$).

A comparison of runoffs per area unit in lake outflows and runoffs per area unit in lake inflows indicates that the lakes Ardung and Sunia were characterized by much lower runoff values in their respective inflows than in their outflows. The above could be attributed to the presence of water from the direct catchment or from internal feed sources in the lakes' water balance. A different situation was observed in the catchment of Lake Bukwałd where runoffs per area unit in the inflow were much higher than in the outflow. The above could be due to the lake's high retention capacity which eased the runoff wave from the catchment, as well as to intense evaporation of surface water.

A correlation analysis between the inflows and outflows of the lakes Bukwałd and Sunia points to a positive correlation within the range $r = < 0.81– 0.93 >$ at $P \le 0.05$ which is indicative of a very strong relationship between the quantity of water flowing in and out of the above water bodies. No correlation was observed between the inflows and outflows of Lake Ardung, most probably due to retention as well as other feed sources (eg underwater springs) in the lake's water balance. The above is validated by significant fluctuations in the inflows and outflows of the lake catchment in the winter and spring.

Mean calcium concentrations in the analyzed water samples were relatively stable throughout the year. Ca^{2+} leaching was most intense during the non-growing season when fluctuations in the levels of the investigated element were accompanied by limited biological sorption [5, 6].

Ca^{2+} leaching from the catchment area of Lake Ardung was most intense in the autumn of 2004 and 2005 when the highest calcium concentrations were reported in the majority of feeders into Lake Ardung. The only exception was the process observed in

Table 1

Seasonal fluctuations in runoffs per area unit in the inflows and outflows of the investigated lakes [$dm^3 \cdot s^{-1} \cdot km^{-2}$]

Catchment of lakes studied	(No. inflow)	2004					2005					2006				
		Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average
Ardung	Forest inflow No. 1	1.4	1.2	0.9	0.9	**1.1**	1.1	0.9	1.2	1.6	**1.2**	1.1	1.3	1.6	1.0	**1.2**
	Forest-fish-pond inflow	7.8	8.1	11.6	10.4	**9.5**	12.5	8.7	7.0	10.8	**9.7**	9.7	6.9	7.4	10.1	**8.5**
	Forest inflow No. 2	1.3	0.6	0.5	0.8	**0.8**	1.1	0.3	0.7	0.4	**0.7**	0.5	0.4	0.7	0.7	**0.6**
	Outflow	5.8	4.2	5.3	8.1	**5.9**	9.2	4.7	4.8	6.7	**6.3**	6.9	4.7	5.2	8.8	**6.4**
Bukwałd	Agricultural inflow No. 1	22.9	4.2	14.5	31.7	**18.3**	17.4	0.0	0.0	0.3	**4.5**	8.9	0.6	17.0	44.0	**17.7**
	Agricultural inflow No. 2	16.5	4.3	9.4	24.5	**13.7**	19.9	0.3	0.0	1.4	**5.4**	8.3	0.2	10.9	29.9	**12.4**
	Wetland inflow	10.2	0.6	3.2	19.4	**8.4**	6.3	0.0	0.0	0.0	**1.6**	3.2	0.0	14.8	31.3	**12.4**
	Forest inflow	3.4	1.2	1.8	8.4	**3.7**	2.6	0.0	0.0	0.0	**0.6**	2.2	0.1	3.7	8.8	**3.7**
	Outflow	12.8	3.6	5.0	20.6	**10.5**	5.4	0.2	0.0	0.1	**1.4**	5.9	0.4	5.8	14.2	**6.5**
Sunia	Agricultural inflow	5.0	4.3	1.0	4.9	**3.9**	2.0	0.0	0.0	0.0	**0.7**	2.6	0.4	1.4	4.7	**2.3**
	Outflow	12.9	3.9	1.0	7.9	**6.4**	9.4	1.1	0.0	0.0	**2.6**	1.7	0.4	3.4	13.4	**4.7**

2006, but the autumn concentrations of that year were only slightly below the winter concentrations. The highest fluctuations in calcium concentrations in the inflows to Lake Ardung were noted in feeder no. 2 (42.6 mg $\cdot$ dm^{-3} in the spring of 2004 – 84.3 mg $\cdot$ dm^{-3} in the winter of 2004), while the lowest Ca^{2+} levels were observed in tributary no. 1 (61.6 mg $\cdot$ dm^{-3} in the autumn of 2006 – 74.8 mg $\cdot$ dm^{-3} in the autumn of 2004) (Table 2). The highest calcium levels in the water of feeders to Lake Ardung were reported in the autumn of 2004, and the lowest – in the spring of 2004.

Calcium concentrations in feed water were clearly influenced by the type of catchment use, as shown by the agricultural catchment of Lake Bukwałd. The highest Ca^{2+} levels in all investigated watercourses were reported in the winter of 2005 in the agricultural runoffs from the catchment of Lake Bukwałd (126.3 mg $\cdot$ dm^{-3} and 114.3 mg $\cdot$ dm^{-3}). The above could result from soil leaching in the months preceding the beginning of the growing season, with limited phytosorption of calcium on arable land. High calcium levels in the inflows to Lake Bukwałd in the winter of 2005 could also be attributed to the intense leaching of this micronutrient from the catchment after the spring and summer draught. The lowest Ca^{2+} content in all investigated tributaries of Lake Bukwałd was observed in the winter of 2006 in the feeder from the lake afforested catchment area (25.0 mg $\cdot$ dm^{-3}), which was also the lowest concentration reported in all of the investigated watercourses.

Low Ca^{2+} levels in outflows from semi-natural areas in comparison with outflows from agriculturally used areas could be attributed mainly to low calcium concentrations in an environment where the investigated element is supplied by precipitation, mineral weathering, organic matter decomposition and calcium migration from the water environment due to sorption. Calcium is a vital macronutrient for plant growth in agricultural areas. In the non-growing season, calcium is intensively leached from the soil and large quantities of this element are also removed with farming crops. For this reason, calcium levels are supplemented by agrotechnical treatments to increase its concentrations in the soil and, consequently, in water which migrates from the area.

Based on a comparison of Ca^{2+} levels in the outflows of the investigated lakes, the highest Ca^{2+} concentrations were noted in the autumn and winter. The highest calcium levels were observed in the runoff from Lake Ardung (from 70.2 mg $\cdot$ year^{-1} in 2004 to 62 mg $\cdot$ year^{-1} in 2006), while the lowest concentrations were determined in the runoff from Lake Sunia (58.2 mg $\cdot$ year$^{-1}_{2004}$ – 47.0 mg $\cdot$ year$^{-1}_{2005}$). Based on a seasonal analysis, the highest calcium levels were noted in the outflow from Lake Sunia in the winter (99.3 mg $\cdot$ season^{-1}), while the lowest – in the summer of 2004 (40.4 mg $\cdot$ season^{-1}) in the outflow of the same lake. Higher concentrations of calcium ions in the autumn and winter season could be attributed to intensified Ca^{2+} flow from the catchment area in the non-growing season. Small quantities of calcium ions are also absorbed by phytoplankton and shore plants [7].

Weather conditions were the main determinant of the quantity of calcium load washed out from the analyzed catchment areas, mostly precipitation intensity and spring thaw intensity. Thick snow cover and its fast thawing could lead to the formation of melt waves, thus increasing the quantity of biogenes which are leached out from the surface of the soil and are fed into the lakes.

Table 2

Seasonal fluctuations in Ca^{2+} concentrations in the inflows and outflows of the investigated lakes [$mg \cdot dm^{-3}$]

Catchment of lakes studied	(No. inflow)	2004					2005					2006				
		Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average
Ardung	Forest inflow No. 1	48.7	71.1	86.1	77.8	**71.0**	67.5	74.7	74.5	65	**70.4**	69.9	74.7	67.4	68.8	**70.2**
	Forest-fish-pond inflow	53.6	72.2	88.3	60.2	**68.6**	63.7	76.7	79.9	62	**70.6**	69.1	71.0	66.3	78.3	**71.2**
	Forest inflow No. 2	42.5	61.6	76.4	84.3	**66.2**	57.9	65.1	72.2	50.5	**61.4**	66.8	66.3	60.4	69.9	**65.9**
	Sources No.1	66.2	62.8	74.8	74.6	**69.6**	65.2	65.2	72.2	64.2	**66.7**	65.9	67.4	61.6	68.5	**65.8**
	Sources No. 2	44.4	63.9	75.9	53.1	**59.3**	71.5	68.6	75.3	69.6	**71.2**	68.9	69.9	61.3	62	**65.5**
	Outflow	67.4	60.4	68.7	84.2	**70.2**	66.7	65.1	61.9	59.2	**63.2**	67.4	56.5	55.4	68.7	**62.0**
Bukwałd	Agricultural inflow No. 1	59.2	85.0	89.3	80.7	**78.5**	60.3	—	—	114.3	**87.3**	88.7	82.6	75.2	72.2	**79.7**
	Agricultural inflow No. 2	73.2	91.4	99.8	86.6	**87.8**	65.2	81.0	—	126.3	**90.8**	95.5	95.8	109.5	79.3	**95.0**
	Wetland inflow	36.1	32.0	28.4	44.0	**35.1**	36.4	—	—	—	**36.4**	27.7	—	39.8	25.0	**30.8**
	Forest inflow	42.0	62.9	71.9	62.8	**59.9**	45.2	—	—	77.1	**61.1**	44.8	49.8	53	42.7	**47.6**
	Outflow	55.6	60.4	64.6	79.4	**65.0**	48.1	55.4	—	60.2	**54.6**	58.4	62.8	54.1	57.2	**58.1**
Sunia	Agricultural inflow	60.5	60.2	74.2	84.0	**69.7**	47.1	—	—	—	**47.1**	59.4	63.5	65.2	77.0	**66.3**
	Outflow	44.2	40.4	48.9	99.3	**58.2**	47.0	47.0	—	—	**47.0**	42.9	65.2	64.5	50.7	**52.9**

An analysis of calcium supply and runoff from the lakes has shown that the calcium load in the catchment of Lake Ardung was relatively balanced throughout the experimental period, reaching from 142792 kg · year^{-1} in 2004 to 160429 kg · year^{-1} in 2005 in the inflow, and from 195396 kg · year^{-1} in 2005 to 205827 kg · year^{-1} in 2004 in the outflow (Table 3). The inflow from the forest and pond catchment (81458–89641 kg · year^{-1}) as well as the inflow from tributary no. 2 (40299–56364 kg · year^{-1}), which accounted for 56–62 % and 28–34 % of the total calcium load respectively, had a significant share in Ca^{2+} transport to the lake. An estimated 90 % of total calcium load reached the lake from the two above feeders. A comparison of inflowing and outflowing loads indicates that 69 % to 82 % of total calcium is fed to the lake from the indirect catchment, while the remaining load is transported with water from the direct catchment and from underwater springs.

The lowest calcium load from the catchment area was reported in 2005, reaching 39 793 kg · year^{-1} in Lake Bukwałd and 528 kg · year^{-1} in Lake Sunia. The calcium runoff from Lake Bukwałd in 2005 was approximately 74–76 % lower than in other years of the experiment (169680 kg · $year_{2004}^{-1}$ and 155305 kg · $year_{2006}^{-1}$), and the runoff from the catchment of Lake Sunia was 91 % lower than in 2004 (5761 kg · $year_{2004}^{-1}$) and 85 % lower than in 2006 (3492 kg · $year_{2006}^{-1}$).

Agricultural feeders had the highest share of Ca^{2+} transport from the catchment to Lake Bukwałd and were responsible for the migration of 75–85 % of total calcium leaving the catchment area. The highest Ca^{2+} runoff was reported in the winter of 2006 (33 072 kg · season^{-1} – tributary no. 1 and 35 543 kg · season^{-1} – tributary no. 2).

Based on a comparison of experimental years, the highest runoff of calcium load was reported in 2004 from Lake Bukwałd (263500 kg · year^{-1}), followed by Lake Sunia (55168 kg · year^{-1}). According to a seasonal analysis, the highest Ca^{2+} migration from both lakes took place in the winter of 2004 (Lake Bukwałd – 149349 kg · season^{-1} and Lake Sunia – 27779 kg · season^{-1}).

A comparison of outflowing and inflowing calcium loads in Lake Sunia shows that the latter had only a 3–10 % share of the load leaving the water body. The above could indicate that a significant part of the Ca^{2+} load was fed to the lake from other sources, including surface and underground runoffs from the direct catchment, precipitation and internal lake supply (sediment resuspension, underwater springs).

The highest level of calcium migration from all feed sources was determined in 2004 in the agricultural catchments of Lake Bukwałd at 455.5 kg · ha^{-1} and in feeders from farming areas at 365.3 kg · ha^{-1}, while the lowest calcium concentrations were observed in 2005 in the afforested catchment of Lake Bukwałd at 9.3 kg · ha^{-1} · year^{-1} and in the agricultural catchment of Lake Sunia at 7.5 kg · ha^{-1} · year^{-1} (Table 4). The noted low level of migration was most likely caused by the draught observed in the investigated period and the resulting absence of surface runoffs. The agricultural catchment of Lake Bukwałd was also characterized by the highest seasonal fluctuations in Ca^{2+} runoff per area unit. The highest migration was noted in the winter of 2006 (244.4 kg · ha^{-1} and 186.6 kg · ha^{-1}), and the lowest in the spring and summer of 2005 when no surface runoffs from the catchment to the lake were observed. An analysis of seasonal calcium runoffs from all catchments to the analyzed lakes shows the lowest inflow values from

Table 3

Seasonal fluctuations in Ca^{2+} load in the inflows and outflows of the investigated lakes [$kg \cdot season^{-1}$]

Catchment of lakes studied	(No. inflow)	2004					2005					2006				
		Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average
Ardung	Forest inflow No. 1	2361	2859	2629	2597	10445	2602	2267	3067	3639	11575	2581	3357	3746	2441	12125
	Forest-fish-pond inflow	14029	19534	34065	20915	88544	26567	22203	18618	22253	89641	22427	16345	16296	26390	81458
	Forest inflow No. 2	704	486	532	919	2642	860	265	677	229	2031	492	288	512	634	1925
	Sources No. 1	156	239	221	245	862	181	180	240	215	818	156	159	316	162	793
	Sources No. 2	7508	9018	14255	9517	40299	14287	13215	16722	12141	56364	14413	14742	7829	12440	49424
	Outflow	47824	31040	43818	83145	205827	74100	36937	36309	48050	195396	57450	31916	35084	73472	197922
Bukwałd	Agricultural inflow No. 1	14101	3663	13518	26577	57860	10942	0	0	378	11320	8170	543	13271	33072	55056
	Agricultural inflow No. 2	18113	5911	14072	31718	69814	19469	383	0	2683	22535	11842	302	17985	35543	65672
	Wetland inflow	1832	93	442	4241	6609	1134	0	0	0	1134	437	0	2918	3883	7238
	Forest inflow	5854	2963	5249	21332	35397	4716	0	0	88	4804	3962	196	7981	15200	27339
	Outflow	64765	20059	29326	149349	263500	23613	925	0	467	25004	31892	2195	28364	73846	136296
Sunia	Agricultural inflow	1646	1430	429	2255	5761	528	0	0	0	528	830	128	531	2003	3492
	Outflow	20162	5572	1655	27779	55168	15676	1797	0	0	17473	2623	994	7763	24063	35443

Table 4

Seasonal fluctuations in Ca^{2+} runoff per ha [$kg \cdot ha^{-1} \cdot season^{-1}$]

Catchment of lakes studied	(No. inflow)	2004					2005					2006				
		Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average	Spring	Summer	Autumn	Winter	Average
Ardung	Forest inflow No. 1	5.4	6.5	6.1	5.7	23.7	5.9	5.2	7.0	8.0	26.1	5.9	7.6	8.6	5.4	27.5
	Forest-fish-pond inflow	33.4	46.5	81.1	48.3	209.3	63.3	52.9	44.4	51.3	211.9	53.5	39.0	38.9	60.9	192.3
	Forest inflow No. 2	4.2	2.9	3.3	5.4	15.8	5.2	1.5	4.1	1.4	12.2	2.8	1.9	3.1	3.8	11.6
	Outflow	31.3	20.3	28.7	52.7	133.1	48.5	24.2	23.8	30.5	127	37.1	20.9	23.0	46.6	127.6
Bukwałd	Agricultural inflow No. 1	107.7	28.2	103.2	196.5	435.5	83.5	0.0	0.0	2.7	86.2	62.5	4.0	101.4	244.4	412.3
	Agricultural inflow No. 2	96.2	31.4	74.8	163.0	365.3	103.4	2.0	0.0	13.8	119.2	62.7	1.6	95.3	182.6	342.2
	Wetland inflow	29.1	1.6	7.2	65.5	103.4	18.4	0.0	0.0	0.0	18.4	7.0	0.0	46.7	60.0	113.7
	Forest inflow	11.5	5.8	10.3	40.3	67.9	9.2	0.0	0.0	0.1	9.3	7.7	0.4	15.6	28.8	52.5
	Outflow	56.4	17.5	25.6	126.0	225.5	20.6	0.8	0.0	0.4	21.8	27.3	1.9	24.7	62.3	116.2
Sunia	Agricultural inflow	24.1	20.5	5.9	31.4	81.8	7.5	0.0	0.0	0.0	7.5	12.1	2.2	7.4	27.9	49.6
	Outflow	45.2	12.4	3.7	60.2	121.5	35.1	4.1	0.0	0.0	39.2	5.9	2.2	17.4	52.2	77.7

the afforested catchment of Lake Ardung (5.2 kg · ha^{-1} and 1.5 kg · ha^{-1} in the summer of 2005). The highest Ca^{2+} surface runoff from the catchment of Lake Ardung was noted in the feeder from the forest and pond catchment (192.3 kg · ha^{-1} · $year^{-1}_{2006}$ – 211.9 kg · ha^{-1} · $year^{-1}_{2005}$). The above can be attributed to high flow intensity and the type of catchment use (the presence of human settlements and the use of tributary flow to feed a fish pond).

In view of an analysis of surface runoff per area unit measured in the outflows from each lake, the highest values were reported in 2004 in the outflow from Lake Bukwałd (225.5 kg · ha^{-1} · $year^{-1}$), mostly due to the high share of Ca^{2+} load supplied from agricultural catchments in the lake total water balance. As regards seasonal fluctuations in Ca^{2+} levels, the highest load was noted in respect of the outflow from Lake Bukwałd (0 kg · ha^{-1} · $season^{-1}$ in the autumn of 2005 – 126.0 kg · ha^{-1} · $season^{-1}$ in the winter of 2004), while the outflow from the mostly afforested catchment (more than 80 %) of Lake Ardung was marked by highest stability (20.30 kg · ha^{-1} · $season^{-1}$ in the summer of 2004 – 52.7 kg · ha^{-1} · $season^{-1}$ in the winter of 2004).

Conclusions

1. Calcium migration from the catchment areas to the lakes was determined by runoff from feed sources, the type of catchment use, differences in altitude, soil type and weather conditions. The agricultural catchment of Lake Bukwałd was characterized by the highest and the most fluctuating runoffs per area unit (0–44.0 dm^{-3} · s^{-1} · km^{-2}), while the lowest runoffs were noted in the afforested catchment of Lake Ardung (0.9–1.6 dm^3 · s^{-1} · km^{-2}). The highest runoffs were observed in the winter, and the lowest – or the absence thereof – in the summer.

2. The type of catchment use strongly determined Ca^{2+} concentrations in water runoffs. The highest calcium levels were determined in the agriculturally used feeders (catchment of Lake Bukwałd – 126.3 mg · dm^{-3}), and the lowest – in the runoff from the swampy catchment of Lake Bukwałd (25.0 mg · dm^{-3}).

3. Ca^{2+} concentrations in runoffs were also strongly determined by weather conditions. The highest calcium levels were noted in the autumn, and the lowest – in the spring.

4. Calcium runoff from the catchments to the lakes reached 12 to 436 kg · $ha^{-1}year^{-1}$. The highest level of calcium migration in all feed sources was observed in the catchment of Lake Bukwałd in runoffs from agricultural catchments (86–436 kg · ha^{-1}), followed by runoffs from the swampy catchment (18–114 kg · ha^{-1}), while the lowest values were reported in respect of the lake afforested catchment (9.3–68 kg · ha^{-1}).

5. The average annual runoff from the investigated lakes ranged from 22 to 226 kg Ca per one hectare of catchment area. The magnitude of calcium migration was determined by the type of catchment use, and it was much higher and marked by the highest fluctuation in the agricultural catchment (293 kg · ha^{-1} on average) than in the afforested catchment (43 kg · ha^{-1} on average).

6. The highest seasonal fluctuations in calcium levels in runoffs were reported in Lake Bukwałd with a high share of the agricultural catchment (0 kg · ha^{-1} · $season^{-1}$ in

the autumn of 2005 – 126.0 kg · ha^{-1} · season^{-1} in the winter of 2004), and the lowest – in Lake Ardung with an afforested catchment (20.30 kg · ha^{-1} · season^{-1} in the summer of 2004 – 52.7 kg · ha^{-1} · season^{-1} in the winter of 2004).

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MIGRACJA JONU WAPNIOWEGO W JEZIORNYCH ZLEWNIACH ROLNICZO-LEŚNYCH

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Abstrakt: Badania nad krążeniem wapnia w zlewniach rolniczo-leśnych prowadzono na Pojezierzu Olsztyńskim w latach 2004–2006. Do badań wytypowano trzy jeziora o zróżnicowanym oddziaływaniu antropogennym na ich zlewnie.

Jezioro Ardung położone jest w środkowo-zachodniej części Pojezierza Mazurskiego, jego powierzchnia wynosi 26,2 ha, a średnia głębokość 1,8 m. Zlewnia badanego jeziora ma powierzchnię 1539 ha i porastają ją zbiorowiska leśne w postaci borów sosnowych o wysokim stopniu naturalności.

Zlewnia jeziora Bukwałd położona jest 20 km na północ od Olsztyna. Jezioro zajmuje 36,2 ha powierzchni, a jego średnia głębokość wynosi 5,0 m. Całkowita zlewnia jeziora zajmuje powierzchnię 1156 ha, w której grunty orne stanowią 60 % z niewielką powierzchnią terenu zajętą przez nieużytki (9 %) oraz lasy (31 %) i rozproszoną zabudową.

Jezioro Sunia położone jest ok. 30 km na północ od Olsztyna. Powierzchnia jeziora wynosi 111,6 ha, a jego średnia głębokość 3,9 m. Całkowita powierzchnia zlewni wynosi 450 ha, z czego 97 % przypada na grunty intensywnie użytkowane rolniczo, a pozostałą część stanowią nieużytki oraz zadrzewienia.

Porównując poszczególne lata badawcze, należy stwierdzić, że w roku 2005 odnotowano najmniejsze wartości przepływów w dopływach i odpływach z jezior Sunia i Bukwałd, natomiast największe zaobserwowano w roku 2004, odmiennie kształtowała się sytuacja w zlewni jeziora Ardung, w którym w ciągu całego okresu badawczego odnotowano względnie wyrównane wartości przepływów we wszystkich dopływach i odpływie z jeziora.

Porównując spływy z badanych zlewni, należy stwierdzić, że największą zawartością Ca^{2+} odznaczały się wody odpływające ze zlewni użytkowanych rolnie jeziora Bukwałd (114,3–126,3 mg · dm^{-3}), natomiast najniższe stwierdzono w wodach odpływających z obszaru podmokłego tego samego jeziora (25,0 mg · dm^{-3}).

Większe zawartości wapnia w wodach odpływających z obszarów rolniczych jest związane z intensywniejszym wymywaniem tego składnika z gleb uprawianych ornie okresowo pozbawionych okrywy roślinnej. Znaczne deniwelacje występujące w zlewniach jezior mogą się także przyczyniać do szybszego odpływu biogenów, zwiększając tym samym swoją zawartość w wodach dopływających do zbiornika.

Słowa kluczowe: jeziora, zlewnia, biogeny, wapń