PRACE GEOGRAFICZNE, zeszyt 143

Instytut Geografii i Gospodarki Przestrzennej UJ
Kraków 2015, 65–84
doi: 10.4467/20833113PG.15.026.4627

PHYSICAL GEOGRAPHIC CONDITIONS IN THE GARDNO LAKE CATCHMENT (WOLIN ISLAND)

Andrzej Kostrzewski, Mariusz Samołyk, Jacek Tylkowski

Abstract: The Gardno Lake catchment on Wolin Island is located within the Wolin Range micro-region. Its coastal location and early glacial terrain within the temperate climate zone are the distinguishing features of this catchment. The catchment is non-run-off in character, and its area is dominated by beech forests and affected by a small degree of human impact. In the Gardno Lake catchment, atmospheric precipitation undergoes both physical and chemical conversion during its permeation in the beech forest zone, and then during infiltration through the slope cover, percolation to aquifers and subsequent drainage down towards the lake. A pattern of increased mineral content and higher pH at subsequent stages of water circulation were also identified. In the period 2010–2014, on a monthly basis, waters at the atmospheric stage (precipitation, throughfall, stemflow), transitional stage (throughflow), and lithospheric stage (groundwaters, lake waters) were examined in the Gardno Lake catchment. The research study described herein allowed to determine changes in water physical and chemical characteristics at individual stages of its cycle and discrete solute loads reaching the studied catchment area. The annual variability of water mineral content circulating in the Gardno Lake geoecosystem – presented in the paper – was calculated via the total concentration of biogenic ions (NO_3^-, NH_4^+, K^+), denudation-originated ions (SO_4^{2-}, Ca^{2+}, Mg^{2+}), and ions resulting from a large supply of marine aerosols (Cl^-–Na^+).

Keywords: water circulation, biogenic ions, denudation ions, sea aerosols, Wolin Island

Introduction

The landscape structure of the Wolin Island is the result of interdependencies and synergies of the area physical characteristics, geographic location, weather conditions formed by the temperate climate zone, hydrological regime of surface and groundwaters, land use and diversified human activities.

The research subject of this paper is to determine the physico-geographical individuality of the Gardno Lake catchment, mechanisms of its operations, ongoing environmental changes and operational characteristics in the landscape structure of the Wolin Island in relation to the dynamics of water circle and solutes.

The regularities presented in the paper are based on the analysis of information and data gathered under the Integrated Environmental Monitoring Programme (Kostrzewski 1993; Kostrzewski *et al.* 1995, 2006), which has been implemented at some test areas within the Gardno Lake catchment. The Gardno Lake catchment with its non-run-off character can be regarded to be a representative catchment for coastal, wooded early-glacial areas – it is of significant importance for comparative studies.

The research methods of water and dissolved matter circulation in the Gardno Lake on the Wolin Island refer to the other limnological studies from the Wolin Island region (Poleszczuk 1994, 1996; Kubiak 2000, 2001; Grzegorczyk *et al.* 2008) and limnological catchment studies of the Polish Baltic coastal zone (Drwal, Cieśliński 2007; Cieśliński 2011).

Materials and methods

Since 1996 the Gardno Lake catchment has been considered experimental and incorporated into the regional monitoring and since 2009 – into the Integrated Environmental Monitoring Programme, which is a subsystem of the National Environmental Monitoring Programme. The measurement data used in this paper – taken from the Integrated Environmental Monitoring Programme database – provides reliable information to be demonstrated in the present studies.

Water circulating within the Gardno Lake catchment were studied on the basis of 12 water quality indicators which allowed to determine the temporal variability of physical and chemical properties: pH, specific electrical conductivity (SEC) at 25°C, ions HCO_3^-, PO_4^{3-}, NH_4^+, Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NO_3^- and Cl^-. Samples of waters (n = 302) were collected in years 2010–2014 once a month. pH 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 Kudelska *et al.* (1994), Namieśnik *et al.* (1995) and Hermanowicz *et al.* (1999) were followed while conducting these measurements and works. The water cycle and water physical and chemical properties were analysed using Ward's cluster analysis, a taxonomic method relying on complete linkages (furthest neighbours) with city-block (Manhattan) distance (Ward 1963).

Results and discussion

Individuality of the physico-geographical environment of the Gardno Lake catchment

According to the division made by Kondracki (2000) the Wolin Island is located within the Central Lowland province, Central-European Coastline sub-province, Szczecin Coastline macro-region, Uznam and Wolin Islands mezo-region.

The Gardno Lake catchment (Fig. 1) is located within the Wolin Range which is made by a piled-up Wolin End Moraine (Borówka, Tomaszewski 1978; Kostrzewski 1983). The area is characterised by the following features: coastal location, no surface run-off, significant variances in altitude, large land declines, almost complete forestation.

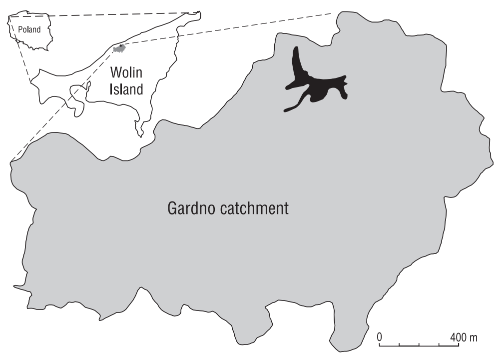

Fig. 1. Location of the research area

Source: authors' own study.

The Gardno Lake catchment (Fig. 2, Fig. 3) is located 220 meters from the sea coast. It can be characterised by the following parameters: area of catchment 2.42 km^2, maximum length 2.52 km, average width 0.97 km, maximum width 1.61 km, drainage divide length 18.06 km, maximum elevation 115.9 m a.s.l., minimum elevation 16.9 m a.s.l., mean elevation 58.2 m a.s.l., average slope gradient 5.8°, forest cover 98.2%, lake density index 1.2%, urban area 0.6% (source: this study). The catchment is elongated in its shape, in line with the SW–NE axis. From S and E its boundary runs through hills reaching over 100 m above sea level, and it is separated from the direct catchment area of the Baltic Sea by hills with their maximum height of 52.5 m above sea level.

The Gardno Lake (which distinguishes itself from other lakes within the Wolin Island by its location) makes a relevant landscape structure of the catchment. It is characterised by its non-run-off surface, supplied primarily by groundwaters and – to a lesser extent – by atmospheric precipitation. Surplus waters are drained underground towards the sea (Kulińska 1986) and to the drain zone made by the Wolin Lake District. A significant contribution of fogs is observed in the precipitation supply (Samołyk, Tylkowski 2012). The Gardno Lake is the only lake within the Wolin Island which has its own island. The lake is located within a several-kilometre depressed area surrounded by forests. It causes that its wave-run as well as its water-overture is minor.

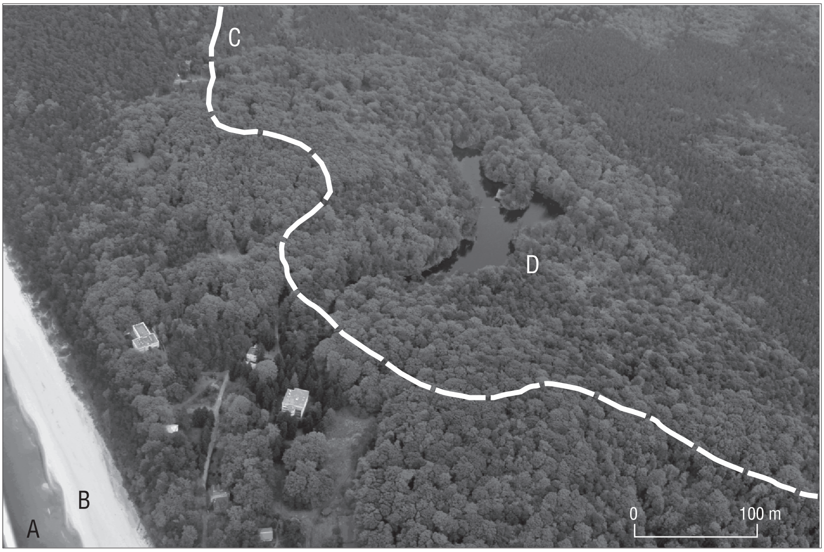

Fig. 2. Gardno Lake catchment (photo by M. Rychlik 12.05.2011, with changes)

A – Baltic Sea, B – beach, C – drainage divide, D – Gardno Lake

Source: authors' own study.

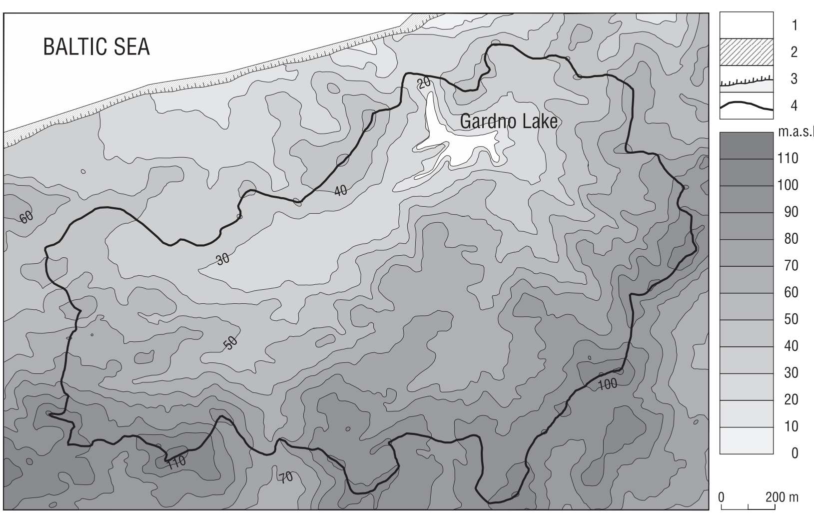

Fig. 3. Hypsometry of the Gardno Lake catchment

1 – lake and sea, 2 – beach, 3 – cliff-type coastline, 4 – drainage divide

Source: authors' own study.

The terrain of the Gardno Lake catchment is related to the glaciotectonic Wolin End Moraine, its age determined to be the oldest Dryas (Żynda 1962; Kostrzewski 1978, 1983). In the Late Glacial period there was intense erosion of sediments caused by proglacial waters and aeolian processes. This was a relevant episode in the development of the Wolin moraine terrain (Borówka *et al.* 1983; Ruszczyńska-Szenajch 1996). The thickness of the Quaternary forms within the catchment area exceeds 70 m. A high level of terrain energy results from glacial-melting processes. In the northern part of the catchment there is a fragment of kame plateau at an altitude of 30 m–40 m. The terrain of the Gardno Lake catchment is enriched with numerous hills and depressions, its local land declines exceed 30°.

The individuality of forest communities within the Gardno Lake catchment is determined by the presence of Pomeranian beeches (Piotrowska 1955). The discussed catchment is almost completely forested (Fig. 4). Within its boundaries there are mainly acidophilous beech forests (*Luzulo pilosae Fagetum*) but also mixed beech / oak forests can be encountered around the lake (*Fago Quaercetum*). Forest communities with Scots pine (*Pinus Silvestris*) are the effect of anthropogenic activities within the Gardno Lake catchment. Few buildings and paved roads occupy approx. 1.6 ha only.

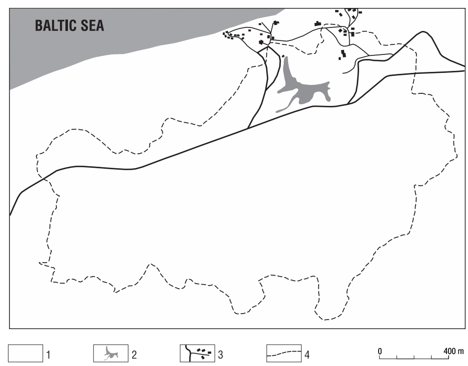

Fig. 4. Land use in the Gardno Lake catchment

1 – forests, 2 – lake, 3 – buildings and transportation areas, 4 – drainage divide

Source: authors' own study.

Characteristics of water and matter circle parameters in the Gardno Lake catchment

In the analysed hydrological period (2010–2014) the average annual air temperature within the cliff coast of the Wolin Island was 9.1°C. This value was 0.5°C higher than in the long-term (1966–2009) air temperature in the coastal zone of the Pomeranian Bay (Tylkowski 2013). The warmest year in the studied five-year period was 2014 with the average annual air temperature 10.4°C. The maximum range of daily temperature variability was from –16.5°C to 32.8°C. The lowest average annual air temperature (8.4°C) was noticed in 2010. The highest thermal amplitude, 54.5°C was observed in 2012, with range from -18.7°C up to 35.8°C (Fig. 5).

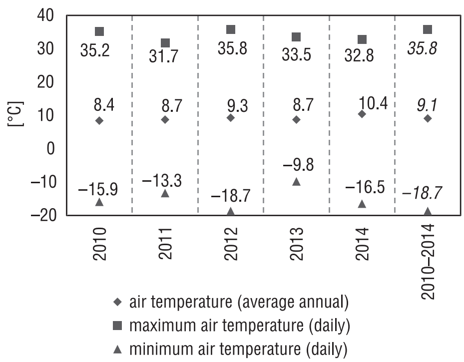

Fig. 5. Temperatures in the Gardno Lake catchment in the hydrologic years 2010–2014

Source: authors' own study.

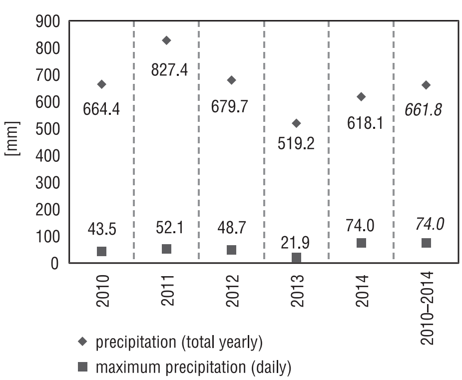

Fig. 6. Precipitation conditions in the Gardno Lake catchment in the hydrologic years 2010–2014

Source: authors' own study.

In terms of the atmospheric supply of water to the Gardno Lake geoecosystem, 2010–2014 hydrological years were characterised by atmospheric precipitation above the average. On average the catchment is supplied with 661.8 mm of water (together with atmospheric precipitation), 827.4 mm in 2011 (the highest) and 519.2 mm in 2013 (the lowest). The average annual atmospheric precipitation in 2010–2014 was by approx. 100 mm higher than the one within the Szczecin Coastland in the 1966–2009 period (Tylkowski 2013). The highest daily total of atmospheric precipitation was found on 3rd August 2014 and it amounted to 74.0 mm (Fig. 6). On average per year within the Gardno Lake catchment atmospheric precipitation occurred on 155 days, which accounted for 42% of the hydrological year. The highest number of days with atmospheric precipitation was recorded in 2013 (186 days) and the lowest – in 2011 (128 days). Atmospheric precipitation in approx. 30% was made by the supply of water along with snowfall. The highest number of days with snowfall was recorded in 2013 (93 days) and the lowest – in 2014 (15 days).

In general, within the Gardno Lake catchment in 2010–2014, its thermal and precipitation conditions favoured the migration of solutes. The proportion of days with the maximum daily air temperature ≤0°C preventing the circle of water and solutes, accounted for only 8.8% of the entire study period. The number of days with the maximum daily temperature ≤0°C ranged from 12 days in 2014 up to 50 days in 2010. The above-average amount of water supplied with atmospheric precipitation favoured the recovery of water resources within the analysed geoecosystem. In contrast, quite high evaporation off free water surfaces (which was 390.0 mm on average in the studied period) was an unfavourable factor in the migration of water and solutes within the Gardno Lake geoecosystem.

The coastal location and almost complete forestation of the Gardno Lake catchment determine the chemical composition and hydrochemical type of waters circulating at various stages of the water cycle. According to the hydrochemical classification by Altowski and Szwiec (Macioszczyk 1987), waters circulating within the Gardno Lake catchment is characterised by a high level of variability of hydrochemical types. This state is the effect of absorption and adsorption of ions as a result of precipitation having a contact with the forest area (throughfall and stemflow) and accumulation and leaching of ions within slope covers (throughflow, groundwaters, lake waters). The Gardno Lake catchment waters are characterised by multi-component hydrochemical type – according Altowski and Szwiec classification (Pazdro, Kozerski 1990) – determined by means of ion proportion in meq (Kolander, Tylkowski 2008). Waters made of at least five-six components prevail which relate primarily to the atmospheric phase of the water cycle – precipitation in the open field (Ca^{2+} Na^{+} NO_3^- Cl^- SO_4^{2-}), throughflow (Cl^- NO_3^- SO_4^{2-} Na^+ Ca^{2+} K^+) and stemflow (Cl^- SO_4^{2-} NO_3^- Na^+ Ca^{2+} K^+). Then waters related with the groundwater circle are mostly made of 2–3 components – throughflow (Ca^{2+} HCO_3^-), groundwaters (Ca^{2+} HCO_3^- Ca^{2+}) and lake waters (Ca^{2+} HCO_3^- Ca^{2+}). The water mineralization within the Gardno Lake geoecosystem is made by the total concentration of biogenic ions (NO_3^- NH_4^+ K^+), denudation-originated ions (SO_4^{2-} Ca^{2+} Mg^{2+}) and ions resulting from a large supply of marine aerosols (Cl^- Na^+).

The spatial analysis of similarities in reaction (pH), mineralization and concentration of solutes in waters circulating within the Gardno Lake catchment allowed to single out two main stages of the water cycle: atmospheric and lithospheric ones (Fig. 7A). The atmospheric stage is associated with the supply of precipitation and its subsequent penetration through the forest zone in the form of throughfall and stemflow. The lithospheric stage is related to the deep percolation of precipitation and occurs in the form of groundwaters and lake waters. Water in the Gardno Lake comes mainly from the drainage of groundwaters and – to a lesser extent – from the direct supply of atmospheric precipitation. The transitional zone between the atmospheric stage and the lithospheric one is made by soil waters, which in the aeration zone occur, among others, in the form of throughflow. However, within the Gardno Lake catchment, throughflow occurs episodically and it does not have any significant role in the circle of water and solutes.

The analysis of similarities of annual variability of ion concentration, electrolytic conductivity and reaction (pH) of waters within the Gardno Lake geoecosystem allowed to separate two hydrochemical groups: biogenic and denudation-originated ones. The biogenic group is characterised by a high degree of similarity in concen-

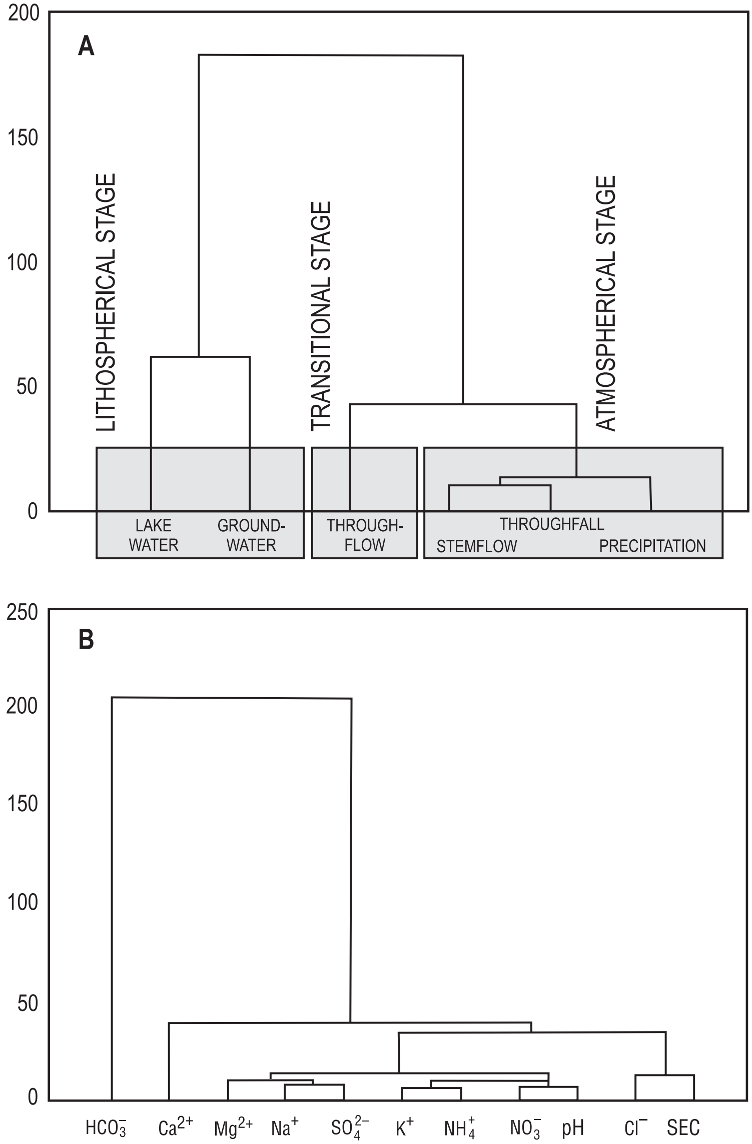

Fig. 7. Hydrochemistry of the Gardno Lake catchment (period: 2010–2014) in the beech stand (cluster analysis; Ward's method based on annual average ion concentration)

A – stages of the water cycle, B – water physical and chemical properties

Source: authors' own study.

tration of nitrate, ammonium and potassium ions and water reaction (pH). Changes in water reaction (pH) are therefore affected mainly by the group of biogenic ions. The denudation-originated group also contains ions derived from the supply with marine aerosols. It is less uniform compared with the biogenic one. It was found that there is a considerable level of similarity in the temporal variability of sulphate, magnesium and sodium ions, and similar dynamics of changes in the concentration of chloride ions and electrolytic conductivity. The least similar temporal dynamics of concentration variability was found for calcium ions, in particular bicarbonate ones for which chemical denudation is the main source of their supply (Fig. 7B).

The atmospheric stage of water supply is characterised by a high proportion of biogenic ions (approx. 40%) and a relatively balanced proportion of denudation-originated ions (approx. 30%) and ions coming from the supply of marine aerosols (approx. 30%).

Among biogenic ions there is a particularly high proportion of nitrates NO_3^- the concentration of which in the total water mineralization was 30.8% in atmospheric precipitation, 29.4% in throughfall and 22.7% in stemflow. A proportion of the concentration of ammonium ions NH_4^+ in the total solutes at the atmospheric water circle ranged 2.3%–5.2%. The concentration of potassium ions K^+ was quite specific with their participation in the mineralization of atmospheric precipitation at 3.4% and in the contact zone of rainwater with the forest area it increased to over 14%. It stands for the active wash-out of potassium ions through throughfall and stemflow. Within the groundwater circle a share of biogenic ions in the mineralization of water is significantly lower than the one in the atmospheric stage. For nitrate ions it decreased from 3.1% in throughflow (the transitional stage) to 1.4% in groundwaters and only 0.3% in the Gardno Lake (the lithospheric stage). A share of ammonium ions is negligible and also decreases from 0.6% in groundwaters to 0.1% in lake waters. Then a share of potassium ions is low but stable and at the lithospheric water circulation it is about 0.3%–0.5%.

Among denudation-originated ions in the atmospheric water circulation water the largest share is made by sulphate and calcium ions. A share of calcium ions during the migration within the plant zone decreased and ranged from 13.6% in atmospheric precipitation to 8.5% in throughfall and 7.3% in stemflow. It looks different when it comes to sulphate ions – its share in the water mineralization was the lowest in throughfall (13.8%) and the highest in stemflow (21.5%). At the transitional and lithospheric stages a share of calcium ions was higher than the one at the atmospheric one and ranged from 22.1% in throughflow up to 17%–18% in groundwaters and lake waters. However, a share of sulphate ions in migrating waters in the groundwater migration system was lower than the one at the atmospheric stage and ranged from 3.1% in throughflow up to 7.3% in lake waters. Among denudation-originated ions magnesium was the most stable ion with its share in the atmospheric and lithospheric stages of the water circle at approx. 2%. In the groundwater circle – as a result of soil leaching – a very high share in the water mineralization is held by bicarbonate ions at approx. 56%–65%.

The coastal location of the Gardno Lake catchment affects a very high share of ions derived from the supply of marine aerosols in the water mineralization. In the contact zone of precipitation waters with the forest area a share of chlorides in the water mineralization was at approx. 20% and of sodium – at approx. 10%. At the lithospheric stage of the water cycle a share of marine-originated ions in the total water mineralization was twice lower (Fig. 8).

The variability of hydro-chemical properties of the water circulating in the Gardno Lake catchment showed their considerable annual variation at the atmospheric and lithospheric stage of the water cycle (Tab. 1, Tab. 2).

Precipitation reaching the forest area had average annual electrolytic conductivity at 1.87 $mS \cdot m^{-1}$. The variability of average annual conductivity ranged from 1.36 $mS \cdot m^{-1}$ in 2011 to 2.47 $mS \cdot m^{-1}$ in 2014. The annual average precipitation reaction (pH) amounted to 5.58 pH. The most acidic precipitation with its pH at 5.27 was found in 2011 and the least acidified rainfall with its 5.97 pH was in 2014. The annual variability of annual rainwater reaction (pH) was lower than the one of electrolytic conductivity. Precipitation waters reaching the Gardno Lake catchment can be classified (in line with the classification made by Jansen *et al.* 1988) as waters with slightly increased conductivity and standard reaction (pH), which proves their good quality. In terms of the concentration of solutes, precipitation waters contain the highest concentration of nitrate (3.47 $mg \cdot dm^{-3}$), chloride (1.63 $mg \cdot dm^{-3}$) and sulphate(1.56 $mg \cdot dm^{-3}$) ions. At further stages of the water circle the highest concentration was held by ions derived from various sources of supply. Within throughfall and stemflow NO_3^-, Cl^- and SO_4^{2-} ions were the highest concentrated. Compared to atmospheric precipitation the concentration of these ions was 3 times higher in throughfall and 4 times higher in stemflow. The area of water flowing through the forest area causes the active incorporation of biogenic-originated ions (especially potassium ions) in the water circle with their average annual concentration in throughfall at 4.95 $mg \cdot dm^{-3}$ and in stemflow at 7.21 $mg \cdot dm^{-3}$. The concentration of K^+ ions in waters passing through the forest zone was therefore approx. 20 times higher than the one in precipitation reaching tree-tops. The average annual value of electrolytic conductivity in throughfall amounted to 7.32 $mS \cdot m^{-1}$ and in stemflow – to 9.84 $mS \cdot m^{-1}$. It allowed to qualify these waters to the class of waters with strongly increased conductivity. The high mineralization of throughfall and stemflow can be evidenced by the significant concentration of chloride and sodium ions supplied with marine aerosols, mainly using advective mists. Rainfall waters penetrating through the forest zone were qualified to the class of waters with standard reaction (pH) (stemflow at 5.84 pH) and slightly increased reaction (throughfall at 6.37 pH) (Tab. 1).

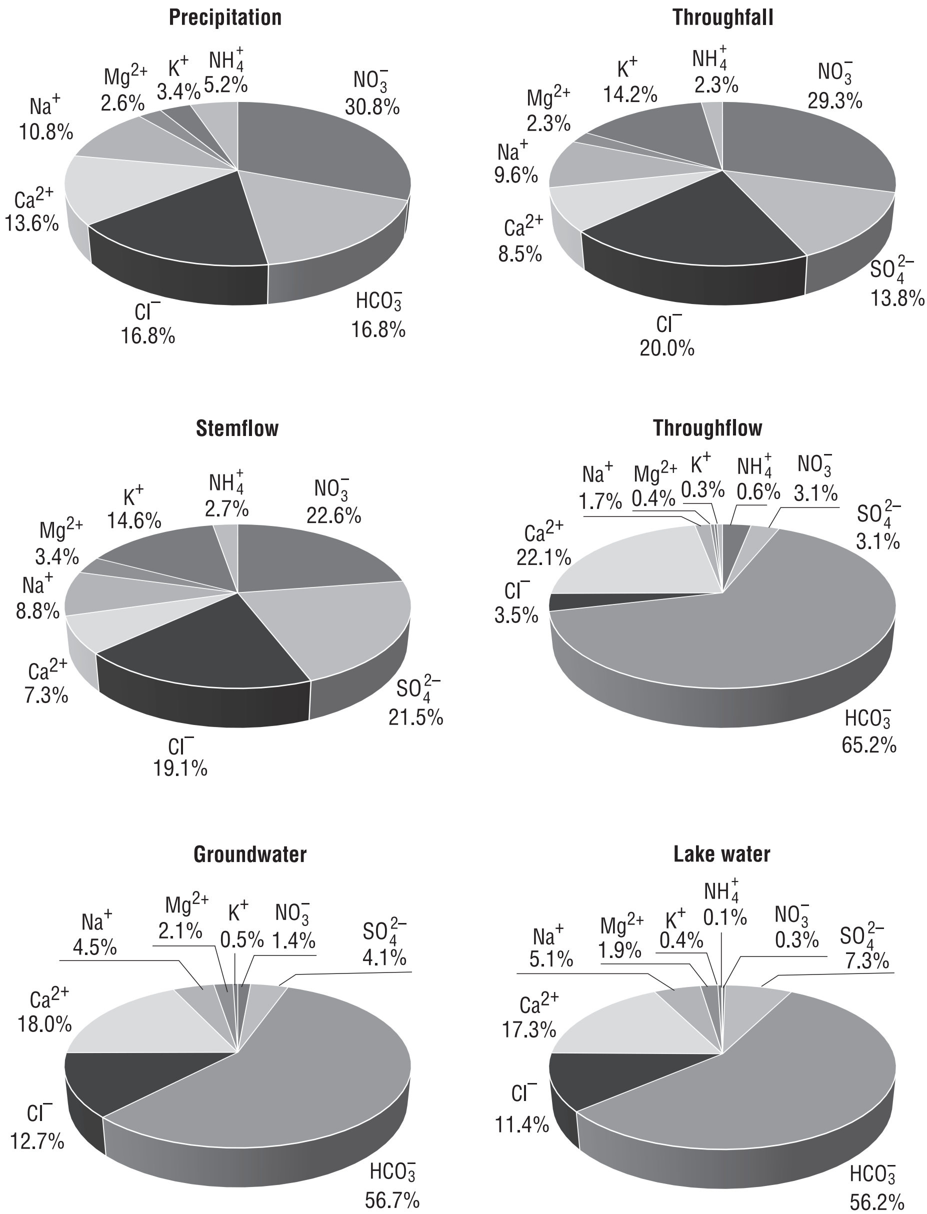

Fig. 8. Percentage of the average annual ion in the water mineral content [mg·dm^{-3}] within the Gardno Lake geoecosystem (2010–2014)

Source: authors' own study.

Table 1. Hydrochemical properties of water circulating at the atmospheric stage (precipitation, throughfall, stemflow) of the water cycle in the Gardno Lake catchment (2010–2014)

Hydrologic year	N	Water quantity	Conductivity	Reaction	Biogenic ions			Denudation ions			Sea aerosols	
			SEC	pH	NO_3^-	NH_4^+	K^+	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Cl^-	Na^+
		[mm]	[$mS \cdot m^{-1}$]	[–]	[$mg \cdot dm^{-3}$]							
Precipitation												
2010	11	664.4	1.82	5.80	4.18	0.31	0.28	1.61	1.63	0.17	1.24	0.95
2011	12	827.4	1.54	5.21	2.88	0.33	0.18	1.23	1.13	0.14	1.09	0.77
2012	11	679.7	2.14	5.69	3.66	0.68	0.30	2.07	1.55	0.29	2.17	1.23
2013	12	519.2	1.36	5.25	2.58	0.39	0.23	1.23	0.91	0.14	0.91	0.67
2014	12	618.1	2.47	5.97	4.07	1.36	0.54	1.66	1.51	0.43	2.75	1.52
max		227.8	4.1	6.9	11.2	1.8	0.8	3.0	5.3	2.3	19.1	8.3
mean		54.7	1.7	5.5	3.2	0.4	0.2	1.5	1.3	0.2	1.7	1.1
min		4.8	0.7	3.9	0.1	0.0	0.1	0.4	0.2	0.1	0.5	0.4
SD		41.5	0.7	0.8	2.9	0.4	0.2	0.7	0.8	0.3	2.7	1.1
CV [%]		75.9	40.8	15.5	93.2	95.4	71.3	47.9	61.9	139.6	153.8	107.2
Throughfall												
2010	10	398.6	5.56	5.81	8.95	0.31	5.12	5.35	3.50	0.67	6.26	2.65
2011	12	496.4	8.13	6.72	10.13	0.26	5.06	4.47	3.49	0.85	6.28	2.96
2012	11	407.8	7.72	6.37	12.03	1.49	5.54	5.75	2.27	1.13	10.69	4.28
2013	12	311.5	7.72	6.83	11.18	0.66	4.78	4.15	1.37	0.83	5.96	2.63
2014	12	370.9	7.50	6.13	10.22	1.39	4.23	5.37	4.54	1.08	11.12	5.55
max		85.1	22.1	7.7	38.6	4.1	22.1	15.5	6.4	2.3	28.6	15.1
mean		18.5	7.3	6.5	10.7	0.7	5.2	5.2	2.6	0.9	7.2	3.1
min		2.5	2.0	4.5	1.1	0.1	0.3	0.5	0.1	0.1	0.9	0.4
SD		13.3	3.9	0.8	7.7	0.9	4.5	3.1	1.7	0.5	5.9	2.4
CV [%]		71.8	53.2	11.8	72.1	125.9	87.7	59.2	63.5	57.9	81.1	77.8
Stemflow												
2010	10	46.5	7.77	5.44	11.91	0.60	7.65	12.94	6.77	0.91	7.70	3.30
2011	12	57.9	11.85	6.24	12.48	0.35	6.96	8.21	3.61	0.78	8.49	4.29
2012	11	47.6	9.74	5.82	9.92	2.46	5.66	9.84	2.82	5.70	17.19	6.60
2013	12	36.3	11.76	6.01	10.89	2.18	8.58	18.03	1.03	1.48	13.90	5.50
2014	12	43.3	8.06	5.71	9.69	1.46	7.22	12.90	4.54	1.21	12.24	5.56
max		4.6	26.3	7.2	36.7	4.9	17.2	60.7	13.4	15.6	54.3	17.4
mean		0.6	10.5	5.9	11.3	1.4	7.2	12.3	3.4	2.2	12.0	5.0
min		0.0	2.8	4.2	0.1	0.1	1.1	1.6	0.1	0.1	1.2	0.7
SD		0.9	6.0	0.7	8.2	1.3	3.9	13.0	3.1	2.8	12.3	4.4
CV [%]		159.2	57.2	12.3	73.0	92.7	53.6	105.8	89.5	124.8	102.8	89.7

Max, mean, min, standard deviation (SD) and coefficient of variation (CV) based on monthly vlues

Source: authors' own study.

Table 2. Hydrochemical properties of water circulating at the transitional stage (throughflow) and the lithospheric stage (groundwater, lake water) of the water cycle in the Gardno Lake catchment (2010–2014)

Hydro-logic year	N	Conductivity	Reaction	Biogenic ions				Denudation ions				Sea aerosols	
		SEC	pH	PO_4^{3-}	NO_3^-	NH_4^+	K^+	SO_4^{2-}	Ca^{2+}	Mg^{2+}	HCO_3^-	Cl^-	Na^+
		[$mS \cdot m^{-1}$]	[–]	[$\mu g \cdot dm^{-3}$]	[$mg \cdot dm^{-3}$]								
Throughflow [60 cm depth]													
2010	3	18.49	7.57	0.30	8.46	0.50	0.77	4.87	47.43	0.84	110.24	3.92	3.48
2011	3	21.67	7.45	0.05	8.39	0.50	0.84	6.16	43.42	1.02	166.98	7.44	3.38
2012	3	18.72	6.93	0.22	5.54	1.95	0.85	9.66	37.11	0.88	113.69	8.30	3.31
2013	3	18.85	7.60	0.02	2.66	1.89	0.31	4.18	40.48	0.73	122.44	4.70	2.67
2014	7	20.25	7.45	0.56	4.84	1.31	0.40	4.90	45.78	0.81	116.98	9.08	4.09
max		26.7	8.0	2.3	17.2	2.9	1.4	16.1	58.9	1.3	182.4	16.2	5.1
mean		19.6	7.4	0.3	5.3	1.3	0.5	5.5	43.1	0.8	123.9	6.9	3.4
min		12.4	6.4	0.0	0.6	0.3	0.2	2.9	25.1	0.5	7.8	2.3	2.3
SD		4.1	0.4	0.6	5.1	0.8	0.4	2.8	10.0	0.2	38.1	4.2	0.8
CV [%]		21.0	5.8	179.1	95.7	63.3	66.6	51.5	23.2	24.4	30.8	61.2	23.2
Groundwater [200 cm depth]													
2010	11	34.62	6.96	0.24	2.81	0.14	1.54	1.17	71.16	6.94	214.78	34.52	14.88
2011	12	37.94	7.23	0.06	2.73	0.14	1.78	1.19	59.59	7.11	258.62	33.89	18.75
2012	12	59.24	6.89	0.53	10.01	0.22	1.88	38.16	74.67	10.23	233.65	63.77	19.29
2013	9	54.20	7.21	0.60	3.23	0.47	1.76	41.77	83.15	10.33	230.79	74.05	21.47
2014	12	46.48	7.82	0.85	9.73	0.20	2.16	5.90	73.69	8.08	214.23	51.47	17.00
max		84.3	8.2	1.8	44.7	0.9	4.5	128.4	119.8	15.5	280.1	142.3	73.6
mean		45.7	7.1	0.3	4.8	0.2	1.7	20.3	70.6	8.5	234.7	50.9	18.3
min		28.0	6.1	0.0	0.2	0.1	0.4	0.2	15.2	1.5	162.3	7.7	4.0
SD		13.4	0.4	0.4	7.0	0.2	0.5	32.7	19.0	2.8	24.6	23.8	9.4
CV [%]		29.4	6.3	139.7	145.6	84.3	30.9	161.4	27.0	33.3	10.5	46.8	51.4
Lake water													
2010	11	31.30	7.42	0.12	0.99	0.14	1.37	25.68	58.43	6.24	158.30	34.76	15.43
2011	8	32.21	7.54	0.14	1.19	0.18	1.35	23.68	49.09	5.86	176.45	34.71	15.36
2012	12	42.52	7.73	0.17	0.39	0.16	1.35	23.05	50.58	6.12	182.65	35.19	15.64
2013	12	36.19	7.88	0.18	0.89	0.19	1.35	19.92	50.65	5.86	180.09	35.12	16.94
2014	12	41.70	8.11	0.08	1.18	0.14	1.55	23.13	64.05	6.51	190.92	40.52	18.00
max		66.7	8.7	0.4	3.3	0.3	1.9	29.5	66.7	7.1	213.6	41.6	18.9
mean		37.0	7.7	0.2	1.1	0.2	1.3	21.4	50.8	5.9	170.0	34.8	16.1
min		19.8	6.3	0.0	0.1	0.1	0.8	9.5	26.7	3.0	119.0	15.8	9.5
SD		9.6	0.6	0.1	0.9	0.1	0.3	4.8	11.0	1.1	26.5	7.1	2.5
CV [%]		26.0	7.2	74.8	82.8	38.2	19.9	22.3	21.6	19.4	15.6	20.5	15.7

Max, mean, min, standard deviation (SD) and coefficient of variation (CV) based on monthly vlues

Source: authors' own study.

The annual variability of concentration of solutes in soil, groundwaters and lake waters did not show as high diversity as at the atmospheric stage of the water circle (Tab. 2). As a result of soil leaching, waters migrating in the lithosphere had a high concentration of denudation-originated ions, in particular bicarbonate and calcium ones. The average annual concentration of HCO_3^- in soil waters amounted to 136.07 mg·dm^{-3}, in groundwaters – 230.41 mg·dm^{-3}, and in the Gardno Lake – 177.68 mg·dm^{-3}. By contrast, the annual concentration of Ca^{2+} at the groundwater stage of the water cycle ranged from 42.48 mg·dm^{-3} in the aeration zone up to 72.45 mg· dm^{-3} in the saturation zone. In the examined period the annual concentrations of denudation-originated ions were relatively stable. However, in the course of the groundwater migration the concentration of biogenic ions was characterised by a higher level of its annual variability. The concentration of biogenic elements in the groundwater circle was also significantly lower than the one in the atmospheric supply. It demonstrates a low level of percolation of biogenic elements in the soil profile. The concentration of potassium, nitrates and ammonium ions was the highest in soils waters, lower in groundwaters and the lowest at the final of the water circle, i.e. in lake waters. A high level of concentration of sodium and chloride ions was a characteristic feature of the Gardno Lake catchment (it reached 51.54 mg·dm^{-3} and 18.28 mg·dm^{-3} in groundwaters, and 36.06 mg·dm^{-3} and 16.27 mg·dm^{-3} in the lake, respectively).

The reaction (pH) of atmospheric precipitation at 5.58 pH penetrating the zone tree-tops increased up to 7.32 pH and stem-flowing was 5.84 pH on average. The largest decrease of acidification (calculated on the basis of pH) was found in soil waters 7.4 when their reaction (pH) increased 1.2 times. The Gardno Lake was characterised by the highest reaction (pH) at 7.74 pH. It demonstrates good buffer capacities of the lake. The maximal dynamics of changes in the concentration of solutes occurred in the transition zone (soil waters) and the lithospheric zone (groundwaters). A reduction of biogenic ions and considerable increase of HCO_3^- (126 times) and Ca^{2+} (13 times) ions (in reference to precipitation reaching the forest floor) was found in throughflow. A further rapid increase in the concentration of denudative ions as well as chlorides and sodium was found in groundwaters (Tab. 3).

The analysis of the concentration of solutes and the amount of water allowed to determine the load of solutes reaching the forest zone together with atmospheric precipitation and slope covers together with throughfall and stemflow (Tab. 4). At every stage the largest load was made by the supply of biogenic elements, especially nitrates and potassium, as well as the supply of marine aerosols in the form of chlorides and sodium. In total, together with atmospheric precipitation the supply of solutes to the forest area averaged 6.20 g·m^{-2} and the load of solutes reaching the forest floor was 14.65 g·m^{-2} (with throughfall) and 2.50 g·m^{-2} (with stemflow). A larger load of solutes in throughfall rather than in atmospheric precipitation resulted

Table 3. Changes in the physical and chemical properties (conductivity [mS·m^{-1}], reaction [pH], concentration of biogenic, denudative ions and marine aerosols [mg·dm^{-3}]) of water circulating in the Gardno Lake catchment (2010–2014) in the beech stand (1 = assumed value of atmospheric precipitation)

Water circulation		SEC	Reaction	NO_3^-	NH_4^+	K^+	HCO_3^-	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Cl^-	Na^+
				biogenic ions			denudation ions				sea aerosols	
ATMOSPHERIC	precipitation	1	1	1	1	1	1	1	1	1	1	1
Atmospheric-Forest *	throughfall	3.9	1.2	3.0	1.3	16.1	1.0	3.2	2.3	3.9	4.9	3.5
	stemflow	5.3	1.1	3.2	2.3	23.5	1.0	7.9	2.8	8.6	7.3	4.9
TRANSITIONAL **	throughflow	2.3	1.2	0.6	1.1	0.1	126.0	0.7	12.6	0.6	0.7	0.8
LITHOSPHERIC ***	groundwater	2.4	1.0	1.0	0.2	2.9	1.8	3.0	1.7	24.7	7.7	5.4
Lithospheric Hydrospheric ****	lake water	0.8	1.1	0.2	0.6	0.8	0.8	1.3	0.8	0.3	0.7	0.9

* atmospheric-forest stage (throughfall, stemflow) in relation to atmospheric precipitation

** transitional stage (throughflow) in relation to the atmospheric-forest stage

*** lithospheric stage (groundwater) in relation to the transitional stage

**** lithospheric-hydrospheric stage (lake water) in relation to groundwater

Source: authors' own study.

from a higher level of mineralization of waters passing through treetops in spite of less water, 397.1 mm on average per year. In contrast, a low load in stemflow was the result of a small amount of water, 46.3 mm on average per year. With regard to atmospheric precipitation reaching the top forest floor at 661.8 mm (100%), throughfall averaged 60%, and stemflow – 7% waters.

In the Gardno Lake catchment, atmospheric precipitation underwent physico-chemical transformation during infiltration in the beech forest zone. Further transformation of the physicochemical properties of waters occurred during infiltration through slope covers and percolation to aquifers and their subsequent drainage to the lake reservoir. The physico-chemical transformation manifested itself by a change in the conductivity and reaction (pH) of waters as well as increased or decreased concentration of solutes. In the Gardno Lake catchment the regularity of increased mineralization and water reaction (pH) at subsequent stages of water circulation was perceived. The lowest value of mineralization expressed by electrolytic conductivity (SEC) was held by atmospheric precipitation waters (1.87 mS·m^{-1}). At the transition of rainfall waters through the beech forest zone, a more than threefold increase in mineralization took place. For stemflow the average conductivity was 7.32 mS·m^{-1} and for groundwater flow it was 9.84 mS·m^{-1}. Rainfall waters infiltrating slope covers were characterised by a significant increase in the mineralization being the effect

Table 4. Atmospheric supply of solute matter via atmospheric precipitation, throughfall, and stemflow in the Gardno Lake catchment in the hydrologic years (2010–2104) for the beech stand

Hydrologic year	Total dissolved matter	Biogenic ions			Denudation ions			Sea aerosols	
		NO_3^-	NH_4^+	K^+	SO_4^{2-}	Ca^{2+}	Mg^{2+}	Cl^-	Na^+
	[g·m⁻²]	[mg·m⁻²]							
Precipitation									
2010	6.60	2,676	153	200	971	1,026	116	824	633
2011	5.72	1,911	249	146	973	884	115	834	606
2012	6.77	1,524	302	196	1,340	861	217	1,569	759
2013	3.87	1,349	204	145	673	523	80	523	373
2014	8.06	2,386	945	361	1,009	934	237	1,378	807
Mean	6.20	1,969	370	210	993	846	153	1,026	635
Throughfall									
2010	13.08	3,566	125	2,039	2,135	1,394	265	2,494	1,057
2011	16.63	5,030	131	2,513	2,220	1,730	422	3,116	1,469
2012	17.61	4,907	607	2,260	2,344	924	460	4,360	1,747
2013	9.83	3,482	204	1,488	1,293	426	258	1,857	821
2014	16.13	3,789	514	1,569	1,990	1,683	402	4,124	2,058
Mean	14.65	4,155	316	1,974	1,996	1,231	362	3,190	1,430
Stemflow									
2010	2.41	554	28	356	602	315	42	358	154
2011	2.62	723	20	403	475	209	45	492	249
2012	2.86	472	117	269	468	134	271	818	314
2013	2.24	396	79	312	655	38	54	505	200
2014	2.37	419	63	312	558	197	52	529	241
Mean	2.50	513	62	330	552	178	93	540	231

Source: authors' own study.

of soil leaching. Groundwater flow waters had approx. 5 times higher conductivity (19.6 mS·m⁻¹) than rainfall waters did passing through the forest zone. Then in turn, groundwaters had average SEC at 46.5 mS·m⁻¹, which was more than twice higher than the one of waters in the aeration zone. Slightly lower conductivity of the Gardno Lake waters at 36.78 mS·m⁻¹ than the one of groundwaters was caused by the dilution of drained groundwaters by weakly mineralized precipitation reaching the water reservoir surface.

Presented in the article the functioning correctness of the Gardno Lake catchment on Wolin Island are in addition to other lacustrine studies from Southern Baltic coast region, e.g. (Cieśliński 2010; Woszczyk *et al.* 2011; Cieśliński, Major 2012).

Conclusions

The geographical individuality of the Gardno Lake catchment is defined by its coastal location within Quaternary forms, no surface run-off, large variances in land highs and lows, almost complete forestation with beech, mixed beech-oak and pine trees. The specified features allow to consider the non-run-off catchment of the Gardno Lake at the Wolin Island to a representative catchment for the coastal early-glacial terrain within the temperate climate zone.

The developed regularities concerning the Gardno Lake geoecosystem and its operation can be passed to other similar landscape structures within the coastal area of the Wolin Island. There is a considerable share of fogs in the catchment precipitation supply. The thermal-precipitation regime of the studied period (2010–2014) is distinguished by the annual average of the warmest year (2014) which was at 10.4°C and the coldest year (2010) which was at 8.4°C. The study period was characterised by precipitation above the average. On average, 661.8 mm water (together with precipitation) is supplied to the catchment per year (from 519.2 mm in 2013 up to 827.4 mm in 2011).

On average the annual rainfall in the catchment occurred on 155 days (42% of the year) which determined the high dynamics of the Gardno Lake geoecosystem and its operation. A high level of variability of the hydrochemical type of circulating waters is a characteristic feature of the analysed geoecosystem. It is dominated by waters made of at least five components covering the atmospheric stage of the water cycle (precipitation in the open field, throughfall, stemflow). Waters connected with the groundwater circle are mainly two-, or three-components (throughflow, groundwaters, lake waters).

Atmospheric precipitation is characterised by the lowest mineralization. During the transition of rainfall waters through the beech forest zone, a more than threefold increase in mineralization takes place. Throughflow waters have 5 times (and groundwaters – even 25 times) higher mineralization compared to the one of rainfall waters. In spite of the dilution of drained groundwaters by low mineralized rainfall waters reaching the Gardno Lake area, their mineralization is 20 times higher than the one of rainfall waters. An extra supply of highly mineralized waters with fogs plays an important role. Mists which emerge from the sea provide a significant load of solutes, especially marine aerosols in the form of chloride and sodium ions.

The above results of the research studies confirm the geographical individuality of the Gardno Lake geoecosystem and its place in the landscape structure of the coastal early-glacial zone.

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".

References

Borówka M., Tomaszewski M., 1978, *Geneza rzeźby i charakterystyka osadów czwartorzędowych wyspy Wolin*, [in:] A. Kostrzewski (ed.), *Studia z geografii fizycznej i ekonomicznej wyspy Wolin*, Poznań, 21–31.

Borówka R.K., Gonera P., Kostrzewski A., Zwoliński Z., 1983, *Geneza i wiek pokryw piaszczystych w obrębie Wolińskiej Moreny Czołowej*, Sprawozdania PTPN 97–99, 135–137.

Cieśliński R., 2010, *Zróżnicowanie typologiczne i funkcjonalne jezior w polskiej strefie brzegowej południowego Bałtyku*, Problemy Ekologii Krajobrazu 26, 135–144.

Cieśliński R., 2011, *Geograficzne uwarunkowania zmienności hydrochemicznej jezior wybrzeża południowego Bałtyku*, Wydawnictwo Uniwersytetu Gdańskiego, Gdańsk.

Cieśliński R., Major M., 2012, *Differences in the abiotic parameters of water in coastal lakes in the light of the EU Water Framework Directive: An example of the polish southern Baltic coast*, Acta Geophysica 60 (4), 1159–1179.

Drwal J., Cieśliński R., 2007, C*oastal lakes and marine intrusions on the southern Baltic coast*, Oceanological and Hydrobiological Studies, 36 (2), 61–75.

Grzegorczyk K., Poleszczuk G., Bucior A., Jóźwik I., 2008, *Shortened evaluation of surface water quality of Warnowskie Lakes (Wolin National Park)*, Limnological Review, 8, (1–2), 21–25.

Hermanowicz W., Dojlido J., Dożańska W., Koziorowski B., Zerbe J., 1999, *Fizycznochemiczne badania wody i ścieków*, Wydawnictwo Arkady, Warszawa.

Jansen W., Block A., Knaack J., 1988, *Acid rain. History, generation, results*, Aura, 4, 18–19.

Kolander R., Tylkowski J., 2008, *Hydrochemical seasons in the Lake Gardno catchment on Wolin Island (North-Western Poland)*, Limnological Review, 8, (1–2), 27–34.

Kondracki J., 2000, *Geografia regionalna Polski*, Wydawnictwo Naukowe PWN, Warszawa.

Kostrzewski A. (ed.), 1978, *Studia z geografii fizycznej i ekonomicznej wyspy Wolin*, Poznań.

Kostrzewski A., 1983, *Morfogeneza zespołu form Wolińskiego Parku Narodowego*, Sprawozdania PTPN, 97–99, 128–134.

Kostrzewski A., 1993, *Zintegrowany Monitoring Środowiska Przyrodniczego. Stan prac, etapy realizacji*, [in:] A. Kostrzewski (ed.), *Zintegrowany Monitoring Środowiska Przyrodniczego w Polsce. Wybrane problemy*, Biblioteka Monitoringu Środowiska, Warszawa, 11–18.

Kostrzewski A., Kruszyk R., Kolander R., 2006, *Zintegrowany Monitoring Środowiska Przyrodniczego. Zasady organizacji, system pomiarowy, wybrane metody badań*, http://www.staff.amu.edu.pl/~zmsp/wyt2006/wyt2006.html (2.02.2016).

Kostrzewski A., Mazurek M., Stach A., 1995, *Zintegrowany Monitoring Środowiska Przyrodniczego. Zasady organizacji, system pomiarowy, wybrane metody badań*, Biblioteka Monitoringu Środowiska, Warszawa.

Kubiak J., 2000, *Ocena naturalnej tolerancji jezior Wolińskiego Parku Narodowego na oddziaływania antropogeniczne*, Materiały IV Limnologicznej Konferencji „Naturalne i antropogeniczne przemiany jezior", Zalesie 18–20.09.2000, Wydawnictwo Uniwersytetu Warmińsko-Mazurskiego, Olsztyn, 133–147.

Kubiak J., 2001, *Hydrochemistry of Wolin Island Lakes*, Folia Universitatis Agriculturae Stettinensis, Piscaria, 218 (28), 63–76.

Kudelska D., Cydzik D., Szoszka H., 1994, *Wytyczne monitoringu podstawowego jezior*, PIOŚ, Biblioteka Monitoringu Środowiska, Warszawa.

Kulińska K., 1986, *Charakterystyka jeziora Gardno*, [in:] A. Kostrzewski (ed.), *Woliński Park Narodowy. Monografia geograficzna*, Poznań, 136–142.

Macioszczyk A., 1987, *Hydrogeochemia*, Wydawnictwa Geologiczne, Warszawa.

Namieśnik J., Łukasiak J., Jamrógiewicz Z., 1995, *Pobieranie próbek środowiskowych do analizy*, PWN, Warszawa.

Pazdro Z., Kozerski B., 1990, *Hydrogeologia ogólna*, Wydawnictwa Geologiczne, Warszawa.

Piotrowska H., 1955, *Zespoły leśne wyspy Wolina*, Prace Komisji Biologicznej PTPN, 16 (5), Poznań, 1–168.

Poleszczuk G., 1994, *Ekosystemy wodne Wolińskiego Parku Narodowego*, Klify, 1, 99–117.

Poleszczuk G., 1996, *Jeziora Wolińskiego Parku Narodowego – status troficzny, tendencje zmian i możliwość przeciwdziałania degradacji*, Materiały Konferencyjne Uniwersytetu Szczecińskiego, 19, 117–139.

Ruszczyńska-Szenajch H., 1996, *Ukierunkowanie wielkoskalowych zaburzeń glacitektonicznych na Wyspie Wolin*, Acta Geographica Lodziensia, Łódź, 40–42.

Samołyk M., Tylkowski J., 2012, *Charakterystyka bilansu wodnego brzegu klifowego wyspy Wolin w latach 2009–2010*, [in:] A. Kostrzewski, J. Szpikowski (eds.), *Funkcjonowanie geoekosytemów w różnych strefach krajobrazowych Polski*, Biblioteka Monitoringu Środowiska, 19, Storkowo, 199–208.

Tylkowski J., 2013, *Temporal and spatial variability of air temperature and precipitation at the Polish coastal zone of southern Baltic Sea*, Baltica, 26 (1), 83–94.

Ward J.H., 1963, *Hierarchical grouping to optimise an objective function*, Journal of the American Statistical Association, 58, 236–244.

Woszczyk M., Bechtel A., Gratzer R., Kotarba M., Kokociński M., Fiebig J., Cieśliński R., 2011, *Composition and origin of organic matter in surface sediments of Lake Sarbsko: A highly eutrophic and shallow coastal lake (northern Poland)*, Organic Geochemistry, 42, 1025–1038.

Żynda S., 1962, *Wyniki wstępnych badań nad moreną czołową wyspy Wolin*, Badania fizjograficzne nad Polską Zachodnią, 9, 159–166.

Andrzej Kostrzewski
Adam Mickiewicz University in Poznań
Institute of Geoecology and Geoinformation
27 Dzięgielowa Str., 61-680 Poznań, Poland
anko@amu.edu.pl

Mariusz Samołyk
Adam Mickiewicz University in Poznań
Institute of Geoecology and Geoinformation
27 Dzięgielowa Str., 61-680 Poznań, Poland
mars@amu.edu.pl

Jacek Tylkowski
Adam Mickiewicz University in Poznań
Institute of Geoecology and Geoinformation
27 Dzięgielowa Str., 61-680 Poznań, Poland
jatyl@amu.edu.pl