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SEA WATER INTRUSIONS TO THE LAKE GARDNO

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Abstract

Lake Gardno, as the central object in the hydrographic structure, is under the influence of land and sea waters. This results in the situation where the lake together with its direct catchment forms a unique geoecosystem which differs from other inland reservoirs performing the role of local or regional recipients in hydrographic systems, in terms of the quality of water as well as the rate and dynamics of transformations occurring in it. This is an effect of overlapping influences of waters inflowing from the catchment and intrusions of sea waters. During intrusions, waters of higher salinity occur and remain during the greater part of the year in the whole water body of the lake, which is conditioned by the shape of the basin facilitating the penetration of salty waters. It was established that the water coming from intrusions remains for at least several days. There is also evidence from reconnaissance measurements that the retention is longer. The easiness of penetration and long retention period result in the fact that only periodically the desaltation effect of potamic waters leads to an almost complete desaltation of water in the whole basin of the lake Gardno.

Key words: catchment, coastal lake, recipient, intrusion, hydrographic structure, element

INTRODUCTION

Lakes situated on the coast of the Southern Baltic Sea function in different conditions than those in which typically inland reservoirs occur. They are situated in the contact zone of two environments: the land and the sea. These reservoirs together with their direct catchments form specific geoecosystems in which the course of physical, chemical and biological processes depends on the fact which of these two environments exerts a stronger influence at a given moment.

One of the lakes which are situated within the contact zone of land and sea is the Gardno Lake. It has conditions for water exchange and is characterised by a considerable dynamics of water circulation (Cyberski and Jędrasik 1992), which indicates the possibility of occurrence and spreading of the sea water intrusions, observed and described in other water bodies of the coast (Van der Tuin 1990, Cieśliński 2004, 2005, 2006, Drwal and Cieśliński 2007, Drwal et al. 2007). This allows to formulate the hypothesis that in the Gardno Lake, phenomena similar to these observed in other hydrographic objects located on the coast should also be recorded. During intrusions of salt waters they are mixed with fresh waters. The proportions of these waters of different origin are variable in time and within the water body, and depend on the impact of the anemobaric and local hydrographic conditions (Drwal et al. 2007). Consequently, this leads to a substantial diversity of water quality within the lake. Some authors even claim that reservoirs with such a specific water circulation belong to the category of estuary objects (Majewski 1972, Balicki 1980, *Jezioro*... 2003). In the light of the above, an attempt was made to determine whether sea water intrusions occur in the Gardno Lake and whether the effects which they can cause are typical of coastal lakes situated on the Polish coast of the southern Baltic or this lake is unique in this respect.

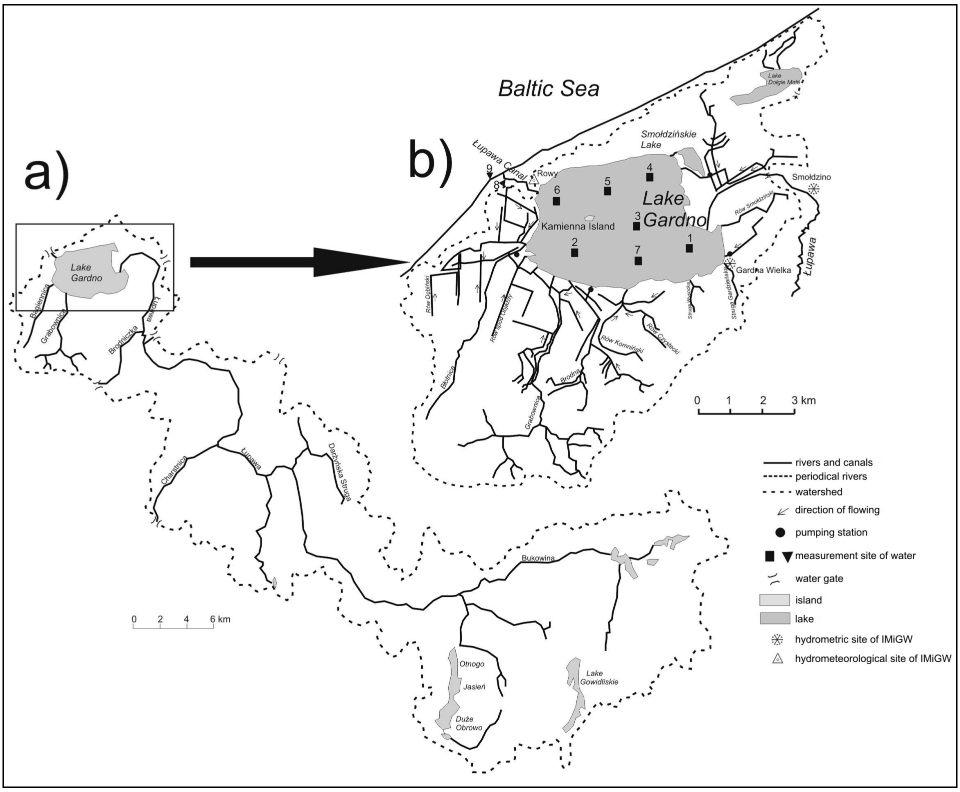

Fig. 1. Location of the Gardno Lake in the Łupawa drainage basin (a) and in the direct catchment (b)

MATERIALS AND METHODS

The employed method involved performing recurring hydrochemical surveys accompanied by a simultaneous determination of the current hydrological situation. In 2002-2006, 16 measurement series in 7 sites were performed (Fig. 1). The measurement sites were localised in the whole water body in characteristic places of the basin bottom relief (3, 4, 5) and in places where the largest tributaries flow into the lake (1, 2, 6, 7). Site 1 was located opposite the Łupawa River, site 2 opposite the Grabownica River, and site 7 opposite the Brodna River. Only site 6 was located opposite the only outflow from the lake – the Łupawa Canal. Water samples were taken from the surface, above-bottom and interstitial layer. Water from the last layer was obtained from the surface bottom sediment collected using Kajak scoop and a Centrifuge. Water samples were analysed in the laboratory of the Hydrology Department of Gdańsk University. Chlorides concentration was determined using the titration method.
The water level in the lake was read off on the water gauge of IMGW (Institute of Meteorology and Water Management) situated in Gardna Wielka, whereas the sea level on the gauge of the Maritime Office in the harbour of Rowy or Ustka.
Measurement results were presented in diagrams so as to emphasise the occurring regularities. They include chlorides concentrations in surface and above-bottom water in particular measurement sites, water level in the Gardno Lake and the sea on the day of samples taking and the preceding day (sometimes days).

Water relations of the area

The direct catchment of the lake Gardno of an area of 125.4 km^2, which is 13.6% of the whole Łupawa drainage basin (Fig. 1), forms a clearly distinctive part of it with water relations characteristic of the Southern Baltic coast seaside plains. In the elementary structure of territorial hydrographic systems (Drwal 1982) such a fragment of a drainage basin should be classified as type ‘recipients’ in which the final balance of water excess occurs (Drwal and Hryniszak 2003). Such recipients occur on the outskirts of a system, in this case of the Kashubian hydrographic system, on the bottoms of ice marginal streamways or valleys of rivers with an importance broader than regional or, as in this case, on a seaside alluvial plain. Water relations of such recipients are characterised by excessive moisture of the surface of the area caused by lateral potamic or ground inflow (Drwal 1984) and hampered outflow.
In the recipient formed by the direct catchment of the lake Gardno, the central hydrographic element is the lake with an area reaching up to 2468 ha, which covers about 20% of the catchment area. The remaining 80% of its area is covered by 6 polders. The lake is shallow with a circle-like shape. Its width is 4.7 km and length 6.8 km. The basin bottom is rather even, the dominating depths are 1.0-1.5 m. Maximum depth reaching 2.2 m occurs in the south-eastern part opposite the mouth of the Łupawa River (Fig. 2). The basin volume is 30 950 thousand m^3. The lake is being heavily silted, mainly by sediments carried by the Łupawa River (Wojcie-

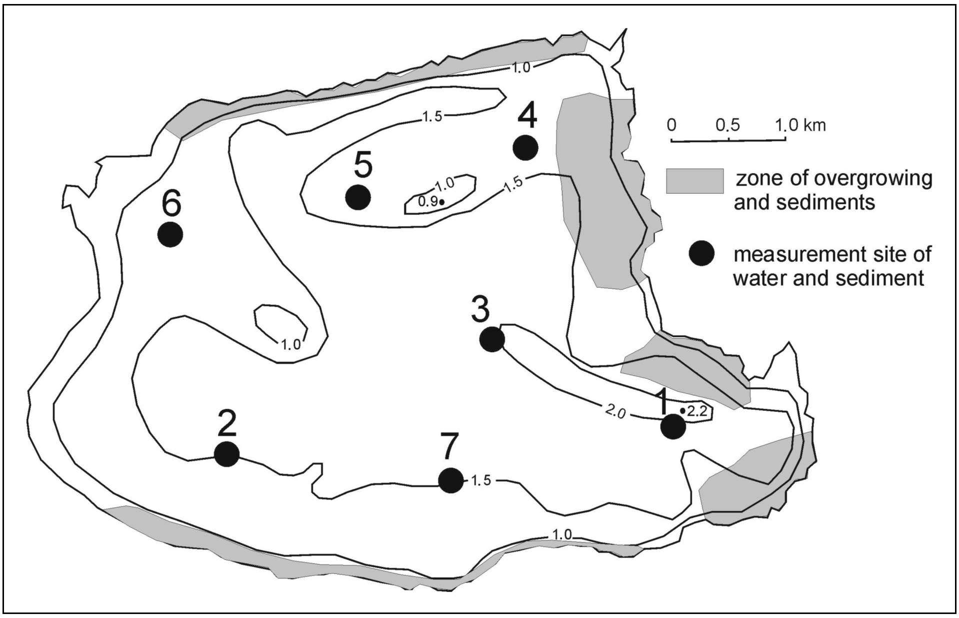

Fig. 2. Hydrographic layout of the Gardno Lake (source: Choiński, Kaniecki 2003 supplemented)

chowski 1990), which have built a backward delta of an area of 8 km^2 (Florek 1992) in the eastern part of the lake catchment. During over 50 years the lake volume has decreased by 6 million m^3 (Balicki 1980), which is about 16% of its volume, and the area has diminished in the last 60 years by about 100 ha, which is 4% of the water surface (Tobolski et al. 1997). The lake is being overgrown in 4% of its area (Balicki 1980).

The Gardno Lake is the recipient for the rivers Łupawa, Bagiennica and Brodna, and canals and ditches draining the southern, western and eastern part of the direct catchment of the lake. Moreover, the Gardno Lake has a connection with the Łebsko Lake through the Łupawa-Łebsko Canal, whereas with the sea through the Łupawa Canal of a width of 15-20 m, length of over 1 km, and grade of 0.11‰. The depth of the canal ranges from about 4 to 5 m.

The Łupawa River provides about 92% of the waters flowing into the lake on the surface and its inflow is estimated at 8.2-8.3 $m^3 \cdot s^{-1}$ (Bogdanowicz 2004) and ranges from 7.04 $m^3 \cdot s^{-1}$ in August to 9.44 $m^3 \cdot s^{-1}$ in March. High water stages occur in February and March (meltwaters) and in summer and autumn (rainfall). Low water stages occur in the period from June to July. The inflow from the direct catchment is estimated at 0.853 $m^3 \cdot s^{-1}$ (Cyberski and Jędrasik 1992). The total amount of water that can be pumped out from polders is 3.39 $m^3 \cdot s^{-1}$ (Cebulak 1984). The total potamic inflow into the Gardno Lake is 9.07 $m^3 \cdot s^{-1}$, which gives a water exchange coefficient, defined as the quotient of the total water inflow from the catchment to the lake volume, of 9.3.

Periodic inflow to the lake through the Łupawa Canal is estimated at 0.57 $m^3 \cdot s^{-1}$ (Balicki 1980). If there was only inflow from the sea, the water exchange coefficient would be 0.6.

RESULTS

Sea water intrusions

Sea water intrusions into the Gardno Lake depend on the relationship between the water levels in the lake and in the sea. This is especially visible in the periods of storms, when in the canal connecting the Gardno Lake with the sea, a change in the direction of water flow is observed, sometimes with a considerable dynamics. Yet, intrusions can occur also during almost windless weather. During the observation carried out for 10 days in May 1989 three clear inflows of sea waters into the Łupawa Canal were observed (Jasińska 1990). Additionally, when the difference between water level in the sea and the lake amounted from +5 cm to –5 cm, two-way flow was observed in the outlet section of the Łupawa during those 10 days.
The water level in the Gardno Lake is under an influence of the changes in the sea level, which is indicated by a similar rhythm of mean monthly stages (Fig. 3). In the lake, a low water level occurs in the period of April-June, which can be attributed to a small inflow from the catchment, and high water level between August and March.

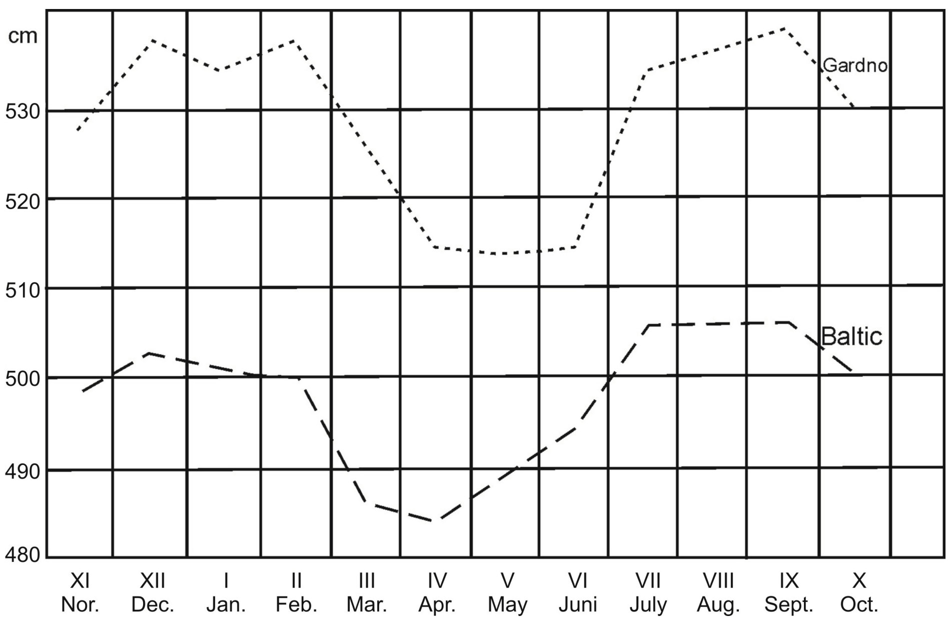

Fig. 3. Fluctuations of the average monthly level of the Gardno Lake and Baltic Sea in 1970--1980 (source: Cyberski 1984)

Table 1

List of mean monthly water stages of the sea and the Gardno Lake and their differences in 1958-1975 (source: Balicki 1980)

Months	XI	XII	I	II	III	IV	V	VI	VII	VIII	IX	X
Average monthly level of water												
the Gardno Lake	532	532	524	522	516	512	506	507	522	522	526	525
the Baltic Sea	506	507	498	497	488	490	489	495	508	504	504	504
Difference	+26	+25	+26	+25	+28	+22	+17	+12	+14	+18	+22	+21
Average monthly low level of water												
the Gardno Lake	515	516	509	508	503	500	496	499	509	511	512	512
the Baltic Sea	468	469	456	463	458	463	468	476	486	481	475	471
Difference	+47	+47	+53	+45	+45	+37	+28	+23	+23	+30	+37	+41
Average monthly high level of water												
the Gardno Lake	550	550	542	536	534	525	517	518	535	538	540	542
the Baltic Sea	557	550	543	538	527	523	511	516	535	531	535	548
Difference	-7	0	-1	-2	+7	+2	+6	+2	0	+7	+5	-6

The fluctuations of the mean monthly water levels are small and range from 506 cm in May to 532 cm in November and December. The lowest of the mean stages occurred in May – 496 cm, the highest in December – 516 cm. This indicates that in this period there are the most favourable conditions for the occurrence of salt water intrusion into the lake. Conversely, in the periods of low and medium stages, the water level in the sea was always higher than in the lake (Tab. 1), which indicates that intrusions could only occur in conditions of short storm damming or short periods of equal levels in the sea and lake.

Chlorides concentrations in waters of the Gardno Lake

The measurements of chlorides concentrations in the waters of the Gardno Lake almost always revealed an elevated value of chlorides ranging from 13.9 to 1512 mg/dm^{-3} (Tab. 2) in the whole water body. A regularity was observed that the highest chlorides concentrations occur near the Łupawa Canal. Moreover, it was noticed that higher values of chlorides concentrations always occurred in the northern part of the lake and that they revealed a clear decreasing tendency eastwards. The lowest chlorides contents occurred in the southern part opposite the mouth of the Łupawa River. It confirms Trojanowski's (2003) observations, who within the confines of the lake

Table 2
Recorded extreme chlorides concentrations (mg Cl^- dm^{-3}) in waters of the Gardno Lake in the period from 2002 to 2006

Point (deep)	**1** (2.0 m)		**2** (1.5 m)		**3** (2.0 m)		**4** (1.5 m)		**5** (1.5 m)		**6** (1.2 m)		**7** (1.5 m)	
Water	max	min	max	min	max	min	max	min	max	min	max	min	max	min
Surface	856	13.9	913	36.6	992	57.1	1315	61.7	1401	61.9	1512	69.3	894	47
Bottom	867	24.8	942	39.5	1024	58.2	1302	64.2	1377	68.1	1498	70.6	905	50.6
Intersticial	908	59.6	1013	240	1086	216	1255	333	1331	377	1429	395	953	211

Gardno marked three zones. He considered the influences of land and sea waters. South and south-east part are the zones where predominate the influences of land waters. The north-west part is the zone where predominate the influences of sea water, meanwhile interior part is characterized by the average conditions. Furthermore, in most of the measurements, higher values were observed in the above-bottom water layer than in the surface one, and the differences ranged from over 10 to frequently 150-200 mg Cl^-/dm^{-3}, and even higher in interstitial waters.

Conditions of chlorides concentrations distribution

The hypothesis formulated in the introduction states that the observed occurrence of elevated chlorides concentrations in the waters of the Gardno Lake, their spatial and temporal variability may be caused by intrusions similar to those which were previously described in the literature on the subject in other hydrographic objects situated on the coast of the Southern Baltic Sea (Szopowski 1962, Szmidt 1967, Mikulski and Bojanowicz 1967, Tadajewski et al. 1979, Choiński and Lange 1996, Heese et al. 1996, Choiński 2001, Trojanowski 2003, Drwal and Cieśliński 2007, Drwal et al. 2007). In fact, sea water intrusions into coastal water bodies occur when the sea water level is higher than in the given water body. Can the measurement results for chlorides concentrations in the waters of the Gardno Lake also be explained by the occurrence of intrusions?

The occurrence of the highest chlorides concentrations was recorded in the waters of the Gardno Lake on 25/06/2003 and 28/10/2006 (Fig. 4). Both situations were an effect of a definite occurrence of intrusions. On the first date, the sea water level was only 1 cm higher than of the lake but on the preceding day the difference was 5 cm. Chlorides concentration in the whole water body ranged from 1512 mg/dm^{-3} (site **6)** to 655 mg/dm^{-3} (site **2**) on the surface and on the bottom from 1498 mg/dm^{-3} (site **6)** to 643 mg/dm^{-3} (site **2**). Thus the distribution of chlorides concentrations illustrates a situation when the intrusion started a day earlier but it lasted also on the day of the measurement but with a smaller intensity.

On the other date, however, the sea water level (in Ustka) was higher than that of the lake by 4 cm exactly on the day of the chlorides concentrations measurement. The con-

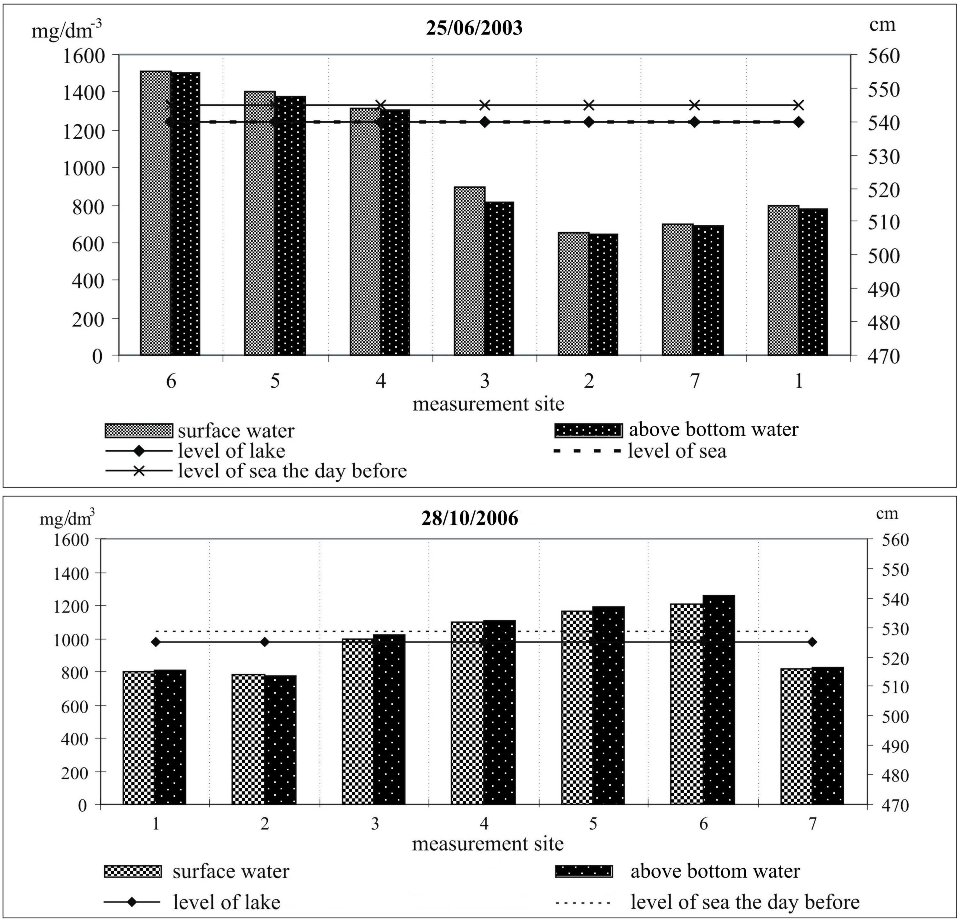

Fig. 4. Distribution of chlorides concentrations in waters of the Gardno Lake in a situation when the lake water level was lower than sea water level on preceding day (25/06/2003) and on measurement day (28/10/2006)

centrations in near-surface waters ranged from 1208 mg/dm^{-3} (site **6**) to 781 mg/dm^{-3} (site **2**), whereas in above-bottom waters from 1257 mg/dm^{-3} (site **6)** to 776 mg/dm^{-3} (site **2**).

Other situations also indicate that the elevated chlorides contents were an effect of earlier intrusions. On 19/05/2004 a higher by 3 cm water level in the Baltic Sea in comparison to that of the Gardno Lake (Fig. 5) was recorded. Chlorides concentrations were increased but with much lower values than in the above described situations. In the surface waters they ranged from 455 mg/dm^{-3} (site **6**) to 289 mg/dm^{-3} (site **1**), whereas in above-bottom waters from 478 mg/dm^{-3} (site **6**) to 304 mg/dm^{-3} (site **1**). These lower concentrations may have resulted from the fact that the measurement was performed on a day between two storms (the 15th-16th of May and the 20th -21th of May) in a period of high potamic inflow.

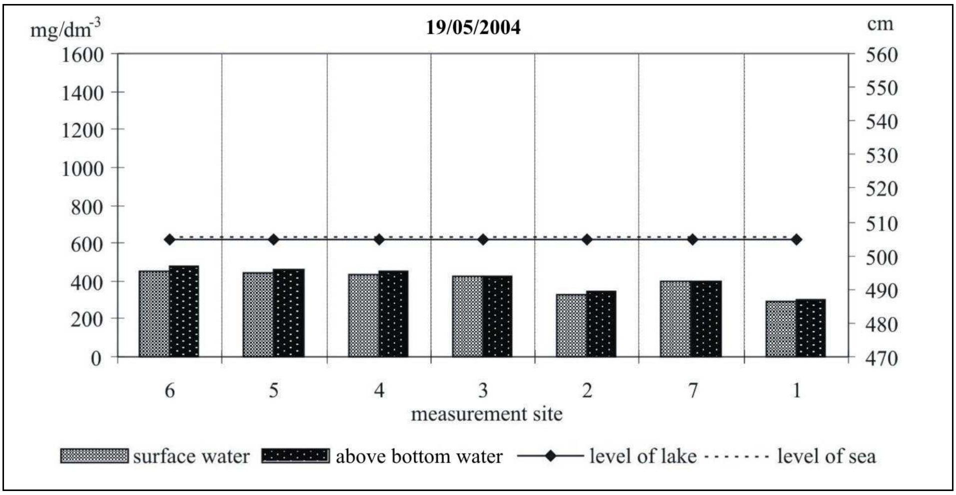

Fig. 5. Distribution of chlorides concentrations in waters of the Gardno Lake recorded in the period between two storms during high potamic inflow

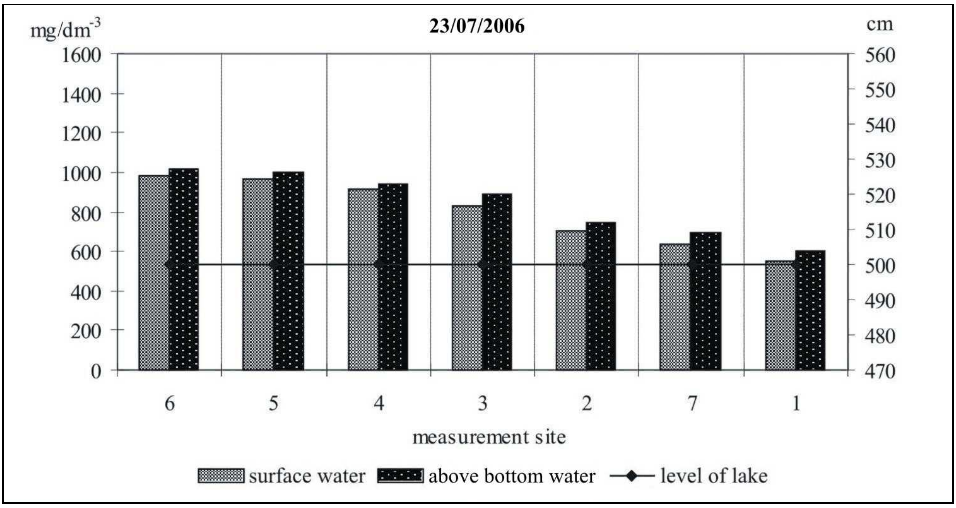

Fig. 6. Distribution of chlorides concentrations in waters of the Gardno Lake recorded in the period of low potamic inflow

However, the measurement performed on 23/07/2006 in a period of low potamic inflow (Fig. 6) revealed increased chlorides concentrations although on the measurement day the level of the sea (in Ustka) was 1 cm lower than that of the lake and on the previous day by 2 cm. In the surface waters, the concentrations ranged from 551 to 985 mg/dm^{-3}. In this case the low potamic inflow did not cause a weakening of the intrusion, which probably occurred between the 18th and the 20th of July.

On the other hand, on 21/11/2004 high chlorides concentrations were also observed although on the measurement day and the previous day the sea level was lower than

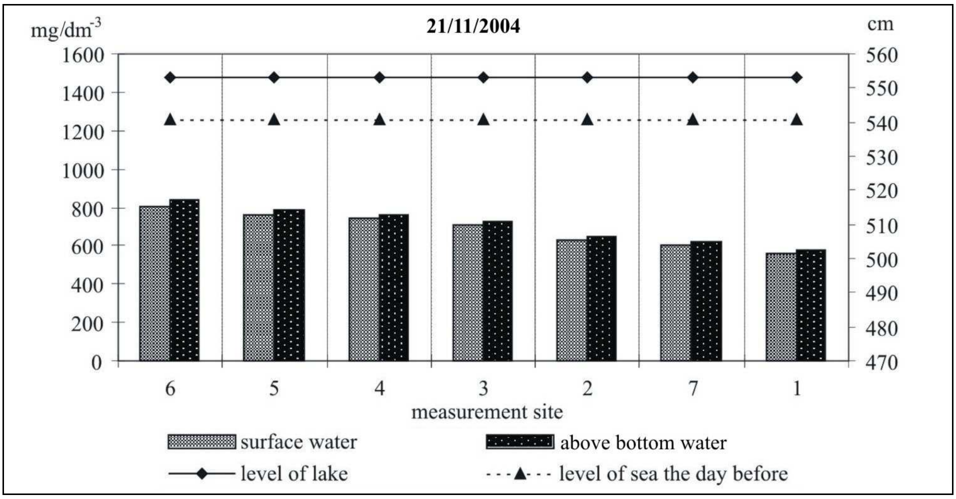

Fig. 7. Chlorides concentrations in waters of the Gardno Lake on 21/11/2004 against levels of the Baltic Sea and the Gardno Lake

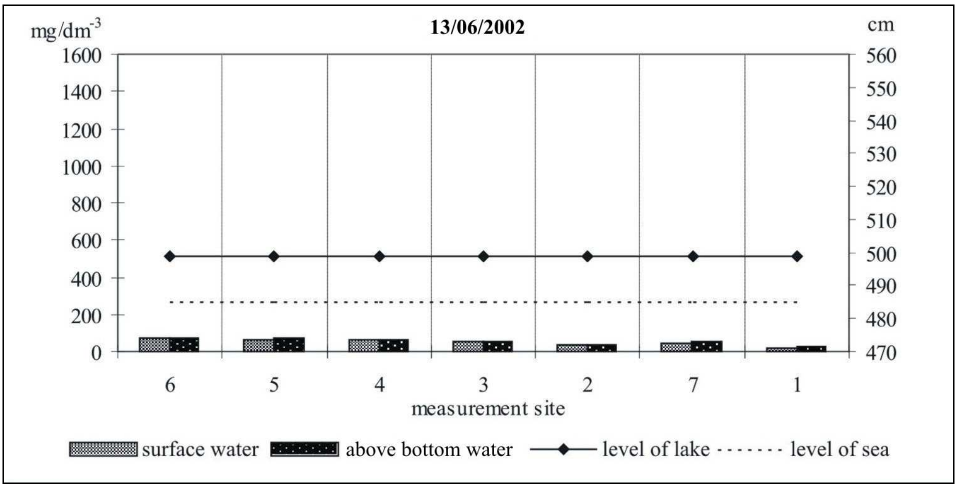

Fig. 8. Chlorides concentrations in waters of the Gardno Lake on 13/06/2002 against levels of the Baltic Sea and the Gardno Lake

the lake level by 4 cm and 20 cm respectively (in Ustka) (Fig. 7). In the surface waters the concentrations ranged from 808 mg/dm^{-3} (site **6**) to 559 mg/dm^{-3} (site **1**), and in above-bottom waters from 843 mg/dm^{-3} (site **6**) to 574 (site **1**). The measurements of water stages were performed after a strong storm which occurred between the 13th and the 17th of November.

In a period when there are no intrusions, the Gardno Lake is under a very strong influence of the waters of the streams inflowing from the direct catchment, mainly from the Łupawa River. As a result, low chlorides concentrations are observed in the

hole water body of the lake. On 13/06/2002 the sea level was 14 cm lower than the lake level, and on the preceding day 15 cm (Fig. 8). Chlorides concentrations in surface waters of the lake ranged from 69 mg dm^{-3} (site **6**) to 14 mg/dm^3 (site **1**), whereas in above-bottom waters from 71 (site **6**) to 25 mg dm^{-3} (site 1).
Traces of the potamic waters impact are also visible in interstitial waters in which the lowest chlorides concentrations occurred though sporadically. Opposite situations were observed more often.

Geographic consequences of water exchange between the sea and lake

The Gardno Lake as the central object in the hydrographic structure is under the influence of sea and lake waters. This results in the fact that the lake together with its direct catchment forms a unique geoecosystem, which differs from other inland reservoirs performing the role of local or regional recipients in hydrographic systems, in terms of water quality but mainly the rate and dynamics of transformations occurring in it. This is an effect of overlapping influences of waters in flowing from the catchment and of sea water intrusions. During intrusions, waters of highier salinity occur and remain during a greater part of the year in the whole water body of the lake, which is conditioned by the shape of the basin facilitating the penetration of salty waters. It was established that the water coming from intrusions remains there for at least several days. There is also evidence from reconnaissance measurements that the retention is longer. The easiness of penetration and long retention period result in the fact that only periodically the desaltation effect of potamic waters leads to an almost complete desaltation of water in the whole basin of the Gardno Lake. This influence is most often clearly observed in the southern part of the reservoir.

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INTRUZJE WÓD MORSKICH DO JEZIORA GARDNO

Streszczenie

W pracy podjęto próbę ustalenia czy w jeziorze Gardno dochodzi do intruzji wód morskich i czy skutki, które mogą one wywoływać są typowe dla jezior przybrzeżnych występujących na polskim wybrzeżu Południowego Bałtyku, czy też pod tym względem jest to jezioro wyjątkowe. Zastosowano metodę wykonywania na jeziorze powtarzalnych zdjęć hydrochemicznych z jednoczesnym określeniem aktualnej sytuacji hydrologicznej. W latach 2002-2006 wykonano 16 serii pomiarów w 7 punktach zlokalizowanych na jeziorze Gardno. Próbki wody pobierano w warstwie powierzchniowej, naddennej oraz interstycjalnej. Wodę z tej ostatniej warstwy uzyskiwano z powierzchniowego osadu dennego pobranego pobierakiem Kajaka poprzez użycie wirówki Centrifuge. Próbki wody analizowano w laboratorium Katedry Hydrologii Uniwersytetu Gdańskiego. Stężenie chlorków określano metodą miareczkową. Poziom wody w jeziorze odczytywano na wodowskazie IMGW zlokalizowanym w Gardnie Wielkiej, natomiast poziom morza na wodowskazie Urzędu Morskiego w Porcie Rowy bądź w Ustce.

Jezioro Gardno jako centralny obiekt w strukturze hydrograficznej jest pod wpływem wód lądowych i morskich. Powoduje to, że jezioro tworzy wraz ze swoja zlewnią bezpośred-

nią bardzo specyficzny geoekosystem, który wyróżnia od innych zbiorników śródlądowych pełniących w systemach hydrograficznych rolę odbiorników lokalnych czy regionalnych nie tylko jakość wód, ale przede wszystkim tempo i dynamika zachodzących w nim przemian. Jest to efekt nakładających się wpływów z jednej strony wód spływających ze zlewni, a z drugiej intruzji wód morskich. Podczas intruzji pojawiają się wody o podwyższonym zasoleniu. Utrzymuje się ono przez większą część roku w całym akwatorium jeziora, czemu sprzyja kształt misy ułatwiający penetrację wód słonych. Stwierdzono, że woda pochodząca z intruzji zalega co najmniej kilka dni. Są także przesłanki wynikające z przeprowadzonych pomiarów rekonesansowych wskazujące na to, że czas zalegania jest dłuższy. Łatwość penetracji i długi okres zalegania powodują, że tylko okresowo działanie wysładzające wód potamicznych doprowadza do prawie całkowitego wysłodzenia wody w całej niecce jeziora Gardno. Najczęściej to oddziaływanie wyraźnie widoczne jest tylko w południowej części zbiornika.