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Changes in hydrological, physical and chemical properties of water in closed/open coastal lakes due to hydrotechnical structures

by

Roman Cieśliński

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Department of Hydrology, Institute of Geography, Faculty of Oceanography and Geography, University of Gdańsk, ul. Jana Bażyńskiego 4, 80-309 Gdańsk, Poland

Abstract

The purpose of the study was to determine quantitative and qualitative changes in the waters of Lake Jamno in northern Poland due to the presence of new hydrotechnical structures in its drainage basin, with a special focus on the effects of a new storm barrier. The study consisted primarily of a review of measurement data, historical records and fieldwork prior to the construction (2002–2008) and following the construction of the storm barrier (2015). Fieldwork included hydrographic surveys and water sampling for laboratory analysis. The main and most easily discernible effect of the construction is the change in water quality in Lake Jamno. This is particularly true in the case of key indicators related to seawater, including conductivity, whose values changed from brackish to fresh water.

Key words: coastal lakes, hydrochemistry, human impact, storm barriers

* Corresponding author: *georc@univ.gda.pl*

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Introduction

While coastal lakes are all found in a similar coastal environment, they are substantially different in terms of hydrochemistry. This is due to their location at different latitudes as well as climate change (Iriarte et al. 2016), human impact (Brauer et al. 2013), tides, and other hydrometeorological conditions, including air circulation patterns that affect coastal areas. Another key issue is the type of sea (open sea, semi-enclosed sea, closed sea) where a given coastline is located. In the case where the sea is connected with the ocean, or in the case of fully open seas, or when the sea is located in the vicinity of straits that connect enclosed seas with oceans, coastal lakes tend to chemically resemble marine water bodies.

However, in the case of semi-enclosed seas and almost completely enclosed seas, such as the Baltic Sea, coastal lakes tend to contain more freshwater supplied through rivers, while water salinity increases only after seawater intrusions. The origin of seawater intrusions can vary. In the case of fully open seas, the main cause of intrusions are sea currents, while in the case of semi-enclosed and almost completely enclosed seas, wind-induced waves produced by storms as well as changes in water levels are the main causes. These differences are illustrated using the examples of lakes located along different stretches of coastline throughout the world by discussing changes in chloride concentrations.

In the case of coastal lakes located near oceans and open seas, very high concentrations of chloride are observed, including the example of Lake Castell de Ferro in Spain, where the maximum chloride concentration is about 14 000 (Pulido-Leboeuf 2004). Other examples include Lake Goksu in Turkey with a chloride concentration of 22 000 mg l^{-1} (Gordu et al. 2001), Lake Grevelingen in the Netherlands with chloride ranging from 22 000 to 32 000 mg l^{-1} (Kamermans et al. 1999), and Lake Coombabah in Australia with chloride ranging from 16 300 to 20 342 mg l^{-1} (Dunn et al. 2007). O'Neill et al. (2015) determined that the concentration of chloride along the coast of Australia ranges from 17 000 to 19 000 mg l^{-1}.

Coastal lakes in Great Britain are characterized by mean chloride concentrations in the range from 500 to 13 250 mg l^{-1} (Davidson et al. 1991). Xiang et al. (2016) determined that the mean chloride concentration of the coastal zone of China ranges from 4000 to 5000 mg l^{-1}. The chloride concentration in coastal areas tends to be quite stable, as illustrated by the example of the Laguna de Terminos in Mexico, where chloride ranges from 33 000 to 37 000 mg l^{-1} (Fichez et al. 2017). The situation in the case of semi-enclosed seas is quite different, where the concentration of chloride varies considerably depending on the season. For example, the coastal zone of Ravenna on the Mediterranean coastline of Italy is characterized by chloride content ranging from 300 to 20 000 mg l^{-1} (Mollema et al. 2013).

On the other hand, lakes located along the Baltic Sea coast tend to experience much lower chloride concentrations compared to lakes located along the Mediterranean Sea due to a greater influx of freshwater from terrestrial drainage basins, the excess of atmospheric precipitation relative to evaporation, and the lack of sea currents. For example, the chloride concentration in lakes such as Rucava and Taurene in Latvia ranges from 50 to 100 mg l^{-1} and 20 to 45 mg l^{-1}, respectively (Dubakova, Florova 2004). Most coastal lakes in Latvia are characterized by a low level of salinity. Other examples include lakes Tolkovas and Siksalas, where the average chloride concentrations are 4 and 3 mg l^{-1}, respectively. In addition, Lake Engure, which is described as a typical lagoon, is characterized by a chloride level of 7 mg l^{-1} (Spriņģe et al. 1999).

There are some examples of lakes in Latvia characterized by higher salinity, including Lake Kisezers with an average chloride concentration of 154 mg l^{-1} (Spriņģe et al. 1999). The situation is also interesting with coastal lakes in Estonia. The mean chloride concentration in lakes featuring a direct surface connection with the sea ranges from 210 to 3380 mg l^{-1} (Timm et al. 2007). However, some Estonian lakes of this type show significantly lower chloride concentrations, ranging from 120 to 150 mg l^{-1}. In the case of lakes without a direct connection with the sea, the chloride level ranges from 7 to 234 mg l^{-1} (Timm et al. 2007). On the other hand, the mean chloride concentration in coastal lakes of Lithuania is about 300 mg l^{-1} (Kavaliauskienė 1999).

The chloride concentration range in coastal lakes of Poland also varies substantially. It is possible to identify three different types of coastal lakes after Cieśliński and Obolewski (2017). The first type comprises lakes with a permanently high concentration of chloride, ranging from 400 to 4100 mg l^{-1}. The second type includes lakes with a chloride content of 20 to 200 mg l^{-1} for most of the year and periodically increased salinity, reaching 1500 mg l^{-1} and caused by seawater intrusions. The third type includes permanently freshwater lakes with salinity levels ranging from 7 to 150 mg l^{-1} (Cieśliński & Obolewski 2017). Prior to the storm barrier construction, Lake Jamno was classified as a Type Two lake, and after the construction – as a Type Three lake. The examples given above show

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that salinity levels in coastal lakes considerably vary. This applies both to lakes located in different types of coastal areas and lakes located in coastal areas of the same type, which may be due not only to environmental conditions, but also human impact.

Human impact serves as an additional factor, which directly or indirectly changes hydrological characteristics of lakes. A number of examples of human impact may be cited for the recent decade or so, but the most visible change appears to be that in Lake Jamno and the Jamno Canal, which connects the lake with the nearby Baltic Sea. The construction of the storm barrier rapidly produced a particularly strong effect on the overall hydrological regime of the lake. This issue is discussed by Lawrie et al. (2010), who describe periodically open and periodically closed estuaries and argue that two distinct mechanisms exist. The first involves changes in the water balance via changes in the quantity of incoming water. The second mechanism relies on water chemistry – the supply of pollutants from a lake's catchment area is not compensated by the influx of clean water from the sea. Closing the estuary connections with the sea leads to the accumulation of nutrients in the lake, which further leads to increases in eutrophication and growth of algae. Potter et al. (2010) showed that shutting the connections between coastal lakes and the sea substantially alters the salinity levels in the lakes. According to Schallenberg et al. (2010), cutting lakes off the seawater inflow results in water quality changes, but also significant changes in the rate of water level changes and fluctuations. In addition, Morris and Tumer (2010) argue that the water circulation pattern in coastal lakes is complex and susceptible to human impact. This applies in particular to periods without seawater inflow, when flood risk increases due to the natural filling of the watercourse estuary section connecting the lake with the sea. Elliot and Whitfield (2011) also report that the closure of connections between coastal lakes and the sea leads to ecological changes in lakes including changes in plant and animal species and habitats.

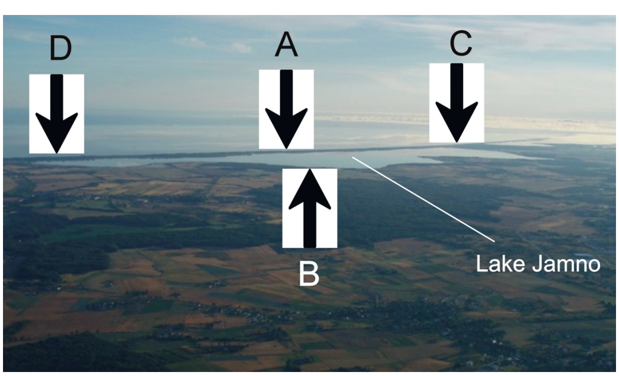

Figure 1

Location of automatic monitoring sites: A – Jamno Canal, B – Koszałek site, C – Łabusz site, D – Mielno site

This study aims at demonstrating the environmental changes in Lake Jamno, a coastal lake located on the mid-western coast of Poland, due to new hydrotechnical installations between the lake and the Baltic Sea. Despite the fact that the consequences of restricted contact between the lake and the sea are commonly known, the author provides quantitative data illustrating the extent of change in the lake ecosystem.

Materials and methods

Methods

Most of the research consisted of a review of source materials and fieldwork prior to the construction (2002–2008) and after the construction of the storm barrier in 2013 (2013–2015). Fieldwork consisted of hydrographic surveys and water sampling for laboratory analysis. Water samples were collected from the surface water by a hydrographic cylinder of 3 dm^3. The collection and storage of water samples was carried out in accordance with the Polish standards. Samples were collected in 1 dm^3 polyethylene bottles (washed with 2M hydrochloric acid and rinsed several times with distilled water). Water samples were collected in characteristic places related to the hydrographic system and morphometric conditions (A–D sites in Fig. 1 and gauging stations in Fig. 2). The time of sampling was related to the characteristics of hydrometeorological conditions and different seasons. A total of 224 samples were collected in Lake Jamno prior to the construction of the storm barrier and another 28 samples were collected in the Jamno Canal. After the construction of the barrier, 75 samples were collected in the lake and 30 samples in the canal.

The most important source of information on changes following the construction of the storm barrier was the online source: www.hydrowskaz.pl. The website included data on water levels and specific conductivity for Lake Jamno and the Jamno Canal. The data were collected by four stationary monitoring sites where measurements were performed automatically. Readings were taken from 25 September 2013 to 9 September 2015. The first gauging site is located in the Jamno Canal (5.57 m a.s.l. Amsterdam), while the remaining three sites are located along Lake Jamno: (1) Koszałek Harbor (5.58 m a.s.l. Amsterdam), (2) Łabusz Harbor (5.59 m a.s.l. Amsterdam), (3) Mielno Harbor

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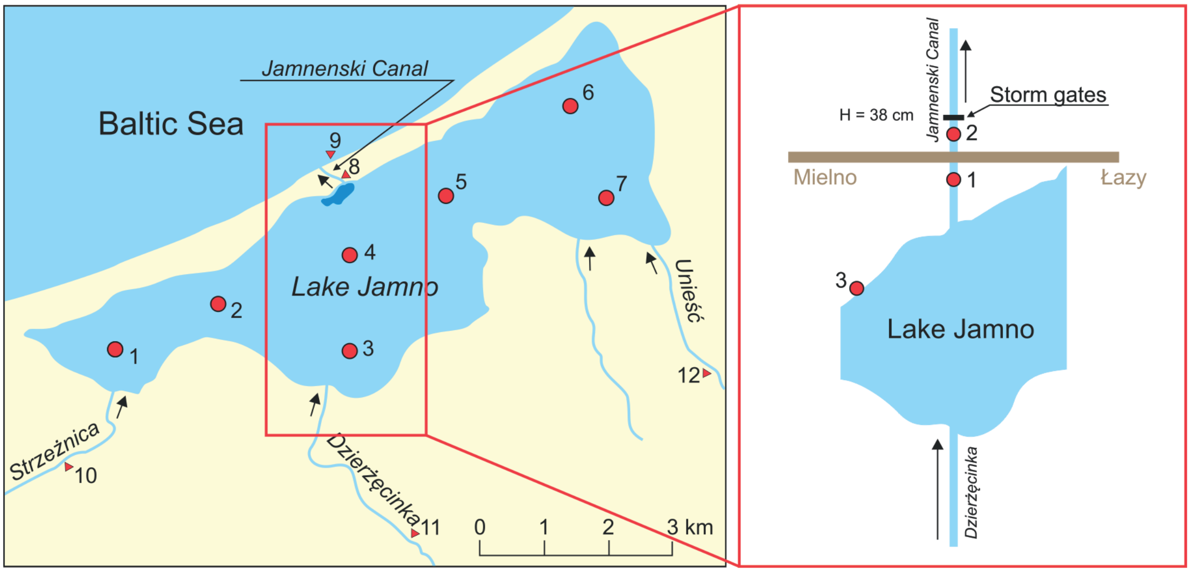

Figure 2

Location of gauging sites on Lake Jamno and the Jamno Canal (Cieśliński 2004) and location of water sampling sites used in the period 2013–2015

(5.58 m a.s.l. Amsterdam) (Fig. 1). Measurements were performed every hour. A total of 52 560 water level and specific conductivity readings were taken.

The most important source of information on water quality in Lake Jamno prior to the construction of the storm barrier is the paper by Cieśliński (2004, 2009a), which was based on eight gauging sites located throughout the lake and one site in the canal (Fig. 2). The data provided by this publication included specific conductivity and chloride concentrations for Lake Jamno as well as the discharge for the Jamno Canal. In addition, several supplementary measurements were performed in 2013–2015 (Fig. 2).

Most laboratory work in this study consisted of the analysis of specific conductivity using two multi-parameter measuring devices (WTW i350 and HachLange HQD40) as well as a Dionex C1100 ion chromatograph designed to measure ion concentrations – chloride in this case. Specific conductivity was measured in situ in the field. Chloride was selected as the best hydrochemical indicator, as it migrates well in the natural environment and does not react with other chemical species. The chloride ion is also used in comparative papers for the southern Baltic coast. Other physical-chemical indicators were not used in this work. Sample analysis error was below 2%.

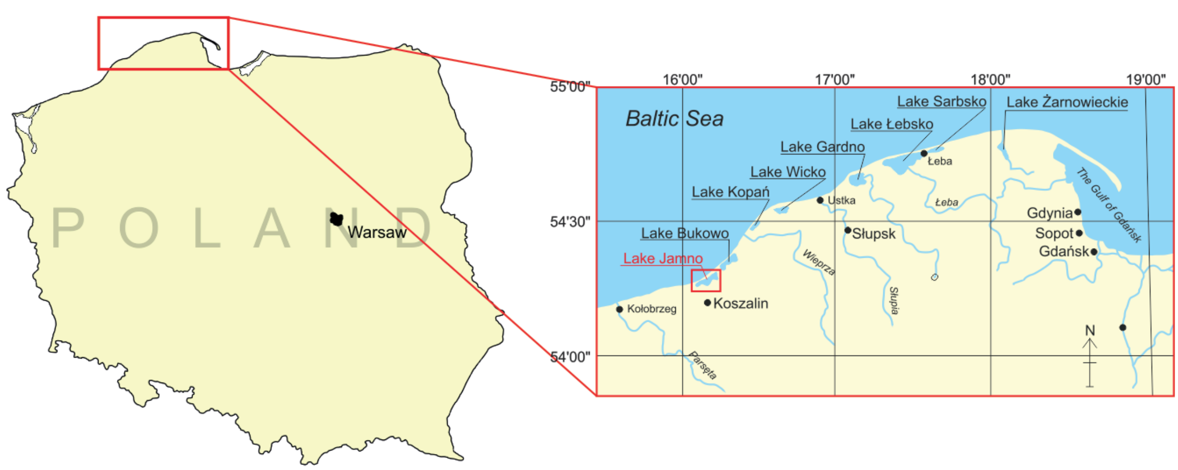

Figure 3

Location of Lake Jamno along the southern coast of the Baltic Sea with respect to other bodies of water in the area (Paturej 2006)

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Figure 4

The Jamno Canal connecting Lake Jamno with the Baltic Sea – a bird's eye view (https://www.google.pl)

To avoid major errors during the analysis, external and internal calibration was performed. The storage time and eluent were also important.

Field site

Lake Jamno is a coastal lake (Fig. 3) separated from the Baltic Sea by a sandbar and connected with the sea by the 360 m long Jamno Canal (Fig. 4). The canal is between 20 and 26 m wide (Cieśliński 2007). The maximum depth of the canal is about 2 m and its mean depth is 0.8 m. Its longitudinal gradient is 0.17‰. When the canal was originally built, it was not reinforced in any way (Fig. 5). However, some of its banks are now reinforced with concrete. The banks were upgraded in 2013 by making the canal walls much higher (Fig. 5). The storm barrier was also constructed across the canal, which is the subject of this paper (Fig. 5).

Lake Jamno has an area of 2207.3 ha and a volume of 38 300 000 m^3. The mean depth of the lake is 1.7 m, while its maximum depth is 3.9 m (Choiński et al. 2014). The shoreline is 28 300 m long. The lake's drainage

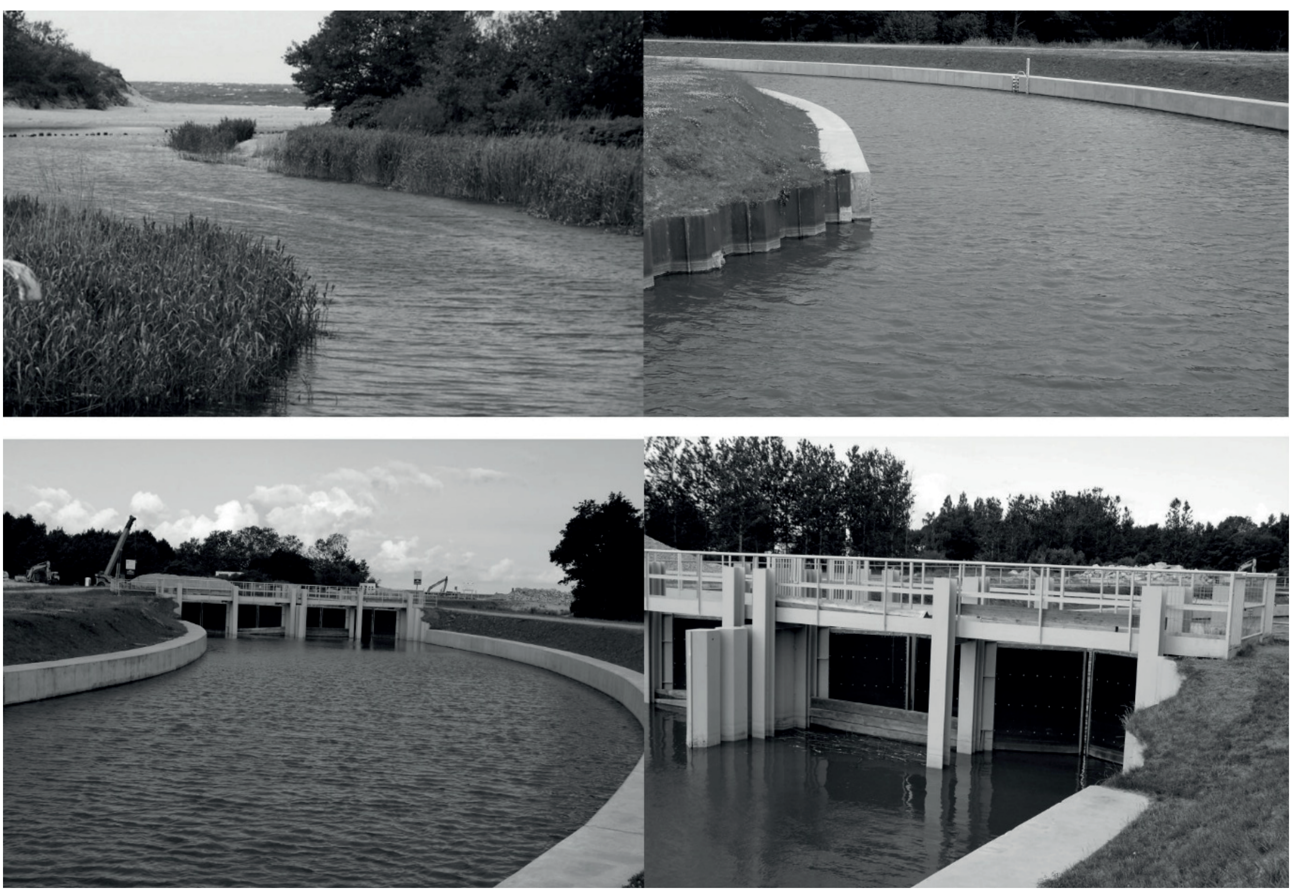

Figure 5

The Jamno Canal before and after the construction of the storm barrier along with a view of the storm barrier

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area is 502.8 km^2. It is a flow-through lake with three larger tributaries and several minor tributaries including drainage ditches. The annual discharge produced by the three main tributaries is estimated at 100 M m^3. The Jamno Canal carries 130.48 M m^3 of water to the Baltic Sea per year. The drainage basin of Lake Jamno has an area of 510.6 km^2.

The influx of seawater into Lake Jamno is subject to strong fluctuations. The research carried out in 1997 (Nowicka, Wronko 1997) indicates that the range of fluctuations between water levels in the sea and in the lake (gauged in the canal) is 1.28 m (minimum of 0.13 and maximum of 1.15). The current general consensus is that the influx of seawater is most abrupt in autumn and winter; however, it is fairly rare.

Prior to the construction of the storm barrier, the Jamno Canal was periodically blocked by debris carried by coastal sea currents – on average 80 days per year. The research by Cieśliński (2009b) conducted in the Jamno Canal in 2002–2008 showed the discharge ranging between 10.0 and 15.0 m^3 s^{-1} in the case of water flow into the sea and about 10.0 m^3 s^{-1} in the case of water flow into the lake.

The water level in Lake Jamno is about 0.10 m higher than that in the Baltic Sea. It is estimated that the influx of seawater constitutes about 16.1% of the total water influx to the lake, which gives about 30 M m^3 of water. The Jamno Canal receives the seawater influx for 91 days of the year (25% of the year).

Results

Changes in water quality

The primary and most easily observable effect of the construction of the storm barrier is the change in water quality in Lake Jamno. This is particularly true in the case of marine-type ions such as chloride and the resulting change in specific conductivity of lake water. Figure 6 shows a spatial distribution of the chloride ion concentration for Lake Jamno prior to the construction of the storm barrier. In the study, the highest chloride concentrations were determined close to the mouth of the Jamno channel.

The study did not provide a spatial distribution of key indicators to compare eastern and western parts of the lake. The research by Cieśliński (2009a, 2009b) confirmed the results of earlier research, which reported higher chloride concentrations in the middle part of the lake (up to 403 mg l^{-1}).

Cieśliński (2009a, 2009b) used data from the years 2002–2008 to observe that the mean concentrations of chloride in Lake Jamno ranged between 173.2 and 297.8 mg l^{-1} (Table 1). The coefficient of variance was high – more than 50%, which suggests substantial variability in terms of lake hydrochemistry due to seawater intrusions (Table 1). At the same time, the mean chloride concentration in the Jamno Canal was 457 mg l^{-1} and the coefficient of variance was 77.8% (Table 2). This suggests even greater hydrochemical instability in the canal compared to the lake.

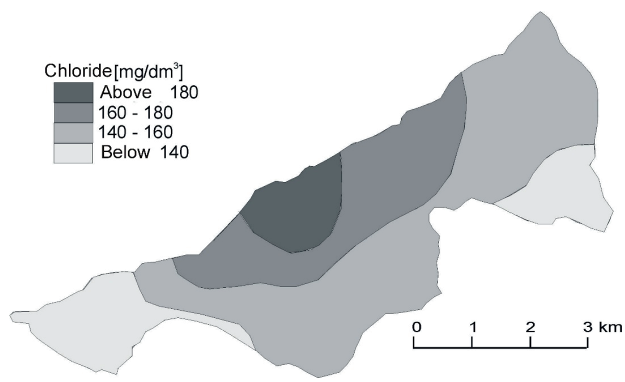

Figure 6

Distribution of chloride concentrations in the surface waters of Lake Jamno on 15 July 2002 (Cieśliński 2009a)

Table 1

Descriptive statistics for the chloride ion (mg l^{-1}) and electric conductivity (µS cm^{-1}) in water of Lake Jamno

Indicator	Arithmetic average		Standard deviation		Maximum value		Minimum value		Coefficient of variation	
	A	B	A	B	A	B	A	B	A	B
Chloride	297.8	173.2	162.8	99.1	698.0	477.0	133.0	70.0	54.7	57.2
Conductivity	1184.8	925.1	540.6	367.2	2870.0	2150.0	693.0	591.0	45.6	39.7

A – point located opposite to the Jamneński Canal, B – point located furthest from the Jamneński Canal

Table 2

Descriptive statistics for the chloride ion (mg l^{-1}) and electric conductivity (µS cm^{-1}) in water of the Jamneński Canal

Indicator	Arithmetic average	Maximum value	Minimum value	Coefficient of variation
Chloride	457.0	925.0	44.0	77.8
Conductivity	1899.0	6995.0	855.0	60.0

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Table 3

Average values of selected physical and chemical data obtained in the field in 2013–2015

Site no.	Chloride (mg l^{-1})	Conductivity (µS cm^{-1})	Location of the measuring point
1	44.0	404	Jamno Canal (400 m from the shoreline of the lake)
2	78.0	508	Jamno Canal (600 m from the shoreline of the lake)
3	38.0	394	Lake Jamno (north–western part)

Despite the relatively high mean chloride concentrations, the water in the lake can be described as freshwater for most of the year. Periodically elevated chloride concentrations in Lake Jamno have always been the result of seawater intrusions. The minimum concentration in 2002–2008 was 70 mg l^{-1}, while the maximum concentration was 698 mg l^{-1} (Table 1). Choiński and Gogołek (2005) studied the lake in 1965–2004 and found chloride concentrations to be between 69.6 and 280.6 mg l^{-1}.

Chloride concentrations were measured in Lake Jamno by the authors in 2013–2015 and the resulting average value was considerably low at 38 mg l^{-1}, however, the chloride content increased toward the sea. The chloride concentration in the Jamno Canal near its junction with the lake was measured to be 44 mg l^{-1}, while the value closer to the sea was 78 mg l^{-1} (Table 3).

A more important indicator in this study is electrical conductivity, as it can be used to compare data for the pre-barrier and barrier periods. The basic conclusion is that the impact of the sea was stronger – based on conductivity values – prior to the construction of the storm barrier. Conductivity values above 1000 µS cm^{-1} serve as evidence of seawater influx (Karus, Feldmann 2013).

Minimum conductivity values in Lake Jamno in 2002–2008 (Cieśliński 2011) ranged from 591 to 693 µS cm^{-1} and maximum values ranged from 2150 to 2870 µS cm^{-1}. The coefficient of variance resembled that for the chloride concentration and ranged between 39.7 and 45.6% (Table 1). The mean value of specific conductivity was found to be 1899 µS cm^{-1} for the only gauging site located on the Jamno Canal, while its range in 2002–2008 was 855 to 6995 µS cm^{-1} (Table 2). The coefficient of variance was calculated at about 60%. Specific conductivity for the Jamno Canal for the period from 25 September 2013 to 20 September 2015 ranged from 250 µS cm^{-1} to 14 430 µS cm^{-1}, which yields a huge difference of 14 180 µS cm^{-1} (Fig. 7). The gauging site is located in front of the storm barrier on the sea side, which provides easy contact between seawater and the canal water.

The mean for the entire period (2013–2015) was 1832 µS cm^{-1}. The results suggest intense marine effects and possible surface runoff effects. On the other hand, specific conductivity for the Koszałek site on Lake Jamno ranged from 110 to 830 µS cm^{-1}, which yields a difference of 720 µS cm^{-1} (Fig. 6). The mean for the entire studied period was 452 µS cm^{-1}. At the Łabusz site on Lake Jamno, specific conductivity ranged from 220 to 680 µS cm^{-1}, which yields a difference of 460 µS cm^{-1} (Fig. 7).

The mean for the entire study period from 25 September 2013 to 20 September 2015 was 424 µS cm^{-1}. Specific conductivity at the third lake gauging site (Mielno) ranged from 290 to 1170 µS cm^{-1}, which yields a difference of 880 µS cm^{-1} (Fig. 7). The mean for the entire period was 712 µS cm^{-1}. These findings were further confirmed by new fieldwork on 15 July

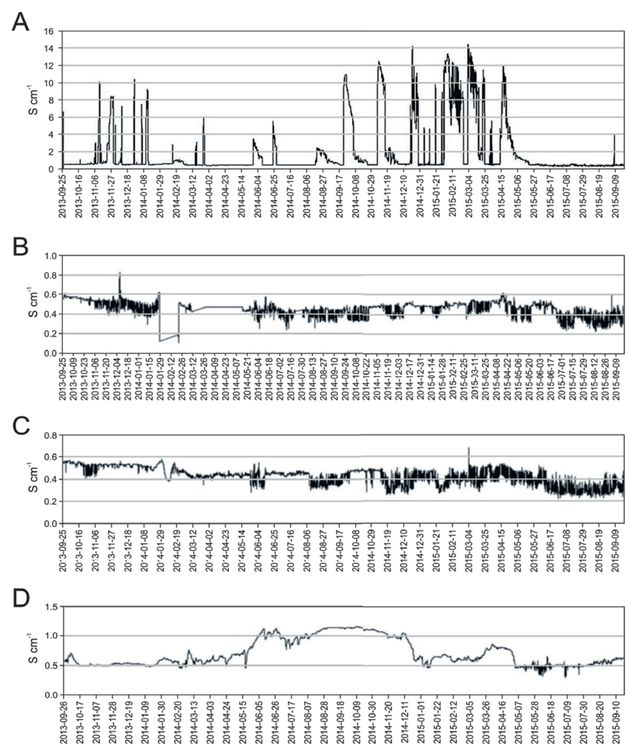

Figure 7

Specific conductivity (S cm^{-1}) in the Jamno Canal (A), Lake Jamno (Koszałek site) (B), Lake Jamno (Łabusz site) (C) and Lake Jamno (Mielno site) (D) between 25 September 2013 and 20 September 2015

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2015, with specific conductivity in Lake Jamno at 394 µS cm^{-1}. Specific conductivity in the Jamno Canal was determined at a site close to the lake (404 µS cm^{-1}) and for a site close to the sea (508 µS cm^{-1}) (Table 1).

Data obtained from automatic sampling probes used in the study indicate that the lake is characterized by specific conductivity below 1000 µS cm^{-1}. The likely reason for elevated values of EC was the saltwater influx via groundwater, as mentioned by Choiński et al. (2014). Woszczyk et al. (2010) also studied the underground influx of seawater from the sea to coastal lakes along the Polish Baltic coastline. What makes this hypothesis even more plausible is the fact that the Mielno site is located along the northern shore of the lake in close proximity to the Baltic seashore. According to Ziętkowiak (1983), there is a direct and marked effect of the sea on changes in the level and chemistry of groundwater, limited to a narrow strip of land with a width of 100 to 150 m. In the first zone, directly adjacent to the sea, with a strip of land between 100 and 150 m wide, the groundwater level largely corresponds to sea level changes (the zone is characterized by the greatest impact of the sea resulting from the direct influx of seawater). In the second zone, isolated from the seacoast and the lake with sand-dune embankments, changes in the groundwater level are long-term and correlated with seasonal changes in the sea level. In the third lake zone, changes in the groundwater level are shaped by the sea level, indirectly affecting changes in the lake water level.

According to the coastal lake classification system provided by Cieśliński (2011) and based on water salinity, prior to the construction of the storm barrier, Lake Jamno was a freshwater lake with occasionally higher salinity levels. The mean chloride concentration did not exceed 200 mg Cl^{-} dm^{-3} (minimum value of 40 mg Cl^{-} dm^{-3}). Periodically higher salinity levels are noted in lakes of this category, with chloride concentrations increasing to nearly 700 mg Cl^{-} dm^{-3}. Currently, Lake Jamno is classified as a coastal lake affected by human impact. This type of lake features fresh water with a chloride concentration ranging from 8 to 40 mg Cl^{-} dm^{-3}. Such lakes have a surface connection with the sea, although the sea does not have any impact due to the forced water circulation and hydrotechnical modifications. The water influx occurs here via underground pathways and surface pathways from the lake's catchment area. Figure 8 presents a tree diagram showing Lake Jamno along with other coastal lakes in Poland. This is a multi-characteristic classification in the form of a dendrite based on Ward's model, which uses the distribution of minimum, maximum and average concentrations of chloride. The left side of the figure shows relationships between coastal lakes found along the southern coastline of the Baltic Sea in Poland – including Lake Jamno prior to the construction of the storm barrier. In this case, coastal lakes are grouped into four different groups. The first one includes lakes with high salinity water that resembles seawater (Lake Łebsko, Lake Ptasi Raj, Lake Karaś). The second

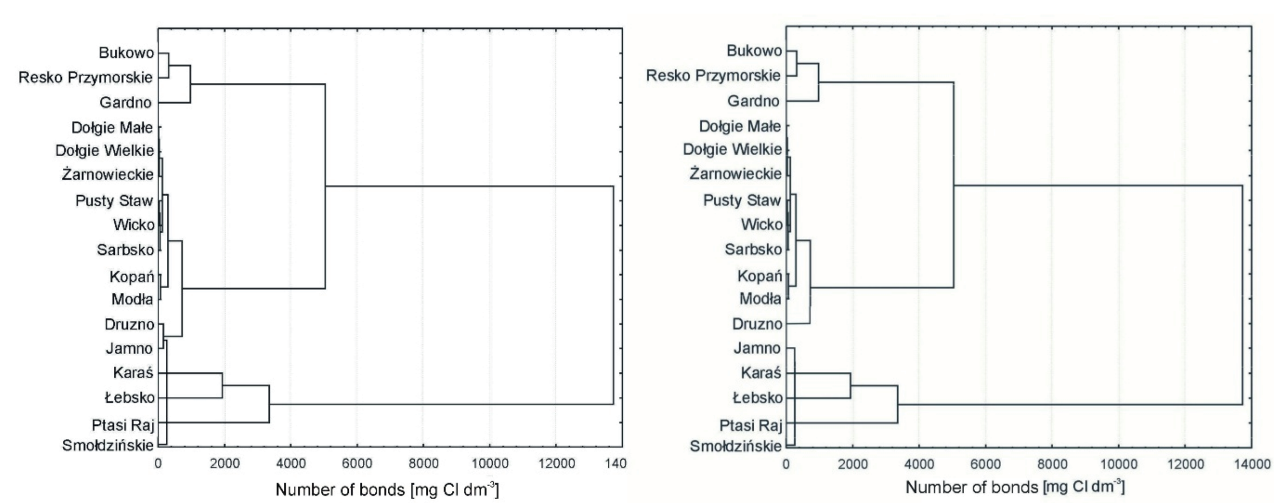

Figure 8

Lake classification tree diagram showing the minimum, maximum and mean chloride concentrations in selected coastal lakes before the construction of the gates on the Jamno Canal (figure on the left) and after their construction (figure on the right)

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group includes coastal lakes with high salinity, but never reaching the salinity levels of the first group (Lake Bukowo, Lake Resko Przymorskie, Lake Gardno). The third group includes lakes Druzno, Jamno, and Smołdzińskie or lakes that contain freshwater for most part of the year and only periodically experience higher levels of salinity. The fourth group includes lakes that contain freshwater throughout the year (Lake Dołgie Małe, Lake Dołgie Wielkie, Lake Żarnowieckie, Lake Pusty Staw, Lake Wicko, Lake Sarbsko, Lake Kopań, Lake Modła). The right side of the figure shows a classification of lakes including Lake Jamno after the construction of the storm barrier. The new classification consists of five groups. Groups no. 1, 2, and 4 do not change, while group no. 3 consists of only one lake (Druzno). This classification includes a new group that comprises lakes Jamno and Smołdzińskie or lakes featuring freshwater with rare and small increases in salinity levels.

In order to better understand differences between chloride concentrations in the studied lakes, including Lake Jamno, prior and after the construction of a storm barrier, principal component analysis (PCA) was used (Fig. 9), which was based on two salinity variables (extreme and average values) to place the studied lakes in different groups. This choice was based primarily on the analysis of lake water salinity. The research results indicate that the lake classification system is similar to that used by Ward. Prior to the construction of the storm barrier, Lake Jamno and Lake Druzno formed a group characterized by freshwater with periodically elevated salinity levels due to seawater intrusions. After the construction of the storm barrier, Lake Jamno was reclassified as a permanently freshwater lake, just like Lake Karaś, Lake Wicko, Lake Żarnowieckie etc. The location of Lake Jamno on the graph changed from square 2 (upper right) to square 4 (lower right). Perkal's comprehensive index and Hellwig's critical range (in this case for k = 0.5) were used to create a classification based on four groups – identical as in the case of principal component analysis.

Changes in water levels

Water levels in Lake Jamno and the Jamno Canal do not appear to change as much as the specific conductivity. According to Dąbrowski (2004), the annual water level change range for Lake Jamno is 139 cm. Data obtained from automated probes in the lake indicate that absolute changes in the water level for each given probe are as follows: Koszałek – 87 cm, Łabusz – 103 cm and Mielno – 95 cm. It is reasonable to infer that the fluctuation range for water levels in Lake Jamno following the construction of the storm barrier is smaller than that reported by Dąbrowski (2004) for the pre-barrier period by 30 to 40 cm.

However, the change in water level in the Jamno Canal is also small and resembles that in Lake Jamno. The change in water level in the canal ranged from 75 to 178 cm, which yields a difference of 103 cm (Fig. 10). The average water level in the canal was 134 cm. The range for gauging sites on the lake was as follows: Koszałek – 1 to 88 cm (mean 43 cm), Łabusz – 45 to 148 cm (mean 99 cm), Mielno – 82 to 177 cm (mean 135 cm; Fig. 10).

It has been observed that the lake's shoreline continues to recede within two years after the construction of the storm barrier. The shoreline has

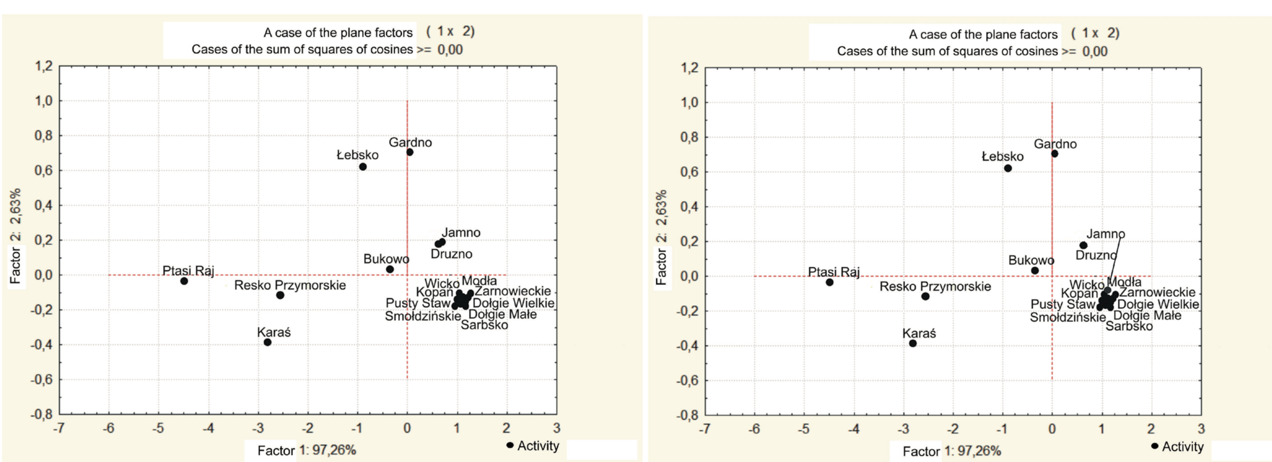

Figure 9

Classification of lakes using the method of principal components showing the minimum, maximum and mean chloride concentrations in selected lakes

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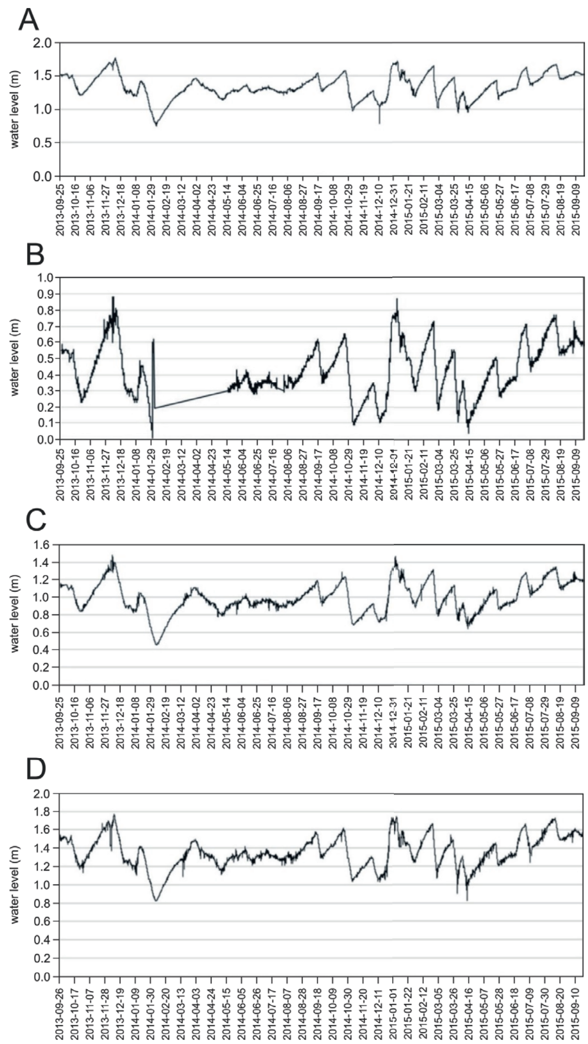

Figure 10

Changes in water levels (m) in the Jamno Canal, Lake Jamno (Koszałek site), Lake Jamno (Łabusz site) and Lake Jamno (Mielno site) between 25 September 2013 and 20 September 2015

Figure 11

Recession of Lake Jamno's shoreline after the construction of the storm barrier

receded about 10 m at the Mielno site (Fig. 11), which suggests a smaller water influx into the lake. These are likely short-term fluctuations. It is important to note that the storm barrier prevents about 30 M m^3 of seawater per year from entering the lake. The second factor is dredging of the Jamno Canal during the implementation of the storm barrier construction project, which has resulted in a lower drainage base and an increase in water loss from the lake.

At present, after the storm gates have been built, blooms and dead fish in the lake have increased (Fig. 12).

Discussion

Intermittently Closed and Open Lakes or Lagoons (ICOLLs) are dynamic coastal systems that may be vulnerable to changes in catchment hydrology (Sadat-Noori et al. 2016).

Intermittently closed and open lakes and lagoons located throughout the world are shallow barrier lakes, which are intermittently connected with the sea and experience saline intrusions. Many of these lakes are open to prevent flooding of surrounding agricultural and urban land and to flush out water of poor quality. According to Schallenberg et al. (2010), there are lakes whose water chemistry does not change upon opening and closing the connections with the sea. This suggests that the exchange of water with the sea is minimal. There are also lakes that respond very rapidly to opening and closing of connections. Their water levels adjust quickly to seawater levels once the connection is opened and marine-type indicator values such as chloride and sodium concentrations as well as electrical conductivity increase, while land-type indicators such as nitrate and bicarbonate concentrations decrease rapidly. On the other hand, when a storm barrier is closed, land-type indicator values increase rapidly and marine-type indicator values decrease in proportion to the length of the closed gate period. Lake Jamno, however, experiences an entirely different process than that described by Schallenberg et al. (2010). In this particular case, the storm barrier is always closed, even in the event of a minimal change in the direction of water flow from the flow into the sea to the flow into the lake. This is strange because in the past Lake Jamno was naturally blocked from the sea by sanding. It lasted 80 days a year and caused periodic quantitative and qualitative changes in the lake. This phenomenon is observed in other regions of the southern Baltic Sea (Suursaar et al. 2014). It is difficult to understand why the seawall was permanently closed. According to Snow and Taljaard's

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Figure 12

Blooms and fish kill in Lake Jamno (Author: Student Group of Koszalin University of Technology)

conceptual model, there should be three dominant mouth states for such objects: open, semi-open and closed (Snow, Taljaard 2007). Intermittently Closed/Open Lakes and Lagoons are of global importance as they provide valuable ecological habitats for many species and are associated with a wide range of management issues due to their cycle of entrance closing and opening (McSweeney et al. 2017). In coastal lagoons with occasional connection to the sea, the role of precipitation and surface runoff from the catchment area is increasing (Collins, Melack 2014). However, this was not observed for Lake Jamno.

As a result, the influx of seawater to the lake is nonexistent and the lake's water chemistry is not subject to change, although in general the waters of the lake have changed from brackish to fresh. The second effect of closing the storm barrier is a rapid increase in the lake's water level due to an influx of water from its catchment and an increase in the concentrations of land-type indicators, including biogenic substances. The larger threat is posed by the outflow of water from the lake when the storm barrier is open and water can flow freely to the sea. The lowering of the drainage base causes a rapid outflow of water from the lake. According to Everett et al. (2007), the most vital element of the proper functioning of coastal lakes in the hydrological and biological sense is the extent of the seawater influx into lakes, which can be physically isolated from the sea for extended periods of time. This is due to the specific circulation at sea and the hydrometeorological conditions in the coastal zone (Westerlund et al. 2018).

This emphasizes the importance of a dynamic cycle of seawater exchange consisting of two distinct stages – open and closed. This cycle varies over time in the case of most coastal lakes. However, it is a static cycle in the case of Lake Jamno and does not provide any chance for brackish water influx when the storm barrier is closed. The gate is deliberately closed once the seawater begins to enter the lake. Therefore, the

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cycle for Lake Jamno may be considered disadvantageous. The storm gate should be closed once a certain threshold is exceeded, as in the case of the East Kleinemonde Estuary in South Africa. In this particular case, the gates are closed when the water level exceeds 2 m above sea level. The gates are opened following a major influx of water from the catchment area (Riddin, Adams 2008).

Estuaries, rias, fjords, coastal lagoons, bahiras, river mouths, tidal creeks, deltas and similar coastal environments are often regarded as a single broad conceptual class. "Brackish", "estuarine", "paralic" and "transitional" are terms used in different contexts to collectively designate this class of environments. However, any term, generated from different historical and scientific perspectives, excludes some of the above-mentioned environments. The analysis provided evidence for the occurrence of two major groups of attributes: hydrological and geomorphic ones. One of them is morphometry which describes physical and geographic characteristics of waterways. Morphometry provides a simple way to define the natural sensitivity or vulnerability of individual systems to external loads and other artificial (primarily anthropogenic) modifications (Haines et al. 2006). On the other hand, according to Hinwood and McLean (2015), mouths of many barrier estuaries open and close intermittently under the influence of a wide range of environmental parameters. At the same time, they have great hydrological and ecological importance to the coastal zone (Saintilan et al. 2016), as confirmed by the research on Lake Jamno.

Conclusions

The main and most easily observable effect of the new storm barrier on the Jamno Canal is the change in water quality in Lake Jamno. This is particularly true for changes related to marine-type indicators such as specific conductivity showing that marine effects were stronger in Lake Jamno prior to the construction of the storm barrier on the Jamno Canal. Specific conductivity at that time very often exceeded 1000 μS cm^{-1}. The construction of the storm barrier resulted in a larger fraction of freshwater retained by Lake Jamno. At present, the conductivity readings no longer reflect brackish waters, except for the seawater influx via underground passageways.

No cases of surface-based seawater influx have been recorded since the construction of the storm barrier on the Jamno Canal. According to the coastal lake classification system for Poland produced by Cieśliński (2011) and based on lake water salinity, prior to the construction of the storm barrier, Lake Jamno was classified as a freshwater lake with occasionally elevated salinity levels. Two years after the construction of the storm barrier, Lake Jamno is classified as a purely freshwater coastal lake affected by human impact.

The second effect of the construction of the storm barrier was the change in the water level fluctuation range in Lake Jamno. The fluctuation range has now been reduced by 30 to 40 cm. The likely reason for this reduction is the same as in the case of salinity levels, i.e. a strongly reduced seawater influx, which had previously abruptly increased the water level in the lake. The current changes are generated by land-based water influx. No surface seawater influx is observed today.

The two effects discussed in this paper have led to substantial hydrological and hydrochemical changes in Lake Jamno, which have resulted in a significantly different classification of the reservoir. In summary, the hydrochemical regime of Lake Jamno has undergone a very substantial change due to the construction of a new hydrotechnical structure.

The construction of hydrotechnical barriers in the world often brings positive effects (reduction of flood risk, improvement of ecological status, etc.). In the case of Lake Jamno, unfortunately, it brought negative effects (changes in the lake water recharge, changes in the water cycle, occurrence of ecological disasters). This applies mainly to changes in water resources and chemical status, which in turn translates into biotic conditions of the lake. Therefore, before commencing such an investment in the area, it is necessary to analyze in detail the risk that may occur in the environment when the construction is commissioned.

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