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Water balance characteristics of the Vistula Lagoon coastal area along the southern Baltic Sea

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Abstract: The purpose of the paper is to provide some calculations on the current water balance for the Vistula Lagoon, which is exceptionally valuable in terms of biology and hydrology. It is located along the southern coast of the Baltic Sea in both Poland and Russia. In the era of marked climate change, but first and foremost the plans of the Polish side of the cross-cutting of the Vistula Spit, there has been a need to update the balance data of the Vistula Lagoon. In the near future, they may be an excellent comparative material to changes in the proportions of individual water circulation components in the Vistula Lagoon and changes in its entire ecosystem, caused by the implementation of the project. In the literature on the subject, balance sheet data from 50 years ago are used (these data were compiled in the initial part of the study), hence the concept of attempting to update them has appeared. Due to the lack of data from the Russian part of the catchment area, the main emphasis in the work was put on the completion and modernization of the components of the balance sheet of the Polish catchment. A novelty at work is the refinement of the potamical inflow to the Vistula Lagoon with small but numerous streams flowing from the Elbląg Upland, as well as the inflow forced by polder discharges. Climate water balance data are shown based on data available from IMGW in Warsaw and include monthly precipitation totals for the period 1996–2010 obtained at six gauging sites located near the Vistula Lagoon. Evaporation was calculated using Tichomirov's formula. River water influx was determined based on data available in Kruk (2011), data from IMGW (Pasłęka River) and data from papers Bogdanowicz (2007, 2009) and documents associated with the Program for biological passages in rivers in Warmińsko-Mazurskie Province (2007). Raw data were also obtained from the Office of Water Management in the city of Elbląg for the period 2006–2011. These data covered water flow moving from the polders. Groundwater influx was estimated using values provided by Silicz (1975). The volume of seawater influx was estimated using the data provided by Silicz (1975) and Chubarenko and Chubarenko (2002). The study confirms that water exchange in coastal lagoons is quite complex due to the presence of several different sources of recharge and several different places where water is lost. The complexity of water cycle is enhanced by a complex hydrographic system of lagoon catchments and a complicated system of water exchange with the sea. The total water volume involved in circulation in the Vistula Lagoon is estimated to be 24,225 mln m^3 per year. The largest part of the water received by a coastal lagoon comes from the sea. In this case, it is about 77% (18,130 mln m^3 per year). In addition, an array of catchment sources yields about 21% of the studied lagoon's water. Its catchment provides an additional 4,974 mln m^3 of water. The Pregolya River produces 55% of the catchment influx. The volume of water forcibly produced by area polders is so small that it does not produce an observable effect on the water balance in the Lagoon (about 0.04% of total influx). The precipitation constitutes 2.3% of the power supply source of the Vistula Lagoon. On the other hand, the Strait of Baltiysk constitutes the main outflow pathway for water exiting the Vistula Lagoon – close to 98% of all outflow (23,694 mln m^3). The remaining 2% is lost due to evaporation.

Keywords • *Vistula Lagoon • water balance • water exchange • water supply • water outflow • components of water balance*

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INTRODUCTION

The southern coastline of the Baltic Sea is characterized by a complex water balance driven by the large variety of hydrographic entities, processes, and phenomena affecting water and matter circulation in the region. The main agent of change in the area is the nearby Baltic Sea, which serves as the primary drainage base for water exiting land sources. In addition, the sea also affects many other elements of the natural environment found in its close proximity: climate, land relief, flora, fauna. In effect, the coastal zone possesses a very different nature in relation with inland areas. This fact is manifested in terms of differences in water exchange pathways, both with respect to the quantity of water and quality of water participating in each given flow. Research studies in the coastal zone have shown that waters in this region may be classified as transitional (Verdonschot *et al.* 2013) or estuarial (de Brye *et al.* 2013).

Studies have also shown that freshwaters in the coastal area are characterized by large changes in water chemistry determined by the area's hydrography, hydraulic contact between land and sea, as well as hydrologic regime (Astel *et al.* 2016). According to Cieśliński (2011), the main driver of water quantity and chemistry in this area is the degree of isolation from the sea. Given the classification system used in Poland, water in the Vistula Lagoon may be classified as "transitional with lagoon-type features" (Krzymiński *et al.* 2004). According Chubarenko and Margoński (2008) or Chubarenko *et al.* (2017) Vistula Lagoon represents the coastal lagoon.

The present-day coastal zone of the southern Baltic Sea features a large number of bodies of water. The most important include the estuary sections of large European rivers as well as smaller coastal rivers. Other features include coastal lakes, lagoons, wetland areas, as well as entities directly associated with human impact such as polders, canals, and drainage ditches. Researchers very often identify many of these features with estuaries (Paturej 2006) as well as quasi-estuaries (Drwal and Cieśliński 2007). Many are associated with frequent changes in the water level and constant changes in physical, chemical, and biological characteristics. The entities of interest are also characterized by significant fluctuations in the level of salinity, pH, water temperature, oxygen content, nutrient content, and organics content (Paturej 2006). In particular, many of these changes occur as a result of interactions between land and sea. First and foremost, seawater intrusions deep inland contribute to the above mentioned changes.

Lagoons are one of the most important bodies of water in the coastal zone, and are most often defined as bodies of water situated along the seacoast, which are separated from the sea by sandy barriers and are open to the sea at some locations. One landmark feature of lagoons is their permanently elevated salinity and its large change over time, often driven by periodic seawater intrusions in inland bodies of water (Cieśliński 2011). On the other hand, Chubarenko *et al.* (2017) defines lagoons as a shallow section of the ocean or sea, which is separated from it by a sand barrier, peninsula or reef, and connected to it via a narrow strait or group of straits. The physical separation of a lagoon by a barrier and its connection with the sea makes it different from an estuary. Lagoons constitute about 9% of the coastline around the world (Chubareno *et al.* 2017). The study of these bodies of water only began in the 1970s; hence, a lack of hydrologic data including water balance data.

The Vistula Lagoon is one example of this type of body of water. It is located along the southern Baltic Sea in northern Poland and western Russia. It is also an example of a body of water for which it is difficult to find papers detailing the components of its water balance. One of the few papers available is that a book by Łazarenko and Majewski (1975), where Silicz (1975) covered its water balance. This particular paper covers the period 1951 – 1965, which today makes it obsolete from a quantitative standpoint. There exists the need for updated data on water influx and distribution in the Vistula Lagoon in order to fill data gaps and provide a new source of research data for studies related to climate change (IPCC 2007, 2014, Pruszak and Zawadzka 2008, Wolski and Wiśniewski 2014). However, this is no easy task given the various problems associated with the accurate determination of the components of the water balance, especially in the area of water exchange between the Vistula Lagoon and the Bay of Gdansk. These problems result from facts such as the location of data at many different government institutions and the associated task of collecting these data from many different sources as well as the lack of monitoring data for river flow for most sites along the Vistula Lagoon due to the occurrence of reverse water flow during seawater intrusion events.

Other difficulties associated with this type of research include the determination of the water influx and outflow values for groundwater – an area where existing data sources remain incomplete. However, the greatest problem is that with the determination of the water volume recharging the Vistula Lagoon from the Bay of Gdańsk via the Strait of Baltiysk. Gauging water flow in the opposite direction is difficult as well. Some data are available in Russian-language sources. The neighboring Russian city of Kaliningrad is home to the Science Center Geogidrobalt, which pursues research work on the hydrology of the Vistula Lagoon. However, data obtained from this Russian research center date back to the 1970s, making them too outdated to be used effectively today (Science Center Geogidrobalt 1971). The issue of data aging also applies to research by Chechko (2004) who uses data from the 1980s. Yet another source of older data is that of Naumenko *et al.* (2012). At this point in time, the most valuable source of data on the water balance in the Vistula Lagoon is a chapter in a book (Chubarenko *et. al.* 2017) compiled by Kosyan (2017), even though the data in this book are also somewhat outdated. Some information on the water balance can be found in Chubareko's and Chubarenko (2002) paper. They concern water dynamics of the Vistula Lagoon, in particular water exchange with the Baltic sea.

The purpose of the paper is to provide some calculations on the current water balance for the Vistula Lagoon, which is exceptionally valuable in terms of biology and hydrology. It is located along the southern coast of the Baltic Sea in both Poland and Russia.

This is perhaps the last chance of such calculations, because in 2018 the Polish government anticipates the construction of a cut through the Vistula Spit, which will cause significant changes in the current balance of the Vistula Lagoon. At the same time, the work attempted to update the data on water balance, whose results are currently based on data from the seventies. The work will give a comparison whether the components of the water balance have changed for nearly 50 years and whether the observed climatic changes have affected the hydrological conditions of the Vistula Lagoon. The work uses the most up-to-date data on power sources and elements of water use, including rivers, where the values of flows of small watercourses flowing from the Elbląg Upland have been added, or inflow of polder waters, which until now has not been included in the calculation of the Vistula Lagoon balance. In the case of the rivers of the Polish part of the Vistula Lagoon, all possible inflows have been covered, which is a novelty of this work. The atmospheric precipitation was based on data for six meteorological stations, which guarantees the determination of its diversity on the entire surface of the Vistula Lagoon. A novelty is the application in the case of Tichomirov evaporation calculations. As a result, it is expected to obtain the most up-to-date and accurate water balance of the Vistula Lagoon.

MATERIAL AND METHODS

The data needed to calculate influx and outflow values for the Vistula Lagoon may be obtained from a number of different sources. Climate water balance data are shown based on data available from IMGW in Warsaw and include monthly precipitation totals for the period 1996 – 2010 obtained at six gauging sites located near the Vistula Lagoon: Gdańsk-Świbno, Elbląg, Tolkmicko, Frombork, Braniewo, Nowa Pasłęka. In addition, this data set includes all the data needed to estimate evaporation from the water surface (air temperature, wind speed, level of humidity) for the same time period – collected at the Gdańsk-Świbno gauging site. In this case, evaporation was calculated using Tichomirov's formula.

River water influx was determined based on data available in Kruk (2011), which lists discharge values for the largest streams flowing into the Vistula Lagoon. It seems that the author has consumed data from other sources, although there is no reference to them at work. Certain values were updated using the latest data from IMGW (Pasłęka River). New values were provided for any streams not covered in Kruk (2011). These covered small streams flowing from the Elbląska Upland and covered in papers by Bogdanowicz (2007, 2009) as well as documents associated with the Program for biological passages in rivers in Warmińsko-Mazurskie Province (2007). Raw data were also obtained from the Office of Water Management in the city of Elbląg for the period 2006 – 2011. These data covered water flow moving from the polders Nowakowo-Batorowo and Rubno "W" to the Vistula Lagoon. There is no data currently available for the part of the catchment area located in Russia. Hence, groundwater influx was estimated using values provided by Silicz (1975). The volume of seawater influx was also estimated using the data provided by Silicz (1975) and Chubarenko and Chubarenko (2002). Water outflow was estimated by calculating the difference.

The final water balance equation for the Vistula Lagoon is as follows:

P (precipitation) + **Hd** (inflow from the catchment) + + **Hm** (inflow from the sea) = **Hw** (outflow to the sea) + + **E** (evaporation)

Characteristics of the Vistula Lagoon

The Vistula Lagoon (Fig. 1) is a silty basin in the form of an elongated rectangle that runs roughly north-south along the Baltic Sea in northern Poland and Russia (Kaliningrad region). It is about 90.7 km long and its average width is 9.2 km, as measured from the Vistula Spit to the Sambian Peninsula and the mouth of the Pregoła River in Russia (Cieśliński 2016). The widest point measures 13 km (Różyński et al. 2015). Its surface area is 838.0 km^2 (Chubarenko and Margoński 2008). The Polish part of the Vistula Lagoon has an area 365 km^2 and a Russian area of 473 km^2 (Różyński *et al.* 2015). Finally, it is separated from the Baltic Sea by a slip of land roughly

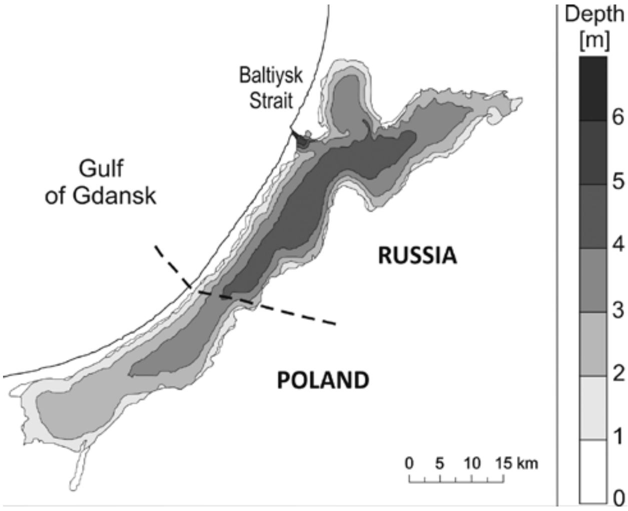

Fig. 1 Bathymetry of the Vistula Lagoon (Witek *et al.* 2001)

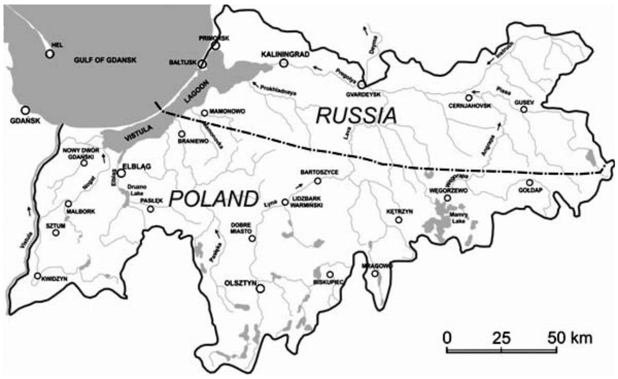

Fig. 2 Catchment area of the Vistula Lagoon

50 km in length. The Lagoon is linked with the Bay of Gdańsk via the Strait of Baltiysk, which is about 2,000 meters long and 400 meters wide. The depth of the strait ranges from 8 to 12 meters (Chubarenko and Margoński 2008, Różyński *et al.* 2015). Overall, the Lagoon as a whole is quite shallow at only 2 to 3 meters of depth (Fig. 1). Only its central "shipping lane" is deeper than 3.0 meters – with maximum depth at 5.2 meters (Chubarenko and Margoński 2008). The water capacity of the Lagoon is estimated to be 2.3 km^3. Its eastern basin provides 1.5 km^3 of this capacity or 64.0% of total water volume. Originally, the Lagoon connected with the extensive backwaters and marshes inside the Vistula delta and had at least periodic connection with the Baltic Sea (Chechko *et al.* 2015).

The Vistula Lagoon is the second largest lagoon along the southern coast of the Baltic Sea. The largest lagoon is called the Curinina Lagoon. The role of seawater in the Lagoon is significant, although its only link with the sea is the Strait of Baltiysk in Russia (Cieśliński 2016). At present, the largest rivers feeding the Lagoon are the Pregolya, Elbląg, and Pasłęka. The surface area of the catchment of the Vistula Lagoon is 23,870.6 km^2 (Chubarenko *et al.* 1998).

The larger part of the catchment area of the Lagoon is located in Poland: 14,757 km^2. The smaller part is found in the Kaliningrad Province of western Russia. A very small part is located in Lithuania – the eastern part of the catchment of Lake Vyshtynec-Vištītis (Fig. 2). The catchment area is asymmetrical in the easterly direction due to the mostly east-west course of the largest river feeding the Lagoon – the Pregolya River in Russia. The Vistula River serves as the western boundary of the Lagoon's catchment area. The southernmost part of the Lagoon's catchment area is the Lyna-Lava river drainage basin. The largest drainage basin that serves the Lagoon is the Pregolya river drainage basin at almost 63% of the Lagoon's current catchment area (Chubarenko *et al.* 1998). The Pregolya is lowland river characterized by flooding throughout the year, but only in downstream river. The second longest river feeding the Lagoon is the Pasłęka whose drainage basin constitutes slightly less than 10% of the catchment area of the Lagoon. Other drainage basins feeding the Lagoon in Poland belong to the Elbląg, Nogat, Szkarpawa, and Tuga rivers, and on the Russian side of the border, the Prochładna River. The Pregolya and the Deyma rivers link the Vistula Lagoon with the somewhat larger Curinina Lagoon (Chubarenko *et al.* 2017).

The Vistula Lagoon is a body of water with a very uneven distribution of water in the context of the location where water is exchanged with the Baltic Sea or the Strait of Baltiysk. In this case, the influx of seawater from the Baltic Sea depends not only on differences in water levels between the Sea and the Lagoon, but also on the given direction and speed of the wind (Jankowski 2000).

RESEARCH RESULTS AND DISCUSSION

Water balance calculated by Silicz (1975)

According to the water balance calculated by Silicz (1975), water exchange occurs in the majority via the Strait of Baltiysk. The Vistula Lagoon currently receives 80% of its water from the Baltic Sea. The total annual flow to the sea is estimated to be 20,480 mln m^3, while influx from the sea is estimated to be 17,000 mln m^3. The influx of water from the land side is estimated to be 3,600 mln m^3 (Łazarenko and Majewski 1975). Average discharge in rivers feeding the Lagoon is about 100 m^3·s^{-1}. Recharge via atmospheric precipitation is estimated to be 500 mln m^3 per year, while evaporation losses are estimated at 650 mln m^3. A comparison of values does show that vertical recharge is of secondary importance for the Vistula Lagoon. The primary form of water exchange is an exchange between the Vistula Lagoon and the Gulf of Gdansk that determine the hydrologic conditions in the Lagoon.

Water exchange through the Strait of Baltiysk depends on hydrologic and meteorologic factors such as water level differences between the Vistula Lagoon and the Bay of Gdańsk as well as wind conditions in the area of the strait. Water residence expressed in the form of a relationship between the Lagoon's volume of water and annual river water influx equals 198 days (Chubarenko *et al.* 2004). On the other hand, residence time calculated for distant parts of the Lagoon (away from the Strait of Baltiysk) ranges between 150 and 200 days (Chubarenko and Margoński 2008). Residence time for the Polish part of the Lagoon equals about one year (Bielecka and Kaźmierski 2003).

Table 1 shows the water balance, as calculated by Silicz (1975).

Table 1 Mean annual water balance for the Vistula Lagoon in 1951 – 1965 (Silicz 1975), calculated by Science Center Geogidrobalt (1971) and calculated by Naumenko *et al.* (2012)

Silicz (1975)		
Elements of water balance	Vistula Lagoon	
	mln m^3	%
Proceeds		
Precipitation	500	2.4
Inflow from the catchment	3 620	17.1
Inflow from the sea	17 000	80.2
Underground inflow	70	0.3
Sum	**21 190**	**100**
Expenditure		
Evaporation	650	3.1
Drain to the sea	20 480	96.9
Sum	**21 130**	**100**
Science Center Geogidrobalt (1971)		
Elements of water balance	Vistula Lagoon	
	mln m^3	%
Proceeds		
Precipitation	500	2.4
Inflow from the catchment	3 600	17.0
Inflow from the sea	17 000	80.3
Underground inflow	70	0.3
Sum	**21 170**	**100**
Expenditure		
Evaporation	650	3.1
Drain to the sea	20520	96.9
Sum	**21 170**	**100**
Naumenko *et al.* (2012)		
Elements of water balance	Vistula Lagoon	
	mln m^3	%
Proceeds		
Precipitation	500	
Inflow from the catchment	3 670	
Inflow from the sea	17 000	
Sum	**21 170**	
Expenditure		
Evaporation	600	
Drain to the sea	20 500	
Sum	**21 100**	

Water balance calculated by the Science Center Geogidrobalt (1971), Chechko (2004), and Naumenko et al. (2012)

The data produced for the water balance of the Vistula Lagoon by Science Center Geogidrobalt (1971) do not differ substantially from those given by Silicz (1975). Atmospheric precipitation is the same, as is water flow to the sea, 500 mln m^3 and 17,000 mln, respectively. There is a small difference in water influx from the catchment, with Science Center Geogidrobalt (1971) listing a value of 3,600 mln m^3. In addition, groundwater influx is estimated to be 70 mln m^3 per year. On the other hand, evaporation is the same as that given by Silicz: 650 mln m^3. There is a small difference in the volume of water flowing from the Lagoon to the Baltic Sea, which is estimated at 20,520 mln m^3. The inflow and outflow of water in the Vistula Lagoon balance each other out. Table 1 is a summary of all the components of the water balance calculated by Science Center Geogidrobalt (1971). Values that are identical to those given above are found in a typewritten text produced by Chechko (2004) who states that they were obtained from materials dating back to 1985. Similar values are also given by Naumenko *et al.* (2012). Table 1 shows all water balance data provided in the above study.

Water balance calculated by Chubarenko et al. (2017)

Chubarenko *et al.* (2017) provides the water balance for the Vistula Lagoon dividing it based on the two countries sharing the Lagoon and lists the surface area share of its drainage basins (Fig. 3). The data are based on Silicz (1971) and Chubarenko (2008). The catchment area of the Vistula Lagoon is shared by three countries: Poland, Russia, and Lithuania. Poland possesses the largest share of the catchment area at 14,561 km^2 or 61.0%. Russia possesses the second largest share at 9,220 km^2 or 38.6%. Lithuania is last with 90 km^2 or 0.4%. The main drainage basin feeding the Vistula Lagoon is that of the Pregolya River in Russia, which is also fed by several smaller basins of the following rivers: Łyna-Lava, Węgorapa-Angrapa, Pisa-Pissa, Istruch, Golubaya (Fig. 3).

The largest source of water for the Vistula Lagoon is the Baltic Sea, which supplies an estimated 17,000 mln m^3 of seawater per year. The Pregolya River supplies 1,530 mln m^3 of water per year or 44% of total river water influx. Other rivers supply a total of 1,969 mln m^3 of water (56%). The largest share of this to-

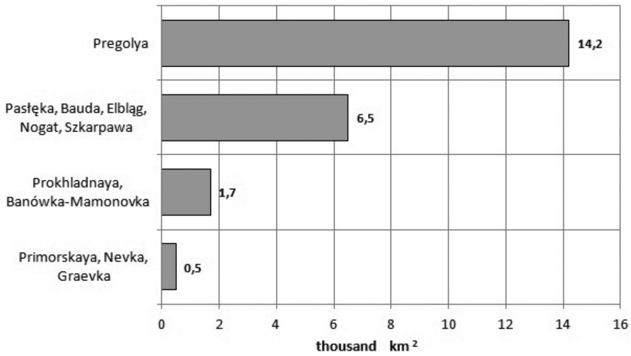

Fig. 3 Drainage basins in the catchment area of the Vistula Lagoon (Chubarenko *et al.,* 2017)

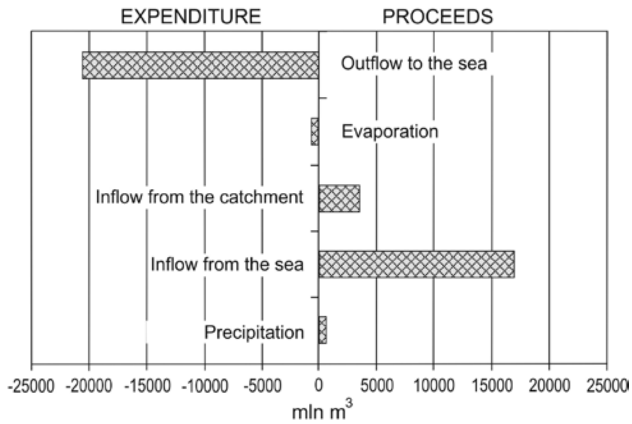

Fig. 4 Water balance for the Vistula Lagoon by Chubarenko *et al.* (2017)

tal is provided by rivers in Poland (Pasłęka, Elbląg, Nogat, Szkarpawa, Bauda), which supply 1,580 mln m^3 of water. Russian rivers supply 314 mln m^3 of water (Primorskaya, Nevka, Graevka). Finally, rivers that begin in Poland and then flow through Russia (Prokhladnaya, Bonuvka-Mamonovka) provide 75 mln m^3 of water. The supply of water via the Pregolya River is reduced by a bifurcation in the river at kilometer 56 of the river – counting from the mouth of the river at the town of Gvardejsk. Discharge in the Pregolya at this site equals 86 $m^3 \cdot s^{-1}$, which yields an annual flow of 2,740 mln m^3. Downstream of Gvardejsk, the river divides into two channels – the Pregolya proper and the Deyma. Pregolya proper supplies water towards the Vistula Lagoon at a rate of 1,810 mln m^3 per year. Some of this water is retained along the way and the Lagoon itself only receives 1,530 mln m^3 per year. The Deyma River flows into the Curinina Lagoon providing a total of 930 mln m^3 per year.

Evaporation-precipitation plays a secondary role in the water balance of the Lagoon. In both the case of precipitation and evaporation, the water volume involved is about 600 mln m^3 per year. The two forms of vertical water exchange balance each other out. Water circulation in the Lagoon involves more than 20,000 mln m^3 of water per year (Fig. 4).

River water influx to the Vistula Lagoon

In the 1960s the estimated river discharge reaching the Vistula Lagoon was 100 $m^3 \cdot s^{-1}$, which yields an annual value of 3,160 mln m^3 of water. More recent studies by Kruk (2011) and Bogdanowicz (2007, 2009) as well as data from the "Biological Program" (2007) suggest that an annual value of 4,895 mln m^3 of water (5,841 mm) is more accurate. The contributing rivers providing the largest volumes of water to the Vistula Lagoon are the Pregoła, Elbląg, and Pasłęka (Tab. 2).

Table 2 Mean discharge calculated for rivers feeding the Vistula Lagoon (Bogdanowicz 2007, 2009, *Biological Program* 2007, Kruk 2011)

River	Average flow in mln $m^3 \cdot year^{-1}$
Pregolya	2728,0
Elbląg	826,0
Pasłęka	567,7
Nogat	224,0
Prokhladnaya	161,0
Bonuvka-Mamonovka	109,0
Bauda	92,7
Primorskaya	80,0
Szkarpawa	74,0
Narusa	11,6
Stradanka	6,2
Grabianka	5,0
Kamienica	2,8
Dąbrówka	2,6
Olszanka	1,6
Kamionka	1,5
Suchacz	1,4
Sum	4895,1

Groundwater influx

The influx of groundwater to the Vistula Lagoon occurs from two different directions: from the mainland side and from the Vistula Peninsula. Influx from the mainland is produced by the Elbląska Upland, Warmińska Plain, Staropruska Lowland, Sambian Upland, as well as theoretically from the Vistula Delta. Water influx from the Delta is complicated and difficult to estimate, as the area is found below sea level. This situation would suggest a reverse flow of groundwater – from the Lagoon to the Delta. Depressed areas also feature polder systems that manage water flow mechanically. Nevertheless, groundwater flow from the Delta to the Lagoon is possible and occurs periodically during high retention periods in the winter and the spring due to the saturation of levees. The main groundwater streams recharging the Lagoon are associated with the drainage basins of the Pregolya and Pasłęka rivers. There is no available data on the Russian part of the Pregolya drainage basin.

According to hydrogeologic documents prepared by Kryza *et al.* (2005), the influx of groundwater to the Lagoon along the 35 km section of coastline from Elbląg to Braniewo is estimated to be 16,600 $m^3 \cdot d^{-1}$ (6.059 mln $m^3 \cdot yr^{-1}$). Much less water is provided by the water table of the Vistula Strait. Kreczko *et al.* (2000) lists this source of groundwater as 5,143 $m^3 \cdot d^{-1}$ (1.887 mln $m^3 \cdot yr^{-1}$), and 5,295 $m^3 \cdot d^{-1}$ (1.933 mln $m^3 \cdot yr^{-1}$) if the mouth section of the Królewiecka Vistula River (152 $m^3 \cdot d^{-1}$) is included. The total for both mainland and peninsula sources supplying groundwater to the Lagoon is rather low at 21,895 $m^3 \cdot d^{-1}$ or 7.992 mln m^3 per year.

Given the lack of data for the Russian side of the border, water balance calculations are based on annual data provided by Silicz (1975): 70,000 mln m^3 (83.5 mm).

Water influx from polders

Forced water flow from polders surrounding the Bay of Elbląg to the Vistula Lagoon alter the water exchange patterns in this area. The Bay of Elbląg is the southernmost part of the Vistula Lagoon. In addition, there is no data available for polders situated to the south of the Vistula Lagoon, as in the case of the Frombork Polder.

The mean annual influx of polder water from areas surrounding the Bay of Elbląg for the period 2006–2011 stood at about 9.176 mln m^3 (0.29 $m^3 \cdot s^{-1}$) (Tab. 3). There is no data available for the Jagodno Polder for the six year period studied in this case. This suggests that this polder was not used to drain areas located adjacent to this part of the Bay of Elbląg. Thus, the estimated influx for the period 2006 – 2011 to the Bay of Elbląg is about 9.2 mln m^3.

Precipitation and evaporation

The mean atmospheric precipitation total for the period 1996 – 2010 for the Vistula Lagoon area is 658 mm per year, which corresponds to a volume of water of 551.4 mln m^3. In years with "extreme" precipitation patterns, the minimum stands at 544 mm (455.9 mln m^3) for a dry year (1996), while the maximum stands at 856 mm (717.3 mln m^3) for a very wet year (2007) (Fig. 5). Evaporation for the same time period ranged from 522 mm (437.4 mln m^3) in 2001 to 782 mm (655.3 mln m^3) in 2002. The evaporation average was 634 mm (531.0 mln m^3).

Hence, in atmospheric water exchange, a positive water balance is noted due to small exceedances of atmospheric precipitation over losses caused by evaporation – a difference of 3.6% or 24 mm (20.1 mln m^3). The hydrologic years 2001 and 2007 were classified as "very wet" using the classification method by Kaczorowska (1962) and were characterized by large dif-

Table 3 Water influx from selected polders – data obtained from the Delta Office of Drainage and Water Management in Elbląg

Year	Annual water dumps [m^3]	
	Nowakowo-Batorowo	Rubno „W"
2006	5 931 360	1 087 200
2007	10 247 040	1 929 600
2008	9 167 040	1 263 600
2009	8 536 320	1 603 800
2010	5 767 200	853 200
2011	7 469 280	1 200 600
Medium discharge from multiple years	7 853 040	1 323 000
Average flow [$m^3 \cdot s^{-1}$]	0,25	0,04
Sum of multiple discharge [m^3]	**9 176 040**	

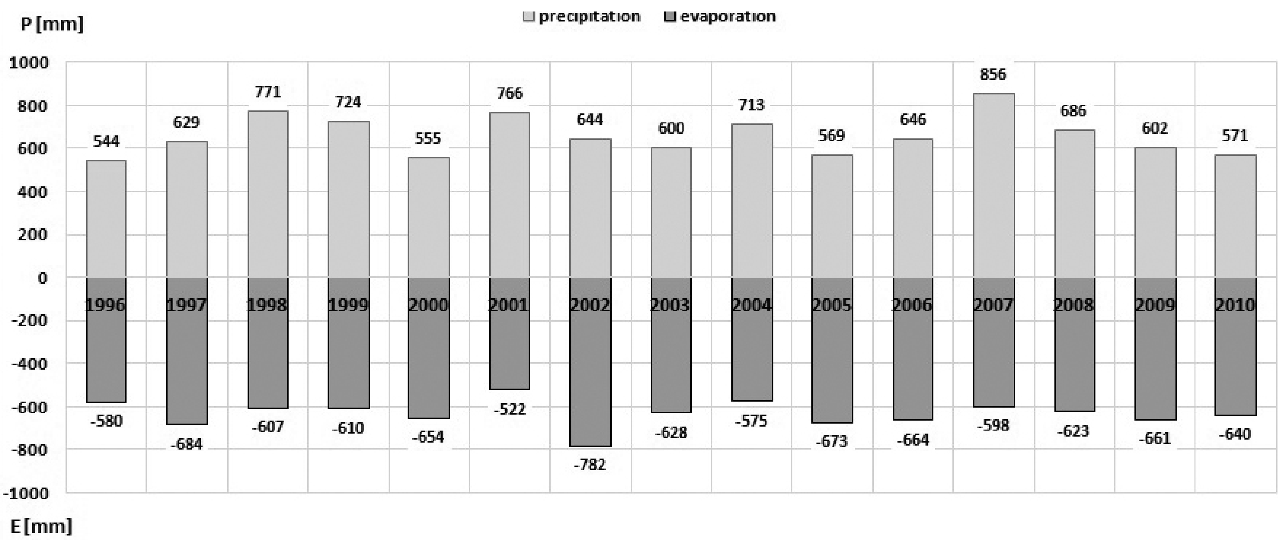

Fig. 5 Average of a year atmospheric precipitation totals calculated for gauging sites at Gdańsk-Świbno, Elbląg, Tolkmicko, Frombork, Braniewo, and Nowa Pasłęka, and evaporation totals for Gdańsk-Świbno for the period 1996–2010

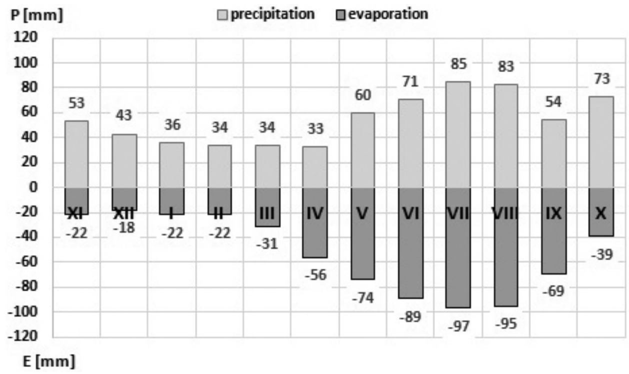

Fig. 6 Mean monthly atmospheric precipitation totals calculated for gauging sites at Gdańsk-Świbno, Elbląg, Tolkmicko, Frombork, Braniewo, and Nowa Pasłęka, and evaporation totals for Gdańsk-Świbno for the period 1996–2010

ferences of 244 mm and 258 mm, which corresponds to an excess of 210.3 mln^3 of water. The two variables were never found to balance each other out during the study period. On the other hand, there were years when outflow was greater than inflow. In some cases, the water deficit exceeded 100 mm, as in the case of the year 2002 (138 mm) and 2005 (104 mm). This yields corresponding water volumes of 87.2 mln m^3 and 115.6 mln m^3.

The highest rainfall amounts are noted in the warmer months of the year. Maximum values are noted in July (Fig. 6). The mean value is 85 mm (71.2 mln m^3). Low precipitation is noted from January to April, with a minimum in April (33 mm – 27.7 mln m^3). Losses due to evaporation from the surface of the water vary seasonally and correspond with changes in air temperature throughout the year. An increase in air temperature in the warmer months of the year corresponds with a marked increase in evaporation rates.

A negative water balance remains in place for the atmospheric phase from April to September, which means that even increasing precipitation cannot compensate for losses due to evaporation. The month of August is characterized by the greatest amount of evaporation at 97 mm (81.3 mln m^3). The smallest losses due to evaporation occur in the winter months. The period from November to February is characterized by an evaporation range of 18 to 22 mm (15.1 mln m^3 to 18.4 mln m^3). Extremely low and high monthly evaporation amounts noted in the study period (1996–2010) were 13 mm (10.9 mln m^3) in December and January of 2001 and 174 mm (145.8 mln m^3) in July of 2006, respectively.

Water flow to and from the sea

Water exchange between the Vistula Lagoon and the Baltic Sea data are not readily available for the study period. The most recent data may be found in Silicz (1975) and Chubarenko and Chubareno (2002). The problem with obtaining current data lies with the Russian side – no data are available for release. Despite efforts to obtain such data, government institutions were willing to provide any current data. No studies were identified that would provide scientific data for this area. Hence, the Silicz (1975) and Chubarenko and Chubarenko (2002) study is still the only study available. The resulting influx from the sea by Silicz (1975) equals 18,700 mln m^3 (22,315 mm). Total water outflow from the Vistula Lagoon to Gdańsk Bay is calculated as a difference and equals 23,694 mln m^3. According to Chubarenko and Chubarenko (2002) the process of water exchange through the Baltiysk Strait is essentially three-dimensional. The data on the currents in the strait are varied. They appeard unidirectional current, two-layer currents, and two-stream currents. The average velocity for total flow through the inlet observed ranges between 0.06 and 0.95 ms^{-1}. The average currents for the two-layer or two-stream regime are usually in the range of 0.1 – 0.2 ms^{-1}. Marine water intrusions into the lagoon are competing with outflow from the lagoon both during the spring period and the minimum run-off period in summer with equal rhythm of tens of hours in order. Accumulative annual inflow of marine water into the Vistula Lagoon (Tab. 4) made up about 18.1 km^3, annual outflow towards the Baltic Sea was ca. 22.5 km^3 in 1994. The annual average values are 17 km^3 and 20.6 km^3 respectively (Chubarenko and Chubarenko 2002).

Comparison of water balance components

The total water volume involved in circulation in the Vistula Lagoon is estimated to be 24,225 mln m^3 per year, which yields more than 28,900 mm when recalculated per surface area of the entire lagoon. Evaporation-precipitation between the surface of the Vistula Lagoon and the atmosphere plays a secondary role in the water balance – only several percent of the total water volume is subject to exchange in this manner (Fig. 7).

Table 4 Monthly averaged discharges through the strait of Baltiysk according the simulation by MIKE21 two-dimensional numerical model (Chubarenko and Chubarenko 2002)

	Month												Annual
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	
Inflow	2.31	0.93	1.69	1.00	1.22	1.84	0.84	1.302	1.569	1.587	2.163	1.677	18.13
Outflow	-2.53	-1.92	-2.64	-2.08	-1.48	-1.76	-1.13	-1.32	-1.572	-1.968	-2.208	-1.932	-22.54

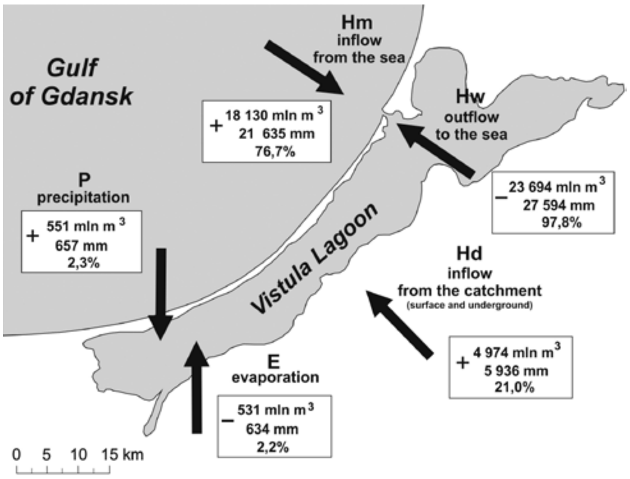

Fig. 7 Water balance for the Vistula Lagoon

In spite of this fact, a water deficit triggered by greater losses due to evaporation in relation with water influx due to rainfall is observed. The main source of water for the Lagoon is the Baltic Sea, estimated at 18,130 mln m^3 per year. This represents more than 77% of the water reaching the Lagoon. Its catchment provides an additional 4,974 mln m^3 of water or less than 21% of all of its water influx. The Pregolya River produces 55% of the catchment influx. The volume of water forcibly produced by area polders is so small that it does not produce an observable effect on the water balance in the Lagoon (about 0.04% of total influx). The size of the water outflow from the Vistula Lagoon is determined via difference. Almost 98% of its water outflow is directed towards the Bay of Gdańsk (23,694 mln m^3). The remaining 2% is lost due to evaporation.

In summary, the main influence on the water balance of the Vistula Lagoon is the horizontal exchange (Chubarenko *et al.* 2005). In this context, the only connection of the Vistula Lagoon with the sea - Strait of Baltiysk - is very important. The role of this sea passage as a "bottleneck", the operation of which can be compared to the phenomenon of a drain trap, inhibits and delays the effects of tides (Bielecka and Różyński 2014).

CONCLUSIONS

The present study confirms that water circulation in coastal lagoons is quite complex due to the presence of several different sources of recharge and several different places where water is lost. The complexity of water cycle is enhanced by a complex hydrographic system of lagoon catchments and a complicated system of water exchange with the sea. The total water volume involved in circulation in the Vistula Lagoon is estimated to be 24,225 mln m^3 per year. The largest part of the water received by a coastal lagoon comes from the sea. In this case, it is about 77% (18,130 mln m^3 per year). In addition, an array of catchment sources yields about 21% of the studied lagoon's water. Its catchment provides an additional 4,974 mln m^3 of water. The Pregolya River produces 55% of the catchment influx. The volume of water forcibly produced by area polders is so small that it does not produce an observable effect on the water balance in the Lagoon (about 0.04% of total influx). The precipitation constitutes 2.3% of the power supply source of the Vistula Lagoon. On the other hand, the Strait of Baltiysk constitutes the main outflow pathway for water exiting the Vistula Lagoon – close to 98% of all outflow (23,694 mln m^3). The remaining 2% is lost due to evaporation. Precipitation and evaporation is not a relevant factor in the water balance of the Lagoon.

The results obtained adjust the values of balance sheet components of the Vistula Lagoon. A comparison of the values present and recorded over 50 years ago indicates differences (although slightly), which are mainly visible in the horizontal exchange of water. This applies to absolute values as well as the percentage share. The total inflow to the Vistula Lagoon according to these comparisons increased by about 3 million m^3 per year, of which the inflow from the sea increased by about 1 million m^3 of water. Also, the river inflow from the catchment has increased by nearly 1.4 million m3 of water. What results obtained indicate that the refinement of the river inflow to the Vistula Lagoon with small but numerous watercourses flowing from the Elbląg Upland was very reasonable, as well as taking into account the inflow forced by polder discharges (although this did not significantly affect the volume of lake maintenance). In the case of the outgoing part of the balance, an increase in the volume of outflow of annual water to the Gulf of Gdansk by over 3 million m^3 was found. The observed changes have affected the percentage share of the listed balance sheet components in the total water exchange in the Vistula Lagoon. As a result, there was a decrease in seawater feed by about 3%, while river rafting from the water catchment increased by about 4%. In turn, the direct outflow into the sea increased by 1%.

It is quite unfortunate that all water balance calculations for the Vistula Lagoons are estimates. This is due to a lack of continuous measurement data on inflow and outflow of groundwater and inflow and outflow of water via the Strait of Baltiysk – the only exit to the sea. Current data are needed in order to produce an accurate water balance for the Lagoon, but this would need to occur in the presence of close collaboration between Poland and Russia. This step is needed in order to determine flood-prone areas affected by global warming, rising sea levels, and now increasingly frequent sea storm events. This type of step would require the creation of a full-fledged quantitative monitoring system for the entire Vistula Lagoon.

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