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Baltica

BALTICA Volume 29 Number 2 December 2016: 121–132
http://dx.doi.org/10.5200/baltica.2016.29.11

Hydrochemical variability of the ecosystem of the Gulf of Elbląg (north-eastern Poland)

Roman Cieśliński

Cieśliński, R., 2016. Hydrochemical variability of the ecosystem of the Gulf of Elbląg (north-eastern Poland). *Baltica, 29 (2), 121–132.* Vilnius. ISSN 0067-3064.

Manuscript submitted 21 September 2016 / Accepted 28 November 2016 / Published online 10 December 2016

Abstract The Vistula Lagoon – one of the main recipients of the central and eastern parts of the Vistula delta – is not homogeneous in terms of its hydrodynamics and hydrochemistry. In the southern part a separate hydrographic object – the Gulf of Elbląg – can be delimited. This delimitation is due to different morphometric and hydrometeorological conditions that prevail in this part of the Vistula Lagoon. In order to determine the nature of the waters, measurements of the selected physico-chemical properties, including chlorides, as well as control hydrological measurements were performed in the years 1997–2007. The study area included the water of the Gulf of Elbląg, the estuary stretch of the Elbląg River, the watercourses flowing from the Elbląg Plateau and the polder areas surrounding the Gulf of Elbląg. One measurement point was located on the Vistula Lagoon. The chloride values in the Gulf of Elbląg ranged from 20 to 2015 $mg \cdot dm^{-3}$. The results may indicate that the Gulf of Elbląg is a reservoir under the hydrodynamic and hydrochemical influence of both the Vistula Lagoon and the watercourses in its mouth, as well as the Vistula delta and the Elbląg Plateau. They dictate the seasonal nature of the waters of the Gulf of Elbląg.

Keywords *Vistula Lagoon, Elbląska Bay, hydrochemical variability, geoecosystem, geographical conditions, circulating water*

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INTRODUCTION

The Baltic Sea including Vistula Lagoon is located in the temperate climate zone. It is almost wholly surrounded by land and is almost completely tideless. The freshwater influx averages 470 km^3 $year^{-1}$ and the ocean water influx averages 430 km^3 $year^{-1}$, which makes the Baltic a brackish water body (Thulin, Andrushaitis 2003). The average salinity along its southern shore is 75 $g\ kg^{-1}$, with a range between 20 $g\ kg^{-1}$ and 90 $g\ kg^{-1}$. Storms at sea as well as low freshwater levels on land cause periodic intrusions of brackish water into freshwater bodies (Jasińska 1997; Pitkänen 2001; Cieśliński, Drwal 2005; Drwal, Cieśliński 2007; Gamo *et al.* 2007; Tarkhov, Treivish 2007).

Not only do intrusions cause the influx of seawater into coastal freshwater bodies, they also halt the flow of water from land-based sources. This results in both large- and small-scale flooding (Hall, Andersen 2002; Pizarro *et al.* 2007), and increases the salinity of freshwater bodies and wetlands (Cieśliński, Drwal 2005; Drwal, Cieśliński 2007). Given their sporadic nature, major intrusions must be treated as extreme events; these, too, are characteristic of the southern Baltic shore (van den Brink *et al.* 2005).

The Vistula Lagoon, sometimes called Świeży (Fresh) or Fryski Lagoon, is the second largest lagoon in the coastal zone of the southern Baltic. Due to its position it belongs to the category of transitional water bodies between land and sea waters. Based on the typology of water in Poland, it can be classified as a transition water body of a lagoon character (Krzymiński *et al.* 2004). Majewski (1994) calls this type of water body an estuary. The Vistula Lagoon was once one of the main recipients of the River Vistula. After cutting off the Vistula River's delta branches from the main channel, the role of the marine factor greatly intensified in the Vistula Lagoon (Kowalik 2016). Currently, it is almost closed. The only contact with the sea waters is via the Strait of Baltiysk in the eastern part of the Vistula Lagoon, in the territory of Russia. Today, water regime and ecological status Vistula Lagoon are highly dependent on the river inflow coming from its catchment (Hesse *et al.* 2015).

The lagoon can be considered as an example of the geosystem that shows the impact of both the sea as well as the land-based background, which are compounded by the human activity (Chubarenko, Tchepikova 2001). The term geosystem should be understood as a spatial entity that has an indefinite taxonomic rank (Kostrzewski 2016). The functioning of a geosystem includes the relationships that exist between its elements and subsystems as well as geosystems situated in the vicinity. The conditions of the functioning of a geosystem include: geographic location, geology, topography, climate, water cycle, fauna and flora and human activity (Kostrzewski 2016). This paper focuses on two conditions, namely climate and water cycle.

The aim of this study was to determine the periodic salinity variation of the Gulf of Elbląg. This volatility will be the basis for assessing the nature of the waters of the Gulf. On its basis it is possible to determine whether in specific hydrometeorological conditions the water of the basin takes more of a maritime character or more inland.

HYDROGRAPHIC SETTING OF THE STUDY AREA

The Vistula Lagoon (Fig. 1) is one of the main recipients of the water from the central and eastern parts of the Vistula delta. According to Cieśliński (2004), it is a longitudinally elongated rectangle basin. Its length is approximately 90.7 km and the average width measured from the Vistula Żuławy to the Sambian Peninsula and the mouth of the River Pregolya – 9.2 km. Its area is 838.0 km^2 (Schiewer 2008). This water body is separated from the Baltic Sea with the Vistula Spit of a length of about 50 km. The only connection between the Vistula Lagoon and the Bay of Gdańsk is through the Strait of Baltiysk, which is approx. 2 km long, approx. 400 m wide and from 8 to 12 m deep (Schiewer 2008). The Vistula Lagoon is a very shallow water body with a shallow basin. Its average depths are only 2–3 m (Fig. 1). Only along the channel running across this water body the depths reach the values greater than 3.0 m and a maximum of 5.2 m (Chubarenko *et al.* 2008). The reservoir capacity is estimated at 2.3 km^3 of water mass, of which 1.5 km^3 (64.0% of the total volume) falls for the eastern part.

The Vistula Lagoon was created by cutting it from the Baltic Sea by the Vistula Spit developed about 6 000 years ago (Littorina Sea) (Kowalik 2016) (Fig. 2). 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) (Fig. 3). The Vistula Lagoon took the present form after the development of the spit into a continuous strip of land and filling the Vistula delta with deposits and its gradual draining observed since the fifteenth century (Kowalik 2016). From digging the canal across the Vistula Spit in 1497 in the vicinity of Pilava (now Bałtijsk) the Vistula Lagoon is in constant contact with the Baltic Sea.

The Gulf of Elbląg is the southernmost part of the Vistula Lagoon. Nowakowska Island, the west boundary of the Gulf of Elbląg, was the final product of the accumulation process of the Vistula delta. Gold Island, the northern section of the Nowakowska Island and presently a part of a nature reserve, is overgrown with reeds and is still developing as a result of terrestrialisation.

In the southern part of the Vistula Lagoon a separate hydrographic object can be delimited which is

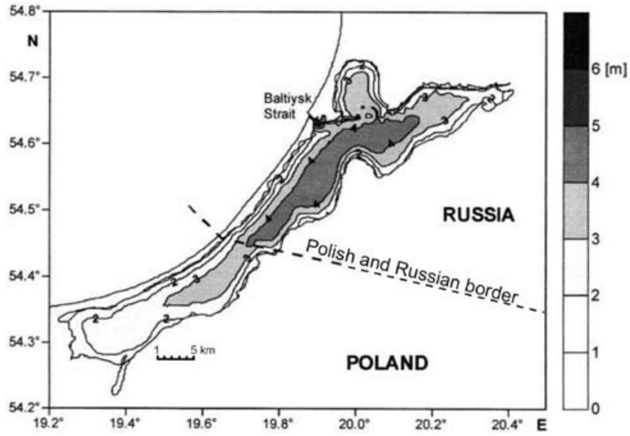

Fig. 1 Bathymetry of the Vistula Lagoon (Witek *et al.* 2001)

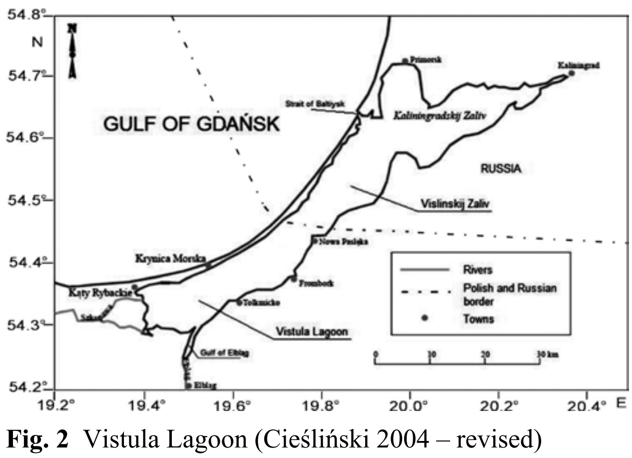

Fig. 2 Vistula Lagoon (Cieśliński 2004 – revised)

the Gulf of Elbląg. This delimitation is due to different morphometric and hydro-meteorological conditions that prevail in this part of the Lagoon. In the literature to date the measurement of salinity variation was limited to seasonal sampling across the Vistula Lagoon. No trial yet has been undertaken to detailed salinity values for its southernmost bay. Through the collected data, though, it is impossible to estimate the nature of the waters of the southern basin.

The Vistula Lagoon's catchment area is 23,870.6 km^2 (Fig. 4). It is located predominantly in Poland: 14,757 km^2, and some parts are in Russia (the Kaliningrad Oblast') and Lithuania (the eastern part of the catchment of Lake Vištytis). As a result of almost latitudinal course of the Pregolya, the largest river flowing into the reservoir, it is asymmetrically developed to the east. The western border of the catchment is the Vistula. The southernmost area of the catchment basin is the catchment of the River Pasłęka. The Pregolya basin takes almost 63% of the catchment of the Vistula Lagoon (Chubarenko *et al.* 1998). The Pregolya and its tributaries make a lowland river system of a high water character throughout the year. The second longest river is the Pasłęka whose basin is slightly less than 10% of the catchment area. On the Polish side the basin of the Vistula Lagoon also includes the catchments of the rivers Elbląg, Nogat and Szkarpowy and Tuga, and from the Russian side – the drainage basin of the Prochladna. Through the rivers Pregolya and Dejma the Vistula Lagoon connects to the Curonian Lagoon and the Neman River.

The hydrographic system of the Vistula Lagoon catchment is quite varied. There are numerous rivers, lakes and springs. In large part these are wetlands. The regime of the estuary sections of rivers flowing into the Vistula Lagoon, due to a slight slope along their riverbeds, is affected by the states in the Lagoon waters. For example, the backwater caused by the water impoundment from the Lagoon to the Pregolya reaches 60–70 km upstream (Chubarenko *et al.* 2004).

The Vistula Lagoon is a shallow body of water with a very disproportionate spread of water resources in relation to the place of water exchange with the Baltic Sea, i.e. the Strait of Baltiysk. The movement of water from the western part of the lagoon is very difficult. The rivers in this part of the Lagoon are located proportionally further than the rivers located in the eastern part. The main "drive" responsible for approx. 80% of the water inflow into the Vistula Lagoon is the horizontal movement of the Baltic waters. The water fluctuations in the Lagoon, including the effects of wind, can be as high as 1.3 m over a period of one month in November (according to the Baltic Sailing Directions). It is conceivable that the inflow of waters from the Gulf of Gdańsk additionally "inhibits" the

Fig. 3 Vistula Lagoon at the beginning of the 13th c. (Bertram 1924)

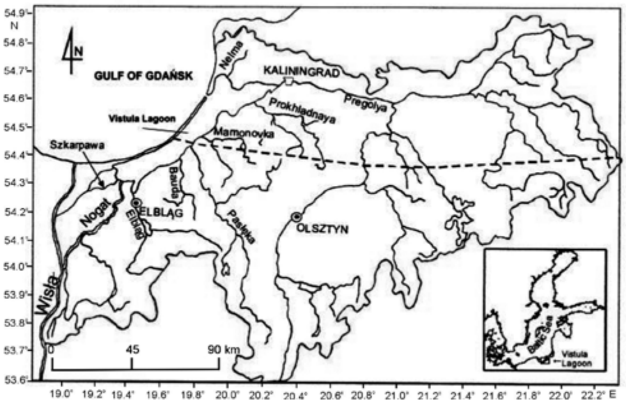

Fig. 4 Catchment basin of the Vistula Lagoon (Witek *et al.* 2001 – revised)

movement of the water from the Polish part of the Vistula Lagoon, so the water from the rivers Elbląg or Nogat reach the open sea much later than the water coming from the rivers Pregolya and Pasłęka. In addition, we are dealing with an important modification of the Baltic horizontal movements of water when passing through the narrow Strait of Baltiysk. 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 *et al.* 2003; Bielecka, Różyński 2014). Namely, when the waters of the Gulf of Gdańsk raise, the difference in water levels in relation to the waters of the Lagoon is aligned by a strong current directed into the Lagoon, while the sinking of the Baltic Sea causes the Lagoon water flow with a delay into the sea, creating a strong current in the strait in the opposite direction (Fig. 5). However, the effects of this "washing" of the Strait of Baltiysk in both directions refer only the closest parts of the Lagoon, i.e. the Russian part. Farther to the west, the horizontal currents levelling the water of the Lagoon with the Gulf of Gdańsk are “extinguished” and thus its westernmost part of the Vistula Lagoon, adjacent to the Vistula Żuławy, may be referred to as “stagnating” (Bielecka, Różyński 2014). According to Bielecka and Kazmierski (2003), the rate of water exchange in the western part of the Polish section of the Lagoon is about one year.

One of the water bodies delimited in the Vistula Lagoon is the Gulf of Elbląg (Fig. 6). It is the southernmost part of the Vistula Lagoon. It has a rectangular shape with a length of 7.5 km and a width of about 1.0 km. Its surface is small and has only 7.0 km^2. The entire body of water is very shallow. The average depth is 1.0–1.5 m. Only at the border of the Gulf and the open waters of the Vistula Lagoon, there are depths of 2.0 m. Its delimitation is associated with different hydrological and hydrochemical conditions. The impact on the Gulf of Elbląg is exerted not only by the Vistula Lagoon, but also by the terrestrial hinterland in the form of potamic runoff from the Vistula delta and the Elbląg Plateau as well as the water drained from the polders surrounding the Gulf.

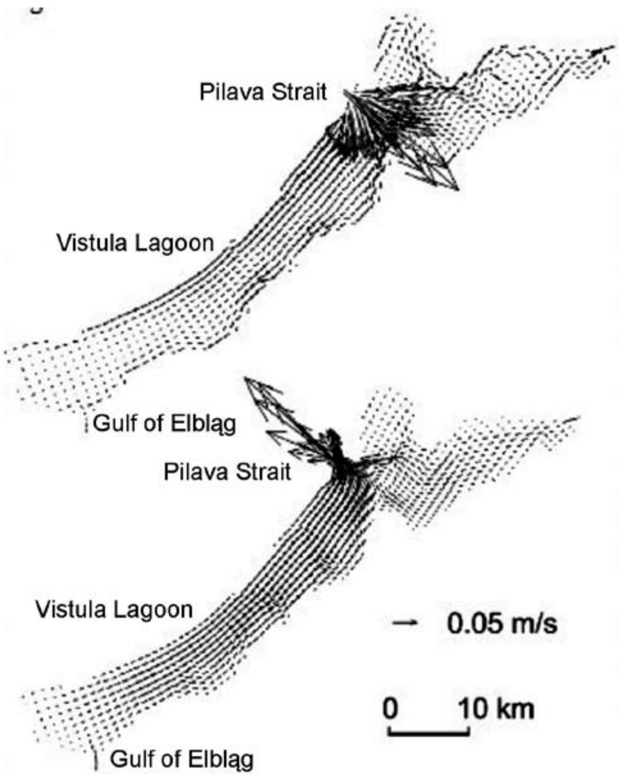

Fig. 5 Water velocity distribution in the Vistula Lagoon during an influx of water from the Baltic Sea (top figure) and its outflow (bottom) (Bielecka *et al.* 2003)

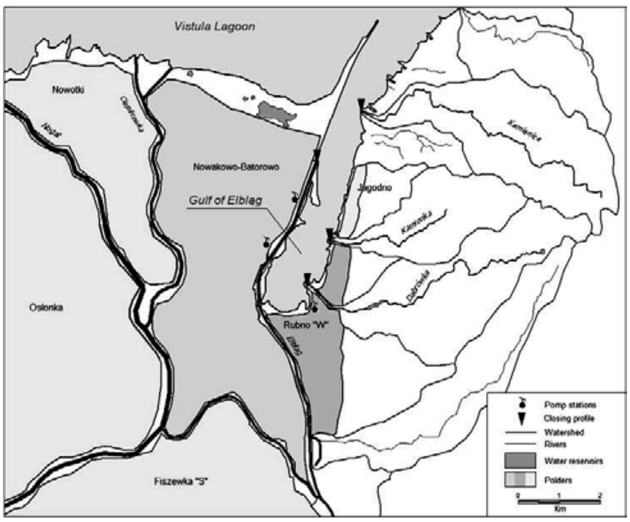

Fig. 6 Reference map of the Gulf of Elbląg

At favourable hydro-meteorological conditions the waters of the Vistula Lagoon can flow into the land water bodies. The hydrographic system of the Gulf of Elbląg – the Elbląg River – Lake Drużno is particularly vulnerable to such impact.

MATERIAL AND METHODS

The major studies were related to fieldwork, during which water was sampled at the selected hydrographic sites for further laboratory analyses, including chloride concentration, and flow rate measurements. Water samples were collected at three measurement points (Fig. 7):

- in the waters of the Gulf of Elbląg at the Batorowo profile,
- on the river Elbląg near its mouth to the Gulf of Elbląg in Nowakowo,
- in the Vistula Lagoon, near the settlement of Tolkmicko.

Laboratory analyses were performed using an ion chromatograph DIONEX ICS 1100. Observations at measurement points were conducted in the years 1997–1999 and 2002–2007 in various hydro-meteorological situations. Flow measurements for all tributaries were carried out by profiling flow-meters StreamPro ADCP and WorkHorse Rio Grande 1200 kHz ZedHed DR ADCP by RD Instruments (river Elbląg), and with an electromagnetic flow - meter VALEPORT 801 with a flat sensor.

The conducted field studies were supplemented by data gathered during the query of source materials, such as the Żuławy Board of Land Reclamation and Water Units in Elbląg and the Regional Inspectorate for Environmental Protection in Elbląg and Olsztyn.

RESULTS

The watercourses feeding the Gulf of Elbląg are responsible for its potamic inflow (see Fig. 6). They are: the Elbląg – supplies water from the side of the Vistula delta and is the main hydrographic axis of the area, as well as the Kamienica, Kamionka and Dąbrówka – watercourses draining the Elbląg Plateau. According

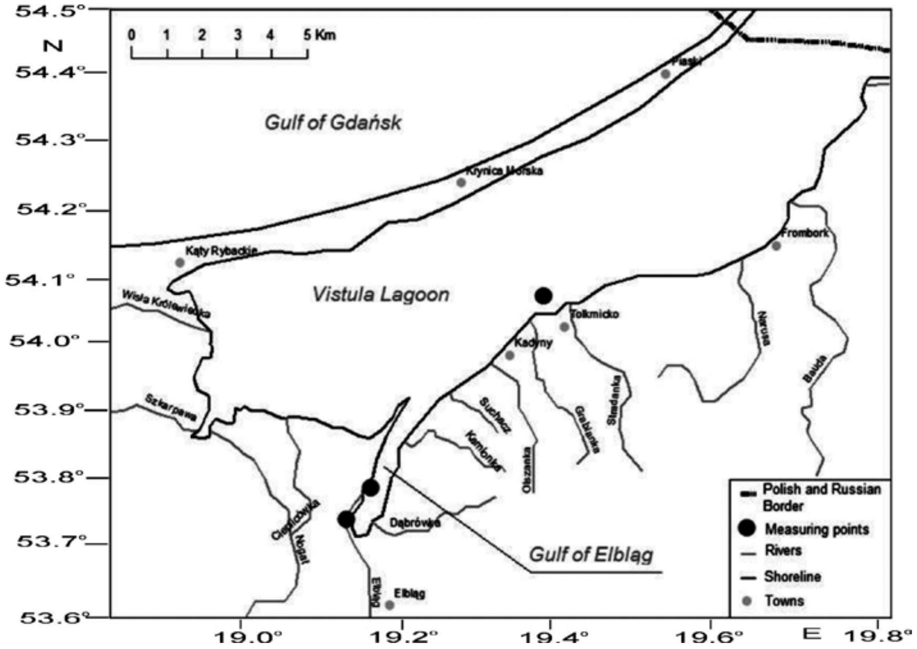

Fig. 7 Measurement points

to Łazarenko and Majewski (1975), the average water flow in the river Elbląg is 6.28 $m^3 \cdot s^{-1}$. Bogdanowicz (2007), however, estimates the average long-term flow of the Elbląg at 6-10 $m^3 \cdot s^{-1}$. These values are reflected in the data from the Regional Inspectorate for Environmental Protection in Olsztyn, which were collected on their behalf and were based on a number of flow measurements on various rivers, including the river Elbląg in 2007 and 2008. The average flow value for those two years was 8.6 $m^3 \cdot s^{-1}$. On the basis of the author's own measurements made in 2002–2007, this flow ranged from 6 to 12 $m^3 \cdot s^{-1}$ when towards the Gulf of Elbląg, and from 10 to 12 $m^3 \cdot s^{-1}$ when towards the hinterland (during storms). The flow value in the watercourses draining the upland ranges from 0.07 to 0.09 $m^3 \cdot s^{-1}$. The author's own measurements in 2002–2007 confirm these data. During this period the flow in these streams ranged from 0.05 to 0.11 $m^3 \cdot s^{-1}$. These values are presented in Table 1. The forced water transfer to the Gulf of Elbląg comes from the polders. Of the three polders located in the immediate vicinity, only two –Nowakowo-Batorowo and Rubno "W" –regularly discharge water. The polder Jagodno does not discharge water. The average annual discharge at multi-year period 2006–2011 was approximately 9.2 million m^3 (0.29 $m^3 \cdot s^{-1}$) (Table 2).

There has been no data on the polder Jagodno for over 6 years, which suggests it was excluded from draining the area adjacent to this part of the Gulf of Elbląg. The estimated value of the forced inflow to the Gulf of Elbląg is approx. 9.2 million m^3 for the years 2006–2011.

The results are based on bar graphs, which are shown in Figure 8. The range of measured values for

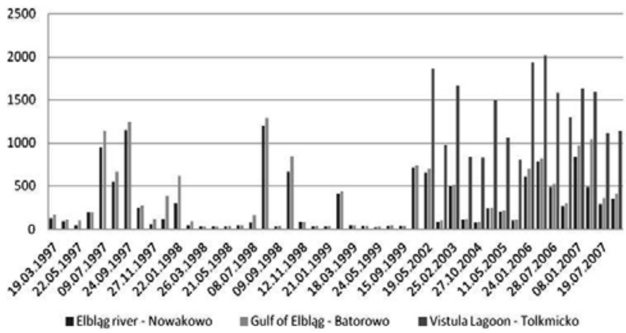

Fig. 8 Concentrations of chloride ions ($mg \cdot dm^{-3}$) in the measurement points in the years 1997–2007

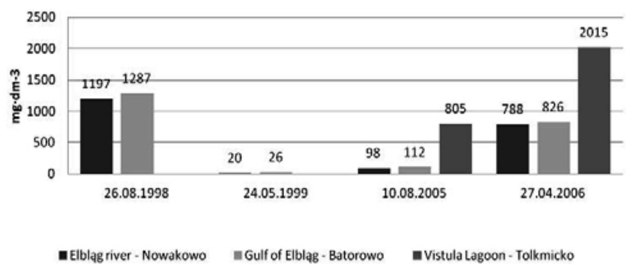

Fig. 9 Selected chloride values at the measurement points

the two sites (river Elbląg, Nowakowo site and the Gulf of Elbląg, Batorowo site) was very close to each other. These values were, respectively, 20 and 1197 $mg \cdot dm^{-3}$, as well 26 and 1287 $mg \cdot dm^{-3}$. In the case of the site located on the Vistula Lagoon, the Tolkmicko site, the range of tested concentrations of chloride was 805–2015 $mg \cdot dm^{-3}$. The extreme values correspond to the minimum and maximum values (Fig. 9). Amplitudes in all three points were very close to each other and were as follows: 1177 for the river Elbląg, 1261 for the Gulf of Elbląg and 1210 for the

Table 1 Mean flow of selected watercourses by various authors

River	Author	Average flow [$m^3 \cdot s^{-1}$]
Elbląg	Regional Inspectorate for Environmental Protection in Olsztyn (2007–2008)	8.6
	Bogdanowicz (2007)	6-11
	Łazarenko and Majewski (1975)	6.28
	Own measurements (2002–2007)	6–12 (the direction of the sea) 10–12 (direction inland)
Dąbrówka	Regional Inspectorate for Environmental Protection in Olsztyn (2007–2008)	0.085
	Bogdanowicz (2007)	0.069
	Own measurements (2002–2007)	0.05–0.1
Kamienica	Regional Inspectorate for Environmental Protection in Olsztyn (2007–2008)	No data
	Bogdanowicz (2007)	0.092
	Own measurements (2002–2007)	0.07–0.11
Kamionka	Regional Inspectorate for Environmental Protection in Olsztyn (2007–2008)	0.08
	Bogdanowicz (2007)	No data
	Own measurements (2002–2007)	0.06–0.09

Table 2 Water discharged from the selected polders (Żuławy Board of Land Reclamation and Water Units in Elbląg)

	Annual water discharge [m^3]		
Year	Nowakowo-Batorowo	Rubno „W"	Jagodno
2006	5931360	1087200	No data
2007	10247040	1929600	No data
2008	9167040	1263600	No data
2009	8536320	1603800	No data
2010	5767200	853200	No data
2011	7469280	1200600	No data
The average dump of several years	7853040	1323000	-
Average flow [$m^3 \cdot s^{-1}$]	0.25	0.04	-
Total discharge of the multi-years [m^3]	**9176040**		

Vistula Lagoon. The average concentrations of chloride were as follows: for the site on the river Elbląg: 294 $mg \cdot dm^{-3}$, for the site on the Gulf of Elbląg: 355 $mg \cdot dm^{-3}$, and for the site located on the Vistula Lagoon: 1365 $mg \cdot dm^{-3}$.

According to the Regional Inspectorate for Environmental Protection in Elbląg, chloride concentrations range from 567 $mg \cdot dm^{-3}$ to 5485 $mg \cdot dm^{-3}$. The seasonally lowest concentration of chlorides occur during spring surface run-off from the catchment, while the highest salinity is recorded during the summer low water levels in the Vistula Lagoon and autumn storms which increase the influx of the Baltic water (Fig. 10). Similar results concerning the seasons in which the observed maximum and minimum salinity obtained Schumann et al. (2006) for Darß-Zingst Bodden Chain. They involve the terms of the inflow of sea water depending of wind direction and strength, water levels and coastal water currents as well as inflow of water from the land and the spring thaw.

Salinity of the Vistula Lagoon also changes spatially (the lowest values occur in its western part). According the Regional Inspectorate for Environmental Protection, the lowest concentrations of chloride are recorded at the measurement point number 8 located in the western part of the Vistula Lagoon, which is within the reach of the waters of the Nogat. The highest values were at the measurement points 1, 2, 3 and 4 located in the north-eastern part of the Vistula Lagoon, near the border with Russia (Fig. 11). According Guiral and Ferhi (1992) on the basis ionic concentrations (K^+ Cl^-) of the Ebrié lagoon established that From a hydrodynamical point of view, the lagoons comprises four distinctive areas. The first is filled with freshwater all the year round (these waters are of continental origin and annually renewed); the second corresponds to oligohaline waters (waters essentially of continental origin and poorly renewed); the third area is constituted of a mixture of waters of continental and marine origins. The latter group can be separated into two subgroups: a group completely renewed by marine water during the dry season or during periods of storm and another group totally renewed by freshwater during the rainy and flood seasons.

Comparing the distribution patterns of the water movement velocity and salinity during the situations of water supply from the open sea to the Vistula Lagoon and its outflow (Fig. 12), we can determine the areas where the current velocity is high and is accompanied by relatively high salinity, and the zone where the water exchange is inhibited, and the salinity reaches lower values, even below 0.5 PSU (Fig. 12). In other words, in the Vistula Lagoon there is an area of the impact of the Baltic Sea, located in the vicinity of the Strait of Baltiysk, and there are zones in which the inflow of fresh water from the land is significant, either through the Żuławy rivers in the Polish section or through the Pregolya in the Russian part of the Vistula Lagoon. The observation by Bielecka and Kaźmierski (2003) are supported by the research by Kruk *et al.* (2011). They present the current situation (Fig. 13) and the one that would arise in the event of a canal built across the Vistula Spit (Fig. 14). According to the authors in the case of a canal being built, in its vicinity (north-western part of the Vistula Lagoon) the salinity would increase from 0.5‰ to about 4.5–5.0‰.

The highest concentrations of chloride ions at the measurement points located on the river Elbląg and the Gulf of Elbląg were mainly reported in summer and autumn, while the lowest – in the winter-spring period. In the period 1997–2007 the lowest chloride values were recorded in winter and spring. Low values in winter indicate residual ice cover in the Gulf of Elbląg, and in spring – surface run-off from the catchment. The highest values of chlorides were recorded in summer and autumn. Summer is characterised by low water level in the Vistula Lagoon, while in the autumn there are storm surges which increa the inflow of the Baltic waters. Another situation occurs at the analysed measurement point located in the Vistula Lagoon. Compared to the other sites, the distribution of concentrations shows an irregular character here. Higher concentrations are recorded in winter and spring, while lower – in summer and autumn. It is worth mentioning that the average concentrations measured in the Vistula Lagoon were about 4–5 times higher than those measured in the Gulf of Elbląg and the River Elbląg. According to Wiktor *et al.* (1997) an increase in salinity in the Vistula Lagoon is observed in October, while a minimum in February when the Lagoon is frozern. In turn, according to Bogdanowicz (2007) maximum salinity is in November, and the minimum in March. In spring a significant influence is exerted by fresh river water, while in autumn – the predominant effect of saline sea water, especially during storms. The shallowness of this water body and

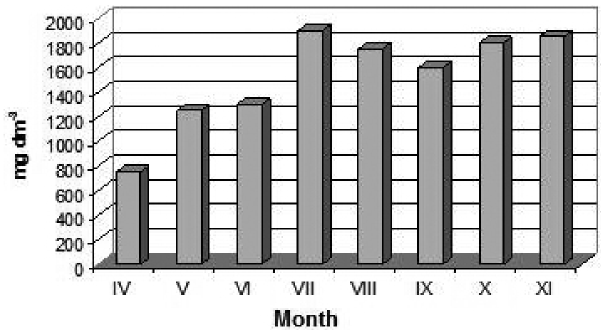

Fig. 10 Monthly mean concentrations of chloride in surface waters of the Vistula Lagoon at 10 measurement points in 1996 (Regional Inspectorate for Environmental Protection in Elbląg)

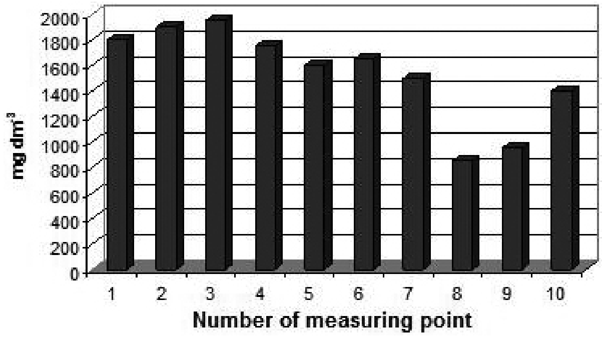

Fig. 11 Mean concentration of chloride in surface waters of the Vistula Lagoon at different measurement points in 1996 (Regional Inspectorate for Environmental Protection in Elbląg)

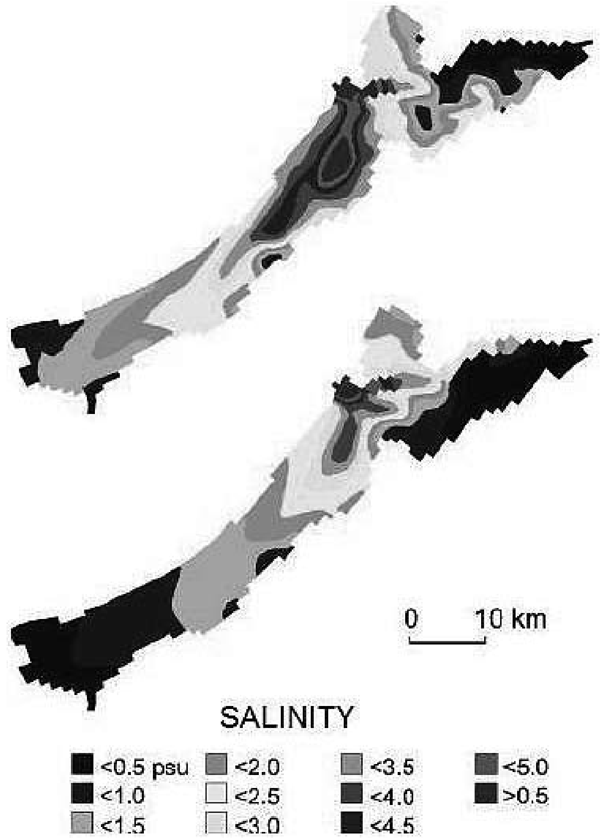

Fig. 12 Salinity of the Vistula Lagoon during water influx from the Gulf of Gdańsk (top figure) and outflow of water from the Lagoon (bottom) calculated on the basis of the Delft3D model (Bielecka *et al.* 2003)

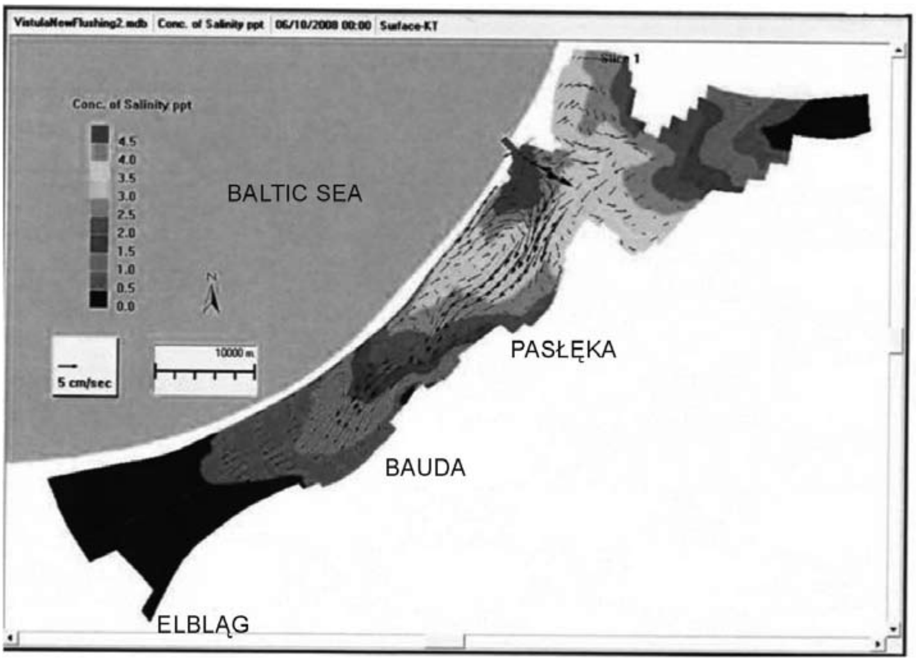

Fig. 13 An example of the spatial distribution of salinity (in PSU), and the direction and speed of ocean currents in the Vistula Lagoon in the case of water inflow from the Baltic Sea through the Strait of Baltiysk, a simulation of the GEMSS model (Kruk *et al.* 2011)

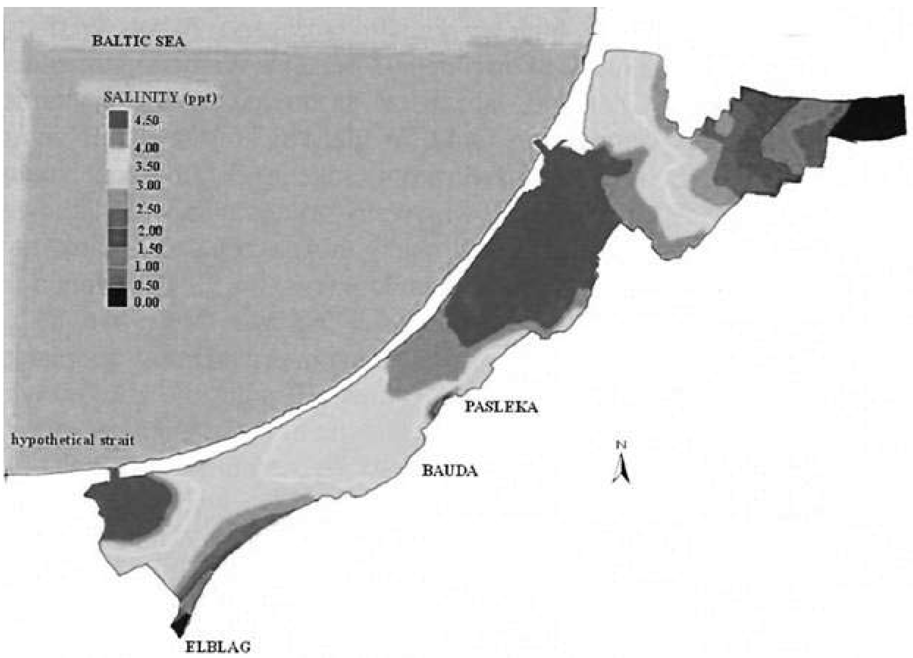

Fig. 14 Example of the salinity spatial distribution (in PSU) in the Vistula Lagoon in the case of opening a canal to the Baltic Sea in the Polish part of the Vistula Lagoon, a simulation of the GEMSS model (Kruk *et al.* 2011)

its relatively large area promotes mixing of the water to the bottom, which results in a uniform physical and chemical structure of the water.

Analysis of chlorine at the measurement points in 1997–1999 and 2002–2007 showed that the waters of the Gulf of Elbląg in **61%** take an inland nature, while in **39%** – maritime character. This track of the results may indicate that the Gulf of Elbląg is a body of water remaining under the hydrodynamic and hydrochemical influence of the Vistula Lagoon and the watercourses feeding it, both from the Vistula delta and the Elbląg Plateau. Based on the results obtained from the measurement points it can be concluded that low concentrations of chloride in winter and spring evidence inland waters in the analysed water body. Similarly – high concentrations of chloride in the summer-autumn period evidence the dominant role of the Vistula Lagoon in the transportation of the sea water, in effect transforming the nature of the waters filling the Gulf of Elbląg. Another factor influencing the salinity is the presence of winds. Northerly winds cause the “pushing” of the water of the Vistula Lagoon to the Gulf of Elbląg, at the same time - due to the shallowness of the basin - causing mixing of the waters down to the bottom and moving the surface layer of bottom sediments. Southern winds, however, cause “pushing” the waters out of the Gulf of Elbląg to the Vistula Lagoon.

An important role is played by the northern winds that push the Vistula Lagoon water into the Gulf of Elbląg, as well as southern winds that push them out (Table 3). Under these conditions, the mixing of the waters also takes place. In addition, the winds also affect the distribution of currents and waves on the Gulf waters. Wind velocity and direction are the conditions that can affect the variability of the chemical composition of coastal lakes’ waters, including, according to Jankowski (2000), the influence exerted on the spatial variability of salinity.

Another factor that affects the periodic “pushing” of water into the Gulf of Elbląg and the river Elbląg, is the amount of water in the Vistula Lagoon. In a situation where storm surges overlap a high level of water in the Vistula Lagoon, there is a high probability of brackish water reaching the very Żuławy Elbląskie. Filling the Vistula Lagoon is conditioned by the level of the waters of the Gulf of Gdańsk, especially at its eastern coast in the region of Baltiysk. A higher water level in this part causes an inflow of sea water through the Strait of Baltiysk to the Vistula Lagoon, thereby increasing the status of its filling. This process occurs mostly when winds direction is W-NW-N. At the same time the winds from these directions push the water from the Vistula Lagoon’ spit side, increasing a water table decline in the Strait of Baltiysk, which further promotes the influx of waters from the Gulf of Gdańsk to the Vistula Lagoon (Table 4).

DISSCUSION

The Baltic Sea including Vistula Lagoon and Gulf of Elbląg are characterized by active water dynamics and circulation of different spatial scales, which reveal in conditions of complex bottom relief and strongly non-uniform hydrological structure (Brekhovskikh, Chubarenko 2006). In the case of lagoons impact on quality has many natural conditions such as the nature and beyond. The most important of them should include fluvial inputs from the land (Kuo *et al*. 2013) and the inflow from the sea (Dailidienė, Davulienė 2007). Although the flow of the sea is periodic, a tributary of the river a permanent the first is of decisive importance for the state of quality of lagoons located in the coastal zone of the southern Baltic. Also, a certain impact on the quality of water in the lagoons is supply via underground (Sena, Condesso de Melo 2012). Particular attention should be paid to extreme events which must include the phenomenon of flooding (Zonta *et al.* 2005) or the phenomenon of a storm at sea (Drwal, Cieśliński 2007; Soomere, Pindsoo 2016). In both cases there is a significant change not only hydrological but also qualitative. Importance of floods in the transport of materials and pollutants from the drainage basin to the lagoon. For a more global causes of changes in water quality lagoons include climate change (Semionova, Smyslov 2006), including the impact of NAO (Kļaviņš *et al.* 2011) and increasingly observed eutrophication. For other important conditions affecting the state of water quality of the coastal zone should include appropriate hydrometeorological conditions in the coastal zone. Direction and wind speed, sea level changes and coastal waters, including the differences between them, the creation of the phenomenon of intrusion (Zeidler *et al.* 1995; Schumann *et al.* 2006). Also, do not forget to replace the vertical, and in particular evaporation, which in the warm period is important for the state of

Table 3 Annual incidence of wind directions (%) in the period 1951–1960 (Łazarenko *et al.* 1975 – revised)

Place	Wind sector								Calm air
	N	NE	E	SE	**S**	SW	W	NW	
Tolkmicko	**5.6**	5.8	8.0	14.0	**18.3**	24.5	10.8	8.8	4.2
Elbląg	**10.9**	6.5	7.6	13.3	**13.9**	12.6	13.4	14.0	7.8

Table 4 Characteristic water levels (cm) in Vistula Lagoon (Cieśliński 2004)

Water level	Measurement point			
	Tolkmicko		Elbląg	
	1961–1980	1947–1983	1961–1980	1946–1983
Highest	**610**	**645**	**610**	**644**
Mean highest	542	558	520	545
Medium	502	501	506	504
Mean lowest	465	542	471	458
Lowest	415	410	410	410

quality lagoons (Yao 2009; Jakimavičius *et al.* 2013). Finally, mention of human activity that causes significant changes in the quality of surface water and groundwater. Data indicated for example that the spatial distribution of water quality parameters was significantly affected by freshwater input via the constructed drainage channels which collect water from a catchment area and discharge water into the lagoon as a point source, thus preventing drainage water to reach the lagoon as a nonpoint source (Yetis *et al.* 2014). Also, it is important to agricultural activities and changes in land use (Zia *et al.* 2013).

Due to the large number of conditions that affect the quality status of the Vistula Lagoon developed several mathematical models (Szymkiewicz 1992; Kwiatkowski *et al.* 1997; Chubarenko, Chubarenko 2002; Bielecka, Kazmierski 2003; Chubarenko *et al*. 2005; Kruk *et al*. 2011). They show that the main determinant affecting the quality, including the chloride concentration is horizontal exchange, and especially the inlet and outlet to the sea and retention in the lagoon. Also affected lagoon morphometry and hydrological features including water budget. Do not forget also about the physical properties of water for example thermal variability or waving wind.

CONCLUSIONS

The Vistula Lagoon, including the Gulf of Elbląg, is an area of continuous mixing of fresh and salt water. Because of the shallowness of the water basin, an important factor determining the dynamics of the water is the impact of wind. It often impacts the entire water mass from the surface to the bottom and causes activation of the surface layer of sediments. The relationship between the share of marine and inland water influences salinity, an important property of the Vistula Lagoon's water. This parameter determines the physic - chemical characteristics of the aquatic environment (Kruk *et al.* 2011).

The salinity of the waters of the Vistula Lagoon is a result of the impact of a number of factors. The most important are the size of fresh water influx and the frequency of sea waters intrusion. The Lagoon's feature is zonality of its salinity. The extent of salinity zones is diverse and may be subject to shifts depending on the direction of constant winds etc. Also, their ranges may move seasonally. The increase in salinity in the Vistula Lagoon is observed in October and a minimum in February, when the Vistula Lagoon is covered with ice (*Wiktor et al., 1997*). According to Bogdanowicz (2007) maximum salinity is in November, and the minimum in March. In spring a significant influence is exerted by fresh river water, while in autumn the predominant is the effect of saline sea water. The Vistula Lagoon waters are transitional and have an average salinity at the level of 3000 mg•dm^{-3}, with an average salinity of the Baltic Sea at the level of 6000 - 8000 mg•dm^{-3}. Salinity decreases with the distance from the Strait of Baltiysk. Mean salinity of water in the vicinity of the strait is approximately 5 500 mg•dm^{-3}, while near the Krynica Marine – about 2 200 mg•dm^{-3}.

ACKNOWLEDGMENTS

The work was the use of funds the Department of Hydrology at the University of Gdansk. The anonymous referees are thanked for their helpful comments that allowed to improve the manuscript.

REFERENCES

Bertram, H.G., 1924. *Physikalische Geschichte des Weichseldeltas: Das Weichsel – Nogat – Delta.* Danzig, 201 pp.

Bielecka, M., Kazmierski, J., 2003. A 3D mathematical model of Vistula Lagoon hydrodynamics – general assumptions and results of preliminary calculations. *Diffuse Pollution Conference, ECSA 8,* Dublin, 140–145.

Bielecka, M., Różyński, G., 2014. Management conflicts in the Vistula Lagoon area. *Ocean and Coastal Management 101*, 24–34.

Bielecka, M., Margoński, P., Lewandowski, A., 2003. Implementation of WFD within transboundary basin of the Vistula Lagoon – extension of the EU MANTRA-East project. *Proceedings of the XXX IAHR Congress – "Water Engineering and Research In a Learning Society: Modern Developments and Traditional Concepts",* Thessaloniki, Greece, 711–715.

Bogdanowicz, R., 2007, The Hydrographic Map on a scale 1:50,000, sheet N–34–63-B, South Elbląg, Pryzmat Publishing House, Częstochowa.

Brekhovskikh, A., Chubarenko, B., 2006. Water circulation modeling in marine area near the Vistula Lagoon outlet. *IEEE US/EU Baltic International Symposium*, **DOI:** 10.1109/BALTIC.2006.7266140

Cieśliński, R., 2004. Application of arithmetic formulae in determining volume of sea waters inflow into Elbląska Bay – river Elbląg – lake Druzno hydrological system. Acta Geophysica Polonica 52 (4), 521–539.

Cieśliński, R., Drwal, J., 2005. Quasi-estuary processes and consequences for human activity, South Baltic. *Estuarine Coastal and Shelf Science 62 (3)*, 477–485.

Chechko, V., Sokolov, A., Chubarenko, B., Dikii, D., Topchaya, V., 2015. Dynamics of sediments disposed in the marine coastal zone near the Vistula Lagoon inlet, south-eastern part of the Baltic Sea. *Baltica 28 (2)*, 189–199.

Chubarenko, I.P., Chubarenko, B.V., 2002. General water dynamics of the Vistula Lagoon. *Environmental and Chemical Physics 24 (4),* 213–217.

Chubarenko, B., Margoński, P., 2008. The Vistula Lagoon. *In* U. Schiewer (Ed.), *Ecology of Baltic Coastal Waters. Ecological Studies* 197, Springer, 167–195.

Chubarenko, I., Tchepikova, I., 2001. Modelling of man-made contribution to salinity increase into the Vistula Lagoon (Baltic Sea). *Ecological Modelling 138 (1–3)*, 87–100.

Chubarenko, B., Chubarenko, I., Baudler, H., 2005. Comparison of Darss-Zingst Bodden Chain and Vistula Lagoon (Baltic Sea) in a view of hydrodynamic numerical modelling. *Baltica 18 (2),* 56–67.

Chubarenko, B.V., Kuleshov, A.F., Chechko, V.A., 1998. Field study of spatial-temporal variability of suspended substances and water transparency in Russian part of the Vistula Lagoon. *In* Monographs in system ecology 2, Klaipėda, Lithuania, 12–17.

Chubarenko, B.V., Koutitonski, V.G., Neves, R., Umgiesser, G., 2004. Modelling concept. *In* J. Wolflin (Ed.), Coastal lagoons: ecosystem processes and modeling for substainable use and developments, *CRC, Boca Ranton*, 231–306.

Dailidienė, I., Davulienė, L., 2007. Long-term mean salinity in the Curonian Lagoon in 1993–2005. *Acta Zoologica Lituanica 17 (2)*, 172–181.

Drwal, J., Cieśliński, R., 2007. Coastal lakes and marine intrusions on the southern Baltic coast. *Oceanological and Hydrobiological Studies 36 (2),* 61–67

Gamo, T., Kato,Y., Hasumoto, H., Kakiuchi, H., Momoshima, N., Takahata, N., Sano, Y., 2007. Geochemical implications for the mechanism of deep convection in a semi-closed tropical marginal basin: Sulu Sea. *Deep-Sea Research Pt. II, 54 (1–2),* 4–13.

Guiral, D., Ferhi, A., 1992. Hydrodynamics of Ebrié lagoon as revealed by a chemical and isotopic study. *Hydrobiologia 245 (2),* 65–74.

Hall, J., Andersen, M., 2002. Handling uncertainty in extreme or unrepeatable hydrological processes – the need for an alternative paradigm. *Hydrological Processes16*, 1867–1870.

Hesse, C., Krysanova, V., Stefanova, A., Bielecka, M., Domnin, D.A., 2015. Assessment of climate change impacts on water quantity and quality of the multi-river Vistula Lagoon catchment. *Hydrological Sciences Journal 60 (5)*, DOI: http://dx.doi.org/10.1080/02626667.2014.967247

Jakimavičius, D., Kriaučiūnienė, J., Gailiušis, B., Šarauskienė, D., 2013. Assessment of uncertainty in estimating the evaporation from the Curonian Lagoon. *Baltica 26 (2),* 177–186.

Jankowski, A., 2000. Wind-induced variability of hydrological parameters in the coastal zone of the southern Baltic Sea – a numerical study. *Oceanological Studies 29 (3),* 5–34.

Jasińska, E., 1997. Hydrodynamics and dynamics of salt water in the Dead Vistula. *Hydrotechnical Transactions 61*, 31–41.

Kļaviņš, M., Kokorīte, I., Rodinovs, V., Avotniece, Z., Spriņge, G., Briede, A., 2011. Hydrometeorological parameters and aquatic chemistry of Lake Engure: Trends of changes due to human impact and natural variability. *Proceedings of the Latvian Academy of Sciences. Section B. Natural, Exact, and Applied Sciences 65 (5–6)*, 138–145.

Kostrzewski, A., 2016. The geoecosystem and its application in research on the present-day morphogenetic system in the temperate climate zone. *Geographical Works 144,* 35–47.

Kowalik, P.J., 2016. Water management in the Vistula delta (Poland). *Meteorology, Hydrology and Water Management 4 (1),* 47–52.

Kruk, M., Kempa, M., Tjomsland, T., Durand, D., 2011. The use of mathematical models to predict changes in the environment of the Vistula Lagoon. *In* M. Kruk, A. Rychter, M. Frost (eds), *Vistula Lagoon – natural environment and modern methods of his research project on the example of Visla*, Publishing PWSZ, Elbląg, 165–180. [In Polish].

Krzymiński, W., Kruk-Dowgiałło, L., Zawadzka-Khlau, E., Dubrawski, R., Kamieńska, M., Łysiak-Pastuszak, E., 2004. Typology of polish marine Waters. *Coastline Reports 4*, 39–48.

Kuo, Y.M., Jang, C.S., Yu, H.L., Chen, S.C., Chu, H.J., 2013. Identifying nearshore groundwater and river hydrochemical variables influencing water quality of Kaoping River Estuary using dynamic factor analysis. *Journal of Hydrology 486*, 39–47.

Kwiatkowski, J., Rasmussen, E., Ezhova, E., Chubarenko, B., 1997. The eutrophication model of the Vistula Lagoon. *Oceanological Studies 1*, 5–33.

Łazarenko, N., Majewski, A., 1975. *Hydrometeorological system of the Vistula Lagoon, Institute of Meteorology and Water Management*, Warszawa, 518 pp/ [In Polish].

Majewski, A., 1994. Natural environmental conditions of the Gulf of Gdansk and its surroundings. *In* J. Błażejowski, D. Schuller (eds), *Pollution and restoration of the Gulf of Gdansk*, Publishing University of Gdańsk, Gdańsk, 35–42. [In Polish].

Pitkänen, H., 2001. Internal nutrient fluxes counteract decreases in external load: the case of the estuarial eastern Gulf of Finland, Baltic Sea. *AMBIO: Journal of the Human Environment 30 (4),* 195–201.

Pizarro, H., Rodrıguez, P., Bonaventura, S.M., O'Farrell, I., Izaguirre, I., 2007. The sudestadas: a hydro-meteorological phenomenon that affects river pollution (River Luján, South America). *Hydrological Sciences Journal 52 (4),* 702–712.

Schiewer, U. (Ed.), 2008. Ecology of Baltic Coastal Waters. *Ecological Studies 197*, 419 pp.

Schumann, R., Baudler, H., Glass, A., Dümcke, K., Karsten, U., 2006. Long-term observations on salinity dynamics in a tideless shallow coastal lagoon of the Southern Baltic Sea coast and their biological relevance. *Journal of Marine Systems 60 (3–4),* 330–344.

Semionova, S., Smyslov, V., 2006. Phytocene state in the russian part of Curonian Lagoon of the Baltic Sea in conditions of anthropogenic eutrophication and global climate warming. *IEEE US/EU Baltic International Symposium*, DOI: 10.1109/BALTIC.2006.7266134.

Sena, C., Condesso de Melo, M.T., 2012. Groundwater–surface water interactions in a freshwater lagoon vulnerable to anthropogenic pressures (Pateira de Fermentelos, Portugal). *Journal of Hydrology 466–467*, 88–102.

Soomere, T., Pindsoo, K., 2016. Spatial variability in the trends in extreme storm surges and weekly-scale high water levels in the eastern Baltic Sea. *Continental Shelf Research 115,* 53–64.

Szymkiewicz, R., 1992. A mathematical model of storm surge in the Vistula Lagoon, Poland. *Coastal Engineering 16,* 181–203.

Tarkhov, S.A., Treivish, A.I., 2007. Geographical location and diffusion of basic innovations. *GeoJournal 26 (3),* 341–348.

Thulin, J., Andrushaitis, A., 2003. The Baltic Sea: its past, present and future. Religion, science and the environment. *Proceedings Religion, Science and the Environment Symposium V Baltic Sea, ICES, CIEM*, 1–11.

Van den Brink, H.W., Können, G.P., Opsteegh, J.D., Van Oldenborgh, G.J., Burgers, G., 2005. Estimating return periods of extreme events from seasonal forecast ensembles. *International Journal of Climatology 25 (10),* 1345–1354.

Wiktor, K., Węsławski, J., Żmijewska, M. I., 1997. *Biogeography of the Sea.* Publishing University of Gdańsk, Gdańsk, 187 pp. [In Polish].

Witek, Z., Zalewski, M., Wielgat-Rychert, M., 2001. *Nutrient Stocks and Fluxes in the Vistula Lagoon at the End of the Twentieth Century*. Sea Fisheries Institute and Pomeranian Academy in Słupsk, Gdynia-Słupsk, 164 pp.

Yao, H., 2009. Long-term study of lake evaporation and evaluation of seven estimation methods: results from Dickie Lake, South-Central Ontario, Canada. *Journal of Water Resource and Protection 2,* 59–77.

Yetis, A.D., Selek, Z., Seckin, G., Davutluoglu, O.I., 2014. Water quality of Mediterranean coastal plains: conservation implications from the Akyatan Lagoon, Turkey. *Environmental Monitoring and Assessment 186 (11),* 7631–7642.

Zeidler, R.B., Wróblewski, A., Miętus, M., Dziadziuszko, Z., Cyberski, J., 1995. Wind, wave, and storm surge regime at the polish Baltic coast. *Journal of Coastal Research 22,* 33–55.

Zia, H., Harris, N.R., Merrett, G.V., Rivers, M., Coles, N., 2013. The impact of agricultural activities on water quality: A case for collaborative catchment-scale management using integrated wireless sensor networks. *Computers and Electronics in Agriculture 96,* 126–138.

Zonta, R., Collavini, F., Zaggia, L., Zuliani, A., 2005. The effect of floods on the transport of suspended sediments and contaminants: A case study from the estuary of the Dese River (Venice Lagoon, Italy). *Environment International 31 (7),* 948–958.