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ESTUARIES OF THE POLISH BALTIC COASTAL ZONE

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Abstract

Estuaries are dynamic ecosystems characterized by great and constant variability of physicochemical gradients and biological parameters. Considerable fluctuations in salinity levels, temperature, pH, concentrations of oxygen, nutrients and organic matter are quite natural in such water bodies. There are many estuarine forms at the Polish Baltic Coast, including open-sea gulfs (the Gulf of Gdańsk and the Pomeranian Gulf), water bodies connected to the Baltic Sea (Lake Łebsko) and periodically closed water bodies connected to the Baltic Sea by channels or through river-mouths (Lake Jamno and Lake Gardno). The mouths of large rivers, like Odra and Vistula, also show features of estuaries. Estuaries perform a very important function of specific natural filters for a variety of chemical compounds contained in waters flowing through this area. In this way they form an effective buffer zone that prevents the penetration of toxic biological substances into seawater.

Key words: estuary, estuarine forms at the Polish coast, genesis of estuaries

INTRODUCTION

An estuary (Latin *aestus* – tide) is a semi-closed coastal body of water which has a free connection with the open sea (Odum 1982). According to the Larousse Encyclopaedia (2003), an estuary (lat. *aestuarium* – seaway) is the wide lower course of a river where its current is met by the tides of the sea. Tidal actions produce erosive effects and widen the river-mouth, thus preventing the formation of a delta from the sediments brought by the river. Estuaries can be divided into open (water from the estuary flows into the open sea) and enclosed (water from the estuary flows into a closed lagoon). The hydrobiological dictionary (Żmudziński et al. 2002) gives two definitions of the term estuary, a narrower and broader one. According to the first definition, an estuary is the funnel-like, wide part of the mouth of a river flowing into the ocean or open sea, formed as a result of destructive tidal action. Tides continuously carry rock material brought by the river to deeper waters, thus preventing the formation of a delta. According to the second definition, an estuary is a semi-closed contact zone where fresh and salt waters mix, containing measurable quantities of marine salts. This environment is characterized by highly variable currents and salinity levels, as well as richness of different life forms, although the species composition is relatively poor. Depending on hydrological conditions (mainly salinity levels), estuarine water bodies can be divided into those with a low salt concentration (the oligohaline zone) – bays, a medium salt concentration (the meso- or polyhaline zone) – limans, and a high salt concentration (the hyperhaline zone) – lagoons. The results of recent research by Telesh (2004) indicate that estuaries are transition zones between the land and the sea which form aquatic ecosystems, often referred to as marginal filters, with a variety of interrelated biotic and abiotic factors.

Estuaries are dynamic ecosystems characterized by great and constant variability of physicochemical gradients and biological parameters. Considerable fluctuations in salinity levels, temperature, pH, concentrations of oxygen, nutrients and organic matter are quite natural in such water bodies (Remane 1934, Remane and Schlieper 1971, Schubel and Pritchard 1971, Majewski 1972, Day et al. 1989, Žaromskis 1996, Telesh 2004).

Estuaries could be considered as transition zones or ecotones between freshwater and saltwater environments, if it were not for the fact that many of the most significant physical and biological features of estuaries are not of temporary nature, but belong to unique phenomena typical of this particular type of zones only. Taking into account mean salinity levels, waters of estuaries (i.e. brackish waters) can be divided into oligo-, meso- and polyhaline. However, it should be kept in mind that in these dynamic ecosystems the salt concentration at a given place may vary greatly depending on the time of the day, season and year (Dethier 1992). A characteristic feature of these environments is great variability of conditions, so the organisms that live there must show a broad tolerance range – they have to be euryhaline and eurythermal species (Remane and Schlieper 1971).

The aim of this review paper concerning estuaries of the Polish Baltic Coastal Zone is to present the state of knowledge about the genesis, salinity levels and role of estuaries in the transfer of organic matter, nutrients and toxic compounds to the sea, as well as about their use for ecological, economic and recreational purposes.

POLISH ESTUARIES

There are many estuarine forms at the Polish Baltic Coast, including open-sea gulfs and closed or semi-closed water bodies that have indirect contact with the sea via other bodies of water only. These are both large water bodies, as the Szczecin Lagoon, the Vistula Lagoon, the Curonian Lagoon, the Gulf of Puck (an inner basin) and smaller or bigger lakes, Drużno, Żarnowieckie, Sarbsko, Łebsko, Gardno, Wicko, Kopań, Bukowo, Jamno, Resko Przymorskie, Liwia Łuża, Koprowo, Wicko Wielkie, Dąbie (Figure 1, Table 1). Despite a similar genesis and geomorphological type, these water bodies are characterized by different hydrological (Majewski 1972) and hydrochemical (Trojanowski et al. 1991) conditions, affected by a predominance of factors of terrestrial or marine character.

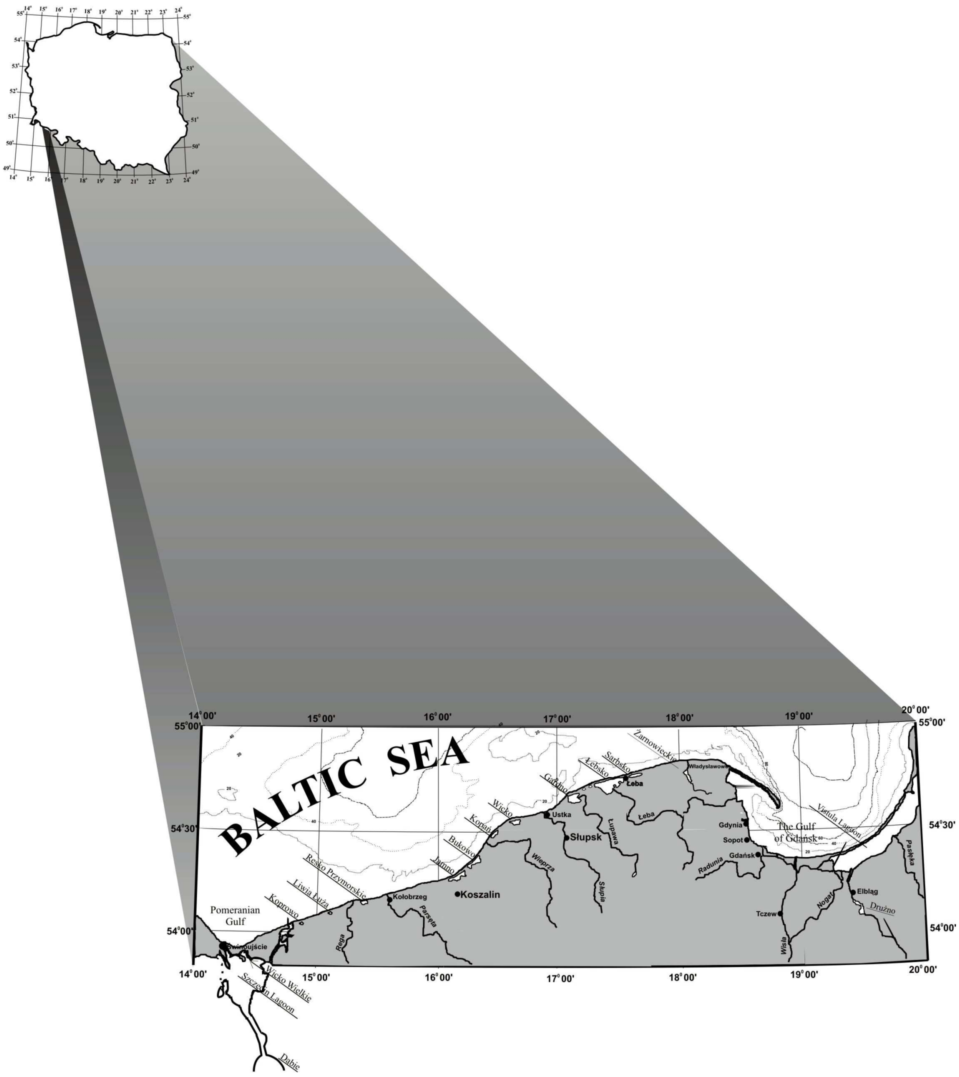

Fig. 1. Estuaries of Polish coastal area of the Baltic Sea

The origin of Polish estuarine water bodies is closely related to the history of the Baltic Sea and the last glaciation. The present shape of the shoreline was affected primarily by Littorina transgression of the Baltic Sea in the Late Subatlantic Period. At that time the shoreline was diversified, with numerous bays and peninsula. As a result of the modeling effects of coastal processes, sand accumulated in bays until they got cut off by newly-formed sandbars. According to Rosa (1977), the main reason for sandbar formation was the process of gradual land rising and bay transformation into coastal lakes, observed within a short period of time. This process resulted in the formation of many Polish coastal lakes, such as Jamno, Bukowo,

Table 1

Morphometric parameters of southern-Baltic coastal waters (Mikulski 1970, modified by Wiktor et al. 1997)

Lake/Lagoon	Area (km^2)	Catchment area (km^2)	Capacity mln m^3	Mean depth (m)	Maximum depth (m)	Height above sea-level (m)
Szczecin Lagoon	968.40 (410)*	122725.0	5571.0	3.4	8.5	
Lake Dąbie	56.00	75500.0**	168.0	3.0	4.2	0.30
Lake Koprowo	4.87	51.1	7.8	1.6	3.1	0.10
Lake Liwia Łuża	2.11	175.5	1.98	0.9	1.7	0.30
Lake Resko Przym.	5.77	315.2	7.7	1.3	2.5	0.30
Lake Jamno	22.39	510.6	31.5	1.4	3.9	0.10
Lake Bukowo	17.47	102.8	32.1	1.8	2.8	0.10
Lake Kopań	7.90	38.5	14.8	1.9	3.9	0.10
Lake Wicko	10.58	107.7	28.5	2.7	6.1	0.20
Lake Gardno	24.68	964.4	30.9	1.3	2.6	0.30
Lake Łebsko	71.40	1594.0	117.5	1.7	6.3	0.30
Lake Sarbsko	6.51	213.3	7.82	1.2	3.2	0.50
Lake Żarnowieckie	14.32		120.8	8.4	19.4	1.50
Lake Drużno	17.9	1423.0	22.4	1.2	2.0	0.30
Vistula Lagoon	838.00 (328)*	23439.0	2300	2.6	5.1	

* area of the Polish part of the lagoons

** including a part of the Odra River Basin, proportionally to the discharge of the Regalica River

Kopań, Gardno, Łebsko, Sarbsko. Lake Gardno and Lake Łebsko were formed following the depression of end moraines, and Lake Jamno is a fragment of a postglacial valley (Rosa 1977, Szmidt 1972). The map compiled by Lubin in 1614 shows that Lake Dołgie Wielkie and Lake Dołgie Małe were once a bay of Lake Gardno, which was then cut through into two parts. This contributed to the displacement of a chain of sand dunes to the south-east. Both lakes are situated in the coastal zone and have no connection to the sea (inland lakes). The genesis of some Polish coastal lakes remains unknown, but beyond a doubt they were formed in various ways. Lake Żarnowieckie is a typical ribbon water body (Roszkówna 1964), Lake Sarbsko is a lagoon one (Rosa 1963), whereas Lake Bukowo is a barrier lake, formed in consequence of sea transgression (Soszka 1968).

A different genesis of southern-Baltic lagoons and lakes was presented by Wypych (1972). This author performed a detailed analysis of deep-sea sediment-cores, including physical, chemical and palynological examinations, which provided a basis for criticism of previous views on the causes and development of transgression at the Polish Baltic coast. In his opinion transgression was affected primarily by eustatic factors, whereas the tectonic factor played a minor role, which indicates that the processes of shoreline development proceeded in a completely different way. Thus, coastal lagoons and lakes are not former sea bays, but water bodies formed on land and cut off from the sea by displacing sandbars and sand-spits during the Littorina Sea transgression. At the Polish coast the transgression began about 5500-6000 years ago. In the initial phase of the process (7500-5500 years ago) the rate of sea level increment was approx. 1 cm/year, and in the next phase – approx. 1 mm/year. The mean sedimentation rate was 1 cm/10 years over this period. This suggests that southern-Baltic coastal water bodies will disappear within the next several thousand years (Wypych 1972).

In recent years researchers have displayed a growing interest in the ecology of estuaries, which are dynamic and heterogenous ecosystems. Interesting and peculiar phenomena, related to the mixing of marine and inland waters, and sometimes also to retention and exposure to the waves, as well as fluctuations in salinity levels and temperature (Table 2), take place in these water bodies. Estuaries have their specific water structure due to circulation caused by the inflow of freshwaters. The energy of freshwater induces complex mixing processes. Friction forces that occur in the boundary layer between the surface water layer and the bottom water layer are responsible for interfacial water mixing in estuaries. This results in water density stratification, whose best measure is salt concentration (Majewski 1972, Dethier 1992). Salinity levels in estuaries may vary greatly (from 0.05 to 35‰), depending on water inflow from the land, wind direction, frequency of seawater inflow, as well as individual factors typical of a given estuary. Coastal lakes and Baltic Sea lagoons are located in the lowest salinity zone, from the mixo-mesohaline to the limnetic zone (from ±10 to ±0.5‰) (Szmidt 1972). This facilitates the processes of saltwater/freshwater mixing, because in many Polish estuaries water level is only 10-30 cm above sea level (Table 1). Due to this difference in water levels marine waters may affect water balance and the physicochemical properties of water in estuaries (Majewski 1972). Marine water inflow to estuarine water bodies is usually non-cyclical and related to the contact between the lake and the sea, as well as the geographical location of the lake. In Poland the highest salt concentration is recorded in the westernmost lakes. Irregular seawater inflow causes considerable fluctuations in salinity and temperature levels. The organisms that live in estuaries have to adapt these changing conditions (Kinne 1971). The fauna that colonize estuaries comprise euryhaline species found in marine, brackish and fresh waters.

The first description of the estuarine waters of the Polish Baltic Coast was provided by Majewski (1972). Typical estuarine areas, in the form of bays supplied with water from rivers, are the Gulf of Gdańsk and the Pomeranian Gulf (Figure 1). The driving force of estuarine processes in the Gulf of Gdańsk is the Vistula River, and in the Pomeranian Gulf – the Odra River and smaller rivers of the Pomeranian Lakeland and the Mecklenburg Lakeland. Within the bays there are numerous primary and secondary estuaries, usually land-locked, but connected to the sea, which permits water mixing.

At the Pomeranian Gulf, a secondary estuary is formed by the Gulf of Greifswald, the Szczecin Lagoon with the Gulf of Achterwasser and Lake Wrzosowskie at the mouth of two rivers, Piana and Dziwna. A tertiary estuary is formed by Lake Dąbie, connected to the Szczecin Lagoon, which receives small amounts of marine salts. Greater diversity of estuarine forms is observed in the Gulf of Gdańsk. These are the flooded estuary of the Small Gulf of Puck, extensive secondary estuaries – the Vistula Lagoon (that has contact with marine waters via the Bałtyjsk Channel) and Dead Vistula, tertiary estuarine waters in Lake Drużno, where marine waters are supplied via the Vistula Lagoon, and in Szkarpawa (a cut-off arm of the Vistula River). A specific estuarine water body is formed by Dead Vistula, which is a ramification of the Vistula River, exposed to strong marine impacts. Freshwater is supplied mainly from rivers of the Vistula Lowlands, as well as Motława and Radunia.

A specific structure of estuarine waters can be observed in the Pomeranian Gulf and the Gulf of Gdańsk (Tables 1 and 2). The Pomeranian Gulf is currently a shallow coastal area at the Baltic Sea, supplied with water from numerous rivers (17.6 km^3). The strongest marine impacts are recorded in the northern part of this Gulf, and in the Gulf of Greifswald. The effects then gradually diminish towards the mouth of the Odra River and Lake Dąbie. Due to a low depth and capacity, considerable freshwater inflow significantly reduces the salt concentration in the aquatic environment. Two mutually destructive tendencies can be observed in the Pomeranian Gulf, i.e. water stratification caused by differences in the density of fresh and sea waters, and damage to this structure caused by water mixing to the bottom at wind strength of about 10 m/s. These processes are conducive to full exchange of sea and river waters, and to a decrease in the salt concentration all over the gulf, not only in the surface layer. The Gulf of Gdańsk is an estuary of a different type. Despite considerable inflow of fluvial waters (34.4 km^3), the salt concentration decreases in the surface layer only, because water depth in the gulf is of the order of several dozen meters. Therefore, waters are permanently stratified (Mikulski 1970, Majewski 1972).

Less extensive estuarine areas are numerous coastal lakes formed mostly by sandbar barriers built on the side of the sea. An example of a lake that is permanently con-

Table 2

Hydrochemical parameters of waters belonging to the Polish marine waters (Krzymiński and Kamińska 2005)

Waters	Salinity (‰)	Mean temperature (°C)	Vertical water mixing	Retention time (days)	Exposure to the waves
Vistula Lagoon	0.5-5	14.1	no stratification	45	harbour of refuge
Puck Lagoon	0.5-5	12.2	no stratification	138	harbour of refuge
Inner Gulf of Puck	5-18	9.0	no stratification	7-30	harbour of refuge
Inner Gulf of Gdańsk	5-18	8.5	partly stratified	<7	partly open
Outlet of the Vistula River - Przekop	0.5-5	9.6	partly stratified	<7	partly open
Outlet of the Dziwna River	0.5-5	10.3	partly stratified	<7	open
Outlet of the Świna River	0.5-5	13.1	partly stratified	<7	open
Szczecin Lagoon	0.5-5	14.1	no stratification	52	harbour of refuge
Kamień Lagoon	0.5-5	10.4	no stratification	>30	harbour of refuge

nected to the sea by a stretch of the Łeba River is Lake Łebsko, with a well-developed reverse delta. Lake Jamno represents another type of estuary, since it is connected to the sea (by a channel known as Nurt Jamneński) temporarily only. The movements of coastal debris result in periodical outflow closing. Lake Gardno also forms an estuary in the current of the Łupawa River, which flows into this lake in its eastern part and flows out in the north-western part, to flow into the Baltic Sea (Majewski 1972).

The largest and most important estuaries in the Polish Baltic Coastal Zone are the Szczecin Lagoon and the Vistula Lagoon (Table 1, Figure 1). The Szczecin Lagoon, divided into the Polish part and the German part (the Large Lagoon and the Small Lagoon), is an estuary isolated from the Sea, but connected to it by three straits: Piana, Świna and Dziwna. Piana and Dziwna play a minor role in water exchange, since both of them form extensive water bodies nearby the outlet to the sea. Marine waters flow into these water bodies, and then flow out to the sea. Therefore, the estuarine relations in the Lagoon are determined primarily by the Świna Strait with the Piastowski Channel and a fairway running through the Lagoon to the mouth of the Odra River and the seaport in Szczecin. The additional connection between Świna and the Lagoon, through Stara Świna, forms a reverse delta, which is conducive to water exchange (Majewski 1972). The water from the Odra River accounts for 95% of the freshwater inflow and carries a considerable pollutant load in the form of soluble compounds and suspended solids. The main sources of pollution are municipal sewage from the city of Szczecin, and industrial effluents from the Chemical Plant "Police". High concentrations of phosphorus compounds and nitrogen compounds in the water (in 1975 the mean levels of phosphates and nitrates were 0.15 and 1.6 $mg \cdot dm^{-3}$, and in 1993 decreased substantially, to 0.1 and 0.75 $mg \cdot dm^{-3}$) are conducive to mass phytoplankton blooms (mainly blue-green algae of the genus *Microcistis*) (Poleszczuk et al. 1995). According to Pastuszak et al. (2001), nutrient concentrations in the Szczecin Lagoon and their long-term variation are affected by varying levels of fluvial water inflows and biogeochemical processes occurring in the Lagoon. It was found that nitrate concentration was strongly correlated with the inflow of water masses, whereas in the case of phosphate concentration this relationship was much weaker. Therefore, the sources of nitrogen recorded in the catchment area of the Odra River are scattered, while phosphorus comes from point sources. This is confirmed by the results obtained by Łysiak-Pastuszak et al. (2004). The pollutants accumulated in the waters of the Lagoon undergo changes and accelerate the eutrophication process. At the same time, the Szczecin Lagoon plays the role of a large, natural "biological sewage treatment plant", and considerably reduces the pollutant load carried by the Odra River to the Baltic Sea.

The Vistula Lagoon is a brackish water body that belongs to the waters of the Baltic Sea, cut off from the Gulf of Gdańsk by the Vistula Sandbar. The Lagoon is connected to the Gulf of Gdańsk by the Pilawa Strait. The border between Poland and Russia runs through the Vistula Lagoon (Kaliningrad District). Before the arms of the Vistula River carrying water masses and debris were cut off, the Lagoon was a body of freshwater, and the impact of marine waters was limited to a small area at the Bałtyjsk Channel. The reconstruction and redevelopment carried out at the outlet of the Vistula River (19th c.) were followed by major changes in the character of estuarine circulation in the Lagoon. The structure of waters of the Vistula Lagoon shows distinct characteristics of an estuary, where the inflow of marine waters through the Bałtyjsk Channel plays a much more important role than the inflow of inland waters. The highest salinity levels are recorded in the vicinity of the Baltic Sea (10‰), and decrease proportionally to the distance from the strait, both to the south-east (towards the Vistula deltas), and to the east (towards the mouth of the Pregoła River). The Lagoon never contains freshwater only (Majewski 1972). Freshwaters are supplied by the following rivers: Pregoła (44% of waters), Nogat (17%), Pasłęka (14%) and Elbląg (6%). The rivers bring considerable amounts of biogenic substances. The main pollutants are municipal sewage from the town of Elbląg and biogenic compounds from agricultural land in the Vistula River Lowlands (Żuławy). In 1977 the mean concentrations of phosphates and nitrates in the waters of the Lagoon were 0.205 and 1.21 $mg \cdot dm^{-3}$ respectively (Różańska and Więcławski 1981), and decreased significantly in 1990 (Kot-Wasik et al. 2004). The constant presence of phosphates and high concentrations of organic mater indicate advanced eutrophication of the Vistula Lagoon, similarly as in the Polish Coastal Zone (Łysiak-Pastuszak et al. 2004).

A characteristic feature of the Szczecin Lagoon is its freshwater character. The Vistula Lagoon is a brackish water body. Both are highly eutrophicated, but differ in the productivity and species composition of planktonic organisms. The phytoplankton of the Szczecin Lagoon is dominated by diatoms, both in terms of the number of species and biomass, but an increase in water temperature is accompanied by the development of blue-green algae. The blue-greens dominate in the Vistula Lagoon – they account for 80% of total phytoplankton biomass (Wiktor et al. 1997). A comparison of the zooplankton of the Vistula Lagoon and the Szczecin Lagoon show that they differ primarily in the species composition of copepodes. Cyclopoidea and Diaptomus dominate in the Szczecin Lagoon, and Calanoidea with *Eurytemora affinis* and *Acartia bifilosa* – in the Vistula Lagoon. The proportion of cladocerans is higher in the Szczecin Lagoon, whereas rotifers dominate in the Vistula Lagoon (Wiktor 1959, Różańska 1967, 1972, Adamkiewicz-Chojnacka 1978, Naumenko 1999). Studies conducted by Giziński et al. (1980), Masłowski (1992), Wolnomiejski and Grygiel (1992) and Żmudziński (2000) provided valuable information on the bottom-dwelling fauna of both Lagoons. In the Szczecin Lagoon mollusks account for 80% to 90% of the total biomass, and the population of bivalves is dominated by *Dreissena polymorpha* whose shoals create favorable conditions for representatives of *Oligochaeta* and *Chironomidae*. Mollusks do not play a significant role in the bottom-dwelling fauna of the Vistula Lagoon (13-14% of the biomass). *Dreissena polymorpha* is almost absent, whereas *Chironomidae* and *Marenzelleria viridis* make up 70% and 60-90% respectively (Wiktor et al. 1997). Rich bottom-dwelling fauna and a relatively rich zooplankton community create excellent conditions for the development of fish, both bottom-dwelling and pelagic. The abundance of fish in particular water bodies is reflected by catch rates. The mean annual catch rates in the Szczecin Lagoon and Vistula Lagoon in the years 1989-1998 were 2627 tons (Garbacik-Wesołowska and Boberski 2000) and 2288 tons (Borowski 2000) respectively.

Table 3

Some productivity indices for Baltic coastal waters (Wiktor et al. 1997)

Water body	Szczecin Lagoon*	Vistula Lagoon	Curonian Lagoon
Primary production(g C/m^2 per annum)	612-761	461	-
Mean benthos biomass(g/m^2)	73	33-119	47
Mean catch yield (kg/ha)	52-68	18-22**	35-58***

* data for the Polish part of the Lagoon
** without the herring
*** without the smelt

The values of productivity indices are lower in the Vistula Lagoon than in the Szczecin Lagoon (Table 3), where more freshwaters rich in biogenes are supplied.

Estuaries, exposed to stronger and stronger anthropopressure, play a very important function of natural filters for a variety of chemical compounds contained in waters flowing through these areas (Sokołowski et al. 2001, Łysiak-Pastuszak et al. 2004). Thus, an estuary is a trophic trap of both physical and biological character. It forms an effective buffer zone that prevents the penetration of toxic biological substances and organic pollutants into seawater (Kowalewska et al. 2003). Organic colloids are present in estuaries at high concentrations. Due to a great number of reactive functional groups, they are capable of forming active and permanent bonds with various toxic metals, such as As, Zn, Pb, U, Se, Co, Cu, Mn, Hg (Orson et al. 1992). Klarer and Millie (1989), who conducted studies in the Old Women Creek estuary, found that in the region of water outflow the concentrations of toxic metals and biogenes decreased by 12-60% and 35-80% respectively, whereas the concentrations of soluble suspended solids reduced as much as sevenfold, compared with the levels recorded in the waters of this estuary. This was possible mainly due to such processes as sorption, sedimentation, bioavailability and geochemical changes. Pohl et al. (1998), who studied the transport of trace metals between the Odra River Bay and the Odra River outlet to the Baltic Sea, found that only a very low percentage of the transported metals reached the Pomeranian Gulf – the majority of them (Fe-80%, Mn-70%, Cd, Pb, Zn-45%, Co-40%, Cu, Ni-35%) were deposited in the estuarine transition zone. In the deep waters of the estuaries the concentrations of organic matter, biogenic substances and toxic metals decrease due to dilution, and then they are incorporated into the bottom deposits. In addition, some of floating suspended solids undergo sedimentation following the contact with marine waters. Therefore, the degree of salinity in the estuaries has a significant effect on pollutant accumulation in the bottom deposits, and the time of their retention depends on oxygen concentration and hydrological conditions in a water body (Kowalewska et al. 2003).

Estuarine waters, i.e. large-area waters of the coastal zones of seas and oceans, play a very important role in human life and activities. They offer good navigability and sailing conditions, so numerous large seaports are located in estuaries (e.g. Szczecin, Gdynia, London, Buenos Aires). Due to high water fertility, these areas are also used for fishing purposes. In addition, estuarine water bodies are often developed into leisure and recreation centers. Studies conducted in the Słowiński National Park (Łebsko and Gardno estuaries) in the years 1997-2000 proved that the number of tourists ranged there between two hundred and over three hundred thousand, and never dropped below a hundred thousand per year in the last 25 years. The high number of tourists is probably a consequence of attractive tourist trails, some of which are located in estuaries (Sobocka 2001).

CONCLUSIONS

1. Despite a similar genesis and geomorphological type, estuaries are characterized by different hydrological and hydrochemical conditions, affected by a predominance of factors of terrestrial or marine character. The distinguishing features of this environment are highly variable currents and salinity levels, as well as richness of different life forms, although the species composition is relatively poor. The fauna that colonize estuaries comprise euryhaline species found in marine, brackish and fresh waters.
2. The origin of Polish estuarine water bodies is closely related to the history of the Baltic Sea and the last glaciation. The present shape of the shoreline was affected primarily by the modeling effects of coastal processes, processes of gradual land rising and bay transformation into coastal lakes, depression of end moraines, and impacts of the glacier.
3. A specific structure of estuarine waters can be observed in the Pomeranian Gulf and the Gulf of Gdańsk, where the main driving forces of estuarine processes are the Vistula River and the Odra River.
4. The largest and most important estuaries in the Polish Baltic Coastal Zone are the Szczecin Lagoon and the Vistula Lagoon. They form an effective buffer zone that prevents the penetration of toxic biological substances and organic pollutants into seawater. Estuaries are trophic traps (of both physical and biological character) for chemical compounds contained in water.

REFERENCES

Adamkiewicz-Chojnacka B., 1978. Występowanie i skład gatunkowy zooplanktonu Zalewu Wiślanego w latach 1974-1975 (Occurrence and species composition of the zooplankton of the Vistula lagoon in the years 1974-1975). *Stud. Mat. Oceanol*., 21, 4, 123-144, (in Polish).

Borowski W., 2000. Stan zasobów ryb Zalewu Wiślanego i warunki ich eksploatacji. W: Oszacowanie stanu zasobów ryb polskiej strefy przybrzeżnej i naturalne warunki ich eksploatacji. Monografia Rybacka. (Fishery resources of the Vistula Lagoon and conditions of their use. In: Estimation of the fishery resources in the Polish Baltic Coastal Zone and natural conditions of their use. Monograph on Fishery Resources). *Stud. Mat.*, *MIR*, Gdynia, B, 72, 9-35, (in Polish).

Day J. W., Jr., Hall C. A. S., Yanez-Arancibia A., 1989. Estuarine Ecology. John Wiley and Sons, New York, 576.

Dethier M. N., 1992. Classifying marine and estuarine natural communities: An alternative to the coward in system. *J. Nat. Areas*, 12, 2, 90-100.

Garbacik-Wesołowska A., Boberski E., 2000. Stan zasobów ryb Zalewu Szczecińskiego oraz strefy przybrzeżnej Wybrzeża Zachodniego i warunki ich eksploatacji. W: Oszacowanie stanu zasobów ryb polskiej strefy przybrzeżnej i naturalne warunki ich eksploatacji. Monografia Rybacka. (Fishery resources of the Szczecin Lagoon and the coastal zone of of the Western Coast and conditions of their use. In: Estimation of the fishery resources in the Polish Baltic Coastal Zone and natural conditions of their use. Monograph on Fishery Resources). *Stud. Mat.*, *MIR*, Gdynia, B, 72, 77-105, (in Polish).

Giziński A., Jagodzińska M., Wolnomiejski N., Grygiel I., 1980. Zoobenthos of the muddy areas of Szczecin Lagoon. *AUNC*, 12, 41-59.

Kinne O., 1971. Physiologische und ökologische Aspekte des Lebens in Ästuarien. *Helgol. Wiss. Meer*., 11, 131-156, (in German).

Klarer D. M., Millie D. F., 1989. Amelioration of stormwater quality by a freshwater estuary. *Archiv. Hydrobiol*., 116, 375-389.

Kot-Wasik A., Dębska J., Namieśnik J., 2004. Monitoring of organic pollutants in coastal waters of the Gulf of Gdańsk. *Mar. Poll. Bull*., 49, 3, 264-276.

Kowalewska G., Konat-Stepowicz J., Wawrzyniak-Wydrowska B., Szymczak-Żyła M., 2003. Transfer of organic contaminants to the Baltic in the Odra Estuary. *Mar. Poll. Bull*., 46, 6, 703-718.

Krzymiński W., Kamińska M., 2005. Wkład wieloletnich badań oceanograficznych Oddziału Morskiego IMGW w Gdyni w opracowanie typologii polskich wód morskich. (Contribution of long-term oceanographic studies conducted at the Maritime Section of the Institute of Meteorology and Water Economy in Gdynia to drawing up a typology of Polish marine waters). *Gaz. Obser. IMGW*, 4, 11-15, (in Polish).

Larousse, 2003. Encyklopedia Powszechna. (Popular Encyclopaedia). Vol. 1, A-Ł. *Wyd. Muza SA*, Warszawa, 885, (in Polish).

Łysiak-Pastuszak N., Drgas N., Piątkowska Z., 2004. Eutrophication in the Polish coastal zone: the past, present status and future scenarios. *Mar. Poll. Bull*., 49, 3, 186-195.

Majewski A., 1972. Charakterystyka hydrologiczna estuariowych wód u polskiego wybrzeża. (Hydrological characteristics of estuarine waters at the Polish Coast). *Prace Państw. Inst. Hydrol.-Meteorol*., 105, 3-40, (in Polish).

Masłowski J., 1992. Bottom macrofauna of the Szczecin Lagoon (north-western Poland). *Acta Hydrobiol*., 34, 3, 253-274.

Mikulski Z., 1970. Wody śródlądowe w strefie brzegowej południowego Bałtyku. (Inland waters in the Southern Baltic coastal zone). *Prace Państw. Inst. Hydrol.-Meteorol*., 98, 25-45, (in Polish).

Naumenko E. N., 1999. Species composition, seasonal and long-term dynamics of zooplankton abundance and biomass in the Vistula Lagoon of the Baltic Sea. In: Proc. of Symp. “Freshwater fish and the herring populations in the coastal lagoons”. Gdynia, *Sea Fish. Inst.*, 161-171.

Odum E. P., 1982. Podstawy ekologii. (Fundamentals of Ecology). *PWRiL*, Warszawa, 175--433, (in Polish).

Orson R. A., Simpson R. L., Good R. E., 1992. A mechanism for the accumulation and retention of heavy metals in tidal freshwater marshes of the upper Delaware River Estuary. *Estuar. Coast. Shelf. Sci*., 34, 171-186.

Pastuszak M., Wielgat M., Sitek S., 2001. Nutrient status in the Szczecin Lagoon – past, present and future prospects. *Oceanol. Stud*., 30, 1-2, 59-86.

Pohl C., Hennings U., Petersohn I., Siegel K., 1998. Trace metal budget, transport, modification and sink in the transition area between the Oder and peene rivers and the southern Pomeranian Bight. *Mar. Poll. Bull*., 36, 8, 598-616.

Poleszczuk G., Garbacik-Wesołowska A., Sitek S., Mutko T., 1995. Status tlenowy i troficzny wód estuarium Odry. (Oxygen and trophic status of the waters of the Odra estuary). *Stud. Mat. MIR*, Gdynia, A, 33, 7-34, (in Polish).

Remane A., 1934. Die Brackwasserfauna. *Zoolog. Anzeig. Suppl*., 7, 34-74, (in German).

Remane A., Schlieper C., 1971. Biology of brackish waters. Binnengewässer, 25, 1-372.

Rosa B., 1963. O rozwoju morfologicznym wybrzeża Polski w świetle dawnych form brzegowych. (Morphological development of the Polish coast in the light of former coastal forms). *Stud. Soc. Scien. Torunensis*, 5, 1-18, (in Polish).

Rosa B., 1977. Wyniki badań geologicznych w rejonie jeziora Gardno. (Results of geological studies in the region of Lake Gardno). *Stud. Mat. Oceanol*., 19, 279-281, (in Polish).

Roszkówna L., 1964. Z morfogenezy okolic Jeziora Żarnowieckiego. (Morphogenesis of the region of Lake Żarnowieckie). *Zesz. Nauk.* Uniw. M. Kopernika w Toruniu, 10, 1-11, (in Polish).

Różańska Z., 1967. Zooplankton i krótka charakterystyka hydrologiczna Zalewu Wiślanego i Zalewu Szczecińskiego w świetle badań XX-lecia. (Zooplankton and a brief hydrological description of the Vistula Lagoon and Szczecin Lagoon in the light of 20-year studies). *Stud. Mat. MIR*, Gdynia, A, 4, 27-37, (in Polish).

Różańska Z., 1972. Zooplankton zalewów przybałtyckich. (Zooplankton of the Baltic lagoons). *Stud. Mat. Oceanol*., 3, 141-147, (in Polish).

Różańska Z., Więcławski F., 1981. Zmiany czynników eutrofizacji wód Zalewu Wiślanego. (Changes in eutrophication factors affecting the waters of the Vistula Lagoon). *Stud. Mat. Oceanol*., 34, 4, 7-31, (in Polish).

Schubel J. R., Pritchard W. D., 1971. What is an estuary? In: Estuarine Environment. (Ed.), R. Schubel, New York, 1-115.

Sobocka B., 2001. Wielkość ruchu turystycznego na terenie Słowińskiego Parku Narodowego. (Tourist traffic density in the Słowiński National Park). *Pracownia Nauk-Eduk., SPN*, Smołdzino, (in Polish).

Sokołowski A., Wołowicz M., Hummel H., 2001. Distribution of Dissolved and Labile Particulate Trace Metals in the Overlying Bottom Water in the Vistula River Plume (Southern Baltic Sea). *Mar. Poll. Bull*., 42, 10, 967-980.

Soszka G., 1968. Wybrane zagadnienia z historii słonawego jeziora Łebsko (Selected problems from the history of brackish Lake Łebsko). *Prace Państw. Inst. Hydrol.-Meteorol*., 1-15, (in Polish).

Szmidt K., 1972. Hydrologia jezior przybałtyckich ze szczególnym uwzględnieniem jeziora Jamno. (Hydrology of Baltic coastal lakes with special emphasis on Lake Jamno). *Stud. Mat. Oceanol*., 3, 21-34, (in Polish).

Telesh I. V., 2004. Plankton of the Baltic estuarine ecosystems with emphasis on Neva Estuary: a review of present knowledge and research perspectives. *Mar. Poll. Bull*., 49, 206-219.

Trojanowski J., Trojanowska Cz., Korzeniewski K., 1991. Trophic state of coastal lakes. *Pol. Arch. Hydrobiol*., 38, 1, 23-34.

Wiktor K. 1959. Zooplankton Zalewu Szczecińskiego. Cz. II. (Zooplankton of the Szczecin Lagoon. Part II). *Prace MIR*, Gdynia, 10, 229-258, (in Polish).
Wiktor K., Węsławski J. M., Żmijewska M. I., 1997. Biogeografia morza. (Biogeography of the sea). *Wyd. Uniw. Gdański*, 156-177, (in Polish).
Wolnomiejski N., Grygiel I., 1992. Biocenoza dna mulistego Zalewu Szczecińskiego. (Biocenosis of the muddy bottom of the Szczecin Lagoon). *Stud. Mat. MIR*, Gdynia, B, 60, (in Polish).
Wypych K., 1972. Geneza zalewów południowo-bałtyckich w świetle nowych badań. (Genesis of Southern Baltic lagoons in the light of recent research). *Prz. Geof.*, 18, 25(3), 15-18, (in Polish).
Žaromskis R., 1996. Oceans, Seas, Estuaries. Debesija, Vilnius, 293, (in Lithuanian).
Żmudziński L., 2000. Long-term changes in macrozoobenthos of the Vistula Lagoon. Sea Environment (Jura ir Aplinka). *Marine Technol. Natural Sc*., 1, 3, 46-50, (Klaipeda University, Laipeda).
Żmudziński L., Kornijów R., Bolałek J., Górniak A., Olańczuk-Neyman K., Pęczalska A., Korzeniewski K., 2002. Słownik hydrobiologiczny. Terminy, pojęcia, interpretacje. (Hydrobiological dictionary. Terms, concepts, interpretations) *Wyd. Nauk*. PWN, Warszawa, 1-287, (in Polish).

ESTUARIA POLSKIEJ STREFY PRZYBRZEŻNEJ BAŁTYKU

Streszczenie

Estuaria są dynamicznymi ekosystemami o bardzo dużej i ciągłej zmienności gradientów fizykochemicznych i parametrów biologicznych. Znaczne fluktuacje w poziomie zasolenia, temperatury, tlenu, pH, stężenia nutrientów oraz materii organicznej są naturalnym zjawiskiem w tych zbiornikach wodnych. Polskie Wybrzeże Bałtyckie obfituje w wiele form typu estuariowego, począwszy od zatopionych zatok w otwartym morzu (Zatoka Gdańska i Zatoka Pomorska) do zbiorników mających stałe połączenie z morzem (jezioro Łebsko) lub okresowo zamkniętych i przez kanały lub ujściowe odcinki rzek kontaktujących się z morzem (jeziora Jamno i Gardno). Cechy estuariów wykazują również ujścia wielkich rzek jak Odra i Wisła. Estuaria pełnią bardzo ważną funkcję jako swoiste naturalne filtry dla różnych związków chemicznych zawartych w przepływającej wodzie. Tworząc skuteczną strefę buforową uniemożliwiają przedostawanie się wielu substancji biologicznie toksycznych do morza.