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Diatom record of progressive anthropopressure in the Gulf of Gdańsk and the Vistula Lagoon

by

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Abstract

This study describes the subfossil diatom flora in the surface sediments of the Polish coastal waters in relation to human impact. The material studied consists of the uppermost parts of seven sediment cores collected from the SW Gulf of Gdańsk and eight cores from the Vistula Lagoon. Our results show the present-day ecological state of both basins just before the planned construction of a navigable channel of the Vistula Spit, which will be the next factor affecting their hydrology. In different parts of the Gulf of Gdańsk, cultural eutrophication resulted in a distinct "anthropogenic assemblage" in the surface sediments. Its structure relates directly to the distance from the mouth of the Vistula River. In the surface assemblages of the Vistula Lagoon, the number of salt-tolerant diatoms increased with the salinity of the basin. Locally, a large number of pollution-resistant taxa was also observed.

Key words: cultural eutrophication, environment pollution, diatoms, Gulf of Gdańsk, Vistula Lagoon

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Introduction

The coastal zone of the Baltic Sea, relatively small and shallow with limited water exchange, is very sensitive to human impact. Due to hydrological regime, cultural eutrophication is one of the most urgent problems of water quality in the Gulf of Gdańsk and the Vistula Lagoon.

Human impact on environmental conditions has increased considerably since the Middle Ages (Starkel 2001). The development of agriculture has resulted in deforestation and a significant reduction in grazing land. Transport of eroded sediments of the river delta surface shows a significant increase due to the development of Vistula River branches. The Nogat, in the past a separate river, merged with the Vistula in the 13th and 14th centuries. The first attempt to regulate the river flow was undertaken after the big flood in 1829. The regulation was completed after the next tragic flood in 1888. An artificial mouth of the Vistula was created near Świbno. Since 1895, the Szkarpawa and the Dead Vistula (in Polish: Martwa Wisła) have been cut off from the main river course, which flows directly into the Gulf of Gdańsk (Makowski 1995). A new hydrological system was completed in 1915, when the Nogat was isolated by the construction of a dam. Urbanization, progressive industrialization and an increase in the wastewater inflow have had a strong environmental impact over the last 200 years, reflected i.a. in clear changes in the hydrological regime. Transport of large amounts of nutrients, organic matter and pollutants by the rivers has resulted in environmental degradation of the Gulf of Gdańsk and its progressive eutrophication in particular (Pliński 1991). The Gulf of Gdańsk and the Vistula Lagoon are considered one of the most polluted regions of the whole Baltic Sea. In the former basin, the content of nitrates increased five times, whereas the content of phosphorus – two times. The eutrophication process causes an increase in biological production, which leads to increased fishery yields. However, many negative effects have also been observed, e.g. increased deposition of organic matter, reduced water transparency and vertical extent of the photic zones, and oxygen deficiency including the occurrence of hypoxia and anoxia periods (e.g. Łysiak-Pastuszak et al. 2004).

Eutrophication has resulted in structural changes in plant and animal communities, and a general decline in biodiversity (Howarth et al. 2000). A decrease in plankton diversity in the Gulf of Gdańsk has been widely discussed (e.g. Witkowski & Pempkowiak 1995; Niemkiewicz & Wrzołek 1998; Leśniewska & Witak 2008; 2011). The so-called "anthropogenic assemblages" with pollution-resistant taxa, i.e. *Cyclotella choctawhatcheeana*, *C. meneghiniana*, *Stephanodiscus hantzschii* and *Thalassiosira levanderi* are indicators of progressive eutrophication of the Gulf of Gdańsk (e.g. Witkowski 1994; Stachura-Suchoples 2001; Witak et al. 2006; Leśniewska & Witak 2008; 2011; Witak 2010). On the other hand, the discharge of river water into the Vistula Lagoon was markedly reduced due to the construction of a dam. The contribution of riverine waters to the general water balance of the basin has decreased (Mikulski 1960). At the same time, the role of seawaters flowing into the lagoon through the Strait of Baltiysk has intensively increased, which is documented by the diatom flora (e.g. Witak & Jankowska 2005). Therefore, the anthropogenic impact on the present-day environment of both basins is still of scientific interest and deserves further discussion. The knowledge of the ecological conditions in the Gulf of Gdańsk and the Vistula Lagoon at the beginning of the 21st century is particularly important, considering the planned excavation of the Vistula Spit. There is no doubt that the development of the shipping transport via the new connection between the two basins will be the next anthropogenic factor affecting their hydrological regime.

The objective of this study was (1) to differentiate the diatom assemblage zones based on floristic spectra and ecological groupings in subbottom sediments of the SW Gulf of Gdańsk and the Vistula Lagoon, (2) to compare the distinguished zones with respect to habitat and salinity preferences of the main species, including autochthonous and allochthonous forms and (3) to perform spatial analysis of cultural eutrophication effects on subfossil diatom flora of both basins with an emphasis on the role of inflows of riverine waters.

Description of the study area

The Gulf of Gdańsk is formally separated from the rest of the Baltic Sea by a line connecting Cape Rozewie in Poland on the western side and Cape Taran in Lithuania on the eastern side (Fig. 1). It constitutes the southern part of the Gdańsk Basin (Majewski 1990). The gulf is part of an elongated trough with a varied bed dip. The shallows occur in its western and eastern parts, as well as in the neighborhood of the Vistula River mouth. In the west, the Hel Peninsula, which is a natural sand barrier, separates the inner part of the Gulf of Gdańsk, i.e. Puck Bay (Majewski 1990). The average depth of the western part of Puck Bay, called the Puck Lagoon, is ca. 3.13 m, while the mean depth of the Outer Puck Bay having a wide connection with

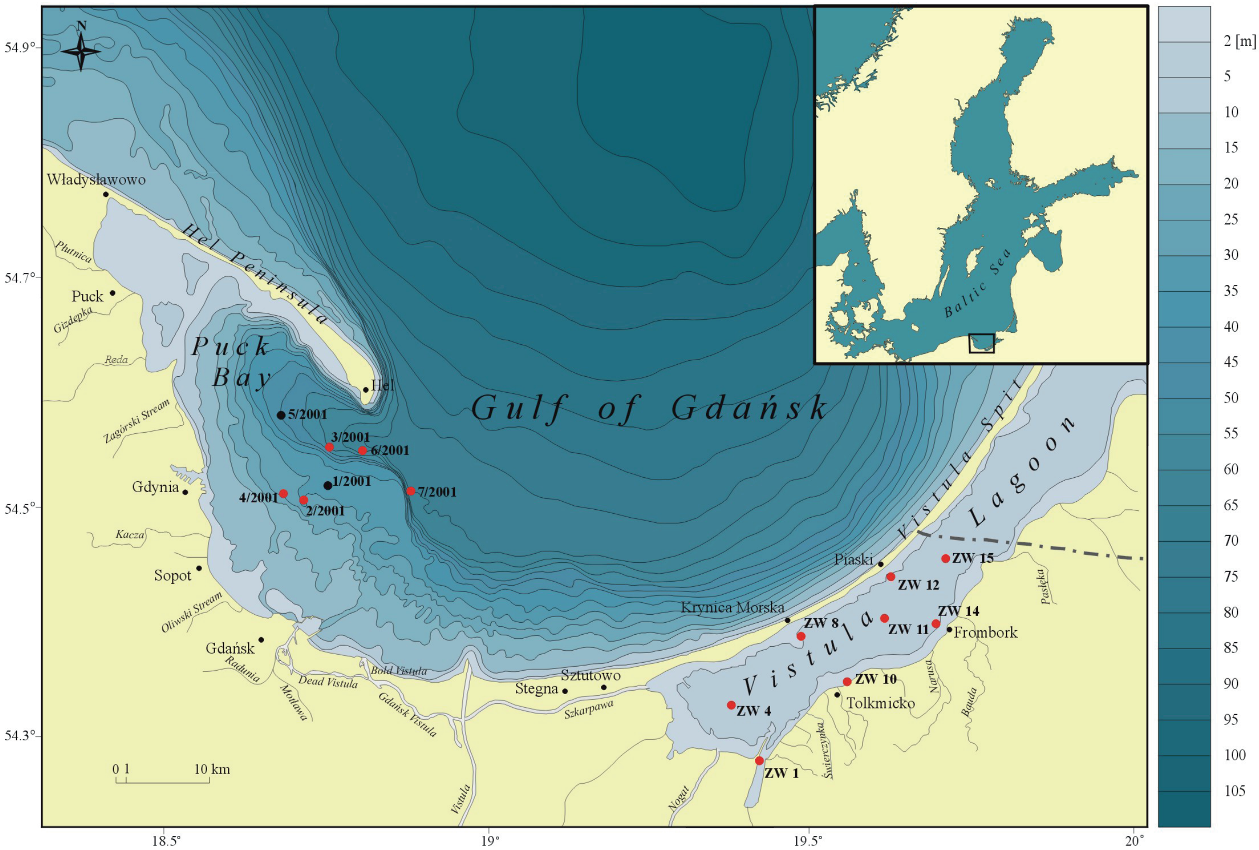

Figure 1

Location of the studied sediment cores. Red dots – superficial sediments with the anthropogenic assemblage

the open waters of the Gulf of Gdańsk was estimated at 20.5 m. The Vistula Lagoon, a relatively narrow and long basin, is separated from the Baltic Sea by a natural sand barrier – the Vistula Spit (Łomniewski 1958). At present, only a narrow strait near the Russian port of Baltiysk enables the exchange of water with the Gulf of Gdańsk. It is a very shallow water body with an average depth of 2.7 m and a maximum depth of 5.2 m. However, its south-western part, known as the Elbląg Lagoon, with an average depth of 2.4 m, is shallower than the rest of the lagoon (Wypych 1975).

The hydrological regime in both basins is associated with the depth, climatic conditions and the inflow of saline waters from the open Baltic Sea. The freshwater discharge from the surrounding coastal areas is another important factor affecting the hydrology of the study area. The Vistula Lagoon is strongly controlled by riverine waters of the Nogat, the Pregola, the Bauda, the Narusa, the Pasłęka, the Mamonovka etc. The hydrological regime in the deeper part of the Gulf of Gdańsk is controlled by the strong runoff from the Vistula mouth. The impact of other rivers, e.g. the Kacza, the Oliwski Stream that discharge into the Outer Puck Bay, is limited to the proximity of their estuaries (Majewski 1972). The E, ENE and ESE winds cause the Vistula runoff to incline westward (Kravtsov et al. 2002). The prevailing winds blowing from W, WNW and WSW deflect riverine waters, which spread toward the east. Winds from the SW, S and SE directions markedly increase the distance of spreading the Vistula waters, whereas those from the N, NW and NE limit the spread to the vicinity of the mouth.

Seasonal stratification in the water column occurs in the SW part of the Gulf of Gdańsk. The 50–60 m deep surface layer is the main part of the waters and is characterized by low variation in seasonal salinity and temperature changes (Cyberska 1990). Pycnocline, halocline and thermocline layers are located in the deeper part of the study area, at depths between 60 and 80 m. Bottom waters with constant temperature and salinity are below a depth of 80 m, which is outside the study area. The mixing affects the entire water column of the Vistula Lagoon due to the limited depth, and therefore vertical stratification usually does not occur (Grekov et al. 1975).

Average annual salinity of the surface water in the SW part of the Gulf of Gdańsk oscillates between 7.25 PSU in the vicinity of the Hel Peninsula tip and 7.21 near the port of Gdynia (Nowacki 1993). In the neighborhood of the Vistula mouth, this value decreases to 4.51 PSU (Cyberska 1992). The Vistula Lagoon is much more freshening. Its salinity fluctuates from 1.65 PSU in the Elbląg Lagoon via 2.76 PSU in the central region to 4.72 PSU near the Baltiysk Strait.

Material and methods

The material studied consists of the uppermost parts of 15 sediment cores collected from two different environmental settings (Fig. 1). Parameters and lithology of the analyzed core parts are included in Table 1. Seven cores were retrieved using a vibro corer from the south-western part of the Gulf of Gdańsk, between the region of Gdańsk and Gdynia and the Hel Peninsula. In five of them (2/2001, 3/2001, 4/2001, 6/2001, 7/2001), anthropogenic assemblages were found in subbottom sediments (Table 2). The Vistula Lagoon sediments were collected at 8 sites using an Eijkelkamp corer. Boreholes ZW 8 and ZW 12 were made near the Vistula Spit, cores ZW 4, ZW 11 and ZW 15 were retrieved from the central part of the lagoon. Additionally, cores ZW 1, ZW 10 and ZW 14 originate from the southern part of the basin. Anthropogenic flora was recorded in all samples collected from the Vistula Lagoon. The whole material used for the diatom analysis was provided by the Polish Geological Institute, the Branch of Marine Geology, Gdańsk.

Diatom samples were prepared according to standard methods (Battarbee 1986). The counting method of Schrader and Gersonde (1978) was used and from 500 to 700 valves were counted in each sample to estimate the percentage abundance of particular taxa. The diatoms were divided into planktic and benthic groups (Round 1981). In addition, autochthonous taxa i.e. typical of a given basin (marine and brackish water) and allochthonous (freshwater) taxa i.e. of riverine origin were distinguished in the planktic group. Diatoms were grouped with respect to their salinity requirements according to Kolbe's (1927) halobian system: euhalobous (salinity > 30 PSU), mesohalobous (5–20 PSU), oligohalobous halophilous (< 5 PSU), and indifferent (0–2 PSU) and halophobous (0 PSU).

The identification and ecological information was obtained from works by Hustedt (1927–1966), Lange-Bertalot & Krammer (1987), Krammer & Lange-Bertalot (1986, 1988, 1991a,b), Pankow (1990), Denys (1991), Vos & de Wolf (1993), Van Dam et al. (1994), Witkowski et al. (2000), Lange-Bertalot (2001).

The percentage content of all ecological groups was calculated in each sample. Diatom assemblage zones (DAZ) were distinguished based on relative abundance of diatom taxa and prevalent ecological groups. All diatom assemblage zones distinguished in the studied material were described in detail by Witak (2010). Brief summary of results on the diatom flora preserved in the sediments of the Gulf of Gdańsk is shown in Table 2, whereas of the Vistula Lagoon in Table 3.

Results

Due to hydrological differences between the Gulf of Gdańsk and the Vistula Lagoon, the diatom flora preserved in their superficial sediments is characterized by diverse structure (Fig. 2). General

Table 1

Parameters of the analyzed cores

Region	Core Nb	φ	λ	Water depth [m]	Lithology
Gulf of Gdańsk	2/2001	54°30.658'N	18°42.768'E	30.0	silt, black (N1), at a depth of 8 cm single shells of *Macoma*, HCl–;
	3/2001	54°33.640'N	18°44.913'E	54.5	muddy sand, dark-grey (N2), HCl–;
	4/2001	54°31.083'N	18°41.349'E	29.8	silt, black (N1), at the top – admixture of sand with grains of gravel; single shells of *Macoma*, HCl–;
	6/2001	54°33.282'N	18°47.938'E	62.0	silty mud, black (N1), organic matter, HCl–;
	7/2001	54°31.008'N	18°52.569'E	65.0	silty mud, black (N1), organic matter, single shells of marine mollusks above a depth of 20 cm, HCl–;
Vistula Lagoon	ZW 1	54°15.75'N	19°23.416'E	2.1	silty mud, black (N1) and olive-black (5Y 2/1);
	ZW 4	54°18.666'N	19°21.583'E	2.7	silty mud, black (N1), HCl–;
	ZW 8	54°22.448'N	19°27.536'E	2.2	mud dark yellowish brown (10YR 4/2), HCl–;
	ZW 10	54°19.631'N	19°31.280'E	1.8	mud, HCl–;
	ZW 11	54°22.1'N	19°43.183'E	3.4	silty mud, green-black, (5GY 2/1) and dark-green (5GY 4/1);
	ZW 12	54°25.566'N	19°36.366'E	2.2	silty mud, green-black (5GY 2/1), HCl–;
	ZW 14	54°22.333'N	19°40.20'E	2.5	sandy mud, with admixture of fine sands, numerous shells of freshwater mollusks, HCl–;
	ZW 15	54°26.40'N	19°43'E	4.3	silty mud, grey-black (N2) and green-black (5G 2/1)

Table 2

Characteristic features of anthropogenic diatom assemblage zones distinguished in the cores from the Gulf of Gdańsk

Diatom Assemblage Zone	Depth [cm]	Diversity number of taxa/number of genera	State of diatoms
2/2001-III *Thalassiosira levanderi – Pauliella taeniata – Stephanodiscus hantzschii* DAZ	19–0	116/41	good
3/2001-IV *Amphora pediculus – Cocconeis neothumensis* DAZ	20–0	106/30	good + some broken valves
4/2001-V *Pauliella taeniata – Cyclotella* spp. *– Stephanodiscus* spp. DAZ	18–0	146/47	good + some broken valves
6/2001-V *Thalassiosira levanderi – Opephora krumbeinii – Cyclotella* spp. DAZ	25–0	144/45	good + some broken valves
7/2001-IV *Thalassiosira levanderi – Skeletonema marinoi – Pauliella taeniata* DAZ	20–0	85/31	good

Table 3

Characteristic features of anthropogenic diatom assemblage zones distinguished in the cores of the Vistula Lagoon

Diatom Assemblage Zone		Depth [cm]	Diversity number of taxa/number of genera	State of diatoms
ZW 1-IV	*Cyclotella choctawhatcheeana – Cyclotella meneghiniana – Stephanodiscus hantzschii - Staurosirella pinnata* DAZ	10–0	58/23	good + some broken valves
ZW 4-IV	*Aulacoseira granulata – Fragilaria heidenii – Stephanodiscus neoastraea* DAZ	30–0	22/11	poor + many broken valves
ZW 8-IV	*Fallacia forcipata – Amphora* spp. *– Cocconeis* spp. *– Fragilaria martyi* DAZ	48–0	59/29	good
ZW 10-IV	*Cyclotella meneghiniana – Fragilaria martyi* DAZ	30–0	67/30	good
ZW 11-IV	*Cyclotella meneghiniana – Staurosira venter – Aulacoseira granulata* DAZ	17–0	26/17	poor
ZW 12-IV	*Fragilaria sopotensis – Opephora guenter-grassii – Amphora* spp. *– Cocconeis* spp. DAZ	52–0	85/29	good + some broken valves
ZW 14-IV	*Opephora mutabilis – Amphora pediculus – Fragilaria martyi – Staurosira* spp. DAZ	30–0	74/38	good + some broken valves
ZW 15-III	*Staurosira venter – Fragilaria martyi – Aulacoseira granulata* DAZ	20–0	19/13	poor

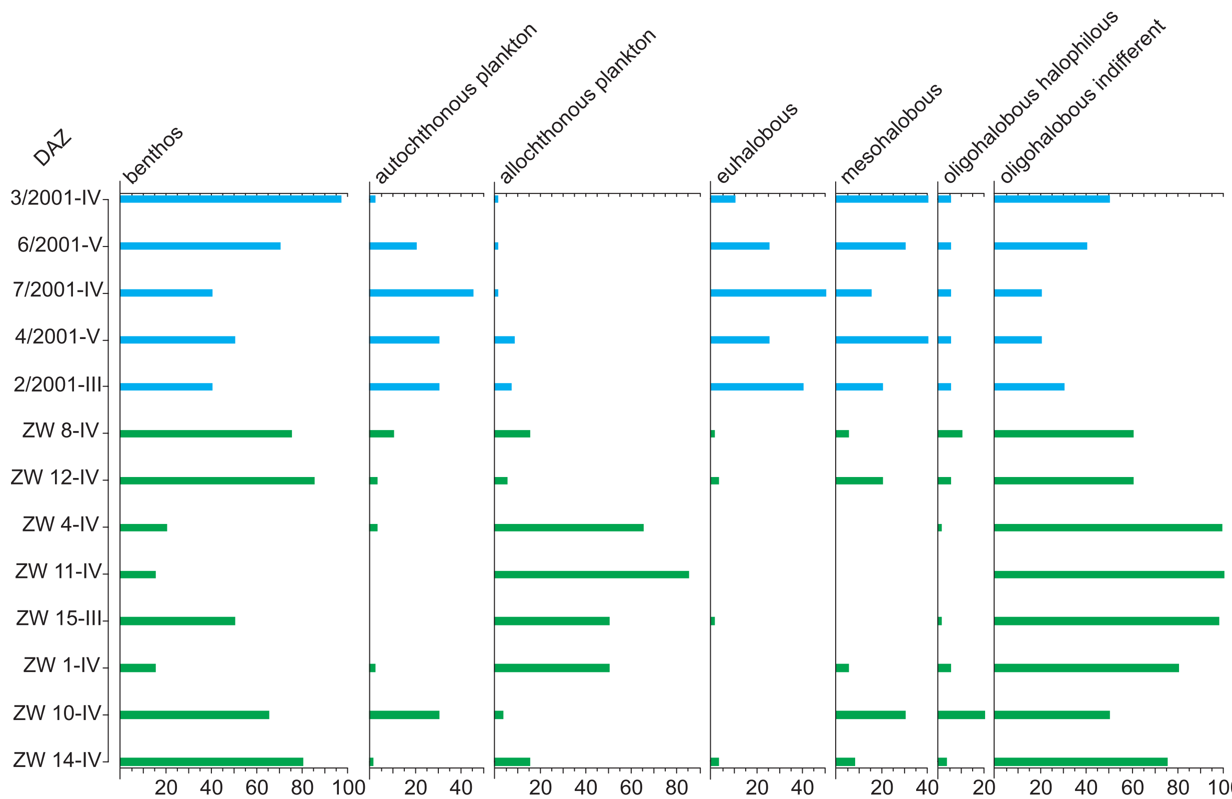

Figure 2

The average percentage content of diatom ecological groups in subbottom sediments of the study area
Gulf of Gdańsk Vistula Lagoon

benthic flora dominated in the assemblages from the first basin, particularly in DAZ 3/2001-IV. In the remaining cores, autochthonous plankton occurs frequently, represented mostly by marine and brackish species. Allochthonous plankton with freshwater and riverine diatoms was observed only in DAZ 2/2001-III and 4/2001-V, in the shallower part of the gulf in the region of the Vistula runoff. Abundant benthic diatoms were found in the coastal zone of the Vistula Lagoon, i.e. near the Vistula Spit (DAZ ZW 8-IV and ZW 12-IV) and in the southern part of the basin (DAZ ZW 10-IV and ZW 14-IV). Riverine planktic diatoms dominated in the central part of the lagoon (DAZ ZW 1-IV, ZW 4-IV, ZW 11-IV, ZW 15-III). Brackish water plankton was observed only near Krynica Morska (DAZ ZW 8-IV) and Tolkmicko (DAZ ZW 10-IV). Freshwater taxa occurred frequently in all diatom assemblages of the Vistula Lagoon.

The Gulf of Gdańsk

The diatom taphocoenose of DAZ 3/2001-IV was strongly dominated by benthic taxa belonging to different salinity groups (Figs 3, 4, Table 2). *Catenula adhaerens* was the main euhalobous species. The group of mesohalobous was formed by e.g. *Cocconeis hauniensis*, *C. scutellum* var. *parva*, *Navicula perminuta*, *Opephora guenter-grassii*, *O. mutabilis*, and *Planothidium delicatulum*. Among the oligohalobous indifferent, *Amphora pediculus*, *Cocconeis neothumensis*, *Cocconeis placentula*, *Karayevia clevei*, *Pseudostaurosira brevistriata* and *Staurosira construens* occurred abundantly. Planktic taxa were observed occasionally and only representatives of *Aulacoseira* reached the relative abundance of 1%.

The clear increase in the abundance of planktic species, preferring marine and brackish water habitats

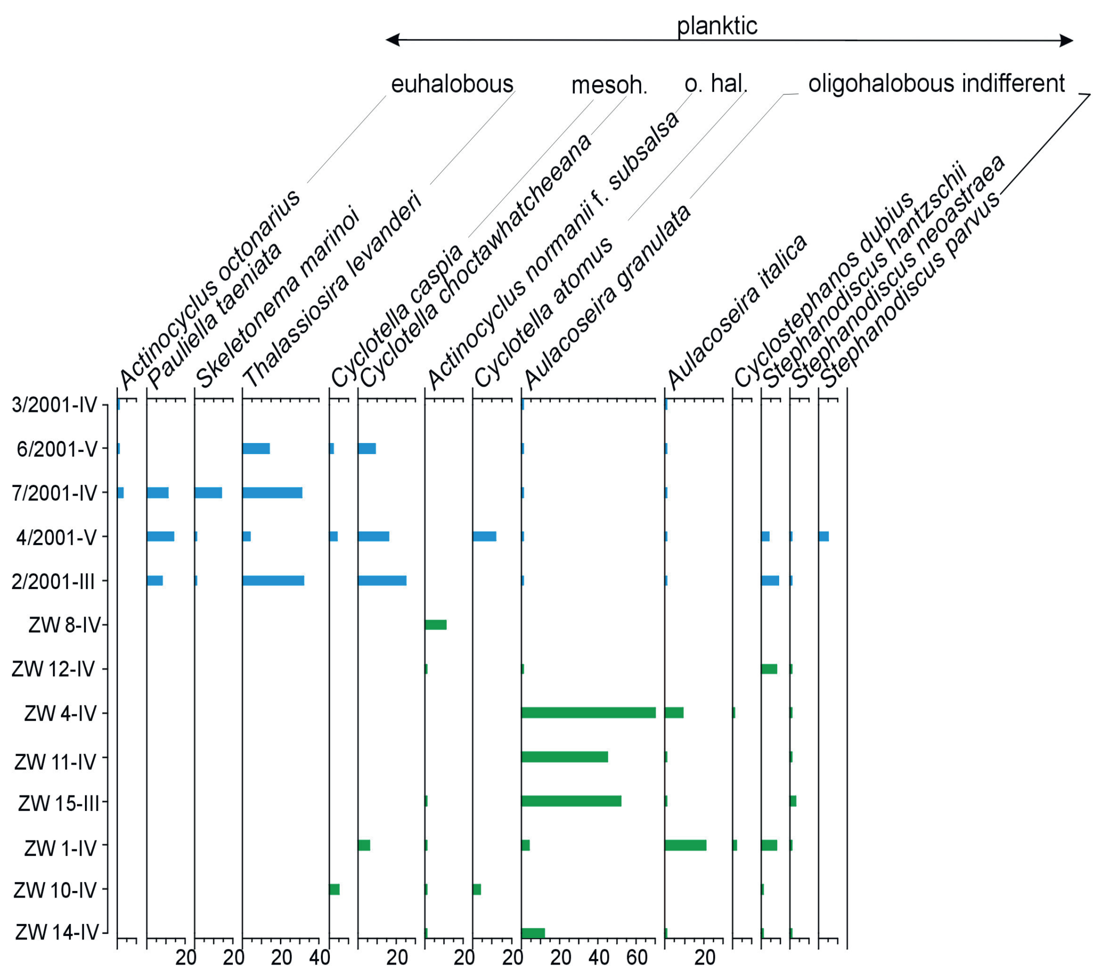

Figure 3

The average percentage content of the main planktic diatoms in subbottom sediments of the study area; mesoh. – mesohalobous, o. hal. – oligohalobous halophilous ▬ Gulf of Gdańsk ▬ Vistula Lagoon

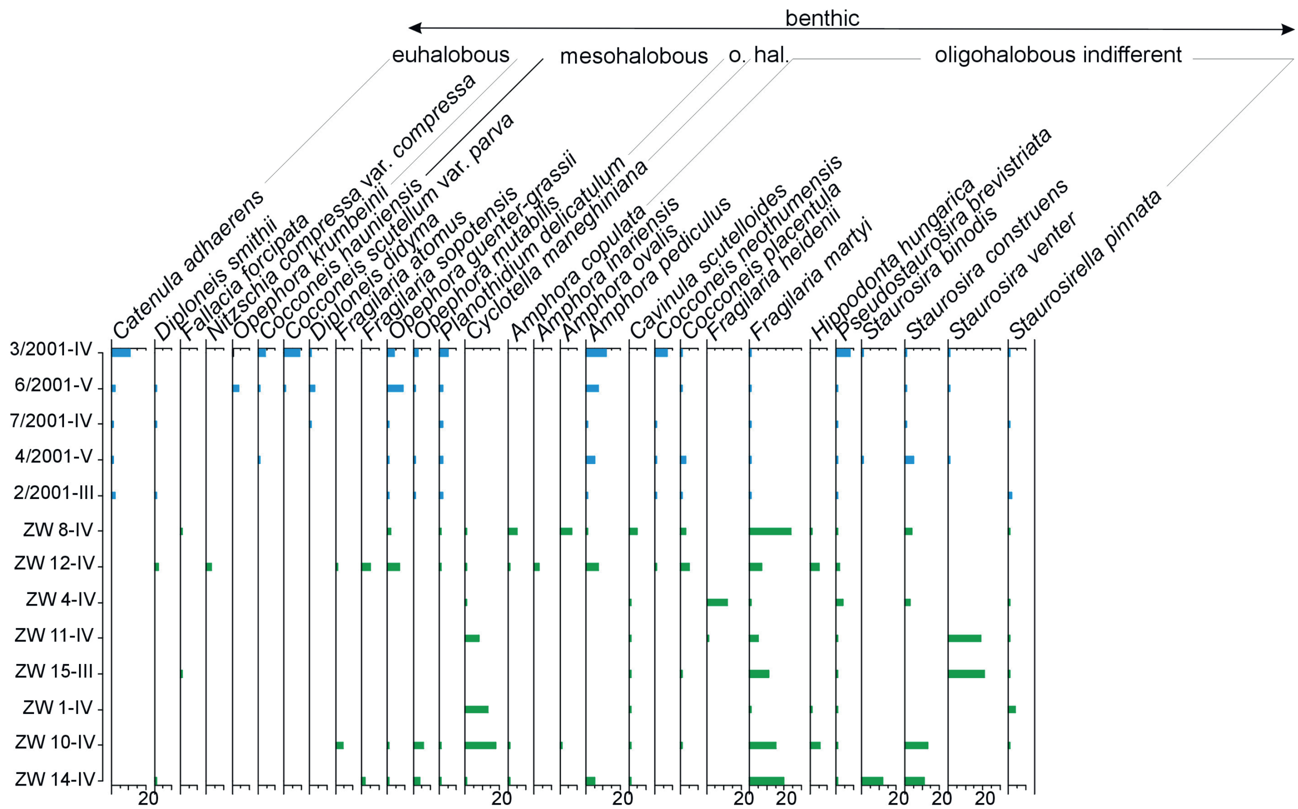

Figure 4

The average percentage content of the main benthic diatoms in subbottom sediments of the study area; o. hal. – oligohalobous halophilous ▬ Gulf of Gdańsk ▬ Vistula Lagoon

was also observed in DAZ 6/2001-V. The former group was represented mostly by *Actinocyclus octonarius*, *Thalassiosira decipiens* and *T. levanderi*, whereas the latter one by *Cyclotella caspia* and *C. choctawhatcheeana*. They were accompanied by freshwater forms, such as *Aulacoseira* spp. and *Stephanodiscus medius*. Benthic diatoms became less frequent toward the upper zone. This change concerned the following taxa: *Amphora pediculus*, *Catenula adhaerens*, *Cocconeis hauniensis*, *C. scutellum* var. *parva*, *Diploneis didyma*, *D. smithii*, *Karayevia bottnica*, *Opephora krumbeinii* and *Planothidium delicatulum*.

A similar change in the composition of diatom species and their frequency was observed in DAZ 7/2001-IV. The benthic group dominated in the lower limit of the zone, including mainly euhalobous species (*Catenula adhaerens*), mesohalobous taxa (*Fragilaria atomus*, *Hyalodiscus scoticus*, *Navicula perminuta*, *Nitzschia constricta*, *Opephora guenter-grassii*, *Planothidium delicatulum*) and oligohalobous (*Amphora inariensis*, *A. pediculus*, *Cocconeis neodiminuta*, *C. neothumensis*, *Nitzschia rosenstockii*, *Pseudostaurosira brevistriata*). At the top of the zone, the above taxa were displaced by marine planktic diatoms. *Actinocyclus octonarius*, *Fragilariopsis cylindrus*, *Pauliella taeniata*, *Skeletonema marinoi* and *Thalassiosira levanderi* were the most important components in the top part of the zone.

The increase in the frequency of planktic forms (up to 60%) was also recorded in DAZ 4/2001-V. This group included marine species such as *Pauliella taeniata*, *Skeletonema marinoi*, *Thalassiosira levanderi* and brackish water taxa such as *Cyclotella caspia* and *C. choctawhatcheeana*. Furthermore, representatives of oligohalobous *C. atomus*, *Stephanodiscus hantzschii* and *S. parvus* were encountered. *Amphora pediculus*, *Catenula adhaerens*, *Cocconeis hauniensis*, *C. neothumensis*, *C. placentula*, *Planothidium delicatulum*, *Pseudostaurosira brevistriata* and *Staurosira construens* were the main components of the benthos. They were accompanied by numerous representatives of *Fragilaria* spp., *Karayevia* spp. and *Opephora* spp.

The most characteristic feature of the assemblage preserved in the subbottom sediments of core 2/2001 is the abundance of the planktic group. Its main components were marine taxa, e.g. *Fragilariopsis* *cylindrus*, *Pauliella taeniata*, *Skeletonema marinoi* and *Thalassiosira levanderi*, brackish water species *Cyclotella choctawhatcheeana*, *Thalassiosira baltica* and freshwater diatoms represented by *Stephanodiscus hantzschii* and *S. neoastraea*. Moreover, another centric species, *Cyclotella meneghiniana* belonging to oligohalobous halophilous showed the same trend. At the same time, the frequency of benthic forms showed the opposite trend. The content of *Planothidium delicatulum*, *Nitzschia rosenstockii*, *Amphora inariensis*, *A. pediculus*, *Cocconeis neothumensis*, *Fragilaria martyi*, *Pseudostaurosira brevistriata* and *Staurosirella pinnata* decreased toward the top of the core. However, the content of *Hyalodiscus scoticus* was stable.

Vistula Lagoon

The taphocoenose DAZ ZW 8-IV was dominated by freshwater benthic diatoms (Figs 3, 4, Table 3), among which *Amphora copulata, A. ovalis, A. pediculus, Cavinula scutelloides, Cocconeis disculus, C. placentula* and its varieties, *Fragilaria martyi* and *Staurosira construens* played the most important role. *Diploneis domblittensis* occurred commonly in the lower part of the zone, whereas *D. parma* was frequent in the upper part. Euhalobous taxa were rare and represented mostly by *Fallacia forcipata*. Mesohalobous forms were observed more frequently. This group was mainly composed of *Opephora guenter-grassii* and *Planothidium delicatulum*. Planktic forms included *Actinocyclus normanii* f. *subsalsa*, belonging to oligohalobous halophilous and *Aulacoseira granulata* and *A. italica*, representing indifferent forms.

Diatoms observed in DAZ ZW 12-IV were dominated by benthic freshwater taxa, however, the content of the remaining halobous groups was generally higher. The major components of the oligohalobous indifferent group were represented by the following taxa: *Amphora copulata, A. inariensis*, *A. pediculus*, *Cocconeis disculus*, *C. neothumensis*, *C. placentula* and its varieties, *Fragilaria martyi*, *Hippodonta hungarica* and *Pseudostaurosira brevistriata.* Diatoms preferring seawater also occurred regularly. *Diploneis smithii* var. *smithii* and *Nitzschia compressa* var. *compressa* were the most important in this group. Brackish water taxa were diverse and numerous. *Fragilaria atomus*, *F. sopotensis*, *Nitzschia levidensis* var. *salinarum* and *Opephora guenter-grassii* were noted particularly frequently. Oligohalobous halophilous forms were represented by benthic (e.g. *Achnanthes lemmermannii*, *Cyclotella meneghiniana*, *Rhoicosphaenia abbreviata*) and planktic taxa (e.g. *Actinocyclus normanii* f. *subsalsa*). Planktic forms were also observed within the indifferent group. The most important was *Stephanodiscus hantzschii*, which was associated with *Aulacoseira* spp. and *S. neoastraea*.

The strong dominance of freshwater planktic species is the most striking feature of the diatom assemblage from DAZ ZW 4-IV. However, the total content of plankton clearly decreased in the upward direction within the core. Its main components were *Aulacoseira granulata* and *A. italica*, associated with *Cyclostephanos dubius* and *Stephanodiscus neoastraea*. Oligohalobous indifferent taxa such as *Fragilaria heidenii*, *F. inflata* var. *istvanffyi*, *F. martyi*, *Pseudostaurosira brevistriata*, *Staurosira construens* and *Staurosirella pinnata* dominated within the group of benthic forms. Marine and brackish water taxa were noted sporadically.

A relatively high content of benthic species was observed in DAZ ZW 11-IV. They were mainly represented by *Fragilaria martyi* and *Staurosira venter*, which were also associated with *Cavinula scutelloides*, *F. heidenii*, *F. inflata* var. *istvanffyi*, *Pseudostaurosira brevistriata* and *Staurosirella pinnata.* Oligohalobous halophilous forms were less frequent, the most abundant of which was *Cyclotella meneghiniana*. *Aulacoseira granulata* was the main component of the plankton. Other forms, e.g. *A. italica* and *Stephanodiscus neoastraea*, occurred rarely. Both euhalobous and mesohalobous taxa were represented by single valves in this zone.

The diatom assemblage observed in DAZ ZW 15-III was also strongly dominated by oligohalobous indifferent taxa. However, the frequency of planktic and benthic diatoms is similar. The former group was represented by *Aulacoseira granulata*, *A. italica* and *Stephanodiscus neoastraea*, while the latter was represented by *Cavinula scutelloides*, *Fragilaria martyi*, *Pseudostaurosira brevistriata*, *Staurosira venter* and *Staurosirella pinnata.* The most important component of the oligohalobous halophilous group was *Actinocyclus normanii* f. *subsalsa*. Marine and brackish water forms were very rare. *Fallacia forcipata* was the main component of the first group.

Planktic forms belonging to various halobous groups in DAZ ZW 1-IV played the most important role. The freshwater species *Aulacoseira granulata*, *A. italica*, *Cyclostephanos dubius* and *Stephanodiscus hantzschii* were very frequent in this zone. The content of mesohalobous *Cyclotella choctawhatcheeana* was smaller. Other planktic taxa such as *Actinocyclus normanii* f. *subsalsa* and *C. atomus* occurred rarely. Benthic forms were also diverse. *Fragilaria martyi* and *Staurosirella pinnata* were often noted among the oligohalobous indifferent forms. These were associated with *Cavinula scutelloides*, *Cocconeis placentula* and its varieties, *Hippodonta hungarica*, *Pseudostaurosira brevistriata*, *Staurosira binodis*, *S. construens* and *S. venter*. Moreover, mesohalobous forms were represented by *Nitzschia compressa* var. *balatonis* and *Planothidium delicatulum*, whereas oligohalobous halophilous taxa were represented by *Cyclotella meneghiniana* and reached a frequency of ca. 20%. Euhalobous forms were found only occasionally.

The diatom community of DAZ ZW 10-IV was dominated by benthic forms. This group was represented by freshwater species, e.g. *Fragilaria martyi*, *Hippodonta hungarica*, *Staurosira binodis*, *S. construens*, *S. venter* and *Staurosirella pinnata*. They co-occurred with halophilous species such as *Cyclotella meneghiniana*, *Rhoicosphaenia abbreviata*, and mesohalobous taxa *Fragilaria atomus*, *F. sopotensis*, *Nitzschia levidensis* var. *salinarum*, *Opephora guenter-grassii*, *O. mutabilis* and *Planothidium delicatulum*. There was a clear increase in the content of this group toward the top of the zone. Planktic forms were generally rarely recorded, and *Cyclotella caspia*, *C. atomus* and *Stephanodiscus hantzschii* were the most abundant among them.

The content of planktic taxa in DAZ ZW 14-IV did not exceed 20%. The main component was *Aulacoseira granulata*, associated with *Stephanodiscus hantzschii* and *S. neoastraea*. *Amphora pediculus*, *Fragilaria martyi* and *Staurosira construens* dominated among the freshwater benthic diatoms. Other species such as *A. copulata, Cavinula scutelloides*, *Fragilaria inflata* var. *istvanffyi* and *Pseudostaurosira brevistriata* were noted less frequently. Mesohalobous forms were usually represented by *Opephora mutabilis*. *Fragilaria sopotensis*, *Opephora guenter-grassii* and *Planothidium delicatulum* were less frequent. Euhalobous forms occurred rarely, and the main taxon was *Diploneis smithii* var. *smithii*. Oligohalobous halophilous taxa were more frequent and these were usually represented by *Achnanthes lemmermannii* and *Cyclotella meneghiniana*.

Discussion

At present, eutrophication of water bodies is an effect of slow natural and fast cultural (anthropogenic) processes, which involve an increase in nutrient concentrations in ecosystems, followed by changes in primary production (HELCOM 2009). In the Baltic Sea, the phosphorus and nitrogen load has increased several times since the turn of the 19th and 20th centuries, whereas phytoplankton production has doubled (Elmgren 1989). Urbanization, agriculture, industrial sewage and soil erosion in the catchment area have become the most important sources of nitrogen and phosphorus load (Rönnberg & Bonsdorf 2004). Biological and ecological effects are particularly pronounced and visible in the coastal zone of the Baltic Sea (e.g. Łysiak-Pastuszak et al. 2004). As a result of reduced light transparency in the water column, the depth of the euphotic layer significantly decreased (Andrén et al. 1999). On the other hand, building dams on rivers significantly reduces the silica load (Humborg et al. 2008). As a result, small centric diatom taxa with poorly silicified cell walls developed well in phytoplankton (Olli et al. 2008). Moreover, indigenous species are replaced by pollution-tolerant taxa, both in planktic and benthic groups. At the same time, the growing toxicity resulting from large cyanobacteria blooms are observed (Mazur-Marzec & Pliński 2009).

The clear human impact on the structure of diatom flora is well documented in the Gulf of Gdańsk. Very specific subfossil, so-called anthropogenic diatom assemblages occurred in the bottom sediments of cores 2/2001, 3/2001, 4/2001, 6/2001 and 7/2001. The most important anthropogenic diatoms are *Cyclostephanos dubius*, *Cyclotella caspia*, *C. choctawhatcheeana*, *Stephanodiscus hantzschii*, *S. medius*, *S. parvus*. All anthropogenic taphocoenoses are generally characterized by a small number of taxa (Table 4).

Some kind of spatial trend can be inferred from the diatom record, although the loss of taxa varies between DAZs. The largest differences, compared to older Post-Littorina diatom assemblage zones, are observed in taphocoenoses preserved in sediments that were retrieved from the eastern part of the study area (i.e. cores 2/2001 and 7/2001). Unfortunately, the youngest sediments of core 1/2001 did not contain diatoms. The number of taxa that disappeared in the youngest deposits is much smaller in the cores collected at the sites located in the north and the west (3/2001, 4/2001, 6/2001). Diatom assemblages affected by human impact did not develop in core 5/2001 drilled in the westernmost part of the study area.

Table 4

Changes in species composition in anthropogenic taphocoenoses of the Gulf of Gdańsk

DAZ	2/2001-III	3/2001-IV	4/2001-V	6/2001-V	7/2001-IV
Number of genera	↓10	↓8	↓7	↓3	↓18
Number of taxa	↓71	↓38	↓30	↓30	↓65

Arrow ↓ indicates a decrease in the number of genera/taxa in relation to the older Post-Littorina diatom flora (Witak 2010).

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This shift indicates that changes in the species composition are associated with the distance from the Vistula River estuary, which is the major source of wastewater in this area.

The increase in the content of eutraphentic benthic forms was recorded in DAZ. An important species, especially in DAZ 2/2001-III, was *Cyclotella meneghiniana*, which is considered one of the most typical indictors of "anthropogenic" assemblages in the study area (Witkowski 1994; Witkowski & Pempkowiak 1995; Stachura & Witkowski 1997; Witak 2000; Leśniewska & Witak 2008; 2011). Its higher content in the near-bottom sediments was also observed in the Szczecin Lagoon and the surrounding area (Andrén 1999; Bąk et al. 2001).

Halophilous benthic species, i.e. *Achnanthes lemmermannii, Epithemia turgida* and *E. sorex*, occurred rarely in the Gulf of Gdańsk. These diatoms were already observed in the subfossil flora (Witkowski 1994; Witkowski & Pempkowiak 1995; Stachura & Witkowski 1997; Witak 2000). *A. lemmermannii* was a component of the anthropogenic assemblage of the Szczecin Lagoon, whereas *Epithemia* spp. were also reported in the Arkona Basin (Andrén et al. 1999; Bąk et al. 2001). Moreover, the frequency of some oligohalobous indifferent taxa, tolerant to polluted environment, increased. Representatives of α-mesosaprobous forms, such as *Amphora copulata*, *A. ovalis* and *A. pediculus,* belonged to this group. These taxa were frequently observed in various parts of the Gulf of Gdańsk (Witkowski 1994; Witkowski & Pempkowiak 1995; Stachura & Witkowski 1997; Witak 2000; Stachura-Suchoples 2006). *Cocconeis placentula* and its varieties, *C. neodiminuta*, *Karayevia clevei*, *Staurosira binodis*, *S. construens* and *S. venter*, which are considered β-mesosaprobous forms, were observed less frequently, but consistently. Other components of this group, e.g. *Cavinula scutelloides* and *Staurosirella pinnata* occurred sporadically. Interestingly, this study of diatoms shows that *Pseudostaurosira brevistriata*, known as an oligosaprobous form, is observed more frequently than *Nitzschia palea*. *N. palea* is considered a species inhabiting strongly polluted waters (Krammer & Lange-Bertalot 1988). The high concentration of the latter species was reported in the wastewater outflows of Rzucewo and Swarzewo in the Puck Lagoon (Witkowski 1994). Most of the aforementioned freshwater taxa were reported in the region of the Oder estuary (Andrén 1999; Bąk et al. 2001). Moreover, *Amphora* spp. and *Cocconeis* spp. were identified in the youngest sediments of the Arkona and Bornholm Basins (Andrén 1999; Andrén et al. 1999). *Catenula adhaerens* reached the highest content in the studied material among the diatom taxa preferring more saline water. This species was considered by Stachura-Suchoples (2001) to be an eutraphentic form, tolerant of high phosphorous concentrations. It occurs permanently in the littoral waters of the Gdańsk Basin (Witak 2000). *Diploneis smithii* and *D. stroemii* do not have such a broad distribution in the bottom sediments of this region, but they are also known from the western part of the Baltic Sea (Andrén 1999; Andrén et al. 1999). *Opephora krumbeinii* was very common in DAZ 6/20010-IV, however, it was also observed in the Gdańsk Deep (Stachura-Suchoples 1998). Some mesohalobous species, such as *Cocconeis hoffmannii*, *C. hauniensis*, *Fragilaria sopotensis* and *Planothidium delicatulum*, preferring waters of higher phosphorous content, also occurred frequently (Stachura & Witkowski 1997; Stachura-Suchoples 2001; Witak 2000). *F. sopotensis,* from this group, tolerates higher concentrations of inorganic nitrogen (Stachura-Suchoples 2001). This species and *P. delicatulum* were described by Bogaczewicz-Adamczak and Dziengo (2003) as eutraphentic forms. According to the latter authors, however, *F. sopotensis* has a higher tolerance to pollution than *P. delicatulum*, because the former belongs to α-mesosaprobous and the latter to β-mesosaprobous forms. Both taxa were also reported from eutrophic waters of the Szczecin Lagoon (Bąk et al. 2001).

A strong human impact on the species composition and abundance of the diatom flora is well documented in the planktic group. The dominance of small-sized species is the most characteristic feature of this group. According to Andrén et al. (1999), this fact can be linked to the decreasing depth of the euphotic zone, which is a result of the eutrophication process. *Cyclotella choctawhatcheeana* and *Thalassiosira levanderi* among the marine and brackish water species constituted the most important components in anthropogenic taphocoenoses. These taxa were abundant in the near-bottom sediments collected from other sites of the Gulf of Gdańsk and the Gdańsk Deep (Witkowski 1994; Witkowski & Pempkowiak 1995; Witak 2000). Maps of the *C. choctawhatcheeana* and *T. levanderi* distribution showed a high frequency below 20 m on the Sopot–Hel transect and in the vicinity of the Vistula Spit (Stachura-Suchoples 1998). These two species were also found in the Szczecin Lagoon, but less frequently (Bąk et al. 2001). The aforementioned species were accompanied by less frequent *Actinocyclus octonarius*, *Cyclotella caspia*, *Thalassiosira baltica* and *T. proschkinae*. These species were also rarely observed in the littoral zone of the Gdańsk Basin (Witkowski 1994; Witak 2000; Stachura-Suchoples 2006). *Actinocyclus octonarius, Cyclotella caspia* and *Thalassiosira baltica* occurred more frequently in the deeper part of the Gdańsk Basin (Witkowski 1994; Stachura-Suchoples 2001). *Thalassiosira baltica* was included in the anthropogenically-affected assemblage in other regions of the Baltic Sea. It was rare in the deposits of the Oder Estuary (Andrén 1999; Bąk et al. 2001). The occurrence of the oligohalobous halophilous representative, *Cyclotella atomus,* is not so widespread in the whole Baltic Sea. However, Stachura-Suchoples (1998) documented its highest frequency near Świbno. Results of studies concerning dominant taxa as bioindicators, preserved in the superficial sediments of the Gulf of Gdańsk, indicate that *C. atomus* and *C. choctawhatcheeana* developed abundantly in waters of higher concentration of phosphorus and inorganic nitrogen (Stachura-Suchoples 2001). On the other hand, the highest abundance of *A. octonarius* and *P. taeniata* was observed in waters with lower concentrations of P and N. *Thalassiosira baltica* and *T. levanderi* are considered tolerant of increased concentrations of both P and N. *T. proschkinae* shows a preference for lower concentrations of inorganic nitrogen, but also the lowest concentrations of phosphorus.

Furthermore, higher content of freshwater taxa was observed in the subfossil plankton preserved in the deposits of the shallower part of the Gulf of Gdańsk (cores 2/2001 and 4/2001). In this group, eutraphentic and pollution-tolerant forms – *Actinocyclus normanii*, *Cyclostephanos dubius*, *Stephanodiscus hantzschii*, *S. medius*, *S. neoastraea* and *S. parvus* – were most important. *S. hantzschii* is recorded as one of the most typical species of wastewaters and an indicator of pollution (Krammer & Lange-Bertalot 1991a). Together with *A. normanii* and *Cyclotella meneghiniana*, it reached the highest abundance in the vicinity of the Vistula mouth (Witkowski 1994; Witkowski & Pempkowiak 1995; Stachura & Witkowski 1997). *Cyclostephanos dubius*, *S. medius* and *S. neoastraea* were less frequent in anthropogenic taphocoenoses of the Gulf of Gdańsk. *S. parvus* was often recorded in the vicinity of the Vistula mouth (Stachura-Suchoples 2001). It was also reported from many sites in the Oder Estuary (Andrén 1999; Bąk et al. 2001). It was associated with other freshwater taxa such as *A. normanii*, *C. dubius* and *S. hantzschii*.

The clear environmental changes associated with human activity are also registered in the Vistula Lagoon. As in the Gulf of Gdańsk, changes in the number of taxa were recorded in the superficial sediments of all DAZs. In this case, however, the influence of this phenomenon is much smaller (Table 5).

Some spatial differences in the extent of this process are observed in the Vistula Lagoon. The number of species is lower in the subsurface sediments in the vicinity of Krynica Morska, whereas the value is higher near Piaski. The species composition was generally slightly poorer in the central and SW parts of the lagoon. A larger number of taxa that disappeared was noted in diatom taphocoenoses of sediments retrieved near Tolkmicko and Frombork. It seems that the difference between the central and southern part of the lagoon resulted from differences in preservation. The diatom floras of DAZ ZW 4-IV, DAZ ZW 11-IV and DAZ ZW 15-III were much less preserved than in DAZ ZW 10-IV and DAZ ZW 14-IV.

The closure of the Nogat river discharge has caused a significant reduction in the abundance of typical freshwater plankton species, e.g. *Aulacoseira granulata* and *A. italica*. Some freshwater benthic taxa, represented by e.g. *Achnanthes nitidiformis*, *A. rupestoides*, *Aneumastus minor*, *A. tusculus*, *Caloneis amphisbaena*, *Cymatopleura solea*, *Diploneis domblittensis*, *D. elliptica*, *D. oblongella*, *Fragilaria exigua*, *Gyrosigma nodiferum*, *Navicula angusta*, *Nitzschia angustatula*, were rarely recorded or even disappeared toward the top core. At the same time, the basin became more saline due to the inflow of seawater through a narrow strait near Baltiyjsk. The intensification of water exchange with the Gulf of Gdańsk is well documented by the presence of diatoms preferring a more saline environment. An increase in the frequency of marine (*Diploneis smithii*, *Fallacia forcipata*, *Nitzschia compressa* var. *compressa*) and brackish taxa (*Fragilaria atomus*, *F. geocollegarum*, *F. schulzii*, *F. sopotensis*, *Nitzschia levidensis* var. *salinarum*, *Navicula perminuta*, *Opephora guenter-grassii*, *Planothidium engelbrechtii*, and *P. robustum*) was observed in the uppermost lagoon sediments. The content of oligohalobous halophilous taxa, such as *A. normanii* f. *subsalsa*, *Cyclotella meneghiniana*, *K. bottnica*, *Placoneis clementis*, *Rhoicosphaenia abbreviata* and *Staurosira punctiformis*, increased toward the top core. Moreover, the following diatoms inhabiting more saline waters

Table 5

Changes in species composition in anthropogenic taphocoenoses of the Vistula Lagoon

DAZ	ZW 1-IV	ZW 10-IV	ZW 14-IV	ZW 4-IV	ZW 11- IV	ZW 15-III	ZW 8- IV	ZW 12- IV
Number of genera	↓3	↓2	↑2	↓2	↑1	↓5	0	↑3
Number taxa	↓7	↓25	↓37	↓9	↓4	↓10	↓9	↑10

Arrow ↓ indicates a decrease in the number of genera/taxa, whereas arrow ↑ indicates an increase in the number of genera/taxa in relation to the older Post-Littorina diatom flora (Witak 2010).

appeared in the subsurface deposits: *Actinocyclus octonarius*, *Achnanthes vistulana*, *Amphora arenicola*, *A. coffeaeformis*, *A. crucifera*, *Caloneis aemula*, *C. crassa*, *Diatoma tenuis*, *Fallacia pygmaea*, *Fragilaria improbula*, *F. parasitica* var. *subconstricta*, *Navicula cancellata*, *N. gregaria*, *Opephora horstiana*, *Thalassiosira visurgis*. The increasing frequency of euhalobous, mesohalobous and halophilous taxa in the near-bottom sediments was also observed by Przybyłowska-Lange (1974) and Bogaczewicz-Adamczak & Miotk (1985).

The abundance of eutraphentic pollution-tolerant taxa was recorded in all diatom taphocoenoses. The benthic flora was dominated by *Amphora pediculus*, *Cavinula scutelloides*, *Cocconeis placentula*, *Fragilaria heidenii*, *Hippodonta hungarica*, *Staurosira binodis*, *S. construens*, *S. venter* and *Staurosirella pinnata.* The abundance of *Amphora* spp., *Cavinula scutelloides*, *Cocconeis* spp., *Fragilaria* spp. *sensu lato* was previously reported from this group (Przybyłowska-Lange 1974; Bogaczewicz-Adamczak & Miotk 1985). Moreover, in a similar way to the subfossil flora of the Gulf of Gdańsk, small planktic taxa of different halobian groups were common and were represented by *Cyclotella atomus*, *C. caspia*, *C. choctawhatcheeana*, *Cyclostephanos dubius* and *Stephanodiscus hantzschii*. The distribution of the latter species, belonging to the polysaprobous group, indicates that the process of environmental degradation is most intensive in the SW part of the lagoon (DAZ ZW 1-IV) and in the vicinity of Piaski (DAZ ZW 12-IV). The degraded water quality is obviously related to the urbanization of Elbląg in the first case. This phenomenon may be associated with the transport of pollution along the Vistula Spit from the Russian part of the basin or with the inefficiency of the sewage treatment plant in Piaski in the second case. On the other hand, the condition of the environment near Krynica Morska, Tolkmicko and Frombork is probably better. The abundance of oligosaprobous species such as *Fragilaria martyi* associated with *Pseudostaurosira brevistriata* can be indicative of the lower pollution. Furthermore, other indicators of clean waters such as *Achnanthes oblongella, Caloneis lauta, Diploneis oblongella, D. parma* were observed in the sediments collected from the vicinity of Krynica Morska.

Conclusions

The environmental change associated with the progressive anthropopressure was registered in the near-bottom sediments of the Gulf of Gdańsk and the Vistula Lagoon. The anthropogenic diatom assemblage of the Gulf of Gdańsk was characterized by a significant decrease in the floristic diversity, the larger number and abundance of eutraphentic and pollution-tolerant taxa, representing both benthic and small-sized planktic forms. The degree of changes in the structure of subfossil assemblages is directly related to the distance from the mouth of the Vistula River. The process of intense eutrophication is also recorded in the Vistula Lagoon. Due to the local factors, the SW and NE regions of the Polish part of the basin are the most polluted ones. The strong reduction in the Nogat river water inflow caused a more intense input of the open sea waters and, as a consequence, the lagoon became more saline. More intense exchange with the Baltic Sea could contribute to the improvement of the environmental condition of the Vistula Lagoon.

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