Response of the Diatom Flora of the Hel Peninsula Vicinity, Puck Bay, Baltic Sea, to Anthropopressure

Dominika Hetko 1, Jarosław Pedzinski 1, Malgorzata Witak 1

1 Institute of Oceanography, University of Gdańsk, al. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland
malgorzata.witak@ug.edu.pl

Abstract. The subject of this study was the diatom taphocoenoses preserved in the surface sediments of the northern part of Puck Bay, southern Baltic Sea. Three subbotom sedimentary cores ZP1/0518, ZP2/0518 and ZP3/0414 collected in the vicinity of the Hel Peninsula from a water depth of 65 m, 47 m and 50.2 m, respectively were analyzed with respect to diatom flora. Over 500 valves of diatoms were counted in each sample in order to estimate the percentage abundance of particular taxa. Habitat, salinity, trophy and saprobity requirements of all identified species were established according to literature. The percentage content of distinguished ecological groups was counted in each core. Diatomological analysis indicates that the diatom flora observed in muddy and silty sediments of the study area was generally abundant, taxonomically diverse and well preserved. However, some valves were mechanically broken or/and chemically destroyed. In all cores anthropogenic assemblage with small sized planktic diatoms tolerating higher nutrient and pollution concentration as well as lower transparency of water column predominated. The most important components were euhalobous species Thalassiosira levanderi and mesohalobous one Cyclotella choctawhatcheeana. Both species achieved the highest frequency (up to ca. 80% and 38%, respectively) in core ZP1/0518. Other eutraphentic, α/β mesosaprobous taxa belonged to oligohalobous halophilous (Actinocyclus normanii f. subsalsa, Cyclotella atomus, C. meneghiniana) and oligohalobous indifferent (A. normanii f. normanii, Cyclosphatehos dubius, Aulacoseira spp.) were observed rarely. Benthos was also dominated by diatoms preferring the high content of nutrients and organic matter. This group was represented by marine/brackish-water taxa (i.e. Catenula adhaerens, Cocconeis hauniensis, C. scutellum, Diploneis didyma, D. smithii, D. stroemii, Opephora krumbeinii) and freshwater ones (i.e. Amphora copulata, A. pediculus, Cocconeis neodiminuta, C. neothumensis). Our results clearly indicate the apparent human impact on the structure of the diatom flora in the northern part of the Puck Bay. At least two sources of anthropopressure can be determined in the vicinity of Hel Peninsula i.e. (1) at a local scale harbor in Hel city and municipal sewage linked to development of tourism, and (2) at a regional scale the Vistula River waters, which is the major source of pollution in the Gulf of Gdańsk.

1. Introduction
Cultural eutrophication resulted in the high concentration of nutrients (nitrogen and phosphorus) as well as saprobication connected to increase input of organic matter and pollutants are the most urgent ecological problem. Anthropopressure is particularly visible in gulfs and bays of southern Baltic Sea, relatively small and shallow with limited water exchange. The main sources of eutrophication and saprobication are agriculture, industries, municipal sewage, river run-off, erosion and atmospheric...
deposition [1]. In case of Puck Bay, being the western part of the Gulf of Gdańsk, human activities increased since the Middle Ages [2]. However, urbanization, 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, mostly by Vistula River, has resulted in environmental degradation of the study area [3]. The content of nitrates increased five times, whereas the content of phosphorus – two times. Apart of regional sources, in the vicinity of the Hel Peninsula important role plays local sources of pollutants linked to development of cities, and of harbor in Hel city as well as intensive tourism.

These environmental changes are well recorded in the diatom flora. Diatoms are sensitive to numerous environmental variables. Amongst others their development is influenced by salinity, concentration of nutrients and the content of organic matter [4], [5]. Therefore, the diatom record reflects water quality. Although the subfossil diatom flora preserved in near-bottom sediments of Puck Bay were described by many authors [6], [7], [8], [9], [10] our knowledge on the relationship between the hydrological regime, particularly water quality and structure of diatom taphocoenoses is still under discussion.

2. Physiographic setting of the study area
The study area is located in the Puck Bay, which constitutes the western part of the Gulf of Gdańsk, the open bay of the southern Baltic Sea. Puck Bay, a semi open area covering 359.2 km², is separated from the open Baltic Sea by a long scythe-shaped spit called the Hel Peninsula (figure 1). Its eastern border constitutes the conventional line connecting the tip of the peninsula and the Orłowo Headland in Gdynia [11]. Its morphogenetic features vary distinctly throughout the bay. The basin includes the eastern inner part, named the Puck Lagoon or Little Puck Bay, and the western outer part with a wide connection to the Gulf of Gdańsk. The Puck Lagoon is a very shallow basin, with an average depth of 3.13 m, covering an area of 102.7 km². The lagoon is separated by a partly submerged sand barrier, i.e. the Seagull Reef, from the deeper Outer Puck Bay, and another very narrow structure, the Rewa Sandbar. The much deeper Outer Puck Bay, covering an area of 256.5 km², constitutes ca. 70% of the whole bay. Its mean depth has been estimated at 20.5 m [12]. The seabed slopes towards the northeast, reaching a depth of 54 m near the end of Hel Peninsula. This part of the reservoir encompasses 94% of water volume because of the greater depth. Hel Peninsula is a 35 km long natural sand bar barrier, which is notable in having the thickest (up to 100 m) Holocene sediments among those recorded in Poland [13].

The hydrological regime in the Outer Puck Bay area is associated with the depth, climatic conditions, inflow of saline waters from the Gulf of Gdańsk and the freshwater discharge from the surrounding coastal areas. The hydrological regime in the deeper part of the Gulf of Gdańsk is controlled by the strong runoff from the Vistula mouth. Easterly, ENE and ESE winds cause the Vistula runoff to incline in a westward direction [14]. Winds from the SW, S and SE directions markedly increase the distance of spreading of Vistula waters. The impact of other rivers e.g. Kacza, Oliwski Stream which discharge into the Outer Puck Bay is limited to the proximity of their outlets [15].

The thermal state is strongly influenced by seasonal changes in air temperatures. An average annual temperature of the surface water is higher than air temperature. In the Outer Puck Bay temperature difference amounts to 1.4°C [16]. The average annual temperature amounts to 9.13°C, whereas in the coastal zone it is 8.7°C. During the winter period the temperature of the surface layer ranged from 1 to 2°C [16]. The minimal average monthly temperature 1.29°C is measured in February. The bottom water is warmer, its temperature achieves 2.5–3°C. Vertical stratification appears at the turn of May and June in the deeper part of the Puck Bay and an increase in the surface water temperature from 4.5 to 12.4°C is observed. During springtime, the bottom waters are still cold.
(3–4°C). The temperature of these waters in the summer period increases to 8°C, whereas the temperature of the surface layer achieves 18.6°C in August - the maximum value for this area.

Figure 1. Location of the studied sediment cores. (RS-Rewa Sanbar, SR-Seagull Reef)

The salinity of the Outer Puck Bay is dependent on the discharge of riverine waters and an inflow of marine water masses. An average yearly salinity of the surface water oscillates between 7.25 psu in the vicinity of the Hel Peninsula tip and 7.21 near the harbour of Gdynia [16]. The maximum salinity (7.67–7.94 psu) caused by thermohaline convection and intensive wind mixing in the Outer Puck Bay occurs during the winter [17]. Salinity increases to ca. 8.2 psu close to the bottom during that time. The salinity drops to its lowest value (6.70–6.90 psu) due to input of meltwater in springtime. The salinity increases to 7.50 psu below a depth of 2 m. The surface water salinity ranged from 7.62 to 6.83 psu during summer, whereas the bottom layer value exceeded 8.40 psu.

3. Material and methods
The material studied consists of three sediment cores 28 – 94 cm long taken from the northern part of Puck Bay, southern Baltic Sea. Sediments with undisturbed structure were obtained from the water depth of 47 to 65 m b.s.l. along the outer part of Hel Peninsula (table 1). Cores ZP3/0414 was retrieved by means of a Niemistö corer during a cruise of ORP “Heweliusz” in April 2014. Rest of the cores, ZP1/0518 and ZP2/0518, were collected with a Rumohr-Lot corer from r/v “Oceanograf” in May 2018. Both cruises were organized by Institute of Oceanography, University of Gdańsk.
Table 1. Parameters of the analysed cores.

| Core       | φ          | λ          | Core length [cm] | Water depth [m] | Number of species | Number of genera |
|------------|------------|------------|------------------|-----------------|-------------------|------------------|
| ZP1/0518   | 54°34.32 N | 18°46.8 E  | 79               | 65.0            | 82                | 34               |
| ZP2/0519   | 54°36.25 N | 18°41.56 E | 94               | 47.0            | 96                | 42               |
| ZP3/0414   | 54°35.24 N | 18°44.48 E | 28               | 50.2            | 138               | 48               |

aNumber of species, subspecies, varieties and forms.

Sediment samples were taken in 1 – 5 cm intervals. In order to prepare a permanent slide from each sample, they were treated according to standard method [18]. The samples were treated with 10 % HCl to remove calcium carbonate and washed several times with distilled water. The organic matter was digested using 30% H2O2, after which mineral matter was removed by decantation. Permanent diatom slides were mounted in Naphrax® (refractive index nD=1.73). Qualitative diatom analysis was carried out with Nikon ECLIPSE 400 microscope at a magnification of × 1000, using an oil immersion objective. Over 500 valves of diatoms were counted in each sample according to Schrader and Gersonde [19] procedure and percentage content of all noted taxa was estimated. The diatoms identified were classified with respect to their ecological preferences. The diatoms were divided into groups according to their biotype requirements; planktic and benthic groups were distinguished [20]. On the basis of Kolbe’s [21] halobian system they were grouped into: euhalobous (marine species), mesohalobous (brackish-water), oligohalobous (freshwater) halophilous and indifferent. Moreover, trophic system with eutraphentic, eu-mesotraphentic, mesotraphentic, oligotraphentic and dysotraphentic taxa [22] was used. Finally, the diatom flora were divided according to saprobic preferences [23] and polisaprobous, α-mesosaprobous, mesosaprobous, oligosaprobous, xenosaprobous diatoms were distinguished in each sample. Next, the percentage content of all ecological groups were counted in the cores. The taxonomy and autecology was based on Omnidia 6.0.8 software.

4. Results and discussions

Progressive anthropopressure manifested by the visible increase of concentration of phosphorus and inorganic nitrogen (called as a cultural eutrophication) and of organic matter and pollutants (known as saprobication) has resulted in structural changes in plant and animal communities [24]. This environmental changes are well registered in diatom communities. Therefore, human impact on trophic and saprobic conditions and water quality in the past is recorded in subfossil diatom flora preserved in sediments.

Diatom taphocoenoses of all sediment cores were abundant. The state of preservation was generally good, however in all samples an admixture of some valves were mechanically broken or/and chemically destroyed. Moreover, diatom detritus was observed, particularly often in the core ZP1/0518 located in the open part of the study area, where hydrodynamics are the highest. A total of 215 species, subspecies, varieties, and forms belonging to 49 genera were recorded in the whole material. The diatom assemblages were dominated by 46 planktic taxa. However, the benthic forms were more diverse (169 taxa).

Mass occurrence of diatom plankton was observed in the core ZP1/0518 (figure 2). Its frequency increased from ca 60% at the bottom to ca 97% at the top of the core. In other cores the abundance reached ca 80%. The distribution of planktic taxa is probably connected to the water depth. Towards the east, the basin become deeper and the content of diatom plankton increases. This tendency is also pronounced in the frequency within the salinity groups. The highest percentage content of euhalobous
(preferring marine conditions) was noted in ZP1/0518. In up core direction its content increased from ca 45 to 80%. In ZP2/0518 and ZP3/0414 marine diatoms were rarely noted (up to ca 60 and 55%, respectively).

In all taphocoenoses marine planktic species *Thalassiosira levanderi* played a key role and constituted the most important component. Its maximum frequency were noted in ZP1/0518, ca 25% at the bottom and ca 78% in the upper part of the record. In ZP2/0518 the content of *T. levanderi* ranged ca 4-55% (figure 3), whereas in ZP3/0414 the value fluctuated from 11 to 31% (figure 4). As an eutraphentic and α-mesosaprobic species, *T. levanderi* is known from marine basin reached in nutrients and organic matter. This taxon was observed in many stations of the Gulf of Gdańsk from the vicinity of the Vistula Spit and Vistula River mouth [25] to the Gdańsk Deep [7], [26] via different parts of the open gulf [9], [27] including the Outer Puck Bay [28], [29]. To group of pollution-tolerant taxa well developed in eutrophic conditions belongs also brackish-water species *Cyclotella choctawhatcheeana*. Although its content was generally lower in all cores, but the distribution is similar to *T. levanderi*. The highest frequency (ca 6-38%) the species attained in ZP1/0518. Less percentage content was observed in ZP2/0518 (ca 2-20, with exception of the top – 53%) and in ZP3/0414 (ca 5-18%). *C. choctawhatcheeana* occurred abundantly in the whole Gulf of Gdańsk [7], [9], [29], [27]. Amongst the group of planktic species well tolerated the higher concentration of phosphorus and inorganic nitrogen as well as of organic matter were also observed freshwater diatoms. They were represented by oligohalobous halophilous (*Actinocyclus normanii* f. *subsalsa*, *Cyclotella atomus*, *C. meneghiniana*) and oligohalobous indifferent (*A. normanii* f. *normanii*, *Aulacoseira* spp., *Cyclostephanos dubius*). However, because of water salinity in the vicinity of the Hel Peninsula these diatoms were noted rare, even sporadically.

![Diatom record of the cores ZP1/0518](image)

**Figure 2.** Diatom record of the cores ZP1/0518. E-meso – Eu-mesotraphentic, Oligo – Oligotraphentic, Un – Unknown.
Figure 3. Diatom record of the cores ZP2/0518. E-meso – Eu-mesotraphentic, Oligo – Oligotraphentic, Un – Unknown.

Figure 4. Diatom record of the cores ZP3/0414. E-meso – Eu-mesotraphentic, Oligo – Oligotraphentic, Un – Unknown.
All taxa mentioned above belongs to so-called “anthropogenic assemblage” recorded in many diatom studies from the Gulf of Gdańsk [7], [25], [26] including the outer part of the Puck Bay [28], [9], [10], [29], [27]. Apart of trophic and saprobic preferences the characteristic feature of anthropogenic species is small-sized valves. According to Andrén et al. [30] this fact can be linked to lower transparency in the water column which is result of the eutrophicication process. Intensive algal blooms reduced the light condition and diminished depth of the euphotic zone.

The important components of all diatom taphocoenoses were also unidentified resting spores of genus Chaetoceros. The abundance of Chaetoceros spp. RS in ZP1/0518 and ZP2/0518 reached ca 40 %, whereas in ZP3/0414 20%. The lack or very low content of Chaetoceros vegetative cells in the material could be ascribed to the dissolution of their weakly silicified frustules during settling through the water column. Heavily silicified resting spores have a much higher preservation potential and therefore these occur more frequently in diatom taphocoenoses. These taxa have a relatively high sinking rate; thus the impact of chemical processes is limited. Formation of resting stages is linked to the last stages of the biological succession during unfavorable conditions [31]. Diatom records from different parts of the Baltic Sea lead to the conclusion that changes of environmental conditions trigger the formation of spores [7], [32], [28], [33]. According to some authors the abundance of these in the fossil record could be related to nutrient supply to the basin [32], [9]. An increasing accessibility of nutrients stimulates the production of Chaetoceros vegetative cells, which in consequence, produce more resting spores.

In all diatom taphocoenoses benthic forms were also identified. In cores ZP1/0518 and ZP2/0515 their summary content visible decreased, from ca 36 to 8% and from 44 to 19%, respectively. In the last core the content of benthos fluctuated between 45 and 35%. This group is represented by species preferring marine, brackish-water and freshwater habitats, however most of these taxa well tolerate higher content of biogenic nutrients. Amongst eutrophic benthic species Catenula adhaerens, Cocconeis haunensis, C. scutellum, Diploneis didyma, D. smithii, D. stroemii, Fragilaria atomus, F. spongiosa, Opephora krumbeinii, O. mutabilis, Planothyridium delicatulum belonged to euhalobous or mesohalobous were recorded in the material studied. Fragilaria schulzii and Navicula perminuta represented brackish-water eu-mesotrophic taxa also occurred. Moreover, many freshwater diatoms (oligohalobous halophilous and indifferent) well developed in eutrophic/eu-mesotrophic conditions were noted. This group is represented mostly by Achnanthes lemmermannii, Amphora copulata, A. pediculus, Cocconeis neodiminuta, C. neothumensis, Epithemia turgida, Fragilaria martii, Pseudostaurosira brevistriata, Staurosira binodis and S. venter. All these taxa were described from the shallow littoral zone of the Gulf Gdańsk [7], [9], [10], [27] including Puck Lagoon [8] and Outer Puck Bay [28], [29]. According to Witak [9] they belong to benthic anthropogenic assemblage. However, noteworthy is their occurrence in relatively deep waters, at the depth of 47-65m. Because of the high content of nutrients and organic matter in the northern part of Outer Puck Bay, the transparency of water column is rather low and the euphotic zone is limited. Therefore, we believe, that most of benthic diatoms, particularly recorded in sediments of ZP1/0518 constitute allochthonous elements transported from the coastal zone of the Hel Peninsula. On the other hand, predominance of eutrophic and eu-mesotrophic diatoms represented α- or β-mesosaprobous provides evidence of high trophy and saprophy in the shallower part of the Outer Puck Bay.

5. Conclusions
At least two sources of anthropopressure can be determined in the vicinity of Hel Peninsula. At a local scale harbor in Hel city and municipal sewage linked to development of tourism, and at a regional scale the Vistula River waters, which is the major source of pollution in the Gulf of Gdańsk. The progressive anthropopressure was well registered in diatom taphocoenoses of near-bottom sediments of northern part of the Outer Puck Bay. The high content of biogenic nutrients as well as organic matter caused the development of anthropogenic diatom assemblage. This group is characterized by
the abundance of small-sized eutrophic and pollution-tolerant plankton habiting the algal blooms diminishing euphotic zone. The occurrence of benthic diatoms preferring high trophy and saproby is related to intensive transport from the nutrient rich coastal zone of the Hel Peninsula.

Acknowledgment(s)
The authors are very grateful to Associate Professor Dorota Burska, Institute of Oceanography, University of Gdańsk, for providing the core ZP3/0414 for this study.

References
[1] P. Wassmann and K. Olli, “Drainage basin nutrient inputs and eutrophication: an integrated approach,” ’Norway: University of Tromsø, 2004.
[2] L. Starkel, “Historia Doliny Wisły od ostatniego zlodowacenia [History of the Vistula River valley since the last glaciation],” Monografia Instytutu Geografii I Przestrzennego Zagospodarowania im. S. Leszczyńskiego, [in Polish], pp. 263. PAN, 2001.
[3] M. Pliński, “Kondyjca ekologiczna Bałtyku [Ecological condition of the Baltic],” In: Zanieczyszczenie i odnowa Zatoki Gdańskiej [The pollution and renewal of the Gulf of Gdańsk], (J. Błażejewski & Schuller D., eds), [in Polish], 17-21, 1991.
[4] F.E. Round, R.M. Crawford and D.G. Mann, “The diatoms. Biology and morphology of the genera,” Cambridge University Press, Cambridge. 747 pp, 1990.
[5] R. W. Battarbee, “Palaeolimnological approaches to climate change, with special regard to the biological record,” Quaternary Science Reviews, 19, 107–124, 2000.
[6] M. Pliński, “Kondyjca ekologiczna Bałtyku [Ecological condition of the Baltic],” In: Zanieczyszczenie i odnowa Zatoki Gdańskiej [The pollution and renewal of the Gulf of Gdańsk], (J. Błażejewski & Schuller D., eds), [in Polish], 17-21, 1991.
[7] A. Witkowski, “Recent and fossil diatom flora of the Gulf of Gdańsk, Southern Baltic Sea,” Bibliotheca Diatomologica, 28, 1-313, 1994.
[8] M. Witak, “Postglacial history of the development of the Puck Lagoon (The Gulf of Gdańsk, Baltic Sea) based on the diatom flora,” In: Diatom Monographs 2 (A. Witkowski, ed), 1-173. A. R. G. Gantner Verlag K. G, Ruggell, 2002.
[9] M. Witak, “Application of diatom biofacies in reconstructing the evolution of sedimentary basins. Records from southern Baltic Sea differentiated by the extent of Holocene marine transgressions and human impact,” [w:] A. Witkowski (red.), Diatom Monographs 12, A.R.G. Gantner Verlag, K. G. Ruggell, 2010.
[10] M. Witak, “A review of the diatoms research of the Gulf of Gdańsk and Vistula Lagoon (southern Baltic Sea),” Oceanological and Hydrobiological Studies 42, 3, 336-346, 2013.
[11] A. Majewski, “Ogólna charakterystyka morfometryczna Zatoki Gdańskiej [Morphometric characteristic of the Gulf of Gdańsk],” In: Zatoka Gdańska [The Gulf of Gdańsk]. (A. Majewski ed.), [in Polish], 10-15. Wydawnictwa Geologiczne, Warszawa, 1990.
[12] J. Nowacki, “Morphometry Zatoki [Morphometry of the bay],” In: Zatoka Pucka [The Puck Bay]. (K. Korzeniewski, red.), [in Polish], 71-79. Fundacja Rozwoju Uniwersytetu Gdańskiego, 1993b.
[13] S. Uścinowicz, “A relative sea-level curve for the Polish Southern Baltic Sea,” Quaternary International, 145-146, 86 – 105, 2006.
[14] V.A. Kravtsov, M.D. Kravchishina, N.A. Pankratova and A.F. Kuleshov, “The recent sedimentation processes in the Curonian and Vistula Lagoons,” In: Geology of the Gdańsk Basin, Baltic Sea. (E.M. Emelyanov ed.), 352-367. Yantarny Skaz, Kaliningrad, 2002a.
[15] A. Majewski, “Charakterystyka hydrologiczna estuarowych wód u polskiego wybrzeża [Hydrology of the estuaries of the Polish coast],” Prace PIHM, [in Polish], 105, 3-40, 1972.
[16] J. Nowacki, “Termika, zasolenie i gęstość wody [Thermal state, salinity and water density],” In: Zatoka Pucka [The Puck Bay]. (K. Korzeniewski, red.), [in Polish], 79-112. Fundacja Rozwoju Uniwersytetu Gdańskiego, 1993c.
[17] J. Nowacki, “Cyrkulacja i wymiana wód [The circulation and water exchange].” In: Zatoka Pucka [The Puck Bay]. (K. Korzeniewski, ed.), [in Polish], 181-206. Fundacja Rozwoju Uniwersytetu Gdańskiego, 1993a.

[18] R.W. Battarbee, “Diatom analysis.” In: Handbook of Holocene Palaeoecology and Palaeohydrology, (B.E. Berglund, ed.), 527-570. London, John Wiley and sons. Ltd., 1986.

[19] H. Schrader and R. Gersonde, “Diatoms and silicoflagellates in the eight meters sections of the lower Pleistocene at Capo Rossello,” Utrecht Micropaleontological Bulletin, 17, 129-176, 1978.

[20] F.E. Round, “The ecology of algae,” Cambridge University Press, Cambridge. 653 pp, 1981.

[21] R.W. Kolbe, “Zur Ökologie, Morphologie, und Systematik der Brackwasser-Diatomeen,” Pflanzenforschung. Jena. 7. 146 pp, 1927.

[22] E. Neumann, “Grundzüge der regionalen Limnologie,” In: Die Binnengewässer. Band 11.(A. Thienemann ed.). E. Schweizerbart’sche Verlagbuchhandlung, Stuttgart, 1932.

[23] R. Kolkwitz, and M. Marsson, “Ökologie der pflanzlichen Saprobien,” Berichte der Deutschen Botanischen Gesellschaft, 26a, 505-519, 1980.

[24] R. Howarth, D. Anderson, J. Cloern, C. Elfring, C. Hopkins, B. Lapointe, T. Malone, K. Mcglathery, A. Sharpley and D. Walker, “Nutrient pollution of coastal rivers, bays, and seas,” Issues in Ecology, 7, 1-15, 2000.

[25] K. Stachura-Suchoples, “The last 200 years as revealed by diatom analysis – preliminary results,” Proceedings of the 15th International Diatom Symposium, 209-226, 1998.

[26] K. Stachura-Suchoples, “Okrzemki jako wskaźniki oddziaływania Wisły na paleoekologię Zatoki Gdańskiej [Diatoms as indicators of Vistula River influence on the paleoecology of the Gulf of Gdańsk],” Unpublished, PhD Thesis; University of Gdańsk [in Polish]: 1-172, 1999.

[27] M. Witak, J. Pędziński, 2018, “The diatom record of progressive anthropopressure in the Gulf of Gdańsk and the Vistula Lagoon,” Oceanological and Hydrobiological Studies 47(2), 167-180, 2018.

[28] M. Witak, “A diatom record of Late Holocene environmental changes in the Gulf of Gdańsk,” Oceanological Studies, 19 (2), 57-74, 2000.

[29] M. Leśniewska, M. Witak, “Diatoms as indicators of eutrophication in the western part of the Gulf of Gdańsk, Baltic Sea,” Oceanological and Hydrobiological Studies 40, 1, 68-81, 2011.

[30] E. Andrén, G. Shimmield and T. Brand, “Environmental changes of the last three centuries indicated by siliceous microfossil records from the southwestern Baltic Sea’’ The Holocene, 9 (1), 25-38,1999.

[31] M.R. Mcquoid, A.Godhe and K. Nordberg, “Viability of phytoplankton resting stages in the sediments of a coastal Swedish fjord,” European Journal of Phycololy, 37, 191-201, 2002.

[32] K. Stachura-Suchoples, A. Zgrundo and A. Witkowski, “Occurrence and significance of Chaetoceros (Bacillariophyceae) resting spores in the Holocene sediments of the Baltic Sea,” Oceanological Studies, 2, 87-92,1998.

[33] M. Witak, J. Dunder, M. Leśniewska, “Chaetoceros resting spores as indicators of Holocene paleoenvironmental changes of the Gulf of Gdańsk, southern Baltic Sea,” Oceanological and Hydrobiological Studies 40, 4, 21-29, 2011.