

Benthic diatoms of the Vistula River estuary (Northern Poland): Seasonality, substrata preferences, and the influence of water chemistry

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SUMMARY

Seasonal studies of water bodies in separate branches of the Vistula River estuary in Northern Poland were conducted over 30 months from May 2005 to October 2007. Diatom samples were collected from different substrata from two sites located in the river mouth, which has physical characteristics as a result of a complex interplay of natural and human influences that have taken place over the last 100+ years. The diatom flora growing on hard surfaces near the river banks such as sand, muddy sand, rocks, macroscopic green algae and/or vascular aquatic plants was recorded. All diatom taxa collected were distinguished based on their morphological features using light (LM) and scanning electron microscopy (SEM). A total of 187 species belonging to 61 genera were identified. A canonical correspondence analysis indicated that the diatom assemblages were definitely associated with salinity as well as nutrient concentrations and substratum type. During the study, malformations of diatom valves were observed in 48% of the microphytobenthos samples. Abnormal outline morphology and ornamentation deformities in several individuals of nine different species were recorded, which were mainly in epilithic and epiphytic communities collected from spring to autumn.

Key words: biodiversity, deformation, diatom, estuary, nutrient, salinity, substrate, Vistula River.

INTRODUCTION

The Vistula River is one of the major European rivers, which runs entirely through Poland and flows into the Gulf of Gdansk (southern Baltic Sea). It is 1074 km long and drains an area of 194 308 km² (Majewski 1990). The drainage basin, with a population of over 22.9 million people (about 60% of Poland's population), has several large urban centers and receives increasing media attention (especially due to its dete-

riorating environmental condition). Every year, a considerable quantity of treated sewage as well as treated and untreated industrial waste flows into the river. Although, in the last few years the quantity of sewage reaching the Vistula River has decreased (Buszewski *et al.* 2005); there are still 15 municipal, industrial and agricultural sites located in the area of the Vistula River basin. They are presently on the list of Baltic Hot Spots (another 15 has been deleted from the list before December 2009) (*List of JCP Hot Spots in the Baltic Sea catchment area* 2009, HELCOM).

Undoubtedly the Vistula River is of primary importance to Poland. However, its diatom flora has not been thoroughly investigated. Diatoms are one of the dominant algal groups identified in the waters of the Gulf of Gdansk (Kruk-Dowgiałło & Szaniawska 2008) but diatom distributions in fresh and brackish water habitats of the Vistula river mouth are still poorly studied and understood. The river's estuary, which should not be treated as an isolated entity, is a fascinating environment, a transition zone between marine and freshwater biotopes. Its spatio-temporal patterns of basic environmental factors are strongly affected by both: sea and river and that is why estuaries should rather be considered a natural continuum between those two water bodies, where boundaries are not clearly defined. Due to land runoff discharge nutrients, estuaries tend to be naturally eutrophic habitats. What is more, estuaries are usually under intensive threat from human activities; are impacted by events far upstream but also can introduce contaminants in the marine environment. Some biologically active compounds (such as pesticides, furans, dioxins, phenols or heavy metals) do not disintegrate rapidly and may cause ecological stress to the many inherent aquatic communities (Wołowicz *et al.* 2007).

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The main aims of our study were to detect major patterns in species composition of diatom assemblages and to determine which ecological factors explained most of the variation. Since diatom flora diversity and distribution are strongly related to water chemistry, identified different diatom assemblages could be bio-indicators for the chemical and physical classification of the water bodies in the Vistula estuary.

MATERIALS AND METHODS

Study area

The Vistula's delta is formed by several old and new river branches. From late evening 31 January to early morning 1 February 1840, a catastrophic flood took place; the Vistula flowed into the Baltic near the city of Gdańsk. After the flood, the river formed a new mouth with the main flow approximately 10 km away from the previous one. The western branch, which had functioned between 1840 and 1895, was sluiced after the opening of a manmade channel near Świbno (Klekot 1972). Construction of the artificial Vistula outlet in 1895 contributed to intensive sedimentation. Due to regulation of the river mouth with the use of groynes, sedimentation is noticeable only directly off the Vistula mouth. Part of the accumulated material is washed off by waves and wave-induced currents (Łomniewski 1958, 1960; Pruszek *et al.* 2005). However, the volumetric balance is significantly positive. That means much less sediment is eroded by action of the sea than is supplied and accumulated by river activity. The Vistula's delta is still evolving. According to archival data, since the building of the new mouth in March 1895, large quantities of sediment have been deposited and the shoreline has advanced approximately 2 km (Gran-

iczny 2005; Pruszek *et al.* 2005). Presently, concrete protection of the banks of the main flow (the Vistula Ditch near the village of Świbno) has been damaged and the bottom is covered by relatively dense submerged vegetation (*Potamogeton* sp., *Ranunculus* sp., *Myriophyllum* sp.) (Jażdżewski *et al.* 2004).

Samples for taxonomic purposes were collected at two different sites from spring 2005 through autumn 2007. The sampling site in Świbno was located in the artificial canal (54,3277° N, 18,9339° E), 20 km away from Gdańsk, while the sampling site in Górkki Zachodnie was situated in an old natural branch, which was formed during the flood of 1840, 10 km away from the city of Gdańsk (54,3497° N, 18,7931° E).

Collection and analysis of materials

Epiphytic diatoms were gathered by collecting macroalgae and vascular aquatic plants and epilithic diatoms were collected by scraping submerged pebbles. Rock substrata of uniform chemical characteristic, size and flatness in shape (naturally rounded sandstone cobbles between 150 and 250 mm in diameter) were selected and thoroughly cleaned by brushing (Kelly *et al.* 1998). A 22 mm-diameter gravity corer was used to sample the sediments and the cores were extruded on site in contiguous 10-mm intervals. Diatom samples were collected from the uppermost 10 mm layer of the extracted short cores. All samples were taken between 0.5 and 1.0 m depth in the vicinity of the river riparian zone.

Water temperature, conductivity, pH and dissolved oxygen were measured in the field with a WTW Multiline probe. Simultaneously, water samples were collected for chemical measurements (nitrite, nitrate, ammonium, phosphate and silicate concentration). The values of these parameters are presented in Table 1.

Table 1. Values of physical and chemical water parameters measured at both sampling stations

Locality	Date	Salinity (PSU)	Temperature (°C)	pH	O ₂ (mg m ⁻³)	NNH ₄ (mg m ⁻³)	NNO ₃ (mg m ⁻³)	PPO ₄ (mg m ⁻³)	SiSiO ₄ (mg m ⁻³)
Świbno	04/05	0	12.5	8.26	103.6	169	1100	92	640
	06/05	0	23.9	8.75	101	97	330	82	620
	05/06	0.1	17.7	8.42	129	470	410	58	530
	08/06	0	17.4	8.43	95.2	470	210	72	560
	10/06	0.3	10.6	8.45	109	160	510	78	560
	03/07	0.1	1.7	6.6	120	8.5	1380	92	680
	05/07	0.3	16	8.2	105	510	500	54	540
	10/07	0.2	12.2	6.64	95	270	580	65	500
Górkki Zachodnie	06/05	6	18.1	8.47	104.4	7.5	150	25	320
	05/06	6.1	12.6	8.51	122	75	150	25	350
	10/06	6	10.2	8.15	113.5	35	120	35	250
	03/07	5.1	3.1	7.78	125	7	750	35	450
	05/07	6.2	12.2	8.2	130	110	160	35	370
	10/07	6	12.7	8.3	105	7.5	15	15	150

Lugol's solution was used to fix the material for further analysis. Samples for diatom analysis were digested with H_2O_2 (30%) and HCl (10%) following a slightly modified protocol by Battarbee (1986). Cleaned diatom suspensions were dried onto glass coverslips and mounted in the high-refraction mountant, Naphrax. Permanent slides were made for each sample. At least 700 (from 700 to 1500, depending on the benthic diatom taxa abundance in the sample) diatom valves were counted on random transects across each slide. Diatoms were examined and identified using a Nikon E400 and Nikon E80i light microscope equipped with Nomarskii contrast system and Eclipse DS-5 camera as well as JEOL JSM 60/60 LW scanning electron microscope. For SEM observations, a few drops of cleaned material were poured onto a Nucleopore polycarbonate filter, which was fixed on a stub. After leaving to completely air dry, the stub was sputter coated with a thin layer of gold. All permanent slides are currently housed in the publically available collections of IO (Institute of Oceanography, University of Gdansk, Poland).

In this study, diatoms were divided into the groups according to their life form (after Denys 1991/92), as follows: euplanktonic, planktonic with epontic origin, planktonic with benthic origin, planktonic with epontic and/or benthic origin, epontic, epontic and benthic, benthic. Species belonging to the three last above-mentioned groups were subsequently considered as true benthic forms. The classification of Van Dam (Van Dam *et al.* 1994) was used to group diatoms in the spectrum of salinity, trophic and saprobity. The observed specimens were identified and classified according to their ecological preferences using the following literature: Krammer and Lange-Bertalot (1986, 1988, 1991a, 1991b), Pankow (1990), Denys (1991/92), Snoeijs (1993), Hofmann (1994), Snoeijs and Vilbaste (1994), Van Dam *et al.* (1994), Snoeijs and Potapova (1995), Snoeijs and Kasperovičienė (1996), Snoeijs and Balashova (1998), Witkowski *et al.* (2000), Rakowska (2001), Stachura-Suchoples (2001), Lange-Bertalot *et al.* (2003), Bąk (2004), Zgrundo *et al.* (2009).

The Shannon-Wiener and evenness indices were calculated with the Primer v.6 programme (Clarke & Gorley 2006). All ordinations were done using CANOCO version 4.5 (ter Braak & Šmilauer 2002). To determine the relationship between the diatom distributions and environmental variables, canonical correspondence analysis (CCA) was carried out on the log-normal transformed abundance data. Statistical significance of the environmental predictor variables was assessed by 999 restricted Monte Carlo permutations. Because we were primarily interested in species that live in benthic communities, we excluded all planktonic species from the analyses. In most cases, only the 40 taxa of benthic diatoms that reached at least 3% relative abundance in at least one sample were included in the dataset.

RESULTS AND DISCUSSION

Diatom community composition

In all 29 samples, a well-preserved diatom flora was found comprising 187 species representing 61 genera (Table 2). Forty-five species were unique to Świbno and 71 to Górkki Zachodnie. Seventy-one taxa were common to both sites. One hundred and twelve species belonged to benthic taxa and 51 to planktonic taxa. However, the diatom flora was dominated by planktonic species in almost 50% of samples. They seemed to increase in numbers especially in spring and autumn, which was probably caused by seasonal blooms of planktonic diatoms. This could be the primary reason why only three dominant species reached the highest relative abundance (over 50% in at least one sample) in the area investigated. They were: *Aulacoseira islandica*, *Cyclotella atomus* and *Diatoma moniliformis* (Fig. 1). The first two taxa are definitely planktonic (not included in the CCA analysis), only the latter is well known to be a benthic form (see Table 2).

In sediment samples collected at the Świbno sampling station, from among the benthic taxa *Navicula gregaria*, *N. tripunctata* and *Nitzschia dissipata* reached the highest relative abundances. However, in each of the samples analyzed, the most numerous were still species described in the literature as planktonic taxa: *Aulacoseira granulata*, *Cyclotella atomus*, *Cyclotella meneghiniana*, *Cyclotella pseudostelligera*, *Stephanodiscus medius* and *Stephanodiscus parvus*. Their strong dominance was evident especially from spring to autumn (Fig. 2). *Cyclotella atomus* and *C. meneghiniana* were the most important components of the assemblages in summer and autumn, while in spring samples higher relative abundances of *Cyclotella pseudostelligera* and various *Stephanodiscus* species were noted.

Four benthic diatom species were dominant in sediment samples from Górkki Zachodnie: *Hippodonta hungarica*, *Navicula gregaria*, *Navicula perminuta* and *Opephora mutabilis* (Fig. 3). The two last mentioned taxa were observed in the material during the whole sampling period. *Hippodonta hungarica* in turn appeared only in the year 2006, as well in spring as in autumn. All samples of sand collected at Górkki Zachodnie station were dominated by originally benthic taxa, except for a winter sample taken on 5 March 2007. In this material, *Aulacoseira islandica* was the most abundant taxon, which accounted for up to 70% of the diatoms identified in the sample. *Aulacoseira islandica* valves occurred in sediment collected from Górkki Zachodnie on 8 May 2007, none the less, its relative abundance was much lower, amounting to only 5%.

Due to the conditions of the sampling area during the study, only three samples of biofilm scraped from

Table 2. Identified taxa, their ecological preferences and codes used in the present studies

Taxon	Code	lf	S	t	s	
<i>Achnanthes brevipes</i> Agardh	ABRE	6	4	1	1	◆
<i>Achnanthes lemmermannii</i> var. <i>lemmermannii</i> Hustedt	ALEM	6	2	0	1	◆◆
<i>Achnanthes leonardii</i> Witkowski & Lange-Bertalot	ALEO	0	0	0	0	◆
<i>Achnanthes minuscula</i> Hustedt	AMIS	8	1	7	0	◆◆
<i>Achnanthes oblongella</i> Østrup	AOBG	7	2	1	1	◆◆
<i>Achnanthes thermalis</i> (Rabenhorst) Schoenfeld var. <i>thermalis</i> Schoenfeld	ATHE	0	3	0	1	•
<i>Achnanthidium minutissimum</i> (Kützing) Czarnecki	ADMI	6	2	7	2	◆◆
<i>Actinocyclus normanii</i> (Gregory) Hustedt morphotype <i>normanii</i>	ANMN	2	3	5	3	•
<i>Amphora</i> cf. <i>tenerrima</i> Aleem & Hustedt	ATNI	0	0	0	0	◆
<i>Amphora coffeaeformis</i> var. <i>coffeaeformis</i> (Agardh) Kützing	ACOF	7	5	5	3	◆
<i>Amphora commutata</i> Grunow	ACOM	3	4	5	3	◆
<i>Amphora copulata</i> (Kützing) Schoeman & Archibald	ACOP	7	2	5	2	◆◆
<i>Amphora helenensis</i> Giffen	AHLN	7	5	0	0	◆
<i>Amphora holsatica</i> Hustedt	AHOL	8	5	5	0	◆
<i>Amphora lineolata</i> Ehrenberg	AMLI	2	0	0	0	◆
<i>Amphora luciae</i> Chlonoky	ALUC	7	5	0	0	◆
<i>Amphora ovalis</i> Kützing	AOVA	7	2	5	2	◆◆
<i>Amphora pediculus</i> (Kützing) Grunow	APED	7	2	5	2	◆◆
<i>Amphora proteus</i> Gregory	APRO	8	5	0	0	◆
<i>Amphora staurophora</i> Juhlin-Dannfelt	AMST	8	5	0	0	◆
<i>Anaulus balticus</i> Simonsen	ANBA	2	0	0	0	◆
<i>Anorthoneis vortex</i> Sterrenburg	ANVO	2	0	0	0	◆
<i>Astartiella bahusiensis</i> (Grunow) Witkowski, Lange-Bertalot & Metzeltin	ABHS	7	4	5	1	◆
<i>Astartiella bremeyeri</i> (Lange-Bertalot) Witkowski & Lange-Bertalot	ABMY	7	4	0	0	◆◆
<i>Asterionella formosa</i> Hassall	AFOR	2	2	4	2	◆◆
<i>Aulacoseira granulata</i> (Ehrenberg) Simonsen	AUGR	2	2	5	2	◆◆
<i>Aulacoseira islandica</i> (O.Müller) Simonsen	AUIS	2	1	7	2	◆◆
<i>Bacillaria paxillifer</i> (O.Müller) Hendey	BPAX	3	4	5	3	◆
<i>Berkeleya fennica</i> Juhlin-Dannfelt	BFEN	6	4	0	0	◆
<i>Berkeleya rutilans</i> (Trentenpohl) Grunow	BRUT	7	4	0	0	◆◆
<i>Brebissonia lanceolata</i> (Agardh) Mahoney & Reimer	BLAN	6	3	0	0	◆◆
<i>Caloneis aemula</i> (Grunow ex A.Schmidt) Cleve	CAEM	2	0	0	0	◆
<i>Catenula adhaerens</i> (Mereschkowsky) Mereschkowsky	CADH	8	5	5	2	◆
<i>Cocconeis disculus</i> (Schumann) Cleve	CDIS	8	3	4	1	◆
<i>Cocconeis hauniensis</i> Witkowski emend. Witkowski	COHA	8	4	5	2	◆
<i>Cocconeis neothumensis</i> Krammer	CNTH	8	1	5	1	◆
<i>Cocconeis pediculus</i> Ehrenberg	CPED	6	3	5	2	◆◆
<i>Cocconeis peltoides</i> Hustedt	CPTO	6	5	5	0	◆
<i>Cocconeis placentula</i> Ehrenberg	CPLA	6	2	5	2	◆◆
<i>Ctenophora pulchella</i> (Ralfs ex Kützing) Williams & Round	CTPU	6	4	5	3	◆
<i>Cyclostephanos dubius</i> (Fricke) Round	CDUB	2	3	5	3	◆◆
<i>Cyclostephanos tholiiformis</i> Soermer, Håkansson & Theriot	CTHO	0	0	0	0	•
<i>Cyclotella atomus</i> Hustedt	CATO	2	3	5	3	◆◆
<i>Cyclotella bodanica</i> Grunow	CBOD	2	2	1	1	◆◆
<i>Cyclotella choctawhatcheeana</i> Prasad	CCHO	2	4	5	4	◆◆
<i>Cyclotella comensis</i> Grunow	CCMS	2	1	4	1	◆
<i>Cyclotella distinguenda</i> Hustedt	CDTG	5	2	5	2	•
<i>Cyclotella meneghiniana</i> Kützing	CMEN	4	3	5	4	◆◆
<i>Cyclotella ocellata</i> Panstocsek	COCE	2	1	4	1	•
<i>Cyclotella pseudostelligera</i> Hustedt	CPST	2	2	5	3	◆◆
<i>Cyclotella radiosa</i> (Grunow) Lemmermann	CRAD	2	2	5	2	◆◆
<i>Cyclotella stelligera</i> Cleve et Grunow	CSTE	2	2	5	1	◆◆
<i>Cymbella helvetica</i> Kützing	CHEL	6	2	3	1	•
<i>Cymbella lanceolata</i> (Ehrenberg) Kirchner	CLAN	2	2	7	2	◆
<i>Diatoma moniliformis</i> Kützing	DMON	8	1	5	2	◆◆
<i>Diatoma tenue</i> Agardh	DITE	3	3	5	3	◆◆
<i>Diatoma vulgare</i> Bory	DVUL	6	2	4	2	◆◆
<i>Diploneis decipiens</i> Cleve-Euler	DDEC	0	0	0	0	◆
<i>Diploneis didyma</i> (Ehrenberg) Cleve	DDID	8	4	3	2	◆

Table 2. Continued

Taxon	Code	lf	S	t	s	
<i>Diploneis litoralis</i> (Donkin) Cleve	DLIT	8	5	5	1	◆
<i>Diploneis smithii</i> var. <i>smithii</i> (Brébisson) Cleve	DSMI	8	4	0	0	◆
<i>Diploneis stroemii</i> Hustedt	DSTR	2	0	0	0	◆
<i>Encyonema caespitosum</i> Kützing	ECAE	2	2	7	3	◆◆
<i>Epithemia sores</i> Kützing	ESOR	6	2	5	2	◆
<i>Fallacia clepsidroides</i> Witkowski	FCLE	8	4	0	0	◆
<i>Fallacia forcipata</i> (Greville) Stickle & D.G.Mann	FFOR	8	5	5	3	◆
<i>Fallacia pygmaea</i> (Kützing) Stickle & D.G.Mann	FPYG	8	3	5	3	◆
<i>Fogedia heterovalvata</i> (Simonsen) Witkowski, Lange-Bertalot & Metzeltin	FHTV	0	4	0	0	◆
<i>Fragilaria capucina</i> var. <i>capucina</i> Desmazieres	FCAP	3	2	3	2	•
<i>Fragilaria capucina</i> var. <i>vaucheriae</i> (Kützing) Lange-Bertalot	FCVA	7	2	5	3	•
<i>Fragilaria cassubica</i> Witkowski & Lange-Bertalot	FCSU	8	3	0	2	◆
<i>Fragilaria crotonensis</i> Kitton	FCRO	2	2	3	2	•
<i>Fragilaria fasciculata</i> (Agardh) Lange-Bertalot	FFAS	6	4	5	3	◆◆
<i>Fragilaria improbula</i> Witkowski et Lange-Bertalot	FIMP	0	0	0	0	•
<i>Fragilaria montana</i> (Krasske) Lange-Bertalot	FMON	0	0	0	0	◆
<i>Fragilaria neoproducta</i> Lange-Bertalot	FNOP	0	1	1	1	◆
<i>Fragilaria sopotensis</i> Witkowski & Lange-Bertalot	FSOP	8	4	5	3	◆◆
<i>Fragilaria ulna</i> (Nitzsch) Lange-Bertalot	FULN	6	2	7	4	•
<i>Fragilaria ulna</i> var. <i>acus</i> (Kützing) Lange-Bertalot	FUAC	6	2	5	3	◆
<i>Geissleria decussis</i> (Østrup) Lange-Bertalot & Metzeltin	GDEC	0	2	4	1	◆◆
<i>Geissleria similis</i> (Krasske) Lange-Bertalot & Metzeltin	GSML	0	0	0	2	•
<i>Gomphonema olivacea</i> (Hornemann) Dawson ex Ross et Sims	GOLI	8	2	5	2	◆◆
<i>Gomphonema minutum</i> var. <i>minutum</i> (Agardh) Agardh	GMIN	0	2	5	2	◆◆
<i>Gomphonema parvulum</i> Kützing	GPAR	6	2	5	4	◆◆
<i>Gomphonema</i> sp. Ehrenberg	GOMS	0	0	0	0	•
<i>Gyrosigma acuminatum</i> (Kützing) Rabenhorst	GYAC	8	2	5	2	◆◆
<i>Gyrosigma attenuatum</i> (Kützing) Rabenhorst	GYAT	8	2	5	2	•
<i>Hantzschia virgata</i> (Roper) Grunow	HVIR	2	5	0	0	•
<i>Hippodonta capitata</i> (Ehrenberg) Lange-Bertalot, Metzeltin & Witkowski	HCAP	8	2	4	3	◆◆
<i>Hippodonta</i> cf. <i>arkonensis</i> Lange-Bert. Metzeltin	HARK	0	0	0	0	◆◆
<i>Hippodonta hungarica</i> (Grunow) Lange-Bertalot, Metzeltin & Witkowski	HHUN	8	2	4	5	◆◆
<i>Hippodonta linearis</i> (Østrup) Lange-Bertalot Metzeltin & Witkowski	HILI	8	4	5	2	◆
<i>Hippodonta neglecta</i> Lange-Bertalot Metzeltin & Witkowski	HNEG	0	0	0	0	◆
<i>Karayevia clevei</i> (Grunow) Round et Bukhtiyarova	KCLE	6	2	4	2	•
<i>Kolbesia amoena</i> (Hustedt) Kingston	KAMO	2	4	0	0	◆◆
<i>Licmophora gracilis</i> (Ehrenberg) Grunow	LGRA	0	0	0	0	◆
<i>Luticola goeppertiana</i> (Bleish) D.G.Mann	LGOE	8	2	5	4	•
<i>Luticola mutica</i> (Kützing) D.G.Mann	LMUT	8	3	5	3	◆
<i>Lyrella sulcifera</i> (Hustedt) Witkowski	LSUL	8	5	0	0	◆
<i>Martyana atomus</i> (Hustedt) Snoeijjs	MATO	3	4	5	0	◆
<i>Martyana martyi</i> (Heribaud) Lange-Bertalot	FMAR	6	2	4	1	◆
<i>Martyana schulzii</i> (Brockmann) Snoeijjs	MSHU	6	4	3	0	◆
<i>Mastogloia baltica</i> Grunow	MBAL	0	0	0	0	•
<i>Melosira lineata</i> (Dillwyn) Agardh	MLIN	3	4	5	2	◆◆
<i>Melosira moniliformis</i> (Müller) Agardh	MMON	3	4	0	0	•
<i>Melosira nummuloides</i> (Dillwyn) Agardh	MNUM	3	4	0	0	◆◆
<i>Melosira</i> sp. Agardh	MELS	0	0	0	0	◆◆
<i>Navicula amphiceropsis</i> Lange-Bertalot & Rumrich	NAAM	8	2	5	3	•
<i>Navicula antonii</i> Lange-Bertalot	NANT	8	2	5	3	◆◆
<i>Navicula armoricana</i> Amossé	NAAR	6	0	0	0	•
<i>Navicula bottnica</i> Grunow in Cleve et Grunow	NBOT	3	0	0	0	◆
<i>Navicula capitatoradiata</i> Germain	NCPR	8	2	5	3	◆◆
<i>Navicula cari</i> Ehrenberg	NCAR	8	2	7	3	•
<i>Navicula cincta</i> (Ehrenberg) Ralfs	NCIN	8	2	5	3	◆
<i>Navicula cryptocephala</i> Kützing	NCRY	8	2	7	3	◆◆
<i>Navicula cryptotenella</i> Lange-Bertalot	NCTE	8	2	7	2	◆◆
<i>Navicula erifuga</i> Lange-Bertalot	NERI	3	3	5	0	•
<i>Navicula germanopolonica</i> Witkowski & Lange-Bertalot	NGEP	8	5	5	2	◆

Table 2. Continued

Taxon	Code	lf	S	t	s	
<i>Navicula gregaria</i> Donkin	NGRE	8	3	5	3	◆◆
<i>Navicula integra</i> (W.Smith) Ralfs	NITG	8	3	5	3	•
<i>Navicula meniscus</i> Schumann	NMNS	8	3	5	1	◆◆
<i>Navicula oestrupi</i> Schultz	NOES	8	2	0	0	◆
<i>Navicula palpebralis</i> Brebisson ex W.Smith var. <i>palpebralis</i>	NPPB	6	5	0	0	◆
<i>Navicula perminuta</i> Grunow	NPNU	7	3	3	5	◆◆
<i>Navicula radiosa</i> Kützing	NRAD	8	2	4	2	◆◆
<i>Navicula ramosissima</i> (Agardh) Cleve	NRAM	6	5	0	0	◆
<i>Navicula reinhardtii</i> (Grunow) Grunow	NREI	8	2	5	2	•
<i>Navicula tripunctata</i> (O.Müller) Bory	NTPT	7	2	5	2	◆◆
<i>Navicula veneta</i> Kützing	NVEN	8	3	5	4	◆
<i>Navicula viminoides</i> Giffen	NVIM	2	0	0	0	◆
<i>Nitzschia acicularis</i> (Kützing) W.Smith	NACI	4	2	5	3	•
<i>Nitzschia archibaldii</i> Lange-Bertalot	NIAR	0	2	5	2	◆◆
<i>Nitzschia bacillum</i> Hustedt	NBCL	0	2	3	2	•
<i>Nitzschia capitellata</i> Hustedt	NCPL	7	4	6	4	◆◆
<i>Nitzschia dissipata</i> Archibald	NDIS	8	2	4	2	◆◆
<i>Nitzschia elegantula</i> Grunow	NELE	3	0	0	0	•
<i>Nitzschia frustulum</i> (Kützing) Grunow var. <i>frustulum</i>	NIFR	7	3	5	2	•
<i>Nitzschia graciliformis</i> Lange-Bertalot et Simonsen	NIGF	0	2	5	2	•
<i>Nitzschia inconspicua</i> Grunow	NINC	8	3	5	3	◆◆
<i>Nitzschia liebetruthii</i> Rabenhorst	NLBT	0	4	5	2	◆◆
<i>Nitzschia linearis</i> (Agardh) W.M. Smith var. <i>linearis</i>	NLIN	8	2	4	2	•
<i>Nitzschia microcephala</i> Grunow	NMIC	8	2	5	3	◆◆
<i>Nitzschia palea</i> (Kützing) W.Smith	NPAL	7	2	6	5	◆◆
<i>Nitzschia paleacea</i> Grunow	NPAE	7	2	5	3	◆◆
<i>Nitzschia pellucida</i> Grunow	NIPE	8	4	0	0	◆
<i>Nitzschia pusilla</i> (Kützing) Grunow	NIPU	8	2	7	2	◆
<i>Nitzschia sigma</i> (Kützing) W.Smith	NSIG	8	4	5	3	◆
<i>Nitzschia sociabilis</i> Hustedt	NSOC	0	2	5	2	•
<i>Nitzschia sublinearis</i> Hustedt	NSBL	0	0	0	0	•
<i>Nitzschia thermaloides</i> Hustedt	NTHE	8	5	5	0	◆
<i>Nitzschia tubicola</i> Grunow	NTUB	7	4	5	5	◆
<i>Opephora krumbeinii</i> Witkowski, Witak & Stachura	OKRU	8	5	0	0	◆
<i>Opephora mutabilis</i> (Grunow) Sabbe & Vyverman	OMUT	6	4	5	2	◆◆
<i>Parlibellus hamulifer</i> (Grunow) De Toni	PHAM	0	0	0	0	◆
<i>Petroneis humerosa</i> (Brebisson ex W.M.Smith) Stickle & Mann	PHUM	2	0	0	0	◆
<i>Placoneis clementis</i> (Grunow) Cox	PCLT	7	3	4	2	◆
<i>Placoneis placentula</i> (Ehrenberg) Heinzerling	PPLC	8	2	5	2	•
<i>Planothidium delicatulum</i> (Kützing) Round & Bukhtiyarova	PTDE	8	4	5	3	◆◆
<i>Planothidium lanceolatum</i> (Brébisson) Round et Bukhtiyarova	PTLA	6	2	5	3	◆◆
<i>Planothidium pericavum</i> (Carter) Lange-Bertalot	PPCV	0	3	0	0	◆
<i>Planothidium rostratum</i> (Østrup) Lange-Bertalot	PRST	6	2	5	3	•
<i>Planothidium septentrionalis</i> (Østrup) Round & Bukhtiyarova	PTSE	8	4	0	0	◆
<i>Pleurosigma aestuarii</i> (Brebisson) W.Smith	PLAE	2	0	0	0	◆
<i>Psammothidium punctulatum</i> (Simonsen) Bukhtiyarova et Round	PPUN	8	4	0	0	◆
<i>Psammothidium rossii</i> (Hustedt) Bukhtiyarova et Round	PROS	0	1	1	1	◆◆
<i>Pseudostaurosira brevistriata</i> (Grunow) Williams et Round	PSBR	8	2	7	1	◆◆
<i>Reimeria sinuata</i> (Gregory) Kociolek & Stoermer	RSIN	7	2	7	2	•
<i>Rhoicosphenia abbreviata</i> (Agardh) Lange-Bertalot	RABB	6	2	5	2	◆◆
<i>Rhopalodia gibba</i> (Ehrenberg) O.Müller	RGIB	8	2	5	2	•
<i>Sellaphora bacillum</i> (Ehrenberg) D.G.Mann	SEBA	8	2	4	2	•
<i>Sellaphora pupula</i> (Kützing) Mereschkowsky	SPUP	8	2	4	3	•
<i>Skeletonema</i> sp. Greville	SKCO	0	0	0	0	◆◆
<i>Staurosira construens</i> Ehrenberg	SCON	7	2	4	2	•
<i>Staurosira elliptica</i> (Schumann) Williams & Round	SELI	8	2	4	2	◆
<i>Stephanodiscus hantzschii</i> Grunow	SHAN	2	2	6	4	◆◆
<i>Stephanodiscus medius</i> Håkansson	SMED	2	2	5	5	◆◆
<i>Stephanodiscus minutulus</i> (Kützing) Cleve & Moller	STMI	3	2	6	3	◆◆

Table 2. Continued

Taxon	Code	lf	S	t	s	
<i>Stephanodiscus parvus</i> Stroemer & Håkansson	SPAV	2	2	6	2	◆◆
<i>Stephanodiscus rotula</i> (Kützinger) Hendey	SROT	2	2	5	2	◆
<i>Surirella angusta</i> Kützinger	SANG	8	2	5	2	•
<i>Surirella brebissonii</i> var. <i>brebissonii</i> Krammer & Lange-Bertalot	SBRE	8	3	5	4	◆◆
<i>Surirella minuta</i> Brébisson	SUMI	8	2	5	3	•
<i>Tabularia waernii</i> Snoeijs	TWAE	8	3	0	0	◆
<i>Thalassiosira baltica</i> (Grunow) Ostensfeld	TBAL	2	4	3	2	◆◆
<i>Thalassiosira</i> sp. Cleve	TASP	0	0	0	0	•
<i>Tryblionella apiculata</i> (Kützinger) Ralfs	TAPI	8	4	5	3	•
<i>Tryblionella calida</i> (Grunow) D.G.Mann	TCAL	0	3	5	3	•

lf, life form: 0, lack of data; 2, euplanktonic; 3, planktonic with epontic origin; 4, planktonic with benthic origin; 5, planktonic with epontic and/or benthic origin; 6, epontic; 7, epontic and benthic; 8, benthic. S, salinity: 0, lack of data; 1, freshwater (<0.2 PSU); 2, fresh-brackish (0.2 PSU–0.9 PSU); 3, brackish-fresh (0.9–1.8 PSU); 4, brackish (1.8–9.0 PSU); 5, marine-brackish and marine (>9.0 PSU). t, trophy: 0, lack of data; 1, oligotrophic; 2, oligo-mezotrophic; 3, mezotrophic; 4, mezo-eutrophic; 5, eutrophic; 6, hypereutrophic; 7, oligo- to eutrophic (hypereutrophic). s, saprobity: 0, lack of data; 1, oligosaprobious; 2, β -mezosaprobious; 3, α -mezosaprobious; 4, α -mezo-/polisaprobious; 5, polisaprobious. ◆ found in Górki Zachodnie. • found in Świbno.

submerged stones were collected in Świbno. Because of this limitation, no conclusions about seasonal changes could be drawn.

Diatoma moniliformis, *Fragilaria fasciculata*, *Gomphonema olivacea*, *Navicula perminuta*, *Nitzschia inconspicua*, *N. microcephala* and *Opephora mutabilis* were the dominant species of epilithic diatoms collected from Górki Zachodnie. Among diatom species some seasonal changes have been observed. In all examined samples, the occurrence of *Fragilaria fasciculata*, *Navicula perminuta* and *Nitzschia inconspicua* were recorded. However, the relative abundance of the previously mentioned taxa was markedly increased in spring. *Navicula perminuta* became a strong dominant in the summer of 2005, accounting for almost 30% of all valves counted in the sample. The abundance of *Diatoma moniliformis*, *Fragilaria fasciculata* and *Gomphonema olivacea* increased in spring and autumn. *Opephora mutabilis* occurred once, being present only in material collected at the beginning of March 2007 (Fig. 4).

Among diatoms recorded from Świbno periphyton samples, inclusive of macroalgae and aquatic plant collections, were seven species known to be benthic taxa: *Cocconeis placentula*, *Diatoma moniliformis*, *Fragilaria capucina*, *Gomphonema minutum* var. *minutum*, *Navicula tripunctata*, *Nitzschia dissipata* and *Nitzschia palea*, which exceeded the level of 10% of relative abundance in at least one sample (Fig. 5). Planktonic taxa were present as well. Among them, the most numerous were *C. atomus* and *C. meneghiniana*, however, each of these species occurred in numbers exceeding the threshold of 10% of all diatoms recorded in a given sample only once. Both samples, in which *Cyclotella* species reached their maximal abundances, were collected in summer. Other common benthic taxa

noted especially in the warm period were *Cocconeis placentula*, *Gomphonema minutum* var. *minutum* and *Nitzschia palea*. In spring, the composition of epiphytic diatoms was different. *Diatoma moniliformis* reached its highest abundances, assuming the overwhelming dominance in spring 2007. Occurrence of *Fragilaria capucina*, *Navicula tripunctata* and *Nitzschia dissipata* in turn was present in spring as well as in autumn.

The structure of diatom communities growing on the macroalgae *Enteromorpha* was an interesting phenomenon. This macroalga was the only taxon collected at the Górki Zachodnie sampling station. Epiphytic diatom communities, inhabiting the surface of their host consisted mainly of four species during the entire study period. *Diatoma moniliformis* was clearly the most abundant taxon, accounting for up to 85% of the diatom valves identified in a sample. Other dominant taxa were: *Navicula perminuta* (2–8%), *Rhoicosphenia abbreviata* (2–10%) and *Fragilaria fasciculata* (1–30%). *Diatoma moniliformis* had maximum relative abundance in the June 2005 collection, while *Fragilaria fasciculata* had peak abundance in May 2007. Percentage abundance of each taxa and the composition of accompanying species has been slightly changing; however, the seasonal variations were almost eliminated.

The composition of the diatom flora inhabiting sediment superficial layers characterized each site. Different substrates supported diatom floras consistent with what would be expected. Considering only the benthic taxa, the epipelagic communities of Świbno were dominated by motile species (e.g. *Navicula gregaria*, *N. tripunctata*, *Nitzschia dissipata*), while epipsammic diatom community composition in Górki Zachodnie was characterized rather by forms firmly attached to the sand grains. Two of the most common species deriving

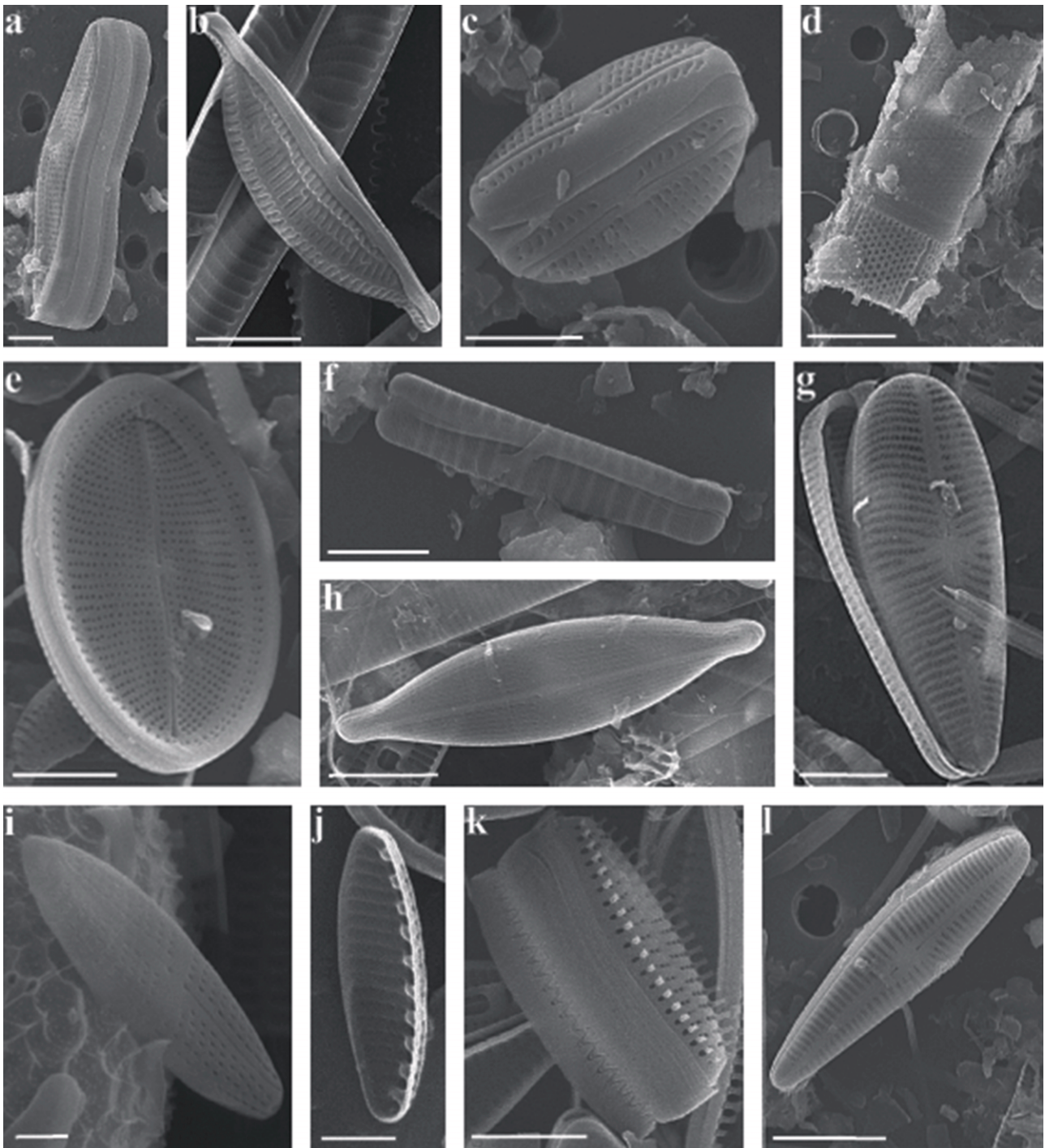
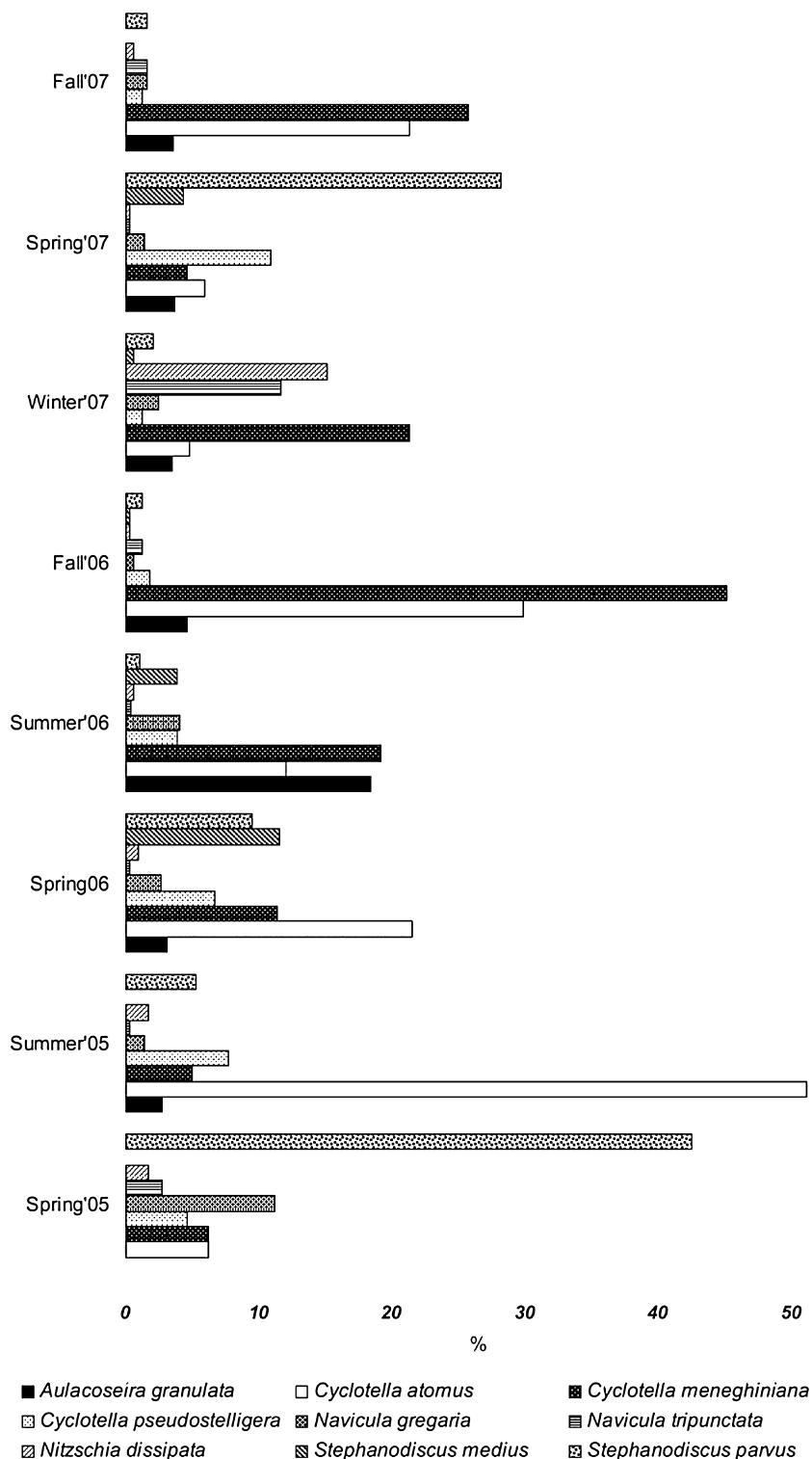


Fig. 1. Scanning electron micrographs of the most common or abundant species: *Achnanthes brevipes* (a), *Amphora* cfr. *coffeaeformis* (b), *Amphora pediculus* (c), *Aulacoseira islandica* (d), *Cocconeis placentula* (e), *Diatoma moniliformis* (f), *Gomphonopsis olivacea* (g), *Navicula gregaria* (h), *Navicula perminuta* (i), *Nitzschia inconspicua* (j), *Opephora mutabilis* (k), *Rhoicosphenia abbreviata* (l).

from Górki Zachodnie were *Navicula perminuta* and *Opephora mutabilis*, which could be found in all samples of sediment. Important components of the flora at this site were adnate *Amphora* and *Cocconeis* species as well as tube-dwelling forms like *Berkeleya rutilans*, which occurred at relatively lower abundances.

The published literature has made a connection between specific taxa with specific habitats; silt (mud) and sand have been widely recognized (Kawecka & Eloranta 1994; Consalvey *et al.* 2004). Typical inhabitants of the sandy sediments are mainly very minute forms of diatoms as some specimens of *Achnanthes*,

Fig. 2. Relative abundances of major diatom species dominating in sediment samples collected in Świbno.



Amphora, *Fragilaria*, *Navicula* or *Nitzschia* genera. More detailed studies have shown that their smaller overall dimensions protect them from mechanical damage, which can occur in the case of larger valves rubbed off by grains of quartz.

The great majority of organisms living on and in the mud are motile. This ability is especially useful in

habitats formed by fine-grained fractions residual on unstable, continuously surged surfaces of riverbeds, where the motility is crucial for survival (Moss 1977). Sessile forms can exist only in places where the influence of river current is insignificant.

The differences in taxonomic composition of diatom communities found in both examined sites seem to

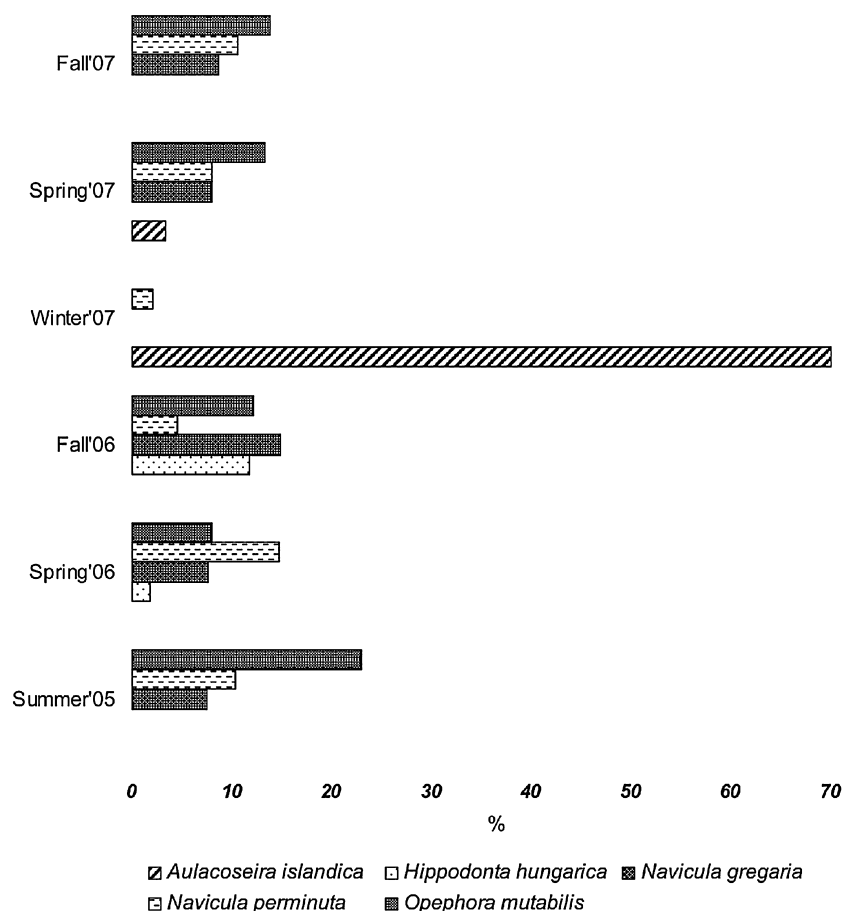


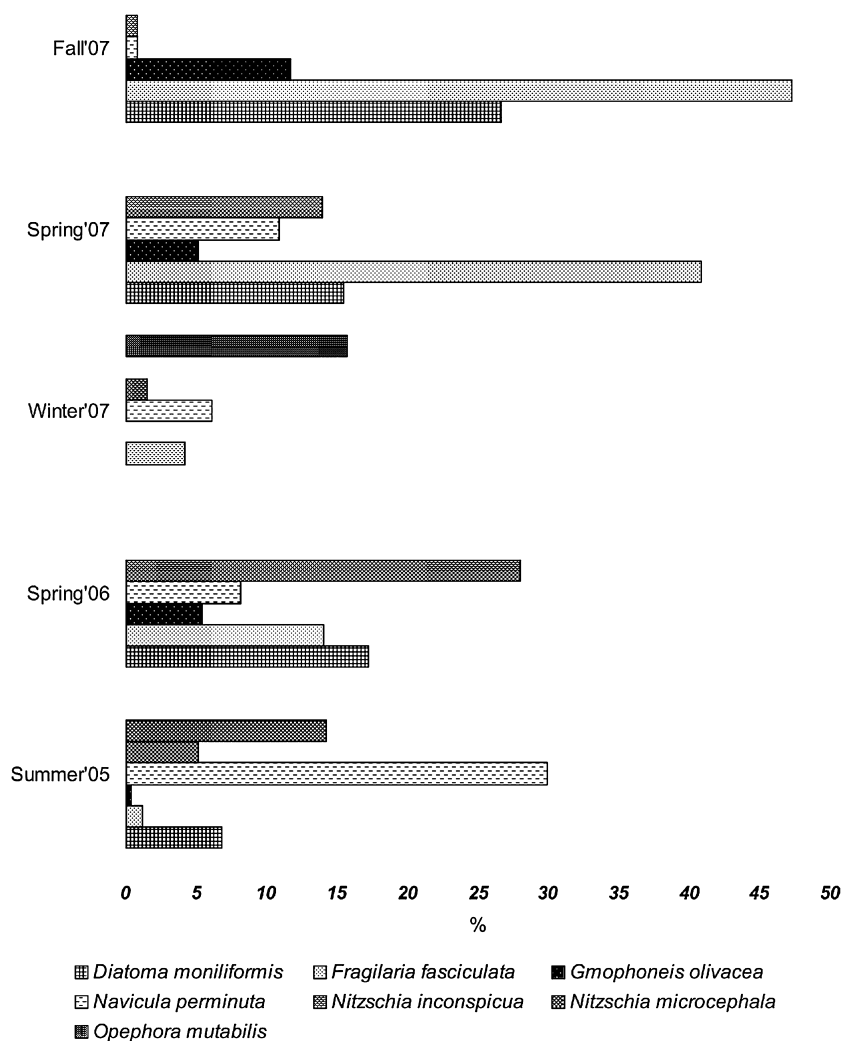
Fig. 3. Relative abundances of major diatom species dominating in sediment samples collected in Górki Zachodnie.

confirm the importance of sediment granulation for the formation of characteristic diatom assemblages.

Moreover, epipsammic and epilithic diatom assemblages were more diverse than epiphytic, which can be observed especially for Górki Zachodnie station as the average value of Shannon-Wiener diversity index varied from 1.22 for epiphytic samples to 2.38 for epilithic and 2.93 for epipsammic samples (Table 3). The kind of sediment could again be an important factor; since it has been proved that the diversity of diatom associations is lower on mud than on sand (Round 1971). The number of diatom taxa recorded varied substantially between the different habitat types. From the natural substrata collected in Świbno, a total of 100 diatom taxa were recorded from sediment (mud), 54 from the rocks and 74 from macroalgae and vascular aquatic plants. From Górki Zachodnie, a total of 118 diatom taxa were counted in all samples of sediment (sand), 81 in samples of biofilm scraped from the rock substratum and 29 in samples of macroalgae. However, it should be noted that the epiphytic communities from Świbno originated from few different species of macroalgae and vascular aquatic plants, from both live and dead material found at the sampling site, while the diatom taxa associated with other living organisms collected in Górki Zachodnie had only one host – *Enteromorpha*.

It is still an open question whether epiphytic microalgae interact with their hosts. Numerous observations indicate that the relation between epiphytic algae and their plant substratum occurs. Many investigators have suggested that this kind of substratum, due to its physical and chemical features, affects distribution as well as the composition of epiphytic communities (Young 1945; Prowse 1959; Eminson & Moss 1980; Pip & Robinson 1984; Kawecka & Eloranta 1994). In contrast, other works suggest that this relationship does not exist and epiphytic microalgae, particularly diatoms, colonize to the same degree on all accessible surfaces (Fritsch 1931; Simonsen 1962; Pieczyńska & Spodniewska 1963; Millie & Lowe 1983). Results of the research led by Hasiuk-Krzak in the years 2005–2006 in the vicinity of littoral zone of the Gulf of Gdansk (Katarzyna Hasiuk-Krzak, unpubl. data, 2008) seem to confirm the substratum hypothesis. Among the examined communities of epiphytic diatoms some significant differences were found, which could be an effect of different preferences of epiphytes with respect to the host organism. The differences have been observed in qualitative as well as quantitative compositions; however, it has not been statistically confirmed in all cases. Most likely the physical characteristic of the substratum is of great importance, since more

Fig. 4. Relative abundances of the major diatom species inhabiting the surface of rock substratum in Górki Zachodnie.



abundant and diverse communities have been noted growing on the rough and easy to colonize surface of *Cladophora* species in comparison with those collected from the smooth thalli of *Enteromorpha* sp. Similar results have been obtained during the present study.

The importance of substrate roughness for the epiphytic microalgae are consistent with the *inter alia* examinations of Chudyba (1965, 1968), Whitton (1970) and Kawecka (1980) (after Kawecka & Eloranta 1994). While Grimes *et al.* (1980) suggested that the physiological condition of the plant substratum can also be essential for epiphyte growth. Accordingly, the epiphytic diatom distribution on the surface of investigated material is non-accidental: erect *Gomphonema* species prefer living stalks and thalli, whereas motile *Navicula* species are more frequently observed covering the dead substrata (after Kawecka & Eloranta 1994). These facts could also partly explain the significantly higher diversity of the epiphytes from Świbno compared to Górki Zachodnie, since (as it has been pointed out previously) material collected at Świbno included the dead pieces of plants.

CCA analyses

Because we were interested only in species that live in benthic communities, we excluded all planktonic species from the analyses. In this case, only the 40 benthic diatom species that reached at least 3% relative abundance (considering benthic and planktonic species originally present in the sample) in at least one sample were included in the dataset.

A possible relationship between the diatom assemblages and the ecological variables was explored by the CCA analysis. The first two axes accounted for 63.9% of the variance. Axis 1 (eigenvalue = 0.51) is most closely associated with salinity as well as nutrient concentrations (nitrogen, phosphorus and silicon). The second axis is less important (eigenvalue = 0.16) and was primarily associated with temperature (T). A clear salinity gradient separates the samples to the left of axis 1, containing species with an affinity for brackish and marine water (e.g. *Amphora coffeaeformis* var. *coffeaeformis*, *Brebissonia lanceolata*, *Ctenophora pulchella*, *Navicula perminuta*, *Planothidium delicatulum* to those

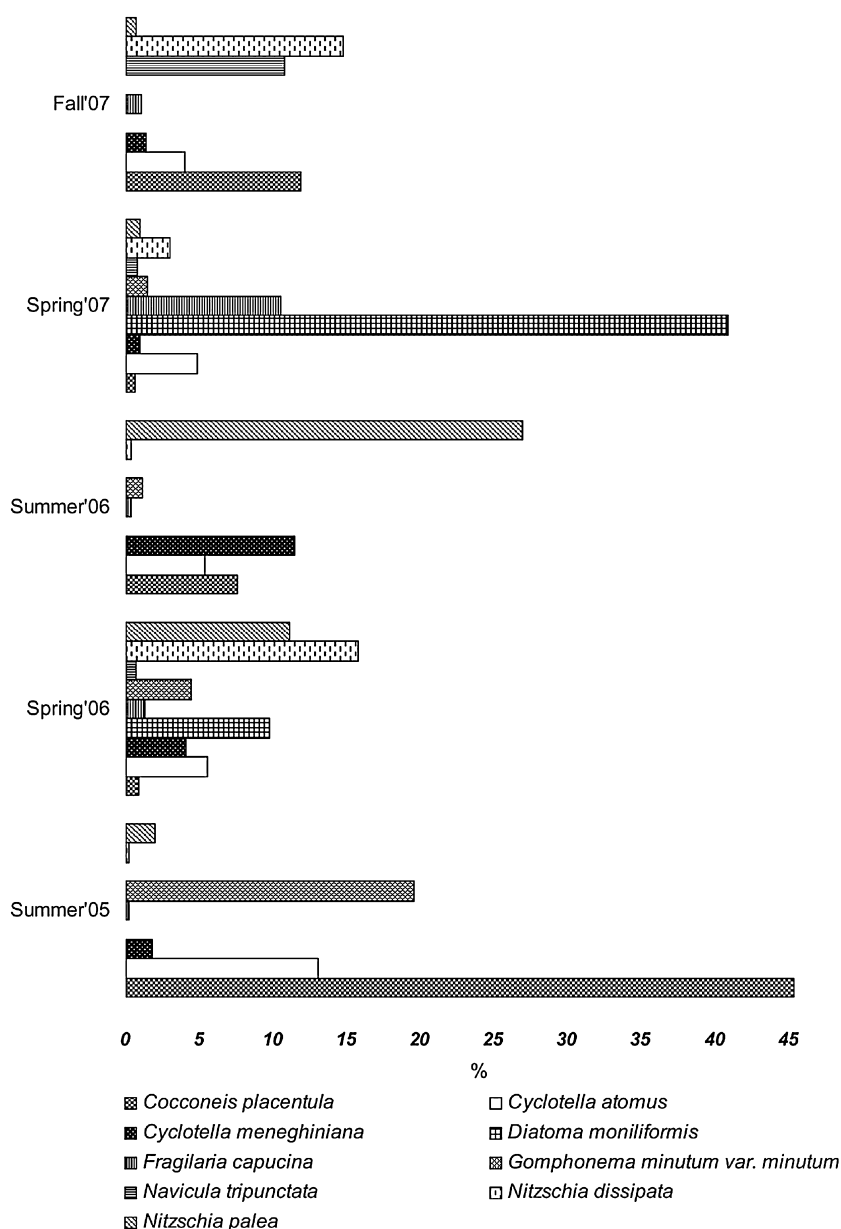


Fig. 5. Proportional relative abundances of the dominant diatom species inhabiting the surface of macroalgae and aquatic vascular plants in Świbno.

Table 3. Median and the average values of evenness and Shannon-Wiener (S-W) diversity indices calculated for samples collected from different substrates

Sampling site	Index	Sediment		Rocks		Macrophytes/aquatic plants		Without substrate distinction	
		Average	Median	Average	Median	Average	Median	Average	Median
Świbno	S-W	2.50	2.70	2.21	2.35	2.07	2.16	2.27	2.31
	evenness	0.69	0.73	0.64	0.67	0.62	0.66	0.68	0.70
Górki Zachodnie	S-W	2.93	3.19	2.38	2.34	1.22	1.22	2.46	2.65
	evenness	0.75	0.80	0.70	0.74	0.43	0.43	0.68	0.74

samples grouped on the right of axis 1 with mostly diatoms typical of freshwater bodies (*Amphora pediculus*, *Cocconeis placentula*, *Fragilaria capucina* var. *capucina*, *Navicula cryptotenella*, *Nitzschia linearis*). The major factor in differentiating the assemblages is

clearly salinity. The CCA biplot also confirmed the relationship between diatom assemblages and changes in nutrient concentrations, with species that prefer high and low biogenic substances concentration located at the extremes of the first CCA axis. Diatom communities

with an affinity for the lowest nutrient concentration were clustered at the negative end of axis 1. Taxa common in these assemblages were mainly those associated with brackish and marine waters as the salinity was negatively correlated with nutrient concentration. By contrast, diatom taxa with broad environmental ranges (e.g. *Amphora copulata*, *Navicula gregaria*, *Nitzschia microcephala*, *Nitzschia palea*, *Rhoicosphenia abbreviata*) were located at or near the centre of the CCA biplot (Fig. 6), indicating that they had no strong affinity towards any of environmental variables in the CCA.

Teratological forms of diatoms

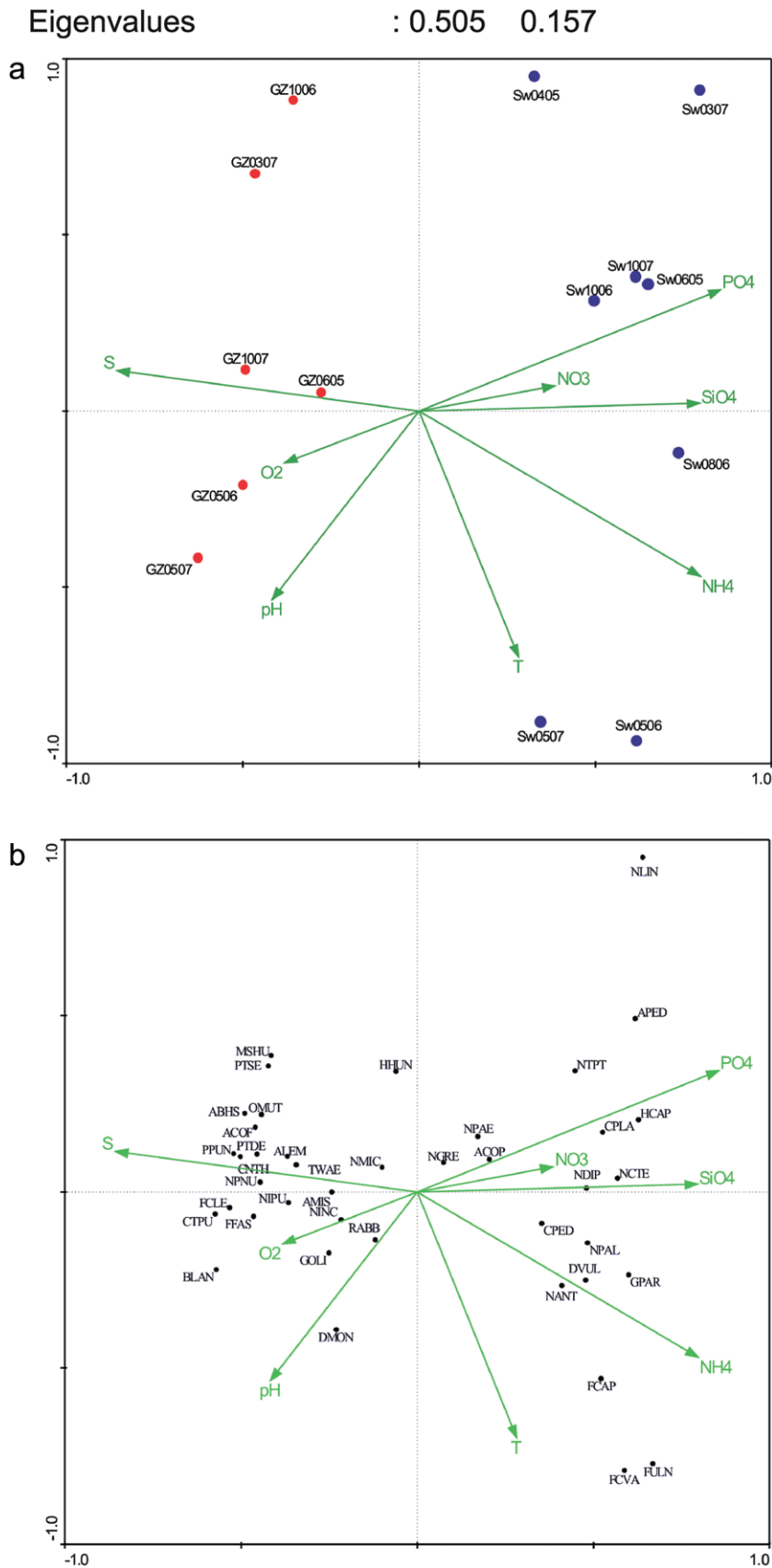
Even though analysis of the occurrence of teratological diatom forms was not one of the main aims of the present study, observations of malformed diatoms in the samples were made.

Incidence of valve deformities in examined populations was observed in 48% of the analyzed samples. Malformations occurred in several individuals of nine species. Abnormal outline morphology and ornamentation deformities were observed in specimens of the taxa: *Cocconeis pediculus* (8.3% of the *C. pediculus* individuals found in the peryphyton sample collected on 14 August 2006 showed aberrant morphology), *Encyonema caespitosum* (22.2% of the *E. caespitosum* individuals found in the peryphyton sample collected on 11 October 2007), *Fragilaria capucina* var. *vaucheriae* (40% of the *F. capucina* var. *vaucheriae* individuals found in the epilithic sample collected on 8 May 2007), *F. fasciculata* (6.7% of the *F. fasciculata* individuals found in the peryphyton sample collected on 8 May 2007), *F. ulna* (4.5% of the *F. ulna* individuals found in the peryphyton sample collected on 24 May 2006), *Gomphonema parvulum* (6.7% of the *G. parvulum* individuals found in the peryphyton sample collected on 30 June 2005) and *Nitzschia palea* (1.4% of the *N. palea* individuals found in the peryphyton sample collected on 14 June 2006) from Świbno station and *Diatoma moniliformis* (6.1% of the *D. moniliformis* individuals found in the peryphyton sample collected on 8 May 2007), *Fragilaria fasciculata* (1.4% of the *F. fasciculata* individuals found in the epilithic sample collected on 8 May 2007; 5.3% in the epilithic sample collected on 25 May 2006; 16.7% in epilithic sample collected on 29 June 2005; 18.2% in epipsammic sample collected on 8 May 2007; 40% in epipsammic sample collected on 30 October 2006), *Tabularia waernii* (15.8% of the *T. waernii* individuals found in the peryphyton sample collected on 29 June 2005; 40% in epipsammic sample collected on 25 May 2006) from Górkki Zachodnie (Fig. 7). Generally, the percentage of teratological forms in the total assemblages, involving all valves counted in the sample col-

lected at certain time and location, was relatively low (0.18–1.1%) and only in peryphyton sample collected in Górkki Zachodnie on 8 May 2007 did it exceed 1%. A slightly higher value of relative abundance of deformities characterized the material from Górkki Zachodnie, where the abnormal valves were present in samples of every analyzed substratum type. In the material from Świbno, teratological forms have been found in all samples of peryphyton growing on macroalgae and vascular plants and in one sample scraped from a rock substratum. No abnormal valves were found in the sediment samples. A significant increase in the percentage content of teratological forms of diatoms has been noted from spring to autumn at both stations.

Formation of diatom cells with deformed cell wall morphology and/or with deformed valve wall ornamentation is still a relatively unknown issue. Extensive research conducted so far has shown that described malformations are the result of unfavorable environmental factors affecting the cell in its initial phase of growth, during both post size regeneration via sexual reproduction and mitotic division (Siemińska 1964; Round *et al.* 1990). However, it is still unclear which of the potentially important factors is determinant of malformations and defect development, what the mechanism of this phenomenon is and if or how the deformities are affecting the physiology of the diatom cell (Falasco *et al.* 2009). Moreover, it is difficult to induce valve abnormalities in culture so few laboratory studies of the causes of deformations have been conducted. Thus, the literature base is scarce and few conclusions can be drawn (Berland *et al.* 1977; Baars 1982; Jahnke & Baumann 1983; Estes & Dute 1994).

As many investigators have implied, an increase in the percentage of aberrant diatom cells in a given population may be connected with a high concentration of heavy metals, e.g. Cu, Cd, Ni, Zn, Cr or Pb (Yang & Duthie 1993; Dickman 1998; Ruggiu *et al.* 1998; Fore & Grafe 2002; Guasch *et al.* 2002; Cooper *et al.* 2003; Nunes *et al.* 2003; Cattaneo *et al.* 2004; Szabó *et al.* 2005; Sgro *et al.* 2007; De Jonge *et al.* 2008; Duong *et al.* 2008; Morin *et al.* 2008a,b,c; Tapia 2008). Other potentially teratogenic factors that have been described from diatom cultures and natural populations are: high temperature (Baars 1982), salinity (Schmid 1979; McMillan & Johansen 1988), increase in nutrient concentration (Kling 1993) as well as nutrient deficiency (Cholnoky-Pfannkuche 1971), increased organic matter concentration in substratum (Witkowski 1991; Bogaczewicz-Adamczak *et al.* 2001, Dziengo-Czaja *et al.* 2008) and other toxic agents, like pesticides, fertilizers, polycyclic aromatic hydrocarbons (PAH) (Rimet *et al.* 2004) or colchicine. Significantly increased abundances of abnormal frustules observed, especially in algal cultures, could be also related to high cell density (Debenest *et al.* 2008). Feldt *et al.*



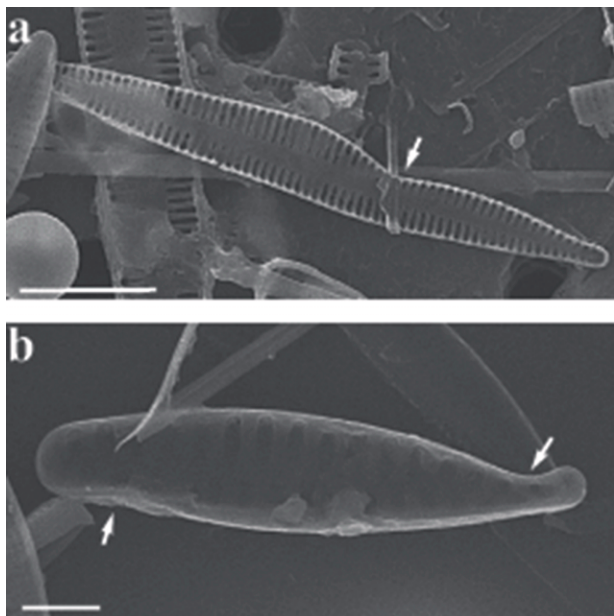


Fig. 7. Deformed valves of *Fragilaria fasciculata* (a) and *Opephora mutabilis* (b). Arrows indicate abnormal transapical asymmetry.

(1973) suggested substrate chemistry was a causative agent of such abnormalities (after Stoermer 1998), while Antoine and Benson-Evans (1984) as well as Cabrol *et al.* (2004) state that the induction of observed deformed frustules was strictly associated with increased light intensity and high UV radiation.

As noted previously, teratological forms of diatoms were not the main object of interest in the present research, therefore no additional analyses that could help to identify the teratogenic factor were made. Nevertheless, using data on circumstances of the abnormal valves occurrence, information about the research area and general knowledge of diatoms, the attempt of indicating the most probable malformations inductor that has been responsible for the observed anomalies has been made.

Research led by Bogaczewicz-Adamczak and Dziengo (2003) and Dziengo-Czaja *et al.* (2008) on the littoral zone of Puck Bay (western part of the Gulf of Gdansk) suggested that the presence of diatom valve deformities in the surface sediments was connected with high concentrations of organic matter and also with an increase in biogenic compound concentrations, especially phosphates and nitrites. Similar results were obtained by Stefaniak (1998) during his work on water quality assessments of Karlikowski stream, which empties into the Gulf of Gdansk. Teratological forms of *Fragilaria fasciculata* were present in high abundance in samples with high concentrations of ammonium nitrogen and nitrites.

As Dziengo-Czaja *et al.* (2008) have argued, the spring peak in teratological forms could be an effect of low oxygen concentration in the water after ice melt, while a summer increase in the incidence of deformities could have resulted from cyanobacterial blooms that have been followed by high concentrations of organic matter and biogenic substances in the substratum. However, in the present study, no clear relationship between oxygen concentration or biogenic substances and abnormal valves number could be found. Potential teratogenic factor could be the ammonia concentration, since its relatively slight increase co-occurred with an increase in the number of deformities in most of the cases analyzed. Still, it is worth noting that results reported in the literature from examination of teratological forms of diatoms collected from the Gulf of Gdansk or in its vicinity were based on analyses of sediment samples only.

At Górki Zachodnie station, where the abnormal frustules quotas were steadily higher, water was characterized by visibly higher transparency compared with those found in Świbno (personal observation). Lower water turbidity could be a direct effect of the fact that mainly sandy fractions were covering the bottom of the Górki Zachodnie sampling site. When the relatively large and heavy grains of sand undergo fast redeposition on the bottom surface, fine grains that form a silty fraction remain suspended in the water column for much longer, considerably limiting the water transparency (Wood & Armitage 1997). Transparent water maximizes the penetration of solar rays and offers less protection from UV radiation and shallow-water benthic communities are particularly sensitive. Periphyton covering rocks and plants includes many immobile species, which cannot seek low UV refuges unlike sediment-dwelling organisms, which are able to migrate horizontally and vertically in the substratum (Happley-Wood 1988; Vincent *et al.* 1993). This could be an explanation for the high number of deformities that occurred in epiphytic and epilithic communities and their seasonality – anomalies were noted from spring to autumn, at the time of the highest UV radiation. At Górki Zachodnie station, in contrast with Świbno, deformed diatom cells were observed also in the sediment, which could be due to the higher water transparency and a different kind of sediment covering the bottom. In spite of the similar depth that all samples have been collected, organisms inhabiting the bottom of Górki Zachodnie could be subjected to the unfavorable effect of UV radiation to a higher degree. It is possible, due to the quartz crystals transparency, that the radiation penetrated also into deeper layers of the shallow water sediments, while silty bottoms are known to be much more absorbent (Kawecka & Eloranta 1994; Garcia-Pichel & Bebout 1996). The probability of developing atypical forms among diatoms seems to be enhanced by increased UV

irradiation (Antoine & Benson-Evans 1983, 1984). Sharp light intensity changes that cause cell damage, can occur relatively often in natural environments. Baars (1982) reported that rain and cloudy weather can reduce the light intensity at a 5 m depth from 18 000 Lux to 4000 Lux in a few minutes. Many aquatic species are not able to adapt themselves to such rapid changes. However, the relationship between the presence of abnormal frustules and UV radiation exposure is difficult to establish in natural aquatic environments. This is because of the medium heterogeneity (various chemical substances and organic matter present in water limit radiation to a different and hard to determine degree) and the difficulty to monitor the real UV irradiation, to which algae are exposed (Garcia-Pichel & Bebout 1996). Furthermore, higher quotas of deformities noted in Górki Zachodnie may be the result of a combination of detrimental physical and chemical factors, which were affecting the benthic organisms especially when the water level had been changing. In contrast, such distinct water level changes have never been observed in case of the other sampling site (Świbno) (personal observation). According to Stoermer and Andresen (2006), abnormalities in diatom valve morphology often appeared in communities associated with habitats that periodically desiccate and, in general, in all populations living in unstable environmental conditions (Schmid 1979), that are typical for many estuarine regions (Jahnke & Baumann 1983).

CONCLUSIONS

The present study is the first examination of benthic diatom composition and distribution from this part of lower Vistula, that is, the Vistula estuary. The diatom flora of the region proved to be heterogeneous. Salinity was the most important influence on diatom community dissimilarities between sites located in different branches of the Vistula river mouth. Future research of this ecological site may clarify the importance of biogenic substances on algal floral diversity. Substratum type appeared to play a fundamental role in determining the taxonomical and ecological differences in estuarine diatom communities. Sandy sediments seemed to be the substratum that was especially conducive to diatom species richness, while communities living on macroalgal hosts were marked by low species diversity. Deformed valves that were found at both of the sampling sites from spring to autumn, were particularly abundant among the epiphytic and epilithic diatom communities.

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