Oceanological Studies
No. 2–3

Polish Academy of Sciences
National Scientific Committee
on Oceanic Research

(39–59)
1997

PL ISSN 0208-421X
Institute of Oceanography
University of Gdańsk

TEMPORAL AND SPATIAL VARIATIONS IN PARTICLE CONCENTRATIONS AND SIZE DISTRIBUTIONS IN THE GULF OF GDAŃSK

KATARZYNA BRADTKE, ADAM LATAŁA, PIOTR CZABAŃSKI

Institute of Oceanography, University of Gdańsk,
Al. Marszałka Piłsudskiego 46, 81-378 Gdynia, Poland

Key words: Gulf of Gdańsk, suspended particles, particle size distribution

Abstract

Measurements of suspended particle (diameter in the 4–30 μm range) concentrations and their sizes (using a Multisizer II Coulter Counter) carried out in the Gulf of Gdańsk from May 1992 to December 1993 were used for studies of the temporal and spatial variability of particle size distributions. The quantity of suspended particles in Puck Bay waters was characteristically less variable both in the vertical and in the horizontal than was the open Gulf of Gdańsk, which is influenced to some extent by the waters of the river Vistula. In Puck Bay, surface particle concentrations were usually in the range $1.6 \cdot 10^3$–$1.0 \cdot 10^4$ cm^{-3}, in the open Gulf of Gdańsk they were $1.6 \cdot 10^3$–$2.0 \cdot 10^4$ cm^{-3}. The Vistula strongly influenced the concentration of larger particles and the shape of the particle size distribution curves just off the river mouth.

The particle size distribution curves characteristic of the Gulf of Gdańsk display, in general, the hyperbolic shape typical of marine suspensions. In waters with a relatively high concentration of particles, some additional increase in particle number in the diameter range of 10–20 μm or just below 10 μm was recorded.

During the year, three periods of maximum particle concentrations occurred. Two of them, in spring and autumn, were found to be related to maximum chlorophyll *a* concentrations. The best correlation between particle numbers and chlorophyll *a* content was found for particles with diameter D>10 μm for two classes of suspensions: with high ($r = 0.88$) and low ($r = 0.82$) particle concentrations occurring in the presence of the same chlorophyll *a* concentration.

INTRODUCTION

The concentration of suspended particulate matter in seawater is related to the basic biological, chemical and physical processes occurring there. Suspended particles regulate the light energy available for photosynthesis and play an important role in the solid-liquid phase exchange of substances or their transport in the sea. The extent to which suspended particles influence these processes depends strongly on their concentration in the water column and their size distribution, *i.e.* the number of particles in a given volume of water as a function of their diameters.

Marine suspended matter consists of organic (cells and fragments of marine organisms) and inorganic (mostly terrigenic material) particles originating from a variety of sources such as marine biological production, fluvial input, sediment erosion and atmospheric transport of particles from land. Seasonal cycles of biological activity and terrigenous run-off of suspended matter are responsible for the significant spatial and temporal variations in the concentrations and physical properties of particles.

In oceans and seas where biological production is a significant source of particles, their size distributions are typical, and are described in detail in Carder *et al.* 1971, Zalewski 1977, Jonasz 1983, and Jonasz *et al.*1996. Particle size distributions in the Baltic Sea have been analysed by Jonasz & Zalewski 1977, Jonasz 1980, 1983. For Baltic waters these authors proposed to approximate the particle size distribution curve by means of a hyperbolic function, although in a slightly more complicated form than is applied to oceans. Since in coastal regions like the Gulf of Gdańsk, suspended particles originate mainly from terrestrial sources such as rivers or sewage outfalls, the properties of suspended particles may differ significantly from the typical (Jonasz 1983, Eisma *et al,*.Kalf 1987). Numerous investigations show that the river Vistula has a strong influence on the physical and chemical properties of the Gulf of Gdańsk waters (Majewski 1990), so this influence is expected to be important as regards suspended matter concentration and particle size distributions close to the river mouth.

This paper presents the preliminary results of studies on the spatial and temporal variability in particle concentrations and size distributions in the south-western Gulf of Gdańsk.

MATERIAL AND METHODS

The data discussed here were collected during 1–3 day expeditions every month from May 1992 to December 1993 with the exception of January and February 1993. The transects at Jastarnia, Puck, Mechelinki, Sopot, Gdańsk, Świbno, Stegna and Krynica Morska in the Gulf of Gdańsk are illustrated in Fig. 1. At least two stations along each transect were sampled at the surface, near the bottom and at

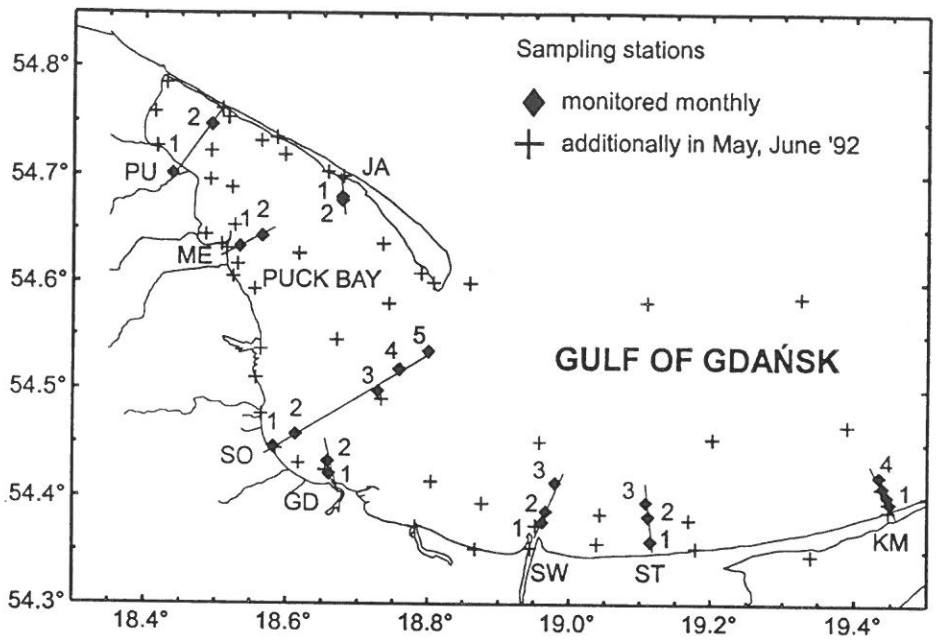

Fig. 1. Localisation of sampling stations
Capital letters denote names of sampling profiles as follows: PU – Puck, ME – Mechelinki, JA – Jastarnia, SO – Sopot, GD – Gdańsk, SW – Świbno, ST – Stegna, KM – Krynica Morska

intermediate depths determined by depths of 0, 5, 10, 15, 20, 25, 30, 35 m (the number depended on the depth at the station). In order to analyse the spatial distribution of particle concentrations in detail, samples from about 40 additional stations were collected at the surface layer in May and June 1992.

In order to estimate particle numbers and sizes, the samples were analysed with a Multisizer II Coulter Counter (method described in Coulter 1985). This was calibrated using filtered (Sartorius 0.2 μm) Baltic seawater with the addition of a Latex suspension (calibration standard – E36). If measurements could not be completed within a few hours after sample collection, they were frozen (volume *ca* 100 ml) on board the ship and analysed later. Using the manometer siphon method, a Coulter counter with a 200 μm orifice and 2000 μl sample volume were used to measure the number of particles per unit volume for 52 size classes of equivalent spherical diameter in the 4–30 μm range. In order to estimate the size of an irregularly-shaped particle, the equivalent spherical diameter was defined as the diameter of a sphere with a volume equal to that of the particle. To limit errors resulting from the inhomogeneous distribution of particles in a water sample, the average particle concentration in every size class of at least 3 measurements was

used to determine the particle size distribution. 296 samples from standard stations and 86 from additional ones in 1992, as well as 322 samples in 1993 were analysed.

The particle size distribution function *F(D)* is defined by the equation

$$dN = F(D)dD, \tag{1}$$

where *dN* is the number of particles with diameter *D* in the range *(D,D+dD)* per unit volume of seawater

The particle size distribution function was determined by differentiating the cumulative particle size distribution *C(D)* expressed by

$$C(D) = \int_D^{\infty} F(D')dD' \tag{2}$$

where *C(D)* is simply the particle number per unit volume for particles with a diameter greater than *D*

F(D) computed by differentiation (given by Jonasz 1983) and histogram $\Delta H(D,\Delta D)$ show an excellent goodness of fit (Fig. 2). The histogram is a set of average values of *F(D)* in each diameter increment ΔD defined as follows:

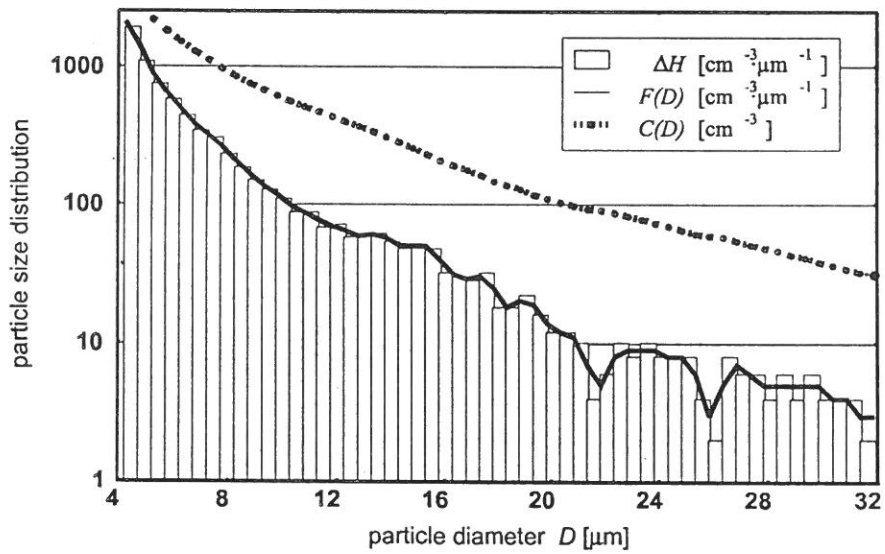

Fig. 2. Particle size distribution characteristic for the Gulf of Gdańsk presented in various manners (in semi-logarithmic scale): as a histogram, ΔH; differential distribution, *F(D)*; cumulative distribution, *C(D)*

$$\Delta H(D,\Delta D)=\left|\frac{C(D+\Delta D)-C(D)}{\Delta D}\right| \tag{3}$$

In further descriptions of the particle size distribution, the differential particle size distribution was used. For the purposes of interpretating the results, measurements of chlorophyll *a* (methods presented in Latała 1993) and suspended matter (standard techniques given by Kramer *et al.* 1994) concentrations were used. The chlorophyll *a* content was measured in the same samples as the particle concentration but only in the surface layer. Suspended matter concentration was determined only at a few stations and depths from June 1992 to April 1993.

RESULTS

The concentration of particles measured in south-western Gulf of Gdańsk in the surface layer ranged from $1.6 \cdot 10^3$ to $3.7 \cdot 10^4$ cm^{-3} but in most cases did not exceed $2.0 \cdot 10^4$ cm^{-3} (Table 1). An example of the surface distribution of particle concentration interpolated from the largest set of values, measured on 20–21 May 1992, is given in Fig. 3a. The highest values were recorded in the open part of the Gulf of Gdańsk. Quantities of particles > $2.0 \cdot 10^4$ cm^{-3} were recorded only near

Table 1

Statistical characteristics of suspended particles concentration expressed in [cm^{-3}] into surface layer at investigated profiles MIN-minimum, MAX-maximum, MEAN-average value, SD-standard deviation, n-number of samples

year	profile	MEAN	MIN	MAX	SD	n
1992	Puck	8022	2900	16407	5935	4
	Mechelinki	5435	748	13434	4362	12
	Jastarnia	6161	1724	20904	5823	12
	Sopot	8314	1683	19243	5818	33
	Gdańsk	10343	2311	23367	7705	12
	Świbno	16603	6181	30507	6936	15
	Stegna	13081	6385	22497	4790	10
	Krynica Morska	13199	4321	20681	5645	21
1993	Puck	4456	2713	6911	1244	10
	Mechelinki	5139	2086	13264	3074	14
	Jastarnia	5607	1924	10162	2335	20
	Sopot	7577	2238	19433	4653	32
	Gdańsk	7486	1600	14512	4473	12
	Świbno	22664	10636	34153	8764	10
	Stegna	17872	6767	37212	11544	7
	Krynica Morska	7503	3511	13734	2770	15

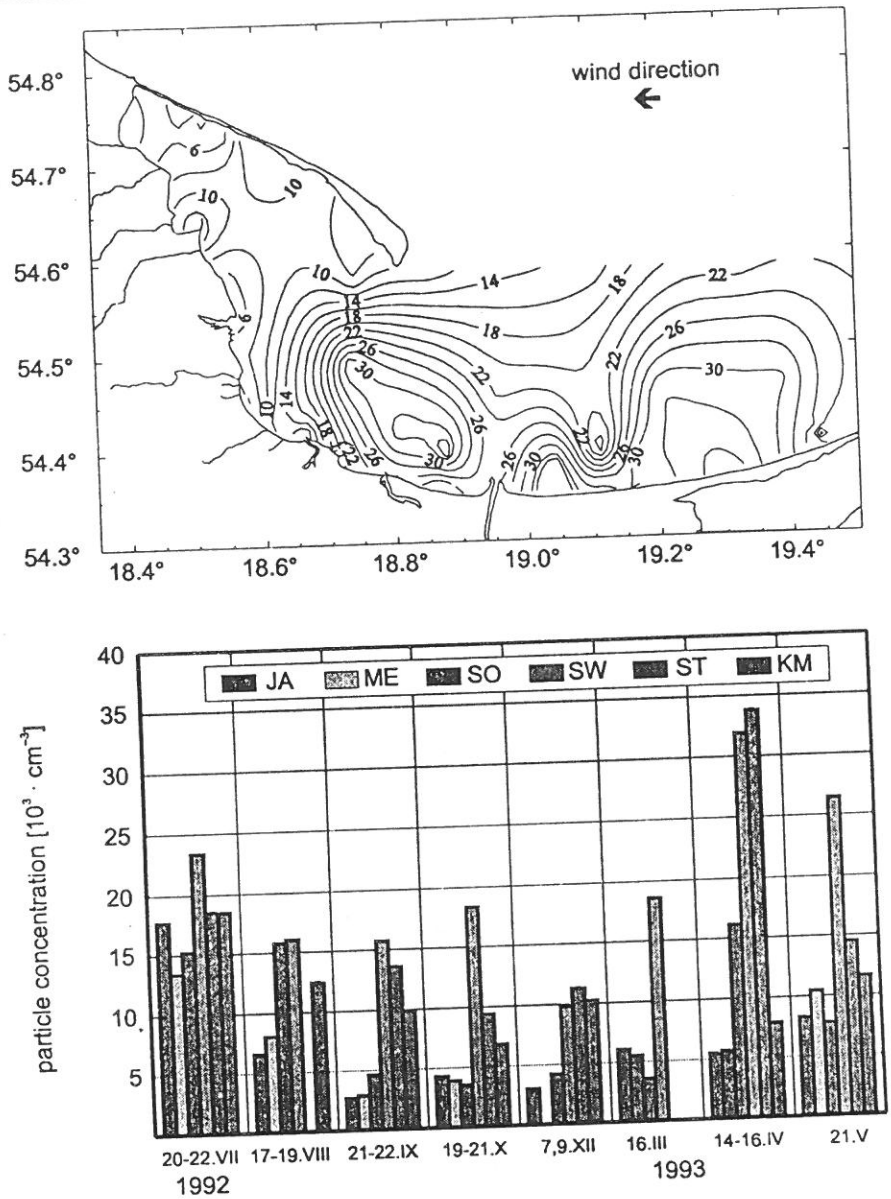

Fig. 3. Concentration of particles [$10^3 \cdot cm^{-3}$] with diameter D in the range of 4–30 μm: (a) surface distribution in 20–22 May 1992, (b) averaged in profiles: PU – Puck, ME – Mechelinki, JA – Jastarnia, SO – Sopot, GD – Gdańsk, SW – Świbno, ST – Stegna, KM – Krynica Morska

the Vistula mouth in spring and summer (April – August). At Krynica Morska (station 3) and Stegna (stations 2 and 3) concentrations were relatively high in December 1992.

In Puck Bay, in most events (> 84%), concentrations were < $1.0 \cdot 10^4$ cm^{-3}. Somewhat higher values (max. $2.1 \cdot 10^4$ cm^{-3}) were measured in this region in spring and summer (April – July) near terrestrial sources of particles, such as the sewage outfall at Mechelinki, the mouth of the river Reda, the Port in Gdynia, and occasionally at Jastarnia.

Except at Świbno, where the particle concentration was always relatively high (Fig. 3b), the numbers of particles in the autumn and winter in all transects were lower (up to three times in November and December) than in the spring and summer.

The numbers of suspended particles tended to increase near the surface, and to decrease with depth, something that was particularly apparent in the open part of the Gulf of Gdańsk. Within the surface layer concentrations were up to three or even four times as high as those deeper down. On occasion, the quantity of particles in the near-bottom water rose somewhat, primarily due to the resuspension of bottom sediments. At some deeper stations in summer, after the thermocline had formed, the particle concentration rose slightly in the layer just above the maximum thermal gradient depth (Fig. 4).

The number of particles suspended in the whole water column generally decreased rapidly with increasing particle diameter (Table 2). On average, particles with a diameter <10 μm made up 80% of the total number in the water.

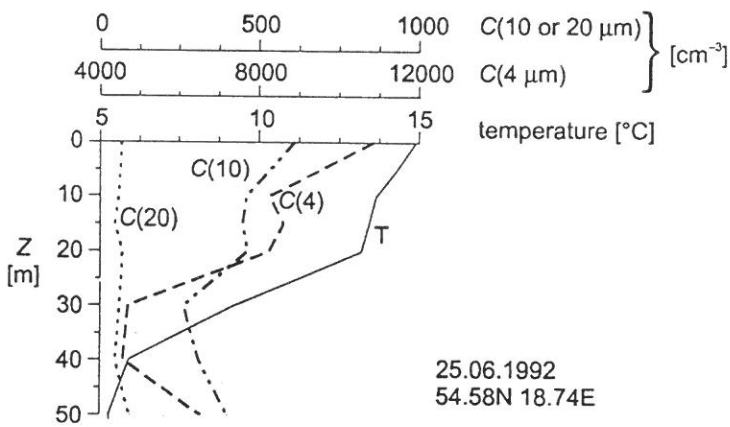

Fig. 4. Vertical distributions of particles concentration (particles with D>4, D>10, D>20 μm respectively) and temperature in 25.06.1992 at 54.58N 18.74E location as an example of characteristic distribution for deep stations in summer

The particle size distributions show that there were two principal types in the study area: 1) the hyperbolic distribution, typical of marine suspensions, and 2) the distribution characterised by the maximum particle number overlapping the hyperbolic distribution in the 10–25 μm diameter range. Both types were recorded in the whole area sampled but type 1 were dominant in the particle size distributions measured. The relationship of types to suspended particle concentration was significant. Type 2 distributions occurred at high particle concentrations (30% of the distributions measured in spring), whereas type 1 were prevalent when these were low. In the open Gulf of Gdańsk, bell-shaped particle size distributions with a maximum of *ca* 10 μm in May and June 1992 and April 1993 were occasionally recorded (Fig. 5).

There are considerable differences between the mean particle size distributions evaluated for Puck Bay and the open Gulf of Gdańsk (Fig. 6), particularly with respect to particles of diameter D <20 μm. The particle size distribution curve in this range of particle diameters for Puck Bay is steeper than for the other part of the study area.

A characteristic feature of the larger particle concentrations were the relatively high values close to river mouths, which decreased rapidly with increasing

Table 2

Statistical characteristics of the particles number, ΔN, expressed in [cm^{-3}], integrated in 2 μm width size classes (samples from whole water column) measured from V '92 to XII '93ΔD *denotes range of diameters; other symbols like in Table 1; n=208 for Puck Bay and 492 in the open part of the Gulf of Gdańsk*

ΔD	PUCK BAY				GULF OF GDAŃSK, THE OPEN PART			
[μm]	MEAN	MIN	MAX	SD	MEAN	MIN	MAX	SD
(4 ; 6]	4396	393	22421	3187	60837	404	21435	3807
(6 ; 8]	1159	115	10316	1110	2113	138	11744	1924
(8 ; 10]	480	56	5092	541	981	66	8092	1142
(10 ; 12]	246	37	3479	303	519	36	5281	712
(12 ; 14]	153	26	2702	222	314	19	3602	459
(14 ; 16]	104	19	2268	176	203	11	2389	311
(16 ; 18]	72	8	1870	146	122	11	1802	198
(18 ; 20]	54	7	1530	143	74	8	1039	117
(20 ; 22]	37	4	1244	103	49	4	779	78
(22 ; 24]	24	3	984	70	35	2	591	54
(24 ; 26]	17	2	770	54	24	2	440	38
(26 ; 28]	13	0	570	40	17	0	336	28
(28 ; 30]	10	0	428	30	13	1	235	21

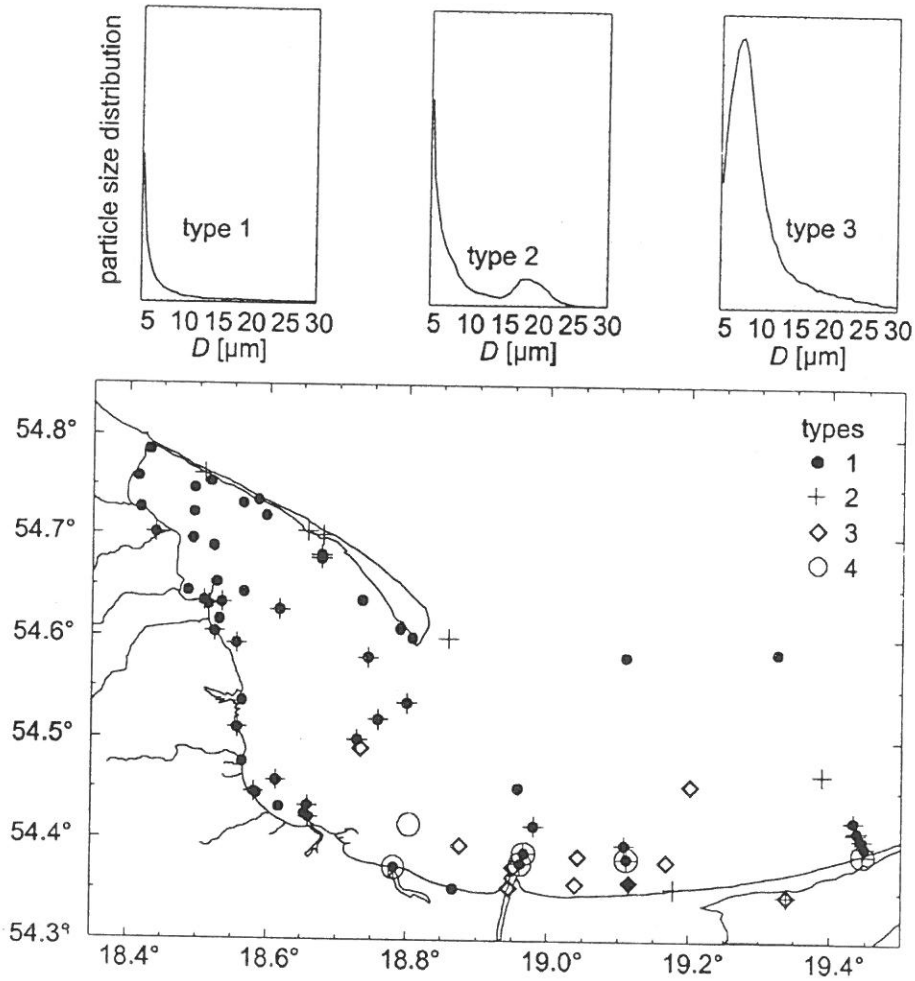

Fig. 5. Locations where different types of particle size distribution curves were observed (V '92-XII '93)
1-hyperbolic, 2-hyperbolic with additional maximum about 10-25 μm, 3-bell-shaped, 4-others

distance from the particle source. This becomes clearer when one uses standardised concentrations according to:

$$X_{ST}(t) = \frac{X(t) - E(X)}{S(X)}, \tag{4}$$

where $X(t)$ is a random variable (here, the measured concentration of particles in a given size class), $X_{ST}(t)$ is the standardised random variable, $E(X)$ and $S(X)$ are the mean and standard deviation of X

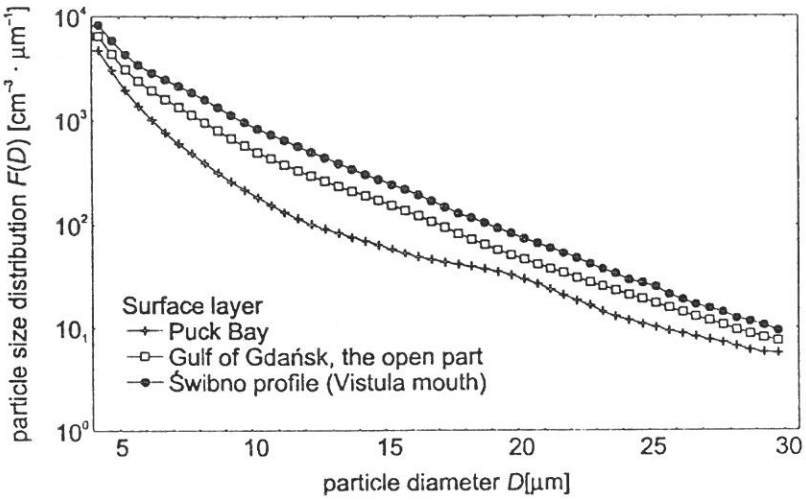

Fig. 6. Mean particle size distributions in surface layers of different parts of the Gulf of Gdańsk (V '92-XII '93)

In the 20–30 µm diameter range, relatively high numbers of particles in the water were recorded no farther than 2 km from their terrrestrial sources. The number of larger particles (D>10 µm) rose significantly only in April and May 1993 (Fig. 7).

The mean particle size distributions in Puck Bay varied only slightly with increasing depth (Fig. 8). Only particles with D>15 µm decreased significantly in concentration below the surface. In the subsurface layer of the open Gulf of Gdańsk, particle concentrations were higher over the entire range of diameters investigated. Gradients were steepest in the 0–5 metre layer. Off the Vistula mouth concentrations of the particles with D<15 µm were high only in the surface layer, whereas those of larger particles down to 10 m.

DISCUSSION

Two principal processes govern the distribution of suspended matter concentrations in the Gulf of Gdańsk. They are the run-off of suspended matter from terrestrial sources, and exchange of water with the open sea, the latter process being obstructed to some degree by the Hel Peninsula. Additionally, during periods of high biological production the amount of suspended particles in the water may be affected by the presence of phytoplankton and zooplankton cells (Krężel *et al.* 1987, Krężel *et al.* 1993). The south-western Gulf of Gdańsk receives suspended

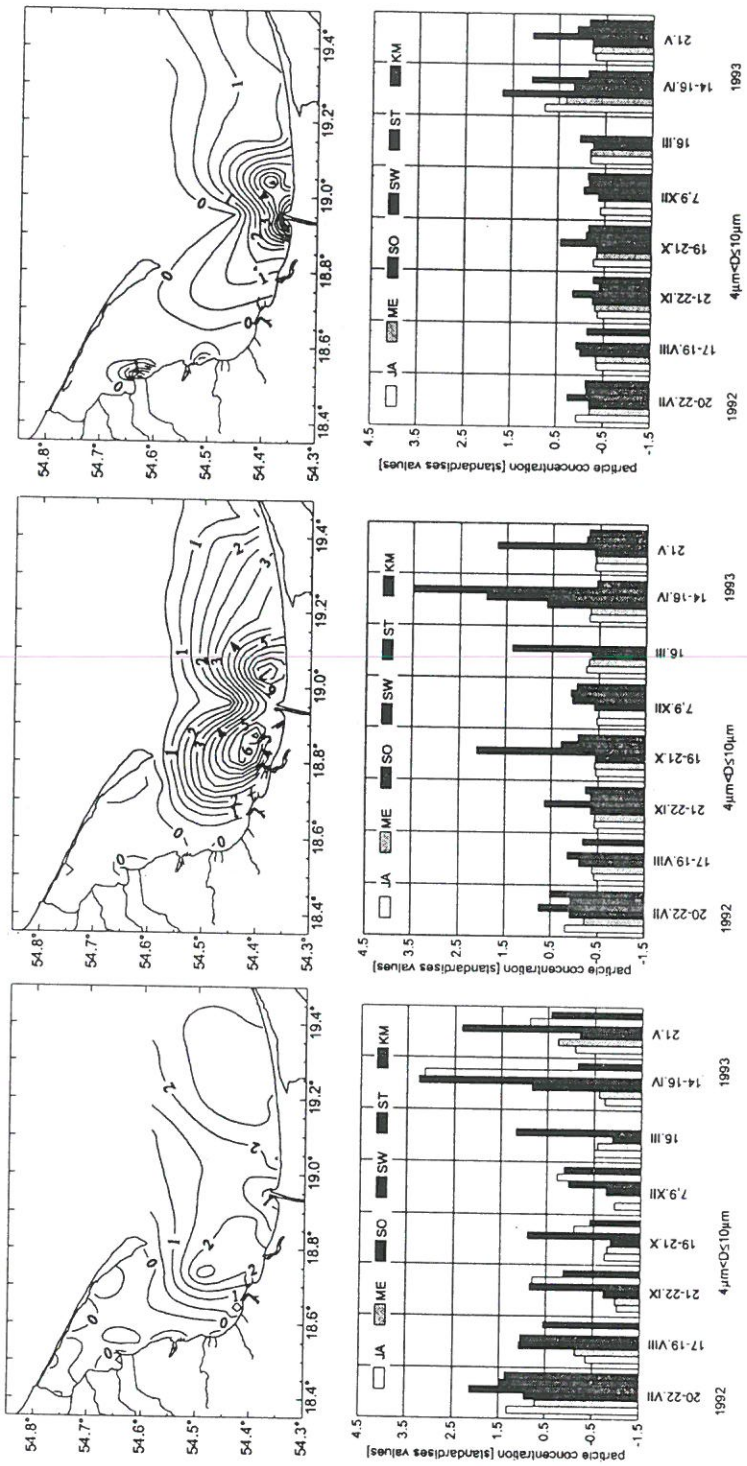

Fig. 7. Concentration of particles [standardised values] in three ranges of particles diameter: 4-10, 10-20 and 20-30 µm: (a) surface distribution in 20–22 May 1992, (b) averaged in profiles: PU – Puck, ME – Mechelinki, JA – Jastarnia, SO – Sopot, GD – Gdańsk, SW – Świbno, ST – Stegna, KM – Krynica Morska

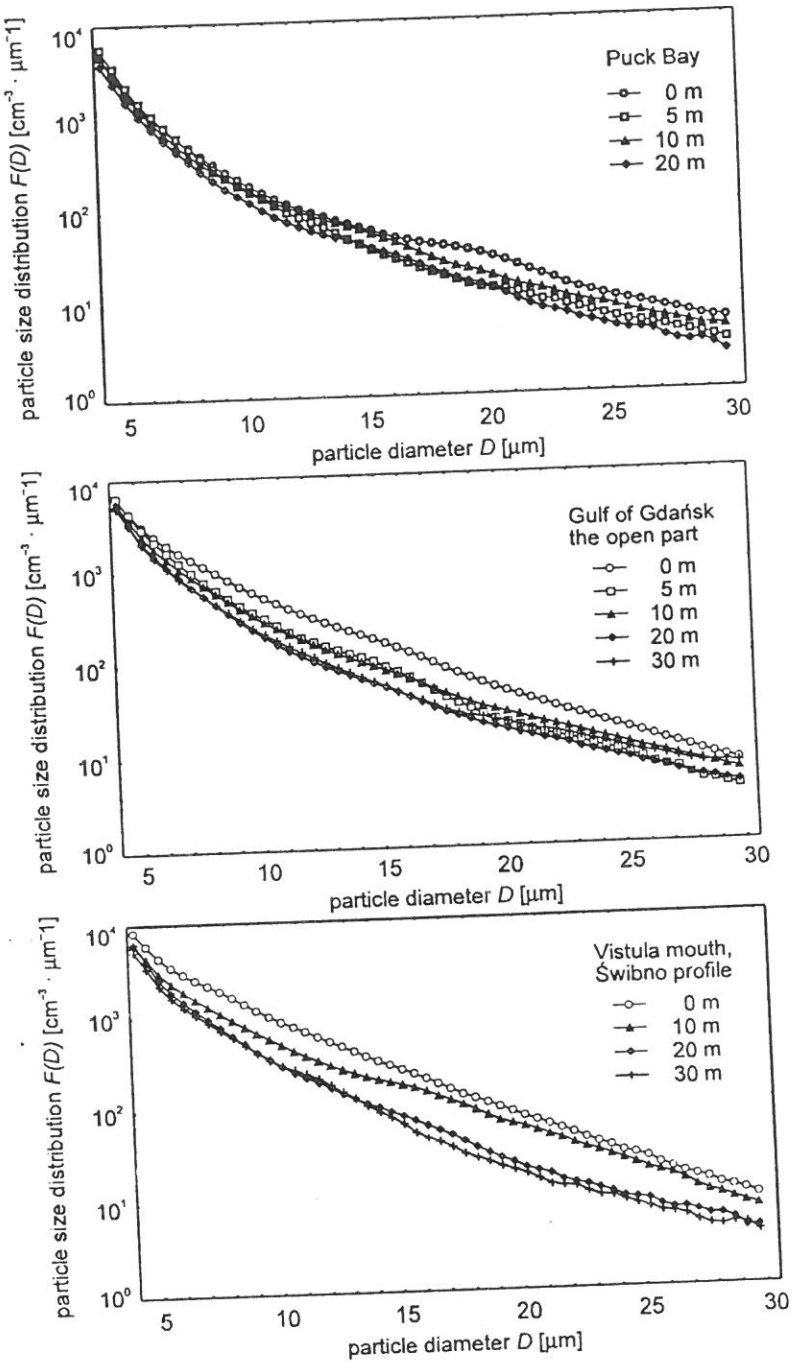

Fig. 8. Mean particle size distributions on different depths in Puck Bay, the open part of the Gulf of Gdańsk and area close to the Vistula River mouth (V '92-XII '93)

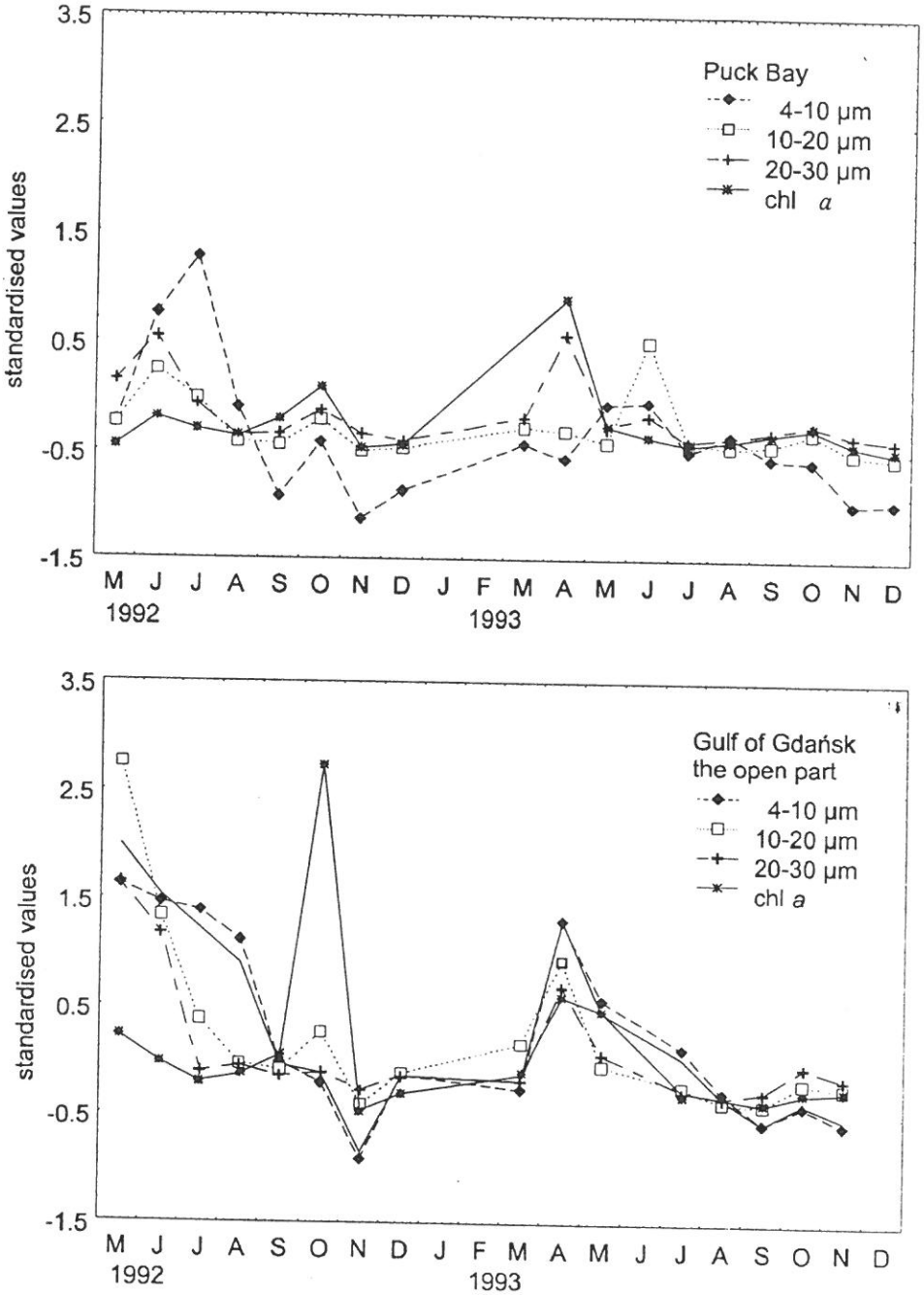

Fig. 9. Temporal variability of monthly means of standardised concentration of particles with diameters in the ranges: 4-10, 10-20, 20-30 µm and chlorophyll *a* in surface layer of Puck Bay and the open part of the Gulf of Gdańsk

matter from terrestrial sources such as the Vistula mouth, the ports of Gdańsk and Gdynia, the Mechelinki sewage outfall and the river Reda.

The spatial distribution of concentrations of particles with D = 4–30 μm measured in the Gulf of Gdańsk displayed the same pattern as those of the long-term, mean suspended matter concentrations (Krężel *et al.* 1993), water transparency (Sagan 1992) and chlorophyll *a* concentration (Latała 1993, 1994). In the open Gulf of Gdańsk the influence of the Vistula waters on the particle concentration was evident. In Puck Bay, the lower suspended particle content and its rather uniform distribution both in the horizontal and in the vertical was due to the relatively lower inflow of suspended matter from the land, and the shallow depth (av. 3–5 m), causing the water to be stirred up from surface to bottom. The data on particle concentrations in the surface layer of the south-western Gulf of Gdańsk show that major distinctions can be drawn between Puck Bay, where characteristic concentrations lie between $1.6 \cdot 10^3$ and $1.0 \cdot 10^4$ cm^{-3} , and the open Gulf of Gdańsk, where the range is $1.6 \cdot 10^3 - 2.0 \cdot 10^4$ cm^{-3}. For comparison, the particle concentration characteristic of southern Baltic waters (D = 4–30 μm) given by Jonasz (1983) is *ca* 10^3 cm^{-3}. In the Gdańsk Deep, Falkowska and Latała (1995) found the mean particle concentration to be *ca* $8.0 \cdot 10^3$ cm^{-3} in June 1992 (when the zooplankton population was burgeoning following the phytoplankton bloom).

The direction and range of spread of suspended matter originating from terrestrial sources depends on the amount of fluvial inflow and the characteristics of the local water dynamics. A favourable wind direction may spread Vistula waters rich in suspended matter as a thin surface layer (due to the density difference) far from the river mouth (Jankowski 1984, Staśkiewicz *et al.* 1995); however, the suspended particle concentration should decrease with increasing distance from the source because of dilution in water exchange processes and the sinking of particles (Fig. 7). According to Stokes' law, the rate of sinking of silica particles >5 μm in diameter is *ca* several metres per day and increases in proportion to the square of the particle diameter. In seawater, real particle sinking rates can even be twice as fast as those calculated from Stokes' law (Dera 1992). On the Świbno transect, the particle concentration measured at station number 2 (located 2.8 km offshore) in comparison to station number 1 (1.7 km offshore) was 1.15 and 1.2 times lower for particles in the 4–10 μm and 10-30 μm diameter ranges respectively, whereas at station 3 (5.7 km offshore) it was 1.3 and 1.7 times lower.

In the investigated area, suspended matter consisted mainly of small particles < 10 μm in diameter (about 80% of all the particles in the water), unlike the river water, where larger particles dominate. Cyberski (1982) found that particles > 10 μm in diameter make up *ca* 60% of the inorganic part of the suspended matter in Vistula water. Despite the significant influence of the Vistula on the small-particle concentration in the open Gulf of Gdańsk, rapid deposition of most of the suspended matter delivered by the river results in a weak correlation between the ses-

ton mass carried by the Vistula and the suspended matter concentration in the Gulf of Gdańsk beyond an area adjacent to the river mouth (Krężel *et al.* 1993).

Terrestrial sources supply the estuary not only with particles but also with the nutrients that control phytoplankton growth (*Vistula River...* 1992). In the Gulf of Gdańsk, the taxa, biomass and sizes of phytoplankton differ significantly during the year, producing variations in suspended particle characteristics and concentrations. Moreover, the phytoplankton biomass usually rises significantly (up to 0.2–0.5 gC · m^{-3}) in March and April as a result of the spring diatom bloom; in autumn, usually in October, there is a somewhat smaller rise brought about by a second diatom bloom (Pliński *et al.* 1985, Witek 1995). The whole biomass is dominated by a phytoplankton fraction with cell diameters from 5 to 20 μm. Phytoplankton with cells less than 5–8 μm in diameter consists mainly of coccal cyanophyta, green algae and flagellates (occurring in summer), whereas diatoms and dinoflagellates usually have larger cells (Witek 1995).

The increase in particle numbers reported in October 1992 and April 1993 both in Puck Bay and the open part of the Gulf of Gdańsk was found to be connected with high chlorophyll *a* concentrations (Fig. 9). Elevated concentrations were usually measured in the surface layer. Taking into account the low Vistula water discharge in October (Fig. 10) and the fact that only the concentration of particles in the 10–20 μm size class increased, variations in total particle concentration can be explained by biological processes. In spring, the high suspended

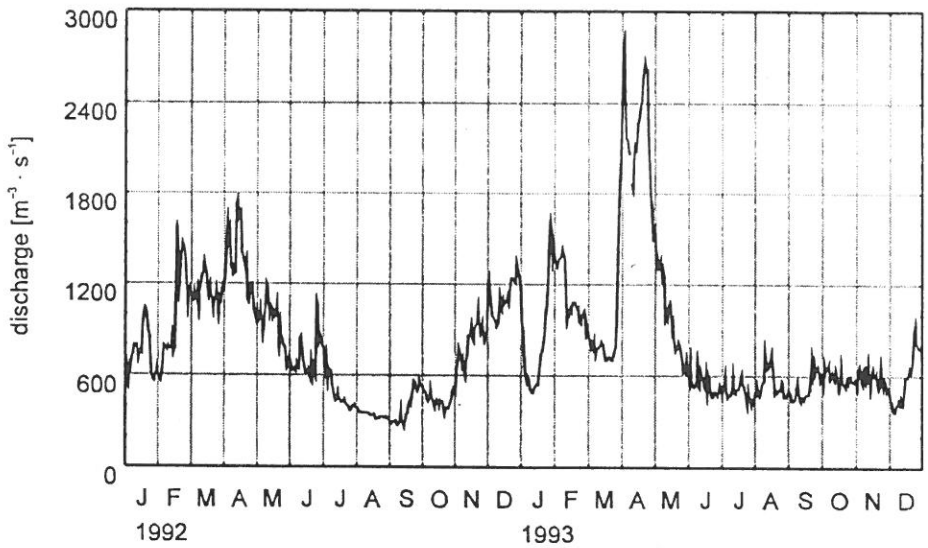

Fig. 10. Mean daily Vistula water discharge measured in Tczew during 1992-93 years (dates from IMGW Słupsk measurements)

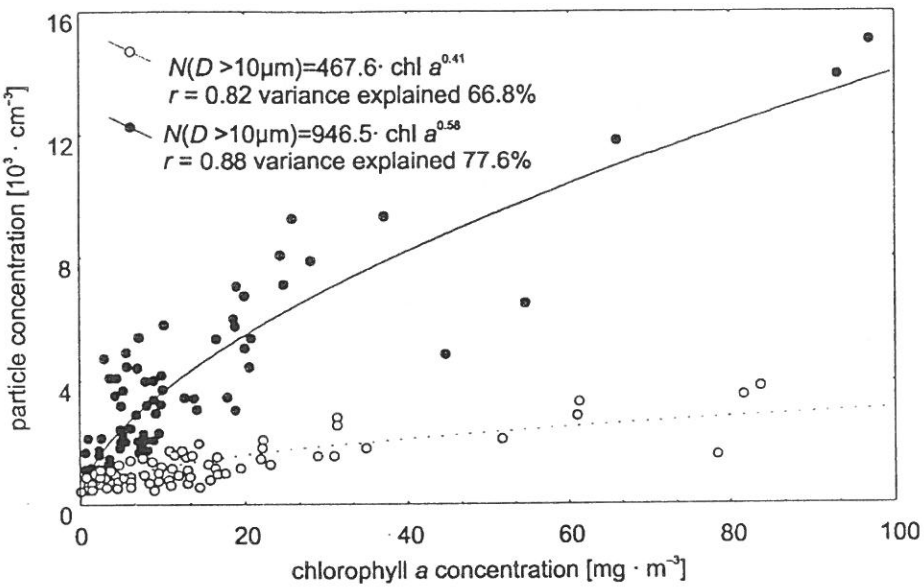

Fig. 11. Correlation between concentrations of particles with diameter D>10 mm and chlorophyll *a*

matter content was caused not only by a higher concentration of organic particles, as would be expected during the period of maximum phytoplankton growth, but also by the relatively high concentrations of mineral particles from the Vistula input. Similarly, the inflow of Vistula waters seems to be the reason for the high particle concentration in May 1992 recorded in the open Gulf of Gdańsk across the entire range of particle diameters investigated.

Relatively high particle concentrations were reported in the summer months, when both the chlorophyll *a* concentration and the Vistula water discharge were rather low (Fig. 9 and 10). In the Gulf of Gdańsk in summer, following the occurrence of dinoflagellates and algae, the biomass decreases (to *ca* 0.1 gC · m^{-3}) and the phytoplankton composition is more varied: green algae, filaments or small coccal cyanophyta and flagellates appear (Witek 1995). Moreover, in this range of particle diameters i.e. 4–30 μm, some unicellular zooplankton like nanoplanktonic flagellates (1.5–8 μm) and heterotrophic dinoflagellates may make a significant contribution to the abundance of particles suspended in water. However, it is difficult to explain the observed variations in particle concentrations without additional information about the composition of the suspended matter and dynamics of other land sources (particularly in Puck Bay).

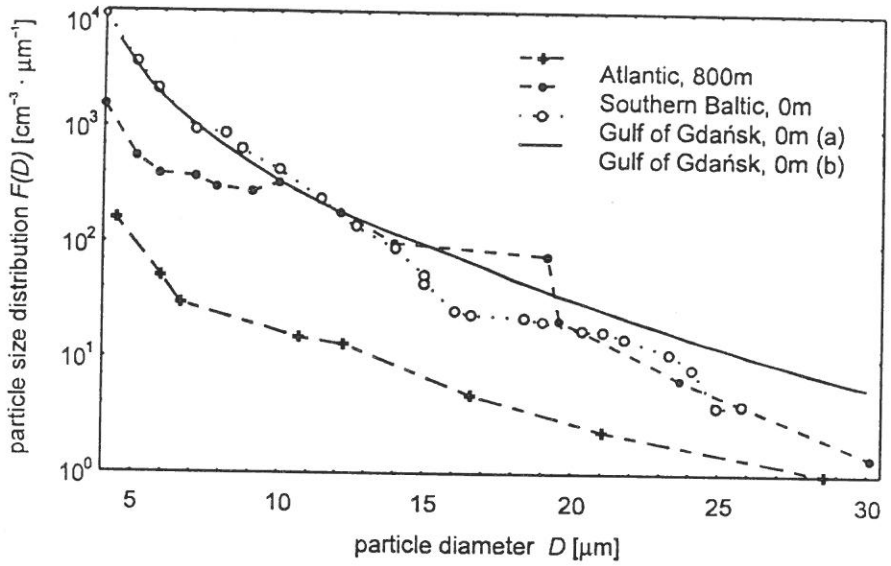

Fig. 12. The particle size distributions typical for an Atlantic waters at 800m depth (Jonasz *et al.* 1977), surface layer of the southern Baltic during a spring phytoplankton bloom (Jonasz 1980) and the Gulf of Gdańsk (a) given by Jonasz *et al.* (1977) and (b) from authors measurements (average from all dataset)

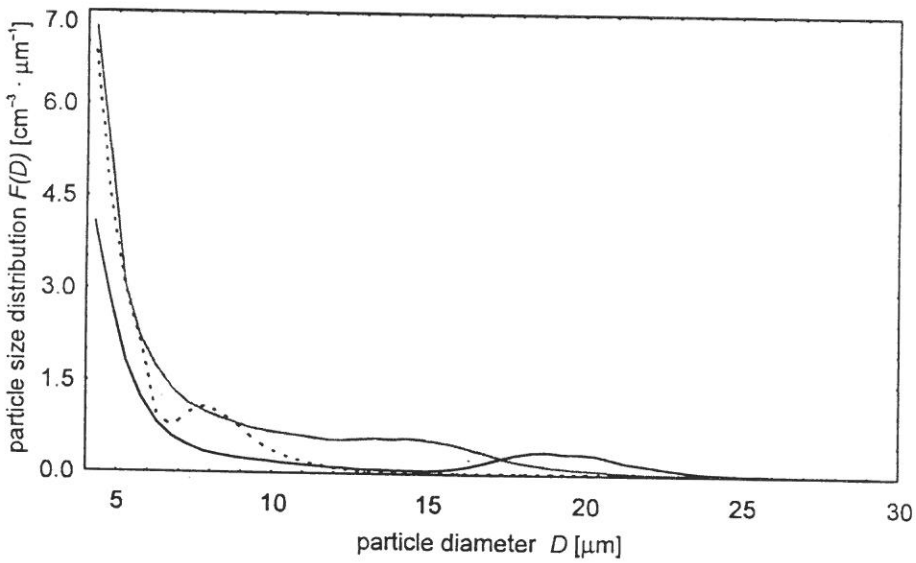

Fig. 13. The most characteristic modifications of hyperbolic particle size distribution curves (classified as a type 2) that have been found in the Gulf of Gdansk from V '92 to XII '93

The characteristic feature of the temporal variations in particle numbers there was the strong differentiation of the small particle (D<10 μm) concentration in relation to the larger particles throughout the water column. Except in areas close to river mouths and other terrestrial sources of suspended matter, concentrations of large particles were usually low and varied within a small range.

The temporal variability in the suspended matter composition (phytoplanktor and zooplankton species and their characteristic sizes as well as the ratio of organic to inorganic particles) results in a slight correlation between particle abundance and the dry mass of suspended matter in the Gulf of Gdańsk. The correlatior coefficient (significance level 0.05) evaluated for all data pairs was < 0.38. The same coefficient evaluated only for June 1992 (thelargest data set) was equal to 0.68. This suggests that the suspended matter composition is less variable in space than in time. Moreover, such low values of the correlation coefficient point ou significant role of particles less than 4 μm of diameter in entire mass of matte suspended in water volume that there are not included in particles number deter mination. The particle fraction of D<4 μm is composed mainly of bacterial plank ton, the abundance of which in the euphotic layer may be of the order of on million cells per cm^3 of water (Witek 1995).

Allowing for the seasonal variability of biological production and the impor tant role of particle run-off from the land, the correlation between chlorophyll and particle concentrations is expected to be weak if the whole range of particl diameters and data from different seasons are included. In different particle diam eter ranges, scatterplots show two distinct groups of data with difference in th number of particles in the presence of the same chlorophyll *a* concentratior (Fig. 11). In order to estimate the correlation coefficients, all data have been cla sified into two classes, taking into account the standardised concentrations. Whe the values for suspended matter were greater than those for chlorophyll *a*, a da pair was classified in class I (dots in Fig. 11), in the other cases in class (circles). As would be expected when taking into account the particle sizes cha acteristic of phytoplankton cells, the best correlations in both classes were note for particles with diameter D>10 μm.

The fluctuations in particle concentrations discussed above resulted in fluct ations in the particle size distribution curves in the Gulf of Gdańsk. Generally, tl particle number in the water decreased with increasing diameter, and the si distribution curve showed goodness of fit with the hyperbolic function characte istic of marine suspensions (Fig. 12). This general dependence did not hold f some cases where there was a clear tendency for particles of D *ca* 10 μ or 10–25 μm to accumulate (Fig. 13). In Baltic waters, the additional peak th appears in the particle size distribution curve at about 10–20 μm is interpreted Jonasz (1983) as being due to biological production. In the Gulf of Gdańsk, ho ever, this kind of distribution curve occurred in the surface layer close to terrest

al sources of seston when the chlorophyll *a* concentration was frequently as low as in during the phytoplankton bloom. Other reasons for modification of the hyperbolic distribution by additional peaks may include the slowly settling particles following the phytoplankton bloom, or rather, the inflow of fluvial waters rich in particles with different characteristics. In the areas close to the Vistula mouth, deviations in the particle size distribution curves from the hyperbolic distribution may be more significant. It was found that the Gaussian distribution of particles sizes may occur in this area (Fig. 5) in connection with the high Vistula water discharges. The steeper particle size distribution curves in Puck Bay than elsewhere in the Gulf of Gdańsk (Fig. 6) showed that small particles made up a large part of all suspended matter in this area. This leads to the lower rates of deposition measured in Puck Bay in comparison to other parts of the Gulf of Gdańsk (Szczepańska *et al.* 1994).

CONCLUSIONS

The Vistula river waters, rich in suspended matter, and the other smaller terrestrial sources of seston influence the distribution of particle concentrations, such that these values are higher in areas close to the river mouth or sewage outfalls. The concentration of small particles (D<10 μm) is affected in the whole area in which fluvial waters spread, whereas, due to their higher sinking rate, larger particles (D = 20–30 μm) are found no farther than 2 km from the mouth.

The open Gulf of Gdańsk was characterised by higher values and a greater variability in particle concentrations (the surface concentration was in the range $1.6 \cdot 10^3$–$3.7 \cdot 10^4$ cm^{-3} and the standard deviation *ca* $9 \cdot 10^3$ cm^{-3}) than Puck Bay (range of values: $1.6 \cdot 10^3$–$2.1 \cdot 10^4$ cm^{-3} , standard deviation $< 5 \cdot 10^3$ cm^{-3}). Differences in the slope of particle size distribution curves in these areas show is less mean particle diameter characteristic in Puck Bay waters that than in the open part of the Gulf of Gdańsk. This results in a lower particle deposition rate in Puck Bay waters.

Three periods of maximum particle concentrations occurred in a year. Two of them, in April and October, were connected with high concentrations of chlorophyll *a*. This suggests that phytoplankton cells may play a significant role in the rise in particle concentrations during the phytoplankton bloom, particularly particles with D>10 μm (correlation coefficient r>0.8). The third maximum may occur between May and July. This difference in particle number in the presence of the same chlorophyll *a* concentrations show that there are others factors controlling the variations in the number of particles during the year.

The particle size distributions in the Gulf of Gdańsk in the 4–30 μm diameter range are of three different shapes:

type 1– typical of marine waters with concentrations rapidly decreasing with increasing particle diameter (hyperbolic distribution); they are dominant in Gulf of Gdańsk waters of low particle concentrations

type 2 – the hyperbolic distribution modified by an additional maximum (or two) between 10 and 20 μm or *ca* 10 μm, dominant in waters with a high concentration of particles, *e.g.* during the phytoplankton bloom or close to the terrestrial sources of particles

type 3 – bell-shaped with the peak at *ca* 10 μm, characteristic of Vistula river waters; may be found in a limited area close to the Vistula river mouth when fluvial input is extremely high.

Among some 700 samples analysed only a few percent had an irregular distribution that could not be placed in one or other of the above categories.

REFERENCES

Carder K.L., G.F. Beardsley Jr., H. Pak, 1971, *Particle Size Distributions in the Eastern Equatorial Pacific*, J. Geophys. Res., vol. 76, 21

Coulter W. H., 1985, *Coulter Multisizer II – Reference Manual.*

Cyberski J., 1982, *Hydrological characteristics,* [in:] *The lower Vistula valley*, B. Augustowski (ed.), Ossolineum, Wrocław, 103–153, (in Polish)

Dera J., 1992, *Marine physics*, Elsevier, Amsterdam-Oxford-New York-Tokyo, 516 pp.

Eisma D., Kalf J., 1987, *The distribution of organic content and particle sizes of suspended matter in the North Sea,* Netherl. J. Sea Res., 21 (4), 265–285

Jankowski A., 1984, *Dynamics of the steady wind-driven circulation in the Gulf of Gdańsk*, Stud. i Mater. Oceanol., 43, 5–79, (in Polish)

Jonasz M., 1980, *The characterisation of physical properties of marine particles using light scattering,* Ph.D. Thesis, Institute of Oceanology, Sopot, 213 pp., (in Polish).

Jonasz M., 1983, *Particle size distributions in the Baltic*, Tellus, 35B, 346–358

Jonasz M., Fournier G., 1996, *Approximation of the size distribution of marine particles by a sum of log-normal functions,* Limns. Oceanogr., 41, 744– 754

Jonasz M., Zalewski M., 1977, *Studies of particle-size distribution in the Baltic,* Stud. i Mater. Oceanol., 17, 51–66, (in Polish)

Kramer K.J.M., Brockmann U.H., Warwick R.M., 1994, *Tidal Estuaries: Manual of Sampling and Analytical Procedures*, A. A. Balkema, Rotterdam, Brookfield, 304

Krężel A., Cyberski J., 1993, *Influence of the Vistula river on suspended matter content in the Gulf of Gdańsk waters*, Stud. i Mater. Oceanol., 64, 27–39

Krężel A., Sagan S., 1987, *Variability of the total light attenuation coefficient in water of the Gulf of Gdańsk,* Stud. i Mater. Oceanol., 51, 49–82, (in Polish)

Latała A., 1993, *The chlorophyll-a contents in the surface waters of the Gulf of Gdańsk,* Stud. i Mater. Oceanol., 64, 187–195

Latała A., 1994, *Concentration and distribution of chlorophyll-a in the Gulf of Gdańsk,* Proc. BMB Symposium, Riga, 1993 (in printing)

Majewski A. (ed.), 1990, *The Gulf of Gdańsk*, Wyd. Geol., Warszawa, 502 pp., (in Polish).

Pliński M., Florczyk I., Picińska J., 1985, *Composition and abundance of phytoplankton in the Gulf of Gdańsk Proper,* Stud. I Mater. Oceanol., 46, 23–64, (in Polish)

Sagan S., 1992, *Light transmission in the Southern Baltic waters,* Rozprawy i Monografie, 2, Inst. Oceanol. PAN, Sopot, 149 pp., (in Polish)

Staśkiewicz A., Walczowski W., 1995, *The Gulf of Gdańsk currents as a indicator of the contamination transport,* [in:] Kruk-Dowgiałło L., Ciszewski P., *The Gulf of Gdańsk – environment condition, 1992 y.,* Instytut Ochrony Środowiska, Warszawa, (in Polish)

Szczepańska T., Uścinowicz S., 1994, *Geochemical atlas of the Southern Baltic,* Instytut Geologii, Warszawa, (in Polish)

Vistula River and Gdańsk Bay, Water quality study, 1992, Delft Hydraulics and IBW-PAN.

Witek Z., 1995, *Biological production and its utilisation within a marine ecosystem in the Western Gdańsk Basin,* Morski Instytut Rybacki, Gdynia, 145 pp., (in Polish)

Zalewski S. M., 1977, *An analysis of size distribution of suspended particles in sea water*, Ph.D. Thesis, Institute of Oceanology, Sopot; Geophysics Institute, Warszawa, (in Polish)