Fine organic particles in a sandy beach system (Puck Bay, Baltic Sea)*

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Abstract

A total of over 550 samples of particulate organic matter (POM) were obtained from swash and groundwater samples taken on a monthly basis from seven localities on the sandy shores of Puck Bay in 2002 and 2003. Sandy sediment cores from the swash zone were collected to assess the amount of POM in the pore waters. The mean annual concentrations of POM varied between localities from 20 to 500 mg in groundwater and from 6 to 200 mg dm^{-3} in swash water. The carbon/nitrogen (C/N) ratio in suspended matter was always higher in groundwater (annual mean 12) than in swash water (annual mean 7). The C/N ratio indicates a local, algal origin of POM in the shallow coastal zone.

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The complete text of the paper is available at http://www.iopan.gda.pl/oceanologia/

1. Introduction

The great diversity of suspended, particulate organic matter (POM) (passing through a 0.5 mm mesh net and retained on a 0.0005 mm filter) makes up a large part of the detritus pool in the marine ecosystem (Verity et al. 2000). It is important as food for filter feeders, a substrate for microbial life, and finally, after sedimentation, as a food source for deposit feeders (Iglesias et al. 1996, Madon et al. 1998, Parent & Morin 1999, Gilek et al. 2001). In permeable sediments (sand and gravel), small particles can be efficiently transported into the sediment during both filtration and bioturbation, but in fine sediments the only efficient means of sediment mixing is bioturbation (Rush et al. 2000, Propp & Propp 2001, Reise 2002). Numerous papers have dealt with organic suspensions in offshore waters (e.g. Shushkina et al. 2000) and estuaries (e.g. Mazzola et al. 2001, Goñi et al. 2003), but in this respect very shallow waters of recreational importance (bathing) have received scant attention. The dynamics of the sea in the breaker zone and the transport of terrestrial POM organics out to sea make swash water very turbid and rich in suspensions (Puleo et al. 2000, Ullman et al. 2003). Furthermore, POM is known to be an important substrate/adsorbent for contaminants, e.g. heavy metals in coastal waters (Sokołowski et al. 2001).

Concern about the quality of bathing waters is associated with reduced water transparency, the threat of excess organic matter deposition and of toxic algal blooms (e.g. the EU bathing waters directive). Hence, an understanding of organic matter turnover in particular recreational areas is a matter of prime concern. In the European coastal zone, the processes of primary production are well known and subject to monitoring (Wasmund et al. 2001, Gazeau et al. 2004), but those of mineralisation and decomposition are still poorly understood (Kunnis 1998, Koelmans & Prevo 2003, Ehrenhauss & Huettel 2004).

The present paper aims to provide novel, fundamental data on the seasonality of fine organic suspensions (POM) in coastal waters. In particular, it focuses on the relationship between ground water, swash water and pore water in sand based on the example of the southern Baltic coast. A separate paper dealing with macrodetritus (litter, debris washout) is to follow (Kotwicki et al., in preparation).

In the present paper we have addressed the following research questions:

- How much POM is free-floating in the pore waters of the swash zone, as compared to POM adhering to sand grains?
- How large is the biomass of fine organic particles (POM) in the swash water and ground water of the beaches along the shore of Puck Bay, and how does it change seasonally?

- How fast does POM fill the sediment in the swash zone under natural conditions?
- What are the carbon and nitrogen contents of the POM examined in this study, and how do they vary seasonally?

2. Material and methods

Particulate matter in the surface water was collected from the swash water (0.5 m depth) a few metres from the water line. Three separate samples (a few metres apart) were taken with a 5 dm^3 plastic pail, then poured into marked 250 cm^3 plastic containers and transported to the laboratory in a cool box.

Particulate matter in the ground water was collected from three holes dug at the drift line (usually a few metres above the water line). From 10 to 50 cm in depth and 20 cm in diameter (depending on the slope of the beach), these holes became filled with ground water within seconds. Three 250 cm^3 samples of water were collected from each hole, and transported to the laboratory in a cool box.

The temperature and salinity of the swash water were measured electronically in situ, accurate to 0.1°C and 0.1 PSU respectively.

Particulate matter from submerged sands was obtained from sediment cores taken from the same site as the swash water with a cylindrical Morduchai-Boltovskij corer (ϕ = 15 cm). Each sand core was placed in a plastic pail and divided into two parts. One part was processed for organic matter content (dried at 65°C, weighed, combusted at 450°C, and reweighed) and granulometry (passed through a set of standard sieves). The other part was rinsed in tap water (multiple flotation and shaking) to remove all the suspended particles from the sand.

The particulate matter was passed through pre-weighed GFF filters, large particles having previously been removed with a 0.5 mm screen. The filters were dried at 65°C to constant weight, and combusted at 450°C to determine the loss on ignition. The sands at this locality are dominated by quartz, so there was no need to correct for calcified elements. The water content in the swash zone sand was assumed to make up 25% of the wet sand weight (cf. Urban-Malinga & Opaliński 2001, samples collected from the same site).

Sand cores retrieved from the swash zone were used for the experiment on the fine-particle infiltration rate. The sand was cleaned of all free-floating particles (see above), dried, placed into three 0.5 mm mesh bags (15 × 15 cm cylinders), and replaced at the same spot in the swash zone from where it had been collected. Samples of untreated original sand, and rinsed (experimental) sand were retained as controls. On each of the first, second and third days, 3×10 cm subsamples were taken from the centres of the three experimental cores. All samples (control and subsequent experimental) were dried, weighed, combusted and reweighed to calculate the loss on ignition.

The filters containing POM were analysed on the CHN analyser at the Chemistry Department of the University of Gdańsk.

All sampling and experiments were carried out on the Sopot municipal beach on a monthly basis between 2002 and 2003; measurements of particulate matter were also made at seven other localities along Puck Bay (Fig. 1). Altogether, 280 samples of swash water and 270 of ground water were analysed for organic matter content. A further 140 samples of POM were analysed for CHN content.

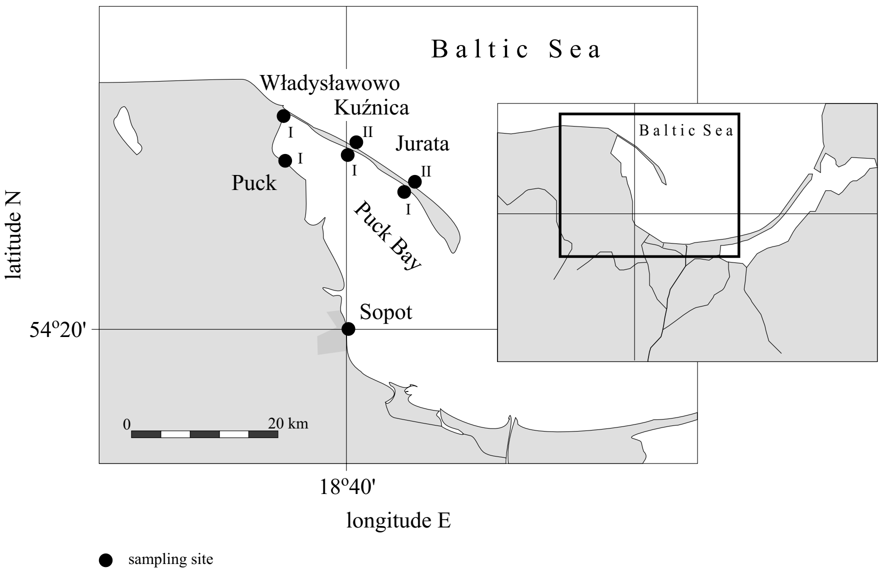

Fig. 1. Location of the sampling sites (sites marked I are on the shores of Puck Bay, sites marked II are on the open sea side)

3. Study area

The Gulf of Gdańsk is a semi-sheltered area of flat, sandy shores on the southern Baltic Sea. The sea is microtidal and the water brackish (5–8 PSU), with surface temperatures ranging from 0°C in winter to >22°C in July and August. Medium and coarse quartz sands (grain diameter 0.15 to 0.3 mm) make up the coastal sediments. The study area is a eutrophic water basin with a high primary production (>150 g C m^{-2} per annum, Gazeau et al. 2004). Beaches are intermediate, with sand bars and a breaker zone. Coastal waves do not normally exceed a height of 1 m during storms. Despite the presence of few large cities on its perimeter, and the resulting microbial contamination, much of the Gulf is given over to seaside recreation (Olańczuk-Neyman 2001). Apart from phytoplankton production, filamentous algae and sea-grass beds contribute to the detritus pool. A summary of the numerous studies of Puck Bay and its general characteristics is accessible at http://www.iopan.gda.pl/projects/puckbay.

4. Results

POM from the swash zone: free-floating POM versus POM adhering to sand grains

Sampled six times, the sediments of the Sopot beach swash zone were treated to remove all floating particles. This experiment showed 40 to 60% of POM to be adhering to the surface of sand grains. 60 to 90% of the pool of free-floating POM was removed after a single rinsing (Fig. 2). Microscopic examination confirmed the presence of diatom cells and bacterial colonies in the microcavities of individual sand grains from the rinsed sample.

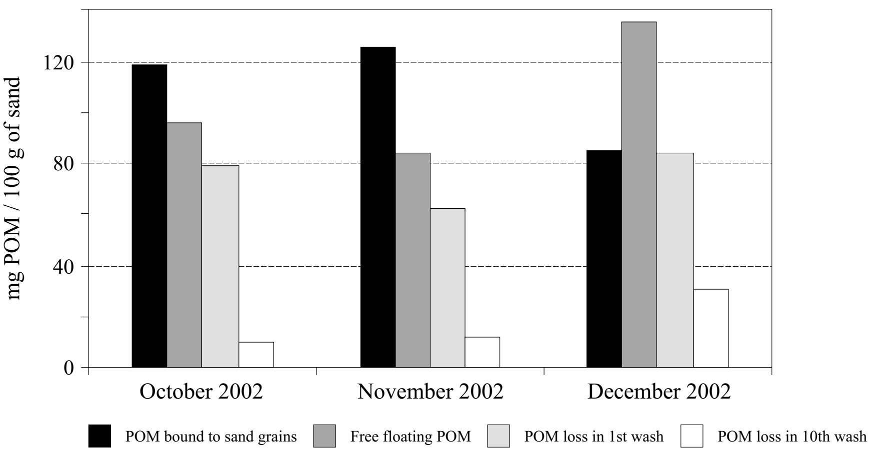

Fig. 2. Loss of free-floating particulate organic matter (POM) due to rinsing of the sand core samples; Sopot 2002

Seasonality and biomass of swash water and ground water POM in the Puck Bay beach system

The highest POM contents were measured in ground waters, the lowest ones in swash waters at all the sampling sites. The maximum (Puck, 6595 mg POM dm^{-3}) and highest mean values (1284 mg POM dm^{-3}) were noted in the ground waters of the inner part of Puck Bay. The minimum (3.4 mg POM) and lowest annual mean values (32.4 mg POM dm^{-3}) were recorded in the ground waters at Sopot (Fig. 3, Table 1). The POM concentration in swash waters was lowest in the relatively exposed sites of Sopot and Jurata (annual mean 10 to 13 mg dm^{-3}), and highest in the inner part of Puck Bay (Puck, annual mean 62 mg dm^{-3}). The concentration of swash water POM was very low (1 mg dm^{-3}) at many localities (Table 1). The average biomass of POM in swash waters in the area examined (a 120 km-long coastline and a 20 m-broad breaker zone 0.5 m deep) is estimated to be 64 tonnes of organic matter during the growing season (Table 3, page 175).

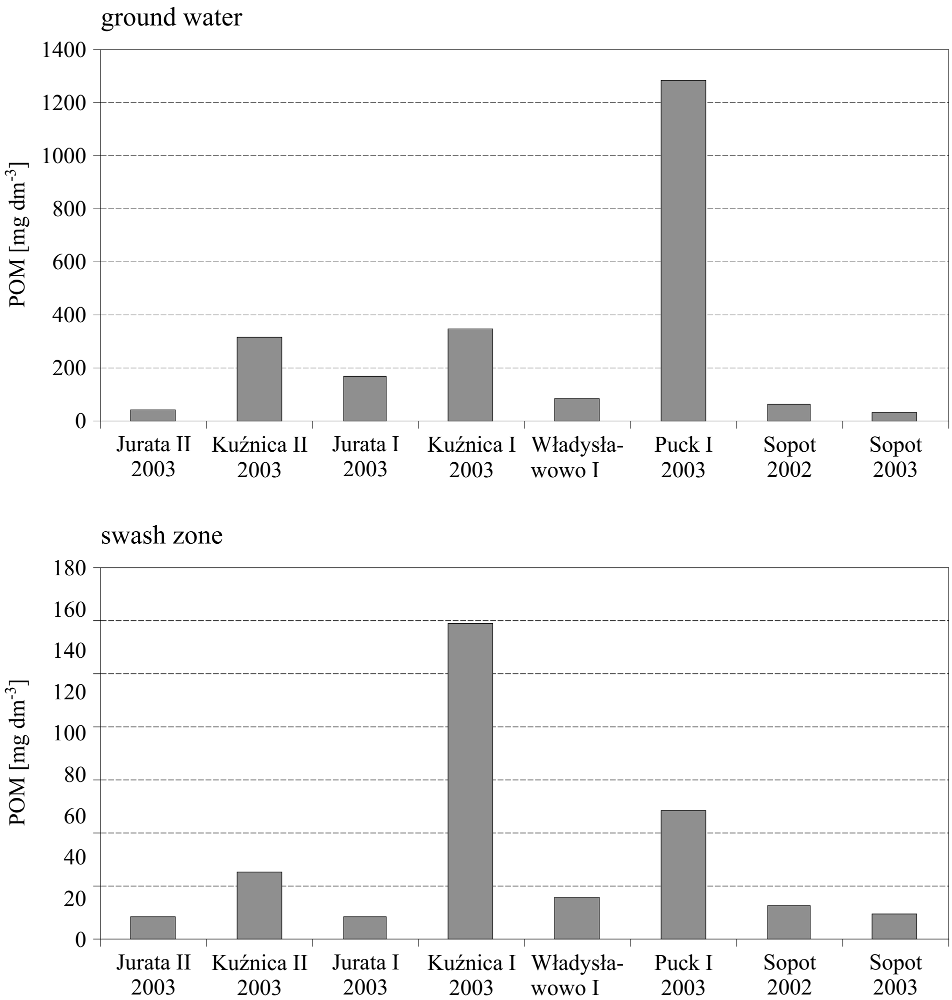

Fig. 3. Annual mean concentration of particulate organic matter (POM) in ground and swash waters from the sites examined in 2002 and 2003 (for site denotations, see caption to Fig. 1)

Table 1. Summary of particulate organic matter (POM) measurements from swash water (280 samples) and ground water (278 samples) collected in 2003

Month	Swash zone	Ground water	Swash zone	Ground water	Swash zone	Ground water
	POM [mg dm^{-3}] minimum–maximum		POM [mg dm^{-3}] mean ± SD		SD/mean	
January	1–40	4–1187	12.6 ± 12	182 ± 348	1.0	1.9
February	2.9–19	10–72	9.9 ± 7	31 ± 25	0.7	0.8
March	1–1023	3–644	74.8 ± 207	107 ± 164	2.8	1.5
April	3.9–348	7–3920	29.6 ± 68	421 ± 946	2.3	2.2
May	1–33	12–3123	11.4 ± 9	321 ± 639	0.8	2.0
June	5–79	26–1920	18.9 ± 15	268 ± 402	0.8	1.5
July	2.3–2540	13–1532	184.0 ± 595	141 ± 300	3.2	2.1
August	0.5–393	4–4600	43.5 ± 91	496 ± 1016	2.1	2.0
September	1–29	18–624	9.2 ± 6	97 ± 174	0.7	1.8
October	1–43	7–2922	15.9 ± 95	158 ± 555	0.6	3.5
November	2–101	4–6596	20.9 ± 25	421 ± 1382	1.2	3.3
December	1–14	7–50	6.1 ± 3	19 ± 13	0.6	0.6

SD – standard deviation.

In situ POM accumulation rate in the swash zone sediment

The experiment to expose cleaned sediment cores in the swash zone demonstrated the rate of POM flow into the sediment. Regardless of season, cleaned sediment exposed to swash water attained particulate matter concentrations similar to those in natural sand within two days (Table 2).

C/N ratio of POM and the seasonality of its chemical characteristics

The C/N ratio of the POM examined here ranged from 4 to 26, with distinct differences between swash waters (annual mean 7) and ground water (annual mean 12). This difference was maintained throughout the year, except in August and December, when the C/N ratios of swash and ground water POM attained the same values (Fig. 4). C/N ratios were generally higher in the winter months (12 and 18 for swash and ground water respectively) and lower in summer (6 and 8 respectively), the lowest value being recorded in swash water POM (3.2 in summer) and the highest in ground water (22.5 in winter). The greatest variability in C/N ratios occurred in swash water, while the SD of these values from ground water

Table 2. Cleaned sediment enrichment in particulate organic matter (POM) after exposure in the swash zone, Sopot 2003

Month	Natural sediment core (POM content) [mg POM (100 g sand)$^{-1}$]	Cleaned sediment core control POM content [mg POM (100 g sand)$^{-1}$]	Cleaned sediment core after 24 h exposure [mg POM (100 g sand)$^{-1}$]	Cleaned sediment core after 48 h exposure [mg POM (100 g sand)$^{-1}$]	Mean amount of POM in swash water [mg dm^{-3}]	Mean mass of POM [tonnes] in 120 km long swash zone (width 20 m, depth 0.5 m)
January	213.6	149.6	191.4	220.1	13	15
February	176.5	109.4			10	12
March	201.6	95.5	179.3	228.2	75	90
April	177.5	93.4	161.9	181.3	30	35
May	152.9	104.0	140.2	147.7	11	14
June	161.0	90.1	126.2	137.1	19	23
July	108.8	97.9	169.2	180.3	184	221
August	127.8	134.0	128.3	135.9	43	52
September	245.0	100.3	157.0	165.1	9	11
October	221.1	111.6	154.8	174.2	16	19
November	221.1	103.0	146.3	178.0	21	25
December	209.8	127.4	196.9	237.5	6	7

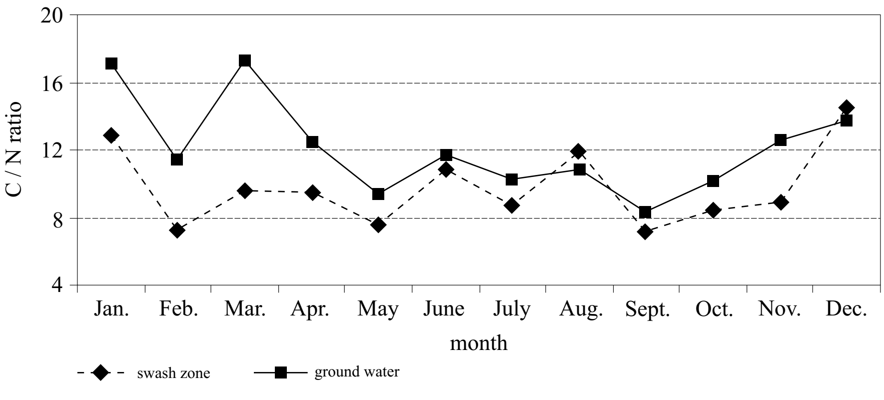

Fig. 4. Carbon/nitrogen ratio in fine suspensions from swash and ground waters; Sopot 2003

samples was more stable, except in March when extreme values were noted (C/N = 22.5) (Fig. 4).

The pattern of seasonal changes in POM concentrations in swash and ground waters and the C/N ratios is similar: two distinct peaks in swash water in March and July, followed by POM peaks in ground waters in May, August and November (Fig. 5).

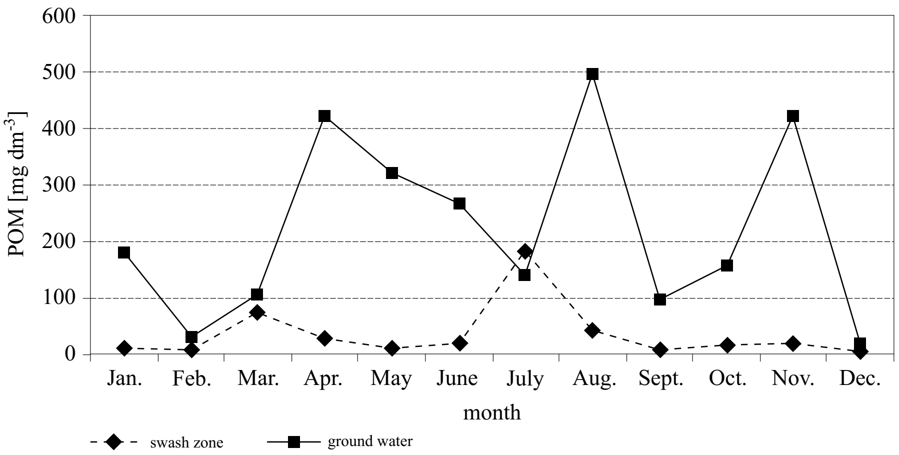

Fig. 5. Particulate organic matter (POM) in swash and ground waters; monthly means; Sopot 2003

5. Discussion

The problem of organic particles adhering to sediment grains is well known to sediment microbiologists, who use ultrasound (sonification techniques) to remove bacteria before counting cells (Crump et al. 1998, Olańczuk-Neyman & Jankowska 2001). Microphytobenthic diatoms are also commonly reported to adhere firmly to sand grains (Snoeijs et al. 1990, Brown & McLachlan 1990). Amorphous detritus not derived from organisms, especially adhesive macromolecules of peptides, polysaccharides (Transparent Extracellular Polymers), is likely to be of importance (Rusch et al. 2001). Schumann et al. (2001) report mucous colloids along the Baltic Sea coast as constituting over 60% of the detritus volume. Of the meiofauna, only some ciliates are known to adhere to sand grains, but these were not abundant in our sampling area (A. Świstulska personal communication). Among the free-moving meiofauna, Turbellaria and Nematoda are readily eluted from the sediment core, unlike pelagic and semi-pelagic animals (Rotatoria, nauplii of Copepoda), which are retained within the sediment (Kotwicki et al. 2002).

The particulate matter from the open Puck Bay is dominated by very small size-fractions, the 2–10 μm fraction makes up 80% of POM in coastal waters (Bradtke et al. 1997). In the Mediterranean, the nano- and pico-fractions of detrital particles in the detritus pool exceed that of larger particles by a factor of 10 (Mostajir et al. 1995). Closer to the shore in more turbid swash waters, large particles may dominate, with 77% of POM consisting of the 80–300 μm fraction (Kotwicki et al. 2002). POM can consist of mesozooplankton and microplankton, faecal pellets, bacteria, algal aggregates or terrigenous matter, depending on the season and location (Lundsgaard et al. 1999, Coban-Yildiz et al. 2000).

The amount of POM reported from the open Gulf of Gdańsk is significantly lower, and ranges from 3–9 mg dm^{-3} (Maksymowska et al. 1997) to 6–180 mg dm^{-3} in turbid swash waters (Table 3). The amount of POM in a turbid Atlantic estuary was similar to our swash water values (Maksymowska et al. 1997). The ground water pool of suspended matter at the beach face has not been reported in the literature, but there are indications that in a number of localities the beachfront acts as a sediment trap and its ground waters may contain elevated quantities of POM (Ullman et al. 2003).

According to Huettel et al. (1996), the question of fine-particle infiltration into sands has been addressed in the literature (e.g. Boudreau et al. 2001, Propp & Propp 2001). The rate of this infiltration has been measured, mainly under experimental conditions, for diatoms and bacteria (Ehrenhauss & Huettel 2004). In sandy sediments the rate of infiltration – advective transport – is relatively fast at 0.01 cm s^{-1} (Precht & Huettel 2004). The sinking rates of POC from detritus in near-shore waters were reported to range from 0.019 to 1.430 g C m^{-2} day^{-1} (Estrum-Yousef et al. 2000). Taking the filtration efficiency to be 140 dm^3 m^{-2} day^{-1}, Precht & Huettel (2004) estimated the daily input of POC into coastal sands at 1.4–2 g m^{-2} day^{-1} (for POC concentration in swash water ranging from 10 to 25 mg dm^{-3}). Thus, active forcing of fine particles into the sand may exceed sedimentation rates.

The C/N ratio of the swash-water POM examined in this study is typical of the phytoplankton-dominated fraction in spring and summer (from 7 to 9): such values were indeed recorded in the open part of the Gulf (Maksymowska et al. 1997, 2000). Elevated winter values (10 to 18) and those from the beach ground water may indicate that the POM here is of terrestrial origin (Maksymowska et al. 1997, 2000). Detritus deposited on the seabed in shallow waters was found to be mainly of pelagic algal origin in the North Sea and Skagerrak (Boon et al. 1999), in Asian waters (Kennedy et al. 2004), and in the Baltic Sea (Schumann et al. 2001, 2003). Other

Table 3. Characteristics of marine suspensions from various coastal regions

Locality	TSM	POM	Phytoplankton	Bacteria	Zooplankton	POC	Source
	[mg dm^{-3}]						
Winyah Bay, USA estuary, Atlantic	0.4–12					0.1–3	Goñi et al. 2003
Marennes-Oléron, estuary, Atlantic	40–180					1–11	Maksymowska et al. 1997
Sopot, Baltic Sea	4–125	7–125		1	0.6–112	8.8	Kotwicki et al. 2002, Jankowska 2001
Sopot, Baltic Sea		2–150				0.5–40	this paper
Gulf of Gdańsk, Baltic Sea	3 to 9					0.3–0.7	Maksymowska et al. 1997
Darss-Zingst Bodden, Baltic Sea						16	Schumann et al. 2003
Gulf of Gdańsk, Baltic Sea			10–500	10	100–1000	0.9–1.9	Witek 1995

TSM – total suspension matter, POM – particulate organic matter, POC – particulate organic carbon.

authors suggest the importance of macrodetritus for the export of organic matter from coastal waters (Boon et al. 1999, Bouchard & Lefeuvre 2000). Mazzola et al. (2001) found 75% of the detritus pool to be of heterotrophic, microplanktonic origin. The C/N ratio of detritus devoid of live algae or bacteria is quite high (35–50, according to Verity et al. (2000)).

The rate of microbial decomposition of detritus in the sea has been studied experimentally and seems to be very fast: from 8 to 11 days for the complete degradation of microalgal detritus (Kunnis 1998, Ploug & Grossart 2000). Taking 10 days to be the mean time required for algal POM decomposition and a growing season of 210 days' duration, we have estimated its production at 32 tonnes of POC (64 tonnes of POM) biomass $\times 21$ decomposition periods = 672 tonnes C, and correspondingly, 96 tonnes of N (from an averaged C/N ratio of 7). Decomposition of macrodetritus in coastal waters is much slower (40–100 days for algal debris, Jędrzejczak 2002). Apart from bacteria, the meiofauna seems to be an important component of detritus decomposition in permeable sands (Sundbäck et al. 1996). The macrofauna, specifically the seston feeders, are also important consumers of POM, since data from the Baltic Sea show that a 6000 tonnes biomass of zebra mussels daily filters 15 tonnes of POM from suspensions in the Neva estuary in the summer season (Orlova et al. 2004).

6. Conclusions

Fine organic particles (POM) reach higher concentrations in the beachfront ground water than in the swash. The main source of POM is pelagic microplankton production. C/N ratios show consistently that POM is decomposed to a higher degree in ground water than in swash water.

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