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SPATIOTEMPORAL VARIATION OF BIOCHEMICAL COMPOSITION OF ORGANIC MATTER AND NUMBER OF BACTERIA IN CORE SEDIMENTS OF SELECTED BEACHES OF THE SOUTHERN BALTIC SEA

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Abstract

Sandy sediments coming from three beaches of the southern Baltic Sea were collected and analyzed. Investigated beaches were divided according to strength of anthropogenic impact and degree of sheltering. The first beach was situated in Ustka on the eastern side of the mouth of the Słupia River, second in Czołpino and the last one in Puck. Core sediment samples were collected seasonally, depending on the influence of the sea water on the examined sediments. At each station, surface sediments (0-5 cm) were collected as well as sediments at the depth of 10-15 cm. The general content of organic matter, proteins, lipids, carbohydrates, organic carbon and total bacterial number were determined. The results of the conducted tests reveal, that anthropopressure, degree of sheltering, the depth where the collected sediments were taken and the direct influence of the sea water on the sediments have impact on the chemical composition of organic matter and bacterial number in beach sediments.

Key words: coastal sediments, total bacterial number, organic matter, profiles of the beach, Baltic Sea

INTRODUCTION

Sandy beaches are important and widespread marine coastal ecosystems characterized by uncontrollable dynamic nature whose structure is determined by wind, sand and water in a state of constant motion (Schoeman et al. 2000, Mudryk and Podgórska 2006). They are contact zones between the land and the sea or ocean. One of the few possible types of coasts are beaches, which are the most common form of littoral accumulation. The beach sediment may be supplied by rivers or by the erosion of highlands adjacent to the coast, and the sea may also contribute to the sediment supply through input of biogenic structures (animal skeletons, coral and shell fragments) (McLachlan and Brown 2006, Maria et al. 2016). Sandy beaches are characterized by a wide spectrum of sizes, morphologies and ranges of exposure to oceanographic conditions and they constitute a buffer zone between the land and the sea (Novitsky and MacSween 1989, Rodil and Lastra 2004, Mudryk et al. 2011).

Those environments are complex systems affected by the interaction of geological, hydrological, physicochemical and biological factors (McLachlan et al. 1996, Schoeman et al. 2000, Rodriguez et al. 2003, Rodil and Lastra 2004, Misic and Fabiano 2005). Very often they are subjected to considerable anthropopressure due to their recreation function. It can be concluded that beaches are squeezed between rising sea level on the marine side and expanding human population and development on the landward side (Schlacher et al. 2008).

In coastal ecosystems, sandy beaches play an important role in energy flow and organic matter turnover. They can be considered as the huge filters through which large amount (10-70 $m^3 \cdot m^{-1} \cdot d^{-1}$) of water is filtered (Nair and Bharathi 1980, Brown and McLachlan 1990, Heymans and McLachlan 1996). The passage of water through a sandy beach, i.e. the degree of drainage, depends on porosity, permeability, compactness and capillarity. During water permeation great amounts of organic matter are adsorbed on the sand grain surfaces in the form of particulate (POM) and dissolved (DOM) organic matter, respectively (Mudryk and Podgórska 2006). The sand of beaches acts as a passive element of cumulative pollution accumulating fecal bacteria from point sources such as municipal wastewater effluents, and non-point sources such as recreational users, fecal droppings from wild animals (mainly birds), agricultural run-off, storm drain and mats of green algae (Craig et al. 2002, Sato et al. 2005, Edge and Hill 2007, Skórczewski et al. 2012). In ordinary ecological conditions, this process leads to the accumulation of matter and energy in the splash and spray zones of sandy beaches and is the reason of development there of a great variety and number of interstitial organisms (Zaitsev 2012).

Bacteria play a key role in the processes of decomposition and transformation of organic matter accumulated in marine beaches (Jędrzejczak 1999) and are considered to be an important component of the sand beach community. Heterotrophic bacteria inhabiting water ecosystems are not a homogeneous group of organisms. They are a population of various physiological groups, which are characterized by the ability to carry out the processes of depolymerization of a very wide spectrum of macromolecular compounds (Krstulović and Solić 1988, Mudryk et al. 1999, Mudryk et al. 2011). Degraer et al. (2003) showed that abundance and species composition along the shore decreased with increasing beach slope and grain size, and with decreasing beach width and relative tidal range. According to Koop and Griffiths (1982) and Phillips et al. (2011) bacteria can mineralize about 70% of the organic matter reaching sea beaches, however productivity of the sand beach is ultimately limited by nutrient input (Khiyama and Makemson 1973).

In the sandy sediments of marine beaches subjected to extreme activity of waves and wind, over 90% of bacteria in fixed to the surface of the sand grains (Meyer-Reil et al. 1978, Mudryk and Podgórska 2006). Sand grain is a well defined habitat for various species of microorganisms (Meadows and Anderson 1968, Nair and Bharathi 1980) including bacteria. Weise and Rheinheimer (1978) and Yamamoto and Lopez (1985) draw attention to the fact that the surface area does not limit the sand grain colonization by bacteria, but their individual topography and shape does. Significantly more bacteria occur on the grains with diverse topography characterized by high degree of irregularity than on grains with smooth surfaces (Mudryk and Podgórska 2006).

According to Martinez et al. (1996) and Unanue et al. (1999) many heterotrophic bacteria are characterized by the ability to carry out the processes of depolymerization of macromolecular compounds to mono- or oligomers. The intensity of decomposition of organic macromolecules in water basins is usually determined not only by the number of bacteria capable of carrying out those processes, but also by the level of activity of their extracellular hydrolytic enzymes

Sandy beaches usually receive large input of organic matter which may constitute an important source of nutrients for offshore production (Brown and McLachlan 1990, Jędrzejczak 1999). Biochemical composition of organic matter (OM) in water basins results from the dynamic equilibrium between external inputs, autochthonous production, and heterotrophic utilization (Incera et al. 2003b). The composition of OM is certainly heterogeneous; it is a mixture of thousands organic molecules of low and high molecular weight (Farrington 1992).

Most of OM in marine ecosystems consists of compounds of a high molecular weight and polymeric structure, mainly proteins, starch, lipids, pectin, cellulose, chitin, nucleic acids, or lignin (Poremba 1995, Arnosti 1998, Unanue et al. 1999). For heterotrophic bacteria, high molecular weight biopolymers constitute an important source of carbon, nitrogen, and energy used for biosynthesis or respiration.

Organic matter (OM) in the marine environment is composed of labile and refractory compounds (Daumas et al. 1983, Fichez 1991, Danovaro et al. 1993, Rowe and Deming 1985, Fabiano et al. 1995). The labile portion mainly consists of simple sugars, fatty acids and proteins that are rapidly mineralised. Conversely, the refractory portion of OM, which is largely composed of complex macromolecules, requires a much longer time to be degraded and, if buried, might be easily lost by the benthic food web (Fabiano and Danovaro 1994, Danovaro et al. 1999a).

Labile OM plays a role in environmental dynamics and cycling of nutrients, as well as toxicity and fate of pharmaceutical, chemical (e.g., residues from herbicides and insecticides), metal, and organic pollutants in soil, sediments, water, and air. Conversely, the refractory portion of OM, which is largely composed of complex macromolecules like humic and fulvic acids or complex carbohydrates, is characterized by lower degradation rates (Handa et al. 1972, Robinson et al. 1982, Sargent et al. 1983, Wilson et al. 1986, Buscail et al. 1990, Biddanda and Riemann 1992), requires a much longer time to be degraded and, if buried, might be easily lost by the benthic food web (Fabiano and Danovaro 1994, Danovaro et al. 1999b). This is why the presented work aimed at:

(1) to investigate the biochemical composition and total bacterial number in three Polish beaches subjected to a different degree of exposure and anthropopression,
(2) obtaining information about the temporal changes in quantity of organic matter composition and total bacterial number in sheltered and exposed beaches,

(3) assessment of variation of above mentioned parameters in horizontal transects and vertical depths.

MATERIALS AND METHODS

The study was carried out on three sandy beaches in Poland (Fig. 1).

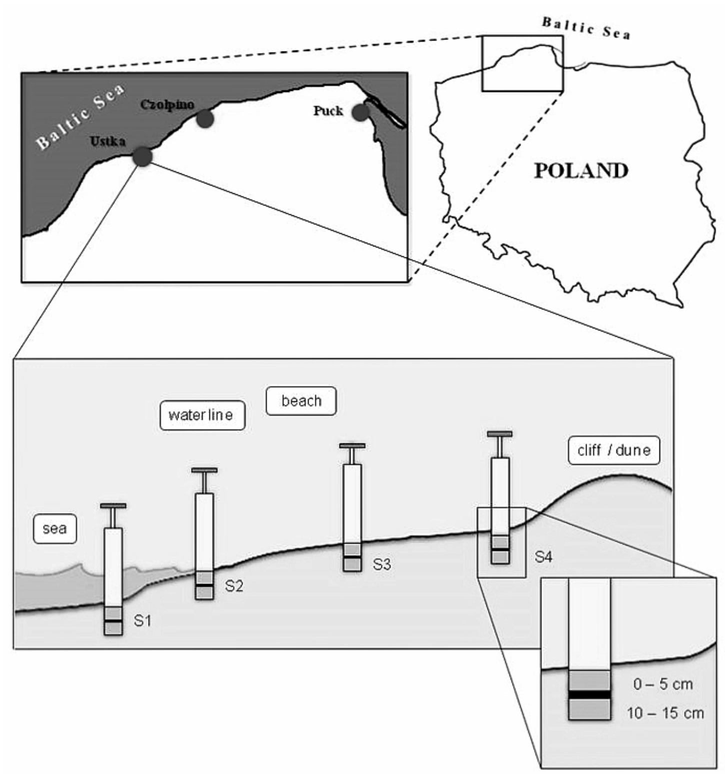


Fig. 1. Location of sampling sites and presentation of the horizontal and vertical profiles of one of the beaches

Samples were collected in the belt of Polish coast in Ustka (54°34'N/16°51'E) on the eastern side of the mouth of the Słupia River, in Czołpino (54°43'N/17°14'E) and in Puck (54°44'N/18°24'E). The most important difference among studied beaches is human impact on the ecosystem and characteristic of an individual beach according to its ecological state and degree of sheltering. The beach in Czołpino is a natural beach and is located in the Słowiński National Park. Ustka and Czołpino beaches, particularly in autumn and winter, is exposed to strong winds that generate high waves, which cause strong erosion onshore. As a result the seashore along the Ustka beach is heavily destroyed and the coastline retreats on average 0.08 m every year (Zawadzka-Kahlau 1999). Therefore, in the classification of Brown and McLachlan (1990) they are attributed to exposed beaches. The Puck beach is located above Puck Bay, where the wave energy is much smaller, and hence it is attributed to sheltered one.

Core sediment samples were collected seasonally (winter, spring, summer and autumn) in 2010 and 2013. A transect was marked along a profile formed perpendicularly to the shoreline. Four in Ustka and Czołpino and three in Puck sampling sites (Fig. 1) were located as follows:

- Site 1 (S1) in the sea, approximately 1.5 to 3 m from the waterline into the water (about 1 m of the water depth),
- Site 2 (S2) at the waterline,
- Site 3 (S3) on the beach, at a 30 m distance from the waterline,
- Site 4 (S4) in the dune, about 60 m away from the waterline.

Cores were taken with a 30 × 15 cm core Morduchaj-Bolkowski sampler, divided into two sections: 0-5 cm (surface layer) and 10-15 cm (subsurface layer), and placed in sterile polyethylene boxes. The samples were placed on ice and transported to the laboratory as soon as possible. Since accomplishment of full microbiological analysis was not possible in relatively short period of time samples were frozen to -60°C, however just before analysis the batch of samples subjected for treatment were defrosted.

Several microbiological and chemical parameters were determined in sand sediments: total bacteria number (TBN), lipids (LIP), proteins (PRT), carbohydrates (CHO), organic matter (OM) and total organic carbon (TOC). Prior chemical analysis sand samples were only mixed, while prior microbiological one they were tenfold diluted in a sterile water buffer (pH = 7.2) and sonicated (Rheinheimer 1977, Ellery and Schleyer 1984) to separate bacteria from sediment. Sonication was done using ultrasonic sonicator Bandelin SONOPLUS HD 2070 (Bandelin, Germany) in time of one minute and frequency of 20 kHz. Measurements of absorption for LIP, PRT and CHO were accomplished using Hitachi U-5100 (Hitachi, Japan) according to deionized water produced by HLP 10 (Hydrolab, Poland) while TBN using epifluorescence microscope Olympus BX41 equipped with excitation-barrier cube UV-2A (excitation λ = 365 nm, emission λ = 420 nm). TBN was established with the acridine orange direct method (DAPI) according to Porter and Feig (1980). OM was determined gravimetrically as the loss during calcination. It was estimated by delimitation of the difference between the mass of the sample dried earlier, and the mass of the sample calcinated in a muffle furnace (in the temperature of 450-500°C) to the solid mass. The sample was previously flooded with 10% chloride acid in order to remove carbonates (Januszkiewicz 1978). TOC was measured by Tiurin's method (Myślińska 2001), PRT according to the method described by Markwell et al. (1978), while CHO were analysed by DuBois et al. (1956) method. Finally, LIP were determined according to method described by Zöllner and Kirsch (1962).

RESULTS

The highest concentration of PRT was determined in core sediments collected in Ustka (379.62 $\mu g \cdot g^{-1}$), while the lowest in samples taken from Czołpino (290.31 $\mu g \cdot g^{-1}$) (Table 1).

Table 1

Organic matter and its labile forms abundance in worldwide beach sediments

Location	**OM** [mg·g-1]	**OC** [mg·g-1]	**CHO** [μg·g-1]	**PRT** [μg·g-1]	**LIP** [μg·g-1]	Reference
Ustka (Poland)	4.53-34.45	3.06-20.46	60.31-2985.13	44.80-046.61	15.26-1745.44	current study
Czołpino (Poland)	3.33-21.06	0.92-19.68	53.28-797.19	79.33-1524.38	6.21-735.05	
Puck (Poland)	4.74-267.08	1.76-160.00	127.95-1864.17	55.70-3861.52	38.17-1427.93	
Sopot (Poland)	0.90-13.00	-	-	-	-	Trojanowski et al. 2007
Czołpino (Poland)	0.40-10.40	-	-	-	-	
Ligurian Sea (Mediterranean Sea)	-	-	7.20-283.10	5.00-287.20	3.20-366.10	Fabiano et al. 2004
Iberian Peninsula (Spain)	-	-	4.00-1783.00	37.00-4160.00	1.00-190.00	Incera et al. 2003a
Ionian and Aegean Sea (Mediterranean Sea)	-	0.40-8.70	1230.00-2510.00	72.00-165.00	58.00-196.00	Danovaro et al. 1993
Marseille (France)	-	1.84-15.80	870.00-4120.00	480.00-2620.00	10.00-660.00	Fichez 1991
Note: (-) - not measured						

Seasonal analysis presented in Fig. 2a revealed that the highest concentration of PRT in Ustka was determined in autumn, while the lowest in spring. In case of core sediment samples collected in Czołpino the highest concentration of PRT was also determined in autumn, while the lowest in winter. Core sediment samples collected in Puck in spring were characterized by the lowest protein content, while those collected in summer were of the highest abundance of PRT. Concentration of PRT was different both in vertical cores (Fig. 2b) as well as horizontal transects (Fig. 2c) of the studied beaches. The highest mean concentration of proteins was found in subsurface layer (10-15 cm) in Puck and Czołpino indicating and ability of vertical infiltration. In Ustka the highest concentration of PRT was found in surface layer. According to horizontal transects the highest PRT concentration was found in S4 in autumn and winter, while in S3 in spring and summer. In Czołpino cores taken from S4 in autumn and winter, S1 in spring and S2 in summer were the most abundant with PRT. In Puck the highest concentration of PRT was found in spring an autumn in sediments in S2, while in S1 and S3 the maximal values were found in summer, and winter, respectively.

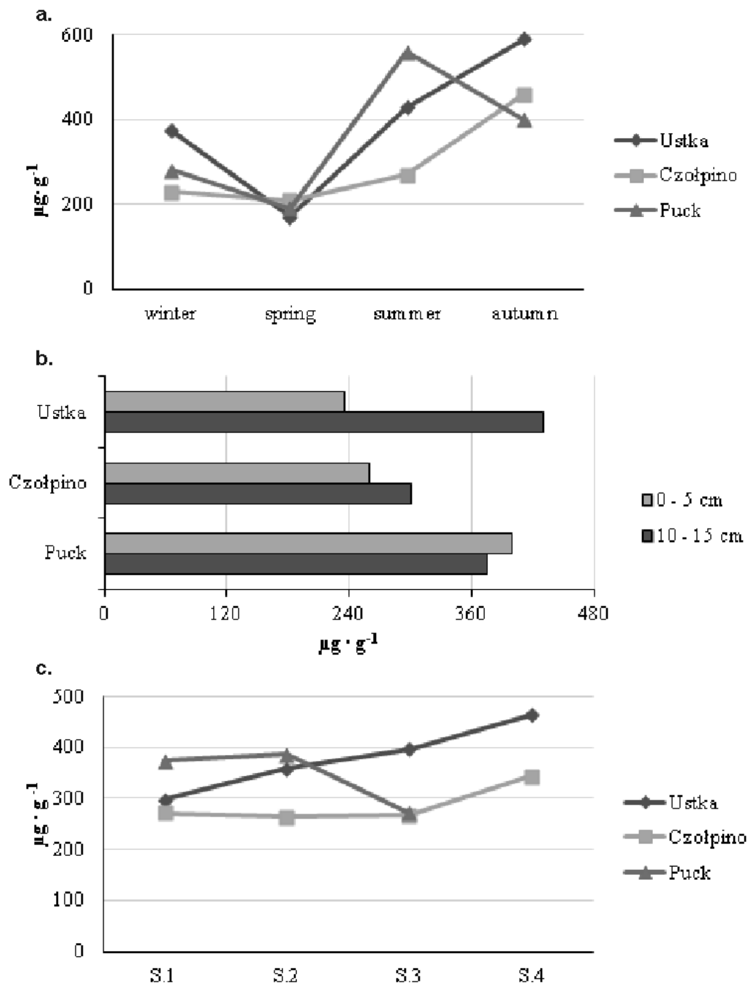


Fig. 2. The content of proteins determined in core sediments according to seasonality, vertical depth and horizontal transects

The comparable mean concentration of LIP was determined in sediment samples collected in Puck (265.01 $\mu g \cdot g^{-1}$) and Ustka (262.04 $\mu g \cdot g^{-1}$), although in Puck the content of LIP varied in the range between 38.17 $\mu g \cdot g^{-1}$ and 1428 $\mu g \cdot g^{-1}$, while in Ustka between 15.26 $\mu g \cdot g^{-1}$ and 1745 $\mu g \cdot g^{-1}$. This is why the highest concentration of LIP was measured in Ustka, while the lowest in Czołpino, where the concentration range varied between 6.21 $\mu g \cdot g^{-1}$ do 735.05 $\mu g \cdot g^{-1}$ (Table 1). Seasonal analysis of LIP concentration (Fig. 3a) revealed that the highest concentration was found in Ustka during spring (473.27 $\mu g \cdot g^{-1}$),while in the rest of seasons it was significantly lower (around 200.00 $\mu g \cdot g^{-1}$). Huge seasonal variation of LIP concentration was found in Puck (the highest concentration was determined in winter, while the lowest in autumn). It was also found that LIP concentration in winter and spring was two times higher than in summer and autumn showing descending trend from the beginning of the year till the end. In core sediments collected in Czołpino the highest concentration of LIP was determined in winter, spring and summer (around 220.00 $\mu g \cdot g^{-1}$), while the lowest in autumn (65.56 $\mu g \cdot g^{-1}$). In the vertical profile (Fig. 3b) of core sediments collected in each of the beaches lipid infiltration along into the profiles is noted. As a result higher mean concentration in subsurface layer (10-15 cm) than in surface layer (0-5 cm) occurs. Despite of this the highest difference in LIP abundance between individual layer was found in samples collected in Puck, while the lowest in those from Czołpino. On the beaches studied concentration of lipids was changeable also along horizontal transects (Fig. 3c). Surprisingly, in dredged material collected in Ustka the highest LIP concentration was determined in S3 (298.90 $\mu g \cdot g^{-1}$), while the lowest in S2 (224.12 $\mu g \cdot g^{-1}$).

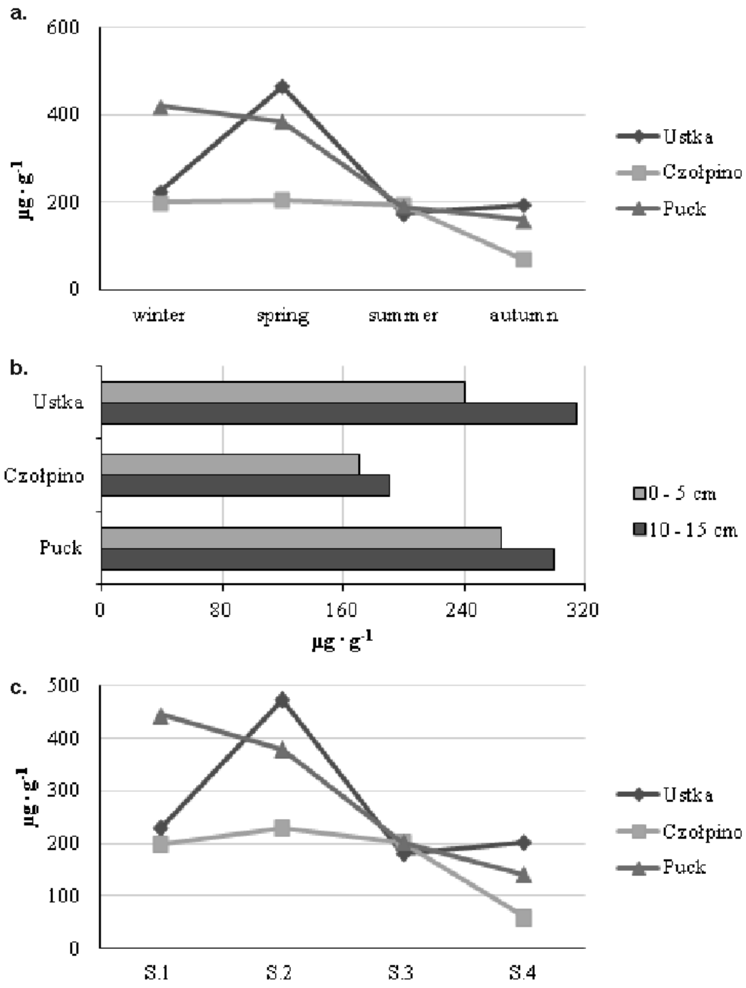


Fig. 3. The content of lipids determined in core sediments according to seasonality, vertical depth and horizontal transects

Both in Czołpino and Puck LIP concentration was decreasing as it moved away from the shoreline. In Czołpino the highest mean lipids concentration was determined in S1, while in remaining points of the horizontal transect it was on similar level (160.00 $\mu g \cdot g^{-1}$). In Puck LIP concentration determined in core sediment collected in the sea was higher by around 100 $\mu g \cdot g^{-1}$ than in the middle of the beach (222.98 $\mu g \cdot g^{-1}$).

In core sediments dredged in Puck mean concentration of CHO was almost two-fold higher than in Czołpino (310.84 $\mu g \cdot g^{-1}$) (Table 1). Seasonal assessment of CHO's concentration (Fig. 4a) revealed increasing trend from winter season till autumn in Ustka and Puck, however minimal concentration in Ustka was determined during summer. Similar characteristic was observed in Czołpino, where maximal concentration of sugars was determined in winter, while minimal one in spring.

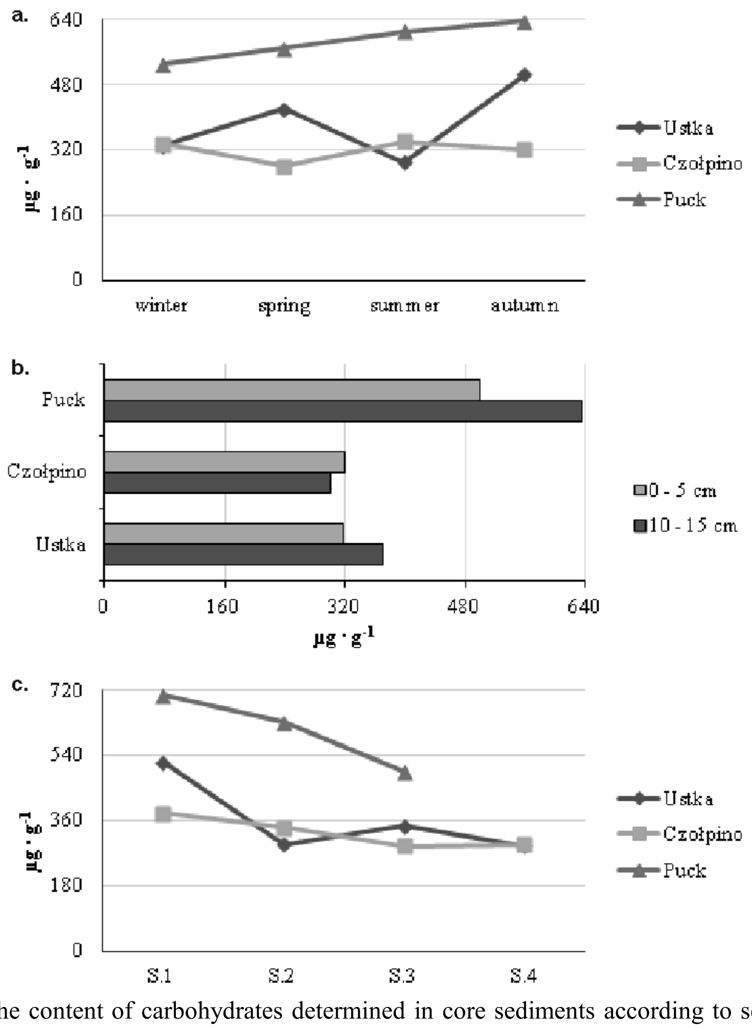
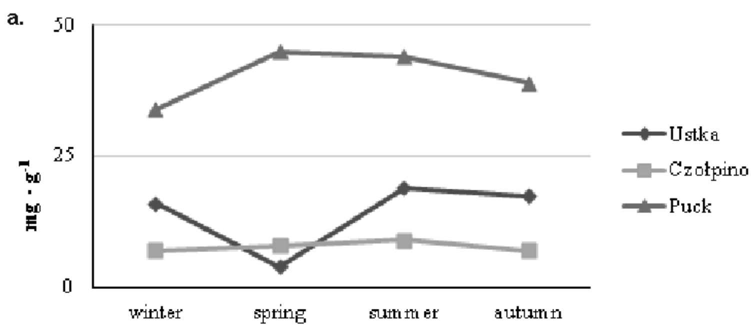


Fig. 4. The content of carbohydrates determined in core sediments according to seasonality, vertical depth and horizontal transects

It is also worth to mention that seasonal differences concerning CHO's concentration in dredged material collected in Czołpino were far smaller than in Ustka and Puck, especially during spring, summer and autumn. In case of vertical profile substantial CHO's infiltration was found in Ustka and Puck, since in subsurface layer sugars' concentration was higher than in surface one. Core sediments collected in Puck in subsurface layer were more abundant with CHO than in Ustka (Fig. 4b). None of vertical infiltration was observed in Czołpino, where in surface layer concentration of CHO was higher than in subsurface one. Generally, in all locations CHO's concentration decreased together with an increase of distance from the waterline (Fig. 4c). As an example determined concentration of sugars in Puck in S1 was 689.00 $\mu g \cdot g^{-1}$ while in the middle of the beach it was only 450.95 $\mu g \cdot g^{-1}$. Obtained results confirm significant impact of the sea on accumulation of carbohydrates in beach sediments as dominant source of this type of organic matter in coastal regions.

In collected dredged material variation of mean concentration of OM according to beach location (Table 1) and seasonality (Fig. 5a) was observed. The highest OM concentration was determined in core sediments collected in Puck (42.95 $\mu g \cdot g^{-1}$) while the lowest in these, collected in Czołpino (9.12 $\mu g \cdot g^{-1}$), indicating substantial anthropogenic impact. In all locations minimal concentrations were determined in winter or spring, while the highest during the peak of touristic season: 18.23 $\mu g \cdot g^{-1}$, 10.50 $\mu g \cdot g^{-1}$, 50.41$\mu g \cdot g^{-1}$ in Ustka, Czołpino and Puck, respectively. In case of vertical profile infiltration deep into the beach sediments was observed only in Puck. As a result OM concentration in subsurface layer was almost two times higher than in layer between 0 and 5 cm depth. In Ustka and Czołpino the content of OM in both layers was comparable (Fig. 5b). Horizontal assessment of OM variability (Fig. 5c) revealed that in Puck its concentration decreases together with increase of distance from the waterline. On S1 mean OM concentration was equal 70.43 $\mu g \cdot g^{-1}$ while in the middle of the beach (S3) it was 12.76 $\mu g \cdot g^{-1}$. The opposite characteristic was found for core sediments dredged in Ustka, where OM concentration increases together with increase of distance from the waterline. As a consequence the lowest concentration was determined in S1 and S2 (15.31 $\mu g \cdot g^{-1}$), while higher in S4 (17.31 $\mu g \cdot g^{-1}$). In Czołpino spatial distribution of OM in horizontal transect was unified. It suggests that major inflow of OM in Puck comes from the sea, in Ustka from the land while in Czołpino both inflows are balanced.



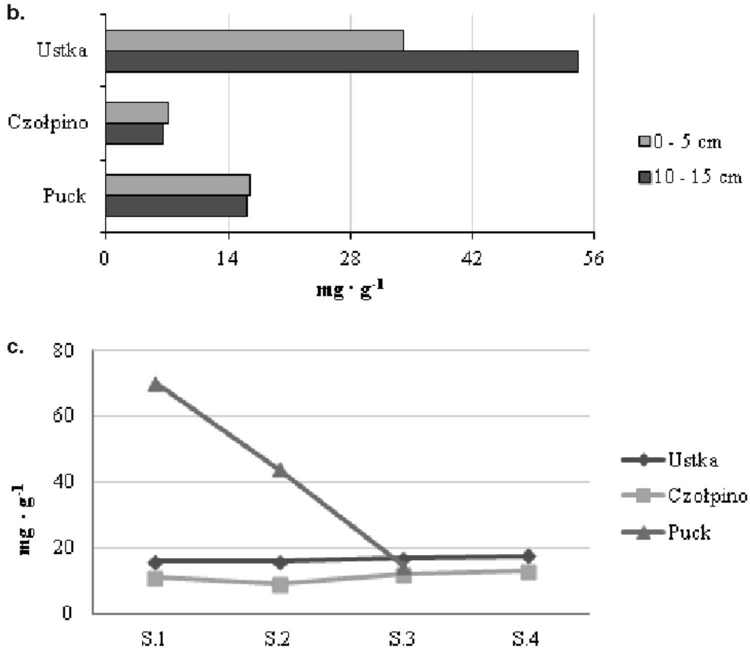
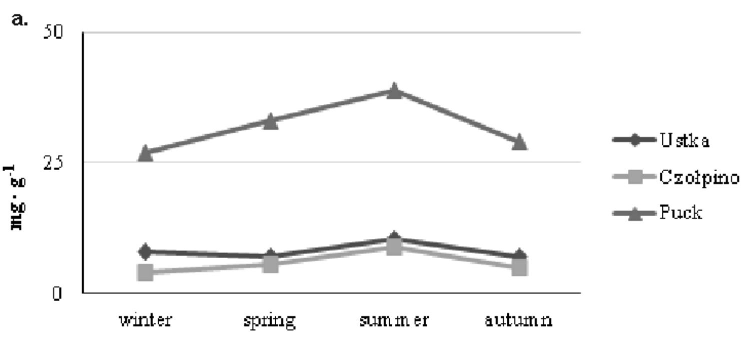


Fig. 5. The content of organic matter determined in core sediments according to seasonality, vertical depth and horizontal transects

The lowest TOC concentration values were determined in winter in Czołpino and Puck, and in spring in Ustka. In the vertical profile (Fig. 6b), the beach sediments of Ustka and Czołpino were characterized by similar content of TOC, with slight increase in surface layer. An opposite characteristic was found in Ustka, where lower deposited sediments were more abundant with TOC. Horizontal assessment of TOC abundance in investigated core sediments revealed analogical variability as described above for OM (Fig. 6c).



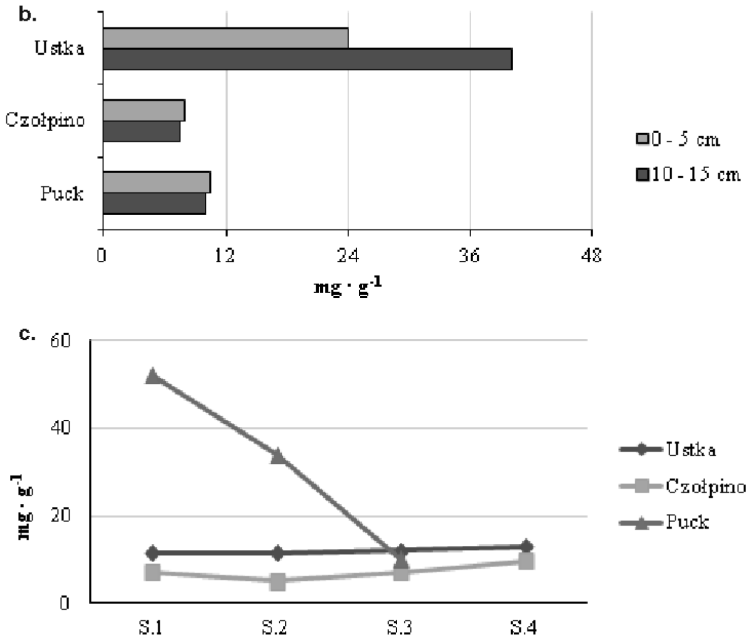
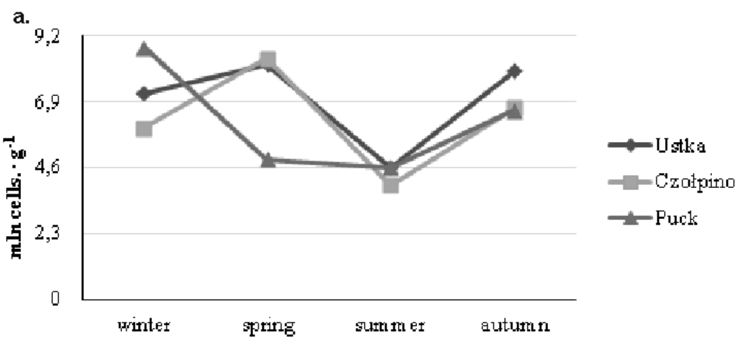


Fig. 6. The content of total organic carbon determined in core sediments according to seasonality, vertical depth and horizontal transects

Within the framework of microbiological tests TBN, as a measure of sanitary pollution of the region, was determined. Obtained results revealed significant differences of TBN according to seasonality, location as well as vertical depth. In core sediments collected in Puck TBN varied in the range between $2.90\cdot10^{6}$ cells$\cdot$g^{-1} and $1.61\cdot10^{6}$ cells$\cdot$g^{-1}, in Czołpino between $1.91\cdot10^{6}$ cells$\cdot$g^{-1} and $1.42\cdot10^{6}$ cells$\cdot$g^{-1} while in Ustka between $1.51\cdot10^{6}$ cells$\cdot$g^{-1} do $1.20\cdot10^{6}$ cells$\cdot$g^{-1}.
Seasonal analysis of TBN (Fig. 7a) indicated that in Ustka and Puck the highest number of cells was determined during winter, while in Czołpino during summer.



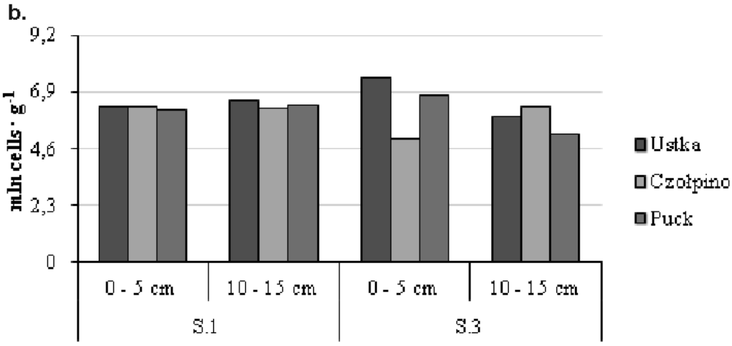


Fig. 7. Total bacteria number determined in core sediments according to seasonality, vertical depth and horizontal profile

In all locations extreme values of TBN were determined in dredged material collected in S3, however in Ustka and Puck higher abundance was observed in surface layer, while in Czołpino in subsurface layer (Fig. 7b).

DISCUSSION

Sandy beaches are dominant type of coasts in Europe. They are a dynamic ecosystem characterized by mutual interactions of lithosphere, hydrosphere, atmosphere as well as humans. As an element of coasts they are subjected both for land originated and marine originated impacts, and this is why variety of pollutants can be delivered to the beach from the land and from the sea (Huettel et al. 2003, Tylkowski and Samołyk 2011). According to intensity and energy of wave motion as well as water level during storms sea water can reach distant locations. Withdrawing water flows through sandy sediments causing its filtration since beach acts as a form of natural filter protecting terrestrial ecosystems against sea originated pollutants (Huettel et al. 2003, Podgórska and Mudryk 2003, Trojanowski et al. 2014). As a consequence organic matter as well as various forms of toxic substances accumulate in beach sediments (Meyer-Reil 1991). According to Podgórska et al. (2008) beaches are able to filtrate 10-91 $m^3 \cdot m^{-1} \cdot d^{-1}$ of sea water per day, however real quantity depends on some crucial physical characteristics of sediments, namely permeability and porosity which limit penetration ability of sea water deep into the beach sediments (McLachlan and Brown 2006).

Chemical composition of beach sediments uncovers the role of sandy coasts in sea water filtration and immobilization of variety of substances. In available references many papers concern organic matter abundance and its labile forms around the world. In Table 1 above results obtained in this study were set up with other results concerning organic matter abundance and its labile forms determined in sandy dredged material collected around the world. As ensues from Table 1 dredge material collected in belt of Polish coast in Ustka and Puck is characterized by much lower concentration of LIP and TOC as those collected in Mediterranean Sea coast

(Fichez 1991, Danovaro et al. 1993, Fabiano et al. 2004) and Atlantic Ocean (Incera et al. 2003a). Wide range in concentration of analytes from different parts of the world result from climate, hydrographic and anthropogenic differences (Danovaro et al. 1993, Trojanowski et al. 2014). According to Trojanowski et al. (2007) in dredge material collected in beaches attractive tourist is characterized by much higher concentration of organic matter as those natural beaches. The obtained data confirm this dependence. The beaches of Ustka and Puck are characterized by high levels of anthropopression, while the beach in Czołpino is located in the Słowiński National Park and its tourist activity is limited.

Despite filtration, sandy sediments participate in regeneration and recycling of biogenic elements in marine ecosystems (Meyer-Reil 1986) since organic matter delivered in dissolved as well as molecular form reach in macromolecules as proteins, lipids and carbohydrates (Mudryk and Skórczewski 2004, Mudryk and Podgórska 2006) undergoes to mineralization and transformation processes.

Heterotrophic bacteria play substantial role in organic matter transformation. In favorable conditions they are able to total mineralization of OM to simple inorganic compounds as ammonia, nitrates and phosphates (McLachlan 1983). OM transported by sea water during tides and wave motions can be infiltrated deep into the beach sediments being food source for microorganisms (Mann 2000, Trojanowski et al. 2007). Its decomposition takes place due to ability of microorganisms to enzymatic synthesis as a result of their adaptation to abundance of appropriate substrates (i.e. proteins, carbohydrates) or environmental factors (i.e. temperature, oxygenation, insolation) (Paluch 1973, McLachlan and Brown 2006). As result bacterial microflora present in sandy sediments play an important role in self-purification of beaches as well as energy and matter flow in marine ecosystems (Oliff et al. 1970, Podgórska and Mudryk 2003, Podgórska et al. 2008).

An assessment of microbiological processes taking place in sandy beaches ecosystem is complemented by total bacteria number. TBN can be used to monitoring purposes since microorganisms violently and rapidly react on every disturbances of regular environmental conditions (Danovaro and Fabiano 1995, Fabiano et al. 2004). One of the most important factors having an effect on TBN is sampling depth. Observed drop of TBN in core sediments collected in S3 from subsurface layer was probably caused by less favorable conditions in comparison to surface layer (higher temperature and insolation as well as better oxygenation) (Fabiano et al. 2003, Rush et al. 2003). Discovered phenomenon fits to results presented before by Fabiano et al. (2004) who determined higher total bacteria number in surface layer on the Ligurian Sea coast.

The TBN can be also limited by seasonality as was observed in dredged material collected on Polish coast. In general TBN increases during seasons of low external temperature: mainly winter in Puck and Ustka, or early spring in Czołpino and Ustka, however according to Danovaro and Fabiano (1995) temperature does not promote bacterial expansion, solely supporting their growth. Results observed in our study are different than presented by Danovaro and Fabiano (1995) who reported decrease of TBN during winter, and increase in summer. Simultaneously Danovaro and Fabiano (1995) emphasized that the more adequate factor to assess annual variability of TBN is quality of organic matter, mutual abundance of proteins, carbon and nitrogen, in particular. Seasonality could be recognized as another important factor determining the concentration of OM and its labile forms in sandy sediments in coastline. In the current study the highest content of OM was generally determined at the turn of spring and summer. Occasionally, maximal concentration was determined in samples taken during winter campaigns. Similar phenomenon was observed on the coast of the Ligurian Sea where the highest concentration of PRT and CHO was determined in spring, LIP in autumn, while maximal abundance of OM was present in winter (Fabiano et al. 1995).

Results obtained in current study revealed some variation in concentration of organic matter and its labile forms according horizontal transect along the beach. In dredged material collected in the most anthropogenically impacted beach in Puck the highest abundance of OM was determined in S1 and S2, which had a direct contact with sea water. Similar phenomenon was observed in Czołpino, however in this case the highest concentration of PRT was determined in the most remote location (S4). Contrarily, in core sediments collected in Ustka the highest concentration values were determined within locations separated from the waterline. The only exception was LIP with the highest concentration value determined in sample taken from S1. Current results generally fit to results presented by others, in particular Incera et al. (2003a) and Rodil et al. (2007) who confirmed the highest abundance of PRT, LIP and CHO in sandy sediments collected in Spain from locations possessing direct contact with the sea. Similarly as them also Cividanes et al. (2002) found the highest abundance of proteins, lipids and carbohydrates in the vicinity of waterline in Galicia. Described above dependencies were confirmed before by Trojanowski et al. (2007) who observed decrease of organic matter abundance accompanying with increase of distance from the waterline in Sopot and Czołpino.

Degree of sheltering impacts on abundance of OM and accompanying substances (PRT, CHO and LIP) in sediments deposited on Polish beaches. According to Covazzi Harriague et al. (2006) in Liguria coast and Incera et al. (2003b) in north-western part of Iberian Peninsula sediments collected in sheltered beaches were at least four to five times more abundant with PRT, CHO and LIP in exposed beaches. Incera et al. (2003b) in exposed beaches indicate results PRT 37.4-801 $\mu g \cdot g^{-1}$, CHO 5.7-266.5 $\mu g \cdot g^{-1}$ and LIP 0.6-56.3 $\mu g \cdot g^{-1}$, while in sheltered beaches PRT 3.8-4,165 $\mu g \cdot g^{-1}$, CHO 3.6-1,783 $\mu g \cdot g^{-1}$ and LIP 3.8-189.9 $\mu g\ g^{-1}$. Covazzi Harriague et al. (2006) indicate results for OM in exposed beaches – 53.9 $gC \cdot m^{-2}$, and in sheltered beaches – 1,174.3 $gC \cdot m^{-2}$.

Results obtained in the current study fully confirm validity of these comparisons. We observed far much higher concentration of OM and TOC in dredged material collected from sheltered beach in Puck in comparison with samples taken in Ustka or Czołpino. The beach in Puck is sheltered against the influence of the open sea by the Hel Peninsula, which separates it from an open Baltic Sea and almost precludes the exchange of water (Incera et al. 2003b).

In order to increase the esthetical characteristic of the beaches and to protect them against erosion and destructive storms, they are subjected to hydrotechnical treatments such as infilling. Infilling is a type of hydrotechnical treatment carried out to protect beach against substantial abrasion of the coast by the use of sand mined from main harbor canal. According to Pusceddu et al. (1999 and 2000) in case of stable beaches together with increasing of distance from waterline concentration of PRT, LIP, CHO and TOC decreases. This is why infilling processes impact on organic matter and its labile forms abundance as well as other chemical compounds content in sandy sediments. Infilling processes introduce variety of allochthonous bacteria displacing autochthonous organisms. Among set of studied beaches infilling campaigns take place in Ustka and Puck increasing overall anthropogenic impact caused by developed urban infrastructure, sea harbors and touristic activities (Trojanowski et al. 2007, Bigus and Trojanowski 2011). In the contrary the beach in Czołpino is located on the area of full ecological protection, almost free from any anthropogenic activities.

CONCLUSIONS

Marine beaches are a dynamic ecosystem characterized by diversity of inhabiting organisms (birds, fish, invertebrates), climatic conditions, sea pressure as well as geological processes (abrasion, sedimentation, sediments accumulation, etc.). Its proper functioning would not have been possible without psammons and protozoa involved in mineralization and transformation of organic matter to ammonium, nitrate and phosphate ions. Factors such as anthropogenic pressure and degree of beach sheltering limit intensity of microbiological and chemical processes taking place in beach sediments.

Beaches in Ustka and Puck are impacted by strong anthropogenic pressure due to vicinity of cities and harbors, while beach in Czołpino is located on the area of Słowiński National Park which is ecologically protected area, free from human impact.

The organic matter load is higher on the sheltered beach than on exposed ones. However, excessive accumulation of OM contributes to the inhibition of mineralization and transformation due to deficiency of oxygen which is essential to OM conversion. To maintain optimal mineralization and transformation sunlight and temperature should also be appropriate. Both factors most affect the surface layer of beach sediments, and hence the lower concentration of OM is observed in that zone. It was clearly observed in Puck indicating OM infiltration deep into the beach sediments. Factors influencing mineralization and transformation of OM also determine an abundance of microorganisms as well as the rate of microbiological processes the run. The higher human pressure the higher OM concentration, and hence the higher abundance of microorganisms. This is why in the case of Puck and Ustka sediments the higher general abundance of bacteria was observed in comparison to sediments collected in Czołpino.

As heat and light play an important role in mentioned above processes higher concentration of labile forms of OM should be expected in warm parts of the calendar year. This was generally confirmed for PRT, LIP, CHO and OC. For these forms of OM the highest concentrations were observed in spring and summer. Exceptions were LIP in dredged material from Puck and CHO in samples from Czołpino where the highest concentrations were recorded in winter. All above mentioned phenomena could be unsettled by infiltration of beaches threatened with destruction due to impact of waves.

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CZASOWA I PRZESTRZENNA ZMIENNOŚĆ BIOCHEMICZNEGO SKŁADU MATERII ORGANICZNEJ I LICZBY BAKTERII W OSADACH WYBRANYCH PLAŻ POŁUDNIOWEGO MORZA BAŁTYCKIEGO

Streszczenie

Pobierano i analizowano piaszczyste osady pochodzące z trzech plaż południowego Bałtyku, które zostały podzielone na podstawie wpływu antropopresji i stopnia osłonięcia plaży. Pierwsza plaża położona była w Ustce we wschodniej części ujścia rzeki Słupi, druga w Czołpinie, a ostatnia w Pucku. Próbki osadów plażowych zbierano sezonowo, w zależności od wpływu wody morskiej na badane osady. Na każdym stanowisku pobierano osady powierzchniowe (0-5 cm), a także osady na głębokości 10-15 cm. Określono zawartość materii organicznej, białek, lipidów, węglowodanów, węgla organicznego i całkowitej liczby bakterii. Wyniki przeprowadzonych badań wykazały, że antropopresja, stopień osłonięcia plaży, głębokość pobieranych osadów i bezpośredni wpływ wody morskiej na osady oddziałują na skład chemiczny materii organicznej i liczbę bakterii w osadach plażowych.