Sediment deposition in the Puck Lagoon (Southern Baltic Sea, Poland)

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Abstract The article describes present-day processes related to sediment flux and deposition in the Puck Lagoon, southern Baltic Sea). In situ sediment traps were used for determining the sediment properties in the lagoon and its tributaries. Both sediment sources and the volume of incoming sediment were taken into account and a distinct zone of sediment deposition was discovered in the central part of the Puck Lagoon. The rate of sediment deposition in the Rzucewo Deep exceeded 8.0 mm y^{-1}, whereas in other parts of the Puck Lagoon it ranged from 1.9-3.9 mm y^{-1}. These findings provide the basis for predicting future sedimentation conditions in the Puck Lagoon.

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INTRODUCTION

In the marine environment, the processes related to the presence and movements of particles on the seabed are described by the terms deposition, accumulation and sedimentation. According to Reineck (1960) and Mc-Kee *et al.* (1983), sediment deposition refers to the temporary placement of particles on the seabed. In shallow and dynamic marine environment, the particles in surficial sediments undergo many episodes of displacement and removal from the seabed. The sum of the episodes of sediment deposition and removal over a longer time scale is defined as accumulation. Sedimentation is the overall process of particle transport to emplacement on, removal from and preservation in the seabed.

A number of studies on sedimentation processes in the Baltic Sea, focusing either on a short or long time scale, were published (Winterhalter *et al.* 1981; Blaszczyszyn 1982; Pempkowiak 1991; Walkusz *et al.* 1992; Pustelnikov 1992, 1994; Szczepańska, Uścinowicz 1994; Christiansen *et al.* 2002; Emeis *et al.* 2002; Hille *et al.* 2006; Mattila *et al.* 2006; Suplińska, Pietrzak-Flis 2008).

Lagoons, being a transit zone for suspended matter on its way from land to the open sea, play a role of sedimentation basins for sedimentary material, which originates from a variety of sources and consists of inorganic (mineral) and organic particles. The sediment inflow and its distribution in the Puck Lagoon are not well known yet. Despite the convenient location and physical features of the Puck Lagoon, so far no research has been done on sediment deposition in this water body.

The aim of this study was to determinate the vertical sediment flux, i.e. the amount of suspended sediment that is settling towards the seabed per unit area and per unit time (Lund-Hansen, Christiansen 1998), and the rate of sediment deposition [mm year^{-1}]. The object of the study is the particle fractions that are the main component of suspended matter and bottom sediments. In order to estimate the sediment input from various sources, we used the results of our study concerning the size of river load into the Puck Lagoon as well as the data about the abrasion material supplied to the lagoon and aeolian transport processes.

STUDY AREA

The Puck Lagoon is the most peripheral, western area of the Gulf of Gdańsk (Fig. 1). It covers 103 km^2, its average depth is 3.13 m (approximately 30% of the
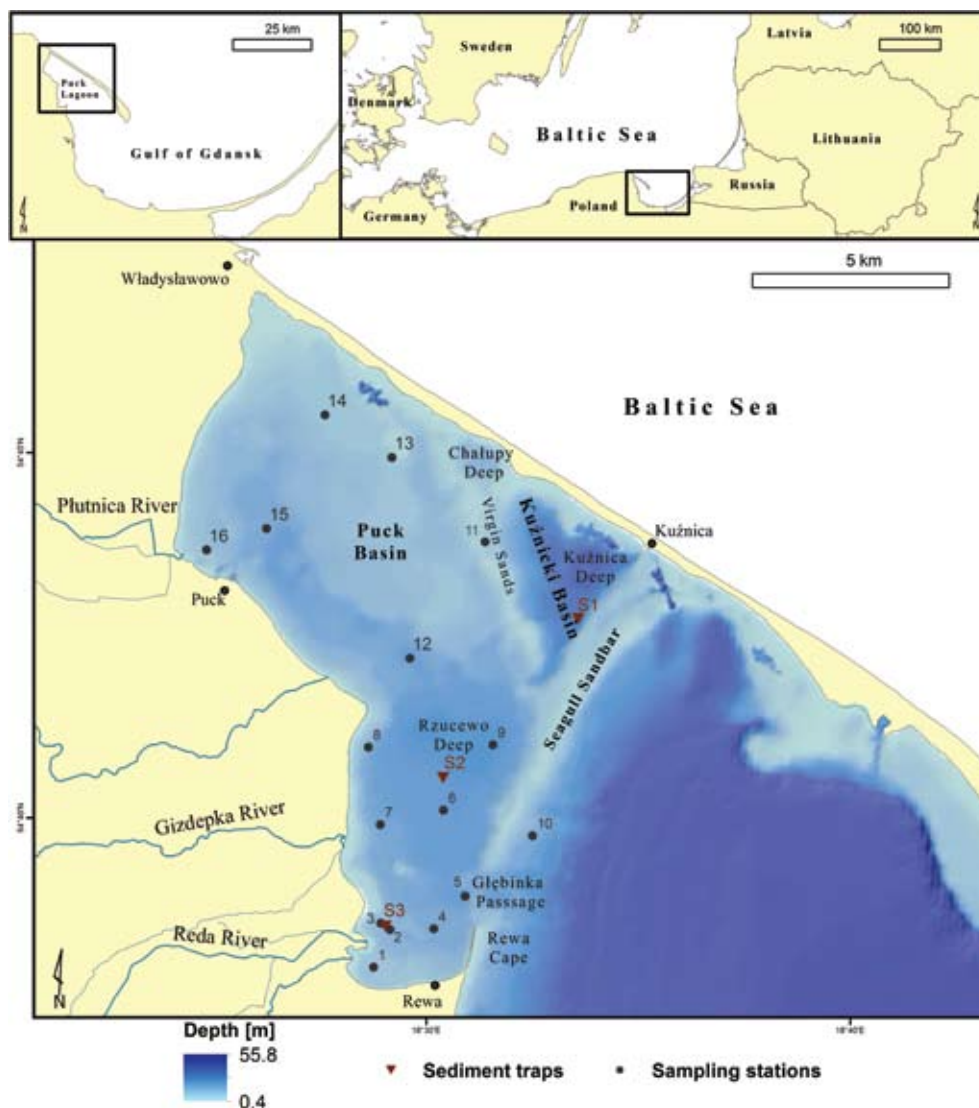
Fig. 1 Location of sampling stations (Nos. 1–16) in the Puck Lagoon

area is situated at 0 to 2 m depth) and the water capacity is 0.32 km³. To the north-east it boarders with the accumulative Hel Spit, while to the south-east with temporarily emerging sand ridge of the Seagull Sandbar and the Rewa Cape. It joins the Gulf of Gdańsk along the 1.8 km wide Głębinka Passage which is an artificially deepened waterway of 3−4 m depth. Another isthmus, 1.3 km wide, is located near Kuźnica. To the west, the Puck Lagoon is surrounded by Pleistocene moraine upland with ice-marginal valleys and erosion river valleys cutting deeply into it.

The characteristic feature of the Puck Lagoon is the varied seabed formation that allows for defining two basins. The Puck Basin runs along the western coast in a form of gully delineated by 3- and 4-m isobaths, whose deepest site is the Rzucewo Deep (max. depth 5.7 m). The Kuźnica Basin runs along the Hel Spit and covers the Kuźnica and Chałupy Deeps (max. depth 9.7 m and 4.0 m, respectively). The exchange of water between the basins is hampered by the shallows of the Virgin Sands reaching from the

Hel Spit in the north-west to the Seagull Sandbar in the south-east. The bottom of the lagoon is in the immediate vicinity of the mouth of ice-marginal valleys with rivers flowing in and the moraine hills forming cliffs on the seashore.

Two genetic types of bottom sediments are present in the Puck Lagoon, i.e. lagoon clastic formations and Late Glacial and Early Holocene freshwater marsh-limnic sediments exposed in rather small seabed areas. Next to the abraded cliff edges, coarse gravels and coarse sands with boulders occur (Fig. 2). Medium-grained sands can be found in the shoreline area, up to the 1 m isobath; they make up shallow water shoals such as the Virgin Sands and the Seagull Sandbar. The dominant type of sediment, which appears in the vast area of the seabed, is fine-grained sand. It can be found in the western and south-western area of the lagoon, in the mouth of the Reda River and on the eastern edge of the Kuźnica Deep. Coarse silty clays are to be found in the deepest areas of the Kuźnica, Chałupy and Rzucewo Deeps. The outcrops of marsh-limnic

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sediments (peats and lime gyttja) occur in the area of the seabed where the ice-marginal valleys of Reda River and Płutnica River are extended (Jankowska 1993). Present-day terrestrial sediments forming on the bottom of the Puck Lagoon originate from river inflow, coastal abrasion and aeolian transport.

The movement of sedimentary material within the Puck Lagoon waters depends on the bathymetry and morphology of the seabed and water circulation. The variability of currents and the resulting exchange of water between the Puck Lagoon and the Gulf of Gdańsk is determined by the wind and wind-induced changes in the sea level, seiche and small (a couple of centimetres high) tides. It must also be noted that the rivers flowing into the Puck Lagoon induce currents in the river mouth areas, which are formed according to the river runoff. The circulation is not stable though because it depends on the wind direction. The main axis of flow and water exchange in the Puck Lagoon is a gully stretching from Głębinka to Puck. Another system is connected with the Kuźnica Basin where the dominant currents move clockwise (Fig. 3).

Salinity (mean 7.3 PSU) is an important factor influencing the sedimentation of suspended particles. Salinity is influenced by seawater masses flowing from the outside of the Puck Bay (0.5 km^3) and freshwater inflow (0.2 km^3). The impact of freshwater is limited only to the river mouth area where the salinity ranges from 0.5 to 5.32 PSU. The variability of salinity in the river mouth areas is extremely important because it determines the process of flocculation. During the year, the mean salinity in the Puck Lagoon varies slightly from 7.2 to 7.5 PSU. The lowest salinity is observed in spring and autumn, which is caused by an increased inflow of freshwater. The highest salinity values occur in winter. Salinity shows no signs of stratification because the lagoon is relatively shallow and high-energy, i.e. the water mixes intensively. The annual outflow of water from the Puck Lagoon into the Gulf of Gdańsk equals ca. 0.8 km^3 (Nowacki 1993). The coefficient of annual water exchange in the lagoon is high (2.5).

MATERIAL AND METHODS

Quantitative analysis of sediment influx

The primary objective of this study was to evaluate the importance of sediment transport into the Puck Lagoon by river runoff, wind and abrasive processes. Rivers are the main source of terrestrial sediment supplied to the Puck Lagoon, transporting about 12 000 tons of sediment annually (Szymczak, Piekarek-Jankowska 2009). Approximately 3 000 tons of this load consists of suspended sediment which becomes suspended matter in the water column. The riverbed
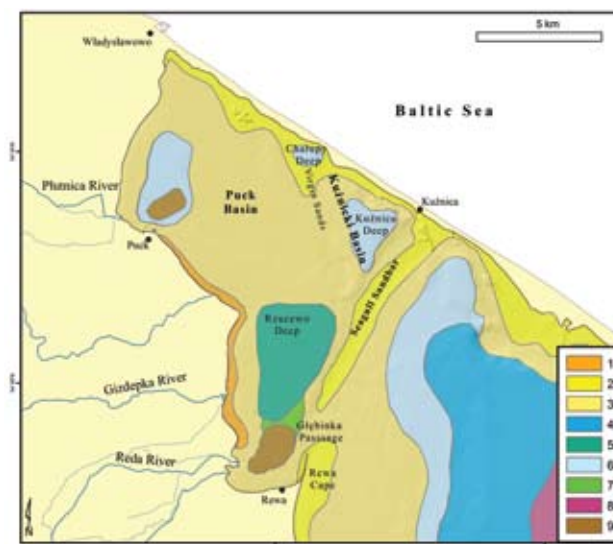
Fig. 2 Sketch of bottom sediments in the Puck Lagoon area (according to H. Jankowska 1993). 1 – pebble gravel, 2 – medium sand, 3 – fine sand, 4 – coarse sand, 5 – coarse silt on calcareous gyttja, 6 – coarse silty clay, 7 – calcareous gyttja, 8 – peat
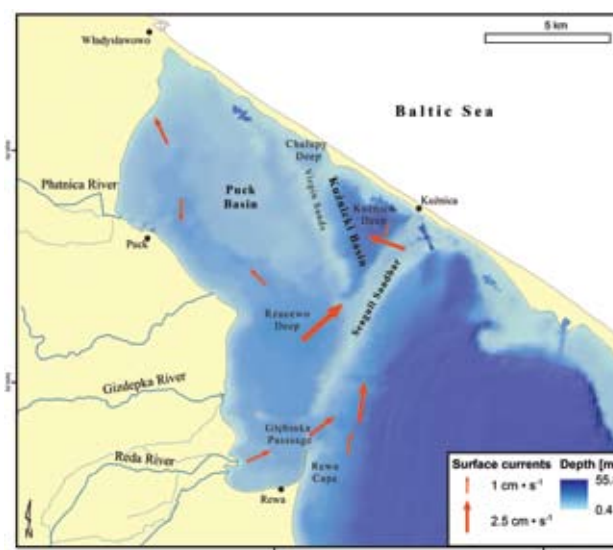
Fig. 3 Average of current surface velocities in the Puck Lagoon (according to J. Nowacki 1993)

load accumulates exclusively next to the river mouth (Szymczak, Piekarek-Jankowska 2007).

The abrasion processes occur on the western cliffed coast of the Puck Lagoon whose length is approximately 7 900 m. The active sections constitute one third of that distance. The abrasion rate has been estimated at 0.11 m yr^{-1} (Zawadzka-Kahlau 1999). The coast of moraine upland is formed by till and fluvioglacial sand and gravel, whereas the coast of ice marginal valleys is built by peat and fluvial silts and sands. Because of abrasion, each year 10 900 tons of sediment reaches the Puck Lagoon which includes 2 300 tons of fine-clastic material (calculations after Bogacka, Rudowski 2001).

The amount of matter transported by wind into the Puck Lagoon is 6.7 tons km^{-2} per month, which amounts to 8 300 tons per year. The weight share of organic matter is about 40%. The other 60% (almost 5 000 tons) consists of various inorganic substances among which the grains of dune sands and atmospheric dust are most common (Pęcherzewski 1994).

The amount of material eroded from the sea bottom is unknown. A total of 31 200 tons of sediment from the aforementioned sources reaches the Puck Lagoon each year, and that includes 45% of fine-grained clastic material being a part of suspended matter.

Fieldwork

The data discussed in this article were collected during fieldwork undertaken in the Puck Lagoon in 2002−2009. During the 2002−2003 season, bottom sediments and water samples from 16 stations were examined (see Fig. 1). At each sampling site, water samples were collected twice (in autumn and spring) from the surface layer, halfway the maximum depth and 0.5 m above the bottom by using bathometer. Surface sediments were collected in spring by using the van Veen grab sampler. During the season 2008−2009, only the samples of near-bottom water were taken with a bathometer before the installation of sediment traps and immediately after their removal.

The sediment trap experiments were conducted in two periods, i.e. from June 2003 to May 2004, and from September 2008 to April 2009. The traps were installed at three stations (Fig. 1) which clearly differed with regard to bathymetry and bottom sediments, and whose characteristics are presented in Table 1. The first experiment was planned in two stages. Two traps were installed at each station in June 2003. In order to analyze seasonal variation in sediment flux, one trap was deployed for 12 months, while the second one was planned to be recovered after six months and re-

placed with the new one for the next six months. After six months, only trap S1/03 was taken out, while traps at stations S2 and S3 were found to have been destroyed, probably by fishermen or diving tourists. At the second stage of experiment in November, traps were installed at the same locations. After six months, in May, traps S2/04 and S3/04 were taken out, while trap S1was found destroyed. The third experiment employing sediment traps started in September 2008. The traps were deployed at the Kuźnica Deep (S1/09) and the Rzucewo Deep (S2/09) for seven months, i.e. until April 2009.

Taking into account the results of studies on the efficiency of sediment traps conducted by other researchers (Gardner 1980; Butman 1986; Butman *et al.* 1986), a decision was made to use cylindrical traps made of polyvinyl chloride, whose inner diameter was 95 mm, height 500 mm and capacity 3.5 l. Such traps ensure the realistic measurement of sediment flux in the environment characterized by high water mobility (Hargrave, Burns 1979; Blomqvist, Kofoed 1981) because the trapped sediment cannot be redeposited. Each trap was vertically mounted on a stand with its outlet 0.7 m above the seabed. Sediment traps before mounting had been filled with seawater from the depth at which they were located. The samples of bottom sediment and water from the depth of trap deployment were collected at each site. Traps were emptied after six or seven months of exposure. The outlet was covered and the trap was carefully brought up to the surface.

Laboratory analysis

In order to estimate the concentration of suspended matter, seawater samples were filtered through re-weighted Whatman GF/F fiberglass filters (0.7 μm). Due to the very low concentration of suspended matter, the filters were rinsed with distilled water to re-

Table 1 The sediment trap locations in the Puck Lagoon and the results of measurements

Station name	Station coordinates/Position	Water depth [m]	Exposure time	Suspended sediment		Sediment in traps		
				Concentration [g·m^{-3}]	Share of organic matter [%]	Dry mass [g]	Mean sediment flux [g m^{-2} day^{-1}]	Share of organic matter [%]
S1/03 Kuźnica Deep	18°33.254' E 54°42.995' N	7,0	VI–XI 2003	3,7	25	31,8	21,25	15
S1/09 Kuźnica Deep			IX 2008– IV 2009	3,4	5	18,4	12,4	16
S2/04 Rzucewo Deep	18°329.316' E 54°42.372' N	5,0	XI 2003– V 2004	12,3	75	70,2	46,94	25
S2/09 Rzucewo Deep			IX 2008– IV 2009	7,8	5	35,9	24,15	18
S3/04 Reda River mouth	18°28.851' E 54°38.730' N	2,8	XI 2003– V 2004	6,8	21	29,4	19,67	11

cover the filtrate for the particle size determination. The grain size of suspended matter was measured by means of a Fritsch laser particle sizer *Analysette 22* (1-2000 μm). The organic matter content in suspension was determined as a loss of weight on ignition (LOI) at 550ºC.

Material from sediment traps was filtered immediately after transport to the laboratory and later dried out at 105ºC. Both surface sediments and the material from the traps were fractionated by means of sieve analysis with 2.0, 1.0, 0.5, 0.25, 0.125 and 0.063 mm mesh size sieves. The fraction less than 0.063 mm was analyzed by pipetting (Łęczyński, Szymczak 2010) to distinguish the fractions of particles with a diameter 0.063–0.032, 0.032–0.004, and < 0.004 mm. The content of organic matter in bottom sediments and the material

deposited in sediment traps was determined by using 30% hydrogen peroxide (Mikutta *et al.* 2001).

RESULTS

Concentration of suspended matter

The concentration of suspended matter, measured at 16 sampling stations (Table 2) in the Puck Lagoon, showed high seasonal variability (2.1−19.8 g m⁻³) which is most likely connected to the seasonality of hydrodynamic phenomena in this area. In the autumn season, the suspended matter concentration in the surface water layer varied from approximately 3.5 to almost 19 g m⁻³ (Fig. 4a). The highest values were observed in the Puck Basin, nearby Puck cliff and to the

Table 2 Sampling stations location and the results of suspended sediment measurements

Station name	Station coordinates/ Position	Suspended sediment concentration [g·m⁻³]		Grain size composition of suspension [%]						
		autumn 2002	spring 2003	<0,004 mm	0,004– 0,008 mm	0,008– 0,016 mm	0,016– 0,032 mm	0,032– 0,063 mm	0,063– 0,125 mm	>0,125 mm
		surface water layer								
		above the seabed								
1	18°28.72' E 54°38.124' N	9.84 9.27	7.85 7.5	1.8	6.3	10.1	13.2	59.9	6.4	2.3
2	18°29.0736' E 54°38.6472' N	4.02 3.39	6.67 6.79	0.5	11.1	8.6	15.4	58.7	3.9	1.8
3	18°28.851' E 54°38.73' N	11.46 13.27	8.33 8.33	0.7	8.2	9.6	12	61.2	5.2	3.1
4	18°30.11' E 54°38.678' N	3.98 18.16	7.12 7.1	1.3	11.5	13.8	20.3	49.6	2.6	0.9
5	18°30.822' E 54°39.14' N	4.06 8.97	5.6 6.97	2.6	9.3	13.7	12.5	57.3	3.4	1.2
6	18°30.24' E 54°40.308' N	6.69 12.41	7.84 7.75	3.7	8.8	10.2	11.7	62.1	2.8	0.7
7	18°28.758' E 54°40.08' N	17.3 6.7	6.88 7.02	2.5	7.6	11.9	13	58.6	4.3	2.1
8	18°28.41' E 54°41.133' N	3.65 3.58	7.37 8.48	3.8	8.9	9.2	9.7	60	5.1	3.3
9	18°31.35' E 54°41.226' N	6.06 6.8	3.51 6.63	2.6	9.7	14.9	20.6	48.7	2.6	0.9
10	18°32.365' E 54°40' N	4.22 6.19	2.13 5.54	5.2	9.3	9.8	17.3	52.2	4.5	1.7
11	18°31' E 54°44' N	9.12 7.65	5.12 7.45	2.3	4.8	15.8	18.7	49.9	5.2	3.3
12	18°29.316' E 54°42.372' N	7.68 6.21	6.44 7.81	4.1	8.9	10.9	12	58.4	3.4	2.3
13	18°28.72' E 54°45.11' N	14.26 10.46	6.23 7.66	1.7	6.8	11.2	17.9	56.7	4.1	1.6
14	18°27.1' E 54°45.66' N	16.32 12.08	6.98 7.69	2.6	8.5	10.1	27.6	47.3	2.6	1.3
15	18°25.818' E 54°44.076' N	19.85 15.61	7.37 7.98	3.3	5.6	11.7	17.8	59.2	1.8	0.6
16	18°24.414' E 54°43.752' N	6.33 5.5	7.47 7.01	1.6	7.3	12.6	26.6	48.4	2.7	0.8

south of the Gizdepka River mouth. Such distribution of suspended matter may be the result of supplying the waters of the lagoon in sediment material from two sources, i.e. from Gizdepka River, a river with the richest river load, and from abrasion of the cliff section. The lowest concentration of suspended matter was observed between the active cliff areas and nearby the Rewa Cape and the Głębinka isthmus.
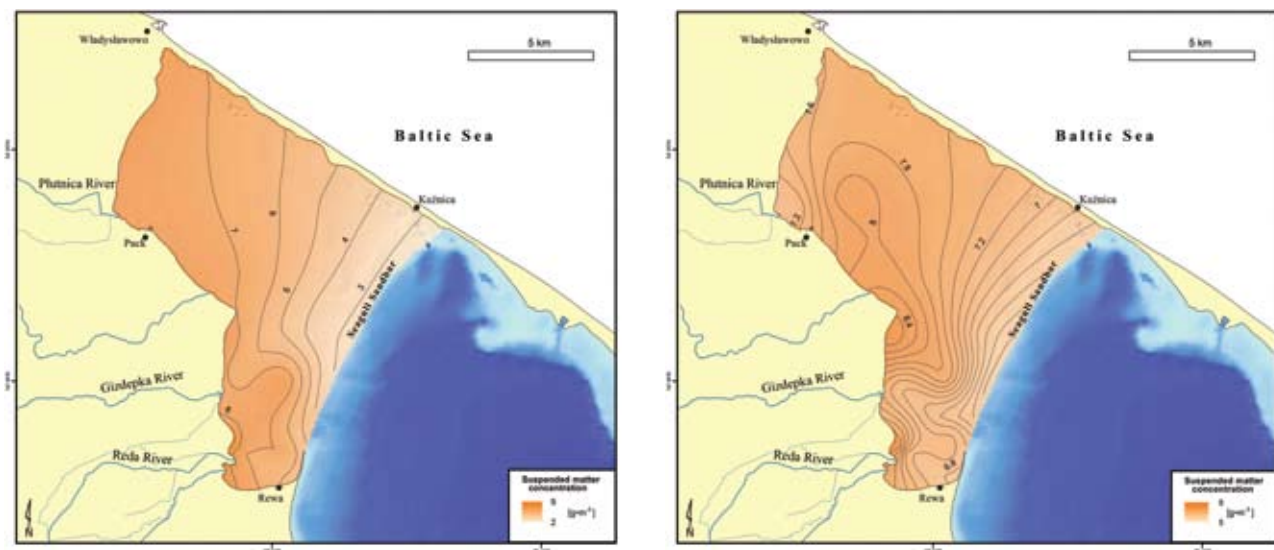
The concentration of suspended matter in the near-bottom water layer was slightly higher than in the surface water layer, and it fluctuated from 3.7 to 15.8 g m^{-3} (Fig. 4b). The lowest values occurred alongside the western coast of the lagoon in the river mouth area. The highest concentrations of suspended matter in the near-bottom layer were observed to the north off Puck cliff and in the Głębinka area, where suspended matter is delivered via Reda River and due to the water exchange between the Puck Lagoon and the Gulf of Gdańsk.

In the spring season, the concentrations of suspended matter in the surface water layer in the Puck Lagoon were lower compared to those in autumn, ranging from 2.1 to almost 8.5 g m^{-3} (Fig. 5a). The highest values of suspended matter were reported along the western edge of the Puck Lagoon and the Reda River mouth area. The isograms of suspended sediment concentration were parallel to the coastline, which proves that the concentration of suspended matter decreases with increasing distance from the source of matter.

The differences in the suspended matter contents in the near-bottom water layer were insignificant; the concentration values ranged from 6.6 to 8.4 g m^{-3} (Fig. 5b). The highest values occurred along the lagoon coast in the area bordering with Puck cliff and the Reda River mouth. A higher share of suspended matter in the near-bottom water layer may have resulted from the resuspension of bottom sediment that often occurs in the shallow areas of this water body.
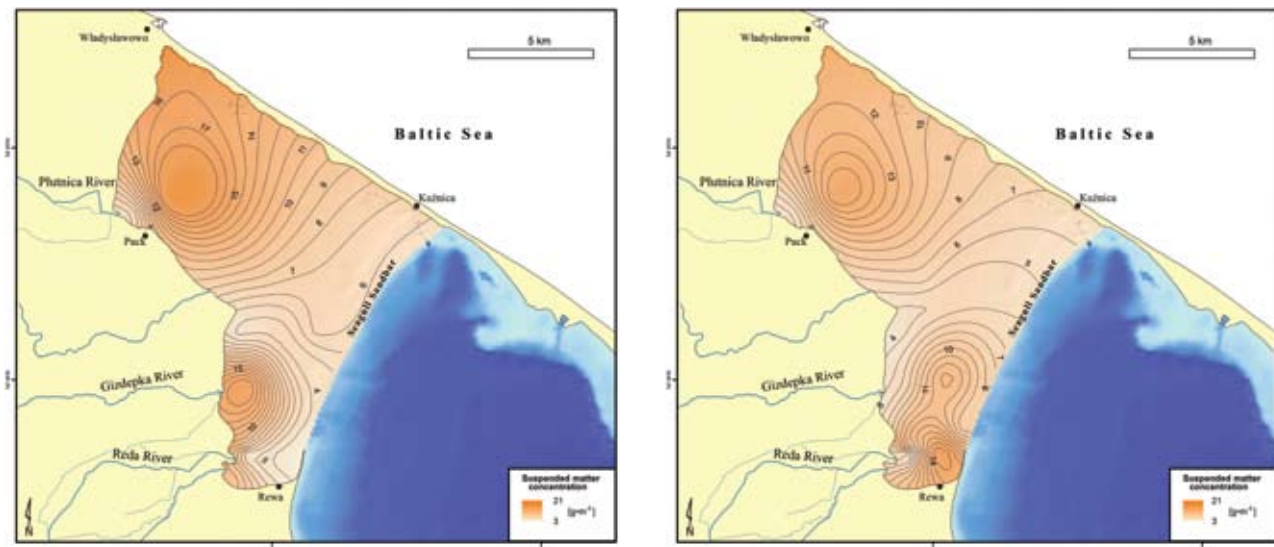
Fig. 4 Average concentration of suspended matter (g m^{-3}) in surface water layer **(a)** and above the seabed **(b)** in autumn 2002

Fig. 5 Average concentration of suspended matter (g m^{-3}) in surface water layer **(a)** and above the seabed **(b)** in spring 2003

Composition of suspended matter

The composition of suspended matter differs greatly between the two seasons. In autumn, the dominant part is inorganic, reaching 70%. In contrast, during spring and summer, the organic matter content in the suspension rises to 45% due to phytoplankton blooms (Pliński 1993; Renk 1993). The phytoplankton growth can increase the suspended matter concentration in the surface water layer by even 3 g m^{-3}.

Increased contents of mineral fraction were observed in the suspended matter samples collected in October and April from the near-bottom water layer; the contents were on average 3% higher compared to those measured in surface water samples. Such variability indicates the occurrence of resuspension processes resulting in the enrichment of suspended matter in mineral fractions at the sea bottom. It also points to the fact that the primary production decreases with increasing depth.

Based on the grain size composition of inorganic suspension in the lagoon waters (see Table 2), grains with the diameter ranging from 0.001 to 0.125 mm were found. Coarse silt (0.063–0.031 mm) and medium silt fractions (0.031–0,016 mm) constituted more than 80% of suspension. The share of sandy fraction was slightly over 8%.

Vertical sediment flux

The significant differences in the suspended sediment concentration in the near-bottom water layer were observed in various areas of the basin immediately before anchoring the sediment traps. In November 2003, the suspension concentration in the Rzucewo Deep (S2/04) was 12.3 g m^{-3}, which is almost half as high as in the Reda River (S3/04) mouth area. In September 2008, the suspension concentration approximately a sediment trap in the Rzucewo Deep was 7.8 g m^{-3}. In June 2003, the lowest value (3.7 g m^{-3}) was measured in the waters of the Kuźnica Deep (S1/03), which is most peripheral to the potential area of sediment origin. The same situation was observed in 2008, when the suspension concentration equalled 3.4 g m^{-3}. This finding is supported by the fact that the suspension concentration depends on the distance from the potential sources of sedimentary material.

The sediments collected inside the traps differed with respect to their quantity and quality. The mean sediment mass collected in the traps within the 6- and 7-month periods varied from 18 to over 70 g (see Table 1).

The values of diurnal vertical flux of sediment per surface area were calculated based on the dry mass of sediment deposited inside the traps in a given exposure time. The highest sediment flux (46.94 g m^{-2} day^{-1})

was typically measured at station S2/04 in the central part of the basin. The sediment flux observed in the Kuźnica Deep (S1/03; 21.25 g m^{-2} day^{-1}) was more than two times lower; this specific site is the deepest and furthest removed from the potential sediment sources among all stations. The Reda River mouth station, which is the shallowest and the closest to the shore site, was characterized by the lowest sediment load per unit surface area. In 2008 and 2009, the sediment flux per unit surface area was definitely lower, and equalled 12.4 and 24.15 g m^{-2} day^{-1} at stations S1/09 and S2/09, respectively.

## Composition of deposited sediments

The material accumulated in sediment traps included 11–25% of organic matter (see Table 1). Material that is more organic was found in the traps located at lower depths further away from the shoreline. The organic matter content in recent lagoon deposits in these parts of the Puck Lagoon was lower and accounted, on average, for 1–10%. The highest values of organic matter concentration in bottom sediments were observed in the immediate vicinity of the Płutnica River mouth as well as at the extension of the estuary of Gizdepka River in the western part of the Rzucewo Deep.

The results of granulometric tests were described by applying Shepard classification (1954) with the sand, silt and clay-size based on a Wentworth grade scale (1922). The material deposited in sediment traps was classified as clayey silt and silt. Sediments from the traps deployed in the Kuznica and Rzucewo Deeps were characterized by increased share of sand (Fig. 6 a, b). On the other hand, sediments from the Reda River mouth displayed the highest share of silt, the lowest share of organic matter (11%) and were rich in clay fractions.

DISCUSSION

The obtained results indicate that the contents of suspended matter in water samples from the Puck Lagoon are comparable with those reported for the entire Gulf of Gdańsk (0.36–35.0 g m^{-3} Burska, Graca 2011), the southern part of the Baltic Sea (0.6–12.4 g m^{-3}) (Emelyanov, Pustelnikov 1982; Emelyanov, Stryuk 2002) and the Pomeranian Bight (1.55–12.02 g m^{-3}) (Jähmilch et al. 2002). In comparison, the mean concentration values of suspended particulate matter in the Vistula Lagoon (Chubarenko et al. 1998) and the Curonian Lagoon (Pustelnikov 1998) range from 20 to 85 g m^{-3} and from 10 to 85 g m^{-3}, respectively.

The percentage share of inorganic matter in the Puck Lagoon is generally larger than in the Baltic Sea, where it accounts for about 46% (Emelyanov, Pustelnikov 1982). Based on the grain size analysis of
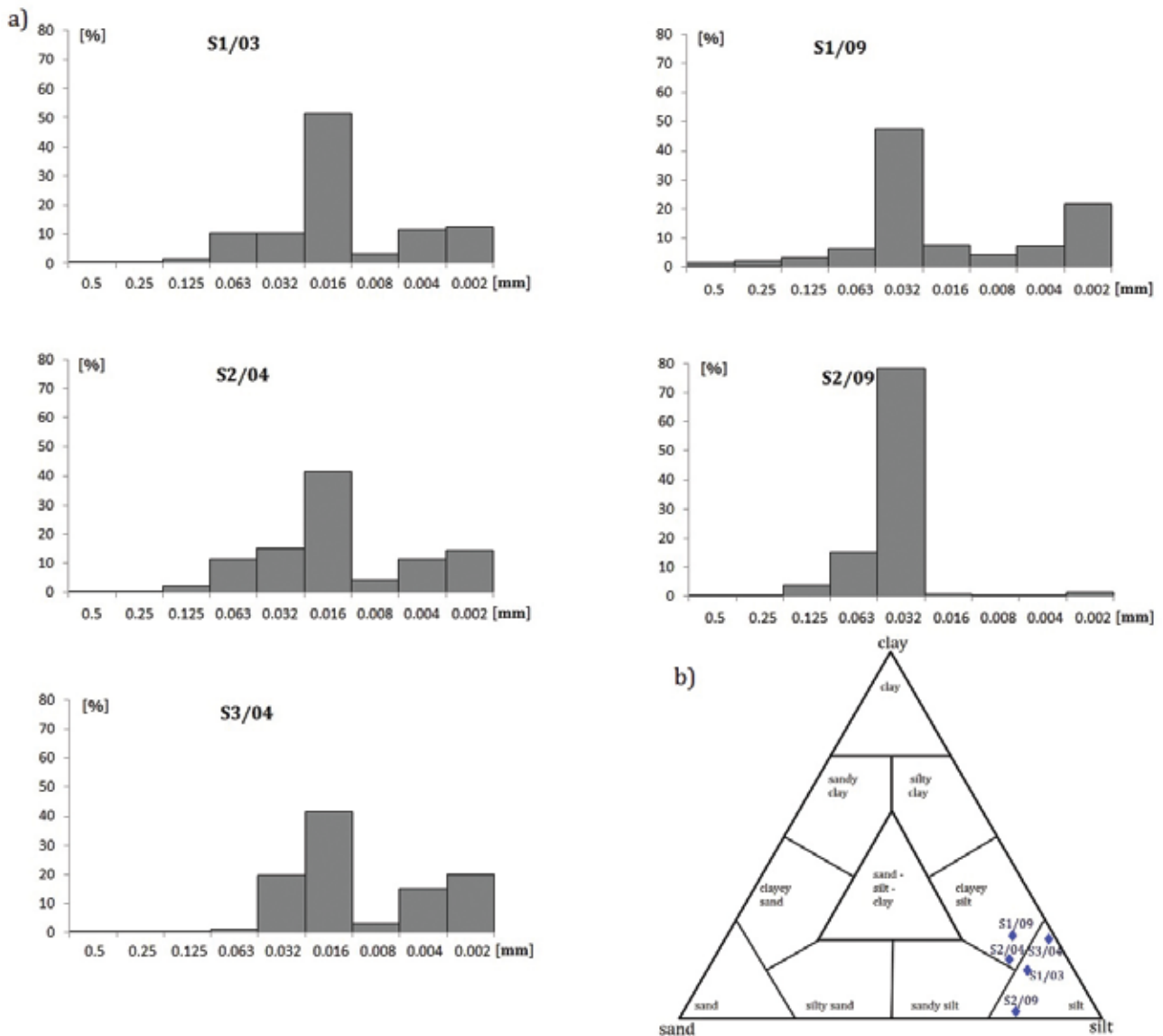
Fig. 6 Histograms of grain size distribution **(a)** and Shepard's (1954) classification triangle of sandy-clayey sediments **(b)**

suspension from the Puck Lagoon, it was determined that the silt fraction dominates. In the open seawaters, it accounts for 72% (Emelyanov, Pustelnikov 1982), while in the other lagoon waters for over 60% of total suspension.

The mean value of sediment flux per unit area in the Puck Lagoon was estimated at 24.88 g m^{-2} day^{-1}. A similar value, namely 28.61 g m^{-2} day^{-1}, was calculated for this area by Żytkowicz (1994). Similar studies were also conducted in other parts of the Baltic Sea. The sediment flux in the Pomeranian Bight, as measured with 50- and 40 cm high traps installed at the depth of 16 m and exposed for 45 days during the summer season, was 75 and 87 g m^{-2} day^{-1}, respectively (Jähmlich *et al.* 2002). Hille *et al.* (2006) reported the vertical flux of sediment of 0.35 ± 0.30 g m^{-2} day^{-1} at a depth of 150 m in the Eastern Gotland Basin.

The sediment transported to the Puck Lagoon from different sources as well as the suspension present in its saline waters is dominated by inorganic fraction with the grain diameters between 0.063 mm and 0.008 mm, which constitutes 80% of the composition. Considering this, it might be expected that the seabed deposit will contain a large amount of silt fraction. However, the grain size analysis conducted by the authors showed that the share of silt and clay fractions (< 0.063 mm) in bottom sediments of the Puck Lagoon accounts for a few percent only, rarely for more than 20% (Fig. 7).

This inconsistency can be explained by the mixing of water masses, accompanied by resuspension of fine sediment fractions that keeps them suspended in the water column where they are subjected to advection towards the final deposition area (Christiensen *et al.* 1997) as well as by the export of suspended matter with the waters out flowing into the open areas of the Gulf of Gdańsk. The suspended matter is transported from the Puck Lagoon by the currents, most probably
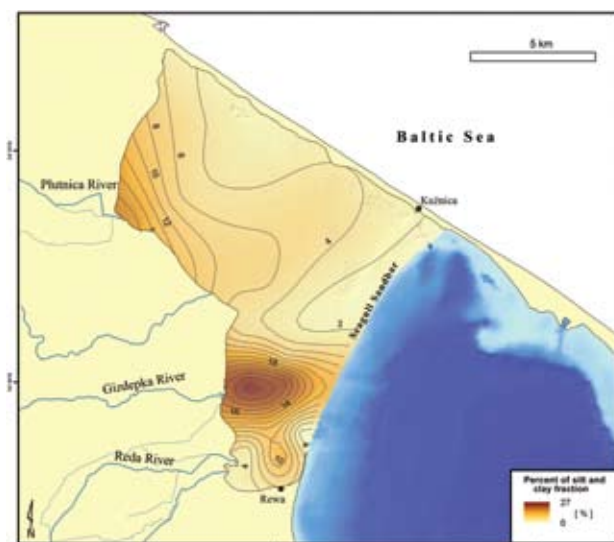
Fig. 7 Share (%) of silt and clay fraction in the surface layer of bottom sediments

in the surface water layer, and moved away according to the direction of circulation, along the shore towards the north, or via the Reda River waters into the area of the Głębinka isthmus. In the river mouth area the process of flocculation may occur, which speeds up the settling of matter.

Due to the existing wind regime, the wave-induced resuspension is a very frequent process in the area of investigation. In shallow waters, resuspension is possible 25% of the total number of days per year, while in the deeper parts of the Puck Lagoon, resuspension is still possible but its frequency is lower. For an average wind speed of 5 m s^{-1}, the current velocities of 1 cm s^{-1} were sufficient to resuspend grains <0.1 mm in diameter. At the current speed higher than 0.4 m s^{-1}, which occurs during storms (wind speed of 10−15 m s^{-1}), the sediment transport including the sandy fraction takes place, and the current velocities are sufficient to erode grains 0.063–2.0 mm in diameter from the seafloor.

The systematic measurements of wind-induced wave action were not conducted in the inner Puck Lagoon therefore it is not possible to analyze seasonal variability of this phenomenon for this particular water body. On the other hand, working under the assumption that wave action in a given basin is proportional to wind speed and by using the data in Table 2 (Łomniewski *et al.* 1975; Miętus, Sztobryn, 2011), it can be stated that the period covering autumn, winter and early spring (from September through April) was characterized by much higher occurrence of storms than the spring-summer period. The mean number of days with a wind speed greater than 15 m s^{-1} increases in September (1.8 days) to reach the maximum value between December and January (4.6 days). The spring-summer period (from May through August)

can be characterized as calm and lacking significant storms (0.8 day). This means that the observed seasonal variability of suspension concentration can be correlated to the overall seasonal variability of hydrodynamic phenomena in the Puck Lagoon.

Suspended matter in the water column as well as the sediment undergoing deposition is much richer in organic matter than bottom sediments. The percentage share of organic and inorganic matter present in suspension was estimated in each collected sample. The highest share of organic matter was observed in the waters surrounding traps in both seasons, particularly at the Rzucewo Deep.

The shallow water areas are often subjected to wave-induced resuspension and contain relatively coarse sediments with only small amount of organic matter. The finest particles with high contents of organic matter are resuspended in shallow water and finally deposited in deeper water, with very infrequent resuspension events. In the Puck Lagoon, just as in other shallow reservoirs, a lower share of organic fraction in the bottom material in comparison to suspension could be caused by the consumption of organic matter by bacteria and benthic fauna (Kranck 1984; Eisma, Kalf 1987).

Rate of sediment deposition

Based on the sediment mass increase in sediment traps and the share of organic and inorganic substance in the deposited material, the mean rate of sediment deposition was calculated at 3.98 mm y^{-1}. The study showed that the rate of sediment deposition varied in different parts of the Puck Lagoon, ranging from 1.97 mm y^{-1} (S1/09) in the deepest part to 8.02 mm y^{-1} (S2/04) in the central part of the area of investigation. In 2003–2004, the mean rate of sediment deposition was higher and reached the value of 4.69 mm y^{-1}. In 2008–2009, the mean rate equalled 2.93 mm y^{-1}.

A general approach to the process of sediment deposition is to consider the local basin as a geomorphic system. Such a system consists of several compartments, each with its own distinct spatial and temporal scale. For each compartment, a sediment system can be identified which contains interacting elements such as, water motion, sediment transport, sediment deposition and morphology at corresponding scales. The water motion results from energy input of wind, waves and currents, while ice phenomena are the driving force behind the sediment transport and sedimentation processes (Dean, Dalrymple 1991; Pruszak *et al.* 2008).

As previously mentioned, the Puck Lagoon is a relatively shallow marine area. It is a well-known fact that when the waves occur in shallow water, the sea bottom is reached by the unsteady fluid motion
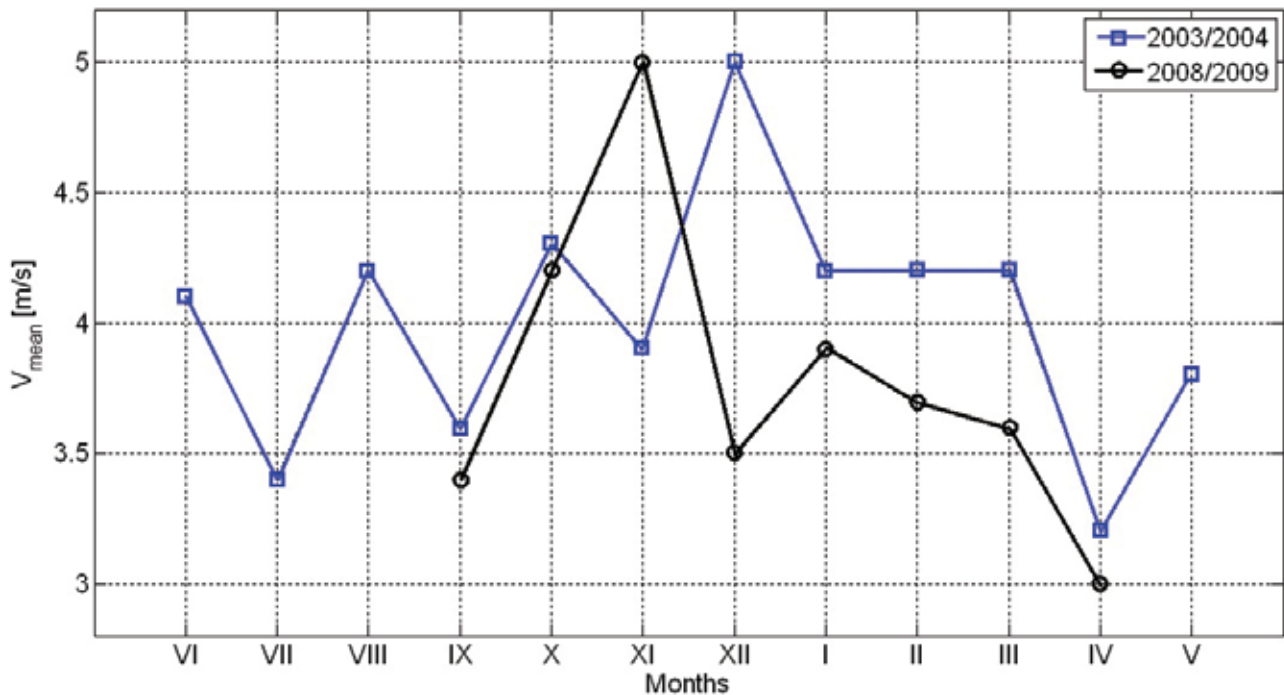
Fig. 8 Series of wind speed recorded in the Puck Lagoon in 2003–2004 and 2008–2009

caused by the wave action (Ostrowski 2004). For low depths, the magnitude of particle displacement and velocity is significant. This unsteady fluid motion at the sea bottom produces hydrodynamic forces that act on the sediment particles and therefore contribute to sedimentation processes. Theoretically, a mathematical model may help to explain the influence of hydrodynamic forces on the deposition rate (Massel 1996; WAMDI Group 1988). However, the Puck Lagoon is a very dynamic region in which the determination of wave and current fields is extremely difficult from the available theoretical models (Robakiewicz 2012). It is mainly because physical processes in this area, apart from their natural randomness, are highly nonlinear and unstable and thus difficult for exact mathematical description (Komar 1998). Bearing in mind that waves and currents in the Puck Lagoon are a result of the wind blowing over a stretch of water surface, a simple analysis of the wind conditions has been carried out. The mean values of wind speed for the periods 2003–2004 and 2008–2009 are presented (Fig 8).

It is noticeable that the mean wind speed during the two separate field surveys depended on the time of measurement. The average wind speed in 2008–2009 was over 5% lower than that in 2003–2004 (Table 3). It should be noted that all mean monthly values of wind speed in 2008 and 2009, excluding November, are lower than the corresponding values in 2003–2004. Therefore, it can be stated that the wind and wave conditions in the Puck Lagoon were calmer during the entire 2008–2009 season. Bearing in mind that the wave height calculated from the Kry-

lov's model (Krylov *et al.* 1976) is proportional to the square of the wind speed, and that the wave force is proportional to the square of the wave height, we can roughly estimate that the sedimentation processes in this shallow basin are proportional to the fourth power of wind speed. This could provide basis for the conclusion that in 2008–2009 a change in the wind speed by 5% led to the ca. 20% increase in the energy state of the wave field. This is one of the possible explanations of a rather large difference between the deposition rates determined in the Puck Basin in 2003–2004 and 2008–2009.

The ice cover in the basin is another factor, which significantly affects the deposition of sediment. On average, in the years 1986-2005, the number of days with ice observed in the Polish coastal zone changed approximately from 10 days in Świnoujscie to two days in Krynica Morska (for all winters, and approx. 20 days and 9 days only in winters when sea ice appeared in a given region) (Miętus, Sztobryn 2011). In the Puck Bay, the highest average number of days with ice was 74. During extremely severe winters, when ice cover in the lagoons is present for more than 128 days, the thickness of ice cover can reach up to 70 cm (Łomniewski *et al.* 1975; Miętus, Sztobryn 2011). Based on the comparison of the 2003–2004 and 2008–2009 ice seasons (Table 4), it can be concluded that the 2008–2009 ice season was calmer and longer, while the 2003–2004 ice season lasted only 26 days, with the ice cover thickness of 50 cm.

To summarize, the differences in the deposition rates result from the impact of two factors. Firstly, poorer anemometric and hydrodynamic conditions

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Table 3 Number of days with wind speed exceeding 10 and 15 m s⁻¹ in the period 1951–1975 in Poland

Month / Wind speed	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
	Number of days											
10 m s⁻¹	7.6	7.4	7.0	4.5	4.2	3.5	3.6	5.0	4.8	4.7	6.4	4.8
15 m s⁻¹	3.1	2.8	3.1	1.6	0.8	0.8	1.0	1.0	1.8	1.8	2.2	4.6

Table 4 The ice seasons in the Puck Lagoon in the periods 2003–2004 and 2008–2009

Date		The maximum thickness of the ice (cm)	Days with ice cover
The term of the first ice	The term decay of the last ice		
09 I 2004	04 II 2004	50	26
26 XII 2008	27 II 2009	10	47

Table 5 The sedimentation rates obtained in various basins of the Baltic Sea

Basin, location	[mm y⁻¹]	Method	References
Arkona Basin	0.30	LSR / ²¹⁰Pb	Schneider, Leipe 2007
Bornholm Basin	0.31		
Landsort Basin	0.31		
Gdańsk Basin	0.21		
Gotland Basin	0.18		
Eastern Gotland Basin	0.17–3.0	LSR / ²¹⁰Pb	Hille *et al.* 2006
Southern Baltic	0.4–2.3	SR / ²¹⁰Pb, ¹³⁷Cs	Pempkowiak 1991
	0.15–2.25		Walkusz *et al.* 1992
Gulf of Finland	0.63–1.12	SR	Pustelnikov 1992
Curonian Lagoon	2.5–3.6		Pustelnikov 1994
	5.0–15.0		Emelyanov *et al.* 1998
Gulf of Gdańsk	7	LAR / ²¹⁰Pb	Damrat *et al.* 2013
	1.4	SR	Emelyanov, Wypych 1987 (*according to Pustelnikov 2008*)
Vistula Lagoon	5.3–7.5		
Puck Bay	1,61	LAR / ²¹⁰Pb	Szmytkiewicz, Zalewska 2014

LSR – linear sedimentation rate, LAR – linear accumulation rate, SR – sedimentation rate.

in 2008–2009 resulted in the lower content of suspended sediment in the water column therefore less particles had been deposited in sediment traps compared to 2003–2004. On the other hand, the winter of 2003–2004 was more dynamic, with a 50-cm-thick ice cover and the ice season in the Puck Bay lasting continuously 26 days. In 2008–2009, the ice cover was frequently disappearing for periods, and the ice season lasted two times longer than in 2003–2004. These findings indirectly prove that the duration of ice season influences the deposition rate in the Puck Bay. The deposition rate increases with decreasing period of ice cover. Two times longer period of ice cover and only 5% lower mean monthly values of wind speed in 2008–2009 resulted in two times lower deposition rate compared to that in 2003–2004.

The values of sediment accumulation rate for the southern area of the Baltic Sea are presented in Table 3. The calculated values of sediment deposition rate in the Puck Lagoon are similar to the values reported by Pustelnikov (1994) and Emelyanov, Wypych (1987) for other lagoons in the southern part of the Baltic Sea. It must be mentioned however, that sediment deposition rate in the Puck Lagoon refers to fresh, not yet compacted sediments temporary placement on the seabed, while the values listed in Table 5 refer to the measurements performed on the cores of partially compacted bottom material.

Under the assumption that the whole sediment (from all sources) spreads evenly, a 0.11 mm thick layer would have been deposited on the sea bottom in the investigated area within a year. Most of the coarse-grained sand and gravel material from the riverbed load and cliff erosion accumulates in the near-shore zones. Fine clastic material would have formed a 0.05 mm thick layer. However, we need to bear in mind that the predicted values do not take into account the inflow of water and suspended sediment from the Gulf of Gdańsk.

In the years 1951–1990, the sea level in the Gulf of Gdańsk was rising 4.02 mm per year. At present, the calculated rate of sea level rise is estimated to be about 1.7 mm per year in the south-eastern Baltic Sea (Helcom 2007). The analysis of inflowing sediment volumes, corresponding deposition rates and the observed sea level changes indicates that the Puck Lagoon is filling at the lower rate than the sea level rise.

CONCLUSIONS

The study showed that the mean sediment flux, calculated from *in situ* experimental data, was variable; it ranged from 19.67 to 46.94 g m^{-2} day^{-1} and strongly depended on hydrodynamic conditions. Those conditions during the study duration (2002–2003 and 2008–2009) differed hence the seasonal and spatial variability of sediment deposition rate ranged from 1.89 to 8.02 mm y^{-1}.

Material undergoing sedimentation was dominated by silt and clay fractions however bottom sediments in the Puck Lagoon contained very little of these two fractions. This indicates that the sedimentation phenomena in the Puck Lagoon are dominated by resuspension and resedimentation processes. The central part of the Puck Lagoon is characterized by enhanced sediment deposition. The deposition is centred in the Rzucewo Deep as indicated by the highest level of sedimentary material in the water column and the high share of organic matter and silt fraction in both the collected material and bottom sediments.

The rapid exchange of water masses between the Puck Lagoon and the Gulf of Gdańsk, caused by currents and wind-generated wave action and countered by the observed intensive deposition of fresh sediments, results in the transport of vast amounts of sediment outside the Puck Lagoon and its deposition at greater depths. The Kuznica Deep is an exception, being a closed basin delineated by 6-m high hillsides with a steep slope in the east. This particular area is supplied in sedimentary material during storms therefore the sediment thickness ranges there from four to five metres.

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