Sediment deposition and accumulation rates determined by sediment trap and ^{210}Pb isotope methods in the Outer Puck Bay (Baltic Sea)

ANGELIKA SZMYTKIEWICZ[1],[*]
TAMARA ZALEWSKA[2]

[1] Institute of Oceanography,
University of Gdańsk,
al. Marszałka J. Piłsudskiego 46, 81–378 Gdynia, Poland;

e-mail: oceaszm@ug.edu.pl

[*]corresponding author

[2] Institute of Meteorology and Water Management,
National Research Institute,
Maritime Branch,
J. Waszyngtona 42, 81–342 Gdynia, Poland

Abstract

Two methods – in situ sediment trap experiments and an isotopic method based on measurements of ^{210}Pb activities in the sediment cores taken near the traps – were applied for determining sediment deposition and sediment accumulation rates in the eastern part of Puck Bay. The sediment deposition rate (1.67 mm year^{-1}) based on the in situ measurement was comparable with the sediment accumulation rate calculated using the Constant Flux:Constant Sedimentation Rate model for the isotopic method. The age of the sediment layers was determined with the Constant Rate of Supply model; the deepest layers had accumulated around 1900.

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

1. Introduction

Sedimentation is defined as the overall process of particle transport to, emplacement on, removal from and preservation in the seabed (McKee et al. 1983). This definition discerns certain phases/stages of the sedimentation process. The first stage is deposition defined as temporary emplacement from and preservation on the seabed and pertains to this relatively short time of sediment formation. Sediment accumulation is the stage pertaining to a decidedly longer period: it is the result of particle deposition and removal, leading to the preservation of the strata. Particle removal may be due to several mechanisms, e.g. physical erosion, biological resuspension and chemical dissolution (McKee et al. 1983). The usual method of determining the deposition rate is the in situ technique relevant to this short sedimentation time, where sediment traps are deployed in the natural conditions of seas, bays or lakes (Faas & Carson 1988, Lund-Hansen et al. 1999, Roos & Valeur 2006). The accumulation rate of the sediment comprising a > 100 year period can be determined only by an isotope method based on the analyses of changes in ^{210}Pb activity in the sediment profile (Musielak 1985, Appleby & Oldfield 1992, Appleby 1997). The rate of accumulation of marine sediments has been a research topic for many years (Nicholas 1989, Pempkowiak 1991, Mojski 1995, Hille et al. 2006, Roos & Valeur 2006). Nevertheless, it remains an important scientific problem because of the still unresolved issues emerging from the variety of methodologies and diverse interpretations of the results. The rate of sediment accumulation has a significant impact on many geochemical processes; it is also vital for the functioning of benthic organisms in this environment, particularly the seabed fauna (Musielak 1983, Kozerski 1994, Żytkowicz 1994, Szczuciński 2007).

Determining the rate of sediment accumulation is usually a complicated task, even when using theoretical models for a perfectly calm water basin. When applying a theoretical approach, it is obvious that not only should gravitational force be considered in order to calculate the sedimentation rate but also other aspects such as eddy viscosity, turbulent diffusion and the grain distribution of suspended sediment (Massel 2010). Theoretically, if in calm waters only gravitation were used as the dominant force, it would be possible to determine what percentage of particles of a specified diameter would settle and which particles would have a velocity too low to ensure settlement. An example of such an approach was given by Imam et al. (1983), who established the vertical velocity field using a finite difference model of the vorticity transport stream function equations with a constant eddy viscosity. The eddy viscosity is obtained by applying a theoretical model. That is, in order to determine the sedimentation rate

other theoretical assumptions should be made; hence, sedimentation has a complex nature, even under idealised theoretical conditions. The main reason for this is that sedimentation, besides its complicated nature, is a highly nonlinear and unstable phenomenon (wave and current forcing) and therefore difficult to subject to rigorous mathematical treatment. Any attempt at describing sedimentation processes requires the simultaneous identification of the mechanisms governing sediment deposition, erosion and the evolution of a number of morphological seabed forms (Pruszak 1990, 1998, Komar 1998).

The rate of sediment accumulation in water basins depends on a number of factors, such as the quantity and quality of sediment being deposited, distance from sediment source, intensity of biological processes (e.g. phytoplankton blooms, bioturbation), seasonal phenomena (e.g. phytoplankton blooms, autumn and winter storm surges), geological seabed composition, depth of seabed and hydrological and hydrodynamic regimes. Moreover, the amount of sediment transported from land to sea may also be affected by the intensity of weathering, erosion and degradation. The sediment supply to Puck Bay from rivers varies seasonally. Sediment discharges peak in late January and early February and fall to a minimum between June and August (Szymczak 2006, Szymczak & Piekarek-Jankowska 2006). In the southern Baltic Sea and the Gulf of Gdańsk it is estimated that the rate of accumulation ranges between 0.5 and 2 mm year^{-1}.

The aim of this study was to determine the recent sediment deposition rate and sediment accumulation rate specific to seabed formation in the eastern part of Puck Bay using two methods: in situ sediment traps and radioisotopes. In order to describe adequately the deposition and accumulation processes, we applied two ways of expressing the rates: (1) the linear rate of accumulation, giving the depth of sediment layer deposited in unit time (linear accumulation rate – LAR), expressed in [mm year^{-1}] and, (2) the mass sediment accumulation, which quantifies the mass of sediment deposited in unit time on unit surface area (mass accumulation rate – MAR) expressed in [g m^{-2} day^{-1}] or [g m^{-2} year^{-1}] (Einsele 2000, Syvitski 2003, Hille et al. 2006).

2. Material and methods

2.1. Study area

Puck Bay (Figure 1) has the shape of an elongated depression deepening south-eastwards to over 50 m (Jankowska & Łęczyński 1993). There are also artificial shallow areas that appeared in 1989–1997, after sediment had been dredged to feed beaches on the open-sea side of the Hel Peninsula so
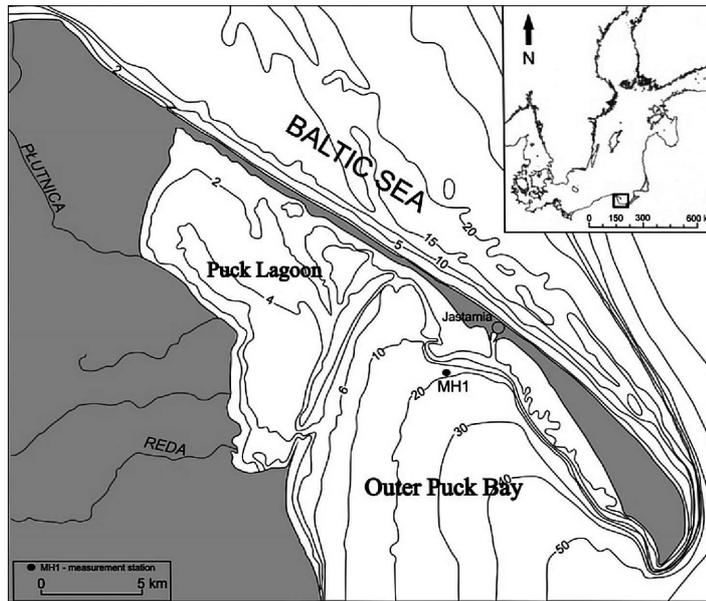
**Figure 1.** Location of the measurement station in the Outer Puck Bay

as to protect them from abrasion. The Outer Puck Bay, which is directly connected with the open sea is much more dynamic. One of the main sources of sediment feeding the Bay's seabed is the discharge of material weathered and eroded in its catchment area.

2.2. In situ experiments

Sedimentation traps

In situ measurements of the rate of sediment accumulation were carried out in 2007–2008 at station MH1, situated in the eastern part of Puck Bay at a depth of about 20 m (Figure 1). To determine the rate of accumulation a measurement setup was prepared. This consisted of four cylindrical traps fixed to a single rod at a depth of about 0.5 m above the seabed. The traps were made from 50 cm long PVC pipes with an internal diameter of 9.5 cm, i.e. an aspect ratio of 5.3 (Figure 2). This type of trap was selected on the basis of earlier in situ investigations of sediment deposition processes in the sea (Hargrave & Burns 1979, Blomqvist & Kofoed 1981, Håkanson et al. 1989, White 1990, Kozerski 1994). All the sediment traps were deployed in September 2008 and were retrieved after 4, 7, 10 and 14 months of exposure.

During the investigations trap no. 4 may have been damaged by a drifting log and begun to leak; in addition, in the difficult weather
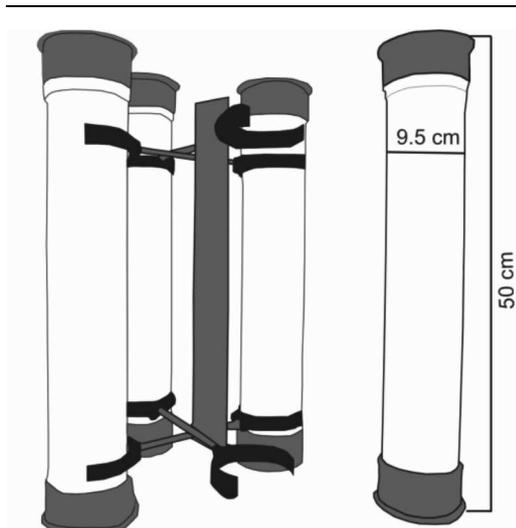
Figure 2. Sediment traps – side view

conditions during its retrieval, some of sediment may have been lost. For this reason, trap no. 4 was excluded from further analysis.

Acquisition of seabed sediment and sea water samples

Seabed sediment samples were taken with a Niemistö corer (i.d. $= 8$ cm) in the form of 20 cm long cores, extracted from the spot where the in situ measurement setup was deployed. Near-bottom water samples were obtained with a small tube, and the core was sliced into 1 and 2 cm long sub-sections. The slices were then dried at room temperature, put into plastic bags and sent to the Institute of Meteorology and Water Management – National Research Institute, Marine Branch, Gdynia, for radioisotopic analysis. Near the sedimentation traps additional surface sediment samples were taken with a van Veen grab for granulometric analysis.

The 4-litre near-bottom water samples were acquired with a bathometer prior to the installation of measurement setup and also after the exposure time of consecutive sediment traps had ended. The water samples were necessary for calculating the sediment concentration near the sediment traps.

2.3. Laboratory analyses

Suspended particulate matter concentration in water samples

To calculate the concentration of suspended particulate matter (SPM) in the near-bottom water, the seawater samples were passed through pre-weighed Whatman GF/F glass fibre filters. Before filtration, the filters

were dried at 105°C for about 60 minutes to remove hygroscopic humidity; they were also weighed to 0.00001 g accuracy. The near-bottom water was filtered on a quadruple Sartorius filtering unit, with about 4 litres of water being passed through each dried filter. If SPM concentrations were high, the volume of filtered water was reduced to 2 litres. After filtration, the filters were rinsed with distilled water to remove salt from the filter pores, dried for 2 hours at 105°C, allowed to cool down and finally weighed again to 0.00001 g accuracy. The mass of SPM was calculated as the remainder from dry filter weights before and after the test; the result was given in $[\text{g m}^{-3}]$.

Granulometric analysis

In order to determine the composition of the material deposited in the sediment traps and of the surface sediments, this was washed through a set of sieves with diameters from 0.5 mm to 0.063 mm. The < 0.063 mm fraction was analysed granulometrically using the pipette method (Myślińska 2001), which is capable of detecting fractions from 0.032 to 0.004 mm and of < 0.004 mm. The results of the granulometric tests were described using the Shepard classification pattern (Figure 3, see p. 95).

Organic matter

The organic matter content from the material deposited in sediment traps was determined using 30% hydrogen peroxide (perhydrol) (Myślińska 2001). This method is used to oxidise easily degradable organic matter. A sediment sample weighing about 10 g was dried at 105°C and then placed in a weighed beaker, to which ca 30 cm^3 30% H_2O_2 was added. In the next step the beaker was covered with a watch glass and gradually warmed up to 60°C in a heated bath. The bath was terminated when bubbles ceased to appear after the addition of successive volumes of H_2O_2. The beaker's contents were then boiled until a dense suspension appeared. After that the contents were dried at 105°C, then weighed to 0.01 g accuracy. The percentage of organic matter was calculated with the formula

$$I_{om} = [(m_{st} - m_u)/(m_{st} - m_t)] \times 100\% ,$$

where I_{om} – organic matter content [%], m_{st} – mass of beaker with sediment sample after drying to constant mass [g], m_u – mass of beaker with sediment sample after oxidation of organic matter and drying to constant mass [g], m_t – mass of dry beaker [g].

2.4. Radioisotope methods

Models for ^{210}Pb dating

Since 1963, when Goldberg (1963) suggested using the ^{210}Pb isotope for sediment dating, many researchers have contributed to the development of this methodology and its applications as a tool for assessing the chronology of geological processes in sediment research in environmental systems like lakes, estuaries and seas (Appleby & Oldfield 1992, Appleby 1997, Zajączkowski et al. 2004, Zaborska et al. 2007, Suplińska & Pietrzak-Flis 2008, Díaz-Asencio et al. 2009, Mulsow et al. 2009).

^{210}Pb identified in sediment samples originates from two sources. One of them stems from the decay of ^{226}Ra (radium) and the resulting lead is termed supported ^{210}Pb (^{210}Pb$_{supp}$); its activity along a vertical profile is practically constant. The second source of ^{210}Pb in bottom sediments is atmospheric precipitation, from which it enters the marine environment. Owing to its substantial reactivity ^{210}Pb is absorbed by suspended organic matter, transported towards the bottom and ultimately deposited on the seabed. The ^{210}Pb isotope originating from precipitation is called unsupported or excess (^{210}Pb$_{ex}$). Its activity decreases with sediment depth and is used for determining the rates of sediment accumulation (mass accumulation rate – MAR), linear accumulation rates (linear accumulation rate – LAR) and for dating consecutive sediment layers. The ^{210}Pb$_{ex}$ activity is determined from the total activity of this isotope ^{210}Pb$_{tot}$ in the sediment layer under examination, from which the activity of one of the products of ^{226}Ra radioactive decay, e.g. ^{214}Bi, ^{214}Pb, should be subtracted.

Several geochronology models based on the vertical distribution of ^{210}Pb and using its radioactive decay equation have been developed. Which model is chosen depends on the environmental conditions of the investigated area, e.g. sediment processes (erosion, deposition), sediment focusing and sediment stability. In the current study, two models of ^{210}Pb activity variability along vertical profiles were employed to investigate the rates of sediment accumulation and sediment dating (Robbins 1978, Appleby 1997). The first model, known as CF:CS (the Constant Flux Constant Sedimentation Rate model), assumes that there is a constant flux of ^{210}Pb and that the rate of sediment deposition is constant as well. With this model the sedimentation rate can be calculated using the slope of the line derived from the linear regression of ln^{210}Pb$_{ex}$ and the depth layer according to the following equations (Bierman et al. 1998):

$$A_x = A_0 e^{-bx} \,, \tag{1}$$

$$v = \frac{\lambda}{b}, \tag{2}$$

where A_x – excess ^{210}Pb activity at depth x [Bq kg^{-1} d.m.], A_0 – activity at the surface layer [Bq kg^{-1} d.m.], b – the slope defined by regression through the data, x – depth [cm], v – sedimentation rate – LAR [cm year^{-1}] and λ – ^{210}Pb radioactive decay constant (0.03114 year^{-1}).

By using this model it is possible to determine sediment MARs, which are a measure of sedimentation where changes in sediment density with depth occur owing to sediment compaction. The sediment MAR is calculated using the slope of the line derived from the linear regression of ln^{210}Pb$_{ex}$ and the cumulative depth (Brush et al. 1982):

$$A_m = A_0 e^{-bm}, \tag{3}$$

$$\omega = \frac{\lambda}{b}, \tag{4}$$

where A_m – excess ^{210}Pb activity at cumulative depth m [Bq kg^{-1} d.m.], A_0 – activity in the surface layer [Bq kg^{-1} d.m.], b – slope defined by regression through the data, m – cumulative depth [g cm^{-2}], ω – mass sediment accumulation rate – MAR [g cm^{-2} year^{-1}] and λ – ^{210}Pb radioactive decay constant (0.03114 year^{-1}]).

The age of a given layer is calculated using the equation:

$$t = \frac{m}{\omega}. \tag{5}$$

The second model, known as CRS (the Constant Rate of Supply model), is based on the assumption that the supply of unsupported ^{210}Pb to the sediment is constant in time while the initial excess ^{210}Pb activity (A_0) varies inversely with the sediment MAR – ω (Goldberg 1963, Boer et al. 2006):

$$A_0 \omega = \text{const.} \tag{6}$$

This model is used to determine the age of sediment at a given depth from the ^{210}Pb vertical profile within the sediment according to the equation (Appleby 1997, Boer et al. 2006):

$$t = \frac{1}{\lambda} \ln \left(\frac{I_0}{I_m} \right), \tag{7}$$

where t – age [year], I_0 – total inventory of excess ^{210}Pb [Bq cm^{-2}] and I_m – inventory of excess ^{210}Pb below the cumulative mass depth m [Bq cm^{-2}].

The MAR can be calculated for each depth interval with the equation of Boer et al. (2006):

$$\omega = \frac{\lambda I_m}{A_m}\,,\tag{8}$$

where A_m – excess ^{210}Pb activity at depth interval m [Bq kg^{-1} d.m.].

The method of sediment dating based on the vertical distribution of the ^{210}Pb concentration was validated by measurements of the activity change of the ^{137}Cs isotope along the vertical profiles of seabed sediments. ^{137}Cs is entirely anthropogenic. The presence of ^{137}Cs in seabed sediments is due principally to the nuclear tests performed since 1945; maximum deposition was recorded in 1963 and after the Chernobyl disaster in 1986. Following the rationale of the sediment dating procedure validation using ^{137}Cs, it is assumed that these historical events should be imprinted in the activity curves of that isotope along the vertical sediment profiles.

Gamma spectrometry measurements

Dried and homogenised sediment samples were placed in counting boxes of appropriate geometry. Activity concentrations of ^{210}Pb and ^{137}Cs isotopes together with ^{214}Bi were measured by the gamma spectrometry method using an HPGe detector with a relative efficiency of 40% and a resolution of 1.8 keV for peak of 1332 keV of ^{60}Co. The detector was coupled to an 8192-channel digital spectrum analyser and GENIE 2000 software.

3. Results and discussion

3.1. In situ investigations

In September 2008 the concentration of SPM near the measurement station MH1, before the deployment of sediment traps, was 28.0 g m^{-3}. The measurements of SPM concentrations after the exposure times of all the sediment traps had ended, demonstrated that the concentration varied seasonally (Table 1).

Table 1. Suspended particulate matter concentration near sediment traps

Location	Suspended particulate matter concentration [g m^{-3}]			
	January 2009	April 2009	August 2009	November 2009
MH1	16.3	2.0	17.2	10.5

The SPM concentration varied between 2.0 and 17.2 g m^{-3}. The largest concentrations were recorded in autumn–winter and in summer. This was

probably due to the intensity of autumn–winter storm surges and the associated increased SPM supply to Puck Bay and to the increase in biological production in summer. The lowest concentration was recorded in April. This figure is encumbered by nontrivial measurement errors resulting from poor weather conditions (a wind speed of about 10 m s^{-1}, a very rough water surface). Those conditions hampered the manoeuvring of the research vessel, making it extremely difficult to obtain water samples from below the surface.

During the in situ investigations the traps captured from 20 to ca 44 grams of sediment (Table 2). The average monthly deposition was roughly 5.10 g between September 2008 and January 2009, 4.30 g from January to April 2009, and 3.23 g from April to August 2009. These results confirm the seasonal nature of sediment deposition in Puck Bay. The sediment supply is greater in autumn–winter, whereas inputs are lower in summer.

Table 2. Mass of sediment deposited in the sediment traps

Location	Mass of sediment deposited in the traps [g]		
	27.09.2008–26.01.2009 after 4 months	27.09.2008–19.04.2009 after 7 months	27.09.2008–07.08.2009 after 10 months
MH1			
	20.39	**33.3**	**42.99**

The respective influxes of sediment per unit bottom surface area were calculated from the dry masses after 4, 7 and 10 months of exposure, i.e. 23.9, 23.0 and 19.3 g m^{-2} day^{-1}. The resulting average rate of deposition per unit bottom surface area was 22.1 g m^{-2} day^{-1}. This value is somewhat different from those calculated for other Baltic Sea regions where such investigations have been conducted. For comparison, the rates of vertical sediment influx in the Puck Lagoon – the shallowest, north-western corner of Puck Bay, situated near the town of Puck – measured using sediment traps were 19.7, 46.9 and 21.3 g m^{-2} day^{-1}. The highest rate related to the relatively deep Jama Rzucewska (Rzucewska Hollow), while the other two refer to shallow water regions of the Lagoon (Szymczak 2006). Investigations in the Pomeranian Bay showed in turn that vertical sediment influxes to the seabed were between 75 and 87 g m^{-2} day^{-1} (Jähmlich et al. 2002). Comparison of these quantities with those from Table 2 shows that sediment accumulation in the Outer Puck Bay takes place under relatively calm conditions.

The granulometric tests of the sediment deposited in the traps indicate that it can be classified as sandy mud and sand-clayey mud (Figure 3).
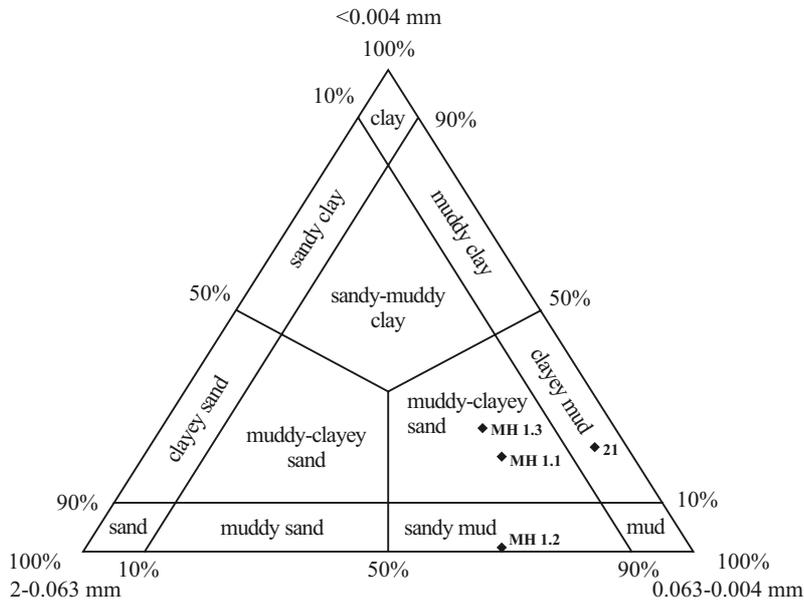
Figure 3. Classification triangle of sandy-clayey sediments (Shepard 1973, after Łydka (1985))

This type of sediment is usually found in this part of the Puck Bay at depths of about 20 m (Jegliński et al. 2009). The grain size of the dominant mud fraction is 0.063–0.032 mm, while that of the prevailing sand fraction is 0.125–0.063 mm (Table 3).

The results of granulometric analysis indicate that the surface sediments belong to the clayey mud class (Figure 3). This type of sediment occurs in Puck Bay, locally forming a transition zone between the sand-mud-clay and muddy clay sediment types (Uścinowicz & Zachowicz 1994).

Apart from the depths, slope and shoreline configuration that contribute to a large extent to local wave and current regimes, a factor exerting a substantial influence on the distribution of sediments in Puck Bay is the Hel Peninsula (Uścinowicz & Zachowicz 1994). Sandy fractions are periodically transported into the deeper parts of Puck Bay when waves propagate from the west. The transported sediments probably originate from shallow areas adjacent to the Hel Peninsula (Passchier et al. 1997).

The proportion of organic matter in the total volume of sediment deposited in the sediment traps varied slightly, between 10 and 11% (Table 4).

These proportions are similar for all periods and are almost twice as high as those reported previously for Puck Bay sediments (Uścinowicz & Zacho-wicz 1993). This discrepancy can be explained by mineralisation processes:

Table 3. Fraction distribution

Diameter		No. sample			
		MH 1.1	MH 1.2	MH 1.3	21
unit φ	mm	Percentage of fraction			
− 2	4	0.00	0.00	0.00	0.00
−1	2	0.00	0.00	0.00	0.00
0	1	0.00	0.00	0.00	0.00
1	0.5	0.69	1.68	0.50	0.00
2	0.25	4.90	6.01	5.17	0.26
3	0.125	7.21	9.92	7.16	0.58
4	0.063	8.68	13.31	8.94	4.43
5	< 0.063	78.52	69.08	78.23	94.74
		0.00	0.00	0.00	0.00
5	0.032	43.54	41.17	27.82	28.93
6	0.016	3.88	7.51	8.58	14.72
7	0.008	5.26	8.20	8.17	21.46
8	0.004	6.10	11.44	7.98	7.86
9	0.002	19.73	0.76	25.67	21.78

Table 4. Percentage of organic matter in sediment traps

Location	Percentage of organic matter in sediment traps [%]		
MH1	27.09.2008–26.01.2009 (after 4 months)	27.09.2008–19.04.2009 (after 7 months)	27.09.2008–07.08.2009 (after 10 months)
	11.0	**10.5**	**11.0**

the amount of organic matter actually supplied to the seabed is greater than that recorded in the deposited sediments, because mineralisation gradually reduces the proportion of organic matter there. An alternative explanation is that the traps are 'better' at collecting material rich in organic matter, e.g. low density particles.

The rate of sediment deposition for each trap was calculated by taking account of the deposited sediment masses and the proportions of organic matter (Table 5). In these calculations the specific density of minerals was set at 2.65 g cm^{-3} and that of organic matter at 1.35 g cm^{-3} (Grabowska-Olszewska & Siergiejew 1977). The average rate of deposition was calculated at 1.67 mm year^{-1}.

The above rates, estimated from in situ experiments, are different from those given by Pempkowiak (1991); for muddy sediments of the southern Baltic Sea the rates vary between 0.1 and 2.3 mm year^{-1}. For the Gulf

Table 5. The rate of sediment deposition

Location	Trap exposure time	Rate of sediment deposition [mm year^{-1}]
MH1	trap No. 1: 4 months	1.79
	trap No. 2: 7 months	1.72
	trap No. 3: 10 months	1.49
	Average deposition rate = **1.67**	

of Gdańsk the rates have been estimated at between 1 and 2 mm year^{-1} (Szczepańska & Uścinowicz 1994, Uścinowicz 1997, Witkowski & Pempkowiak 1995). These discrepancies can be explained by the knowledge that the trapped sediment could not be compacted. Moreover, the rates calculated with the isotopic method may be greater, because the traps prevent erosion of freshly accumulated sediment, whereas in reality erosion processes are continually occurring in the seabed.
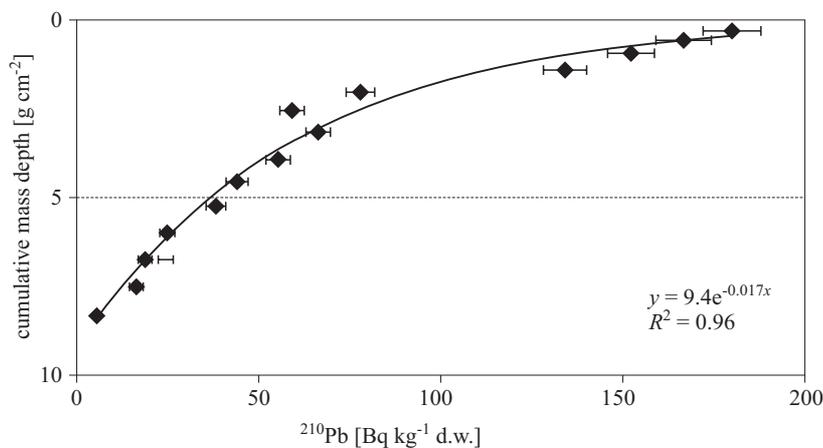
3.2. Sedimentation rate from radioisotopes ^{210}Pb and ^{137}Cs

Activity concentrations of ^{210}Pb, both total and excess, varied exponentially along the sediment profile (Table 6, Figure 4). The respective maximum concentrations – 198.6 Bq kg^{-1} and 180.1 Bq kg^{-1} – were measured in the uppermost sediment layer. The minimum activity of ^{210}Pb$_{ex}$ (5.7 Bq kg^{-1}) was found at 15.6–16.8 cm depth. Activity concentrations of ^{214}Bi, corresponding to ^{210}Pb$_{supp}$ activities, varied in a relatively narrow range from 16.1 to 23.2 Bq kg^{-1} throughout the sediment profile. Such characteristics permit the CF:CS model to be applied to the assessment of accumulation rates (recent sedimentation rate) of sediments typical of a given study area. To this end, ^{210}Pb$_{ex}$ activity curves were drawn using the logarithmic scale as functions of sediment thickness, depth being expressed in cm and cumulative mass depth in g cm^{-2} (to eliminate the nonlinear dependence between the accumulated dry mass and sediment depth due to different water contents and sediment compaction) (Figure 5). The linear rate of sediment accumulation (LAR) and sediment mass accumulation rate (MAR) were calculated using equations (2) and (4). The LAR of 1.61 mm year^{-1} is comparable to the value determined from the in situ measurements (1.67 mm year^{-1}).

The figure of 2.58 g m^2 day^{-1} obtained for MAR using ^{210}Pb dating differs considerably from that based on precipitated material collected in the sediment traps. The mean sediment accumulation rate obtained from sediment traps was as high as 22.1 g m^2 day^{-1}. However, the accumulation figures determined by the isotopic method were averaged over

Table 6. Vertical distribution of ^{210}Pb and ^{137}Cs in dated layers and in the material deposited in trap No. 3

Depth [cm]	Dry mass [g]	Cumulative depth [g cm^{-2}]	^{210}Pb$_{total}$ [Bq kg^{-1} d.m.]	^{214}Bi [Bq kg^{-1} d.m.]	^{210}Pb$_{ex}$ [Bq kg^{-1} d.m.]	^{137}Cs [Bq kg^{-1} d.m.]	Year
0–1.2	11.463	0.30	**198.6 ± 8.7**	**18.6 ± 1.3**	**180.1 ± 7.9**	**195.7 ± 3.0**	2009
1.2–2.4	11.429	0.60	183.7 ± 8.5	16.9 ± 1.3	166.8 ± 7.7	205.7 ± 3.1	2003
2.4–3.6	13.894	0.96	169.1 ± 7.2	16.7 ± 1.1	152.4 ± 6.5	190.1 ± 2.6	1999
3.6–4.8	17.556	1.41	151.5 ± 6.7	17.1 ± 1.6	134.4 ± 5.9	186.2 ± 2.3	1994
4.8–6.0	23.679	2.03	94.2 ± 4.7	16.3 ± 0.8	77.9 ± 3.8	124.5 ± 1.6	1987
6.0–7.2	20.583	2.56	78.6 ± 4.9	19.4 ± 1.0	59.1 ± 3.7	70.2 ± 1.2	1982
7.2–8.4	24.138	3.19	82.5 ± 4.4	16.1 ± 0.8	66.4 ± 3.5	71.2 ± 1.1	1975
8.4–9.6	28.728	3.94	72.0 ± 4.2	16.7 ± 0.8	55.4 ± 3.2	52.4 ± 1.0	1967
9.6–10.8	24.009	4.56	61.5 ± 4.1	17.4 ± 0.8	44.1 ± 2.9	38.8 ± 0.9	1960
10.8–12.0	27.044	5.26	59.9 ± 4.3	21.6 ± 0.9	38.3 ± 2.7	32.0 ± 0.8	1953
12.0–13.2	28.201	6.00	48.2 ± 3.9	23.2 ± 0.9	24.9 ± 2.0	11.3 ± 0.6	1945
13.2–14.4	27.906	6.72	38.2 ± 3.8	19.5 ± 0.9	18.7 ± 1.9	5.4 ± 0.4	1937
14.4–15.6	30.457	7.51	33.8 ± 3.5	17.2 ± 0.8	16.6 ± 1.7	3.4 ± 0.4	1929
15.6–16.8	31.502	8.33	23.4 ± 3.3	17.8 ± 0.8	5.7 ± 0.8	0.9 ± 0.3	1920
MH 1.3	–	–	**239.1 ± 8.7**	**19.6 ± 1.3**	**219.5 ± 8.0**	**203.9 ± 8.7**	–

The chart shows cumulative mass depth [g cm^{-2}] on the y-axis (0 to 10) and ^{210}Pb [Bq kg^{-1} d.w.] on the x-axis (0 to 200), with fitted equation:

$$y = 9.4e^{-0.017x}$$
$$R^2 = 0.96$$

Figure 4. Changes in ^{210}Pb$_{ex}$ activity concentrations in the sediment core

the entire period of accumulation and relate to sedimentation processes in the entire study area. In contrast to this, the results obtained in situ characterise deposition processes at a particular moment. Roos & Valeur (2006) pointed out that the mass sediment flux in a trap situated in a certain location could change over a very wide range, from 1 to 175 g m^2 day^{-1}, depending mostly on the season.

The age of consecutive layers was determined using two models: the CF:CS model according to equation (5) (Table 6) and the CRS model based on equation (7) (Figure 6). The relation between layer age and cumulative depth can be described by a second-degree polynomial equation (Figure 6). The deepest sediment layers, at depths between 14.4 and 15.6 cm, were deposited around 1900. The results obtained using the two models hardly vary at all (Figure 7). The increase in ^{137}Cs isotope activity after 1945 could be attributed to the beginning of atmospheric nuclear tests. However, although no specific peaks appeared corresponding to the increase in test intensity between 1958 and 1963, ^{137}Cs activity did increase continuously towards younger layers in the vertical profile. Moreover, the curve of caesium activity changes in time did not show a clear peak relating to the Chernobyl accident in 1986. As a result of this accident, when large amounts of ^{137}Cs were released into the Baltic Sea (it was estimated that 4.7 TBq of ^{137}Cs were introduced into the sea through precipitation (HELCOM 1995, 2003, 2009, Nielsen et al. 1999)), considerable increases in ^{137}Cs concentrations were also recorded in the marine sediments.

After 1997, the increase in ^{137}Cs activity stabilised at the level of 190 Bq kg^{-1} d.w., which can be linked to changes in the water column. Since 1991, the ^{137}Cs activity in the water column has been declining
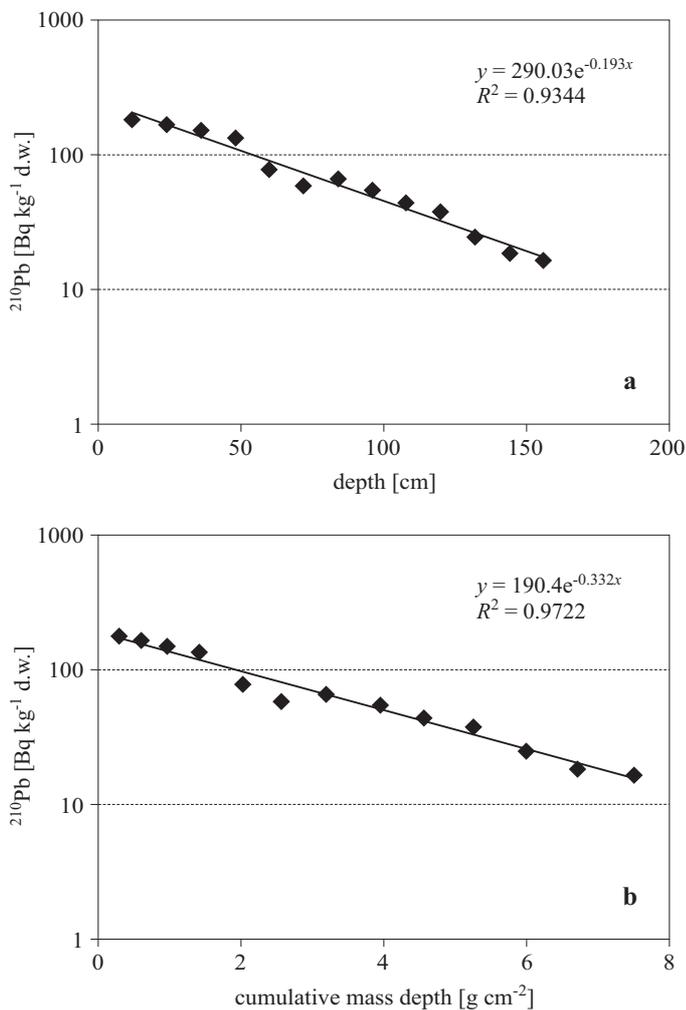
Figure 5. $^{210}Pb_{ex}$ activity concentrations on a logarithmic scale versus depth (a) and cumulative mass depth (b) in the sediment core

continuously (Zalewska & Lipska 2006), mainly as a result of radioactive decay and exchange of water with the North Sea; these processes are also reflected by the recently observed lower activities of that isotope in the seabed.

A typical distribution of ^{137}Cs concentrations was not identified in the sediment profile; this may be due to the redistribution of radiocaesium within the sediment column. Such redistribution could have been due to two main processes: (i) physical and biological mixing at or near the sediment-water interface (in the Outer Puck Bay undisturbed sedimentation is not

$y = -0.0004x^2 + 1.3222x - 1221$
$R^2 = 0.9988$
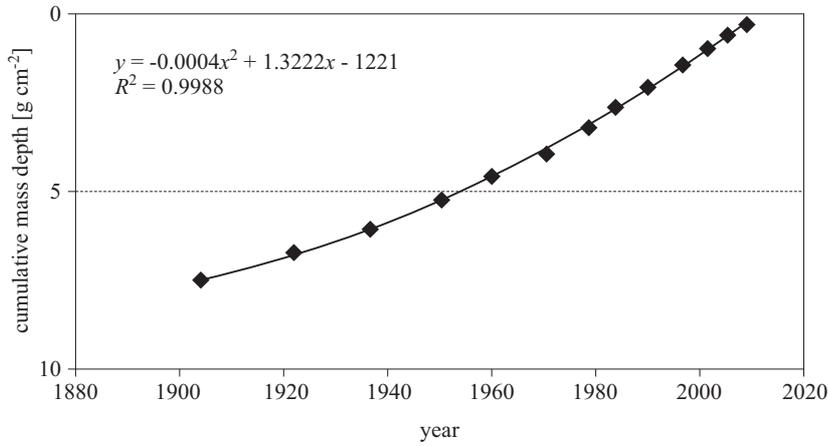
Figure 6. Age and cumulative mass depth profile obtained on the basis of the CRS model
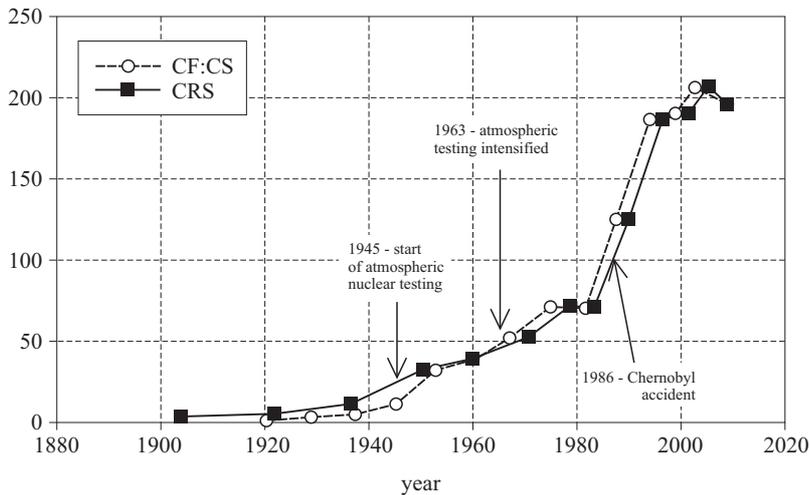
Figure 7. Changes in ^{137}Cs activity concentrations in dating with CF:CS and CRS model profiles

really possible owing to the high dynamics of the water) and (ii) chemical diffusion or advection within the pore water.

Sediment mixing typically results in a flattening of the ^{210}Pb activity profile versus depth in the surficial sediment layers, this being the case with the results obtained in the present work (Figure 4).

Nevertheless, it can be assumed that the acquired characteristics confirm the correctness of the adopted research methodologies for assessing the rates of sediment accumulation and dating. At the same time, because of the

complexity and multitude of processes that may influence final results, the interpretation of activity curves is rarely straightforward and unequivocal.

To compare the material collected in the sediment traps with the surface sediment layer from core sampling, activity measurements of ^{210}Pb and ^{214}Bi were conducted in material collected in trap No. 3 (Table 6). The measured activity of ^{210}Pb$_{tot}$ (239.1 Bq kg^{-1} d.w.) was only slightly higher than the value found in the core surface sediment, whereas the ^{214}Bi activity concentration was identical. Moreover, the activities of ^{137}Cs in both materials were also very similar, indicating that both the isotopic and the in situ methods yield comparable results.

4. Conclusions

- The rate of sediment deposition calculated from sediment trap measurements (1.67 mm year^{-1}) is comparable with the rate established by the isotopic method (1.61 mm year^{-1}). This results from the fact that the trapped sediment cannot be redeposited, which is contrary to natural conditions, where strong hydrodynamic regimes can give rise to seabed erosion.

- The established rates of sediment accumulation confirm that sedimentation conditions in the Outer Puck Bay are fairly calm and that the proportion of muddy and clayey fractions is consistent with general sediment sorting patterns in marine basins.

- The rates of accumulation, calculated from in situ experiments, are somewhat different from the rates obtained with the same method for other areas of Puck Bay. In the vicinity of the Reda river mouth the rate of accumulation can reach up to 4.5 mm year^{-1}, which is due to the transport of river sediments into the Lagoon. Moreover, these rates can vary from 1.3 to 3.8 mm year^{-1} in man-made post-dredging holes in the Lagoon.

- The rates of accumulation of marine sediments depend on the intensity of the hydrodynamic conditions, the sources of the sediments and the level of biological production in a basin. The accumulation rates obtained here indicate that moderately calm sedimentation conditions prevail in the Outer Puck Bay.

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