doi:10.5697/oc.55-4.937
OCEANOLOGIA, 55 (4), 2013.
pp. 937–950.

Sedimentation from suspension and sediment accumulation rate in the River Vistula prodelta, Gulf of Gdańsk (Baltic Sea) *

KEYWORDS
Sedimentation from suspension
Sediment accumulation rates
Sediment redeposition
River discharge
Gulf of Gdańsk
Baltic Sea

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Received 27 May 2013, revised 23 August 2013, accepted 18 September 2013.

Abstract

The River Vistula is one of the largest suppliers of fresh water and terrigenous matter to the Baltic Sea. The impact of this river on the Baltic coastal system and the fate of the sediment delivered to the Gulf of Gdańsk are not well understood. Spatial transport patterns, as well as the settling, deposition and accumulation of the sediments were studied at the Vistula prodelta in different seasons from January

* The project within which this paper was prepared was funded by the Institute of Oceanology, Polish Academy of Sciences, and the National Science Centre, grant No. 2011/01/B/ST10/06529.

2012 to January 2013. The concentration of suspended matter in the water column was measured with optical methods, the sedimentation rate was determined with sediment traps, and the sediment accumulation rate was estimated using ^{210}Pb dating. Our data shows that the annual supply of sediment to the sediment-water interface exceeds the annual rate of sediment accumulation in the outer Vistula prodelta by a factor of three. Sediment trapping during rough weather showed that significant sediment redeposition was taking place, even at depths of 55 m. The dynamic sedimentary processes occurring in the Vistula prodelta mean that that more than two-thirds of the sediment mass can be remobilized and then redeposited in deeper parts of the Gdańsk Basin.

1. Introduction

The River Vistula is 1022 km long and drains water from a basin of 193 960 km^2. The mean Vistula water discharge into the Gulf of Gdańsk is 1080 m^3 s^{-1} (CSO 2011) with an average sediment load of 14.6 mg dm^{-3}; however, this fluctuates considerably from 8 to 40 mg dm^{-3} (authors' own data from Świbno, Figure 1, see p. 939). The impact of the Vistula on the Baltic coastal system has been the subject of numerous publications (e.g. Pruszak et al. 2005, Voss et al. 2005, Zajączkowski et al. 2010), but most of these have been restricted to extreme flood situations or particular seasons. According to Pruszak et al. (2005), the annual sediment transport into the Gulf of Gdańsk ranges from 0.6 to 1.5 million m^3 of sediment. Anthropogenic influences impact the natural delta progradation, affecting sediment transport and deposition in riverine distributary channels (Syvitski et al. 2005). Since 1895 the whole Vistula outflow to the sea passes along an artificial channel, and the shoreline around the Vistula mouth has moved seaward by 1.5 km on the eastern side and by ca 2.5 km on the western side. During the 105 years since the opening of the modern Vistula mouth the volume of sediment stored in the lobe has reached 133.39 million m^3, and a facies model of the contemporary delta lobe of the Vistula primarily comprises sand facies of up to 13 m thick (Koszka-Maroń 2009). Estimated sediment accumulation rates in the central Gulf of Gdańsk range from 176 to 966 g m^{-2} y^{-1} (Kunzendorf et al. 1998, Suplińska & Pietrzak-Flis 2008, Szczepańska et al. 2012), but the spatial variability of the sediment accumulation rate in relation to sediment supply has not been evaluated.

A study of the pathway of sediment from the shallow area at the river mouth to the depositional area in the Pomeranian Bight and Arkona Basin has demonstrated the part played by redeposition and has shown that the bight is not the final storage area of riverine material (Emeis et al. 2002). Since the Vistula prodelta is intensively wave dominated, there is a need for a quantitative study of sediment dynamics in the Vistula prodelta. The aim of the present study was to compare sedimentation rates, from suspension in different seasons to the long-term sediment accumulation rate in the Vistula prodelta. The annual sedimentation rate from suspension was estimated at the sampling station using in situ sediment trap experiments in different seasons, for different sea states and on daily river discharge data, while the long-term sediment accumulation rate was based on ^{210}Pb dating.

2. Material and methods

The study was conducted during five cruises of r/v 'Oceania' in January, May, August, November 2012 and January 2013 at two anchored stations in the Vistula prodelta and at Świbno, 3 km upstream from the river mouth (Figure 1).

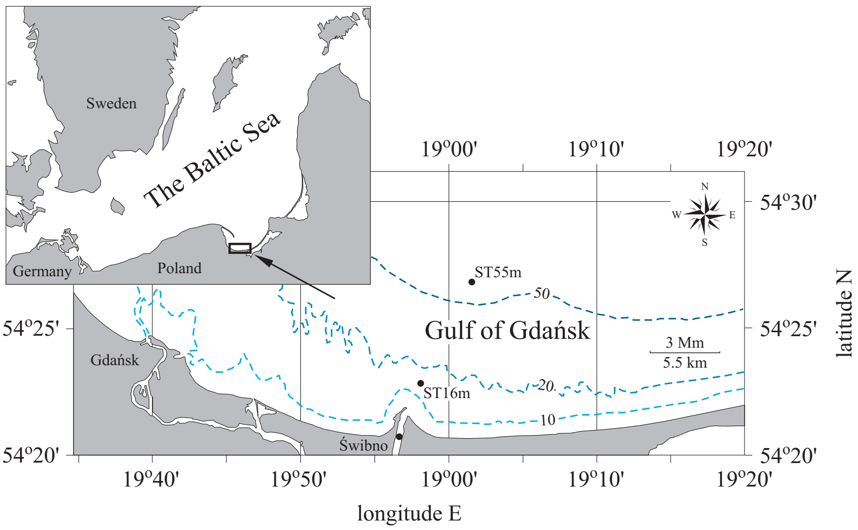


Figure 1. Locations of the sampling stations

The hydrological properties of the water column were measured with a CTD Sensordata SD 204 equipped with a Seapoint turbidity meter emitting light at 880 nm at scattering angles of 15–150°. The data on water turbidity are presented in formazin turbidity units (FTU).

Double cylindrical sediment traps with diameters of 6 cm and lengths of 0.6 m were anchored 2 m above the sea bottom and stabilized with underwater floaters according to the method described by Zajączkowski (2002). The sedimentation rate (SR) was measured for at least 24 h. The sediment collected was vacuum-filtered onto pre-weighed filters (MN GF5 with 0.4 μm openings) and rinsed with distilled water. Organisms visible to the naked eye were removed from the filters. The filters were dried at 60°C for 24 h, weighed to determine sediment dry mass, combusted at 450°C for

24 h, and then re-weighed to obtain the amount of settled organic matter from weight loss. The river water samples collected in the middle of the river channel at Świbno were filtered and examined using the same methods.

The meteorological data were recorded from the ship's equipment during the cruises. In the periods between the cruises, wind speed and direction data were collected from the meteorological station at Gdańsk Airport available at www.wunderground.com. The data on Vistula river flows at the Tczew station were obtained online from the Polish Institute of Meteorology and Water Management at www.pogodynka.pl.

Undisturbed sediment cores 20 cm in length were retrieved with a box corer and then carefully sub-sampled with 9 cm diameter plastic tubes. A standard extruder with a threaded shaft was used to separate 1 cm sediment slices. The sediment samples were frozen on board the ship and later transported to the laboratory.

Sediment samples were freeze-dried and ground in the laboratory. Sediment moisture and porosity was calculated. The linear accumulation rates (LAR) and mass accumulation rates (MAR) were obtained with the ^{210}Pb method. The ^{210}Pb activity concentration was measured indirectly with alpha spectrometry by counting its daughter nuclide ^{210}Po. The sediment samples were stored for several months prior to analysis to allow them to reach secular equilibrium between ^{210}Pb and ^{210}Po. Radiochemical separation of ^{210}Po was performed with the method presented in Flynn (1968) and developed by Zaborska et al. (2007). In brief, the sediment samples were spiked with ^{209}Po, a chemical yield tracer, and then digested. The polonium isotopes were spontaneously deposited onto silver discs, after which these were analysed for ^{210}Po and ^{209}Po activity concentration in a multi-channel analyser (Canberra) equipped with Si/Li detectors. The samples were counted for one day. The activity concentration of ^{210}Po in the samples was determined based on chemical recovery by comparing the measured and spiked activity concentrations of ^{209}Po. Blanks and standards were measured to verify the efficacy of the separation procedure and detection. Standard reference materials (e.g. IAEA-326) were measured to verify the efficacy of the separation procedure and detection. One blank sample without sediment was measured with every seven sediment samples. The environmental background was negligible.

Profiles of total ^{210}Pb activity concentrations as a function of sediment depth [cm] and mass depth [g cm^{-2}] were prepared. The sediment core collected at station ST55m was not long enough to reach the layers where total ^{210}Pb was constant, and only supported ^{210}Pb was present. Thus, ^{210}Pb$_{supp}$ (^{226}Ra) activity concentrations were determined by measuring ^{214}Pb (at 295 and 352 keV) and ^{214}Bi (at 609 keV). 30 grams of combined sediment samples (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm) were placed in counting vials. Gamma emitting radionuclides were measured in Canberra high-purity, planar germanium detectors for three to four days. The detector efficiency was calibrated using several sources and confirmed using IAEA standard material (IAEA-300).

The $^{210}Pb_{ex}$ was determined by subtracting the $^{210}Pb_{supp}$ activity concentration (average of ^{214}Pb and ^{214}Bi activities) from the total ^{210}Pb activity concentration derived from alpha counting at each depth interval. Sediment accumulation rates were estimated from the profile of $^{210}Pb_{ex}$ activity concentration versus porosity-corrected sediment depth [cm] and mass sediment depth, which was calculated using sediment porosity. The sediment porosity was computed using measured water content, an average grain density of 2.45 g cm^{-3}, and a mean density of pore water (the mean density of sea water) equal to 1.00 g cm^{-3}.

The sediment linear accumulation rate (LAR) and the sediment mass accumulation rate (MAR) were calculated assuming an exponential decrease in $^{210}Pb_{ex}$ with sediment depth:

$$A_t = A_0 \, e^{-\lambda t} \, ,$$

where A_t – ^{210}Pb activity at time t, A_0 – activity at time 0, λ – radionuclide decay constant (for ^{210}Pb, $\lambda = 0.031$).

When t is replaced by $t = x/v$ (x – depth of a given sediment layer, v – accumulation rate) the above formula can be rewritten as

$$A_t = A_0 \, e^{-\lambda \; x/v}$$

$$\ln A \; ^{210}\mathrm{Pb}_{\mathrm{ex}}(x) = \ln A \; ^{210}\mathrm{Pb}_{\mathrm{ex}}(0) - (\lambda/v)x \, ,$$

where $A \; ^{210}\mathrm{Pb}_{\mathrm{ex}}(x)$ – activity at layer x, $A \; ^{210}\mathrm{Pb}_{\mathrm{ex}}(0)$ – activity at surface (layer 0), λ – decay constant, v – sediment accumulation rate.

3. Results

The surface water salinity at station ST16m ranged from 1.7 in January 2012 to 5.5 PSU in May 2012 (Figure 2). A well-mixed 1.5–3.5 m layer of brackish water was recorded in all the seasons studied. A sharp pycnocline defined the extent of surface water mixing and also revealed a highly turbid water layer. The highest concentration of suspended particulate matter (SPM) in surface water (7.5 FTU) was noted in January 2012; it decreased to 1.5 FTU in August. Salinity increased under the surface brackish layer, and maximum values of 6.5–7.8 PSU were recorded near the bottom. In January, May and August 2012 relatively high SPM concentrations were measured in the deeper part of the water column.

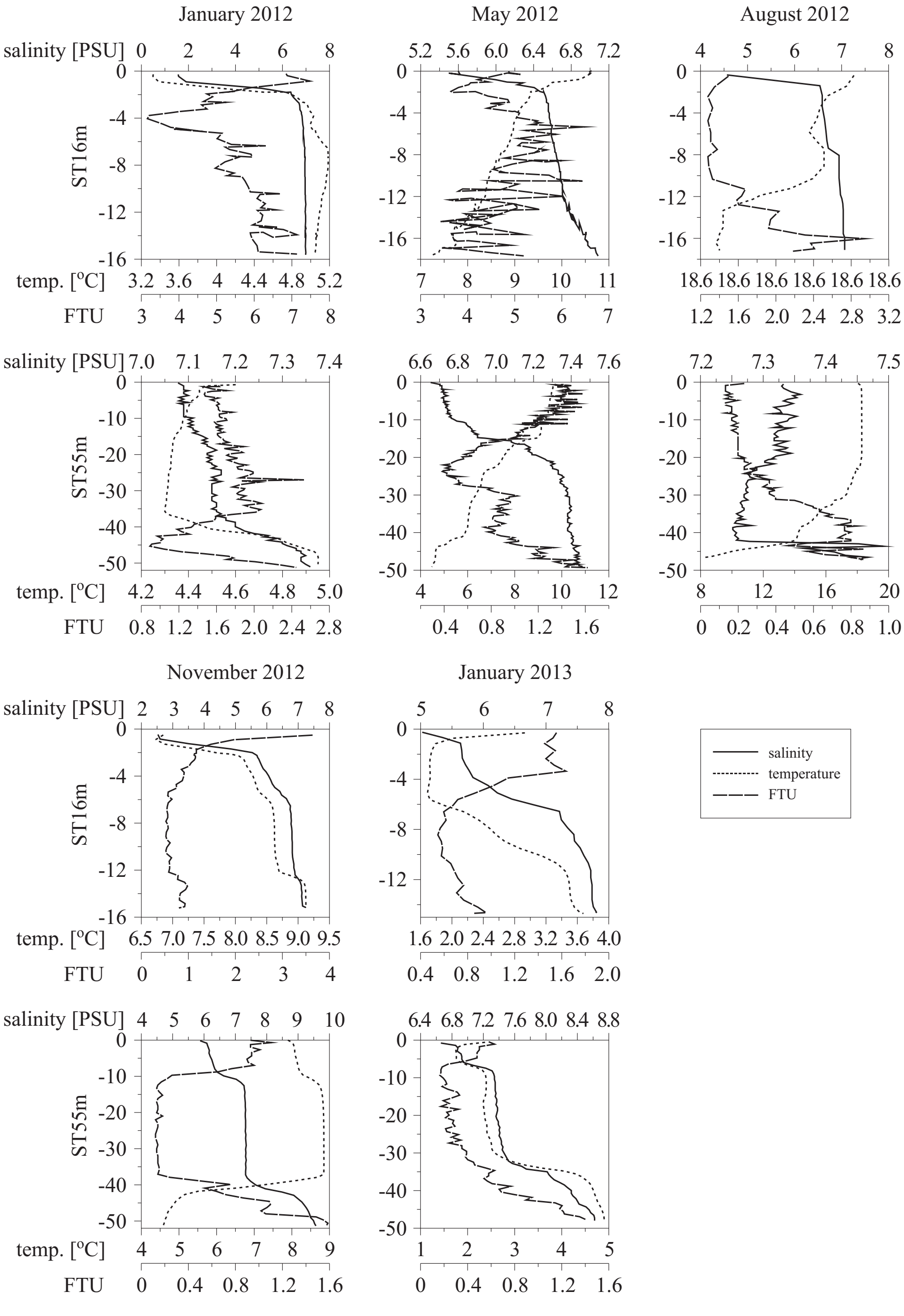


Figure 2. Salinity [PSU], temperature [°C] and turbidity [FTU] at sampling stations ST16m and ST55m

Surface salinity at station ST55m, 15.5 km distant from the river mouth, ranged from 6.5 in May to 7.32 PSU in August (Figure 2). Pycnal stratification decreased at this station because of progressive water mixing. The thickness of the brackish water layer increased to several metres, but this layer was not present in August. The SPM concentration decreased seawards in the surface water (0.2–1.6 FTU) but increased significantly near the bottom (0.9–2.6 FTU).

A high level of sedimentation was recorded in January 2012 during a strong gale (9 B): 702 g m^{-2} 24 h^{-1} and 3084 g m^{-2} 24 h^{-1} at stations ST16m and ST55m respectively (Figure 3). In May the SR was 115.5 g m^{-2} 24 h^{-1} and 29.5 g m^{-2} 24 h^{-1} at stations ST16m and ST55m respectively. The lowest SR values at ST55m were recorded in August (2.2 g m^{-2} 24 h^{-1}) and January 2013 (1.4 g m^{-2} 24 h^{-1}).

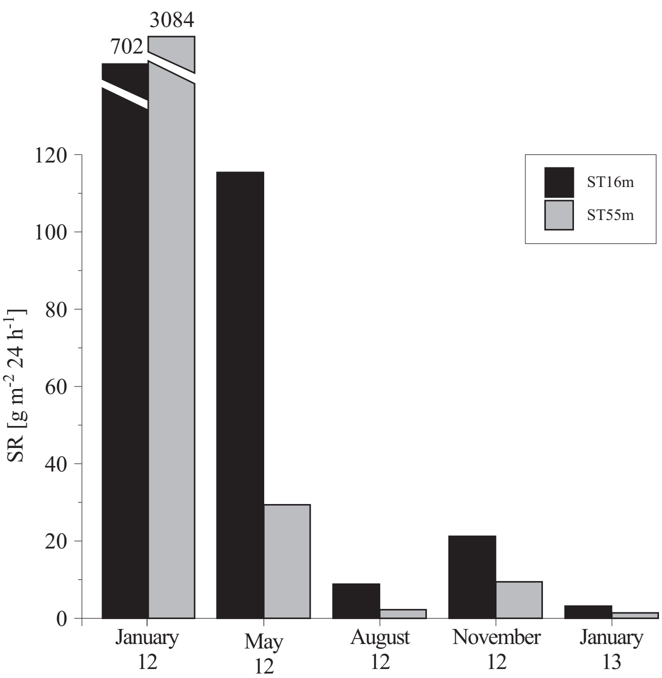


Figure 3. Sedimentation rates at sampling stations ST16m and ST55m

The strongest wind was recorded in January 2012 with gusts of > 20 m s^{-1} from the north-west. During the other seasons, moderate westerly winds (10 m s^{-1}) occurred twice in May and August. Weaker southerly winds were measured January 2013 (7.5 m s^{-1}) and November 2012 (5 m s^{-1}).

Sediment accumulation rates (LAR and MAR) were estimated with the ^{210}Pb method. Total ^{210}Pb activity concentrations decreased from 639 ± 30 Bq kg^{-1} in the uppermost sediment layer to 239 ± 10 Bq kg^{-1} in the lowest part of the core in the 20–21 cm layer. ^{210}Pb activity concentrations exhibited exponential decreases down the core, but layers in which only supported ^{210}Pb was present were not noted. Supported ^{210}Pb values were therefore measured with gamma spectrometry. The activity of ^{210}Pb$_{\mathrm{supp}}$ (^{226}Ra) was determined by measuring ^{214}Pb and ^{214}Bi, the mean value being 30 ± 2 Bq kg^{-1}. Estimating the accumulation rate in this study was mathematically forced considering the exponential decrease of ^{210}Pb$_{\mathrm{ex}}$ activity observed in the profile (Figure 4). LAR and MAR were estimated to be 0.70 ± 0.07 cm y^{-1} and 1900 ± 200 g m^{-2} y^{-1} respectively.

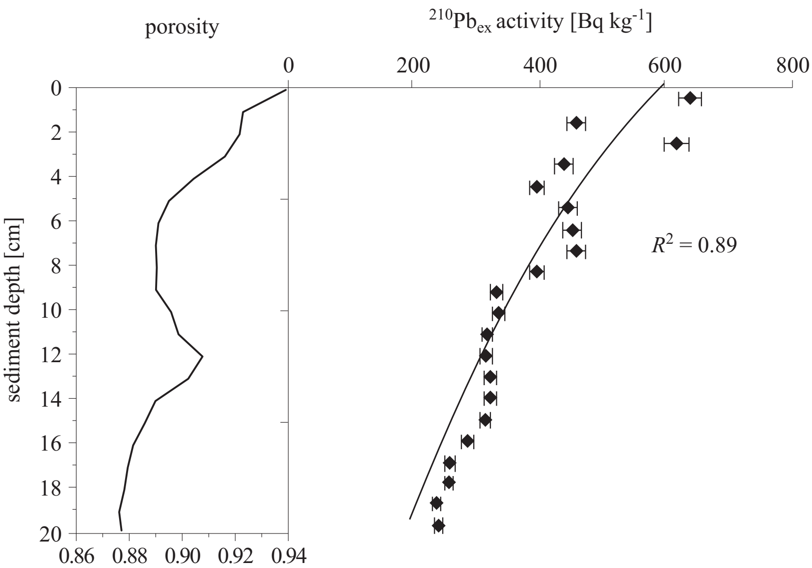


Figure 4. Porosity and ^{210}Pb activity concentrations as a function of sediment depth at sampling station ST55m

4. Discussion

Performing detailed comparisons between sedimentation rates from sediment traps and sediment accumulation rates is difficult since sediment trap data reflect only the short periods of the trapping experiment (usually 1–2 days per season). Therefore, we decided to compare the daily SR to wind conditions in the Gulf of Gdańsk, and use daily river discharge to estimate annual sedimentation rates in the outer Vistula prodelta.

Our data on water turbidity shows rapid suspension settling in the upper prodelta (ST16m). Progressive surface water mixing caused significant increases in suspension concentrations (FTU) in the lower part of the water column at a distance of 15.5 km from the river mouth at station ST55m. Hence, there was no correlation between SR and wind direction periods of average river flow, since the suspensions transported by the river are removed from the surface water in the vicinity of the river mouth (Figure 2). According to Voss et al. (2005) and Zajączkowski et al. (2010), large amounts of turbid river water discharge during floods produce surface plumes that extend from the river mouth up to 25 km northwards and 80 km eastwards, depending on the wind direction. Our data show the spatial distribution of turbid water during average river flows: there are linear correlations between river discharge and SR at both sampling stations, except during the period of snow melt (I, January 2013) and when there were significant waves on the sea (II, January 2012) (Figures 5a,b). During the short period of snow melt in January 2013, the river banks were still frozen, so the faster river flow was not related to higher sediment loads; hence, disproportionately low SR values and a high river flow were noted at both sampling stations. During the strong gales in January 2012, the high SR (3084 g m^{-2} 24 h^{-1} at ST55m and 701 g m^{-2} 24 h^{-1} at ST16m) was due to sediment redeposition. The sediment collected in the traps contained several per cent coarse sand and gravel, which indicated significant sediment transport along the bottom caused by the interaction of the storm waves and the opposite direction of the riverine current. Therefore, we decided to exclude days of rough weather (>8 B) from the estimates of annual SR. There was such weather on fewer than 5% of the days in the study period.

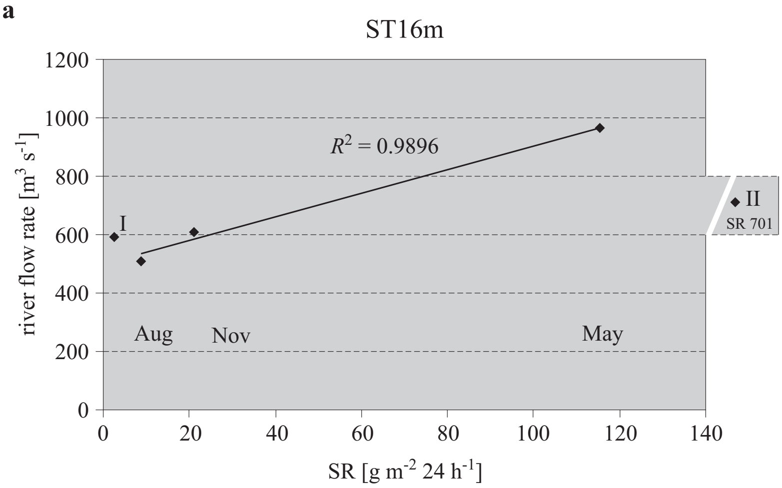
Equation (1) of the linear regression between river discharge and SR from trapping (Figure 5b) was used to calculate daily and annual SR at station ST55m, according to the transformed formula (2).

$$y = 16.957x + 462.21 \tag{1}$$

$$\mathrm{SR} = (\mathrm{RF} - 462.21)/16.957 \tag{2}$$

where $x = \mathrm{SR}$ – sedimentation rate; $y =$ river flow.

For the 12 days with river flows < 463 m^3 s^{-1}, negative SR results were replaced with 0.1 g m^{-2} 24 h^{-1}. The results of the calculated daily SR and river flows show that the largest sediment load is deposited in the outer Vistula prodelta (ST55m) between February and May, whereas the summer and autumn are characterized by the lowest sedimentation from suspension (Figure 6). The data on the Vistula flow in the study period represents the typical hydrological regime of this river with maximum discharge near the mouth in late winter and early spring (Łajczak et al. 2006).



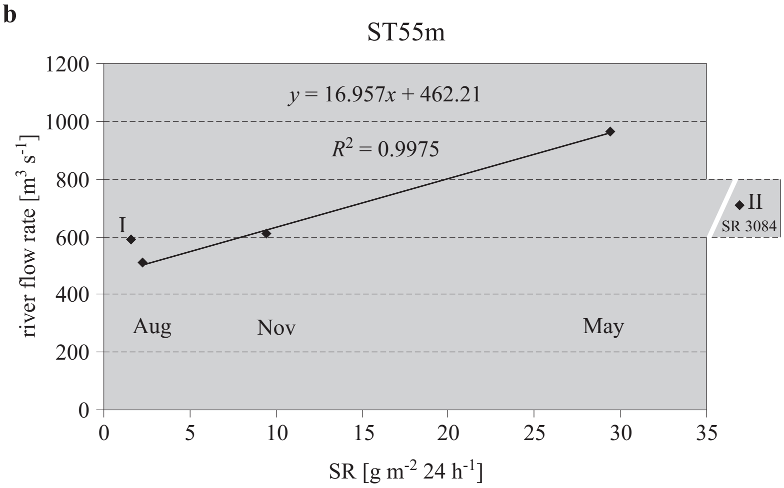


Figure 5. Correlation between sedimentation rates (SR) [g m^{-2} 24 h^{-1}] and Vistula flow rate [m^3 s^{-1}]. a) station ST16m, b) station ST55m. I – January 2013, II – January 2012

The annual sum of daily SR determined with equation (2) was estimated at 6553 g m^{-2} y^{-1} (Figure 7), whereas the sediment accumulation rate (MAR) determined from ^{210}Pb activity was 1900 g m^{-2} y^{-1} at station ST55m. According to Kunzendorf et al. (1998) and Suplińska & Pietrzak-Flis (2008), the annual MAR in the deepest part of the Gdańsk Basin is considerably lower; the first paper gives a value of 966 g m^{-2} y^{-1}, the second one 543 g m^{-2} y^{-1}. The Gdańsk basin serves as a depositional area for the terrigenous matter supplied by the River Vistula. However, the distance from the river mouth significantly influences

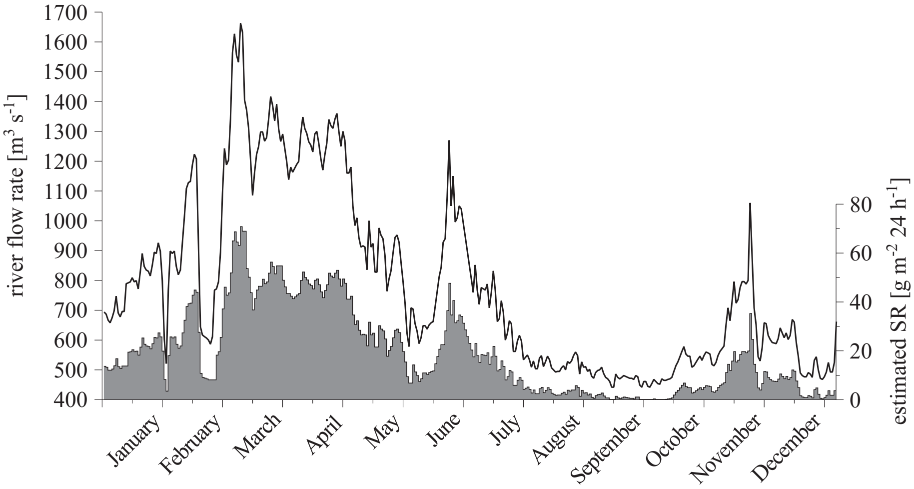


Figure 6. Daily Vistula discharges in 2012 (IMGW) (upper curve) and estimated daily SR values calculated with equation (2) for ST55m (lower curve)

sediment accumulation rates and the fate of the sediments in the Gulf of Gdańsk.

Estimated sedimentation from suspension in the outer Vistula prodelta is more than three times higher than the accumulation rate. This difference can be explained by sediment redeposition and its later transport into the deeper parts of the Gdańsk basin along the bottom. During the rough weather in January 2012, sediment redeposition was noted even at a depth of 55 m. Since waves in the Gulf of Gdańsk are relatively short (40–60 m) during a severe gale, sediment redeposition at this depth occurs below the wave base or on its edge. We assume that sediment redeposition starts in the upper part of the prodelta during stormy weather, whereas subsequent sediment transport is caused by near-bottom currents. The numerous landslide chutes and subsidence areas observed with acoustic methods in the upper part of the prodelta indicate a gravitational mass movement of sediment that is caused by waves and is supported by the force of gravity on a slope inclination of 5–6%. The inclination of the outer Vistula prodelta does not exceed 1%; however, sediment movement initiated in the upper part of the prodelta can be halted by turbidity currents resulting from density gradients produced by contrasting concentrations of suspended particles in the water (Allen 1985, Zajączkowski & Włodarska-Kowalczuk 2007). Our findings remain in good agreement with the results obtained by Emeis et al. (2002) during the study on sediment fate in the Pomeranian Bight. They conclude that within one year sediment deposited

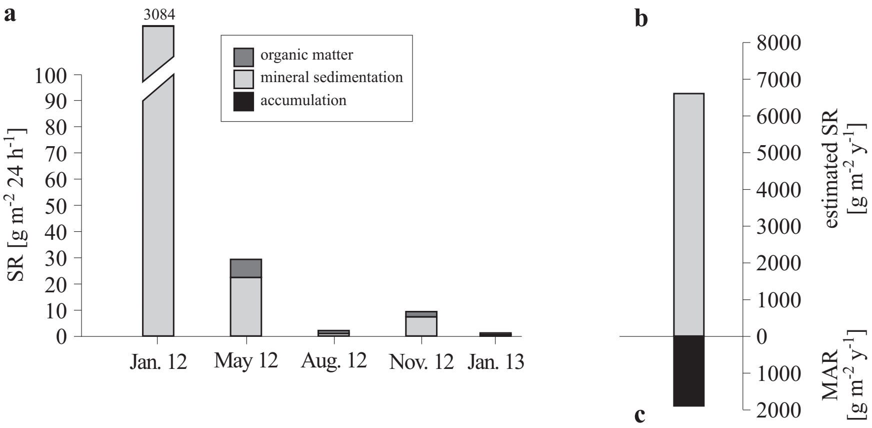


Figure 7. Comparison of sedimentation rates (daily – a and annual – b) and sediment accumulation (c) in the outer Vistula prodelta (ST55m)

in the shallow bight is remobilized and transported to the deeper coastal basins.

Budillon et al. (2005) also point out that sea storms reworking sediment near the Bonea Stream (southern Italy) causes the maximum rate of sand deposition on the depth 40–60 m. Thick tempestite sandy layers at depths on or just below the wave base may be linked to the intensity of sea storms eroding the shoreface, delta front and bars (Keen et al. 2004).

5. Conclusions

Sediment deposition/accumulation in Vistula prodelta is controlled by a range of processes, including the magnitude and the dynamics of the riverine supply of terrigenous matter, waves on the sea, water mixing (e.g. impacting flocculation, hypopycnal plume), as well as gravity and wave induced sediment remobilization on the slopes of the upper prodelta.

During average river flow, large sediment loads are deposited in the outer Vistula prodelta, where they can subsequently be redeposited. Extreme phenomena, such as severe winter storms, can cause more than two-thirds of the sediment mass to be redeposited.

This study confirms that sedimentary material discharged by the River Vistula is transported to deeper areas; the Gdańsk Basin thus serves as a sink for riverine matter.

The sediment instability in the Vistula prodelta could significantly impact on numerous processes including biota distribution and contaminant deposition.

Acknowledgements

The authors appreciate the assistance of the crew of r/v 'Oceania' and students from the University of Gdańsk.

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