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## Distribution of Suspended Sediment in the Gulf of Gdansk off the Vistula River mouth (Baltic Sea, Poland)

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**Abstract.** The Vistula River mouth is situated on the southern coast of the Gulf of Gdańsk (Poland). Considering the average flow and draining area of the Vistula River, it is one of the largest rivers in the Baltic Sea catchment area. It is also one of the largest sources of terrigenous material supplied to the Baltic Sea. The particle size analysis of the material transported in suspension shows that it consists of fractions ranging in size between 1 and 600  $\mu\text{m}$ . The silt fraction constitutes the biggest share (55%), while the medium and fine sands amount to 30%. Close to 15% of the material transported in suspension belongs to the clay fraction. During field research in April 2014, many parameters were measured at the stations in the Gulf of Gdansk. The variation in suspension characteristics and water parameters was determined with the LISST-25X sensor and CTD probe, respectively. The flow and current directions were assessed by means of ADCP. In the Vistula River mouth, the mean concentration of suspended matter in the surface layer (0–3 m) varied from 30 to 1 099  $\mu\text{L/L}$ . The Sauter mean diameter of suspended sediment ranged from 44 to 172  $\mu\text{m}$ , wherein the smallest and the biggest particle sizes were 22  $\mu\text{m}$  and 360  $\mu\text{m}$ , respectively. At a depth of 10 m, differences in mean diameter (36–54  $\mu\text{m}$ ) and concentration (16–47  $\mu\text{L/L}$ ) were much lower. The changes observed in these waters occurred over time, reflecting changes in the intensity of the Vistula River discharge. As distance from the river mouth increases, at the surface and at depth of 10 m, the average particle concentration and the mean particle diameter were lower. In deeper water layers (below the developing thermocline), the mean concentration of suspended sediment was clearly lower (2.5  $\mu\text{L/L}$ ), while the mean particle diameter was higher (32  $\mu\text{m}$ ). Different characteristics of water masses containing suspension were recorded in the marine waters, which are not directly influenced by the Vistula River freshwater inflow. In marine waters, the mean values of suspension concentration ranged from 1 to 2  $\mu\text{L/L}$ , with relatively large particle sizes between 50 and 60  $\mu\text{m}$ . As the distance from the Vistula River mouth increased, the influence of riverine waters on the particle size distribution and suspension concentration became increasingly less visible. The observed distributions of salinity, temperature and suspension concentration indicate that freshwater is spreading in the surface layer in a fan-shaped form. The spreading of suspension occurs along the dominant directions of the river water movement. Changes in the suspension concentration and particle size in the water column are caused by flocculation.



## 1. Introduction

River inflow is the main source of terrigenous material that is supplied to sedimentary basins at sea. This scenario also applies to the Baltic Sea and the Gulf of Gdansk. Vistula River, the longest river in the catchment area, transports the biggest amount of sedimentary material and thus has a significant influence on the sedimentation and sediment sorting in the Gulf of Gdansk [1, 2, 3]. The annual input of material transported in suspension has been estimated at 909 000 tons [4] or 1 200 000 tons [5], which constitutes close to 1/5 of all material delivered via suspension to the Baltic Sea.

The particle size analysis of bed load in the Vistula river mouth [6] showed that the transported particles range in size from 1 to 600  $\mu\text{m}$ . The most abundant size fraction consists of particles ranging from 2 to 63  $\mu\text{m}$ , amounting to 55%. The largest particles ( $>63 \mu\text{m}$ ) constitute ca. 30%. Almost 15% of all material transported in suspension is smaller than 2  $\mu\text{m}$ . Based on the chemical composition analysis of suspended particles, it was established that 50% of the material is composed of carbonates and silicates, while the remaining part consists of clay minerals and mixed-layer clay minerals [7] which are classified as chemically-reactive soil surfactants [8].

In the river mouths areas, due to the gradients in water density, the inflowing riverine waters spread in the surface layer in the form of a fan [9, 10]. The small-size fractions of suspended load carried by the riverine waters are transported farther, undergoing gradual sedimentation. The suspended load is not only subjected to mechanical sedimentation in accordance with Stoke's law. Due to the high content of active particles in suspension, sedimentation is dominated by the processes that are specific to these particles. Transformations connected to the changing ionic composition of aquatic environment take place due to increased salinity, altered pH and varying temperature. Under such conditions, the transported components of suspension undergo flocculation [11, 12, 13], i.e. formation of aggregates from the solid phase particles via interactions and surface binding mediated by, among others, organic matter [8]. Heavy and porous aggregates, so-called flocs, are formed which, due to gravity, start to descend with the sedimentation rate defined by Stoke's law. The described process also occurs in the Vistula river mouth [1, 2, 3].

The extent of Vistula waters in the Gulf of Gdansk is visible in the distance ranging from 2 to 15 nautical miles from the river mouth. The vertical extent of fresh water varies from 0.5 to 12 m [14, 15, 16, 17]. The variability of riverine water spread, including the transported suspension, depends on, among others, the hydrological factors connected to flow intensity, sea state or wave motion [18].

The aim of the conducted research was to analyze the mechanism of suspension differentiation in the suspended load in relation to the changes in particle size and factors influencing the spread and sedimentation of suspended material.

## 2. Methods

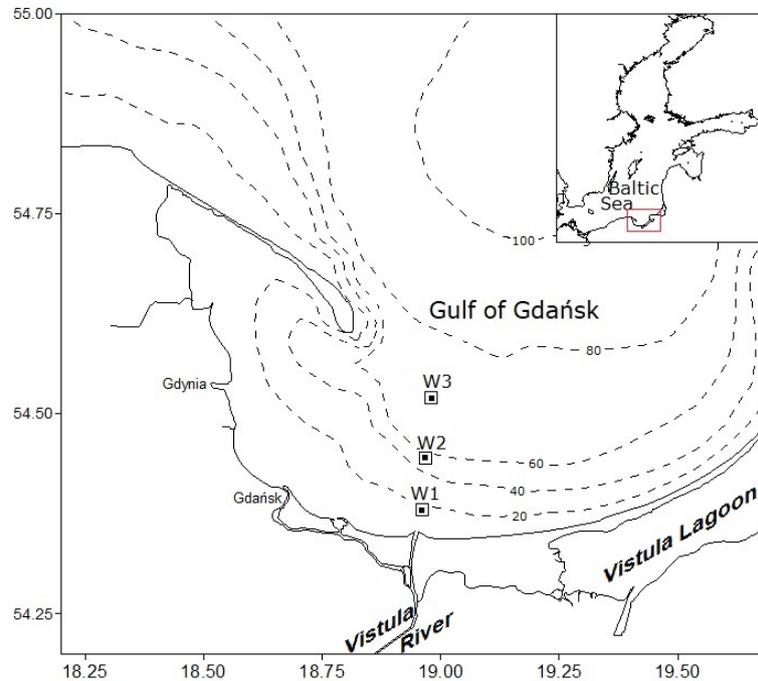
The investigations were conducted along the transect extending from the Vistula river mouth into the sea (figure 1) on 12–13 April 2014 from onboard ORP Heweliusz. The collected suspension was characterized by measuring its in situ particle size and volumetric concentration. To this end, a LISST-25X Sequoia Scientific sensor was used to perform both aforementioned measurement in real time. The LISST-25X interprets the two measured sums of dissipated light and then calculates the total volume of particles and particle concentration. The collected data are used to calculate Sauter mean diameter (SMD). The sensor registers the mean size and mean concentration of particles in the range of 2.5–500  $\mu\text{m}$ .

Measurements were performed sequentially at stations W3, W2 and W1 (figure 1) in the surface, intermediate (below the forming thermocline) and near-bottom layers.

A measurement at each depth lasted ca. one hour at a sampling rate of 3 sec, which resulted in 650 to 1 150 data points depending on how long the sensor was active. At station W1, which was in the closest proximity to the Vistula river mouth, the measurements were performed three times per day, while at the remaining stations, only once.

The obtained results were analyzed in relation to the thermohaline characteristics of water masses (CTD Sea Bird V19 probe) spreading in the Vistula river mouth, and later correlated to the mass

concentration of suspension determined in the water column at specific levels from the surface to the bottom, taking into consideration the distribution of water currents, sea level variability, and the intensity of Vistula River flow.



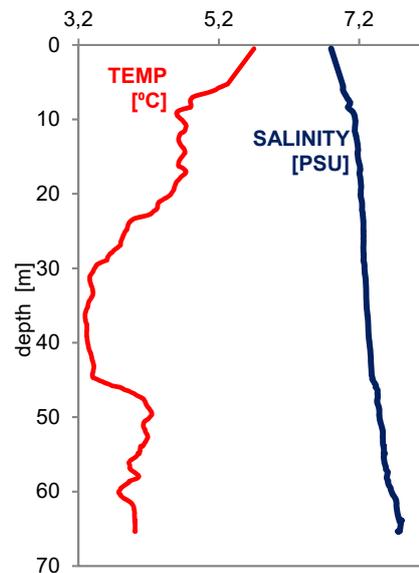
**Figure 1.** Study area, location of sampling stations

### 3. Results and discussions

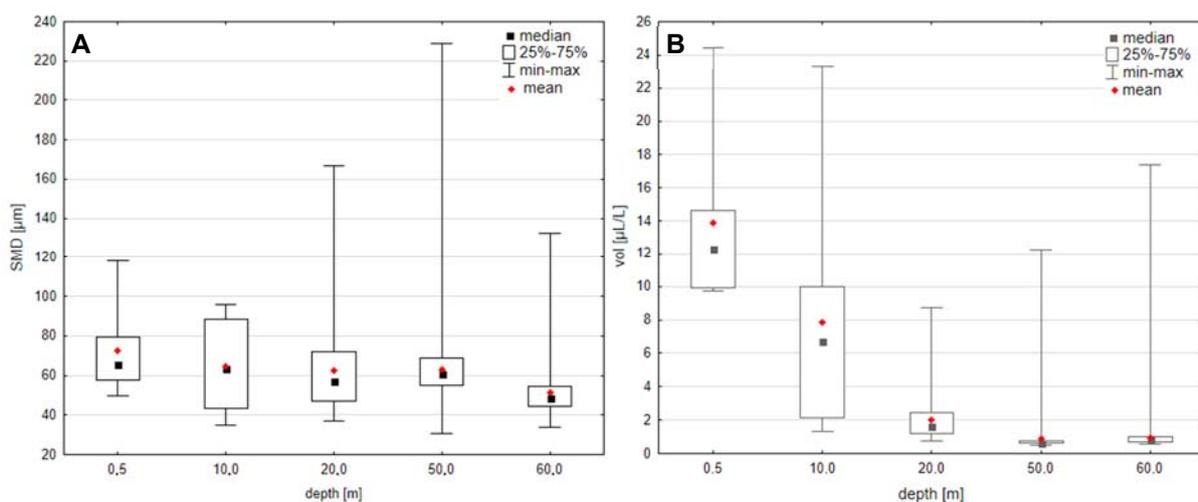
The investigations were conducted in the spring season which is characterized by the highly dynamic intensity of Vistula River flow. In this period, the observed discharge values in the river mouth area were lower than the mean values ( $1046 \text{ m}^3/\text{s}$ ), varying from  $650$  to  $850 \text{ m}^3/\text{s}$  and reaching  $1270 \text{ m}^3/\text{s}$  two days after the completion of data collection.

Station W3, the deepest ( $65 \text{ m}$ ) and most distant from the river mouth, was visibly influenced by winter marine waters, as indicated by the thermohaline stratification. Along the entire transect, the salinity increased from  $6.9$  to  $7.7 \text{ PSU}$ , and the temperature dropped from  $5.7$  to  $4^\circ\text{C}$  with increasing depth. The biggest temperature gradients were observed between  $20$  and  $45 \text{ m}$  depth ( $4.7\text{--}3.3^\circ\text{C}$ ) (figure 2). During the research period, the surface currents with low flow rates ( $0.05 \text{ m/s}$ ) directed marine waters towards the Vistula river mouth.

The mean particle size of suspended matter in the surface layer ( $0.5 \text{ m}$ ) was  $72.6 \mu\text{m}$ . The particle sizes ranged between  $49.5$  and  $118 \mu\text{m}$ , while the  $>63 \mu\text{m}$  size fraction constituted  $40\%$  of total suspension. With increasing depth, the mean diameter of suspended particles decreased ( $63\text{--}52 \mu\text{m}$ ), which was accompanied by the lowered share of largest particles. At ca.  $20 \text{ m}$  depth, despite decreasing mean diameter of suspended particles, the percentage increase in the  $>63 \mu\text{m}$  size fraction was observed ( $41.6\%$ ). At a depth of  $50 \text{ m}$ , the highest differentiation of particle sizes was noted ( $30\text{--}228 \mu\text{m}$ ) (figure 3A). The suspension concentration along the transect was low; it decreased with increasing depth (mean values  $13.9\text{--}0.97 \mu\text{L/L}$ ) (figure 3B).

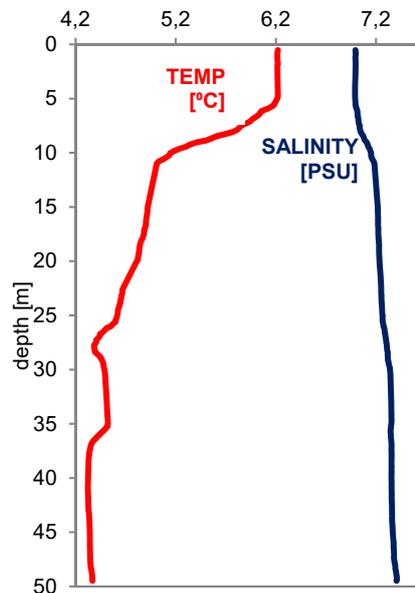


**Figure 2.** Vertical profiles showing the change in temperature, salinity with depth at station W3

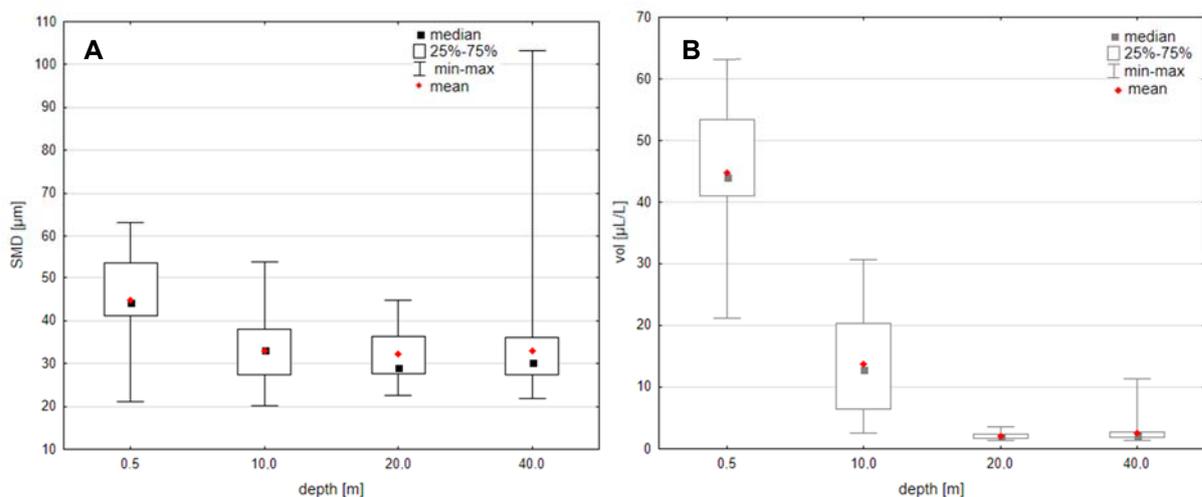


**Figure 3.** Variability of SMD (A) and volume concentration (B) at station W3

At station W2, located at 50 m depth, the temperature ranged from 6.2°C in the surface layer to 4.4°C above the bottom (thermocline at 6–10 m), while the salinity increased from 7.2 to 7.4 PSU with increasing depth (figure 4). Currents detected in the surface layer (0.11 m/s) pushed water in NNE direction. The mean diameter of suspended particles was the highest in the surface layer (44.8 µm), while in the remaining parts of the transect, it amounted to ca. 33 µm. The particle sizes in the near-bottom layer (22–103 µm) were more differentiated compared to those in the water column (22–54 µm). In the deepest zone, a small share of particles >63 µm was observed (1.2%); the particles of this size were not present at other depths (figure 5A). The volumetric concentration of suspension was higher than at station W3, which points to the influence of the Vistula River. With increasing depth, the suspension concentration decreased from 44.7 µL/L at the surface to 2.5 µL/L above the bottom (figure 5B).



**Figure 4.** Vertical profiles showing the change in temperature, salinity with depth at station W2



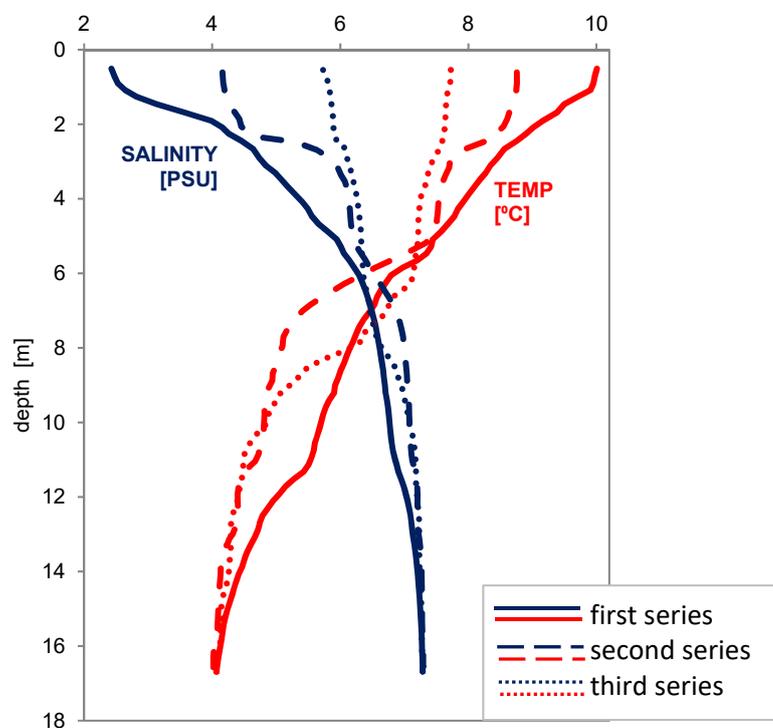
**Figure 5.** Variability of SMD (A) and volume concentration (B) at station W2

At station W1, which was the shallowest (16 m) and the closest to the Vistula river mouth, the measurements were performed three times. The hydrological parameters assessed in the surface layer were changing fast, i.e. a drop in temperature from 10 to 7.7°C, and the salinity increase from 2.4 to 5.7 PSU (figure 6). Initially, the surface currents were heading north (0.24 m/s), but later changed their direction and pushed the Vistula waters towards east (0.3 m/s), enabling the upwelling of marine waters. This resulted in the described increase in salinity and decrease in temperature in the surface waters.

In comparison to data collected at other stations and along the entire depth profile, the suspension concentration at station W1 in the surface layer, determined via three consecutive series of measurements, was the highest. Initially, the suspension concentration, which depends on the direct inflow of Vistula water, widely varied in the range of 29–8 966 µL/L, reaching the mean value of 1 099 µL/L (figure 7B). During the first series of measurements, the size fraction distribution of suspension was characterized by the visible presence of multiple populations (22–360 µm) and

multiple modes. The share of particles  $>63\ \mu\text{m}$  was 74%, thus the mean diameter of suspended particles equalled  $170\ \mu\text{m}$  (figure 7A). The other two series of measurements were performed during decreasing wave action and changing surface currents. The determined values of suspension concentration showed a decreasing trend, i.e. 85 and  $51\ \mu\text{L/L}$  for respective two series. The mean particle diameter also decreased, reaching 55 and  $51\ \mu\text{m}$ , respectively. Moreover, a significantly lower share of particles  $>63\ \mu\text{m}$  in suspension was observed (respective values of 50 and 33%). The short-term variation of suspension concentration and particle size indicates that the oscillations of water masses and suspended matter must have been connected to wave motion. The characteristics of these oscillations visibly faded away with increasing depth.

With increasing depth in the river mouth (W1), the salinity increased from 5.3 to 6.3 PSU, while the temperature dropped from 8 to  $7.3^\circ\text{C}$  (figure 6). At 3–4 m depth, the suspension concentration decreased, assuming the following mean values in consecutive measurements: 196, 36 and  $27\ \mu\text{L/L}$  (figure 7B). At the same time, the share of smaller size fractions increased, mainly consisting of very coarse-grained silt, which resulted in lowered mean diameter of  $45\ \mu\text{m}$  (figure 7A).



**Figure 6.** Vertical Profiles showing the change in temperature, salinity with depth at station W1

At ca. 10 m depth, the thermohaline conditions ( $7.3\ \text{PSU}$ ,  $4.1^\circ\text{C}$ ) (figure 6) as well as suspension concentration were stable, the latter not changing in a significant way during the three consecutive series of measurements. The maximum instantaneous value of suspension concentration did not exceed  $65\ \mu\text{L/L}$ , while the mean suspension concentration remained at the level of  $11\ \mu\text{L/L}$  (figure 7B). The grain-size distribution of suspended matter was visibly unimodal. The dominant fraction was very coarse-grained silt ( $63\text{--}31.3\ \mu\text{m}$ ), whose share increased compared to the content in the layer above (figure 7A).

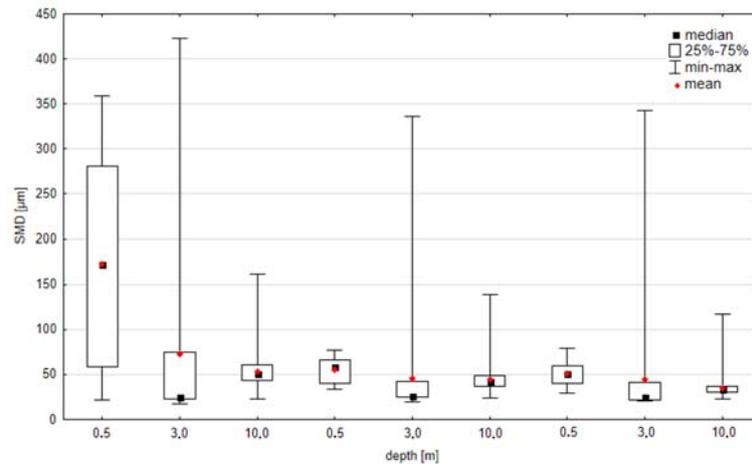


Figure 7A. Variability of SMD at station W1

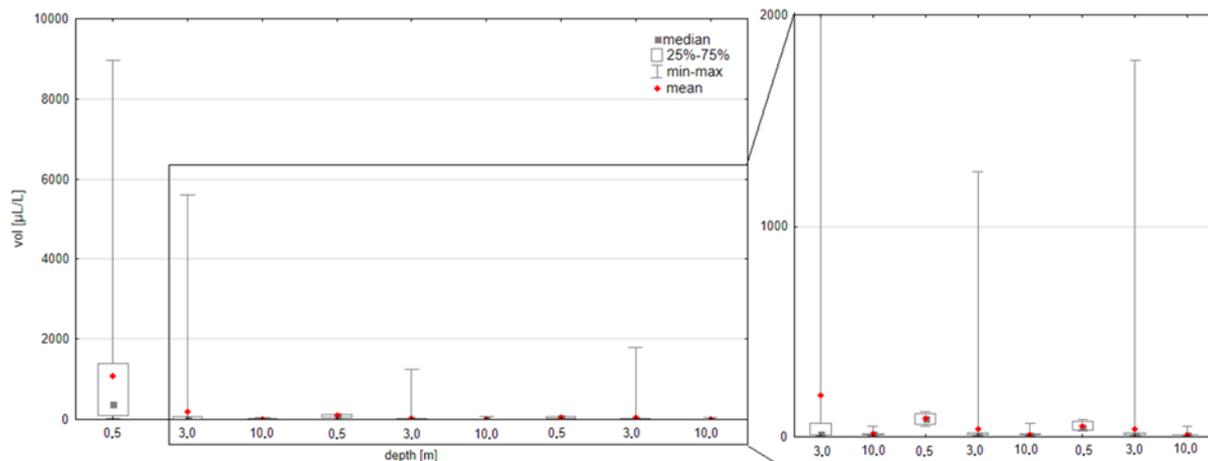


Figure 7B. Variability of volume concentration at station W1

In the surface layer, particularly in the proximity of the Vistula river mouth, the suspension was poorly sorted. Because riverine waters were highly saturated with the discharged mineral material, the sorting process was lagging behind. The transport of suspension occurred under conditions of high and moderate turbulence. At 3–4 m depth, the sorting of suspension was moderate. In this layer, the coarse fractions were less abundant because they settled out of suspension, which resulted in a noticeable large share of smaller fractions. From the sedimentation point of view, this particular depth can be considered as transit zone characterized by a deficit of material. The suspended particles present at a depth of 10 m directly by the river mouth area were well sorted. In this zone, the waters are saturated with sedimentary material which precipitates in the form of flocs, causing an increase in the mean particle diameter.

The sorting of suspension was good and very good along the transects located at deeper depths (W2 and W3) for both the surface layer and water column. The unimodal grain-size distributions indicate that the sedimentation conditions there were more homogeneous, i.e. the suspension was transported under conditions of low turbulence. The increase in the mean particle diameter and higher differentiation of particle size observed below the density gradient and above the bottom testify to the occurrence of flocculation or resuspension. The velocities of near-bottom currents, mainly close to the river mouth but also at deeper depths, enable the resuspension of surface sediments [2].

#### 4. Conclusions

The presented results are in agreement with the general rules of sediment differentiation in the river mouth areas [10], including the ones described for the Vistula river mouth [2, 3]. With increasing depth and distance from the Vistula river mouth, the mean particle diameter and volumetric concentration of suspended matter decreased. The distribution of the aforementioned parameters depends on, among others, the pattern of surface currents determining the direction in which the Vistula waters are transported. Variable thermohaline conditions are another factor influencing the distribution of suspension in the Vistula river mouth. Below the density gradient, the increase in the number of particles with larger diameters was observed, which resulted from the process of flocculation. In situ measurements of particle size, which have been obtained for the first time, confirm the significance of flocculation in the sedimentation of suspended matter as well as demonstrate that the <63  $\mu\text{m}$  size fraction is carried out of the river mouth area and the zone influenced by the Vistula River waters.

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