Characteristics of Sediments in a Changing Environmental Conditions in Vistula Lagoon (Poland)

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Abstract. The Vistula Lagoon has been evolving since its formation in the late Atlantic period. At the beginning, the changes were mainly driven by the stabilization of the Baltic Sea level, and the development of hydrographic network. Later on, anthropogenic activities have become an important factor. Hydrotechnical works conducted at the turn of the 20th century, aimed at regulating the outflow of the Vistula River waters, have significantly limited the riverine input into the lagoon. In the past, the Vistula Lagoon contained freshwater and was constantly filing with sediments that made the basin shallow. With time, the lagoon has filled with brackish water, while its area became subjected to strong interactions between the driving forces of marine and terrestrial origin. As a result, the regime of sedimentation processes in the lagoon have been changed. The interpretation of sedimentation conditions for clastic sediments was based on the analysis of grain-size parameters that had been determined on the samples of bottom sediments and suspension collected in November 2016. The obtained results were compared to the pertinent data on bottom sediments collected by the Polish Geological Institute National Research Institute in 1994. Significant contrasts in particle size distributions were found. Also, the conducted study allowed the determination of underlying causes of these changes. Due to the shallow depth of the Vistula Lagoon, the sedimentation processes in this basin are significantly influenced by resuspension phenomenon. Resuspension is responsible for the differentiation and redistribution of sediment that originates from various sources, on the bottom of the basin. The process takes place in shallower areas, but this study indicates that its effectiveness increases in the deeper areas of the lagoon, which manifests itself in the replacement of clayey silt with silt. In connection with the plans of the Polish side of the cross-cutting of the Vistula Spit, the sedimentation conditions of Vistula Lagoon will be changed.

1. Introduction
The sediments, and specifically their grain-size spectrum and textural parameters, are used as indicators of sedimentation conditions and the evolution of depositional environments. Transient sedimentary environments, such as the Vistula Lagoon, remain under the influence of both terrestrial and marine determinants. In modern times, the functioning of the aforementioned environments is also affected by human activities, e.g. river engineering, utilization of the surrounding areas, bank reinforcement, input of pollutants, and overexploitation of resources [1].

Coastal lagoons are mostly supplied with sedimentary material via rivers carrying terrestrial material, while some input may originate from the erosion of the river bed or marine sources [2, 3].
The lagoonal sediments are subjected to particularly complex processes which determine their distribution, differentiation and sedimentation. In the case of the Vistula Lagoon, the analysis of sedimentary processes is simpler due to the fact that the tides are not present and there is only limited inflow of seawater through the Baltiysk Strait located in the eastern part of this body of water. The Vistula Lagoon belong to the class of non-tidal lagoons and choked lagoons [4].

The paper presents the results of sedimentological studies of bottom and suspended sediments collected in 2016 compared to results from 1994. Its main goal is to analyse the textural changes of sediments. Statistical grain size parameters were used to interpret the present-day depositional conditions and sedimentation changes. Additionally in the era of plans of the Polish side of the cross-cutting of the Vistula Spit, there was a need to update the data of the sediments of Vistula Lagoon. Previously, comprehensive sediment studies were conducted in the years 1959–1965, which resulted in the publication of the first map of bottom sediments, including the sediment characterization [5]. Since the 1990s, subsequent sediment studies in the Polish part of the lagoon [6] as well as in its Russian area have been continued [7–12].

2. Study area
The Vistula Lagoon, located in the southern Baltic Sea (figure 1), spans two countries, i.e. Poland and Russia (Kaliningrad Oblast). The lagoon is separated from the sea by the Vistula Spit, while the only passage leading to the Gulf of Gdansk is through the narrow Baltiysk Strait. The Vistula Lagoon is 91 km long, of which 35.1 km spans the Polish territory; the mean width is 9.2 km. The surface area of the lagoon within the Polish borders equals 365 km$^2$, while the mean and maximal depths are 2.4 and 4.4 m, respectively [13]. The mean salinity in the Polish part of the lagoon varies seasonally; it ranges from 1.5 to 3.5 PSU in the western part, and from 3.5 to 5.0 PSU in the eastern part of the area [14].

![Figure 1. Vistula Lagoon and the location of study sites](image)

The Vistula Lagoon is a semi-enclosed, shallow body of water, which is reflected in the characteristics of bottom sediments. At present, the source of sedimentary material that enters the lagoon is river discharge (i.a. Nogat, Szkarpawa, Elbląg, Pasłęka and Bauda), the erosion of the river bed and coastal zone, the water exchange via Baltiysk Strait, and the production in the basin [15].

Since its origin in the early Atlantic period until the Middle Ages, the Vistula Lagoon was subjected to natural processes only. From the seaside, the inflow of seawater was shaping this body of water with the intensity that tended to decrease with increasing stability of the sea level and the
development of the Vistula Spit [16]. On land, it was the Vistula River discharge, forming a large river mouth, and smaller watercourses that influenced the lagoon. At that time, the drainage basin of the Vistula Lagoon encompassed the entire Vistula river basin. Deforestation and agricultural use of land resulted in the increased amount of bedload transported by the rivers. As a consequence, the lagoon became strongly brackish, while the Vistula river mouth expanded into the lagoon due to bedload accumulation, which had made the lagoon even shallower and smaller [17]. Human interference in the hydrographic network had caused a drastic change in the water balance in the Vistula river mouth, which manifested in numerous floods. At the turn of the 20th century, the regulation of Vistula River became unavoidable. The artificial river mouth has been built through which 90% of river discharge is directly channelled into the sea.

Due to the aforementioned river engineering, the influence of the Vistula river discharge on hydrological cycles, the dynamics of both suspension and sediment, and the bathymetric profile of the Vistula Lagoon has significantly decreased. The lagoon became a brackish water basin exposed to the driving forces of marine and terrestrial origin. The mean water level of the Vistula Lagoon decreased due to the reduction of river inflow and thus, the Baltic Sea waters could easily enter the lagoon. Prior to river engineering, predominant currents were flowing out of the water basin, as confirmed by the observed changes in salinity in the Polish part of the Vistula Lagoon. The mean salinity values calculated for the periods 1950–75 and 1993–2015 equal 2.41 and 3.35 PSU, respectively [14].

Despite a number of hydrotechnical engineering projects, rivers still remain the main source of sedimentary material entering the Vistula Lagoon [11]. The sedimentation rate estimated for the time period of ca. 100 yrs was 0.4 mm/yr [11]. However, the rate based on the radiocarbon (14C - 5180±150) dating of a 5.6 m long sediment core sampled in 1994 was two times higher [6]. The exchange of water between the Vistula Lagoon and the Baltic Sea, which depends on the sea level, favors the transport of sedimentary material outside the lagoon [13]. The annual outflow of water from the lagoon amounts to ca. 41.5%, while the annual inflow, to 25.5%. Mixed currents constitute 27.6%, and the remaining 5.4% are the periods of no water flow.

According to the mechanism of differentiation, coarse-grained sediments are deposited at shallow depths, while the fine-grained sedimentary material is transported to the deepest central part of the water basin and also outside the lagoon via Baltiysk Strait. Wind waves, the exchange of water through the Baltiysk Strait (mainly from the eastern part of the basin), maritime transport, and the movement of vessels are other determinants that influence the characteristics of sediment. The prevalent wind waves in the Vistula Lagoon come from the west [18]. The wave motion stabilizes after ca. 1–2 hrs of wind action, and quickly disappears once the wind stops blowing. The observed maximum wave height does not exceed 1.5 m [19]. The amplitude of wave motion is the highest in the south-western part of the lagoon, that is, at the farthest distance from the Baltiysk Strait [20]. The wave motion during storms reaches the bottom, which results in the resuspension of bottom sediments [18, 19]. The aforementioned factors determine the quantitative and qualitative properties of bottom clastic sediments as represented by different sediment fractions, i.e. sand, silty sand, sandy silt, silt and clayey silt [5, 6].

3. Material and methods
Field research was conducted in the Polish part of the Vistula Lagoon on November 25 and 26, 2016. The samples of bottom sediments were collected from 15 sites with a van Veen grab sampler (figure 1). The characteristic of suspension was assessed by in situ measurements of sediment grain size. To that end, a LISST–25x suspended sediment sensor, equipped with a laser diode, was employed to make measurement in real time. The measurement was recorded in the surface water layer at a depth of 0.5 m at all stations (figure 1).
The collected bottom sediments were granulometrically analyzed by means of either dry sieving or wet sieving and pipette analysis. In addition, raw data from the granulometric analysis of bottom sediments sampled in 1994 were also used. The data were collected within the framework of the geochemical mapping of the Vistula Lagoon sediments that had been conducted by the Polish Geological Institute (PIG) [6]. These archival data were made available by the Central Geological Archive, PIG. The statistical parameters of grain size for the samples of bottom sediments (collected in 1994 and 2016) and suspension were calculated by using Gradistat program and the Folk and Ward logarithmic method [21].

4. Results
The grain size parameters of sediment samples collected in 1994 and 2016 were analyzed and compared. According to the Shepard’s classification system [22], samples collected in 1994 mostly consisted of clayey silt (figure 2), having the silt content of 67–79%, clay content of 15–31%, and the mean sand content of ca. 4.5% (figure 3). Silts contained over 80% of grains with a diameter ranging from 4 to 8 phi and the fractions of clay and sand (ca. 2%). The dominant fraction of sandy sediments constituted over 90% (figure 3).

Recent bottom sediments were mainly represented by silt and sandy silt (figure 2), with the respective contents of dominant fraction ranging from 81 to 94%, and from 55 to 78% (figure 3). The share of clay fraction in the aforementioned sediments was low, and did not exceed 2% (figure 3). Sands occur in the area of southern coast between the river mouths of Bauda and Pasłęka rivers (figure 2). In the western part of the lagoon along the extension of Vistula Królewiecka river mouth, and between the Nogat river mouth and the Elbląg Bay silty sands were found that contained from 62 to 71% of sand fraction (figure 3).

In parallel with the analysis of bottom sediments, the grain size analysis of suspension was also conducted. The grain-size distribution of suspended sediment closely corresponded to the characteristics of bottom sediment (figure 3). The size fractions between 5.74 and 1.4 phi, corresponding to silt and sand, were present in the suspension.
All sediments sampled in 1994 were characterized by a unimodal grain-size distribution (figure 3). On the other hand, some sediments sampled in 2016 were characterized by a higher content of sand fractions (over 30%), and displayed a bimodal grain-size distribution (figure 3). The other samples from 2016 sampling series contained material concentrated in one fraction, i.e. 5 phi, which was unimodally distributed.

The differentiation of compared sediments has been confirmed by the Folk and Ward (1957) statistical parameters of grain size. The values of mean grain diameter ($M_z$) equaled 1.8–7.1 phi and 1.77–4.51 phi for the first (1994) and second (2016) measurement series, respectively. The $M_z$ values for the suspension samples ranged between 4.01 and 5.37 phi.

The samples of silt and clayey silt collected in 1994 were poorly sorted, while the samples of sandy sediment were moderately or even moderately well sorted (figure 4a). The finest sediments from the second sampling series (2016), i.e. silt and sandy silt were well, moderately well, or moderately sorted. The samples of silty sand were poorly sorted. The coarsest sediments, i.e. sand were moderately well sorted. The sediment in suspension was either very well or well sorted (figure 4a). Based on the analysis of the grain-size parameters for the first sampling series (1994), it was found that sorting ($\sigma_i$) deteriorated with decreasing mean grain diameter ($M_z$), while both sorting and the mean grain diameter of fine-grained sediments showed a low level of differentiation. In the case of samples collected in 2016, an increase in grain diameter was associated with diminished sorting, while sorting of fine-grained sediments displayed a higher degree of differentiation. Similar findings were observed in the case of suspension samples (figure 4a); suspended sediments were very well sorted.

The skewness ($S_{sk}$) values for the samples collected in 1994 were only positive numbers, which shows that fine fractions had been transported to the sediment. The negative skewness values observed in the samples from 2016 were associated with a diminished level of sorting (figure 4b), the latter being connected to the transfer of fine and very fine silt fractions to the suspension. A larger share of these fractions was found in suspension in the vicinity of stations 1, 7, 12 and 14. Recent sediments characterized by positive skewness had formed during bedload transport or under conditions that were favorable for deposition, such as those occurring in the deepest areas of the Vistula Lagoon. It should be stressed that sediments with positive skewness values were well or moderately well sorted. The relationships between the parameters calculated for sediments are reflected by the corresponding relationships for suspension.
The analysis of kurtosis ($K_G$) values for the grain-size distributions (figure 4c) demonstrated that in sediments sampled in 1994 mesokurtic distributions were dominant, with some platykurtic and leptokurtic distributions also present, which represent sediments originating from the eastern part of the lagoon. Silty sand and some sandy silt sampled in 2016 displayed platykurtic distributions of grain sizes. Sediments with one dominant fraction, i.e. sand or silt had mesokurtic grain-size distributions. In the remaining part of the Vistula Lagoon, where sediments are characterized by the presence of one grain-size fraction, the kurtosis values were typical of leptokurtic distribution.

![Figure 4. Scatter diagrams of grain size parameters a) mean vs. sorting; b) sorting vs. skewness; c) mean vs. kurtosis](image)

Based on CM diagram [23, 24], it can be concluded that the analyzed sediment and suspension samples are grouped in Field VIII (only sediments sampled in 1994), Fields VI and VII (dominated by sediments and suspension collected in 2016), and Fields IV and V (figure 5).

![Figure 5. Location of samples on the C/M diagram](image)
Pelagic suspension had mainly been the source of sediments collected in 1994 (clayey silt and silt). As in the case of the dominant share of silt and sandy silt sampled in 2016, sandy silt had been deposited under low-turbulence conditions from suspension described as homogeneous, but characterized by differentiated grain-size parameters. Fractions suspended in the water column can be found in Fields VI and VII. Sand and silty sand are the only sedimentary materials assigned to Fields IV and V, respectively. The deposition of the aforementioned sediments occurred from the material transported by saltation and traction under high-turbulence conditions, or from a graded suspension containing small amounts of fractions < 0 phi that had accumulated due to traction under moderate-turbulence conditions.

5. Discussion
The results of conducted investigations allow the conclusion that the bottom sediments, collected from the same locations 22 years apart, differ. Based on the available report [5] and the cartographic study [6] of the Polish part of the Vistula Lagoon, it can be stated that clayey silt is the predominant type of bottom sediment (figure 2). Among the sediment samples collected in 2016 none has been classified as clayey silt. According to the commonly accepted Shepard’s classification system [22], that has also been used by the authors of the papers cited in the present study, clayey silt should contain at least 10% of clay fraction. The clay content in the samples analyzed in this study did not exceed 2% (figure 3). The clay fraction was not present in the suspension samples, which can be explained by clay flocculation and the occurrence of clay aggregates instead of clay particles.

Based on the analysis of the grain-size parameters, it can be concluded that the sedimentation conditions in the Vistula Lagoon have changed. In 2016, the observed lower share of clay fractions and fine-grained silt, and the higher share of coarse-grained silt were associated with the increase in mean grain diameter (figure 4a).

In the case of sediments sampled in 1994, a decrease in mean grain diameter was associated with the decreased degree of sediment sorting. On the other hand, coarse-grained sediments sampled in 2016 were well sorted, which is typical of direct deposition from suspension. The observed earlier dominant mode of sedimentation of poorly sorted material that had been transported in suspension was replaced, at least temporarily, by the processes of less differentiated dynamics, which depended on wave motion and affected the bottom. The resuspension of bottom sediments determines changes in the grain-size parameters of both sediments and suspension in the water column. Silt and sandy silt, which presently predominate in the lagoonal sediments, are well sorted. The suspension is also well sorted; the sorting of suspension occurs via resuspension. The unimodal grain-size distribution that predominates in the samples from 1994 may indicate stable sedimentation conditions. In the case of sandy sediments collected in 2016, the occurrence of multimodal grain-size distribution points to the variable dynamics of environmental conditions during sediment formation.

The analysis of skewness values for sediment samples collected in 1994 indicates a higher input of fine-grained fractions and lower dynamics of depositional environment. At present, we can rather observe the elimination of fine-grained fraction, i.e. fine and very fine silt (figure 4b) and thus, the enrichment of sediment with coarser fractions. This is an obvious indication of a trend toward the redeposition of bottom sediments. The values of kurtosis also prove that the environmental hydrodynamics has increased (figure 4c). The normal grain-size distribution and the presence of only one sediment fraction in the samples from 1994 prove that depositional environment at that time was stable and governed by rather homogeneous dynamics. In the eastern part of the Vistula Lagoon, which is deeper, the kurtosis values were lower than those typical of normal distributions. Such low kurtosis values characterize a depositional environment that is saturated with mineral material. The kurtosis values of samples collected in 2016 were frequently high, which can be related to a deficit of sedimentary material in the large part of the Vistula Lagoon. This assumption has also been indirectly
The characteristic changes in the lithology of sediments in the Vistula Lagoon have also been noted by Chechko [9] and Chubarenko et. al [25], who underlines that the biggest differences concern the areas, including those located in the Russian part of the lagoon, of the finest sediment occurrence, i.e. clayey silt. These smallest fractions have been replaced by coarser sediments. According to the author, shallow depth and wave motion are the determining factors that alter the sediment characteristics. Some recent studies confirm that, with the exception of the ice season [9], sedimentation is affected by sediment resuspension due to wind action and wave motion; the affected area ranges in size from 40 to 100% of the total surface area of the lagoon.

Based on the investigations conducted by the Institute of Hydro-Engineering of the Polish Academy of Sciences, it can be stated that the transport of bottom sediments in the Vistula Lagoon occurs when the near-bottom current velocity reaches 20 cm s\(^{-1}\), the wind velocity equals 20 m s\(^{-1}\), and the wave height is 1.2 m [20]. The average wave-generated orbital velocities in the near-bottom layer under strong wind conditions (30 m s\(^{-1}\)) can reach the values between 20 and 35 cm s\(^{-1}\), with the exception of sheltered areas close to the shoreline [19]. The near-bottom current velocities under extreme wind conditions, calculated for the purposes of hydrotechnical works, locally ranged from 60 to 80 cm s\(^{-1}\) [26]. Such velocities are sufficient to pick up the particles of sediment ranging in size from 0.03 to 0.7 mm, and from 0.007 to 4.0 mm, respectively, and transport them to suspension (based on [27]). The aforementioned particle sizes correspond to the sizes of particles of which the bottom sediments are composed. The winds of storm strength constitute over 25% of all winds recorded annually. Considering that the particles of bottom sediment remain in the water column for 41 hrs [28], it should be stated that the process of sediment resuspension is also associated with the high concentration of suspension in the water column [15]. According to Witek et al. [29], the process of resuspension almost doubles the sedimentation of suspension in the Vistula Lagoon. Research conducted by Chubarenko [30] indicate more intensive wind waves in the Vistula Lagoon in the future which will enhance processes of wind-wave resuspension and the coastal erosion and the contribution of the waves to the total water dynamic in lagoon.

6. Conclusions
Undoubtedly, the regulation of the tributary of the Vistula River at the turn of the 20th century has had a decisive effect on the characteristics of bottom sediments and their spatial distribution in the Vistula Lagoon. Recently, we can observe the effects of the performed river engineering. The distribution of sediment types in the lagoon is still determined by the water depth. The coarse-grain fractions are present in the shallowest and most hydrodynamically active areas of coastal zone, while fine material accumulates in deeper and less active areas. The conducted investigations indicate that sedimentary material originating from various sources does not form stable deposits on the bottom, while wind-generated wave motion causes its erosion and resuspension. As a result, recent processes of sedimentation are characterized by redistribution of sedimentary material within the basin’s boundary, with the accompanying flow of fine-grained material to the sea. The Polish part of the Vistula Lagoon confirmed by the analysis of averaged concentration of suspension in the surface layer that was performed on the samples from 1998–2014. The obtained results indicate a significant reduction in kurtosis at the beginning of the second decade of the 21st century in comparison to the values observed 10–15 years earlier. However, there is no clue whether the observed decrease in suspension concentration is temporary, or whether it marks a constant tendency [15]. The higher occurrence of platykurtic grain-size distribution in the coastal zone points to the fluctuating changes in the energy level of depositional environment. Such sedimentation conditions has been confirmed by the bimodal grain-size distribution of the aforementioned samples. In the case of fine-grained sediments, changes in their sedimentation conditions are perfectly visible in CM diagram (figure 5). The unobstructed sedimentation from pelagic suspension in the central part of the Vistula Lagoon has been replaced by the deposition of graded suspension under low-turbulence conditions.
has become a transit-type sedimentary basin. Presently, the sediment distribution indicates that the sediment sorting and grain-size differentiation occur in accordance with the hydrodynamic conditions resulting from wind-generated wave motion. Consequently, the biggest changes were observed in the areas previously covered with the finest sediments, i.e. clayey silt that are being replaced with the coarser fractions.

In the near future the planned investment, namely, the construction of a navigable canal cutting across the Polish part of Vistula Spit, will once again, change the characteristics of bottom sediments in the lagoon.

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