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Characteristics of morphodynamic conditions in the shallows of Puck Bay (southern Baltic Sea)

by

Ewa Szymczak[1,*], Maria Rucińska[2]

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[1]Division of Marine Geology, Faculty of Oceanography and Geography, Institute of Oceanography, University of Gdańsk, Al. M. Piłsudskiego 46, 81-378 Gdynia, Poland

[2]Division of Marine Geophysics, Faculty of Oceanography and Geography, Institute of Oceanography, University of Gdańsk, Al. M. Piłsudskiego 46, 81-378 Gdynia, Poland

* Corresponding author: ewa.szymczak@ug.edu.pl

Abstract

Puck Bay is an unusual and thus interesting coastal water region, as it combines two different environments – a lagoon and the sea. They differ from each other in their seabed morphology, salinity, dynamics and water exchange. Their common elements are the extensive shallows and the vicinity of the Hel Peninsula. The shallows of Puck Bay have developed at various stages of its evolution, which began several thousand years ago and continues to this day. They have been shaped by varying morphogenetic factors resulting from changes in sea level and accompanying evolution phases of sand barriers, e.g. washover fans, as well as the intensity and directions of sediment transport. At present, the shallows cover more than 35% of the seabed area and are influenced by hydrodynamic factors and availability of sediments. The study area was divided into five fields, taking into account morphological and genetic criteria as well as recent hydrodynamic conditions. This study provides an updated map with classification and distribution of surface sediments and describes grain size parameters for sediment samples collected in the selected fields. Based on a comprehensive assessment of grain size parameters, lithodynamic equilibrium zones were determined and areas of sediment deposition and redeposition were identified.

Key words: sediments, coastal shallows, sand barrier, grain size parameters, Puck Bay

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1. Introduction

In terms of nature, Puck Bay is a unique area in the Polish coastal zone. Its uniqueness results from, among other things, the course of geological processes accompanying the evolution of the bay, the variety of seabed forms (Rudowski & Tobolewski 1973; Kramarska et al. 1993, 1994, 1995; Tomczak 1995; Furmańczyk & Musielak 2015; Badyukova et al. 2017), as well as biodiversity, including in particular benthic organisms and underwater meadows (Opioła & Kruk-Dowgiałło 2009). For these reasons, Puck Bay is part of a landscape park and is included in the HELCOM and Natura 2000 network of Baltic Sea Protected Areas.

Puck Bay is a water region that connects the lagoonal and marine environments. The two parts differ in their seabed morphology, salinity, water exchange and hydrodynamic processes. The common feature of the two parts is the Hel Peninsula that shields the bay from the north, as well as the adjacent shallows. The lack of tides is one of the most important hydrodynamic factors affecting the transformation and the course of depositional processes both in the coastal areas and in the lagoonal environment. In the case of the Baltic Sea shore, where no tidal effects occur, these impacts mainly result from wave motion and wave-induced currents (Ostrowski 2004). The shallows of Puck Bay have been formed at various stages of its evolution, which began several thousand years ago and continues to this day. They have been shaped by varying morphogenetic factors resulting from relative sea-level changes during the Holocene and the accompanying evolution phases of sand barriers, including washover fans, as well as the intensity and directions of the sediment transport (Furmańczyk & Musielak 2015). At present, the shallows cover more than 1/3 of the Puck Bay seabed area. The spatial diversity of lithological types of sediments that build the described geomorphological forms has been affected by geological structure of eroded sections of the coastal zone, the processes leading to the formation of these forms, as well as the nature of transport and deposition of sediments.

The research carried out to date in this area has covered i.a. issues related to the genesis of the geomorphological forms (Rosa 1963; Rudowski & Tobolewski 1973; Rosa & Wypych 1980; Filipowicz 1982; Uścinowicz et al. 2004; Tomczak 1999, 2005; Jegliński 2009) and the general lithology of the surface sediments (Musielak 1984; Uścinowicz & Zachowicz 1992, 1994; Pikies & Jurowska 1994, 1995; Szymczak & Piekarek-Jankowska 2009).

Given the unique nature of the Puck Bay ecosystem, scientists turn their attention to sediments as an important environmental driver that determines the type of macrophyte vegetation and associated fauna (e.g. Węsławski et al. 2013; Snoeijs-Leijonmalm & Andrén 2017; Pniewski et al. 2018; Ziółkowska et al. 2018) as well as the location of geochemical processes (e.g. Bolałek et al. 1991; Brodecka-Goluch et al. 2019). To date, no detailed study on grain size distribution or lithodynamic interpretation of surface sediments of the shallows in Puck Bay has been carried out based on a large number of analyzed sediment samples. The Seagull Sandbar, the Bórzyńska Shoal and the Long Shoal are the least explored and described shallows.

The main objectives of the presented study were: (1) to provide insight into the characteristics of sediment distribution in the Puck Bay shallows based on an updated map of sediment types and (2) to determine the current state of geomorphological forms and their lithodynamics in the heterogeneous environment of this non-tidal semi-enclosed inland sea.

2. Study area

Puck Bay is located in the southern part of the Baltic Sea (Fig. 1) where the shore is composed of glacial deposits as well as recent fluvial and aeolian sediments. The bottom of Puck Bay is a morphological depression between a moraine plateau with an ice-marginal valley and a sand barrier – the Hel Peninsula. The bay is clearly divided across a partially submerged barrier – the Seagull Sandbar – into two areas with varied relief: the Inner Puck Bay, the

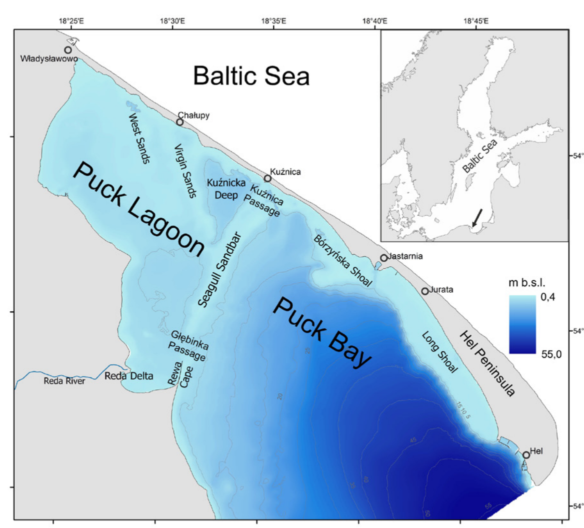

Figure 1
Location of the study area

so-called Puck Lagoon, and the Outer Puck Bay. The water exchange between the lagoon and the sea takes place through the Głębinka Passage and the Kuźnica Passage. The two parts differ in their evolution, seabed morphology, hydrodynamic processes and water exchange.

The evolution of the basin, currently occupied by the waters of Puck Bay, thus its inner part – the Puck Lagoon, was significantly influenced by the process of deglaciation as well as the Littorina transgression in the final phase of the Atlantic period (Furmańczyk & Musielak 2015). Before the deglaciation, the Puck Lagoon was developing in terrestrial conditions and was occupied by large lakes and peat bogs (Kramarska et al. 1993, 1994, 1995). As the Littorina transgression progressed, the surface area of lakes gradually increased, eventually transforming into a freshwater lagoon, separated from the open sea by the Hel Peninsula and the Seagull Sandbar raised above sea level. The bay took on a shape similar to the contemporary one at the turn of the Subboreal and Subatlantic periods, i.e. c. 2500 years ago (Witkowski & Witak 1993).

The inner part of the bay, i.e. the Puck Lagoon has an average depth of about 3 m and a maximum natural depth of 9.4 m in the Kuźnica Hollow and up to 13 m in post-dredging pits. Approximately 30% of the Puck Lagoon seabed is at a depth of up to 2 m (Nowacki 1993a). The depth in the area of the coastal shallows does not exceed 2–4 m. The shallows along the shores of the Hel Peninsula are transformed by numerous washover fans (Tomczak 1999). The Seagull Sandbar and the Rewa Cape, characterized by a varying length depending on sea level (Kubowicz-Grajewska et al. 2018), are the eastern limit of the Puck Lagoon. The outer part of Puck Bay is much deeper, with an average depth of about 20 m and a maximum depth of 54 m. The relief of the seabed in this part is less varied, but is distinguished by a significant variation in the inclination. In general, the seabed is inclined toward the north-east. The coastal shallows stretch along the Hel Peninsula, forming underwater "shelves" with a depth ranging from 0.5 m to about 4 m and a width of 1000–1200 m. The boundary of the shallows is clearly visible in the form of a sharp increase in the seabed inclination, which steeply descends to a depth of 40–50 m. The maximum slope of the seabed is located at the tip of the Hel Peninsula and ranges from 5 to 7° (average) to a maximum of 20° (Rucińska-Zjadacz & Rudowski 2009; Rucińska-Zjadacz & Wróblewski 2018). Although Puck Bay covers a relatively small area (359 km^2), it is a very diverse water region in terms of both seabed configuration and lithodynamic conditions.

For the purpose of the conducted research, five fields (Fig. 2) were selected based on the morphological criterion, taking into account the genesis and controlling factors. The coastal shallows of the tip of the Hel Peninsula (I) are an abrasion platform, within which no longshore sediment supply is observed except for the material supplied directly from the eroded seashore (Furmańczyk & Musielak, 2015). The Long Shoal and the Bórzyńska Shoal (II) stretch along the bayward shores of the Hel Peninsula from Hel to Kuźnica, forming underwater shelves up to 1200 m wide and 0.5–2 m deep. According to Tomczak (2005), the shallows were formed as a result of sea level rise and flooding in the coastal parts of the Hel Peninsula in the 10th century. The third field covers the shallows of the Puck Lagoon: Virgin Sands (III), Western Sands (III) and a strip of shallows stretching along the shore from Kuźnica to Władysławowo. The 6500 m long form of Virgin Sands is probably the preserved initial form of a sandy barrier with a surface area contemporary transformed by overwashes and the impact of brash ice (pack ice). The genesis of Western Sands is clearly related to overwashes (Tomczak 1999). An extensive strip of coastal shallows stretches between these geomorphological forms (Virgin and Western Sands) along the bayward shores, which are characterized by a flat and almost levelled bottom. The shallows border directly on the dune coast of the Hel Peninsula.

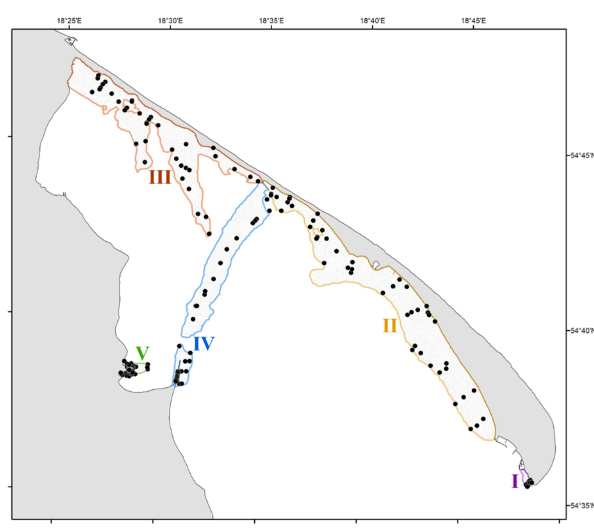

Figure 2

Location of the sampling sites and the surveyed fields (I–V, bounded by a 4 m isobath) in Puck Bay : I – Tip of the Hel Peninsula; II – Long Shoal and Bórzyńska Shoal; III – Virgin Sands and Western Sands; IV – Seagull Sandbar and Rewa Cape; V – Delta Reda

The shoals that form the boundary between the inner and outer parts of the Bay, i.e. the Seagull Sandbar and the Rewa Cape, represent a different hydrodynamic area. The Seagull Sandbar (IV) is a sandy barrier developed on an inundated depositional plain from sediments of a paleo-barrier that was subject to transformations and migration during the Littorina transgression (Rucińska-Zjadacz et al. 2009). The barrier is a stable form, adapted to the current hydrodynamic conditions (Kubowicz-Grajewska et al. 2018). The genesis of the Rewa Cape (IV) is connected with the convergence of two littoral cells (Rosa 1963; Rotnicki & Rotnicka 2010). This narrow sandy peninsula is an arrow-shaped spit (Leontiew et al. 1982). The fifth surveyed field – the Reda Delta (V) – is the youngest (just 200 years old) depositional form resulting from the relocation of the Reda River mouth (Jegliński 2009) and the bedload accumulation (Szymczak & Piekarek-Jankowska 2009).

The shore of the Inner Puck Bay is varied, with lowland sections associated with the presence of ice-marginal valleys and cliffs steeply dipping over the bay. The shallows are located on the lowland stretches of the shore and along the Hel Peninsula. These shores are partially protected by seawalls. Within the Puck Bay, artificial supply is provided near Puck and in the Kuźnica area (Zachowicz et al. 2007). In addition, in recent years, camping sites along the lagoon shores of the Hel Peninsula have been illegally extended toward the bay by destroying and backfilling reed beds with sand (Kubowicz-Grajewska 2021).

2.1. Surface sediments and hydrodynamical conditions

The complex process of the study area evolution has contributed to the diversity of surface sediments in Puck Bay, both in terms of lithology and genesis. Recent marine and lagoonal sediments occur here along with outcrops of older, genetically terrigenous, paludal-limnic sediments, often partially covered with a few centimeters of recent sediments (Musielak 1984; Jankowska 1993). In general, the relation between the increase in sediment dispersion and the depth is maintained. The grain size variation is high, ranging from clay fractions to pebbles and boulders. Gravel and coarse-grained sand, often with pebbles and boulders, occur along eroded sections of cliffs (Jankowska 1993; Uścinowicz & Zachowicz 1992, 1994). Medium-grained sands cover the Long and Bórzyńska shoals, the Seagull Sandbar, Virgin Sands, and locally the coastal areas of the Puck Lagoon along the shores of the Hel Peninsula and sites at the Rewa Cape (Jankowska 1993; Uścinowicz & Zachowicz 1992, 1994). Most of the Puck Lagoon is covered with lagoonal fine sands, which occur up to a depth of 10–15 m in the Outer Puck Bay. Lagoonal silt, sandy silt and silty sand are deposited in the depressions of the Puck Lagoon. In the Outer Puck Bay, sandy silt and silty sand occur on the slope of the seabed at depths exceeding 10–15 m. Marine silty clay and clayey silt occur at depths below 20–25 m (Uścinowicz & Zachowicz, 1992, 1994). The processes of intensive erosion of morainic plateaus (Zawadzka-Kahlau 1999), fluvial supply (Szymczak & Szmytkiewicz 2014), aeolian processes (Pęcherzewski 1994), and overwashes (Wróblewski 2009) are the main source of the clastic material.

Recent changes in sea level in Puck Bay depend primarily on the anemobaric situation over the Southern Baltic. Water-level rise in Puck Bay is induced by wind from SW through N to NE sectors, while wind from other sectors causes the water level to drop. Local winds have only a minor effect on water levels (Nowacki 1993b). Similarly to other parts of the Polish coast, winds from the western sector prevail (40–50%) in the study area, with a relatively significant contribution of winds from E to S sectors (30–40%), while winds from N, NE and E sectors are the least common (Cyberski & Szefler 1993). Due to the predominance of winds from the western sector, the water level in Puck Bay is most often sloping from east to west, hence the average water level in the Outer Puck Bay is 502.73 cm, while in the Puck Lagoon – over 2 cm lower (Dziadziuszko & Wróblewski 1990; Nowacki 1993b). Changes in water levels in the study area range from −0.95 to +1.65 m. The amplitude of extreme water levels in the study area reaches 2.60 m. The average annual sea level rise over more than a hundred years is 1.2 mm year^{-1} in the Gulf of Gdańsk (Rotnicki & Borówka 1991).

The seabed morphology and topographic features of the coastline contribute to the existence of different circulation systems in the inner and outer parts of Puck Bay, as well as at the boundary between the two parts and the associated geomorphological forms (Seagull Sandbar, Rewa Cape and the straits between them). Spatial systems of the currents follow the course of the shallows and the shoreline (Rotnicki & Rotnicka 2010). Average surface current velocities (0–5 m) are about 9 cm s^{-1} in the Outer Puck Bay and 4–5 cm s^{-1} in the Inner Puck Bay. In estuaries, currents can also be generated by stream flows, which are the strongest in the case of the Reda River. With the largest flows, the range of the Reda river stream is visible in the Głębinka Passage (Nowacki 1993b).

The Seagull Sandbar prevents free exchange of waters between the basins, hence most exchange takes place mainly through the Głębinka Passage and, to a lesser extent, through the Kuźnica Passage. Flows through the Głębinka Passage are mostly bidirectional. Maximum current velocities (50–80 cm·s^{-1}) were observed in these straits as a result of windstorm from the west (Nowacki 1993b). At sea levels above 520 cm, which occur several times a year, water exchange takes place throughout the cross-section of the Seagull Sandbar.

Wind is a generator of short-term waves that have not been sufficiently studied in this area. Few models and observations prove that average parameters of wind-generated waves in the inner part are much lower compared to the outer part of the bay. The reason for this is the difference in the seabed and shoreline configuration as well as the wind fetch. Consequently, the largest waves occur at the limit of the Gulf of Gdańsk, with winds from the east (Jarosz & Kowalewski 1993).

Differences related to the depth of individual parts of Puck Bay determine the course of the glacial phenomena. The water in the shallow, lagoonal part of the bay cools down faster throughout its entire mass, from the surface to the bottom, due to the low thermal capacity of this basin (Szefler 1993), hence ice in this area appears earlier and stays longer compared to the outer part where glacial phenomena occur mostly at the shore and in the shoal areas. Almost all forms of ice are observed. Solid ice is mainly found in the Puck Lagoon, covering the entire area of the bay. Ridged ice is observed on the shore along the Hel Peninsula. Brash ice barriers occur in the shallows and areas of small depths and can reach a height of up to 8 m (Stanisławczyk 2005; Dyrcz 2017). It is usually only at the end of winter when the solid ice cover breaks up. During strong winds, ice floes move on low and flat shores and the formation of ice hummocks and seabed erosion can be observed (Filipowicz 1982; Girjatowicz 2001, 2015). Changes on the sheltered Puck Bay shore are small and result mainly from ice scour in winter (Furmańczyk & Musielak 2015).

3. Materials and methods

The material for lithological analysis consisted of 312 surface sediment samples collected in the shallows of Puck Bay from a depth of up to 4 m (which constitutes the limit of these forms) using a Van Veen grab sampler (Fig. 2). All samples were collected during the summer seasons of 2011–2014. Samples were collected under moderate wind and wave conditions.

Sediment grain size analysis was carried out using the sieve method (Folk 1980). A standard sieve set with mesh diameters ranging from 4.0 mm (–2.0 phi) to 0.0625 mm (5.0 phi) was used in the analysis. Parameters of grain size distribution: mean grain size (M_Z), sorting (σ_G), skewness (S_K) and kurtosis (K_G) were calculated employing the logarithmic method of Folk and Ward (1957) and using the GRADISTAT software (Blott & Pye 2001).

Lithological characteristics of sediments were determined based on calculated grain size parameters. Morphodynamic conditions related to erosion, transport and accumulation were interpreted using a comprehensive assessment of parameters based on a pooled analysis of grain size anomalies. Standard deviation confidence intervals were determined separately for each surveyed field and divided into three subsets. The first subset contains values within the range of standard deviation from the median of the whole set. The two other subsets differ positively and negatively from the central subset (Table 1). The central set presents the effect of factors that are typical for a given environment and is considered to be in lithodynamic equilibrium. Lithodynamic ranks, indicating the intensity of redeposition and deposition processes or lithodynamic equilibrium, can be assigned to all parameters considered together and their interrelations. The dominance of symbols "0" in the code indicates a region typical for the surveyed area. If the code assumes the following configuration M_Z–, σ_I+, Sk_I–, K_G+, the region in question

Table 1

Anomalies of lithological parameters

Grain size parameters of rock debris (phi scale)	Anomalies of lithological parameters		
	confidence interval of the mean	positive anomalies	negative anomalies
mean grain size	0	D	R
sorting	0	R	D
skewness	0	D	R
kurtosis	0	R	D

0 – lithodynamic equilibrium, D – deposition, R – redeposition

is characterized by increased dynamic activity. The reduced dynamic activity of the environment is indicated by the code M_Z+, σ_I–, Sk_I+, K_G–. The main features of the lithodynamic interpretation are parameters M_Z and σ_I, because momentary and pulsatory changes in the environmental energy can cause the Sk_I and K_G parameters to deviate from the presented pattern. This method was proposed and used in the comprehensive morpholithodynamic interpretation in the Polish coastal zone by Baraniecki & Racinowski (1990) and Racinowski et al. (2001).

To reconstruct the dynamics of the depositional environment, the C/M diagram was also used (Passega & Byramjee 1969).

Based on the collected and processed data, maps of the spatial distribution of grain-size parameters and lithodynamic characteristics were prepared in ESRI ArcGIS 10 software.

4. Results

The sediments of the shallows are represented by sands of various fractions – from fine- to coarse-grained sands; also gravel is found locally (Fig. 3). The smallest variation in mean grain size was determined in the coastal shallows of the Hel Peninsula – from Władysławowo to the Long Shoal, where medium-grained and fine-grained sands occur. The median of mean grain size varies in a narrow range of 1.9–1.71 phi. At the tip of the Hel Peninsula (I), coarse to medium-grained sediments occur with a median of 0.96 phi. The barrier forms: the Seagull Sandbar and the Rewa Cape (IV), as well as the Reda Delta (V) are

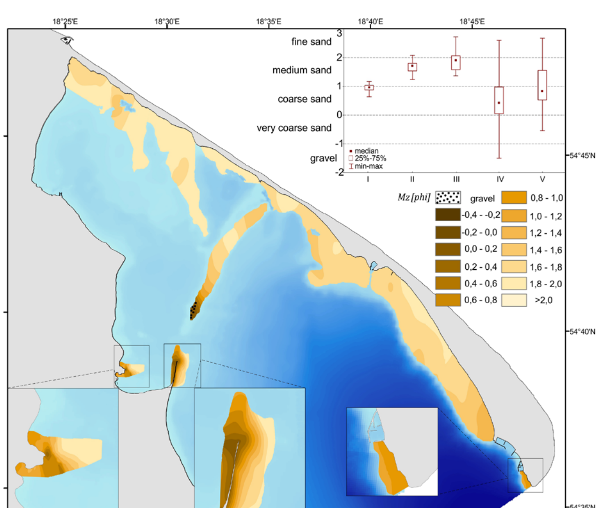

Figure 3

Spatial distribution of mean grain size M_z (in phi units)

characterized by greater variation in the mean grain size – from fine- to very coarse-grained sands with the presence of gravel fractions. The medians of their mean size are 0.43 phi and 0.83 phi, respectively.

Sorting of sediments in most of the study area, the coastal shallows in particular, is good and moderately good (Fig. 4). The median of standard deviation has the lowest value (0.43) in the Long Shoal and the Bórzyńska Shoal (II). In the other parts of the shallows, the median is 0.65. Sediments of the Hel Peninsula are mostly moderately well sorted (0.54); the value of this parameter indicates that very well-sorted sediments occur also at the tip of the Hel Peninsula (I). Sediments of the Seagull Sandbar and the Rewa Cape (IV) are moderately well sorted (0.83), similarly to sediments of the Reda Delta (V) (0.98). This applies primarily to the fractions of medium- and coarse-grained sands.

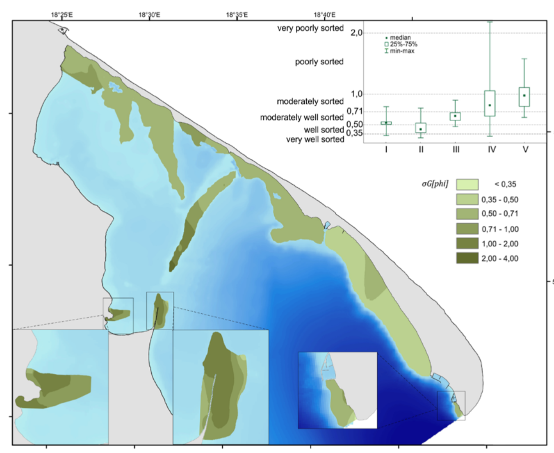

Figure 4

Spatial distribution of standard deviation σ_G (in phi units)

The skewness of grain-size distribution (S_K) along the Hel Peninsula (I) usually assumes values typical for symmetrical distribution. The median of this parameter in the study area ranges from −0.08 to 0.0 (Fig. 5). In the area of sediment enrichment with coarser gravel fractions, the skewness is slightly negative and the median assumes negative values (from −0.19 to −0.14). In the area of sediment enrichment with fine fractions (Long Shoal, Rewa Cape – IV at the outer part of Puck Bay, part of the Reda Delta – V), the skewness was slightly positive.

The kurtosis of sediments in the coastal shallows (Fig. 6) is in the range of 0.73–1.5, while in the other areas it varies from 0.54 to 2.39. Median kurtosis assumes similar values across the surveyed area in the range of 0.98–1.1. The lowest values of this parameter were determined in the shallows adjacent to Głębinka.

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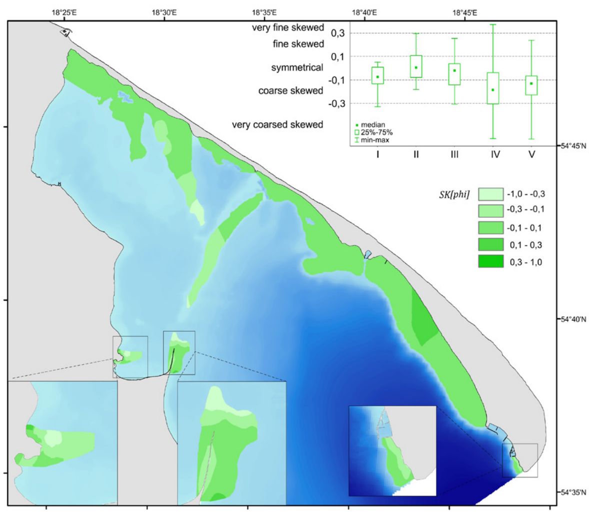

Figure 5

Spatial distribution of skewness S_K (in phi units)

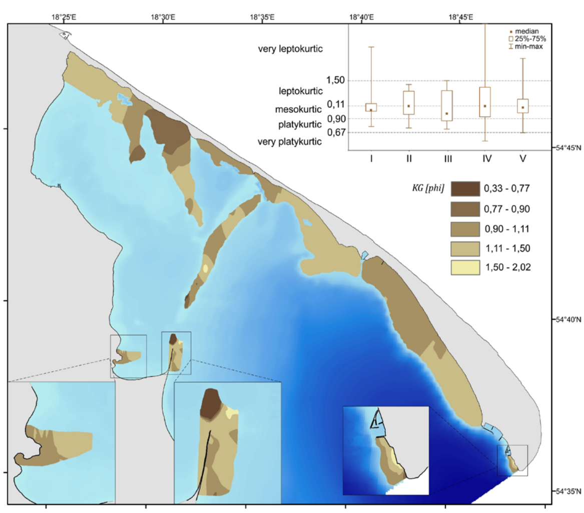

Figure 6

Spatial distribution of kurtosis K_G (in phi units)

The analysis of sediment samples collected in this area showed polymodal grain-size distributions.

The lithodynamic interpretation of the environment was carried out through the analysis of the relationships between all four parameters.

The vast majority of the grain size parameters of the analyzed samples from the coastal shoal zone are in the range of the median confidence interval, which indicates lithodynamic equilibrium between deposition and redeposition (Fig. 7). In the area of the Long and Bórzyńska shoals, deposition from suspension dominates (IV – 87%), while the content of grains deposited by traction is small (I – 13%; Table 2). Areas with deposition were locally identified. They are located in the area of Virgin Sands where deposition by traction (I – 45% and II – 11%) and by saltation (IV – 22%) as well as fractional suspension (V – 22%) occur. A similar pattern occurs in the coastal parts of the Long Shoal. The zone of redeposition is located near the shore of the Hel Peninsula. Coarse-grained sands in this area could have been deposited by traction (I – 89%), and medium-grained sands by saltation (IV – 11%).

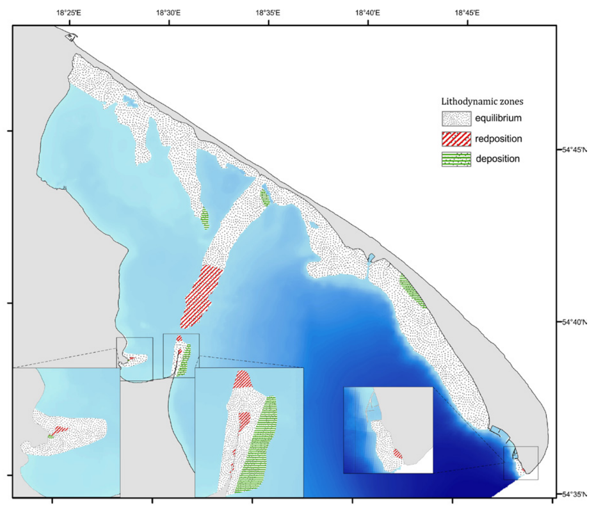

Figure 7

Lithodynamic characteristic of surface sediments

The situation is different in the areas of sandy barriers characterized by greater heterogeneity of lithodynamic conditions. In the northern part of the Seagull Sandbar, fractional deposition (V – 3%) and deposition by traction with a small amount of suspension occur (Table 2). The dominant part of the barrier, like the adjacent shoals in the north, is characterized by equilibrium. Deposition by traction (I – 84%) occurs in this part. Redeposition dominates in the southern part, closer to Głębinka Passage, hence deposition by traction is accompanied in this area by deposition by traction and saltation (IV – 3%; Table 2). Sediments from the closest proximity to the shore of the Rewa Cape as well as from the vicinity of Głębinka indicate the dominance of redeposition processes. As indicated by the values of the parameters characteristic of the lithodynamic equilibrium, the conditions stabilize with increasing depth (Fig. 7). Sediments in the lagoonal part were deposited by traction with a small contribution of suspension (I – 100%), while deposition by traction dominates in the outer part, closer to the shore (I and II – 60%), which with increasing depth is replaced by deposition from graded suspension transported in the conditions of high (IV – 33%) and moderate (V – 7%) turbulence (Table 2).

Table 2

Content of samples according to the types of depositional environments (Passega & Byramjee 1969)

Surveyed fields			Field in the C/M diagram (percentage of samples)			
			I	II	IV	V
I	Tip of Hel Peninsula		89	-	11	-
II	Long Shoal and Bórzyńska Shoal		13	-	87	-
III	Virgin Sands		45	11	22	22
	Western Sands		61	-	31	8
IV	Rewa Cape	inner part	100	-	-	-
		outer part	50	10	33	7
	Seagull Sandbar		84	3	10	3
V	Delta Reda		88	12	-	-

Due to different average median values adopted for each parameter of the grain size distribution, the lithodynamics in the Reda mouth was described only in relation to the parameters of sediments originating from this area. Deposition by traction with a small contribution of grains from suspension (I – 88% and II – 12%) takes place directly at the extension of the distribution channel; as the distance from the river mouth increases, the relation between redeposition and deposition is in equilibrium (stabilized). A redeposition zone was determined in the northern part of the Reda mouth (Fig. 7). These processes are conditioned by the dynamics of the water body rather than by the impact of the river current that moves towards Głębinka along with the bedload, resulting in a deficit of sediments in this area.

5. Discussion

The heterogeneous area of Puck Bay provides favorable conditions for research on factors determining the distribution and differentiation (lithodynamics) of sediments. Both the physical features of the bay and the lack of tidal effects contribute to the fact that the area is treated as a model water body.

The lagoonal part of the study area is characterized by the lithodynamic equilibrium determined by the absence of a source of sediment supply. The intensity of coastal erosion and aeolian processes is negligible, thus the accumulation rate of sediments is very slow (Uścinowicz & Zachowicz 1994). Low hydrodynamics does not cause erosion and washout. Poor dynamics of processes was also confirmed by the investigations of dredging pits located in the shallows along the Hel Peninsula in the Puck Lagoon (Fig. 1). They showed a minor mineral sedimentation of deposits that settled through the water column from suspended matter induced by dredging works. Sedimentary material in this area was also identified as originating from sliding down, cascading and creeping along the slope of a pit (Piekarek-Jankowska et al. 2009; Rudowski et al. 2009), thus confirming its low accumulation. Organic matter sedimentation occurs in this area, the source of which is the direct inflow from land and primary production (Graca & Burska 2009; Burska 2011). Habitats of phytobenthos (macrophytes) occurring on the seabed additionally reduce the shear stress at the sediment to lower levels compared to the non-vegetated bottom (Teeter et al. 2001). Seagrass beds slow down the water movement, damp waves, trap and hold sediments (Fonseca 1996). On the other hand, its fronds are fragile and easily destroyed by waves and sand traction (Węsławski 2009). The Virgin Sands are an exception in the southern part of the lagoon where deposition is noticeable and contains mainly fractions transported in suspension, as confirmed by the Passega diagram analysis.

The Long and Bórzyńska shoals are characterized by the lithodynamic equilibrium with balanced processes of accumulation and erosion (Fig. 7). Local and periodical erosion of the seashore and wave processes inducing redeposition of the material are potential sources of the material in this part (Uścinowicz & Zachowicz 1994). Deposition of moderately well-sorted 1.8–2 phi fractions was observed in the isolated fields (Fig. 3 and Fig. 4).

Due to the seabed morphology (underwater shelf), exposure to wave processes, the tip of the Hel Peninsula is characterized by higher hydrodynamics. Redeposition of the material is pronounced in the shallowest part of the field, with the rest of the field being in lithodynamic equilibrium. The energy of waves approaching the bay-facing shores of the Hel tip cannot dissipate due to the relief of the seabed at the tip. The edge of the coastal shoal along the western side of the tip is located about 500 m from the shore; it is a sharp edge between a steep slope and the shallow and levelled bottom of the shoal (Rucińska-Zjadacz 2015; Rucińska-Zjadacz & Rudowski 2015). Thus, the waves break close to the shore and only a small part of the energy is dissipated. Furthermore, most of the sediment supplied from the sea-facing shores reaches directly the deep bottom along the extension of the Hel Peninsula axis. All these factors, coupled with abrasion of the bay-facing shores, which are usually not reconstructed after storms due to sediment deficit, may cause "narrowing" of the distal end of the Hel Peninsula.

Water exchange, strong flows/currents in Głębinka (Matciak et al. 2011) prevent accumulation of sediments, hence sediments in the southern part of the Seagull Sandbar have features of redeposition. The lack of conditions conducive to sedimentation in this region was also evidenced by research conducted using sediment traps (Szymczak & Szmytkiewicz 2014). Due to the coastline configuration and seabed topography, the Seagull Sandbar is exposed to waves from the NW direction (common – 12%) and SE (very rare). The southern part of the barrier, within which wave transformation occurs, is the most exposed to these processes. The remaining part of the barrier is adapted to hydrodynamic conditions, hence the performed analysis indicates a lithodynamic equilibrium between the accumulation and erosion. During strong storms, occurring usually in autumn and winter, the exchange of waters takes place along the entire length of the Seagull Sandbar (Klekot 1980).

The Rewa Cape, adjacent to the Seagull Sandbar from the south, is a landform fed by longshore sediment transport (Uścinowicz & Zachowicz, 1992). Extreme storm events have the largest impact on the formation of this form (Kubowicz-Grajewska et al. 2018). The Rewa Cape is a stable form with a balance between erosion and accumulation processes. The lithodynamics in its northern part is significantly influenced by water exchange between the inner and outer part through the Głębinka Passage.

In the Reda Delta, the processes of deposition are a consequence of a constant and stable supply of sediments in the form of bedload, wash load and suspended load (Szymczak & Piekarek-Jankowska 2007). Rapid deposition of the material, conditioned by the reduced current and its poor differentiation at the extension of the distribution channels, was confirmed by values of the grain size parameters. They indicate weaker sorting and the presence of enrichment zones with fine and coarser fractions according to the sediment deposition pattern in the delta environment (Boggs 2006).

During harsh winters, especially in the Puck Lagoon, ice can freeze into sediment. Wind-induced ice movement can cause erosion of the seabed and sediment melting from ice floes.

6. Conclusions

The least diversified grain size distribution parameters were determined for the coastal shoals stretching along the bay-facing shores of the Hel Peninsula and the shallows located in the inner part of Puck Bay. Despite different hydrodynamic conditions, the seabed configuration differs only in the nature of sediment deposition, indicating slightly higher dynamics in the outer part. Wave processes have the greatest impact on the movement of sediments in the Long and Bórzyńska shoals, with the rarely occurring wind from the southern sector. Due to lagoonal conditions, the shoals in the northern part of the Puck Lagoon are exposed to wave processes to a limited extent. The preserved similarity of the lithological characteristics of sediments building this part of the study area (II, III and northern part IV) results primarily from the genesis of the forms and origin (source) of the material related to the development and evolution of the Hel Peninsula.

The largest differences in the grain size distribution parameters were determined for the southern part of the Seagull Sandbar, the Rewa Cape and the Reda Delta. These forms have been shaped by wave processes and available sediments originating from coastal abrasion and fluvial supplies. The mechanism of sediment differentiation clearly indicates zones with higher dynamics, not conducive to the accumulation of fine-grained sediments, resulting in the shift of particle-size distributions toward coarser fractions. Water exchange through the Głębinka Passage plays an important role in the sediment transport. The Reda Delta receives continuous supplies of bedload, which is distributed in the underwater part of the delta and is carried along with water currents to the Outer Puck Bay.

The research has shown that the sediments in most sections of the shallows of Puck Bay are not subject to transformations and are in the lithodynamic equilibrium.

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