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Indicators for the assessment of a degraded marine ecosystem as illustrated by the example of post-dredging pits in the Puck Bay

Wskaźniki oceny stanu zdegradowanego ekosystemu morskiego na przykładzie wyrobisk poczerpalnych w Zatoce Puckiej

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Abstract: Between 1989 and 1996, almost as much as 7 000 000 m3 of sand was excavated from the seabed of the Puck Bay for the purposes of protection of shores of the Hel Peninsula. Remnants of these activities are five pits of varied cubature and depth, exceeding natural depths by several times. All studies performed in the area of the pits so far have indicated that a permanent degradation of the environment has taken place at the sites. Between 2007 and 2008, complex yearly environmental studies were conducted in order to establish the bases and conditions for actions aiming at rehabilitation of the degraded areas of the Puck Bay. As a result, measurements and surveys of 58 parameters, both chemical and biological, were carried out. The aim of those analyses was to point to the parameters which, irrespective of the date of conducting the study, will enable the assessment of seabed degradation resulting from the dredging works carried out. For this purpose, Wilcoxon's test for dependent samples was used. 23 parameters used in statistical tests were studied throughout the whole year. The performed statistical analysis indicated that 7 out of the 23 analysed parameters meet the above-mentioned condition, and they may be used in the future in diagnosing the state of the environment affected by anthropogenic interference in seabed areas.

Keywords: indicators for the assessment of the state of the environment, post-dredging pits, Puck Bay

Streszczenie: W latach 1989–1996 z dna Zatoki Puckiej, na potrzeby ochrony brzegu Półwyspu Helskiego, wyczerpano prawie 7 000 000 m3 piasku. Pozostałością tych działań jest pięć wyrobisk o różnej kubaturze i głębokości, przekraczającej kilkukrotnie głębokości naturalne. Wszystkie dotychczasowe badania prowadzone w obrębie wyrobisk wskazują, że w tych miejscach doszło do trwałej degradacji środowiska. W latach 2007–2008 przeprowadzono kompleksowe, całoroczne badania środowiskowe, których celem było określenie podstaw i uwarunkowań przeprowadzenia działań rekultywacyjnych, zdegradowanych obszarów Zatoki Puckiej. W ich wyniku wykonano pomiary i badania 58 parametrów, zarówno chemicznych, jak i biologicznych. Celem niniejszych analiz było wskazanie takich parametrów, które niezależnie od czasu prowadzenia badań, pozwolą określić degradację dna morskiego, wynikającą z przeprowadzonych prac czerpalnych. W tym celu użyto testu Wilcoxona dla par zależnych. Do testów statystycznych wykorzystano 23 parametry, które były badane przez cały rok. Przeprowadzona analiza statystyczna wykazała, że 7 spośród 23 analizowanych parametrów spełnia wskazany wyżej warunek i mogą być one wykorzystane w przyszłości do diagnozowania stanu środowiska, po antropogenicznej ingerencji w obszarach dna morskiego.

Słowa kluczowe: wskaźniki oceny stanu środowiska, wyrobiska poczerpalne, Zatoka Pucka

INTRODUCTION

Dredging works in the Puck Bay performed from 1989 to 1996 were dictated by the need to obtain substantial amounts of sand to protect the Hel Peninsula against breakage due to destructive activities of the sea. The consequence was emergence of post-dredging pits, the total area of which amounts to 105 ha, and which - even many years after termination of dredging works - are still characterized by unfavourable environmental conditions. On the one hand, there was a need to prevent the damage done by the forces of nature (protection against destruction and reconstruction of the sea shore of the Hel Peninsula), but on the other hand, it has led to the occurrence of vast and obstinate changes in the Bay.

In the course of works connected with shore protection which were carried out at various intensity and with use of dredged material from the seaward side of the Hel Peninsula, a total of 8 520 000 m3 of sand was used for reinforcement, 6 980 000 m3out of which was obtained from the Puck Bay [20]. In the area of the Puck Bay, there appeared five post-dredging pits, the names of which stem from the names of towns on the Hel Peninsula (Władysławowo, Chałupy, Kuźnica II, Kuźnica I and Jastarnia), and with varied cubature and depth [33] (Figure 1/).

Dredging and silting works in the area of the Puck Bay and the Hel Peninsula did not have any durable protective effects on the seaward side of the peninsula, yet they led to obstinate changes (pits) in the coastal zone of the Puck Bay.

The decision on how to extract sand may be seen as a sectoral policy decision, and thus, an example of a one-dimensional approach in the management of the Puck Bay. It was reduced to the role of a reservoir of material used in shoreline replenishment, without recognizing it as an important, multidimensional, and complex ecosystem which fulfils numerous functions – both natural ones, and those serving other purposes, including broader economic aims (i.e. fishing, tourism, shipping) .

In case of the dredging works carried out in the northern part of the Puck Bay, management was limited to the very extraction process. It primarily consisted of setting new sites for obtaining sand, and direct control over the dredging and silting works. Despite the appearance of information on possible adverse effects on the environment of the Puck Bay [6, 8, 11], and even on the need to take corrective measures aimed at limiting the negative impact of the carried out dredging works [5, 7, 12, 15, 16, 17, 19], no activities were undertaken for this purpose in that period. It was not until there appeared results of multiannual environmental studies, especially the ones obtained for the purposes of development of a program on reclamation of the degraded seabed areas [26], that the attitude changed towards the acceptance of the decision to recognize the caused environmental damage and, as a consequence, to undertake corrective measures [31]. The activities performed so far, however, have not indicated which of the studied parameters may serve in the future as indicators of seabed degradation. The programme for reclamation of the dredged pits in the Puck Bay was based on multidisciplinary, full-year environmental research. In the future, due to financial, organizational, and time limits, it may be difficult or even plainly impossible to perform such extensive studies. Hence the need to point out the minimum scope of tests on the basis of which it will be possible to assess the poor state of the studied environment.

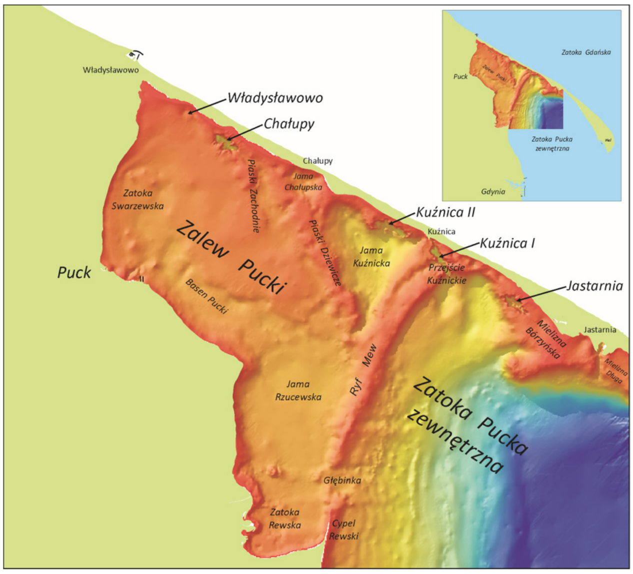

Fig 1. Location of post-dredging pits in the Puck Bay.

The aim of this paper was to find an effective method for diagnosing negative changes for the natural communities in seabed areas at the sites where dredging works are performed. It was assumed that statistical analysis of parameters investigated in years 2007 – 2008 in all research stations will bring out the stations and parameters which, irrespective of the date of performing the test, will indicate degradation of the seabed area.

MATERALS AND METHODS

The basis for statistical analyses consisted of results of environmental studies performed in all five dredged sites in the Puck Bay in different seasons between 2007 and 2008. Altogether, there were 58 parameters analysed with regard to the chemistry of seabed sediments, interstitial and near-bottom water, microbiology of seabed sediments and near-bottom water, as well as macrozoobenthos and phytobenthos. The tests were carried out at a total of 45 stations, which were situated in the vicinity of dredged pits, including 15 stations located within the dredged pits [30]. The total sample collection and all laboratory analyses were performed within the framework of the research – development project no. R14 042 03 funded by the Ministry of Science and Higher Education, and implemented by the Maritime Institute in Gdańsk [4, 22, 25, 30, 32].

In all of the five studied pits, the samples were taken from three sources: seabed sediments, interstitial water, and near-bottom

Tab. I. Results of Wilcoxon's test for pairs of observations (values of probability of making error of the first type, p<0.05 are marked orange).

NO.	PARAMETER PAIRS OF VARIABLES	SEASON			
		AUTUMN	WINTER	SPRING	SUMMER
1.	CHLOROPHYLL-A IN SEDIMENTS				
	RS – EDGE	0.892	0.345	0.892	0.500
	RS – SLOPE	0.345	0.138	0.079	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
2.	PHAEOPHYTIN IN SEDIMENTS				
	RS – EDGE	0.138	0.043	0.892	0.043
	RS – SLOPE	0.043	0.043	0.079	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
3.	ORGANIC CARBON IN SEDIMENTS				
	RS – EDGE	0.500	0.138	0.500	0.138
	RS – SLOPE	0.043	0.043	0.079	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
4.	TOTAL NITROGEN IN SEDIMENTS				
	RS – EDGE	0.043	0.685	0.500	0.138
	RS – SLOPE	0.043	0.079	0.138	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
5.	MOISTURE IN SEDIMENTS				
	RS – EDGE	0.043	0.177	0.224	0.079
	RS – SLOPE	0.043	0.043	0.043	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
6.	ORGANIC MATTER (LOI) IN SEDIMENTS				
	RS – EDGE	0.079	0.715	0.500	0.079
	RS – SLOPE	0.043	0.067	0.108	0.079
	RS – BOTTOM	0.043	0.043	0.043	0.043
7.	TOTAL PHOSPHORUS IN SEDIMENTs				
	RS – EDGE	0.079	0.500	0.079	0.345
	RS – SLOPE	0.079	0.892	0.043	0.043
	RS – BOTTOM	0.043	0.043	0.043	0.043
8.	PH IN SEDIMENTS				
	RS – EDGE	0.685	0.345	0.685	0.892
	RS – SLOPE	0.345	0.500	0.345	0.685
	RS – BOTTOM	0.685	0.345	0.224	0.224
9.	EH IN SEDIMENTS				
	RS – EDGE	0.500	0.345	0.685	0.500
	RS – SLOPE	0.685	0.138	0.079	0.685
	RS – BOTTOM	0.500	0.043	0.043	0.224
10.	MINERAL PHOSPHORUS IN SEDIMENTS				
	RS – EDGE	0.345	0.589	0.345	0.892
	RS – SLOPE	0.715	0.224	0.500	0.138
	RS – BOTTOM	0.079	0.043	0.043	0.067
11.	HYDROGEN SULPHIDE IN INTERSTITIAL WATER				
	RS – EDGE	0.685	0.654	0.043	0.345
	RS – SLOPE	0.685	0.179	0.345	0.500
	RS – BOTTOM	0.715	0.108	0.500	0.224

12.	**SULPHATES IN INTERSTITIAL WATER**				
	RS – EDGE	0.043	0.043	0.465	0.685
	RS – SLOPE	0.043	0.043	0.465	0.685
	RS – BOTTOM	0.043	0.043	0.465	0.685
13.	**NITRITES IN INTERSTITIAL WATER**				
	RS – EDGE	0.345	0.067	0.273	0.892
	RS – SLOPE	0.224	0.067	0.273	0.500
	RS – BOTTOM	0.079	0.043	0.067	0.079
14.	**NITRATES IN INTERSTITIAL WATER**				
	RS – EDGE	0.043	0.500	0.144	–
	RS – SLOPE	0.224	0.345	0.144	–
	RS – BOTTOM	0.043	0.685	0.144	–
15.	**PHOSPHATES IN INTERSTITIAL WATER**				
	RS – EDGE	0.043	0.224	0.144	0.500
	RS – SLOPE	0.043	0.043	0.465	0.043
	RS – BOTTOM	0.079	0.043	0.465	0.079
16.	**AMMONIA IN INTERSTITIAL WATER**				
	RS – EDGE	0.345	0.043	0.144	0.138
	RS – SLOPE	0.079	0.500	1.000	0.079
	RS – BOTTOM	0.500	0.500	0.144	0.079
17.	**OXYGEN IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.138	0.685	0.224	0.892
	RS – SLOPE	0.043	0.500	0.138	0.500
	RS – BOTTOM	0.043	0.079	0.079	0.500
18.	**HYDROGEN SULPHIDE IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.273	–	–	–
	RS – SLOPE	0.465	–	–	0.285
	RS – BOTTOM	0.079	–	0.108	–
19.	**SULPHATES IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.043	0.224	0.685	0.500
	RS – SLOPE	0.043	0.067	0.685	0.418
	RS – BOTTOM	0.043	0.043	0.500	0.079
20.	**NITRITES IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.285	0.892	0.715	0.715
	RS – SLOPE	0.892	0.715	0.138	0.465
	RS – BOTTOM	0.108	0.345	1.000	0.201
21.	**NITRATES IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.043	0.144	0.892	0.685
	RS – SLOPE	0.079	0.285	0.500	0.345
	RS – BOTTOM	0.079	0.144	0.892	0.345
22.	**PHOSPHATES IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.043	0.892	0.345	0.715
	RS – SLOPE	0.043	0.892	0.892	0.224
	RS – BOTTOM	0.138	0.685	0.345	0.144
23.	**AMMONIA IN NEAR-BOTTOM WATER**				
	RS – EDGE	0.079	0.043	0.079	0.043
	RS – SLOPE	0.685	0.079	0.500	0.224
	RS – BOTTOM	0.345	0.043	0.138	0.224

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water. All samples were collected simultaneously at the profiles starting on the edge of the pit (EDGE), in the middle part of the slope (SLOPE), and on the bottom of the pit by the slope (BOTTOM). For the purposes of these analyses, one station located closest to the station on the pit's edge was chosen out of several sampling stations located around a given pit, and it was treated as a reference station (hereinafter: RS) for this pit.

The basic assumption for the choice of optimal parameters for the assessment of environmental degradation in the area of the dredged pits was: the analysed parameter should display a statistically valid variation between the values in the reference area (RS) and degraded areas (EDGE, SLOPE, BOTTOM) irrespective of the date of sample collection. Out of all the the studied parameters, only chemical parameters were analysed in all four seasons (chlorophyll-a, phaeophytin, organic carbon, total nitrogen, moisture, organic matter (LOI), total phosphorus, pH, Eh and mineral phosphorus in sediments; hydrogen sulphide, sulphates, nitrites, nitrates, phosphates and ammonia in interstitial water; oxygen, hydrogen sulphide, sulphates, nitrites, nitrates, phosphates and ammonia in near-bottom water). The remaining ones were tested in two seasons: microbiological parameters were tested in the autumn and spring, while the biological ones were analysed in the autumn and summer. Hence, in order to find parameters that would best describe degraded conditions of the environment irrespective of the date of sampling, the 23 parameters that had been analysed in all four seasons were subjected to further analyses.

Values of the analysed parameters in the reference areas of particular pits varied. On this ground, it was assumed that variation of these parameters between the areas of the seabed in particular pits does not reflect solely the degree of their degradation, but it is, to a certain extent, determined by local conditions or natural variability. Having this in mind, to eliminate the impact of the analysed parameter's variability between the pits on the results of statistical analyses, values of the analysed parameter in the (SR) area and in particular parts of the pits (EDGE, SLOPE, BOTTOM) obtained for each of the pits were considered to be associated (or dependent) variables. Statistical significance of the differences in distribution of values of the studied variables was analysed with use of Wilcoxon's signed-rank test, which is a non-parametric alternative to Student's t-test for associated variables. The null hypothesis assuming there are no differences in the distribution of values of an analysed parameter between the (SR) area and the particular parts of the pits (EDGE, SLOPE, BOTTOM) was verified at a 0.05 significance level vis-a-vis the alternative hypothesis assuming the existence of differences (two-tailed test). In statistical calculations, the STATISTICA 6.0 program package was used.

RESULTS

In Table I/, results of the Wilcoxon's test for dependent samples are presented for parameters where regardless of the season, statistically valid differences between the reference area and particular parts of the pit occurred.

Table I. Results of Wilcoxon's test for pairs of observations (values of probability of making error of the first type, $p<0.05$ are marked orange).

Out of the 23 analysed parameters, seven exhibit, irrespective of the season, statistically valid differences between the reference and the degraded area within a pit, i.e. content of: chlorophyll-a, phaeophytin, organic carbon, nitrogen, total phosphorus, organic matter and sediment moisture in sediments. In case of the RS–BOTTOM observation pairs, the differences occurred in every season and in all of the seven parameters. Moreover, such differences were noted in every season for moisture in sediments on the pit's slope (RS–SLOPE). In three cases, namely that of total nitrogen and moisture in sediments in the autumn, and phaeophytion in the summer, regardless of the place from which the samples were taken within the area of a pit, there occurred valid statistical differences.

In the remaining cases, valid statistical differences occurred irregularly, both in the context of the season and the place. Only sulphates and phosphates in interstitial water and sulphates in near-bottom water in the autumn season, irrespective of the place, exhibited valid differences. In the case of sulphates in interstitial water, such a situation also occurred during the winter season. In the other seasons, however, such differences occurred irregularly. In case of three parameters, namely pH in sediments, and content of hydrogen sulphide and nitrites in near-bottom water, no statistically valid differences could be observed for any pair of variables.

DISCUSSION OF RESULTS

Activities connected with the extraction of aggregates from the seabed have been carried out for many decades now, and all over the world. Seabed sediments are extracted and transported for several essential reasons:

- necessary maintenance of parameters of navigational shipping routes, especially waterways to ports and harbours,
- construction of new waterways,
- acquisition of aggregates for economic ends,
- acquisition of sand for protection of seashores against erosion.

In the United States, solely because of the necessary maintenance of shipping routes, there are over 300 million cubic yards extracted every year (over 230 000 000 m3) [9]. In Europe (the north-eastern Atlantic Ocean, the North, Baltic, Greenland and Norwegian Seas), over 53 000 000 m3 of sands and gravel is obtained every year from licensed areas [1].

What is more, on the Polish marine areas there occur aggregate resources which can be extracted. In three locations – southern part of the Central Bank (Ławica Środkowa), the Slupsk Bank

(Ławica Słupsk) and the Koszalin Bay (Zatoka Koszalińska), a total of 159 300 000 m3 of sand and gravel was potentially identified for extraction. There also exist smaller accumulations of sand, where the extracted material is primarily used in the protection of seashores (to the north of the Rozewie Cape, to the north-east of Jastarnia, to the east of Władysławowo, to the north of Dziwnów). Altogether, 16 500 000 m3 of sand was identified in these locations (ibidem). There are also other places from where aggregates may possibly be extracted, e.g. The Oder Bank (Ławica Odrzana) in the Pomeranian Bay.

In each case, agitation and relocation of seabed sediments constitutes a serious interference in the environment both at the time of the very dredging, and long after that. Directly at the site of sand and gravel extraction, animal and plant organisms living on the seabed are destroyed [2, 3, 14, 21].

Another effect of dredging works are changes in seabed topography, including overdeepenings, which – depending on location, size, shape, and relative depth – may constitute an additional, lasting cause of negative interference into marine environment. The interference may be considered at many levels: geomorphological, hydrological, physical, chemical, and biological. It may be particularly noticeable in the immediate vicinity of the seashore, including bay and estuary areas. All over the world, such regions provide examples of numerous, often mutually exclusive activities being implemented at one site, which may be a result of their economic exploitation on the one hand, and the necessity to preserve their natural qualities on the other. Hence the need to manage those areas by looking for compromises and continually trying to reconcile different business matters and values. Nowadays, institutions managing the areas try to balance out the varied services provided by the ecosystem as they are switching from sector-specific management model to management based on the ecosystem approach [29]. To meet these ends, scenarios taking into account interests of various social groups are drawn, also ones based on a balanced use of natural resources.

A significant element of decision-making in the management of bay and estuary areas is knowledge on the environmental state. The information may be obtained with the use of an adequate set of indicators.

Ecological indicators are employed in environmental assessment, in detection of warning signals for changes in the environment, and in diagnosis of occurring environmental problems. Perfectly adjusted indicators should contain information on the structure, functioning, and elements of an ecological system. Hence, ecological indicators should be able to capture the ecological complexity, and yet remain simple enough to be easily and continuously monitored. Ecological indicators should meet the following criteria:

- be relatively easily measurable, including being relatively inexpensive,
- be sensitive to tensions in the ecosystem,
- react to stress in a predictable manner,
- be pre-emptive, i.e. point out dangers of the occurrence of changes in the ecosystem,
- point out the changes which may be avoided if adequate actions are taken,
- be integrative, i.e. encompass the full range of the ecosystem's basic parameters,
- show familiar reactions to interferences, anthropogenic tensions, and take into account the changes occurring over time,
- be unambiguous, i.e. leave as little doubt as possible while being interpreted [13].

According to Kuuppo et al. [27], there are not many single indicators which meet all of the above-mentioned criteria, and it is necessary to use sets of indicators which together can comprehend all the requirements.

The problem of pointing out the most significant variables in environmental studies is mentioned in numerous publications [10, 23, 24, 28, 34, 35]. All of them were aimed at limiting the number of variables analysed during complex, time-consuming and expensive environmental studies without a loss of important information on the studied ecosystems of lakes and water bodies. King et al. [24] were investigating links between epiphytic groups of algae and 17 environmental variables basing on 17 lakes with diverse trophic states situated in Lake District in England. As a result of using statistical analyses (the canonical analysis CCA), it was stated that two of the analysed variables, i.e. concentrations of total phosphorus and calcium are what determines the distribution of the studied species of algae. Strobl et al. [34] used artificial neural networks to achieve similar objectives. They had at their disposal as many as 110 parameters describing East Lake in the USA. After a preliminary selection, 60 parameters were subjected to further analyses, 6 out of which were next chosen on the basis of a simulation of various neural networks as the ones which are probably of greatest significance in the determination of the trophic state of lakes, and thus influencing classification of lakes with respect to their eutrophication.

In case of the dredged pits in the Puck Bay, to assess degradation of the environment resulting from the implementation of dredging works, irrespective of the time-frame for the performance of tests, 7 out of 23 analysed parameters may be indicated as ones which always exhibit significant differences between the area of the pit's bottom, and reference area unaffected in the course of works carried out. Among them, the greatest number of pairs of variables in case of which statistically valid differences were noted belongs to moisture in sediments. When it comes to moisture, also on the pits' slopes, irrespective of the analysed period of time, there occurred significant statistical differences. While analysing particular pits in separation, Graca and Burska [22] also pointed moisture out as a parameter that changes most often between the pits and their neighbouring areas. The other parameters may be considered a good indicator of seabed degradation, irrespective of the analyses' time-frame, but only in case of samples being taken at the bottom of the pits.

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SUMMARY AND CONCLUSIONS

Over the period of 2007 – 2008, complex environmental studies were carried out at all five dredged pits. On their basis, specified clearly was the need to take remedial actions aimed at improvement of the state of environment in the northern part of the Puck Bay. Bearing in mind the dredging works to be performed in the future, the possibility of diagnosing the state of environment at dredging sites with use of fewer parameters should be considered an important element of managing both the reclamation process of the already existing pits, and sand extraction form new areas. Out of 23 parameters, 7 may be used for this purpose, irrespective of the time-frames of research performance, namely: content of chlorophyll-a, phaeophytin, organic carbon, nitrogen, total phosphorus, organic matter and sediment moisture in sediments. The best places for the samples to be collected are the bottoms of the pits.

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