INDEX COPERNICUS
INTERNATIONAL

ORIGINAL ARTICLE

Bulletin of the Maritime Institute in Gdańsk

Preliminary results of monitoring studies on macrophytes in the area of brine discharge from the creation of gas storage caverns (Puck Bay, Baltic)

Wstępne wyniki badań monitoringowych makrofitów w rejonie zrzutu solanki powstałej w wyniku budowy kawern do przechowywania gazu (Zatoka Pucka, Bałtyk)

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Article history: Received: 08.01.2017 Accepted: 24.03.2017 Published: 05.05.2017

Abstract: The coastal zone of the Puck Bay (near Mechelinki cottage), in the area protected within the Natura 2000 network (Puck Bay and Hel Peninsula PLH 220032), is subjected to the influence of two media – wastewaters discharged through a collector of the sewage treatment plant in Dębogórze and brine effluent discharged through a pipeline because of construction of the underground gas storage – UGS Kosakowo. The results of the monitoring studies in 2009, 2012, and 2015 showed that, after 40 years, macrophytes were again noted in the area (in 2012 and 2015). They occur in small amounts, but slightly increase their bottom coverage. It indicates the improvement of the environment state being under pressure of two media and points indirectly to the fact that environmentally friendly technical solutions were applied for discharge of the effluents.

Keywords: brine, environmental impact, macrophytes, Baltic

Streszczenie: Strefa przybrzeżna Zatoki Puckiej (w rejonie Mechelinek), położona w obszarze Zatoka Pucka i Półwysep Helski PLH 220032 chronionym w sieci Natura 2000, znajduje się pod wpływem oddziaływania dwóch mediów – ścieków zrzucanych głębokowodnym kolektorem z oczyszczalni ścieków w Dębogórzu oraz solanki zrzucanej podmorskim rurociągiem jako efekt budowy podziemnego magazynu gazu – PMG Kosakowo. Wyniki uzyskane w trakcie badań monitoringowych w latach 2009, 2012 i 2015 wykazały, że po około 40 latach braku występowania makrofitów w tym rejonie, od 2012 roku zaczęto notować makrofity zakorzenione w dnie. Występują one w niewielkiej ilości, ale nieznacznie powiększa się zasięg ich występowania. Obserwowane zjawisko wskazuje na poprawę stanu środowiska w rejonie będącym pod presją dwóch mediów oraz pośrednio, że zastosowano dobre dla środowiska rozwiązania techniczne do odprowadzania obu zrzutów.

Słowa kluczowe: solanka, oddziaływanie, makrofity, Bałtyk

Introduction

Description of the investment

Building of gas underground storage facilities – caverns in the Kosakowo district, by salt body leaching is the second investment of that kind in Poland. However, for the first time, brine (hypersaline effluent) is being discharged to the marine environment of the Puck Bay (Mechelinki cottage) – the area protected within the Natura 2000 network, Puck – Bay, and Hel Peninsula PLH 220032 [29]. Technology applied to discharge the brine is a pipeline with a system of diffusers – a solution never used in the area of the Baltic Sea.

The pipeline for brine discharge into the Puck Bay was built in 2009, 2.3 km away from the coastline, ended with diffusers at 8 m depth. The investment began operation in January 2012, when brine oxygenation reached 9 ml·dm^{-3} and salt concentration was of 250 kg·m^{-3}, which corresponds to salinity between 180 and 218. According to the administrative decision issued by the Pomeranian Governor [39], increase of the water salinity in the near field of the diffusers (up to 200 m away) could not exceed 0.5 [29]. The value specified by the authority is within the range of natural fluctuations of salinity in the Puck Bay, ±2 [15, 30, 35].

In the area of brine discharge, pre-investment monitoring studies were carried out in 2009, and monitoring of the operation phase was conducted in 2012 and 2015. The survey covered abiotic and biotic elements of the environment, including macrophytes. Assessment of the impact of brine discharge on the environment was influenced by an additional factor – the discharge of waste waters from the Sewage Treatment Plant Group (STPG) "Dębogórze." The municipal waste waters have been discharged to the Puck Bay since 1964 with a coastal outlet that, in December 2009, was rebuilt into a deep-water pipeline ending with a diffuser. The diffuser was situated about 425 meters from the brine diffusers. Treated waste waters are used for building caverns (lixiviation of salt deposits) and are discharged into the Puck Bay in the amount of 10-fold greater than the brine per day (assuming the maximum discharge of both effluents).

Monitoring studies of brine discharge into the Puck Bay was conducted by the Maritime Institute in Gdańsk, on the commission of the Gas Storage Poland Ltd. (formerly Investgas SA, later Operator Systemu Magazynowania Ltd.).

Impacts on macrophytes

Macrophytes form a community of large, at least several millimetres high, plants. They include rooted vascular plants (Angiospermae) and macroalgae (Phycophyta), which either attach themselves to the hard surface of stones and mussels or float freely in the near-bottom water layer (so called „algal mats"). Macrophytes are classified as bio-indicators, organisms sensitive to changes in environmental conditions, including salinity [2, 16, 19, 37, 45].

Most studies on environmental impact associated with brine discharge into the marine environment are large and related exclusively to the operation of desalination plants, built mainly in the Southern Europe, North Africa, and the Middle East [14, 32]. The severity of the environmental effects, or lack thereof, vary widely, depending on: a) the hydrogeological nature of the marine body (bathymetry, depth, tides, waves, currents); b) the nature of the concentrate and to what degree it is diluted and dispersed; c) the biological sensitivity of the species [9, 14].

Contrary to the literature related to brine discharge effects associated with seawater desalination, no published material was found on the effects on macrophytes associated with the discharge of brine produced by lixiviation of salt deposits. The desalination process produces brine, which is essentially concentrated seawater, eventually containing additional substances, e.g., anti-scale additives and biocides [47]. No such additives are in the brine resulting from salt deposit lixiviation in Kosakowo [33]. Therefore, a potential environmental effect can be exerted mainly due to an increase in the ambient salinity.

Ecological studies on impact of brine from desalination plants on macrophytes, largely seagrasses, are scarce and have found variable effects, ranging from no significant impacts on seagrasses to widespread alterations of community structure in seagrasses, especially when discharges are released in poorly flushed areas. Usually, environmental effects appeared to be limited to within 10s of meters of outfalls [42]. Much of the laboratory and field research focused on seagrasses *Posidonia oceanica* (Linnaeus) Delile – a stenohaline species endemic to Mediterranean Sea, and *Cymodocea nodosa* (Ucria) Ascherson – a common species in the Mediterranean Sea and the Eastern Atlantic (average salinity 38). Monitoring of *P. oceanica* adjacent to plant outfalls revealed lower vitality of the species, exhibited by low shoot abundance, a significant reduction in leaf size, an overload of epiphytes, and some alterations in the physiology of plants compared to unaffected homologous areas [11, 43]. Gacia et al. [12] observed reduced growth and presence of necrotic tissue in seagrass in the area affected by brine, but no extensive meadow decline. Studies conducted in Canary Island showed the discharge from the desalination plant was associated with the disappearance of the seagrass *C. nodosa*, in areas near the outfall; farther away, the grass was present but in poor condition, but at even farther distances, it was in good condition [38]. Garrote-Moreno et al. [13] confirmed the high sensitivity of *C. nodosa*, which near the brine discharge showed lower growth, higher mortality (at least at the locality submitted to a higher salinity), and higher percentage of horizontal shoots as opposed to plants far from the brine discharge. It must be emphasised that the abovementioned studies were conducted where pipelines were devoid of diffusers and produced brine reached salinity between 44-90. Salinity increase was higher than 0.5 above average salinity in the area up to 4 km from the discharge.

Considering the obtained results, it can be concluded there is a potential impact of brine effluent from gas storage caverns on macrophytes in the vicinity of discharge into the Puck Bay. The objective of the paper was to assess the state of macrophytes in the area of brine outfall based on monitoring data gathered in 2012 and 2015 regarding the results of data from pre-investment monitoring studies in 2009 and earlier ones. Wastewaters form the STPG "Dębogórze" near the brine outlet were also considered as a factor potentially affecting macrophytes.

Material and methods

Study area

Study area is located in the Puck Bay, specifically in its southern part, called the Outer Puck Bay (Fig. 1). The sea bottom is

BMI, 2017; 32(1): 50-57 DOI: 10.5604/01.3001.0009.7976 www.bullmaritimeinstitute.com

of a relatively undifferentiated surface covered with medium and coarse sands. The Outer Puck Bay, including the study area, is under strong influence of marine waters – from the Gulf of Gdańsk, and freshwaters – mostly from the Vistula River. The salinity varies during the year, on average 7.5 [15, 30, 35, 36]. Study area is characterized by the lowest water transparency in the Puck Bay [36], and elevated, compared to a deeper part of the Puck Bay, concentrations of nutrients permanently discharged from land sources, mainly from the wastewaters from STPG "Dębogórze" and Reda River [27]. In 2009-2012, the sewage treatment plant "Dębogórze" discharged treated municipal wastewaters in the amount of about 50 000 $m^3 \cdot 24h^{-1}$ [1, 6-8]. The average pollution loads discharged with sewages during 10 months in 2012 are presented in Table I.

Tab. I The average loads and concentrations of pollutants in wastewaters discharged by a deep-water pipeline from STPG „Dębogórze" to the Outer Puck Bay in period from 1 January to 31 October 2012 (according to the Water Supply and Sewerage Company in Gdynia).

AMOUNT OF SEWAGE ($m^3 \cdot 24h^{-1}$)	46 904
COD (Chemical Oxygen Demand)	
concentration ($mg \cdot dm^{-3}$)	23.22
load ($mg \cdot 24h^{-1}$)	1.089
BOD (Biochemical Oxygen Demand)	
concentration ($mg \cdot dm^{-3}$)	0.55
load ($mg \cdot 24h^{-1}$)	0.026
Suspended organic matter	
concentration ($mg \cdot dm^{-3}$)	2.389
load ($mg \cdot 24h^{-1}$)	0.112
Total nitrogen	
concentration ($mg \cdot dm^{-3}$)	7.53
load ($mg \cdot 24h^{-1}$)	0.353
Ammonium nitrogen	
concentration ($mg \cdot dm^{-3}$)	0.54
load ($mg \cdot 24h^{-1}$)	0.025
Nitrates	
concentration ($mg \cdot dm^{-3}$)	5.55
load ($mg \cdot 24h^{-1}$)	0.260
Total phosphorous	
concentration ($mg \cdot dm^{-3}$)	0.6
load ($mg \cdot 24h^{-1}$)	0.028

Sampling

Monitoring studies of macrophytes started in 2009 (June), *i.e.*, before constructing the offshore pipeline in 2010. Then, every three years, operational monitoring was performed, *i.e.*, in 2012 (June, July, August) and 2015 (June and September). Grid of 12 sampling stations was placed within the area of the potential propagation of brine [30] (Figure 1). These stations were in a depth range of 4-13 m, at a distance of 0.1-4 km from the diffusers.

Field studies were performed by a diver, who took underwater photos, assessed percentage cover of plants at the station (area of 20 m^2), and then collected samples of macrophytes for taxonomic analyses.

To assess the state of macrophytes in the area of brine discharge, only data on plants rooted in the bottom were used, while the general floristic description of the study area was based on data regarding all macrophytes: rooted in the sea bed and ones deposited on the bottom or attached to mussels. Plants unattached to the bottom have mobile nature, i.e., are moved with the currents and, therefore, are not good indicators for assessing the impact of various types of pressure on macrophytes.

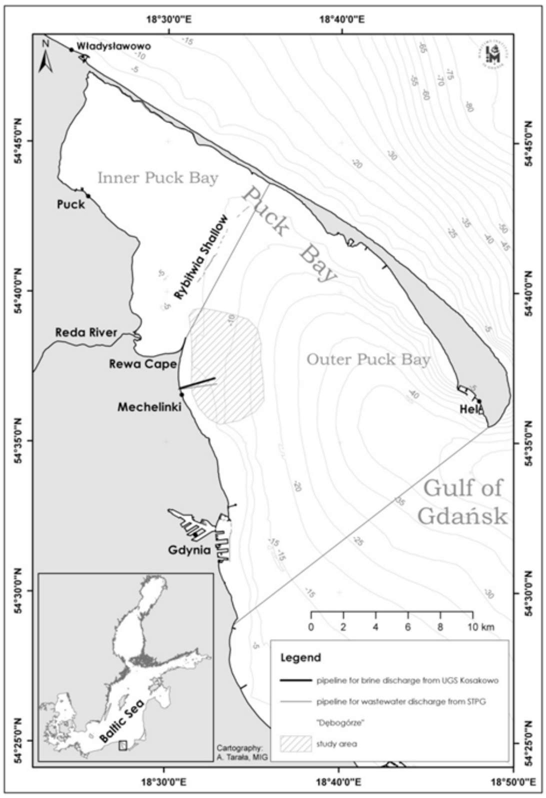

Fig. 1. Area of monitoring studies of macrophytes.

Results

The monitoring studies performed in the area of brine discharge showed presence of 31 taxa of macrophytes: rooted plants and macroalgae loosely-lying on the bottom or attached to single specimens of mussels living on the sandy bottom (Table II).

In the study area, macrophytes unattached to the bottom strongly dominated. They were deposited on sandy bottom as "algal mats" / single patches of filamentous brown algae *Pylaiella littoralis* and *Ectocarpus siliculosus* or as remains of plants, both macroalgae and vascular. Also, macroalgae growing on small aggregations of *Mytilus trossulus* Gould or single shells of *Mya arenaria* L. were observed. In 2009, unattached vegetation was found in the area at 29% of the stations, located to the north side from the brine pipeline, at 4-9 m. In 2012 and 2015, it occurred throughout the whole study area at all stations (Figure 2).

Plants rooted in the sea bed were observed for the first time in 2012 (Table III, Figure 3). Single specimens of three species of vascular plants: *Potamogeton pectinatus*, *Zannichellia palustris*, and *Zostera marina*, were recorded at two stations located to the north from the pipeline: station 4 at a distance of 1.4 km (4 m) and station 1 – at a distance of 4 km (5 m). Leaves of *P. pectinatus* were overgrown with epiphytes of *Ceramium*. Studies in 2015 confirmed the presence of *P. pectinatus* and *Z. palustris* on the abovementioned stations; however, at station 4, *Z. palustris* increased bottom coverage and formed a small patch with single specimens of *P. pectinatus*. Specimen of *Z. palustris* was noted at station 10 – 2.1 km to the south from the pipeline (8 m).

Discussion

The earliest studies on macrophytes in the coastal area of Mechelinki were conducted in 1885 [31]. Later, several investigations were carried out in coastal waters from Mechelinki to Rewa Cape. In the 1950s and in the late 1960s, it was reported that unattached macroalgae, such as *Fucus vesiculosus* L. and *Furcellaria lumbricalis*, and underwater meadows, mostly *Zannichellia palustris*, occurred to 10 m depth [5, 17, 18, 40]. Launching the operation of wastewater coastal discharge from STPG "Dębogórze" in 1964 affected the macrophytes. Until 1994, wastewaters were treated only mechanically. In the 1970s, macroalgae and meadows of *Z. palustris* were no longer observed in the area (Kruk-Dowgiałło unpublished data). Absence of rooted macrophytes was also confirmed in the 1990s [20, 22-24].

The latest data on macrophytes in the study area derives from surveys conducted at the beginning of the XXI century, when unattached macroalgae were observed – "algal mats" deposited on the sea bed [21] and beach-casted specimens [46]. Monitoring studies in 2009, 2012, and 2015 confirmed their presence in the area of brine discharge. Comparison of the taxonomic composition of the unattached macrophytes identified at the beginning of the XXI century indicates the random nature of their occurrence. Number of taxa recorded in the period 2003-2015 [21, 46, present studies] ranged from 7 to 22. Such a diverse plant material is carried out from different marine regions, not only from the Puck Bay (e.g., Orłowo Cliff), but also from distant open waters (Słupsk Bank), due to the changeable water currents in the Gulf of Gdańsk [4, 26]. Species diversity of unattached macrophytes in the area of brine discharge is constantly changing over the time.

Monitoring studies showed presence not only of unattached macrophytes, but also of macrophytes rooted in the seabed (Table II). These plants occurred in a shallow zone, corresponding to vegetation depth limit in the Gulf of Gdańsk – 8 m [20, 34]. Below this depth – at stations at 11-14 m depth – there were only

Tab. II. List of macrophytes noted during monitoring studies (* the only species in the area rooted in the sandy bottom).

	2009	2012	2015
CHLORPOPHYTA			
Chaetomorpha linum (O.F.Müller) Kützing	●		
Cladophora glomerata (L.) Kützing		●	●
Spirogyra sp.		●	
Ulva sp.		●	●
Ulva clathrata (Roth) C. Agardh	●	●	
Ulva compressa L.		●	●
Ulva intestinalis L.		●	
Ulva cf. lactuca L.			●
Ulva prolifera O.F.Müller			●
CHAROPHYTA			
Chara sp.		●	
Chara baltica A. Bruzelius		●	
Tolypella nidifica (O.F.Müller) Leonhardi		●	
OCHROPHYTA			
Desmarestia viridis (O.F.Müller) J.V.Lamouroux			●
Ectocarpus siliculosus (Dillwyn) Lyngbye		●	●
Pylaiella littoralis (L.) Kjellman	●	●	●
RHODOPHYTA			
Acrochaetium sp.			●
Aglaothamnion sp.			●
Aglaothamnion tenuissimum (Bonnemaison) Feldmann-Mazoyer			●
Ceramium sp.		●	●
Ceramium diaphanum (Lightfoot) Roth		●	
Ceramium tenuicorne (Kützing) Waern			●
Furcellaria lumbricalis (Hudson) J.V.Lamouroux			●
Polysiphonia cf. elongata (Hudson) Sprengel			●
Polysiphonia fucoides (Hudson) Greville	●	●	●
Rhodomela confervoides (Hudson) P.C.Silva		●	●
ANIGIOSPERMAE			
Ceratophyllum demersum L.		●	●
Myriophyllum spicatum L.		●	●
Potamogeton pectinatus L.*	●	●	●
Potamogeton sp.	●		
Zannichellia palustris L.*	●	●	●
Zostera marina L.*		●	●
Sum	7	20	22

Tab. III. The average coverage of macrophytes rooted in the sea bottom in the area of brine discharge.

	2009	2012	2015
Potamogeton pectinatus L.	0%	0.5%	1%
Zannichellia palustris L.	0%	0.5%	1.5%
Zostera marina L.	0%	0.5%	0 %

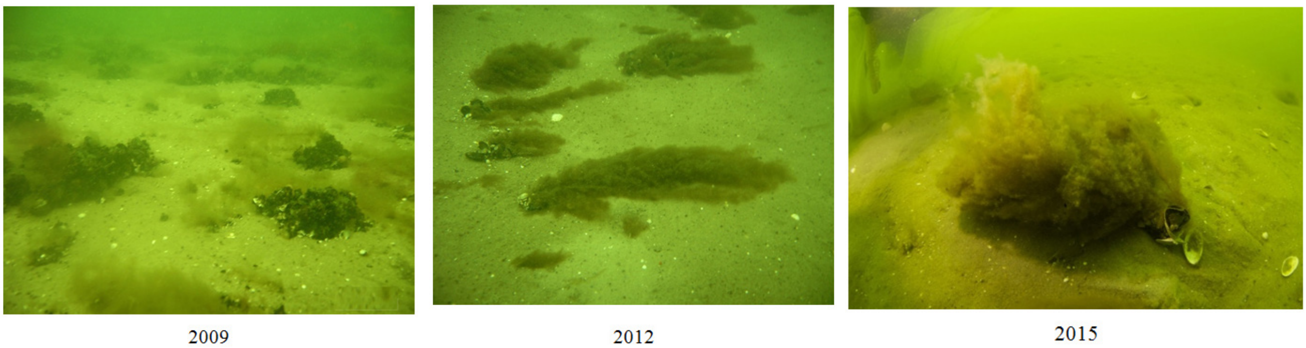

Fig. 2. Macrophytes unattached to the bottom (mainly filamentous brown algae) in the study area in 2009-2015.

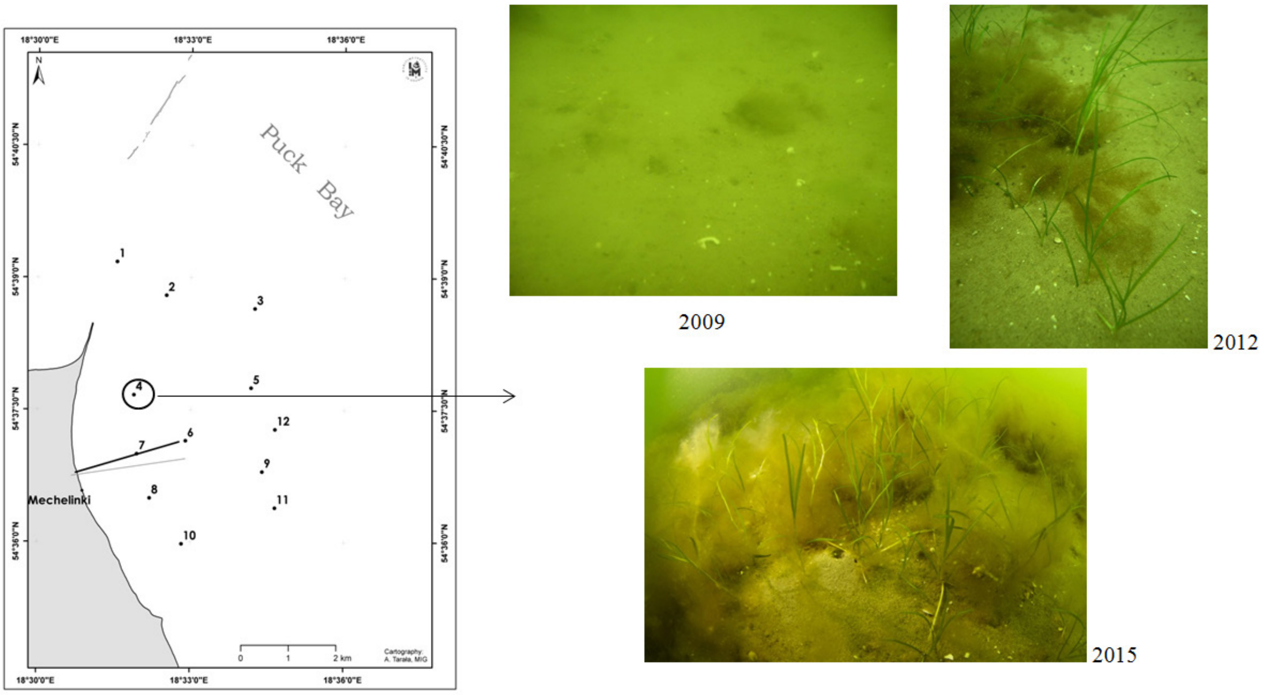

Fig. 3. Succession of rooted macrophytes at station 4 in 2009-2015.

significant organic matter deposits with the remains of plants. In the area of these stations, there are unfavourable environmental conditions to the development of flora. Investigations by Kruk-Dowgiałło [28] showed that surface sediments are subjected to the influence of sewage matter, being deposited in the area permanently, regardless of the seasons. Poor conditions for plant growth are enhanced by low water transparency. Monitoring studies in 2009, 2012, and 2015 year revealed that water transparency within a year ranged from 3.9 to 6.8 m, what is generally typical for that area in the Puck Bay [36].

Among the macrophytes rooted in the sea bed, *Zannichellia palustris* and *Potamogeton pectinatus* occurred (Table II). These plants are characterized by a wide ecological amplitude. They are classified as euryhaline species, *i.e.*, those that tolerate a broad range of salinity. They are commonly present in the coastal waters of the Baltic Sea [10], in the areas of low and higher salinity (e.g. Estonia – 1.3, Denmark – 27) [44]. They are typical of eutrophic waters [44, 48]. In favourable conditions, they reach high abundance, occupy vast areas, and form dense underwater meadows. Both *Z. palustris* and *P. pectinatus* are commonly observed in the highly eutrophicated water bodies in Poland: in the Puck Bay, where natural annual fluctuations of salinity do not exceed 2 [20, 25], and in the Vistula Lagoon, near the river mouths, where salinity drops to 0.8 [3].

Results obtained during monitoring studies showed that rooted macrophytes slightly enlarge their bottom coverage (Table III). In 2009, macrophytes were absent in the area, while three years later, single specimens of species rooted in the bottom were recorded. Results from 2015 suggest that rooted macrophytes increase their range of occurrence in the area of brine discharge. For the first time since the monitoring studies in 2009, a small meadow of *Z. palustris* was noted in 2012 (station 4). This confirms the assumptions taken by Kruk-Dowgiałło et al. [28] about the beginning of succession of macrophytes in the area. Presumably, the factor initiating and stimulating the process is the improvement of the sediment conditions in the area, especially their oxygenation. It could be a consequence of discharging well-saturated brine to the environment and the modernization of the pipeline for wastewater discharge from the STPG "Dębogórze" in 2009 (moving pipeline outlet away from the shore and greater dilution of wastewaters by installing a diffuser at the outlet). Studies conducted in 2003 and 2004 [21] showed that in the area of STPG "Dębogórze" coastal outlet, at depth 1-6 m, the quality of sediment was very poor. There was intensive mineralization and decomposition of organic matter, pH below 7 (acidification of sediments) and reduced redox potential, even below 0 mV at 6 m. Sediments contained high concentrations of phosphorus and nitrogen compounds, which indicated a high potential of secondary eutrophication and high content of organic matter, mostly of allochtonic origin. Monitoring carried out in 2012 in the area of brine discharge showed improved quality of sediments at depths <10 m, compared to conditions in 2009. A decrease in average organic carbon content and the redox potential above 100 mV at each station was recorded [28].

The fact the discharge from STPG "Dębogórze" affects the waters of the Outer Puck Bay and is the main source of nutrients in the area is shown by the elevated concentrations of phosphorus and nitrogen compounds in the area of the collector outlet, with maximum concentrations near the outlet. In 2003 and 2004, the highest concentrations of nitrogen compounds were within the range 380-420 $\mu mol \cdot dm^{-3}$ near the outlet, while in the further field, the concentrations were significantly lower, 40-70 $\mu mol \cdot dm^{-3}$. For phosphorus compounds, maximum concentrations ranged between 5 and 16 $\mu mol \cdot dm^{-3}$ and in the further field only 0.3-0.4 $\mu mol \cdot dm^{-3}$ [21]. Higher concentrations of nutrients near the outlet were confirmed during baseline studies performed in 2008, *i.e.*, before building offshore pipeline for wastewater discharge from STPG "Dębogórze" [46] and during monitoring studies regarding brine discharge in 2009 and 2012 [27, 28]. It indicates that the area is constantly subjected to strong eutrophication pressure, resulting mainly from discharge of sewage from the STPG "Dębogórze". During monitoring studies in 2012 and in 2015, no effect of brine or sewage discharge on the temperature of water in the study area was observed [28, 36].

Monitoring of hydrological parameters in the area of brine discharge, conducted in 2009, 2012, and 2015 showed the water salinity in the study area fluctuates around 7 and rarely exceeds deviation ±2 [36]. The results are similar to values recorded in the last decades in the Outer Puck Bay [15, 30, 35]. Additional salinity measurements conducted constantly from 2010 to 2012, showed that slight salinity increase resulting from brine discharge occurs at the bottom in the near field of the diffusers (up to 200 m away) and ranges between 0.12 and 0.49 [41]. It is in accordance with the decision issued by the Pomeranian Governor [39], which states that the increase of the water salinity in the near field of the diffusers could not exceed 0.5. Therefore, at this stage of the environmental monitoring studies, it can be assumed that no negative impact of brine discharge, regarding salinity on macrophytes, is generated.

Future monitoring studies will provide information whether the succession of macrophytes in the coastal area of Mechelinki, degraded in the 1970s, is progressing. However, it is necessary to monitor the abiotic factors of the environment that are crucial for developing macrophytes, such as chemical properties of sediments (organic matter load, redox potential), to identify the factors driving growth of macrophytes in the area.

Conclusions

Monitoring studies of macrophytes conducted in 2009, 2012 and 2015 in the area of brine discharge in the Puck Bay have shown the following:

- Macrophytes unattached to the sea bed dominate and are the characteristic element of the area. They are transported with the water currents from other parts of the Puck Bay and offshore waters.
- In 2012, after about 40 years, rooted macrophytes were recorded for the first time in the area. They occurred in small amounts, however slightly increased their in bottom coverage, probably because of the improvement of aerobic conditions in the sediments.
- The presence of rooted macrophytes, after 40 years of their absence near the discharge of two media – brine and treated wastewaters – suggests indirectly that the environmentally friendly technology for discharges was employed.

Acknowledgements

The authors are grateful to Anna Tarała for producing maps and to two anonymous reviewers for precious comments and suggestions that improved the manuscript.

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Word count: 3300 Page count: 8 Tables: 3 Figures: 3 References: 48

Scientific Disciplines: Life Science

DOI: 10.5604/01.3001.0009.7976

Full-text PDF: http://bullmaritimeinstitute.com/resources/html/articlesList?issueId=9519

Cite this article as: Brzeska-Roszczyk P., Kruk-Dowgiałło L.: Preliminary results of monitoring studies on macrophytes in the area of brine discharge from the creation of gas storage caverns (Puck Bay, Baltic): BMI, 2017; 32(1): 50-57

Competing interests: The authors declare that they have no competing interests.

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