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Deep sea habitats in the chemical warfare dumping areas of the Baltic Sea

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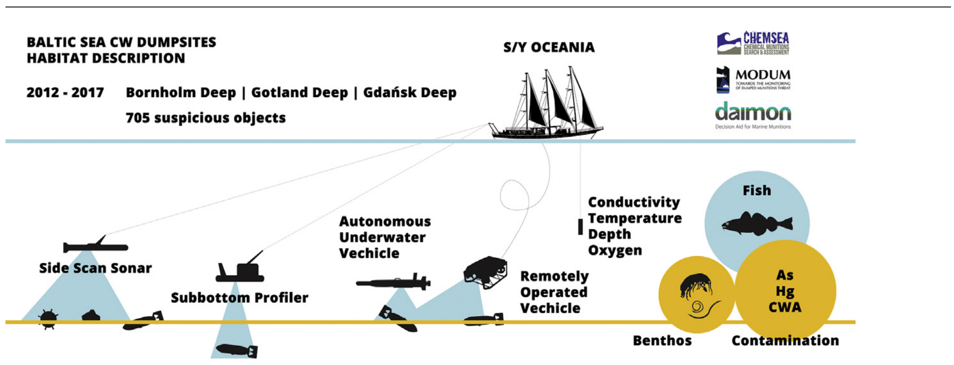
HIGHLIGHTS

- Habitats in three Baltic Sea Chemical Warfare dumpsites were described as Deep-Sea Muddy Sands.
- All investigated basins belong to so-called "benthic-deserts".
- Multidisciplinary studies have been performed.
- Dumpsites were investigated before, during and after a Major Baltic Inflow event.
- Temporary Return of benthic macrofauna was observed in one basin.

GRAPHICAL ABSTRACT



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ABSTRACT

The Baltic Sea is a severely disturbed marine ecosystem that has previously been used as a dumping ground for Chemical Warfare Agents (CW). The presence of unexploded underwater ordnance is an additional risk factor for offshore activities and an environmental risk for the natural resources of the sea. In this paper, the focus is on descriptions of the marine habitat based on the observations arising from studies linked to the CHEMSEA, MODUM and DAIMON projects. Investigated areas of Bornholm, Gotland and Gdańsk Deeps are similarly affected by the Baltic Sea eutrophication, however, at depths greater than 70 m several differences in local hydrological regimes and pore-water heavy metal concentrations between those basins were observed. During the lifespan of presented studies, we were able to observe the effects of Major Baltic Inflow, that started in December 2014, on local biota and their habitats, especially in the Bornholm Deep area. Reappearance of several meiofauna taxa and one macrofauna specimen was observed approximately one year after this phenomenon, however it's ecological effects already disappeared in March 2017. According to our findings and to the EUNIS Habitat Classification, the three reviewed areas should be characterized as Deep Sea Muddy Sands, while the presence of suspicious bomb-like objects both beneath and on top of the sediments confirms their CW dumpsite status.

1. Introduction

Underwater unexploded ordnance is now recognized to pose serious threats to the marine environment and its users (Greenberg et al., 2016). This is a very different attitude compared to that of the mid-20th century, when sea-dumping was a common practice (Elmgren, 2001). Oceans and seas were believed to be a limitless and safe place to dispose of unused munitions until the London Convention in 1972. Sea-dumping operations took place worldwide at all depths and both conventional and chemical warfare (CW) materials were submerged (Edwards and Bełdowski, 2016; Greenberg et al., 2016). The combination of

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administrative, political and military issues left the dumpsites unmonitored for many decades (Knobloch et al., 2013). Ongoing natural processes together with offshore activities such as fishery have significantly expanded the areas of potential exposure (Sanderson et al., 2009). Not only do the munitions contain explosives and toxic agents, but they are also considered as a source of heavy metals and metalloids, mainly arsenic, to the environment (Bełdowski et al., 2016b). Every dumping area is characterized by a different set of environmental parameters and various types or quantities of disposed warfare material. Site-specific risk assessments should be performed on a case-by-case basis.

Covering a surface area of 415,000 km^2, the Baltic Sea is relatively shallow, with an average depth of 52 m. It was formed during the last glaciation and the present level of salinity stabilized 2000 years ago, becoming one of the largest brackish ecosystems in the world. Salinity values in the Baltic Sea range between 1 and 20 PSU, with an average of 7 PSU. This young ecosystem provides multiple natural services for a large human population living in the catchment area, while being highly sensitive to many forms of human impact (Elmgren, 2001).

Numerous reports and reviews including Knobloch et al. (2013), Bełdowski et al. (2016a) and Greenberg et al. (2016) indicate that soon after the end of World War II, the Baltic Sea began to be used as a dumpsite for at least 40,000 tons of chemical warfare agents (CWA). The toxic loads accounted for up to 15,000 tons, 80% of it which was mustard gas (Knobloch et al., 2013). It was during the pioneering MERCW project - Modelling of Ecological Risks Related to Sea-Dumped Chemical Weapons (http://mercw.org) - when the existence of submerged munitions in the Bornholm Deep area was confirmed. It has resulted in first scientific observations of several completely corroded casings (Missiaen et al., 2010) and allowed researchers to indicate potential site-specific hazards related to the CWA presence in the sediments (Sanderson et al., 2010). In subsequent CHEMSEA project - Chemical Munitions, Search and Assessment (www.chemsea.eu) - both CWA and their degradation products were detected in pore-water and sediments detected in roughly 40% of cases (Bełdowski et al., 2016a) thanks to the newly-developed methods (Popiel et al., 2014). Also, first indications of adverse effects on Baltic Fish were reported (Bełdowski et al., 2016a). Follow-on work under the MODUM project - Towards the Monitoring of Dumped Munitions Threat (http://www.iopan.gda.pl/MODUM) - focused on creation of monitoring network and assessing the environmental risk of CWAs in the Baltic Sea which included testing the toxicity of selected degradation products (Christensen et al. 2016) and Weight of Evidence (WoE) analyses (Bełdowski et al., 2017). Interdisciplinary research is nowadays continued in the DAIMON project - Decision Aid for Marine Munition (http://www.daimonproject.com) - with the aim to develop the risk assessment algorithms and the decision support system.

1.1. Study area

Little Belt, Bornholm and Gotland Deeps are recognized to be the most important, officially designated CWA dumpsite areas in the Baltic Sea. The CW dumping area commonly referred to as the 'primary dumpsite', is located in the Bornholm Deep centred on a point with surface coordinates 55°20′N, 15°37′E. Its northern part is currently marked on sea charts as 'larger explosives dumping ground'. Sea-dumping operations in the Gotland Deep took place between May and September 1947, when approximately 2000 tons of CW materiel consisting of 1000 tons of CWA were dumped. On the other hand, studies performed in CHEMSEA project confirmed the existence of an unofficial dumpsite in the Gdańsk Deep (Bełdowski et al., 2016a). The suspicion about CWA presence in Gdańsk Deep arose after two incidents, the first with a mustard gas bomb recovered by a fishing trawler and a second with similar bomb being washed ashore on the Hel Peninsula in 1954 (Szarejko and Namieśnik, 2009). The CWA presence was finally verified by pore-water (Bełdowski et al., 2016a). The total volume of dumped conventional munitions in Gdańsk Deep until 1954 was approx. 60 tons, however the load of CWA is still unknown (Knobloch et al., 2013).

Although the loads of sea-dumped CWA are believed to pose a possible threat to the Baltic Sea ecosystem, there is already an existing environmental degradation linked with nutrient overload that caused reduction of dissolved oxygen (DO) concentrations in bottom waters and creation of a "benthic deserts" below the halocline (Diaz and Rosenberg, 2008). Water stagnation has negative impacts on marine ecosystems, especially in accumulation basins, since states of hypoxia and anoxia not only negatively influence organisms (Vaquer-Sunyer and Duarte, 2008), but also their habitats (Conley et al., 2009).

During more than 100 years of Baltic Sea research (Elmgren, 2001), the areas of Bornholm, Gdańsk and Gotland Deeps have been widely studied. Among studies of singular basins, several comparisons have been performed (i.e. Vallius and Kuzendorf, 2001, Christoffersen et al., 2007). The aim of this study was a site-specific identification of the ecological status of CW dumpsites located in those three deeps of the Baltic Sea. A detailed description of factors governing the conditions in the dumpsite areas can be a useful tool for researchers representing various scientific fields. The presented set of environmental and modelling data relies on recent findings and is designed to serve as background information for researchers and stakeholders engaged with the issue.

2. Materials and methods

Presented habitat characterization is based on the location of the CWA dumpsites in Baltic Proper, exceeding depths of 70 m (Fig. 1). Datasets were collected during the CHEMSEA, MODUM and DAIMON – Decision Aid for Marine Munitions research projects. Three deep-sea Baltic CW dumpsites were investigated during 10 expeditions of S/Y Oceania, R/V Walther Herwig III and R/V Nord 3 between 2012 and 2017 (Table 1). While the CHEMSEA project focused on locating suspicious looking objects, in both MODUM and DAIMON projects those stations where CWA were detected have been revisited.

2.1. Depth, salinity and dissolved oxygen profiles of water column

The CTD (Conductivity, Temperature, Depth) probe SeaBird 49, additionally equipped with an oxygen sensor was used during all cruises. Measurements were performed at every sampling station. The accuracies of the conductivity and pressure sensors were 0.005 mS·cm^{-1} and 0.1% of the full-scale range, respectively. The conductivity sensor is calibrated annually by the manufacturer to ensure accuracy. The profiles of DO concentration were obtained with the Rinko-I sensor. The accuracy of the sensor was ±2% (1 Atm, 25 °C) with a resolution of 0.01 to 0.4% (2 to 8 μg·L^{-1}).

2.2. Water exchange and bottom currents modelling

Baltic Sea water exchange forecasts and suitable representations of actual bottom currents are available thanks to employment of the POP - Parallel Ocean Program (Smith and Gent, 2004). For bottom currents modelling, the hindcast was based upon a 20-years simulation period. The POP model is widely used and refers to global and regional models and was successfully applied for the Baltic Sea. It has a horizontal resolution of 2 km and 66 vertical levels, 50 of which are 5 m in depth.

2.3. Acoustic sediment characterization, sea bottom and sub bottom mapping

Two types of sonars were used to collect acoustic data. The EdgeTech DF-1000 towed sonar was used for preliminary sea bottom mapping,

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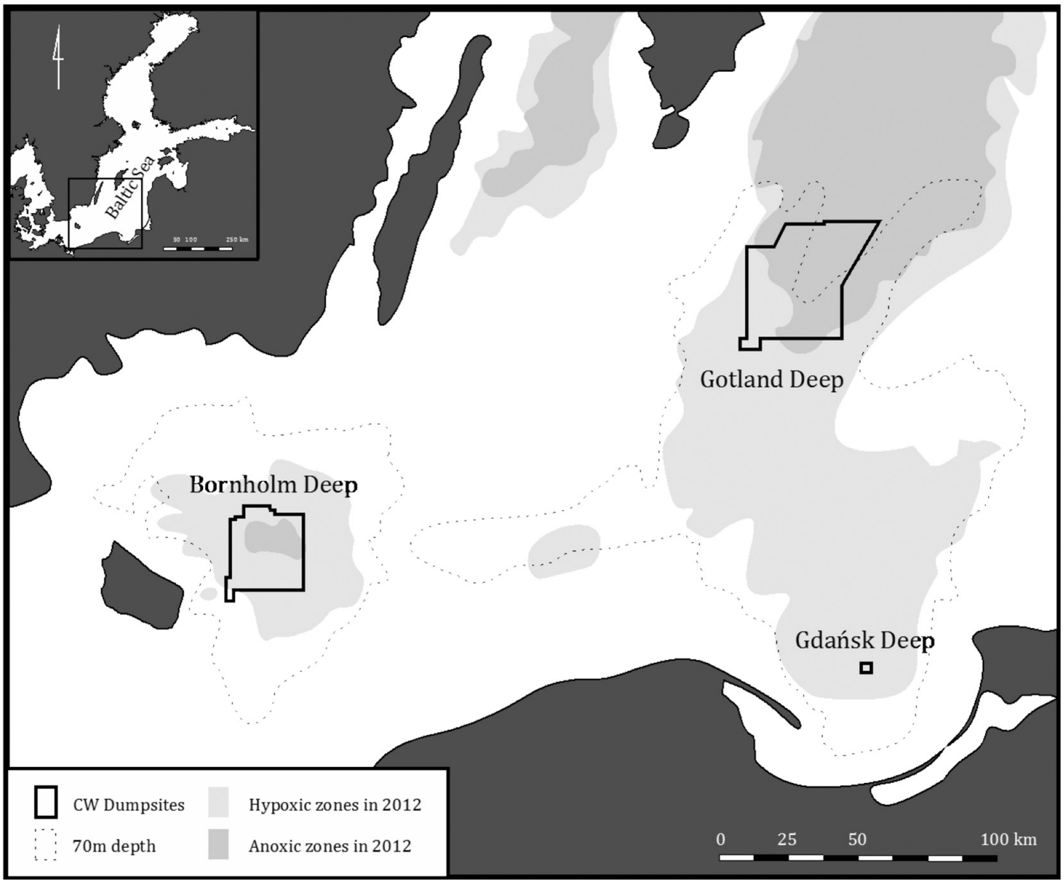

Fig. 1. Locations of deep-sea Chemical Warfare (CW) dumpsites in Baltic Sea area. Anoxic and hypoxic zones in 2012 are redrawn from Carstensen et al. (2014).

performing data acquisition at two resolutions: standard – 100 ± 10 kHz and high resolution – 400 ± 20 kHz, with towing speed of 3 knots (kn), and height above the bottom ranging between 10 and 15 m. Detailed seabed imaging was performed by means of the Ocean Server's AUV IVER-2 with hull-mounted Klein L-3 UUV – 3500, dual frequency side scan sonar (455 kHz and 900 kHz), working at a speed of 2.5 kn at a height ranging from 2.5 to 10 m from the bottom. Collected sonar data served as an input for post processing in HYPACK 2013 software. During the investigation of Gdańsk Deep in September 2015, information about subsurface sediment layers became available thanks to 30 surveys performed by EdgeTech SB3200 XS Sub-Bottom profiler. Additionally, around 200 launches of the Saab Falcon ROV, provided visual information for sea bottom recognition.

2.4. Sediment sampling and analyses

Samples for sediment analyses were collected by means of Van Veen grab and Box Corer at distances <100 m from the suspicious objects. The top 5-cm sediment layer was preserved for two-step grain size analysis. The coarse fraction was separated by passing the sediment through sieves with varying mesh diameters: 2000 μm, 1000 μm, 500 μm, 250 μm, 125 μm, and each fraction was weighed. The fraction smaller than 125 μm was left for subsequent laser measurements performed with MALVERN Mastersizer 2000. Results were later calculated in GRADISTAT 4.0. The organic matter (OM) content of the sediment was calculated based upon the loss on ignition (LOI), after heating the samples at 480 °C for 8 h.

Table 1
Sampling campaigns for sea-dumped Chemical Warfare, including types of collected data.

Year	Area	Project	Vessel	Sediment				CW Detection				Water column
				Type	Metal.	Meio	Macro	SSS	AUV	SUB	ROV	CTDO
2012	*Gotland Deep*	CHEMSEA	OCE	+++	+++	+	+	+			+	+
2012	*Bornholm Deep*	CHEMSEA	WH	+++	+++	+	+					+++
2012	*Gdańsk Deep*	CHEMSEA	OCE	+++	+++	+	+	+			+	+
2014	*Bornholm Deep*	MODUM	OCE	+++	+++			+			+	+
2014	*Gt/Gd Deeps*	MODUM	OCE	+++	+++	+++		+	+		+	+++
2015	*Bornholm Deep*	MODUM	OCE	+	+++	+++		+	+		+	+++
2015	*Gdańsk Deep*	MODUM	OCE/NOR	+	+++	+++		+	+	+++	+	+
2016	*Bornholm Deep*	MODUM	OCE	+	+++	+++		+	+++		+	+
2016	*Gdańsk Deep*	MODUM/DAIMON	OCE	+	+++			+	+++		+++	+
2017	*Bornholm Deep*	DAIMON	OCE	+	+++	+++		+	+++		+++	+

+++ - data presented in this paper; + - data collected during expeditions.
OCE – S/Y Oceania, WH – R/V Walter Herwig III, NOR – Nord 3.
Type – samples for sediment grain size analyses; Metal. – samples for metalloids and heavy metals concentrations; Meio – samples for taxonomical analyses of meiofauna; Macro – samples for taxonomical analyses of macrofauna; SSS – Side-Scan Sonar surveying; AUV – Autonomous Underwater Vehicle surveying; SUB – Sub-bottom profiler surveying; ROV – missions of Remotely Operated Vehicle; CTDO – Conductivity, Temperature, Depth and Oxygen profiling of water.

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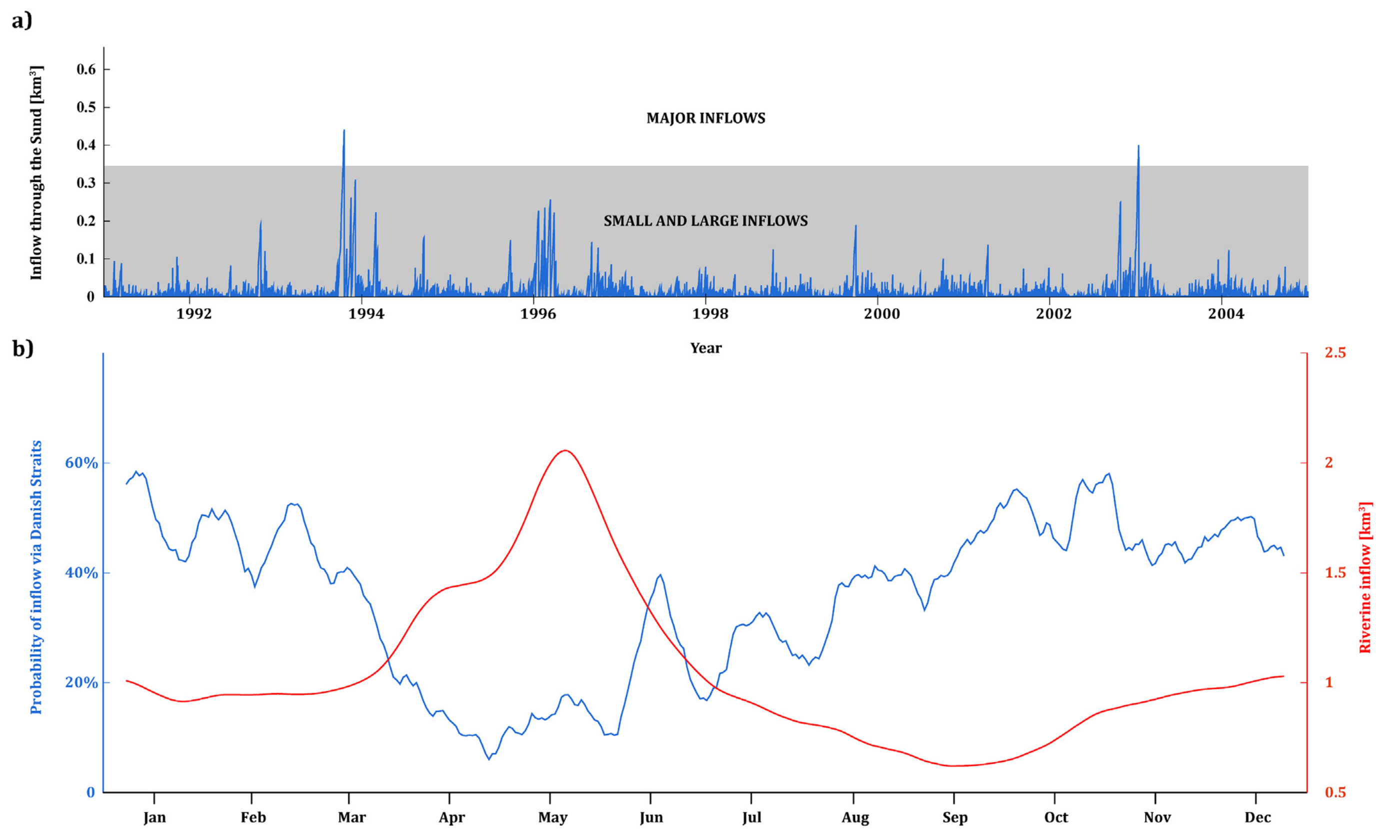

Fig. 2. Inflows of saline waters (a) from North Sea through the Sund strait since 1991 to 2005. The exchange of waters is driven by complexity of factors, however, the probability of inflows increases during autumn and winter, when the riverine inflow is the smallest.

Sediment samples for total arsenic were prepared as in Loska and Wiechuła (2006) by dry digestion for further analysis on hydride generation Atomic Absorption Spectrophotometry (HG-AAS) (Bełdowski et al., 2016b). After digestion, other samples for the concentrations of lead, zinc, iron and manganese were measured with Inductively Coupled Plasma Mass Spectrometry (ICP-MS) using a Perkin Elmer ELAN 9000. Mercury concentrations were measured by Atomic Absorption Spectrometry using an AMA-254 spectrometer. After wet digestion in acids, sub-samples for the analysis of lead, zinc, iron and manganese concentrations were measured with ICP-MS detector (Perkin Elmer ELAN 9000) combined with seaFAST pre-concentration mode (CF-IDA) containing Iminodiacetic acid immobilized on a vinylbenzyl copolymer was used for measurements of lead and cadmium concentrations.

2.5. Meiofauna sampling and analyses

Samples for taxonomical analyses of benthic meiofauna were collected by means of Van Veen grab, Box Corer or ROV at distances <50 m from the suspicious objects. The top 5-cm sediment layer was subsampled by 10 cm^2 Plexiglas cores and preserved in 10% formalin solution. Organisms were extracted using standard method (Burgess, 2001), by a 10-minute long tripled centrifuging at 1900 RPM in 1,2 $g \cdot mL^{-1}$ LUDOX solution. Samples were later stained using Rose Bengal and analysed under stereoscopic microscopes.

3. Results and discussion

3.1. Pelagic zone

Conditions in bottom waters of the Baltic Proper are controlled by inflows of saline water from the North Sea through the shallow Danish Straits. While most of the exchange is driven by sea level difference between Kattegat and the Baltic Proper only the so-called Major Baltic Inflows (MBI) have a direct impact on sediments and vertical mixing of the whole water column (Carstensen et al., 2014). MBI are characterized by an exceptionally high volume, salinity levels and long duration allowing those dense inflows to penetrate water column down below halocline of the Baltic Proper.

The MBI occur only around ten times per century (Fig. 2a) and are most likely to happen during winter and autumn (Fig. 2b). The MBI from December 2014 was the first large-scale water exchange between the Baltic and North Seas in a decade, bringing approximately 198 km^3 of dense and oxygen-rich water (Morholz et al., 2015). In February/March 2015 MBI effects have been observed in the Bornholm Deep (Fig. 3). As expected, inflow waters appeared below the halocline and were characterized by an exceptionally high salinity, 21 PSU, and relatively homogenous temperature. Observed salinity levels of the freshly

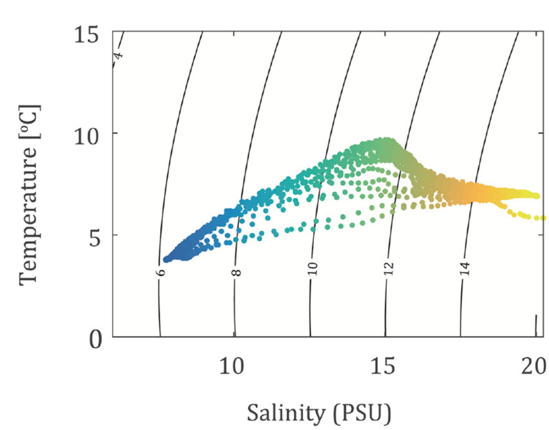

Fig. 3. TS plot based on the data collected in February 2015 from the Bornholm Deep areas exceeding 70 m.

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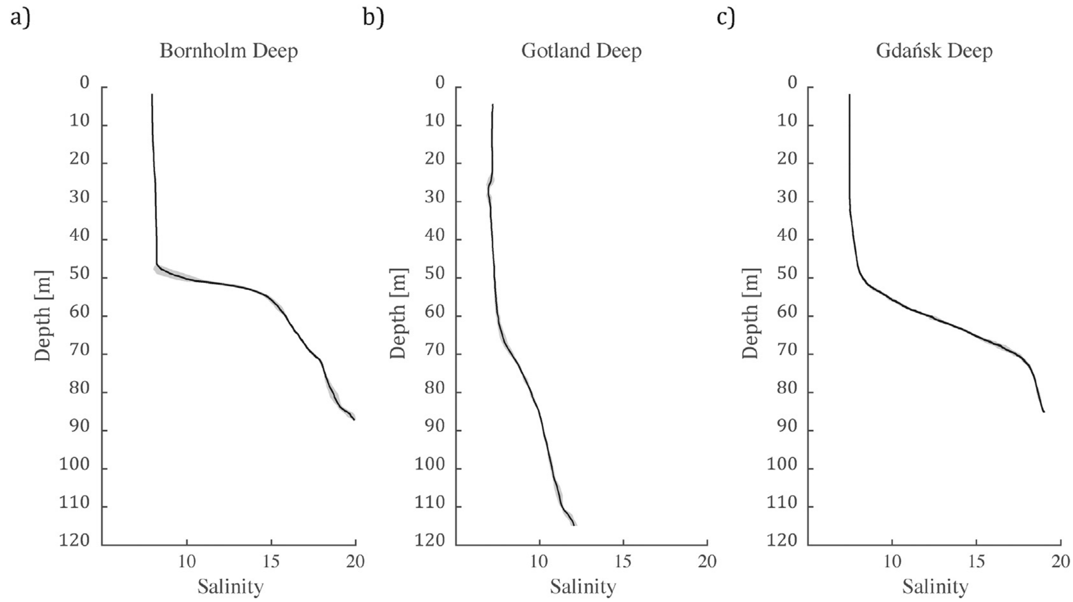

Fig. 4. Mean salinity profiles measured in three investigated dumpsites. The profiles are based on 5 cases at each station: a) Bornholm Deep – February 2015 (55°14.3′N, 15°51.5′E), b) Gotland Deep – September 2015 (56°01.5′N, 18°46.1′E) and c) Gdańsk Deep - October 2015 (55°13.4′N, 15°54.1′E).

transported water were 3 PSU higher than multiyear mean values for bottom waters at Bornholm Deep region (Rak and Wieczorek, 2012).

Among all investigated sites, the dumpsite area of Gotland Deep was the deepest, with depths ranging from 103 to 122 m. Depths at Bornholm Basin varied from 92 to 101, and in Gdańsk Deep from 95 to 108 m. The bathymetries of three investigated basins are therefore slightly different and their depths significantly exceed the average depth of the Baltic Sea.

While the salinity in surface layers was similar at each region investigated with levels around 7 PSU, the deep layers varied greatly with the

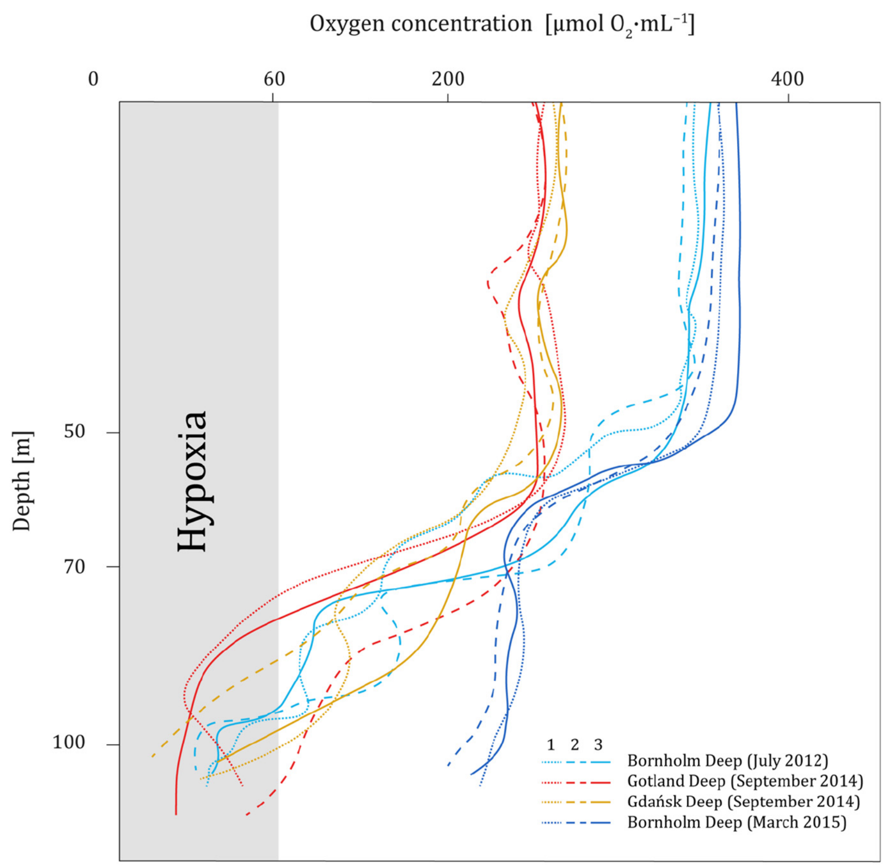

Fig. 5. Dissolved oxygen concentrations in water column at investigated dumpsites: Bornholm Deep in May 2012 (1. 55°12.0′N, 15°42.5′E; 2. 55°21.3′N, 15°48.2′E; 3. 55°20.5N, 15°37.2′E) in March 2015 (1. 55°18.6′N, 15°37.6′E; 2. 55°21.6′N, 15°30.9′E; 3. 55°21.6′N, 15°37.8′E), Gotland Deep in September 2014 (1. 56°01.6′N, 18°46.1′E; 2. 56°00.0′N, 18°46.8′E; 3. 56°01.9′N, 18°45.2′E) and Gdańsk Deep (1. 54°50.5′N, 19°11.0′E; 2. 54°45.2′N, 19°09.9′N Profiles end at the sea bottom. At all measurements from before 2015, dissolved oxygen conditions in bottom waters were extremely poor resulting in severe hypoxia.

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difference between Bornholm and Gotland Deep of approximately 6 PSU (Fig. 4). The salinity of the bottom layers decreases with distance from the Danish Straits and is a result of the connection with Atlantic Ocean. At investigated stations, the halocline depths varied from 50 m in Bornholm Deep to 70 m in the Gotland Deep (Fig. 4). In the Baltic Proper it usually forms at approximately 70 m (Carstensen et al.,

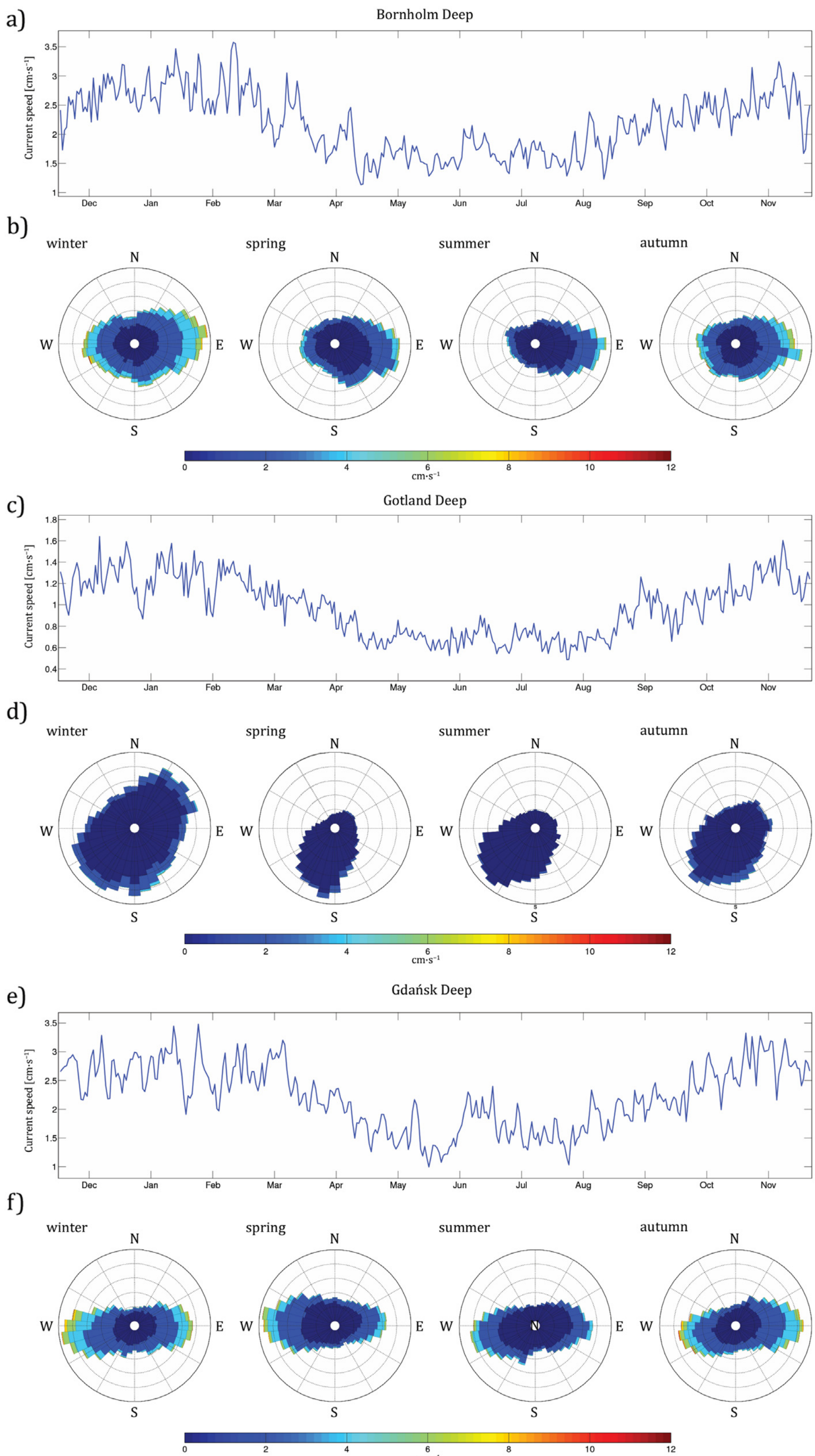

Fig. 6. Mean annual cycle (a, c, e) and current roses (b, d, f) for seasonally averaged near-bottom current speeds: winter, spring, summer and autumn, at three stations: Bornholm Deep (a, b), Gotland Deep (c, d) and Gdańsk Deep (e, f). Modelling has been performed for stations located in Bornholm Deep at 55°19.6′N, 15°38.1′E, in Gotland Deep at 56°01.6′N, 18°46.1′E and in Gdańsk Deep at 54°44.8′N, 19°46.2′E.

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2014). Strong stratification of the water column limits vertical mixing, causing hypoxic and anoxic conditions in benthic habitats disturbed by high eutrophication. Prior to the MBI of 2014, DO concentrations in bottom waters at all investigated dumpsites did not exceed 60 $\mu mol \cdot L^{-1}$ (Fig. 5) which is, in part, why MBIs are so crucial for Baltic marine organisms and benthic ecosystems.

Although currents can ventilate bottom waters, under specific conditions they may also act as a dispersal agent for CWA (Bulczak et al., 2016). Seasonal variability of near-bottom currents at investigated areas is represented in Fig. 6. Each plot represents the mean annual cycle of current velocity, while rose diagrams characterize the radial distribution of near-bottom current speed. Those diagrams show the frequency distribution of current velocity binned into classes of current directions. The radial length of each spoke around the circle represents the percentage of time that current flows in a specific direction. Different colours at each spoke represent relative shares of different current speed classes.

Current velocities are similar in the Gdańsk Deep and the Bornholm Deep, and less than half as strong in the Gotland Deep. The mean current speeds in the Gdańsk, Bornholm and Gotland Deeps are 2.13 $cm \cdot s^{-1}$, 2.14 $cm \cdot s^{-1}$ and 0.9 $cm \cdot s^{-1}$, respectively and are characterized by a strong seasonal variability. In general, increased near-bottom current speeds are observed from autumn to early spring (Fig. 6a, c, e). This is likely caused by stronger winds and more frequent storms occurring in the Baltic Sea region in this period. Overall, those areas are low-dynamic sedimentation basins where only occasional, above-mean-value current velocities exceed the 4 $cm \cdot s^{-1}$ sediment resuspension threshold (Bulczak et al., 2016).

The current rose for the Bornholm Deep (Fig. 6b) reveals that in summer the frequency of eastward flow is about 45% (in the direction between 45 and 135°). In this current direction, the frequency of velocities in the range of 0–2 $cm \cdot s^{-1}$ is about 26%, in the range of 2–4 $cm \cdot s^{-1}$ is about 13%, and above 4 $cm \cdot s^{-1}$ is 3%, respectively. A graphical presentation is designed in a way that all directions of bottom currents meet in the centre of the chart, with their beginnings at the edge of the rose. In summer the eastward near-bottom currents are observed about 3 times more often than currents from other directions. Baltic Sea near-bottom currents are mostly topographically steered as their directions are dictated by local bathygraphic features of the sea bottom, thus the prevailing currents in Bornholm Deep are directed inward the Baltic Sea. Seasonal variability observed at this station is likely driven by storms that occur most often in spring and autumn. A similar situation is observed in the Gotland Deep (Fig. 6d). The annual cycle is a result of storms that disturb the mean southwestward current in autumn and winter. In the Gdańsk Deep, a strong annual cycle of the current velocity is observed, while current directions do not change significantly on a seasonal scale (Fig. 6f) what can be explained by the location of the station - the deepest part of the Gdańsk Deep, where the influence of storms is negligible. At each station, stronger winter currents are also driven by inflows from the North Sea. Probability of inflow is the highest in the winter period and larger amounts of water enter the Baltic Sea during winter months (Matthäus and Franck, 1992; Fischer and Matthäus, 1996).

3.2. Benthic zone

Benthic habitats are defined as structural parts of the environment that attract organisms and serve as a centre of biological activity (Peters and Cross, 1992). This definition includes the variety of sediment types as well as the co-occurring structures. At each investigated site, highly-detailed acoustic maps of the sea bottom were created for possible target recognition. Acoustic methods are a very effective, non-invasive tool for seafloor classification (Anderson et al., 2008). In general, all three investigated regions are flat areas covered by soft sediment (Fig. 7). Acoustic mapping results correspond with grain-size laboratory analyses of sediments (Table 2). GRADISTAT results indicate that surface sediments from investigated stations belonged to the sandy muds textural group in Bornholm Basin and to the muddy sands group in both Gotland and Gdańsk Basins. The top 5 cm of sediments from all investigated areas were highly liquefied, with mean water content ranging from 76 to 89%.

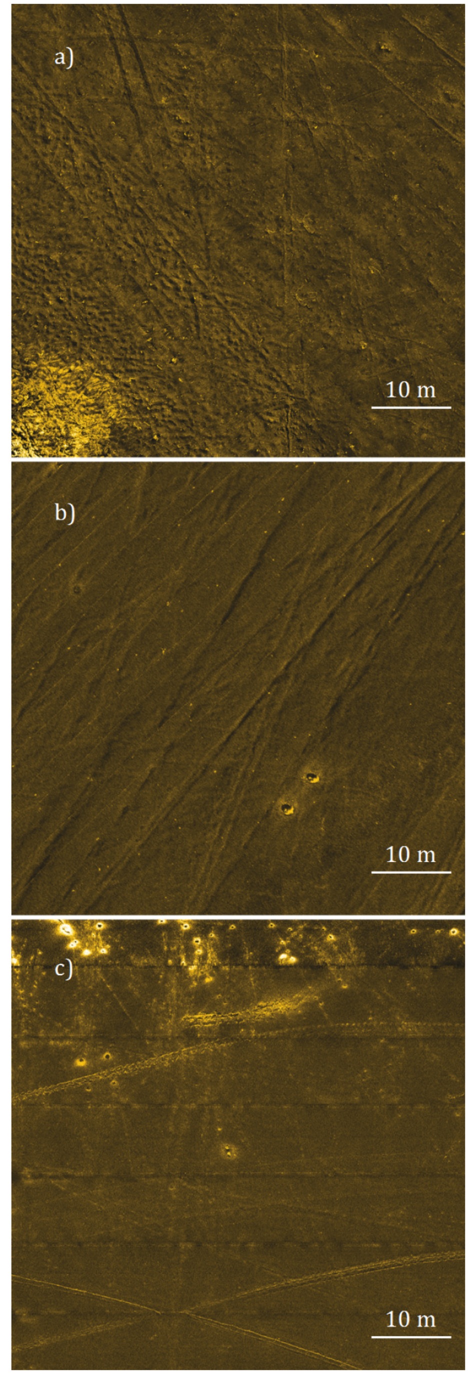

Fig. 7. Results of acoustic sea bottom mapping performed by IVER-2 post-processed in HYPACK 2013 from a) Bornholm Deep – 55°19.0′N, 19°09.7′E, b) Gotland Deep – 56°01.4′N, 18°46.1′E and c) Gdańsk Deep – 54°45.3′N, 15°37.7′E. Dark colours represent soft sediments, while light reflexions originate from various debris laying on top of sediment: a) parts of a shipwreck, b) sea-mines, c) scattered metallic objects. Trawl marks are visible as continuous lines on all images.

The most actual Sub-bottom profiler surveys in the Gdańsk Deep (Bełdowski et al., 2017) correspond with the previous findings from the Bornholm Deep where large fraction of bomb-like objects was observed beneath the soft sediments surface (Missiaen et al., 2010). It also detected large gas pockmarks at similar depths in the sediment.

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Table 2
Sediment properties and Arsenic (As) and heavy metals: Mercury (Hg), Cadmium (Cd), Lead (Pb), Zinc (Zn), Iron (Fe) and Manganese (Mn) concentrations at investigated CW dumpsites.

Area	Mean depth [m]	Textural group	<0.063 [%]	OM [%]	H_2O [%]		Metalloids and heavy metals					
							As [$\mu g \cdot g^{-1}$]	Hg [$ng \cdot g^{-1}$]	Pb [$\mu g \cdot g^{-1}$]	Zn [$\mu g \cdot g^{-1}$]	Fe [$mg \cdot g^{-1}$]	Mn [$\mu g \cdot g^{-1}$]
Bornholm Deep	97	Sandy muds	84.7	15	76	Min.	12.5	4.9	16.9	38.5	14.79	614.6
						Max.	22.9	211.1	51.7	237.0	49.92	4328.4
						Mean	17.2	56.6	33.4	**193.4**	43.06	2238.7
						Ref.	*22*	*80*	*43*	*110*		
Gotland Deep	115	Muddy sands	77.7	11	74	Min.	3.7	11.9	8.3	61.1	12.96	147.1
						Max.	23.2	289.9	142.2	275.6	76.13	2663.8
						Mean	13.7	58.4	29.5	**161.0**	40.38	564.6
						Ref.	*14*	*80*	*36*	*98*		
Gdańsk Deep	99	Muddy sands	76.9	19	89	Min.	1.1	9.5	6.1	14.4	4.88	122.5
						Max.	22.6	296.8	64.8	231.1	71.67	544.5
						Mean	15.4	**146.0**	36.6	**180.3**	36.18	362.6
						Ref.	*16*	*100*	*54*	*122*		

<0.063 – fine grained sediment fraction; OM – organic matter; H_2O – water content.
Bold values in Metalloids and Heavy Metals concentrations represent mean values higher than in *Ref.* – reference (Uścinowicz, 2011).

Since there are several gas pockmarks described in the Gulf of Gdańsk (Majewski and Klusek, 2014) and Bornholm Basin (Christoffersen et al., 2007), the methane fluxes may act as an avenue for contaminated pore-waters and move CWA degradation products to surficial sediments.

In the analysed samples, mean OM content in sediments was 11% in Gotland Deep, 15% in Bornholm Deep and 19% in Gdańsk Deep (Table 2). Sedimentary OM is a source of nutrients for benthic communities and it may also be a vector for heavy metals as cadmium, zinc and mercury tend to bond with OM (Pearson, 1963; Fitzgerald and Lamborg, 2005; Callender, 2005). Sedimentation rates in the Gdańsk Deep vary from 0.70 ± 0.13 to 3.90 ± 0.31 mm yr^{-1} (Suplińska and Pietrzak-Flis, 2008). According to Hille et al. (2006), the mean linear sedimentation rate for the whole Gotland Deep is 0.93 ± 0.67 mm yr^{-1}, with values ranging from 3 to 5 mm in central areas (Vallius and Kuzendorf, 2001). Sedimentation rates in Bornholm Deep are the lowest among those three areas, with a range from 0.52 ± 0.02 up to 0.82 ± 0.10 mm yr^{-1} (Suplińska and Pietrzak-Flis, 2008).

Although surface sediment layers have similar morphology, the acoustic mapping revealed minor differences in geological features between investigated areas (Fig. 7). These differences are a result of geographical location. In the Bornholm Basin, situated east of the Bornholm Island, the sedimentary supply originates mainly from coastal erosion, with all remaining part originating from suspending material and atmospheric dust (Stryuk et al., 1995). The vicinity of a major source of coastal material explains why western parts of the investigated area were partially covered by small rocks (Fig. 7a). There were hard sediment patches in Gdańsk Deep (Fig. 7c), where munitions burial in the sediment would be impossible. Located in the south-eastern part of Baltic Proper, this basin is heavily influenced by the largest river of the Baltic Sea catchment area. The Vistula River is an important source of OM and fluvial material in the region, responsible for deposition of sands in the southern parts of the Gdańsk Deep (Damrat et al., 2013).

While the 80% of CW disposed in the Baltic Sea were mustard gas loads, the remaining part consisted of arsenic-based blistering agents such as Adamsite, Clark I and II, Chloroacetophenone and killing agent Tabun (Knobloch et al., 2013). Therefore, Vallius and Kuzendorf (2001), in comparison studies of the geochemistry of Bornholm and Gotland Deeps, linked the elevated arsenic concentrations around Bornholm with CW dumping. Mean values of arsenic concentrations measured from 2012 to 2016 during CHEMSEA and MODUM campaigns in Bornholm, Gotland and Gdańsk Deeps were 17.2 $\mu g \cdot g^{-1}$, 13.7 $\mu g \cdot g^{-1}$ and 15.4 $\mu g \cdot g^{-1}$ respectively (Table 2). Slightly elevated values were observed in one sample from Bornholm Deep, and in nearly 30% of samples from Gdańsk and Gotland Deeps. Detected levels are, however, comparable to arsenic biogeochemical background and do not significantly exceed the geochemical background established for Baltic Sea fine sediments (Uścinowicz, 2011). In previous years, Emelyanov et al. (2010) reported arsenic concentrations in Bornholm Deep with mean value of 82 $\mu g \cdot g^{-1}$ (range 21–210 $\mu g \cdot g^{-1}$) with the highest concentration noted in the centre of Bornholm secondary dumpsite. Paka and Spiridonov (2002) reported 18 and 150 $\mu g \cdot g^{-1}$ in sediments collected in years 1997–2001. In Gotland Deep CW dumpsite, the concentrations ranged from 1 to 19 $\mu g \cdot g^{-1}$ with a mean value of 8 $\mu g \cdot g^{-1}$ and the highest noted value in the dumpsite area, spatially decreasing from the dumpsite (Garnaga et al., 2006). Similar research from Paka and Spiridonov (2002) reported values between 18 and 28 $\mu g \cdot g^{-1}$ sediments collected from 1997 to 2001.

Overall observation, from all presented studies, is that arsenic concentrations in surface sediments from Baltic Sea CW dumpsites decrease year after year. However, both Emelyanov et al. (2010) and Paka and Spiridonov (2002) used total X-Ray diffraction (TXRF), which is characterized by low sensitivity. This may have resulted in some extremes, while the methodology used in this study always represents values averaged across a sample aliquot. If the observed trend is real, then either the contaminated sediments are being covered with recent sedimentary material and the peak concentration of arsenic originating from CWA should be observed deeper in the sediment, or the source of pollution is spreading. Sanderson et al. (2010) detected the degradation products of arsenic-based warfare agents in sediments outside of the primary dumpsite. In his studies, Bełdowski et al. (2016b) indicated that behaviour of arsenic in CW dumpsites differs from typical Baltic Sea sediments, where it bonds with OM, iron and manganese oxyhydroxides, thus, reported lower and/or negative values of Pearson correlation coefficients was possibly explained by a local source of arsenic.

Mercury concentrations at investigated areas exceeded geochemical background values in numerous samples (Table 2), which is corresponding with similar research reported by Gębka et al. (2016). This element tends to bind with OM and its elevated concentrations correlate with high contents of fine grained sediment fraction (<0.063 mm). The biogeochemical cycle enables mercury re-emission from sediments depending on REDOX conditions. Also, measured lead concentration values remained within the range of geochemical background values for this element (Table 2). Only in 3 samples from Bornholm Deep, 2 samples from Gdańsk Deep and 3 samples from Gotland Deep out of total samples of 130, were the concentrations slightly higher than values reported by Uścinowicz (2011).

The highest observed difference between given geochemical background and obtained results was observed for zinc (Table 2). Mean zinc concentrations of 193 $\mu g \cdot g^{-1}$, 180 $\mu g \cdot g^{-1}$ and 161 $\mu g \cdot g^{-1}$were reported in sediments from Bornholm, Gdańsk and Gotland Deeps respectively. In most samples, measured concentrations were nearly twofold higher than reported geochemical background levels. Potentially there could be a link between high zinc concentrations and munitions dumping operations as zinc was incorporated into various munition shells and casings. Uścinowicz (2011) suggests that elevated concentrations of zinc in the Baltic Sea basins are the results of the transport of contaminants from distant coasts.

3.3. Biota

Even during their undisturbed state, Baltic Sea deeps had relatively low biodiversity when compared to Baltic Sea coastal zones and similar depths in more saline seas (Snoeijs-Leijonmalm et al., 2017). However, it was the possible risk of CWA bioaccumulation in food chains that brought wide scientific interest in research of interactions between benthic organisms and sea-dumped munitions. Medvedeva et al. (2009) reported enhanced numbers of mustard gas-resistant bacteria in the bottom waters at Baltic dumpsites together with a decreasing biodiversity of bacteria near the identified objects. This indicated a probable leakage of munitions content while new research from Silva and Chock (2016) describes microbial-induced corrosion of shell casings in Hawaiian dumpsites.

Meiobenthic communities at investigated CW dumpsites in years from 2014 to 2017 show a great dominance of Nematoda (Fig. 8). Nematoda were the only noted taxon, except from the situation observed in Bornholm Deep in March 2016, when singular individuals of Polychaeta, Oligochaeta, Pripulida, Ostracoda, Harpacticoida and Cnidaria appeared in the sediment samples. As for now, meiofauna was represented only by Nematoda (Grzelak and Kotwicki, 2016), which also included first observations of ovoviviparous reproductive behaviour of *Halomonhystera disjuncta* in the Baltic Sea. In similar studies, Kotwicki et al. (2016), observed statistically significant differences between Nematoda communities from dumpsites in Bornholm, Gdańsk and Gotland Deeps that were most likely linked with differences of type, source and quantities of deposited OM.

Observation of single-year shift in local biodiversity of meiofauna, can be only explained as a temporary effect of MBI from 2014, which, as already mentioned, reached Bornholm Deep in March 2015, back when only Nematoda individuals were noted (Fig. 8). It turns out that favourable conditions lasted at least until March 2016 allowing i.e. a Copepod: Thalestridae (Fig. 9), belonging to the order Harpacticoida, characterized by relatively high oxygen demand (Giere, 2009), to colonize investigated areas. Undisputed dominance of Nematoda returned in March 2017, when all other taxa already disappeared.

March 2016 was also exceptional for macrofauna communities' status, as during the ROV inspections of Bornholm Deep, numerous active individuals of benthic Amphipoda were observed directly in the dumpsite area, however no recorded footage is available. At depths exceeding 90 m, it has probably been *Monoporeia* sp. (Snoeijs-Leijonmalm et al., 2017) and was also most likely an effect of the 2014 MBI. As for now, the total absence of benthic macrofauna, in the exact areas of CW dumpsites in the Baltic Sea was reported (Grzelak and Kotwicki, 2016).

Temporal returns of macrofauna and increases in oxygen levels are therefore likely to attract larger numbers pelagic and demersal fish to stay longer in CWA contaminated areas. Some species of demersal fish are already present, since individuals of European flounder (*Platichthys flesus*) and Atlantic cod (*Gadus morhua*) were observed both before, during and after the MBI thanks to the ROV investigation of sea-dumped

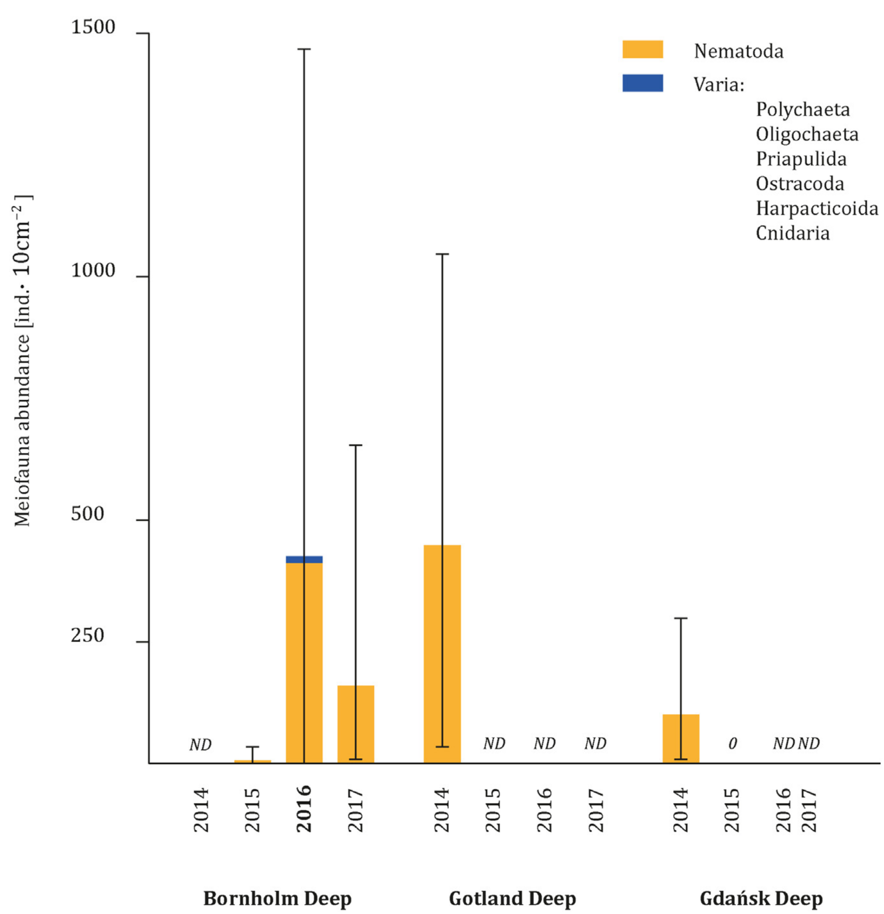

Fig. 8. Meiofauna taxa noted in sediments collected at CW dumpsites from Bornholm, Gotland and Gdańsk Deeps. Graph visualises maximum and minimum numbers of individuals found in samples and mean quantities from a site. Most dominant taxon – Nematoda, was present in all investigated samples, beside one from September in 2015 from Gdańsk Deep, when no organisms were observed. Blue colour represents other taxa: Polychaeta, Oligochaeta, Priapulida, Ostracoda, Harpacticoida and Cnidaria, that were present only in sediment samples from Bornholm Deep collected in March 2016. ND – no data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Fig. 9. Individual of Harpacticoida belonging to Thalestridae Sars, 1905 found in one of the subsamples collected by means of VanVeen during S/Y Oceania cruise in March 2016.

munitions (Fig. 10). *G. morhua* is one of the most abundant demersal fish species inhabiting almost the entire Baltic Sea.

Two cod stocks have been identified in the Baltic Sea: the western and the eastern stock. First, primarily inhabits the Danish Straits and Arkona Deep, while the second, often considered to represent a subspecies (*Gadus morhua callarias* L.), is abundant in the Deeps of Arkona, Bornholm, Gdańsk, and Gotland up to the western Gulf of Finland. The geographical borderline between these stocks is assumed to be at the island of Bornholm (Aro, 1989).

The two Baltic cod stocks mainly differ in spawning season and the preferred spawning grounds. While the western stock spawns from February to May, the eastern stock spawns from June to September. In present times, the more successful spawning sites of the eastern stock include the deepest parts of the Bornholm Basin and the Arkona Sea (Bagge et al., 1994; Wieland et al., 2000). Spawning activity and the success of cod are greatly influenced by hydrographic conditions, including the MBI. Because of their specific density, spawned and fertilised eggs of Baltic cod require a minimum salinity of ≥11 to prevent them from sinking into the anoxic conditions of the bottom. For the successful survival and development of embryos, a minimal oxygen concentration of $\geq 2\ \mathrm{ml \cdot L^{-1}}$ is required (Nissling et al., 1994, Wieland et al., 2000). Since the Bornholm Basin is not only the most important spawning area for eastern cod, but also the major CWA dumpsite in the Baltic Sea, a risk of exposure to CWA for both early life stage and adult cod during their stay in the spawning grounds cannot be excluded.

According to Eero et al. (2015), the development of the Baltic cod stock is subject to numerous ecological factors that are still poorly understood. Stressors which may negatively influence the health of cod stocks, and which have so far been largely neglected in stock assessments, might be due to the effects of contaminants to which fish are exposed and/or to infection/infestation with diseases and parasites. To assess the impact of such environmental stressors, cod have been studied on a regular basis as part of national environmental monitoring programmes (Lang, 2002). Methodologies applied in fish health monitoring are mainly based on the activities of Expert Groups under the International Council for the Exploration of the Sea (ICES) (Bucke et al., 1996).

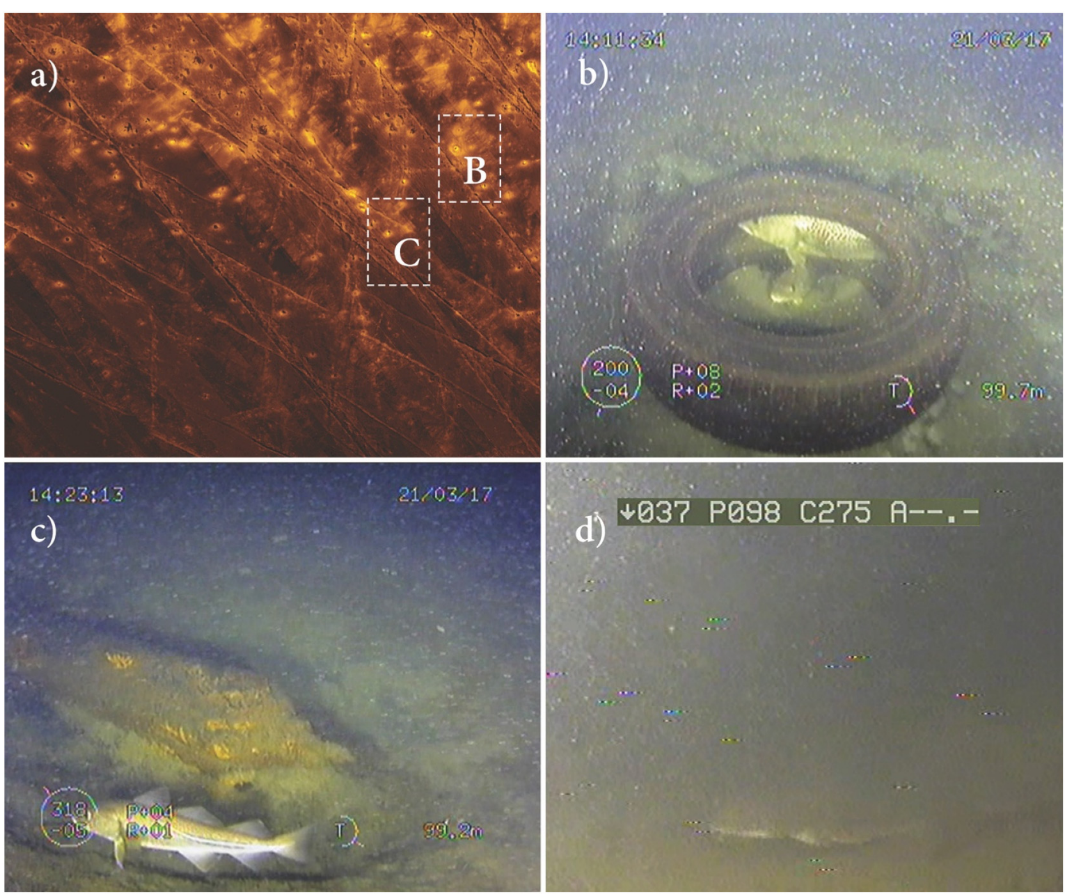

Fig. 10. Side scan sonar acoustic mosaic from March 2017 CW dumpsite area investigation of Gdańsk Deep (a), with corresponding ROV images (b - B and c - C). Atlantic cod (*Gadus morhua*) was regularly observed in close vicinity of various anthropogenic debris like tires (b) and gas tanks (c). Other specimen of demersal fish - European flounder (*Platichthys flesus*), was noted mostly in Bornholm Deep (d). Presented ROV images were taken at depths ranging from 98 to 99,7 m.

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Table 3
Habitat characterization of investigated CW dumpsites.

Area	Habitat classification	CW dumpsite			Environmental conditions		Fauna		
		Status	*CWA*	*Objects*	*Dynamics*	*DO*	*Meio*	*Macro*	*G. morhua*
Bornholm Deep	Deep Sea Muddy Sands	Official	+	316	Accumulative basin	Oxic **Hypoxic** Anoxic	+	*Monoporeia* sp.	East/West
Gotland Deep	Deep Sea Muddy Sands	Official	+	76	Accumulative basin	**Hypoxic** Anoxic	+	Not observed	East
Gdańsk Deep	Deep Sea Muddy Sands	Unofficial	+	313	Accumulative basin	**Hypoxic** Anoxic	+	Not observed	East

DO – dissolved oxygen (bold – most dominant conditions); + - detected presence; East/West – spawning area for Eastern or Western stocks of Baltic Cod (*Gadus morhua*).

Bełdowski et al. (2016a) applied these methodologies along with the measurement of other biological indicators to study adverse effects of dumped CWA on the health status of cod. The results revealed no major difference in prevalence of common, externally visible diseases and parasites between cod from the deep dumpsites in the Bornholm and Gotland Basins and the reference sites. However, cod from the Bornholm dumpsite were characterized by low condition indices and some stress responses (kidney pathology, biomarkers for genotoxicity, neurotoxicity and oxidative stress) compared to cod from the other areas studied.

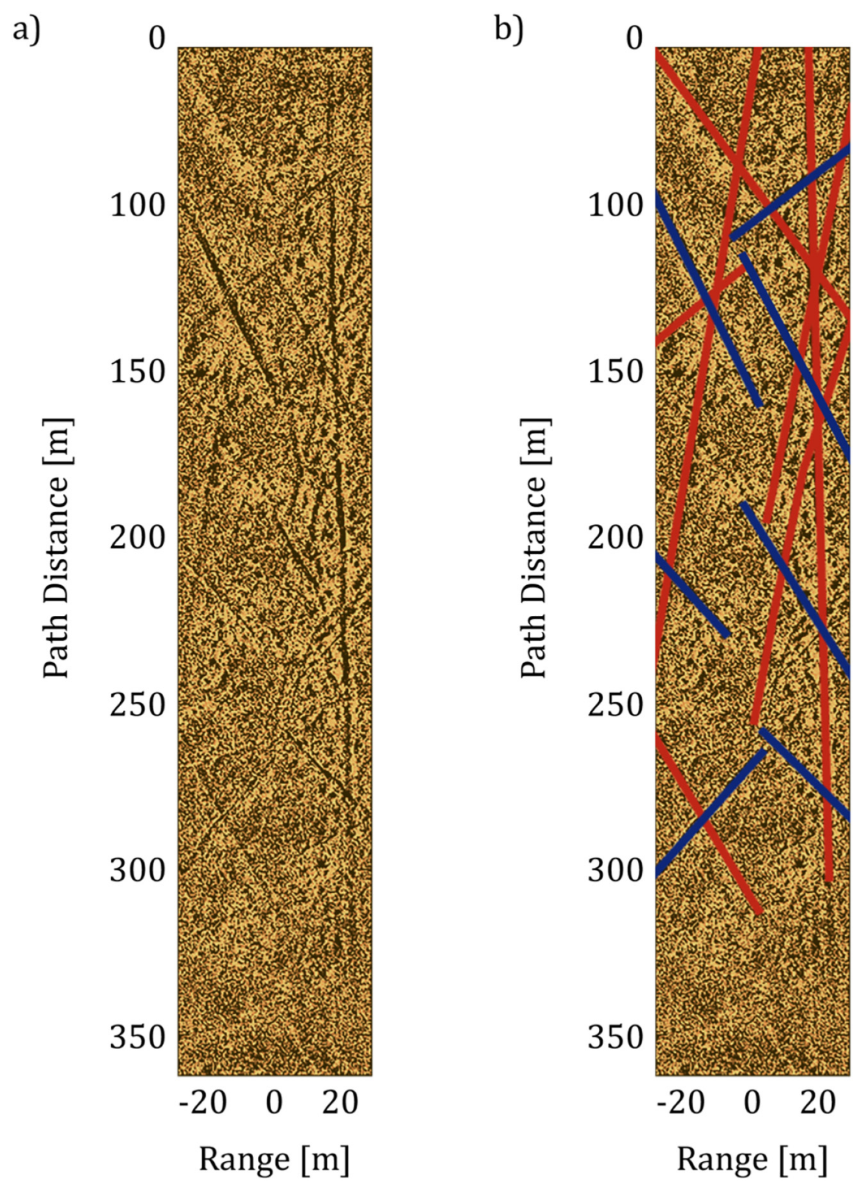

Fig. 11. Examples of high resolution (900 kHz frequency) side-scan sonar images of sea bottom with visible trawl marks. Post processing was performed for better visualisation. Colour-marked lines present supposed generations of scars (b) – younger as blue and older as red. The images were obtained near the Bornholm dumpsite at 55°19.2′N, 15°37.6′E. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3.4. Anthropogenic disturbances

In overall, 705 suspicious objects lying on top and beneath the sediment surface, including actual wrecks, bombs, mines, torpedoes and barrels, have been recorded by acoustic and magnetic methods during the investigations of the three dumpsites (Table 3). 90% of those objects were detected in Bornholm and Gdańsk Deeps.

Despite the prohibition of fishery activities in CW dumpsites, traces of bottom trawling are commonly visible on the sonar images in all investigated areas (Fig. 11). In general, the trawl marks are linear or faintly curvilinear. The images retrieved from the AUV sonar show many generations of scars. Apart from differences in sharpness of plough edges and their depth, the long history of trawling is especially visible in points where lines intersect. Beyond their influence on faunal assemblages, trawling is likely responsible for the dispersion of munitions into nearby areas.

4. Conclusions

Detected presence of sea-dumped munitions both on top and beneath sediments in all three studied areas confirms their CW dumpsite status. According to performed studies, all investigated areas fall within habitats described by EUNIS as A6.4 - Deep Sea Muddy Sands (Hill et al., 2004). There is also a complexity of factors governing ecological interactions in the CW dumpsites located in deep parts of the Baltic Sea, however, the limitations of dissolved oxygen concentrations play the most crucial role in shaping the quality of investigated ecosystem. Observed differences in various parameters among the sites are results of their varying geographical locations, bathymetry, local hydrological regimes and the sources and types of suspended material. It is worth noting that the conditions at each dumpsite correspond with the overall situation of the whole Baltic Proper. Although arsenic concentrations can still be recognized as a possible indicator of CWA and their degradation products presence in Baltic Sea sediments, the observed variability of background concentrations makes the actual anthropological sources hard to spot.

The biodiversity of all studied areas is low, however, due at to recent hydrological phenomena, the 2014 MBI and the replenished oxygen supply at depth, we have observed significant changes in both meiofauna and macrofauna assemblages in the dumpsite area of the Bornholm Deep. Regardless of the MBI, two species of demersal fish were observed in three investigated dumpsite areas during the whole lifespan of CHEMSEA and MODUM projects. On the other hand, temporary improvements of oxygen conditions in bottom waters are believed to increase the risk of fish exposure to possible negative effects originating from CWA presence in the sediments. Due to numerous environmental disturbances that already exist in the Baltic Sea, in situ verification if there is a significant threat caused by sea dumped CW for biota is difficult. Presented results should serve as a baseline comparison data for further studies to determine what are the actual effects of sea-dumped CW on Baltic Sea ecosystem.

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