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Abstract

The objective of this work is to review studies on the development of environmental research on the Baltic Sea region in this millennium. In this century, the environmental problems of the Baltic Sea region have attracted the attention of many researchers. The Baltic Sea is one of the most affected seas in the world. Anthropogenic activities, such as agriculture, aquaculture and fisheries, combined with the impact of climate change have led to high levels of pollution and eutrophication. Over the years, new aspects of environmental problems, including contamination from dumped munitions and microplastic pollution, pharmaceutical waste and the spread of non-indigenous species, have become matters of great interest for researchers. The findings of this report show that most of the earlier studies focused on pollution, eutrophication and climate change, in different combinations.

Key words: Baltic Sea region, environmental problems, pollution, climate change, eutrophication

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1 Introduction

The Baltic Sea is one of the largest brackish shallow water basins. The Baltic Sea region is densely populated and consists of 10 countries[1]. The Baltic Sea is rapidly warming due to climate change, anthropogenic activities are still causing eutrophication and the spread of hypoxic and anoxic areas. Low resistance to pollution makes the task of the Baltic Sea difficult.

A method used in this study is a literature review aimed at quantifying and mapping the research carried out on the Baltic Sea region's environmental problems since the beginning of the millennium. To identify the main environmental challenges and scientific achievements for the Baltic Sea region over the past two decades, a systematic literature review was carried out on a total of over 500 articles, classified according to date and topic of publication, methods used and main discoveries. The relevance was determined by the content of the article rather than by formal attributes. Articles published in 2023 were included for the first half of the year. Though not all relevant publications on the topic are included in the study, it is assumed that the presented selection of articles is sufficient to identify the main trends in environmental studies on the Baltic Sea region. The articles were categorised according to themes, and attributed with several indices, if necessary. The review was carried out in chronological order using the search engines ResearchGate and ScienceDirect with the terms "environmental challenges" and "climate change" and "Baltic Sea", and manually assessed as relevant to the Baltic Sea region's environmental challenges. Searches were restricted to the English language.

The key topics for the categorisation process were derived from the lists of top environmental challenges provided by governmental and non-governmental environmental organisations (NGOs) (see Table 1). Environmental issues will continue to be on the agenda for decades and become even more topical. Nevertheless, over the course of time and the development of science, priorities and emphases tend to change.

Table 1. The top five environmental risks in the Global Risk Reports published by the World Economic Forum (WEF) and by the International Institute for Sustainable Development

2010 Word "environmental"	2015 by likelihood Word "environmental"	2020 by likelihood over the next 10 years Word "environmental"	2020 by severity of impact	2021 by likelihood Word "environmental"	2021 by severity of impact
Extreme weather	Extreme weather events	Extreme weather events	Failure of climate change mitigation and adaptation	Extreme weather	Climate action failure
Droughts and desertification	Major biodiversity loss and ecosystem collapse	Failure of climate change mitigation and adaptation	Weapons of mass destruction	Climate action failure	Biodiversity loss
Water scarcity	Major natural catastrophes	Major natural disasters	Major biodiversity loss and ecosystem collapse	Human environmental damage	Natural resource crises
NatCat: Cyclone, Earthquake, Inland flooding, Coastal flooding	Man-made environmental catastrophes	Major biodiversity loss and ecosystem collapse	Extreme weather events	Biodiversity loss	Human environmental damage
Air pollution		Human-made environmental damage and disasters	Water crises		Extreme weather

Source: https://www.iisd.org/

1 Denmark, Estonia, Finland, Germany, Latvia, Lithuania, Norway, Poland, Russia and Sweden

Greenpeace, the World Wildlife Fund (WWF) and Earth Org. also publish lists of environmental challenges, which could be divided into several groups: climate change, environmental justice, pollution, resource depletion and waste problems.

Table 2. Top environmental challenges identified by non-governmental environmental organisations

	Greenpeace	WWF* (2022)	Earth.Org** (2022)
Climate change	+	+	+
Global warming from fossil fuels			+
Greenhouse effect			
Rising sea levels			+
Environmental justice	+		
Poor governance			+
Illegal wildlife trade		+	
Illegal fishing		+	
Pollution		+	
Air pollution			+
Plastic pollution	+		+
Food and water insecurity			+
Ocean acidification			
Resource depletion			
Deforestation	+	+	+
Forest degradation		+	
Overfishing		+	
Biodiversity loss			+
Agriculture	+		+
Water scarcity		+	
Soil erosion and degradation		+	
Waste problems			
Fast fashion and textile waste			+
Food waste			
Other			
Bacteria resilience			
Overpopulation			

* https://www.worldwildlife.org/threats
** https://earth.org/the-biggest-environmental-problems-of-our-lifetime/

This list roughly corresponds to the top topics of environmental science, including studies related to the environmental problems in the Baltic Sea region, such as climate change, eutrophication, pollution (chemical and heavy metal contamination, pollution by organic substances, radioactive contamination, pharmaceutical waste pollution, plastic pollution and litter, and munition dumpsite pollution), maritime traffic and oil and gas transportation pollution. The total number of publications found on environmental problems in the Baltic Sea region for 24 years (from 2000 to the first half of the 2023) was 562.

Pollution was the most common theme among the aforementioned studies (331), eutrophication was the second most common (152) and climate change impact was third (96). Many articles dealt with two or more environmental problems simultaneously, and therefore the total number of observations numbers 1,318. The studies were divided into five time periods: 2000–2005, 2006–2010, 2011–2015, 2016–2020 and 2021–2023 (see Table 3).

Table 3. A division of environmental studies concerning the Baltic Sea region by theme

Year	Climate change	Eutrophication	Pollution	Chemical and heavy metal contamination	Bio- and geno pollution	Plastic pollution and litter	Resources management	Waste treatment	Oil and gas contamination	Maritime traffic	Atmospheric pollution	Methods of study	Environmental management	Pharmaceutical waste	Agriculture waste	Munition dumpsites	Radioactive contamination
2000	-	4	7	4	1	1	2	1	-	-	1	1	-	-	2	-	-
2001	1	5	8	3	1	1	2	1	-	-	2	7	2	-	-	-	-
2002	2	9	16	9	2	-	5	1	-	-	1	10	3	-	4	-	2
2003	4	11	19	7	1	-	3	4	1	2	3	6	5	-	5	-	6
2004	5	7	14	5	1	-	3	1	1	2	1	5	2	-	1	-	3
2005	1	6	8	4	1	-	1	1	-	-	-	5	-	-	1	-	1
2006	3	1	10	4	-	-	1	1	-	-	1	5	2	-	-	-	4
2007	-	3	6	3	1	-	1	-	-	1	-	1	3	-	-	-	2
2008	1	9	13	7	-	-	2	3	4	-	2	3	6	-	2	1	-
2009	3	3	14	13	1	-	4	5	-	1	2	3	2	-	-	2	-
2010	5	8	12	10	1	-	2	2	3	1	1	6	4	-	2	1	-
2011	7	5	17	7	-	-	6	1	1	3	2	4	6	1	2	-	5
2012	10	6	9	4	1	-	5	1	3	2	3	4	6	1	2	-	1
2013	1	4	8	1	1	-	2	1	-	-	1	3	3	-	-	-	4
2014	5	10	13	6	-	-	3	1	1	2	2	5	8	-	-	-	3
2015	10	8	8	3	1	-	5	-	1	2	1	4	9	1	2	-	1
2016	4	4	14	6	3	-	2	8	-	1	-	3	-	2	1	3	3
2017	2	6	12	5	2	2	1	4	-	2	2	2	4	1	1	-	-
2018	8	9	20	7	-	5	3	4	-	2	1	5	8	2	2	1	1
2019	9	8	23	6	1	8	3	8	1	6	1	4	7	1	2	3	-
2020	5	8	18	5	-	4	3	10	-	3	-	7	3	2	1	6	-
2021	2	8	28	9	1	11	2	3	1	6	6	8	4	-	2	1	1
2022	7	3	27	9	-	7	3	6	-	3	1	7	3	2	-	2	3
2023	1	7	7	2	1	3	-	1	-	1	-	6	1	-	1	2	1
	96	**152**	**331**	**139**	**21**	**42**	**64**	**68**	**17**	**40**	**34**	**114**	**91**	**13**	**33**	**22**	**41**

2. Literature review for the period 2000–2005

Auer and Nilenders (2001) identified 132 hot spots of pollution in the Baltic Sea region based on the results of the Joint Comprehensive Environmental Action Programme. Shevagin (2001) studied the environmental problems of the Baltic Sea region from the Russian point of view with an emphasis on pollution challenges. In turn, Laitinen and Neuvonen (2001) analysed references to published information on the environmental aspects of the Baltic Sea and created a database of more than 11,000 references within the framework of the Baltic Marine Environment Protection Commission.

Dave (2001) assessed the Swedish monitoring system for the marine and coastal environment of the Baltic Sea according to the major threats to the marine environment, i.e. eutrophication, toxic organic pollutants/metals and physical disturbance. Schiewer and Gerald (2004) examined the anthropogenic pressure (eutrophication, traffic, harbours, tourism and offshore wind parks) on the coastal ecosystems of the Baltic Sea. Selin and Vandeveer (2004) compared the environmental strategies of the Baltic Sea region countries aimed at reducing hazardous substances and human health risks.

Climate change: the environmental problems of the Baltic Sea connected to the negative effects of climate change started to draw more attention among researchers. Possible responses to changing climate in the Baltic Sea and the regions around it were studied from different angles. It became clear that the Baltic Sea is different from other seas and extremely sensitive to possible climate changes and exists in a very narrow climatological niche (Stipa and Attila 2003). Stigebrandt and Gustafsson (2003) prepared models for the possible responses of the Baltic Sea salinity to climate change. Winsor et al. (2001) showed that climate control scenarios must cover several decades due to the large variations in freshwater supply to the Baltic Sea. Graham (2004) proved that climate change in the Baltic Sea region will lead to changes in river flows into the sea. Such changes will potentially impact many sectors of society, ranging from basic water supply to large-scale environmental consequences. Semmler and Jacob (2004) simulated climate change effects on the occurrence of extreme precipitation events for the Baltic Sea region and found that they are very pronounced. Also, the sea level rise for the Baltic Sea region caused by global warming has been studied (Staudt and Kordalski, 2005). Staudt et al. (2004) modelled flooding events caused by climate change and predicted severe impacts on the spatial development of cities and regions in the Baltic Sea region.

The connection between eutrophication and climate change became a field of study. Rönnberg and Bonsdorff (2004) pointed to the climate change negative impact on eutrophication processes in the Baltic Sea and to the fact that the amounts of nutrients in the Baltic Sea have increased several times during the 20th century due to global warming. Neumann and Schernewski (2005) simulated the consequences of the combination of climate change with nutrient load reductions and showed that this will cause imbalances in the Baltic Sea's ecosystem for decades before a new system state will be reached.

Several climate models and reconstructions were developed to analyse possible climate changes in the Baltic Sea. Different types of models using long-term accumulated measurement data were proposed by Hurk et al. (2002). Kont et al. (2002, 2003) studied climate change scenarios based upon assessments of the water resources of Estonian rivers running into the Baltic Sea and proved that the environment of Estonia is sensitive to climate change and rises in sea level.

The dependence of fish resources in the Baltic Sea on climate change variations was surveyed by, for example, Orlowski (2003) and Kallio-Nyberg et al. (2004). Long-term climate instability can strongly affect the temporal distribution of fish, and annual environmental factors, such as sea surface temperature variations, have an influence on the survival of fish.

Eutrophication: Persson and Jonsson (2000) studied the eutrophication level of the Baltic Sea in the past century and proposed a reduction in nutrient discharges to the level of the 1950s and the 1920s. The nutrient loads and the long-term nutrient trends for the southern part of the Baltic Sea (the Gulf of Riga) from agriculture were evaluated by Vagstad et al. (2000) and Yurkovskis (2004). These researchers found that the nutrient trends are extremely complex and require the environmental management of agricultural land. According to Meyer-Reil and Köster (2000), the effects of eutrophication on sediments caused by nutrient loads remain a serious problem in the southern Baltic Sea. Nilsson and Jansson (2002) examined the turnover of phosphorus and nitrogen in a low salinity estuary in the Bothnian Sea. The negative impact of nutrient enrichment became evident in the northern Baltic Sea and involved the reduction of seagrass biomass and the loss of valuable faunal habitats (Boström et al., 2002). Hart (2003) reported on the problem of the eutrophication of coastal waters of the Baltic Sea (Sweden) caused by nitrogen pollution.

Fish farms in the region as a source of nutrition loads on the Baltic Sea became a matter of concern. Peuhkuri (2002) studied the debate on water eutrophication and the fish farming industry in the Finnish Archipelago Sea in southwest Finland. Correspondingly, Nordvarg and Johansson (2002) assessed fish farms' negative effects on the nutrient load in the Baltic Sea in the Åland archipelago.

The history of eutrophication in the southern Baltic Sea confirmed that the Gulf of Gdańsk retained nitrogen and phosphorus loads (Witek et al., 2003; Łysiak-Pastuszak et al., 2004). The Baltic Sea lagoons, such as the Szczecin Lagoon, influenced by eutrophication and changes in oxygen content, may release pollutants into the sea (Kowalewska, 2003). Lehtoranta et al. (2004) wrote on the eutrophication of the estuary of the river Neva and the estuarial Baltic Sea area caused by the high nutrient load from St. Petersburg. Feuerpfeil et al. (2004) pointed to the differences in the degrees of eutrophication of the Southern Baltic and the need for managing the coastal ecosystems. Savchuk (2005) showed that the Baltic Sea annually delivers to Skagerrak masses of nutrients, equivalent to 15% of nitrogen and 45% of phosphorus inputs from land and the atmosphere.

The nature of cyanobacterial blooms in the Baltic Sea and their connection to eutrophication have been analysed by, for example, Gisselson et al. (2002), Kanoshina et al. (2003) and Stal et al. (2003). High or unbalanced nutrient loads and weather conditions, including rising temperatures, are responsible for the blooms.

Multiple methods to assess the level of eutrophication in the Baltic Sea were developed. Savchuk (2002) described the model for the Gulf of Riga's major nutrient fluxes and showed that the most effective nutrient reduction scenario is combined nitrogen and phosphorus reduction. Nutrient emissions from fish cage farms and its eutrophication impact on the Baltic Sea were evaluated by Nordvarg and Håkanson (2002) and Gyllenhammar and Håkanson (2005) using models that predict the impact of farm-emitted phosphorus. In turn, Sagert et al. (2005) studied the abiotic effects on eutrophication in the Baltic Sea, evaluating the influence of decreased salinity on marine species (phytoplankton and microphytobenthos) along the Danish Baltic Sea coastal areas.

Kangas and Syri (2002) described the regional nitrogen deposition model DAIQUIRI, which represents the spatial deposition pattern for the Baltic Sea near Finland. Tett et al. (2003) introduced a screening model for the OAERRE project assessing eutrophication along the Baltic coast of Sweden. Kauppila et al. (2003) presented an empirical model to predict bottom oxygen concentration from nutrient load or morphometry in the coastal waters of the Baltic Sea.

Another model for evaluating eutrophication factors in the Helsinki Sea area was presented by Korpinen et al. (2004). Kowalewska (2005) proposed a method of quantitative comparison of eutrophication for the Baltic Sea based on the pigment content in sediments. In turn, Gren and Folmer (2003) developed a model for allocating the abatement of nitrogen emissions among the countries surrounding the Baltic Sea.

Stålnacke et al. (2003) showed that cuts in nutrient inputs from agriculture do not necessarily cause an immediate positive response in reducing eutrophication for the southern Baltic Sea. Archambault (2004) studied ecological modernisation of agricultural practices in the Baltic Sea region aimed at reducing nutrient emissions into the Baltic Sea, with southern Sweden as an example. Hart and Brady (2002) described the development of an optimal control model for the cost-effective management of leachates from agriculture, and Elofsson (2003) calculated cost-effective solutions to nutrient load reductions in the Baltic Sea. Paludan et al. (2002) analysed the possible use of wetlands management around the Baltic Sea to minimise eutrophication in the region.

Governmental programmes for environmental protection in the Baltic Sea region have been approached from the eutrophication point of view by several scholars. Skei et al. (2000) summarised the results of the Swedish research programme EUCON for the problems of eutrophication and contaminants in the Baltic Sea. Lundberg et al. (2005) assessed coastal eutrophication of the Baltic Sea using data from the Finnish environmental eutrophication monitoring programme. According to Räike et al. (2003), improvements in wastewater treatment in Finland clearly decreased phosphorus concentrations in Finnish rivers and lakes running into the Baltic Sea.

Pollution management: Kohonen (2003) rated the inter-governmental conventions on the protection of the Baltic Sea and Finnish strategies for pollution control, concluding that the highest annual cost will be environmental support to agriculture. Gasoline lead reduction regulations in Europe and in the Baltic Sea region were evaluated by Von Storch et al. (2003) with a retrospective analysis of the extent of regional-scale lead pollution performed. Mickwitz (2003) pointed to the uncertainties of permit limits for discharges of the Finnish pulp and paper industry.

Evaluation of pollution and emissions for the Baltic Sea region was performed. Reimann et al. (2000) introduced a geochemical data set of potentially toxic elements in agricultural soils for the countries surrounding the Baltic Sea. Pacyna (2003) investigated long-term usage and emissions for toxic pesticide components and showed that the decrease was mainly caused by the implementation of abatement measures (EU POPCYCLING-Baltic project).

Chemical and heavy metal pollution: chemical pollution in the Baltic Sea region has been studied by several researchers. For instance, Fromberg et al. (2000) calculated the impact of chemical pollution on fishery. Hlawatsch et al. (2002) reported on anthropogenic metal emissions started in the second half of the 19th century. In turn, Leipe et al. (2005) wrote on the environmental effects of the industrial waste material from dumping sites in the Baltic Sea from late 1950s and early 1960s. Kremling and Streu (2000) noted a significant decrease of the Cd, Cu, Ni, Zn and Pb concentrations in Baltic surface waters between

1982 and 1995. Anthropogenic contamination by metals was assessed for the different regions of the Baltic Sea, including the Polish zone of the southern Baltic Sea (Sokolowski et al., 2001).

Atmospheric chemical and heavy metal pollution started to attract more attention. Urba et al. (2000) investigated gaseous mercury pollution for the region during the summer months. Sofiev et al. (2001) introduced atmospheric transport models for the investigation of airborne heavy metal pollution and depositions over the Baltic Sea. Vana and Tamm (2002) estimated an experimental-observational method applicable for the study of particulate air pollution propagation in the Baltic Sea region. Müller (2002) supported the earlier hypothesis that the lagoons may act as flow-through areas for heavy metals despite being an initial trap for heavy metals.

New methods of chemical and heavy metal contamination evaluation were developed for the mercury contamination determination and measurement (Wurl et al., 2001; Marks, 2002). Biochemical parameters as biomarkers for estimating the effects of the contamination levels were proposed by Nyman et al. (2003) and Napierska and Podolska (2005).

Karl et al. (2002) evaluated the daily intake of dioxins from fish consumption in Germany. Denafas et al. (2004) predicted that carbon dioxide and sulphur dioxide emissions from power production in the Baltic region will increase. Nilsson et al. (2002) and Szefer et al. (2002) observed chemical contamination and metal concentrations in the Baltic Sea's fauna, seals, and mussels in particular. No clear reduction of the metal burden has been observed since the 1970s. Later Szefer et al. (2003) studied fish heavy metal pollution.

Floods in the Baltic Sea region enhanced the transport of anthropogenic elements and elevated levels of chemical and heavy metal contamination (Pohl et al., 2002 and Glasby et al., 2004). Dippner and Pohl (2004) analysed heavy metal concentrations from annual sampling in the period 1993–2000 using empirical orthogonal functions.

Pollution by organic substances: studies of pollution of the Baltic Sea by organic substances in the early 2000s produced controversial findings. For example, Kot-Wasik et al. (2004) observed changes in organic pollution of the coastal waters of the Gulf of Gdańsk (the Baltic Sea) by volatile and semi-volatile organic pollutants. Roose and Roots (2005) monitored hazardous substances in Estonian rivers and in the coastal Baltic Sea. These researchers reported that pollutant levels were not high.

Gesine (2002) followed polycyclic aromatic hydrocarbons PAHs in the seawater of the whole Baltic Sea during different seasons. In winter, PAH concentrations rose, hot spots were observed mainly in the western Baltic Sea and in estuarine samples. Joukainen and Yli-Halla (2003) investigated the influence of sulfidic materials on the quality of drainage water. Organochlorine compounds (polychlorinated biphenyls or PCBs) and other persistent organic pollutants showed no clear decline in the Baltic Sea (Kiviranta et al., 2003 and Sapota, 2004). Ecotoxicological risks associated with herbicides and organotins in North and Baltic Sea marinas had not diminished (Biselli et al., 2000). The contamination of the Gdańsk Bay with various organic compounds originated from different sources (Biziuk, 2001). De Wit (2002) pointed to the high level of contamination from cities and agriculture in the Baltic region, brominated flame-retardant levels were increasing. Analysis of water and bottom sediment samples from the Odra River shores determined all basic organic pollutants (Wolska et al., 2003).

Wodarg et al. (2004) determined concentrations of PCB in the Baltic Sea region and proposed a method for evaluating PCB concentrations in seawater. Contamination of persistent organic pollutants in fish, birds and mammalian predators (seals) in the Baltic Sea region was studied by Falandysz et al. (2004), Norström et al. (2004) and Routti et al. (2005). Albalat et al. (2002) assessed organotin pollution along the Polish coast (Baltic Sea) by using mussels and fish as sentinel organisms. Matson et al. (2004) compared genetic damage from pollution to birds in the Baltic and Beaufort Seas and found the Baltic Sea more polluted.

Schernewski and Jülich (2001) calculated the risk of virus infections in the Oder estuary (southern Baltic) caused by sewage and pollution problems in the Baltic Sea region and found that the risk is limited to a small area of several kilometres close to the river mouth.

Radioactive contamination: studies of radioactive contamination of the Baltic Sea region attracted a lot of attention and concentrated on the consequences of the Chernobyl disaster. As an example, Saxén and Ilus (2001) investigated the transportation of radionuclides (Caesium-137 and Strontium-90) by rivers to the Gulf of Finland since 1986. Anthropogenic 137Cs in the Baltic Sea have been identified as a result of the Chernobyl disaster (Povinec et al., 2003). Toscano-Jimenez and García-Tenorio (2004) developed a model for the dispersion of radioactive substances in marine ecosystems and applied it to the Baltic Sea after the Chernobyl disaster. Lepicard et al. (2004) developed a computer code for the model, assessing the radiological consequences of radioactive releases into the marine environment and applied it to the coastal areas of the Baltic Sea. Toscano-Jimenez et al. (2005) published on scenarios of radioactive contamination of the Baltic Sea based on the models and algorithms predicting the transportation of radioactive spots to the Atlantic Ocean.

The concentration, distribution and sources of radioactive materials (plutonium and uranium) in water and sediments, as well as in fish, were studied by Skwarzec et al. (2002), Skwarzec (2003) and Strumińska and Skwarzec (2004). Kumblad et al. (2005) evaluated the bioaccumulation of radioactive 51Cr, 63Ni and 14C in Baltic Sea benthos. Knapinska-Skiba et al. (2003) wrote on the concentration of caesium-137 in seawater and plankton (the Southern Baltic Sea) before and after the flood in 1997 and found that the flood wave did not contribute to releasing the nuclide from eroded soil particles. Hou et al. (2002) and Alfimov et al. (2004) showed that more than 95% of 129I in the Baltic Sea originates from reprocessing emissions (the French nuclear fuel reprocessing plant at La Hague) from the North Sea via the Skaggerak basin.

An environmental threat posed by a repository for radioactive operational waste (carbon-14) and the nuclear fuel reprocessing (technetium-99) was examined by Kumblad et al. (2003) and Lindahl et al. (2003). The fuel reprocessing plant in Sellafield (UK) was found to be responsible for most of the 99Tc in the coastal waters of western Sweden.

Plastic pollution and litter: in the early 2000s, pollution of the Baltic Sea by microplastic and litter did not attract much research attention. However, Galgani et al. (2000) pointed to the environmental dangers of litter and debris in European seas, including the Baltic Sea.

Maritime transportation: the environmental risks related to maritime transportation were evaluated by studies of emissions from fuel combustion in a Swedish cod fishery (Ziegler and Hansson, 2003) and oil discharges from ships (Kostianoy et al., 2004). Eriksson et al. (2004) showed that recreational boats and ferryboats may cause a significant negative impact on the richness of the Baltic Sea's species and aquatic vegetation in the Stockholm archipelago. Barsiene et al. (2005) assessed the increase of the environmental mutagenesis in fish from the coastal areas of the Baltic Sea caused by oil spills.

In the early 2000s (in the years 2000–2005), research on the environmental problems of the Baltic Sea region intensified and became more multidirectional. The unique position of the Baltic Sea and the difficulties of solving environmental problems in this area was recognised by the scientific community. Pollutants, eutrophication and climate change were considered to be the main threats. The pollution problems of the Baltic Sea region were at the top of the list of priorities for researchers, and databases for the monitoring of the environmental situation were created. Different strategies for pollution control and problems of pollution management were developed. The negative effects of chemical and heavy metal pollution on fishery attracted the attention of researchers. The radioactive contamination of the Baltic Sea region was, for the most part, considered as a result of the Chernobyl disaster. Studies on microplastic pollution were rare, but this problem gradually became a matter of concern. More attention was paid to the interdependent effects of climate change and eutrophication. The problem of eutrophication was closely connected to the development of agriculture and the fish farming industry in the region.

3. Literature review for the period 2006–2010

Uggla (2007) studied the legal regulations for the particularly sensitive Baltic Sea areas and interactions between the freedom of the high sea and environmental protection law. Larsen (2008) provided a summary of the development of Baltic Sea environmental policies since the early 1970s, including inter-governmental policies. Salomon (2009) pointed out the necessity of a strategy for sustainable use of the marine environment under recent developments in European policies. The HELCOM environmental indicators and their role in shaping regional Baltic Sea environmental policy was emphasised by Backer (2008). Nechiporuk and Nozhenko (2010), in turn, evaluated the implementation of the HELCOM recommendations for eliminating eutrophication sources in the Kaliningrad region of Russia. Dimante and Atstāja (2010) analysed environmental management practices in the Baltic Sea region in connection with the economies of the countries in the region.

Climate change: the warming of the Baltic Sea and its consequences was the subject of deeper investigations in 2006–2010. The rapid warming in 1982–2006 was confined in the Baltic Sea also at rates 2–4 times the global mean rate. The extremely rapid surface warming in the enclosed and European Seas may have resulted from the observed terrestrial warming (Belkin, 2009). Looking at greenhouse gas emission scenarios for the period 1960 to 2100, the results showed that the expected warming of the Baltic Sea is 1–4 degrees (Neumann, 2010). Omstedt and Hansson (2006) studied how climate warming makes the water and air temperatures differ due to changes in the surface heat balance components, making the Baltic Sea sensitive to changes in the heat and water balance components. Hünicke (2010) applied a statistical downscaling approach for climate model simulations in the Baltic Sea and showed a significant trend in the rise in sea level for this century. The hypoxic zone in the Baltic Sea caused by climate change was evaluated by using historical data, proving the sensitively of this large, enclosed sea to anthropogenic perturbations (Zillén et al., 2008).

New climate change models were developed for environmentally friendly management in the Baltic Sea region, estimating the possible impacts of changing sea levels in the region (Schmidt-Thomé et al., 2006) and climate change effects on Baltic Sea fauna (Gröger and Rumohr, 2006).

A connection between climate change and pollution levels was discovered. Augustsson et al. (2009) modelled climate change impacts on the metal pollution of the Baltic Sea and concluded that it might have a substantial impact on groundwater trace metal concentrations. Similarly, the negative effects of climate change on the Baltic Sea fauna and fishery were reported by Kotta et al. (2009).

A new approach to climate change studies in the region was proposed by Schmidt-Thomé et al. (2010). Climate change projections and calculations were based on geoscience to support decision making for the Baltic Sea. The impacts of climate change and eutrophication on Baltic Sea fauna and the interactions between eutrophication and climate variables were important only for zooplankton.

Climate change models showed that fishery and fish resources in the Baltic Sea will experience negative effects from rising temperatures and require management decisions and risk analysis (Brandt and Kronbak, 2010; Margonski et al., 2010).

Eutrophication: spatial and temporal patterns of nutrient fluxes and their limitations were reviewed in plans for eutrophication reduction in the Baltic Sea region (Rahm and Danielsson, 2007; Danielsson et al., 2008). According to Hänninen et al. (2007), nutrient levels decrease from the mainland towards the outer Finnish Archipelago, the northern Baltic Sea. Lehtoranta et al. (2008) explained regional variation in phosphorus concentrations between the Baltic Sea sub-basins by eutrophication-driven sediment microbial processes. Ojaveer and Kalejs (2008) proposed principles of differentiation of large geographical units on an ecosystem basis that could be applied in research and for the assessment and management of ecosystems and resources in the Baltic Sea. Vaalgamaa and Conley (2008) studied sediment nutrient concentrations in the Gulf of Finland. Schmid et al. (2008) calculated the flow of phosphorus to the Baltic Sea from the consumption and production of food for an average inhabitant of a Swedish city, Linköping, from 1870 until 2000.

High levels of eutrophication were observed for the Curonian and Vistula lagoons (Aleksandrov, 2010), as well as for the Neva Estuary (Kuuppo et al., 2006, Golubkov and Alimov, 2010) in the Baltic Sea. Kotta et al. (2009) examined the separate and combined impacts of nutrient loading and climate change on fauna in the Gulf of Riga.

Nikulina and Dullo (2009) estimated changes in eutrophication in the Flensburg Fjord (Germany) and found that sediments from the inner fjord contained more organic material in 2006 than in 1972. Eutrophication trends in the Gulf of Bothnia (1980–2007) showed warning signals for the future (Lundberg et al., 2009), with a need for new perspectives on rainbow trout aquaculture (Saikku and Asmala, 2010).

Future eutrophication scenarios showed increased nutrition fluxes from the northern catchments draining into the Gulf of Bothnia and the Gulf of Finland and the Gulf of Riga (Eriksson et al., 2010), and rising demand for the clean water endangered by eutrophication in the Gulf of Finland, the Baltic Sea. Artioli et al. (2008) evaluated the effectiveness of policies to reduce anthropogenic nutrient inputs to European seas and noted success in the area of phosphorus input decrease in the Baltic Sea.

Neumann and Schernewski (2008) used a 3D ecosystem simulation model to predict eutrophication in the Baltic Sea and showed a strong dependence of the Baltic Sea ecosystem on forcing conditions. Gren and Elofsson (2007) examined nutrient trading market designs for total costs and the achievement of stipulated nutrient reduction targets for the Baltic Sea. Kowalkowsk (2009) presented the chemometric approach to the classification of nutrient emission for the Vistula River basin (Poland).

The negative effects of agriculture on eutrophication in the Baltic Sea region were reported by Granstedt et al. (2008) based on the example of 12 Swedish farms, with a proposal of an ecological recycling agriculture system. Malmaeus and Karlsson (2010) reviewed measures to reduce phosphorus leakage from Swedish agriculture to achieve environmental goals. Larsson and Granstedt (2010) studied the impact of the governance of agriculture on the environment of the Baltic Sea, evaluating different scenarios for the Baltic States and Poland.

Pollution management: Gren (2008) compared the cost-effectiveness of transboundary water pollution mitigation strategies and measures to improve assistance for decision making and environmental management. Otremba and Andrulewicz (2008) reviewed the maritime environmental regulations on existing and planned technical installations in the Baltic Sea.

Staniškis et al. (2008) focused on the application of preventive innovations and use of an integrated water resource management model as a tool to reduce pollution load in the Baltic Sea. Skowrońska et al. (2009) studied chemical pollution problems in the Baltic Sea region in relation to socio-economic drivers. The marine ecosystem of the Baltic Sea is under strong atmospheric and anthropogenic pressure because of climatic regime shifts (Möllmann et al., 2009).

Olenin et al. (2007) proposed a method to evaluate the impact at five different levels of bio-pollution and the introduction of alien species to marine environments as a factor that can be viewed as a pollution agent.

Chemical and heavy metal contamination: Pempkowiak et al. (2006) evaluated the heavy metal contamination level in zooplankton from the Southern Baltic and found them to be elevated in nearshore samples compared to the open sea. In the Baltic Sea, the fish contamination level is affected by agricultural waste pesticides (Szlinder-Richert et al., 2008). Polak-Juszczak (2009) and Routti et al. (2010) confirmed the decreased levels of heavy metals concentrations in fish and in Baltic ringed seals.

Anthropogenic contamination by metals was calculated for the Gulf of Riga (Yurkovskis and Poikāne, 2008), and it was found that the Daugava estuary shows higher contamination by Cd, Pb and Zn compared to the average values for world rivers. In the Gulf of Finland, historical sediment heavy metal distributions are modified by human actions, and the most important factor affecting the sediment accumulation rate is the level of agriculture in the catchment (Vaalgamaa and Conley, 2008). Bindler et al. (2009) studied the negative effects of pre-industrial mining on waterborne metal pollution in lake sediments from the Bergslagen region in central Sweden and showed that the background level of a pollutant element cannot always be defined as the concentration that occurred at the time prior to the actual start of industrialisation.

New methods of biomarker application for an assessment of environmental chemical and metal pollution of the Baltic Sea were developed by Broeg and Lehtonen (2006) and Hendożko et al. (2010). Lehtonen and Schiedek (2006) evaluated the efficiency of the environmental monitoring programmes in the Baltic Sea region regarding the biological effects of contaminants.

Sources of mercury contamination are diversified for the Southern Baltic Sea (Bełdowski and Pempkowiak, 2007) and concentrations at the air/sea interface were over 10 times greater than those observed in bulk surface water (Saniewska et al., 2010). Mercury contamination has significant concentration differences between species in the food chain (Nfon et al., 2009). Pollution of the Baltic Sea by perfluorochemicals, flame retardants and brominated hydrocarbons have been researched by, for example, Ahrens et al. (2010), Barska and Grabic (2010) and Gieroń et al. (2010).

Pollution by organic substances: studies showed positive trends in pollution of the Baltic Sea by organic substances and pointed to the decrease of organochlorine compounds (PCB) and dioxin content. Pikkarainen and Parmanne (2006) and Karl and Ruoff (2007) showed that the dioxin content in spring herring seems to have decreased between 1996 and 2004. According to Milukaite (2006), the benzo(a) pyrene concentration on the eastern coast of the Baltic Sea in atmospheric air has decreased since 1999. Koistinen et al. (2008) compared organohalogen contaminants in Baltic herring in the Gulf of Finland and found it less polluted than in the Bothnian Bay or the Bothnian Sea. Pandelova et al. (2008) studied the contamination of fish (PCDD/F and PCB concentrations) in the Baltic Sea from four areas of the Estonian coastal waters.

Szlinder-Richert et al. (2009a, b) argued that no further decrease to levels lower than those from 2001 was observed. Also, according to Karl et al. (2010) PCB levels in herring showed no obvious change in contamination levels since 2003.

Negative trends were noted in the pulp and paper industry in Finland and in the Russian part of the Baltic Sea. Verta et al. (2007) and Salo et al. (2008) confirmed dioxin heavy pollution from a chlorophenol production plant in the town of Kuusankoski, Finland. Shelepchikov et al. (2008) showed that in some cases dioxin pollutant levels of Russian Baltic fish essentially exceeded current regulatory values.

Sellström et al. (2009) analysed dioxin contamination of the Baltic Sea caused by atmospheric depositions and found strong correlations to the concentration of soot. Ulevicius et al. (2010) evaluated the impact of air pollution in the Baltic Sea region caused by forest fires and found regional biomass fire emissions as a source. Another biomarker method to evaluate pollution levels and the effects on the Baltic Sea was developed by Pikkarainen (2006). Armitage et al. (2009) assessed the methods of evaluating the contamination of the Baltic Sea with dioxins in relation to restrictions on the marketing and consumption of Baltic Sea fish.

Radioactive contamination: numerous tests were conducted in the Baltic Sea region and the results showed the presence of radioactive contamination. The activity concentration of 137Cs in Baltic Sea water was the highest when compared with data for the world's oceans (Davuliene et al., 2006) and a clear correlation was found with the content of clay particles at the sampling depth of seawater (Lujanien et al., 2006). Strontium showed slower changes in activities (Zalewska and Lipska, 2006). Lukšienė et al. (2006) demonstrated heterogeneous spatial distributions of radionuclides in the soil layers on the Baltic coast of Lithuania. Aldahan et al. (2007) pointed to the liquid releases from the reprocessing facilities at Sellafield and La Hague as a source of Iodine-129. According to Skwarzec and Fabisiak (2007), marine birds are a very important link in polonium transfer from the atmosphere to the water environment in the Polish part of the Baltic Sea.

Munition dump sites: munitions dump site-related environmental problems became a new trend in research. The release of chemical warfare agents (CWAs) in the Baltic Sea is expected to peak over the next decades. The potential indirect human health risks due to the consumption of CWA-contaminated fish would not change fishing limitations in the dumpsites (Sanderson et al., 2008 and 2009). The evaluation results for a chemical munitions dump site in the Baltic Sea indicate that the contamination is widely spread (Missiaen et al., 2010). Szarejko and Namieśnik (2009) discussed analytical methods for the detection of chemical warfare agents from the long-term disposal of munitions underwater. Frenzel et al. (2009) presented the results of experimental sediment dumping and the environmental impact on southern Baltic Sea fauna.

Oil and gas transportation: the transportation of oil and gas on the Baltic Sea became a topic of environmental study when new gas pipeline construction started in the Baltic Sea. The Baltic Sea's ecological safety and the risks of hydrocarbon transportation on the Baltic Sea were studied by Karm (2008) and Koivurova and Pölönen (2010). The environmental problem of possible oil spills in the Baltic Sea was discussed by Hassler (2008) and Kreitsberg et al. (2010) regarding the regions of Sweden and Estonia. Hassler (2010) analysed environmental safety in Baltic Sea oil transportation and concluded that similar drivers of bilateral and sub-regional initiatives targeting specific aspects of marine safety and contributing to overall collective benefits from improved environmental protection. Knudsen (2010) approached maritime rules and policies from the environmental point of view of Russian oil exports on the Baltic Sea. Valeur et al. (2008) reported on the environmental risks of construction of gas pipelines connecting Russia and Germany and found no long-term impacts on the marine life of the Baltic Sea.

In 2006–2010, the three main environmental problems remained the same. More studies were conducted on the general environmental policies and regulations in the Baltic Sea region. Studies of pollution mitigation strategies and measures continued. The development of studies on organic pollution in the Baltic Sea region showed new trends and negative effects. Interest in radioactive contamination studies slightly declined compared to the previous period, although new sources of such contamination were identified. Studies on environmental problems caused by munitions dump sites in the Baltic Sea made it possible to do risk assessments. Climate change studies continued following the global trend, with more attention paid to regional differences and various scenarios based on sophisticated models. the interdisciplinary approach to climate change research became common, such as the use of geoscience methods. Measures for reducing the level of eutrophication in the Baltic Sea region were proposed, especially for the agricultural sector and nutrient trading markets. Following the start of construction of gas pipes in the Baltic Sea, more research was conducted on the environmental risks to maritime transportation.

4. Literature review for the period 2011–2015

Environmental policies: environmental policies in the Baltic Sea region were analysed by Kapaciauskaite (2011) and Tynkkynen (2013), who pointed to the emergent role of environmental non-governmental actors and to the need for highly institutionalised inter-state and transnational environmental cooperation. Later, Tynkkynen (2015a) proposed the development of international governance of the Baltic Sea environment by political trade-offs, taking Russia as an example. Rapport and Hildén (2013) investigated the role of ecological indicators for the evaluation of the environmental conditions of the Baltic Sea and their role in the improvement of policy responses. Hegland et al. (2015) studied the implementation of ecosystem-based marine fisheries management in the Baltic Sea.

Climate change: Lépy (2012) applied a geographical approach to understanding climate and marine processes and their environmental consequences in the Baltic Sea and emphasised the importance of ice studies. A cross-ecosystem approach was used to assess the climate change impacts in coastal areas of the Baltic Sea showing that projections for Baltic shore ecosystems are bound to be highly speculative (Strandmark et al., 2015). Friedland et al. (2012) modelled a combination of climate change with nutrient load reductions according to the Baltic Sea Action Plan, which will cause an increase in the water temperature and a salinity decrease until 2100. Climate change showed only a limited effect on loads in the western Baltic Sea. The modelling of the combined effect of climate change and changes in nutrient inputs also pointed to the possibility of more frequent anoxic events (Neumann et al., 2012). According to Meier et al. (2012), a model of a future climate and water quality will be deteriorated compared to present conditions. Omstedt et al. (2015) followed the development of climate science regarding the Baltic Sea from when observations began in the 18th century to the early 21st century.

The connection between climate change and eutrophication became one of the most studied areas among the Baltic Sea's environmental problems. Voss et al. (2011) investigated the evolution of eutrophication in the Baltic Sea and future climate change scenarios, which may lead to changed nutrient and organic matter input in the Baltic Sea. According to climate change scenarios, nutrient fluxes in the Baltic Sea will increase significantly, with regional variations (Donnelly et al., 2011). For Finnish catchments, the negative effects of climate change and agricultural are expected to increase nitrogen and phosphorus loading in the Baltic Sea (Huttunen et al., 2015). Ahlvik and Hyytiäinen (2015) predicted negative economic impacts caused by climate change through increased nutrient runoff into the Baltic Sea. According to Horn et al. (2015), climate warming led to a reduced time-lag between the phytoplankton bloom and an microzooplankton biomass maximum. Gubelit (2015) analysed the impact of climatic factors on the macroalgal community in the Baltic Sea. Mackenzie et al. (2012) showed how climate change and eutrophication will affect the populations and ecosystems of the Baltic Sea by coupling three oceanographic models of the Baltic Sea to two regional atmosphere model simulations.

Oxygen conditions in the Baltic Sea will deteriorate under global warming and hypoxic and anoxic areas will very likely increase (Meier et al., 2011). This will be caused by the combined effects of decreased oxygen solubility and increased respiration rates (Bendtsen and Hansen, 2013). According to projections (Lessin et al., 2014) until the end of the 21st century, anoxic conditions will frequently occur in the Baltic Sea (an example of the Gulf of Finland).

Furthermore, Harff et al. (2011) showed the effects of the changing climate on the natural and socio-economic environment of the Baltic Sea region, proving the need for downscaling of global climate models to regional levels. A model of combined future impacts of climate change and industrial and agricultural practices in the Baltic Sea catchment on the Baltic Sea ecosystem were developed by Meier et al. (2012).

The potential future climate change impact on the North Sea and the Baltic Sea ecosystem were compared by Pushpadas et al. (2015), showing an increase in sea surface temperature and a reduction in sea ice in the Baltic Sea, resulting in an increase in primary production in the Baltic Sea.

Connections between climate change and pollution were further investigated by Beldowska et al. (2012), showing possible transformations of Hg in the air associated with climate changes. The influence of climate change will bring an additional amount of water to the Baltic Sea, with a significant load of chemical substances (Szymczycha, 2015).

Several articles were published concerning environmental management and strategies. Piwowarczyk et al. (2012) pointed to the low level of awareness of environmental managers of climate change. Hoppe et al. (2012) noted that effects of climate change diminished the effectiveness of environmental measures imposed in the Baltic Sea region. Elmgren et al. (2015) analysed environmental policies including climate change and found that environmental problems are still handled separately. The combined effects of ocean acidification, eutrophication and climate change in the Baltic Sea and the implications for current management strategies were studied by Kong et al. (2014).

The problems of the Baltic Sea region's fisheries related to climate change have been examined from various viewpoints. Hinrichsen (2011) and Voss (2012) showed how rising temperatures and the decline in oxygen conditions negatively impact the fishery in the Baltic Sea. The climate change effects on Baltic Sea salinity and the potential effects on fish ecology and fisheries would be extensive (Vuorinen et al., 2015). Pekcan-Hekim et al. (2011) studied the effects of changing temperature conditions on pikeperch fisheries. Philippart et al. (2011) showed that semi-enclosed seas, such as the Baltic Sea, are more vulnerable to the loss of endemic species than open seas under climate change pressure. Bartolino et al. (2014) and Pecuchet et al. (2014) forecasted different scenarios for the fish stock in the Baltic Sea with warming climate conditions and environmental variables. Thøgersen et al. (2015) predicted severe biological and economic consequences under the current cod management plan for the Baltic Sea under climate change.

Eutrophication: Voss et al. (2011) described the evolution of eutrophication in the Baltic Sea and the projections of possible changes in nutrient and organic matter input caused by climate change. Andersen et al. (2015) studied the eutrophication problem in the Baltic Sea over a long period of time and set a baseline for the implementation of the ecosystem-based management strategies and policies. On the basis of the assessment of the development over time in 13 coastal ecosystems in the Baltic Sea region during the past two decades, eutrophication is the most important pressure impacting the ecosystem in the Baltic Sea (Olsson et al., 2015). Ojaveer and Eero (2011) addressed the methodological challenges and related uncertainties involved in marine ecosystem evaluations, using the central Baltic Sea as a case study.

Rousi et al. (2013) showed a rising trend for near-bottom temperature from the late 1960s and a negative trend for oxygen in the northern Baltic Sea. Caballero-Alfonso (2015) demonstrated that managing nutrients can create positive feedback for oxygen recovery in the coastal zone of the Baltic Sea.

Lundberg (2013) inspected the approaches to the eutrophication problem in the northern part of the Baltic Sea. Jönsson (2011) discussed media representations of the environmental risks in Sweden, with eutrophication being considered as the main threat. Varjopuro et al. (2014) studied the problem from the point of view of decision making and criticised systemic delays in reducing eutrophication of the Baltic Sea. Tynkkynen et al. (2014) pointed to the main challenges at various governance levels, which included differences between coastal countries in terms of environmental conditions, overlapping of policies at different levels, and a lack of policy integration. Jutterström et al. (2014) argued that present management strategies do not consider temporal trends and potential ecosystem change due to warming and/or acidification. Decision making to reduce eutrophication in the Baltic Sea region should consider the roles of nitrogen versus phosphorus reductions causing different eutrophication effects, the role of time, and the role spatial dimension (Ahtiainen et al., 2014). Saaltink et al. (2014) investigated the spatial distribution of trends in nitrogen and phosphorus and found that the focus of management strategies should be more on P reduction rather than on N reduction. Tynkkynen (2015b) analysed how the scientific community in Finland defines the problem of eutrophication of the Baltic Sea in connection to the transnational policy regime and found that the scientific-technical nature of the problem restricts the possibilities of public engagement. Kiedrzyńska et al. (2014b) presented possible solutions to reduce nutrient pollution in the lowland river catchment in the southern Baltic Sea (central Poland) based on the ecohydrological concept and ecological engineering.

Agriculture and food production as a main source of eutrophication in the Baltic Sea region became a matter of concern. Asmala et al. (2011) studied the nutrient balance of the food production and consumption system in seven countries in the Baltic Sea drainage area and suggested a reduction in nutrient fluxes by the more efficient use of fertilizers. Agriculture and the food chain are largely responsible for eutrophication and negatively affect the marine environment in the Baltic Sea region (Vorne et al., 2012). Bongghi et al. (2012) described the net anthropogenic nitrogen/phosphorus input Calculator Toolbox (NANI/NAPI) designed to assess nutrient loads in the Baltic Sea from agriculture. Kiedrzyńska et al. (2014a) found phosphorus and nitrogen loads in the Baltic Sea were related to the number of pigs and the human population associated with wastewater treatment plants per unit area. Granlund et al. (2015) compared model results from three catchments in southern and western Finland and suggested ecological recycling agriculture to reduce nutrient inputs in the Baltic Sea.

A connection between the impact of climate change and eutrophication in the Baltic Sea region has been studied by Meier et al. (2011, 2012a, b) with an emphasis on oxygen conditions, plausible nutrient load changes and agricultural practices in the Baltic Sea catchment. Cvetkova and Alekseev (2013) confirmed that deep retreatment of effluents from St. Petersburg is not enough to prevent eutrophication of the Baltic Sea. Lessin et al. (2014) evaluated the response of nutrient and chlorophyll fields to climate change by the end of the 21st century in the Gulf of Finland, predicting a decrease of near-bottom oxygen concentrations and anoxic conditions frequently occurring. According to Skogen et al. (2014), in the future climate scenarios, most of the Baltic Sea region will experience more eutrophication problems, except for the Bothnian Bay,.

Ranft et al. (2011) evaluated the eutrophication status of the Baltic Sea's protected areas using GIS technologies and found those areas being affected by eutrophication. Undeman et al. (2014) evaluated a new version of the physical–biogeochemical model BALTSEM-POP designed to calculate nutrient/carbon cycles and eutrophication in the Baltic Sea. Schernewski et al. (2015) used an integrative modelling approach which links the river basin flux model to a three-dimensional ecosystem model of the Baltic Sea to re-calculate target nutrient concentrations for German coastal waters and the western Baltic Sea.

Chemical and heavy metal contamination: assessment of relative emissions trends for basic types of pollution within the countries of the Baltic Sea region showed variations from country to country (Batóg and Batog, 2011). According to Ojaveer and Eero (2011), the results of marine ecosystem estimates are affected by a broad spectrum of human activities and natural processes, including pollution by hazardous substances. The cumulative impact of anthropogenic pressures on the Baltic Sea depends on the population densities of the adjacent catchment areas (Korpinen et al., 2012).

The levels of many polluting substances in the Baltic Sea have been reduced, but pollution from already banned substances remains a problem (Elmgren et al., 2015). Garnaga-Budrė (2013) showed that integrated monitoring of hazardous substances and their effects on aquatic organisms in the Baltic Sea region is an important tool to reduce pollution levels.

Karlsson et al. (2011) investigated how present governance relates to risks and objectives, concluding that the key environmental objectives are not likely be met for the handling of hazardous chemicals in the Baltic Sea. Nechiporuk (2014) analysed new patterns of interaction on environmental issues in the Baltic Sea region in relation to the need for transboundary regional environmental protection.

The situation with chemical and heavy metal contamination continued to be a top concern in studies. Bełdowska et al. (2014) studied variations throughout a whole year of mercury input in the southern part of the Baltic Sea, stating that the contributions of Poland to the total deposition of Hg in the Baltic Sea were overestimated. Zalewska et al. (2015) showed a significant increase in heavy metal input occurring in the offshore areas of the southern Baltic Sea after the year 1920. The Gulf of Gdansk experiences greater anthropogenic stress due to chemical contamination, especially by polybrominated diphenyl ethers when compared with other localities within the southern Baltic Sea area (Waszak et al., 2012).

Biomonitoring methods were proposed for mercury contamination assessments by Polak-Juszczak (2011) and Raisa et al. (2014). Contamination of five commercially valuable fish species in the Baltic Sea was rated for organic mercury by Kwaśniak et al. (2012), and no danger in food consumption was found. Koponen et al. (2015) examined the contamination of fish in the Baltic Sea through perfluoroalkyl acids, confirming that in the Finnish diet the consumption of domestic fish is a source of PFAAs. Dabrowska et al. (2014) documented chemical genotoxic agents causing biological effects in flounder along the southern Baltic coast. Baršienė et al. (2012) evaluated genotoxicity risk levels of native fish species, such as flounder, herring, and eelpout, in the Baltic Sea.

A major source of atmospheric pollution by mercury in the Baltic Sea region is the combustion of fossil fuels, especially coal burning used for home heating, with concentrations elevating in the winter (Siudek et al., 2011; Beldowska et al., 2012; Siudek et al., 2014). Shatalov et al. (2012) used an atmospheric modelling approach to trace the origin and contribution of dioxins in the Baltic Sea region. Lewandowska and Falkowska (2013) demonstrated that aerosol microparticles (inorganic species, organic and elemental carbon) are more than the permitted value set and a source of pollution. Omstedt et al. (2015) studied atmospheric depositions of sulphate, nitrate and ammonium from land and shipping in the Baltic Sea. The acidification contribution of shipping is one order of magnitude less than that of land emissions.

Pollution by organic substances: pollution of the Baltic Sea region by organic substances again showed a declining trend. Niemirycz and Jankowska (2011) assessed concentrations of carcinogenic organic substances in the coastal zone of the south Baltic Sea and found they exceeded the value of 'ecologically clean' regions. Peltonen et al. (2014) determined that the concentration of most organochlorine compounds or PCBs was lower in 2010 than in 2001 and 2002. Staniszewska et al. (2011) determined emission sources that have an influence on the content of hydrophobic contaminants in benthic sediments in the Gulf of Gdansk, with the highest concentrations of contaminants being determined in the Port of Gdansk. The fate of persistent organic chemicals in the Baltic Sea region environment under changing climate conditions were evaluated by Kong et al. (2014), who evaluated them using the POPCYCLING-Baltic multimedia chemical fate model.

The fishery sector in the Baltic Sea region is still affected by persistent organic pollution. Hutniczak and Grønbæk (2011) pointed to its negative effect on the regulation and economic value of the Baltic salmon. Baltic salmon and herring on the Polish market contained high values of organic pollution (Szlinder-Richert et al., 2011), and the dioxin contamination levels of the fish from the Baltic Sea posed potential risks for consumers (Struciński et al., 2013).

Wallin et al. (2015) analysed ecotoxicological risks for the western coast of Finland in the Baltic Sea region and found a high risk of deterioration of ecosystems from acid sulphate soils fluxes from river estuaries. The introduction of alien species into the Baltic Sea (biocontamination) as an environmental threat was studied by Jabłońska-Barna et al. (2013). They found 10 non-indigenous species in the Vistula Lagoon (south-eastern Baltic Sea, Poland).

Pharmaceuticals: Zhang et al. (2011) pointed out that the contamination of the Baltic Sea through natural and synthetic hormones (steroids) used in farming is an ever-growing problem. Oskarsson et al. (2012) evaluated the effect of human pharmaceutical contamination on Baltic Sea biota. Borecka et al. (2015) for the first time evaluated the occurrence of 13 pharmaceuticals in seawaters collected from the southern Baltic Sea, finding them to be too low to cause acute toxic effects.

Plastic pollution: Stolte et al. (2015) showed that city discharges, industrial production sites, fishing activity and tourism were the most likely sources for the highest microplastic concentrations in beach sediments along the German Baltic coast.

Radioactive contamination: a reduction of radioactive contaminants in the Baltic Sea could be a slow process for iodide and iodate (129I and 127I) (Hansen et al., 2011). The concentration of 129I in the Baltic Sea that originates from water flowing from the North Sea through the Danish Straits had increased by a factor of six from 1999 to 2012 (Lehto et al., 2012). In general, the impact of 129I's hazardous radioactivity on human being is not serious in the short term and in the Bothnian Sea concentrations were two to four times lower than in the Baltic Sea Proper (Yi et al., 2013 and 2015). Another possible source of contamination in the Baltic Sea is radiocarbon from the expanding construction of nuclear industrial plants and nuclear power stations in Russia (Kulkova et al., 2011)

An important source of plutonium contamination in the Baltic Sea environment is a result of its runoff from the Vistula River drainage area, originally atmospheric fallout from nuclear weapon tests and the Chernobyl disaster (Skwarzec et al., 2011; Lujanienė et al., 2014). The Odra River and the Pomeranian River are also a source of such contamination, with distribution depending on the season, the weather conditions and the geological structure of the river bed (Strumińska-Parulska et al., 2012; Strumińska-Parulska, 2014). Global atmospheric fallout was the source of plutonium contamination for seabirds in the region (Strumińska-Parulska et al., 2011).

Zalewska and Suplińska (2013a, 2013b) discussed the distribution patterns and trends in activity concentrations of 137Cs and 90Sr in the marine environment of the southern Baltic Sea, which showed a decreasing trend in fish. The fallout from Chernobyl added to the amount of 90Sr in the same areas where the increase of 137Cs can be detected, whereas this is not the case for 241Am, which is more evenly distributed in the sea bottom (Hutri et al., 2013). The Bothnian Sea sediments are severely contaminated by the radionuclide 137C and which are not permanently buried but may be redeposited by currents or anthropogenic activities (Zaborska et al., 2014).

Maritime traffic: maritime transportation as a source of pollution was studied by Burskyte et al., 2011) for the environmental impacts of the Klaipeda Seaport (Lithuania) expansion on the eastern coast of the Baltic Sea. Kalli et al. (2012) evaluated maritime traffic in the Gulf of Finland to find solutions for decreasing lower shipborne CO_2 and NOx emissions. Höglund and Meier (2012) assessed the location of the optimal maritime routes in the Baltic Sea to minimise the dangers of oil spills. Lehmann et al. (2014) identified the higher risk of ship accidents for potential pollution in the Baltic Sea, that is, along the shipping routes and along the routes approaching harbours. Hongisto (2014) observed the impact of ship traffic emissions on airborne depositions in the Baltic Sea, showing seasonal variations. Bagočius (2015) determined the potential risks for migrating fish caused by piling activity from LNG terminal construction in the Baltic Sea (high noise levels).

Oil and gas transportation: pollution risk control and regulations in the Baltic Sea were evaluated by Kornfeld (2012), Haelg (2012), Lidskog and Elander (2012) and Aseev et al. (2014) in relation to the construction of the Nord Stream pipeline. Inari et al. (2011) compared the effectiveness of different oil combating methods from an ecological perspective, proving that the efficiency of combating oil in the Baltic Sea is highly dependent on prevailing environmental conditions and can be severely limited in many ways.

In 2011–2015 the overall amount of environmental research had risen and climate change research for the Baltic Sea region reached its peak. Studies of the connection between climate change and eutrophication increased, also when preparing the new environmental protection strategies. Research on the role of international cooperation and non-governmental actors in achieving environmental targets in the region had intensified. Biocontamination and pharmaceutical waste pollution emerged as new trends in environmental studies for the region. Eutrophication continued to be a matter of interest among researchers, with an emphasis on the history and evolution of eutrophication in the Baltic Sea region. Environmental risk assessments for the pipelines in the Baltic Sea, for which construction was still under way, also continued.

5. Literature review for the period 2016–2020

The cost-effectiveness of environmental protection measures became an area of concern for researchers. As an example, Leibus and Mazure (2017) argued that the application of fiscal instruments for the solution of environmental problems is insufficient in Latvia. Gren and Ang (2019) calculated the abatement costs of achieving multiple environmental targets under different policy regimes applied to the Baltic Sea.

Tynkkynen (2017) analysed the problem of governance barriers in implementing the evolution of the EU governance of the Baltic Sea environment. Kern and Söderström (2018) examined socio-spatial relations and their connections with ecosystem management in the Baltic Sea region. Asadov and Asadov (2020) studied environmental cooperation using the example of the Baltic region and identified the problem areas that require the application of a responsible environmental policy. Interaction between Swedish society and the Baltic Sea environment in understanding environmental risks was reviewed by Cederqvist et al. (2019).

Climate change: climate change-related studies regarding the Baltic Sea region intensified in 2016–2020. For instance, climate environmental research was performed by Charrieau et al. (2019), based on benthic foraminifera and sediment geochemistry data for the last 200 years for Öresund in the Baltic Sea. Rapid environmental responses to climate-induced hydrographic changes in the Baltic Sea entrance were noted. Holt et al. (2016) confirmed that the enclosed regional seas are more highly impacted by climate change. Gustafsson and Gustafsson (2020) showed the sensitivity of pH and the carbonate system to potential future changes in the Baltic Sea, including climate change.

Some researchers believe that changing socio-economic factors in the Baltic Sea region (land use, agricultural practices, atmospheric deposition and wastewater emissions) may have a greater impact on nutrient loads in the Baltic Sea compared to climate change by mid-century (Bartosova et al., 2019). Pihlainen et al. (2020) also supported the assumption that societal drivers outweigh the impacts of climate changing (food demand is affecting land use and nutrient loads from agricultural lands).

Coastal erosion and natural extreme phenomena (storms, floods) in the Baltic Sea caused by climate change explain the higher levels of chemical pollution (Bełdowska et al., 2016). They also lead to a mercury increase in zooplankton and in the trophic chain in the coastal zone of the Baltic Sea (Bełdowska and Mudrak-Cegiołka, 2017). More mercury is introduced into the Baltic Sea by rivers because river flow magnitude is rising with climate change (Gębka et al., 2018).

Ecosystem-based management for the Baltic Sea region has been developed in several studies. For example, Nainggolan et al. (2018) evaluated land-based climate change mitigation measures for the Baltic Sea region with a focus on water quality. In turn, Keessen (2018) assessed climate change policies of the EU Member States for the Baltic Sea region. Furthermore, Andersen et al. (2020) ranked climate anomalies as one of the top ranked stressors of the entire study area.

Projections for the fishery in the Baltic Sea under climate change effects have remained low. Voss et al. (2019) studied the effects of climate change on the triple bottom line (ecological, economic, social) of the Western Baltic cod fishery and found a drastic decrease in cod fishing. Eero et al. (2020) projected stock biomass to remain low considering current climate warming trends. LaMere et al. (2020) stated that climate change may pose a challenge for Baltic salmon management. Lehikoinen et al. (2019) discovered environment-indicator relationships within coastal fish communities in the northern Baltic Sea using machine learning-based classifiers.

Eutrophication: Eutrophication has attracted more attention as well. Retrospective studies and prognoses have become more frequent. For example, Jokinen et al. (2018) examined 1500-year multiproxy records of near-bottom water redox changes from the coastal zone of the northern Baltic Sea, concluding that the modern aggravation of coastal hypoxia is unprecedented, and it must have been forced by excess human-induced nutrient loading. Meier et al. (2019) observed development patterns of eutrophication in the Baltic Sea, including the warming effect. Szymczak-Żyła et al. (2019) showed that eutrophication events occurred in the southern Baltic Sea in the past few millennia and most probably were caused by climate warming in favourable nutrient and hydrological conditions. Simulations of eutrophication processes for past (1976–2005) and future (2069–2098) periods in the Baltic Sea were performed by Saraiva et al. (2019a, b), estimating uncertainties in projections using a climate model, combining an impact of changing nutrient loads from land, and changing climate during the 21st century. Agricultural and land use nutrition run offs into the Baltic Sea and their connections to climate change were studied by Rankinen et al. (2016) and Tamm et al. (2018). Strååt et al. (2018) predicted a significant increase in nutrition load in the entire Baltic Sea in some climate change scenarios. The impact of climate warming leading to an increase of anoxic and hypoxic zones was evaluated by Ryabchenko et al. (2016) and Śliwińska-Wilczewska et al. (2019). Wulff et al. (2018) surveyed the effects of climate change on a Baltic Sea summer microplanktonic community, including decreased salinity and elevated CO2 concentrations.

Andrén et al. (2017) examined the eutrophication and nitrogen conditions in the Bothnian Sea and discovered that maximum nutrient discharges occurred between 1945 and 1990. Ning at al. (2018) assessed environmental degradation, including cultural eutrophication, in the Baltic coastal zone for the last 1000 years. They argue that anthropogenic activities in the 20th century have caused unprecedented ecosystem changes in the coastal inlet. Räsänen (2018) analysed discussions on nutrient pollution in the Baltic Sea in Finland and Sweden from the 1950s to the early 1970s. Meier et al. (2019) have studied the patterns of eutrophication and their connection to hypoxia in the Baltic Sea and their observations extend until 1850.

Coastal hypoxia in the Baltic Sea is caused by the enhanced terrestrial nutrient loading, as seen in the depositional history of sediments in the Fårö basin reconstruction (Reed et al., 2016). Other scholars have concluded that nutrient modifications have a higher impact within fjord/estuarine systems (Andersen et al., 2020).

Nausch et al., 2017 examined the increased nutrition loads from human settlements and livestock farms in the Warnow River, Germany. A modelling approach was proposed by Hansen et al. (2018) to evaluate local-scale mitigation measures for the Baltic Sea basin. Bohman (2018) studied regulatory problems of diminishing eutrophication in the Baltic Sea region caused by agricultural activities and animal production. Svanbäck et al. (2019) inspected agriculture management practices, which include mineral agriculture fertilisers and feed in the catchment, and consequently increased nutrient flow into the Baltic Sea. Investments in measures to reduce excessive inputs of nutrients in the Baltic Sea are not effective enough to lower the level of eutrophication (Haddaway et al., 2019). Dregulo and Rodionov (2020) analysed the hot spots of eutrophication in the Gulf of Finland caused by livestock complexes located in the Leningrad region of Russia. Silvenius et al. (2017) presented the environmental impacts of rainbow trout farming in Finland on eutrophication in the Baltic Sea and proposed measures to avoid external nutrient flows.

Alekseev and Smirnova (2016) and Smirnova and Alexeev (2017) suggested methods to reduce nutrient inputs from wastewater treatment systems into the Baltic Sea from the river basin of north-west Russia. Rydin et al. (2017) assessed a geo-engineering method that demonstrates a quick recovery of eutrophicated marine ecosystems in coastal areas of the Baltic Sea. In turn, Koskiaho et al. (2020) evaluated ecotechnologies for the recovery and reuse of carbon and nutrients from various waste streams to the Baltic Sea and proposed a combined set of measures. According to Raudsepp et al. (2019), nutrient input from shipping does not have a significant effect on the Baltic Sea ecosystem and its eutrophication compared to other nutrition sources.

The socio-economic characteristics of a country in the Baltic Sea region define the effectiveness of nutrient abatement measures in the agricultural sector (Elofsson and Brömssen, 2017). Pelagic fisheries management models and policy instruments were analysed by Hammarlund et al. (2018) and Nielsen et al. (2019) with a goal of achieving the reduction of nutrient flows and lower eutrophication in the Baltic Sea region.

Jetoo (2018) compared governance processes in transboundary ecosystems (the Baltic Sea and the North American Great Lakes) to identify barriers to eutrophication mitigation. Correspondingly, Murray et al. (2019) evaluated scenarios of implementation of the regional ecosystem-based nutrient management strategy, the HELCOM Baltic Sea Action Plan. Management strategies for reducing nutrient flows to the Baltic Sea need to target both nitrogen and phosphorus reduction (Vigouroux et al., 2020). Skov et al. (2020) tested the application of fine-scale ecosystem models for assessing cost-benefits or food-web consequences of management decisions in relation to the water quality of the coastal waters of the Baltic Sea.

Chemical and heavy metal contamination: Polak-Juszczak (2017) and Remeikaitė-Nikienė et al. (2018) studied the potential metal pollution sources in the Baltic Sea and their distribution patterns from sediments and concentration dependence on an increasing amount of fine-grained fraction and organic carbon. In a similar manner, Jędruch et al. (2017) concluded that mercury pollution of the coastal regions of the Baltic Sea depended on the water dynamics and the composition of organic matter. The largest load of mercury from the catchment area is introduced to the Baltic Sea during downpour/flood (Gębka et al., 2019). The impact of climate change on mercury inflow to the Baltic Sea and its increase in the trophic chain have been reviewed, for example, by Bełdowska et al. (2016), Bełdowska and Mudrak-Cegiołka (2017) and Gębka et al. (2018). The researchers have found that the consequences of mercury contamination in the Baltic Sea for the benthic food web and for human consumption present a high risk (Sonne et al., 2019; Jędruch, 2020).

Karl et al. (2016) combined the analysis of organic and inorganic contaminants in cod from different fishing areas. The highest concentrations were found in the Baltic Sea. Chemical (Cadmium) pollution of the Baltic Sea can influence nitrogen cycling in marine sediments and enhance nitrification (Broman et al., 2019). Arsenic pollution in the Baltic Sea remains at a natural level, but its extended presence in deep water will increase the toxic effects (Li et al., 2018). Staniszewska and Boniecka (2018) showed that the current approach to the assessment of contamination in the sediments within the Polish coastal zone of the Baltic Sea overestimates the level of contamination.

Pollution by organic substances: New types of chemicals of emerging concern, such as organochlorine contaminants (current-use flame retardants), in Baltic Sea fauna were studied by Falkowska et al. (2016) and De Wit (2020). In turn, Lang et al. (2018) presented the first comprehensive dataset on contaminant chemical activities of polychlorinated biphenyls (PCBs) in Baltic Sea sediments, with the highest levels observed in the western Baltic Sea. Persistent organic pollutants showed decreasing trends for the past 30–50 years (Bjurlid et al., 2018). According to Assefa et al. (2019), as primary air emissions of polychlorinated dibenzo-p-dioxins and furans (PCDD/Fs) decline, contamination by tetrachlorophenol (TCP) and pentachlorophenol of atmospheric background (PCP/AB) in the Baltic Sea will require more attention.

Larsson et al. (2018) evaluated the impact of pollution on the marine environment using multi-biomarker analysis (blue mussels). Similarly, Golubkov et al. (2019) examined carbon fluxes from St. Petersburg's wastewaters into the Baltic Sea ending in benthic food webs.

Radioactive contamination: radioactive contamination of the Baltic Sea region after the 2011 Fukushima accident has been studied by Saniewski and Zalewska (2016). 90Sr and 137Cs activities elevated, and the major source of 90Sr and 137Cs to the Gulf of Gdansk is the river Vistula. Daraoui et al. (2016) presented new data on radioactive pollution in the North Sea and the Baltic Sea in 2005 and 2009. Zaborska et al. (2017) found higher concentrations of heavy metals and 137Cs large fraction of pelite sediments along the Polish coast of the Baltic Sea. Salinity variations affected the transfer of 137Cs through the food web (Maderich et al., 2018).

Saniewski et al. (2018) concluded that 90Sr will become the major anthropogenic isotope having an impact on the level of radioactivity in the Gulf of Gdansk. The growing role of 90Sr in the overall radioactivity in the southern Baltic Sea as compared to 137Cs was also confirmed by Zalewska et al. (2016). For their part, Saremi et al. (2018) reconstructed the accumulation of radioactive caesium in marine mammals in the

Baltic Sea after the Chernobyl disaster and found that activity concentrations were still elevated. Activity concentrations in herring, the main prey of seals, were 3.5–9 times higher.

Pharmaceutical waste pollution: Siedlewicz (2016) developed an efficient method for determining antibiotic residues in the southern Baltic Sea using liquid chromatography coupled with tandem mass spectrometry. Multiple human pharmaceuticals are transported to the Baltic Sea from Swedish catchments. Metformin, Paracetamol and Ibuprofen showed the highest amounts in 2011 (Lindim et al., 2017). Björlenius et al. (2018) proposed a grey box model as a tool for predicting environmental concentrations of organic substances in water. A target analysis approach was developed to determine ultra-trace pharmaceuticals in the seawater off the German coast (Kötke et al., 2019).

The Baltic Sea is contaminated by rivers delivering pharmaceuticals and ultraviolet filters (UV-filters), with wastewater treatment plants identified as an indirect source (Fisch et al., 2017). A potential high risk of contamination for the Baltic Sea sediments by antibiotic compounds was discovered by Siedlewicz et al. (2018). Submarine groundwater discharges are an important source of pharmaceutical and caffeine residues in the southern Baltic Sea (Szymczycha et al., 2020). Świacka et al. (2020) noted the impact of diclofenac concentrations in the Baltic Sea on the bay mussel.

Microplastic pollution: the bottom layers of the Baltic Sea are more contaminated with microplastic than the surface, and fibres are the prevailing type (Bagaev et al., 2017; Hengstmann et al., 2019). The seafloor of the Baltic Sea may act as a sink for once sedimented microplastic (Näkki et al., 2019). Ory et al. (2020) studied microplastic contamination in the Baltic Sea region (Kiel Fjord) to detect unusual acute contamination, especially during periods of snow and melting ice.

Beer et al. (2018) conducted the first long-term study on microplastic in the Baltic Sea. The stability of plastic concentration and contamination over time indicates that the type and level of microplastic pollution depend on human activities in a region rather than on global plastic consumption. If microplastic concentrations in sea ice increase, it may impact sea ice albedo (Geilfus et al., 2019).

Zobkov and Esiukova (2017) proposed modifications for the laboratory methods to evaluate microplastics in bottom sediments. Budimir et al. (2018) presented a method for microplastic extraction from fish guts. Schönlau et al. (2020) supported the importance of using standardised methodologies to achieve comparable data microplastic contamination in the Baltic Sea.

Rummel et al. (2016) investigated plastic ingestion by pelagic and demersal fish from the North Sea and Baltic Sea. All collected samples from the Baltic Sea near Sweden contained plastics (Gewert et al., 2017), all beaches at the northwest coast of the Isle of Rugen were contaminated by marine litter (83% of litter was plastic) (Hengstmann et al. (2017). The levels of plastic-derived contaminants in the sediments from the Gulf of Gdansk and the Szczecin Lagoon were generally not high (Lubecki and Kowalewska, 2019). According to Urban-Malinga et al. (2020), the occurrence and composition of microplastic along the Polish coast of the Baltic Sea depends on the level of urbanisation, and it is not related to the sediment grain size. Microplastic contamination in the South Funen Archipelago in Denmark was at a relatively low level, which can be explained by low population pressure (Tamminga et al., 2018). Bollmann et al. (2019) studied the connection between micropollutants and microplastic contamination in the Baltic Sea with urban wastewater treatment.

Marine litter pollution: other types of marine litter in the Baltic Sea were also analysed. Haseler et al. (2019) gathered samples of meso-litter and large micro-litter on German sandy beaches. Cigarette butts were the most common litter item. In a similar way, Katarżytė et al. (2020) compared levels of pollution by cigarette butts of the Baltic Sea coastal line for Germany and Lithuania, and they found that the number of cigarette butts was significantly higher in Germany than in Lithuania. Cieślikiewicz et al. (2018) evaluated the level of management of dumping sites in the southern Baltic Sea.

According to Zablotski and Kraak (2019), the share of plastic in the Baltic benthic litter (35%) was below the world average (70%) and fishery-originated litter in the Baltic Sea was lower than it was previously reported for the Baltic Sea (4–24%). Lewin et al. (2020) conducted the first study on lost fishing tackle as marine litter in the Baltic Sea.

The Baltic Sea pollution with litter is three times lower than the North Sea (Kammann et al., 2018). Compared to other Baltic Sea coastal areas, the southern Baltic seafloor is less polluted with marine litter (Urban-Malinga et al., 2018). Setälä (2016) compared two methods for marine microlitter sampling in the Gulf of Finland.

Munitions dump sites: high levels of environmental genotoxicity in fish were recorded along CW (chemical weapons) transport routes, close to the Bornholm CW dumping area (Baršienė et al., 2016) and near corroding warfare materials in the Baltic Sea (Lastumäki et al., 2020). Bełdowski et al. (2016a, b) showed an elevated arsenic content in dump site areas in the Baltic Sea compared to reference areas and evaluated the potential spreading of chemical war agent pollution in the dump sites, showing that munitions are more scattered on the seafloor than suspected.

Dumping areas in the Baltic Sea are sources of mercury for marine bottom sediments. Conventional and chemical munitions act as a local total mercury source in the environment (Bełdowski et al., 2019). Concentrations are lower compared to 1990s (Siedlewicz et al., 2020).

Toxic explosive compounds from a dump site in the Baltic Sea are accumulated in fish and pose a risk to human food safety (Koske et al., 2020a, b). Nawała et al. (2020) analysed potentially explosive samples of lumps and sediments taken from the contaminated Baltic seabed, which affects the marine ecosystem.

Biomarker methods using mussel and cod were tested for assessing bioaccumulation of dumped chemical warfare agents and their negative effects by Lasota et al. (2018), Höher et al. (2019) and Niemikoski et al. (2020). Miętkiewicz (2020) prepared a catalogue of dumped conventional warfare munitions in the Baltic Sea.

Maritime traffic: Turner et al. (2017) studied the effectiveness of environmental monitoring programmes for ship emissions (five different groups of pollutants) in the Baltic Sea region. Ringbom (2018) compared the existing rules on ship-source pollution from the perspectives of regulatory layers and governance structures in shipping. Freese et al. (2019) showed how maritime environmental legislation affects the environmental protection of the Baltic Sea, pointing to the fact that organisational capacities are more important for environmental protection than exterior determinants. Urbanyi-Popiołek (2019) examined ecological requirements and sustainable logistics for the cruise industry in the Baltic Sea region. Shipwrecks and underwater objects of the southern Baltic Sea may cause environmental impacts in the surrounding soft bottom (Balazy et al., 2019).

Karl et al. (2019) evaluated the effects of ship emissions on air quality in the Baltic Sea region using The Community Multiscale Air Quality Modeling System. Claremar et al. (2017) generated a database of shipping and scrubber scenarios for atmospheric deposition for the period from 2011 to 2050.

Kozaczka and Grelowska (2018) studied the contamination of the Baltic Sea environment by noise from sea transport and evaluated the underwater noise produced by ships in the Gdansk Bay area. Ytreberg et al. (2019, 2020) determined the volume of grey water produced and discharged from ships into the Baltic Sea and showed that scrubber wash water and grey water discharged from ships produce acidic and metals contaminants. Depellegrin et al. (2020) presented a geospatial methodology to evaluate the richness of marine ecosystem services and to analyse areas of exposure to human impacts (from ports and shipping) in the Lithuanian sea space. Wilewska-Bien et al. (2016) assessed food waste loads from ships legally discharged into the Baltic Sea. Vaneeckhaute and Fazli (2020) identified best management practices for ship-generated nutrient-rich organic waste that causes eutrophication of the Baltic Sea. Lu et al. (2019) presented a Bayesian Network model for estimating oil spill recovery effectiveness in winter conditions in the Baltic Sea and showed that the effectiveness of mechanical means is relatively low.

In 2016–2020, environmental governance barriers and the application of measures to reduce anthropogenic load in the Baltic Sea were studied from different points of view, including cost-effectiveness and socio-spatial relations. Pollution by new types of organic substances was calculated using biomarker methods. The radioactive contamination consequences of the Fukushima disaster in 2011 for the Baltic Sea region attracted the attention of researchers. Microplastic pollution and marine litter pollution in the Baltic Sea has become one of the main areas of study, with various studies on the negative effects and regional differences. Even more studies were conducted on the history of eutrophication in the Baltic Sea, and new methods for reducing nutrient flows into the Baltic Sea were proposed, including waste treatment. Two areas of study developed quickly: munitions dump sites as sources of contamination and health risks and maritime traffic emissions.

6. Literature review for the period 2021–2023

Fidrya (2021) studied how local communities in the Baltic Sea region perceive environmental risks, using the Kaliningrad community's response to the construction of a potassium and magnesium salt mine as an example. Dobrzycka-Krahel and Bogalecka (2022) assessed the different aspects of anthropopressure in the Baltic Sea (nutrients: nitrogen, phosphorus, and hazardous substance loading). Bocharnikova (2022) showed that the interpretation of environmental problems in the media is significantly different from objective scientific information about the pollution of the Baltic Sea.

Brizga et al. (2022) calculated the environmental impact of consumption and production in the Baltic Sea region and the drivers behind this impact. The new EU Member States try to copy consumption patterns of more advanced economies with a higher ecological footprint and this leads to higher pollution levels. Prishchepenko et al. (2023) showed results of the different stages of the anthropogenic impact on the geological environment and ecosystem of the Eastern Gulf of Finland. Ojaveer et al. (2023) presented the first quantitative case study estimating the impact of widespread non-indigenous species on the fishery and other ecosystem services in the Baltic Sea, such as water supply, climate regulation and recreational benefits.

Climate change: climate studies concerning the Baltic Sea region have received a new impetus. As a sign of this, Meier et al. (2022a, b) analysed climate change studies in the Baltic Sea region and projected the impact of a changing climate on biogeochemical cycling in the Baltic Sea until the year 2100, which results in greater mixing in the northern Baltic Sea during and reduced sea-ice cover in winter. Schibalski et al. (2022) applied interacting ecosystem services to climate change and land use adaptation to predict future results in yearly steps from 2010 to 2100. According to Różyński and Lin (2021), climate change can cause erosion of sedimentary structures in the Baltic Sea and affect the environment. Climate change-related erosion can also increase the inflow of selected trace metals to the marine environment (Bełdowska et al., 2022). Seidel et al. (2023) assumed an amplified effect of prolonged warming deeper in the sediment, which could result in elevated concentrations of toxic compounds and greenhouse gases for the Baltic Sea region. According to Dettner and Hilpert (2023), technological solutions will not be sufficient to achieve the 1.5 °C target and mitigate CO2 emissions in the North Sea and the Baltic Sea.

Eutrophication: Kaiser and Lerch (2022) studied the eutrophication status of the Baltic Sea and rivers from its catchment area since 1860 using faecal lipids as indicators of Baltic Sea sewage pollution and population growth. Adolph (2023) reviewed eutrophication and contamination trends for the past 670 years influenced by sewage discharge and catchment population density in Lake Schwerin, Germany.

According to Gauss et al. (2021), agriculture and transport are the main contributing sectors to nitrogen deposition in the Baltic Sea, and Germany, Poland and Denmark are the main contributors. Czajkowski et al. (2021) estimated the potential cost-effectiveness of focusing on reduction nutrient loadings from agriculture rather than following spatial scale reduction targets in the Baltic Sea region. Nitrogen reduction programmes for the agriculture sectors in Denmark and Sweden showed a positive effect (Kyllmar et al., 2023).

Jutterström et al. (2021) evaluated the scenarios of shipping emissions on the eutrophication level in the Baltic Sea region. Shipping will still have an impact on excesses for eutrophication in 2040. Bossier et al. (2021) studied the scenarios of the separate and integrated impacts of climate and riverine nutrient load changes on the full food web in the entire Baltic Sea. Higher nutrient loads resulted in a decrease in cod and an increase in sprat and herring.

Dybowski and Dzierzbicka-Głowacka (2023) analysed the impact of nutrients (nitrates and phosphates) supplied from the land on the waters of the Puck Lagoon (the Gdansk Basin, the southern Baltic Sea) using numerical modelling. Njock et al. (2023) proposed a flexible methodology for quantifying the eutrophication risk status of coastal subbasins of the Baltic Sea. Kruk (2023) applied the predictive and explanatory ensemble XGBoost-SHAP modelling for the hyper-eutrophy estimate in the Vistula Lagoon in the southern Baltic Sea.

Smirnova and Tokareva (2021) studied methods of dephosphation of wastewater using industrial waste the Neva Bay area to reduce eutrophication in the Baltic Sea. Capell et al. (2021) evaluated the impact of eutrophication diminishing measure scenarios on the Baltic Sea and showed that eutrophication reduction measures must be directed at sea outlets.

Lønborg and Markager (2021) assessed the complex nitrogen budget in the Baltic Sea. The recovery of the Baltic Sea is only possible if the reduction targets are considerably higher than existing plans. Dalsgaard et al. (2023) proposed a new feed concept minimising the environmental impact of net cage farming to reduce nutrition loads in the Baltic Sea. According to Vigouroux et al. (2021), coastal eutrophication mitigation needs both local catchment and whole-sea management.

Chemical and heavy metal contamination: Nedzarek et al. (2021) confirmed the possibility of using mussels' shells in the calculations of heavy metal pollution levels. Ek et al. (2021) presenting a method for handling multiple confounding variables in contaminant monitoring based on Baltic blue mussels. The Baltic Sea ecosystem strongly biomagnifies more than 250 contaminants through the trophic chain (Rebryk and Haglund, 2022). Lin et al. (2023) used a model based on radioactive radiotracers to evaluate the environmental pollution risks associated with 'a memory effect'. The Baltic Sea can retain pollutants/ nutrients for decades.

For the first time, a risk analysis was conducted on the health effects of mercury contamination on marine biota in the Baltic Sea compared to the Greater North Sea and the North Atlantic. The estimated risk for Baltic populations was not higher in the Baltic Sea than in the bordering waters (Dietz et al., 2021). Mixing processes and the settling of particles affecting mercury cycling in the southern Baltic Sea were studied by Saniewska et al. (2022). The total arsenic levels in sediments from the southern Baltic Sea can be considered low and do not pose a serious threat to marine organisms, but arsenic-based Chemical Warfare Agents (CWA) from munitions dump sites can be a local source of arsenic in the environment (Szubska and Bełdowski, 2023). However, toxic inorganic arsenic content in Baltic fishes is below international standards (Polak-Juszczak and Szlinder, 2021). Coastal erosion is an important source of metals in the marine environment (Bełdowska et al., 2022).

Shahabi-Ghahfarokhi et al. (2021) established the pre-industrial values of copper, arsenic, cobalt, and uranium concentrations in Baltic Sea sediments. Arsenic concentrations are higher in the Gulf of Bothnia than in the Baltic Proper. Sharov et al. (2022) estimated cadmium pollution and its effects on the biotas in the eastern part of the Gulf of Finland and found that the problem is not critical. A sufficient decrease of gaseous and particulate air pollutants over the Baltic Sea, such as sulphur dioxide and sulphate concentrations, has been achieved since 1981 (Davuliene et al., 2021). Fossil fuel-related combustion, traffic emission and shipping are the major sources of microparticle contamination in coastal-urban region of the southern Baltic Sea (Siudek, 2021).

Organotin and heavy metals pollution studies were conducted by Zhakovskaya et al. (2022) and Kucharski et al. (2022b). Bottom sediments are the repository of heavy metals and tributyltin, which is used as a biocide in antifouling paints. Pollutions of Baltic Sea bottom sediments exceeds the ecological standards. Correspondingly, Rebryk and Haglund (2022) showed that the Baltic Sea ecosystem biomagnifies chemical contaminants, more than 250 contaminants showed significant trophic magnification.

Pollution by organic substances: Rebryk et al. (2022) and Polak-Juszczak et al. (2022) observed a decline in regulated persistent organic pollutant and the dioxin and polychlorinated biphenyl (PCB) in the Baltic Sea biota. But this decrease is not enough to make the Baltic fish safe for frequent consumers (Mikolajczyk et al., 2021). Bacterial communities from marine sediments still contain high loads of persistent organic pollutants at high concentrations (Rodríguez et al., 2021). Szklarek et al. (2021) evaluated ecotoxicological effects of municipal wastewater effluent in the Baltic Sea catchment in Poland. Undeman et al. (2022) analysed micropollutants in effluents from wastewater treatment plants in the Baltic Sea region and assessed the differences between countries.

Radioactive contamination: the Chernobyl disaster caused radioactive (137C, 241Pu) contamination level that are still high in the Baltic Sea sediments (Kotilainen et al., 2021; Strumińska-Parulska and Olszewski, 2022). However, Lujanienė et al. (2022) identified no risk for biota from 241Am and Pu isotopes in the south-eastern Baltic Sea. Lin et al. (2022) confirmed an established budget scheme of 236U in the Baltic Sea and a strong memory effect for pollutants in the Baltic Sea.

Microplastic and plastic litter: sandy beaches along the southern Baltic Sea are heavily contaminated with microplastic and plastic litter. Most of the litter on the seafloor of the North Sea and the Baltic Sea are plastics (Int-Veen et al., 2021). The abundance of beach litter correlated with tourist consumption (Lenz et al., 2023). Plastic pollution of the Polish coastal zone is a significant problem comparable with the rest of the Baltic Sea (Mazurkiewicz et al., 2022). On the other hand, in national parks and protected areas, the level of microplastic contamination is at the same level as other beaches (Esiukova et al., 2021b). Tourism is also the most important source of beach macrolitter (over 80%) on the southern Baltic coast (Zalewska et al., 2021). Nogueira et al. (2023) introduced visual litter quantification in the southernmost Baltic Sea as a method for assessing bottom pollution.

Microplastic depositions from the atmosphere in the coastal zone of the Baltic Sea were compared to the open Baltic Sea and to the Gotland Island. Atmospheric transport enables the long-range transportation of microplastic across the Baltic Sea (Szewc et al., 2021; Ferrero et al., 2022). The most prevalent particle shape of microplastic is fibre in the Gulf of Riga and the Eastern Gotland Basin (Aigars et al., 2021) and the most abundant polymer type was polyethylene (Hänninen et al., 2021). In coastal seagrass beds in the Baltic Sea, Estonia blue fibre was the prevalent microplastic (Kreitsberg et al., 2021). The underwater slopes in the Baltic Sea covered by seagrasses accumulate microplastic particles and are more polluted than the surrounding waters and sediments (Esiukova et al., 2021a). The main sources of pollution in the Baltic Sea are the river Vistula, the river Oder, and the river Neman (Pärn et al. (2023).

Microplastics do not sink to the densities of original plastics and the water column can contain more microplastic than surface water (Uurasjärvi et al., 2021). Eventually microplastics end up in the bottom sediments of the Baltic Sea Proper (Chubarenko et al., 2022).

Microplastic contamination of the Baltic Sea biota was studied by Sainio et al. (2021) for the microplastic ingestion by small coastal fish from the northern Baltic Sea (found in 9% of all sampled fish) and for the key Baltic fish species by Białowąs et al. (2022) and Walls et al. (2022). All studies confirmed a high level of contamination. Szewc, Graca and Dołęga (2021) examined the quantitative and qualitative compositions of microplastics (MPs) deposited from the atmosphere in the coastal zone of the southern Baltic Sea area.

Methods based on mass-quantitative analysis of the microplastics load in blue mussels for evaluating microplastic pollution in the Baltic Sea were proposed by Halbach et al. (2022). Murawski et al. (2022) modelled microplastic transportation in the Baltic Sea to identify high concentration zones of contamination. New marine litter clean-up technologies for the Baltic Sea were assessed by Frantzi et al. (2021) considering legal, institutional and financial drivers and barriers.

Pharmaceutical waste pollution: the highest concentration levels of the pharmaceutically active compounds were found in sediments near wastewater treatment plants in the Baltic Sea (Kucharski et al., 2022a). Kołecka et al. (2022) determined the correlation between the sales of anti-inflammatory drugs and their concentration in the wastewater treatment plants in the Baltic Sea region. The substantial mass of diclofenac was released from wastewater treatment plants into the Baltic Sea.

Munitions compounds: munitions compounds were detected in over 98% of organisms collected in the southwest Baltic Sea (Beck et al., 2022). Hazardous toxic chemical ammunition from the World War II wrecks sunk in the Baltic Sea present ecological and food safety risks in all the Baltic Sea states. (Rafał, 2022). Zalewska et al. (2023) proposed a warning system for potential releases of chemical warfare agents from dumped munitions in the Baltic Sea based on an arsenic indicator.

Maritime traffic: Maiorov and Dobrovolskaia (2022) analysed the level of possible pollution of the Baltic Sea by marine ferry routes, proving the need for the integrated measurement systems of several transport links. Ytreberg et al. (2021) assessed damage costs on the marine environment in the Baltic Sea as being in the same range as atmospheric impacts (€2.9 billion in 2010). According to Gren et al. (2021), the total cost to the Baltic Sea of NOx emission of shipping in the Sea is €240 million annually.

Maritime shipping and leisure boating are two significant sources of polycyclic aromatic hydrocarbons PAHs and metals to the Baltic Sea (Kuprijanov et al., 2021; Ytreberg et al., 2021), especially near the ports and along the ship traffic routes. Large-scale construction of new port facilities negatively affects biomass and taxonomic composition of phytoplankton in the Neva Estuary, the northeastern Baltic Sea (Golubkov et al., 2022).

The waste streams from shipping lanes in the Baltic Sea contains several hundred contaminants, and the southwestern Baltic Sea and the Gulf of Finland have the highest pressure by shipborne pollution (Maljutenko et al., 2021). Gren et al. (2022) estimated shipping to account for up to 38% of the number of aquatic non-indigenous species appearing in the Baltic Sea.

Mrozowska (2021) modelled decision support data to ensure the safety of oil and gas activities in maritime areas of the Baltic Sea to avoid the occurrence of spills. Parviainen et al. (2022) analysed decision-making policies for oil spill risk assessment and management in the Gulf of Finland.

In 2021–2022 and the first half of 2023, environmental studies in the Baltic Sea region continued in the direction of a multi-area approach, evaluating various anthropogenic impacts. A large-scale review of the current knowledge of the effects of global warming on past and future changes in the climate of the Baltic Sea region was conducted. Plastic pollution studies remained at the top of the list, as well as the risk estimates for munitions dump sites. Eutrophication reduction and new methods for its evaluation continued to be a matter of concern.

7. Conclusions

The Baltic Sea region forms a unique ecosystem which is very different from other coastal seas and experiences a strong anthropogenic pressure. One of the largest brackish seas in the world, a shallow and semi-enclosed water basin which receives pollutants from the surrounding territories. Its vulnerability and importance in environmental protection was widely recognised by the scientific community by the end of the 20th century.

At the beginning of the period described, the environmental research agenda in the Baltic Sea region intensified and more attention was paid to developing strategies for environmental management. Interest in environmental management of the Baltic Sea region and its problems remained high during all these years. The environmental consequences of EU enlargement also attracted the attention of the researchers. Such topics as EU environmental regulations, national environmental policies of the coastal countries, international cooperation and the role of non-governmental actors continued to be a priority.

New areas of study, such as microplastic contamination and the problem of munitions dumps sites, emerged. However, the three major challenges remained: pollution, eutrophication and the negative effects of climate warming. These three environmental problems remained at the top of the list of priorities for researchers and forming various combinations.

The level of polluting substances in the Baltic Sea has been greatly reduced over the last decades, but legacy pollution slows recovery. Pollution remains the main theme for studies, with chemical and heavy metal contamination, radioactive contamination and waste treatment being the main sub-themes. Radioactive contamination studies concerning the Baltic Sea region at first concentrated on consequences of the Chernobyl disaster and later the Fukushima disaster. Research on organic contamination evolved into analysis of the new types of substances investigated by using biomarker methods. By the 2020s, microplastic and marine litter pollution of the Baltic Sea and its negative effects became a new and wide area of study. Also, an increasing interest is noted in the problems of pharmaceutical waste pollution and munitions dump sites as sources of contamination in the Baltic Sea.

Climate change studies concerning the Baltic Sea region followed the global trends and reached a peak between 2010–2015. The negative effects of warming on resources and the socio-economic aspects of life on the shores of the Baltic Sea and its enhancement of pollution levels were constant subjects of research. the methods of climate change studies developed with new approaches, such as a geographical and cross-ecosystem approach. A large-scale review of the current state of knowledge concerning climate change was conducted by a team of researchers in 2022.

Interest in eutrophication as one of the main challenges for the Baltic Sea region remained high through all the described periods. Its negative effects and connection to agricultural development in countries adjacent to the Baltic Sea and to global warming were analysed by numerous approaches. Recently, the history and evolution of eutrophication in the Baltic Sea region as a tool for understanding future changes has become a new trend in research. New methods for reducing nutrient flows into the Baltic Sea are being proposed, including waste treatment intensification.

The reviewed literature suggests that although the main environmental challenges facing the Baltic Sea region remain the same, new directions in environmental research emerge with the development of scientific methods. A multi-area approach to environmental studies is gaining more influence than ever before.

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