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The share of Poland in the actual pollution status of Baltic Sea waters with nitrates in the light of HELCOM PLC research

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Abstract. The aim of the study was to analyze the results of the current research in the HELCOM PLC project on Poland's share in the pollution of the Baltic Sea waters. The analysis considers annual update of the HELCOM Core Pressure Indicator, which monitors the implementation of maximum allowable nutrient loads (MAI), covering data from 1995 to 2018, assessment of progress in achieving national nutrient input limits (NIC assessment), covering data for the years 1995–2020, assessment of sources and pathways of nutrients to the Baltic Sea environment by 2020 and comparative analysis at the level of source data from 1995 to 2018 for Poland. Analysis of the nutrient input trend over the 1995–2018 observation period showed a statistically significant 20 percent reduction in total nitrogen input to the entire Baltic Sea. Poland reduced the nitrogen input to all HELCOM basins from the 1997–2003 reference period by 11–26% and it has reached inflow limits in all basins, except the Baltic Proper (BAP), where the reduction remaining to be achieved before 2020 was 30578 t, i.e. 20% of the NIC. The main loads of total nitrogen from Poland to the Baltic Sea are delivered via inland waters (indirect sources) and come from agriculture (57%). Actions at the European Union level, including monitoring the Baltic Sea environment and indicating sources of threat, are necessary for continuous implementation.

Keywords: HELCOM, Pollution Load Compilation (PLC), Baltic Sea, nitrate pollution, Nutrient Input Ceiling, Poland

INTRODUCTION

The intensification of food production that has occurred over last decades has led to far-reaching changes in agriculture and in natural ecosystems (Zadura, 2009; Zegar, 2023). Agriculture has moved far away from certain rules governing natural processes, which has disrupted the natural nitrogen cycle in nature. Extensive forms of agriculture have been replaced by conventional agriculture of an industrial nature. The changes were related to, among other things, the introduction of engine-driven machines, the larger-scale use of mineral fertilizers, the introduction of chemical plant protection products, the use of breeding methods and greater specialization and intensity of production (Kostrowicka et al., 1984).

Agriculture has a large share in the pollution and degradation of water resources (Linderhof et al., 2021; Oppeltová et al., 2021). According to the Environmental Protection Inspectorate, the general condition of rivers, lakes, transitional waters and coastal waters in Poland is poor and despite many regulations regarding the method of fertilization, such as the Act of 10 July 2007 on fertilizers and fertilization, agriculture is the main cause of this problem (Skorupski et al., 2012; Kuczyńska et al., 2021).

The quality of surface waters in Poland is constantly deteriorating. According to Kupiec (2023), analysis of the state of river waters in the long term indicates that this trend has been ongoing at least since the 1960s. In the years 1964–1990, the share of waters classified as class I decreased drastically. In just 25 years, there was a 26%

decrease in the share of waters classified as this class. The number of river sections classified as class II increased slightly, by only 0.8%. On the other hand, the number of sections classified as class III and non-class sections increased by 14.8% and 12%, respectively. Therefore, a significant leap in quality from class I to class III and beyond is observed.

The intensification of agriculture and excessive pollutant emissions observed over the last decades have caused also changes in the physicochemistry of groundwater in many places (Masoud et al., 2022; Singh et al., 2022). Analyzing the quality of groundwater since 2004, i.e. since Poland's accession to the European Union, minor changes can be observed in this area (Kupiec, 2023). The most favorable situation was observed for 2007. It was characterized by the largest percentage of class I and II waters (total 57.3%). After 2007, until 2013, a sharp decline in groundwater quality was observed. The share of class I and II in 2011 dropped to 6.6% in total. During this period, the largest share of groundwater in class III was recorded. Since agriculture is one of the main participants in the deterioration of the quality of these waters, it is necessary to monitor this sector.

Agriculture is one of the main causes of degradation of natural ecosystems, including aquatic ones. Pollution of surface waters in the country results in degradation of the Baltic Sea (Dobrzycka-Krahel, Bogalecka, 2022). The Baltic Sea is an inland sea with a relatively low water exchange. The obligation to monitor the quality of the marine environment of the Baltic Sea, within the framework of the national environmental monitoring (SEM), results from Poland's reporting obligations specified in the Convention on the Protection of the Marine Environment of the Baltic Sea Area, drawn up in Helsinki on 9 April 1992. At the same time, the assessment of the quality of the Baltic Sea waters as a recipient of pollutants discharged from its catchment area is used for the purposes of management and assessment of the effectiveness of water resources protection, implemented on the basis of the Water Law Act of 20 July 2017.

A detailed inventory of pollution sources and farm monitoring is the most important preventive measure to assess the current state of pressure. The environmental standards in force in the European Union in the field of water protection obligate Poland to improve the ecological status of water bodies. This is one of the most important objectives of the European Union's environmental policy. The Water Framework Directive of 2000, implemented in Poland, imposes on Poland the obligation to achieve at least good water status by 2027. The Nitrates Directive, which is one of the most important EU legal acts in the field of water protection after the Water Framework Directive, requires actions aimed at reducing pollution of surface and groundwater. It should be remembered that Poland is an agricultural country (approx. 60% of its area is agricultural land), so most of the surface waters in Poland are subject to pressure from agriculture. The reason for the unsatisfactory state of water quality is the excessive inflow of physical, chemical and biological pollutants. Surface waters are a very important element of the environment. They also affect water retention in the area, which has a positive effect on adjacent ecosystems, but also on agricultural crops. Surface waters are the basis for the functioning of plant and animal organisms and are a valuable element of the landscape structure. There is therefore a need to control and monitor of farms, which will allow for limiting the causes of water and all ecosystems dependent on water degradation.

Rationalization of activities in the area of monitoring agricultural production is a very important element in protective and preventive activities in the area of reducing pollutant emissions and the ongoing degradation of the Baltic Sea waters. The condition of surface waters translates directly into the condition of coastal and marine waters. Currents are a transit element, carrying pollutants over long distances. The quality of water in rivers, but also in water reservoirs and lakes through which they flow, influences the formation of the ecological condition of salt waters. Poland is located in the Baltic Sea water catchment area, the ecosystem of which is a subject of enormous pressure from the economies of the countries lying in its basin. One of the factors of pressure is agricultural production. In order to protect this sensitive marine ecosystem, the Baltic Marine Environment Protection Commission, also known as Helsinki Commission or HELCOM was established. Poland, together with countries such as Denmark, Estonia, Finland, Lithuania, Latvia, Germany, Russia, Sweden and the European Union, is a signatory to the Commission. It is an international organization proclaimed by the so-called Helsinki Convention of 1974 (Convention, 1974, Decision 94/157/EC) as its executive body. HELCOM was established fifty years ago thanks to intergovernmental cooperation, in order to protect the marine environment of the Baltic Sea from all sources of pollution. Within the Commission's work, there are several working groups whose scope of work covers, among others, such sectors of the economy as agriculture, fisheries, water management, maritime economy, environment, health and science. HELCOM's vision for the future assumes the improvement of the state of the Baltic Sea environment, while maintaining the diversity and balance of biological components, which will ensure good ecological status and enable a wide range of sustainable economic and social activities. HELCOM's task is also to monitor the natural environment of the Baltic Sea. It is carried out by a team of experts who collect information on the state of the environment and pollutants released into the sea. This data is analyzed and on their basis recommendations are developed for the member states, encouraging them to take specific actions aimed at protecting the Baltic area.

The Helsinki Commission adopted the Baltic Sea Action Plan (BSAP) in 2007. This is a programme that aims to restore the good environmental status of the Baltic Sea. Previous arrangements concerned the implementation of this goal by 2021, but during the HELCOM Ministerial Conference in Lübeck (Germany) on 20 October 2021, the BSAP was updated. This plan covers, among others, such problems as counteracting eutrophication, limiting emissions of hazardous substances into waters and protecting biodiversity and nature. One of the main tools developed by HELCOM is the nutrient reduction programme (N and P). It is an approach that allows all countries located in the Baltic Sea catchment area to bear the burden of nutrient reduction at the regional level.

The occurrence of nitrates in groundwater is associated with the phenomenon of mineralization of organic matter or the nitrification process. Human activity often causes the nitrification process to prevail over the denitrification process, which leads to the accumulation of nitrates and, consequently, to the contamination of groundwater and the eutrophication of lakes. Due to the fact that the nitrate form is the most mobile form of nitrogen in the soil, it can become one of the factors polluting water and causing many diseases. High levels of nitrates can be extremely dangerous to humans, especially pregnant women, newborns and small children, because it can cause hypoxia. Excessive accumulation of nitrates also poses a threat to other living organisms, including farm animals and those living in water bodies, because it leads to, among others things, fish poisoning (Akinnawo, 2023).

The Nitrates Directive concerns actions aimed at reducing water pollution by nitrates from agricultural sources and preventing further pollution. It obliges each Member State of the European Union to monitor surface and groundwater and assess the degree of eutrophication of waters. In addition, Member States of the European Union are obliged to inform the European Commission of any changes made and to submit a report from each four-year period of implementation of the provisions of the Nitrates Directive.

The main source of environmental pressure on the Baltic Sea ecosystem remains land-based pollution. This pressure includes eutrophication, caused by excessive supply of nutrients (including nitrogen) to the marine environment. Providing the most up-to-date information on the loads of nutrients and selected hazardous substances to the marine environment from land, their sources and pathways is handled by one of the largest projects of the Baltic Marine Environment Protection Commission or HELCOM Pollution Load Compilation (PLC). An integral part of the HELCOM assessment system since 1987 is the compilation of data on pollutant loads. The system includes annual and periodic reporting of national data and other related assessment publications. The assessment is scientific in nature and allows Member States to monitor progress at regional and national level in achieving environmental objectives, to take preventive measures against pollution of the Baltic Sea environment (Article 16 of the Helsinki Convention) (Convention, 1974) and to assess their effectiveness. Polish experts are involved in the HELCOM research. The aim of the study was to analyze the results of the join work with particular attention to Poland's share in the pollution of the Baltic Sea waters in the light of current research in the HELCOM PLC-7 project.

METHODOLOGY

The study is based on the results of the HELCOM PLC experts' work, presented systematically in many publications. The data used in this study, coming from: the latest seventh edition of the Summary of the HELCOM Seventh Pollution Load Compilation (PLC-7) entitled: „Pollution load on the Baltic Sea for the years 2012-218 (Pollution load, 2023), the Technical Report Nutrient Input Ceiling (NIC) assessment 1995-2023 (Larsen, Sveden, 2021) and

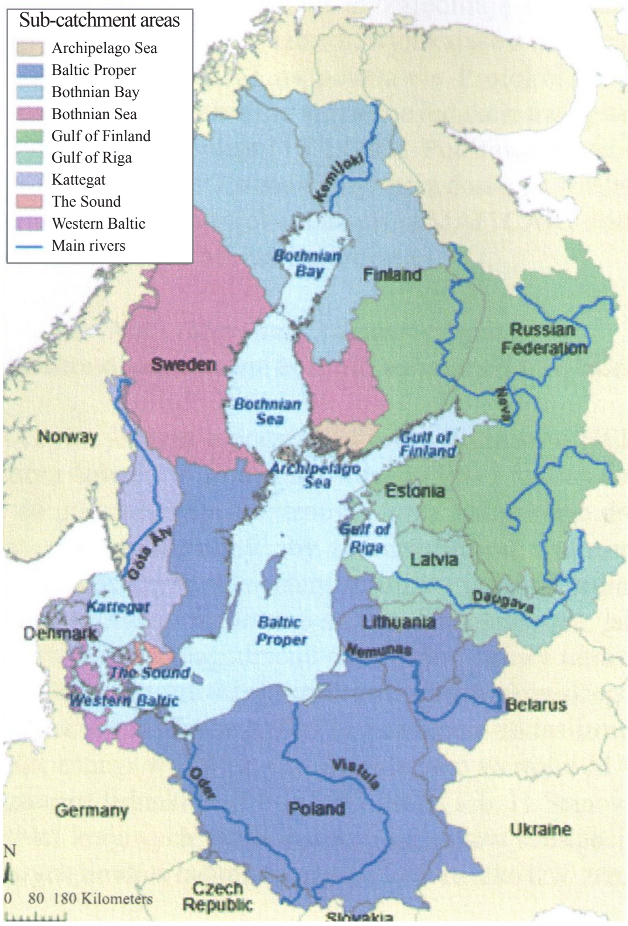

Figure 1. The catchment area and basins of the Baltic Sea covered by PLC monitoring.
Source: Nutrient Input Ceiling ..., 2023.

the National (Polish) report on the work within the PLC-7 balance sheet (Development of the balance ..., 2020).

The analysis considers the following elements:

1. Annual update of the HELCOM Core Pressure Indicator, which monitors the implementation of maximum allowable nutrient loads (MAI), covering data from 1995 to 2018,
2. Assessment of progress in achieving national nutrient input limits (NIC assessment), covering data for the years 1995–2020,
3. Assessment of sources and pathways of nutrients to the Baltic Sea environment by 2020,
4. Comparative analysis at the level of source data from 1995 to 2018 for Poland.

The HELCOM PLC project is based on national data on the loads of all water-soluble substances from the Member States, obtained mainly through programmed national monitoring. The monitored areas cover about 90% of the Baltic Sea catchment area (Fig. 1). The monitoring methodology is harmonized across all areas of the region and takes into account the regularly updated HELCOM PLC-water guidelines (HELCOM, 2022) and HELCOM Recommendation 37-38/1 (HELCOM, 2021). The nutrient load from non-monitored areas (10% of the Baltic Sea catchment area) is estimated by countries using appropriate national calculation methods. Nutrient data are reported in a standardized form using the online reporting tools of the HELCOM PLC-water database. These tools provide also an initial verification of the data quality based on technical protocols and statistical analysis. In addition, the data quality is manually verified by reporters and quality assurance officers, based on national data. HELCOM experts also fill in the gaps in the remaining data using statistical tools and expert assessment. Final approval of all data is done by the national representatives in the PLC project.

RESULTS

MAI – Maximum Allowable Inputs

The nitrogen load is one of the basic HELCOM indicators. The MAI indicator defines the maximum level of total nitrogen (TN) and total phosphorus (TP) loads introduced to the individual Baltic Sea basins by water and air, which is permissible to meet the requirements of a sea not affected by eutrophication. This indicator is a fundamental element of the nutrient load reduction scheme. Such target values for each Member State were first defined in the Baltic Sea Action Plan in 2007 (BSAP, 2021).

Progress towards achieving the MAI for nitrogen

The latest assessment (Pollution load ..., 2023) shows, that by 2018 significant reductions in nutrient inputs were achieved throughout the Baltic Sea and that the standardized nitrogen input was reduced by 12% since the reference period (1997–2003) (Fig. 2). The MAIs for nitrogen during this period were achieved in the Bothnian Bay, the Bothnian Sea, the Danish Straits and the Kattegat (Table 1).

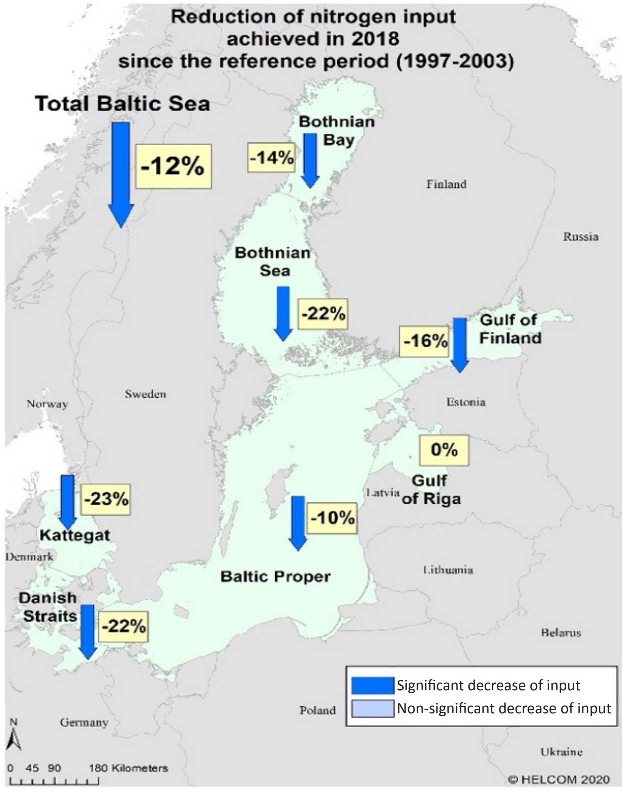

Figure 2. Reduction of the total nitrogen (TN) input since the reference period 1997–2003.
Source: Pollution load ..., 2023

Analysis of the nutrient input trend over the entire observation period, from 1995 to 2018, showed a statistically significant 20 percent reduction in total nitrogen input to the Baltic Sea (Fig. 3). A continuous downward trend illustrating the reduction of nitrogen input to the entire Baltic Sea was observed until 2008. However, no reduction in nitrogen input has been observed in the last decade.

NIC – National ceilings for net input of nutrients

The net nutrient load is the estimated amount of nutrients that enter the Baltic Sea basin from a given country. The PLC project estimates include loads delivered by water (direct sources from coastal points and discharges from rivers), from the air (atmospheric deposition from a specific country or group of countries) and transboundary loads (discharges from rivers from another country).

Table 1. Trend-based estimate for normalized annual inputs of total nitrogen (TN) in 2018.

Baltic Sea basin	MAI#	N input 2018	Statistical uncertainty 2018	N input including stat. uncertainty 2018	Exceedance of MAI in 2018	Input 2018 including statistical uncertainty	Classification of achieved reduction
	t year^{-1}					% MAI	
Bothnian Bay (BOB)	57622	53 628	1452	55080	-	96	●
Bothnian Sea (BOS)	79372	68541	2073	70615	-	89	●
Baltic Proper (BAP)	325000	404613	9977	414590	89590	128	●
Gulf of Finland (GUF)	101800	108468	7202	115671	13871	114	●
Gulf of Riga (GUR)	88417	89308	3751	93059	4642	105	●
Danish Straits (DS)	65998	56619	1964	58683	-	89	●
Kattegat (KAT)	74000	66434	1472	67906	-	92	●
Baltic Sea	792209	864148	14515	873 663	86454	111	●

As adopted by HELCOM Copenhagen Ministerial Meeting (2013)
”-” – not applicable
Classification of MAI achieving: ● = MAI fulfilled, ● = MAI not fulfilled
Source: Pollution load ..., 2023

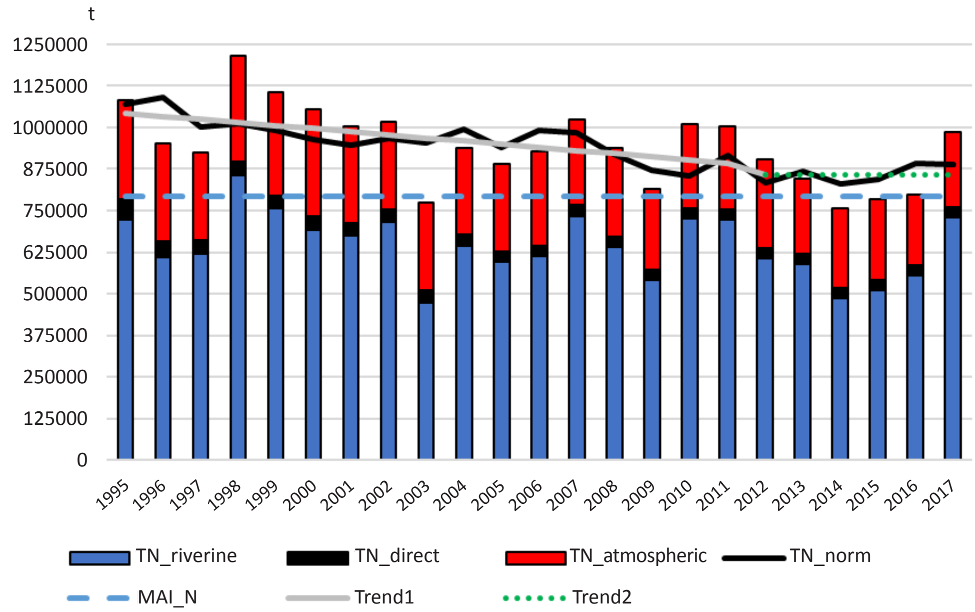

Figure 3. Actual total annual input of total nitrogen (TN) transported by air and water to the Baltic Sea and basins from 1995 to 2018 [t]. Normalized annual TN inputs are given as black line. Trend lines for normalized TN inputs are given as lines with markers.
Source: Pollution load ..., 2023

The national limit of the net nutrient load is the maximum permissible amount of nutrient discharged from a given country to a given Baltic Sea basin, ensuring good environmental status of the Baltic Sea in terms of eutrophication. The sum of the limits set for all countries discharging nutrient loads to individual basins corresponds to the MAI value for these basins.

Table 2. Country – Baltic Sea basin total nitrogen input ceilings in tons per year (2021).

Country	Baltic Sea basin#						
	BOB	BOS	BAP	GUF	GUR	DS	KAT
Germany (DE)	947	3920	34105	1645	1747	23647	4661
Denmark (DK)	280	1148	9025	421	462	28067	28538
Estonia (EE)	113	404	1478	11334	13099	22	24
Finland (FI)	35087	28700	1827	20457	295	76	89
Lithuania (LT)	108	495	25878	305	8820	66	80
Latvia (LV)	73	330	6457	246	43074	31	34
Poland (PL)	668	3125	151969	1407	1596	1480	1443
(Russia (RU)	839	1993	10317	61503	3296	238	245
Sweden (SE)	17718	32633	30690	626	525	6056	32799
Other countries	1375	5008	26947	2986	2188	4933	4502
Baltic Sea shipping (BSS)	284	1141	5180	675	345	651	701
North Sea shipping (NOS)	131	475	2427	196	150	729	884
Belarus (BY)	-	-	13456	-	12820	-	-
Czech Republic (CZ)	-	-	3551	-	-	-	-
Ukraine (UA)	-	-	1693	-	-	-	-
MAI	**57622**	**79372**	**325000**	**101800**	**88417**	**65998**	**74000**

”-” – not applicable
see Table 1
Source: Nutrient Input Ceiling ..., 2023.

Table 3. Total nitrogen (TN) input ceilings in tons per year for the total as well as the country contribution to each of the transboundary rivers (2021).

River	Basin#	NIC	Country								
			DE	FI	LT	LV	PL	RU	BY	CZ	UA
Nemunas	BAP	29338	-	-	18934	-	-	-	10404	-	-
Barta	BAP	957	-	-	427	530	-	-	-	-	-
Venta	BAP	6033	-	-	2896	3137	-	-	-	-	-
Lielupe	GUR	15863	-	-	7255	8608	-	-	-	-	-
Daugava	GUR	38800	-	-	1103	22243	-	2634	12820	-	-
Oder	BAP	49298	1824	-	-	-	43923	-	-	3551	1693
Wisła	BAP	74807	-	-	-	-	70062	-	3052	-	-
Pregolya	BAP	5493	-	-	-	-	2498	2995	-	-	-
Neva	GUF	43476	-	4856	-	-	-	38620	-	-	-

”-” – not applicable
see Table 1
Source: Nutrient Input Ceiling ..., 2023.

Tables of current NIC values

The NIC values for individual HELCOM countries and Baltic Sea basins are presented in the updated BSAP (BSAP, 2021) and the methods for their calculation are described in the information report (HELCOM, 2021). National nitrogen load targets are expressed as nutrient input limits (Table 2). Further limits have been agreed for 9 transboundary rivers (Table 3). The assessment is based on annual nutrient input data from air and water for the years 1995–2020 in each country by basin and comparing the estimated total nitrogen inputs in 2020 with the NIC values from BSAP2021.

Implementation of national nitrogen load limits

The procedure for assessing the achievement of the NIC is described in detail in the works of Larsen and Svendsen

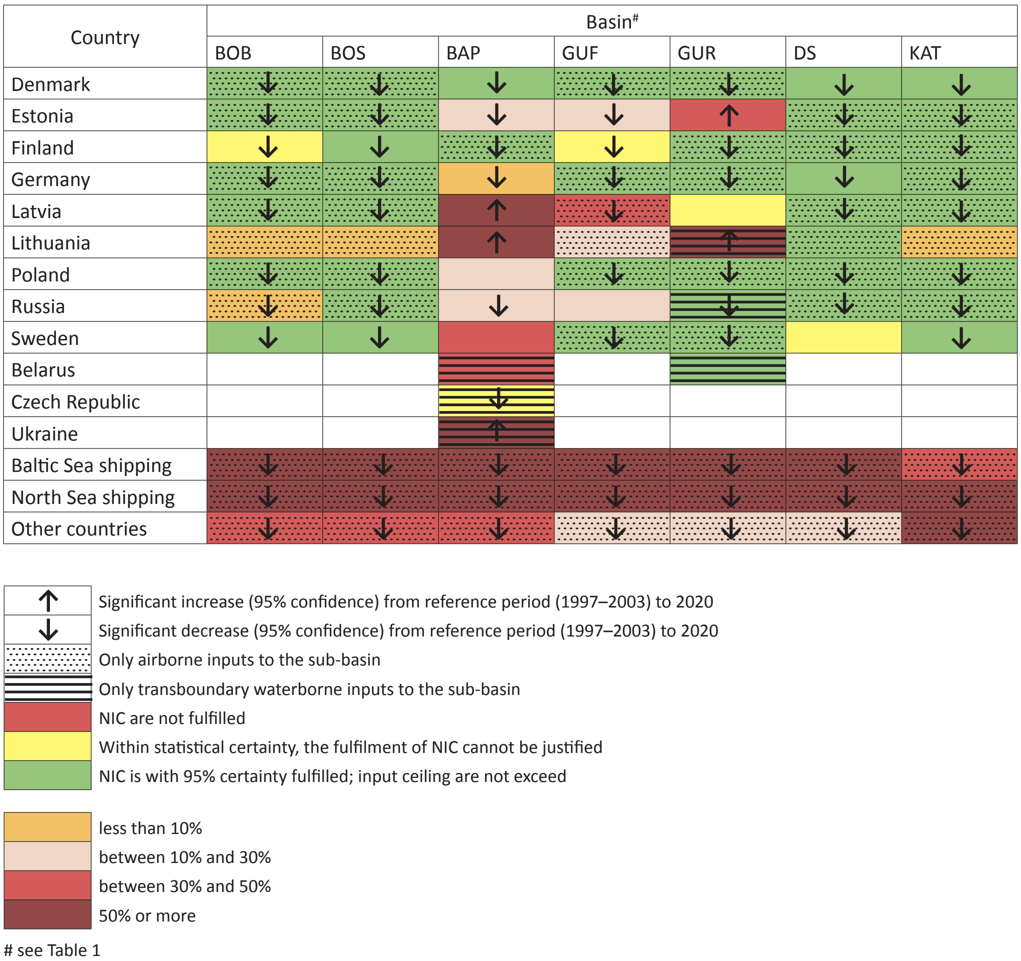

Figure 4. Overall progress results towards NIC implementation by 2020 in terms of total nitrogen (TN) input.
Source: Nutrient Input Ceiling ..., 2023.

(2021) and HELCOM Guidelines (HELCOM, 2022). The basis for determining the NIC is the MAI for the Baltic Sea basin, and the achievement of the NIC ensures the achievement of the MAI. A prerequisite for calculating the MAI was that the average nutrient input was equal to the MAI. The target eutrophication state of the sea will eventually be achieved (as an average value) in the long term. In the adopted methodology, the MAI (or NIC) is considered to be achieved only if it can be shown that the amount of nutrients is below the MAI (or NIC, depending on which indicator is being analysed).

Figure 4 provides an overview of the progress towards achieving the total nitrogen input limits by 2020 estimated for the Baltic Sea basin countries. Green indicates the achievement of the NIC, as is the case for Denmark for all seven basins. Redddish colors indicate which basins are not fulfilled by 2020, as is the case for Baltic Sea shipping and North Sea shipping, and other countries for all sub-basins and for the Baltic Sea Proper (BAP), except for Denmark and Finland. The graduated red indicates how far from the NIC (in percentage) the 2020 inputs are (see legend below Fig. 4). For some catchments it is not possible to assess whether the NIC will be realized by 2020 (marked in yellow) because although the estimated load is lower than the NIC, this is not the case when adding the uncertainty of estimated inflows, e.g. in the case of Sweden to the Danish Straits (DS).

Remaining reduction requirements to be implemented in order to meet NIC

The remaining reduction requirements mainly concern the Baltic Proper (BAP), Gulf of Finland (GUF) and Gulf of Riga (GUR). Tables 4 and 5 summarize the remaining reductions in HELCOM member states by catchment area, expressed in percentages of NIC (Table 4) and in tons (Table 5). Information on the remaining reductions in percentages and in tons is important because a remaining small percentage reduction requirement may cover the necessary reduction by many tons, while a remaining large percentage reduction requirement may cover only a few tons of the required reduction (e.g. in Germany the 4% remaining reduction of loads to BAP is about 1507 tons TN, while the 117% remaining reduction for Ukraine to BAP is 1977 tons TN).

The NIC Report (NIC, 2023) presents more detailed results of the assessment of progress towards the NIC by 2020 for total nitrogen for each country separately. In the case of Poland (Table 6), the reduction remaining to be achieved before 2020 was 30578 t, i.e. 20% of the NIC or 30245 t (20%) taking into account the additional reduction in the neighboring basin. The changes presented were

Table 4. Remaining nitrogen reduction country by basin in percentages of NIC by 2020.

Country	Baltic Sea basin#						
	BOB	BOS	BAP	GUF	GUR	DS	KAT
Denmark	-	-	-	-	-	-	-
Estonia	-	-	13	12	34	-	-
Finland	1.6	-	-	4.2	-	-	-
Germany	-	-	4.4	-	-	-	-
Latvia	-	-	105	14	3.1	-	-
Lithuania	8.8	4.5	123	22	62	-	5.5
Poland	-	-	20	-	-	-	-
Russia	3	-	11	28	-	-	-
Sweden	-	-	32	-	-	9	-
Belarus	n/a	n/a	31	n/a	n/a	n/a	n/a
Czech Republic	n/a	n/a	20	n/a	n/a	n/a	n/a
Ukraine	n/a	n/a	117	n/a	n/a	n/a	n/a
Baltic Sea shipping	77	74	66	63	86	59	43
North Sea shipping	122	105	104	108	108	76	61
Other countries	36	35	30	26	27	27	35

”-” – no remaining reduction, n/a – not applicable
abbreviations – see Table 1
Source: Nutrient Input Ceiling ..., 2023.

Table 5. Remaining nitrogen reduction country in tons by 2020.

Country	Baltic Sea basin#						
	BOB#	BOS	BAP	GUF	GUR	DS	KAT
Denmark	-	-	-	-	-	-	-
Estonia	-	-	193	1392	4473	-	-
Finland	555	-	-	858	-	-	-
Germany	-	-	1507	-	-	-	-
Latvia	-	-	6780	35	1328	-	-
Lithuania	9.5	22	31807	68	5476	-	4
Poland	-	-	30578	-	-	-	-
Russia	22	-	1120	16960	-	-	-
Sweden	-	-	9910	-	-	559	-
Belarus	n/a	n/a	4173	n/a	n/a	n/a	n/a
Czech Republic	n/a	n/a	708	n/a	n/a	n/a	n/a
Ukraine	n/a	n/a	1977	n/a	n/a	n/a	n/a
Baltic Sea shipping	218	841	3408	427	296	381	305
North Sea shipping	160	498	2522	212	162	553	543
Other countries	491	1755	8065	786	587	1316	1559

”-” – no remaining reduction, n/a – not applicable
abbreviations – see Table 1
Source: Nutrient Input Ceiling ..., 2023.

Table 6. Assessment of progress towards total nitrogen NIC by 2020 for Poland by Baltic Sea basins.

Total N (TN)	Baltic Sea basin#						
	BOB	BOS	BAP	GUF	GUR	DS	KAT
A: Input Ceiling (NIC BSAP2021) [t]	668	3125	151969	1407	1596	1480	1443
B: Estimated input 2020 [t]	556	2468	170361	1317	1248	1125	1210
C: Inputs 2020 [t] incl. uncertainty (test value)	570	2529	182547	1349	1278	1153	1240
Extra reduction by 2020 (A-C) [t]	98	596	-	58	318	327	203
Remaining reduction to fulfill NIC by 2020 [t]	-	-	30578	-	-	-	-
Remaining in % ceiling	-	-	20	-	-	-	-
Accounting for extra reduction	-	-	-333	-	-	-	-
Remaining taking into account extra reduction [t]	-	-	30245	-	-	-	-
Remaining in % ceiling taking into account extra reduction	-	-	20	-	-	-	-
Extra reduction in DS, GUF i GUR is used to reduce the remaining reduction requirements in BAP with 33 t TN							
Significant changes (%) since reference period to 2020	-25	-25	-11	-25	-25	-26	-25

”-” no remaining reduction
see Table 1
Source: Nutrient Input Ceiling ..., 2023

statistically significant, therefore the last row of the table presents further percentage changes in loads from the reference period to 2020. They ranged from -11% in the Baltic Proper (BAP) basin to -25 – -26% in the other basins.

Implementation of NIC and sources of nutrients

To facilitate monitoring of progress towards the NIC in 2020 and responses to remaining reduction requirements, in order to identify the main sources of nitrogen for each Baltic Sea basin and country, the status of the NIC implementation was compared with the results from the latest source apportionment estimate from the PLC-7 project (HELCOM by Svendsen and Tornbjerg, 2022). The NIC Report showed that all countries provided sources of airborne and waterborne TN at a rather aggregated level. Five countries, including Poland, provided more detailed sources of these loads. The remaining percentage reduction to be achieved was calculated as the remaining reduction (in tons) divided by the value of the load in 2020.

In the case of Poland, 30245 t of TN loads remain to be reduced in the Baltic Proper Basin (BAP), which is 18% of the estimated loads in 2020 (Table 7). More than half (65%), i.e. almost 111000 t of loads, are other dispersed water sources. Point sources (from sewage treatment plans, industrial plants with separate discharges and aquaculture plants) discharging loads to inland fresh waters and directly to the sea, and atmospheric sediments at sea, account for 15% each, i.e. approx. 25000 t each.

A more detailed breakdown of sources in Table 8 shows that the main loads of total nitrogen from Poland to the Baltic Sea are delivered via inland waters (indirect sources) and come from agriculture (57%), atmospheric inputs to inland surface waters (18%), forestry (14%) and municipal sewage (11%), as well as directly in the form of atmospheric sediments in the sea (15%).

Comparative analysis at the level of source data from 1995–2018 for Poland

The subject of this analysis was to determine trends in river nutrient loads discharged from the territory of Poland to the Baltic Sea, to present changes in pressures considered key in shaping anthropogenic nutrient loads, and to attempt to assess whether and to what extent the protective measures undertaken so far have affected the size of river nutrient loads. In general, the assumption of the analysis was to base it on data from the years 1995–2018, however, in many cases the available data series covered only part of this period (Development of the balance..., 2020).

Standardized loads of nutrients discharged into the Baltic Sea

The analysis was carried out on the basis of the database of standardized nitrogen loads maintained by HELCOM (Igras, Jadczyszyn, 2008). The so-called standardized loads are loads corrected to correspond approximately to the loads that would be expected in a given year with river flows corresponding to the averages for the period covered by the data series.

Such normalization is extremely helpful in data analysis because it allows to largely eliminate the influence of variable hydrometeorological conditions on the observed river loads. It should be emphasized that this influence can be very strong. First of all, the rate of transport of nutrients from the landscape, primarily through surface and intracover runoff, depends on the intensity of rainfall and river feeding. Secondly, the volume of flows in rivers has a large impact on the processes that result in the retention of nutrients in rivers, such as sedimentation, denitrification, and sediment re-suspension.

Table 7. NIC assessment results of Poland for total nitrogen (TN) from Table 6 (taking into account extra reduction in neighboring basins) combined with the results of the PLC-7 (HELCOM by Sveden and Tornbjerg, 2022) source apportionment assessment for the main sources indicated for Poland.

Baltic Sea basin[#]	TN NIC assessment[##]	Remain tons	Remain % 2020 input	TN input 2020 [t]	Main TN sources [%]			
					natural background loads	other diffuse waterborne sources	point[###] sources	atmospheric deposition on the sea
BOB	↓	0	0	556	-	-	-	100
BOS	↓	0	0	2468	-	-	-	100
BAP		30245	18	170361	4.9	65	15	15
GUF	↓	0	0	1317	-	-	-	100
GUR	↓	0	0	1248	-	-	-	100
DS	↓	0	0	1125	-	-	-	100
KAT	↓	0	0	1210	-	-	-	100

„Input 2020" is the estimated input from Table 6
see Table 1
legend see Figure 4
from wastewater treatment plants, industrial plants with separate discharges and aquaculture plants
"-" not applicable
Source: Nutrient Input Ceiling..., 2023

Table 8. Total nitrogen TN inputs to the Baltic Sea basins compared with detailed source apportionment. As in Table 7, but with a more detailed breakdown of sources.

Poland	Discharging into inland waters TN [%]									Discharging directly into the sea TN [%]			
	AGL	ATL	MFL	NBL	SCL	SWL	AQL	INL	MWL	AQL	INL	MWL	ATM
BOB[#]	-	-	-	-	-	-	-	-	-	-	-	-	-
BOS	-	-	-	-	-	-	-	-	-	-	-	-	-
BAP	57	18	14	4.9	3.6	0.88	0.79	3.0	11	0	0.001	0.38	15
GUF	-	-	-	-	-	-	-	-	-	-	-	-	-
GUR	-	-	-	-	-	-	-	-	-	-	-	-	-
DS	-	-	-	-	-	-	-	-	-	-	-	-	-
KAT	-	-	-	-	-	-	-	-	-	-	-	-	-

AGL – agricultural loads, ATL – atmospheric inputs on inland surface waters, MFL – managed forestry, NBL – natural background load, SCL – scattered dwelling load, SWL – storm water loads, AQL – aquaculture load, INL – industrial loads, MWL – municipal wastewater, ATM – atmospheric deposition on the sea
"-" not applicable
abbreviations see Table 1
Source: Nutrient Input Ceiling ..., 2023

Long-term trends at the Baltic Proper level (BAP)

The loads discharged into the Baltic Proper (BAP) are of key importance for the quality of the Polish Baltic Sea waters. Apart from Poland, nutrients are also discharged into this basin by rivers from Denmark, Germany, Estonia, Lithuania, Latvia, Russia and Sweden, and indirectly also from Belarus, the Czech Republic and Ukraine. However, loads discharged from Poland clearly predominate (Fig. 5). In 2017, Poland was responsible for 61% of nitrogen (and 61% of phosphorus) reaching the Baltic Proper directly by rivers (some small loads of river origin, mainly nitrogen, move from other regions of the Baltic Sea as a result of water mixing).

In the period 1995–2017, the river load of nitrogen discharged into the Baltic Proper showed a statistically significant ($p<0.05$) slight downward trend of about 14% (Fig. 6). It is worth emphasizing that this trend was primarily the result of changes in loads originating from Poland – the regression line indicates a statistically significant ($p<0.05$) decrease in loads by about 19%, while the trend from the other countries was statistically insignificant ($p>0.05$) and indicated a decrease by 6%.

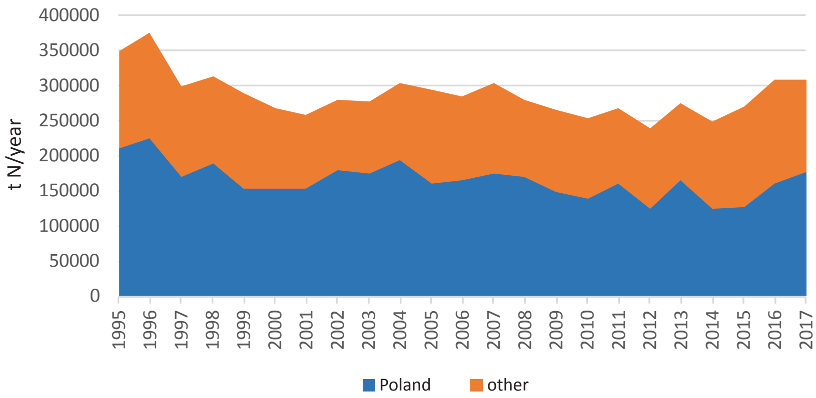

Figure 5. Cumulative, standardized annual nitrogen loads discharged into the Baltic Sea Proper (BAP) by Poland and other countries.
Source: Development of the balance..., 2020

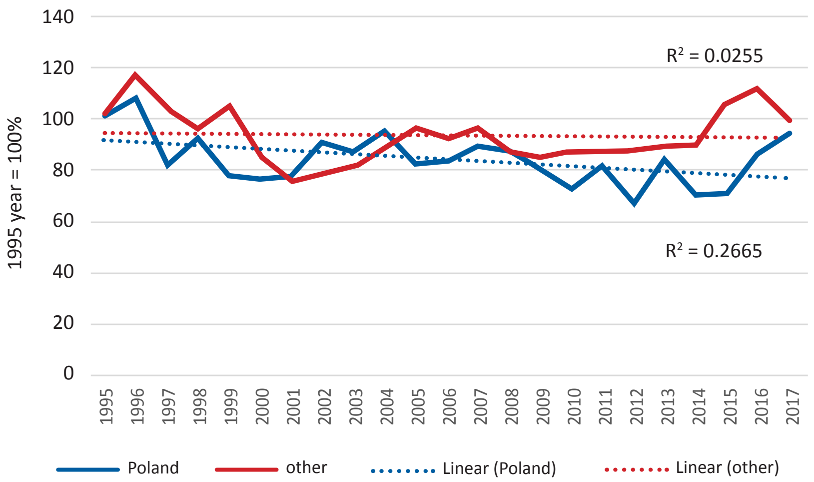

Figure 6. Relative changes in nitrogen loads discharged by Poland and other countries into the Baltic Sea Proper.
Source: Development of the balance..., 2020, modified by the author

Medium-term trends at the level of Polish rivers reported to HELCOM

In discussions on long-term changes in eutrophication pressure in Poland, there is a view that the most significant reductions in external water nutrient load were achieved at the beginning of the transformation period. It was related to the initial collapse and subsequent deep structural changes in agriculture and the impact of the first projects in sewage management. The projects were particularly economically effective because they were limited to the modernization or construction of treatment plants, which were intended to intercept raw sewage from existing sewage systems. There is also a view that in recent years, progress in reducing eutrophication pressures has slowed down significantly or even that the situation is getting worse. This unfavorable change is supposed to be caused, on the one hand, by the depletion of simple reserves in the scope of organizing sewage management, and on the other hand, by the intensification and industrialization of agriculture. To test these theses, the period 1995–2018 was divided into 3 eight-year sub-periods:

- 1995–2002 (period 1, corresponding to the times of transformation and rapid charge reduction),
- 2003–2010 (period 2, temporary),
- 2011–2018 (period 3, slow progress in reducing loads).

For each of these periods, linear regression analyses were performed for nitrogen, separately for: the Vistula, the Oder, 10 coastal rivers and 12 Polish rivers draining directly to the Baltic Sea. The results of the analyses are illustrated in Figures 7, 8 and 9. Each figure presents a bar chart with 4 bars, corresponding to the long-term trend (1995–2018) and medium-term trends of the three periods mentioned above. Green bars indicate statistically significant trends ($p < 0.05$), gray bars – statistically insignificant trends ($p > 0.05$). The height of the bar indicates the relative change in load predicted by the linear regression curve for the period under study.

In the Vistula River, the long-term trend (1995–2018) of nitrogen (Fig. 7) was significant and downward (-24%). Medium-term trends were statistically insignificant, but clearly suggesting a slowdown in reduction, and in period 3 – an upward trend.

On the Oder River, the long-term trend (1995–2018) of nitrogen (Fig. 8) was statistically insignificant and slightly decreasing (-5%). Medium-term trends were statistically insignificant, with decreasing trends in periods 1 and 2, and strongly increasing in period 3.

Data on 10 rivers of the Pomerania region were aggregated due to the relatively small loads carried by them (Fig. 9). The obtained nitrogen trends were statistically insignificant for all four periods. It should be emphasized, however, that the trends from the three medium-term periods form a coherent sequence. In the period 1, a statistically insignificant decrease was -17%, in period 2 -12%, while in period 3, a statistically insignificant, but still 3% increase was noted.

Figure 10 presents aggregated data for the Polish part of the Baltic Sea basin (excluding the Neman and Pregolya rivers). The picture emerging from them, similarly to the previous figures, is a strong argument for the thesis that the greatest reductions were achieved in the first years of transformation, and in the recent period there has been not only a slowdown in the rate of reduction, but also a reversal of trends, which, although not yet statistically significant, are clearly increasing. Thus, in the case of nitrogen, the long-term trend is a statistically significant decrease by 17%, with periods 1, 2 and 3 showing a decrease by 24%, a decrease by 15% and an increase by 22%, respectively (all statistically insignificant).

Long-term downward trends in river loads discharged by Poland in the period 1995–2018 were statistically significant. However, analysis of the same data divided into three eight-year periods indicates that the rate of nutrient reduction has been decreasing over time, and currently, in the case of nitrogen, we can speak of a trend reversal, although this is not yet a statistically significant trend. This situation is presented in Figure 10.

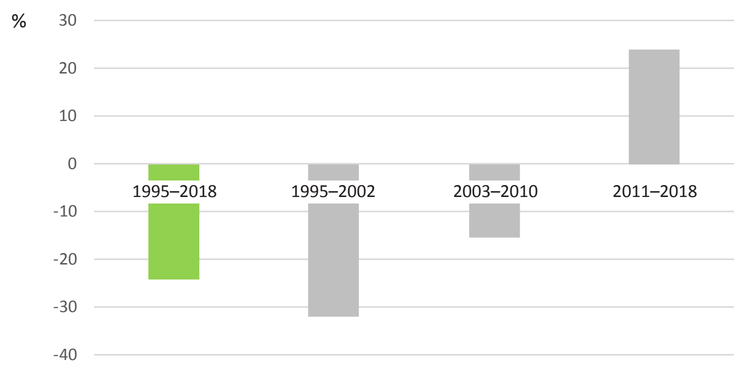

Figure 7. Medium-term trends in nitrogen loads discharged into the Baltic Sea via the Vistula River compared to the long-term trend 1995–2018.
Green color – statistically significant trend, grey color – statistically insignificant trend
Source: Development of the balance..., 2020

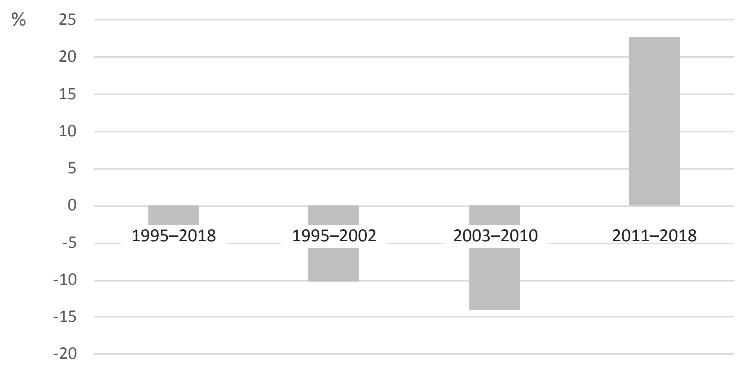

Figure 8. Medium-term trends in nitrogen loads discharged into the Baltic Sea via the Oder River compared to the long-term trend 1995–2018.
grey color – statistically insignificant trend
Source: Development of the balance..., 2020

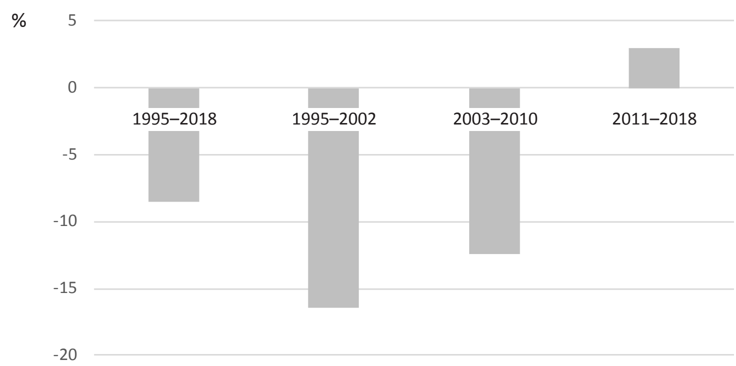

Figure 9. Medium-term trends in nitrogen loads discharged into the Baltic Sea via the coastal rivers compared to the long-term trend 1995–2018.
grey color – statistically insignificant trend
Source: Development of the balance..., 2020

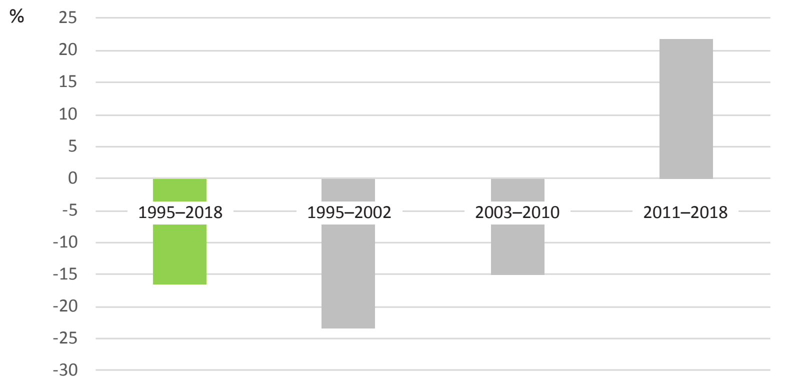

Figure 10. Medium-term trends in nitrogen loads discharged into the Baltic Sea by 12 Polish rivers compared to the long-term trend 1995–2018.
Green color – statistically significant trend, grey color – statistically insignificant trend
Source: Development of the balance..., 2020

Changes in agriculture

The absolute dominant source of nutrients reaching inland waters and the Baltic Sea is agriculture (NIC, 2023; Linderhof et al., 2021; Oppeltová et al., 2021). However, quantification of loads from agriculture is definitely difficult and burdened with certain errors. Moreover, in the context of this analysis, the difficulty is the fact that only a few agricultural activities were explicitly dedicated to the protection of waters against eutrophication (e.g. manure pads or buffer zones by streams), but even they are not monitored in a way that allows for clear linking the activities with the effects. This is not only because monitoring of area pollution is generally very difficult, but also because the vast majority of activities that can reduce the impact on waters (including the activities dedicated to water protection listed here) are at the same time, or perhaps primarily, activities aimed at optimizing agricultural management as such. Losses of fertilizers to waters are not only water pollution, but from the point of view of the agricultural producer, also losses of a valuable means of production. Therefore, in this analysis, attempts to assess the effectiveness of specific investments, programmes, regulations, etc. were abandoned. The problem was approached in general, trying to answer the question of whether, as a result of all these changes taken together, it was possible to at least partially make the growth of agricultural production independent of the negative impacts on water, and if so, whether the degree of this independence is sufficient to cause a significant decrease in the level of pollutants discharged into waters.

Agricultural production

There is no doubt that agricultural production in Poland shows a long-term upward trend (Fig. 11). In the years 2002–2018, the value of global agricultural production in Poland, expressed in constant prices, increased by 118%, and commercial production by as much as 174%, with a simultaneous increase in the share of commercial production from 63% to 79%. The concept of production value is, however, a purely economic concept. It means that changes in value do not necessarily fully translate into changes in the volume of production expressed in natural units, and it is this production that has a real effect on environmental impacts.

Figure 12 shows changes in the volume and structure of crop production in Poland, expressed in kg of crops per ha of agricultural land. It turns out that the level of this production is quite stable (on average) in its structure. First of all, there was a significant decrease in potato production, compensated about 3500 kg of main crops per ha of agricultural land, although there have been some shifts by a gradual increase in the production of industrial plants – sugar beet and rapeseed.

The situation in the animal production sector is presented in Figures 13, 14 and 15. In the period 2002–2019, the cattle population grew quite slowly but systematically (an increase of 32%), the number of poultry grew very dynamically, especially since 2012 (over 60%), while the pig population fell by 32%. In this context, it is worth recalling that in terms of the size of the „environmental footprint", taking into account not only the impact on water, but also on climate, resource consumption, etc., cattle generally fare the worst, while poultry fares the best. The total population measured in the conventional LSU unit has been almost constant since the beginning of the series (2004), with a shallow trough in the years 2012–2016 (Fig. 13).

To sum up, the above data show that neither crop production nor animal population has increased in the last dozen or so years. What has clearly changed is the scale of animal production expressed in natural units. Production of livestock for slaughter (Fig. 14) has increased by 82% since 1995, and by 73% since 2000, with this increase resulting almost entirely from the development of poultry farming, an industry that has relatively the least impact on the environment. Apart from livestock, a dynamic increase in egg production (87% since 1995) and a certain increase in milk production (22% since 1995) have also been noted (Fig. 15). The fact that such a large increase in animal production was achieved with a constant population indicates its high intensification, expressed among others by a faster rate of growth of

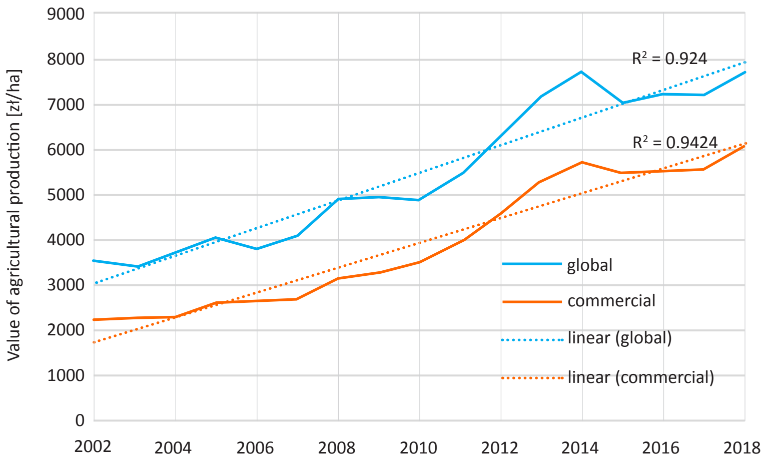

Figure 11. Value of agricultural production in Poland per ha of agricultural land (constant prices of 2001).
Source: Development of the balance..., 2020

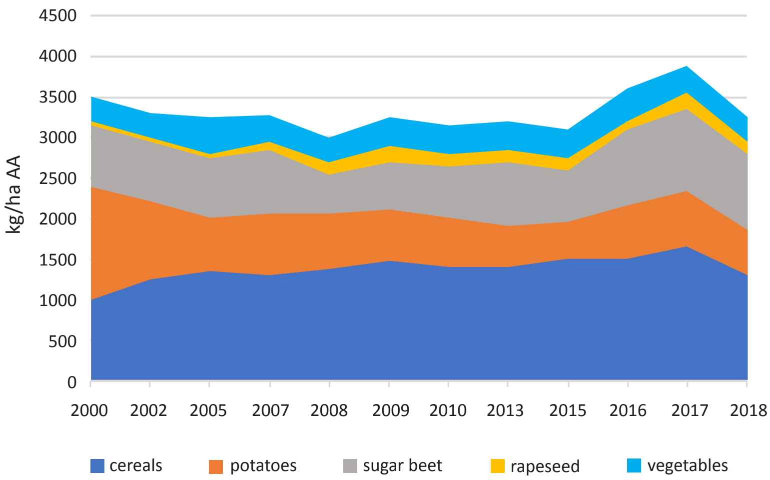

Figure 12. The volume and structure of crop production in Poland in terms of the production of the main crops
Source: Development of the balance..., 2020

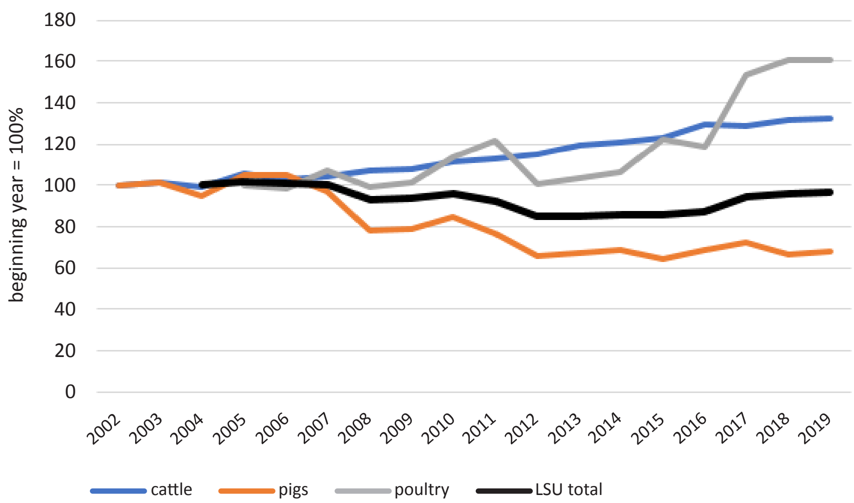

Figure 13. Relative changes in the livestock population in Poland
Source: Development of the balance..., 2020

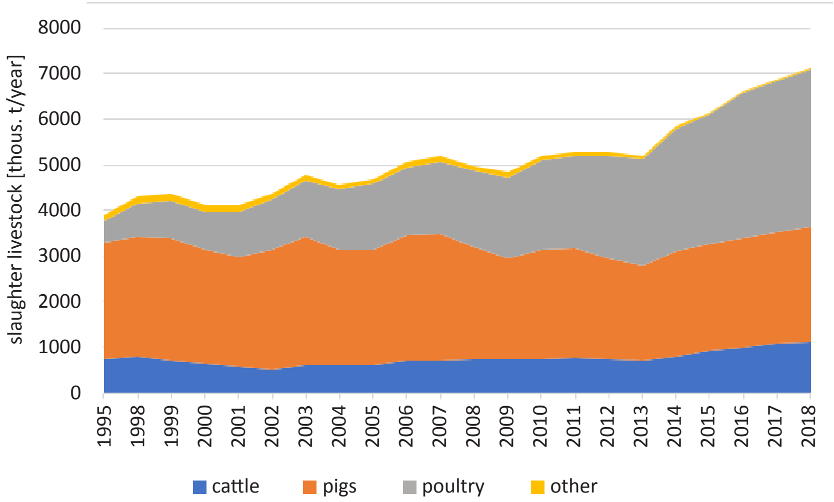

Figure 14. Production of livestock for slaughter in Poland.
Source: Development of the balance..., 2020

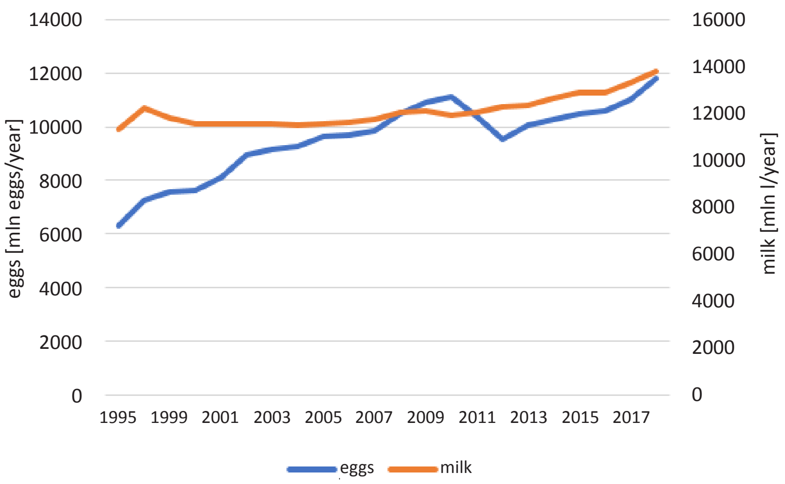

Figure 15. Egg and milk production in Poland.
Source: Development of the balance..., 2020

animals for slaughter, higher egg laying hens and higher milk yield of cows.

The data presented so far suggest that the growth in the value of agricultural production is slightly faster than the growth in production expressed in natural units and that both the one and the other growth results primarily from animal production. It should of course be remembered that for animal production to be possible, plant production for feed is necessary – it also had to be intensified.

Fertilizer economy

The basis for the intensification of agriculture is the use of mineral fertilizers. Their consumption in Poland in the years 1998–2018 is shown in Figure 16. It turns out that the trend in the consumption of nitrogen fertilizers (the period 1998–2019) is positive, and the trend line has increased by 25%. An important conclusion can be drawn from the above, namely that agricultural production expressed in monetary value, and probably also expressed in natural units, is growing significantly faster than the consumption of fertilizers. This should be considered a measure of the effectiveness of various types of good agricultural practices in reducing the impact of agriculture on the environment, including water. The second element of the fertilizer balance in agriculture is natural fertilizers. Figure 17 shows the estimate of the production of natural fertilizers in thousands t of nitrogen, based on indicators resulting from the nitrate program. About 650 thousand tons of nitrogen per year come from natural fertilizers, which is less than 40% of the total nitrogen pool contained in fertilizers (Fig. 18).

An important parameter that may indicate the risk of negative impacts on water is the nutrient balance in the field, i.e. the amount that after the annual production cycle and harvesting remains in the environment as a surplus, which accumulates in the soil, evaporates into the air or migrates into water. The results of estimating the nitrogen (and phosphorus) balance for Poland since 1990 are available in EUROSTAT resources. They are presented in Figure 19. It seems that they generally reflect the development phases of Polish agriculture well. The early 1990s saw the collapse of the wasteful economy and a sharp decline in nutrient surpluses. Then, there was a slow recovery of the surplus level, which accelerated rapidly in the first years after joining the EU. The successive declines in subsequent years are a manifestation not so much of the difficult situation of agriculture, but of the optimization of agricultural management, including the dissemination of various good agricultural practices. The recovery observed in recent years, i.e. since 2015, is worrying, and is partly synchronized with the increase in the use of mineral fertilizers.

The fact that at a given level of agricultural culture, the level of mineral fertilization largely determines the size of the balance surplus potentially dangerous to waters is confirmed by the data presented in Figure 20. They illustrate a strong and statistically significant relationship between the level of mineral fertilization and balance surpluses. It should be emphasized that it is by no means the case that mineral fertilizers are more harmful to water than natural ones. In general, it is quite the opposite, which is associated with difficulties in precise dosing of natural fertilizers, as well as their storage. However, the supply of natural fertilizers is quite stable, and mineral fertilizers can be easily purchased in „good times”, which results in total doses of natural and mineral fertilizers exceeding the needs of plants.

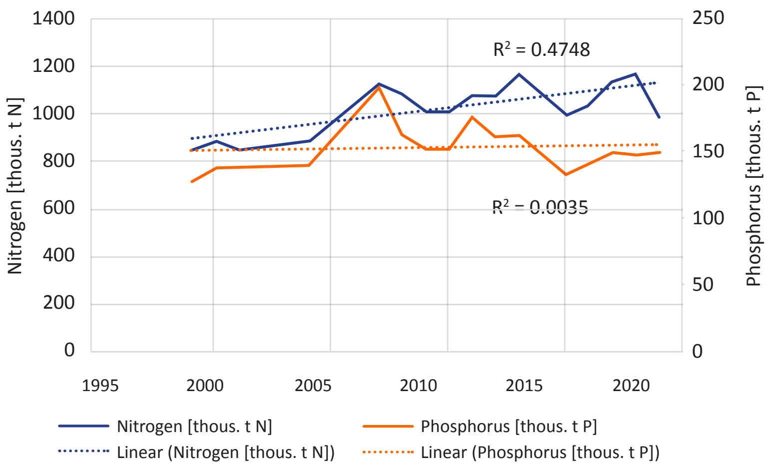

Figure 16. Consumption of mineral fertilizers in Poland.
Source: Development of the balance..., 2020

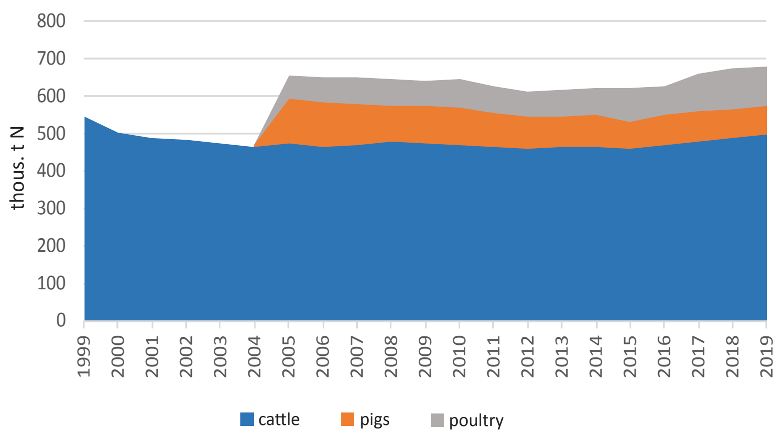

Figure 17. Nitrogen in natural fertilizers in Poland.
Source: Development of the balance..., 2020

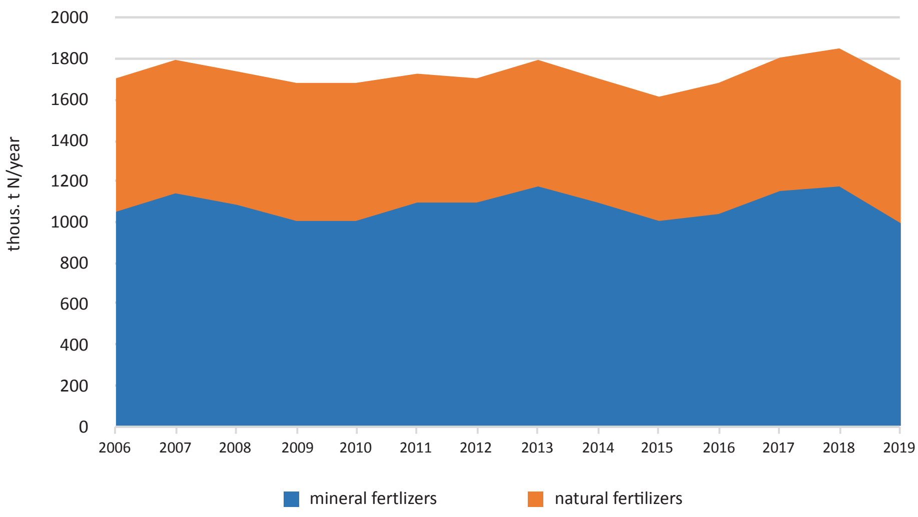

Figure 18. Total nitrogen from mineral and natural fertilizers used in Poland
Source: Development of the balance..., 2020

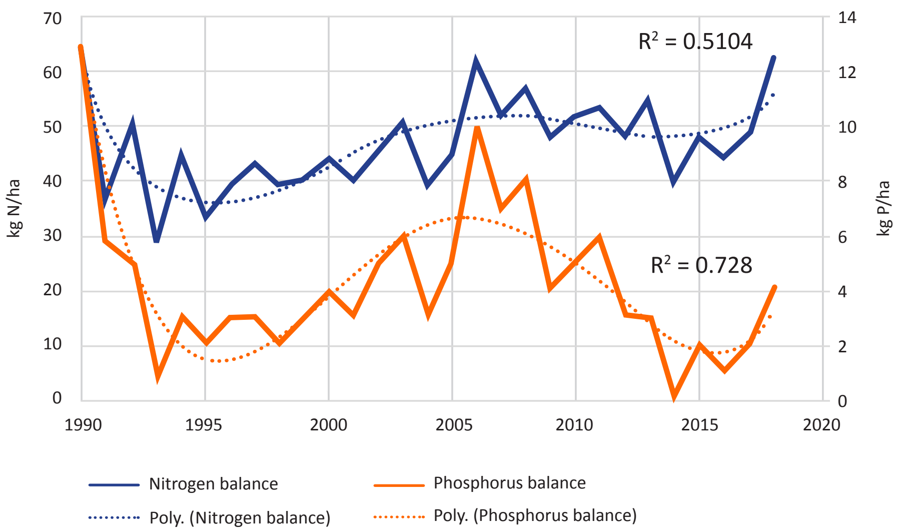

Figure 19. Gross nitrogen (and phosphorus) balance for Poland according to EUROSTAT
Source: Development of the balance..., 2020

The relationship between fertilizers and nutrient loads discharged into the Baltic Sea

As stated above, there are solid grounds for assuming that the growth in agricultural production, especially expressed in terms of money, has become independent to some extent of the growth in fertilizer consumption, i.e. that the growth in fertilizer consumption is less than directly proportional to the growth in production. Nevertheless, agriculture remains by far the dominant source of eutrophication pressure. Despite the above-mentioned beneficial phenomena, the relationship between the amount of fertilizers used and the amounts of nutrients reaching waters, at least in the case of nitrogen, remains unbroken. This is evidenced by Figure 22, which compares the total consumption of natural and mineral fertilizers in Poland with the river loads discharged into the Baltic Sea. Each increase in fertilizer consumption is accompanied by an increase in the loads reaching the sea. This also indicates the rate of movement of a significant part of the nitrogen pool.

The strong impact of fertilizers on the sea is confirmed by Figure 21, which illustrates a strong ($R^2 = 0.47$) and statistically significant ($p<0.05$) relationship between fertilizer consumption and loads reaching the Baltic Sea from Poland.

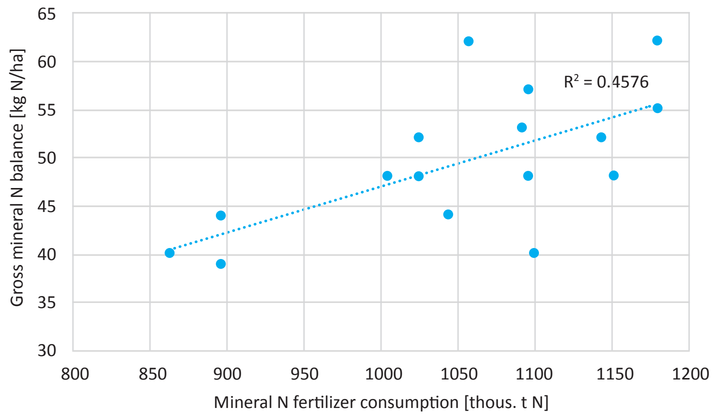

Figure 20. Dependence of the gross nitrogen balance for Poland on the consumption of mineral nitrogen fertilizers in Poland.
Source: Development of the balance..., 2020.

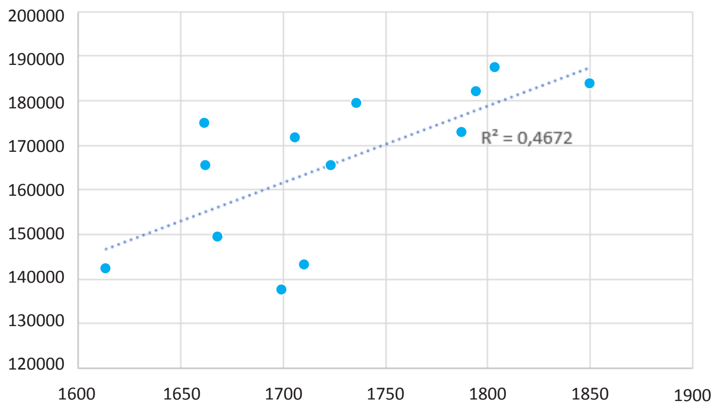

Figure 21. Nitrogen loads discharged from Poland to the Baltic Sea against the background of the total consumption of mineral and natural nitrogen fertilizers.
Source: Development of the balance..., 2020.

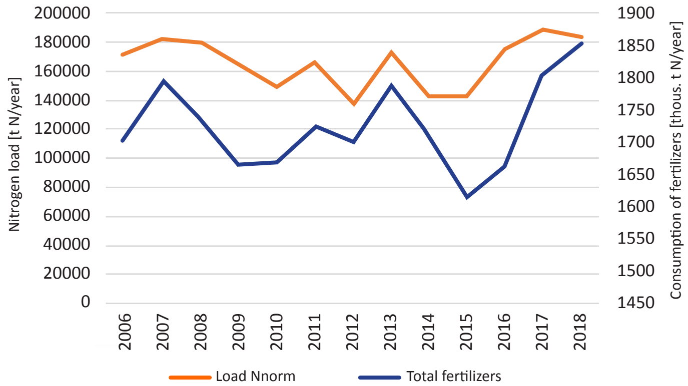

Figure 22. Dependence of nitrogen loads discharged from Poland to the Baltic Sea on the total consumption of mineral and natural nitrogen fertilizers in Poland.
Source: Development of the balance..., 2020.

SUMMARY

Analysis of the nutrient input trend over the 1995 to 2018 observation period showed a statistically significant 20 percent reduction in total nitrogen input to the entire Baltic Sea. Poland reduced the nitrogen input to all HELCOM basins from the 1997–2003 reference period by 11–26% and it has reached inflow limits in all basins, except the Baltic Proper (BAP), where the reduction remaining to be achieved before 2020 was 30578 t, i.e. 20% of the NIC or 30245 t (20%) taking into account the additional reduction in the neighboring basin. The main loads of total

nitrogen from Poland to the Baltic Sea are delivered via inland waters (indirect sources) and come from agriculture (57%), atmospheric inputs on inland surface waters (18%), forestry (14%) and municipal sewage (11%), as well as directly in the form of atmospheric sediments in the sea (15%). In 2017, Poland was responsible for 61% of nitrogen reaching the Baltic Proper directly by rivers.

In the period 1995–2017, the river load of nitrogen discharged into the Baltic Proper showed a statistically significant ($p<0.05$) slight downward trend of about 14%. This trend was primarily the result of changes in loads originating from Poland. The most significant reductions in external water nutrient load were achieved at the beginning of the transformation period. In recent years, progress in reducing eutrophication pressures has slowed down significantly or even the situation is getting worse. This unfavorable change is supposed to be caused, on the one hand, by the depletion of simple reserves in the scope of organizing sewage management, and on the other hand, by the intensification and industrialization of agriculture.

Agriculture remains by far the dominant source of eutrophication pressure. It is the absolute dominant source of nutrients reaching inland waters and the Baltic Sea. Agricultural production in Poland showed a long-term (2002–2018) upward trend. However, the growth in the value of agricultural production was slightly faster than the growth in production expressed in natural units and that both the one and the other growth results primarily from animal production. The volume of production expressed in natural units is this production that has a real effect on environmental impacts. It should of course be remembered that for animal production to be possible, plant production for feed is necessary – it also had to be intensified.

The relationship between the amount of fertilizers used and the amounts of nutrients reaching waters, at least in the case of nitrogen, remains unbroken. There was strong ($R^2 = 0.47$) and statistically significant ($p<0.05$) relationship between fertilizer consumption and loads reaching the Baltic Sea from Poland found. It was evidenced in Poland that each increase in fertilizer consumption is accompanied by an increase in the loads reaching the sea.

Due to dynamic changes in the inflow of nutrients to the Baltic Sea, actions at the European Union level, including monitoring the Baltic Sea environment and indicating sources of threat, are necessary for continuous implementation.

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